Supplementary Information

Deacylative Transformations of Ketones via Aromatization-Promoted C−C Bond Activation

Yan Xu[1], Xiaotian Qi[2], Pengfei Zheng[1,3], Carlo C. Berti[1], Peng Liu[2,]* and Guangbin Dong[1,]*

[1]*Department of Chemistry, University of Chicago, Chicago, IL 60637, USA*
[2]*Department of Chemistry, University of Pittsburgh, Pittsburgh, PA 15260, USA*
[3]*College of Pharmacy, Army Medical University, Chongqing 400038, China*

1. General consideration

Unless otherwise noted, all experiments were carried out under air atmosphere. 1,4-dioxane was distilled over Na. The 3Å and 4Å molecule sieves were pre-dried overnight at 110 °C in an oven, and then flame-dried under *vacuo* for 30 minutes. Other reagents and solvents were directly used from the supplier without further purification unless noted. Analytical thin-layer chromatography (TLC) was carried out using 0.2 mm commercial silica gel plate (silica gel 60, F254, EMD chemical). The vials (1 dram, 15×45 mm or 2 dram, 17×60 mm, with PTFE lined cap attached) were purchased from Qorpak and used directly. Infrared spectra were recorded on a Nicolet iS5 FT-IR Spectrometer using neat thin film technique. High-resolution mass spectra (HRMS) were obtained on an Agilent 6224 Tof-MS spectrometer and are reported as m/z. Accurate masses are reported for the molecular ion $[M+H]^+$ or $[M]^+$. Nuclear magnetic resonance spectra (^1H NMR and ^{13}C NMR) were recorded with a Bruker Avance 400 instrument (500 MHz, ^1H at 400 MHz, ^{13}C at 101 MHz) unless noted. For $CDCl_3$ solutions, the chemical shifts are reported as parts per million (ppm) referenced to residual protium or carbon of the solvents; $CHCl_3$ δ H (7.26 ppm) and $CDCl_3$ δ C (77.16 ppm). For C_6D_6 solutions the chemical shifts are reported as parts per million (ppm) referenced to residual protium or carbon of the solvents; C_6D_5H δ H (7.16 ppm) and C_6D_6 δ C (128.06 ppm). Coupling constants are reported in Hertz (Hz). Data for ^1H NMR spectra are reported as follows: chemical shift (ppm, referenced to protium: s = singlet, d = doublet, t = triplet, q = quartet, p = pentet (quintet), dd = doublet of doublets, td = triplet of doublets, ddd = doublet of doublet of doublets, m = multiplet, coupling constant (Hz), and integration).

2. Substrate preparation

Compounds **S1**[1], **D1**[2], **L2**[3], **13**[2], **27**[4], **36**[5], **40**[6], **51**[7], **82**[8], **87**[9], **S10**[10], **104**[11], **S11**[12], and **150**[13] were synthesized according to the previously reported literatures. Compounds **1**, **5**, **7**, **9**, **11**, **15**, **17**, **19**, **25**, **31**, **33'**, **49**, **53**, **54**, **55**, **56**, **57**, **58**, **59**, **60**, **61'**, **62**, **63**, **64**, **65**, **66**, **112**, **S12**, **S13**, **142**, **144**, and **152** were prepared according to the following procedures (Fig. S1). The others were commercially available and were used as received.

Figure S1 | Substrates synthesized for this study

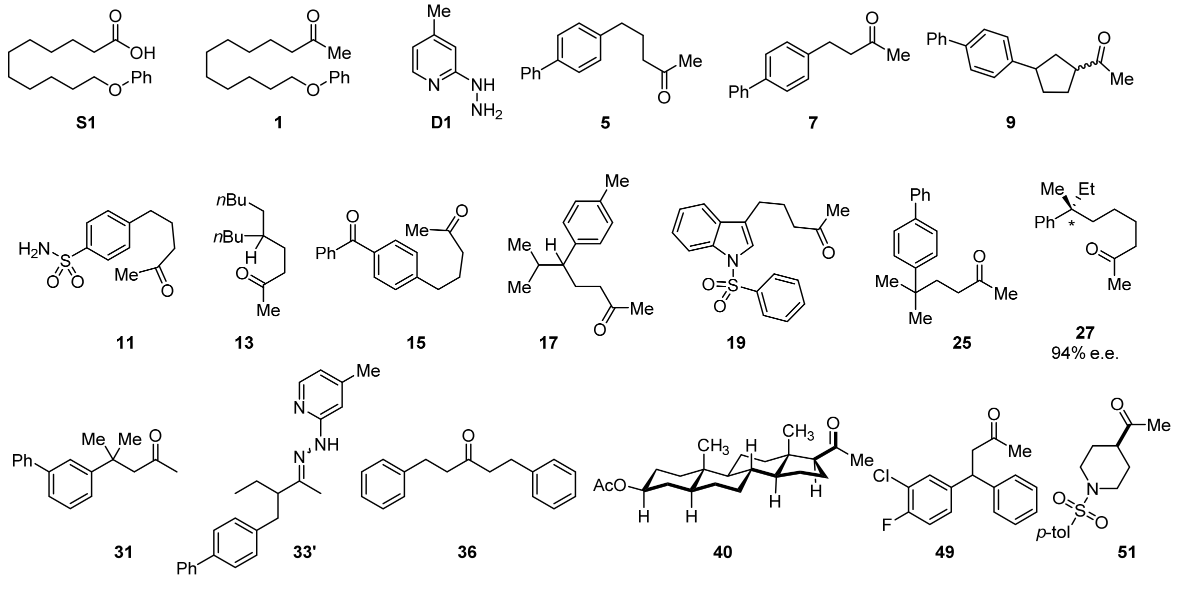
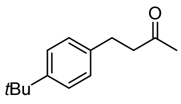
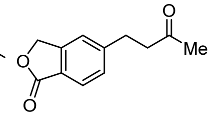
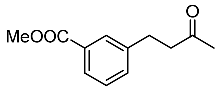
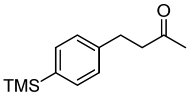


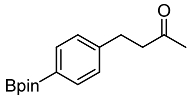
Figure S1 | Substrates synthesized for this study (continued)

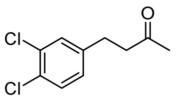

53

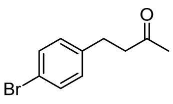

54

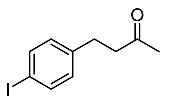

55

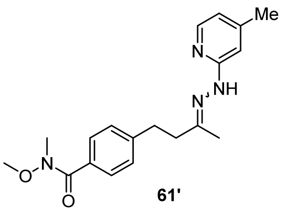

56

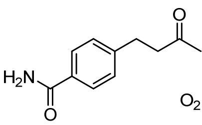

57

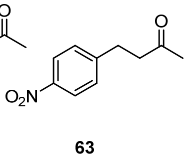

58

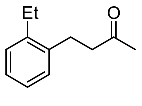

59

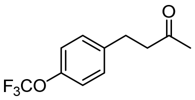

60

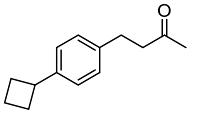

61'

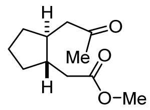

62

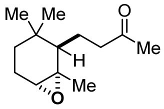

63

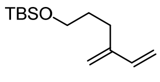

64

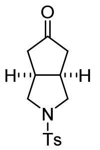

65

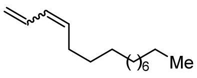

66

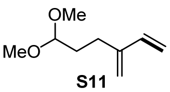

82

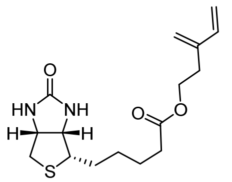

87

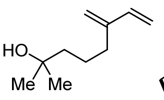

S10

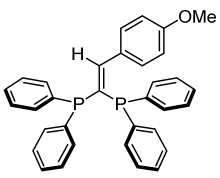

104

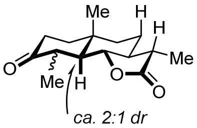

112

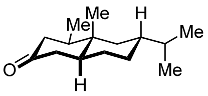

S11

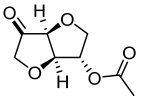

S12

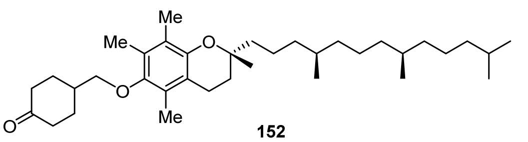

S13

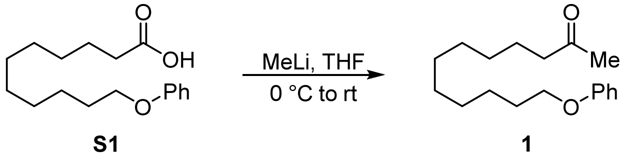

L2


ca. 2:1 dr
142


144

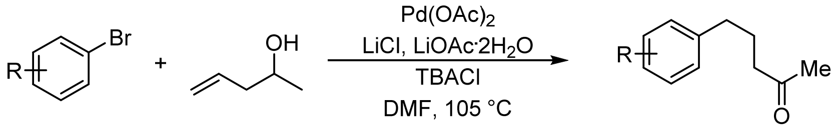

150


152

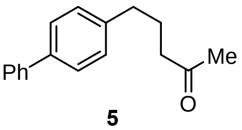

S1 **1**

S1 was prepared according to a known procedure[1]. A THF solution of MeLi (18 mmol, 1.6M, 11.25 mL, 2.5 equiv) was added to a flame-dried 50 mL round bottom flask charged with THF (15 mL). To this, a THF (15 mL) solution of **S1** (2 gram, 7.2 mmol) was added slowly at 0 °C over 5 mins. The reaction mixture was stirred at 0 °C for 3 hours, and then at room temperature for 2 hours. The reaction mixture was treated with aqueous NH_4Cl (sat.) (50 mL), extracted with DCM, and dried over $MgSO_4$. The filtrate was concentrated under *vacuo* and further purified by flash column chromatography over silica (hexane/ethyl acetate, from 100:1 to 20:1) to give product **1** as a colorless oil (900 mg, 45% yield). $R_f = 0.6$ (hexane/ethyl acetate = 10:1). ^1H NMR (400 MHz, $CDCl_3$) δ 7.30 – 7.21

(m, 2H), 7.00 – 6.80 (m, 3H), 3.95 (t, *J* = 6.5 Hz, 2H), 2.42 (t, *J* = 7.5 Hz, 2H), 2.13 (s, 3H), 1.78 (p, *J* = 6.8 Hz, 2H), 1.63 – 1.51 (m, 2H), 1.45 (p, *J* = 6.7 Hz, 2H), 1.40 – 1.19 (m, 10H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 209.48, 159.25, 129.53, 120.57, 114.62, 67.99, 43.96, 30.00, 29.64, 29.52, 29.52, 29.51, 29.43, 29.31, 26.19, 24.00. IR (KBr) 3066, 3040, 3030, 2930, 2853, 1721, 1601, 1585, 1502, 1472, 1358, 1247, 1172 cm^{-1}. HRMS: calcd. 277.2162 $[M+H]^+$ Found: 277.2168.

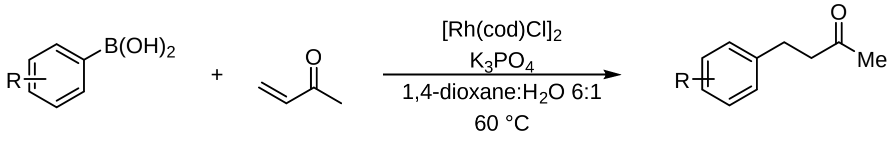


General procedure S-1 for the synthesis of 5-arylpentan-2-one through Pd-catalyzed cross-coupling reactions (*at 2 mmol scale*): Following a modified procedure from literature[14], a 20 ml vial was charged with aryl bromide starting material (2 mmol, 1.0 equiv), $Pd(OAc)_2$ (200 mg, 0.9 mmol, 0.45 equiv), TBACl (1.12 g, 4 mmol, 2.0 equiv), LiCl (80 mg, 2 mmol, 1.0 equiv), $LiOAc{\cdot}2H_2O$ (520 mg, 5 mmol, 2.5 equiv), DMF (4 mL), and pent-4-en-2-ol (260 mg, 3 mmol, 1.5 equiv). The reaction mixture was heated at 105 °C for 24-48 hours (monitored by TLC). After cooled to room temperature, the reaction mixture was poured into 100 mL brine, extracted with Et_2O (100mL × 2), and dried over Na_2SO_4. The filtrate was concentrated under *vacuo* and further purified by flash column chromatography to give the coupling products.



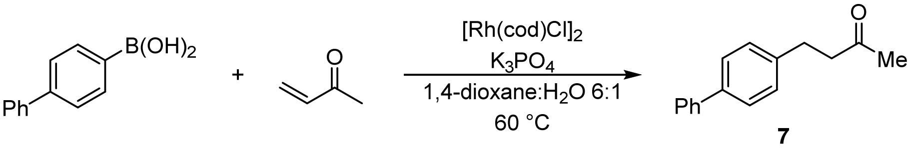
5

5: Following **General procedure S-1,** the reaction was conducted at 1.3 mmol scale. The titled compound was obtained as a white solid (155 mg, 50% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.62 – 7.55 (m, 2H), 7.52 (d, *J* = 8.1 Hz, 2H), 7.43 (t, *J* = 7.6 Hz, 2H), 7.33 (t, *J* = 7.3 Hz, 1H), 7.25 (d, *J* = 8.6 Hz, 2H), 2.67 (t, *J* = 7.6 Hz, 2H), 2.48 (t, *J* = 7.4 Hz, 2H), 2.14 (s, 3H), 1.95 (p, *J* = 7.5 Hz, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 208.87, 141.16, 140.83, 139.09, 129.03, 128.87, 127.27, 127.20, 127.13, 43.01, 34.80, 30.14, 25.32. IR (KBr) 3028, 2942, 2890, 1707, 1492, 1409, 1356, 1158, 838, 763 cm^{-1}. HRMS: calcd. 239.1430 $[M+H]^+$ Found: 239.1424.



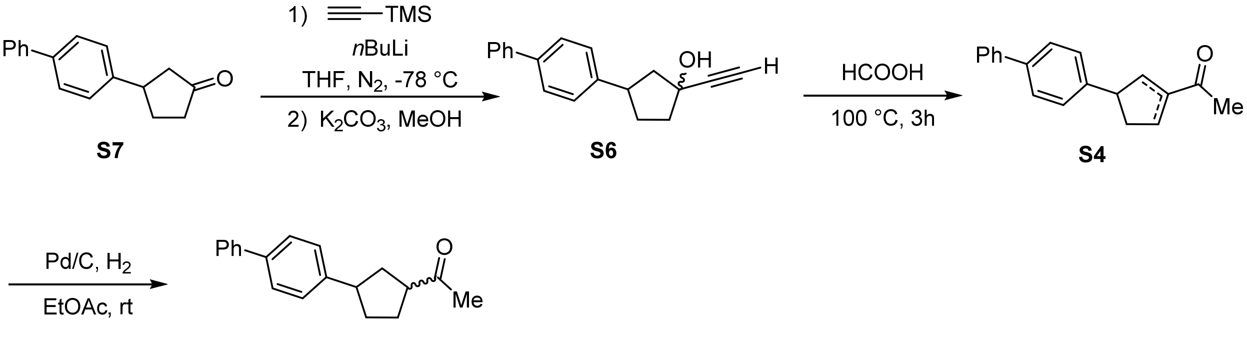
General procedure S-2 for the synthesis of 4-arylbutan-2-one through Rh-catalyzed 1,4-additions (*at 2 mmol scale*): A 8 mL vial was charged with phenylboronic acid (2.0 mmol, 1.0 equiv), $[Rh(cod)Cl]_2$ (30 mg), aqueous K_3PO_4 (3M, 0.66 mL, 2.0 mmol, 1.0 equiv), 1,4-dioxane (4 mL), and methy vinyl ketone (210 mg, 3 mmol, 1.5

equiv). The mixture was heated overnight at 60 °C. After cooled to room temperature, the reaction mixture was extracted with EA and dried over Na_2SO_4. The filtrate was concentrated under *vacuo* and further purified by flash column chromatography over silica (hexane/ethyl acetate) to give the product.



7

7: Following modified **General procedure S-2,** a 20 mL vial was charged with [1,1'-biphenyl]-4-ylboronic acid (900 mg, 4.5 mmol, 1.5 equiv), $[Rh(cod)Cl]_2$ (45 mg, 0.09 mmol, 0.03 equiv), aqueous K_3PO_4 (3M, 1.5 mL, 4.5 mmol, 1.5 equiv), 1,4-dioxane (9 mL), and methy vinyl ketone (250 mg, 3 mmol, 1.0 equiv). The mixture was heated overnight at 60 °C. After cooled to room temperature, the reaction mixture was extracted with EA and dried over Na_2SO_4. The filtrate was concentrated under *vacuo* and further purified by flash column chromatography over silica (hexane/ethyl acetate, from 50:1 to 20:1) to give product **1l** as a white solid (610 mg, 91% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.58 (d, J = 7.3 Hz, 2H), 7.53 (d, J = 8.1 Hz, 2H), 7.44 (t, J = 7.6 Hz, 2H), 7.34 (t, J = 7.8 Hz, 1H), 7.27 (d, J = 7.5 Hz, 2H), 2.95 (t, J = 7.6 Hz, 2H), 2.81 (t, J = 7.5 Hz, 2H), 2.17 (s, 3H). The spectrum matches the reported literature.[15]

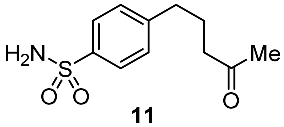


9

S7 was prepared according to a known procedure[16]. To an ethynyltrimethylsilane (882 mg, 9 mmol, 1.5 equiv) solution in THF (10 mL) was added nBuLi (2.5 M, 2.9 mL, 7.2 mmol, 1.2 equiv) dropwise at -78 °C under N_2. The mixture was further stirred at this temperature for 30 mins. A solution of **S7** (1.4 g, 6 mmol, 1.0 equiv) in THF (3 mL) was then added, and the mixture was allowed to warm to room temperature and stirred for 4 hours. The reaction mixture was quenched with aqueous NH_4Cl (sat.), extracted with DCM, and dried over Na_2SO_4. The filtrate was concentrated under *vacuo*. The residue was treated with K_2CO_3 (828 mg, 6 mmol, 1.0 equiv) and MeOH (12 mL) at room temperature overnight. The reaction mixture was filtered and concentrated under *vacuo* to yield crude product **S6** (ca. 1.3 g), which was used directly for the next step without further purification.

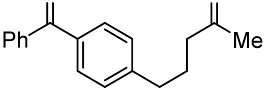
A formic acid solution (8 mL) of the crude **S6** (1.04 g) was stirred at 100 °C for 3 hours. After cooled to room temperature, the reaction mixture was diluted with brine and Et_2O (1:1) and neutralized by KOH (solid) at 0 °C. The resulting mixture was extracted with Et_2O, and dried over Na_2SO_4. The filtrate was concentrated under *vacuo* and further purified by flash column chromatography over silica (hexane/ethyl acetate, 15:1) to give compound **S4** as a pair of inseparable isomers (colorless oil, 810 mg, 78% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.61 – 7.51 (m, 5H), 7.47 – 7.41 (m, 2H), 7.36 – 7.30 (m, 2H), 6.85 – 6.79 (m, 0.65H), 6.74 (q, *J* = 2.0 Hz, 0.35H), 3.62 (p, *J* = 8.2 Hz, 0.65H), 3.09 (ddd, *J* = 17.6, 9.0, 2.9 Hz, 1.35H), 2.85 – 2.48 (m, 3H), 2.38 (d, *J* = 2.9 Hz, 3H).

The compound **S4** (800 mg) was treated with ethyl acetate (12 mL) and Pd/C (10% wt.%, 300 mg), and the resulting mixture was stirred at room temperature under H_2 atmosphere for 8 hours. The reaction mixture was filtered, concentrated in *vacuo*, and then purified by flash column chromatography over silica (hexane/ethyl acetate, 20:1) to give product **9** as a pair of diastereomers (colorless oil, 690 mg, 86% yield). R_f = 0.6 (hexane/ethyl acetate = 10:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.59 (d, *J* = 7.2 Hz, 2H), 7.54 (d, *J* = 8.2 Hz, 2H), 7.44 (t, *J* = 7.6 Hz, 2H), 7.34 (dd, *J* = 8.4, 4.9 Hz, 3H), 3.25 – 3.04 (m, 2H), 2.45 – 2.30 (m, 1H), 2.22 (s, 3H), 2.19 – 2.06 (m, 2H), 2.05 – 1.82 (m, 2H), 1.82 – 1.69 (m, 1H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 210.67, 210.51, 144.14, 143.65, 141.14, 141.12, 139.30, 139.17, 128.84, 127.61, 127.55, 127.24, 127.22, 127.19, 127.13, 52.08, 51.46, 46.17, 44.71, 37.35, 36.19, 34.81, 33.94, 29.09, 28.98, 28.88, 27.87. IR (KBr) 3058, 3034, 2951, 2870, 1709, 1488, 1449, 1360, 1180, 1008 cm^{-1}. HRMS: calcd. 265.1587 $[M+H]^+$ Found: 265.1590.



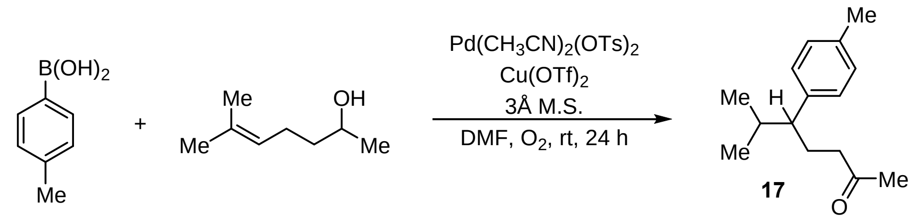
11

11: Following **General procedure S-1,** the reaction was conducted at 2 mmol scale. After purified by the flash column chromatography over silica, the crude product (290 mg) was further recrystallized from refluxed methanol to furnish **11** as a white solid (120 mg, 25% yield). M.p. = 110-112 °C (Et_2O). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.84 (d, *J* = 8.4 Hz, 2H), 7.32 (d, *J* = 8.4 Hz, 2H), 4.93 (br, 2H), 2.78 – 2.62 (m, 2H), 2.45 (t, *J* = 7.2 Hz, 2H), 2.13 (s, 3H), 1.91 (p, *J* = 7.4 Hz, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 208.42, 147.39, 139.79, 129.30, 126.77, 42.65, 34.98, 30.18, 24.88. IR (KBr) 3338, 3240, 3113, 2957, 2938, 2865, 1709, 1573, 1409, 1318, 1158 cm^{-1}. HRMS: calcd. 242.0845 $[M+H]^+$ Found: 242.0850.

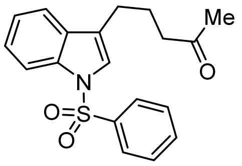


15

15: Following **General procedure S-1,** the reaction was conducted at 2 mmol scale. The titled compound was obtained as a yellow solid (280 mg, 53% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.90 – 7.73 (m, 4H), 7.61 (t, *J* = 7.9 Hz, 1H), 7.50 (t, *J* = 7.7 Hz, 2H), 7.31 (d, *J* = 7.9 Hz, 2H), 2.73 (t, *J* = 7.6 Hz, 2H), 2.50 (t, *J* = 7.2 Hz, 2H), 2.16 (s, 3H), 1.97 (p, *J* = 7.1 Hz, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 208.50, 196.56, 146.90, 137.96, 135.59, 132.37, 130.55, 130.08, 128.52, 128.37, 42.81, 35.16, 30.16, 24.96. The spectra match the reported literature.[17]

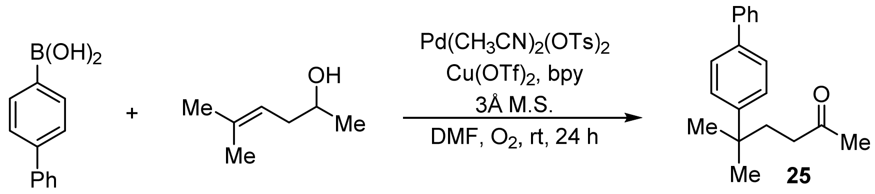


17: A suspension of $Pd(CH_3CN)_2(OTs)_2$ (15.9 mg, 0.03 mmol, 0.06 equiv), $Cu(OTf)_2$ (5.4 mg, 0.015 mmol, 0.03 equiv) and 3Å M.S. (75 mg) in DMF (8 mL) was stirred at room temperature for 10 mins. To this, a DMF (2 mL) solution of *p*-tolylboronic acid (228 mg, 1.5 mmol, 3.0 equiv) and 6-methylhept-5-en-2-ol (64 mg, 0.5 mmol, 1.0 equiv) was added through syringe, and the resulting mixture was stirred at room temperature for 24 hours. The reaction mixture was then filtered through Celite, concentrated under *vacuo,* and further purified by flash column chromatography over silica (hexane/ethyl acetate, from 40:1 to 20:1) to give product **17** as a colorless oil (43 mg, 39% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.09 (d, *J* = 7.7 Hz, 2H), 6.97 (d, *J* = 7.7 Hz, 2H), 2.32 (s, 3H), 2.23 – 2.05 (m, 4H), 2.00 (s, 3H), 1.88 – 1.69 (m, 2H), 0.95 (d, *J* = 6.6 Hz, 3H), 0.71 (d, *J* = 6.7 Hz, 3H). The spectrum matches the reported literature.[18]

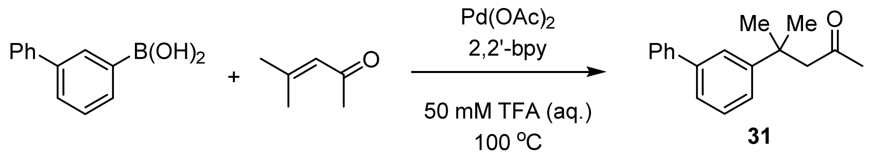


19

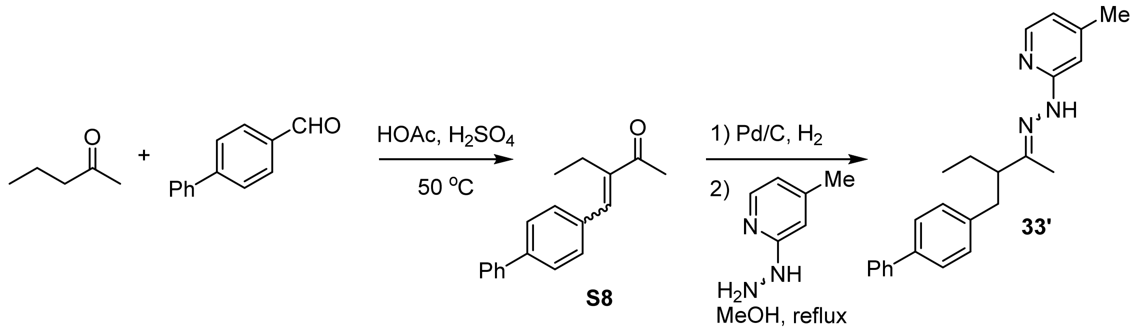
19: Following **General procedure S-1,** the reaction was at 2 mmol scale. The titled compound was obtained as a yellow solid (300 mg, 44% yield). M.p. = 110-112 °C (Et_2O). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.99 (d, *J* = 8.2 Hz, 1H), 7.86 (d, *J* = 7.9 Hz, 2H), 7.55 – 7.46 (m, 2H), 7.46 – 7.37 (m, 2H), 7.38 – 7.28 (m, 2H), 7.23 (t, *J* = 7.5 Hz, 1H), 2.67 (t, *J* = 7.6 Hz, 2H), 2.47 (t, *J* = 7.2 Hz, 2H), 2.12 (s, 3H), 1.95 (p, *J* = 7.4 Hz, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 208.48, 138.37, 135.52, 133.79, 131.03, 129.31, 126.80, 124.91, 123.28, 122.87, 122.85, 119.68, 113.88, 42.92, 30.15, 24.27, 22.93. IR (KBr) 3408, 3109, 3066, 2942, 2861, 1713, 1611, 1447, 1368, 1178, 1119 cm^{-1}. HRMS: calcd. 342.1158 $[M+H]^+$ Found: 342.1158.



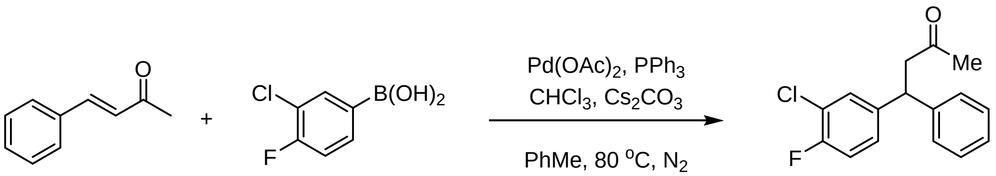
25: Following a modified procedure of literature,[4] a suspension of $Pd(CH_3CN)_2(OTs)_2$ (32 mg, 0.06 mmol, 0.06 equiv), $Cu(OTf)_2$ (10.8 mg, 0.03 mmol, 0.03 equiv), 2,2'-bipyridine (14 mg, 0.09 mmol, 0.09 equiv) and 3Å M.S. (150 mg) in DMF (16 mL) was stirred at room temperature for 10 mins. To this, a DMF (4 mL) solution of 4-biphenylylboronic acid (600 mg, 3 mmol, 3.0 equiv) and 5-methylhex-4-en-2-ol (114 mg, 1.0 mmol, 1.0 equiv) was added through syringe, and the resulting mixture was stirred at room temperature for 24 hours. The reaction mixture was then filtered through Celite, concentrated under *vacuo,* and further purified by flash column chromatography over silica (hexane/ethyl acetate, from 40:1 to 20:1) to give product **25** as a colorless oil (175 mg, 66% yield). ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.65 – 7.58 (m, 2H), 7.56 (d, *J* = 8.5 Hz, 2H), 7.44 (t, *J* = 7.6 Hz, 2H), 7.39 (d, *J* = 8.5 Hz, 2H), 7.37 – 7.30 (m, 1H), 2.26 – 2.19 (m, 2H), 2.05 (s, 3H), 2.01 – 1.92 (m, 2H), 1.36 (s, 6H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 209.17, 147.54, 140.95, 138.68, 128.87, 127.24, 127.09, 127.05, 126.37, 39.78, 37.68, 37.17, 30.09, 29.09. IR (KBr) 3030, 2966, 2876, 1721, 1488, 1367, 1164 cm^{-1}. HRMS: calcd. 267.1743 [M+H]$^+$ Found: 267.1741.



31: To a 20 mL vial was added Pd(OAc)$_2$ (0.15 mmol, 24 mg), 2,2'-bpy (0.18 mmol, 28 mg) and aqueous TFA solution (50 mM, 1.5 mL). The vial was capped, and stirred at 100 °C for 10 minutes. After cooled to room temperature, the vial was further charged with the aryl boronic acid (4 mmol, 0.8 g) and 4-methylpent-3-en-2-one (3 mmol, 294 mg). The vial was further stirred at 100 °C for additional 15 hours. The reaction mixture was then extracted with ethyl acetate, dried over Na$_2$SO$_4$, and concentrated under *vacuo*. The residue was further purified by column chromatography over silica gel to give the titled compound as a yellowish oil (660 mg, 87% yield). R$_f$ = 0.6 (hexane/ethyl acetate = 5:1). ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.64 – 7.54 (m, 3H), 7.52 – 7.33 (m, 6H), 2.81 (s, 2H), 1.86 (s, 3H), 1.50 (s, 6H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 208.07, 148.84, 141.70, 141.37, 128.86, 128.81, 127.40, 127.37, 125.09, 124.71, 124.63, 57.08, 37.59, 32.02, 29.11. IR (KBr) 3064, 3033, 3033, 1718, 1606, 1482, 1415, 1364, 1162, 917 cm^{-1}. HRMS: calcd. [M+H]$^+$ 253.1587 Found: 253.1581.

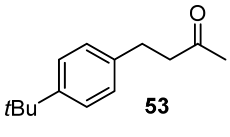


33': Following a modified literature procedure[19], acetic acid (7.2 mL), 2-pentanone (860 mg, 10 mmol), and biphenyl-4-carboxaldehyde (910 mg, 5 mmol) were added to a 25 mL round-bottom flask equipped with a reflux condenser under nitrogen atmosphere. Subsequently, sulfuric acid (740 mg) was added slowly, and the resulting mixture was stirred at 50°C for 24 hours. After the addition of 20 mL of water, the mixture was neutralized with NaOH (25% in water) and extracted with ethyl acetate. The organic phase was washed with aqueous NaHCO$_3$ and then saturated NaCl solution, and dried over anhydrous MgSO4. After filtration, the solvent was evaporated under *vacuo*, and the residue was purified by flash column chromatography to give the crude **S8** as a colorless oil (350 mg, 27% yield). An ethyl acetate solution of the crude **S8** (350 mg, 1.37 mmol) and Pd/C (5 wt.%, 100 mg) was stirred under hydrogen atmosphere for 6 hours. The reaction mixture was filtered through a short plug of Celite, and concentrated under *vacuo*. The residue was added into a MeOH (6 mL) solution of 2-hydrazineyl-4-methylpyridine (175 mg, 1.42 mmol), and then stirred under reflux overnight. The reaction mixture was concentrated in *vacuo*, and purified through column chromatography over silica gel to give the compound **33'** as a yellowish oil (445 mg, 91% yield). R_f = 0.2 (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.95 (d, *J* = 5.1 Hz, 1H), 7.64 (s, 1H), 7.60 – 7.54 (m, 2H), 7.53 – 7.47 (m, 2H), 7.41 (dd, *J* = 8.3, 6.8 Hz, 2H), 7.36 – 7.29 (m, 1H), 7.24 (d, *J* = 1.9 Hz, 1H), 7.04 – 6.97 (m, 1H), 6.60 – 6.50 (m, 1H), 2.93 (dd, *J* = 13.7, 7.7 Hz, 1H), 2.79 (dd, *J* = 13.7, 7.3 Hz, 1H), 2.64 (p, *J* = 7.3 Hz, 1H), 2.29 (s, 3H), 1.80 (s, 3H), 1.65 – 1.50 (m, 2H), 0.89 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 157.73, 149.65, 149.36, 147.29, 141.14, 139.84, 138.89, 129.61, 128.82, 127.13, 127.09, 127.05, 116.90, 107.84, 51.30, 38.93, 25.28, 21.54, 13.23, 11.92. IR (KBr) 3182, 3030, 2971, 2929, 1614, 1566, 1443, 1133 cm^{-1}. HRMS: calcd. $[M+H]^+$ 358.2278 Found: 358.2287.



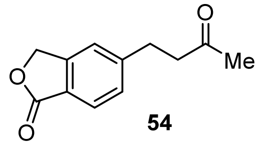
49

49: A toluene solution of 4-phenyl-3-buten-2-one (290 mg, 2 mmol), (3-chloro-4-fluorophenyl)boronic acid (700 mg, 4 mmol), $Pd(OAc)_2$ (22.4 mg, 0.1 mmol), PPh_3 (52 mg, 0.2 mmol), and $CHCl_3$ (20 μL) was heated at 80 °C under nitrogen atmosphere for 24 hours. After cooled to room temperature, the reaction mixture was filtered through a short plug of Celite, concentrated under *vacuo*, and further purified by column chromatography over silica gel to give the titled compound as a colorless oil (275 mg, 50% yield). R_f = 0.4 (hexane/ethyl acetate = 5:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.34 – 7.27 (m, 2H), 7.26 – 7.15 (m, 4H), 7.12 – 7.00 (m, 2H), 4.56 (t, *J* = 7.5 Hz, 1H), 3.15 (dd, *J* = 7.5, 1.6 Hz, 2H), 2.11 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 206.21, 156.85 (d, *J* = 247.7 Hz), 143.09, 141.17 (d, *J* = 3.8 Hz), 129.87, 128.95, 127.70, 127.57 (d, *J* = 7.3 Hz), 126.98, 121.03 (d, *J* = 17.7 Hz), 116.70 (d, *J* = 20.9 Hz), 49.56, 45.00, 30.82. IR (KBr) 3095, 3033, 3005, 1718, 1502, 1415, 1367, 1252, 1164, 1063 cm^{-1}. LRMS: 276 (M^+, 46), 233 (23), 219 (100), 183 (90), 155 (20).



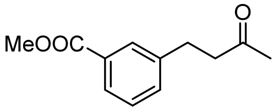
53

53: The titled compound was synthesized following **General procedure S-2** at 2 mmol scale. Colorless oil (300 mg, 75% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.31 (d, *J* = 8.3 Hz, 2H), 7.12 (d, *J* = 8.3 Hz, 2H), 2.96 – 2.81 (m, 2H), 2.76 (dd, *J* = 8.1, 6.3 Hz, 2H), 2.15 (s, 3H), 1.31 (s, 9H). The spectrum matches the reported literature.[20a]



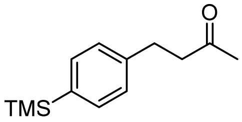
54

54: The titled compound was synthesized following **General procedure S-2** at 2 mmol scale. Colorless oil (230 mg, 56% yield). ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.77 (dd, *J* = 7.9, 2.7 Hz, 1H), 7.46 – 7.29 (m, 2H), 5.24 (s, 2H), 2.99 (t, *J* = 7.3 Hz, 2H), 2.81 (t, *J* = 7.3 Hz, 2H), 2.13 (s, 3H). ^{13}C NMR (126 MHz, CDCl$_3$) δ 206.99, 171.04, 148.47, 147.26, 129.60, 125.77, 123.83, 122.10, 69.53, 44.51, 30.13, 29.82. IR (KBr) 2938, 2873, 1771, 1701, 1625, 1353, 1282, 1046 cm^{-1}. HRMS: calcd. [M+H]$^+$ 205.0859 Found: 205.0866.



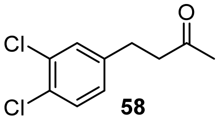
55

55: The titled compound was synthesized following **General procedure S-2** at 2 mmol scale. Colorless oil (320 mg, 78% yield). ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.90 – 7.83 (m, 2H), 7.41 – 7.30 (m, 2H), 3.91 (s, 3H), 2.94 (t, *J* = 7.5 Hz, 2H), 2.79 (t, *J* = 7.5 Hz, 2H), 2.15 (s, 3H). The spectrum matches the reported literature.[20b]



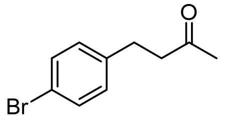
56

56: The titled compound was synthesized following **General procedure S-2** at 2 mmol scale. Colorless oil (300 mg, 68% yield). R_f = 0.5 (hexane/ethyl acetate = 5:1). ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.45 (d, *J* = 7.9 Hz, 2H), 7.20 – 7.15 (m, 2H), 2.89 (dd, *J* = 8.2, 6.6 Hz, 2H), 2.85 – 2.64 (m, 2H), 2.15 (s, 3H), 0.25 (s, 9H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 208.04, 141.72, 137.98, 133.70, 127.88, 45.18, 30.18, 29.78, -0.96. IR (KBr) 3067, 2960, 2898, 1712, 1606, 1361, 1249, 1111 cm^{-1}. HRMS: calcd. [M+H]$^+$ 221.1356 Found: 221.1355.



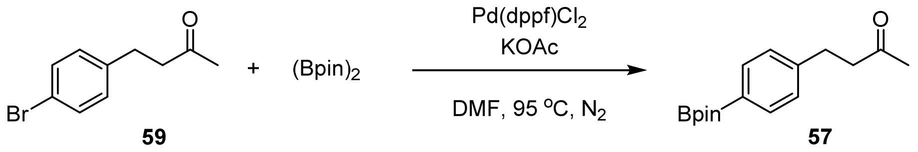
58

58: The titled compound was synthesized following **General procedure S-2** at 2 mmol scale. Colorless oil (300 mg, 69% yield). ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.33 (d, *J* = 8.2 Hz, 1H), 7.27 (d, *J* = 2.1 Hz, 1H), 7.05 – 6.99 (m, 1H), 2.84 (td, *J* = 7.1, 1.0 Hz, 2H), 2.79 – 2.67 (m, 2H), 2.14 (s, 3H). The spectrum matches the reported literature.[21]

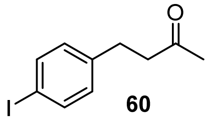


59

59: The titled compound was synthesized following **General procedure S-2** at 2 mmol scale. Colorless oil (400 mg, 88% yield). ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.43 – 7.34 (m, 2H), 7.11 – 6.99 (m, 2H), 2.84 (t, *J* = 7.4 Hz, 2H), 2.78 – 2.69 (m, 2H), 2.17 – 2.04 (m, 3H). The spectrum matches the reported literature.[22]

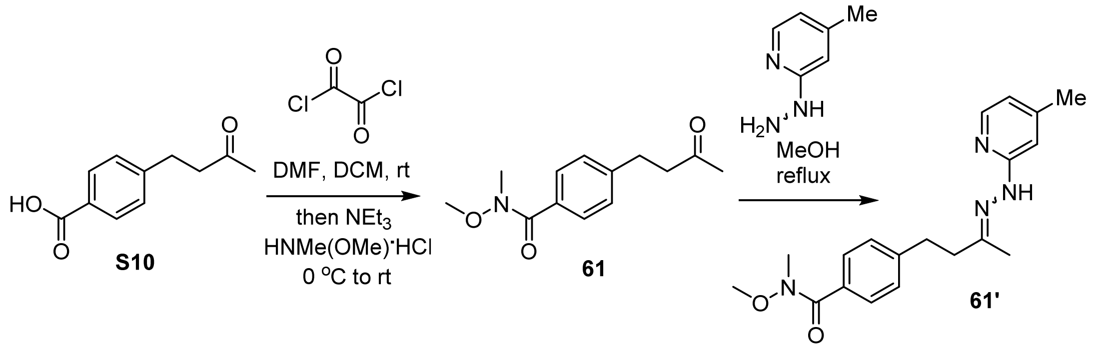


57: To a 20 mL vial was added Pd(dppf)Cl$_2$ (25 mg, 0.03 mmol), KOAc (300 mg, 3 mmol), **59** (227 mg, 1 mmol) and DMF (6 mL) under nitrogen atmosphere. The vial was sealed and heated at 95 ^{o}C overnight. After cooled to room temperature, the reaction mixture was concentrated under *vacuo*, and further purified by column chromatography over silica gel to give the titled compound as a colorless oil (230 mg, 84% yield). R$_f$ = 0.2 (hexane/ethyl acetate = 5:1). ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.73 (d, *J* = 8.0 Hz, 2H), 7.22 – 7.14 (m, 2H), 2.90 (t, *J* = 7.7 Hz, 2H), 2.82 – 2.68 (m, 2H), 2.13 (s, 3H), 1.33 (s, 12H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 207.99, 144.58, 135.24, 127.95, 83.90, 45.16, 30.31, 30.12, 25.06. IR (KBr) 2977, 2932, 1721, 1611, 1400, 1367, 1322, 1145, 1091 cm^{-1}. HRMS: calcd. [M+H]$^{+}$ 275.1813 Found: 275.1821.

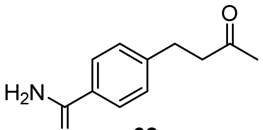


60

60: The titled compound was synthesized following **General procedure S-2** at 2 mmol scale. Colorless oil (310 mg, 57% yield). ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.59 (d, *J* = 8.3 Hz, 2H), 6.94 (d, *J* = 8.4 Hz, 2H), 5.30 (s, 0H), 2.89 – 2.77 (m, 2H), 2.77 – 2.67 (m, 2H), 2.13 (s, 3H). The spectrum matches the reported literature.[23]

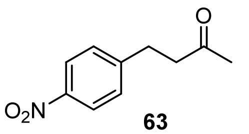


S10 was synthesized following **General procedure S-2.** To a DCM (6 mL) solution of **S10** (380 mg, 2 mmol) and DMF (one drop) was added oxalyl chloride (380 mg, 3 mmol) slowly over 5 minutes at room temperature. The reaction was stirred at room temperature for additional two hours, and then charged with a DCM solution (3 mL) of NEt_3 (1.01 g, 10 mmol) and *N,O*-dimethylhydroxylamine hydrochloride (300 mg, 3 mmol). The reaction mixture was stirred overnight, and then concentrated under *vacuo*. The residue was further purified through column chromatography over silica gel to give the crude amide product **61** as a yellowish oil ($R_f = 0.45$ in hexane/acetone = 1:1). The crude **61** was then added into a MeOH (6 mL) solution of 2-hydrazineyl-4-methylpyridine (246 mg, 2 mmol), and stirred under reflux overnight. The reaction mixture was concentrated in *vacuo*, and further purified through column chromatography over silica gel to give the compound **61'** as a yellowish oil (550 mg, 81% yield). $R_f = 0.2$ (hexane/acetone = 2:3). ^1H NMR (400 MHz, $CDCl_3$) δ 7.94 (d, *J* = 5.1 Hz, 1H), 7.70 (s, 1H), 7.66 – 7.46 (m, 2H), 7.30 – 7.24 (m, 2H), 7.13 – 6.96 (m, 1H), 6.56 (ddd, *J* = 5.2, 1.6, 0.7 Hz, 1H), 3.53 (s, 3H), 3.34 (s, 3H), 2.97 (dd, *J* = 9.4, 6.6 Hz, 2H), 2.64 (dd, *J* = 9.2, 6.8 Hz, 2H), 2.30 (s, 3H), 1.88 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 169.99, 157.57, 149.49, 147.30, 146.76, 144.75, 131.80, 128.59, 128.16, 117.01, 107.65, 61.10, 40.31, 33.99, 32.80, 21.53, 15.26. IR (KBr) 2932, 1642, 1611, 1569, 1443, 1375, 1167, 1094 cm^{-1}. HRMS: calcd. $[M+H]^+$ 341.1972 Found: 341.1983.



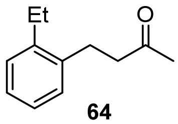
62

62: The titled compound was synthesized following **General procedure S-2** at 2 mmol scale. Colorless oil (200 mg, 51% yield). ^1H NMR (400 MHz, acetone-d_6) δ 7.84 (d, *J* = 8.3 Hz, 2H), 7.37 (br, 1H), 7.33 – 7.26 (m, 2H), 6.55 (br, 1H), 2.91 – 2.86 (m, 2H), 2.83 – 2.80 (m, 2H), 2.10 (s, 3H). The spectrum matches the reported literature.[24]



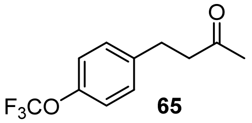
63

63: The titled compound was synthesized following **General procedure S-2** at 2 mmol scale. Colorless oil (285 mg, 74% yield). ^1H NMR (400 MHz, $CDCl_3$) δ 8.14 (d, *J* = 8.7 Hz, 2H), 7.39 – 7.30 (m, 2H), 3.00 (t, *J* = 7.3 Hz, 2H), 2.81 (t, J = 7.3 Hz, 2H), 2.16 (s, 3H). The spectrum matches the reported literature.[25]



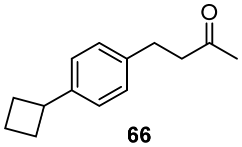
64

64: The titled compound was synthesized following **General procedure S-2** at 2 mmol scale. Colorless oil (300 mg, 85% yield). R_f = 0.5 (hexane/ethyl acetate = 5:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.21 – 7.09 (m, 4H), 2.96 – 2.86 (m, 2H), 2.78 – 2.69 (m, 2H), 2.65 (q, J = 7.5 Hz, 2H), 2.17 (s, 3H), 1.23 (t, J = 7.5 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 208.20, 142.00, 138.54, 128.93, 128.66, 126.60, 126.15, 44.94, 30.19, 26.46, 25.66, 15.46. IR (KBr) 3019, 2971, 2935, 2873, 1718, 1493, 1457, 1367, 1162 cm^{-1}. HRMS: calcd. $[M+H]^+$ 177.1274 Found: 177.1272.



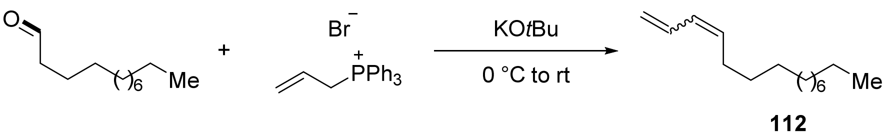
65

65: The titled compound was synthesized following **General procedure S-2** at 2 mmol scale. Colorless oil (350 mg, 75% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.20 (d, J = 8.8 Hz, 2H), 7.12 (dd, J = 8.8, 1.0 Hz, 2H), 2.95 – 2.84 (m, 2H), 2.84 – 2.70 (m, 2H), 2.15 (s, 3H). The spectrum matches the reported literature.[26]



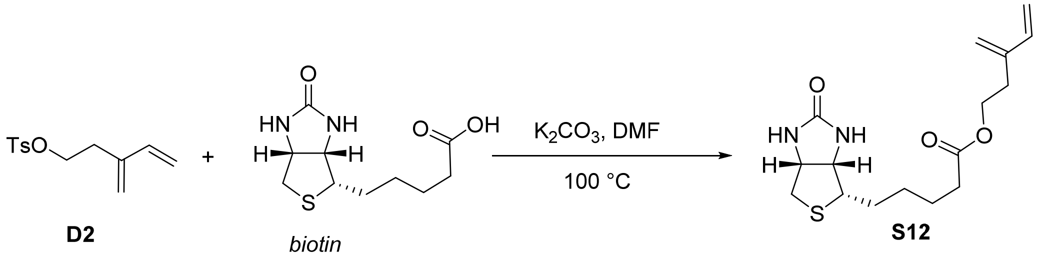
66

66: The titled compound was synthesized following **General procedure S-2** at 1 mmol scale. Colorless oil (170 mg, 84% yield). R_f = 0.5 (hexane/ethyl acetate = 5:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.12 – 7.00 (m, 4H), 3.43 (p, J = 8.7 Hz, 1H), 2.84 – 2.75 (m, 2H), 2.75 – 2.62 (m, 2H), 2.25 (qt, J = 7.8, 2.4 Hz, 2H), 2.15 – 1.98 (m, 5H), 1.96 – 1.84 (m, 1H), 1.83 – 1.70 (m, 1H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 208.24, 144.21, 138.36, 128.22, 126.57, 45.44, 40.15, 30.21, 29.97, 29.47, 18.38. IR (KBr) 2966, 2938, 2862, 1718, 1519, 1412, 1361, 1162 cm^{-1}. HRMS: calcd. $[M+H]^+$ 203.1431Found: 203.1432.

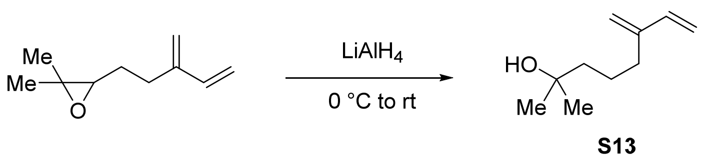


112

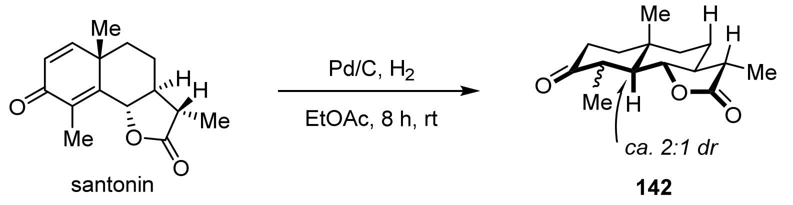
112: To a flame dried 250 mL round bottom flask, anhydrous THF (50 mL), allyl triphenylphosphonium bromide (3.52 g, 9.2 mmol, 1.6 equiv) and potassium *tert*-butoxide (1.03 g, 9.2 mmol, 1.6 equiv) were added and cooled to 0 °C. Dodecanal (1.06 g, 5.75 mmol, 1 equiv) was added dropwise, and the reaction was stirred for 16 hours while warming to room temperature. The reaction mixture was diluted with hexane and filtered. The filtrate was concentrated *in vacuo* and purified by flash column chromatography over silica (hexane/ethyl acetate, 40:1) to give **112** as a colorless oil (1.01 g, 83% yield, ca 1:1.2 *Z*/*E*). $R_f = 0.8$ (hexane/ethyl acetate = 30:1). ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.65 (dt, *J* = 16.8, 10.6 Hz, 0.46H), 6.31 (dt, *J* = 17.0, 10.3 Hz, 0.54H), 6.11 – 5.92 (m, 1H), 5.71 (dt, *J* = 14.7, 7.0 Hz, 0.54H), 5.46 (dt, *J* = 10.9, 7.8 Hz, 0.46H), 5.18 (dd, *J* = 16.9, 1.9 Hz, 0.46H), 5.12 – 5.05 (m, 1H), 4.95 (dd, *J* = 10.2, 1.7 Hz, 0.54H), 2.18 (qd, *J* = 7.6, 1.5 Hz, 0.92H), 2.08 (q, *J* = 7.2 Hz, 1.08H), 1.46 – 1.35 (m, 2H), 1.35 – 1.23 (m, 16H), 0.88 (t, *J* = 6.9 Hz, 3H). ^{13}C NMR (126 MHz, $CDCl_3$) carbon signals were found at δ 137.51, 135.60, 133.06, 132.48, 131.08, 129.33, 116.71, 114.62, 32.78, 32.15, 29.91, 29.90, 29.88, 29.87, 29.85, 29.85, 29.84, 29.75, 29.74, 29.59, 29.59, 29.47, 29.46, 29.44, 27.93, 22.91, 14.27. The spectra match the reported literature.[27]



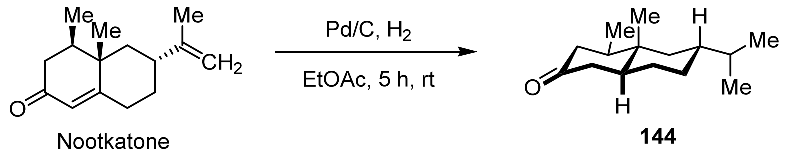
S12: A DMF (16 mL) suspension of **D2** (150 mg, 0.6 mmol, 1.0 equiv), biotin (800 mg, 3.2 mmol, 5.3 equiv), and K_2CO_3 (870mg, 6.4 mmol, 10.7 equiv) was heated at 100 °C for 4 hours in a 40 mL vial under N_2 atmosphere. After cooled to room temperature, the reaction mixture was partitioned between water and ethyl acetate. The organic layer was separated, and the aqueous layer was extracted with ethyl acetate. The organic phase was combined, washed with brine, and dried over $MgSO_4$. The filtrate was concentrated *in vacuo* and purified by flash column chromatography over silica (DCM/MeOH, 30:1) to give **S12** as a white solid (110 mg, 57% yield, ca. 90~95% purity). $R_f = 0.35$ (DCM/MeOH = 20:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.38 (dd, *J* = 17.6, 10.9 Hz, 1H), 5.43 (s, 1H), 5.27 (d, *J* = 17.6 Hz, 1H), 5.13 – 5.08 (m, 2H), 5.05 (s, 2H), 4.51 (dd, *J* = 7.7, 4.9 Hz, 1H), 4.37 – 4.30 (m, 1H), 4.22 (t, *J* = 7.1 Hz, 2H), 3.16 (q, *J* = 7.0 Hz, 1H), 2.92 (dd, *J* = 12.8, 5.0 Hz, 1H), 2.73 (d, *J* = 12.8 Hz, 1H), 2.55 (t, *J* = 7.1 Hz, 2H), 2.33 (t, *J* = 7.4 Hz, 2H), 1.76 – 1.64 (m, 5H), 1.51 – 1.37 (m, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 173.71, 163.38, 142.26, 138.46, 117.79, 113.96, 63.07, 62.05, 60.22, 55.48, 40.70, 34.03, 30.75, 28.47, 28.41, 24.91. IR (KBr) 3228, 2926, 2857, 1739, 1699, 1468, 1267, 1174 cm^{-1}. HRMS: calcd. 325.1581 $[M+H]^+$ Found: 325.1591.



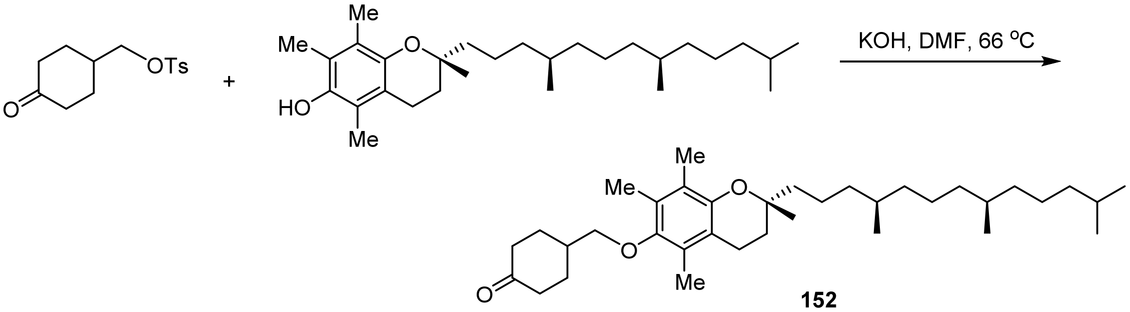
S13: Myrcene oxide was prepared according to a literature.[28] To a flame dried 100 mL round bottom flask, myrcene oxide (2.66 g, 17.5 mmol, 1 equiv) and 50 mL anhydrous THF were added and cooled to 0 °C. Lithium aluminum hydride (0.750 mg, 19.7 mmol, 1.12 equiv) was added portion-wise and the mixture was stirred at room temperature for 18 hours. The reaction was slowly quenched with sat. aqueous Rochelle's Salt (25 mL), diluted with H_2O (25 mL), and extracted with diethyl ether (3x30 mL). Organic extracts were dried over Na_2SO_4, filtered, and concentrated. Crude product was purified by flash column chromatography over silica (hexane/diethyl ether, 1:1) to give **S4** as a colorless oil (1.89 g, 70% yield). R_f = 0.40 (hexane/ether = 1:1). ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.37 (dd, *J* = 17.6, 10.8 Hz, 1H), 5.23 (d, *J* = 17.6 Hz, 1H), 5.04 (dd, *J* = 24.1, 10.3 Hz, 3H), 2.26 – 2.20 (m, 2H), 1.61 – 1.55 (m, 2H), 1.53 – 1.47 (m, 2H), 1.22 (s, 6H). The spectrum matches the reported literature.[29]



142: An ethyl acetate (10 mL) suspension of Santonin (600 mg, 1.0 equiv) and Pd/C (5 wt.%, 150 mg) was stirred at room temperature for 8 hours under H_2 atmosphere (balloon pressure). The mixture was then filtered through Celite. The filtrate was concentrated *in vacuo* and purified by flash column chromatography over silica (hexane/ethyl acetate, 3:1) to give **142** as a white solid (450 mg, 75% yield, mixture of diastereomers). R_f = 0.5 (hexane/ethyl acetate = 1:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 4.32 (dd, *J* = 11.3, 4.5 Hz, 0.35H), 3.98 (dd, *J* = 11.4, 9.8 Hz, 0.42H), 3.89 (t, *J* = 10.3 Hz, 0.23H), 2.85 – 2.21 (m, 4H), 2.12 – 1.53 (m, 7H), 1.34 – 1.13 (m, 10H). ^{13}C NMR (101 MHz, $CDCl_3$) carbon signals were found at δ 213.86, 212.98, 211.55, 179.31, 179.14, 178.59, 83.23, 82.11, 79.69, 53.64, 53.01, 50.90, 49.21, 45.10, 44.31, 43.95, 42.30, 41.85, 41.62, 41.55, 40.82, 40.76, 40.33, 40.11, 37.44, 36.73, 36.59, 35.84, 35.81, 35.20, 30.70, 27.95, 24.29, 23.45, 23.22, 20.24, 18.52, 15.13, 14.01, 13.85, 12.70, 12.64, 12.59. IR (KBr) 2977, 2936, 2878, 1774, 1709, 1458, 1148, 1008 cm^{-1}. HRMS: calcd. 251.1642 $[M+H]^+$ Found: 251.1649.



144: An ethyl acetate (10 mL) suspension of Nootkatone (400 mg, 1.0 equiv) and Pd/C (5 wt.%, 80 mg) was stirred at room temperature for 5 hours under H_2 atmosphere (balloon pressure). The mixture was then filtered through Celite. The filtrate was concentrated *in vacuo* and purified by flash column chromatography over silica (hexane/ethyl acetate, 20:1) to give **144** as a white solid (310 mg, 78% yield). R_f = 0.6 (hexane/ethyl acetate = 5:1). ^{1}H NMR (400 MHz, Toluene-d_8) δ 2.09 – 2.04 (m, 1H), 1.96 (ddd, *J* = 14.5, 3.6, 2.2 Hz, 1H), 1.84 – 1.69 (m, 2H), 1.57 – 1.45 (m, 2H), 1.30 – 0.87 (m, 6H), 0.82 (dd, *J* = 6.8, 5.4 Hz, 6H), 0.76 – 0.65 (m, 1H), 0.60 (d, *J* = 6.7 Hz, 3H), 0.51 (s, 3H), 0.37 (t, *J* = 12.6 Hz, 1H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 211.41, 46.73, 46.05, 45.27, 44.17, 41.84, 38.84, 36.18, 33.05, 29.63, 29.16, 20.15, 19.71, 15.15, 10.77. IR (KBr) 2961, 2920, 2872, 1715, 1468, 1445, 1389, 1291, 1245 cm^{-1}. HRMS: calcd. 223.2057 $[M+H]^+$ Found: 223.2054. The spectra match the reported literature.[30]



152

152: A 20 mL vial was charged with (4-oxocyclohexyl)methyl 4-methylbenzenesulfonate[31] (282 mg, 1 mmol, 1 equiv), KOH (48 mg, 1.2 equiv), Vitamin E (430 mg, 1 equiv) and DMF (6 mL). The reaction was stirred at room temperature for 1 hour before heated to 66 °C for 6 hours under N_2 atmosphere. After cooled to room temperature, the reaction mixture was partitioned between water and ethyl acetate. The organic layer was separated, and the aqueous layer was extracted with ethyl acetate. The organic phase was combined, washed with brine, and dried over $MgSO_4$. The filtrate was concentrated *in vacuo* and purified by flash column chromatography over silica (hexane/ethyl acetate, 30:1) to give **152** as a colorless oil (350 mg, 65% yield, mixture of diastereomers). $R_f = 0.75$ (hexane/ethyl acetate = 10:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.56 (d, *J* = 5.9 Hz, 2H), 2.57 (t, *J* = 6.8 Hz, 2H), 2.52 – 2.37 (m, 4H), 2.29 (td, *J* = 12.5, 11.9, 3.0 Hz, 3H), 2.16 (s, 3H), 2.12 (s, 3H), 2.08 (s, 3H), 1.78 (ddq, *J* = 20.1, 13.4, 6.9 Hz, 2H), 1.65 (ddt, *J* = 12.1, 6.0, 3.2 Hz, 2H), 1.57 – 1.48 (m, 3H), 1.46 – 1.03 (m, 21H), 0.87 (s, 3H), 0.87 – 0.82 (m, 9H). ^{13}C NMR (101 MHz, $CDCl_3$) carbon signals were observed at δ 211.89, 147.98, 147.94, 127.78, 125.78, 123.11, 117.76, 76.44, 74.94, 40.68, 40.13, 39.51, 37.60, 37.59, 37.55, 37.42, 37.26, 32.94, 32.83, 31.42, 29.74, 28.13, 24.95, 24.59, 24.03, 22.87, 22.78, 21.16, 20.80, 19.90, 19.81, 12.81, 11.95, 11.93. IR (KBr) 2951, 2930, 2866, 1717, 1461, 1381, 1261, 1089 cm^{-1}. HRMS: calcd. 541.4615 $[M+H]^+$ Found: 541.4621.

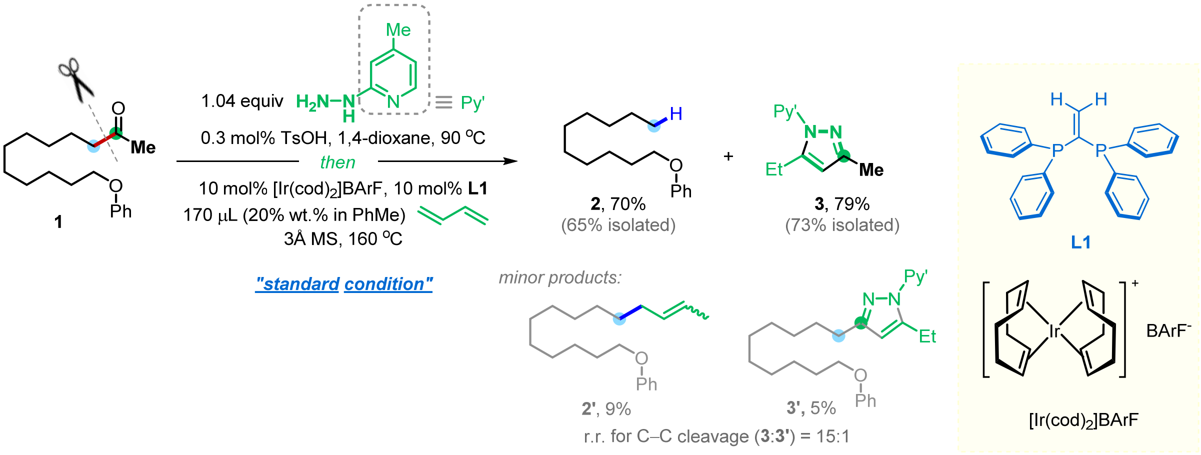
3. Deacylative transformations of ketones *via* aromatization-promoted C−C activation

3.1 Condition optimization

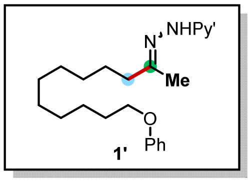
12-phenoxydodecan-2-one (**1**) was selected as the model substrate to investigate and optimize the reaction. After screening over different metal catalysts, ligands, and other reaction parameters, we found that the ketone substrate, upon treatment with 4-methyl-2-pyridyl hydrazine and 1,3-butadiene in toluene, underwent efficient α-C−C bond cleavage using cationic $[Ir(cod)_2]BArF$ and *1,1-bis(diphenylphosphino)ethylene* (**L1**) as the optimal metal/ligand combination (*"standard condition"*). The pyrazole product **3** was formed in 79% yield, along with deacetylation product **2** in 70% yield. A minor deacylative crotylation product (**2'**) was also observed in 9% yield, which should come from coupling of the alkyl fragment with 1,3-butadiene. Resulted from cleavage at the alternative methyl side, compound **3'** was isolated in 5% yield.

A number of control experiments were then carried out to probe the role of each reactant (Table S1). Unsurprisingly, the cationic Ir catalyst was indispensable (entry 1); in contrast, a neutral Ir complex gave no conversion of the hydrazone (entry 2), and the cationic Rh was much less efficient (entry 3). Omitting or replacing **L1** with either monodentate PPh_3 or bidentate dppe ligands resulted in dramatically decreased reactivity (entries 4-6). The pyridyl moiety in hydrazine was also found to be critical for this transformation, as replacing the pyridyl group with a phenyl group led to no desirable conversion of the hydrazone intermediate. It is likely that the pyridyl moiety chelates with the cationic Ir catalyst thereby promoting the [3+2] cycloaddition with 1,3-diene. High reaction conversion can be obtained at 130 °C albeit with diminished selectivity due to the formation of more C−C coupling product **2’** (entry 7). Finally, use of the pre-formed hydrazone **1’** directly as the substrate instead of **1** gave comparable yields and similar product distribution (entry 8), supporting hydrazone to be an intermediate for this reaction.

Table S1 | Condition optimization



entry	deviation from above	yield **2** (%)[b]	**3** (%)[b]	entry	deviation from above	yield **2** (%)[b]	**3** (%)[b]
1	without Ir	0[c]	0	5	with PPh_3	3[c]	3
2	with $[Ir(cod)Cl]_2$	0[c]	0	6	with dppe	16[d]	20
3	with $[Rh(cod)_2]BF_4$	13[d]	14	7	130 °C	56[e]	83
4	without **L1**	11[d]	12	8	using pre-formed hydrazone **1'**	72	79



1'

[a] The reactions were conducted with 0.05 mmol **1**, 0.05 mmol of 4-methyl-2-pyridyl hydrazine, and 0.5 mmol 1,3-butadiene. [b] Determined by ^1H NMR using 1,1,2,2-tetrachloroethane as the internal standard. [c] The hydrazone of the ketone (**1’**) was recovered in > 90% yield. [d] The hydrazone of the ketone (**1’**) was recovered in > 70% yield. [e] 26% of **2’** was generated. r.r., regioselectivity ratio. cod, 1,5-cyclooctadiene. dppe, 1,2-bis(diphenylphosphino)ethane; Py’, 4-methyl-2-pyridyl.

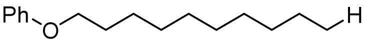
Detailed experimental procedures for section 3.1:

“Standard condition” in Table S1:

For a 0.05 mmol scale reaction, a 1,4-dioxane (1 mL) solution of the ketone substrate **1** (13.8 mg, 0.05 mmol, 1.0

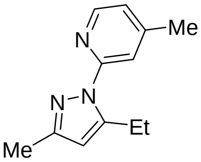
equiv), 2-hydrazineyl-4-methylpyridine (**D1**) (6.4 mg, 0.052 mmol, 1.04 equiv), and *p*-TsOH·H$_2$O (*stock solution in 1,4-dioxane*, 0.05 M, 3.0 µL, 0.003 equiv) was heated at 90 °C for 5 hours under nitrogen atmosphere in a 8 mL vial. After cooled to room temperature, the vial was charged first with [Ir(cod)$_2$]BArF (6.4 mg, 0.005 mmol, 0.1 equiv) and **L1** (2.0 mg, 0.005 mmol, 0.1 equiv) under air atmosphere, and then with 3Å molecular sieve (pre-dried, 100 mg) and 1,3-butadiene (20 wt.% in PhMe, 170 µL, ca. 10 equiv, purchased from *Sigma-Aldrich*) in a glovebox. The vial was sealed and heated at 160 °C under stirring for 72 hours. After cooled to room temperature, the reaction mixture was filtered through a short plug of Celite and concentrated *in vacuo* before 1,1,2,2-tetrachloroethane (0.1 mmol, 16.7 mg) was added. The yields of the products were determined by ^{1}H NMR using 1,1,2,2-tetrachloroethane as the internal standard. Products **2**, **3**, **2'**, and **3'** could also be isolated by flash column chromatography over silica (from hexane to hexane/ethyl acetate, 15:1). *The reported isolation yields were based on average of 3 runs.*

<u>General procedure for hydrazones preparation from the corresponding ketones and 2-hydrazineyl-4-methylpyridine **D1**:</u> A MeOH solution (1 M) of the ketone substrate (1 equiv) and 2-hydrazineyl-4-methylpyridine **D1** (1 equiv) was heated at 60 °C for 2-4 hours (monitored by TLC). After cooled to room temperature, the reaction mixture was concentrated *in vacuo* and purified by flash column chromatography over silica (hexane/ethyl acetate, typically from 10:1 to 3:1) to give the hydrazone product in generally >90% yield.



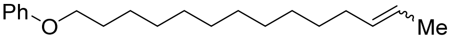
2

2: The reaction was conducted at 0.05 mmol scale. Three parallel reactions were conducted (0.05 mmol for each, 0.15 mmol in total) and combined, giving compound **2** as a colorless oil (22.8 mg, 65% yield). R$_f$ = 0.3(hexane). ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.28 (t, *J* = 8.0 Hz, 2H), 7.09 – 6.77 (m, 3H), 3.96 (t, *J* = 6.6 Hz, 2H), 1.79 (p, *J* = 6.8 Hz, 2H), 1.53 – 1.44 (m, 2H), 1.38 – 1.24 (m, 12H), 0.89 (t, *J* = 6.5 Hz, 3H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 159.27, 129.53, 120.57, 114.64, 68.03, 32.06, 29.74, 29.72, 29.57, 29.48, 29.46, 26.23, 22.84, 14.27. The spectra match the reported literature.[32]



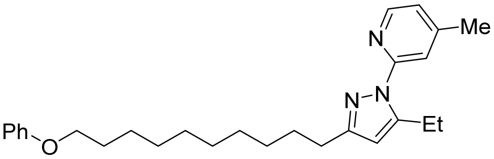
3

3: The reaction was conducted at 0.05 mmol scale. Three parallel reactions were conducted (0.05 mmol for each, 0.15 mmol in total) and combined, giving compound **3** as a colorless oil (22.1 mg, 73% yield). R$_f$ = 0.65 (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, CDCl$_3$) δ 8.25 (d, *J* = 5.1 Hz, 1H), 7.63 (t, *J* = 0.8 Hz, 1H), 6.96 (ddd, *J* = 5.0, 1.5, 0.7 Hz, 1H), 6.02 (s, 1H), 3.09 (qd, *J* = 7.5, 0.9 Hz, 2H), 2.38 (t, *J* = 0.7 Hz, 3H), 2.30 (s, 3H), 1.23 (t, *J* = 7.5 Hz, 3H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 153.78, 149.76, 149.73, 148.00, 147.35, 122.18, 116.88, 106.87, 21.43, 21.26, 13.83, 13.27. IR (KBr) 3066, 3026, 2977, 2930, 2874, 1614, 1575, 1480, 1443, 1419, 1358, 1024 cm^{-1}. HRMS: calcd. 202.1339 [M+H]$^+$ Found: 202.1344.



2'

2': The reaction was conducted at 0.05 mmol scale. Three parallel reactions were conducted (0.05 mmol for each, 0.15 mmol in total) and combined, giving compound **2'** as a colorless oil (4.1 mg, 9% yield). $R_f = 0.2$ (hexane). ^{1}H NMR (400 MHz, Chloroform-*d*) δ 7.31 – 7.25 (m, 3H), 6.96 – 6.87 (m, 3H), 5.41 (dt, *J* = 9.4, 4.7 Hz, 2H), 3.95 (t, *J* = 6.6 Hz, 2H), 2.07 – 1.90 (m, 2H), 1.78 (p, *J* = 6.7 Hz, 2H), 1.69 – 1.57 (m, 3H), 1.46 (dt, *J* = 14.7, 6.8 Hz, 2H), 1.28 (s, 14H). ^{13}C NMR (101 MHz, $CDCl_3$) carbon signals were found at δ 159.28, 131.84, 131.06, 129.53, 124.67, 123.74, 120.58, 114.64, 68.04, 32.77, 31.75, 29.78, 29.76, 29.74, 29.73, 29.71, 29.68, 29.56, 29.46, 29.36, 27.00, 26.22, 22.81, 18.08, 15.44, 14.31, 14.28, 12.90. IR (KBr) 3025, 2932, 2859, 1606, 1496, 1471, 1246, 1041 cm^{-1}. HRMS: calcd. 289.2526 $[M+H]^+$ Found: 289.2526.



3'

3': The reaction was conducted at 0.05 mmol scale. Three parallel reactions were conducted (0.05 mmol for each, 0.15 mmol in total) and combined, giving compound **3'** as a colorless oil (3 mg, 5% yield). $R_f = 0.7$ (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.26 (d, *J* = 5.0 Hz, 1H), 7.64 (s, 1H), 7.31 – 7.26 (m, 2H), 7.01 – 6.83 (m, 4H), 6.04 (s, 1H), 3.95 (t, *J* = 6.6 Hz, 2H), 3.10 (q, *J* = 7.5 Hz, 2H), 2.70 – 2.57 (m, 2H), 2.40 (s, 3H), 1.78 (p, *J* = 6.7 Hz, 2H), 1.68 (p, *J* = 8.0, 7.5 Hz, 2H), 1.47 – 1.29 (m, 12H), 1.24 (t, *J* = 7.5 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 159.28, 154.61, 153.90, 149.72, 147.82, 147.36, 129.53, 122.17, 120.57, 117.06, 114.65, 105.72, 68.04, 29.78, 29.71, 29.65, 29.65, 29.61, 29.55, 29.46, 28.63, 26.22, 21.52, 21.29, 13.28. IR (KBr) 3028, 2932, 2856, 1608, 1569, 1474, 1423, 1252, 1041 cm^{-1}. HRMS: calcd. 420.3009 $[M+H]^+$ Found: 420.3005.

3.2 Preliminary mechanistic investigation

3.2.1 Experimental studies

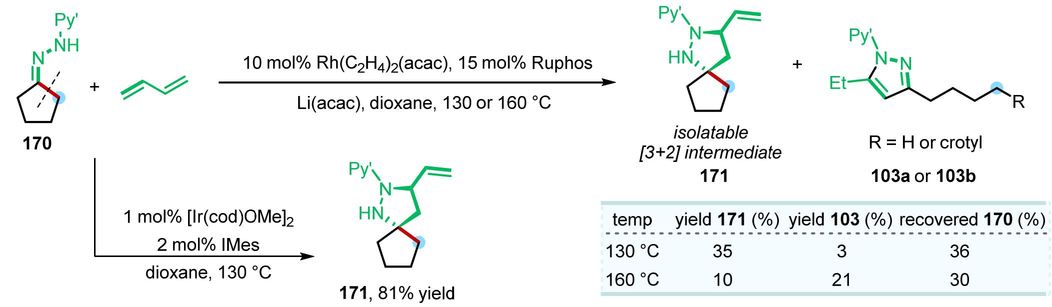
Preliminary experimental studies were carried out to elucidate the primary pathway of this C−C activation reaction (Fig. S2). First, [3+2] adducts between hydrazones and 1,3-dienes were frequently observed during the condition optimizations with various Rh and Ir catalysts (Fig. S2a). For instance, using $Rh(C_2H_4)_2(acac)$ and Ruphos, spirocycle **171** was observed in 35% yield along with a trace amount of C−C cleavage products (**103a**) at 130 °C, while at 160 °C pyrazole **103** became the major product with spirocycle **171** being observed in 10% yield. The same [3+2] adduct (**171**) could also be isolated in a high yield by using $[Ir(cod)OMe]_2$/IMes as a catalyst. A set of control experiments were then conducted to elucidate the intermediacy of the [3+2] adduct (Fig. S2b). Cyclohexanone-derived substrate was chosen due to the convenience of identifying the series of products generated in this reaction. Under the "standard" conditions, using either hydrazone **172** or the [3+2] adduct (**173**), the C−C cleavage reaction happened to give similar yields and distributions of products (entries 1 and 2). In the absence of the Ir catalyst, no reaction was observed with the [3+2] adduct, suggesting that Ir plays an important role in catalyzing the C−C cleavage step (entry 3). As the diene fragment has already been incorporated into the [3+2] adduct, omitting 1,3-butadiene from the standard condition still furnished pyrazole product **91** in high efficiency; interestingly, under such conditions hydrazone **172** was formed in 10% yield, indicating that the [3+2] cycloaddition is reversible (entry 4). The reversibility of the [3+2] cycloaddition was further confirmed by the observation of the "*cross-product*" **176** by treating the 1,3-butadiene-derived **173** with *isoprene* under otherwise standard conditions (entry 5). When the model reaction with **172** was conducted in *darkness*, identical results were achieved as in entry 1.

Furthermore, no C−C cleavage was observed when hydrogenated [3+2] product (**177**) was employed as the substrate (Fig. S2b, eq. 1); in the absence of the olefin moiety, the proposed pre-aromatic intermediate cannot be formed through olefin migration. In addition, compound **179**, prepared from the corresponding hydrazone **178**, was subjected to the "standard" condition (Fig. S2b, eq. 2). This substrate contains the same pyridyl motif and an allylic C−C bond similar to **Int II** but cannot aromatize due to lack of a cyclic structure. Again, no C–C cleavage product was detected with **179**, indicating that the allylic C−C motif alone cannot promote C−C cleavage. These results support that aromatization is a key driving force for this C−C activation reaction.

Finally, the C−C cleavage step also seems to be distinct from a typical TM-mediated β-carbon elimination process.[33,34] When using 1-indanone as the ketone substrate, no C-aryl cleavage was observed, indicating that the C-alkyl bond is easier to be cleaved than the C-aryl bond from the key pre-aromatic [3+2] intermediate (Fig. S2d); in contrast, β-carbon elimination normally favors cleavage of a C-aryl bond in less strained systems.[35]

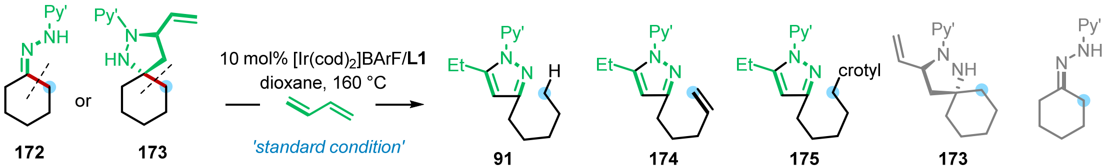
Figure S2 | Preliminary mechanistic investigation

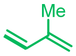
a. observation and synthesis of the [3+2] adduct



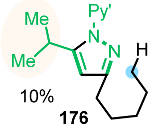
temp	yield **171** (%)	yield **103** (%)	recovered **170** (%)
130 °C	35	3	36
160 °C	10	21	30

b. study of the intermediacy of the [3+2] adduct

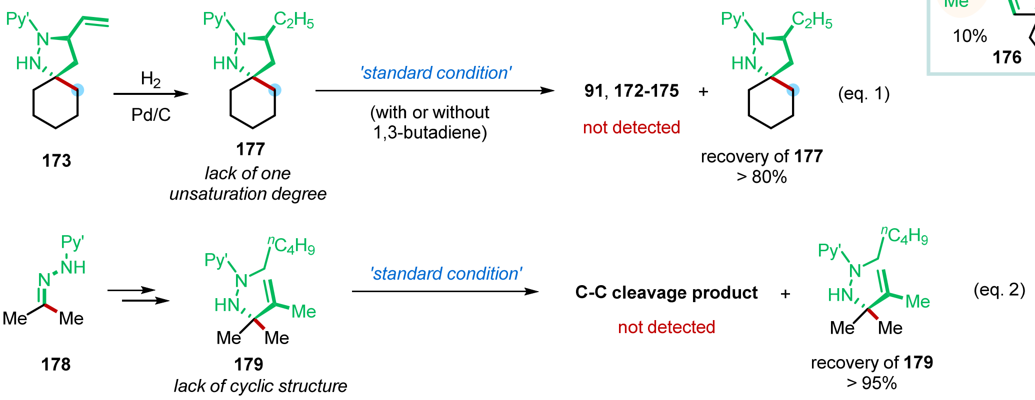


	entry	condition	**91** desired product	**174** dehydrogenation	**175** crotylation	**173** [3+2] adduct	*172*
using **172**	1	*'standard condition'*	70%	5%	6%	n.d.	n.d.
using **173**	2	*'standard condition'*	64%	7%	7%	n.d.	n.d.
	3	omitting [Ir]	n.d.	n.d.	n.d.	95% recovered	n.d.
	4	omitting 	69%	5%	0%	n.d.	10%
	5	using  instead	40%	8%	0% *crotylation* + 20% *prenylation*	n.d.	n.d.

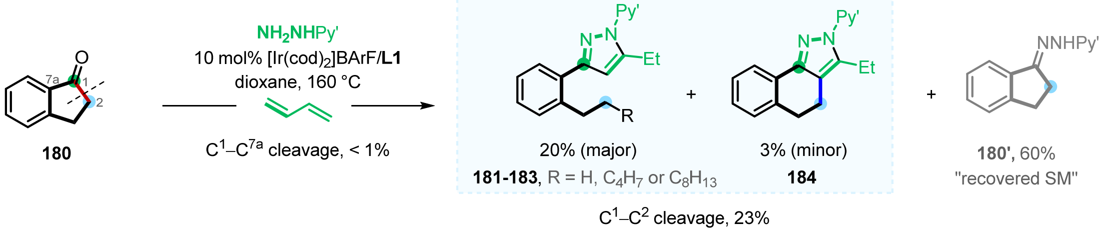
'cross-product'



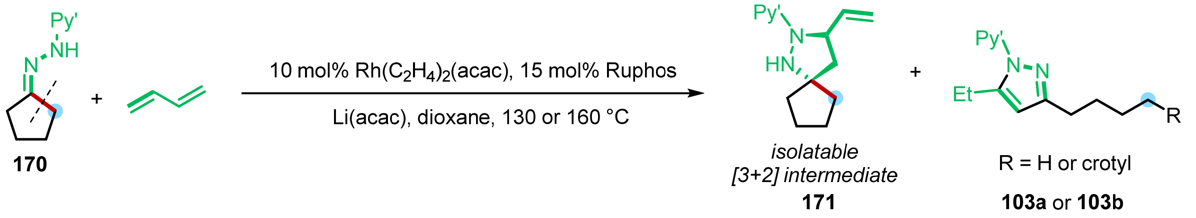
c. control experiments with non-aromatizable substrates



d. selectivity of C(aryl)–C vs. C(alkyl)–C cleavage



Detailed experimental procedures for section 3.2.1:



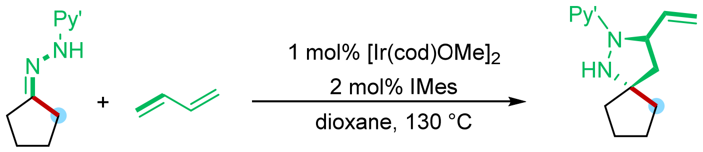
170

171

103a or **103b**

temp	yield **171** (%)	yield **103** (%)	recovered **170** (%)
130 °C	35	3	36
160 °C	10	21	30

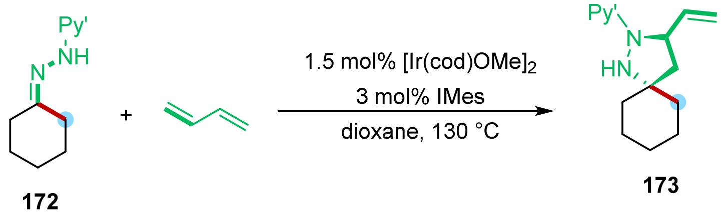
A 4 mL vial was charged with hydrzone **170** (18.9 mg, 0.1 mmol, 1.0 equiv), $Rh(C_2H_4)_2(acac)$ (2.6 mg, 0.01 mmol, 0.1 equiv), RuPhos (7 mg, 0.015 mmol, 0.15 equiv), Li(acac) (2.7 mg, 0.025 mmol, 0.25 equiv) and 1,4-dioxane (1 mL). The vial was sealed and transferred into the glove box, and then opened and purged under N_2 atmosphere for 5 mins. 1,3-Butadiene (20 wt.% in PhMe, 400 µL, ca. 12 equiv) was then added. The vial was sealed, transferred out of the glove box, and heated in a pie-block at 160 or 130 °C under stirring for 60 hours. After cooled to room temperature, the reaction mixture was concentrated *in vacuo* before 1,1,2,2-tetrachloroethane (0.1 mmol, 16.7 mg) was added. The yields of the products were determined by ^1H NMR using 1,1,2,2-tetrachloroethane as the internal standard. For reaction running at 130 °C, compound **171** could further be isolated by flash column chromatography over neutral Al_2O_3 (hexane/ethyl acetate, 40:1) as a colorless oil (7 mg, 29% yield). R_f = 0.4 (hexane/ethyl acetate = 3:1). ^1H NMR (400 MHz, $CDCl_3$) δ 8.00 (dd, J = 5.1, 0.8 Hz, 1H), 7.02 (dt, J = 1.6, 0.8 Hz, 1H), 6.44 (ddd, J = 5.1, 1.6, 0.6 Hz, 1H), 6.04 (ddd, J = 17.1, 10.3, 5.0 Hz, 1H), 5.26 (dt, J = 17.1, 1.6 Hz, 1H), 5.08 (dt, J = 10.3, 1.6 Hz, 1H), 4.81 (dddt, J = 9.3, 7.9, 5.0, 1.5 Hz, 1H), 2.34 (dd, J = 12.1, 7.8 Hz, 1H), 2.25 (s, 3H), 1.86 (dd, J = 12.1, 9.2 Hz, 1H), 1.82 – 1.71 (m, 3H), 1.69 – 1.59 (m, 3H), 1.44 (ddd, J = 10.6, 6.6, 3.7 Hz, 1H), 1.21 – 1.12 (m, 1H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 162.65, 147.59, 147.24, 139.94, 115.14, 113.27, 109.33, 71.35, 62.87, 47.30, 36.66, 35.05, 25.08, 24.50, 21.49. IR (KBr) 3086, 3052, 2955, 2869, 1642, 1597, 1479, 1350, 1294, 1204, 1148 cm^{-1}.



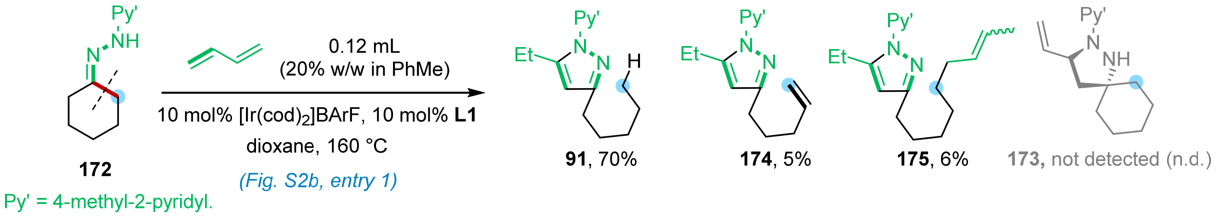
170

171, 81% yield

A 4 mL vial was charged with the **170** (18.9 mg, 0.1 mmol, 1.0 equiv), $[Ir(cod)OMe]_2$ (0.7 mg, 0.001 mmol, 0.01 equiv), IMes (0.6 mg, 0.002 mmol, 0.02 equiv) and 1,4-dioxane (1 mL). The vial was sealed and transferred into the glove box, and then opened and purged under N_2 atmosphere for 5 mins. 1,3-Butadiene (20 wt.% in PhMe, 400 µL, ca. 12 equiv) was then added. The vial was sealed, transferred out of the glove box, and heated in a pie-block at 130 °C under stirring for 80 hours. After cooled to room temperature, the reaction mixture was concentrated *in vacuo*. The residue was further purified by flash column chromatography over neutral Al_2O_3 (hexane/ethyl acetate, 40:1) to give compound **171** as a colorless oil (19.6 mg, 81% yield). The characterization data for compound **171** has been reported *vide supra*.

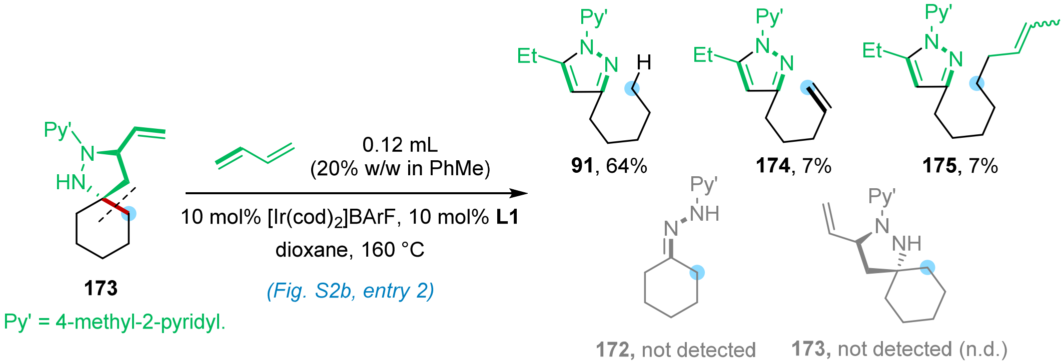


173: the compound **173** was synthesized using the same protocol as described for **171.** A 4 mL vial was charged with the **172** (20.3 mg, 0.1 mmol, 1.0 equiv), [Ir(cod)OMe]$_2$ (1 mg, 0.0015 mmol, 0.015 equiv), IMes (0.9 mg, 0.003 mmol, 0.03 equiv) and 1,4-dioxane (1 mL). The vial was sealed and transferred into the glove box, and then opened and purged under N$_2$ atmosphere for 5 mins. 1,3-Butadiene (20 wt.% in PhMe, 400 µL, ca. 12 equiv) was then added. The vial was sealed, transferred out of the glove box, and heated in a pie-block at 130 °C under stirring for 60 hours. After cooled to room temperature, the reaction mixture was concentrated *in vacuo*. The residue was further purified by flash column chromatography over neutral Al$_2$O$_3$ (hexane/ethyl acetate, 40:1) to give compound **173** as a colorless oil (22 mg, 86% yield). R$_f$ = 0.4 (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.99 (d, *J* = 5.1 Hz, 1H), 7.08 (s, 1H), 6.43 (d, *J* = 4.8 Hz, 1H), 6.01 (ddd, *J* = 16.7, 10.2, 4.8 Hz, 1H), 5.25 (dd, *J* = 17.0, 1.7 Hz, 1H), 5.06 (dd, *J* = 10.3, 1.6 Hz, 1H), 4.91 (dddt, *J* = 8.4, 6.6, 4.9, 1.5 Hz, 1H), 3.76 (s, 1H), 2.36 (dd, *J* = 12.2, 8.2 Hz, 1H), 2.26 (s, 3H), 1.80 – 1.40 (m, 8H), 1.33 – 1.11 (m, 3H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 162.71, 147.54, 147.23, 139.99, 115.05, 113.02, 109.34, 63.47, 61.88, 46.56, 36.02, 33.86, 26.15, 23.99, 23.03, 21.47. IR (KBr) 3244, 3014, 2935, 2861, 1611, 1558, 1479, 1451, 1409, 1291 cm^{-1}. HRMS: calcd. 258.1965 [M+H]$^+$ Found: 258.1941.

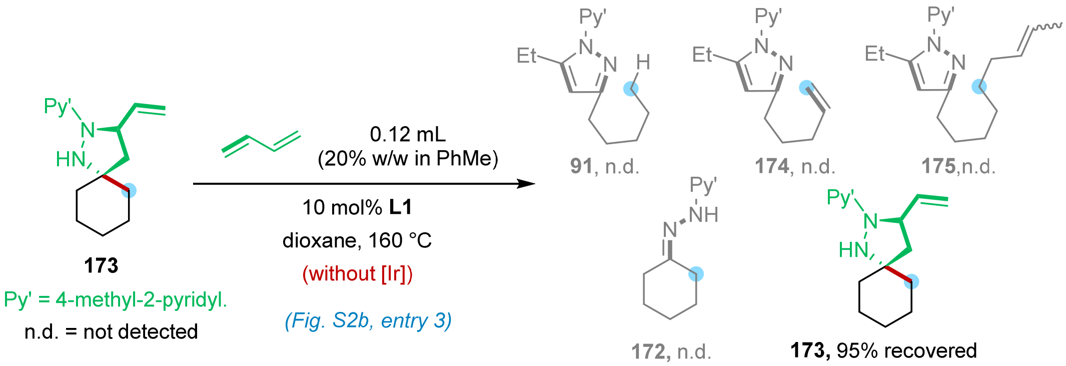


A 4 mL vial was charged with **172** (10.2 mg, 0.05 mmol, 1.0 equiv), [Ir(cod)$_2$]BArF (6.4 mg, 0.005 mmol, 0.1 equiv), **L1** (2.0 mg, 0.005 mmol, 0.1 equiv) and 1,4-dioxane (0.5 mL), and was stirred at room temperature for 5 mins. The vial was transferred into the glove box. 1,3-Butadiene (20 wt.% in PhMe, 120 µL, ca. 7.2 equiv) was then added. The vial was sealed and heated in a pie-block at 160 °C under stirring for 24 hours. After cooled to room temperature, the reaction mixture was concentrated *in vacuo* before 1,1,2,2-tetrachloroethane (0.1 mmol, 16.7 mg) was added. The yields of the products were determined by ^{1}H NMR using 1,1,2,2-tetrachloroethane as the internal standard.

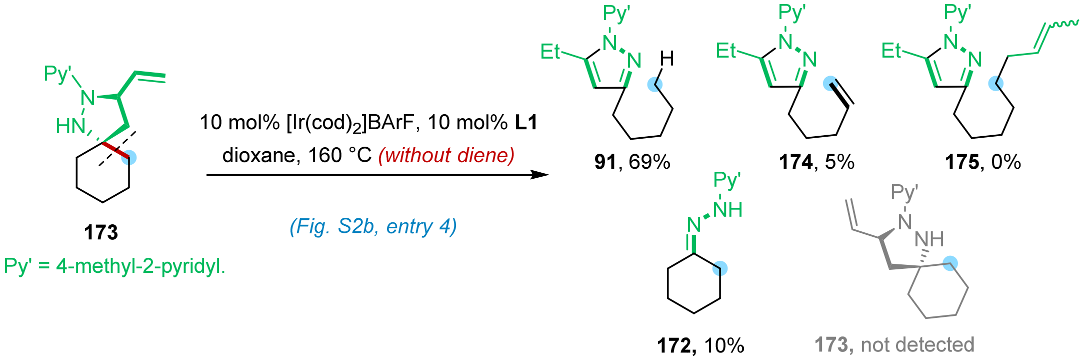
Five parallel reactions at 0.05 mmol scale were set up in order to isolate and characterize the minor product **174.** After cooled to room temperature, the reactions were combined and concentrated *in vacuo.* The residue was purified by flash column chromatography over silica (hexane/ethyl acetate, 20:1) to give **174** as a colorless oil (3.2 mg, 5% yield). R$_f$ = 0. 39 (hexane/ethyl acetate = 10:1) (*slightly more polar than compound* ***91***). ^{1}H NMR (400 MHz, CDCl$_3$) δ 8.26 (d, *J* = 5.1 Hz, 1H), 7.64 (s, 1H), 6.97 (d, *J* = 4.5 Hz, 1H), 6.04 (s, 1H), 5.86 (ddt, *J* = 16.9, 10.1, 6.7 Hz, 1H), 5.05 (dd, *J* = 17.1, 1.8 Hz, 1H), 4.98 (dd, *J* = 10.2, 1.1 Hz, 1H), 3.10 (q, *J* = 7.5 Hz, 2H), 2.74 – 2.59 (m, 2H), 2.40 (s, 3H), 2.16 (q, *J* = 7.2 Hz, 2H), 1.79 (p, *J* = 7.7 Hz, 2H), 1.25 (td, *J* = 7.5, 1.1 Hz, 3H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 154.15, 153.91, 149.72, 147.87, 147.36, 138.74, 122.20, 117.06, 114.82, 105.77, 33.69, 28.96, 28.05, 21.51, 21.28, 13.27. IR (KBr) 3067, 2971, 2932, 1614, 1569, 1474, 1420, 1361 cm^{-1}. HRMS: calcd. 256.1808 $[M+H]^+$ Found: 256.1813.



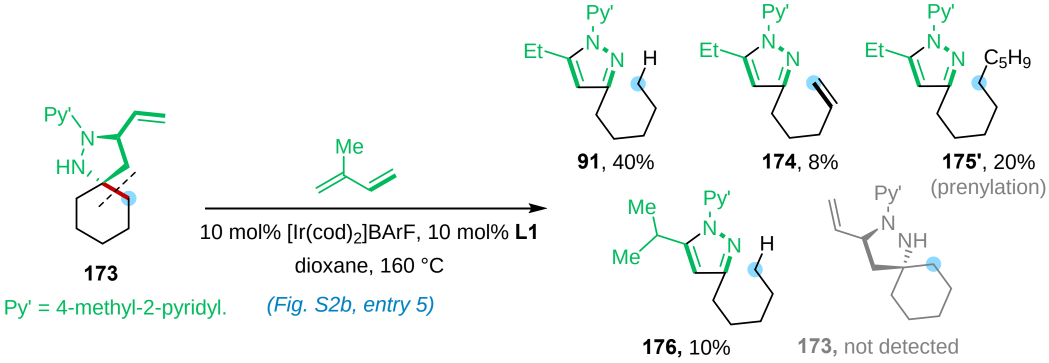
A 4 mL vial was charged with **173** (12.9 mg, 0.05 mmol, 1.0 equiv), [Ir(cod)$_2$]BArF (6.4 mg, 0.005 mmol, 0.1 equiv), **L1** (2.0 mg, 0.005 mmol, 0.1 equiv) and 1,4-dioxane (0.5 mL), and was stirred at room temperature for 5 mins. The vial was transferred into the glove box. 1,3-Butadiene (20 wt.% in PhMe, 120 μL, ca. 7.2 equiv) was then added. The vial was sealed and heated in a pie-block at 160 °C under stirring for 24 hours. After cooled to room temperature, the reaction mixture was concentrated *in vacuo* before 1,1,2,2-tetrachloroethane (0.1 mmol, 16.7 mg) was added. The yields of the products were determined by ^{1}H NMR using 1,1,2,2-tetrachloroethane as the internal standard.



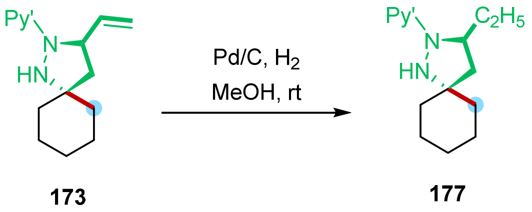
A 4 mL vial was charged with **173** (12.9 mg, 0.05 mmol, 1.0 equiv), **L1** (2.0 mg, 0.005 mmol, 0.1 equiv) and 1,4-dioxane (0.5 mL), and was stirred at room temperature for 5 mins. The vial was transferred into the glove box. 1,3-Butadiene (20 wt.% in PhMe, 120 μL, ca. 7.2 equiv) was then added. The vial was sealed and heated in a pie-block at 160 °C under stirring for 24 hours. After cooled to room temperature, the reaction mixture was concentrated *in vacuo* before 1,1,2,2-tetrachloroethane (0.1 mmol, 16.7 mg) was added. The yields of the products were determined by ^{1}H NMR using 1,1,2,2-tetrachloroethane as the internal standard.



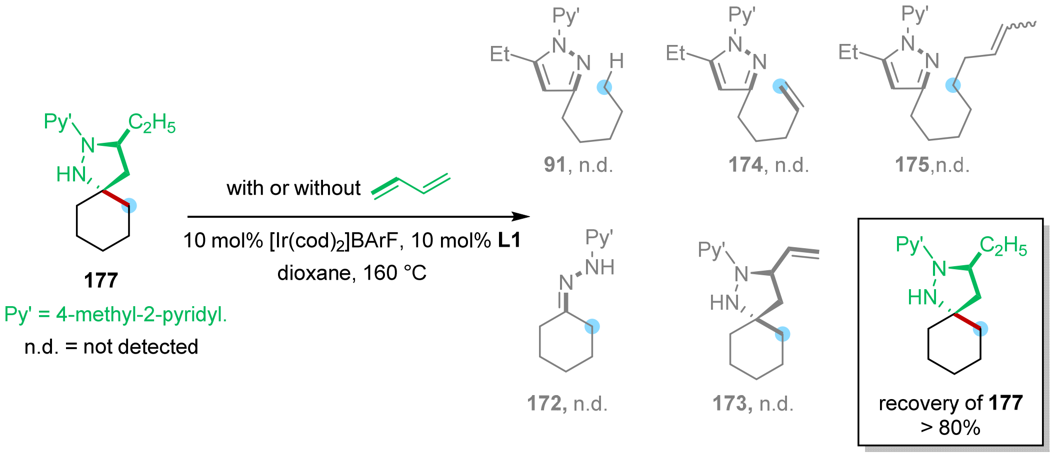
A 4 mL vial was charged with **173** (12.9 mg, 0.05 mmol, 1.0 equiv), [Ir(cod)$_2$]BArF (6.4 mg, 0.005 mmol, 0.1 equiv), **L1** (2.0 mg, 0.005 mmol, 0.1 equiv) and 1,4-dioxane (0.5 mL). The vial was transferred into the glove box and purged under nitrogen atmosphere for 3 mins. The vial was then sealed and heated in a pie-block at 160 °C under stirring for 24 hours. After cooled to room temperature, the reaction mixture was concentrated *in vacuo* before 1,1,2,2-tetrachloroethane (0.1 mmol, 16.7 mg) was added. The yields of the products were determined by ^{1}H NMR using 1,1,2,2-tetrachloroethane as the internal standard.



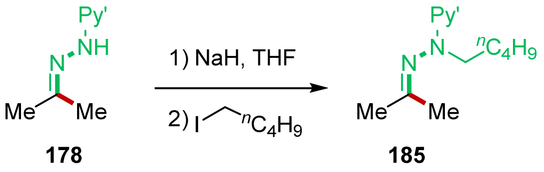
A 4 mL vial was charged with **173** (12.9 mg, 0.05 mmol, 1.0 equiv), [Ir(cod)$_2$]BArF (6.4 mg, 0.005 mmol, 0.1 equiv), **L1** (2.0 mg, 0.005 mmol, 0.1 equiv) and 1,4-dioxane (0.5 mL), and was stirred at room temperature for 5 mins. The vial was transferred into the glove box. Isoprene (36 μL, 7.2 equiv) was then added. The vial was sealed and heated in a pie-block at 160 °C under stirring for 24 hours. After cooled to room temperature, the reaction mixture was concentrated *in vacuo* before 1,1,2,2-tetrachloroethane (0.1 mmol, 16.7 mg) was added. The yields of the products were determined by ^{1}H NMR using 1,1,2,2-tetrachloroethane as the internal standard.



The compound **173** (48 mg) was treated with MeOH (2.5 mL) and Pd/C (10% wt.%, 30 mg), and stirred at room temperature under H_2 atmosphere for 1.5 hours. The reaction mixture was filtered through Celite and concentrated in *vacuo*, yielding **177** as a colorless oil without further purification (46 mg, 96% yield). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.96 (d, *J* = 5.1 Hz, 1H), 7.05 (s, 1H), 6.39 (d, *J* = 4.6 Hz, 1H), 4.35 (qd, *J* = 8.1, 4.6 Hz, 1H), 3.66 (s, 1H), 2.25 (d, *J* = 7.1 Hz, 4H), 2.01 – 1.87 (m, 1H), 1.76 – 1.34 (m, 9H), 1.30 – 1.05 (m, 3H), 0.94 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 162.92, 147.36, 147.00, 114.58, 109.31, 63.39, 61.16, 45.59, 36.24, 33.85, 28.75, 26.20, 24.01, 22.99, 21.43, 10.35. IR (KBr) 3056, 2932, 2857, 1609, 1555, 1484, 1411, 1289 cm^{-1}. HRMS: calcd. 260.2121 $[M+H]^+$ Found: 260.2128.

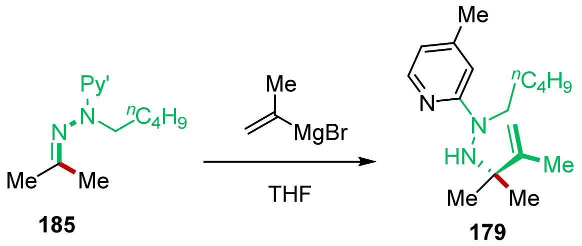


A 4 mL vial was charged with **177** (13.0 mg, 0.05 mmol, 1.0 equiv), $[Ir(cod)_2]BArF$ (6.4 mg, 0.005 mmol, 0.1 equiv), **L1** (2.0 mg, 0.005 mmol, 0.1 equiv). The vial was transferred into the glove box. 1,4-Dioxane (0.5 mL) and 1,3-butadiene (20 wt.% in PhMe, 120 µL, ca. 7.2 equiv) was then added *(or without the addition of diene)*. The vial was sealed and heated in a pie-block at 160 °C under stirring for 24 hours. After cooled to room temperature, the reaction mixture was concentrated *in vacuo* before 1,1,2,2-tetrachloroethane (0.1 mmol, 16.7 mg) was added. The yields of the products were determined by ^{1}H NMR using 1,1,2,2-tetrachloroethane as the internal standard. The recovery of **177** was further confirmed through isolation by preparative thin layer chromatography.

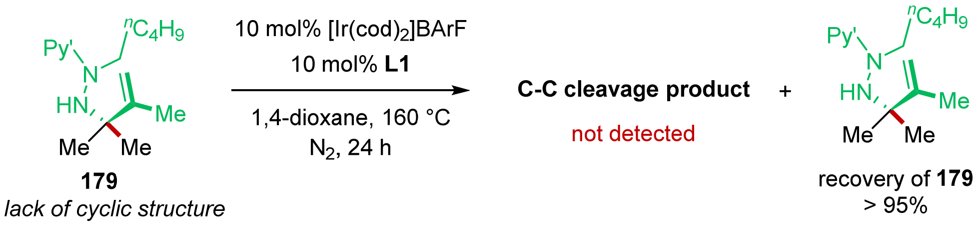


To a THF (20 mL) solution of **178** (815 mg, 5.0 mmol, 1.0 equiv) in a flame-dried 50 mL round bottom flask was added NaH (60 w/w%, 1.2 g, 30 mmol, 6.0 equiv) at 0 ^{o}C. The resulting mixture was stirred at this temperature for 30 minutes. 1-Iodopentane (1.09 g, 5.5 mmol, 1.1 equiv) was added dropwise over 5 minutes, and the suspension was then stirred at room temperature for 6 hours. Most of the solvent was removed *in vacuo,* and the residue was carefully quenched with H_2O at 0 ^{o}C. The resulting mixture was extracted with Et_2O and dried over Na_2SO_4. The filtrate was concentrated under *vacuo* and further purified by flash column chromatography over neutral Al_2O_3

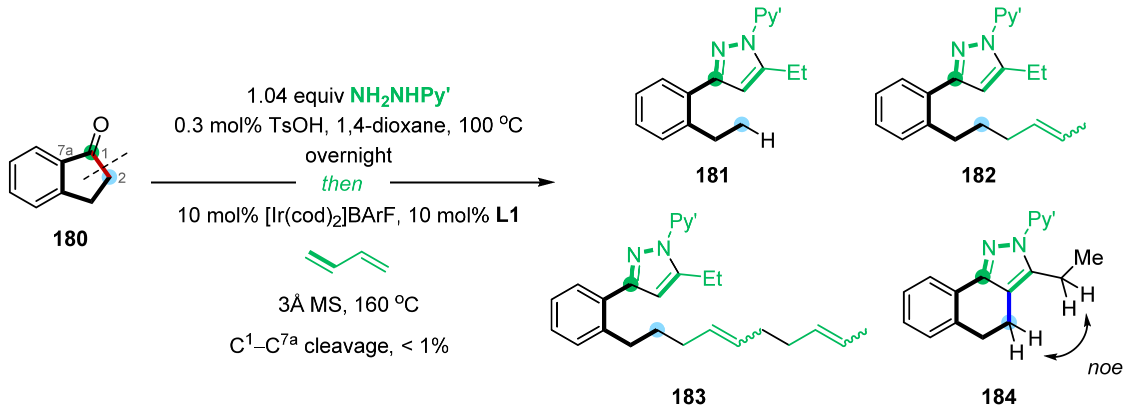
(hexane/ethyl acetate, from 100:1 to 10:1) to give product **185** as a yellowish oil (650 mg, 56% yield). R_f = 0.5 (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, C_6D_6) δ 8.25 (d, *J* = 5.0 Hz, 1H), 6.48 (s, 1H), 6.26 (dd, *J* = 5.0, 0.8 Hz, 1H), 4.05 – 3.91 (m, 2H), 1.89 (s, 3H), 1.76 (s, 5H), 1.53 (s, 3H), 1.28 – 1.18 (m, 4H), 0.78 (t, *J* = 7.0 Hz, 3H). ^{13}C NMR (101 MHz, C_6D6) δ 171.42, 160.35, 148.22, 147.59, 115.49, 108.98, 51.74, 29.99, 27.13, 24.62, 23.04, 21.24, 19.11, 14.35. IR (KBr) 2959, 2925, 2862, 1607, 1560, 1452, 1413, 1295 cm^{-1}. HRMS: calcd. 234.1970 $[M+H]^+$ Found: 234.1970.



A THF (5 mL) solution of **185** (233 mg, 1.0 mmol, 1.0 equiv) was cooled to -78 °C under N_2 atmosphere. To this, a isopropenylmagnesium bromide solution (in THF, 0.5 M, 2.2 mL, 1.1 mmol, 1.1 equiv) was added dropwise over 5 minutes. The reaction was stirred at the same temperature for 1 hour, and afterwards was allowed to slowly warmed to room temperature. Most of the solvent was removed *in vacuo,* and the residue was carefully quenched with H_2O at 0 °C. The resulting mixture was extracted with Et_2O and dried over Na_2SO_4. The filtrate was concentrated under *vacuo* and further purified by preparative thin layer chromatography over neutral Al_2O_3 (hexane/ethyl acetate, 30:1) to give product **179** as a yellowish oil (42 mg, 15% yield). R_f = 0.8 (hexane/ethyl acetate = 20:1, on an Al_2O_3 TLC plate). ^{1}H NMR (400 MHz, C_6D_6) δ 8.05 (dd, *J* = 5.1, 0.7 Hz, 1H), 6.58 (s, 1H), 6.16 (dd, *J* = 5.1, 1.3 Hz, 1H), 5.54 (s, 1H), 5.04 (dd, *J* = 1.8, 0.8 Hz, 1H), 4.85 (p, *J* = 1.4 Hz, 1H), 3.47 (br, 2H), 1.88 (s, 6H), 1.64 – 1.53 (m, 2H), 1.26 (s, 6H), 1.17 – 1.05 (m, 4H), 0.75 (t, *J* = 7.0 Hz, 3H). ^{13}C NMR (101 MHz, C_6D6) δ 162.01, 151.19, 147.52, 147.15, 114.89, 111.28, 109.39, 60.16, 53.46, 29.77, 25.64, 25.32, 22.96, 21.26, 19.57, 14.29. IR (KBr) 2963, 2930, 2863, 1607, 1555, 1461, 1416, 1295, 1156 cm^{-1}. HRMS: calcd. 276.2440 $[M+H]^+$ Found: 276.2433.



A 4 mL vial was charged with **179** (9.1 mg, 0.033 mmol, 1.0 equiv), [Ir(cod)$_2$]BArF (4.2 mg, 0.0033 mmol, 0.1 equiv), **L1** (1.3 mg, 0.0033 mmol, 0.1 equiv). The vial was transferred into the glove box. 1,4-Dioxane (0.4 mL) was then added. The vial was sealed and heated in a pie-block at 160 °C under stirring for 24 hours. After cooled to room temperature, the reaction mixture was concentrated *in vacuo* before pyrazine (6.0 mg, 0.075 mmol) was added. No C–C cleavage product was observed through either TLC or crude ^{1}H NMR analysis. The starting material **179** was found to remain in >95% yield determined by ^{1}H NMR analysis in C_6D_6 using pyrazine as the internal standard.



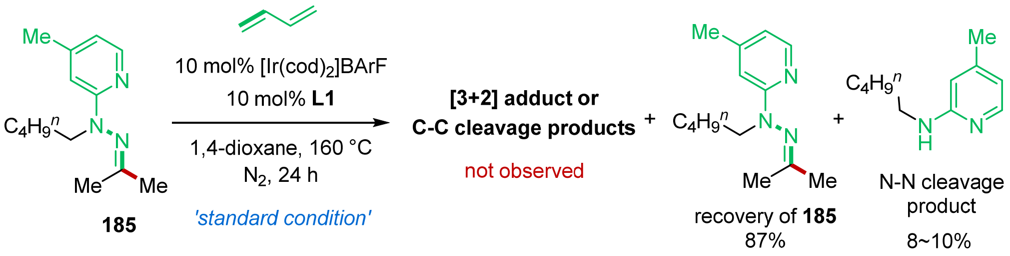
The reaction was conducted following modified **General procedure D:** A 4 mL vial was charged with the ketone substrate **180** (6.6 mg, 0.05 mmol, 1.0 equiv) and 2-hydrazineyl-4-methylpyridine **D1** (6.4 mg, 0.052 mmol, 1.04 equiv), and transferred into a glove box. 1,4-Dioxane (0.5 mL) and a stock solution of *p*-TsOH·H_2O in 1,4-dioxane (0.05 M, 10 µL, 0.01 equiv) was then added. The vial was sealed, transferred out of the glove box, and heated in a pie-block at 100 °C overnight. After cooled to room temperature, the vial was charged with [Ir(cod)$_2$]BArF (6.4 mg, 0.005 mmol, 0.1 equiv) and **L1** (2.0 mg, 0.005 mmol, 0.1 equiv), transferred into the glove box, and purged under N_2 atmosphere for 3 mins. Pre-dried 3Å molecular sieve (50 mg) and the 1,3-butadiene (20 wt.% in PhMe, 230 µL) were then added. The vial was sealed and heated in a pie-block at 160 °C under stirring for 72 hours. 10 parallel reactions were set up accordingly. After cooled to room temperature, these reactions were combined and filtered through a short plug of Celite. The filtrate was concentrated *in vacuo* and further purified by flash column chromatography over silica (hexane/ethyl acetate, from 80:1 to 30:1) to give the pyrazole products **181**, **182**, **183**, and **184**.

181 was obtained as a colorless oil (11.3 mg, 8% yield). R_f = 0.5 (hexane/ethyl acetate = 5:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.30 (d, *J* = 5.1 Hz, 1H), 7.78 (s, 1H), 7.55 (d, *J* = 7.4 Hz, 1H), 7.31 (d, *J* = 4.3 Hz, 2H), 7.25 – 7.21 (m, 1H), 7.00 (d, *J* = 5.0 Hz, 1H), 6.36 (s, 1H), 3.23 (q, *J* = 7.5 Hz, 2H), 2.91 (q, *J* = 7.5 Hz, 2H), 2.41 (s, 3H), 1.32 (t, *J* = 7.5 Hz, 3H), 1.24 (t, *J* = 7.5 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 154.12, 152.55, 149.77, 147.71, 147.27, 142.82, 132.97, 129.92, 129.22, 128.24, 125.82, 122.36, 117.10, 107.36, 27.00, 21.71, 21.36, 15.93, 13.35. IR (KBr) 3061, 2969, 2929, 2870, 1611, 1575, 1448, 1400, 1355, 1052 cm^{-1}. HRMS: calcd. 292.1808 $[M+H]^+$ Found: 292.1816.

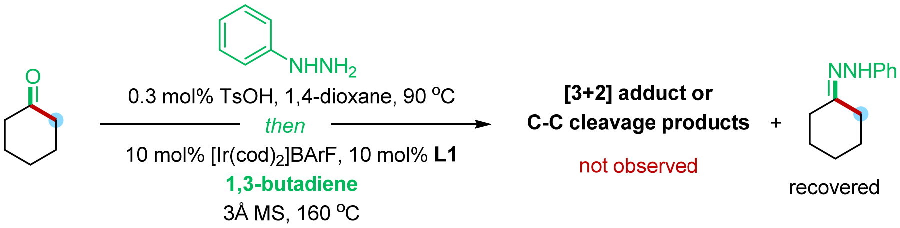
182 and **183** were obtained as an inseparable mixture (colorless oil, 21.6 mg, 12% yield combined). R_f = 0.55 (hexane/ethyl acetate = 5:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.30 (d, *J* = 5.0 Hz, 1H), 7.79 (s, 1H), 7.55 (d, *J* = 7.2 Hz, 1H), 7.31 – 7.27 (m, 2H), 7.25 – 7.20 (m, 1H), 7.03 – 6.96 (m, 1H), 6.36 (s, 1H), 5.53 – 5.22 (m, 2.6H), 5.03 – 4.83 (m, 0.4H), 3.23 (q, *J* = 7.4 Hz, 2H), 3.02 – 2.80 (m, 2H), 2.41 (s, 3H), 2.19 – 1.87 (m, 4H), 1.70 (dt, *J* = 15.3, 7.7 Hz, 2H), 1.65 – 1.55 (m, 3H), 1.32 (t, *J* = 7.4 Hz, 3H). IR (KBr) 3022, 2969, 2926, 2856, 1611, 1572, 1445, 1445, 1046 cm^{-1}. HRMS: calcd. 346.2277 [**182**, M+H]$^+$; 400.2747 [**183**, M+H]$^+$ Found: 346.2267; 400.2737.

184 was obtained as a colorless oil (4.8 mg, 3% yield). R_f = 0.4 (hexane/ethyl acetate = 5:1). ^{1}H NMR (400 MHz, DCM-*d*$_2$) δ 8.29 (d, *J* = 5.1 Hz, 1H), 7.88 (d, *J* = 7.3 Hz, 1H), 7.79 (s, 1H), 7.34 – 7.18 (m, 3H), 7.03 (d, *J* = 5.0 Hz, 1H), 3.15 (q, *J* = 7.4 Hz, 2H), 2.98 (t, *J* = 7.2 Hz, 2H), 2.76 (t, *J* = 7.2 Hz, 2H), 2.45 (s, 3H), 1.20 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 154.17, 149.76, 149.05, 147.47, 142.33, 137.46, 129.82, 128.45, 127.92, 126.92, 122.79, 122.30, 117.21, 116.86, 29.80, 21.37, 19.63, 19.02, 13.93. IR (KBr) 3070, 2926, 2851, 1606, 1569, 1485, 1462, 1412, 1350, 1086 cm^{-1}. HRMS: calcd. 290.1652 [M+H]$^+$ Found: 290.1659.

Additional control experiments



A 4 mL vial was charged with **185** (23.3 mg, 0.1 mmol, 1.0 equiv), [Ir(cod)$_2$]BArF (12.7 mg, 0.01 mmol, 0.1 equiv), **L1** (4.0 mg, 0.01 mmol, 0.1 equiv). The vial was transferred into the glove box. 1,4-Dioxane (0.4 mL) and 1,3-butadiene (20 wt.% in PhMe, 400 µL) were then added. The vial was sealed and heated in a pie-block at 160 °C under stirring for 24 hours. After cooled to room temperature, the reaction mixture was concentrated *in vacuo* before pyrazine (9.0 mg, 0.01125 mmol) was added. No [3+2] adduct or C–C cleavage product was observed through either TLC or crude ^{1}H NMR analysis. The starting material **185** was found to remain in 87% yield determined by ^{1}H NMR in C_6D_6 using pyrazine as the internal standard. The recovery of **185** was further confirmed through isolation by preparative thin layer chromatography. A N–N cleavage by-product was also observed and isolated in about 8-10% yield.



A 4 mL vial was charged with cyclohexanone (9.8 mg, 0.1 mmol, 1.0 equiv) and phenylhydrazine (10.8 mg, 0.1 mmol, 1.0 equiv), and transferred into a glove box. 1,4-Dioxane (1 mL) and a stock solution of *p*-TsOH·H_2O in 1,4-dioxane (0.05 M, 10 µL, 0.005 equiv) was then added. The vial was sealed, transferred out of the glove box, and heated in a pie-block at 90 °C overnight. After cooled to room temperature, the vial was charged with [Ir(cod)$_2$]BArF (12.7 mg, 0.01 mmol, 0.1 equiv) and **L1** (4.0 mg, 0.01 mmol, 0.1 equiv), *immediately* transferred into a glove box, and purged under N_2 atmosphere for 3 mins. Pre-dried 3Å molecular sieve (100 mg) and 1,3-butadiene (20 wt.% in PhMe, 400 µL) were then added. The vial was sealed and heated in a pie-block at 160 °C under stirring for 24 hours. After cooled to room temperature, the reaction was filtered through a short plug of Celite. The filtrate was *immediately* concentrated *in vacuo* before pyrazine (8.0 mg, 0.1 mmol) was added. No [3+2] adduct or C–C cleavage product was observed through either TLC or crude ^{1}H NMR analysis. A large amount of phenyl hydrazone of cyclohexanone was recovered as determined by ^{1}H NMR analysis using pyrazine as the internal standard.

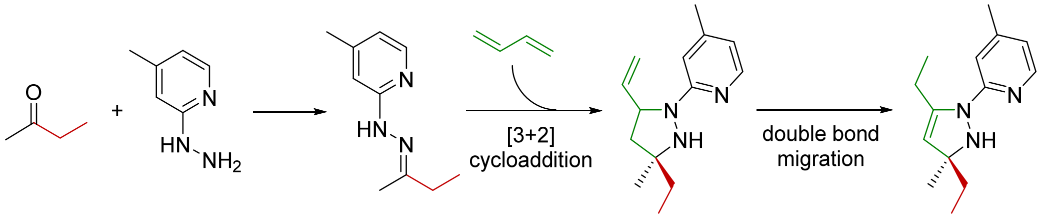
3.2.2 Density functional theory (DFT) studies

3.2.2.1 Computational Details

All geometry optimizations and single-point energy calculations were carried out using Gaussian 09.[36] Geometries of intermediates and transition states were optimized using the B3LYP functional[37] with a mixed basis set of SDD for Ir and 6-31G(d) for other atoms in the gas phase. Vibrational frequency calculations were performed for all the stationary points to confirm if each optimized structure is a local minimum or a transition state structure. Solvation energy corrections were calculated in 1,4-dioxane solvent with the SMD continuum solvation model[38] based on the gas-phase optimized geometries. The M06-L functional[39] with a mixed basis set of SDD for Ir and 6-311+G(d,p) for other atoms was used for solvation single-point energy and the Mulliken spin density calculations. Because the computed energy of the singlet diradical transition states (**160-TS** and **160'-TS**) may be overestimated due to spin-contamination, we performed spin projection corrections using the procedure proposed by Yamaguchi and co-workers using the same method and basis set.[40] This energy results are used for energy discussion. The nucleus-independent chemical shifts (NICS) calculations[41] were performed using the NICS(1)$_{zz}$ method at the B3LYP/6-311+G(d,p)−SDD level of theory in the gas phase using Gaussian 09 and Multiwfn.[42] Previous studies indicated the NICS(1)$_{zz}$ aromaticity index provides good correlation with aromatic stabilization energies of mono- and heterocyclic five-membered rings.[43] Therefore, the NICS(1)$_{zz}$ values provide a reliable, quantitative description of local aromaticity. Previous benchmark calculations indicated the NICS(1)$_{zz}$ values calculated at the B3LYP/6-311+G(d,p)−SDD level of theory provide good agreement with experimental chemical shifts.[44]

3.2.2.2 Detailed Discussions of Computational Studies of the C–C Bond Activation Mechanisms

Scheme S1 | The formation of dihydropyrazole **165** from ketone and hydrazine



165'

165

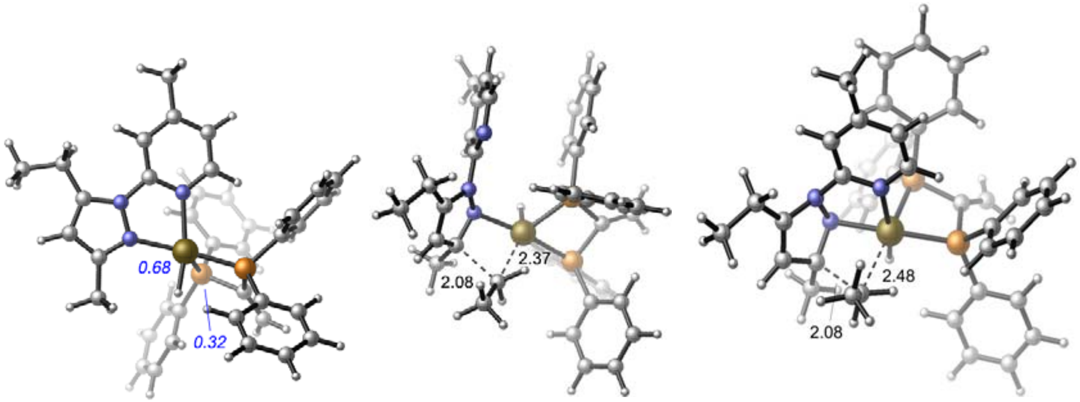
To investigate the mechanism and the driving force of the C–C bond cleavage, we performed density functional theory (DFT) calculations at the M06-L/6-311+G(d,p)−SDD/SMD(1,4-dioxane)//B3LYP/6-31G(d)−SDD level of theory. Experimental mechanistic studies (see *Supplementary Information, Section 3.2.1*) suggested the C–C bond activation of unstrained ketone takes place via a [3+2] cycloaddition between 1,3-butadiene and the hydrazone intermediate to give pyrazolidine **Int I** (Fig. 1b), which then undergoes double bond migration to generate dihydropyrazole **Int II**. In our DFT calculations, dihydropyrazole **165** (Scheme S1) was used as a model substrate, in which an ethyl group was used to model the long alkyl chain in ketone **1**. The computed energy profiles of the Ir-catalyzed C–C bond cleavage of **165** are shown in Extended Data Fig. 3. Dihydropyrazole **165** is expected to bind to the iridium(I) catalyst in a bidentate fashion to form a square planar complex **155**. Subsequent N–H oxidative addition[45] affords an Ir(III) hydride complex **157** via transition state **156-TS**. The oxidative addition is slightly exergonic by 3.2 kcal/mol and requires an activation free energy of activation of 20.3 kcal/mol. Complex

157 is square-based pyramidal with the hydride at the apical position. Complex **157** then undergoes pseudorotation[46] to isomerize to a trigonal bipyramidal isomer **159**. The pseudorotation requires a relatively low barrier (via transition state **158-TS**) and is almost thermoneutral, suggesting a rapid equilibrium between these two Ir(III) hydride isomers.[47] Our DFT calculations indicated the most favorable C–C bond cleavage process occurs from complex **159** (see Figure S5 for C–C bond cleavage pathways from **157** and other Ir complexes). From **159**, three different C–C bond cleavage mechanisms were considered computationally. The most favorable pathway involves a homolytic cleavage of the exocyclic $C(sp^3)$–$C(sp^3)$ bond to form a free ethyl radical and an Ir(II) complex **161** through an open-shell singlet transition state **160-TS**. This homolytic C–C bond cleavage requires a surprisingly low activation Gibbs free energy of 29.5 kcal/mol with respect to **159**, indicating such process is kinetically feasible under the experimental conditions (120-160 °C). The bond dissociation enthalpy (BDE) of the breaking C–C bond in **159** is only 36.5 kcal/mol, which is unusual for an acyclic C–C bond involving a primary carbon.[48] This homolytic C–C bond cleavage is facilitated by the formation of a stable aromatic pyrazole complex **161**.[49] The NICS$(1)_{zz}$ calculations indicated a significant increase of aromaticity of the five-membered pyrazole ring in **161** compared to the dihydropyrazole complex **159**.[50] The relatively long cleaving C–C bond distance in **160-TS** (2.40 □) indicates that the bond cleavage transition state is relatively late. As such, a substantial amount of aromaticity is already building up in **160-TS**, and thus stabilizing the transition state. As a comparison, without the driving force of aromatization, the corresponding C–C cleavage from pyrazolidine **165'** requires a significantly higher activation energy (Extended Data Fig. 3b)

The homolytic C–C bond cleavage forms an ethyl radical and an Ir complex **161**. The spin density in **161** is delocalized to the Ir through an inner-sphere single electron-transfer from the pyrazole ligand to reduce the Ir(III) center to Ir(II).[51] The DFT calculations indicated the spin density of **161** resides primarily on the Ir (Figure S3), and thus the formal oxidation state of Ir in this radical intermediate should be Ir(II). The subsequent recombination between **161** and the ethyl radical forms a new Ir−Et bond and generate an Ir(III) complex **162**. This radical recombination process is highly exothermic and is expected to be very fast. Although we cannot locate a transition state for the radical recombination, the reaction coordinate for the Ir−C bond formation to form **162** was computed and is shown in Figure S4. Complex **162** then undergoes facile C–H reductive elimination (via **163-TS**) to extrude ethane and subsequent ligand exchange to release the pyrazole product **3**.

An alternative mechanism to form the Ir(III) complex **162** from **159** is via a four-membered cyclic β-carbon elimination.[52] This would be a concerted process without formation of an alkyl radical intermediate. The β-carbon elimination transition state (**168-TS**) requires a very high activation free energy of 43.7 kcal/mol with respect to **159**. The high barrier to β-carbon elimination is largely due to the unfavorable distortion in the fused cyclic transition state (Figure S3). Dissociation of the pyridine ligand would relieve such ring strain in the β-carbon elimination. However, this alternative β-carbon elimination process (**167-TS**) requires an even higher barrier, due to the unfavorable dissociation of the pyridine ligand to form **166**. Therefore, the DFT calculations suggest that the β-carbon elimination pathways are unlikely due to the significant distortion of the pyridine ligand in the transition state.

Taken together, these DFT calculations indicated that the most favorable C–C bond cleavage mechanism is via an outer-sphere homolytic cleavage to generate a free alkyl radical and a transient Ir(II) complex. These two species then rapidly recombine to form an alkyl−Ir(III) intermediate before liberating the alkane and pyrazole products.



161 **167-TS** **168-TS**

Figure S3 | Optimized structures of intermediate **161,** transition states **167-TS** and **167-TS**. Bond lengths are shown in Å. The Mulliken spin populations of the radical intermediate **161** are shown in blue.

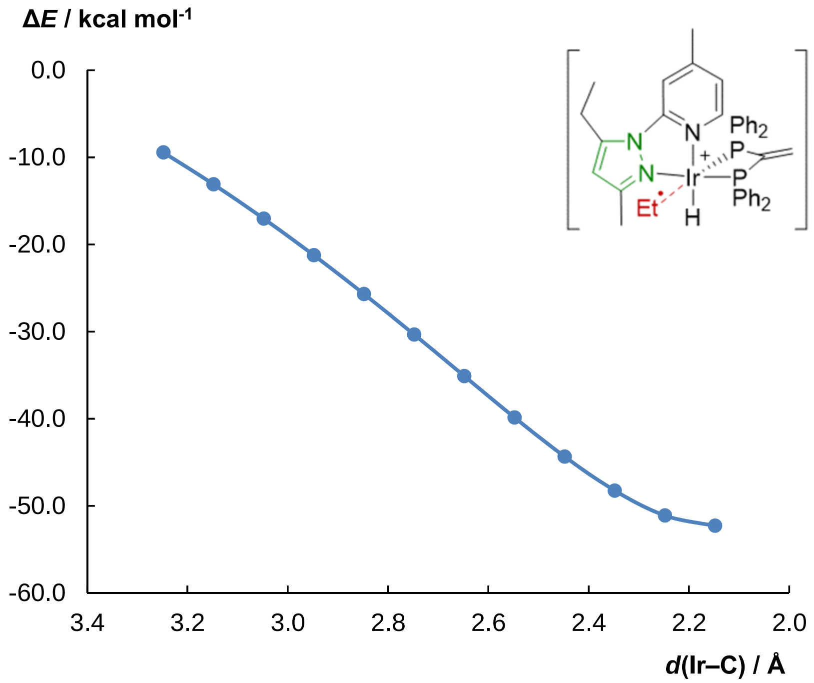


Figure S4 | Computed reaction coordinate of the radical recombination of the ethyl radical with the iridium(II) hydride complex **161**. The vertical axis is the relative energy with respect to separated iridium(II) hydride complex **161** and ethyl radical.

3.2.2.3 Other possible homolytic C–C cleavage pathways

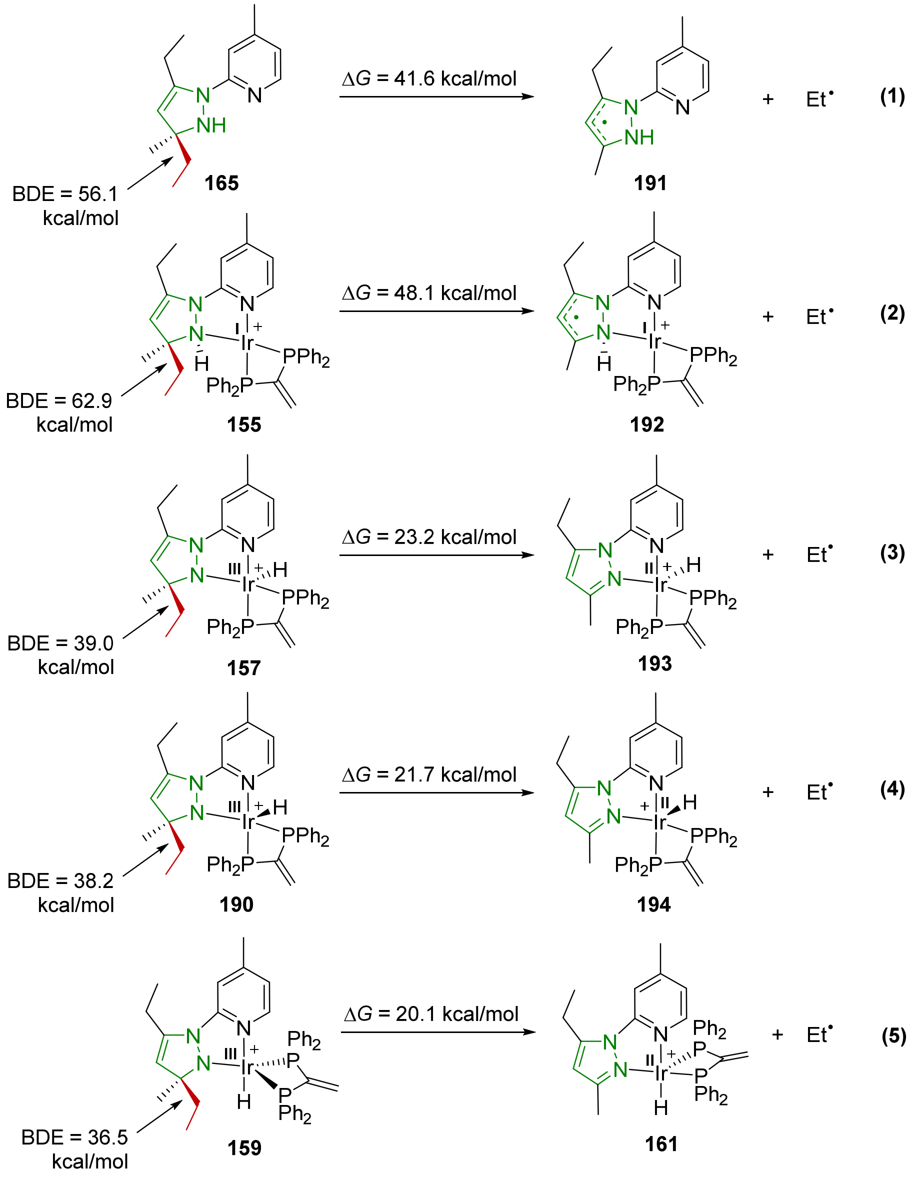


Figure S5 | Other possible homolytic C–C cleavage pathways from dihydropyrazole **165**, Ir(I) hydride complex **155**, Ir(III) hydride complex **157** and **190**. The bond dissociation energy (BDE) of the C–C bond in every complex and the Gibbs free energies (ΔG_{diss}) are shown.

To provide further insights into the thermodynamic driving force of the C–C bond cleavage step, we compared a series of computed bond-dissociation enthalpies (BDE) and Gibbs free energies (ΔG_{diss}) of dihydropyrazole and pyrazolidine complexes with or without coordination to an Ir catalyst (Figure S5). These calculations indicate that without the coordination to the Ir, the BDE of the exocyclic C–C bond in dihydropyrazole **165** is 56.1 kcal/mol, which is 19.6 kcal/mol higher than that in Ir(III) complex **159** (36.5 kcal/mol, eq 5). The homolytic C–C cleavage of Ir(I) complex **155** (eq 2) is also highly disfavored, because a stabilizing aromatic ring is not formed in this case. The homolytic C–C cleavage processes from Ir(III) hydride isomers **157**, **159**, and **190** are all relatively favorable

(BDE = 36~39 kcal/mol), as all reactions form aromatic pyrazole complexes with Ir(II). The C–C cleavage from complex **159** is slightly more favorable thermodynamically than from the other two Ir(III) hydride conformers.

3.2.2.4 An alternative pathway to form Ir(III) hydride 159

Oxidation addition with the N–H bond in **195**, which is the diastereomer of **155**, was also considered by the DFT study. The computed energy profile from **195** to **159** is shown in Figure S4. Complex **195** is only slightly less stable than its diastereomer **155**. The N–H oxidation towards the metal center generates Ir(III) hydride isomer **190** via transition state **156b-TS**. The following pseudorotation occurs through transition state **158b-TS**, which leads to the same intermediate **159** from the N–H oxidation addition/pseudorotation of **155**. The activation free energy of transition state **156b-TS** is 20.7 kcal/mol, which is similar to that of transition state **156-TS** (20.3 kcal/mol). The relative free energies of **158b-TS** and **158-TS** are also similar.

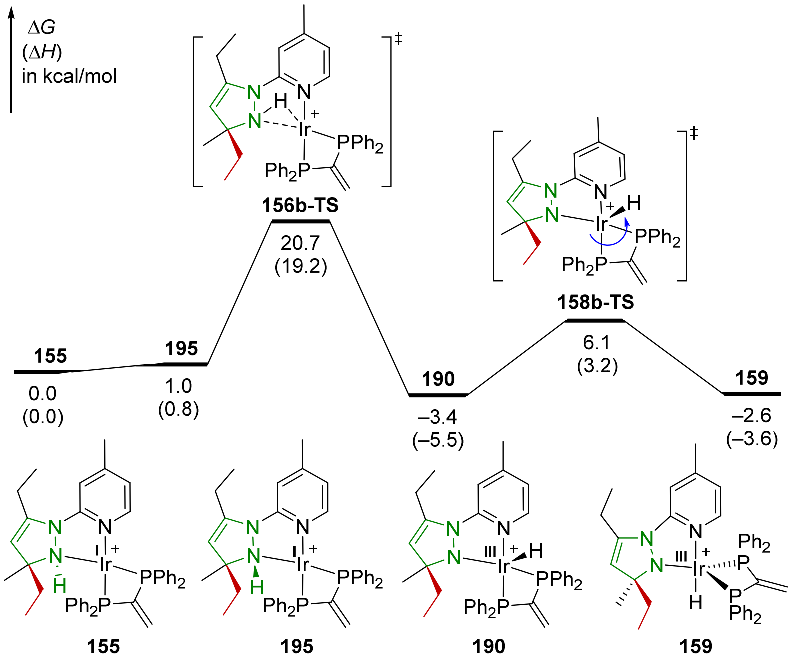


Figure S6 | An alternative pathway to form Ir(III) hydride **159** through N–H oxidation addition to form iridium(III) hydride isomer **190** and subsequent pseudorotation.

3.2.2.5 Benchmark of Computational Methods

The activation free energies of the C–C bond cleavage step were calculated using a few different levels of theories. Single point calculations using the M06-L, B3LYP-D3(BJ),[53] M06,[54] and M11-L[55] functionals were performed for the C–C bond cleavage transition states **168-TS** and **160-TS** in 1,4-dioxane (Table S1). A different implicit solvation model (CPCM) and a different basis set (def2-TZVP) were also considered (entries 5 and 6). In general, the M06-L, B3LYP-D3(BJ), and M11-L functionals give similar results (entries 1, 2, and 4), while M06 gives higher activation energies (entry 3), especially for the open-shell singlet transition state **160-TS**. Neither the solvation model nor the basis set has a significant impact on the computed barriers. We also reoptimized the structures of **155**, **168-TS**, and **160-TS** using M06-L/6-31G(d)−SDD/SMD in 1,4-dioxane, and then calculated the single-point energies in solution at M06-L/6-311+G(d,p)−SDD/SMD level of theory (entry 7). The results are consistent with those in entry 1. These results indicate the use of B3LYP and M06-L in geometry optimization gives comparable results. Because the computed energy of the singlet diradical transition state **160-TS** may be overestimated due to spin-contamination, we performed spin projection corrections using the procedure proposed by Yamaguchi and co-workers.[40] The free energies of **160-TS** decrease by around 3.0 kcal/mol after spin projection. This value is used for energy discussion in this work. These results show that M06 functional overestimate the free energy of the open-shell singlet transition state **160-TS**, while M06-L, B3LYP-D3(BJ), and M11-L afford similar results. Taken together, most computational methods considered here provide similar activation energies for the C–C bond cleavage. M06 appears to overestimate the energy of the open-shell singlet transition state **160-TS**. Most importantly, calculations at all levels of theories indicate the homolytic C-C bond cleavage (**160-TS**) is more favorable than the β-C elimination (**168-TS**).

Table S1 | Comparison of Computational Methods for the Activation Energies of the C–C Bond Cleavage.

		ΔG_{solv}[a]			
Entry	Method[b]	**155**	**168-TS**	**160-TS**[c]	**160-TS-SP**[d]
1	M06-L/6-311+G(d,p)−SDD/SMD	0.0	41.1	29.9	26.9
2	B3LYP-DJ(BJ)/6-311+G(d,p)−SDD/SMD	0.0	40.1	31.5	28.2
3	M06/6-311+G(d,p)−SDD/SMD	0.0	46.4	39.4	36.0
4	M11-L/6-311+G(d,p)−SDD/SMD	0.0	41.8	34.9	32.4
5	M06-L/6-311+G(d,p)−SDD/CPCM	0.0	39.6	29.8	26.8
6	M06-L/def2-TZVP/SMD	0.0	41.3	28.3	25.3
7	M06-L/6-311+G(d,p)−SDD/SMD//M06-L[e]	0.0	41.0	32.1	29.0

[a] All energies are in kcal/mol with respect to **155**.
[b] Geometries were optimized at the B3LYP/6-31G(d)−SDD level of theory in the gas phase except entry 7.
[c] Relative Gibbs free energy of **160-TS** without spin projection.
[d] Relative Gibbs free energy of **160-TS** after spin projection. This value is used for energy discussion.
[e] The structures were optimized at M06-L/6-31G(d)−SDD/SMD level in 1,4-dioxane.

3.2.2.6 Additional experimental evidence for Ir(II)/alkyl radical recombination

The recombination of the Ir(II) and alkyl radical intermediates could be indirectly supported by the observation of a small amount of olefin product **174** from **172** under the standard condition, which is likely generated through *β*-H elimination from a Ir(III)-alkyl species (Figure S2). By fine-tuning the ligand, a new bisphosphine ligand **L3** was found to further promote the *β*-H elimination process. A preliminary result shows that the olefin product **196** can be isolated in 50% yield using ligand **L3** from cyclopentanone-derived hydrazone **170** (Figure S7).

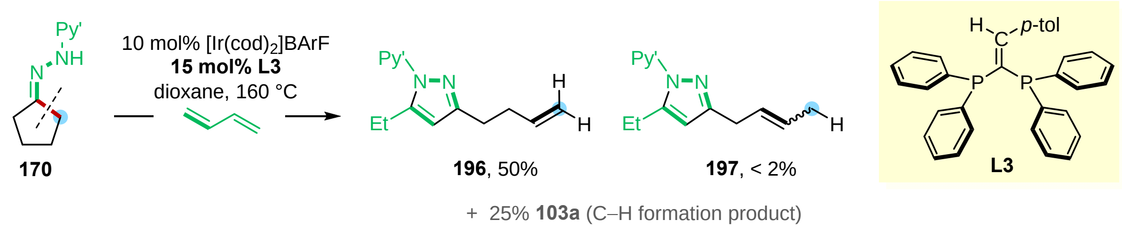


Figure S7 | Olefin formation through *β*-H elimination

Detailed experimental procedures for section 3.2.2.6: A 4 mL vial was charged with the **170** (9.5 mg, 0.05 mmol, 1.0 equiv), [Ir(cod)$_2$]BArF (6.4 mg, 0.005 mmol, 0.1 equiv) and **L3** (3.6 mg, 0.0075 mmol, 0.15 equiv). The vial was transferred into the glove box. 1,4-Dioxane (0.5 mL) and 1,3-butadiene (20 wt.% in PhMe, 160 µL, ca. 12 equiv) were then added. The vial was sealed, transferred out of the glove box, and heated in a pie-block at 160 °C under stirring for 18 hours. Two parallel reactions were set up. After cooled to room temperature, the reactions were combined, concentrated *in vacuo*, and further purified by flash column chromatography over silica (hexane/ethyl acetate, from 40:1 to 20:1) to give the pyrazole products**.** The protonation product **103a** was obtained as a colorless oil (6.0 mg, 25% yield), whose spectra have been reported *vide supra*. Olefin compound **196** was obtained as a colorless oil (12.0 mg, 50% yield). R_f = 0.29 (Hex/EA = 10:1) (slightly more polar than compound **103a**). ^{1}H NMR (400 MHz, CDCl$_3$) δ 8.27 (d, *J* = 5.1 Hz, 1H), 7.64 (s, 1H), 6.97 (d, *J* = 4.4 Hz, 1H), 6.06 (s, 1H), 5.92 (ddt, *J* = 16.9, 10.2, 6.6 Hz, 1H), 5.09 (dd, *J* = 17.1, 1.8 Hz, 1H), 5.00 (dd, *J* = 10.2, 1.2 Hz, 1H), 3.10 (q, *J* = 7.4 Hz, 2H), 2.86 – 2.68 (m, 2H), 2.45 (q, *J* = 7.6, 7.1 Hz, 2H), 2.40 (s, 3H), 1.24 (t, *J* = 7.5 Hz, 3H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 153.90, 153.65, 149.75, 147.90, 147.37, 138.31, 122.24, 117.07, 115.02, 105.80, 33.71, 28.09, 21.51, 21.29, 13.28. IR (KBr) 3059, 2977, 2929, 1611, 1569, 1479, 1420, 1001 cm^{-1}. HRMS: calcd. 242.1652 [M+H]$^+$ Found: 242.1661.

3.2.2.7 Cartesian coordinates and energies of optimized structures

3
B3LYP SCF energy: -630.55767519 a.u.
B3LYP enthalpy: -630.289585 a.u.
B3LYP free energy: -630.347765 a.u.
M06L SCF energy in solution: -630.65239754 a.u.
M06L enthalpy in solution: -630.384307 a.u.
M06L free energy in solution: -630.442487 a.u.

Cartesian coordinates

ATOM	X	Y	Z
C	2.167054	-1.668284	-0.000046
C	2.837009	-3.008624	-0.000072

H	2.084940	-3.802159	-0.000107
H	3.475183	-3.136152	-0.883116
H	3.475157	-3.136204	0.882983
N	0.846586	-1.576236	-0.000064
N	0.571760	-0.234331	-0.000037
C	-0.785733	0.162303	-0.000040
C	-1.791205	-0.820359	0.000123
C	-2.321233	1.849332	-0.000192
C	-3.122716	-0.416395	0.000108
H	-1.511690	-1.865680	0.000268
H	-2.494749	2.924206	-0.000292
C	-3.389798	0.963686	-0.000041
N	-1.035096	1.470767	-0.000194
H	-4.410659	1.335576	-0.000023
C	-4.245263	-1.424900	0.000147
H	-4.886401	-1.299356	0.881268
H	-4.884485	-1.301488	-0.882676
H	-3.863425	-2.449859	0.001761
C	1.729503	0.529559	0.000000
C	2.765591	-0.380518	-0.000008
H	3.820926	-0.150058	0.000029
C	1.794518	2.031877	0.000048
H	1.248802	2.421526	0.866514
H	1.248949	2.421575	-0.866490
C	3.232078	2.564450	0.000186
H	3.226425	3.659516	0.000225
H	3.784650	2.232164	0.886311
H	3.784798	2.232231	-0.885871

155

B3LYP SCF energy: -2501.33147623 a.u.
B3LYP enthalpy: -2500.546704 a.u.
B3LYP free energy: -2500.676393 a.u.
M06L SCF energy in solution: -2501.65947032 a.u.
M06L enthalpy in solution: -2500.874698 a.u.
M06L free energy in solution: -2501.004387 a.u.

Cartesian coordinates

ATOM	X	Y	Z
C	-3.890545	0.424156	1.146567
H	-4.321567	1.409393	1.315845
H	-4.467199	-0.424129	1.510164
C	-2.702617	0.268821	0.557044
P	-1.428048	1.500099	0.052818
P	-1.611956	-1.222791	0.390112
C	-2.313907	-2.251007	-0.974330
C	-2.859143	-1.613572	-2.101681
C	-2.235873	-3.653398	-0.963267
C	-3.320661	-2.361530	-3.184561
H	-2.929864	-0.530918	-2.138082
C	-2.696916	-4.399106	-2.050570
H	-1.836664	-4.173506	-0.098265
C	-3.239753	-3.755886	-3.163299
H	-3.747227	-1.852824	-4.044450
H	-2.636631	-5.483477	-2.021431

H	-3.601871	-4.336685	-4.006698
C	-1.870492	-2.208813	1.922709
C	-0.940151	-2.078859	2.966457
C	-3.010807	-3.006284	2.122386
C	-1.135651	-2.742813	4.178793
H	-0.076682	-1.432542	2.826692
C	-3.204561	-3.666976	3.336291
H	-3.742981	-3.123152	1.329113
C	-2.267051	-3.539475	4.364182
H	-0.408215	-2.634149	4.978479
H	-4.088336	-4.282459	3.478381
H	-2.420491	-4.056935	5.306829
C	-1.933900	2.147771	-1.594501
C	-0.950478	2.371301	-2.570826
C	-3.277532	2.418346	-1.903815
C	-1.301076	2.875275	-3.824453
H	0.086290	2.132184	-2.353245
C	-3.625898	2.916664	-3.160329
H	-4.055836	2.230370	-1.169633
C	-2.637855	3.149583	-4.120228
H	-0.531619	3.044203	-4.572500
H	-4.668090	3.120154	-3.389557
H	-2.910929	3.536242	-5.097883
C	-1.530399	2.936341	1.200154
C	-2.139335	4.154102	0.860450
C	-0.973046	2.781476	2.482366
C	-2.198017	5.193866	1.792013
H	-2.563657	4.298506	-0.127796
C	-1.038784	3.820198	3.409479
H	-0.482779	1.846175	2.740674
C	-1.651959	5.028545	3.065449
H	-2.670597	6.133076	1.518727
H	-0.607403	3.689487	4.397974
H	-1.699180	5.839280	3.786931
Ir	0.306332	0.031045	0.138442
C	2.156899	-2.602991	-0.651014
C	1.597143	-2.398777	-2.077311
H	1.788246	-3.336373	-2.616505
H	0.509558	-2.291264	-2.002053
C	2.172351	-1.229019	-2.880311
H	1.753720	-1.235531	-3.892171
H	1.907529	-0.269464	-2.423487
H	3.262302	-1.290227	-2.968886
C	1.468908	-3.792499	0.028996
H	0.391750	-3.630227	0.116092
H	1.623071	-4.696486	-0.567942
H	1.882925	-3.978879	1.026944
N	1.962035	-1.370174	0.244855
H	1.882809	-1.740011	1.196460
N	3.248436	-0.679441	0.260138
C	3.223725	0.704188	0.148072
C	4.399368	1.480322	0.175975
C	1.950972	2.649532	0.013212
C	4.338665	2.864668	0.094181
H	5.359873	1.003545	0.287689
H	0.958576	3.077933	-0.017735
C	3.065671	3.457268	0.007027

N	1.998559	1.292569	0.072028
H	2.947346	4.534327	-0.047927
C	5.587383	3.706043	0.113207
H	5.689826	4.267544	-0.823324
H	5.549907	4.441287	0.925356
H	6.486506	3.097798	0.243977
C	4.251989	-1.623838	-0.152589
C	3.659725	-2.725603	-0.624318
H	4.177214	-3.614236	-0.958426
C	5.727951	-1.386253	0.033587
H	5.899244	-0.973904	1.036532
H	6.075321	-0.628240	-0.680084
C	6.576255	-2.650999	-0.148785
H	7.630612	-2.416100	0.023629
H	6.282777	-3.433797	0.557857
H	6.488118	-3.051372	-1.163871

156-TS

B3LYP SCF energy: -2501.29184251 a.u.
B3LYP enthalpy: -2500.513965 a.u.
B3LYP free energy: -2500.641210 a.u.
M06L SCF energy in solution: -2501.62268473 a.u.
M06L enthalpy in solution: -2500.844807 a.u.
M06L free energy in solution: -2500.972052 a.u.
Imaginary frequency: -1199.5043 cm-1

Cartesian coordinates

ATOM	X	Y	Z
C	-3.574858	-0.158276	1.825704
H	-4.031776	0.733828	2.250214
H	-3.975003	-1.113272	2.159958
C	-2.552324	-0.083145	0.970073
P	-1.548482	1.357823	0.422408
P	-1.440087	-1.383234	0.271235
C	-2.235287	-1.963089	-1.279551
C	-3.528197	-2.514162	-1.275727
C	-1.555938	-1.811307	-2.496849
C	-4.122677	-2.915139	-2.470817
H	-4.070036	-2.633553	-0.341555
C	-2.153887	-2.216982	-3.692306
H	-0.564734	-1.366995	-2.503098
C	-3.435075	-2.769255	-3.679896
H	-5.122242	-3.340190	-2.460169
H	-1.619730	-2.097626	-4.630623
H	-3.901269	-3.083184	-4.609458
C	-1.514150	-2.815582	1.422821
C	-1.376304	-2.590195	2.803871
C	-1.636255	-4.133154	0.954790
C	-1.372799	-3.661018	3.696372
H	-1.273327	-1.577424	3.182590
C	-1.625808	-5.203177	1.852829
H	-1.745271	-4.328916	-0.106951
C	-1.496514	-4.970193	3.222307
H	-1.273591	-3.473676	4.761761
H	-1.723055	-6.218158	1.478323

H	-1.492857	-5.803607	3.918820
C	-2.428176	2.072562	-1.025026
C	-1.693753	2.451621	-2.159424
C	-3.824544	2.226048	-1.031090
C	-2.340527	2.999341	-3.268447
H	-0.618173	2.302713	-2.182942
C	-4.468401	2.770770	-2.142417
H	-4.413330	1.908274	-0.175419
C	-3.726937	3.162585	-3.259855
H	-1.762333	3.289609	-4.141064
H	-5.548793	2.883022	-2.137947
H	-4.230568	3.584415	-4.124826
C	-1.565419	2.645075	1.732160
C	-2.367469	3.794945	1.667388
C	-0.733417	2.447325	2.848653
C	-2.345070	4.724044	2.710242
H	-3.003171	3.973712	0.806467
C	-0.719599	3.375418	3.888435
H	-0.092207	1.570609	2.888738
C	-1.526298	4.514968	3.820900
H	-2.967690	5.612147	2.650739
H	-0.073833	3.214437	4.747038
H	-1.511113	5.240543	4.629125
Ir	0.345048	0.096161	0.044100
C	2.553076	-2.429460	0.048146
C	1.965482	-3.249869	-1.131679
H	2.297998	-4.288704	-1.005479
H	0.874153	-3.258723	-1.020493
C	2.343632	-2.753155	-2.527993
H	1.866334	-3.372589	-3.294720
H	2.020060	-1.717569	-2.680457
H	3.425986	-2.795866	-2.689974
C	2.145450	-3.065885	1.389960
H	1.060086	-3.122875	1.491897
H	2.543759	-4.084485	1.453663
H	2.551000	-2.488365	2.226936
N	2.118723	-0.998173	-0.041883
N	3.272880	-0.201052	-0.243165
C	3.093169	1.139613	-0.407751
C	4.134747	2.063858	-0.684437
C	1.562380	2.913135	-0.358906
C	3.871881	3.414881	-0.786365
H	5.143779	1.714562	-0.826554
H	0.534135	3.213301	-0.210007
C	2.536838	3.846792	-0.599255
N	1.797032	1.572001	-0.286641
H	2.273639	4.897872	-0.650631
C	4.964080	4.407461	-1.085269
H	5.045704	5.148766	-0.281191
H	5.936632	3.921049	-1.200035
H	4.747034	4.958985	-2.007968
C	4.439387	-1.025608	-0.176208
C	4.048454	-2.295039	-0.025378
H	4.711417	-3.142484	0.075515
C	5.851482	-0.507099	-0.244732
H	5.987641	0.285667	0.501756
H	6.031136	-0.048409	-1.226011

C	6.904861	-1.597575	-0.015555
H	7.905762	-1.159500	-0.068705
H	6.791444	-2.062561	0.968866
H	6.842435	-2.381260	-0.777306
H	1.391966	-0.578638	1.184308

157

B3LYP SCF energy: -2501.33561433 a.u.
B3LYP enthalpy: -2500.555046 a.u.
B3LYP free energy: -2500.681368 a.u.
M06L SCF energy in solution: -2501.66370247 a.u.
M06L enthalpy in solution: -2500.883134 a.u.
M06L free energy in solution: -2501.009456 a.u.

Cartesian coordinates

ATOM	X	Y	Z
C	3.853363	1.194586	-0.320813
H	4.126110	2.246396	-0.259369
H	4.649710	0.508553	-0.600803
C	2.605366	0.776750	-0.097402
P	1.072132	1.745012	0.220074
P	1.829733	-0.893354	-0.342961
C	2.457137	-1.943066	1.033403
C	2.551074	-1.393574	2.323484
C	2.772110	-3.298352	0.845093
C	2.959260	-2.182680	3.398048
H	2.308334	-0.349212	2.494991
C	3.179655	-4.084485	1.924946
H	2.708840	-3.744276	-0.142060
C	3.273655	-3.529854	3.201888
H	3.033940	-1.743416	4.388704
H	3.424727	-5.130367	1.763890
H	3.592544	-4.142568	4.040104
C	2.566192	-1.600672	-1.867919
C	1.788314	-1.697787	-3.031498
C	3.917206	-1.991789	-1.910923
C	2.350658	-2.175293	-4.217299
H	0.745110	-1.399244	-3.003985
C	4.475047	-2.463472	-3.098494
H	4.530987	-1.947018	-1.015966
C	3.692767	-2.555794	-4.253004
H	1.737955	-2.250555	-5.111074
H	5.518778	-2.763426	-3.121166
H	4.129139	-2.927167	-5.175770
C	1.049762	2.205858	1.997480
C	-0.118152	1.994400	2.745233
C	2.177446	2.764049	2.623839
C	-0.162567	2.346798	4.095907
H	-0.984528	1.542824	2.270682
C	2.131619	3.106825	3.974954
H	3.091600	2.930216	2.061177
C	0.960949	2.901135	4.711135
H	-1.071998	2.182213	4.666559
H	3.008408	3.534311	4.452775
H	0.928012	3.169967	5.763016

C	1.201084	3.332449	-0.697509
C	1.004248	4.574213	-0.073493
C	1.459366	3.292443	-2.079979
C	1.073069	5.754127	-0.818971
H	0.802073	4.625821	0.991146
C	1.533880	4.472678	-2.816682
H	1.603788	2.338409	-2.579572
C	1.340141	5.706264	-2.187230
H	0.920811	6.709523	-0.325141
H	1.741757	4.430112	-3.881938
H	1.396519	6.625198	-2.763513
Ir	-0.341512	0.003054	-0.406623
C	-1.566595	-2.938313	0.243595
C	-0.979503	-3.239476	1.651458
H	-0.973628	-4.331385	1.771172
H	0.066453	-2.920501	1.660210
C	-1.721071	-2.595873	2.824762
H	-1.236667	-2.864649	3.769558
H	-1.711494	-1.503499	2.743118
H	-2.764462	-2.925282	2.878120
C	-0.740620	-3.646553	-0.845171
H	0.306718	-3.336756	-0.811541
H	-0.775920	-4.731617	-0.696160
H	-1.139245	-3.417331	-1.837536
N	-1.626772	-1.465320	-0.005633
N	-2.999703	-1.128357	-0.120370
C	-3.291083	0.178930	-0.348031
C	-4.591859	0.745683	-0.379221
C	-2.373748	2.291130	-0.804295
C	-4.765276	2.088633	-0.647836
H	-5.454891	0.131304	-0.179829
H	-1.467455	2.860530	-0.967844
C	-3.610976	2.877233	-0.878972
N	-2.189449	0.969108	-0.533297
H	-3.691864	3.934966	-1.105706
C	-6.136196	2.710805	-0.689579
H	-6.219200	3.521571	0.044131
H	-6.332776	3.149879	-1.675199
H	-6.921969	1.979797	-0.480309
C	-3.812347	-2.300233	-0.055709
C	-3.009990	-3.348103	0.151115
H	-3.333081	-4.375778	0.237960
C	-5.307013	-2.300630	-0.233071
H	-5.564685	-1.778562	-1.163425
H	-5.778200	-1.736442	0.582959
C	-5.908523	-3.710427	-0.266696
H	-6.991281	-3.646719	-0.408996
H	-5.493660	-4.301400	-1.089409
H	-5.725815	-4.247088	0.669894
H	0.073362	0.543240	-1.844753

158-TS

B3LYP SCF energy: -2501.32136778 a.u.
B3LYP enthalpy: -2500.542000 a.u.
B3LYP free energy: -2500.666481 a.u.

M06L SCF energy in solution: -2501.64825875 a.u.
M06L enthalpy in solution: -2500.868891 a.u.
M06L free energy in solution: -2500.993372 a.u.
Imaginary frequency: -39.1583 cm-1

Cartesian coordinates

ATOM	X	Y	Z
C	-3.683894	1.702311	-0.258328
H	-4.577746	1.187842	-0.604521
H	-3.780278	2.773517	-0.091033
C	-2.526581	1.063387	-0.076065
P	-2.013255	-0.675957	-0.446418
P	-0.857251	1.704336	0.380959
C	-0.854188	1.927468	2.204965
C	-1.824916	2.725138	2.836492
C	0.095570	1.253910	2.985560
C	-1.835134	2.849573	4.225238
H	-2.572296	3.249931	2.248291
C	0.086318	1.386745	4.375910
H	0.830389	0.617885	2.500856
C	-0.877796	2.182695	4.995966
H	-2.589154	3.466479	4.705540
H	0.828772	0.864297	4.972289
H	-0.887777	2.282262	6.077562
C	-0.719424	3.391252	-0.333248
C	-1.005886	3.568022	-1.698456
C	-0.313814	4.497264	0.429653
C	-0.900300	4.828778	-2.283030
H	-1.314953	2.721220	-2.305230
C	-0.204547	5.757722	-0.162585
H	-0.084312	4.381418	1.483615
C	-0.498903	5.926327	-1.515812
H	-1.131189	4.954605	-3.336921
H	0.109282	6.606488	0.438151
H	-0.415829	6.908041	-1.972980
C	-2.822053	-1.759707	0.802780
C	-3.001802	-1.304956	2.119898
C	-3.190811	-3.076426	0.477896
C	-3.549043	-2.148076	3.086808
H	-2.723638	-0.291635	2.392971
C	-3.733739	-3.917500	1.451623
H	-3.068572	-3.444410	-0.536390
C	-3.914830	-3.455288	2.755951
H	-3.693444	-1.781175	4.098923
H	-4.020599	-4.930935	1.185796
H	-4.342519	-4.108705	3.510827
C	-2.770464	-1.173676	-2.042698
C	-1.952954	-1.350811	-3.168857
C	-4.161182	-1.344998	-2.168115
C	-2.516548	-1.686694	-4.402052
H	-0.878448	-1.224232	-3.074597
C	-4.719581	-1.671734	-3.402882
H	-4.807439	-1.242859	-1.300761
C	-3.897997	-1.842309	-4.521310
H	-1.874515	-1.826995	-5.266925
H	-5.794650	-1.799172	-3.491620
H	-4.335763	-2.101112	-5.481129

Ir	0.268991	-0.148035	-0.390168
C	3.076996	1.338279	-1.065313
C	3.017862	2.581205	-0.132510
H	3.611961	3.371985	-0.609442
H	1.985025	2.943362	-0.122851
C	3.515760	2.361047	1.297539
H	3.392124	3.275294	1.888106
H	2.956035	1.563085	1.796591
H	4.576973	2.091764	1.319744
C	2.619885	1.738106	-2.485178
H	1.605170	2.146498	-2.455996
H	3.289263	2.501438	-2.897939
H	2.628314	0.868559	-3.148603
N	2.256804	0.212657	-0.549136
N	3.116614	-0.847886	-0.261463
C	2.546312	-2.007330	0.146940
C	3.250924	-3.178401	0.541598
C	0.512267	-3.105302	0.568767
C	2.568890	-4.307953	0.930589
H	4.328598	-3.184363	0.550063
H	-0.565642	-3.031441	0.590566
C	1.146799	-4.257781	0.934773
N	1.169721	-1.967753	0.177129
H	0.560594	-5.117971	1.240949
C	3.288398	-5.561616	1.350755
H	3.015922	-5.843904	2.375074
H	3.013035	-6.403593	0.703758
H	4.374508	-5.441622	1.307949
C	4.463066	-0.508469	-0.618288
C	4.454548	0.742493	-1.088903
H	5.322913	1.284732	-1.435600
C	5.639524	-1.436625	-0.481219
H	5.444073	-2.363679	-1.035078
H	5.765861	-1.721224	0.571840
C	6.949860	-0.821366	-0.986618
H	7.765772	-1.539648	-0.864536
H	6.886230	-0.561561	-2.048110
H	7.211432	0.081526	-0.425404
H	-0.039734	0.583735	-1.764107

159

B3LYP SCF energy: -2501.33562700 a.u.
B3LYP enthalpy: -2500.554670 a.u.
B3LYP free energy: -2500.682757 a.u.
M06L SCF energy in solution: -2501.66135285 a.u.
M06L enthalpy in solution: -2500.880396 a.u.
M06L free energy in solution: -2501.008483 a.u.

Cartesian coordinates

ATOM	X	Y	Z
C	-4.029936	-0.582967	0.361256
H	-4.666585	-0.706778	-0.513155
H	-4.472994	-0.828447	1.324829
C	-2.759438	-0.185288	0.252321
P	-1.662621	-0.016956	-1.234430

P	-1.382032	-0.170620	1.488007
C	-1.731467	-1.450301	2.758007
C	-1.823787	-2.797394	2.365996
C	-1.921736	-1.114797	4.107337
C	-2.108792	-3.785280	3.305869
H	-1.668589	-3.071515	1.327199
C	-2.196828	-2.111345	5.046858
H	-1.857753	-0.081697	4.431157
C	-2.292507	-3.444669	4.649541
H	-2.182260	-4.822293	2.990930
H	-2.338722	-1.839902	6.088938
H	-2.508415	-4.217257	5.381821
C	-1.437395	1.424660	2.386964
C	-0.257193	1.909570	2.974557
C	-2.629978	2.149236	2.537653
C	-0.274278	3.096426	3.707892
H	0.671330	1.357419	2.857520
C	-2.639930	3.341065	3.264423
H	-3.551323	1.782727	2.094978
C	-1.464235	3.814462	3.850978
H	0.641341	3.461432	4.164233
H	-3.567022	3.895925	3.376572
H	-1.475584	4.740126	4.419154
C	-2.292734	-1.131201	-2.548137
C	-1.712754	-2.393854	-2.739322
C	-3.385383	-0.744606	-3.343785
C	-2.223571	-3.260974	-3.706497
H	-0.860656	-2.686706	-2.134979
C	-3.894455	-1.617585	-4.305058
H	-3.829541	0.239297	-3.224534
C	-3.315094	-2.875918	-4.487177
H	-1.764752	-4.234606	-3.853151
H	-4.738944	-1.312080	-4.916113
H	-3.710209	-3.551142	-5.240706
C	-1.899938	1.663080	-1.931510
C	-1.075602	2.053817	-3.001896
C	-2.852846	2.564115	-1.435010
C	-1.210210	3.320623	-3.566674
H	-0.332317	1.365705	-3.396563
C	-2.980055	3.835786	-2.001557
H	-3.500915	2.275776	-0.613683
C	-2.161830	4.214695	-3.066219
H	-0.573560	3.610217	-4.397737
H	-3.724360	4.525108	-1.613093
H	-2.265747	5.201578	-3.507877
Ir	0.295229	-0.506604	-0.067306
C	2.781950	-2.487320	-0.018004
C	2.347921	-3.378013	-1.212138
H	2.829148	-4.355309	-1.075156
H	1.267780	-3.545011	-1.121077
C	2.678379	-2.825789	-2.599975
H	2.332922	-3.516912	-3.376265
H	2.188613	-1.860343	-2.766303
H	3.756943	-2.687540	-2.733185
C	2.381958	-3.159426	1.311916
H	1.298850	-3.308930	1.349755
H	2.876904	-4.132438	1.405488

H	2.676396	-2.536100	2.161520
N	2.157220	-1.134312	-0.105256
N	3.194344	-0.191349	-0.128745
C	2.814610	1.123645	-0.170360
C	3.702607	2.223398	-0.240723
C	0.996517	2.590902	-0.170073
C	3.213073	3.517065	-0.270945
H	4.768061	2.063922	-0.275172
H	-0.080209	2.691800	-0.141906
C	1.812336	3.695964	-0.230462
N	1.461768	1.315959	-0.142601
H	1.373557	4.688054	-0.249666
C	4.138281	4.703685	-0.347887
H	3.943012	5.291823	-1.252641
H	3.986606	5.372606	0.507684
H	5.188894	4.400750	-0.360350
C	4.465970	-0.847102	-0.092956
C	4.249630	-2.165852	-0.040514
H	5.019073	-2.923490	0.001146
C	5.788033	-0.128487	-0.107242
H	5.835127	0.572747	0.736138
H	5.870013	0.474451	-1.021202
C	6.989044	-1.078566	-0.032097
H	7.918340	-0.501736	-0.046551
H	6.973887	-1.669729	0.889122
H	7.007519	-1.766613	-0.883317
H	-0.240044	-2.017590	-0.070794

160-TS

B3LYP SCF energy: -2501.27189044 a.u.
B3LYP enthalpy: -2500.495881 a.u.
B3LYP free energy: -2500.629516 a.u.
M06L SCF energy in solution: -2501.59904813 a.u.
M06L enthalpy in solution: -2500.823039 a.u.
M06L free energy in solution: -2500.956674 a.u.
Imaginary frequency: -382.7487 cm-1

Cartesian coordinates

ATOM	X	Y	Z
C	3.537746	1.770305	0.831470
H	4.483353	1.525818	0.351129
H	3.525346	2.667328	1.447812
C	2.442545	1.029713	0.642229
P	2.126202	-0.351445	-0.559689
P	0.687644	1.342495	1.149227
C	0.463957	3.159655	1.277461
C	0.915487	3.986848	0.233064
C	-0.218682	3.737314	2.360478
C	0.699318	5.362780	0.281221
H	1.437447	3.555451	-0.616147
C	-0.440307	5.115416	2.398168
H	-0.571578	3.117031	3.178180
C	0.018689	5.930495	1.362470
H	1.061760	5.992639	-0.526380
H	-0.966301	5.550626	3.243165

H	-0.150409	7.002862	1.396889
C	0.511464	0.726678	2.872403
C	-0.664230	0.055694	3.239802
C	1.513782	0.931975	3.835552
C	-0.838867	-0.396422	4.549832
H	-1.439109	-0.113236	2.497703
C	1.340268	0.471135	5.140560
H	2.429385	1.452047	3.569116
C	0.163445	-0.192213	5.499501
H	-1.755067	-0.910489	4.826458
H	2.121217	0.633431	5.878070
H	0.029724	-0.548026	6.517044
C	3.206276	-0.097265	-2.021587
C	2.659336	0.387363	-3.218581
C	4.586823	-0.354951	-1.948731
C	3.481247	0.619236	-4.323335
H	1.591499	0.574581	-3.278520
C	5.404229	-0.115155	-3.052816
H	5.021818	-0.758450	-1.038657
C	4.852586	0.372644	-4.240734
H	3.048255	0.987706	-5.249015
H	6.469877	-0.315726	-2.988222
H	5.490679	0.552714	-5.101201
C	2.793437	-1.892208	0.193385
C	2.899761	-3.043046	-0.608875
C	3.131114	-1.974078	1.552720
C	3.340452	-4.247005	-0.060424
H	2.648772	-2.996117	-1.665422
C	3.570277	-3.183415	2.098036
H	3.059580	-1.097094	2.188011
C	3.676153	-4.319675	1.294763
H	3.426771	-5.126465	-0.692222
H	3.836455	-3.232234	3.150125
H	4.023349	-5.257059	1.719837
Ir	-0.150785	0.083235	-0.637298
C	-2.883409	1.494833	-1.502811
C	-2.913233	1.070387	-3.867498
H	-3.730700	1.734868	-4.138758
H	-1.916146	1.481233	-4.003418
C	-3.095320	-0.397053	-4.047367
H	-3.059862	-0.675712	-5.113803
H	-2.297183	-0.961204	-3.548236
H	-4.065552	-0.737186	-3.665206
C	-2.269725	2.855318	-1.653512
H	-1.294540	2.805856	-2.141480
H	-2.928138	3.507127	-2.233768
H	-2.120047	3.306926	-0.664882
N	-2.156276	0.446590	-1.031613
N	-3.064520	-0.514291	-0.599841
C	-2.537527	-1.710498	-0.122250
C	-3.314597	-2.851682	0.138237
C	-0.616781	-2.834284	0.540908
C	-2.718326	-4.004450	0.636132
H	-4.374259	-2.848943	-0.064589
H	0.455703	-2.790164	0.672417
C	-1.327466	-3.974297	0.851933
N	-1.188373	-1.706997	0.050688

H	-0.802612	-4.840339	1.241987
C	-3.523663	-5.244285	0.923074
H	-3.155611	-6.093385	0.335102
H	-3.441319	-5.526440	1.979620
H	-4.582898	-5.104059	0.690687
C	-4.373742	-0.024190	-0.715570
C	-4.266292	1.224834	-1.256978
H	-5.082765	1.895759	-1.477142
C	-5.616584	-0.745931	-0.272733
H	-5.473368	-1.131371	0.745104
H	-5.794270	-1.621360	-0.912790
C	-6.865939	0.143752	-0.302594
H	-7.732721	-0.423770	0.048236
H	-6.748204	1.018068	0.345428
H	-7.085574	0.493112	-1.316558
H	0.331992	1.336061	-1.513529

161

B3LYP SCF energy: -2422.12390982 a.u.
B3LYP enthalpy: -2421.413788 a.u.
B3LYP free energy: -2421.538820 a.u.
M06L SCF energy in solution: -2422.43330392 a.u.
M06L enthalpy in solution: -2421.723182 a.u.
M06L free energy in solution: -2421.848214 a.u.

Cartesian coordinates

ATOM	X	Y	Z
C	3.312444	1.546290	1.280690
H	4.312319	1.267664	0.953251
H	3.239715	2.419174	1.926917
C	2.228826	0.876090	0.877975
P	2.071672	-0.434557	-0.428760
P	0.436830	1.300837	1.102944
C	0.335712	3.128809	1.260967
C	0.888557	3.929672	0.243948
C	-0.337302	3.748366	2.326155
C	0.782600	5.318022	0.303752
H	1.404361	3.465813	-0.592012
C	-0.448161	5.139856	2.375316
H	-0.770236	3.150844	3.121699
C	0.111796	5.927110	1.368827
H	1.223097	5.925289	-0.482126
H	-0.968035	5.606225	3.207440
H	0.028096	7.009160	1.412387
C	-0.057665	0.661711	2.755409
C	-1.387922	0.253790	2.944098
C	0.837536	0.590378	3.835199
C	-1.816365	-0.208911	4.189737
H	-2.089254	0.304562	2.115412
C	0.409445	0.117159	5.076325
H	1.868318	0.907995	3.709327
C	-0.917374	-0.281802	5.255786
H	-2.849845	-0.514679	4.326661
H	1.110408	0.066514	5.904794
H	-1.249059	-0.646670	6.223631

C	3.405684	-0.171665	-1.661216
C	3.107067	0.385247	-2.913143
C	4.738221	-0.498909	-1.352421
C	4.126199	0.620123	-3.838420
H	2.077298	0.626346	-3.157830
C	5.753102	-0.254650	-2.276932
H	4.982991	-0.959203	-0.399111
C	5.448330	0.305544	-3.520581
H	3.884683	1.044439	-4.808831
H	6.779971	-0.508549	-2.029754
H	6.239872	0.488788	-4.241597
C	2.524824	-2.045471	0.337623
C	2.677395	-3.164977	-0.500635
C	2.656500	-2.208594	1.724564
C	2.960854	-4.418278	0.040499
H	2.587767	-3.055170	-1.578311
C	2.937783	-3.467479	2.262868
H	2.546122	-1.356749	2.387561
C	3.090903	-4.572213	1.424170
H	3.085816	-5.273148	-0.618005
H	3.044712	-3.579740	3.338121
H	3.315812	-5.548319	1.844365
Ir	-0.125891	0.102344	-0.880718
C	-2.642774	1.694254	-2.042890
C	-1.860155	2.897373	-2.456397
H	-1.038523	2.615542	-3.123107
H	-2.509190	3.606334	-2.976843
H	-1.419630	3.400405	-1.589174
N	-2.072694	0.628089	-1.476770
N	-3.078728	-0.288778	-1.229544
C	-2.698728	-1.507581	-0.633225
C	-3.588691	-2.565999	-0.419660
C	-0.972640	-2.719525	0.322915
C	-3.147457	-3.738182	0.194445
H	-4.617138	-2.494303	-0.734463
H	0.072641	-2.738734	0.600596
C	-1.800615	-3.795838	0.581593
N	-1.391888	-1.587130	-0.285064
H	-1.394680	-4.674729	1.071984
C	-4.079367	-4.898229	0.426674
H	-3.740364	-5.783941	-0.123789
H	-4.106828	-5.170943	1.488073
H	-5.099791	-4.671063	0.106386
C	-4.300516	0.222175	-1.648855
C	-4.030193	1.471580	-2.163619
H	-4.749843	2.157473	-2.583319
C	-5.636060	-0.460229	-1.539842
H	-5.812214	-0.764371	-0.499512
H	-5.633045	-1.381483	-2.138389
C	-6.799780	0.424590	-2.004721
H	-7.742192	-0.119698	-1.895900
H	-6.868913	1.340381	-1.409185
H	-6.695044	0.703430	-3.057949
H	0.547017	1.317522	-1.679125

162

B3LYP SCF energy: -2501.36360856 a.u.
B3LYP enthalpy: -2500.582968 a.u.
B3LYP free energy: -2500.713253 a.u.
M06L SCF energy in solution: -2501.68683230 a.u.
M06L enthalpy in solution: -2500.906192 a.u.
M06L free energy in solution: -2501.036477 a.u.

Cartesian coordinates

ATOM	X	Y	Z
C	3.127666	1.602899	1.661662
H	4.159512	1.340160	1.435417
H	2.978007	2.470960	2.301099
C	2.099172	0.921265	1.147969
P	2.126267	-0.381806	-0.167356
P	0.286262	1.324223	1.185796
C	0.186009	3.159380	1.328832
C	0.714157	3.939688	0.284117
C	-0.425864	3.800826	2.415480
C	0.641400	5.330630	0.335243
H	1.184510	3.456362	-0.567986
C	-0.506050	5.195664	2.456847
H	-0.839419	3.219087	3.232597
C	0.027982	5.962267	1.421569
H	1.060721	5.921932	-0.474063
H	-0.983000	5.679625	3.304473
H	-0.032112	7.046174	1.458220
C	-0.355737	0.703925	2.795246
C	-1.704440	0.318181	2.862765
C	0.432929	0.626068	3.954114
C	-2.254429	-0.129473	4.065055
H	-2.325761	0.375113	1.972687
C	-0.115983	0.167645	5.153001
H	1.475842	0.927317	3.923886
C	-1.459667	-0.209514	5.210545
H	-3.301039	-0.417994	4.107124
H	0.504203	0.111466	6.043219
H	-1.885744	-0.562578	6.145265
C	3.596335	-0.086903	-1.224309
C	3.465871	0.591187	-2.445690
C	4.873629	-0.491651	-0.796649
C	4.592906	0.862996	-3.223314
H	2.482956	0.897057	-2.786169
C	5.996987	-0.210902	-1.574041
H	4.993229	-1.036112	0.135408
C	5.858340	0.465680	-2.788478
H	4.479372	1.380118	-4.171798
H	6.979159	-0.526676	-1.234093
H	6.733947	0.676851	-3.395611
C	2.510194	-1.989298	0.641237
C	2.708178	-3.116821	-0.177245
C	2.561627	-2.139179	2.034672
C	2.955116	-4.365718	0.391057
H	2.678717	-3.017391	-1.259077
C	2.807375	-3.393901	2.599969
H	2.415138	-1.280349	2.681391
C	3.004524	-4.506728	1.781519

H	3.114258	-5.227256	-0.251119
H	2.851194	-3.496579	3.680557
H	3.201373	-5.479507	2.222976
Ir	-0.018646	0.058717	-0.901362
C	-2.546216	1.679974	-2.004068
C	0.158453	-1.046331	-2.734668
H	1.173563	-1.453470	-2.816128
H	-0.510667	-1.916084	-2.654435
C	-0.165970	-0.290896	-4.028594
H	-0.070518	-0.948517	-4.904892
H	-1.189598	0.101458	-4.032521
H	0.510539	0.557970	-4.186428
C	-1.758362	2.867869	-2.452538
H	-0.925471	2.561516	-3.091697
H	-2.400442	3.552643	-3.012647
H	-1.339733	3.408204	-1.597010
N	-1.982046	0.610729	-1.447961
N	-2.994099	-0.284023	-1.162400
C	-2.627196	-1.501844	-0.549307
C	-3.529088	-2.551903	-0.344816
C	-0.929204	-2.712880	0.442912
C	-3.107197	-3.719351	0.293140
H	-4.547923	-2.481660	-0.689743
H	0.113285	-2.740917	0.728984
C	-1.769529	-3.781957	0.703818
N	-1.332615	-1.585842	-0.175694
H	-1.376903	-4.658622	1.208802
C	-4.051991	-4.869942	0.522030
H	-3.689607	-5.774969	0.020661
H	-4.129591	-5.103349	1.590373
H	-5.055855	-4.653223	0.146997
C	-4.220400	0.248786	-1.539890
C	-3.943749	1.486658	-2.075053
H	-4.662793	2.186000	-2.472998
C	-5.566086	-0.401993	-1.371175
H	-5.695788	-0.718873	-0.328092
H	-5.618108	-1.312866	-1.983175
C	-6.728898	0.518267	-1.763610
H	-7.678177	-0.003201	-1.611201
H	-6.742595	1.428439	-1.155662
H	-6.672960	0.806982	-2.817897
H	0.676702	1.265237	-1.671178

163-TS

B3LYP SCF energy: -2501.31641777 a.u.
B3LYP enthalpy: -2500.538493 a.u.
B3LYP free energy: -2500.670830 a.u.
M06L SCF energy in solution: -2501.64722629 a.u.
M06L enthalpy in solution: -2500.869302 a.u.
M06L free energy in solution: -2501.001639 a.u.
Imaginary frequency: -977.3691 cm-1

Cartesian coordinates

ATOM	X	Y	Z
C	3.182589	1.639061	1.703555

H	4.213354	1.311225	1.580979
H	3.030538	2.565182	2.254580
C	2.162706	0.959474	1.168804
P	2.183684	-0.445343	-0.026513
P	0.372328	1.396231	1.007094
C	0.293309	3.234144	0.878041
C	1.020216	3.862584	-0.147982
C	-0.477308	4.018690	1.748018
C	0.987753	5.248368	-0.289474
H	1.609023	3.261105	-0.835344
C	-0.518797	5.407416	1.593506
H	-1.042607	3.553979	2.548999
C	0.214179	6.024346	0.579986
H	1.561577	5.723618	-1.080259
H	-1.120332	6.004407	2.273166
H	0.185196	7.104200	0.465963
C	-0.417118	1.035135	2.632842
C	-1.781453	0.705471	2.657415
C	0.289342	1.100824	3.843713
C	-2.428297	0.456575	3.868949
H	-2.336497	0.644892	1.725945
C	-0.356164	0.838748	5.053430
H	1.344670	1.355678	3.845455
C	-1.715479	0.518772	5.068390
H	-3.486172	0.208801	3.876624
H	0.201967	0.889565	5.984121
H	-2.216847	0.318413	6.010947
C	3.686184	-0.265274	-1.069019
C	3.647348	0.590473	-2.182450
C	4.891976	-0.905958	-0.740043
C	4.791050	0.797465	-2.953416
H	2.718332	1.092445	-2.438103
C	6.034176	-0.695288	-1.514721
H	4.942292	-1.574102	0.113828
C	5.985736	0.153779	-2.621690
H	4.748292	1.457511	-3.815227
H	6.960823	-1.198032	-1.252899
H	6.875119	0.312389	-3.224801
C	2.461950	-2.003546	0.910440
C	2.513683	-3.215401	0.197403
C	2.556302	-2.030896	2.309067
C	2.665427	-4.425922	0.872404
H	2.445811	-3.213028	-0.887812
C	2.700996	-3.247224	2.982849
H	2.520117	-1.105709	2.875161
C	2.757384	-4.444018	2.267843
H	2.714930	-5.354153	0.310066
H	2.776072	-3.255223	4.066537
H	2.876263	-5.387431	2.792971
Ir	0.084376	-0.046442	-0.813898
C	-2.408269	1.640090	-1.964586
C	0.343767	-1.266305	-2.783973
H	1.379020	-1.451694	-3.087579
H	0.011374	-2.163757	-2.252081
C	-0.540054	-1.002797	-4.005511
H	-0.501200	-1.854846	-4.695560
H	-1.586882	-0.850320	-3.725371

H	-0.214845	-0.115084	-4.560553
C	-1.542234	2.745182	-2.475544
H	-0.565654	2.359354	-2.778389
H	-2.021260	3.234698	-3.329063
H	-1.371897	3.503053	-1.703024
N	-1.911700	0.538786	-1.399291
N	-2.990270	-0.259496	-1.070525
C	-2.738935	-1.538009	-0.509376
C	-3.666377	-2.583211	-0.577647
C	-1.242143	-2.849107	0.642088
C	-3.365622	-3.804292	0.032872
H	-4.596246	-2.471197	-1.116345
H	-0.258011	-2.915920	1.093840
C	-2.122558	-3.921857	0.670698
N	-1.535855	-1.673837	0.062049
H	-1.834313	-4.844362	1.165159
C	-4.341300	-4.952193	0.002749
H	-4.760417	-5.127893	1.001336
H	-5.172999	-4.760414	-0.680932
H	-3.848768	-5.879962	-0.307622
C	-4.175482	0.370451	-1.406501
C	-3.818617	1.571347	-1.980341
H	-4.490791	2.327371	-2.356744
C	-5.556980	-0.156792	-1.126721
H	-5.573383	-0.634039	-0.139213
H	-5.813644	-0.941840	-1.851551
C	-6.635373	0.933394	-1.186246
H	-7.610870	0.501740	-0.943836
H	-6.431175	1.736869	-0.471382
H	-6.708188	1.372997	-2.186062
H	0.650749	0.071845	-2.349050

164

B3LYP SCF energy: -2421.54639507 a.u.
B3LYP enthalpy: -2420.844678 a.u.
B3LYP free energy: -2420.967909 a.u.
M06L SCF energy in solution: -2421.85717867 a.u.
M06L enthalpy in solution: -2421.155462 a.u.
M06L free energy in solution: -2421.278693 a.u.

Cartesian coordinates

ATOM	X	Y	Z
C	3.385891	0.502470	-1.850490
H	3.641006	1.480625	-2.254235
H	3.935822	-0.346577	-2.252170
C	2.420242	0.348276	-0.940411
P	1.154287	1.526107	-0.306136
P	1.589714	-1.168206	-0.287377
C	2.550281	-1.675598	1.195307
C	3.951969	-1.767799	1.167937
C	1.870061	-1.940913	2.393645
C	4.655138	-2.145094	2.311907
H	4.496830	-1.536595	0.256737
C	2.576692	-2.320624	3.536616
H	0.790713	-1.822876	2.432800

C	3.967759	-2.427278	3.495639
H	5.738862	-2.213369	2.281236
H	2.041149	-2.522859	4.459910
H	4.517640	-2.718932	4.385891
C	1.837155	-2.484131	-1.551586
C	1.125698	-2.360152	-2.758556
C	2.678174	-3.590180	-1.364217
C	1.266949	-3.317248	-3.762170
H	0.454221	-1.516860	-2.899282
C	2.812562	-4.549925	-2.371471
H	3.224813	-3.712408	-0.435181
C	2.111919	-4.414650	-3.570207
H	0.714400	-3.210245	-4.691462
H	3.465921	-5.403536	-2.214588
H	2.218730	-5.162371	-4.350892
C	1.884088	2.347200	1.167260
C	1.054742	2.666109	2.254279
C	3.250825	2.661581	1.232793
C	1.579635	3.307696	3.376752
H	0.002898	2.394649	2.229838
C	3.773504	3.299016	2.359151
H	3.910499	2.398243	0.410889
C	2.938388	3.626146	3.429811
H	0.930330	3.548969	4.213676
H	4.832949	3.535294	2.401870
H	3.347611	4.119725	4.306653
C	0.930102	2.858679	-1.556757
C	1.510729	4.130205	-1.431784
C	0.155232	2.566118	-2.693762
C	1.326763	5.087687	-2.432488
H	2.102912	4.377717	-0.556651
C	-0.021371	3.523654	-3.691488
H	-0.309702	1.587428	-2.784888
C	0.564917	4.786200	-3.562288
H	1.780202	6.069123	-2.326247
H	-0.619390	3.287143	-4.567175
H	0.424474	5.533038	-4.338565
Ir	-0.425924	-0.096395	0.002653
C	-1.998261	-2.910490	0.357004
C	-0.830478	-3.834490	0.247761
H	-0.034706	-3.562933	0.946552
H	-1.148388	-4.855734	0.473492
H	-0.408350	-3.822675	-0.761311
N	-1.905995	-1.579917	0.275863
N	-3.196977	-1.089790	0.416970
C	-3.362740	0.308008	0.378152
C	-4.598539	0.941993	0.539724
C	-2.315397	2.355802	0.103860
C	-4.689376	2.332969	0.476004
H	-5.493614	0.369504	0.717028
H	-1.388625	2.879885	-0.084419
C	-3.504350	3.045225	0.247204
N	-2.220476	1.006984	0.170311
H	-3.503193	4.128374	0.180558
C	-6.009065	3.039302	0.638979
H	-5.957645	3.781379	1.443923
H	-6.275614	3.577894	-0.278360

H	-6.818564	2.341521	0.869249
C	-4.096368	-2.133442	0.578635
C	-3.345133	-3.285072	0.543310
H	-3.715774	-4.293934	0.637431
C	-5.586368	-2.019249	0.750026
H	-6.014297	-1.466545	-0.096707
H	-5.812244	-1.435826	1.652738
C	-6.282679	-3.382088	0.855563
H	-7.360068	-3.235628	0.973546
H	-6.122120	-3.984125	-0.044282
H	-5.925177	-3.948986	1.720896

165

B3LYP SCF energy: -710.34502775 a.u.
B3LYP enthalpy: -709.994113 a.u.
B3LYP free energy: -710.058863 a.u.
M06L SCF energy in solution: -710.45172165 a.u.
M06L enthalpy in solution: -710.100807 a.u.
M06L free energy in solution: -710.165557 a.u.

Cartesian coordinates

ATOM	X	Y	Z
C	2.391638	-0.544558	0.098556
C	2.364458	-1.452124	-1.158523
H	1.498188	-1.149168	-1.759275
H	3.252820	-1.220247	-1.762367
C	2.291456	-2.957704	-0.882756
H	2.156571	-3.513039	-1.817893
H	3.203544	-3.335671	-0.406813
H	1.444371	-3.187378	-0.227815
C	3.525903	-0.922695	1.058647
H	3.377995	-1.923604	1.478993
H	4.488529	-0.917061	0.535590
H	3.590446	-0.205067	1.884866
N	1.082305	-0.648424	0.823160
H	1.271466	-0.462257	1.811525
N	0.300846	0.475462	0.378509
C	-1.042186	0.245486	0.081032
C	-1.666432	-0.955035	0.489744
C	-3.009468	1.030136	-0.793332
C	-3.017925	-1.141006	0.225571
H	-1.082166	-1.717330	0.988984
H	-3.514225	1.846560	-1.308760
C	-3.712075	-0.111865	-0.435971
N	-1.705848	1.222962	-0.552106
H	-4.770083	-0.203493	-0.664532
C	-3.723335	-2.411215	0.635007
H	-4.565362	-2.196074	1.304501
H	-4.134232	-2.932400	-0.238647
H	-3.046662	-3.098843	1.151254
C	1.177863	1.446980	-0.191253
C	2.405479	0.918095	-0.307063
H	3.278865	1.443641	-0.673443
C	0.761088	2.857176	-0.500885
H	-0.011981	2.850440	-1.273289

H	1.641120	3.368029	-0.910047
C	0.234031	3.622411	0.723737
H	0.009368	4.660558	0.453976
H	-0.685776	3.164047	1.097937
H	0.973122	3.633864	1.533250

166

B3LYP SCF energy: -2501.27638962 a.u.
B3LYP enthalpy: -2500.497442 a.u.
B3LYP free energy: -2500.630753 a.u.
M06L SCF energy in solution: -2501.60592700 a.u.
M06L enthalpy in solution: -2500.826979 a.u.
M06L free energy in solution: -2500.960290 a.u.

Cartesian coordinates

ATOM	X	Y	Z
C	-2.808546	-1.159363	2.533743
H	-3.314280	-2.119015	2.443681
H	-2.804388	-0.704147	3.522573
C	-2.193395	-0.586943	1.494866
P	-1.801807	-1.231848	-0.199338
P	-1.010693	0.840682	1.445124
C	-0.202865	1.019159	3.074333
C	1.114246	0.572098	3.257097
C	-0.906056	1.576037	4.157548
C	1.716103	0.670349	4.512939
H	1.669783	0.167974	2.416549
C	-0.299805	1.665968	5.409867
H	-1.915548	1.953890	4.020838
C	1.010135	1.211885	5.588556
H	2.739411	0.331803	4.645787
H	-0.846281	2.097447	6.243455
H	1.481790	1.289855	6.563893
C	-1.969242	2.381826	1.205592
C	-1.273214	3.604685	1.210813
C	-3.353168	2.376709	0.976633
C	-1.956069	4.799853	0.993949
H	-0.202674	3.623701	1.398763
C	-4.030531	3.578403	0.756836
H	-3.905104	1.442430	0.974583
C	-3.335474	4.788231	0.764256
H	-1.413268	5.740545	1.008709
H	-5.103046	3.566273	0.585752
H	-3.865664	5.721143	0.596367
C	-1.747789	-3.062743	-0.110933
C	-0.966169	-3.678624	0.882875
C	-2.414916	-3.860953	-1.052471
C	-0.868547	-5.068198	0.938731
H	-0.441279	-3.075460	1.618727
C	-2.305173	-5.252196	-0.996701
H	-3.023457	-3.403088	-1.825519
C	-1.536204	-5.857734	-0.002512
H	-0.273463	-5.534962	1.718559
H	-2.827678	-5.860495	-1.729243
H	-1.457696	-6.940062	0.041832

C	-3.218541	-0.819223	-1.284576
C	-2.967798	-0.398511	-2.599687
C	-4.545611	-0.932718	-0.838273
C	-4.028266	-0.097678	-3.456869
H	-1.943265	-0.313741	-2.953263
C	-5.601893	-0.626391	-1.695806
H	-4.755469	-1.259162	0.176450
C	-5.344299	-0.208575	-3.004750
H	-3.825985	0.223399	-4.474540
H	-6.625599	-0.715641	-1.343807
H	-6.169099	0.028836	-3.670305
Ir	0.167987	0.071494	-0.399722
C	1.729476	1.530400	-2.462434
C	0.552089	2.473827	-2.126757
H	0.783938	2.989706	-1.190950
H	-0.353394	1.851177	-1.937307
C	0.193751	3.496528	-3.209627
H	1.058170	4.126495	-3.448671
H	-0.145771	3.021055	-4.134753
H	-0.607111	4.154325	-2.857333
C	1.504217	0.785727	-3.800978
H	0.512831	0.316032	-3.820524
H	1.588399	1.474856	-4.647081
H	2.259711	0.004502	-3.924281
N	1.815116	0.511688	-1.361921
N	3.166756	0.311377	-1.138704
C	3.924222	1.371979	-1.704163
C	3.106650	2.142269	-2.440285
H	3.410308	2.975233	-3.057279
C	5.413121	1.457391	-1.524792
H	5.850663	0.479110	-1.767296
H	5.635389	1.617639	-0.465328
C	6.066855	2.544519	-2.383517
H	7.147534	2.554654	-2.212648
H	5.896246	2.372544	-3.451742
H	5.681945	3.538837	-2.131737
H	0.849733	-0.993372	0.492606
C	3.616123	-0.687663	-0.247152
C	3.167604	-2.008062	-0.395415
C	4.948395	-1.250687	1.518680
C	3.645048	-2.990154	0.476633
H	2.477623	-2.259438	-1.194039
C	4.559818	-2.586596	1.460611
H	5.663290	-0.916592	2.268013
H	4.970634	-3.304774	2.164074
N	4.481157	-0.301744	0.696379
C	3.232380	-4.433443	0.326262
H	3.413373	-4.997322	1.246378
H	2.172464	-4.523835	0.066092
H	3.807629	-4.917523	-0.473273

167-TS

B3LYP SCF energy: -2501.22261653 a.u.
B3LYP enthalpy: -2500.446780 a.u.
B3LYP free energy: -2500.578595 a.u.

M06L SCF energy in solution: -2501.55617998 a.u.
M06L enthalpy in solution: -2500.780343 a.u.
M06L free energy in solution: -2500.912158 a.u.
Imaginary frequency: -455.5239 cm-1

Cartesian coordinates

ATOM	X	Y	Z
C	2.313836	2.612378	1.634944
H	3.365768	2.853358	1.493049
H	1.725409	3.329524	2.204399
C	1.770317	1.510955	1.108024
P	2.484986	0.301923	-0.104926
P	-0.007264	1.011439	1.019617
C	-0.984490	2.560726	0.967314
C	-0.737755	3.486825	-0.061678
C	-1.938963	2.860492	1.950662
C	-1.419372	4.701026	-0.090468
H	-0.007973	3.263205	-0.835179
C	-2.627256	4.075639	1.909765
H	-2.143900	2.155396	2.748927
C	-2.365430	4.998161	0.897048
H	-1.211646	5.416761	-0.880800
H	-3.362056	4.300700	2.677230
H	-2.894092	5.946840	0.874692
C	-0.457274	0.166895	2.577606
C	-1.527665	-0.744202	2.573011
C	0.230187	0.425303	3.774680
C	-1.900125	-1.384408	3.755845
H	-2.080148	-0.943707	1.660312
C	-0.146244	-0.223228	4.951272
H	1.053505	1.132593	3.792162
C	-1.209058	-1.129590	4.942538
H	-2.732896	-2.081419	3.747454
H	0.389501	-0.018778	5.873741
H	-1.499713	-1.633422	5.859809
C	3.579559	1.232653	-1.241144
C	3.089872	1.640879	-2.492010
C	4.891776	1.572386	-0.868808
C	3.897487	2.386120	-3.352751
H	2.082191	1.367723	-2.791938
C	5.693000	2.319183	-1.732298
H	5.293870	1.241659	0.084507
C	5.196972	2.727585	-2.973206
H	3.513871	2.691763	-4.321887
H	6.706620	2.576380	-1.438719
H	5.825805	3.303783	-3.645701
C	3.596422	-0.846099	0.789542
C	4.297939	-1.804198	0.035095
C	3.714819	-0.852234	2.186896
C	5.106622	-2.745032	0.671020
H	4.230010	-1.803932	-1.050109
C	4.525220	-1.798414	2.818585
H	3.184537	-0.117404	2.783717
C	5.220108	-2.744530	2.064082
H	5.650194	-3.475772	0.079235
H	4.616428	-1.790458	3.900926
H	5.851162	-3.477488	2.558095

Ir	0.322867	-0.422427	-0.746176
C	-0.998116	-2.449162	-1.989861
C	0.673226	-2.765402	-0.798186
H	0.690692	-2.212385	0.191977
H	1.655826	-2.697677	-1.271877
C	0.428894	-4.224075	-0.405012
H	-0.510734	-4.352419	0.138159
H	0.402653	-4.869181	-1.290634
H	1.247913	-4.579502	0.233535
C	-0.325132	-2.569716	-3.348379
H	0.385754	-1.753755	-3.509020
H	0.208404	-3.521494	-3.443355
H	-1.085682	-2.527344	-4.137554
N	-1.437251	-1.164989	-1.586005
N	-2.653222	-1.346816	-0.921067
C	-3.043626	-2.679197	-0.992865
C	-2.057607	-3.374186	-1.628938
H	-2.074825	-4.429041	-1.855601
C	-4.379455	-3.167434	-0.506797
H	-5.168743	-2.570620	-0.981612
H	-4.470118	-2.951924	0.563019
C	-4.619502	-4.656820	-0.774793
H	-5.602997	-4.949058	-0.394707
H	-4.593808	-4.884284	-1.845828
H	-3.870673	-5.281471	-0.275452
H	0.115749	0.910322	-1.541387
C	-3.498106	-0.226220	-0.735890
C	-3.439485	0.859681	-1.620613
C	-5.166410	0.737052	0.483973
C	-4.310597	1.932581	-1.425500
H	-2.745247	0.837910	-2.452403
C	-5.197251	1.857401	-0.339549
H	-5.844219	0.655932	1.331364
H	-5.904905	2.657578	-0.143156
N	-4.325524	-0.292518	0.310899
C	-4.307878	3.123321	-2.350604
H	-5.326241	3.393702	-2.650432
H	-3.872069	3.996793	-1.850462
H	-3.724573	2.928767	-3.255431

168-TS

B3LYP SCF energy: -2501.25603065 a.u.
B3LYP enthalpy: -2500.479277 a.u.
B3LYP free energy: -2500.607670 a.u.
M06L SCF energy in solution: -2501.58724113 a.u.
M06L enthalpy in solution: -2500.810487 a.u.
M06L free energy in solution: -2500.938880 a.u.
Imaginary frequency: -598.1565 cm-1

Cartesian coordinates

ATOM	X	Y	Z
C	-3.325158	1.498700	1.451975
H	-4.322899	1.332051	1.049487
H	-3.267487	2.028990	2.400846
C	-2.233358	1.040978	0.832156

P	-2.103020	-0.101194	-0.625427
P	-0.487574	0.962827	1.451264
C	-0.518670	0.771328	3.270166
C	-0.374194	-0.497494	3.851468
C	-0.722637	1.891771	4.095622
C	-0.446667	-0.644232	5.237610
H	-0.192812	-1.360233	3.221135
C	-0.800889	1.736323	5.479018
H	-0.807442	2.884515	3.663215
C	-0.664191	0.468873	6.051218
H	-0.326114	-1.628519	5.680800
H	-0.961414	2.605705	6.110026
H	-0.719296	0.351816	7.129679
C	0.306294	2.591865	1.186026
C	1.664644	2.717517	1.528669
C	-0.376818	3.698728	0.662941
C	2.322291	3.933180	1.350592
H	2.202650	1.870408	1.946689
C	0.288357	4.914493	0.484908
H	-1.427930	3.619019	0.405798
C	1.635980	5.032953	0.826661
H	3.369018	4.024273	1.626318
H	-0.250977	5.769589	0.087401
H	2.149300	5.980956	0.693517
C	-3.582803	-1.190225	-0.619808
C	-3.545713	-2.407998	0.079379
C	-4.764973	-0.814373	-1.280523
C	-4.672734	-3.229303	0.121937
H	-2.636743	-2.711691	0.588024
C	-5.889317	-1.639095	-1.232759
H	-4.808231	0.114198	-1.841060
C	-5.845254	-2.846510	-0.532564
H	-4.631656	-4.170989	0.661689
H	-6.797621	-1.339264	-1.747473
H	-6.720354	-3.489150	-0.501512
C	-2.305269	0.903636	-2.149881
C	-1.934178	0.316125	-3.372794
C	-2.825136	2.206168	-2.147401
C	-2.083685	1.019771	-4.567313
H	-1.530996	-0.693590	-3.391431
C	-2.968535	2.910191	-3.346153
H	-3.128337	2.669753	-1.213906
C	-2.598799	2.319380	-4.555303
H	-1.797927	0.554568	-5.506269
H	-3.374267	3.917789	-3.333056
H	-2.713150	2.867471	-5.485972
Ir	0.045628	-0.837881	0.085426
C	1.808402	-2.859886	0.596558
C	0.519555	-2.996100	-1.031645
H	-0.427704	-2.445852	-1.246284
H	0.143286	-3.961303	-0.688448
C	1.306923	-3.074788	-2.332720
H	1.645138	-2.085393	-2.662332
H	2.195394	-3.706318	-2.234702
H	0.696101	-3.495672	-3.144008
C	1.154557	-3.765324	1.620513
H	0.133737	-3.460016	1.853741

H	1.134028	-4.796475	1.254890
H	1.748016	-3.746802	2.542159
N	1.856235	-1.486445	0.871665
N	3.005417	-1.007025	0.132039
C	2.807709	0.071134	-0.731206
C	3.871137	0.880822	-1.160525
C	1.309486	1.331480	-1.972994
C	3.643391	1.915604	-2.064203
H	4.863425	0.707714	-0.763708
H	0.276835	1.493330	-2.255734
C	2.319599	2.127974	-2.484469
N	1.532042	0.312444	-1.118283
H	2.073680	2.922672	-3.181225
C	4.767311	2.787872	-2.559228
H	4.921682	2.645333	-3.635834
H	4.537304	3.848221	-2.405485
H	5.709065	2.563211	-2.051100
C	3.811066	-2.120738	-0.212475
C	3.128796	-3.243792	0.096393
H	3.483260	-4.259406	-0.005795
C	5.193542	-1.973102	-0.777472
H	5.788577	-1.346114	-0.099132
H	5.141021	-1.423611	-1.727522
C	5.909564	-3.309144	-1.004130
H	6.908819	-3.133000	-1.413099
H	6.022862	-3.864971	-0.067685
H	5.363613	-3.939568	-1.713657
H	-0.811545	-1.702728	1.108268

159'

B3LYP SCF energy: -2501.32586565 a.u.
B3LYP enthalpy: -2500.544912 a.u.
B3LYP free energy: -2500.674588 a.u.
M06L SCF energy in solution: -2501.64823364 a.u.
M06L enthalpy in solution: -2500.867280 a.u.
M06L free energy in solution: -2500.996956 a.u.

Cartesian coordinates

ATOM	X	Y	Z
C	-4.070384	0.221614	-0.049885
H	-4.588890	0.936027	0.587393
H	-4.665039	-0.264634	-0.821370
C	-2.763185	-0.018027	0.084032
P	-1.464318	0.876014	1.058672
P	-1.570801	-0.900755	-1.026989
C	-2.245610	-0.888954	-2.733281
C	-1.852594	0.107831	-3.638986
C	-3.191926	-1.849293	-3.131367
C	-2.404520	0.148682	-4.920005
H	-1.112439	0.841288	-3.338437
C	-3.743023	-1.800311	-4.411959
H	-3.489813	-2.641243	-2.450852
C	-3.350925	-0.802114	-5.307010
H	-2.091021	0.920739	-5.616923
H	-4.473377	-2.546286	-4.711918

H	-3.777660	-0.769968	-6.305378
C	-1.566457	-2.673730	-0.558473
C	-0.538643	-3.489682	-1.062740
C	-2.553137	-3.240765	0.261290
C	-0.507247	-4.849288	-0.757525
H	0.235465	-3.061339	-1.694225
C	-2.513950	-4.603448	0.569259
H	-3.356169	-2.624585	0.653389
C	-1.494034	-5.408195	0.060107
H	0.287570	-5.472813	-1.156730
H	-3.284746	-5.034354	1.201919
H	-1.467345	-6.467729	0.297696
C	-2.043857	2.597820	1.334994
C	-1.841070	3.571649	0.343622
C	-2.740349	2.944247	2.505114
C	-2.332032	4.865248	0.517512
H	-1.296232	3.313526	-0.558288
C	-3.228237	4.241167	2.673665
H	-2.897806	2.209810	3.288196
C	-3.026059	5.202425	1.681975
H	-2.167713	5.611292	-0.254810
H	-3.763426	4.498774	3.583113
H	-3.404272	6.211591	1.817493
C	-1.402911	0.138828	2.736170
C	-0.278685	0.401443	3.537481
C	-2.444053	-0.648592	3.250086
C	-0.203616	-0.109979	4.832253
H	0.536415	1.004607	3.146409
C	-2.361072	-1.164987	4.545661
H	-3.322616	-0.852099	2.645835
C	-1.243567	-0.895656	5.337347
H	0.666763	0.102768	5.446273
H	-3.172974	-1.771908	4.936129
H	-1.182856	-1.295067	6.345608
Ir	0.252336	0.410619	-0.433415
C	2.559025	2.132071	-1.807712
C	2.365453	3.462054	-1.033464
H	2.699179	4.273133	-1.694678
H	1.287631	3.596663	-0.888245
C	3.070851	3.586288	0.320321
H	2.816192	4.543699	0.786963
H	2.760290	2.792165	1.008295
H	4.162709	3.557530	0.225936
C	1.810212	2.213554	-3.144630
H	0.764627	2.493678	-2.993566
H	2.278572	2.970441	-3.783837
H	1.840148	1.250861	-3.664798
N	2.050366	0.990022	-0.993571
N	3.148641	0.303883	-0.479609
C	2.895454	-0.676209	0.429733
C	3.910384	-1.390370	1.108635
C	1.253532	-1.907904	1.529854
C	3.568288	-2.386052	2.005844
H	4.948804	-1.163208	0.908498
H	0.194592	-2.082483	1.669169
C	2.193384	-2.650047	2.207357
N	1.572729	-0.920000	0.654629

H	1.869975	-3.425684	2.893880
C	4.618589	-3.169536	2.749536
H	4.504491	-3.044990	3.833152
H	4.526622	-4.241880	2.539323
H	5.629132	-2.854596	2.475544
C	4.462060	0.810813	-0.926006
C	4.046626	1.783321	-2.047657
C	5.392627	-0.258710	-1.440781
C	6.693054	-0.310871	-1.150822
H	7.347466	-1.049965	-1.602940
H	-0.429910	1.533428	-1.348673
H	4.938681	1.345292	-0.094602
H	4.157333	1.282776	-3.015201
H	4.688704	2.667290	-2.060898
H	4.951385	-0.965190	-2.144161
H	7.155959	0.390722	-0.459381

160'-TS

B3LYP SCF energy: -2501.23935653 a.u.
B3LYP enthalpy: -2500.464488 a.u.
B3LYP free energy: -2500.598331 a.u.
M06L SCF energy in solution: -2501.56131142 a.u.
M06L enthalpy in solution: -2500.786443 a.u.
M06L free energy in solution: -2500.920286 a.u.
Imaginary frequency: -228.8304 cm-1

Cartesian coordinates

ATOM	X	Y	Z
C	-3.531204	-1.331159	1.403534
H	-4.480133	-1.252342	0.876286
H	-3.518680	-1.969361	2.285133
C	-2.432689	-0.708214	0.968141
P	-2.130410	0.180377	-0.635442
P	-0.675840	-0.864767	1.539925
C	-0.476632	-2.536540	2.271099
C	-0.875500	-3.661890	1.526643
C	0.133345	-2.726001	3.521679
C	-0.681181	-4.945780	2.032546
H	-1.340480	-3.532377	0.553574
C	0.333281	-4.015609	4.019124
H	0.446415	-1.871235	4.112356
C	-0.074188	-5.126280	3.279269
H	-1.003744	-5.806682	1.453539
H	0.802226	-4.148550	4.990001
H	0.077646	-6.127960	3.670947
C	-0.472760	0.295514	2.951661
C	0.732987	1.001585	3.078253
C	-1.478732	0.477645	3.915588
C	0.933255	1.869101	4.154235
H	1.511249	0.873315	2.331652
C	-1.278711	1.351170	4.984651
H	-2.417303	-0.062858	3.834138
C	-0.072302	2.046500	5.106006
H	1.871584	2.408878	4.245576
H	-2.062342	1.485949	5.724901

H	0.081492	2.724842	5.940347
C	-3.242631	-0.539474	-1.906239
C	-2.728030	-1.410688	-2.877163
C	-4.618326	-0.247262	-1.902697
C	-3.576181	-1.987222	-3.824650
H	-1.664307	-1.627008	-2.887648
C	-5.462326	-0.831701	-2.846524
H	-5.029437	0.448520	-1.176600
C	-4.942425	-1.702261	-3.808238
H	-3.167595	-2.654789	-4.578060
H	-6.523890	-0.601562	-2.835932
H	-5.600894	-2.150973	-4.546530
C	-2.771033	1.893787	-0.443043
C	-2.854263	2.710307	-1.585561
C	-3.116469	2.429380	0.806408
C	-3.279896	4.033556	-1.476809
H	-2.595767	2.308596	-2.561951
C	-3.540167	3.756882	0.910689
H	-3.062021	1.814253	1.698754
C	-3.623099	4.559704	-0.227698
H	-3.347953	4.652138	-2.367180
H	-3.811360	4.158825	1.882782
H	-3.957688	5.589783	-0.144775
Ir	0.136520	-0.293484	-0.597033
C	2.819343	-1.898677	-1.130489
C	2.789879	-1.492852	-3.741569
H	1.724841	-1.683640	-3.645481
H	3.080846	-0.447063	-3.670190
C	3.643185	-2.431942	-4.525761
H	4.711981	-2.290021	-4.321355
H	3.389944	-3.480732	-4.329926
C	2.185747	-3.246700	-1.224905
H	1.168456	-3.179872	-1.615085
H	2.781595	-3.906293	-1.861909
H	2.129663	-3.704383	-0.226668
N	2.150562	-0.813322	-0.801232
N	3.053792	0.226343	-0.509179
C	2.550524	1.509245	-0.510267
C	3.386664	2.641399	-0.523228
C	0.665859	2.858153	-0.400947
C	2.829259	3.913041	-0.471256
H	4.460936	2.515110	-0.553846
H	-0.414064	2.899270	-0.353744
C	1.425926	4.009712	-0.400670
N	1.197292	1.614133	-0.463175
H	0.933106	4.975216	-0.351229
C	3.691039	5.148386	-0.495321
H	3.476814	5.791116	0.366513
H	4.755929	4.900756	-0.481282
H	3.492194	5.742761	-1.395429
C	4.448155	-0.167369	-0.825895
C	4.299076	-1.702882	-0.921558
H	4.914939	-2.133759	-1.713505
C	5.452159	0.251790	0.215588
C	6.643072	0.778716	-0.070859
H	7.366529	1.004095	0.706719
H	-0.374557	-1.755678	-1.018446

H	4.599001	-2.181932	0.023515
H	4.725816	0.248422	-1.804541
H	3.515739	-2.279292	-5.611837
H	5.174297	0.034776	1.246898
H	6.945138	0.995380	-1.093717

161'

B3LYP SCF energy: -2422.08344499 a.u.
B3LYP enthalpy: -2421.374599 a.u.
B3LYP free energy: -2421.498893 a.u.
M06L SCF energy in solution: -2422.38910800 a.u.
M06L enthalpy in solution: -2421.680262 a.u.
M06L free energy in solution: -2421.804556 a.u.

Cartesian coordinates

ATOM	X	Y	Z
C	3.128081	1.642973	1.509412
H	4.160723	1.401703	1.264488
H	2.971879	2.513414	2.143903
C	2.106235	0.932051	1.024134
P	2.116608	-0.383888	-0.287180
P	0.285760	1.283546	1.109084
C	0.086325	3.102117	1.269604
C	0.695128	3.942855	0.319256
C	-0.727593	3.672871	2.261518
C	0.506405	5.322623	0.374382
H	1.319915	3.516921	-0.460516
C	-0.919938	5.055491	2.306109
H	-1.206354	3.043441	3.004607
C	-0.303294	5.883072	1.367077
H	0.992549	5.961526	-0.357777
H	-1.547669	5.483952	3.082435
H	-0.450006	6.958552	1.407758
C	-0.299185	0.603579	2.715869
C	-1.569440	0.009990	2.771634
C	0.473746	0.676120	3.887117
C	-2.061637	-0.494927	3.977222
H	-2.171644	-0.055890	1.869985
C	-0.017403	0.164425	5.088425
H	1.458809	1.133105	3.863287
C	-1.285710	-0.420850	5.135240
H	-3.048046	-0.949038	4.010359
H	0.587934	0.226170	5.988432
H	-1.666488	-0.817600	6.072001
C	3.557954	-0.092267	-1.383817
C	3.369838	0.470835	-2.654569
C	4.860597	-0.402012	-0.953559
C	4.467180	0.728377	-3.478531
H	2.363728	0.698704	-2.992819
C	5.953684	-0.135765	-1.777535
H	5.022322	-0.865930	0.015302
C	5.758395	0.429863	-3.040476
H	4.311323	1.157147	-4.464415
H	6.956598	-0.376684	-1.436768
H	6.611102	0.630055	-3.682981

C	2.524978	-1.979165	0.533760
C	2.835609	-3.090543	-0.271045
C	2.468746	-2.138970	1.926134
C	3.089639	-4.332945	0.309298
H	2.891085	-2.982945	-1.351231
C	2.723049	-3.385958	2.502855
H	2.230989	-1.294432	2.564604
C	3.033314	-4.483008	1.698084
H	3.336817	-5.181576	-0.322199
H	2.683547	-3.495402	3.582937
H	3.235525	-5.450103	2.149478
Ir	-0.036788	0.111864	-0.952146
C	-2.449394	1.617899	-2.370570
C	-1.648321	2.727937	-2.954927
H	-0.583439	2.492157	-2.936175
H	-1.966997	2.920468	-3.985948
H	-1.809025	3.654958	-2.387548
N	-1.954439	0.655188	-1.657970
N	-2.986154	-0.194216	-1.204185
C	-2.602809	-1.469142	-0.812734
C	-3.535770	-2.510143	-0.676306
C	-0.887201	-2.860561	-0.113179
C	-3.114698	-3.764237	-0.243836
H	-4.581186	-2.328421	-0.888618
H	0.169868	-2.958550	0.096508
C	-1.748427	-3.929263	0.044147
N	-1.287187	-1.639240	-0.535502
H	-1.359328	-4.882781	0.386119
C	-4.083686	-4.908071	-0.096073
H	-3.833116	-5.720439	-0.788996
H	-4.042600	-5.326466	0.916292
H	-5.112613	-4.597198	-0.296345
C	-4.262643	0.121406	-1.897027
C	-3.947315	1.522918	-2.476160
H	-4.416290	2.318899	-1.880071
C	-5.458387	0.126784	-0.981702
C	-6.630323	-0.431507	-1.286117
H	-7.487510	-0.349286	-0.624828
H	0.690658	1.372849	-1.630340
H	-4.306905	1.640801	-3.502681
H	-4.416166	-0.600697	-2.711913
H	-5.330941	0.681928	-0.052511
H	-6.781832	-0.982962	-2.212181

190

B3LYP SCF energy: -2501.33387911 a.u.
B3LYP enthalpy: -2500.553408 a.u.
B3LYP free energy: -2500.679741 a.u.
M06L SCF energy in solution: -2501.66388706 a.u.
M06L enthalpy in solution: -2500.883416 a.u.
M06L free energy in solution: -2501.009749 a.u.

Cartesian coordinates

ATOM	X	Y	Z
C	-3.714430	-0.217611	-1.478184

H	-4.257212	0.675320	-1.782504
H	-4.108271	-1.169336	-1.829354
C	-2.603243	-0.143080	-0.742178
P	-1.609863	1.322638	-0.232963
P	-1.379116	-1.438681	-0.252061
C	-1.511607	-2.824195	-1.449166
C	-1.454230	-2.531697	-2.823206
C	-1.590034	-4.163742	-1.037775
C	-1.491473	-3.558729	-3.764520
H	-1.378966	-1.501114	-3.158490
C	-1.619084	-5.189565	-1.985399
H	-1.633399	-4.412177	0.017448
C	-1.572891	-4.890276	-3.347164
H	-1.453984	-3.319937	-4.823480
H	-1.680415	-6.222378	-1.654828
H	-1.598752	-5.689859	-4.081753
C	-2.015029	-2.063659	1.354975
C	-1.309635	-1.793971	2.535939
C	-3.251039	-2.730054	1.429050
C	-1.820918	-2.200359	3.770350
H	-0.363420	-1.263521	2.487055
C	-3.757476	-3.135044	2.662691
H	-3.817407	-2.936966	0.525432
C	-3.041758	-2.872650	3.834727
H	-1.265194	-1.988923	4.679384
H	-4.710796	-3.653502	2.710053
H	-3.438967	-3.189105	4.794937
C	-1.965864	2.694139	-1.405205
C	-1.417154	2.640935	-2.699356
C	-2.782894	3.780521	-1.053017
C	-1.690318	3.648383	-3.623099
H	-0.770322	1.814330	-2.979782
C	-3.049957	4.789124	-1.981407
H	-3.209575	3.843906	-0.057613
C	-2.507331	4.724579	-3.265372
H	-1.260825	3.596514	-4.619479
H	-3.682497	5.625177	-1.697375
H	-2.716184	5.511224	-3.984643
C	-2.245832	1.880650	1.392725
C	-1.346143	2.447754	2.309754
C	-3.600422	1.760694	1.740456
C	-1.798966	2.902372	3.548494
H	-0.291284	2.524669	2.059104
C	-4.047315	2.209914	2.984166
H	-4.304335	1.308437	1.048099
C	-3.149089	2.783425	3.886923
H	-1.097140	3.342438	4.251167
H	-5.096194	2.109194	3.247888
H	-3.499569	3.131763	4.854198
Ir	0.396878	0.097055	-0.228322
C	2.455124	-2.347557	0.289400
C	2.312986	-2.944252	-1.143269
H	2.670980	-3.981631	-1.094743
H	1.245437	-2.992966	-1.382447
C	3.054445	-2.197229	-2.253749
H	2.891830	-2.696308	-3.215099
H	2.692064	-1.167757	-2.348870

H	4.134301	-2.167476	-2.072611
C	1.659804	-3.201430	1.288711
H	0.602145	-3.253554	1.018584
H	2.051741	-4.224580	1.294392
H	1.741926	-2.794037	2.300325
N	2.021600	-0.916783	0.338708
N	3.207639	-0.146202	0.449540
C	3.102162	1.187821	0.226925
C	4.159069	2.131880	0.328499
C	1.642511	2.918376	-0.400630
C	3.938719	3.466271	0.058225
H	5.147625	1.809136	0.611122
H	0.637271	3.179951	-0.704722
C	2.631845	3.862745	-0.323545
N	1.841176	1.598485	-0.120697
H	2.406733	4.897579	-0.558615
C	5.047009	4.481391	0.154046
H	5.202218	4.979798	-0.810476
H	4.797325	5.263183	0.881552
H	5.992941	4.024191	0.457004
C	4.315269	-0.990073	0.770877
C	3.898924	-2.257580	0.699661
H	4.507716	-3.128414	0.897550
C	5.682617	-0.487344	1.149234
H	5.591104	0.241873	1.964726
H	6.131587	0.045716	0.300855
C	6.635439	-1.607007	1.584609
H	7.605398	-1.181193	1.857607
H	6.246170	-2.146548	2.453845
H	6.802412	-2.327647	0.777592
H	0.227245	0.220181	-1.794928

191

B3LYP SCF energy: -631.09111959 a.u.
B3LYP enthalpy: -630.812933 a.u.
B3LYP free energy: -630.871679 a.u.
M06L SCF energy in solution: -631.19044983 a.u.
M06L enthalpy in solution: -630.912263 a.u.
M06L free energy in solution: -630.971009 a.u.

Cartesian coordinates

ATOM	X	Y	Z
C	-2.724124	-1.054530	0.041752
C	-3.794343	-2.089919	0.019142
H	-3.836376	-2.661277	0.957831
H	-4.769495	-1.618080	-0.132451
H	-3.649048	-2.819521	-0.792159
N	-1.392043	-1.420533	0.256138
H	-0.934548	-2.205197	-0.207131
N	-0.604423	-0.256244	0.154626
C	0.763775	-0.440470	0.048274
C	1.710392	0.608213	0.155639
C	2.440617	-1.990425	-0.239970
C	3.060241	0.314944	0.043825
H	1.398309	1.626334	0.343828

H	2.697401	-3.038549	-0.391034
C	3.439745	-1.030943	-0.164641
N	1.131832	-1.730999	-0.142050
H	4.484851	-1.312246	-0.250916
C	4.104567	1.398060	0.155005
H	4.803382	1.189181	0.974885
H	4.701982	1.465357	-0.763266
H	3.653826	2.378866	0.336502
C	-1.473003	0.844975	0.045741
C	-2.772263	0.324655	-0.020152
H	-3.672941	0.917287	-0.095929
C	-1.018800	2.268896	-0.032420
H	-0.304420	2.396163	-0.860506
H	-0.469139	2.552504	0.879298
C	-2.177323	3.255007	-0.227210
H	-1.796249	4.279931	-0.280458
H	-2.723689	3.049278	-1.154038
H	-2.888299	3.203624	0.604640

192

B3LYP SCF energy: -2422.07497540 a.u.
B3LYP enthalpy: -2421.363299 a.u.
B3LYP free energy: -2421.487460 a.u.
M06L SCF energy in solution: -2422.38697662 a.u.
M06L enthalpy in solution: -2421.675300 a.u.
M06L free energy in solution: -2421.799461 a.u.

Cartesian coordinates

ATOM	X	Y	Z
C	-3.296087	1.842088	1.092376
H	-3.291561	2.919065	1.250071
H	-4.147833	1.296740	1.494597
C	-2.290256	1.217294	0.473992
P	-0.624692	1.818102	-0.040239
P	-1.886293	-0.578846	0.306043
C	-2.710070	-1.148590	-1.233950
C	-4.034399	-0.793026	-1.539386
C	-1.985018	-1.935565	-2.142152
C	-4.627946	-1.238049	-2.720775
H	-4.600711	-0.159726	-0.862059
C	-2.582950	-2.380963	-3.322512
H	-0.947226	-2.178349	-1.930866
C	-3.904481	-2.036101	-3.610982
H	-5.652161	-0.957165	-2.949079
H	-2.013532	-2.988295	-4.020496
H	-4.367823	-2.378916	-4.531723
C	-2.717015	-1.453517	1.697463
C	-2.165376	-1.296318	2.981761
C	-3.854039	-2.258401	1.537086
C	-2.748611	-1.921103	4.083120
H	-1.275947	-0.683461	3.109405
C	-4.431897	-2.887882	2.643083
H	-4.288936	-2.403470	0.553699
C	-3.883969	-2.719511	3.915025
H	-2.316639	-1.788509	5.071223

H	-5.311452	-3.510600	2.506314
H	-4.336377	-3.209806	4.772250
C	-0.779209	2.427105	-1.764829
C	0.265889	2.184591	-2.669912
C	-1.916347	3.126985	-2.198839
C	0.182705	2.652904	-3.981896
H	1.133124	1.613837	-2.349952
C	-1.997881	3.589611	-3.512886
H	-2.742499	3.302242	-1.515525
C	-0.947481	3.356356	-4.403869
H	0.995329	2.459994	-4.676616
H	-2.882516	4.127556	-3.841576
H	-1.014002	3.715159	-5.427001
C	-0.211450	3.292579	0.979688
C	-0.244452	4.602510	0.477516
C	0.140935	3.081377	2.325242
C	0.059678	5.681710	1.311246
H	-0.504733	4.784642	-0.560140
C	0.437999	4.161899	3.153980
H	0.186261	2.066026	2.711566
C	0.397291	5.464628	2.647675
H	0.031405	6.691906	0.912830
H	0.706071	3.988460	4.192416
H	0.632294	6.306288	3.292945
Ir	0.375913	-0.199154	0.294398
C	0.935713	-3.455343	0.256467
C	-0.373809	-4.010219	0.685364
H	-1.225552	-3.536748	0.182345
H	-0.403470	-5.078804	0.453779
H	-0.539754	-3.897055	1.765793
N	1.357981	-2.128569	0.702328
H	1.357500	-2.096386	1.731610
N	2.750137	-2.037453	0.288903
C	3.312234	-0.768397	0.302351
C	4.702992	-0.586316	0.376836
C	2.977858	1.527323	0.362590
C	5.240429	0.695445	0.397887
H	5.350075	-1.450966	0.447508
H	2.263124	2.338965	0.398852
C	4.335456	1.774788	0.386453
N	2.444903	0.281050	0.301134
H	4.688785	2.800208	0.420370
C	6.726794	0.926375	0.461755
H	7.076222	1.444849	-0.439544
H	6.988335	1.559386	1.317476
H	7.280252	-0.012503	0.548367
C	3.077730	-3.174455	-0.486130
C	1.974013	-4.020983	-0.452625
H	1.933520	-4.993426	-0.923203
C	4.378543	-3.320751	-1.210857
H	5.205791	-3.434455	-0.493342
H	4.593094	-2.396320	-1.766601
C	4.398502	-4.512623	-2.176635
H	5.365745	-4.563183	-2.684765
H	4.252783	-5.460092	-1.647286
H	3.619215	-4.420948	-2.940186

193

B3LYP SCF energy: -2422.11626986 a.u.
B3LYP enthalpy: -2421.407432 a.u.
B3LYP free energy: -2421.529941 a.u.
M06L SCF energy in solution: -2422.43060890 a.u.
M06L enthalpy in solution: -2421.721771 a.u.
M06L free energy in solution: -2421.844280 a.u.

Cartesian coordinates

ATOM	X	Y	Z
C	3.649283	1.385282	-0.718990
H	3.818643	2.448343	-0.877538
H	4.498514	0.731353	-0.903868
C	2.458724	0.907340	-0.344887
P	0.853851	1.760054	-0.074134
P	1.855726	-0.832995	-0.160467
C	2.684037	-1.508720	1.346031
C	2.806733	-0.687998	2.480181
C	3.128505	-2.838844	1.421243
C	3.368892	-1.184311	3.655590
H	2.469133	0.343365	2.449761
C	3.687105	-3.333159	2.602081
H	3.053639	-3.491136	0.557458
C	3.809058	-2.508553	3.720840
H	3.464683	-0.534054	4.520465
H	4.030829	-4.362918	2.642067
H	4.246566	-2.893613	4.637367
C	2.562699	-1.789081	-1.564782
C	1.737329	-2.169250	-2.633564
C	3.937689	-2.080795	-1.625697
C	2.273062	-2.834281	-3.738754
H	0.678007	-1.932823	-2.600138
C	4.469799	-2.738122	-2.734739
H	4.593446	-1.811175	-0.802958
C	3.638492	-3.117525	-3.792040
H	1.622150	-3.128011	-4.557421
H	5.533057	-2.957554	-2.771016
H	4.055239	-3.632757	-4.652691
C	0.965762	2.676863	1.517845
C	0.069202	2.361698	2.549428
C	1.953141	3.652836	1.740267
C	0.148751	3.018499	3.779719
H	-0.677433	1.587416	2.388208
C	2.036018	4.299759	2.972586
H	2.655676	3.912660	0.953549
C	1.132270	3.985512	3.992360
H	-0.552252	2.769014	4.571153
H	2.804728	5.049325	3.137404
H	1.198983	4.492541	4.950687
C	0.647341	3.054562	-1.364359
C	0.259314	4.367945	-1.055775
C	0.827348	2.691986	-2.711011
C	0.061055	5.301806	-2.076495
H	0.118765	4.669891	-0.022963
C	0.637425	3.629747	-3.723925

H	1.114475	1.675933	-2.965625
C	0.252361	4.936417	-3.408918
H	-0.237533	6.315588	-1.825203
H	0.787762	3.340328	-4.760057
H	0.102822	5.665058	-4.200458
Ir	-0.389742	-0.187326	-0.142793
C	-1.401256	-3.246405	0.243851
C	-0.063570	-3.902944	0.273693
H	0.536416	-3.537607	1.113240
H	-0.184739	-4.983424	0.388111
H	0.497826	-3.720961	-0.648796
N	-1.565816	-1.918000	0.128985
N	-2.938125	-1.688742	0.159558
C	-3.365435	-0.361264	0.052198
C	-4.712057	0.026597	0.053895
C	-2.709635	1.855810	-0.204665
C	-5.062336	1.367114	-0.071880
H	-5.492341	-0.710440	0.148526
H	-1.888620	2.547631	-0.334210
C	-4.013047	2.296047	-0.210678
N	-2.358137	0.549094	-0.060783
H	-4.214992	3.355865	-0.327524
C	-6.501253	1.809215	-0.069180
H	-6.692185	2.513826	0.749270
H	-6.753170	2.326503	-1.002811
H	-7.185575	0.964063	0.045143
C	-3.623059	-2.890534	0.302414
C	-2.655416	-3.870189	0.353794
H	-2.827299	-4.929493	0.467250
C	-5.113738	-3.064079	0.385126
H	-5.586205	-2.664644	-0.522692
H	-5.511018	-2.480332	1.226726
C	-5.535744	-4.528752	0.557299
H	-6.626304	-4.593723	0.609941
H	-5.203842	-5.142925	-0.285788
H	-5.129407	-4.957106	1.479102
H	-0.386552	-0.143625	-1.754515

194

B3LYP SCF energy: -2422.11692142 a.u.
B3LYP enthalpy: -2421.408339 a.u.
B3LYP free energy: -2421.531882 a.u.
M06L SCF energy in solution: -2422.43202728 a.u.
M06L enthalpy in solution: -2421.723445 a.u.
M06L free energy in solution: -2421.846988 a.u.

Cartesian coordinates

ATOM	X	Y	Z
C	3.527643	0.902964	-1.437122
H	3.755538	1.928337	-1.720719
H	4.210515	0.139515	-1.802822
C	2.446075	0.593351	-0.711820
P	1.058075	1.644756	-0.133001
P	1.708149	-1.052551	-0.306093
C	2.755088	-1.804478	1.011686

C	3.241627	-0.981758	2.041225
C	3.024105	-3.181485	1.057739
C	3.987380	-1.524642	3.086659
H	3.042933	0.085638	2.030029
C	3.769001	-3.721726	2.108581
H	2.665110	-3.837291	0.271353
C	4.252213	-2.895836	3.123807
H	4.362884	-0.874774	3.871897
H	3.972648	-4.788596	2.128277
H	4.833574	-3.316894	3.938952
C	1.952861	-2.106144	-1.794870
C	0.864089	-2.331095	-2.651282
C	3.216667	-2.612745	-2.146730
C	1.032040	-3.053588	-3.834470
H	-0.113185	-1.932350	-2.388969
C	3.381548	-3.328291	-3.333009
H	4.069753	-2.462855	-1.491501
C	2.290427	-3.551040	-4.177144
H	0.180605	-3.226456	-4.486671
H	4.362006	-3.714935	-3.596104
H	2.422145	-4.112079	-5.097856
C	1.625016	2.606393	1.327113
C	0.824128	2.661694	2.477319
C	2.849671	3.296008	1.308679
C	1.234043	3.405368	3.585812
H	-0.106761	2.103571	2.511487
C	3.260120	4.030319	2.421245
H	3.487157	3.258786	0.429993
C	2.450903	4.088698	3.559466
H	0.606552	3.442118	4.471741
H	4.210885	4.555168	2.399988
H	2.772498	4.661261	4.424708
C	0.710896	2.904047	-1.432714
C	0.730188	4.284479	-1.182468
C	0.370356	2.444587	-2.717830
C	0.421025	5.188286	-2.203223
H	0.989718	4.659436	-0.198026
C	0.071128	3.349662	-3.733670
H	0.339579	1.376666	-2.918903
C	0.094714	4.724376	-3.477458
H	0.440727	6.254985	-1.998776
H	-0.182153	2.983722	-4.724633
H	-0.141271	5.429136	-4.269625
Ir	-0.384436	-0.131624	0.171737
C	-1.704366	-3.051149	0.566585
C	-0.432011	-3.824246	0.634859
H	0.238112	-3.408202	1.394260
H	-0.643180	-4.864559	0.896076
H	0.095898	-3.816945	-0.324841
N	-1.743890	-1.729411	0.337572
N	-3.080775	-1.357429	0.398836
C	-3.369786	0.004675	0.256248
C	-4.670372	0.518141	0.187235
C	-2.490295	2.146986	0.049302
C	-4.884443	1.887923	0.062803
H	-5.520343	-0.144021	0.219767
H	-1.604336	2.762092	-0.026221

C	-3.744150	2.711838	0.002849
N	-2.270879	0.807559	0.164911
H	-3.836590	3.788749	-0.095165
C	-6.272376	2.466171	-0.008017
H	-6.461291	3.133834	0.841647
H	-6.402826	3.062230	-0.919043
H	-7.038154	1.685594	-0.000408
C	-3.875373	-2.466201	0.664525
C	-3.009825	-3.534373	0.761657
H	-3.281679	-4.558630	0.965378
C	-5.368698	-2.469896	0.833928
H	-5.853143	-2.149696	-0.099012
H	-5.655046	-1.738036	1.600909
C	-5.921141	-3.845949	1.227053
H	-7.007101	-3.787183	1.343362
H	-5.707483	-4.597850	0.460654
H	-5.499025	-4.189883	2.176629
H	-0.068950	-0.170588	1.748353

195

B3LYP SCF energy: -2501.33366719 a.u.
B3LYP enthalpy: -2500.548877 a.u.
B3LYP free energy: -2500.678095 a.u.
M06L SCF energy in solution: -2501.65829211 a.u.
M06L enthalpy in solution: -2500.873502 a.u.
M06L free energy in solution: -2501.002720 a.u.

Cartesian coordinates

ATOM	X	Y	Z
C	-3.742577	0.365763	-1.443567
H	-4.313911	-0.501904	-1.768770
H	-4.099153	1.335845	-1.784401
C	-2.641641	0.239717	-0.698291
P	-1.680903	-1.252709	-0.199604
P	-1.342607	1.460031	-0.199813
C	-1.952386	2.251825	1.345395
C	-3.174236	2.945293	1.384782
C	-1.210208	2.110471	2.527141
C	-3.632066	3.498668	2.579645
H	-3.769378	3.056221	0.482539
C	-1.669104	2.668357	3.722717
H	-0.288492	1.534894	2.509445
C	-2.878234	3.364030	3.749511
H	-4.577901	4.032582	2.599290
H	-1.087013	2.550572	4.632399
H	-3.238060	3.795021	4.679422
C	-1.363169	2.792322	-1.475581
C	-1.243513	2.421375	-2.827015
C	-1.430503	4.155317	-1.149105
C	-1.209651	3.391888	-3.827105
H	-1.181438	1.370449	-3.096030
C	-1.388605	5.125728	-2.154323
H	-1.521390	4.465471	-0.113281
C	-1.281492	4.747491	-3.492597
H	-1.127637	3.090642	-4.867709

H	-1.445258	6.177168	-1.886927
H	-1.254676	5.503040	-4.272511
C	-2.423470	-1.879063	1.358964
C	-1.580896	-2.432470	2.336029
C	-3.805277	-1.818418	1.598308
C	-2.115070	-2.938181	3.521699
H	-0.506945	-2.447633	2.172972
C	-4.335404	-2.319280	2.788500
H	-4.467246	-1.369555	0.863412
C	-3.492202	-2.883686	3.748348
H	-1.455704	-3.365061	4.272211
H	-5.405550	-2.264782	2.966969
H	-3.906827	-3.271787	4.674328
C	-1.987779	-2.560929	-1.459237
C	-2.888075	-3.618660	-1.259987
C	-1.296929	-2.468190	-2.681274
C	-3.100109	-4.559981	-2.270334
H	-3.420553	-3.713556	-0.319176
C	-1.515274	-3.407746	-3.687862
H	-0.583687	-1.660867	-2.831023
C	-2.418491	-4.455008	-3.483696
H	-3.798290	-5.375838	-2.105983
H	-0.977305	-3.326994	-4.628333
H	-2.585798	-5.189253	-4.266608
Ir	0.303005	-0.144291	-0.058765
C	2.857975	1.908385	-0.688855
C	2.248612	3.313988	-0.525392
H	2.799160	3.963578	-1.217245
H	1.216640	3.295964	-0.888019
C	2.299762	3.927460	0.880346
H	1.946328	4.962771	0.844118
H	1.650923	3.406737	1.596824
H	3.315729	3.936085	1.289449
C	2.741000	1.427020	-2.141646
H	1.697930	1.448799	-2.470619
H	3.334683	2.078489	-2.792405
H	3.120499	0.406345	-2.250464
N	2.171069	0.917218	0.251302
N	3.224246	-0.013184	0.657083
C	2.996804	-1.355888	0.361617
C	4.015466	-2.323405	0.438154
C	1.463014	-3.012579	-0.203973
C	3.740127	-3.662184	0.189591
H	5.020819	-2.031485	0.699401
H	0.440963	-3.238962	-0.476547
C	2.416935	-4.004608	-0.142707
N	1.721194	-1.702862	0.045836
H	2.137494	-5.030913	-0.356744
C	4.817720	-4.711342	0.265780
H	4.562727	-5.476558	1.008472
H	4.929814	-5.223926	-0.697012
H	5.785763	-4.282095	0.537817
C	4.476627	0.698342	0.534356
C	4.282320	1.809079	-0.183113
H	5.031353	2.563716	-0.383684
C	5.717969	0.258818	1.269650
H	6.271254	-0.480355	0.675470

H	5.416305	-0.247460	2.194849
C	6.669244	1.417405	1.600847
H	7.531629	1.041418	2.159447
H	7.049825	1.898627	0.694097
H	6.171818	2.178029	2.210949
H	1.982976	1.436165	1.111909

156b-TS

B3LYP SCF energy: -2501.29163347 a.u.
B3LYP enthalpy: -2500.513705 a.u.
B3LYP free energy: -2500.641006 a.u.
M06L SCF energy in solution: -2501.62209019 a.u.
M06L enthalpy in solution: -2500.844162 a.u.
M06L free energy in solution: -2500.971463 a.u.
Imaginary frequency: -1204.9250 cm-1

Cartesian coordinates

ATOM	X	Y	Z
C	3.867098	-0.427774	1.123579
H	4.447524	0.396415	1.533167
H	4.313087	-1.417101	1.205944
C	2.665100	-0.240294	0.573856
P	1.603201	1.266950	0.471498
P	1.427143	-1.441225	-0.086383
C	1.531254	-2.936357	0.980535
C	1.488373	-2.770428	2.376380
C	1.582777	-4.233213	0.447600
C	1.511013	-3.880586	3.218822
H	1.438316	-1.773374	2.805422
C	1.599635	-5.342991	1.296322
H	1.616174	-4.382603	-0.626639
C	1.566358	-5.169647	2.680055
H	1.486488	-3.740021	4.295722
H	1.642910	-6.341971	0.871954
H	1.583917	-6.033749	3.337944
C	2.044552	-1.969827	-1.736180
C	1.263571	-1.719596	-2.874514
C	3.304749	-2.574890	-1.887650
C	1.728443	-2.079070	-4.141977
H	0.297454	-1.235886	-2.762529
C	3.766716	-2.929453	-3.154180
H	3.925003	-2.775695	-1.018646
C	2.977866	-2.684043	-4.282577
H	1.114877	-1.883203	-5.016717
H	4.741002	-3.397638	-3.261394
H	3.340068	-2.962583	-5.268059
C	1.662145	2.102260	2.105676
C	0.561612	1.994182	2.969211
C	2.810700	2.789609	2.537394
C	0.607215	2.565387	4.242984
H	-0.323323	1.458845	2.637342
C	2.853453	3.353141	3.812089
H	3.665546	2.899815	1.876210
C	1.751987	3.242409	4.665780
H	-0.251760	2.481402	4.902711

H	3.744506	3.882301	4.137600
H	1.787312	3.686015	5.656681
C	2.414293	2.441353	-0.694329
C	2.286259	3.831869	-0.538695
C	3.092278	1.941192	-1.818861
C	2.830393	4.701996	-1.486339
H	1.781812	4.241589	0.331625
C	3.637762	2.814241	-2.759514
H	3.202812	0.870044	-1.959094
C	3.506749	4.195754	-2.596870
H	2.730623	5.775069	-1.349734
H	4.168118	2.414347	-3.619002
H	3.933374	4.873445	-3.330613
Ir	-0.300238	0.106721	-0.119465
C	-2.614626	-2.332030	-0.182545
C	-2.175557	-3.089016	1.098627
H	-2.506048	-4.128653	0.977408
H	-1.082448	-3.119807	1.123138
C	-2.711823	-2.542847	2.424671
H	-2.322700	-3.138993	3.256720
H	-2.405545	-1.503929	2.597549
H	-3.805465	-2.576905	2.466740
C	-2.111671	-3.082232	-1.433270
H	-1.023256	-3.194476	-1.406969
H	-2.557297	-4.082295	-1.479688
H	-2.385263	-2.538807	-2.342453
N	-2.124243	-0.916716	-0.215273
N	-3.247628	-0.066802	-0.364400
C	-3.012165	1.267424	-0.519378
C	-4.017799	2.246098	-0.734462
C	-1.382925	2.952153	-0.614804
C	-3.685763	3.576758	-0.890263
H	-5.053856	1.956371	-0.787310
H	-0.327013	3.184339	-0.584808
C	-2.316814	3.932333	-0.828932
N	-1.692327	1.634653	-0.457227
H	-1.997693	4.960978	-0.958234
C	-4.739628	4.625992	-1.127500
H	-5.744973	4.196450	-1.148639
H	-4.710969	5.390022	-0.341298
H	-4.568087	5.140756	-2.080539
C	-4.445146	-0.847980	-0.327006
C	-4.103988	-2.136700	-0.227830
H	-4.799483	-2.961560	-0.168536
C	-5.836249	-0.273810	-0.378108
H	-5.989089	0.244050	-1.333961
H	-5.949544	0.481748	0.409965
C	-6.932316	-1.333579	-0.214065
H	-7.915238	-0.854920	-0.249959
H	-6.893657	-2.077826	-1.015823
H	-6.845322	-1.853792	0.745132
H	-1.345650	-0.586290	0.999698

158b-TS

B3LYP SCF energy: -2501.32240088 a.u.

B3LYP enthalpy: -2500.543070 a.u.
B3LYP free energy: -2500.668160 a.u.
M06L SCF energy in solution: -2501.64897691 a.u.
M06L enthalpy in solution: -2500.869646 a.u.
M06L free energy in solution: -2500.994736 a.u.
Imaginary frequency: -41.4638 cm-1

Cartesian coordinates

ATOM	X	Y	Z
C	3.777076	1.502888	-0.063509
H	4.641598	0.969099	-0.452020
H	3.932078	2.550196	0.189054
C	2.584831	0.917506	0.067223
P	1.968815	-0.747282	-0.462172
P	0.952996	1.623850	0.558071
C	0.934295	3.362837	-0.038291
C	1.168199	3.609079	-1.402860
C	0.689475	4.445749	0.820204
C	1.166916	4.913132	-1.893954
H	1.353710	2.782083	-2.082769
C	0.682831	5.750638	0.321216
H	0.502847	4.277576	1.875477
C	0.922496	5.986872	-1.032536
H	1.354718	5.091317	-2.948864
H	0.490938	6.580638	0.995043
H	0.918315	7.002565	-1.417299
C	0.908396	1.726860	2.390622
C	-0.219021	1.253947	3.078115
C	1.987498	2.257988	3.118163
C	-0.272919	1.322992	4.471684
H	-1.044953	0.823921	2.519225
C	1.932498	2.317180	4.510711
H	2.870908	2.624659	2.603498
C	0.801698	1.852190	5.188370
H	-1.151238	0.957465	4.995929
H	2.771325	2.726905	5.065980
H	0.761640	1.900341	6.272746
C	2.720941	-1.145441	-2.087548
C	4.103316	-1.371476	-2.219268
C	1.906799	-1.186022	-3.228978
C	4.657478	-1.617236	-3.474451
H	4.745278	-1.375176	-1.342745
C	2.465662	-1.441160	-4.483528
H	0.838681	-1.017209	-3.128715
C	3.839433	-1.651370	-4.607923
H	5.726162	-1.787690	-3.568084
H	1.826291	-1.476171	-5.360924
H	4.273914	-1.847153	-5.584017
C	2.689876	-1.981364	0.698664
C	2.829714	-1.661168	2.059547
C	3.030047	-3.272985	0.262320
C	3.312221	-2.609903	2.960422
H	2.568956	-0.670711	2.419525
C	3.508540	-4.220597	1.170152
H	2.934613	-3.539575	-0.785808
C	3.652383	-3.891016	2.518565
H	3.425574	-2.346232	4.008049

H	3.774118	-5.213515	0.818676
H	4.030156	-4.627248	3.222099
Ir	-0.280007	-0.087299	-0.350213
C	-3.006518	1.617427	-0.790746
C	-2.638028	2.125814	-2.212713
H	-3.212010	3.045603	-2.387399
H	-1.580675	2.415914	-2.193859
C	-2.888860	1.136376	-3.352076
H	-2.592224	1.577729	-4.309763
H	-2.310231	0.217505	-3.210675
H	-3.947356	0.863250	-3.424701
C	-2.766703	2.742936	0.239877
H	-1.733823	3.096433	0.196027
H	-3.422902	3.594401	0.026889
H	-2.980701	2.388834	1.252972
N	-2.242628	0.395637	-0.435349
N	-3.159588	-0.611354	-0.130422
C	-2.652438	-1.830593	0.175805
C	-3.416846	-2.986300	0.498388
C	-0.679626	-3.077582	0.446191
C	-2.794758	-4.179081	0.786491
H	-4.493013	-2.936507	0.520113
H	0.400692	-3.070589	0.433162
C	-1.372970	-4.212658	0.755517
N	-1.276068	-1.877987	0.156598
H	-0.832497	-5.125668	0.982576
C	-3.578300	-5.418698	1.126418
H	-3.369875	-6.220323	0.407168
H	-3.297952	-5.797898	2.116742
H	-4.655908	-5.232840	1.125157
C	-4.499481	-0.134990	-0.309522
C	-4.427428	1.140793	-0.701997
H	-5.275009	1.778935	-0.908267
C	-5.735365	-0.962376	-0.080655
H	-5.743380	-1.337614	0.951087
H	-5.716008	-1.843647	-0.734767
C	-7.032742	-0.185994	-0.335979
H	-7.893246	-0.836739	-0.155424
H	-7.119574	0.678849	0.329525
H	-7.090329	0.167278	-1.370509
H	0.058052	0.749289	-1.656772

Et-radical

B3LYP SCF energy: -79.15638618 a.u.
B3LYP enthalpy: -79.091818 a.u.
B3LYP free energy: -79.120879 a.u.
M06L SCF energy in solution: -79.16373148 a.u.
M06L enthalpy in solution: -79.099163 a.u.
M06L free energy in solution: -79.128224 a.u.

Cartesian coordinates

ATOM	X	Y	Z
C	-0.694173	0.000000	-0.000792
H	-1.109487	-0.887624	-0.493946
H	-1.109487	0.887615	-0.493961

H	-1.096026	0.000009	1.028853
C	0.795475	0.000000	-0.023075
H	1.353594	0.927789	0.051128
H	1.353595	-0.927789	0.051128

Ethane

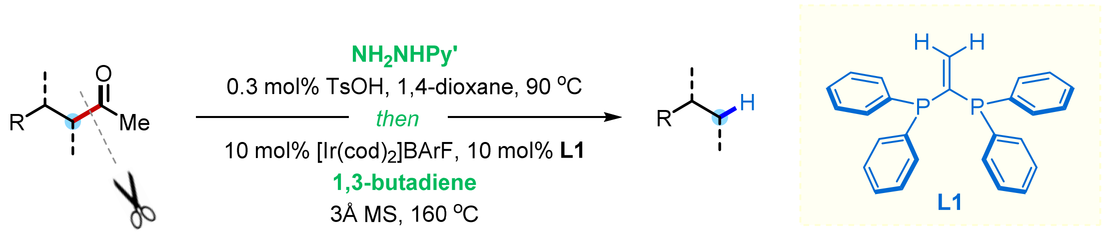
B3LYP SCF energy: -79.82901345 a.u.
B3LYP enthalpy: -79.749353 a.u.
B3LYP free energy: -79.776877 a.u.
M06L SCF energy in solution: -79.83616205 a.u.
M06L enthalpy in solution: -79.756502 a.u.
M06L free energy in solution: -79.784026 a.u.

Cartesian coordinates

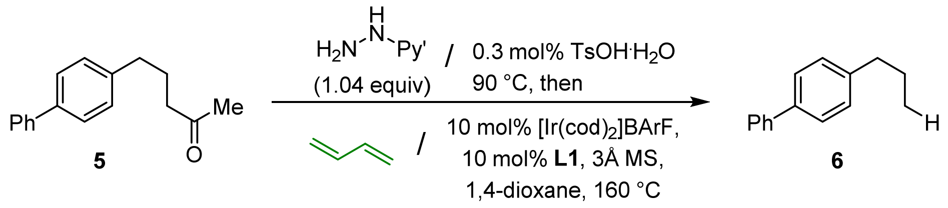
ATOM	X	Y	Z
C	-0.765350	0.000000	0.000000
H	-1.164448	-0.512045	0.883332
H	-1.164448	-0.508992	-0.885095
H	-1.164471	1.020998	0.001763
C	0.765359	-0.000002	0.000000
H	1.164416	0.512034	-0.883384
H	1.164416	0.509049	0.885107
H	1.164485	-1.021033	-0.001723

3.3 Synthetic applications

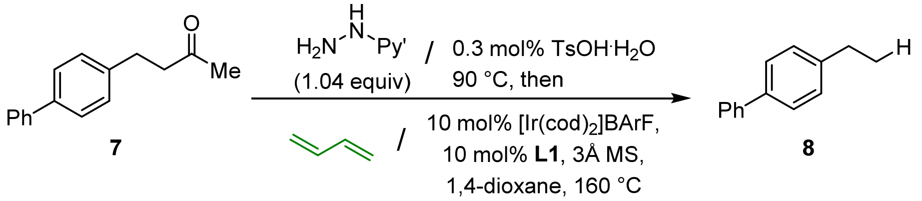
3.3.1 Deacetylation of methyl ketones



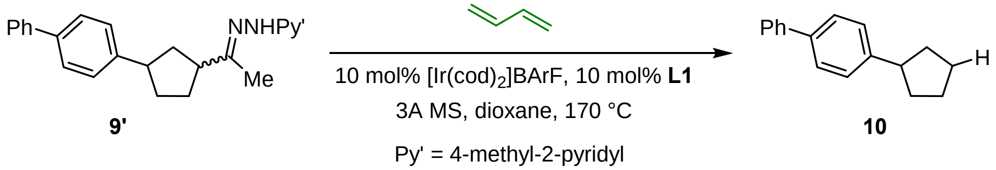
General procedure A: For a 0.05 mmol scale reaction, a 1,4-dioxane (1 mL) solution of the ketone substrate (0.05 mmol, 1.0 equiv), 2-hydrazineyl-4-methylpyridine (**D1**) (6.4 mg, 0.052 mmol, 1.04 equiv), and p-TsOH·H$_2$O (*stock solution in 1,4-dioxane*, 0.05 M, 3.0 µL, 0.003 equiv) was heated at 90 °C for 5 hours under nitrogen atmosphere in a 8 mL vial. After cooled to room temperature, the vial was charged first with [Ir(cod)$_2$]BArF (6.4 mg, 0.005 mmol, 0.1 equiv) and **L1** (2.0 mg, 0.005 mmol, 0.1 equiv) under air atmosphere, and then with 3Å molecular sieve (pre-dried, 100 mg) and 1,3-butadiene (20 wt.% in PhMe, 170 µL, ca. 10 equiv) in a glovebox. The vial was sealed and heated at 160 °C under stirring for 72 hours. After cooled to room temperature, the reaction mixture was filtered through a short plug of Celite, concentrated *in vacuo*, and further purified by flash column chromatography over silica (hexane/ethyl acetate) to give the products**.** *The reported yields were based on average of 2 or 3 runs***.**



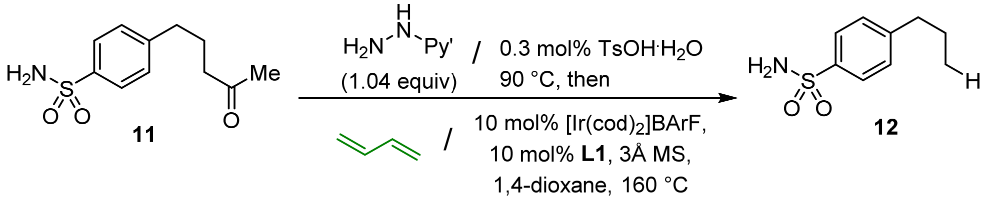
43: Following **General procedure A,** the reaction was conducted at 0.05 mmol scale with 11.9 mg **5** as the ketone substrates and 190 µL 1,3-butadiene (in PhMe, 20 wt.%). Two parallel reactions were conducted (0.05 mmol for each, 0.1 mmol in total) and combined, giving the titled compound as a colorless oil (13.6 mg, 70% yield). $R_f = 0.4$ (hexane). ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.58 (d, J = 7.2 Hz, 2H), 7.51 (d, J = 8.0 Hz, 2H), 7.42 (t, J = 7.7 Hz, 2H), 7.32 (t, J = 7.1 Hz, 1H), 7.27 – 7.22 (m, 2H), 2.72 – 2.55 (m, 2H), 1.68 (h, J = 7.4 Hz, 2H), 0.97 (t, J = 7.3 Hz, 3H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 141.99, 141.32, 138.71, 129.02, 128.83, 127.13, 127.10, 127.08, 37.85, 24.72, 14.05. The spectra match the reported literature.[56]



8: Following **General procedure A,** the reaction was conducted at 0.05 mmol scale with 11.2 mg **7** as the ketone substrates. Two parallel reactions were conducted (0.05 mmol for each, 0.1 mmol in total) and combined, giving the titled compound as a colorless oil (12.3 mg, 68% yield). $R_f = 0.4$ (hexane). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.60 (dd, J = 8.2, 1.3 Hz, 2H), 7.54 (d, J = 8.2 Hz, 2H), 7.44 (t, J = 7.6 Hz, 2H), 7.37 – 7.31 (m, 1H), 7.29 (d, J = 8.4 Hz, 2H), 2.72 (q, J = 7.6 Hz, 2H), 1.30 (t, J = 7.6 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 143.53, 141.34, 138.76, 128.84, 128.42, 127.22, 127.15, 127.10, 28.67, 15.73. The spectra match the reported literature.[57]

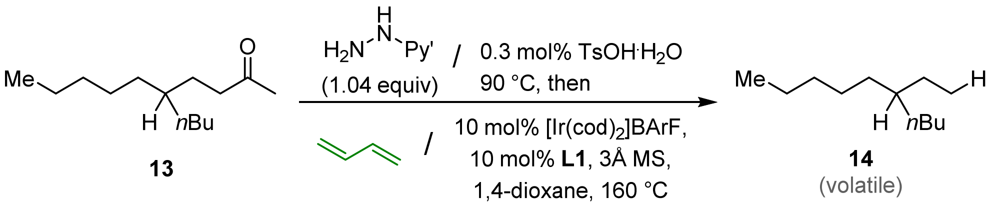


10: The reaction was conducted following modified **General procedure A**: An 8 mL vial was charged with the hydrazone **9'** (17.8 mg, 0.05 mmol, 1.0 equiv) which was derived from its corresponding ketone **9** following *General procedure for hydrazones formation (vide supra)*, $[Ir(cod)_2]BArF$ (6.4 mg, 0.005 mmol, 0.1 equiv), dppm (1.9 mg, 0.005 mmol, 0.1 equiv) and 1,4-dioxane (1 mL). The vial was transferred into the glove box and charged with 1,3-butadiene (20 wt.% in PhMe, 140 μL). The vial was sealed, transferred out of the glove box, and heated in a pie-block at 170 °C under stirring for 72 hours. After cooled to room temperature, the reaction mixture was filtered through a short plug of Celite, concentrated *in vacuo*, and further purified by flash column chromatography over silica (hexane). Combining 2 parallel reactions furnished **10** in 70% yield (15.5 mg) as a white solid. $R_f = 0.4$ (hexane). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.59 (d, J = 7.6 Hz, 2H), 7.53 (d, J = 8.1 Hz, 2H), 7.43 (t, J = 7.5 Hz, 2H), 7.41 – 7.29 (m, 3H), 3.05 (ddd, J = 16.9, 9.6, 7.5 Hz, 1H), 2.18 – 2.00 (m, 2H), 1.90 – 1.79 (m, 2H), 1.78 – 1.60 (m, 4H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 145.83, 141.33, 138.80, 128.83, 127.66, 127.15, 127.13, 127.08, 45.79, 34.80, 25.70. The spectra match the reported literature.[58]

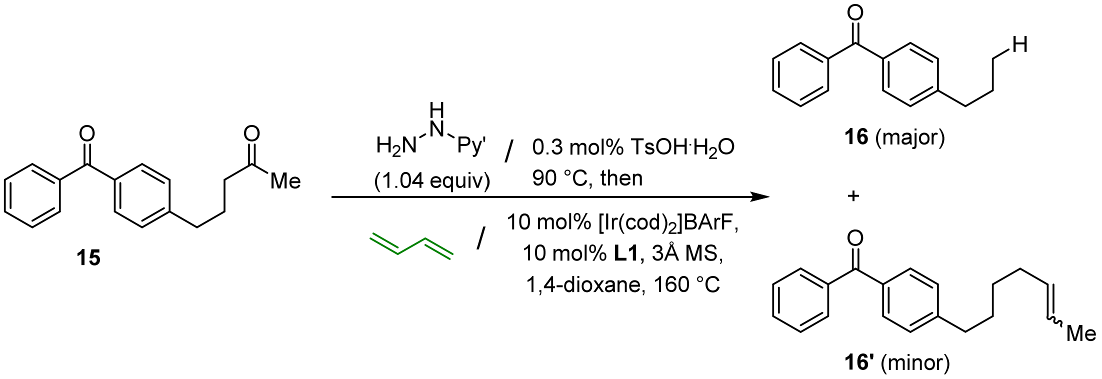


12: Following **General procedure A,** the reaction was conducted at 0.05 mmol scale with 12.1 mg **11** as the ketone substrates and 180 μL 1,3-butadiene (in PhMe, 20 wt.%) for 96 hours. Two parallel reactions were conducted (0.05

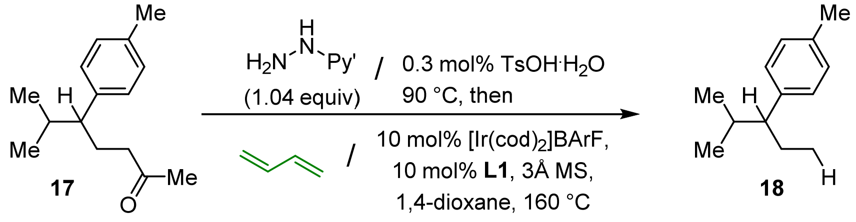
mmol for each, 0.1 mmol in total) and combined, giving the titled compound as a colorless oil (10.1 mg, 51% yield). R_f = 0.75 (hexane/acetone = 1:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.83 (d, *J* = 8.4 Hz, 2H), 7.32 (d, *J* = 8.4 Hz, 2H), 4.87 (s, 2H), 2.66 (t, *J* = 7.6 Hz, 2H), 1.66 (h, *J* = 7.4 Hz, 2H), 0.95 (t, *J* = 7.3 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 148.45, 139.36, 129.32, 126.61, 38.00, 24.37, 13.83. The spectra match the reported literature.[59]



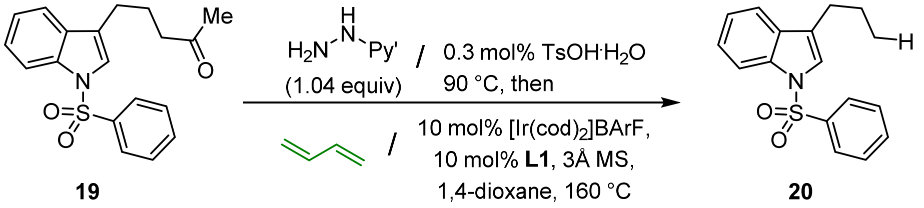
14: Following **General procedure A,** the reaction was conducted at 0.05 mmol scale with 10.6 mg **13** as the ketone substrates. Two parallel reactions were conducted (0.05 mmol for each, 0.1 mmol in total) and combined, giving the titled compound as a colorless oil (10.1 mg, 60% yield) (*cautious: the product is volatile!*). R_f = 0.8 (hexane). ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.42 – 1.20 (m, 17H), 1.05 – 0.69 (m, 9H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 39.01, 33.35, 33.06, 32.55, 29.17, 26.58, 26.07, 23.33, 22.89, 14.33, 14.29, 11.04. The spectra match the reported literature.[60]



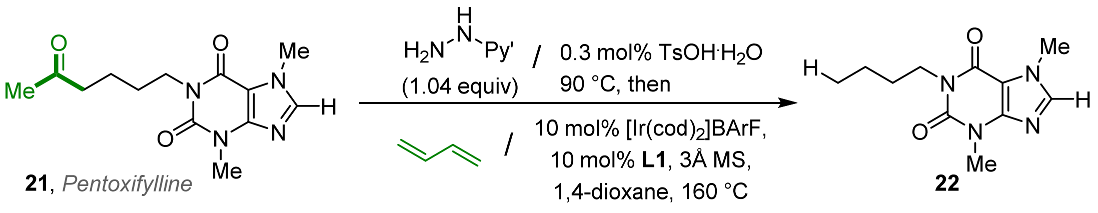
16: Following **General procedure A,** the reaction was conducted at 0.05 mmol scale with 13.3 mg **15** as the ketone substrates. Two parallel reactions were conducted (0.05 mmol for each, 0.1 mmol in total) and combined. The compound **16** was isolated as a colorless oil along with a minor inseparable deacetylative crotylation by-product (ca. 17%). Based on ^{1}H-NMR analysis of the isolated products, the desired product **16** was obtained in 67% yield (14.9 mg). R_f = 0.3 (hexane/ethyl acetate = 20:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.80 – 7.74 (m, 2H, **16 & 16'**), 7.71 (d, *J* = 7.9 Hz, 2H, **16 & 16'**), 7.57 – 7.51 (m, 1H, **16 & 16'**), 7.44 (t, *J* = 7.6 Hz, 2H, **16 & 16'**), 7.25 (d, *J* = 7.9 Hz, 2H, **16 & 16'**), 5.54 – 5.06 (m, 0.35H, **16'**), 2.64 (t, *J* = 7.6 Hz, 2H, **16 & 16'**), 2.08 – 1.93 (m, 0.35H, **16'**), 1.75 – 1.55 (m, 2.5H, **16 & 16'**), 1.45 – 1.35 (m, 0.35H, **16'**), 0.94 (t, *J* = 7.3 Hz, 2.5H, **16**). ^{13}C NMR (101 MHz, $CDCl_3$) major signals (for compound **16**): δ 196.62, 148.04, 138.13, 135.28, 132.26, 130.43, 130.07, 128.52, 128.33, 38.21, 24.40, 13.93; minor signals (from compound **16'**) was also observed at δ 131.24, 130.46, 128.47, 125.17, 36.03, 32.51, 30.77, 29.31, 18.05. The spectra match the reported literature.[61]



18: Following **General procedure A,** the reaction was conducted at 0.05 mmol scale with 10.9 mg **17** as the ketone substrates. Two parallel reactions were conducted (0.05 mmol for each, 0.1 mmol in total) and combined, giving the titled compound as a colorless oil (10.0 mg, 57% yield). R_f = 0.65 (hexane). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.08 (d, *J* = 7.7 Hz, 2H), 6.99 (d, *J* = 7.8 Hz, 2H), 2.32 (s, 3H), 2.12 (ddd, *J* = 11.1, 7.5, 4.2 Hz, 1H), 1.79 (dqd, *J* = 14.0, 7.2, 4.2 Hz, 2H), 1.62 – 1.48 (m, 1H), 0.93 (d, *J* = 6.7 Hz, 3H), 0.78 – 0.65 (m, 6H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 141.47, 135.13, 128.71, 128.62, 54.69, 33.26, 25.82, 21.17, 21.16, 20.83, 12.61. IR (KBr) 3024, 2963, 2932, 2876, 1512, 1464, 1385 cm^{-1}. HRMS: calcd. 177.1638 $[M+H]^+$ Found: 177.1631.

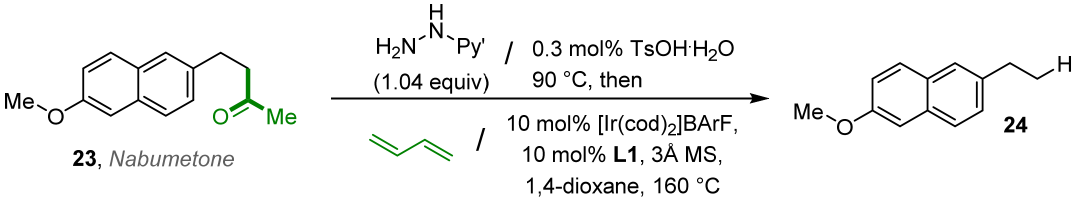


20: Following **General procedure A,** the reaction was conducted at 0.05 mmol scale with 17.1 mg **19** as the ketone substrates and 180 µL 1,3-butadiene (in PhMe, 20 wt.%). Two parallel reactions were conducted (0.05 mmol for each, 0.1 mmol in total) and combined, giving the titled compound as a colorless oil (15.4 mg, 52% yield). R_f = 0.65 (hexane/ethyl acetate = 3:1). M.p. = 90-92 °C (Et_2O). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.99 (d, *J* = 8.2 Hz, 1H), 7.85 (dd, *J* = 7.8, 1.7 Hz, 2H), 7.54 – 7.45 (m, 2H), 7.41 (t, *J* = 7.7 Hz, 2H), 7.34 – 7.28 (m, 2H), 7.23 (t, *J* = 7.5 Hz, 1H), 2.63 (t, *J* = 7.5 Hz, 2H), 1.71 (h, *J* = 7.5 Hz, 2H), 0.96 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 138.45, 135.58, 133.70, 131.40, 129.27, 126.80, 124.74, 123.79, 123.16, 122.76, 119.70, 113.91, 27.06, 22.23, 14.06. The spectra match the reported literature.[62]

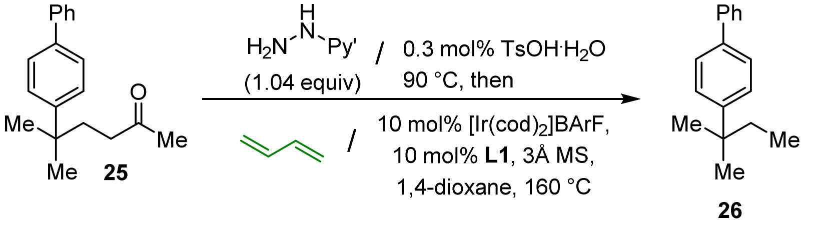


52: Following **General procedure A,** the reaction was conducted at 0.05 mmol scale with 13.9 mg **21** as the ketone substrates and 180 µL 1,3-butadiene (in PhMe, 20 wt.%). Two parallel reactions were conducted (0.05 mmol for each, 0.1 mmol in total) and combined. The reaction mixture was purified by flash column chromatography over silica (hexane/acetone, from 10:1 to 2.5:1) to give product **22** as a colorless oil (15.3 mg, 65% yield). R_f = 0.5

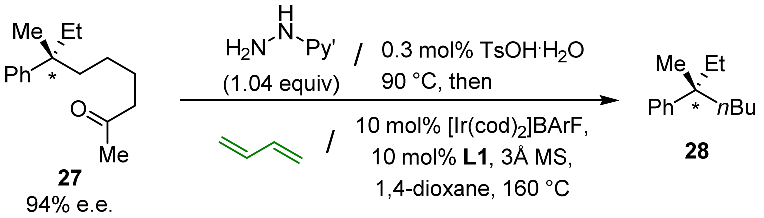
(hexane/acetone = 1:1). ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.49 (s, 1H), 4.05 – 3.92 (m, 5H), 3.56 (s, 3H), 1.68 – 1.58 (m, 2H), 1.44 – 1.34 (m, 2H), 0.94 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 155.48, 151.64, 148.86, 141.45, 107.83, 41.39, 33.70, 30.29, 29.80, 20.39, 13.94. The spectra match the reported literature.[63]



24: Following **General procedure A,** the reaction was conducted at 0.05 mmol scale with 11.4 mg **23** as the ketone substrates and 170 µL 1,3-butadiene (in PhMe, 20 wt.%) in a 8 mL vial (with 1 mL 1,4-dioxane). Two parallel reactions were conducted (0.05 mmol for each, 0.1 mmol in total) and combined after the key reaction was finished. A hydrogenation reaction with Pd/C (10% wt.%, 20 mg) in ethyl acetate (1 mL) under H_2 atmosphere (monitored by TLC) was conducted to hydrogenate a small amount of the deacetylative crotylation by-product (ca. 15%) in order to achieve better separation *via* flash column chromatography over silica. The compound **24** was obtained as a colorless oil (11.3 mg, 61% yield). R_f = 0.5 (hexane/ethyl acetate = 10:1). ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.68 (dd, *J* = 9.4, 3.0 Hz, 2H), 7.56 (s, 1H), 7.32 (dd, *J* = 8.4, 1.4 Hz, 1H), 7.17 – 7.07 (m, 2H), 3.92 (s, 3H), 2.79 (q, *J* = 7.6 Hz, 2H), 1.32 (t, *J* = 7.6 Hz, 3H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 157.24, 139.59, 133.05, 129.33, 129.03, 127.68, 126.82, 125.56, 118.72, 105.85, 55.43, 28.98, 15.75. The spectra match the reported literature.[64]



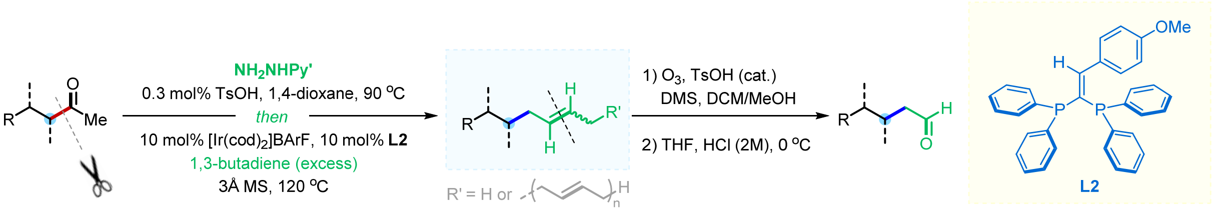
25: Following **General procedure A,** the reaction was conducted at 0.05 mmol scale with 13.3 mg **26** as the ketone substrates. Two parallel reactions were conducted (0.05 mmol for each, 0.1 mmol in total) and combined, giving the titled compound as a colorless oil (13.4 mg, 60% yield). R_f = 0.4 (hexane). ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.65 – 7.58 (m, 2H), 7.58 – 7.52 (m, 2H), 7.47 – 7.38 (m, 4H), 7.37 – 7.30 (m, 1H), 1.69 (q, *J* = 7.4 Hz, 2H), 1.33 (s, 6H), 0.74 (t, *J* = 7.5 Hz, 3H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 148.79, 141.21, 138.25, 128.82, 127.13, 127.08, 126.80, 126.52, 37.91, 37.00, 28.61, 9.33. The spectra match the reported literature.[65]



Compound **27** was prepared according to the previously reported literatures.[4] The racemic sample was prepared by replacing the chiral ligand[4] with 2,2'-bipyridine under otherwise identical reaction condition. The enantiomeric excess (ee) value was measured to be 94% as determined by HPLC analysis on a chiral stationary phase (hexane:*i*PrOH = 99:1, 0.4 mL/min, chiral IF). Following **General procedure A,** the reaction was conducted at 0.05 mmol scale with 11.6 mg **27** as the ketone substrates. Two parallel reactions were conducted (0.05 mmol for each, 0.1 mmol in total) and combined, giving the chiral compound **28** as a colorless oil (12.1 mg, 64% yield). R_f = 0.7 (hexane). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.34 – 7.25 (m, 4H), 7.20 – 7.12 (m, 1H), 1.80 – 1.63 (m, 2H), 1.60 – 1.46 (m, 2H), 1.31 – 1.17 (m, 5H), 1.16 – 1.06 (m, 1H), 0.99 – 0.88 (m, 1H), 0.83 (t, *J* = 7.3 Hz, 3H), 0.67 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 148.17, 128.00, 126.63, 125.26, 42.87, 41.10, 35.75, 26.61, 23.62, 23.57, 14.21, 8.80. IR (KBr) 3064, 3030, 2966, 2929, 2879, 1499, 1465, 1381 cm^{-1}. LRMS (EI): 190.2 (M^+, 8), 161.2 (28), 133.2 (53), 105.1 (69), 91.1 (100). $[\alpha]_D^{20}$ = 6.1 (1.15 c, $CDCl_3$).

3.3.2 Carbenoid-free homologation of aliphatic linear ketones

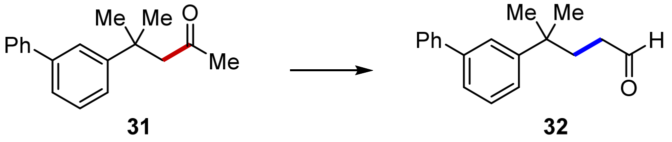
3.3.2.1 Formal 1,2-oxo-migration



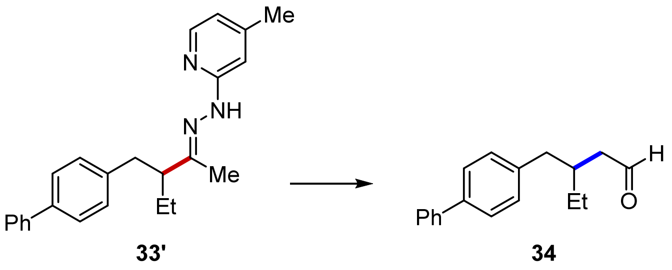
General procedure B1: For a 0.2 mmol scale reaction, a 1,4-dioxane (0.2 mL) solution of the ketone substrate (0.2 mmol, 1.0 equiv), 2-hydrazineyl-4-methylpyridine (**D1**) (26.1 mg, 0.212 mmol, 1.06 equiv), and *p*-TsOH·H_2O (*stock solution in 1,4-dioxane*, 0.05 M, 12 µL, 0.003 equiv) was heated under nitrogen atmosphere in a 4 mL vial at 90-100 °C for 5-12 hours monitored by TLC. After cooled to room temperature, the vial was charged first with $[Ir(cod)_2]BArF$ (25.6 mg, 0.02 mmol, 0.1 equiv) and **L2** (10.0 mg, 0.02 mmol, 0.1 equiv) under air atmosphere, and then with 3Å molecular sieve (pre-dried, 200 mg) and 1,3-butadiene (20 wt.% in PhMe, 2.5 mL) in a glovebox. The vial was sealed and heated at 120 °C under stirring for 12-24 hours until the full consumption of the corresponding hydrazone of the ketone substrate (monitored by TLC). After cooled to room temperature, the reaction mixture was filtered through Celite, concentrated, and purified by flash column chromatography over silica to give the allylation products. A flow of O_3/ O_2, generated from a regular ozone generator, was passed through a MeOH/DCM solution (1:1, 6 mL in total) of the allylation products and *p*-TsOH·H_2O (4.0 mg) at -78 °C for several minutes until the solution turned blue. A flow of N_2 was passed through the solution for 2 minutes. Dimethyl sulfide (0.8 mL) was added, and the reaction was allowed to warm to room temperature and stirred overnight. The reaction was concentrated and purified by flash column chromatography over silica to give the dimethyl acetal. A THF (3 mL) and HCl (2M, 1 mL) solution of the dimethyl acetal was stirred at room temperature for 20 minutes, and left overnight in a 0 ^{o}C freezer, leading to a generally spot-to-spot deprotection of the acetal. The reaction mixture was extracted by Et_2O (3 mL × 3), concentrated, and purified by flash column chromatography over silica to give the aldehyde product.

Note: Albeit in slightly lower yields, the aldehyde products could be directly isolated by replacing the *p*-TsOH·H_2O with K_2CO_3 (20 mg) in the ozonolysis step.

Note: The product of the first step contains a mixture of mono- and multi-allylation products (*as more than one 1,3-diene could be trapped*). For each example shown below, the R_f range for the allylation products was reported. The R_f range for the allylation products could also be easily identified by applying a $KMnO_4$ stain onto the TLC plate (*the allylation products would rapidly turn yellow in a few seconds*).

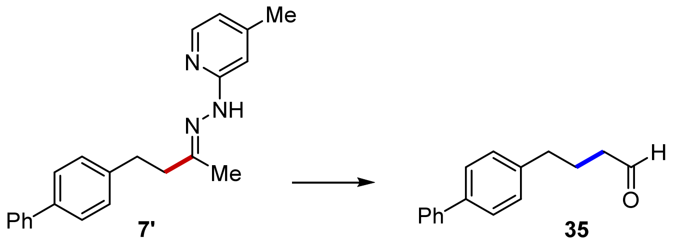


32: Following modified **General procedure B1,** the reaction was conducted at 0.2 mmol scale at 130 ^{o}C. The titled compound was isolated as a colorless oil (27.7 mg, 55% yield). R_f = 0.7 (hexane/ethyl acetate = 5:1). R_f for allylation products before ozonolysis = 0.5-0.8 (hexane/ethyl acetate = 40:1). ^{1}H NMR (400 MHz, C_6D_6) δ 9.11 (d, *J* = 0.9 Hz, 1H), 7.51 – 7.44 (m, 3H), 7.30 (dt, *J* = 7.8, 1.3 Hz, 1H), 7.23 – 7.13 (m, 3H), 7.12 (d, *J* = 1.3 Hz, 1H), 7.01 (ddd, *J* = 7.8, 2.0, 1.1 Hz, 1H), 1.64 (s, 4H), 1.02 (s, 6H). ^{13}C NMR (101 MHz, C_6D_6) δ 200.39, 148.98, 142.23, 141.86, 129.14, 129.08, 127.67, 127.55, 125.21, 125.11, 125.09, 40.09, 37.20, 35.96, 28.80. IR (KBr) 3064, 3032, 2967, 2876, 1727, 1601, 1484, 1411 cm^{-1}. HRMS: calcd. $[M]^+$ 252.1509 Found: 252.1501.

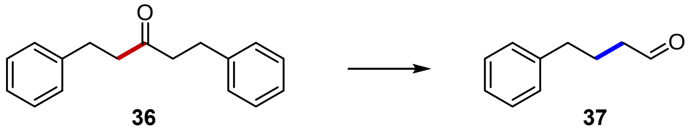


34: Following modified **General procedure B1,** the reaction was conducted at 0.2 mmol scale using the pre-condensed hydrazone of the ketone **33** as the starting material. The titled compound was isolated as a colorless oil (32.6 mg, 65% yield). R_f = 0.4 (hexane/ethyl acetate = 10:1). R_f for allylation products before ozonolysis = 0.6-0.8 (hexane/ethyl acetate = 40:1). ^{1}H NMR (400 MHz, C_6D_6) δ 9.24 (s, 1H), 7.46 (d, *J* = 7.0 Hz, 2H), 7.39 (d, *J* = 8.2 Hz, 2H), 7.18 (t, *J* = 7.5 Hz, 2H), 7.07 (d, *J* = 7.3 Hz, 1H), 6.97 (d, *J* = 8.1 Hz, 2H), 2.36 (dd, *J* = 13.5, 6.8 Hz, 1H), 2.24 (dd, *J* = 13.5, 7.4 Hz, 1H), 1.94 (p, *J* = 6.6 Hz, 1H), 1.88 – 1.74 (m, 2H), 1.22 – 0.99 (m, 2H), 0.65 (t, *J* =

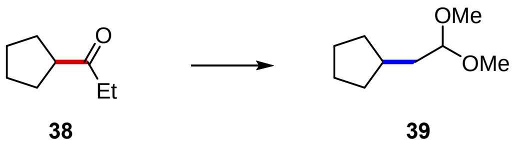
7.4 Hz, 3H). ^{13}C NMR (101 MHz, C_6D_6) δ 200.86, 141.51, 139.64, 139.60, 130.03, 129.11, 127.47, 127.40, 127.38, 47.41, 39.85, 36.52, 26.55, 11.14. IR (KBr) 3033, 2963, 2924, 1724, 1488, 1409, 1013 cm^{-1}. HRMS: calcd. [M]$^+$ 252.1509 Found: 252.1496.



35: Following modified **General procedure B1,** the reaction was conducted at 0.2 mmol scale using the pre-condensed hydrazone of the ketone **7** as the starting material. The titled compound was isolated as a colorless oil (27.2 mg, 61% yield). R_f = 0.3 (hexane/ethyl acetate = 10:1). R_f for allylation products before ozonolysis = 0.6-0.8 (hexane/ethyl acetate = 40:1). R_f = 0.35 (hexane/ethyl acetate = 5:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.79 (s, 1H), 7.64 – 7.56 (m, 2H), 7.53 (d, J = 8.1 Hz, 2H), 7.43 (t, J = 7.6 Hz, 2H), 7.33 (t, J = 7.3 Hz, 1H), 7.25 (d, J = 6.1 Hz, 2H), 2.71 (t, J = 7.6 Hz, 2H), 2.50 (t, J = 7.3 Hz, 2H), 2.01 (p, J = 7.4 Hz, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 202.39, 141.11, 140.46, 139.25, 129.03, 128.88, 127.34, 127.24, 127.14, 43.32, 34.79, 23.76. IR (KBr) 3030, 2934, 2857, 2726, 1725, 1488, 1411 cm^{-1}. HRMS: calcd. 207.1168 [M+H–H_2O]$^+$ Found: 207.1170.

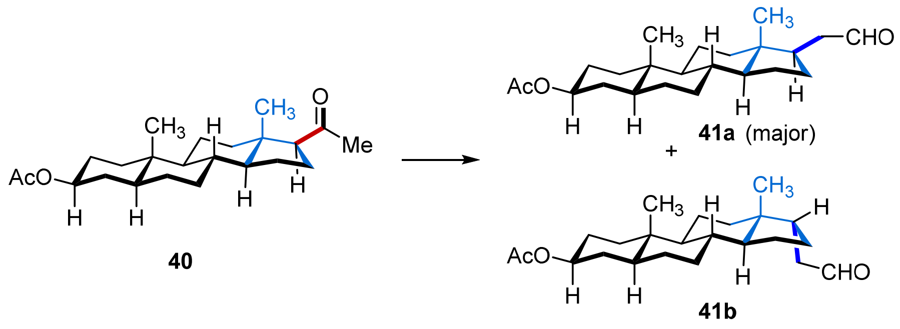


37: Following **General procedure B1,** the reaction was conducted at 0.2 mmol scale. The titled compound was isolated as a colorless oil (24.8 mg, 84% yield). R_f = 0.6 (hexane/ethyl acetate = 5:1). R_f for allylation products before ozonolysis = 0.3-0.7 (hexane/ethyl acetate = 40:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.76 (s, 1H), 7.29 (dd, J = 8.1, 6.6 Hz, 2H), 7.24 – 7.10 (m, 3H), 2.66 (t, J = 7.6 Hz, 2H), 2.46 (td, J = 7.3, 1.7 Hz, 2H), 1.97 (p, J = 7.4 Hz, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 202.47, 141.34, 128.59, 128.59, 126.23, 43.28, 35.14, 23.78. The spectra match the reported literature.[66]



39: Following modified **General procedure B1,** the reaction was conducted at 0.2 mmol scale at 130 °C. Due to the volatility of the corresponding aldehyde, the product was isolated as the acetal as a colorless oil (20 mg, 63% yield).

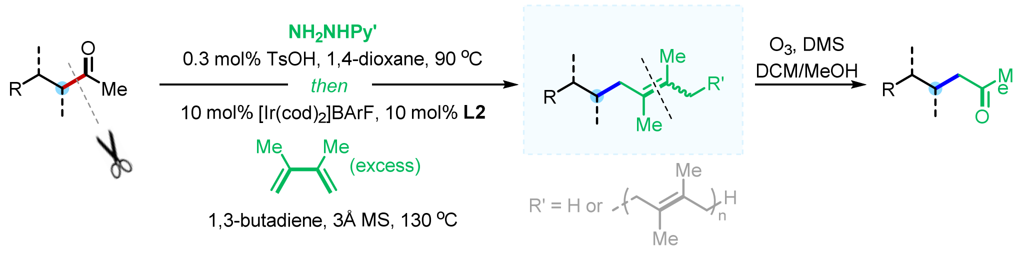
R$_f$ = 0.7 (hexane/ethyl acetate = 5:1). R$_f$ for allylation products before ozonolysis = 0.4-0.7 (hexane/ethyl acetate = 40:1). ^{1}H NMR (400 MHz, C$_6$D$_6$) δ 4.36 (t, *J* = 5.9 Hz, 1H), 3.11 (s, 6H), 1.90 – 1.78 (m, 1H), 1.74 – 1.58 (m, 4H), 1.54 – 1.32 (m, 4H), 1.04 – 0.91 (m, 2H). ^{13}C NMR (101 MHz, C$_6$D$_6$) δ 104.13, 52.05, 38.84, 36.53, 33.12, 25.28. IR (KBr) 2949, 2868, 2829, 1453, 1366, 1194, 1127, 1058 cm^{-1}.



60% yield, **41a**:**41b** = 5:1

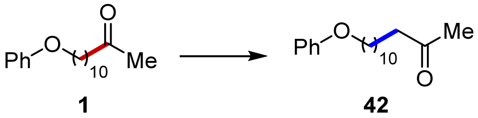
41: Following modified **General procedure B1,** the reaction was conducted at 0.2 mmol scale at 170 ^{o}C. The titled compound was isolated as an inseparable 5:1 mixture of diastereomers (colorless wax, 43.1 mg, 60% yield, dr = 5:1 determined by ^{1}H NMR analysis). The major diastereomer was tentatively assigned as **41a** based on 2D-NOESY experiments. R$_f$ = 0.5 (hexane/ethyl acetate = 5:1). R$_f$ for allylation products before ozonolysis = 0.6-0.8 (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, C$_6$D$_6$) δ 9.39 (t, *J* = 2.2 Hz, 0.16H), 9.35 (dd, *J* = 2.4, 1.5 Hz, 0.84H), 4.81 (tt, *J* = 11.4, 5.0 Hz, 1H), 1.99 (ddd, *J* = 15.8, 6.0, 1.6 Hz, 1H), 1.94 – 1.86 (m, 1H), 1.85 – 1.73 (m, 2H), 1.71 (s, 3H), 1.66 – 1.52 (m, 2H), 1.51 – 1.37 (m, 4H), 1.34 – 1.23 (m, 2H), 1.23 – 1.13 (m, 1H), 1.11 – 0.81 (m, 8H), 0.81 – 0.60 (m, 4H), 0.60 – 0.52 (m, 5.5H), 0.36 – 0.22 (m, 1.5H). ^{13}C NMR (101 MHz, C$_6$D6) **41a**: δ 201.31, 169.79, 73.49, 54.06, 50.90, 47.42, 44.70, 43.06, 42.20, 36.99, 35.98, 35.64, 34.54, 34.51, 32.65, 28.85, 28.83, 27.95, 25.92, 21.25, 21.12, 20.64, 12.24. carbon signals of the **41b** was observed at: δ 201.04, 169.78, 55.25, 54.48, 45.25, 44.77, 44.73, 42.26, 37.72, 36.96, 35.66, 35.63, 34.51, 32.22, 28.81, 28.47, 24.85, 21.13, 12.83, 12.25. IR (KBr) 2941, 2851, 2716, 1732, 1479, 1454, 1364, 1364, 1249, 1035 cm^{-1}. HRMS: calcd. [M+H]$^{+}$ 361.2737 Found: 361.2717. LRMS: 360 (M^{+}, 19), 345 (15), 316 (21), 300 (33), 285 (49), 215 (100).

3.3.2.2 Homologation of methyl ketones

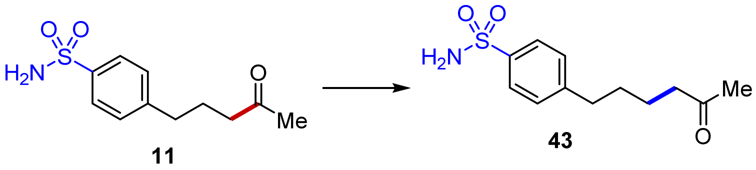


General procedure B2: For a 0.2 mmol scale reaction, a 1,4-dioxane (0.2 mL) solution of the ketone substrate (0.2 mmol, 1.0 equiv), 2-hydrazineyl-4-methylpyridine (**D1**) (26.1 mg, 0.212 mmol, 1.06 equiv), and *p*-TsOH·H$_2$O (*stock solution in 1,4-dioxane*, 0.05 M, 12 μL, 0.003 equiv) was heated under nitrogen atmosphere in a 4 mL vial at 90-100 °C for 5-12 hours monitored by TLC. After cooled to room temperature, the vial was charged first with [Ir(cod)$_2$]BArF (25.6 mg, 0.02 mmol, 0.1 equiv) and **L2** (10.0 mg, 0.02 mmol, 0.1 equiv) under air atmosphere, and then with 3Å molecular sieve (pre-dried, 200 mg), 2,3-dimethyl-1,3-butadiene (0.6 mL, 5.3 mmol, 26.4 equiv), and 1,3-butadiene (20 wt.% in PhMe, 260 μL, ca. 3.9 equiv) in a glovebox. The vial was sealed and heated at 130 °C under stirring for 12-24 hours until the full consumption of the corresponding hydrazone of the ketone substrate (monitored by TLC). After cooled to room temperature, the reaction mixture was filtered through Celite, concentrated, and purified by flash column chromatography over silica to give the allylation products. A flow of O_3/ O_2, generated from a regular ozone generator, was passed through a MeOH/DCM solution (1:1, 6 mL in total) of the allylation products at -78 ^{o}C for several minutes until the solution turned blue. A flow of N_2 was passed through the solution for 2 minutes. PPh_3 (600 mg) (*or dimethyl sulfide, 0.8 mL*) was added, and the reaction was allowed to warm to room temperature and stirred overnight. The reaction was then concentrated and purified by flash column chromatography over silica to give the ketone product.

Note: The product of the first step contains a mixture of mono- and multi-allylation products (*as more than one 1,3-diene could be trapped*). For each example shown below, the R_f range for the allylation products was reported. The R_f range for the allylation products could also be easily identified by applying a $KMnO_4$ stain onto the TLC plate (*the allylation products would rapidly turn yellow in a few seconds*).

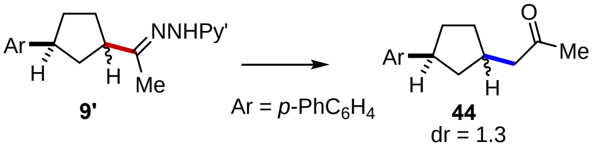


42: Following **General procedure B2,** the reaction was conducted at 0.2 mmol scale. The titled compound was isolated as a colorless oil (34.6 mg, 60% yield). R_f = 0.065 (hexane/ethyl acetate = 5:1). R_f for allylation products before ozonolysis = 0.2-0.5 (hexane/ethyl acetate = 40:1). ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.23 (dd, *J* = 6.6, 2.0 Hz, 2H), 6.94 – 6.80 (m, 3H), 3.91 (t, *J* = 6.6 Hz, 2H), 2.38 (t, *J* = 7.5 Hz, 2H), 2.10 (s, 3H), 1.80 – 1.69 (m, 2H), 1.53 (p, *J* = 7.2 Hz, 2H), 1.42 (p, *J* = 6.8 Hz, 2H), 1.24 (s, 12H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 209.55, 159.23, 129.52, 120.56, 114.60, 67.98, 43.96, 30.00, 29.67, 29.65, 29.57, 29.52, 29.43, 29.31, 26.19, 24.00. IR (KBr) 3060, 2934, 2920, 2853, 1711, 1589, 1474, 1411 cm^{-1}. HRMS: calcd. [M+H]$^+$ 291.2319 Found: 291.2321.

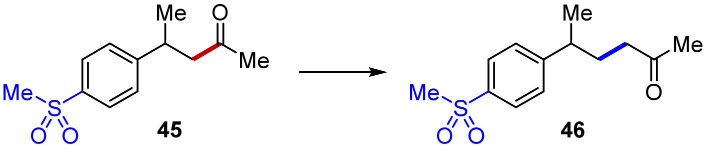


43: Following **General procedure B2,** the reaction was conducted at 0.2 mmol scale. The titled compound was isolated as a colorless wax (23.3 mg, 46% yield). R_f = 0.4 (hexane/acetone = 1:1). R_f for allylation products before ozonolysis = 0.3-0.75 (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.83 (d, *J* = 8.1 Hz, 2H), 7.31 (d, *J* = 8.1 Hz, 2H), 4.91 (s, 2H), 2.77 – 2.60 (m, 2H), 2.46 (t, *J* = 6.5 Hz, 2H), 2.13 (s, 3H), 1.67 – 1.57 (m, 4H). ^{13}C

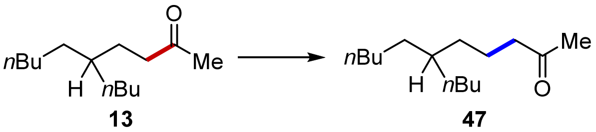
NMR (101 MHz, $CDCl_3$) δ 208.95, 147.84, 139.59, 129.22, 126.68, 43.47, 35.75, 30.61, 30.12, 23.32. IR (KBr) 3568, 3340, 3263, 2936, 2861, 1707, 1336, 1162 cm^{-1}. HRMS: calcd. $[M+H]^+$ 256.1002 Found: 256.1006.



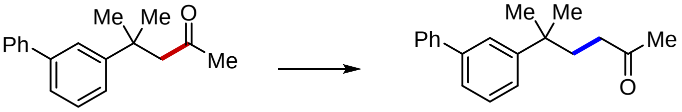
44: Following modified **General procedure B2,** the reaction was conducted at 0.2 mmol scale using pre-condensed hydrazone of ketone **9** as the starting material. The titled compound was isolated as an inseparable mixture of diastereomers (colorless oil, 37 mg, 67% yield, dr = 1.3). R_f = 0.3 (hexane/ethyl acetate = 10:1). R_f for allylation products before ozonolysis = 0.5-0.85 (hexane/ethyl acetate = 40:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.63 – 7.56 (m, 2H), 7.53 (d, J = 8.2 Hz, 2H), 7.47 – 7.40 (m, 2H), 7.37 – 7.29 (m, 3H), 3.27 – 3.04 (m, 1H), 2.67 – 2.41 (m, 3H), 2.36 – 2.28 (m, 0.45H), 2.22 – 1.95 (m, 5.55H), 1.81 – 1.67 (m, 1.55H), 1.50 – 1.37 (m, 0.45), 1.35 – 1.23 (m, 1H). ^{13}C NMR (101 MHz, $CDCl_3$) carbon signals were observed at δ 208.89, 145.58, 145.05, 141.18, 138.94, 138.88, 128.82, 127.56, 127.52, 127.17, 127.15, 127.11, 50.76, 50.35, 45.35, 44.14, 42.05, 40.32, 35.62, 35.12, 34.77, 33.40, 33.25, 31.93, 30.35, 30.30. IR (KBr) 3060, 3028, 2947, 2870, 1715, 1599, 1490, 1354, 1182, 1008 cm^{-1}. HRMS: calcd. $[M+H]^+$ 279.1744 Found: 279.1744.



46: Following **General procedure B2,** the reaction was conducted at 0.2 mmol scale (300 µL of 1,3-butadiene in PhMe was used). The titled compound was isolated as a colorless oil (38 mg, 75% yield). R_f = 0.4 (hexane/acetone = 1:1). R_f for allylation products before ozonolysis = 0.1-0.3 (hexane/ethyl acetate = 10:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.85 (d, J = 8.4 Hz, 2H), 7.35 (d, J = 8.3 Hz, 2H), 3.04 (s, 3H), 2.85 – 2.74 (m, 1H), 2.29 (qdd, J = 17.5, 8.8, 6.2 Hz, 2H), 2.06 (s, 3H), 1.98 – 1.75 (m, 2H), 1.26 (d, J = 6.9 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 208.34, 153.30, 138.51, 128.11, 127.77, 44.63, 41.49, 39.37, 31.53, 30.11, 22.13. IR (KBr) 3613, 3009, 2965, 2928, 1711, 1601, 1411, 1312, 1156, 1093 cm^{-1}. HRMS: calcd. $[M+H]^+$ 255.1050 Found: 255.1057.

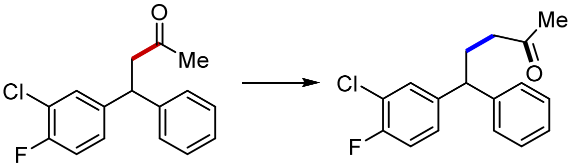


47: Following **General procedure B2,** the reaction was conducted at 0.2 mmol scale. The titled compound was isolated as a colorless oil (34.7 mg, 77% yield). R_f = 0.55 (hexane/ethyl acetate = 10:1). R_f for allylation products before ozonolysis = 0.7-0.85 (hexane/ethyl acetate = 40:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.39 (t, J = 7.5 Hz, 2H), 2.13 (s, 3H), 1.58 – 1.48 (m, 2H), 1.33 – 1.14 (m, 17H), 0.87 (td, J = 7.0, 1.8 Hz, 6H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 209.55, 44.41, 37.43, 33.59, 33.32, 33.31, 32.47, 30.00, 29.03, 26.46, 23.27, 22.85, 21.22, 14.30, 14.27. IR (KBr) 2961, 2922, 2859, 1721, 1462, 1360, 1164 cm^{-1}. HRMS: calcd. [M+H]$^+$ 227.2370 Found: 227.2368.



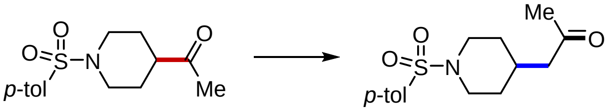
31 **48**

48: Following **General procedure B2,** the reaction was conducted at 0.2 mmol scale. The titled compound was isolated as a colorless oil (30 mg, 56% yield). R_f = 0.3 (hexane/ethyl acetate = 10:1). R_f for allylation products before ozonolysis = 0.3-0.7 (hexane/ethyl acetate = 40:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.60 (d, J = 6.9 Hz, 2H), 7.54 (s, 1H), 7.50 – 7.29 (m, 6H), 2.28 – 2.18 (m, 2H), 2.04 (s, 3H), 2.02 – 1.94 (m, 2H), 1.38 (s, 6H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 209.20, 148.88, 141.68, 141.26, 128.86, 128.77, 127.35, 127.34, 124.91, 124.89, 124.79, 39.72, 37.68, 37.41, 30.09, 29.09. IR (KBr) 3056, 3032, 2963, 1715, 1603, 1482, 1366, 1366, 1164 cm^{-1}. HRMS: calcd. [M+H]$^+$ 267.1744 Found: 267.1744.



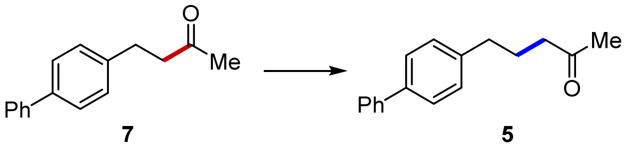
49 **50**

50: Following **General procedure B2,** the reaction was conducted at 0.2 mmol. The titled compound was isolated as a colorless oil (42.5 mg, 73% yield). R_f = 0.4 (hexane/ethyl acetate = 5:1). R_f for allylation products before ozonolysis = 0.3-0.7 (hexane/ethyl acetate = 40:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.33 – 7.16 (m, 6H), 7.12 – 7.01 (m, 2H), 3.86 (t, J = 7.8 Hz, 1H), 2.44 – 2.32 (m, 2H), 2.32 – 2.22 (m, 2H), 2.08 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 208.22, 156.78 (d, J = 247.5 Hz), 143.34, 141.72 (d, J = 3.9 Hz), 129.86, 128.90, 127.84, 127.49 (d, J = 7.0 Hz), 126.89, 120.95 (d, J = 17.6 Hz), 116.64 (d, J = 20.9 Hz), 49.43, 41.76, 30.23, 29.16. IR (KBr) 3060, 2940, 2896, 1715, 1496, 1451, 1370, 1249, 1062 cm^{-1}. HRMS: calcd. [M+H]$^+$ 291.0947 Found: 291.0934.

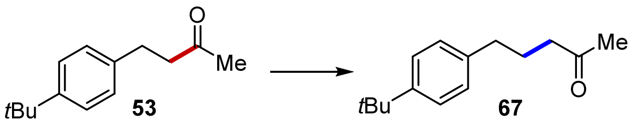


51 **52**

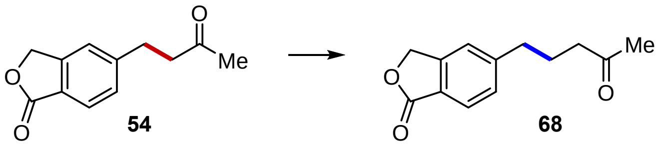
52: Following modified **General procedure B2,** the reaction was conducted at 0.2 mmol using 300 µL toluene solution of 1,3-butadiene at 140 °C. The titled compound was isolated as a colorless oil (44 mg, 75% yield). R_f = 0.3 (hexane/ethyl acetate = 1:1). R_f for allylation products before ozonolysis = 0.5-0.8 (hexane/ethyl acetate = 5:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.56 (d, J = 8.3 Hz, 2H), 7.25 (dd, J = 8.6, 0.7 Hz, 2H), 3.80 – 3.57 (m, 2H), 2.37 (s, 3H), 2.28 (d, J = 6.4 Hz, 2H), 2.17 (td, J = 12.0, 2.5 Hz, 2H), 2.03 (s, 3H), 1.77 – 1.61 (m, 3H), 1.29 – 1.18 (m, 2H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 207.50, 143.60, 133.00, 129.71, 127.83, 49.66, 46.43, 31.35, 30.81, 30.72, 21.66. IR (KBr) 2926, 2849, 1719, 1597, 1445, 1362, 1253, 1164, 1099 cm^{-1}. HRMS: calcd. [M+H]$^+$ 296.1315 Found: 296.1322.



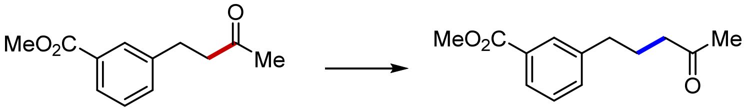
5: Following **General procedure B2,** the reaction was conducted at 0.2 mmol scale. The titled compound was isolated as a colorless oil (35.6 mg, 75% yield). R$_f$ = 0.4 (hexane/ethyl acetate = 5:1). R$_f$ for allylation products before ozonolysis = 0.2-0.6 (hexane). The characterization data for compound **5** has been reported *vide supra*.



53: Following **General procedure B2,** the reaction was conducted at 0.2 mmol scale. The titled compound was isolated as a colorless oil (33.8 mg, 78% yield). R$_f$ = 0.5 (hexane/ethyl acetate = 5:1). R$_f$ for allylation products before ozonolysis = 0.4-0.7 (hexane). ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.31 (d, J = 7.8 Hz, 2H), 7.11 (d, J = 7.8 Hz, 2H), 2.60 (t, J = 7.6 Hz, 2H), 2.45 (t, J = 7.4 Hz, 2H), 2.13 (s, 3H), 1.91 (p, J = 7.5 Hz, 2H), 1.32 (s, 9H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 209.03, 148.85, 138.58, 128.22, 125.37, 43.11, 34.60, 34.48, 31.53, 30.07, 25.34. IR (KBr) 3056, 2963, 2866, 1715, 1518, 1462, 1362, 1269, 1164 cm^{-1}. HRMS: calcd. [M+H]$^+$ 219.1744 Found: 219.1742. The spectrum matches the reported literature.[17]

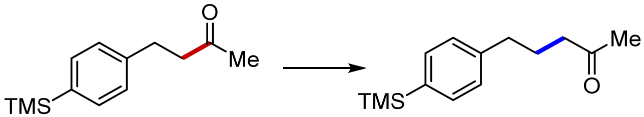


68: Following modified **General procedure B2,** the reaction was conducted at 0.2 mmol. The titled compound was isolated as a colorless oil (29.7 mg, 68% yield). R$_f$ = 0.1 (hexane/ethyl acetate = 5:1). R$_f$ for allylation products before ozonolysis = 0.1-0.2 (hexane/ethyl acetate = 10:1). ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.82 (d, J = 7.8 Hz, 1H), 7.42 – 7.28 (m, 2H), 5.27 (s, 2H), 2.74 (dd, J = 8.7, 6.8 Hz, 2H), 2.47 (t, J = 7.2 Hz, 2H), 2.13 (s, 3H), 1.97 – 1.88 (m, 2H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 208.23, 171.15, 149.10, 147.30, 129.76, 125.83, 123.85, 121.94, 69.58, 42.65, 35.47, 30.17, 25.04. IR (KBr) 2946, 1766, 1718, 1620, 1364, 1249, 1052 cm^{-1}. HRMS: calcd. [M+H]$^+$ 219.1016 Found: 219.1018.



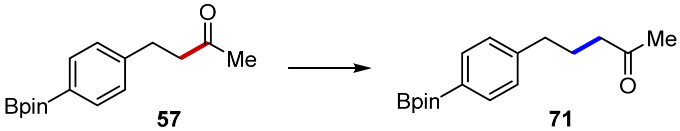
55 **69**

69: Following **General procedure B2,** the reaction was conducted at 0.2 mmol scale. The titled compound was isolated as a colorless oil (32.4 mg, 74% yield). R$_f$ = 0.1 (hexane/ethyl acetate = 5:1). R$_f$ for allylation products before ozonolysis = 0.2-0.3 (hexane/ethyl acetate = 40:1). ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.91 – 7.79 (m, 2H), 7.39 – 7.31 (m, 2H), 3.90 (s, 3H), 2.71 – 2.55 (m, 2H), 2.43 (t, *J* = 7.3 Hz, 2H), 2.11 (s, 3H), 1.91 (p, *J* = 7.5 Hz, 2H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 208.60, 167.30, 142.02, 133.21, 130.34, 129.62, 128.57, 127.41, 52.20, 42.79, 34.89, 30.11, 25.13. IR (KBr) 3001, 2951, 1717, 1593, 1447, 1281, 1202, 1109 cm^{-1}. HRMS: calcd. [M+H]$^+$ 221.1172 Found: 222.1162.



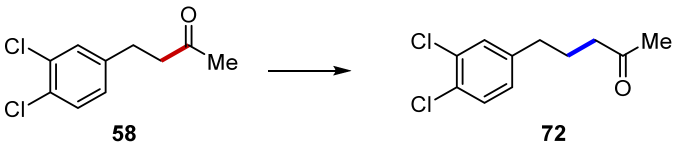
56 **70**

70: Following **General procedure B2,** the reaction was conducted at 0.2 mmol scale. The titled compound was isolated as a colorless oil (37.2 mg, 80% yield). R$_f$ = 0.5 (hexane/ethyl acetate = 5:1). R$_f$ for allylation products before ozonolysis = 0.4-0.7 (hexane). ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.45 (d, *J* = 7.4 Hz, 2H), 7.18 (d, *J* = 7.4 Hz, 2H), 2.62 (t, *J* = 7.6 Hz, 2H), 2.45 (t, *J* = 7.4 Hz, 2H), 2.13 (s, 3H), 1.92 (p, *J* = 7.5 Hz, 2H), 0.26 (s, 9H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 208.92, 142.32, 137.75, 133.59, 128.07, 43.04, 35.12, 30.10, 25.22, -0.93. IR (KBr) 3009, 2957, 2896, 2863, 1719, 1603, 1368, 1251, 1111 cm^{-1}. HRMS: calcd. [M+H]$^+$ 235.1513 Found: 235.1515.

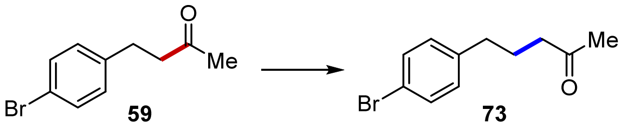


57 **71**

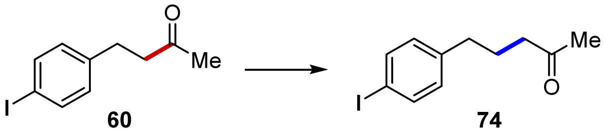
71: Following modified **General procedure B2,** the reaction was conducted at 0.2 mmol scale. The titled compound was isolated as a colorless oil (22.8 mg, 40% yield). R$_f$ = 0.4 (hexane/ethyl acetate = 5:1). R$_f$ for allylation products before ozonolysis = 0.1 (hexane/ethyl acetate = 40:1). ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.73 (d, *J* = 7.9 Hz, 2H), 7.18 (d, *J* = 7.8 Hz, 2H), 2.63 (t, *J* = 7.5 Hz, 2H), 2.41 (t, *J* = 7.4 Hz, 2H), 2.10 (s, 3H), 1.90 (p, *J* = 7.5 Hz, 2H), 1.34 (s, 12H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 208.86, 145.09, 135.06, 128.07, 83.81, 42.85, 35.28, 30.11, 25.08, 24.99. IR (KBr) 2979, 2936, 1717, 1611, 1403, 1368, 1148, 1091 cm^{-1}. HRMS: calcd. [M+H]$^+$ 289.1970 Found: 289.1972.


58 **72**

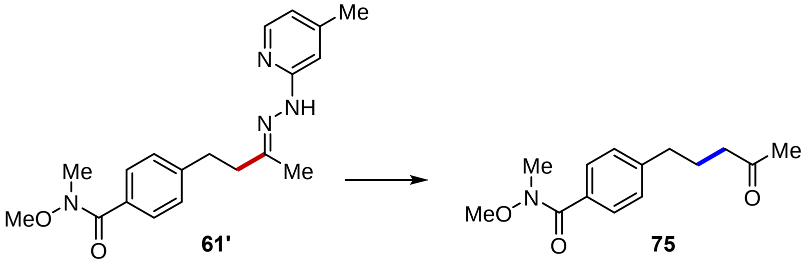
72: Following **General procedure B2,** the reaction was conducted at 0.2 mmol scale. The titled compound was isolated as a colorless oil (36.8 mg, 80% yield). R_f = 0.4 (hexane/ethyl acetate = 5:1). R_f for allylation products before ozonolysis = 0.6-0.8 (hexane/ethyl acetate = 50:1). ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.33 (d, J = 8.2 Hz, 1H), 7.25 (d, J = 2.1 Hz, 1H), 7.00 (dd, J = 8.2, 2.1 Hz, 1H), 2.62 – 2.51 (m, 2H), 2.43 (t, J = 7.2 Hz, 2H), 2.12 (s, 3H), 1.86 (p, J = 7.4 Hz, 2H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 208.34, 141.99, 132.34, 130.47, 130.40, 129.99, 128.02, 42.59, 34.21, 30.16, 24.87. IR (KBr) 2938, 2861, 1717, 1563, 1474, 1368, 1131, 1032 cm^{-1}. HRMS: calcd. [M+H]$^+$ 231.0338 Found: 231.0327. The spectra match the reported literature.[67]


59 **73**

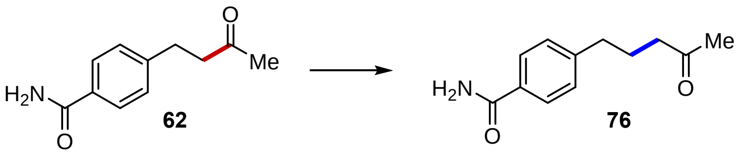
73: Following **General procedure B2,** the reaction was conducted at 0.2 mmol scale. The titled compound was isolated as a colorless oil (38.4 mg, 80% yield). R_f = 0.35 (hexane/ethyl acetate = 5:1). R_f for allylation products before ozonolysis = 0.4-0.7 (hexane). ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.39 (d, J = 8.4 Hz, 2H), 7.04 (d, J = 8.7 Hz, 2H), 2.64 – 2.49 (m, 2H), 2.42 (t, J = 7.3 Hz, 2H), 2.11 (s, 3H), 1.95 – 1.78 (m, 2H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 208.61, 140.65, 131.55, 130.32, 119.81, 42.73, 34.50, 30.13, 25.08. IR (KBr) 3024, 2940, 2861, 1717, 1490, 1370, 1077, 1016 cm^{-1}. HRMS: calcd. [M+H]$^+$ 241.0223 Found: 241.0211.


60 **74**

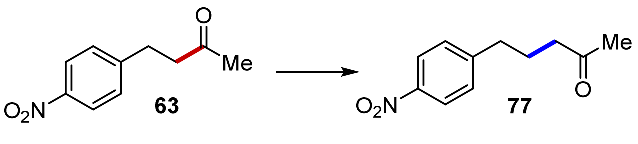
74: Following **General procedure B2,** the reaction was conducted at 0.2 mmol scale. The titled compound was isolated as a colorless oil (37.8 mg, 66% yield). R_f = 0.35 (hexane/ethyl acetate = 5:1). R_f for allylation products before ozonolysis = 0.4-0.7 (hexane). ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.59 (d, J = 8.3 Hz, 2H), 6.92 (d, J = 8.4 Hz, 2H), 2.65 – 2.49 (m, 2H), 2.42 (t, J = 7.3 Hz, 2H), 2.11 (s, 3H), 1.86 (p, J = 7.4 Hz, 2H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 208.59, 141.33, 137.52, 130.68, 91.12, 42.72, 34.59, 30.13, 25.03. IR (KBr) 2938, 2857, 1715, 1484, 1358, 1164, 1008 cm^{-1}. HRMS: calcd. [M+H]$^+$ 289.0084 Found: 289.0084.



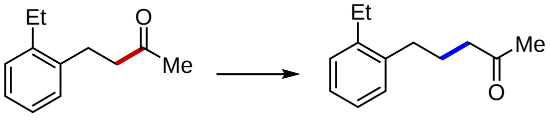
75: Following modified **General procedure B2,** the reaction was conducted at 0.2 mmol scale using the pre-formed hydrazone of the ketone **61** as the starting material and 300 µL toluene solution of 1,3-butadiene. The titled compound was isolated as a colorless oil (34.8 mg, 70% yield). R_f = 0.5 (hexane/acetone = 2:1). R_f for allylation products before ozonolysis = 0.5-0.6 (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.59 (d, *J* = 8.2 Hz, 2H), 7.24 – 7.13 (m, 2H), 3.54 (s, 3H), 3.33 (s, 3H), 2.70 – 2.56 (m, 2H), 2.42 (t, *J* = 7.3 Hz, 2H), 2.10 (s, 3H), 1.95 – 1.85 (m, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 208.65, 169.91, 144.54, 131.75, 128.46, 128.13, 61.05, 42.70, 34.90, 33.91, 30.05, 24.89. IR (KBr) 3504, 2997, 2940, 2872, 1717, 1640, 1421, 1376, 1218, 1186 cm^{-1}. HRMS: calcd. $[M+H]^+$ 250.1438 Found: 250.1441.



76: Following **General procedure B2,** the reaction was conducted at 0.2 mmol scale. The titled compound was isolated as a white solid (28.5 mg, 70% yield). M.p. = 117 – 119 °C. R_f = 0.2 (hexane/acetone = 3:2). R_f for allylation products before ozonolysis = 0.2-0.6 (hexane/acetone = 3:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.73 (d, *J* = 8.3 Hz, 2H), 7.22 (d, *J* = 8.2 Hz, 2H), 6.31 (br, 2H), 2.64 (t, *J* = 7.6 Hz, 2H), 2.42 (t, *J* = 7.3 Hz, 2H), 2.10 (s, 3H), 1.95 – 1.80 (m, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 208.76, 169.81, 146.05, 131.25, 128.68, 127.64, 42.68, 34.88, 30.07, 24.87. IR (KBr) 3388, 3198, 2940, 2890, 1713, 1646, 1620, 1567, 1409, 1302, 1146 cm^{-1}. HRMS: calcd. $[M+H]^+$ 206.1176 Found: 206.1177. The spectrum matches the reported literature.[68]

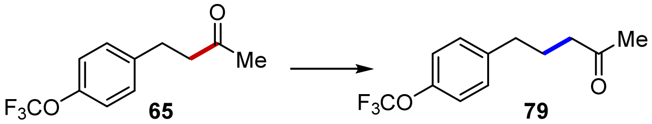


77: Following **General procedure B2,** the reaction was conducted at 0.2 mmol scale. The titled compound was isolated as a colorless oil (31.5 mg, 76% yield). R_f = 0.3 (hexane/ethyl acetate = 3:1). R_f for allylation products before ozonolysis = 0.4 (hexane/ethyl acetate = 40:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.18 – 8.08 (m, 2H), 7.39 – 7.28 (m, 2H), 2.76 – 2.68 (m, 2H), 2.46 (t, *J* = 7.2 Hz, 2H), 2.13 (s, 3H), 1.99 – 1.85 (m, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 208.14, 149.68, 146.56, 129.33, 123.81, 42.58, 34.98, 30.17, 24.72. IR (KBr) 3080, 2942, 2861, 1713, 1603, 1522, 1348, 1182, 1113 cm^{-1}. HRMS: calcd. $[M+H]^+$ 208.0968 Found: 208.0959.



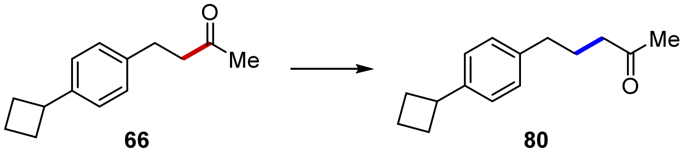
64 **78**

78: Following **General procedure B2,** the reaction was conducted at 0.2 mmol scale. The titled compound was isolated as a colorless oil (27.6 mg, 73% yield). R_f = 0.25 (hexane/ethyl acetate = 10:1). R_f for allylation products before ozonolysis = 0.6-0.8 (hexane/ethyl acetate = 50:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.23 – 7.09 (m, 4H), 2.71 – 2.58 (m, 4H), 2.50 (t, *J* = 7.3 Hz, 2H), 2.14 (s, 3H), 1.88 (p, *J* = 7.5 Hz, 2H), 1.23 (t, *J* = 7.6 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 208.86, 142.09, 139.22, 129.27, 128.58, 126.40, 125.93, 43.33, 31.90, 30.09, 25.55, 25.00, 15.52. IR (KBr) 3017, 2967, 2874, 1715, 1492, 1453, 1368, 1158 cm^{-1}. HRMS: calcd. $[M+H]^+$ 191.1431 Found: 191.1425.



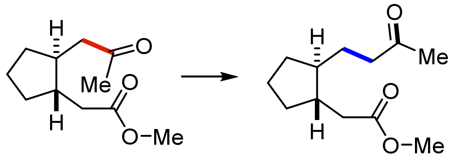
65 **79**

79: Following **General procedure B2,** the reaction was conducted at 0.2 mmol scale. The titled compound was isolated as a colorless oil (35.0 mg, 71% yield). R_f = 0.4 (hexane/ethyl acetate = 5:1). R_f for allylation products before ozonolysis = 0.6-0.8 (hexane/ethyl acetate = 50:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.18 (d, *J* = 8.6 Hz, 2H), 7.12 (d, *J* = 8.3 Hz, 2H), 2.62 (t, *J* = 7.6 Hz, 2H), 2.44 (t, *J* = 7.3 Hz, 2H), 2.12 (s, 3H), 1.89 (p, *J* = 7.4 Hz, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 208.60, 147.61 (q, *J* = 1.8 Hz), 140.48, 129.78, 121.10, 120.63 (q, *J* = 256.6 Hz), 42.78, 34.44, 30.12, 25.21. IR (KBr) 3046, 2949, 2861, 1719, 1512, 1368, 1271, 1166 cm^{-1}. HRMS: calcd. $[M+H]^+$ 247.0941 Found: 247.0934.



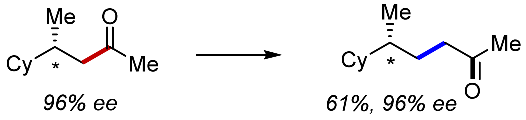
66 **80**

80: Following modified **General procedure B2,** the reaction was conducted at 0.2 mmol scale. The titled compound was isolated as a colorless oil (34 mg, 79% yield). R_f = 0.5 (hexane/ethyl acetate = 5:1). R_f for allylation products before ozonolysis = 0.7-0.8 (hexane/ethyl acetate = 40:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.19 – 7.06 (m, 4H), 3.52 (p, *J* = 8.7 Hz, 1H), 2.59 (t, *J* = 7.5 Hz, 2H), 2.44 (t, *J* = 7.4 Hz, 2H), 2.39 – 2.25 (m, 2H), 2.21 – 2.07 (m, 5H), 2.07 – 1.95 (m, 1H), 1.95 – 1.78 (m, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 209.03, 144.02, 138.95, 128.39, 126.44, 43.04, 40.19, 34.74, 30.09, 30.00, 25.41, 18.38. IR (KBr) 3052, 2963, 2863, 1717, 1516, 1415, 1356, 1164 cm^{-1}. HRMS: calcd. $[M+H]^+$ 217.1587 Found: 217.1587.



82 **83**

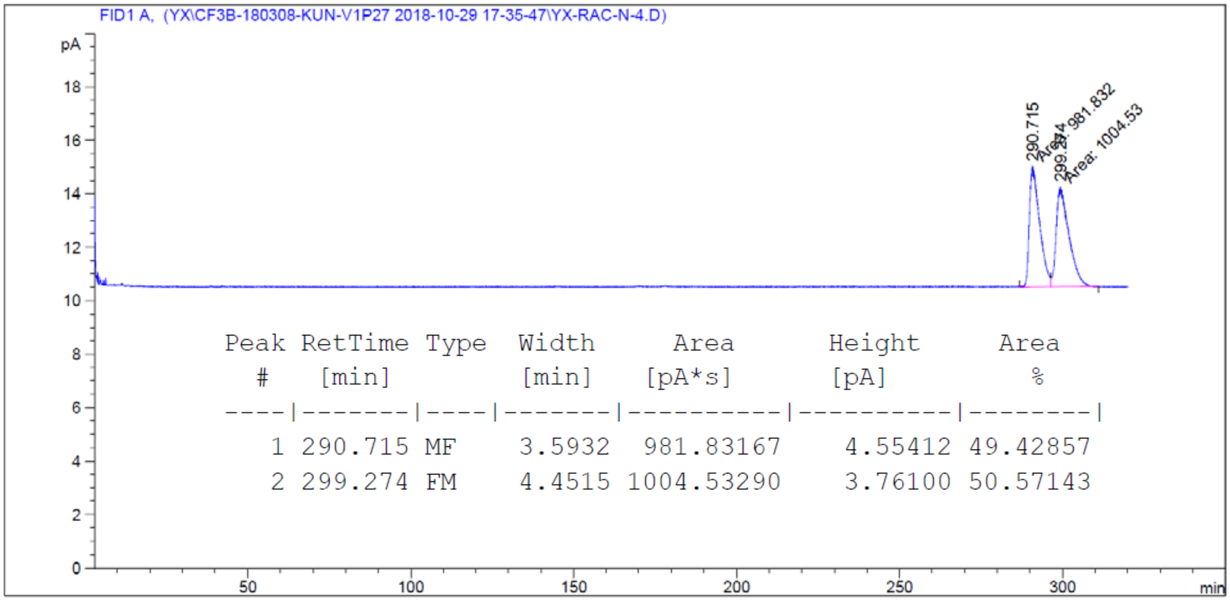
83: Following modified **General procedure B2,** the reaction was conducted at 0.2 mmol using 300 μL toluene solution of 1,3-butadiene. The titled compound was isolated as a colorless oil (31.6 mg, 75% yield). R_f = 0.3 (hexane/ethyl acetate = 5:1). R_f for allylation products before ozonolysis = 0.1 (hexane/ethyl acetate = 40:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.65 (s, 3H), 2.52 – 2.33 (m, 3H), 2.20 – 2.07 (m, 4H), 1.94 – 1.73 (m, 4H), 1.61 – 1.51 (m, 2H), 1.42 – 1.30 (m, 2H), 1.27 – 1.12 (m, 2H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 209.18, 173.89, 51.56, 44.99, 42.61, 42.18, 39.35, 32.31, 31.79, 30.00, 28.51, 23.56. IR (KBr) 3001, 2953, 2866, 1735, 1715, 1435, 1360, 1170, 1156 cm^{-1}. HRMS: calcd. $[M+H]^+$ 213.1485 Found: 213.1494.



85 **86**

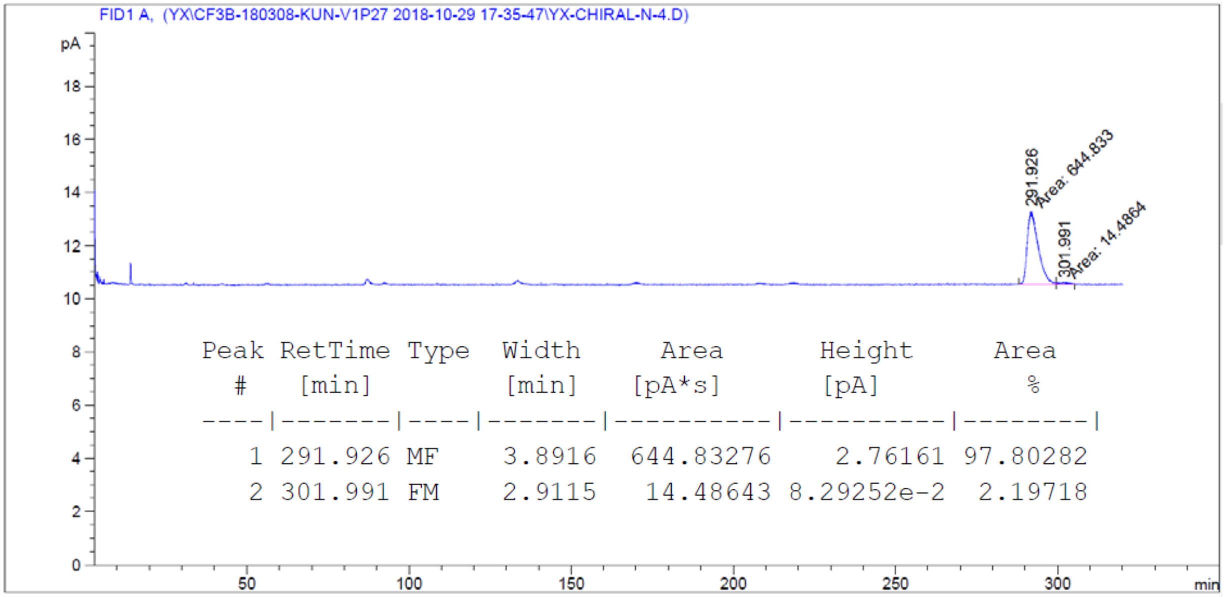
86: Substrate **85** was synthesized according to known procedure[69] using (*S*)-(+)-(3,5-Dioxa-4-phospha-cyclohepta[2,1-a;3,4-a']dinaphthalen-4-yl)bis[(1*R*)-1-phenylethyl]amine (*CAS Number: 415918-91-1*) as the chiral ligand. Following modified **General procedure B2,** the key reaction was conducted at 0.2 mmol using 300 μL toluene solution of 1,3-butadiene. The titled compound was isolated as a colorless oil (22.1 mg, 61% yield). R_f = 0.5 (hexane/ethyl acetate = 10:1). R_f for allylation products before ozonolysis = 0.5-0.8 (hexane/ethyl acetate = 50:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.50 – 2.30 (m, 2H), 2.14 (s, 3H), 1.77 – 1.69 (m, 2H), 1.69 – 1.57 (m, 4H), 1.36 (dddd, *J* = 13.4, 9.7, 8.8, 5.5 Hz, 1H), 1.17 (ddd, *J* = 12.9, 8.8, 2.7 Hz, 4H), 1.13 – 1.06 (m, 1H), 1.00 (ddd, *J* = 24.7, 12.0, 3.3 Hz, 2H), 0.81 (d, *J* = 6.7 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 209.85, 42.75, 42.23, 37.83, 30.73, 30.03, 28.76, 28.15, 27.02, 26.94, 26.90, 16.06. IR (KBr) 2929, 2856, 1721, 1449, 1355, 1266.00, 1163 cm^{-1}. HRMS: calcd. $[M]^+$ 182.1671 Found: 182.1676. The enantiomeric excess (ee) value was measured to be 96% as determined by chiral GC analysis (70ISO320).

Racemic sample:

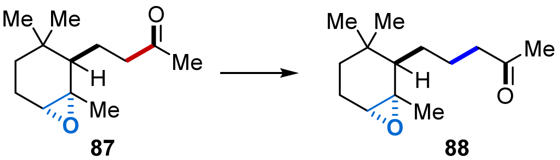


```
Peak RetTime Type  Width     Area      Height     Area
  #   [min]        [min]   [pA*s]      [pA]        %
----|-------|----|-------|----------|----------|--------|
   1 290.715 MF    3.5932  981.83167   4.55412 49.42857
   2 299.274 FM    4.4515 1004.53290   3.76100 50.57143
```

Chiral sample:



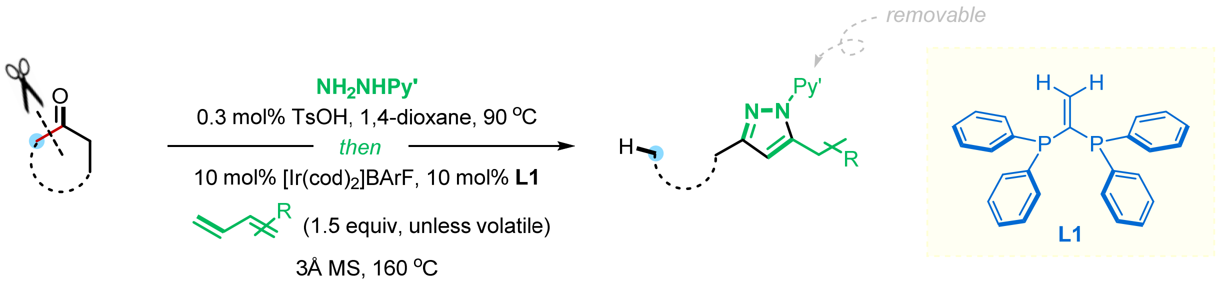
```
Peak RetTime Type  Width     Area      Height     Area
  #   [min]        [min]   [pA*s]      [pA]        %
----|-------|----|-------|----------|----------|--------|
   1 291.926 MF    3.8916  644.83276   2.76161 97.80282
   2 301.991 FM    2.9115   14.48643 8.29252e-2 2.19718
```



87 **88**

88: Following modified **General procedure B2,** the reaction was conducted at 0.2 mmol scale using 300 μL toluene solution of 1,3-butadiene. The titled compound was isolated as a colorless oil (31.2 mg, 70% yield). R_f = 0.5 (hexane/ethyl acetate = 3:1). R_f for allylation products before ozonolysis = 0.7-0.8 (hexane/ethyl acetate = 10:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.99 – 2.89 (m, 1H), 2.58 – 2.34 (m, 2H), 2.14 (s, 3H), 1.95 – 1.75 (m, 3H), 1.69 – 1.61 (m, 1H), 1.37 – 1.20 (m, 7H), 0.87 (s, 3H), 0.85 – 0.70 (m, 4H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 209.38, 60.28, 59.79, 47.24, 44.71, 31.50, 29.99, 27.86, 27.45, 27.26, 27.06, 26.94, 23.96, 22.20. IR (KBr) 2961, 2932, 2872, 1717, 1441, 1366, 1162 cm^{-1}. HRMS: calcd. $[M+H]^+$ 225.1849 Found: 225.1850.

3.3.3 Deconstructive pyrazole synthesis from ketones



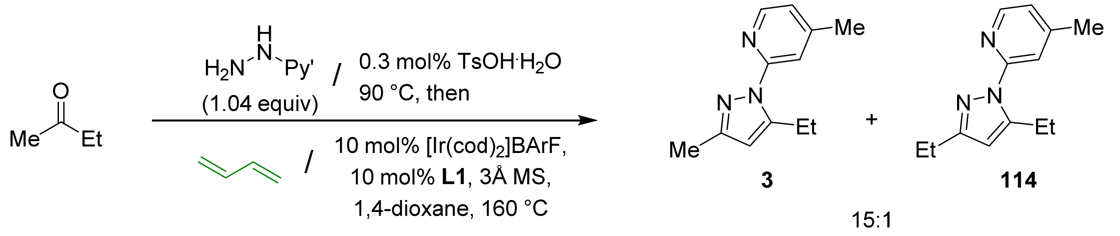
General procedure C1 *(with non-volatile dienes, e.g. >9 carbons)*: For a 0.3 mmol scale reaction, a 1,4-dioxane (0.15 mL) solution of the ketone substrate (0.3 mmol, 1.0 equiv), **D1** (38.4 mg, 0.312 mmol, 1.04 equiv), and *p*-TsOH·H_2O (*stock solution in 1,4-dioxane*, 0.05 M, 18 μL, 0.003 equiv) was heated at 90 °C for 5 hours in a 4 mL vial. After cooled to room temperature, the vial was charged first with $[Ir(cod)_2]BArF$ (38 mg, 0.03 mmol, 0.1 equiv) and **L1** (12 mg, 0.03 mmol, 0.1 equiv) under air atmosphere, and then with 3Å molecular sieve (pre-dried, 220 mg) and 1,3-diene (0.45-0.60 mmol, 1.5-2.0 equiv) in a glovebox. The vial was sealed and heated at 160 °C under stirring for 24-36 hours monitored by TLC. After cooled to room temperature, the reaction mixture was filtered through a short plug of Celite, concentrated *in vacuo*, and further purified by flash column chromatography over silica (hexane/ethyl acetate) to give the products**.**

General procedure C2 *(with volatile dienes, such as 1,3-butadiene and isoprene)*: 1 mL 1,4-dioxane and 100 mg 3Å molecular sieve was used for a 0.1 mmol scale reaction. Due to the volatility, 0.7-1.2 mmol 1,3-diene (7-12 equiv) was used as coupling partner. The rest is the same as **General procedure C1**.

Note 1: When 1,3-butadiene was used as the 1,3-diene coupling partner, its solution in PhMe was used (purchased from *Sigma-Aldrich*, 20 wt.%). For a 0.1 mmol scale reaction, 240-400 μL was used (0.7-1.2 mmol, 7-12 equiv, *see infra*).

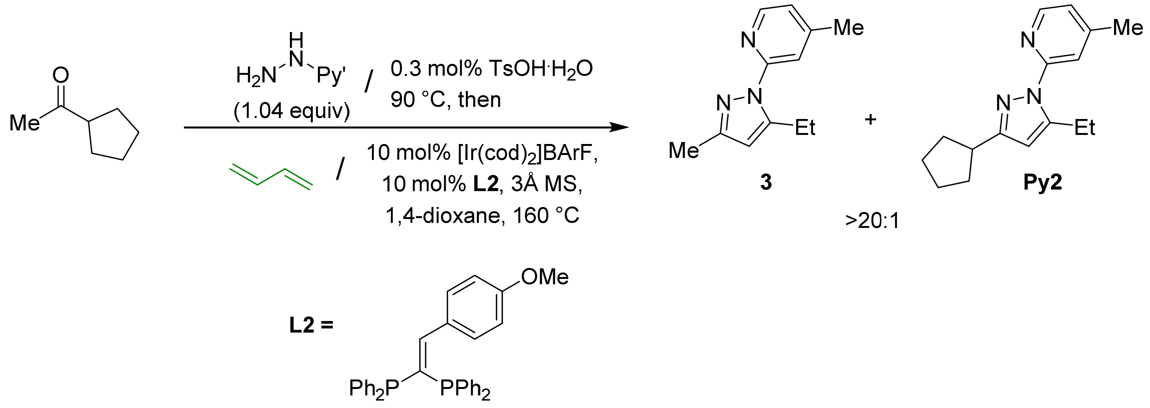
Note 2: When *cyclohexanones* was used as the ketone substrates, a slightly modified procedure was used. After the addition of $[Ir(cod)_2]BArF$ and **L1,** the resulting mixture was stirred at room temperature for 2-3 mins before adding other reaction components. The rest is the same as the general procedure.

3.3.3.1 Study on the site-selectivity of the C–C activation

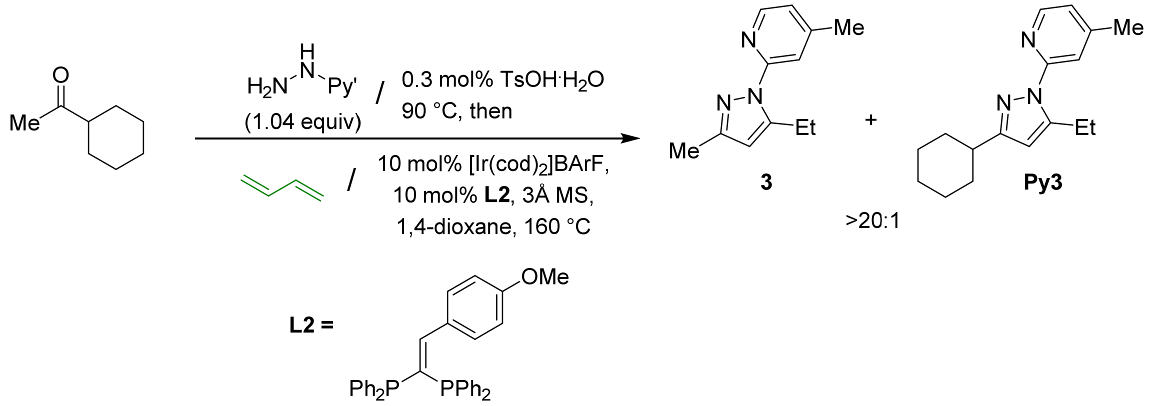


Following **General procedure C2,** the reaction was conducted at 0.1 mmol scale with 7.2 mg 2-butanone and 400 μL 1,3-butadiene (in PhMe, 20 wt.%). Two parallel reactions were conducted (0.1 mmol for each, 0.2 mmol in total) and combined, yielding pyrazoles **3** and **114** in 15:1 ratio as determined by ^{1}H NMR analysis of the crude mixture. The compound **3** was isolated as a colorless oil (31.1 mg, 78% yield). The compound **114** was isolated as a colorless oil (1.9 mg, 4% yield). The characterization data for compound **3** has been reported *vide supra*.

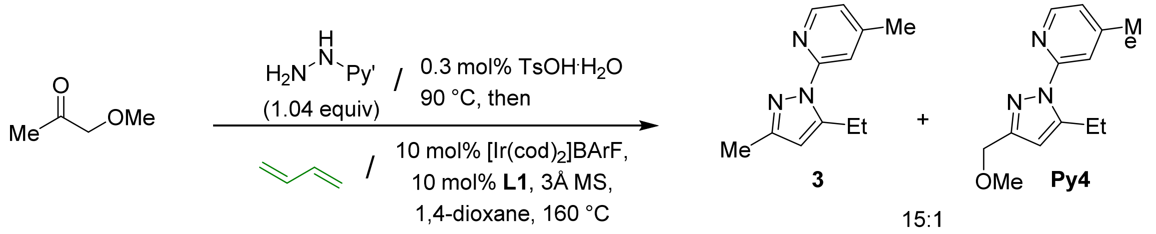
114: R_f = 0.7 (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.26 (dd, *J* = 5.0, 0.8 Hz, 1H), 7.73 – 7.57 (m, 1H), 6.96 (ddd, *J* = 5.1, 1.5, 0.7 Hz, 1H), 6.06 (s, 1H), 3.10 (qd, *J* = 7.5, 0.9 Hz, 2H), 2.68 (q, *J* = 7.6 Hz, 2H), 2.39 (s, 3H), 1.26 (dt, *J* = 14.8, 7.6 Hz, 6H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 155.71, 153.85, 149.71, 147.87, 147.34, 122.17, 116.98, 105.24, 21.77, 21.50, 21.26, 13.95, 13.25. IR (KBr) 3064, 3021, 2971, 2930, 2873, 1613, 1571, 1478, 1421, 1358, 1304, 1050, 1010 cm^{-1}. HRMS: calcd. 216.1495 $[M+H]^+$ Found: 216.1500.



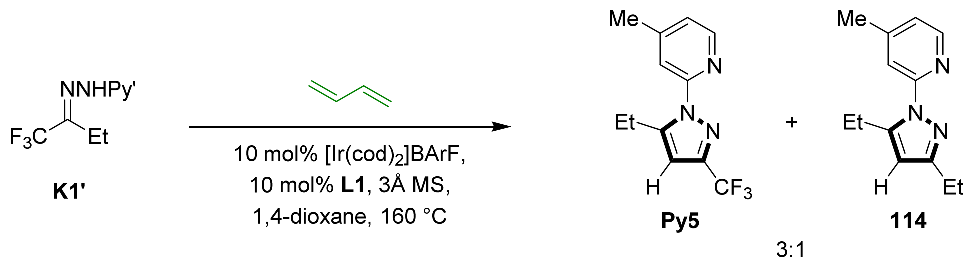
Following slightly modified **General procedure C2,** the reaction was conducted at 0.1 mmol scale with 11.2 mg 1-cyclopentylethan-1-one as the ketone substrates, **L2** as the ligand (5.0 mg), and 400 μL 1,3-butadiene (in PhMe, 20 wt.%). Two parallel reactions were conducted (0.1 mmol for each, 0.2 mmol in total) and combined, giving compound **5** as a colorless oil (28 mg, 78% yield). The ratio between compounds **3** and **Py2** was determined to be >20:1 according to the ^{1}H NMR analysis of the crude mixture. The characterization data for compound **3** has been reported *vide supra*.



Following slightly modified **General procedure C2,** the reaction was conducted at 0.1 mmol scale with 12.6 mg 1-cyclohexylethan-1-one as the ketone substrates, **L2** as the ligand (5.0 mg), and 400 µL 1,3-butadiene (in PhMe, 20 wt.%). Two parallel reactions were conducted (0.1 mmol for each, 0.2 mmol in total) and combined, giving compound **3** as a colorless oil (32 mg, 80% yield). The ratio between compounds **3** and **Py3** was determined to be >20:1 according to the ^{1}H NMR analysis of the crude mixture. The characterization data for compound **3** has been reported *vide supra*.



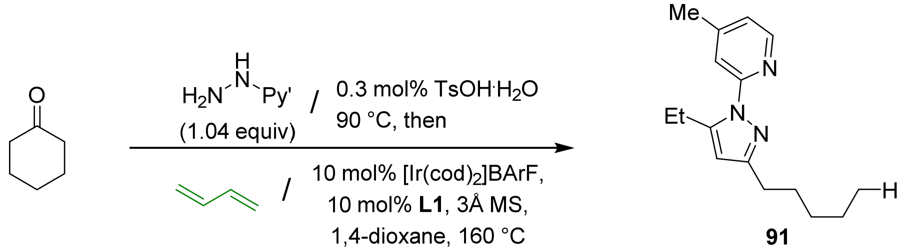
Following **General procedure C2,** the reaction was conducted at 0.1 mmol scale with 8.8 mg 1-methoxypropan-2-one as the ketone substrates and 400 µL 1,3-butadiene (in PhMe, 20 wt.%). Two parallel reactions were conducted (0.1 mmol for each, 0.2 mmol in total) and combined, giving compound **3** as a colorless oil (34 mg, 85% yield). The ratio between compounds **3** and **Py4** was determined to be >20:1 according to the ^{1}H NMR analysis of the crude mixture. The characterization data for compound **3** has been reported *vide supra*.



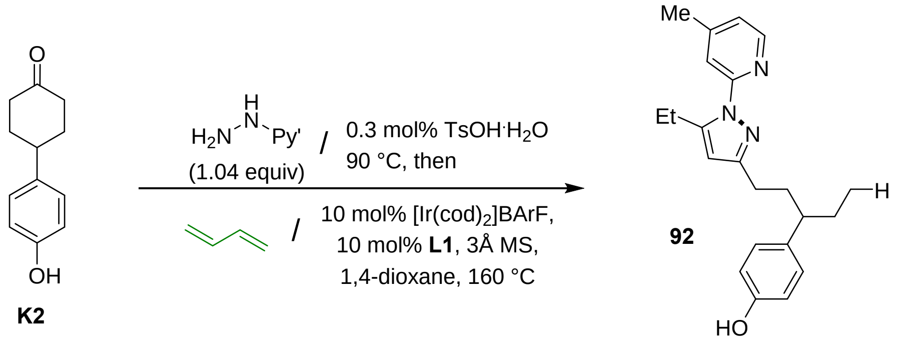
The reaction was conducted following modified **General procedure C2**: A 4 mL vial was charged with the hydrazone **K1’** (21.7 mg, 0.1 mmol, 1.0 equiv) which was derived from its corresponding ketone, $[Ir(cod)_2]BArF$ (12.8 mg, 0.01 mmol, 0.1 equiv), **L1** (4.0 mg, 0.01 mmol, 0.1 equiv) and 1,4-dioxane (1 mL). The vial was transferred into the glove box, and was charged with 1,3-butadiene (20 wt.% in PhMe, 200 μL, ca. 12 equiv). The vial was sealed, transferred out of the glove box, and heated at 160 °C under stirring for 24 hours. After cooled to room temperature, the reaction mixture was filtered through a short plug of Celite, concentrated *in vacuo*, and further purified by flash column chromatography over silica (hexane/ethyl acetate, from 30:1 to 20:1). Combining 2 parallel reactions furnished **Py5** in 50% yield (25.3 mg) as a colorless oil, and **114** in 16% yield (6.9 mg). The characterization data for compound **114** has been reported *vide supra*.

Py5: R_f = 0.5 (hexane /ethyl acetate = 3:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.32 (dd, *J* = 5.0, 0.7 Hz, 1H), 7.75 – 7.61 (m, 1H), 7.10 (ddd, *J* = 5.1, 1.5, 0.7 Hz, 1H), 6.48 (s, 1H), 3.23 – 3.07 (m, 2H), 2.44 (s, 3H), 1.28 (t, *J* = 7.5 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 153.04, 150.48, 148.95, 147.53, 143.08 (q, *J* = 38.1 Hz), 123.81, 121.49 (q, *J* = 268.8 Hz), 117.99, 104.46 (q, *J* = 2.0 Hz), 21.32, 21.30, 13.01. IR (KBr) 3068, 2975, 2932, 2880, 1611, 1573, 1490, 1419, 1247, 1137, 1052, 973 cm^{-1}. HRMS: calcd. 256.1056 $[M+H]^+$ Found: 256.1061.

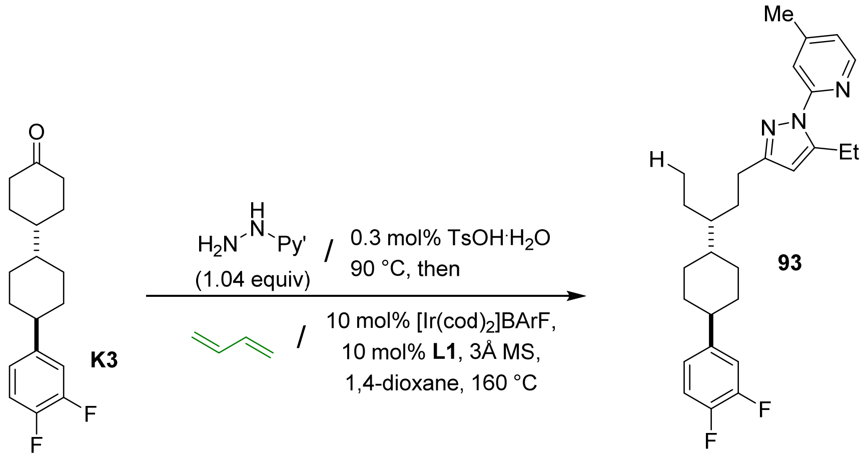
3.3.3.2 Deconstructive pyrazole synthesis



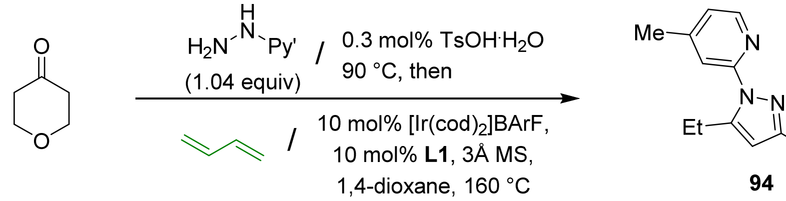
91: Following **General procedure C2,** the reaction was conducted at 0.05 mmol scale with 4.9 mg cyclohexanone and 120 μL 1,3-butadiene (in PhMe, 20 wt.%). Three parallel reactions were conducted (0.05 mmol for each, 0.15 mmol in total) and combined, giving the titled compound as a colorless oil (23.4 mg, 61% yield). R_f = 0. 4 (hexane/ethyl acetate = 10:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.26 (d, *J* = 5.0 Hz, 1H), 7.64 (s, 1H), 6.96 (d, *J* = 5.0 Hz, 1H), 6.04 (s, 1H), 3.10 (q, *J* = 7.5 Hz, 2H), 2.70 – 2.58 (m, 2H), 2.39 (s, 3H), 1.68 (p, *J* = 7.4 Hz, 2H), 1.42 – 1.32 (m, 4H), 1.24 (t, *J* = 7.5 Hz, 3H), 0.91 (t, *J* = 6.8 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 154.62, 153.89, 149.71, 147.80, 147.35, 122.16, 117.05, 105.71, 31.89, 29.47, 28.60, 22.68, 21.51, 21.28, 14.20, 13.26. IR (KBr) 2961, 2932, 2863, 1614, 1575, 1476, 1476, 1417, 1362, 1006, 913 cm^{-1}. HRMS: calcd. 258.1965 $[M+H]^+$ Found: 258.1971.



92: Following **General procedure C2,** the reaction was conducted at 0.05 mmol scale with 9.5 mg **K2** and 120 µL 1,3-butadiene (in PhMe, 20 wt.%). Three parallel reactions were conducted (0.05 mmol for each, 0.15 mmol in total) and combined, giving the titled compound as a colorless oil (30.3 mg, 58% yield). R$_f$ = 0. 35 (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, CDCl$_3$) δ 8.26 (d, *J* = 5.0 Hz, 1H), 7.57 (s, 1H), 6.97 (d, *J* = 8.6 Hz, 3H), 6.91 – 6.60 (m, 3H), 6.00 (s, 1H), 3.05 (q, *J* = 7.5 Hz, 2H), 2.50 (t, *J* = 7.7 Hz, 2H), 2.40 (tt, *J* = 9.8, 5.0 Hz, 1H), 2.32 (s, 3H), 2.06 – 1.95 (m, 1H), 1.95 – 1.83 (m, 1H), 1.75 – 1.62 (m, 1H), 1.58 – 1.46 (m, 1H), 1.22 (t, *J* = 7.4 Hz, 3H), 0.76 (t, *J* = 7.3 Hz, 3H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 154.66, 154.37, 153.41, 150.02, 147.86, 147.34, 136.80, 128.79, 122.51, 117.61, 115.33, 105.70, 46.99, 36.51, 29.90, 26.61, 21.24, 21.19, 13.17, 12.29. IR (KBr) 3169, 2967, 2926, 2874, 1611, 1567, 1516, 1474, 1421, 1362, 1237 cm^{-1}. HRMS: calcd. 350.2227 [M+H]$^+$ Found: 350.2234.

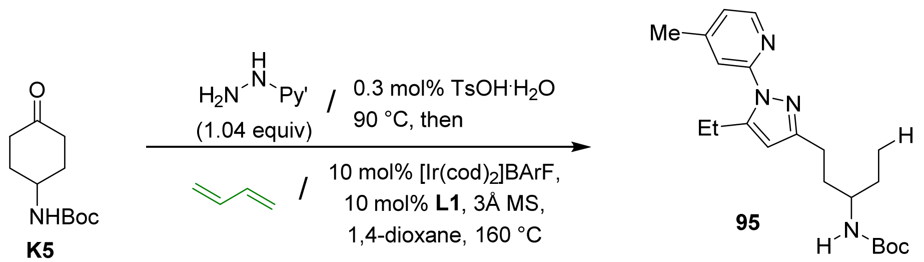


93: Following **General procedure C2,** the reaction was conducted at 0.05 mmol scale with 14.6 mg **K3** as the ketone substrates and 120 µL 1,3-butadiene (in PhMe, 20 wt.%). Three parallel reactions were conducted (0.05 mmol for each, 0.15 mmol in total) and combined, giving the titled compound as a colorless oil (42.5 mg, 63% yield). R$_f$ = 0. 3 (hexane/ethyl acetate = 10:1). ^{1}H NMR (400 MHz, CDCl$_3$) δ 8.27 (d, *J* = 5.0 Hz, 1H), 7.65 (s, 1H), 7.10 – 6.94 (m, 3H), 6.89 (dd, *J* = 6.9, 3.5 Hz, 1H), 6.06 (s, 1H), 3.11 (q, *J* = 7.5 Hz, 2H), 2.65 (pt, *J* = 10.4, 5.5 Hz, 2H), 2.40 (s, 4H), 1.90 (d, *J* = 12.8 Hz, 2H), 1.85 – 1.69 (m, 3H), 1.67 – 1.57 (m, 1H), 1.51 – 1.33 (m, 5H), 1.32 – 1.20 (m, 6H), 0.93 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, CDCl$_3$) carbon signals were observed at δ 154.72, 153.86, 151.57, 151.44, 149.92, 149.79, 149.72, 149.11, 148.99, 147.85, 147.48, 147.38, 145.00, 144.96, 144.91, 122.67, 122.64, 122.61, 122.58, 122.20, 117.06, 116.96, 116.79, 115.63, 115.46, 105.62, 44.69, 44.08, 39.26, 34.76, 30.38, 29.91, 29.74, 26.86, 23.19, 21.50, 21.28, 13.28, 12.22. IR (KBr) 3060, 2928, 2857, 1605, 1573, 1518, 1423, 1360, 1275, 1208, 1008 cm^{-1}. HRMS: calcd. 452.2872 [M+H]$^+$ Found: 452.2892.



94

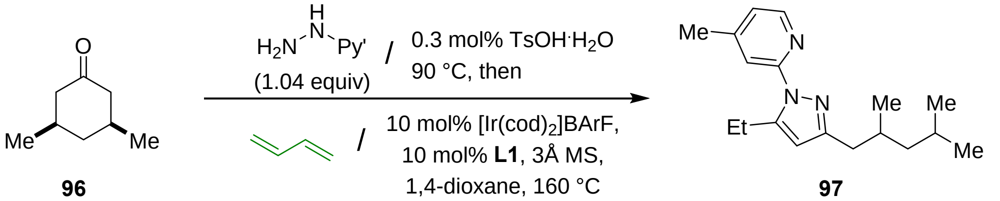
94: Following **General procedure C2,** the reaction was conducted at 0.05 mmol scale with 5.0 mg tetrahydro-4*H*-pyran-4-one and 120 µL 1,3-butadiene (in PhMe, 20 wt.%). Three parallel reactions were conducted (0.05 mmol for each, 0.15 mmol in total) and combined, giving the titled compound as a colorless oil (21.6 mg, 56% yield). $R_f = 0.4$ (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.26 (d, *J* = 5.1 Hz, 1H), 7.63 (s, 1H), 6.97 (d, *J* = 5.0 Hz, 1H), 6.10 (s, 1H), 3.73 (t, *J* = 7.3 Hz, 2H), 3.54 (q, *J* = 7.0 Hz, 2H), 3.08 (q, *J* = 7.5 Hz, 2H), 2.95 (t, *J* = 7.3 Hz, 2H), 2.39 (s, 3H), 1.27 – 1.15 (m, 6H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 153.76, 151.13, 149.75, 147.85, 147.37, 122.31, 117.10, 106.27, 70.03, 66.30, 29.27, 21.43, 21.26, 15.35, 13.20. IR (KBr) 2977, 2930, 2870, 1607, 1571, 1478, 1421, 1360, 1109, 1006 cm^{-1}. HRMS: calcd. 260.1757 $[M+H]^+$ Found: 260.1764.



K5

95

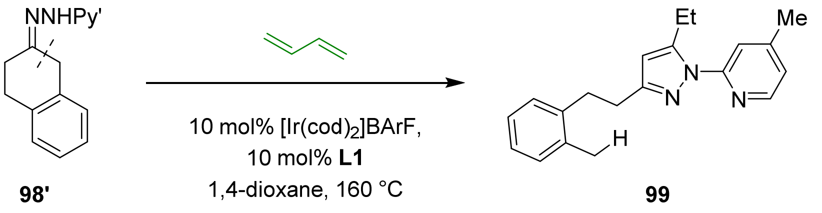
95: Following **General procedure C2,** the reaction was conducted at 0.05 mmol scale with 10.7 mg **K5** and 120 µL 1,3-butadiene (in PhMe, 20 wt.%). Two parallel reactions were conducted (0.05 mmol for each, 0.1 mmol in total) and combined, giving the titled compound as a colorless oil (19.2 mg, 52% yield). $R_f = 0.\ 4$ (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.26 (d, *J* = 5.0 Hz, 1H), 7.62 (s, 1H), 6.97 (d, *J* = 5.0 Hz, 1H), 6.05 (s, 1H), 4.39 (d, *J* = 9.1 Hz, 1H), 3.60 (br, 1H), 3.09 (q, *J* = 7.4 Hz, 2H), 2.70 (qdd, *J* = 14.9, 10.1, 5.9 Hz, 2H), 2.40 (s, 3H), 1.89 (s, 1H), 1.72 (s, 1H), 1.44 (s, 11H), 1.24 (t, *J* = 7.4 Hz, 3H), 0.93 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 155.93, 153.82, 149.75, 147.93, 147.39, 122.27, 117.09, 105.86, 78.97, 52.21, 34.85, 28.59, 25.21, 21.46, 21.29, 13.26, 10.36. IR (KBr) 3340, 2969, 2935, 2881, 1701, 1611, 1479, 1420, 1364, 1249, 1170 cm^{-1}. HRMS: calcd. 373.2598 $[M+H]^+$ Found: 373.2611.



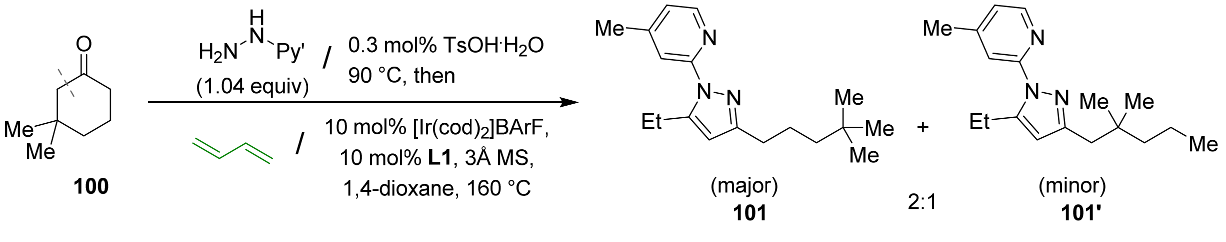
96

97

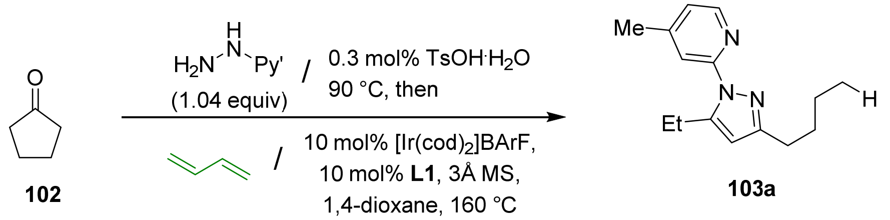
97: Following **General procedure C2,** the reaction was conducted at 0.05 mmol scale with 6.3 mg **96** as the ketone substrates and 110 μL 1,3-butadiene (in PhMe, 20 wt.%). Three parallel reactions were conducted (0.05 mmol for each, 0.15 mmol in total) and combined, giving the titled compound as a colorless oil (19.0 mg, 44% yield). R_f = 0.4 (hexane/ethyl acetate = 10:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.26 (d, *J* = 5.1 Hz, 1H), 7.64 (s, 1H), 6.96 (d, *J* = 4.7 Hz, 1H), 6.02 (s, 1H), 3.10 (q, *J* = 7.5 Hz, 2H), 2.63 (dd, *J* = 14.1, 5.8 Hz, 1H), 2.47 – 2.34 (m, 4H), 1.97 – 1.83 (m, 1H), 1.71 (dp, *J* = 13.0, 6.6 Hz, 1H), 1.28 – 1.19 (m, 5H), 1.10 (ddd, *J* = 13.9, 8.7, 5.8 Hz, 1H), 0.95 – 0.83 (m, 9H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 153.93, 153.48, 149.71, 147.68, 147.32, 122.16, 117.18, 106.36, 46.69, 36.46, 31.21, 25.45, 23.68, 22.26, 21.48, 21.29, 19.86, 13.28. IR (KBr) 3060, 2957, 2926, 2872, 1607, 1569, 1480, 1423, 1362, 1004 cm^{-1}. HRMS: calcd. 286.2278 $[M+H]^+$ Found: 286.2279.



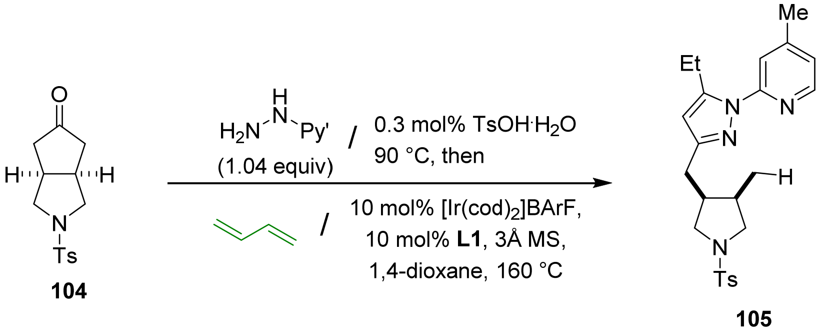
99: The reaction was conducted following modified **General procedure C2** using the pre-formed hydrazone as the substrate: An 4 mL vial was charged with the hydrazone **98'** (12.5 mg, 0.05 mmol, 1.0 equiv) which was derived from its corresponding ketone following *General procedure for hydrazones formation (vide supra)*, $[Ir(cod)_2]BArF$ (6.4 mg, 0.005 mmol, 0.1 equiv), **L1** (2.0 mg, 0.005 mmol, 0.1 equiv) and 1,4-dioxane (0.5 mL). The vial was transferred into the glove box, and was charged with 1,3-butadiene (20 wt.% in PhMe, 120 μL, ca. 7 equiv). The vial was sealed, transferred out of the glove box, and heated at 160 °C under stirring for 24 hours. After cooled to room temperature, the reaction mixture was filtered through a short plug of Celite, concentrated *in vacuo*, and further purified by flash column chromatography over silica (hexane/ethyl acetate, from 30:1 to 20:1). Combining 2 parallel reactions furnished **99** in 66% yield (20.0 mg) as a colorless oil**.** R_f = 0.7 (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.29 (d, *J* = 5.0 Hz, 1H), 7.66 (s, 1H), 7.26 – 7.20 (m, 1H), 7.20 – 7.10 (m, 3H), 6.99 (d, *J* = 4.4 Hz, 1H), 6.05 (s, 1H), 3.11 (q, *J* = 7.5 Hz, 2H), 3.06 – 2.97 (m, 2H), 2.97 – 2.89 (m, 2H), 2.42 (s, 3H), 2.37 (s, 3H), 1.25 (t, *J* = 7.5 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 153.85, 153.67, 149.79, 147.90, 147.41, 140.21, 136.17, 130.27, 128.92, 126.19, 126.13, 122.31, 117.17, 105.84, 33.34, 29.27, 21.46, 21.31, 19.50, 13.29. IR (KBr) 3064, 3022, 2973, 2932, 2874, 1609, 1571, 1474, 1417, 1364, 1016 cm^{-1}. HRMS: calcd. 306.1965 $[M+H]^+$ Found: 306.1973.



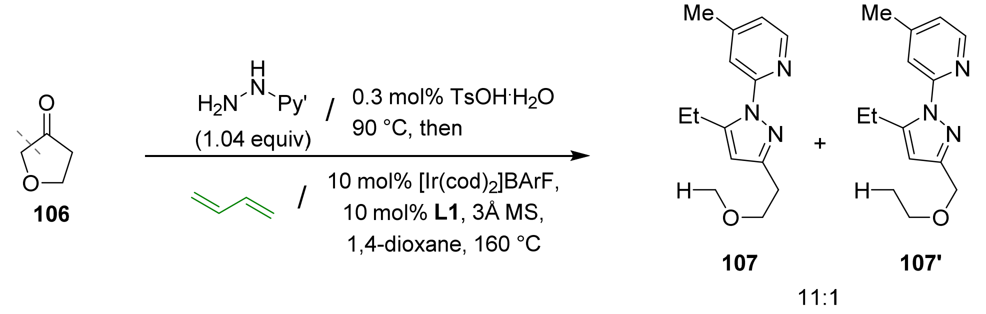
Following **General procedure C2,** the reaction was conducted at 0.05 mmol scale with 6.3 mg **100** as the ketone substrates and 120 μL 1,3-butadiene (in PhMe, 20 wt.%). Two parallel reactions were conducted (0.05 mmol for each, 0.1 mmol in total) and combined after the key reaction was finished. A hydrogenation reaction with Pd/C (5% wt.%, 30 mg) in ethyl acetate (1 mL) under H_2 atmosphere was conducted to hydrogenate a small amount of the crotylation by-product (ca. 5%) in order to achieve better separation *via* flash column chromatography over silica. The pyrazoles **101** and **101'** were then isolated in 2:1 ratio with a combined yield of 27% (colorless oil, 7.7 mg). The pure sample for compound **101** was obtained by preparative thin layer chromatography for characterization. **101**: R_f = 0.45 (hexane/ethyl acetate = 10:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.27 (d, *J* = 5.1 Hz, 1H), 7.64 (d, *J* = 0.8 Hz, 1H), 6.97 (d, *J* = 5.0 Hz, 1H), 6.05 (s, 1H), 3.11 (q, *J* = 7.5 Hz, 2H), 2.61 (t, *J* = 7.8 Hz, 2H), 2.40 (s, 3H), 1.65 (tdd, *J* = 11.7, 7.9, 6.2 Hz, 2H), 1.30 – 1.20 (m, 5H), 0.89 (s, 9H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 154.66, 153.90, 149.74, 147.86, 147.36, 122.18, 117.06, 105.69, 44.26, 30.50, 29.58, 29.48, 25.04, 21.53, 21.29, 13.27. IR (KBr) 3064, 2955, 2868, 1607, 1571, 1476, 1417, 1364, 819 cm^{-1}. HRMS: calcd. 286.2278 [M+H]$^+$ Found: 286.2284.



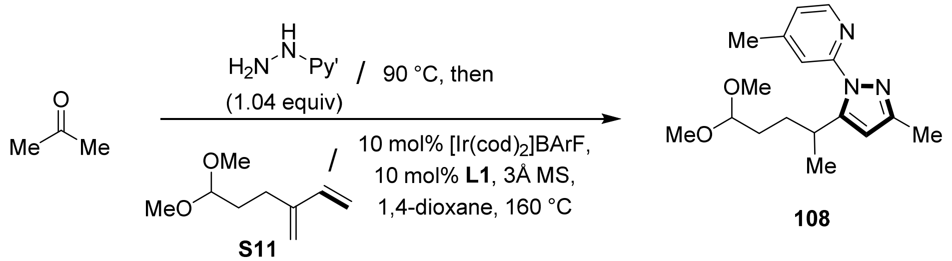
Following **General procedure C2,** the reaction was conducted at 0.05 mmol scale with 4.2 mg cyclopentanone as the ketone substrates and 170 µL 1,3-butadiene (in PhMe, 20 wt.%). Two parallel reactions were conducted accordingly (0.05 mmol for each, 0.1 mmol in total). When the key reaction was finished, the reaction mixture from the two parallel reactions was combined, filtered through a short plug of Celite, and concentrated in *vacuo*. The residue was further treated with ethyl acetate (1 mL) and Pd/C (5% wt.%, 30 mg), and stirred at room temperature under H_2 atmosphere for 10 hours. The reaction mixture was filtered, concentrated in *vacuo*, and then purified by flash column chromatography over silica (hexane/ethyl acetate, 20:1) to give the product **103a** as a colorless oil (16.9 mg, 70% yield). R_f = 0.3 (hexane/ethyl acetate = 10:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.26 (d, *J* = 5.0 Hz, 1H), 7.64 (s, 1H), 6.96 (dd, *J* = 5.0, 1.5 Hz, 1H), 6.04 (s, 1H), 3.10 (q, *J* = 7.5 Hz, 2H), 2.84 – 2.56 (m, 2H), 2.39 (s, 3H), 1.67 (p, *J* = 7.6 Hz, 2H), 1.47 – 1.39 (m, 2H), 1.24 (t, *J* = 7.5 Hz, 3H), 0.95 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 154.57, 153.87, 149.71, 147.79, 147.34, 122.16, 117.04, 105.71, 31.91, 28.30, 22.74, 21.49, 21.27, 14.09, 13.25. IR (KBr) 3062, 2959, 2932, 2874, 1607, 1569, 1476, 1423, 1364, 994 cm^{-1}. HRMS: calcd. 244.1808 [M+H]$^+$ Found: 244.1814.



105: Following **General procedure C2,** the reaction was conducted at 0.05 mmol scale with 14.0 mg **104** as the ketone substrates and 170 μL 1,3-butadiene (in PhMe, 20 wt.%). Two parallel reactions were conducted (0.05 mmol for each, 0.1 mmol in total) and combined, giving the titled compound as a colorless oil (20.5 mg, 47% yield). R$_f$ = 0.3 (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, CDCl$_3$) δ 8.27 (d, *J* = 5.1 Hz, 1H), 7.71 (d, *J* = 8.0 Hz, 2H), 7.56 (s, 1H), 7.30 (d, *J* = 7.9 Hz, 2H), 6.99 (d, *J* = 5.1 Hz, 1H), 5.93 (s, 1H), 3.41 (td, *J* = 9.8, 6.5 Hz, 2H), 3.17 – 2.99 (m, 4H), 2.64 (dd, *J* = 13.1, 4.9 Hz, 1H), 2.53 – 2.30 (m, 8H), 2.29 – 2.20 (m, 1H), 1.22 (t, *J* = 7.5 Hz, 3H), 0.82 (d, *J* = 7.1 Hz, 3H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 153.63, 151.69, 149.82, 147.99, 147.41, 143.30, 134.31, 129.70, 127.58, 122.46, 117.11, 105.86, 54.93, 51.37, 41.96, 35.45, 26.91, 21.65, 21.38, 21.31, 13.40, 13.21. IR (KBr) 3060, 2967, 2926, 2876, 1607, 1573, 1476, 1417, 1344, 1160, 1093, 1050 cm^{-1}. HRMS: calcd. 439.2162 [M+H]$^+$ Found: 439.2175.

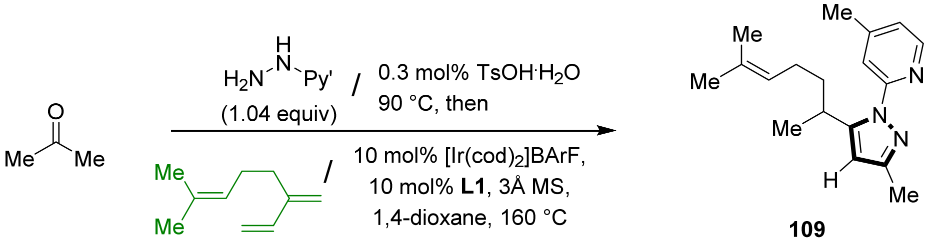


Following **General procedure C2,** the reaction was conducted at 0.05 mmol scale with 4.3 mg **106** as the ketone substrates and 170 μL 1,3-butadiene (in PhMe, 20 wt.%). Two parallel reactions were conducted (0.05 mmol for each, 0.10 mmol in total) and combined, yielding pyrazoles **107** and **107'** in 11:1 ratio as determined by ^{1}H NMR analysis of the crude mixture. The compound **107** was isolated as a colorless oil (9.7 mg, 40% yield). **107**: R$_f$ = 0.5 (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, CDCl$_3$) δ 8.27 (d, *J* = 5.0 Hz, 1H), 7.64 (s, 1H), 6.98 (d, *J* = 4.6 Hz, 1H), 6.10 (s, 1H), 3.71 (t, *J* = 7.0 Hz, 2H), 3.40 (s, 3H), 3.10 (q, *J* = 7.5 Hz, 2H), 2.95 (t, *J* = 7.0 Hz, 2H), 2.40 (s, 3H), 1.25 (t, *J* = 7.5 Hz, 3H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 153.81, 151.07, 149.76, 147.96, 147.39, 122.33, 117.13, 106.21, 72.17, 58.81, 29.13, 21.48, 21.29, 13.21. IR (KBr) 2973, 2928, 2874, 2825, 1607, 1569, 1476, 1417, 1362, 1119 cm^{-1}. HRMS: calcd. 246.1601 [M+H]$^+$ Found: 246.1604.

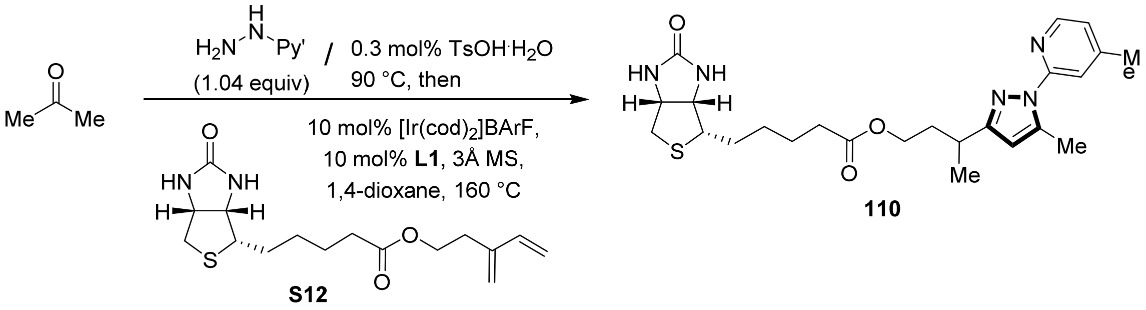


108: Following **General procedure C1,** the reaction was conducted at 0.2 mmol scale with 5.8 mg acetone and 63 mg **S11** (2 equiv) in 0.07 ml 1,4-dioxane. No *p*-TsOH was used for the condensation step. **108** was isolated as a colorless oil (36.2 mg, 60% yield). R$_f$ = 0.4 (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, CDCl$_3$) δ 8.25 (dd, *J*

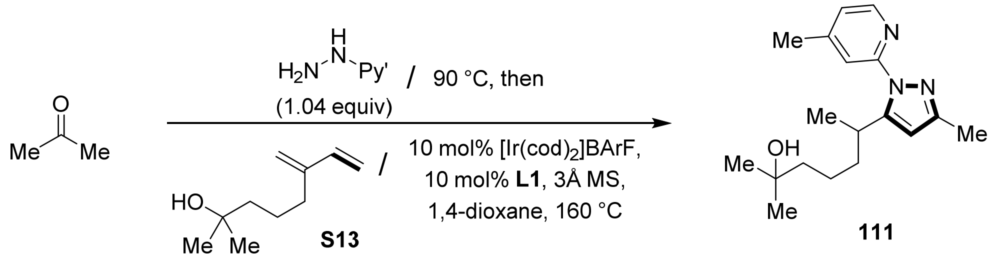
= 5.0, 0.7 Hz, 1H), 7.59 (s, 1H), 6.98 (dd, *J* = 5.0, 0.8 Hz, 1H), 6.03 (s, 1H), 4.28 (t, *J* = 5.4 Hz, 1H), 3.87 (p, *J* = 6.7 Hz, 1H), 3.23 (d, *J* = 3.2 Hz, 6H), 2.39 (s, 3H), 2.29 (s, 3H), 1.73 – 1.64 (m, 1H), 1.62 – 1.47 (m, 3H), 1.23 (d, *J* = 6.9 Hz, 3H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 153.83, 151.56, 149.81, 149.74, 147.37, 122.45, 117.71, 105.37, 104.57, 52.82, 52.43, 32.09, 30.81, 30.23, 21.24, 20.81, 13.84. IR (KBr) 2957, 2932, 2828, 1608, 1572, 1457, 1136, 1060 cm^{-1}. HRMS: calcd. 304.2020 [M+H]$^+$ Found: 304.2023.



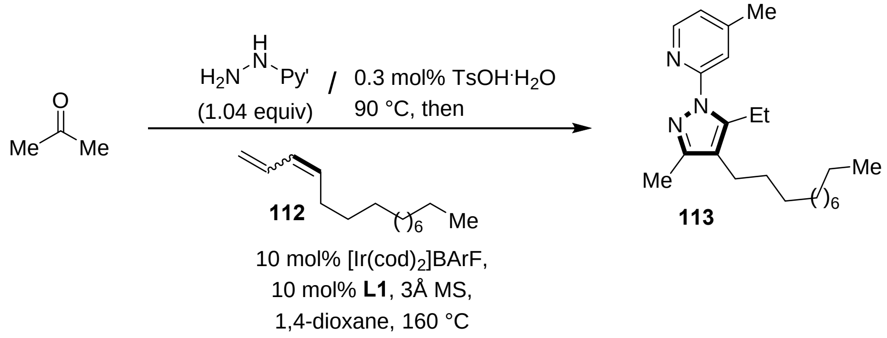
109: Following **General procedure C1,** the reaction was conducted at 0.2 mmol scale with 5.8 mg acetone and 69 µL myrcene (2 equiv) in 0.07 ml 1,4-dioxane. **109** was isolated as a colorless oil (42.3 mg, 75% yield). R_f = 0.3 (hexane/ethyl acetate = 10:1). ^{1}H NMR (400 MHz, CDCl$_3$) δ 8.27 (d, *J* = 5.0 Hz, 1H), 7.67 – 7.39 (m, 1H), 7.11 – 6.84 (m, 1H), 6.03 (s, 1H), 5.02 (ddq, *J* = 7.2, 5.7, 1.5 Hz, 1H), 3.82 (h, *J* = 6.9 Hz, 1H), 2.40 (s, 3H), 2.31 (s, 3H), 1.95 (q, *J* = 7.7 Hz, 2H), 1.72 – 1.61 (m, 4H), 1.51 – 1.41 (m, 4H), 1.24 (d, *J* = 6.9 Hz, 3H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 153.89, 152.08, 149.73, 149.71, 147.41, 131.59, 124.41, 122.44, 117.80, 105.22, 37.39, 30.68, 25.91, 25.81, 21.25, 20.61, 17.68, 13.86. IR (KBr) 3064, 3024, 2969, 2918, 2861, 1605, 1573, 1455, 1415, 1381, 1018 cm^{-1}. HRMS: calcd. 284.2121 [M+H]$^+$ Found: 284.2132.



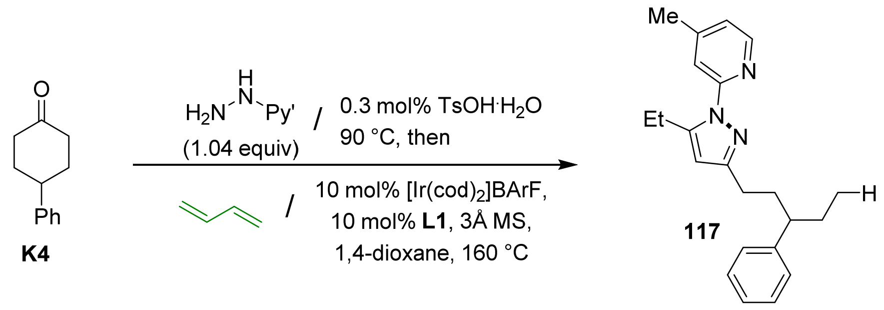
110: Following **General procedure C1,** the reaction was conducted at 0.1 mmol scale with 5.8 mg acetone and 87 mg **S12** (2.7 equiv) in 0.05 ml 1,4-dioxane for 48 h. **110** was isolated as a colorless oil (18.7 mg, 40% yield, inseparable mixture of diastereomers). R_f = 0.35 (DCM/MeOH = 10:1. ^{1}H NMR (400 MHz, CDCl$_3$) δ 8.26 (d, *J* = 5.0 Hz, 1H), 7.61 (s, 1H), 7.00 (d, *J* = 4.8 Hz, 1H), 6.05 (s, 1H), 5.76 (d, *J* = 16.8 Hz, 1H), 5.32 (s, 1H), 4.48 (dd, *J* = 7.8, 5.0 Hz, 1H), 4.27 (dd, *J* = 7.5, 4.8 Hz, 1H), 4.14 – 3.95 (m, 3H), 3.17 – 3.06 (m, 1H), 2.88 (dd, *J* = 12.9, 4.5 Hz, 1H), 2.71 (d, *J* = 12.8 Hz, 1H), 2.40 (s, 3H), 2.30 (s, 3H), 2.24 – 2.17 (m, 2H), 2.01 (dqd, *J* = 13.8, 6.9, 2.7 Hz, 1H), 1.83 (ddd, *J* = 12.1, 7.5, 5.9 Hz, 1H), 1.71 – 1.57 (m, 4H), 1.45 – 1.36 (m, 2H), 1.27 (dd, *J* = 6.9, 1.9 Hz, 3H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 173.69, 163.62, 153.72, 150.84, 150.82, 149.99, 149.97, 149.83, 147.36, 122.57, 117.63, 117.61, 105.53, 62.87, 62.05, 60.22, 55.48, 40.67, 35.92, 35.88, 33.95, 28.45, 28.34, 24.84, 24.82, 21.29, 20.92, 13.84. IR (KBr) 3252, 2934, 2863, 1709, 1609, 1458, 1413, 1267, 1182 cm^{-1}. HRMS: calcd. 472.2377 $[M+H]^+$ Found: 472.2387.



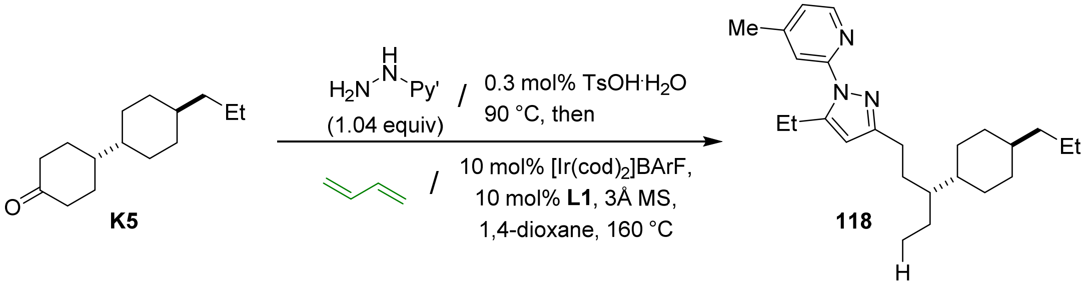
111: Following **General procedure C1,** the reaction was conducted at 0.2 mmol scale with 5.8 mg acetone and 62 mg **S13** (2 equiv) in 0.07 ml 1,4-dioxane. No *p*-TsOH was used for the condensation step. **111** was isolated as a colorless oil (37.8 mg, 63% yield). R_f = 0.35 (hexane/ethyl acetate = 1:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.26 (d, *J* = 0.7 Hz, 1H), 7.58 (s, 1H), 6.99 (dd, *J* = 5.1, 0.8 Hz, 1H), 6.02 (s, 1H), 3.82 (h, *J* = 6.9 Hz, 1H), 2.39 (s, 3H), 2.30 (s, 3H), 1.65 (dq, *J* = 13.9, 7.0 Hz, 1H), 1.49 – 1.42 (m, 1H), 1.40 – 1.27 (m, 4H), 1.22 (d, *J* = 6.9 Hz, 3H), 1.14 (d, *J* = 3.0 Hz, 6H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 153.84, 152.08, 149.87, 149.76, 147.39, 122.54, 117.95, 105.15, 71.02, 43.84, 37.83, 30.86, 29.46, 29.19, 22.07, 21.24, 20.79, 13.86. IR (KBr) 3407, 2969, 2935, 2867, 1614, 1563, 1457, 1415, 1367 cm^{-1}. HRMS: calcd. 302.2227 $[M+H]^+$ Found: 302.2236.



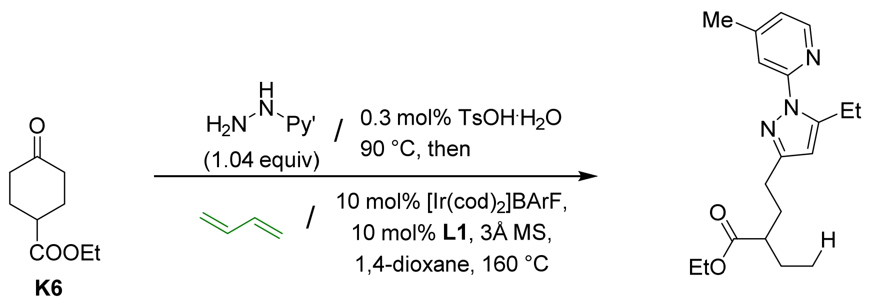
113: Following modified **General Procedure C1**, the reaction was conducted at 0.05 mmol scale using 10 equiv of diene **112** (104 mg, 1.0 mmol) in 0.4 mL 1,4-dioxane for 48 h. Two parallel reactions were conducted (0.05 mmol for each, 0.1 mmol in total) and combined, giving compound **113** as a colorless oil (15.8 mg, 45% yield). R_f = 0.7 (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, C_6D_6) δ 8.06 (d, *J* = 5.0 Hz, 1H), 8.00 (s, 1H), 6.32 (dd, *J* = 5.0, 1.5 Hz, 1H), 3.26 (q, *J* = 7.3 Hz, 2H), 2.32 (t, *J* = 7.6 Hz, 2H), 2.29 (s, 3H), 1.76 (s, 3H), 1.46 (p, *J* = 7.2 Hz, 2H), 1.36 – 1.20 (m, 19H), 0.91 – 0.81 (m, 3H). ^{13}C NMR (101 MHz, C_6D_6) δ 155.01, 149.17, 148.88, 147.26, 143.69, 121.31, 119.79, 116.36, 32.36, 31.58, 30.18, 30.14, 30.14, 30.08, 30.02, 29.84, 23.76, 23.15, 20.79, 19.91, 14.95, 14.41, 12.65. IR (KBr) 2926, 2853, 1608, 1583, 1445, 1412 cm^{-1}. HRMS: calcd. 466.3060 $[M+H]^+$ Found: 466.307.



117: Following **General procedure C2,** the reaction was conducted at 0.05 mmol scale with 8.7 mg **K4** and 120 µL 1,3-butadiene (in PhMe, 20 wt.%). Three parallel reactions were conducted (0.05 mmol for each, 0.15 mmol in total) and combined, giving the titled compound as a colorless oil (30.0 mg, 60% yield). R_f = 0. 3 (hexane/ethyl acetate = 10:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.26 (d, *J* = 5.0 Hz, 1H), 7.62 (s, 1H), 7.30 (t, *J* = 7.3 Hz, 2H), 7.24 – 7.14 (m, 3H), 6.96 (d, *J* = 4.9 Hz, 1H), 5.98 (s, 1H), 3.08 (q, *J* = 7.4 Hz, 2H), 2.53 (dq, *J* = 15.0, 9.3, 8.9 Hz, 3H), 2.39 (s, 3H), 2.07 (tt, *J* = 11.3, 5.8 Hz, 1H), 2.01 – 1.89 (m, 1H), 1.76 (dp, *J* = 14.0, 7.2 Hz, 1H), 1.63 (dq, *J* = 13.3, 6.7, 5.8 Hz, 1H), 1.23 (t, *J* = 7.5 Hz, 3H), 0.79 (t, *J* = 7.3 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 154.30, 153.84, 149.72, 147.75, 147.34, 145.53, 128.39, 128.00, 126.06, 122.18, 117.04, 105.74, 47.88, 36.37, 29.69, 26.76, 21.48, 21.29, 13.24, 12.34. IR (KBr) 3026, 2967, 2928, 2876, 1607, 1571, 1476, 1419, 1014 cm^{-1}. HRMS: calcd. 334.2278 $[M+H]^+$ Found: 334.2278.



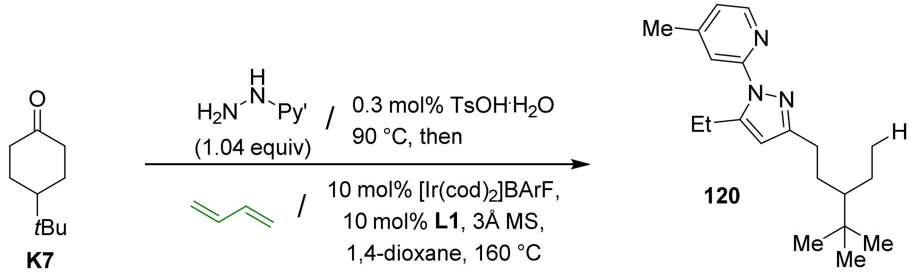
118: Following **General procedure C2,** the reaction was conducted at 0.05 mmol scale with 11.1 mg **K5** and 120 µL 1,3-butadiene (in PhMe, 20 wt.%). Three parallel reactions were conducted (0.05 mmol for each, 0.15 mmol in total) and combined, giving the titled compound as a colorless oil (37.5 mg, 66% yield). R_f = 0.35 (hexane/ethyl acetate = 10:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.26 (d, *J* = 4.9 Hz, 1H), 7.64 (s, 1H), 6.96 (d, *J* = 5.0 Hz, 1H), 6.05 (s, 1H), 3.10 (q, *J* = 7.4 Hz, 2H), 2.62 (tp, *J* = 15.7, 7.9, 7.1 Hz, 2H), 2.39 (s, 3H), 1.81 – 1.03 (m, 22H), 0.92 – 0.85 (m, 6H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 154.91, 153.86, 149.67, 147.78, 147.33, 122.13, 117.03, 105.62, 44.86, 39.94, 37.84, 33.81, 30.41, 29.84, 29.66, 26.86, 23.19, 21.50, 21.27, 20.18, 14.56, 13.27, 12.25. IR (KBr) 3062, 2961, 2926, 2853, 1609, 1571, 1478, 1421, 1360, 1006 cm^{-1}. HRMS: calcd. 382.3217 $[M+H]^+$ Found: 382.3229.



K6

119

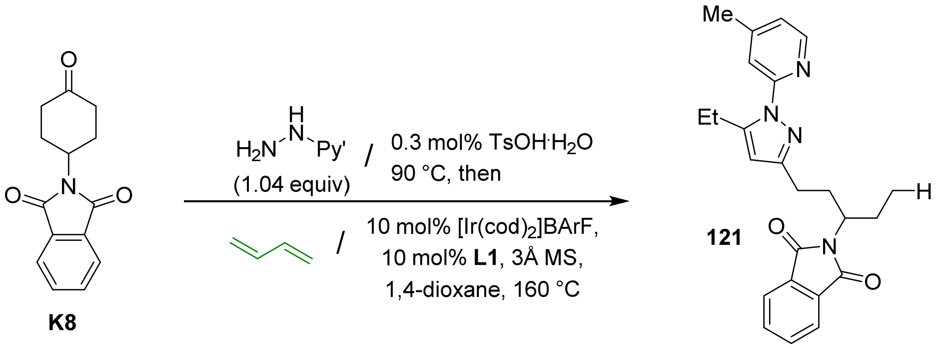
119: Following **General procedure C2,** the reaction was conducted at 0.05 mmol scale with 8.5 mg **K6** and 120 μL 1,3-butadiene (in PhMe, 20 wt.%). Three parallel reactions were conducted (0.05 mmol for each, 0.15 mmol in total) and combined, giving the titled compound as a colorless oil (32.4 mg, 66% yield). $R_f = 0.5$ (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.26 (d, *J* = 5.0 Hz, 1H), 7.62 (s, 1H), 6.96 (d, *J* = 4.8 Hz, 1H), 6.04 (s, 1H), 4.16 (q, *J* = 7.1 Hz, 2H), 3.17 – 3.03 (m, 2H), 2.64 (t, *J* = 8.1 Hz, 2H), 2.39 (s, 4H), 2.01 (dq, *J* = 15.7, 8.8, 7.3 Hz, 1H), 1.92 – 1.79 (m, 1H), 1.68 (dt, *J* = 15.4, 7.7 Hz, 1H), 1.63 – 1.53 (m, 1H), 1.29 – 1.21 (m, 6H), 0.91 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 175.84, 153.50, 153.15, 149.40, 147.55, 147.03, 121.91, 116.72, 105.46, 59.89, 46.72, 31.45, 26.15, 25.19, 21.15, 20.95, 14.18, 12.91, 11.53. IR (KBr) 3062, 2965, 2938, 2878, 1731, 1607, 1571, 1474, 1421, 1158 cm^{-1}. HRMS: calcd. 330.2176 $[M+H]^+$ Found: 330.2184.



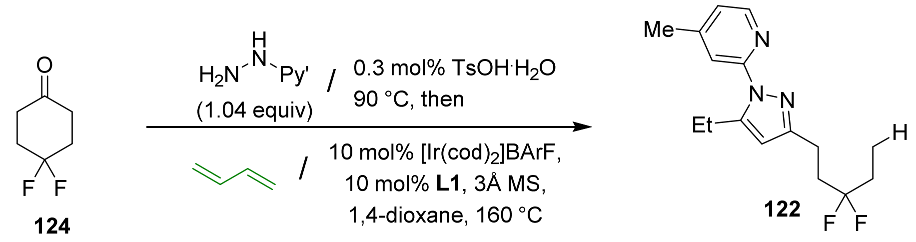
K7

120

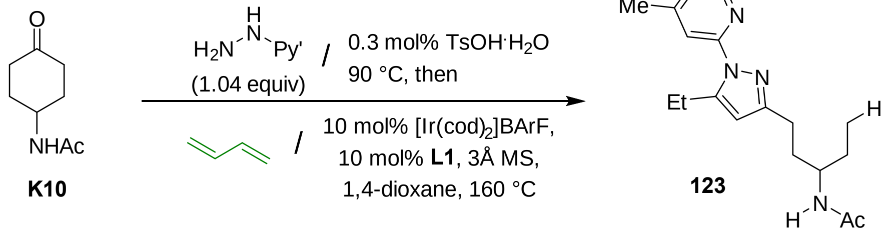
120: Following **General procedure C2,** the reaction was conducted at 0.05 mmol scale with 7.7 mg **K7** and 120 μL 1,3-butadiene (in PhMe, 20 wt.%). Three parallel reactions were conducted (0.05 mmol for each, 0.15 mmol in total) and combined, giving the titled compound as a colorless oil (30.5 mg, 65% yield). $R_f = 0.\ 4$ (hexane/ethyl acetate = 10:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.26 (d, *J* = 5.0 Hz, 1H), 7.70 – 7.61 (m, 1H), 6.96 (d, *J* = 5.0 Hz, 1H), 6.06 (s, 1H), 3.10 (q, *J* = 7.5 Hz, 2H), 2.74 (ddd, *J* = 14.6, 11.4, 5.2 Hz, 1H), 2.61 (ddd, *J* = 14.5, 11.3, 5.9 Hz, 1H), 2.39 (s, 3H), 1.90 – 1.81 (m, 1H), 1.57 (dtd, *J* = 14.0, 7.5, 3.6 Hz, 1H), 1.51 – 1.37 (m, 1H), 1.25 (t, *J* = 7.5 Hz, 3H), 1.18 (dt, *J* = 14.2, 7.3 Hz, 1H), 1.02 – 0.93 (m, 4H), 0.89 (s, 9H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 154.88, 153.87, 149.71, 147.79, 147.34, 122.16, 117.07, 105.63, 50.61, 34.17, 31.11, 28.89, 28.00, 23.85, 21.50, 21.28, 14.70, 13.27. IR (KBr) 3062, 2967, 2876, 1611, 1571, 1482, 1417, 1366, 1008 cm^{-1}. HRMS: calcd. 314.2591 $[M+H]^+$ Found: 314.2598.



121: Following **General procedure C2,** the reaction was conducted at 0.05 mmol scale with 12.2 mg **K8** as the ketone substrates and 120 µL 1,3-butadiene (in PhMe, 20 wt.%). Three parallel reactions were conducted (0.05 mmol for each, 0.15 mmol in total) and combined, giving the titled compound as a colorless oil (39.3 mg, 65% yield). R_f = 0.3 (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, CDCl$_3$) δ 8.19 (d, *J* = 5.0 Hz, 1H), 7.72 (dd, *J* = 5.4, 3.1 Hz, 2H), 7.61 (dd, *J* = 5.5, 3.1 Hz, 2H), 7.57 (s, 1H), 6.93 (d, *J* = 5.0 Hz, 1H), 5.98 (s, 1H), 4.23 (tt, *J* = 10.1, 5.0 Hz, 1H), 2.94 (q, *J* = 7.4 Hz, 2H), 2.76 – 2.50 (m, 3H), 2.38 (s, 3H), 2.20 – 2.03 (m, 2H), 1.82 (dt, *J* = 13.5, 6.8 Hz, 1H), 1.17 (t, *J* = 7.4 Hz, 3H), 0.87 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 168.83, 153.66, 152.92, 149.56, 147.79, 147.13, 133.69, 131.86, 122.95, 122.05, 116.83, 105.77, 53.95, 31.51, 26.07, 25.80, 21.45, 21.26, 13.08, 11.18. IR (KBr) 3062, 2973, 2928, 2878, 1769, 1711, 1607, 1571, 1476, 1370, 1048 cm^{-1}. HRMS: calcd. 403.2129 [M+H]$^+$ Found: 403.2118.



122: Following **General procedure C2,** the reaction was conducted at 0.05 mmol scale with 6.7 mg **124** as the ketone substrates and 120 µL 1,3-butadiene (in PhMe, 20 wt.%). Three parallel reactions were conducted (0.05 mmol for each, 0.15 mmol in total) and combined, giving the titled compound as a colorless oil (27.5 mg, 63% yield). R_f = 0. 25 (hexane/ethyl acetate = 10:1). ^{1}H NMR (400 MHz, CDCl$_3$) δ 8.27 (d, *J* = 5.1 Hz, 1H), 7.62 (s, 1H), 6.98 (d, *J* = 5.2 Hz, 1H), 6.06 (s, 1H), 3.09 (q, *J* = 7.5 Hz, 2H), 2.93 – 2.78 (m, 2H), 2.40 (s, 3H), 2.34 – 2.16 (m, 2H), 2.02 – 1.80 (m, 2H), 1.24 (t, *J* = 7.4 Hz, 3H), 1.04 (t, *J* = 7.5 Hz, 3H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 153.71, 152.50, 149.84, 148.08, 147.42, 125.17 (t, *J* = 240.6 Hz), 122.41, 117.11, 105.67, 35.75 (t, *J* = 25.7 Hz), 29.78 (t, *J* = 26.1 Hz), 21.50 (t, *J* = 5.6 Hz), 21.42, 21.29, 13.22, 6.79 (t, *J* = 5.7 Hz). IR (KBr) 3064, 2973, 2942, 2890, 1607, 1571, 1478, 1421, 1362, 1202, 1137, 1050, 1018 cm^{-1}. HRMS: calcd. 294.1776 [M+H]$^+$ Found: 294.1788.



123: Following **General procedure C2,** the reaction was conducted at 0.05 mmol scale with 7.8 mg **K10** as the ketone substrates and 120 µL 1,3-butadiene (in PhMe, 20 wt.%). Three parallel reactions were conducted (0.05 mmol for each, 0.15 mmol in total) and combined, giving the titled compound as a white solid (25.7 mg, 55% yield). R_f = 0.4 (hexane/acetone = 1:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.26 (d, J = 5.1 Hz, 1H), 7.59 (s, 1H), 6.97 (d, J = 5.1 Hz, 1H), 6.05 (s, 1H), 5.47 (d, J = 9.0 Hz, 1H), 3.95 (dtd, J = 13.8, 8.7, 5.2 Hz, 1H), 3.06 (q, J = 7.5 Hz, 2H), 2.68 (t, J = 7.8 Hz, 2H), 2.39 (s, 3H), 1.96 – 1.89 (m, 4H), 1.75 (dt, J = 13.6, 7.5 Hz, 1H), 1.57 (dq, J = 13.7, 6.9 Hz, 1H), 1.46 (td, J = 13.4, 12.1, 6.3 Hz, 1H), 1.22 (t, J = 7.5 Hz, 3H), 0.91 (t, J = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 169.86, 153.75, 153.67, 149.79, 147.98, 147.43, 122.36, 117.09, 105.88, 50.92, 34.05, 28.00, 25.06, 23.64, 21.37, 21.28, 13.22, 10.34. IR (KBr) 3283, 3072, 2969, 2932, 2876, 1644, 1611, 1569, 1474, 1421, 1372, 1302, 1014 cm^{-1}. HRMS: calcd. 315.2179 $[M+H]^+$ Found: 315.2190. Metrical parameters for the structure of **123** are available from the Cambridge Crystallographic Data Centre (https://www.ccdc.cam.ac.uk/) under reference numbers CCDC 1876535.

X-ray structure for **123:**

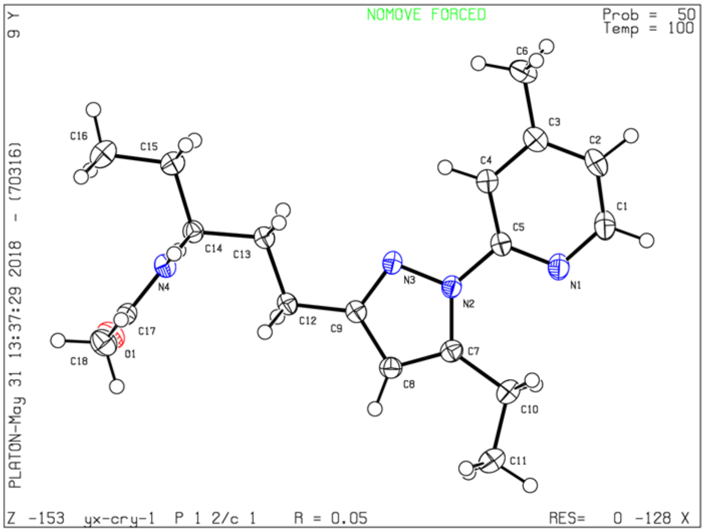
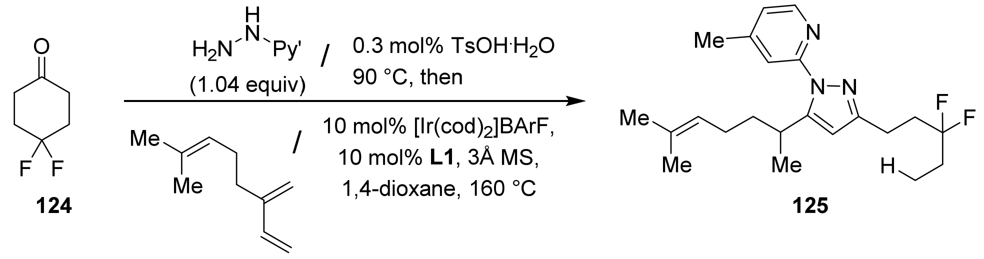


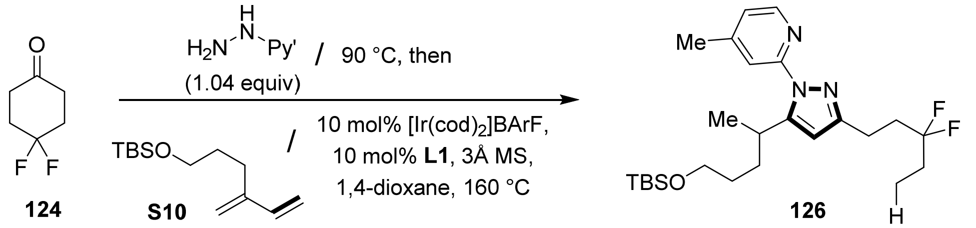
Table S2 | Crystal data and structure refinement for compound **123**.

Identification code	yx-cry-1
Empirical formula	$C_{18}H_{26}N_4O$
Formula weight	314.43
Temperature/K	100(2)
Crystal system	monoclinic

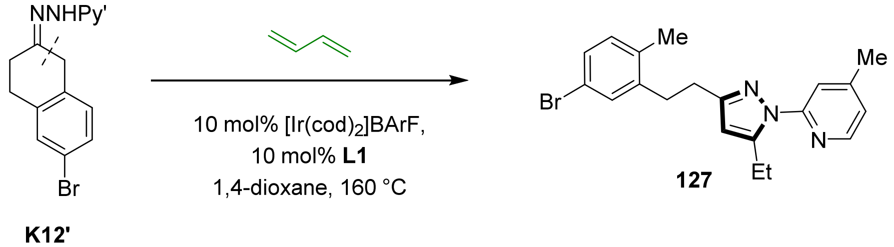
Space group	P2/c
a/Å	24.8508(14)
b/Å	4.9391(3)
c/Å	14.6038(9)
α/°	90
β/°	105.180(2)
γ/°	90
Volume/Å^3	1729.94(18)
Z	4
ρ_{calc}g/cm^3	1.207
μ/mm^{-1}	0.077
F(000)	680.0
Crystal size/mm^3	0.1 × 0.1 × 0.1
Radiation	MoKα (λ = 0.71073)
2Θ range for data collection/°	5.096 to 61.12
Index ranges	-35 ≤ h ≤ 35, -7 ≤ k ≤ 7, -20 ≤ l ≤ 20
Reflections collected	23460
Independent reflections	4802 [R_{int} = 0.0360, R_{sigma} = 0.0377]
Data/restraints/parameters	4802/0/212
Goodness-of-fit on F^2	1.031
Final R indexes [I>=2σ (I)]	R_1 = 0.0502, wR_2 = 0.1156
Final R indexes [all data]	R_1 = 0.0788, wR_2 = 0.1283
Largest diff. peak/hole / e Å^{-3}	0.33/-0.21



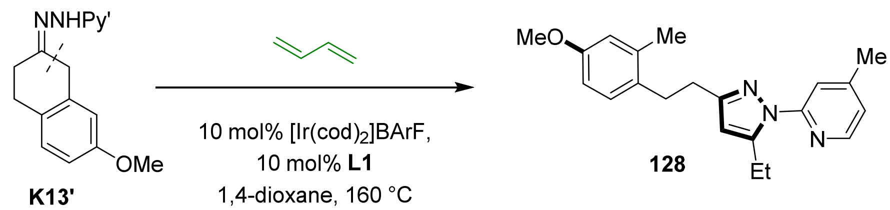
125: Following **General procedure C1,** the reaction was conducted at 0.3 mmol scale with 40.2 mg **124** and 78 μL myrcene. The titled compound was isolated as a colorless oil (68.3 mg, 61% yield). R_f = 0.65 (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, CDCl$_3$) δ 8.28 (d, J = 5.1 Hz, 1H), 7.56 (dd, J = 1.7, 0.9 Hz, 1H), 7.00 (dd, J = 5.1, 1.4 Hz, 1H), 6.06 (s, 1H), 5.01 (dddd, J = 7.2, 5.7, 2.9, 1.4 Hz, 1H), 3.79 (h, J = 6.9 Hz, 1H), 2.92 – 2.79 (m, 2H), 2.40 (s, 3H), 2.32 – 2.17 (m, 2H), 1.97 – 1.82 (m, 4H), 1.74 – 1.56 (m, 4H), 1.52 – 1.36 (m, 4H), 1.24 (d, J = 6.9 Hz, 3H), 1.03 (t, *J* = 7.5 Hz, 3H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 153.78, 152.45, 152.15, 149.84, 147.48, 131.63, 125.18 (t, *J* = 240.7 Hz), 124.32, 122.66, 118.03, 104.00, 37.36, 35.75 (t, *J* = 25.7 Hz), 30.67, 29.76 (t, *J* = 26.1 Hz), 25.88, 25.80, 21.53 (t, *J* = 5.5 Hz), 21.27, 20.58, 17.66, 6.79 (t, *J* = 5.7 Hz). IR (KBr) 3064, 2973, 2926, 2861, 1605, 1575, 1478, 1419, 1372, 1198 cm^{-1}. HRMS: calcd. 376.2559 [M+H]$^+$ Found: 376.2555.



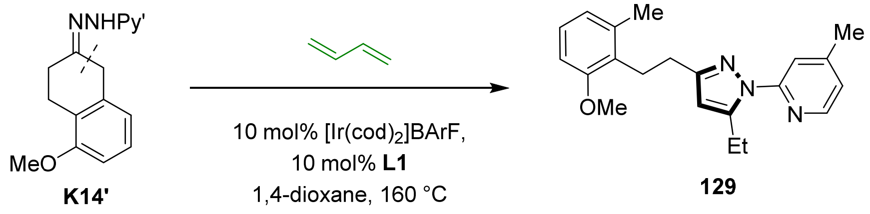
126: Following **General procedure C1,** the reaction was conducted at 0.2 mmol scale with 26.8 mg **124** and 59 mg **S10** in 0.07 mL 1,4-dioxane. No *p*-TsOH was used for the condensation step. The titled compound was isolated as a colorless oil (53.5 mg, 58% yield). R_f = 0.65 (hexane/ethyl acetate = 5:1). ^{1}H NMR (400 MHz, CDCl$_3$) δ 8.31 – 8.20 (m, 1H), 7.57 (s, 1H), 7.00 (dd, *J* = 5.0, 0.8 Hz, 1H), 6.06 (s, 1H), 3.82 (h, *J* = 6.7 Hz, 1H), 3.52 (t, *J* = 6.2 Hz, 2H), 2.89 – 2.77 (m, 2H), 2.40 (s, 3H), 2.35 – 2.17 (m, 2H), 1.89 (tt, *J* = 16.5, 7.5 Hz, 2H), 1.69 – 1.59 (m, 1H), 1.55 – 1.44 (m, 3H), 1.23 (d, *J* = 6.9 Hz, 3H), 1.03 (t, *J* = 7.5 Hz, 3H), 0.85 (s, 9H), -0.01 (s, 6H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 153.82, 152.43, 152.02, 149.88, 147.47, 125.17 (t, *J* = 240.6 Hz), 122.67, 117.98, 104.08, 63.29, 35.73 (t, *J* = 25.7 Hz), 33.44, 30.80, 30.61, 29.76 (t, *J* = 26.2 Hz), 26.07, 21.52 (t, *J* = 5.5 Hz), 21.27, 20.82, 18.45, 6.79 (t, *J* = 5.7 Hz), -5.18. IR (KBr) 3064, 2955, 2930, 2857, 1609, 1569, 1474, 1417, 1255, 1200, 1097 cm^{-1}. HRMS: calcd. 466.3060 [M+H]$^+$ Found: 466.3070.



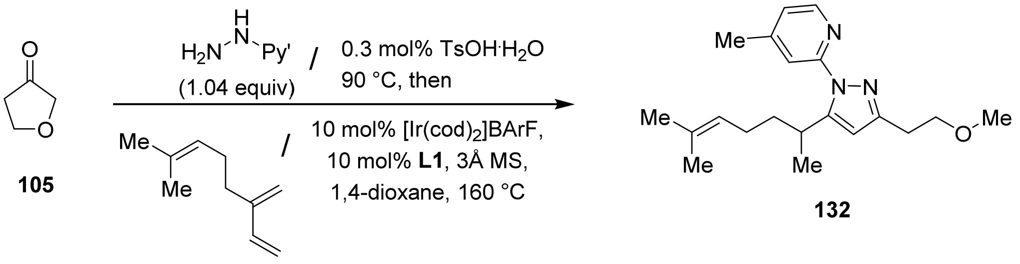
127: The compound **127** was synthesized using the same protocol as described for **99** with 16.5 mg pre-formed hydrazone **K12’** and 120 μL 1,3-butadiene (in PhMe, 20 wt.%). Two parallel reactions were conducted (0.05 mmol for each, 0.1 mmol in total) and combined, giving the titled compound as a colorless oil (26.7 mg, 70% yield). R_f = 0.6 (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, CDCl$_3$) δ 8.33 – 8.24 (m, 1H), 7.68 – 7.58 (m, 1H), 7.36 (d, *J* = 2.1 Hz, 1H), 7.24 (dd, *J* = 8.1, 2.2 Hz, 1H), 7.05 – 7.00 (m, 1H), 7.00 – 6.97 (m, 1H), 6.01 (s, 1H), 3.10 (qd, *J* = 7.5, 0.9 Hz, 2H), 3.00 – 2.83 (m, 4H), 2.42 (s, 3H), 2.28 (s, 3H), 1.24 (t, *J* = 7.5 Hz, 3H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 153.78, 153.07, 149.84, 147.97, 147.42, 142.45, 135.13, 131.84, 131.82, 129.08, 122.39, 119.53, 117.22, 105.82, 33.11, 28.98, 21.42, 21.32, 19.03, 13.29. IR (KBr) 3019, 2971, 2928, 2872, 1607, 1573, 1478, 1419, 1362, 1018 cm^{-1}. HRMS: calcd. 384.1070 [M+H]$^+$ Found: 384.1065.



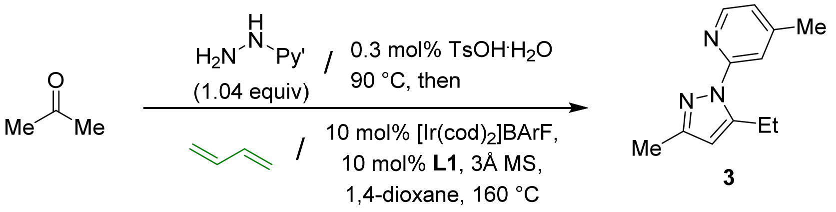
128: The compound **128** was synthesized using the same protocol as described for **99** with 14.1 mg pre-formed hydrazone **K13’** and 120 µL 1,3-butadiene (in PhMe, 20 wt.%). Two parallel reactions were conducted (0.05 mmol for each, 0.1 mmol in total) and combined, giving the titled compound as a colorless oil (24.0 mg, 72% yield). R_f = 0.5 (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, CDCl$_3$) δ 8.28 (d, *J* = 5.0 Hz, 1H), 7.64 (s, 1H), 7.13 (d, *J* = 8.2 Hz, 1H), 6.99 (d, *J* = 5.1 Hz, 1H), 6.77 – 6.67 (m, 2H), 6.04 (s, 1H), 3.79 (s, 3H), 3.10 (q, *J* = 7.5 Hz, 2H), 2.99 – 2.81 (m, 4H), 2.41 (s, 3H), 2.33 (s, 3H), 1.25 (t, *J* = 7.5 Hz, 3H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 157.91, 153.83, 153.75, 149.80, 147.87, 147.42, 137.45, 132.45, 129.85, 122.32, 117.18, 115.94, 111.14, 105.85, 55.34, 32.58, 29.59, 21.45, 21.32, 19.79, 13.30. IR (KBr) 3019, 2967, 2940, 1609, 1569, 1506, 1476, 1421, 1253 cm^{-1}. HRMS: calcd. 336.2071 [M+H]$^+$ Found: 336.2080.



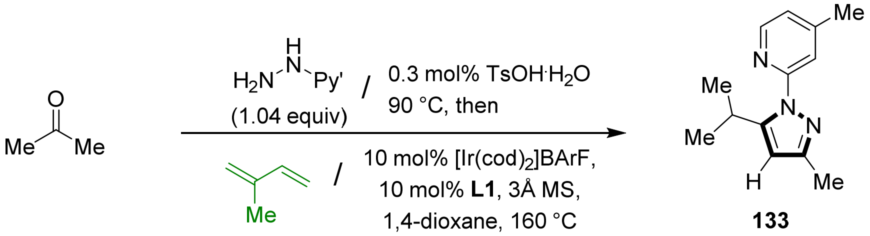
129: The compound **129** was synthesized using the same protocol as described for **99** with 14.1 mg pre-formed hydrazone **K14’** and 120 µL 1,3-butadiene (in PhMe, 20 wt.%). Two parallel reactions were conducted (0.05 mmol for each, 0.1 mmol in total) and combined, giving the titled compound as a colorless oil (23.0 mg, 69% yield). R_f = 0.55 (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, CDCl$_3$) δ 8.36 – 8.18 (m, 1H), 7.66 (dd, *J* = 1.6, 0.8 Hz, 1H), 7.10 (t, *J* = 7.9 Hz, 1H), 6.98 (ddd, *J* = 5.0, 1.5, 0.8 Hz, 1H), 6.77 (dd, *J* = 15.3, 7.9 Hz, 2H), 6.05 (s, 1H), 3.83 (s, 3H), 3.11 (qd, *J* = 7.5, 0.8 Hz, 2H), 3.07 – 2.98 (m, 2H), 2.87 – 2.74 (m, 2H), 2.41 (s, 3H), 2.32 (s, 3H), 1.25 (t, *J* = 7.5 Hz, 3H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 157.81, 154.34, 153.90, 149.74, 147.74, 147.38, 137.72, 128.93, 126.52, 122.64, 122.22, 117.19, 108.08, 105.90, 55.56, 27.89, 26.63, 21.46, 21.31, 19.66, 13.32. IR (KBr) 3017, 2971, 2928, 1608, 1573, 1417, 1263, 1085 cm^{-1}. HRMS: calcd. 336.2071 [M+H]$^+$ Found: 336.2078.



132: Following **General procedure C1,** the reaction was conducted at 0.3 mmol scale with 26 mg **105** and 104 µL myrcene (2.0 equiv) in 0.1 mL 1,4-dioxane. The titled compound was isolated as a colorless oil (43.8 mg, 45% yield). The other C–C cleavage regioisomer was not observed from the reaction mixture. **132**: R_f = 0.6 (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.27 (dd, *J* = 5.0, 0.7 Hz, 1H), 7.58 (s, 1H), 6.99 (dd, *J* = 5.1, 0.8 Hz, 1H), 6.09 (s, 1H), 5.02 (ddt, *J* = 8.7, 5.8, 1.4 Hz, 1H), 3.81 (p, *J* = 6.9 Hz, 1H), 3.69 (t, *J* = 7.2 Hz, 2H), 3.39 (s, 3H), 2.94 (t, *J* = 7.2 Hz, 2H), 2.39 (s, 3H), 1.94 (q, *J* = 7.5 Hz, 2H), 1.72 – 1.64 (m, 1H), 1.61 (s, 3H), 1.49 (s, 3H), 1.48 – 1.38 (m, 1H), 1.23 (d, *J* = 6.9 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 153.84, 151.96, 150.94, 149.75, 147.42, 131.57, 124.37, 122.56, 118.00, 104.55, 72.19, 58.77, 37.33, 30.69, 29.14, 25.90, 25.80, 21.25, 20.53, 17.65. IR (KBr) 2965, 2926, 2870, 1609, 1567, 1474, 1421, 1119 cm^{-1}. HRMS: calcd. 328.2384 $[M+H]^+$ Found: 328.2394.



Following **General procedure C2,** the reaction was conducted at 0.1 mmol scale with 5.8 mg acetone as the ketone substrates and 400 µL 1,3-butadiene (in PhMe, 20 wt.%). Two parallel reactions were conducted (0.1 mmol for each, 0.20 mmol in total) and combined, yielding compound **3** as a colorless oil (30.2 mg, 75% yield). The characterization data for compound **3** has been reported *vide supra*.

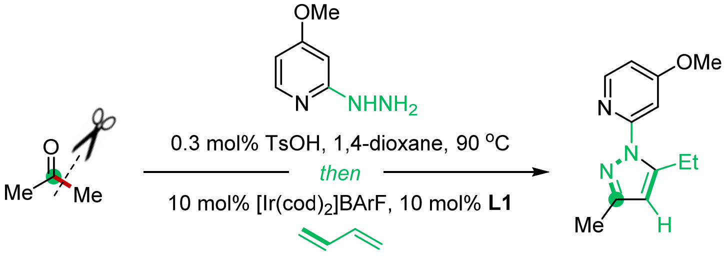


133: Following **General procedure C2,** the reaction was conducted at 0.1 mmol scale with 5.8 mg acetone as the ketone substrates and 120 µL isoprene. Two parallel reactions were conducted (0.1 mmol for each, 0.2 mmol in total) and combined, giving the titled compound as a colorless oil (33.4 mg, 78% yield). R_f = 0.65 (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.27 (dd, *J* = 5.1, 0.7 Hz, 1H), 7.68 – 7.47 (m, 1H), 6.98 (ddd, *J* = 5.0, 1.6, 0.8 Hz, 1H), 6.04 (s, 1H), 3.93 (pd, *J* = 6.9, 0.7 Hz, 1H), 2.39 (s, 3H), 2.30 (s, 3H), 1.21 (d, *J* = 6.8 Hz, 6H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 153.90, 152.95, 149.79, 149.65, 147.43, 122.43, 117.64, 104.92, 26.16, 22.86, 21.25, 13.83. IR (KBr) 3064, 3023, 2971, 2928, 2874, 1609, 1571, 1461, 1381, 1358, 1299, 1095, 1018 cm^{-1}. HRMS: calcd. 216.1495 $[M+H]^+$ Found: 216.1503.

133 could also be synthesized following slightly modified **General procedure C2** *<u>with the use of less diene coupling partner</u>*: A 2 mL vial was charged with acetone (5.8 mg, 0.1 mmol, 1.0 equiv) and

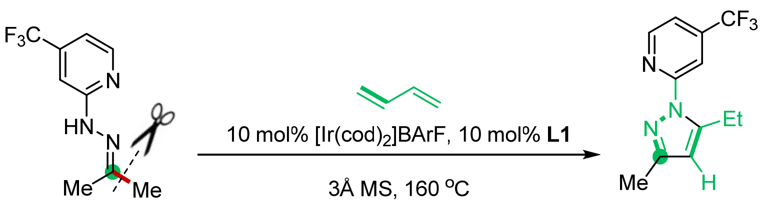
2-hydrazineyl-4-methylpyridine **D1** (12.8 mg, 0.104 mmol, 1.04 equiv), and transferred into a glove box. 1,4-Dioxane (0.5 mL) and a stock solution of TsOH·H_2O in 1,4-dioxane (0.05 M, 6.0-10.0 μL, 0.003-0.005 equiv) was added. The vial was sealed, transferred out of the glove box, and heated in a pie-block at 90 °C for 5 hours. After cooled to room temperature, the vial was charged with $[Ir(cod)_2]BArF$ (12.8 mg, 0.01 mmol, 0.1 equiv) and **L1** (4.0 mg, 0.01 mmol, 0.1 equiv), transferred into the glove box, and purged under N_2 atmosphere for 3 mins. Pre-dried 3Å molecular sieve (100 mg) and isoprene (60 μL, 6 equiv) were then added. The vial was sealed, transferred out of the glove box, and heated in a pie-block at 160 °C under stirring for 72 hours. After cooled to room temperature, the reaction mixture was filtered through a short plug of Celite, concentrated *in vacuo*, and further purified by flash column chromatography over silica (hexane/ethyl acetate, from 40:1 to 20:1). Combining 2 parallel reactions furnished **133** in 77% yield (33.0 mg) as a colorless oil.

Test of other pyridyl directing groups



3b, 82%

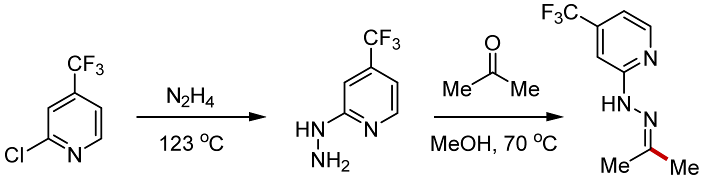
A 4 mL vial was charged with acetone (5.8 mg, 0.1 mmol, 1.0 equiv) and 2-hydrazineyl-4-methoxypyridine[2] (14.5 mg, 0.104 mmol, 1.04 equiv), and transferred into a glove box. 1,4-Dioxane (1 mL) and a stock solution of *p*-TsOH·H_2O in 1,4-dioxane (0.05 M, 10 μL, 0.005 equiv) was then added. The vial was sealed, transferred out of the glove box, and heated in a pie-block at 90 °C for 5 hours. After cooled to room temperature, the vial was charged with $[Ir(cod)_2]BArF$ (12.7 mg, 0.01 mmol, 0.1 equiv) and **L1** (4.0 mg, 0.01 mmol, 0.1 equiv), transferred into a glove box, and purged under N_2 atmosphere for 3 mins. Pre-dried 3Å molecular sieve (100 mg) and 1,3-butadiene (20 wt.% in PhMe, 400 μL) were then added. The vial was sealed and heated in a pie-block at 160 °C under stirring for 24 hours. After cooled to room temperature, the reaction mixture was filtered through a short plug of Celite, concentrated *in vacuo*, and further purified by flash column chromatography over silica (hexane/ethyl acetate = 10:1) to give the products **3b** as a colorless oil (17.7 mg, 82% yield). $R_f = 0.7$ (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.20 (d, $J = 5.7$ Hz, 1H), 7.34 (d, $J = 2.3$ Hz, 1H), 6.69 (dd, $J = 5.8$, 2.4 Hz, 1H), 6.02 (s, 1H), 3.90 (s, 3H), 3.10 (qd, $J = 7.4$, 0.9 Hz, 2H), 2.30 (s, 3H), 1.23 (t, $J = 7.5$ Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 167.41, 155.41, 149.81, 148.47, 148.21, 109.13, 107.05, 100.70, 55.57, 21.56, 13.83, 13.25. IR (KBr) 2974, 2938, 2883, 1604, 1580, 1441, 1411, 1355, 1209, 1032 cm^{-1}. HRMS: calcd. 218.1293 $[M+H]^+$ Found: 218.1294.



3c, 70%

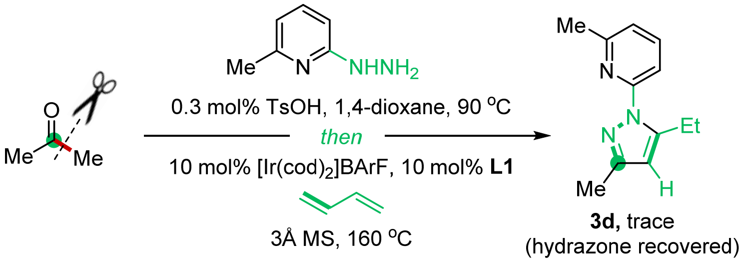
A 4 mL vial charged with 2-(2-(propan-2-ylidene)hydrazineyl)-4-(trifluoromethyl)pyridine (21.7 mg, 0.1 mmol, 1.0 equiv), [Ir(cod)$_2$]BArF (12.7 mg, 0.01 mmol, 0.1 equiv) and **L1** (4.0 mg, 0.01 mmol, 0.1 equiv) was transferred into a glove box. Pre-dried 3Å molecular sieve (100 mg), 1,4-dioxane (1 mL) and 1,3-butadiene (20 wt.% in PhMe, 400 μL) were then added. The vial was sealed and heated in a pie-block at 160 °C under stirring for 24 hours. After cooled to room temperature, the reaction mixture was filtered through a short plug of Celite, concentrated *in vacuo*, and further purified by flash column chromatography over silica (hexane/ethyl acetate = 10:1) to give the products **3c** as a colorless oil (17.8 mg, 70% yield). R_f = 0.8 (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, CDCl$_3$) δ 8.55 (d, *J* = 5.1 Hz, 1H), 8.17 (dt, *J* = 1.7, 0.8 Hz, 1H), 7.35 – 7.28 (m, 1H), 6.06 (s, 1H), 3.15 (qd, *J* = 7.5, 0.9 Hz, 2H), 2.32 (s, 3H), 1.27 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 154.54, 150.93, 148.75, 148.65, 140.59 (q, *J* = 34.2 Hz), 122.78 (q, *J* = 273.5 Hz), 115.84 (q, *J* = 3.1 Hz), 111.83 (q, *J* = 3.8 Hz), 108.12, 21.97, 13.85, 13.25. IR (KBr) 2970, 2941, 1582, 1442, 1412, 1339, 1176, 1143, 1084 cm^{-1}. HRMS: calcd. 256.1062 [M+H]$^+$ Found: 256.1050.

*Procedure for making 2-(2-(propan-2-ylidene)hydrazineyl)-4-(trifluoromethyl)pyridine (**3c-S1**)*:



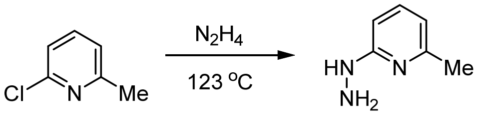
3c-S1

A mixture of 2-chloro-4-(trifluoromethyl)pyridine (2 mL) and hydrazine monohydrate (10 mL) was stirred under N$_2$ atmosphere at 123 °C in a sealed 20 mL vial for 36 hours. After cooled to room temperature, the reaction mixture was extracted with Et$_2$O (30 mL * 2) and dried over Mg$_2$SO$_4$. The filtrate was then concentrated under *vacuo* to yield 2-hydrazineyl-4-(trifluoromethyl)pyridine as a yellowish solid (1.9 g, 69%) that contains ~5% unknown impurity. A mixture of crude 2-hydrazineyl-4-(trifluoromethyl)pyridine (354 mg, 2.0 mmol, 1.0 equiv), acetone (128 mg, 2.2 mmol, 1.1 equiv) and TsOH·H$_2$O (ca. 5 mg) in MeOH (3 mL) was stirred under N$_2$ atmosphere at 70 °C in a sealed 8 mL vial for 18 hours until full consumption of the starting material. After cooled to room temperature, the reaction mixture was concentrated *in vacuo* and further purified by flash column chromatography over silica (hexane/ethyl acetate = 5:1) to give the products **3c-S1** as a colorless oil (380 mg, 88% yield). R_f = 0.3 (hexane/ethyl acetate = 3:1). ^{1}H NMR (500 MHz, CDCl$_3$) δ 8.24 – 8.16 (m, 1H), 7.89 (s, 1H), 7.46 – 7.38 (m, 1H), 6.88 (dd, *J* = 5.2, 1.6 Hz, 1H), 2.06 (s, 3H), 1.89 (s, 3H).^{13}C NMR (101 MHz, CDCl$_3$) δ 158.06, 148.98, 147.17, 140.28 (q, *J* = 33.4 Hz), 123.21 (q, *J* = 273.2 Hz), 110.62 (q, *J* = 3.4 Hz), 103.45 (q, *J* = 4.1 Hz), 25.40, 16.06. IR (KBr) 2921, 1618, 1571, 1441, 1331, 1170, 1275, 1129 cm^{-1}. HRMS: calcd. 218.0905 [M+H]$^+$ Found: 218.0915.



A 4 mL vial was charged with acetone (5.8 mg, 0.1 mmol, 1.0 equiv) and 2-hydrazineyl-6-methylpyridine (12.8 mg, 0.104 mmol, 1.04 equiv), and transferred into a glove box. 1,4-Dioxane (1 mL) and a stock solution of *p*-TsOH·H_2O in 1,4-dioxane (0.05 M, 10 µL, 0.005 equiv) was then added. The vial was sealed, transferred out of the glove box, and heated in a pie-block at 90 °C for 5 hours. After cooled to room temperature, the vial was charged with [Ir(cod)$_2$]BArF (12.7 mg, 0.01 mmol, 0.1 equiv) and **L1** (4.0 mg, 0.01 mmol, 0.1 equiv), transferred into a glove box, and purged under N_2 atmosphere for 3 mins. Pre-dried 3Å molecular sieve (100 mg) and 1,3-butadiene (20 wt.% in PhMe, 400 µL) were then added. The vial was sealed and heated in a pie-block at 160 °C under stirring for 24 hours. After cooled to room temperature, the reaction mixture was subjected to TLC and crude ^{1}H NMR analysis. Only trace amount of the C–C cleavage product **3d** was observed, and the hydrazone derived from acetone and 2-hydrazineyl-6-methylpyridine was recovered.

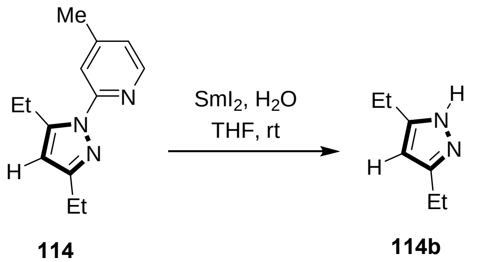
*Procedure for making 2-hydrazineyl-6-methylpyridine (**3d-S1**)*:



3d-S1

A mixture of 2-chloro-6-methylpyridine (2 mL) and hydrazine monohydrate (10 mL) was stirred under N_2 atmosphere at 123 °C in a sealed 20 mL vial for 24 hours. After cooled to room temperature, the reaction mixture was extracted with Et_2O (30 mL * 2) and dried over Mg_2SO_4. The filtrate was then concentrated under *vacuo* to yield **3d-S1** as a white solid (1.85 g, 82%). R_f = 0.1 (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.45 – 7.31 (m, 1H), 6.63 – 6.41 (m, 2H), 5.98 (br, 1H), 3.79 (br, 2H), 2.39 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 161.19, 156.78, 138.00, 113.88, 103.57, 24.40. IR (KBr) 3295, 2921, 1599, 1577, 1458, 1333, 1234, 1156 cm^{-1}. HRMS: calcd. 124.0875 [M+H]$^+$ Found: 124.0863.

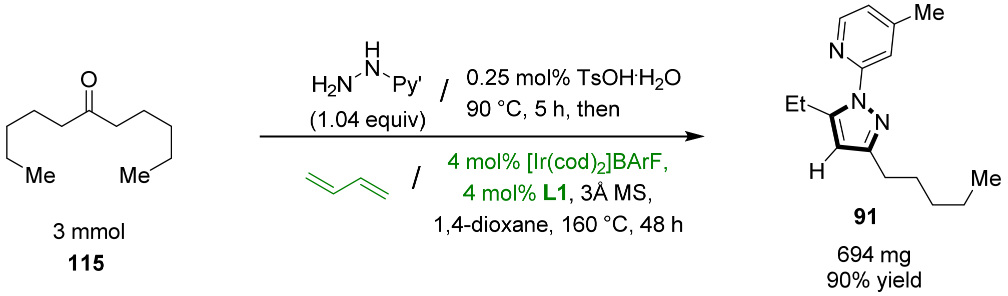
3.3.3.3 Deprotection of the pyridyl group



114 **114b**

A THF solution of SmI_2 (0.1M, 10.5 mL, 1.05 mmol, 7 equiv) was added to a 25 mL round-bottom flask charged with **114** (32 mg, 0.15 mmol, 1.0 equiv) under N_2 atmosphere using a syringe. Degassed H_2O (81 µL, 4.5 mmol, 30 equiv) was then added using a syringe. The reaction mixture was stirred at room temperature for 15 mins and then concentrated under *vacuo*. The residue was treated with aqueous NH_4Cl (sat.) (5 mL), H_2O (5 mL), and DCM (10 mL), and was stirred vigorously at room temperature for 45 mins. The reaction mixture was then extracted with DCM and dried over Na_2SO_4. The filtrate was concentrated under *vacuo* and purified by flash column chromatography over silica (DCM/MeOH, from 30:1 to 15:1) to give product **114b** as a colorless oil (16.1 mg, 87% yield). R_f = 0. 35 (DCM/MeOH = 10:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 9.93 (br, 1H), 5.88 (s, 1H), 2.65 (q, *J* = 7.6 Hz, 4H), 1.25 (t, *J* = 7.6 Hz, 6H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 150.73, 101.08, 20.44, 13.70. The spectra match the reported literature.[70]

3.3.3.4 Scalability

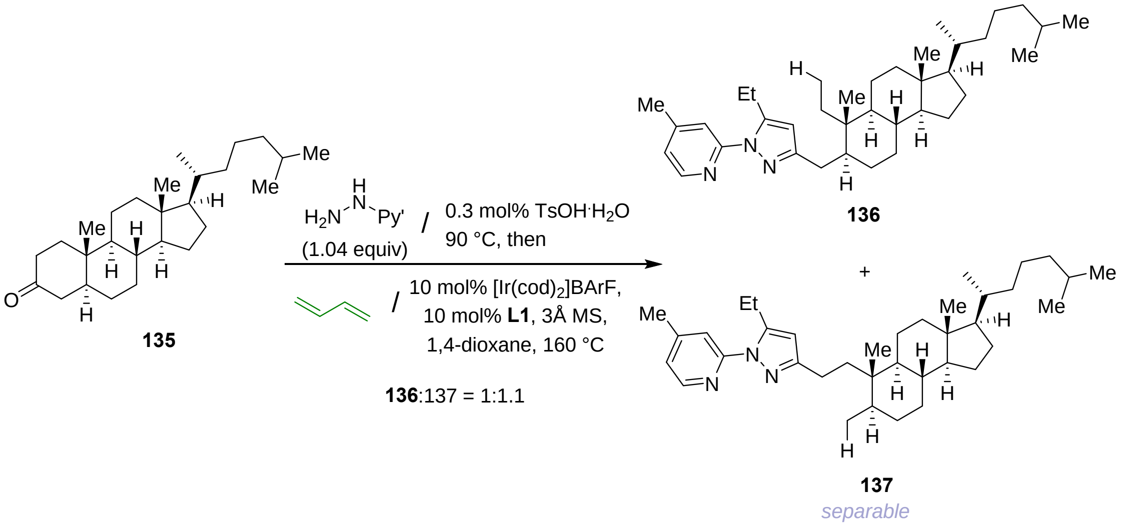


115 **91**

<u>*Semi-gram-scale preparation of **91** with 4% catalyst*</u>*:* A 40 mL vial was charged with **115** (510 mg, 3 mmol, 1.0 equiv) and 2-hydrazineyl-4-methylpyridine **D1** (384 mg, 3.12 mmol, 1.04 equiv), and transferred into a glove box. 1,4-Dioxane (2.5 mL) and a stock solution of TsOH·H_2O in 1,4-dioxane (0.05 M, 150 µL, 0.0025 equiv) was added. The vial was sealed, transferred out of the glove box, and heated in a pie-block at 90 °C for 5 hours. After cooled to room temperature, the vial was charged with $[Ir(cod)_2]$BArF (153 mg, 0.12 mmol, 0.04 equiv) and **L1** (48 mg, 0.12 mmol, 0.04 equiv), transferred into the glove box, and then purged under N_2 atmosphere for 6 mins. Pre-dried 3Å molecular sieve (2.5 g) and the 1,3-butadiene (20 wt.% in PhMe, 12 mL) were then added. The vial was sealed and heated at 160 °C under stirring for 48 hours. After cooled to room temperature, the reaction mixture was filtered through a short plug of Celite, concentrated *in vacuo*, and further purified by flash column chromatography over silica (hexane/ethyl acetate, from 40:1 to 20:1) to give the pyrazole product **91** as a colorless oil (694 mg, 90% yield). R_f = 0.75 (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.26 (dd, *J* = 5.1, 0.7 Hz, 1H), 7.64 (dt, *J* = 1.5, 0.8 Hz, 1H), 7.03 – 6.86 (m, 1H), 6.04 (s, 1H), 3.10 (qd, *J* = 7.5, 0.9 Hz, 2H), 2.69 – 2.59 (m, 2H), 2.39 (s, 3H), 1.77 – 1.60 (m, 2H), 1.42 – 1.33 (m, 4H), 1.24 (t, *J* = 7.5 Hz, 3H), 0.90 (t, *J* = 7.0 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 154.61, 153.87, 149.71, 147.78, 147.33, 122.16, 117.04, 105.70, 31.88, 29.47, 28.58, 22.67, 21.50,

21.27, 14.20, 13.25. IR (KBr) 3060, 3023, 2959, 2924, 2861, 1607, 1569, 1480, 1423, 1362, 1006 cm^{-1}. HRMS: calcd. 258.1965 $[M+H]^+$ Found: 258.1970.

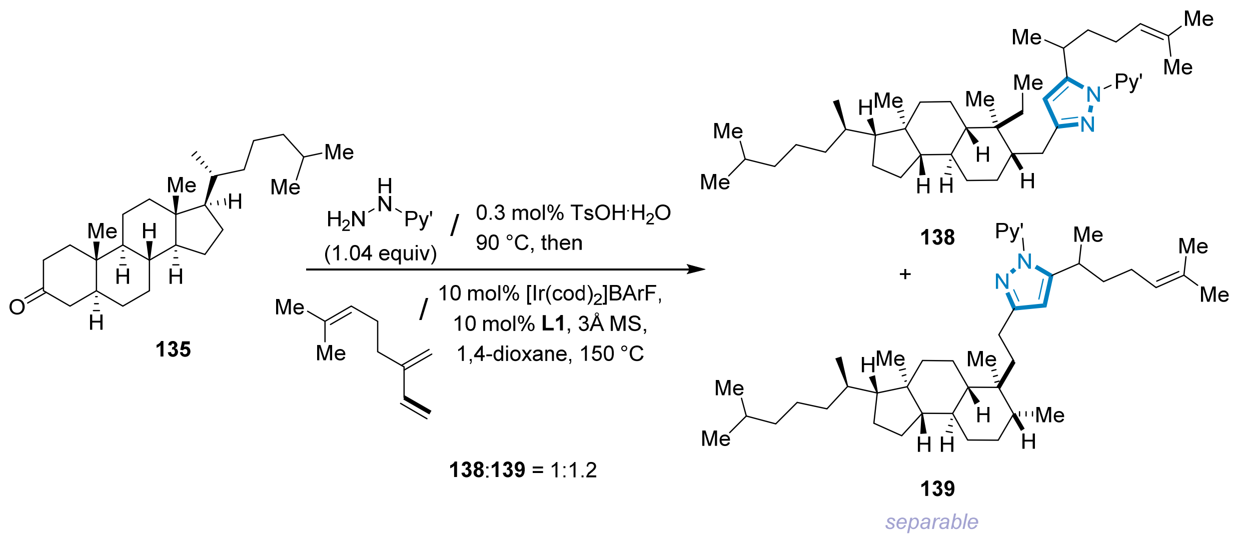
3.3.3.5 Introducing pyrazoles into complex ketones via C−C cleavage



Following **General procedure C2,** the reaction was conducted at 0.05 mmol scale with 19.3 mg **135** and 120 μL 1,3-butadiene (in PhMe, 20 wt.%). Three parallel reactions were conducted (0.05 mmol for each, 0.15 mmol in total) and combined, yielding pyrazoles **136** and **137** in 1:1.1 ratio after isolation. The characterization data for **136** and **137** are listed as follows:

136: colorless oil (20.5 mg, 25.5% yield). $R_f = 0.35$ (hexane/ethyl acetate = 10:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.26 (d, $J = 5.0$ Hz, 1H), 7.64 (s, 1H), 6.96 (d, $J = 5.1$ Hz, 1H), 5.99 (s, 1H), 3.10 (q, $J = 7.4$ Hz, 2H), 2.79 (dd, $J = 14.0, 2.5$ Hz, 1H), 2.39 (s, 3H), 2.21 (dd, $J = 14.0, 11.2$ Hz, 1H), 1.98 (dt, $J = 12.6, 3.4$ Hz, 1H), 1.79 (ddd, $J = 14.6, 9.4, 5.3$ Hz, 1H), 1.72 – 1.41 (m, 8H), 1.36 – 0.95 (m, 19H), 0.93 – 0.70 (m, 16H), 0.65 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) carbon signals were observed at δ 154.49, 153.92, 149.67, 147.85, 147.30, 122.09, 117.10, 105.87, 57.00, 56.47, 47.00, 42.51, 42.05, 40.34, 39.67, 38.44, 36.33, 35.95, 35.46, 32.08, 29.03, 28.54, 28.43, 28.17, 26.92, 24.42, 23.99, 22.97, 22.71, 21.54, 21.43, 21.29, 18.82, 16.64, 13.28, 12.12, 6.72. IR (KBr) 3060, 2963, 2870, 2851, 1609, 1571, 1476, 1423, 1379, 1010 cm^{-1}. HRMS: calcd. 546.4781 $[M+H]^+$ Found: 546.4798.

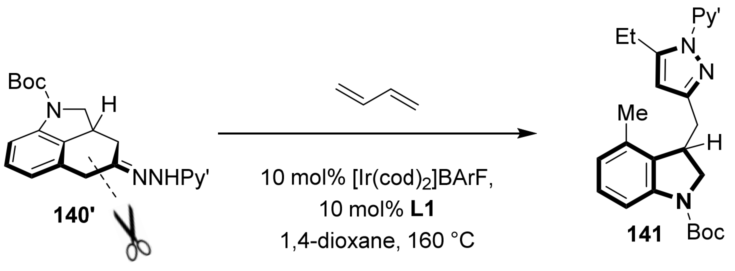
137: colorless oil (22.5 mg, 27.5% yield). $R_f = 0.4$ (hexane/ethyl acetate = 10:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.26 (d, $J = 5.0$ Hz, 1H), 7.64 (s, 1H), 6.96 (d, $J = 5.1$ Hz, 1H), 6.03 (s, 1H), 3.09 (q, $J = 7.5$ Hz, 2H), 2.51 (tt, $J = 13.3, 6.3$ Hz, 2H), 2.40 (s, 3H), 1.98 (dd, $J = 12.6, 3.4$ Hz, 1H), 1.88 – 1.77 (m, 1H), 1.74 – 1.50 (m, 7H), 1.47 – 1.22 (m, 11H), 1.21 – 0.98 (m, 9H), 0.93 – 0.81 (m, 13H), 0.77 (s, 3H), 0.66 (s, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) carbon signals were observed at δ 155.07, 153.89, 149.69, 147.83, 147.35, 122.15, 117.09, 105.47, 56.98, 56.48, 47.67, 42.52, 40.30, 39.68, 38.47, 36.89, 36.33, 36.30, 35.96, 35.52, 32.37, 30.68, 28.45, 28.17, 24.45, 24.00, 22.98, 22.72, 21.52, 21.49, 21.30, 21.16, 18.82, 16.15, 15.80, 13.29, 12.14. IR (KBr) 3060, 2959, 2934, 2874, 1611, 1571, 1478, 1419, 1381, 1362, 1014 cm^{-1}. HRMS: calcd. 546.4781 $[M+H]^+$ Found: 546.4789.



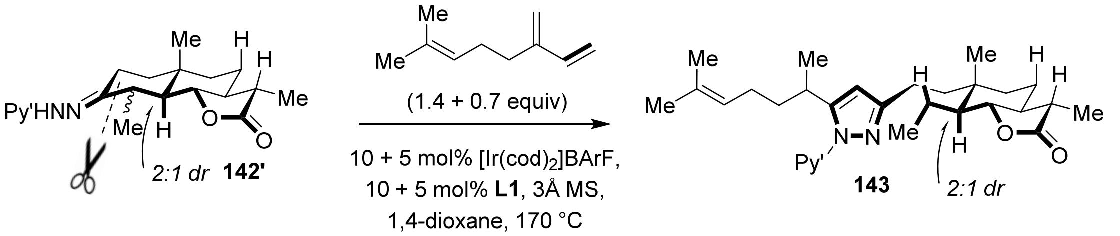
Following **General procedure C1,** the reaction was conducted at 0.3 mmol scale with 116 mg **135** and 70 μL myrcene (1.35 equiv) in 0.1 ml 1,4-dioxane at 150 °C. Pyrazoles **138** and **139** were isolated in 1:1.2 ratio. The characterization data for **138** and **139** are listed as follows:

138: colorless oil (47 mg, 25% yield, inseparable mixture of diastereomers). R_f = 0.7 (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, CDCl$_3$) δ 8.26 (d, *J* = 5.0 Hz, 1H), 7.57 (s, 1H), 6.98 (d, *J* = 1.5 Hz, 1H), 5.99 (s, 1H), 5.20 – 4.96 (m, 1H), 3.82 (h, *J* = 6.8 Hz, 1H), 2.78 (dd, *J* = 14.1, 2.6 Hz, 1H), 2.39 (s, 3H), 2.30 – 2.14 (m, 1H), 1.96 (dd, *J* = 18.0, 5.6 Hz, 3H), 1.86 – 1.74 (m, 1H), 1.70 – 1.51 (m, 10H), 1.49 – 1.40 (m, 5H), 1.39 – 0.94 (m, 20H), 0.93 – 0.79 (m, 15H), 0.76 – 0.69 (m, 1H), 0.65 (s, 3H). ^{13}C NMR (101 MHz, CDCl$_3$) carbon signals were found at δ 154.43, 153.99, 151.91, 151.86, 149.69, 147.36, 131.57, 131.56, 124.48, 124.45, 122.36, 118.05, 118.01, 104.26, 104.08, 57.01, 56.46, 47.00, 42.51, 42.06, 42.04, 40.34, 39.67, 38.44, 37.46, 37.34, 36.33, 35.95, 35.43, 32.09, 30.78, 30.71, 29.07, 29.02, 28.55, 28.44, 28.17, 26.92, 26.88, 25.98, 25.91, 25.84, 25.83, 24.42, 23.99, 22.98, 22.72, 21.41, 21.29, 20.74, 20.50, 18.82, 17.66, 17.64, 16.65, 16.64, 12.12, 6.75, 6.74. IR (KBr) 3062, 2961, 2932, 2872, 1609, 1470, 1417, 1376, 1012 cm^{-1}. HRMS: calcd. 628.5564 [M+H]$^+$ Found: 628.5549.

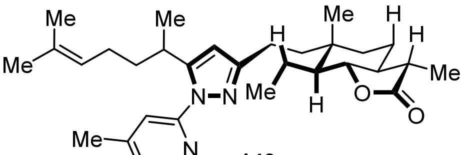
139: colorless oil (57.5 mg, 31% yield, inseparable mixture of diastereomers). R_f = 0.8 (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, CDCl$_3$) δ 8.27 (dd, *J* = 5.1, 0.6 Hz, 1H), 7.65 – 7.54 (m, 1H), 6.98 (dd, *J* = 5.0, 0.8 Hz, 1H), 6.02 (s, 1H), 5.03 (ddt, *J* = 8.7, 5.7, 1.4 Hz, 1H), 3.81 (h, *J* = 6.9 Hz, 1H), 2.60 – 2.43 (m, 2H), 2.40 (s, 3H), 1.95 (q, *J* = 8.3 Hz, 3H), 1.80 (ddd, *J* = 14.6, 9.1, 5.3 Hz, 1H), 1.73 – 1.50 (m, 14H), 1.49 – 1.40 (m, 2H), 1.29 (dd, *J* = 38.4, 7.2 Hz, 10H), 1.19 – 0.94 (m, 9H), 0.93 – 0.82 (m, 13H), 0.77 (s, 3H), 0.65 (s, 3H). ^{13}C NMR (101 MHz, CDCl$_3$) carbon signals were found at δ 155.00, 153.96, 151.89, 149.69, 147.40, 131.56, 124.46, 122.39, 117.99, 103.78, 56.96, 56.46, 47.64, 42.50, 40.30, 39.67, 38.47, 37.41, 36.87, 36.32, 36.23, 35.96, 35.50, 32.36, 30.75, 30.67, 28.44, 28.16, 25.97, 25.84, 24.44, 24.00, 22.98, 22.72, 21.48, 21.29, 21.17, 20.58, 18.80, 17.68, 16.16, 15.80, 12.13. IR (KBr) 2961, 2930, 2868, 1605, 1565, 1472, 1415, 1379, 1016 cm^{-1}. HRMS: calcd. 628.5564 [M+H]$^+$ Found: 628.5576.



141: The reaction was conducted following modified **General procedure C2** using the pre-formed hydrazone as the substrate: An 4 mL vial was charged with the hydrazone **140'** (12.5 mg, 0.05 mmol, 1.0 equiv) that was derived from its corresponding ketone following *General procedure for hydrazones formation (vide supra, 94% yield)*, [Ir(cod)$_2$]BArF (6.4 mg, 0.005 mmol, 0.1 equiv), **L1** (2.0 mg, 0.005 mmol, 0.1 equiv) and 1,4-dioxane (0.5 mL). The vial was transferred into the glove box and charged with 1,3-butadiene (20 wt.% in PhMe, 170 µL, ca. 10 equiv). The vial was sealed and heated at 160 °C under stirring for 24 hours. 2 Parallel reactions were conducted. After cooled to room temperature, the reactions were combined, filtered through a short plug of Celite, concentrated *in vacuo*, and further purified by flash column chromatography over silica (hexane/ethyl acetate, 10:1) to furnished **141** as a colorless oil (25 mg, 58% yield). R_f = 0.55 (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, CDCl$_3$) δ 8.28 (d, *J* = 5.1 Hz, 1H), 7.68 – 7.61 (m, 1H), 7.11 (t, *J* = 7.9 Hz, 1H), 7.00 (dt, *J* = 5.2, 1.1 Hz, 1H), 6.80 (dt, *J* = 7.6, 0.9 Hz, 1H), 5.92 (s, 1H), 4.11 – 3.95 (m, 1H), 3.95 – 3.80 (m, 1H), 3.65 (t, *J* = 9.6 Hz, 1H), 3.08 (q, *J* = 7.4 Hz, 2H), 3.00 (dd, *J* = 14.7, 3.6 Hz, 1H), 2.72 (dd, *J* = 14.7, 10.1 Hz, 1H), 2.42 (s, 3H), 2.36 (s, 3H), 1.52 (s, 9H), 1.22 (t, *J* = 7.5 Hz, 3H). ^{13}C NMR (101 MHz, CDCl$_3$) carbon signals were found at δ 153.79, 151.29, 149.83, 148.00, 147.39, 128.09, 124.01, 122.43, 117.30, 112.49, 106.39, 53.18, 32.83, 28.61, 21.41, 21.34, 18.54, 13.26. IR (KBr) 2973, 2932, 1701, 1607, 1474, 1466, 1387, 1170, 1144 cm^{-1}. HRMS: calcd. 433.2598 [M+H]$^+$ Found: 433.2603.

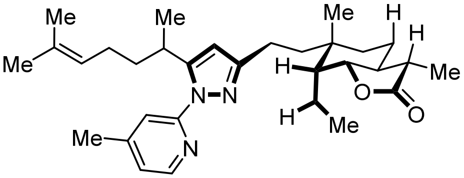


An 4 mL vial was charged with the hydrazone **142'** (107 mg, 0.3 mmol, 1.0 equiv) that was derived from its corresponding ketone following *General procedure for hydrazones formation (vide supra, 95% yield)*, [Ir(cod)$_2$]BArF (38 mg, 0.03 mmol, 0.1 equiv), **L1** (12.0 mg, 0.03 mmol, 0.1 equiv) and 1,4-dioxane (0.1 mL). The vial was transferred into the glove box and charged with myrcene (72 µL, 1.4 equiv). The vial was sealed and heated at 170 °C under stirring for 48 hours. Additional 5 mol% of [Ir(cod)$_2$]BArF (19 mg) and **L1** (6 mg), together with 0.7 equiv of myrcene (36 µL) and 3Å MS (50 mg), was added to the reaction in a glovebox. The resulting mixture was further heated at 170 °C for 12 hours. The reaction was then filtered through a short plug of Celite, concentrated *in vacuo*, and purified by flash column chromatography over silica (hexane/ethyl acetate) to furnished **143a** and **143b** (24.5 mg combined, 17% yield).



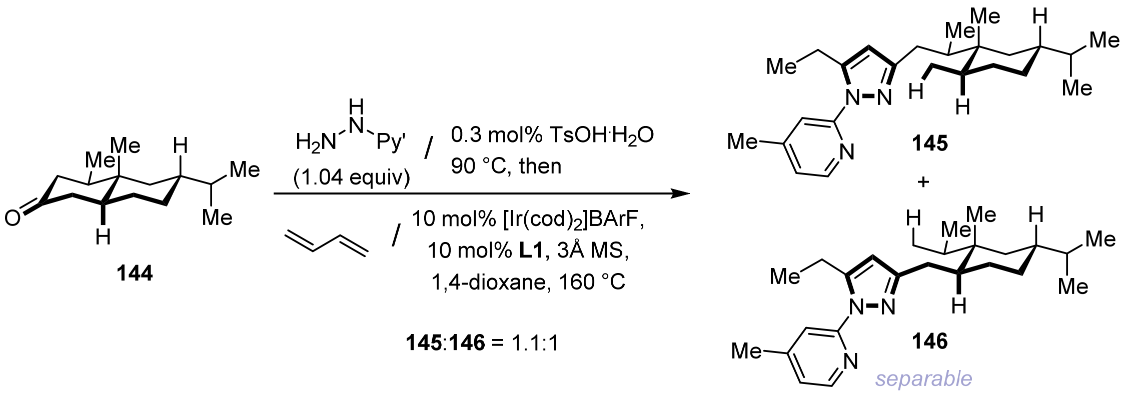
143a

143a: colorless oil (16.5 mg, 11.5% yield). R_f = 0.3 (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, CDCl$_3$) δ 8.28 (d, *J* = 5.1 Hz, 1H), 7.56 (d, *J* = 1.4 Hz, 1H), 7.00 (dd, *J* = 5.0, 1.4 Hz, 1H), 6.04 (s, 1H), 5.02 (t, *J* = 6.2 Hz, 1H), 3.83 (t, *J* = 10.5 Hz, 1H), 3.80 – 3.72 (m, 1H), 2.74 – 2.53 (m, 2H), 2.41 (s, 3H), 2.34 – 2.18 (m, 1H), 1.94 (q, *J* = 7.4 Hz, 2H), 1.84 (dq, *J* = 12.3, 3.1 Hz, 1H), 1.75 (p, *J* = 7.9 Hz, 2H), 1.71 – 1.55 (m, 8H), 1.51 – 1.32 (m, 7H), 1.27 – 1.20 (m, 6H), 1.07 (t, *J* = 7.4 Hz, 3H), 0.93 (s, 3H). ^{13}C NMR (101 MHz, CDCl$_3$) carbon signals were found at δ 180.01, 154.16, 153.80, 152.06, 149.82, 147.51, 131.64, 124.36, 122.62, 118.06, 103.82, 86.44, 52.36, 49.43, 41.47, 41.44, 39.10, 37.40, 37.38, 37.33, 30.70, 25.92, 25.82, 23.80, 22.60, 21.56, 21.29, 20.59, 20.58, 20.11, 17.68, 14.69, 12.66. IR (KBr) 3056, 2965, 2932, 2878, 1778, 1607, 1569, 1472, 1458, 1417, 1379, 1121, 1073 cm^{-1}. HRMS: calcd. 492.3585 $[M+H]^+$ Found: 492.3594.



143b

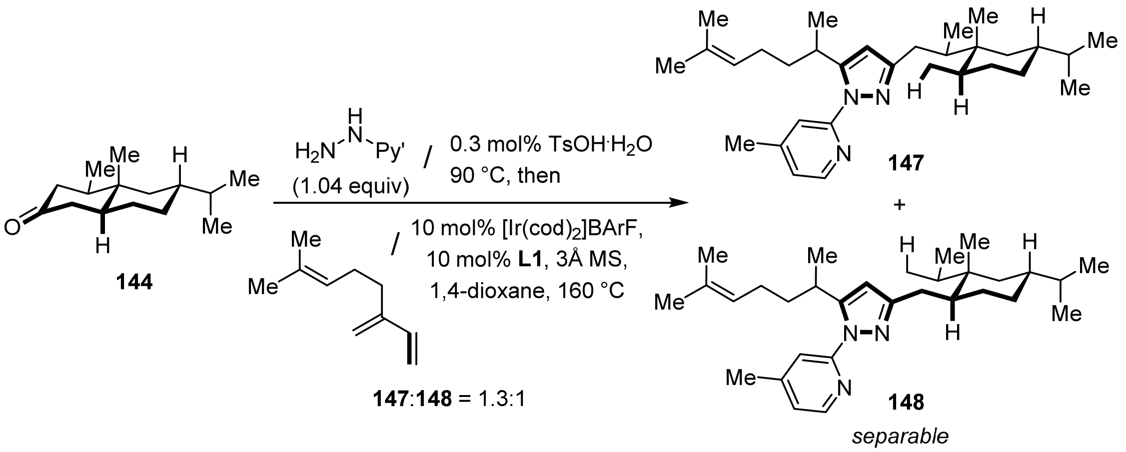
143b: colorless oil (8 mg, 5.5% yield). R_f = 0.27 (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, CDCl$_3$) δ 8.28 (d, *J* = 5.1 Hz, 1H), 7.56 (s, 1H), 7.06 – 6.94 (m, 1H), 6.04 (s, 1H), 5.03 (dddd, *J* = 8.7, 7.2, 3.7, 2.3 Hz, 1H), 4.29 (dd, *J* = 11.1, 4.6 Hz, 1H), 3.79 (h, *J* = 6.9 Hz, 1H), 2.74 – 2.59 (m, 2H), 2.41 (s, 3H), 2.25 (dq, *J* = 11.9, 6.9 Hz, 1H), 1.98 – 1.86 (m, 3H), 1.86 – 1.61 (m, 8H), 1.53 – 1.37 (m, 9H), 1.27 – 1.21 (m, 6H), 1.15 (s, 3H), 1.03 (t, *J* = 7.5 Hz, 3H). ^{13}C NMR (101 MHz, CDCl$_3$) δ 179.73, 154.12, 153.85, 152.03, 149.82, 147.50, 131.65, 124.38, 122.61, 118.06, 103.76, 83.38, 45.88, 45.18, 41.83, 41.28, 38.50, 37.38, 33.74, 30.72, 25.93, 25.83, 24.14, 24.10, 22.41, 21.30, 20.59, 17.68, 17.26, 15.58, 12.68. IR (KBr) 2963, 2936, 2878, 1780, 1609, 1567, 1474, 1462, 1415, 1381, 1239, 1170, 1008 cm^{-1}. HRMS: calcd. 492.3585 $[M+H]^+$ Found: 492.3590.



Following **General procedure C2,** the reaction was conducted at 0.05 mmol scale with 11.1 mg **144** and 120 µL 1,3-butadiene (in PhMe, 20 wt.%). Two parallel reactions were conducted (0.05 mmol for each, 0.1 mmol in total) and combined, yielding pyrazoles **145** and **146** in 1.1:1 ratio after isolation. The characterization data for **145** and **146** are listed as follows:

145 was isolated as a colorless oil (11.2 mg, 30% yield). R_f = 0.3 (hexane/ethyl acetate = 10:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.26 (dd, *J* = 5.1, 0.7 Hz, 1H), 7.65 (t, *J* = 0.8 Hz, 1H), 6.96 (ddd, *J* = 5.1, 1.6, 0.8 Hz, 1H), 6.03 (s, 1H), 3.11 (qd, *J* = 7.5, 0.8 Hz, 2H), 2.80 (dd, *J* = 13.9, 2.5 Hz, 1H), 2.40 (s, 3H), 2.32 (dd, *J* = 13.9, 11.7 Hz, 1H), 1.86 (dqd, *J* = 11.6, 6.8, 2.5 Hz, 1H), 1.65 (dp, *J* = 12.4, 3.2 Hz, 1H), 1.55 – 1.43 (m, 2H), 1.39 – 1.19 (m, 7H), 1.01 – 0.87 (m, 5H), 0.87 – 0.80 (m, 9H), 0.77 (d, *J* = 6.7 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 155.05, 153.91, 149.71, 147.88, 147.32, 122.13, 117.13, 105.84, 41.54, 38.88, 38.28, 36.05, 34.78, 33.37, 31.46, 30.28, 29.89, 21.56, 21.29, 20.15, 19.80, 18.76, 15.40, 13.26, 12.75. IR (KBr) 2969, 2934, 2876, 1607, 1573, 1472, 1423, 1362, 1004 cm^{-1}. HRMS: calcd. 382.3217 $[M+H]^+$ Found: 382.3217.

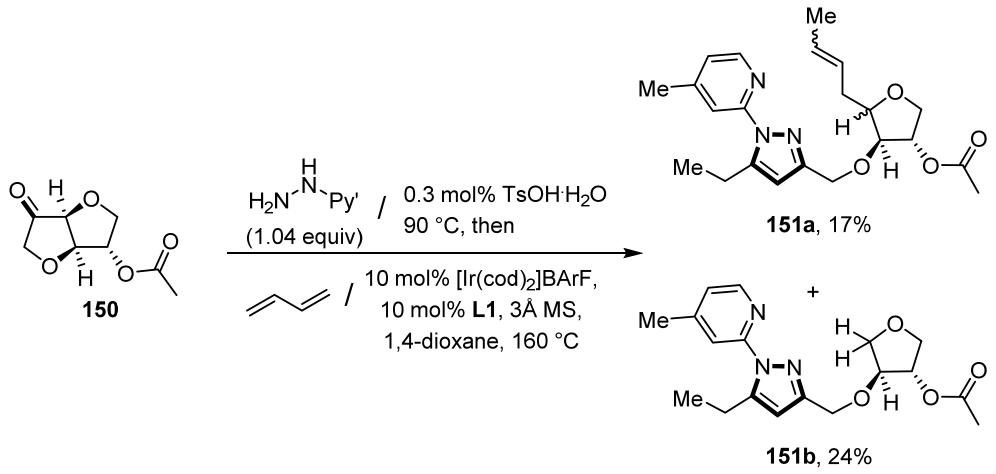
146 was isolated as a colorless oil (10.4 mg, 27% yield). The titled compound was isolated as a colorless oil (10.4 mg, 27% yield). R_f = 0.26 (hexane/ethyl acetate = 10:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.37 – 8.19 (m, 1H), 7.66 – 7.55 (m, 1H), 6.96 (ddd, *J* = 5.1, 1.6, 0.8 Hz, 1H), 6.00 (s, 1H), 3.10 (qd, *J* = 7.5, 0.9 Hz, 2H), 2.81 (dd, *J* = 14.1, 2.5 Hz, 1H), 2.39 (s, 3H), 2.13 (dd, *J* = 14.1, 11.4 Hz, 1H), 1.90 (p, *J* = 6.9 Hz, 1H), 1.69 (tt, *J* = 11.7, 3.0 Hz, 1H), 1.64 – 1.58 (m, 2H), 1.39 – 1.16 (m, 7H), 0.96 (d, *J* = 6.8 Hz, 3H), 0.93 – 0.87 (m, 6H), 0.87 – 0.72 (m, 8H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 154.39, 153.90, 149.69, 147.86, 147.30, 122.12, 117.12, 105.77, 41.89, 38.75, 37.97, 34.71, 34.04, 33.35, 29.55, 28.32, 27.62, 21.54, 21.30, 20.21, 19.72, 19.08, 17.42, 16.56, 13.27. IR (KBr) 2957, 2930, 2872, 1609, 1567, 1476, 1419, 1362 cm^{-1}. HRMS: calcd. 382.3217 $[M+H]^+$ Found: 382.3227.



Following **General procedure C1,** the reaction was conducted at 0.3 mmol scale with 67 mg **144** and 78 µL myrcene (1.5 equiv) in 0.1 ml 1,4-dioxane. Pyrazoles **147** and **148** were isolated in 1.3:1 ratio. The characterization data for **147** and **148** are listed as follows:

147: colorless oil (32 mg, 23% yield, inseparable mixture of diastereomers). R_f = 0.8 (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.27 (d, *J* = 5.1 Hz, 1H), 7.59 (s, 1H), 6.98 (dd, *J* = 5.2, 1.4 Hz, 1H), 6.03 (d, *J* = 1.9 Hz, 1H), 5.03 (ddddd, *J* = 14.5, 7.1, 5.7, 2.9, 1.5 Hz, 1H), 3.83 (h, *J* = 6.9 Hz, 1H), 2.80 (d, *J* = 14.0 Hz, 1H), 2.40 (s, 3H), 2.38 – 2.27 (m, 1H), 2.01 – 1.82 (m, 3H), 1.72 – 1.55 (m, 6H), 1.56 – 1.45 (m, 5H), 1.39 – 1.16 (m, 7H), 0.99 – 0.88 (m, 5H), 0.87 – 0.73 (m, 12H). ^{13}C NMR (101 MHz, $CDCl_3$) carbon signals were found at δ 154.97, 154.94, 153.99, 151.93, 151.86, 149.70, 149.68, 147.35, 131.55, 124.47, 124.44, 122.37, 122.35, 118.03, 117.99, 104.28, 104.10, 41.50, 38.86, 38.26, 37.45, 37.37, 36.04, 34.77, 33.36, 31.45, 30.78, 30.71, 30.29, 30.24, 29.88, 25.98, 25.88, 25.83, 25.82, 21.27, 20.72, 20.53, 20.14, 19.79, 18.75, 17.66, 17.62, 15.41, 15.39, 12.75, 12.69. IR (KBr) 3062, 2963, 2924, 2872, 1607, 1573, 1470, 1419, 1376, 1010 cm^{-1}. HRMS: calcd. 464.3999 $[M+H]^+$ Found: 464.3994.

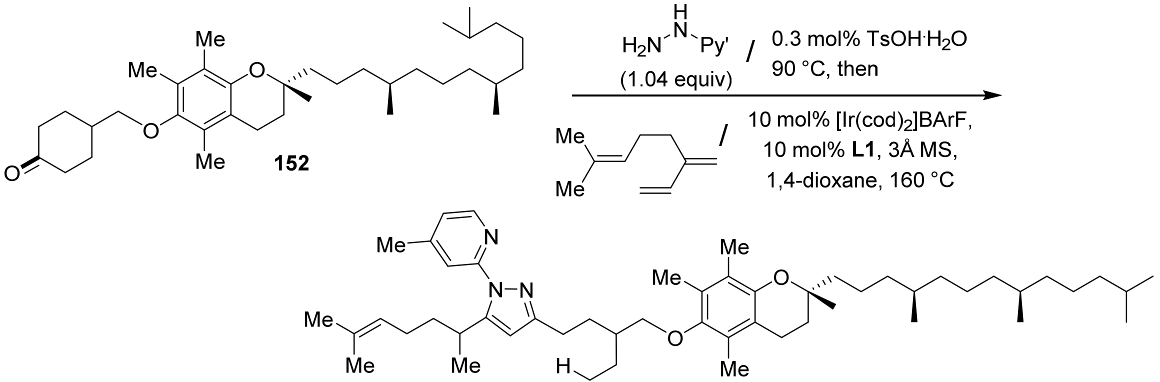
148: colorless oil (24.5 mg, 18% yield). R_f = 0.7 (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.27 (dd, *J* = 5.1, 0.7 Hz, 1H), 7.64 – 7.51 (m, 1H), 6.98 (ddd, *J* = 5.1, 1.6, 0.8 Hz, 1H), 5.99 (s, 1H), 5.05 (ddt, *J* = 8.6, 5.8, 1.4 Hz, 1H), 3.82 (h, *J* = 6.9 Hz, 1H), 2.80 (dd, *J* = 14.2, 2.6 Hz, 1H), 2.40 (s, 3H), 2.14 (dd, *J* = 14.1, 11.5 Hz, 1H), 2.03 – 1.85 (m, 3H), 1.74 – 1.54 (m, 8H), 1.50 – 1.42 (m, 3H), 1.38 – 1.17 (m, 7H), 0.95 (d, *J* = 6.9 Hz, 3H), 0.93 – 0.86 (m, 7H), 0.86 – 0.71 (m, 7H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 154.32, 153.98, 151.93, 149.69, 147.35, 131.57, 124.48, 122.36, 118.01, 103.99, 41.89, 38.74, 37.97, 37.34, 34.71, 34.06, 33.35, 30.78, 29.57, 28.32, 27.59, 25.99, 25.84, 21.29, 20.73, 20.21, 19.71, 19.10, 17.63, 17.41, 16.57. IR (KBr) 3062, 2967, 2932, 2873, 1607, 1569, 1470, 1415, 1376, 1013 cm^{-1}. HRMS: calcd. 464.3999 $[M+H]^+$ Found: 464.4004.



Following **General procedure C2,** the reaction was conducted at 0.05 mmol scale with 9.3 mg **150** and 120 μL 1,3-butadiene (in PhMe, 20 wt.%). Two parallel reactions were conducted (0.05 mmol for each, 0.1 mmol in total) and combined, yielding pyrazoles **151a** and **151b** in 41% yield combined. The characterization data for **151a** and **151b** are listed as follows:

151a: colorless oil (6.8 mg, 17% yield, inseparable mixture of diasteroermers). R_f = 0.25 (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.28 (d, *J* = 5.0 Hz, 1H), 7.64 (s, 1H), 7.01 (d, *J* = 4.9 Hz, 1H), 6.25 (s, 1H), 5.90 – 5.30 (m, 2H), 5.25 – 5.15 (m, 1H), 4.77 – 4.66 (m, 1H), 4.66 – 4.54 (m, 1H), 4.05 – 3.97 (m, 1H), 3.97 – 3.89 (m, 1H), 3.89 – 3.72 (m, 2H), 3.11 (q, *J* = 7.5 Hz, 2H), 2.50 – 2.28 (m, 5H), 2.12 – 2.02 (m, 3H), 1.70 – 1.60 (m, 3H), 1.26 (t, *J* = 7.5 Hz, 3H). ^{13}C NMR (101 MHz, $CDCl_3$) carbon signals were observed at δ 170.55, 153.66, 150.00, 149.91, 148.48, 147.45, 128.13, 126.70, 125.52, 122.73, 117.33, 106.22, 87.03, 86.93, 83.84, 78.86, 71.93, 66.39, 36.59, 21.48, 21.31, 21.21, 18.20, 13.16, 13.12. R (KBr) 2973, 2926, 2874, 1741, 1609, 1569, 1421, 1372, 1241, 1099 cm^{-1}. HRMS: calcd. 400.2231 $[M+H]^+$ Found: 400.2238.

151b: The titled compound was isolated as a colorless oil (8.2 mg, 24% yield). R_f = 0.15 (hexane/ethyl acetate = 3:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.29 (d, *J* = 5.1 Hz, 1H), 7.63 (s, 1H), 7.11 – 6.92 (m, 1H), 6.26 (s, 1H), 5.25 (d, *J* = 4.3 Hz, 1H), 4.71 (d, *J* = 11.9 Hz, 1H), 4.61 (d, *J* = 11.9 Hz, 1H), 4.16 (dd, *J* = 4.8, 2.3 Hz, 1H), 4.06 (ddd, *J* = 14.1, 10.3, 4.7 Hz, 2H), 3.87 – 3.77 (m, 2H), 3.10 (qd, *J* = 7.5, 0.9 Hz, 2H), 2.41 (s, 3H), 2.07 (s, 3H), 1.25 (t, *J* = 7.5 Hz, 4H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 170.28, 153.48, 149.82, 149.78, 148.38, 147.33, 122.65, 117.28, 106.11, 82.59, 77.55, 72.00, 71.77, 65.78, 21.30, 21.17, 21.05, 13.02. R (KBr) 2977, 2936, 2874, 1739, 1609, 1423, 1239, 1090 cm^{-1}.



152

153, 67%

Following **General procedure C1,** the reaction was conducted at 0.3 mmol scale with 162.3 mg **152** and 78 μL myrcene (1.5 equiv). **153** was isolated as a colorless oil (156.1 mg, 67% yield, inseparable mixture of diastereomers). R_f = 0.7 (hexane/ethyl acetate = 5:1). ^{1}H NMR (400 MHz, CDCl$_3$) δ 8.28 (d, *J* = 5.0 Hz, 1H), 7.60 (s, 1H), 7.05 – 6.93 (m, 1H), 6.09 (d, *J* = 1.6 Hz, 1H), 5.03 (t, *J* = 6.7 Hz, 1H), 3.84 (h, *J* = 7.5, 7.0 Hz, 1H), 3.60 (d, *J* = 4.4 Hz, 2H), 2.76 (td, *J* = 8.0, 1.8 Hz, 2H), 2.57 (t, *J* = 6.8 Hz, 2H), 2.40 (s, 3H), 2.19 (s, 3H), 2.14 (s, 3H), 2.09 (s, 3H), 2.00 – 1.51 (m, 17H), 1.48 – 0.95 (m, 30H), 0.90 – 0.82 (m, 12H). ^{13}C NMR (101 MHz, CDCl$_3$) carbon signals were found at δ 154.35, 153.99, 151.91, 149.70, 148.47, 147.74, 147.39, 131.56, 128.00, 125.96, 124.45, 122.93, 122.41, 117.92, 117.63, 104.06, 75.52, 75.50, 74.85, 40.60, 40.58, 40.16, 39.52, 37.63, 37.60, 37.57, 37.43, 37.39, 32.95, 32.85, 31.50, 30.74, 30.67, 30.64, 28.13, 26.22, 25.92, 25.83, 24.95, 24.59, 24.03, 23.85, 22.88, 22.78, 21.28, 21.18, 20.83, 20.61, 19.91, 19.81, 17.68, 12.91, 12.05, 11.94, 11.37. IR (KBr) 2953, 2922, 2868, 1607, 1569, 1466, 1415, 1374, 1259, 1089 cm^{-1}. HRMS: calcd. 782.6558 $[M+H]^+$ Found: 782.6578.

4. References

1. Bhattacharya, S.; De, S.; Subramanian, M. *J. Org. Chem.* **1998**, *63*, 7640–7651.
2. Xu, Y.; Young, M. C.; Dong, G. *J. Am. Chem. Soc.* **2017**, *139*, 5716–5719.
3. Kazankova, M. A.; Shulyupin, M. O.; Chirkov, E. A.; Beletskaya, I. P. *Synlett* **2005**, 658–660.
4. Mei, T.-S.; Patel, H. H.; Sigman, M. S. *Nature* **2014**, *508*, 340–344.
5. Franco, L. L.; Almeida, M. V. D.; Silva, L. F. R. E.; Vieira, P. P. R.; Pohlit, A. M.; Valle, M. S. *Chem. Biol. Drug Des.* **2012**, *79*, 790–797.
6. Shingate, B. B.; Hazra, B. G.; Pore, V. S.; Gonnade, R. G.; Bhadbhade, M. M. *Tetrahedron* **2007**, *63*, 5622–5635.
7. Soulard, V.; Villa, G.; Vollmar, D. P.; Renaud, P. *J. Am. Chem. Soc.* **2018**, *140*, 155–158.
8. Enholm, E. J.; Kinter, K. S. *J. Org. Chem.* **1995**, *60*, 4850–4855.
9. Chakraborty, A.; Kar, G. K.; Ray, J. K. *Tetrahedron* **1997**, *53*, 8513–8518.
10. Cleary, L.; Yoo, H.; Shea, K. J. *Org. Lett.* **2011**, *13*, 1781–1783.
11. Kavanagh, Y.; Chaney Cíara M.; Muldoon, J.; Evans, P. *J. Org. Chem.* **2008**, *73*, 8601–8604.
12. Wu, J. Y.; Moreau Benoît; Ritter, T. *J. Am. Chem. Soc.* **2009**, *131*, 12915–12917.
13. Tokic-Vujosevic, Z.; Čekovic, Z. *Heterocycl. Commun.* **2001**, *7*, 43–48.

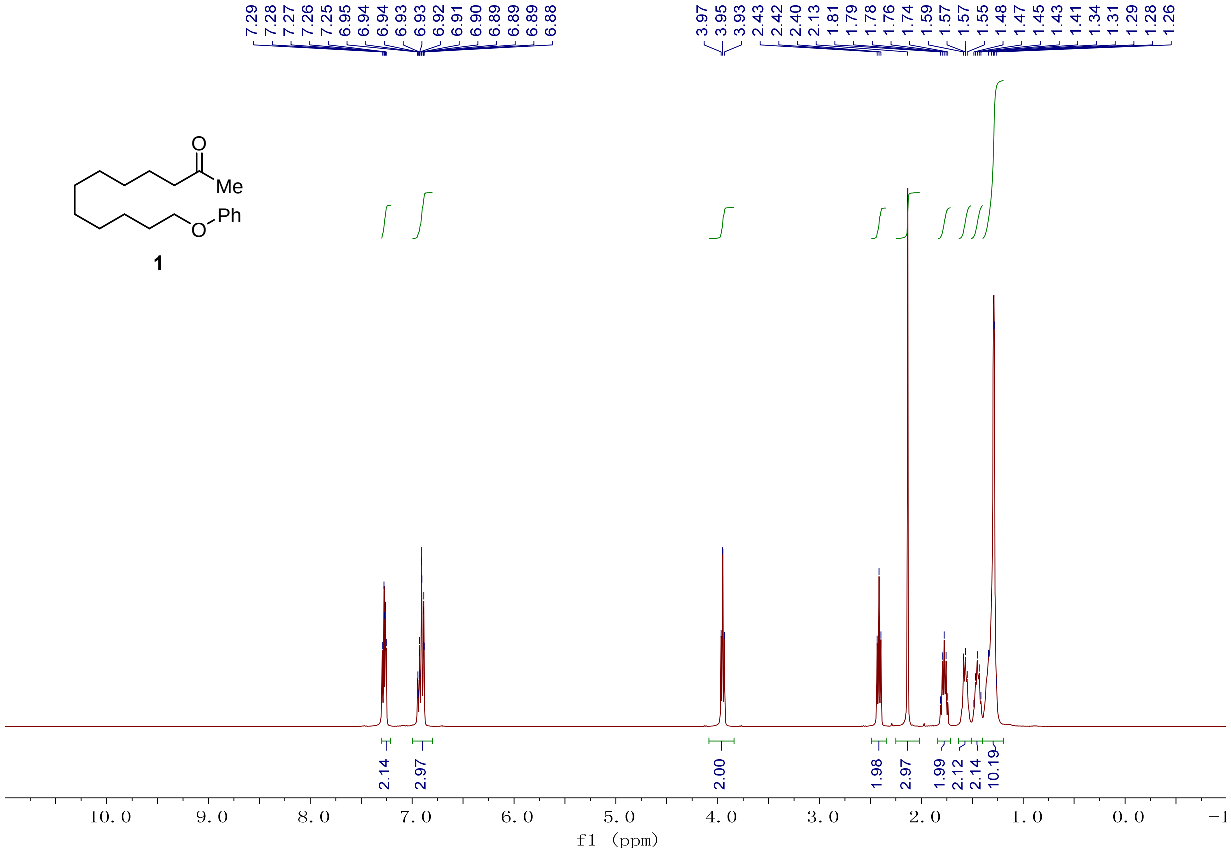
14. Taylor, E. C.; Wang, Y. *Heterocycles* **1998**, *48*, 1537–1554.
15. Kerr, W. J.; Mudd, R. J.; Paterson, L. C.; Brown, J. A. *Chem. Eur. J* **2014**, *20*, 14604–14607.
16. Huang, Z.; Sam, Q. P.; Dong, G. *Chem. Sci.* **2015**, *6*, 5491–5498.
17. Doucet, H.; Santelli, M.; Berthiol, F. *Synthesis* **2005**, 3589–3602.
18. Fukuda, M.; Ohkoshi, E.; Makino, M.; Fujimoto, Y. *Chem. Pharm. Bull.* **2006**, *54*, 1465–1468.
19. Silva, R. M.; Okano, L.T.; Rodrigues, J. A. R.; Clososki, G. C. *Tetrahedron: Asymmetry*, **2017**, 28, 939 – 944.
20. (a) Berthiol, F.; Doucet, H.; Santelli, M. *Tetrahedron* **2006**, 62, 4372–4383. (b) Ohno, H.; Wakayama, R.; Maeda, S.-I.; Iwasaki, H.; Okumura, M.; Iwata, C.; Mikamiyama, H.; Tanaka, T. *J. Org. Chem.* **2003**, *68*, 5909–5916.
21. Hangeland, J. J.; Abell, L. M.; Adam, L. P.; Jiang, J.; Friends, T. J.; Haque, L. E.; Neels, J.; Onorato, J. M.; Chen, A. Y. A.; Taylor, D. S.; Yin, X.; Harrity, T. W.; Basso, M. D.; Yang, R.; Sleph, P. G.; Gordon, D. A.; Huang, C. S.; Wexler, R. R.; Finlay, H. J.; Lawrence, R. M. *ACS Med. Chem. Lett.* **2018**, *9*, 673–678.
22. Arman, S. A. V.; Zimmet, A. J.; Murray, I. E. *J. Org. Chem.* **2016**, *81*, 3528–3532.
23. Saito, T.; Nishimoto, Y.; Yasuda, M.; Baba, A. *J. Org. Chem.* **2007**, *72*, 8588–8590.
24. Pfizer, limited; Jessica, B.; Edward, F. A.; Morris, G. D.; Frances, M. C. **Patent:** WO2008/44127 A1, **2008.**
25. Peng, C.-K.; Zeng, T.; Xu, X.-J.; Chang, Y.-Q.; Hou, W.; Lu, K.; Lin, H.; Sun, P.-H.; Lin, J.; Chen, W.-M. *Eur. J. Med. Chem.* **2017**, *127*, 187–199.
26. Zhou, M.; Ni, C.; He, Z.; Hu, J. *Org. Lett.* **2016**, *18*, 3754–3757.
27. Habrant, D.; Stengel, B.; Meunier, S.; Mioskowski, C. *Chem. Eur. J.* **2007**, *13*, 5433–5440.
28. Hioki, H.; Ooi, H.; Hamano, M.; Mimura, Y.; Yoshio, S.; Kodama, M.; Ohta, S.; Yanai, M.; Ikegami, S. *Tetrahedron* **2001**, *57*, 1235–1246.
29. Stevens, K.; Jurd, L.; Manners, G. *Tetrahedron* **1972**, *28*, 1939–1944.
30. Laine, R.; Sauer, A.; Crowe, W.; Henderson, G. *Synlett* **2010**, 445–448.
31. Yin, T. K.; Lee, J. G.; Borden, W. T. *The J. Org. Chem.* **1985**, *50*, 531–534.
32. Thangaraj, M.; Bhojgude, S. S.; Mane, M. V.; Biju, A. T. *Chem. Comm.*, **2016**, *52*, 1665–1668.
33. Cramer, N.; Seiser, T. *Synlett*, **2011**, 449–460.
34. Murakami, M.; Ishida, N. *J. Synth. Org. Chem. Jpn.* **2015**, *73*, 29–38.
35. Zhao, P.; Hartwig, J. F. *Organometallics* **2008**, *27,* 4749–4757.
36. Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Scalmani, G.; Barone, V.; Mennucci, B.; Petersson, G. A.; Nakatsuji, H.; Caricato, M.; Li, X.; Hratchian, H. P.; Izmaylov, A. F.; Bloino, J.; Zheng, G.; Sonnenberg, J. L.; Hada, M.; Ehara, M.; Toyota, K.; Fukuda, R.; Hasegawa, J.; Ishida, M.; Nakajima, T.; Honda, Y.; Kitao, O.; Nakai, H.; Vreven, T.; Montgomery, J. A., Jr.; ; Peralta, J. E.; Ogliaro, F.; Bearpark, M.; Heyd, J. J.; Brothers, E.; Kudin, K. N.; Staroverov, V. N.; Kobayashi, R.; Normand, J.; Raghavachari, K.; Rendell, A.; Burant, J. C.; Iyengar, S. S.; Tomasi, J.; Cossi, M.; Rega, N.; Millam, N. J.; Klene, M.; Knox, J. E.; Cross, J. B.; Bakken, V.; Adamo, C.; Jaramillo, J.; Gomperts, R.; Stratmann, R. E.; Yazyev, O.; Austin, A. J.; Cammi, R.; Pomelli, C.; Ochterski, J. W.; Martin, R. L.; Morokuma, K.; Zakrzewski, V. G.; Voth, G. A.; Salvador, P.; Dannenberg, J. J.; Dapprich, S.; Daniels, A.

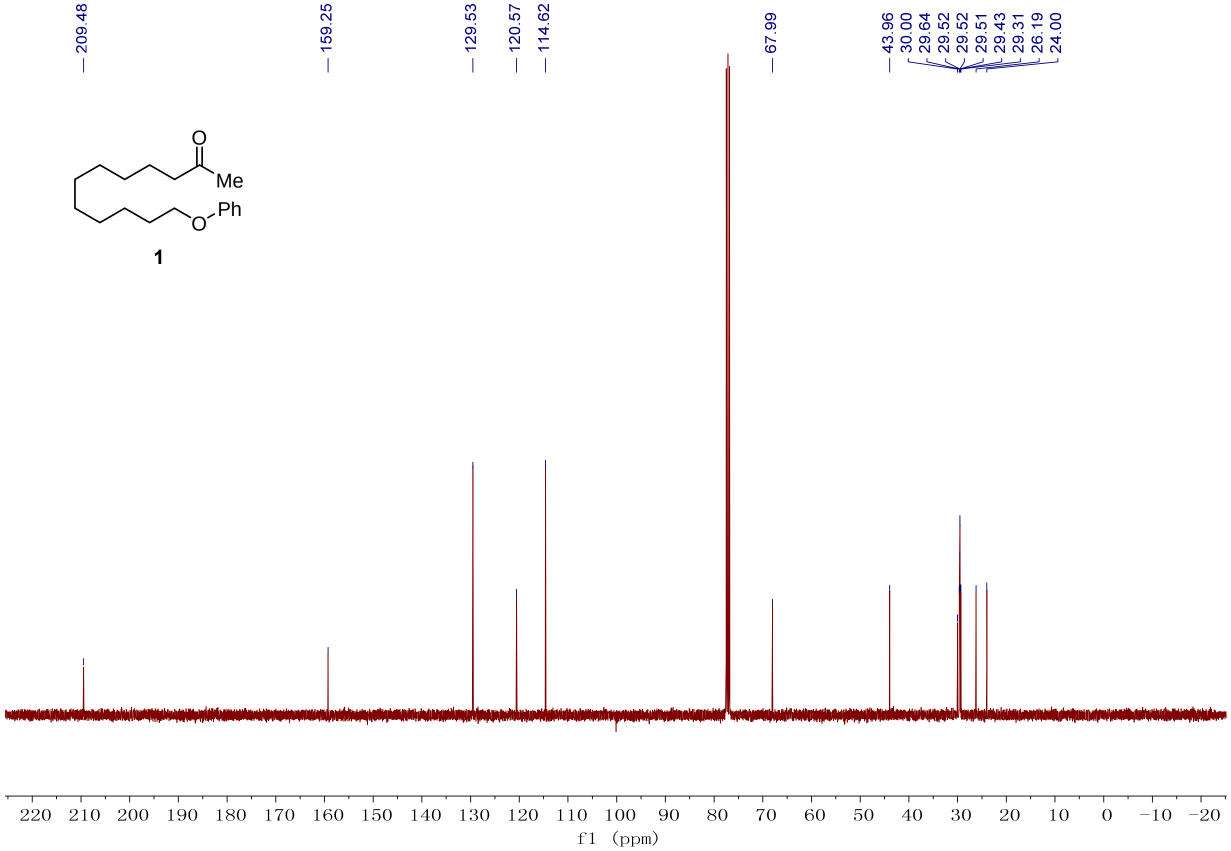
D.; Farkas, O.; Foresman, J. B.; Ortiz, J. V.; Cioslowski, J.; Fox, D. J., *Gaussian 09*, Revision D.01; Gaussian, Inc.: Wallingford, CT, 2013.

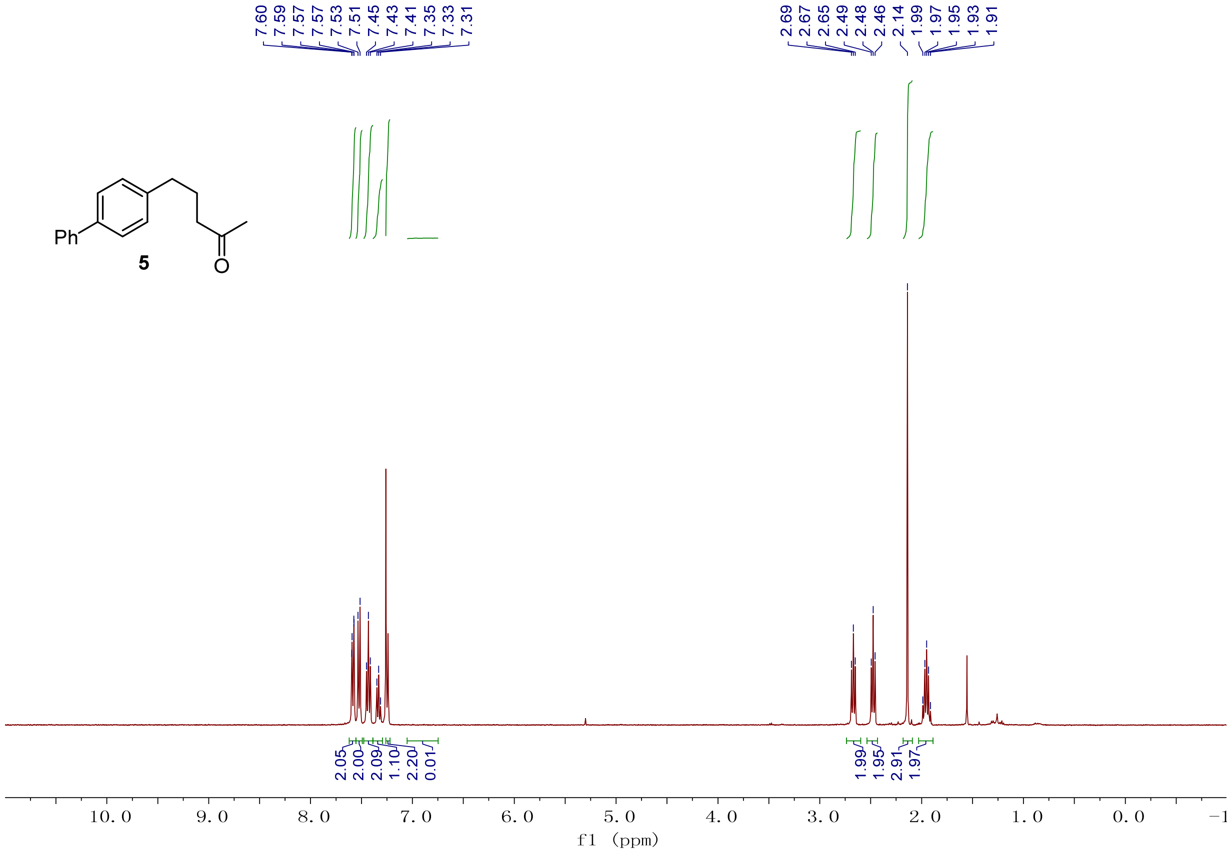
37. (a) Timokhin, V. I.; Stahl, S. S. *J. Am. Chem. Soc.* **2005**, *127*, 17888-17893; (b) Lee, C.; Yang, W.; Parr, R. G. *Physical Review B* **1988**, *37*, 785-789.
38. Dong, G.; Teo, P.; Wickens, Z. K.; Grubbs, R. H. *Science* **2011**, *333*, 1609-1612.
39. Campbell, A. N.; Stahl, S. S. *Acc. Chem. Res.* **2012**, *45*, 851-863.
40. (a) Reznichenko, A. L.; Hultzsch, K. C. *J. Am. Chem. Soc.* **2012**, *134*, 3300-3311; (b) Senn, H. M.; Blöchl, P. E.; Togni, A. *J. Am. Chem. Soc.* **2000**, *122*, 4098-4107.
41. (a) Teo, P.; Wickens, Z. K.; Dong, G.; Grubbs, R. H. *Org. Lett.* **2012**, *14*, 3237-3239; (b) Corminboeuf, C.; Heine, T.; Seifert, G.; Schleyer, P. v. R.; Weber, J. *Phys. Chem. Chem. Phys.* **2004**, *6*, 273-276; (c) Lu, G.; Liu, R. Y.; Yang, Y.; Fang, C.; Lambrecht, D. S.; Buchwald, S. L.; Liu, P. *J. Am. Chem. Soc.* **2017**, *139*, 16548-16555.
42. Yin, G.; Mu, X.; Liu, G. *Acc. Chem. Res.* **2016**, *49*, 2413-2423.
43. Kočovský, P.; Bäckvall, J.-E. *Chem.-Eur. J.* **2015**, *21*, 36-56.
44. Beller, M.; Seayad, J.; Tillack, A.; Jiao, H. *Angew. Chem. Int. Ed.* **2004**, *43*, 3368-3398.
45. (a) Ryu, J. S.; Marks, T. J.; McDonald, F. E. *J. Org. Chem.* **2004**, *69*, 1038-1052; (b) Ahlquist, M. S.; Norrby, P. O. *Angew. Chem. Int. Ed.* **2011**, *50*, 11794-11797.
46. (a) Bickelhaupt, F. M.; Houk, K. N. *Angew. Chem. Int. Ed.* **2017**, *56*, 10070-10086; (b) Couzijn, E. P.; Slootweg, J. C.; Ehlers, A. W.; Lammertsma, K. *J. Am. Chem. Soc.* **2010**, *132*, 18127-18140; (c) Utsunomiya, M.; Kuwano, R.; Kawatsura, M.; Hartwig, J. F. *J. Am. Chem. Soc.* **2003**, *125*, 5608-5609.
47. (a) Goldfogel, M. J.; Roberts, C. C.; Meek, S. J. *J. Am. Chem. Soc.* **2014**, *136*, 6227-6230; (b) Lee, J. M.; Ahn, D. S.; Jung, D. Y.; Lee, J.; Do, Y.; Kim, S. K.; Chang, S. *J. Am. Chem. Soc.* **2006**, *128*, 12954-12962.
48. (a) Johnson, E. R.; Keinan, S.; Mori-Sanchez, P.; Contreras-Garcia, J.; Cohen, A. J.; Yang, W. *J. Am. Chem. Soc.* **2010**, *132*, 6498-6506; (b) Wagner, J. P.; Schreiner, P. R. *Angew. Chem. Int. Ed.* **2015**, *54*, 12274-12296.
49. Bäckvall, J.-E.; Bjoerkman, E. E.; Pettersson, L.; Siegbahn, P. *J. Am. Chem. Soc.* **1985**, *107*, 7265-7267.
50. Yin, G.; Wu, Y.; Liu, G. *J. Am. Chem. Soc.* **2010**, *132*, 11978-11987.
51. (a) Fernandez, I.; Bickelhaupt, F. M. *Chem. Soc. Rev.* **2014**, *43*, 4953-4967; (b) Fernández, I. *Phys. Chem. Chem. Phys.* **2014**, *16*, 7662-7671; (c) Liu, S.; Lei, Y.; Qi, X.; Lan, Y. *J. Phys. Chem. A* **2014**, *118*, 2638-2645; (d) Levandowski, B. J.; Hamlin, T. A.; Bickelhaupt, F. M.; Houk, K. N. *J. Org. Chem.* **2017**, *82*, 8668-8675.
52. Bäckvall, J.-E.; Bjoerkman, E. E.; Pettersson, L.; Siegbahn, P. *J. Am. Chem. Soc.* **1984**, *106*, 4369-4373.
53. (a) Yang, X. H.; Lu, A.; Dong, V. M. *J. Am. Chem. Soc.* **2017**, *139*, 14049-14052; (b) Grimme, S.; Ehrlich, S.; Goerigk, L. *J. Comput. Chem.* **2011**, *32*, 1456-1465.
54. McDonald, R. I.; Liu, G.; Stahl, S. S. *Chem. Rev.* **2011**, *111*, 2981-3019.
55. Baker, R.; Halliday, D. E. *Tetrahedron Lett.* **1972**, *13*, 2773-2776.
56. Jiang, M.; Liu, L. P.; Shi, M.; Li, Y. *Org. Lett.*, **2010**, *12*, 116–119.
57. Zheng, X.; Yang, L.; Du, W.; Ding, A.; Guo, H. *Chem. Asian J.* **2014**, *9*, 439–442.

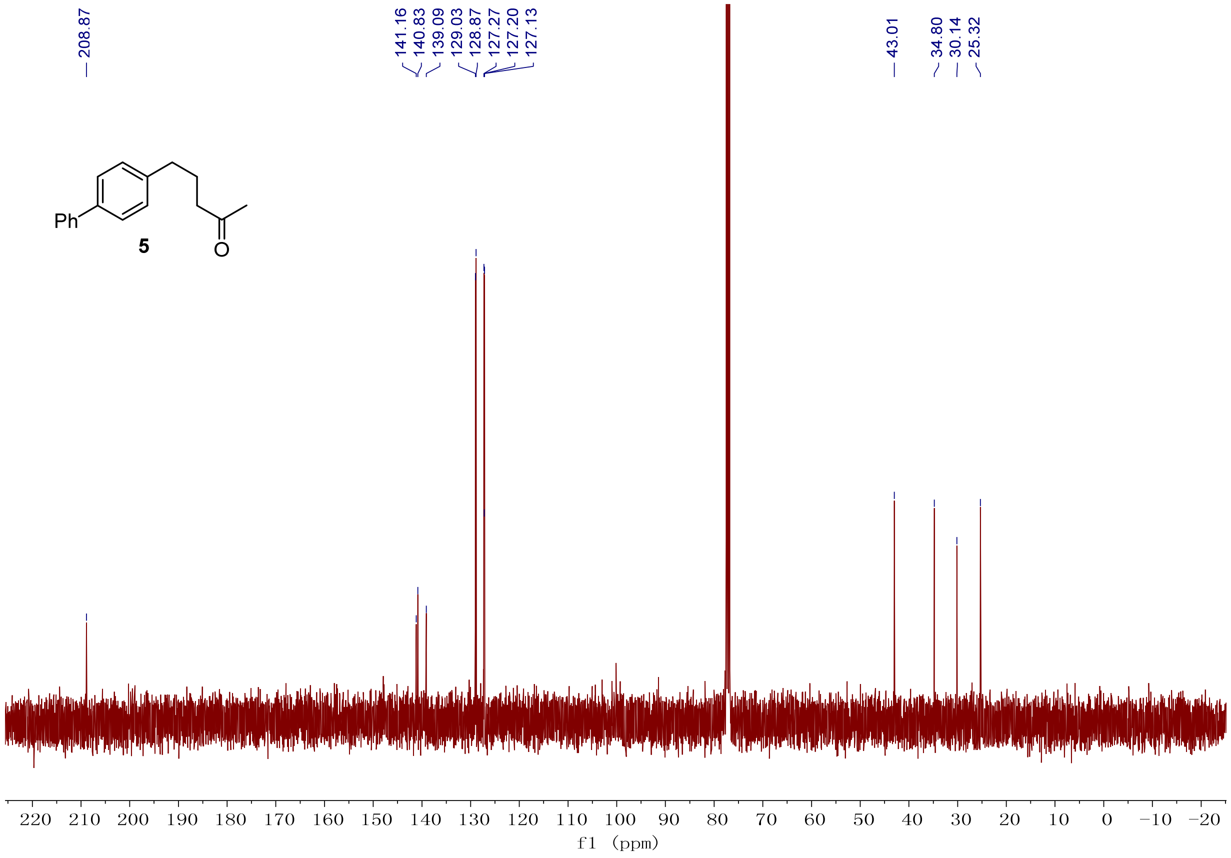
58. Toriyama, F.; Cornella, J.; Wimmer, L.; Chen, T.-G.; Dixon, D. D.; Creech, G.; Baran, P. S. *J. Am. Chem. Soc.* **2016**, *138*, 11132–11135.
59. Imamura, Y.; Higuchi, T.; Otagiri, M.; Nagumo, S.; Akita, H. *Bioorg. Chem.* **1994**, *22* (4), 387–394.
60. Iwasaki, T.; Imanishi, R.; Shimizu, R.; Kuniyasu, H.; Terao, J.; Kambe, N. *J. Org. Chem.* **2014**, *79*, 8522–8532.
61. Tran, P. H.; Hansen, P. E.; Pham, T. T.; Huynh, V. T.; Huynh, V. H.; Tran, T. D. T.; Huynh, T. V.; Le, T. N. *Synth. Commun.* **2014**, *44*, 2921–2929.
62. Ketcha, D. M.; Gribble, G. W. *J. Org. Chem.* **1985**, *50*, 5451–5457.
63. Larsen, A. T.; May, E. M.; Auclair, K. *J. Am. Chem. Soc.* **2011**, *133*, 7853–7858.
64. Saito, K.; Kondo, K.; Akiyama, T. *Org. Lett.* **2015**, *17*, 3366–3369.
65. Ando, S.; Mawatari, M.; Matsunaga, H.; Ishizuka, T. *Tetrahedron Lett.* **2016**, *57*, 3287–3290.
66. Bailey, C. L.; Joh, A. Y.; Hurley, Z. Q.; Anderson, C. L.; Singaram, B. *J. Org. Chem.* **2016**, *81*, 3619–3628.
67. Sumitomo Chemical Company, Limited; Mitsudera, Hi.; Awasaguchi, K.; Awano, T.; Ujihara, K. **Patent:** EP2952096 A1, **2015.**
68. Ohno, H.; Okumura, M.; Maeda, S.-I.; Iwasaki, H.; Wakayama, R.; Tanaka, T. *J. Org. Chem.* **2003**, *68*, 7722–7732.
69. Alexakis, A.; Albrow, V.; Biswas, K.; Daugustin, M.; Prieto, O.; Woodward, S. *Chem. Commun*., **2005**, 2843-2845.
70. Du Pont De Nemours and Company, **Patent**: WO2007/14290 A2, **2007.**

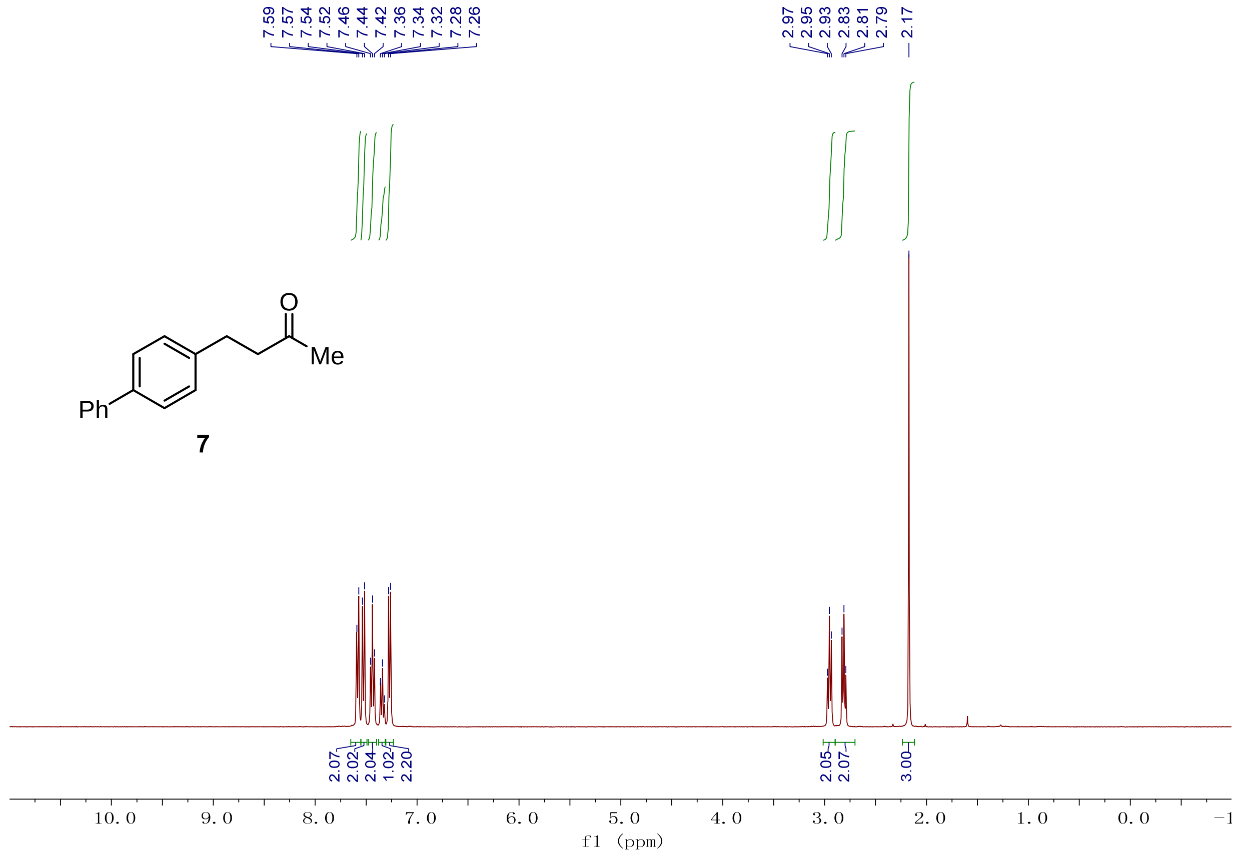
5. Spectra


7.29
7.28
7.27
7.26
7.25
6.95
6.94
6.94
6.93
6.93
6.92
6.91
6.90
6.89
6.89
6.89
6.88
3.97
3.95
3.93
2.43
2.42
2.40
2.13
1.81
1.79
1.78
1.76
1.74
1.59
1.57
1.57
1.55
1.48
1.47
1.45
1.43
1.41
1.34
1.31
1.29
1.28
1.26
O
Me
O
Ph
1
2.14
2.97
2.00
1.98
2.97
1.99
2.12
2.14
10.19
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)


209.48
159.25
129.53
120.57
114.62
67.99
43.96
30.00
29.64
29.52
29.52
29.51
29.43
29.31
26.19
24.00
O
Me
O
Ph
1
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

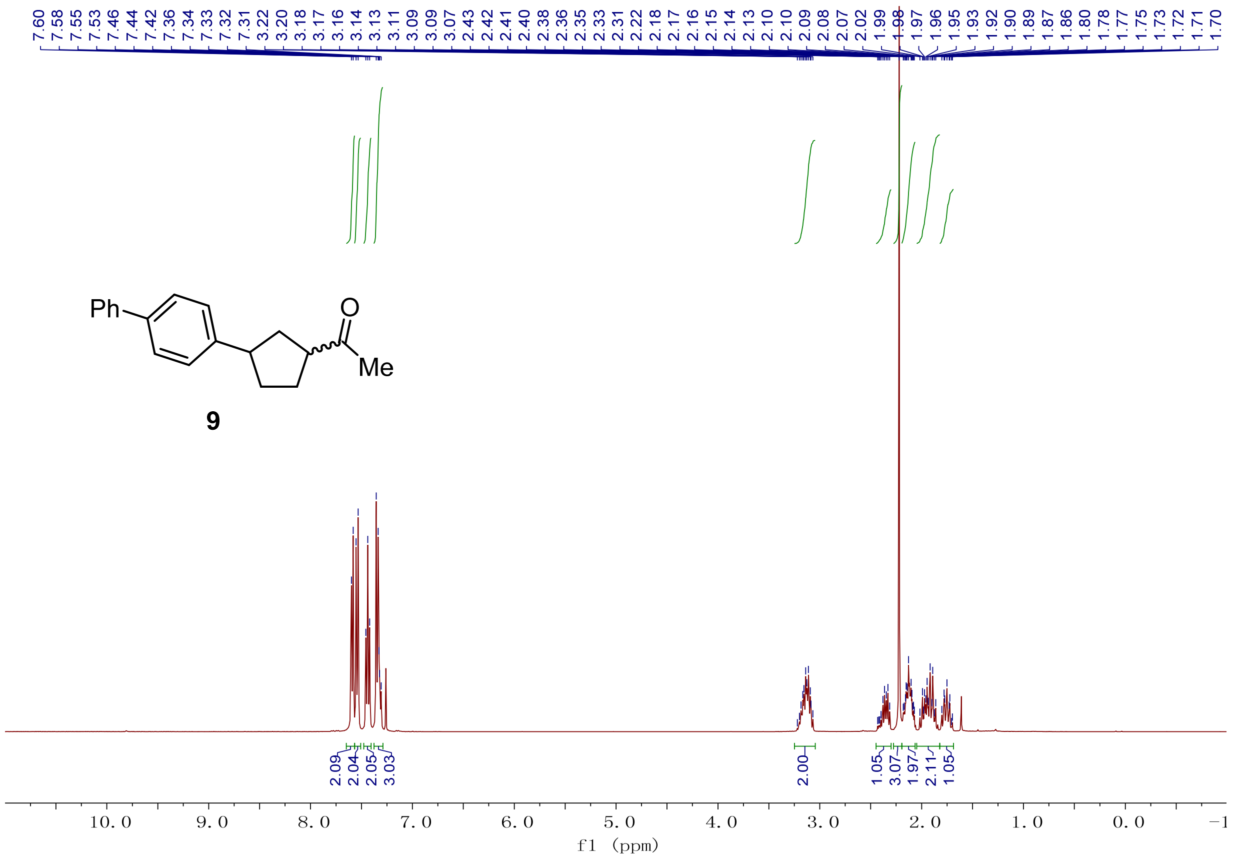

7.60
7.59
7.57
7.57
7.53
7.51
7.45
7.43
7.41
7.35
7.33
7.31
2.69
2.67
2.65
2.49
2.48
2.46
2.14
1.99
1.97
1.95
1.93
1.91
Ph
5
O
2.05
2.00
2.09
1.10
2.20
0.01
1.99
1.95
2.91
1.97
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

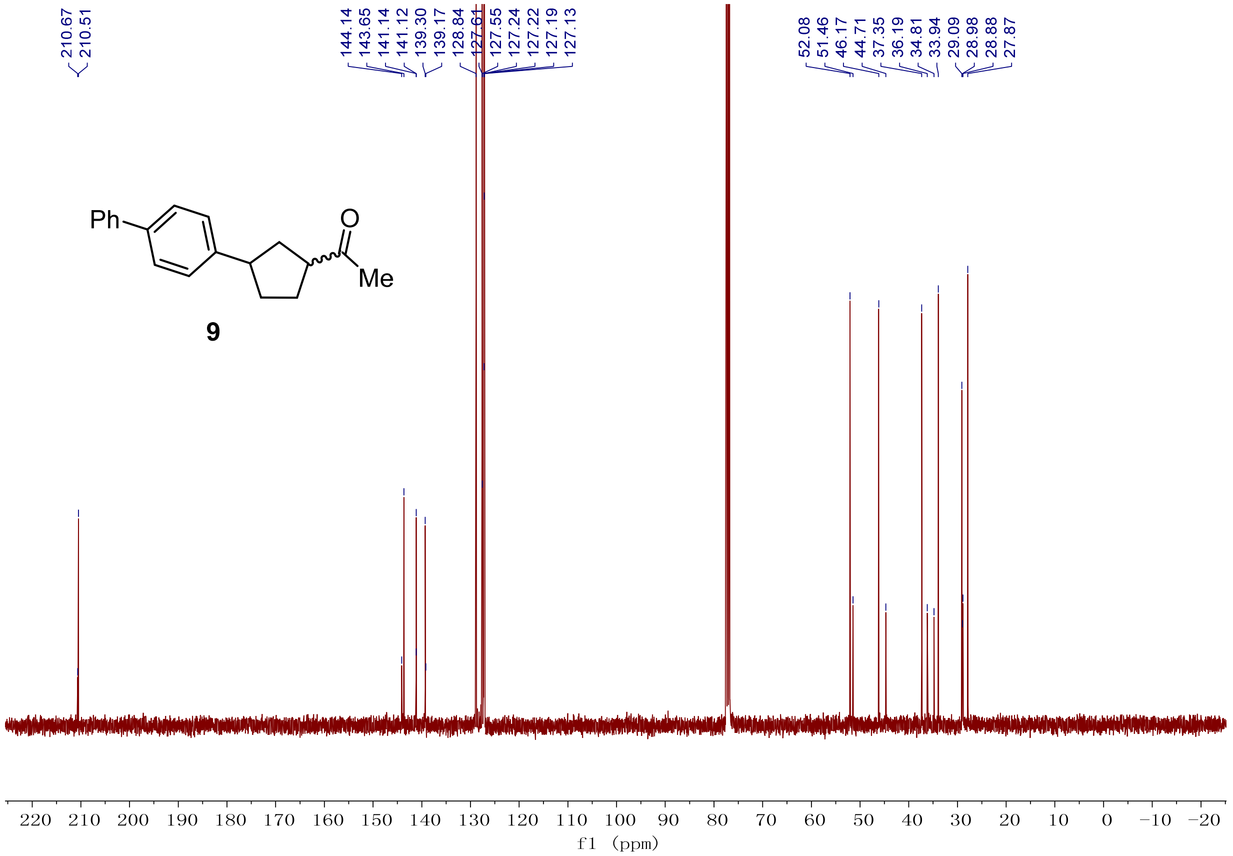

208.87
141.16
140.83
139.09
129.03
128.87
127.27
127.20
127.13
43.01
34.80
30.14
25.32
Ph
5
O
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

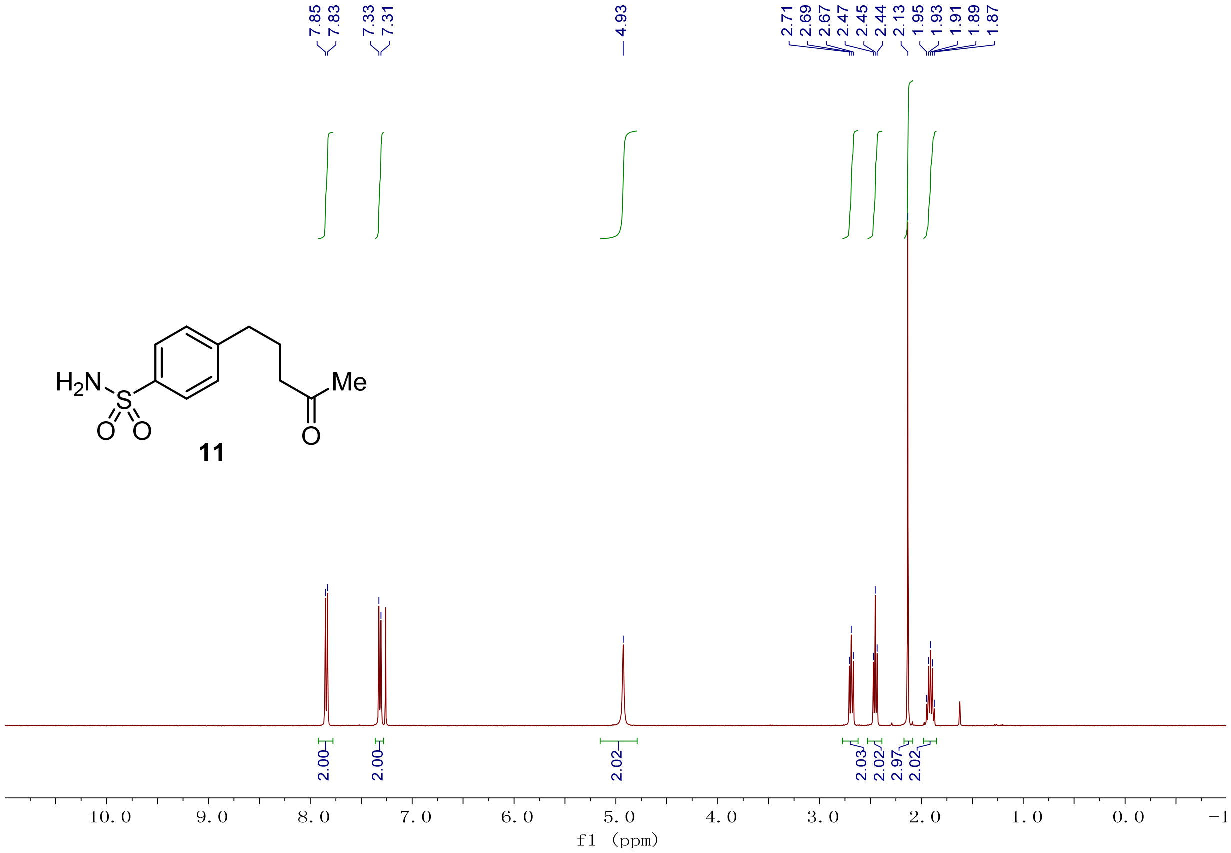


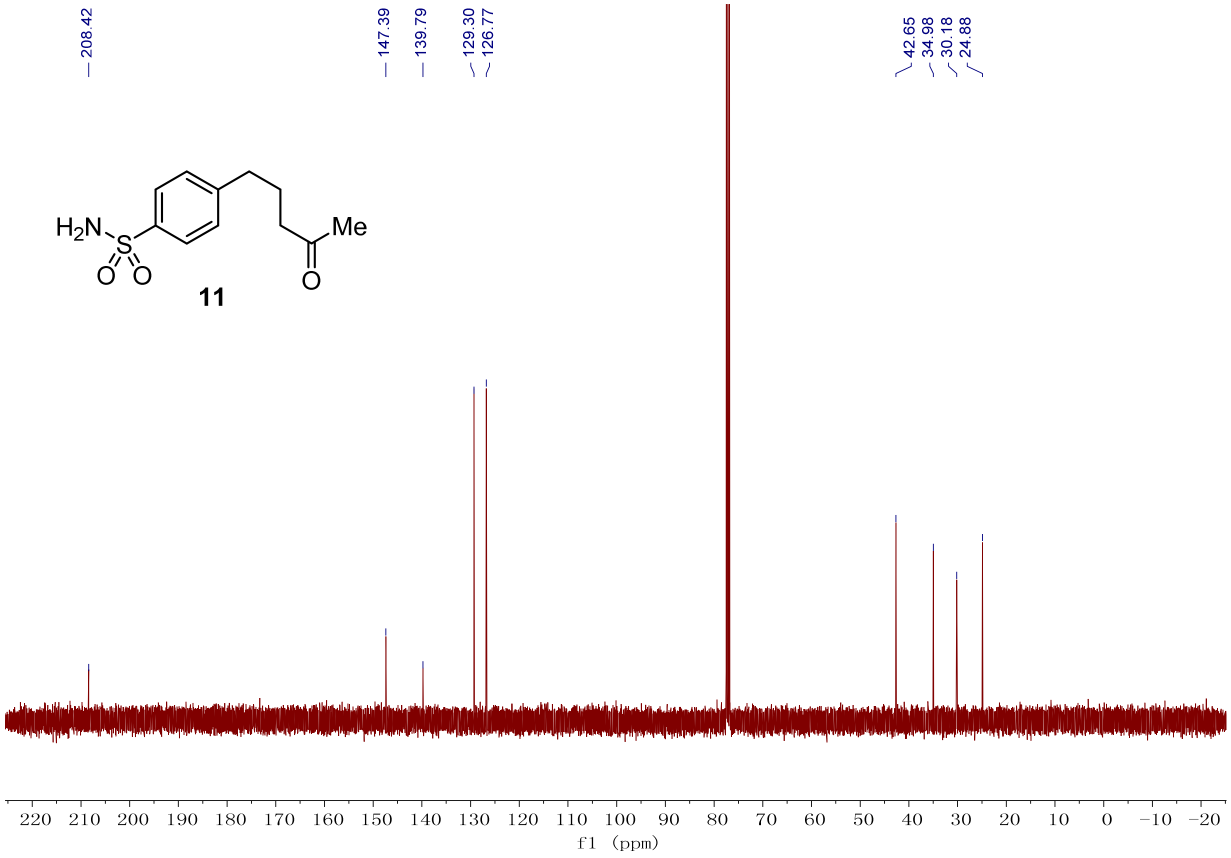
7

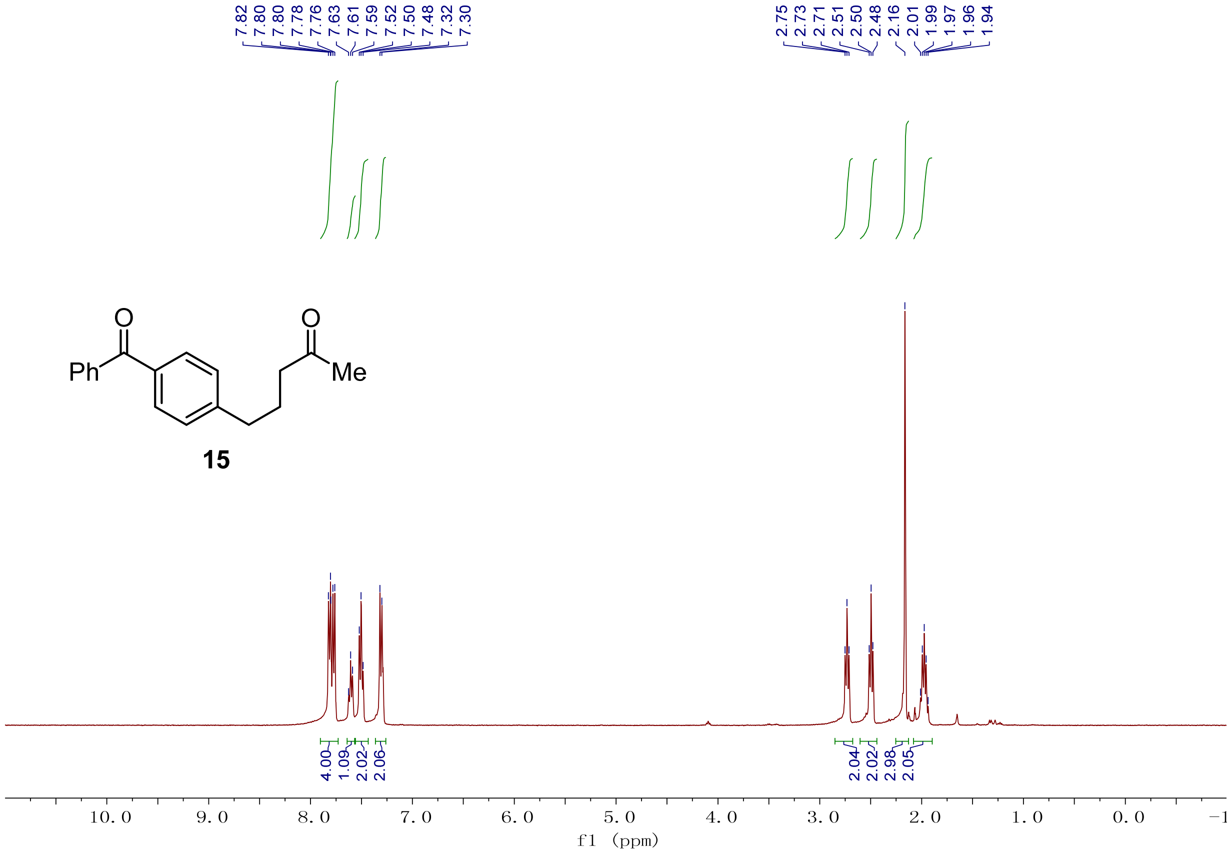
7.59
7.57
7.54
7.52
7.46
7.44
7.42
7.36
7.34
7.32
7.28
7.26
2.97
2.95
2.93
2.83
2.81
2.79
2.17
O
Me
Ph
2.07
2.02
2.04
1.02
2.20
2.05
2.07
3.00
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

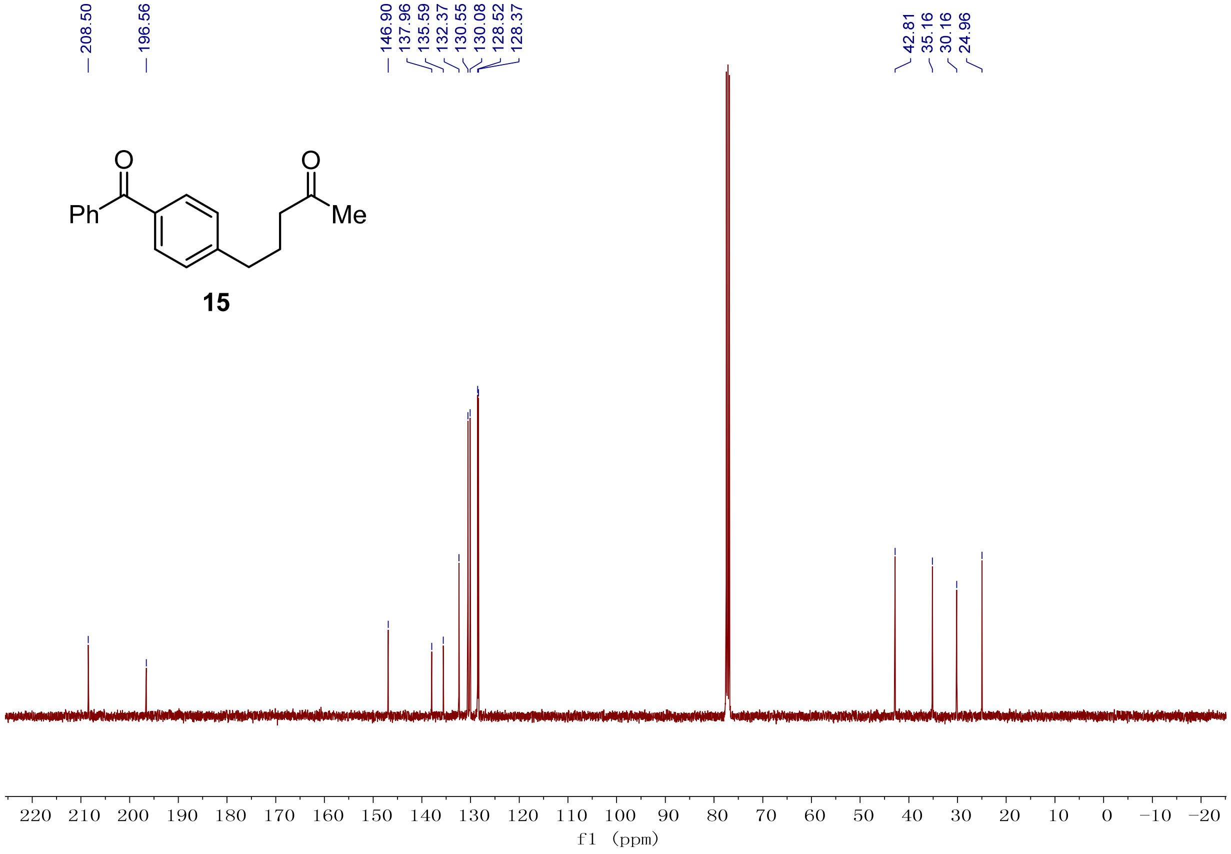

7.60
7.58
7.55
7.53
7.46
7.44
7.42
7.36
7.34
7.33
7.32
7.31
3.22
3.20
3.18
3.17
3.16
3.14
3.13
3.11
3.09
3.09
3.07
2.43
2.42
2.41
2.40
2.38
2.36
2.35
2.33
2.31
2.22
2.18
2.17
2.16
2.15
2.14
2.13
2.10
2.10
2.09
2.08
2.07
2.02
1.99
1.98
1.97
1.96
1.95
1.93
1.92
1.90
1.89
1.87
1.86
1.80
1.78
1.77
1.75
1.73
1.72
1.71
1.70
Ph
O
Me
9
2.09
2.04
2.05
3.03
2.00
1.05
3.07
1.97
2.11
1.05
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

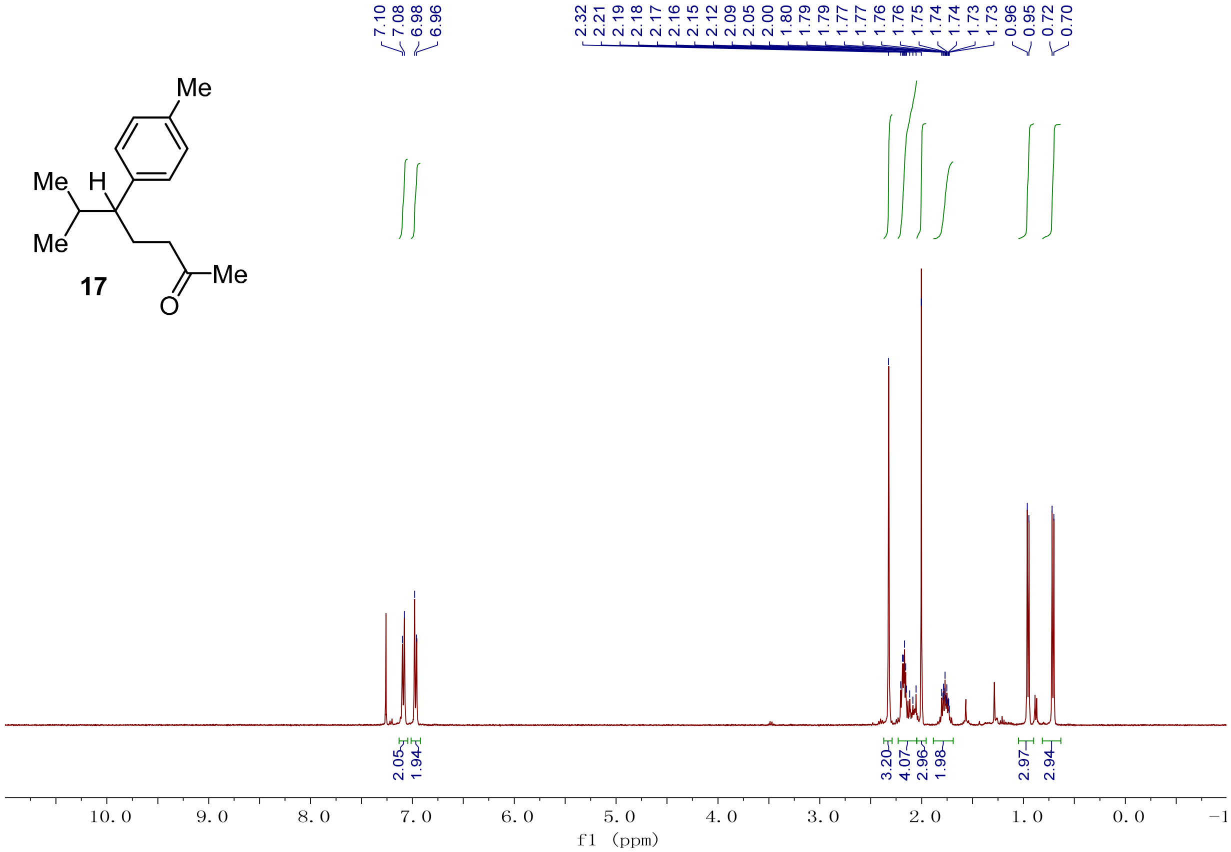

210.67
210.51
144.14
143.65
141.14
141.12
139.30
139.17
128.84
127.61
127.55
127.24
127.22
127.19
127.13
52.08
51.46
46.17
44.71
37.35
36.19
34.81
33.94
29.09
28.98
28.88
27.87
Ph
O
Me
9
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)


7.85
7.83
7.33
7.31
4.93
2.71
2.69
2.67
2.47
2.45
2.44
2.13
1.95
1.93
1.91
1.89
1.87
H2N
S
O
O
Me
O
11
2.00
2.00
2.02
2.03
2.02
2.97
2.02
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)


208.42
147.39
139.79
129.30
126.77
42.65
34.98
30.18
24.88
H2N
S
O
O
Me
O
11
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

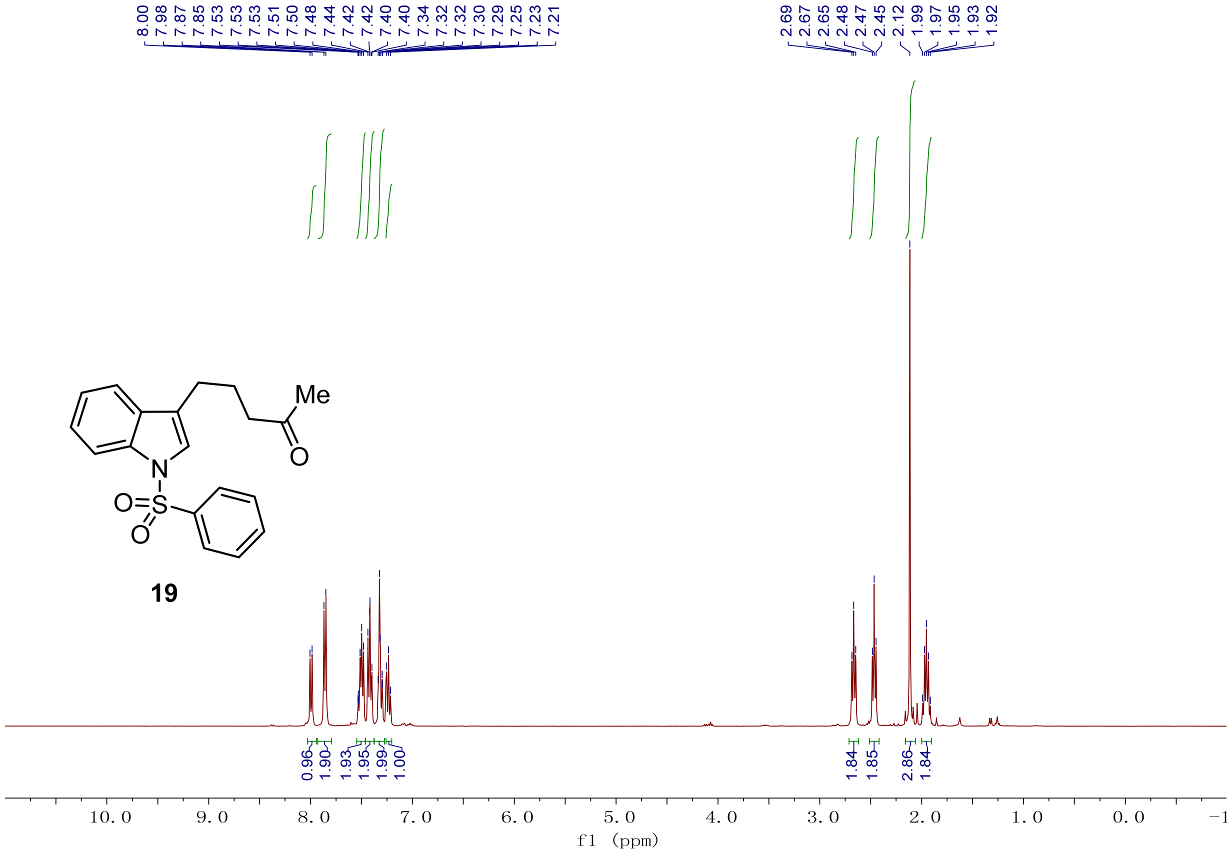

15
7.82
7.80
7.80
7.78
7.76
7.63
7.61
7.59
7.52
7.50
7.48
7.32
7.30
2.75
2.73
2.71
2.51
2.50
2.48
2.16
2.01
1.99
1.97
1.96
1.94
Ph
O
O
Me
4.00
1.09
2.02
2.06
2.04
2.02
2.98
2.05
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

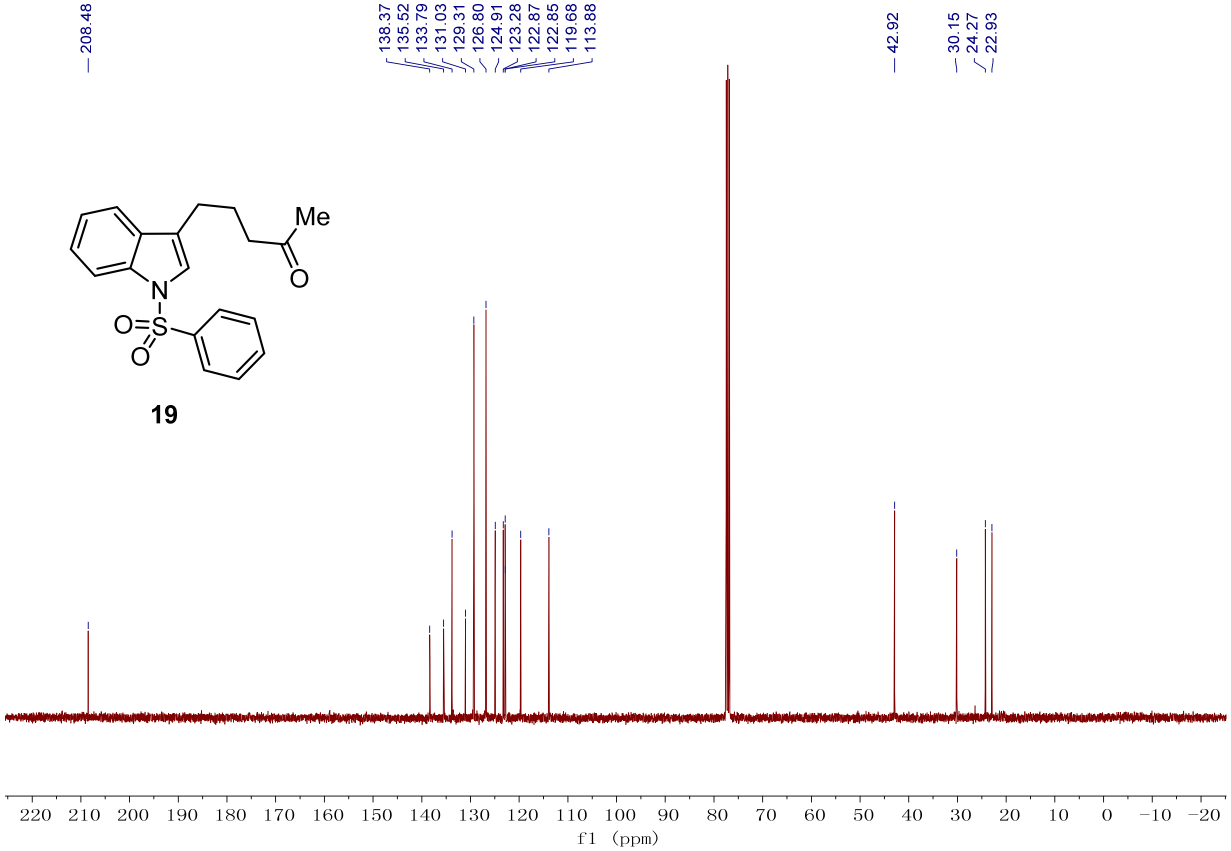

15
208.50
196.56
146.90
137.96
135.59
132.37
130.55
130.08
128.52
128.37
42.81
35.16
30.16
24.96
Ph
O
O
Me
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

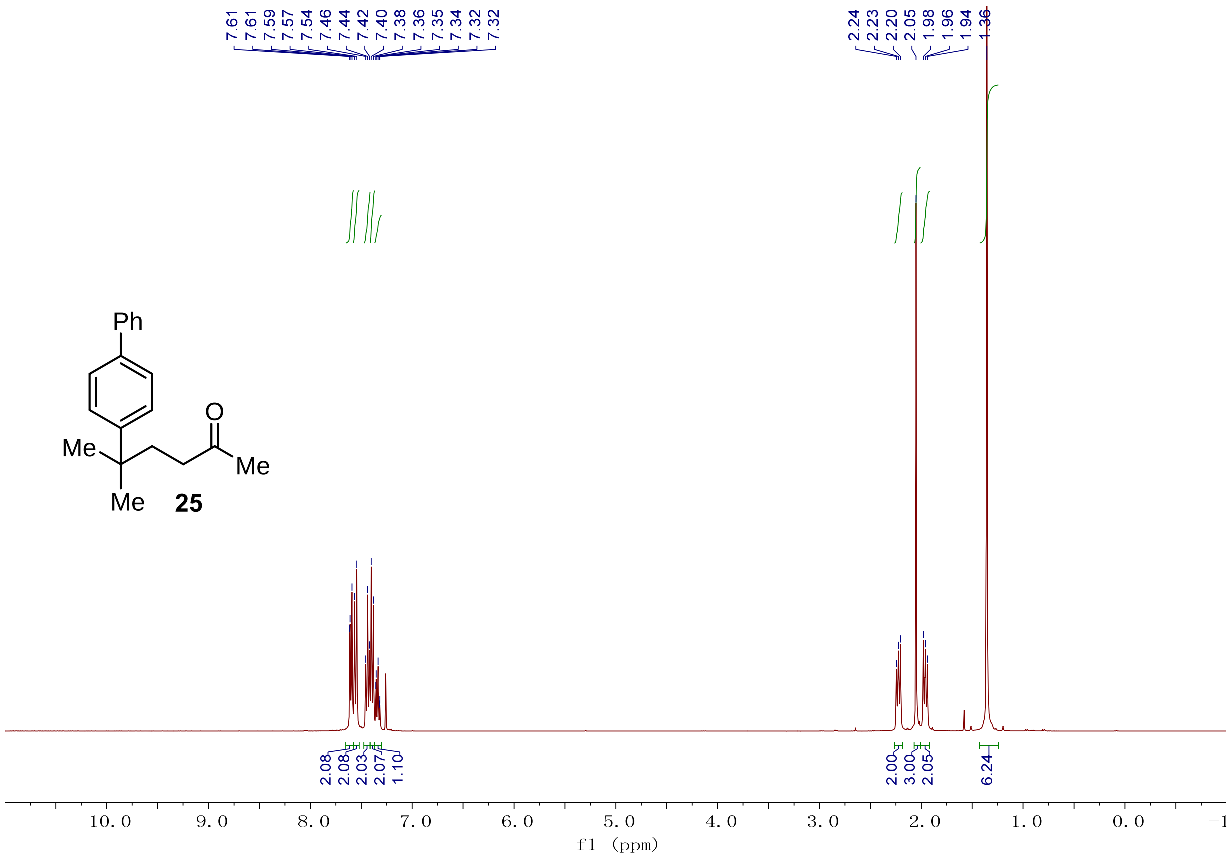

Me
Me
H
Me
O
Me

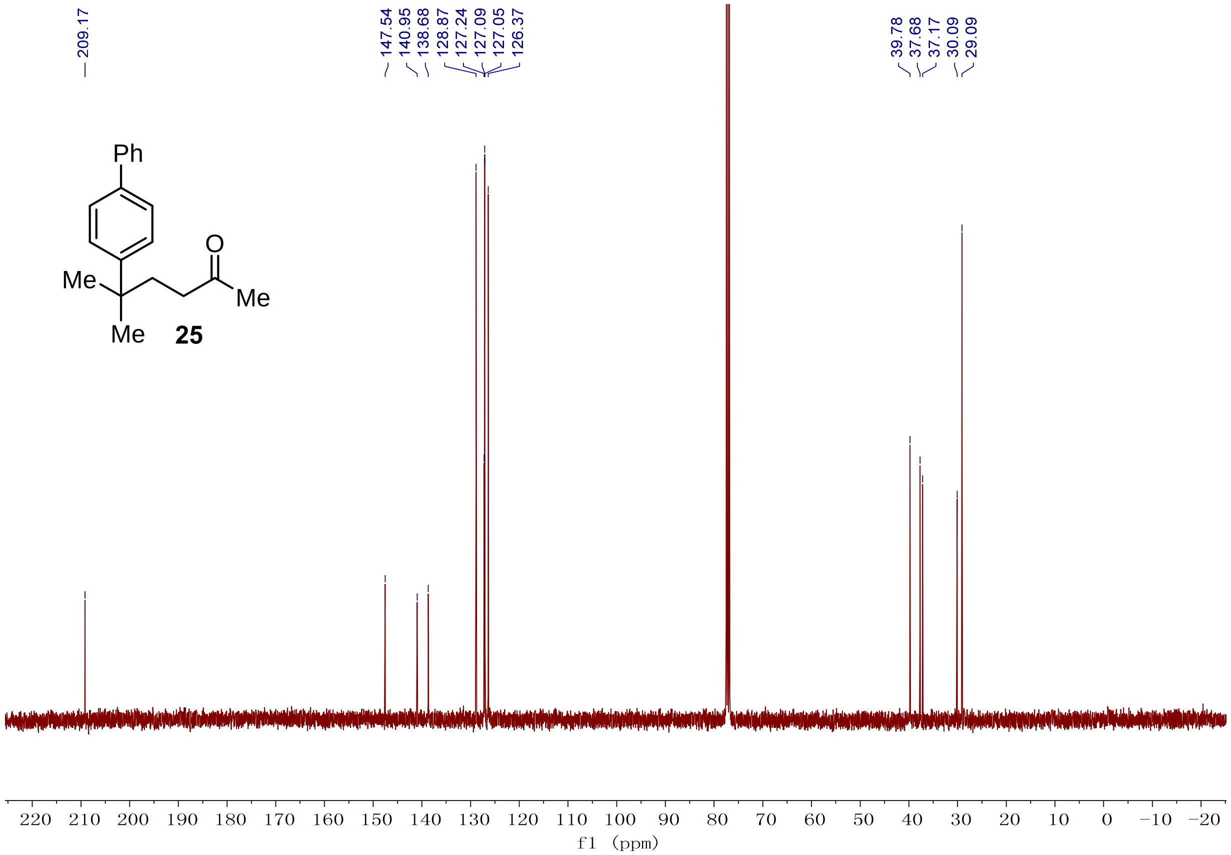
17

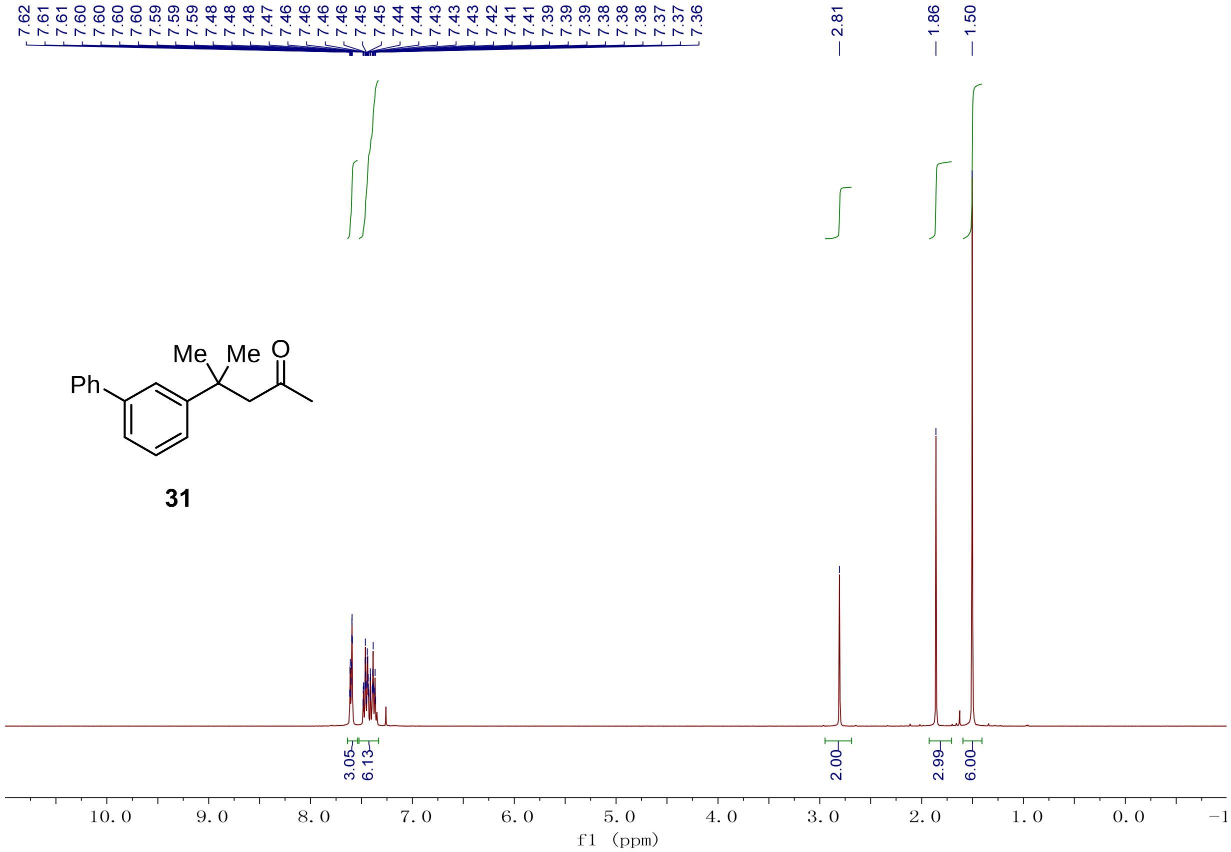
7.10
7.08
6.98
6.96
2.32
2.21
2.19
2.18
2.17
2.16
2.15
2.12
2.09
2.05
2.00
1.80
1.79
1.79
1.77
1.77
1.76
1.76
1.75
1.74
1.74
1.73
1.73
0.96
0.95
0.72
0.70
2.05
1.94
3.20
4.07
2.96
1.98
2.97
2.94
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

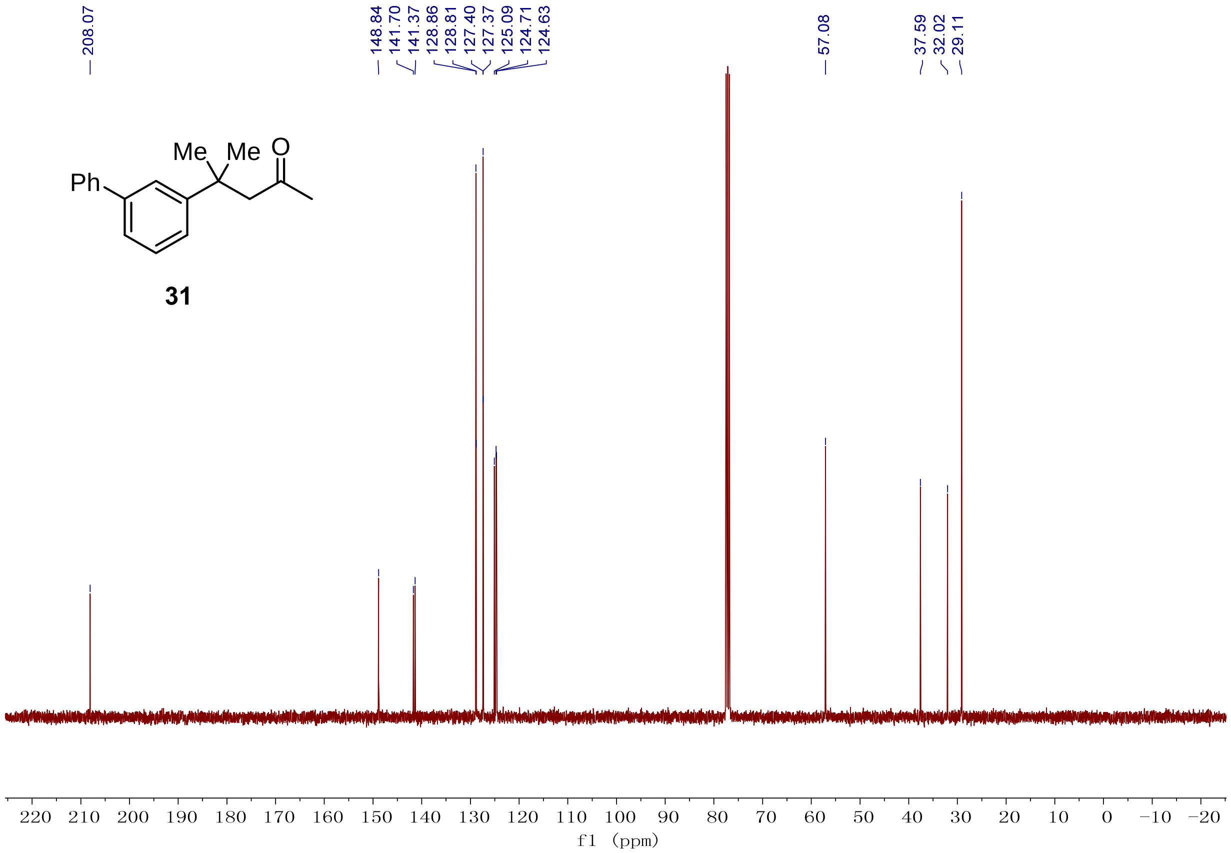

8.00
7.98
7.87
7.85
7.53
7.53
7.53
7.51
7.50
7.48
7.44
7.42
7.42
7.40
7.40
7.34
7.32
7.32
7.30
7.29
7.25
7.23
7.21
2.69
2.67
2.65
2.48
2.47
2.45
2.12
1.99
1.97
1.95
1.93
1.92
Me
O
N
O=S
O
19
0.96
1.90
1.93
1.95
1.99
1.00
1.84
1.85
2.86
1.84
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

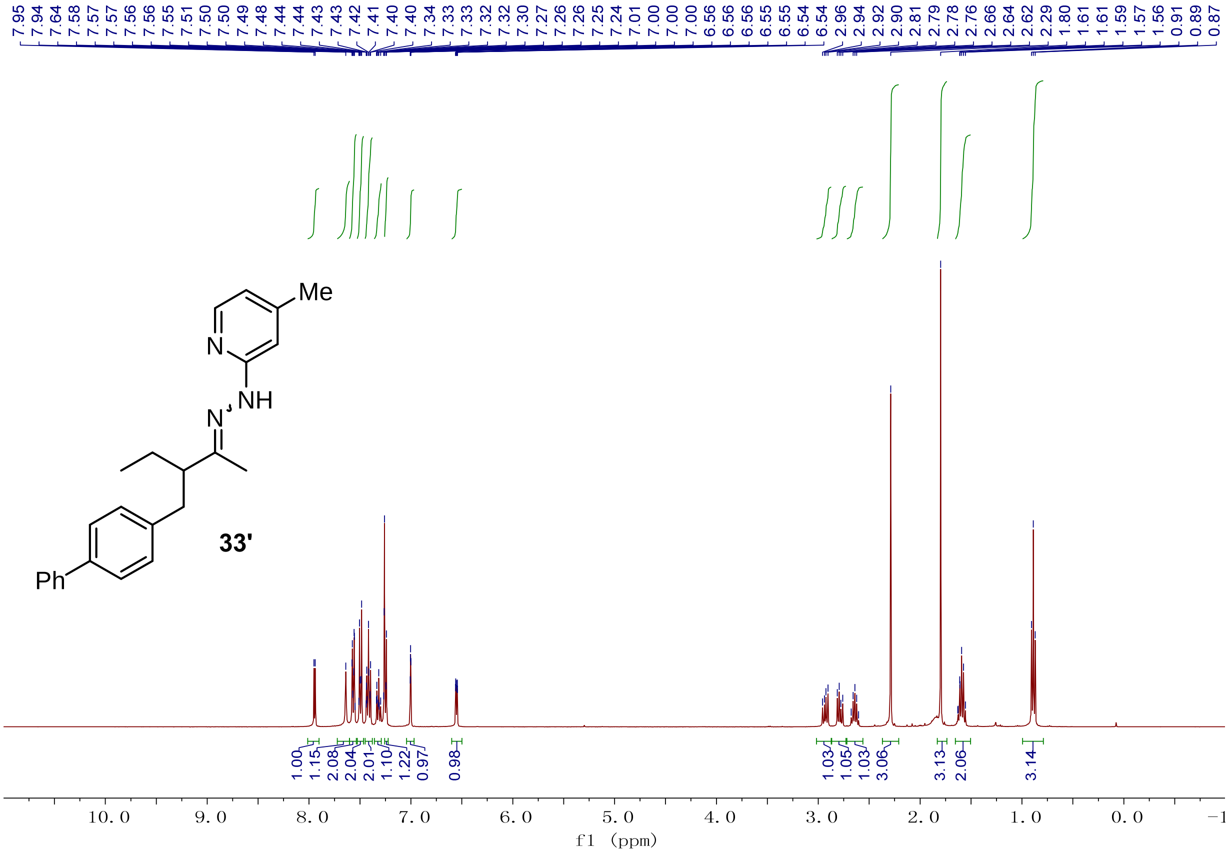

208.48
138.37
135.52
133.79
131.03
129.31
126.80
124.91
123.28
122.87
122.85
119.68
113.88
42.92
30.15
24.27
22.93
Me
O
N
O=S
O
19
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

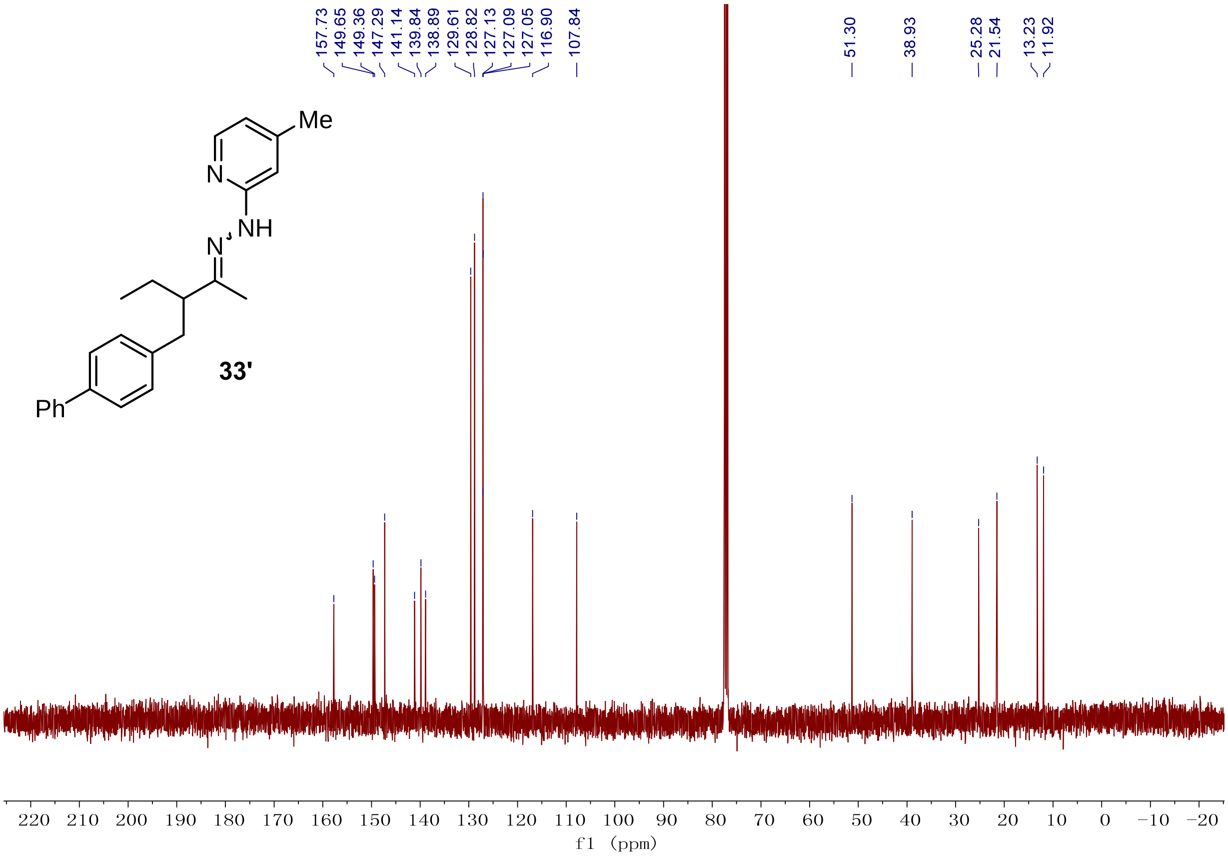

7.61
7.61
7.59
7.57
7.54
7.46
7.44
7.42
7.40
7.38
7.36
7.35
7.34
7.32
7.32
2.24
2.23
2.20
2.05
1.98
1.96
1.94
1.36
Ph
O
Me
Me
Me
25
2.08
2.08
2.03
2.07
1.10
2.00
3.00
2.05
6.24
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

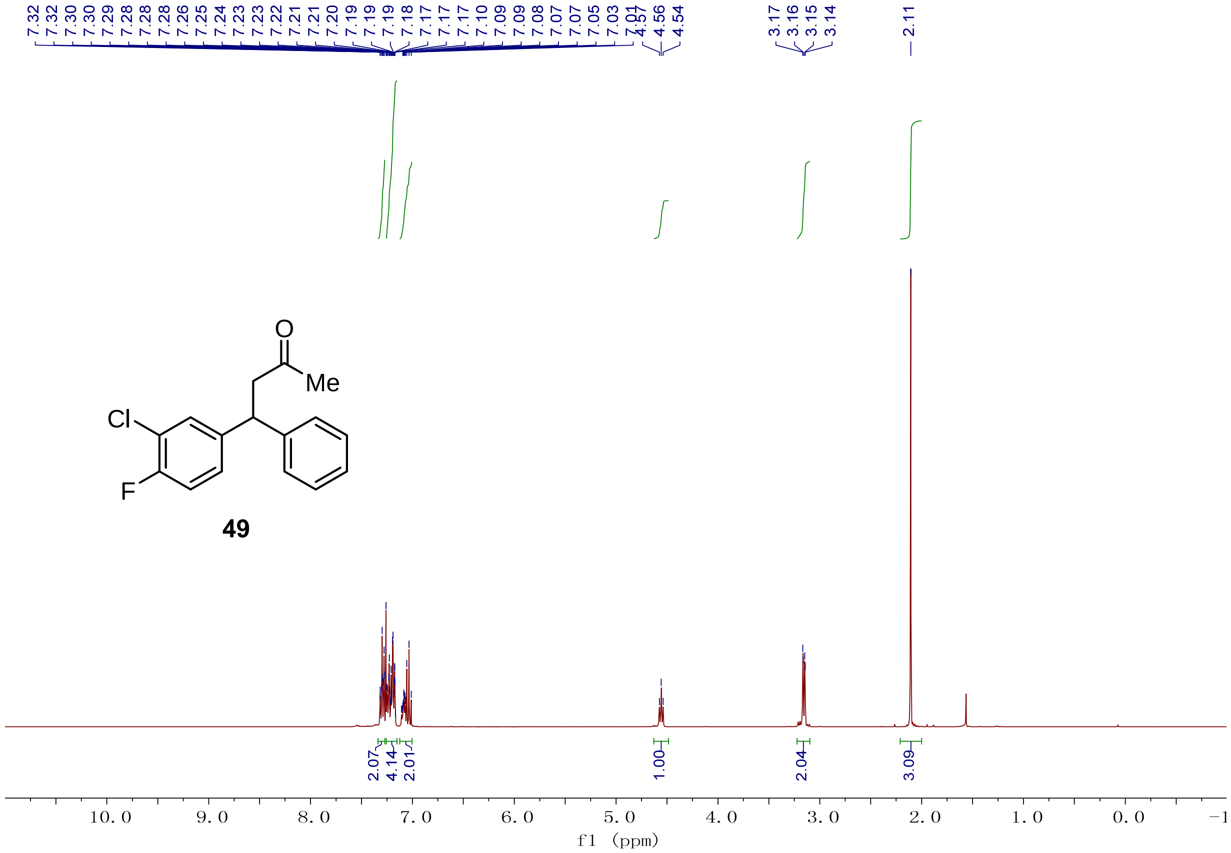

209.17
147.54
140.95
138.68
128.87
127.24
127.09
127.05
126.37
39.78
37.68
37.17
30.09
29.09
Ph
O
Me
Me
Me
25
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

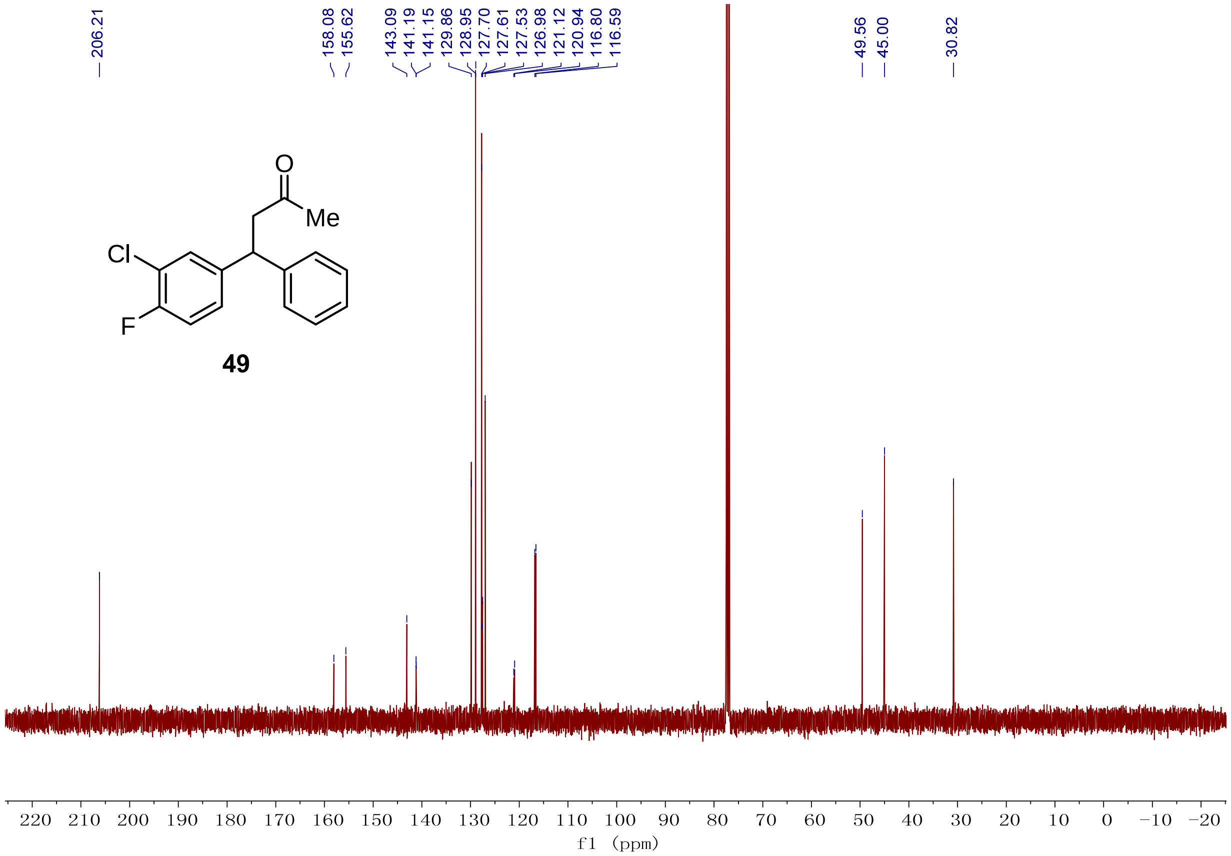

7.62
7.61
7.61
7.60
7.60
7.60
7.59
7.59
7.59
7.48
7.48
7.47
7.46
7.46
7.46
7.46
7.45
7.45
7.44
7.44
7.43
7.43
7.43
7.42
7.41
7.41
7.39
7.39
7.39
7.38
7.38
7.38
7.37
7.37
7.36
2.81
1.86
1.50
Me
Me
O
Ph
31
3.05
6.13
2.00
2.99
6.00
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

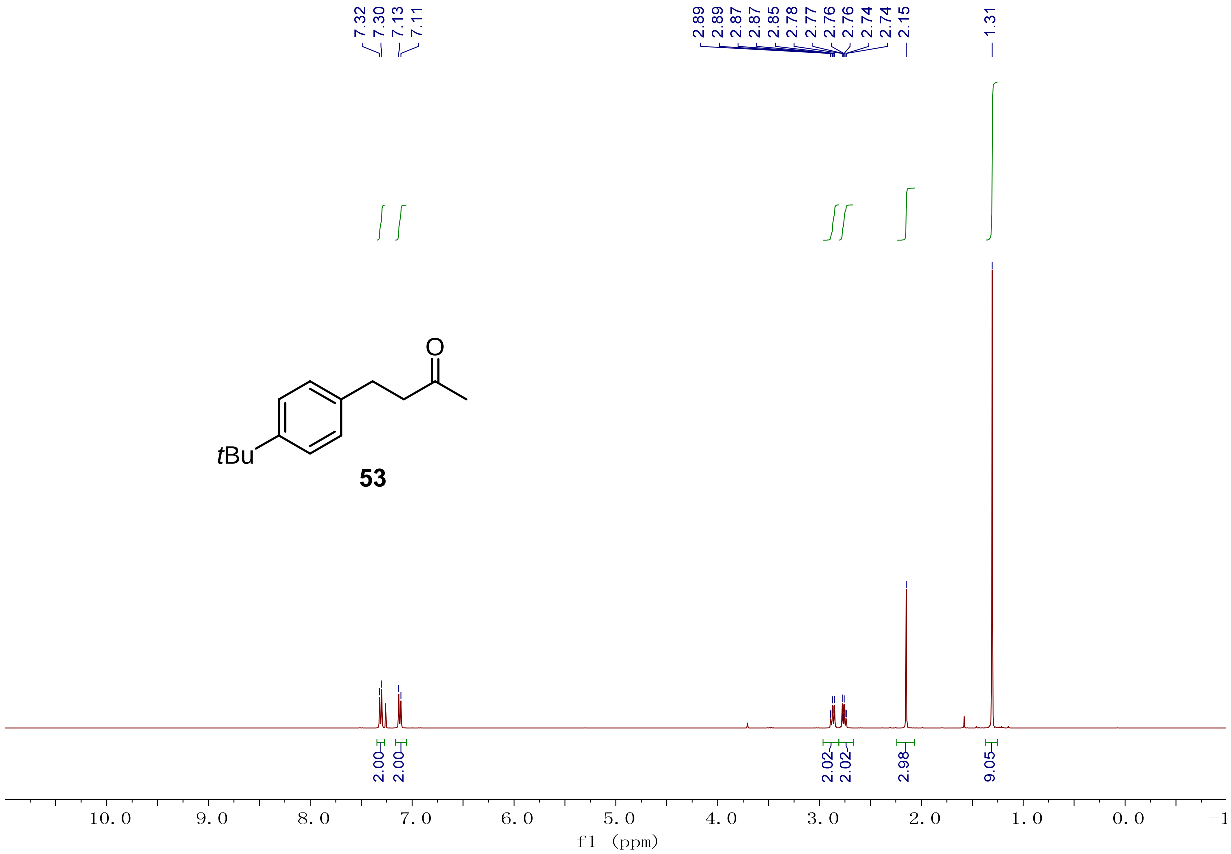

208.07
148.84
141.70
141.37
128.86
128.81
127.40
127.37
125.09
124.71
124.63
57.08
37.59
32.02
29.11
Me
Me
O
Ph
31
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

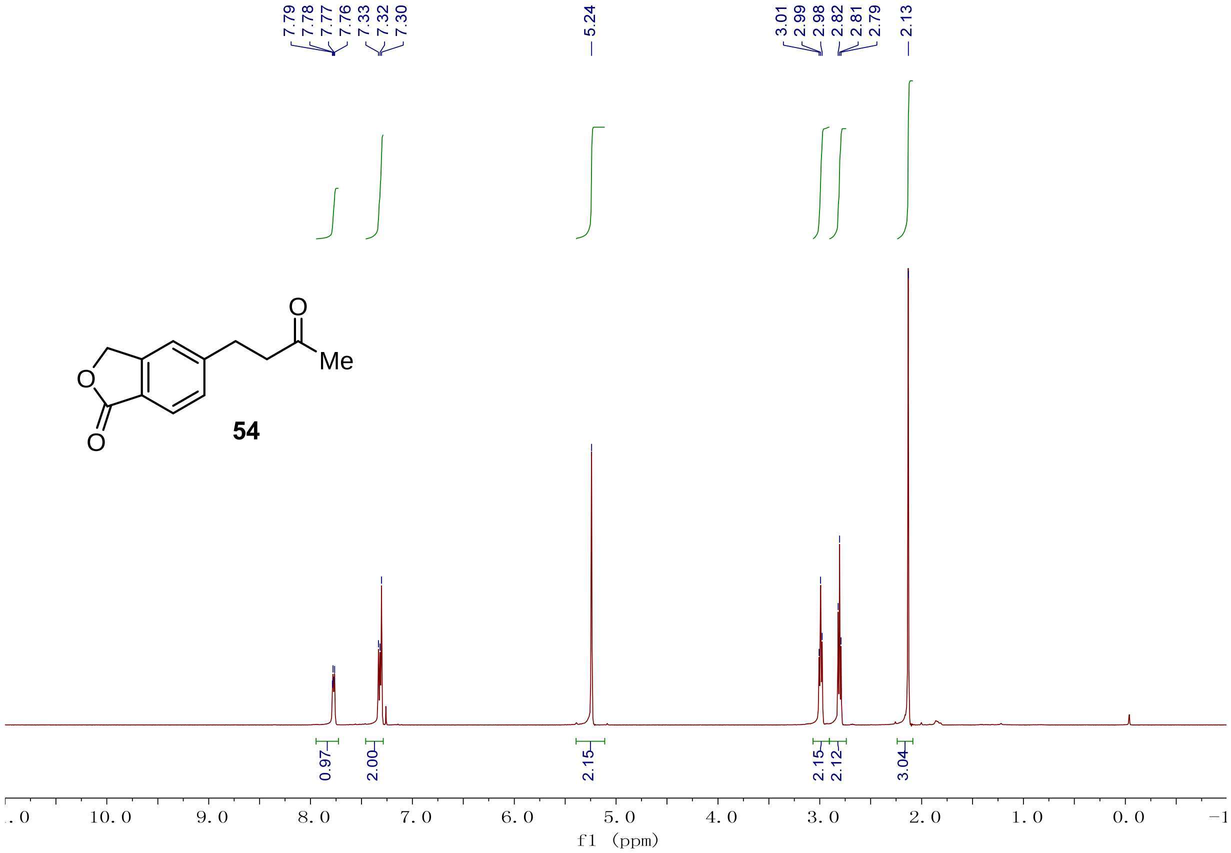

7.95
7.94
7.64
7.58
7.57
7.57
7.56
7.56
7.55
7.51
7.50
7.50
7.49
7.48
7.44
7.44
7.43
7.43
7.42
7.41
7.40
7.40
7.34
7.33
7.33
7.32
7.32
7.30
7.27
7.26
7.26
7.25
7.24
7.01
7.00
7.00
6.56
6.56
6.55
6.55
6.54
6.54
2.96
2.94
2.92
2.90
2.81
2.79
2.78
2.76
2.66
2.64
2.62
2.29
1.80
1.61
1.61
1.59
1.57
1.56
0.91
0.89
0.87
Me
N
NH
N
Ph
33'
1.00
1.15
2.08
2.04
2.01
1.10
1.22
0.97
0.98
1.03
1.05
1.03
3.06
3.13
2.06
3.14
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

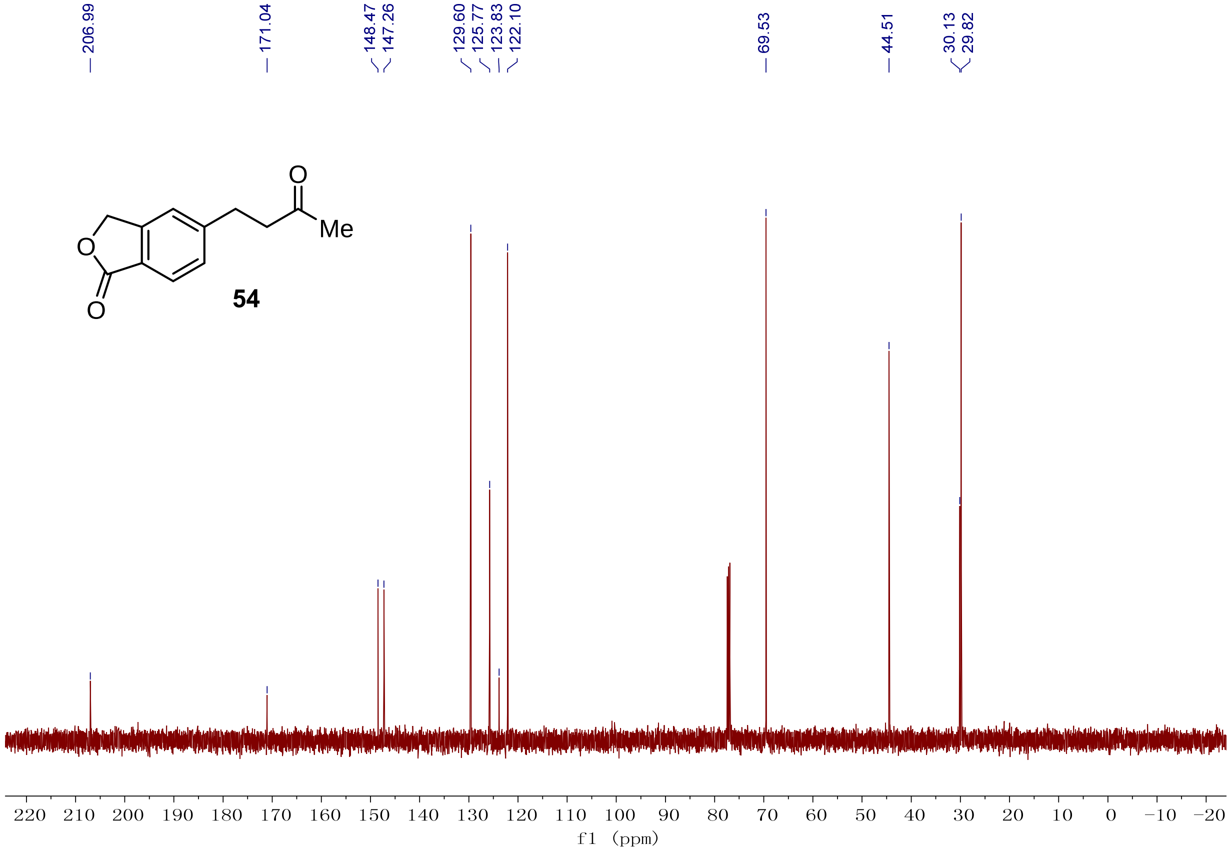

157.73
149.65
149.36
147.29
141.14
139.84
138.89
129.61
128.82
127.13
127.09
127.05
116.90
107.84
51.30
38.93
25.28
21.54
13.23
11.92
Me
N
NH
N
Ph
33'
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

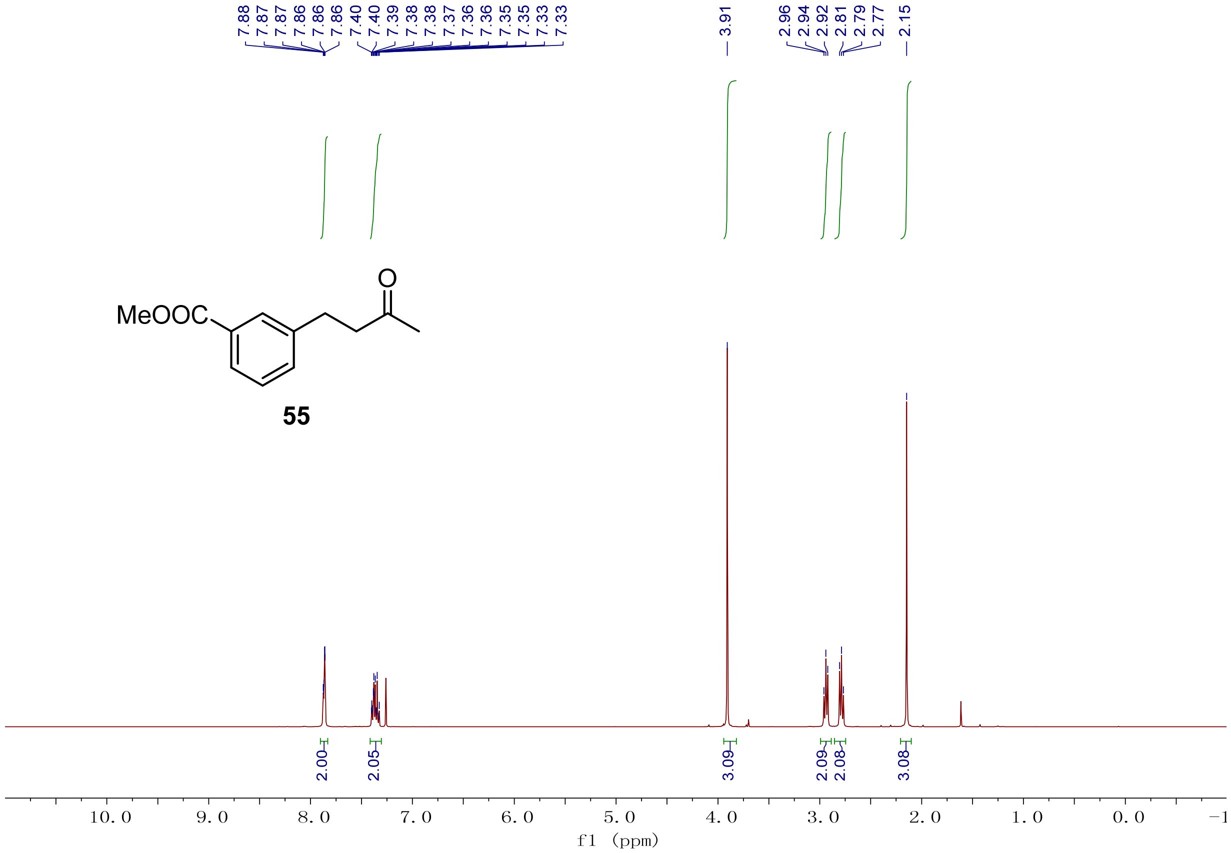

7.32
7.32
7.30
7.29
7.28
7.28
7.26
7.25
7.24
7.23
7.22
7.21
7.21
7.20
7.19
7.19
7.19
7.18
7.17
7.17
7.17
7.10
7.09
7.09
7.08
7.07
7.07
7.05
7.03
7.01
4.57
4.56
4.54
3.17
3.16
3.15
3.14
2.11
O
Me
Cl
F
49
2.07
4.14
2.01
1.00
2.04
3.09
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)


206.21
158.08
155.62
143.09
141.19
141.15
129.86
128.95
127.70
127.61
127.53
126.98
121.12
120.94
116.80
116.59
49.56
45.00
30.82
O
Me
Cl
F
49
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

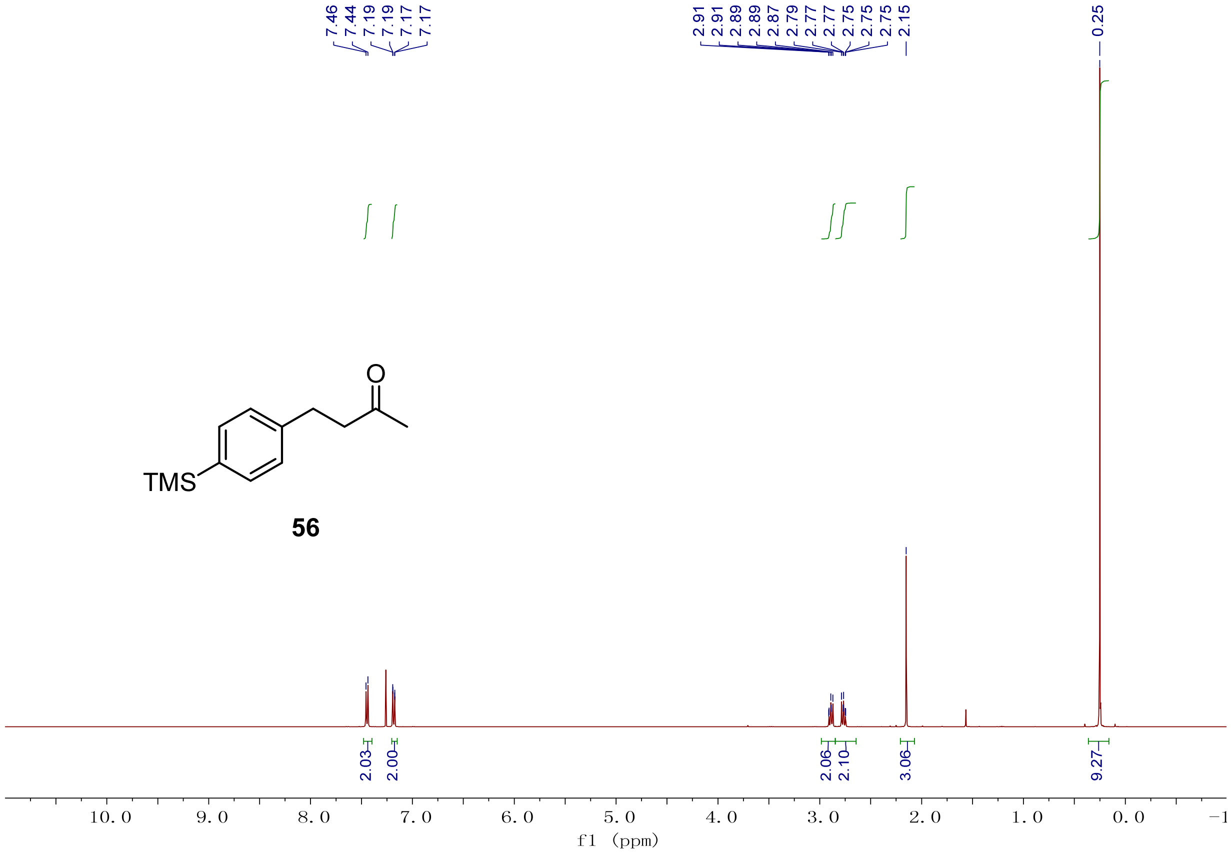

7.32
7.30
7.13
7.11
2.89
2.89
2.87
2.87
2.85
2.78
2.77
2.76
2.76
2.74
2.74
2.15
1.31
O
tBu
53
2.00
2.00
2.02
2.02
2.98
9.05
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)


7.79
7.78
7.77
7.76
7.33
7.32
7.30
5.24
3.01
2.99
2.98
2.82
2.81
2.79
2.13
O
Me
O
O
54
0.97
2.00
2.15
2.15
2.12
3.04
. 0
10. 0
9. 0
8. 0
7. 0
6. 0
5. 0
4. 0
3. 0
2. 0
1. 0
0. 0
−1
f1 (ppm)

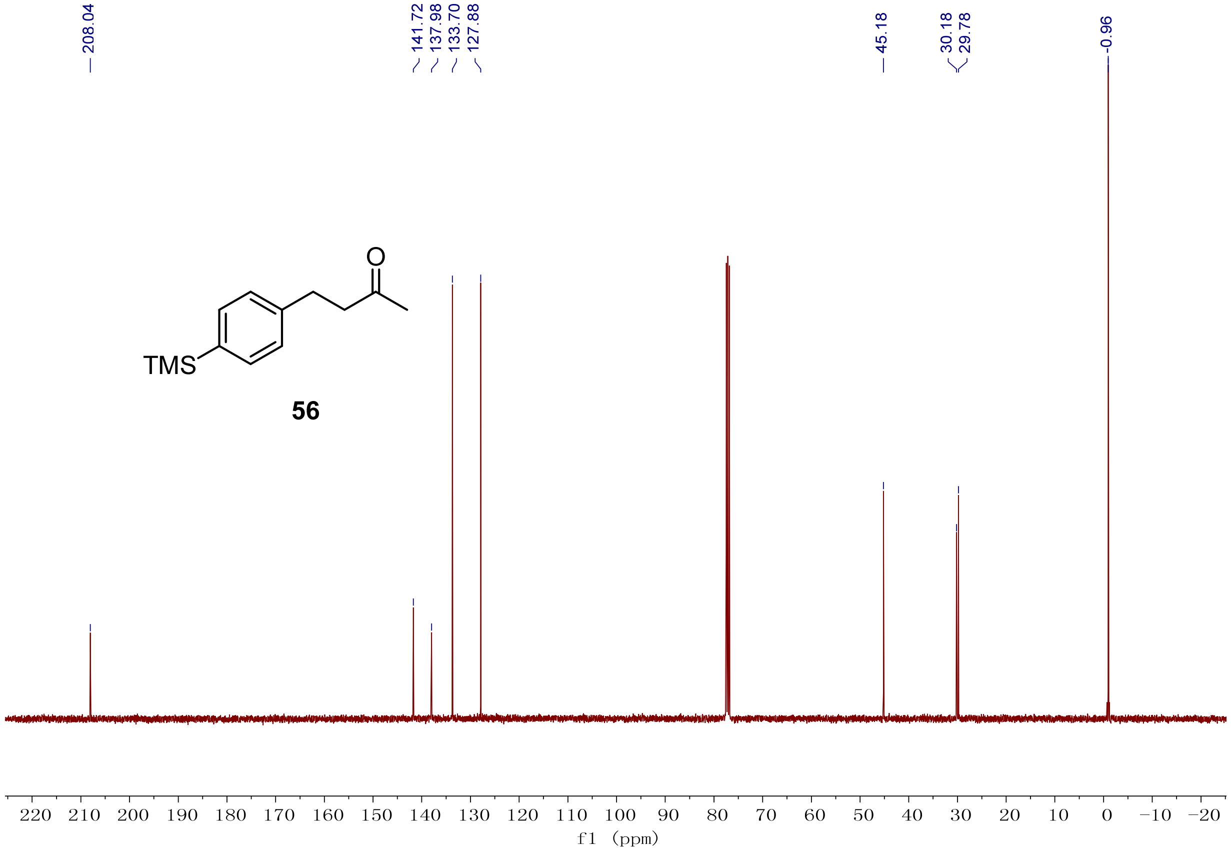

206.99
171.04
148.47
147.26
129.60
125.77
123.83
122.10
69.53
44.51
30.13
29.82
O
Me
O
O
54
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
−10
−20
f1 (ppm)


7.88
7.87
7.87
7.86
7.86
7.86
7.40
7.40
7.39
7.38
7.38
7.37
7.36
7.36
7.35
7.33
7.33
3.91
2.96
2.94
2.92
2.81
2.79
2.77
2.15
MeOOC
O
2.00
2.05
3.09
2.09
2.08
3.08
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

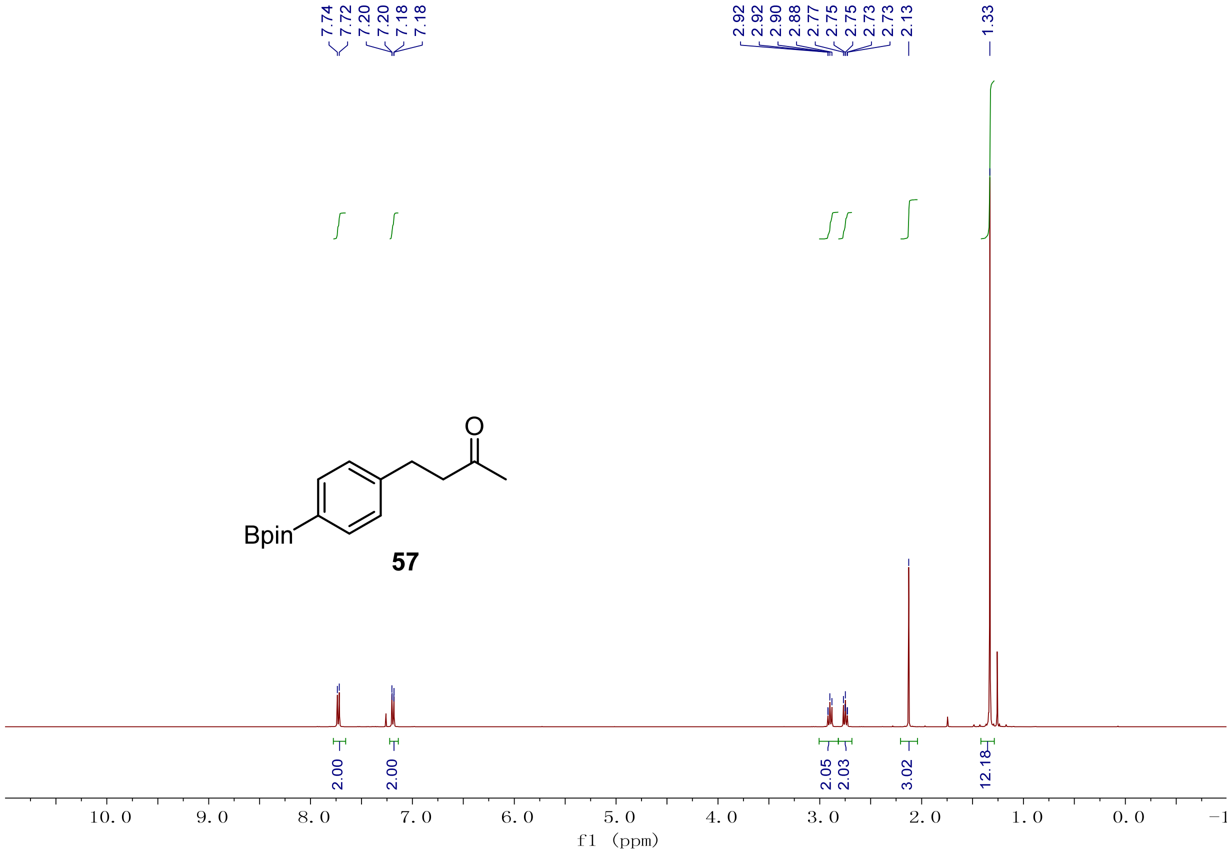
55

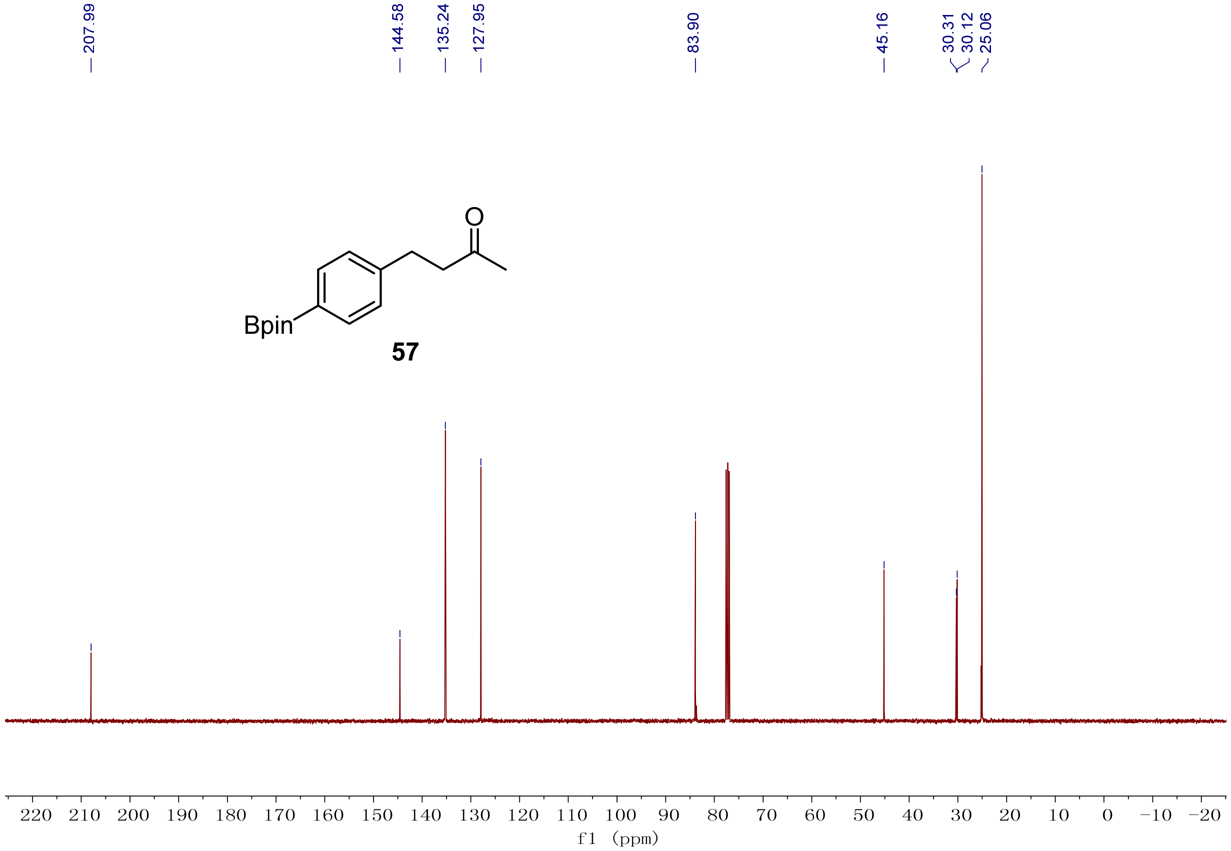

7.46
7.44
7.19
7.19
7.17
7.17
2.91
2.91
2.89
2.89
2.87
2.79
2.77
2.77
2.75
2.75
2.75
2.15
0.25
2.03
2.00
2.06
2.10
3.06
9.27
TMS
O
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

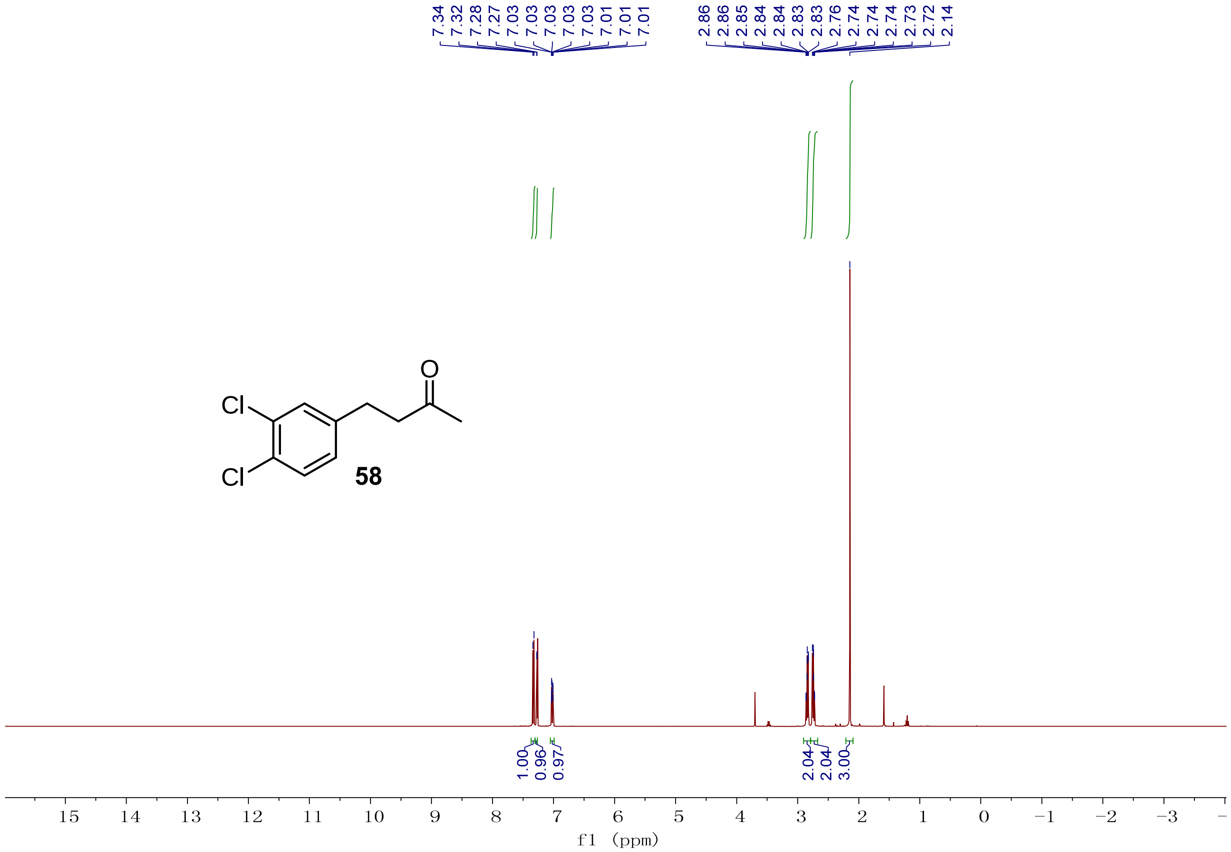
56


208.04
141.72
137.98
133.70
127.88
45.18
30.18
29.78
-0.96
TMS
O
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

56

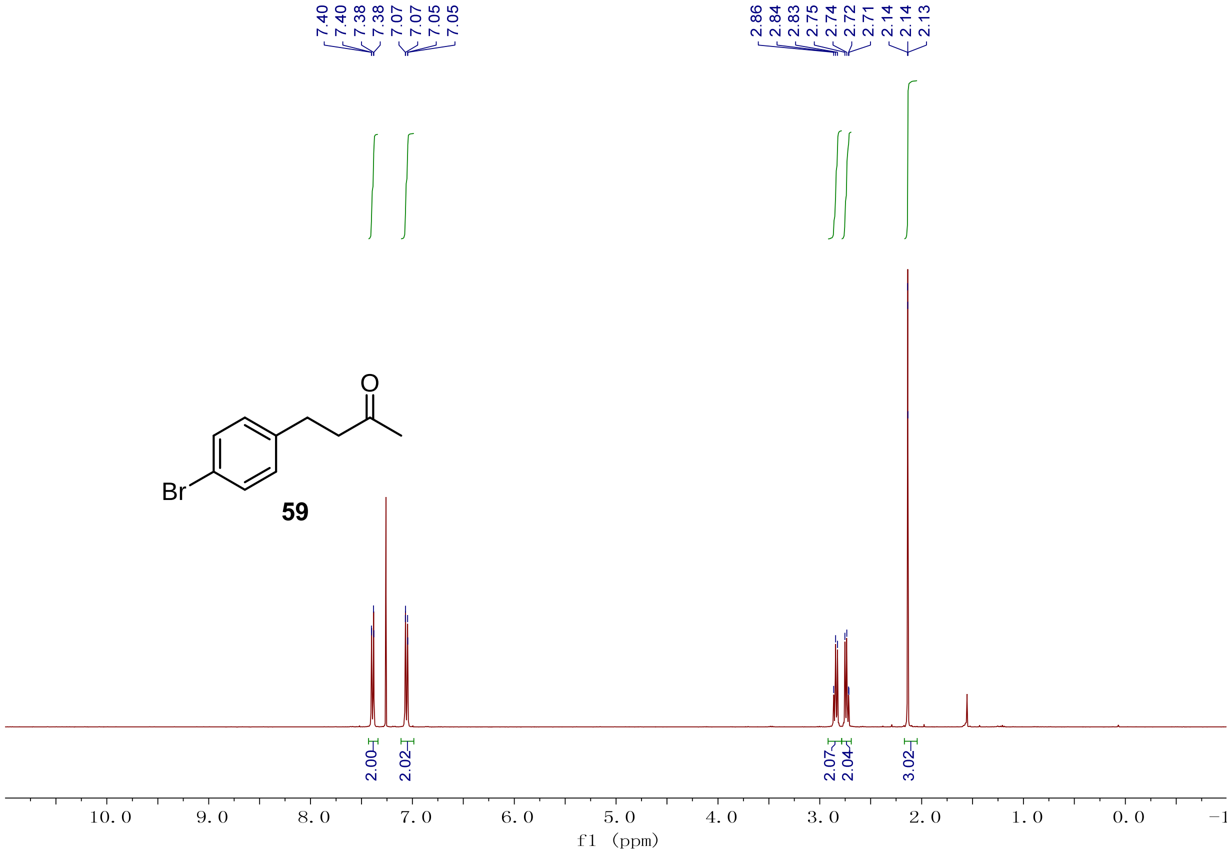

7.74
7.72
7.20
7.20
7.18
7.18
2.92
2.92
2.90
2.88
2.77
2.75
2.75
2.73
2.73
2.13
1.33
Bpin
O
57
2.00
2.00
2.05
2.03
3.02
12.18
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)


207.99
144.58
135.24
127.95
83.90
45.16
30.31
30.12
25.06
Bpin
O
57
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)



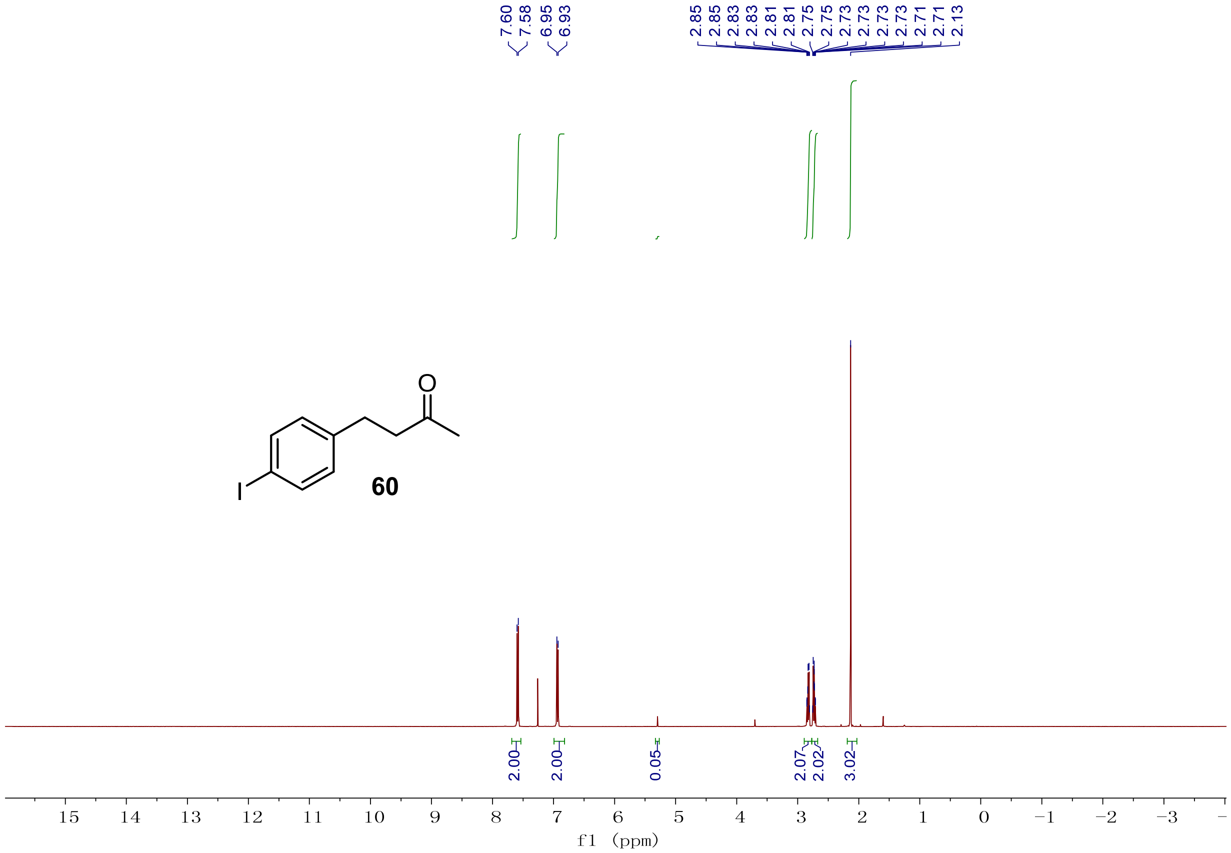
58

7.34
7.32
7.28
7.27
7.03
7.03
7.03
7.03
7.01
7.01
7.01
2.86
2.86
2.85
2.84
2.84
2.83
2.83
2.76
2.74
2.74
2.73
2.72
2.14
Cl
Cl
O
1.00
0.96
0.97
2.04
2.04
3.00
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
−1
−2
−3
f1 (ppm)



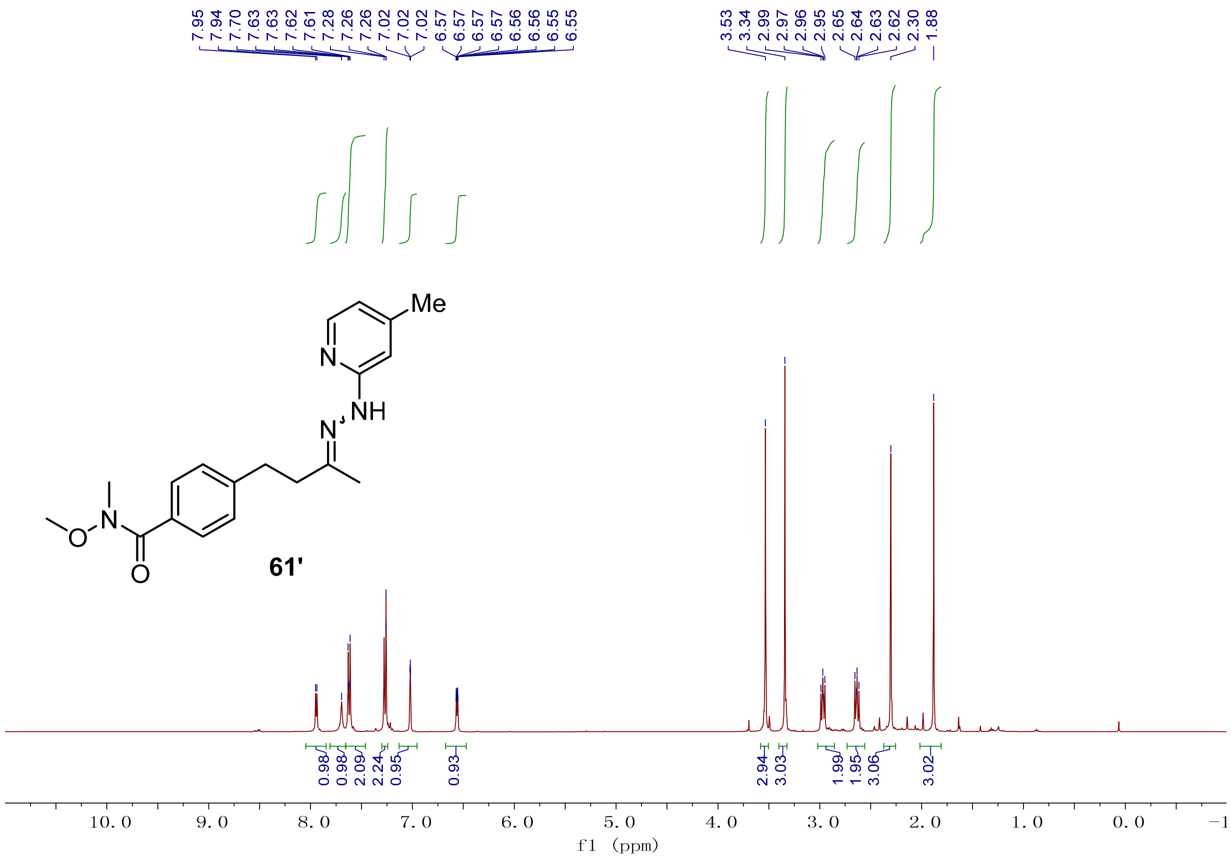
59

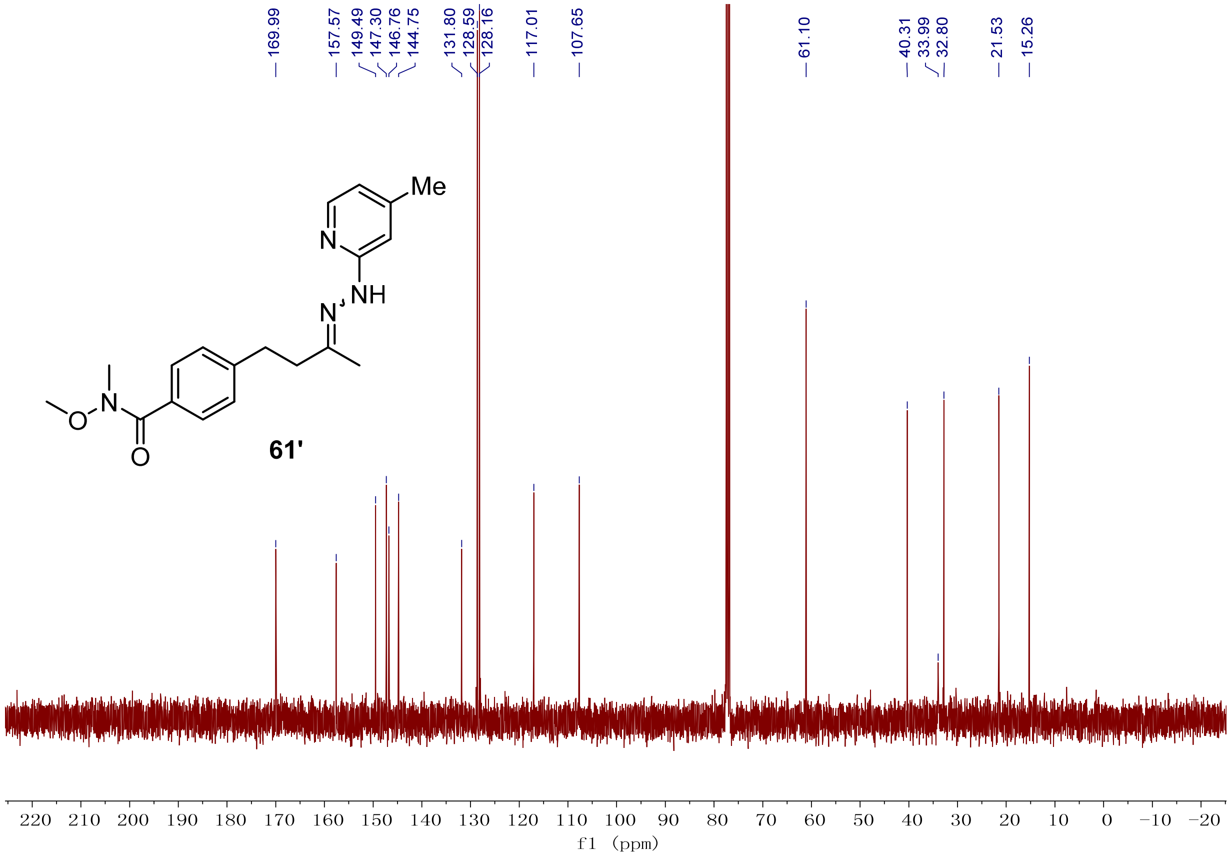
7.40
7.40
7.38
7.38
7.07
7.07
7.05
7.05
2.86
2.84
2.83
2.75
2.74
2.72
2.71
2.14
2.14
2.13
Br
O
2.00
2.02
2.07
2.04
3.02
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
−1
f1 (ppm)

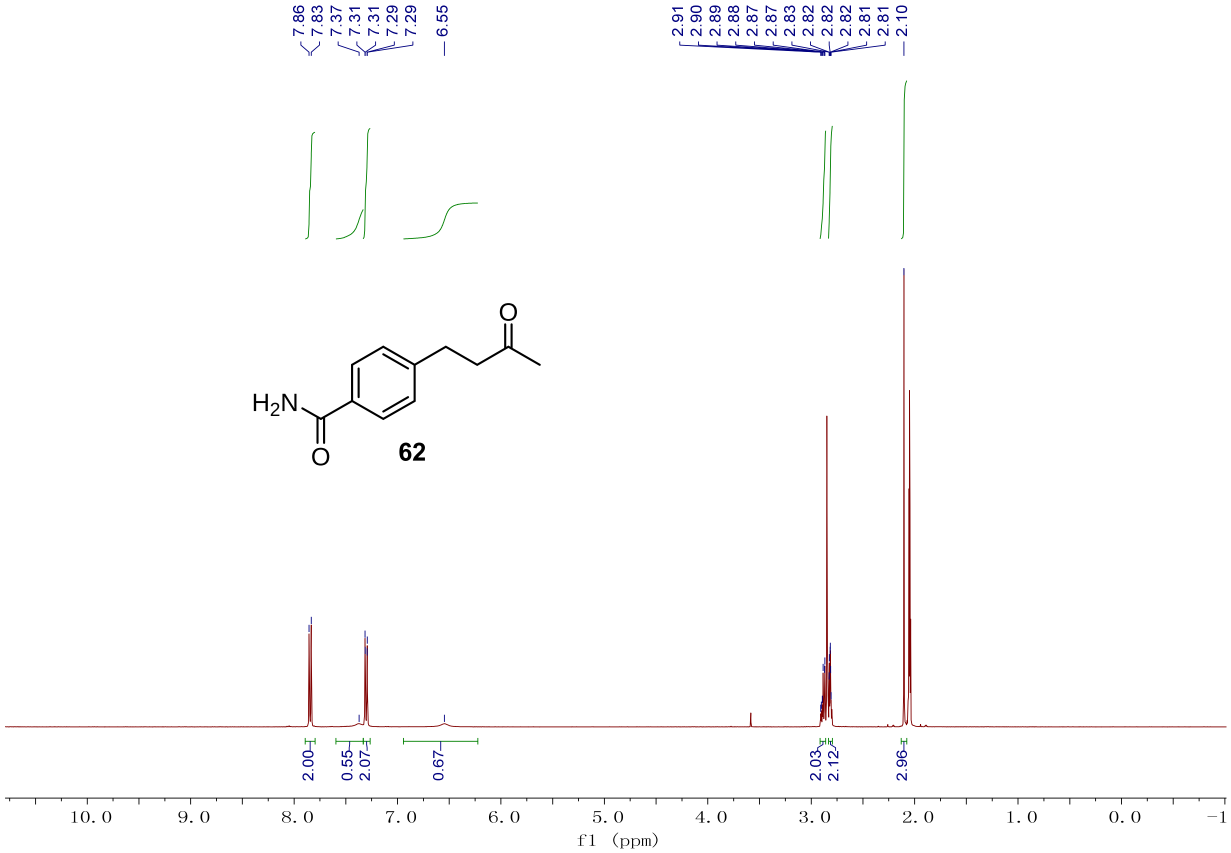


60

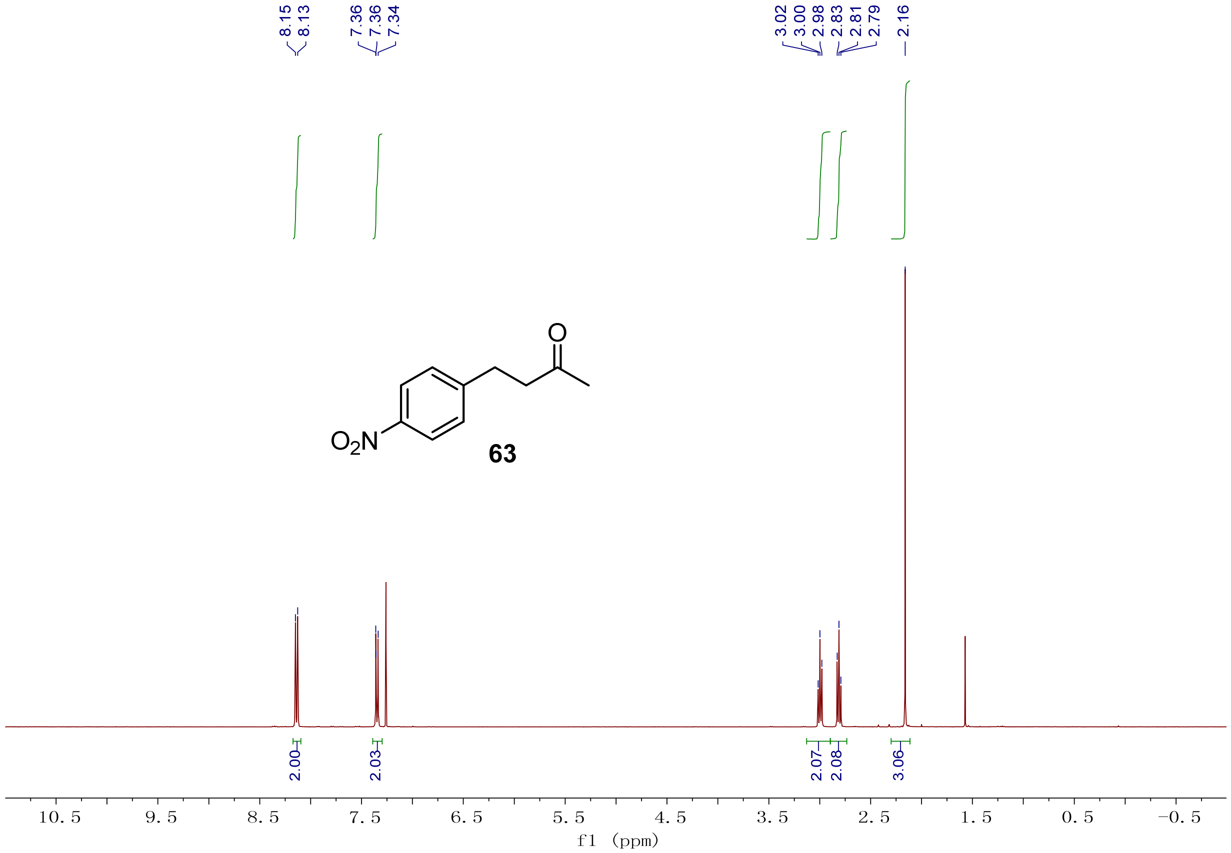
7.60
7.58
6.95
6.93
2.85
2.85
2.83
2.83
2.81
2.81
2.75
2.75
2.73
2.73
2.73
2.73
2.71
2.71
2.13
O
I
2.00
2.00
0.05
2.07
2.02
3.02
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
−1
−2
−3
f1 (ppm)


7.95
7.94
7.70
7.63
7.62
7.61
7.28
7.26
7.26
7.02
7.02
7.02
6.57
6.57
6.57
6.56
6.56
6.55
6.55
3.53
3.34
2.99
2.97
2.96
2.95
2.65
2.64
2.63
2.62
2.30
1.88
Me
N
NH
N
O
N
O
61'
0.98
0.98
2.09
2.24
0.95
0.93
2.94
3.03
1.99
1.95
3.06
3.02
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

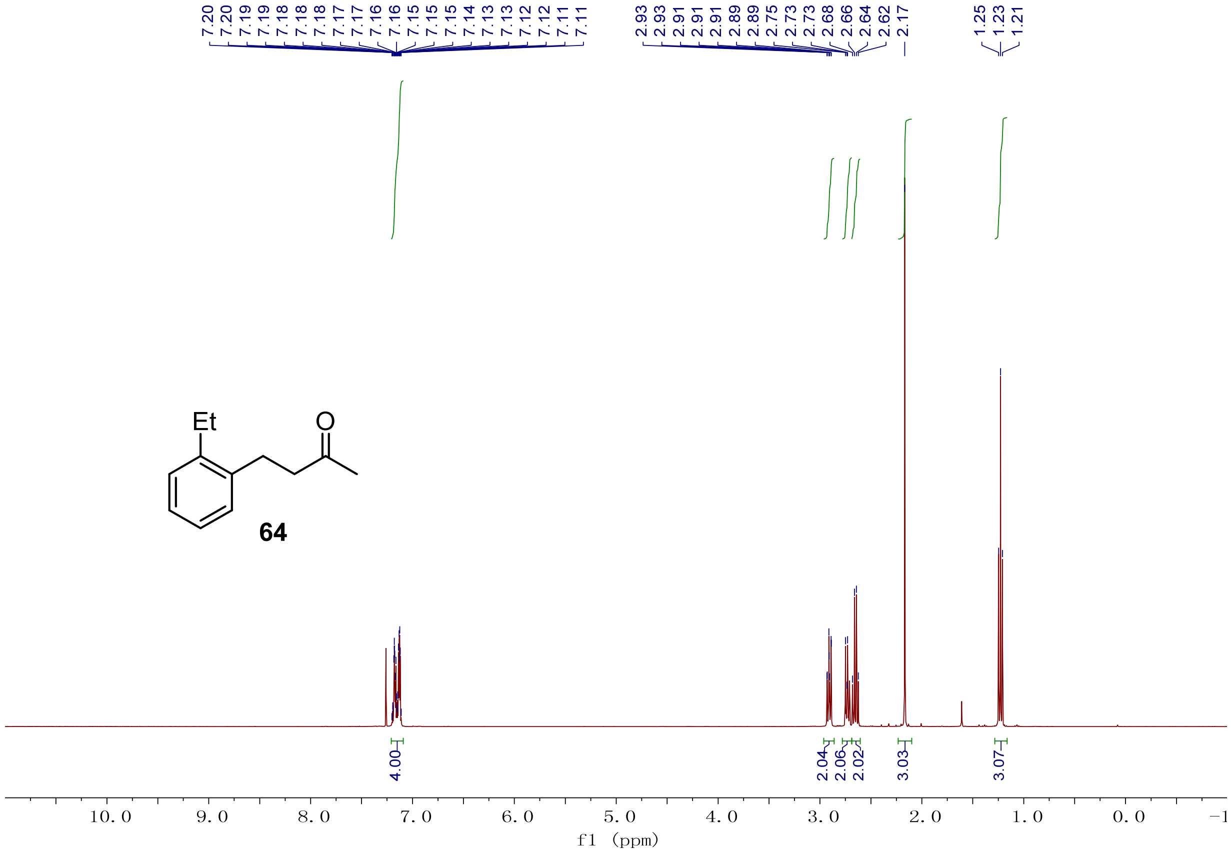

169.99
157.57
149.49
147.30
146.76
144.75
131.80
128.59
128.16
117.01
107.65
61.10
40.31
33.99
32.80
21.53
15.26
Me
N
NH
N
O
N
O
61'
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

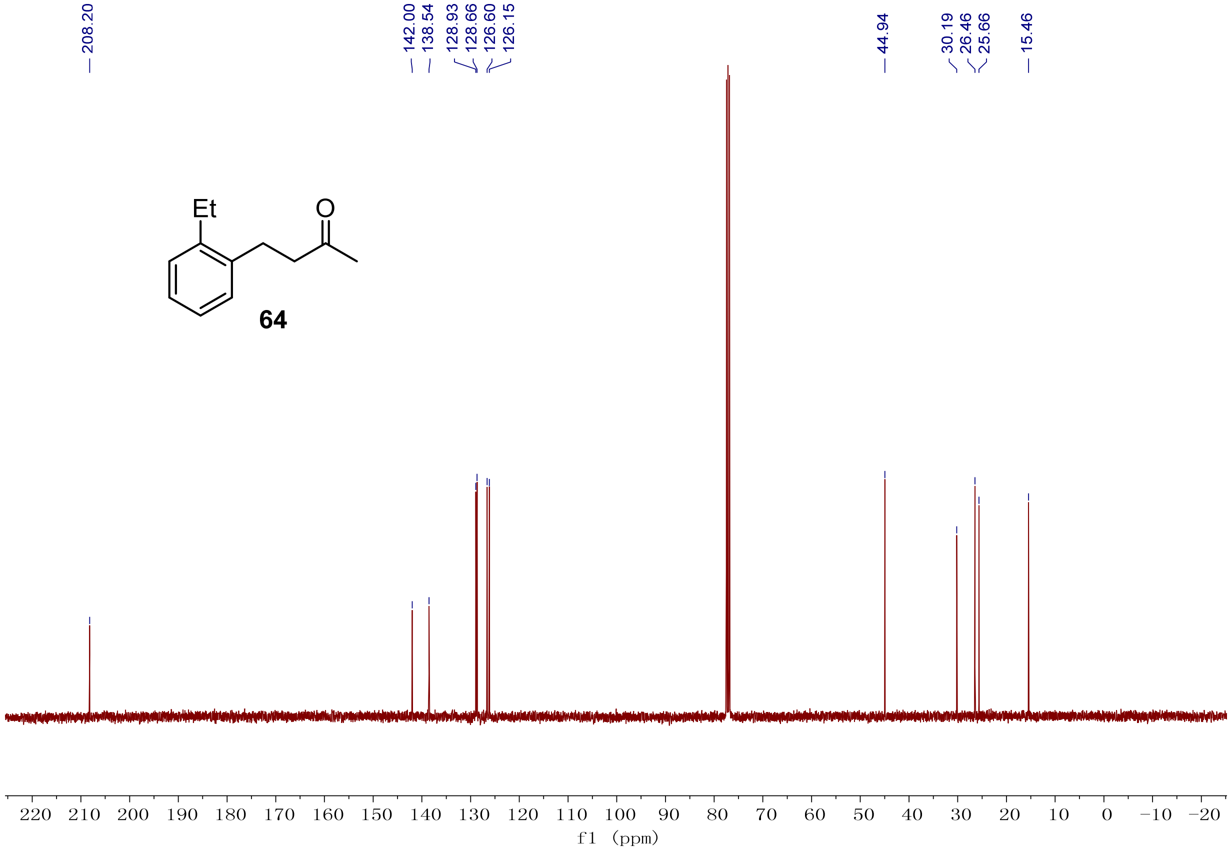

7.86
7.83
7.37
7.31
7.31
7.29
7.29
6.55
2.91
2.90
2.89
2.88
2.87
2.87
2.83
2.82
2.82
2.82
2.81
2.81
2.10
H2N
O
O
2.00
0.55
2.07
0.67
2.03
2.12
2.96
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

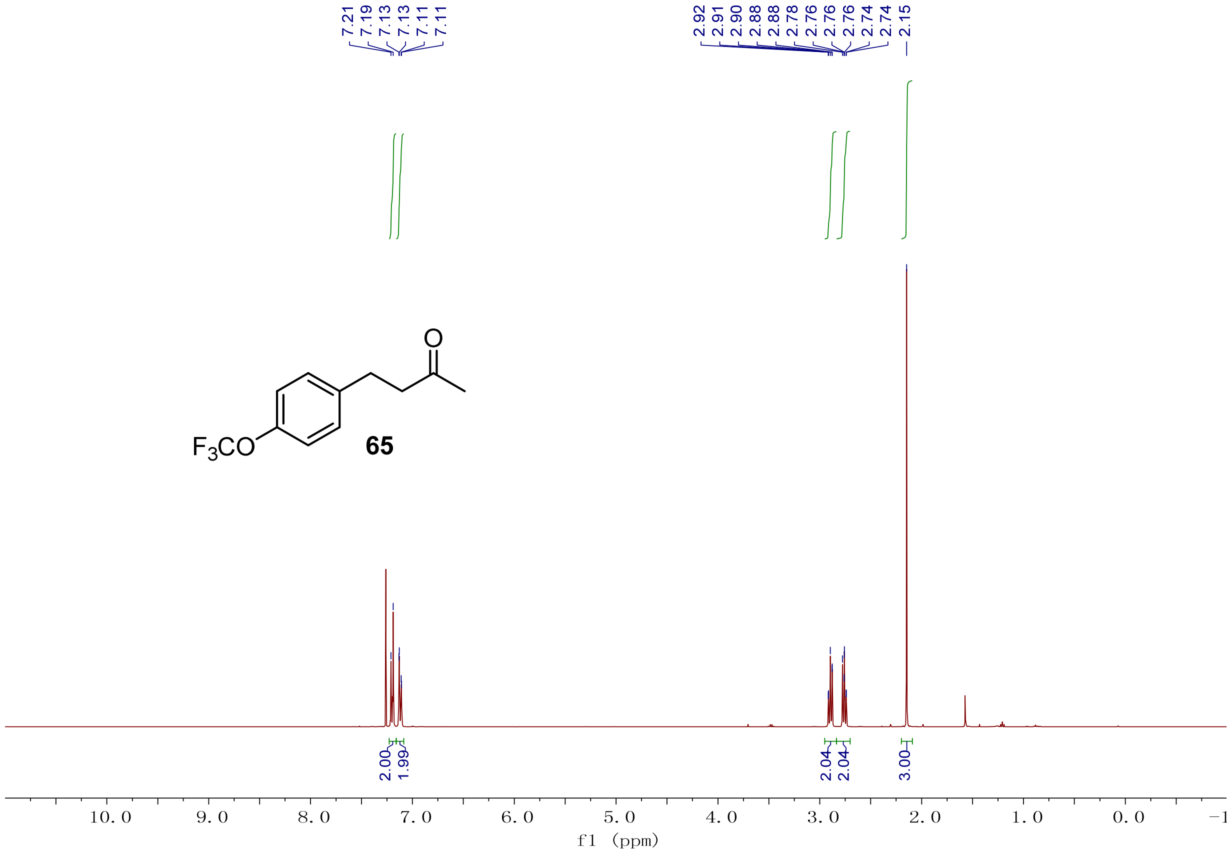
62

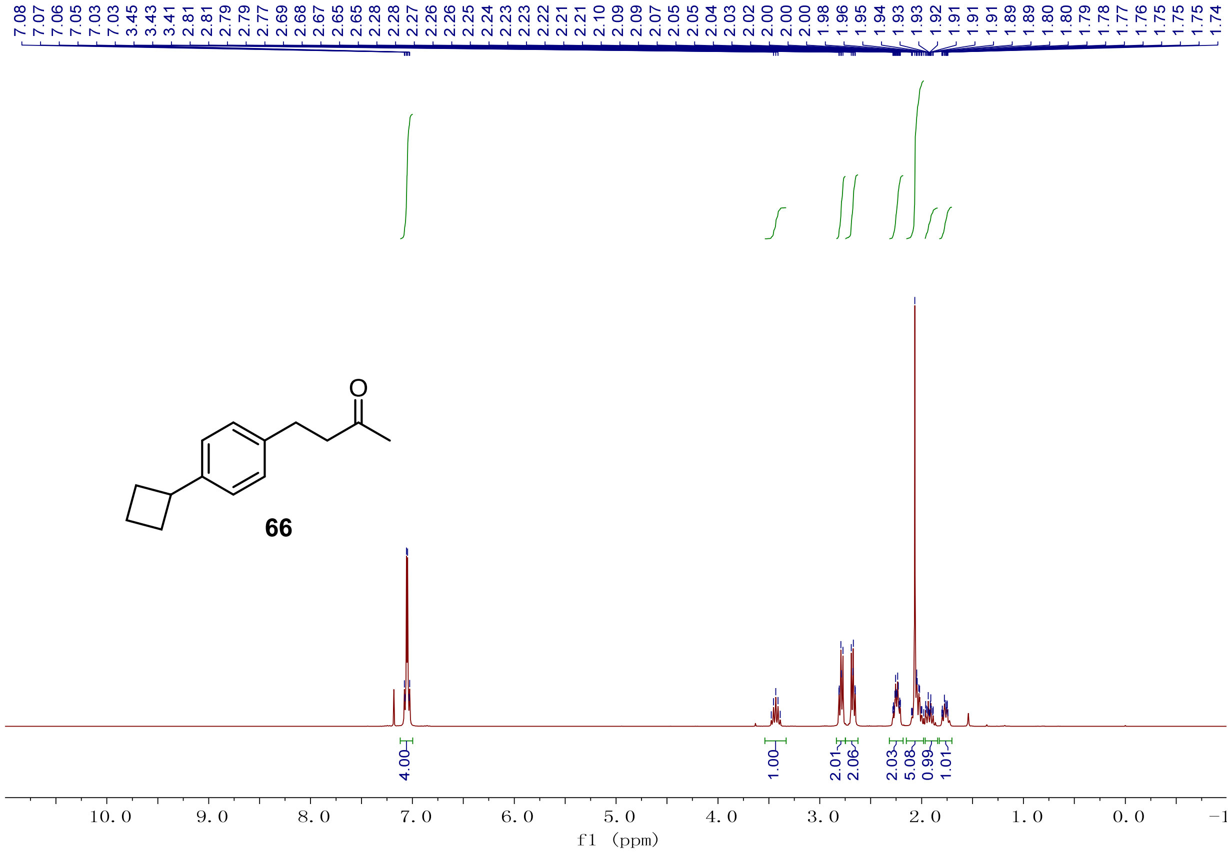

8.15
8.13
7.36
7.36
7.34
3.02
3.00
2.98
2.83
2.81
2.79
2.16
O
O2N
2.00
2.03
2.07
2.08
3.06
10.5
9.5
8.5
7.5
6.5
5.5
4.5
3.5
2.5
1.5
0.5
-0.5
f1 (ppm)

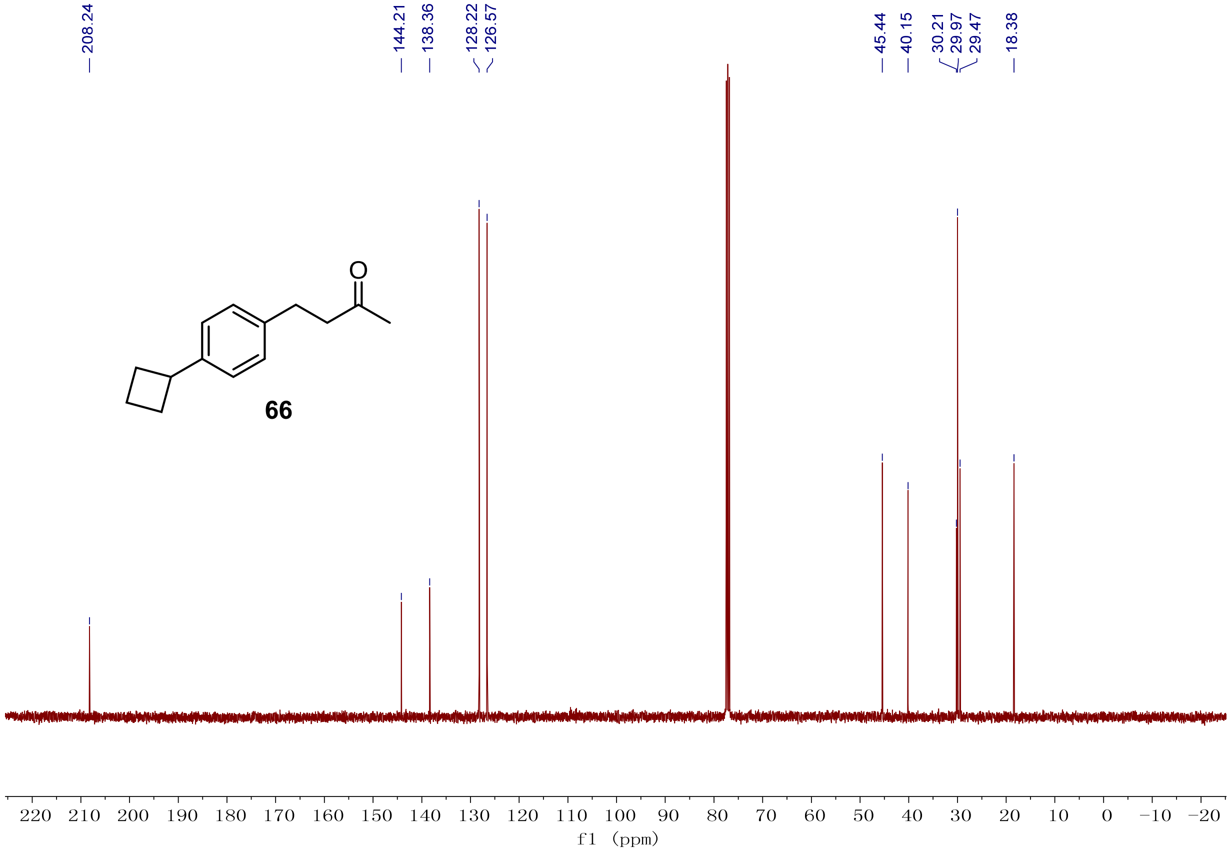
63

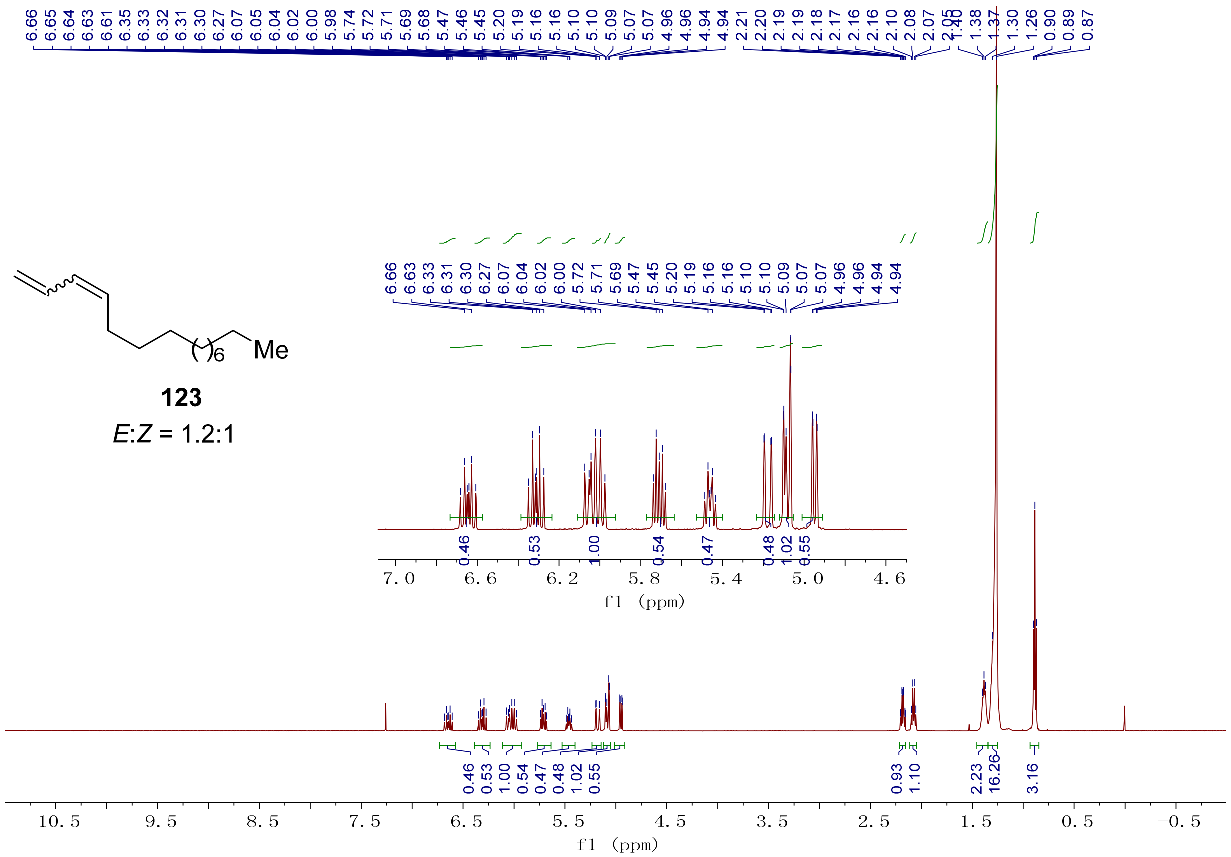

7.20
7.20
7.19
7.19
7.18
7.18
7.18
7.17
7.17
7.16
7.16
7.15
7.15
7.15
7.14
7.13
7.13
7.12
7.12
7.11
7.11
2.93
2.93
2.91
2.91
2.91
2.89
2.89
2.75
2.73
2.73
2.68
2.66
2.64
2.62
2.17
1.25
1.23
1.21
Et
O
64
4.00
2.04
2.06
2.02
3.03
3.07
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)


208.20
142.00
138.54
128.93
128.66
126.60
126.15
44.94
30.19
26.46
25.66
15.46
Et
O
64
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)


7.21
7.19
7.13
7.13
7.11
7.11
2.92
2.91
2.90
2.88
2.88
2.78
2.76
2.76
2.76
2.74
2.74
2.15
O
F3CO
65
2.00
1.99
2.04
2.04
3.00
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

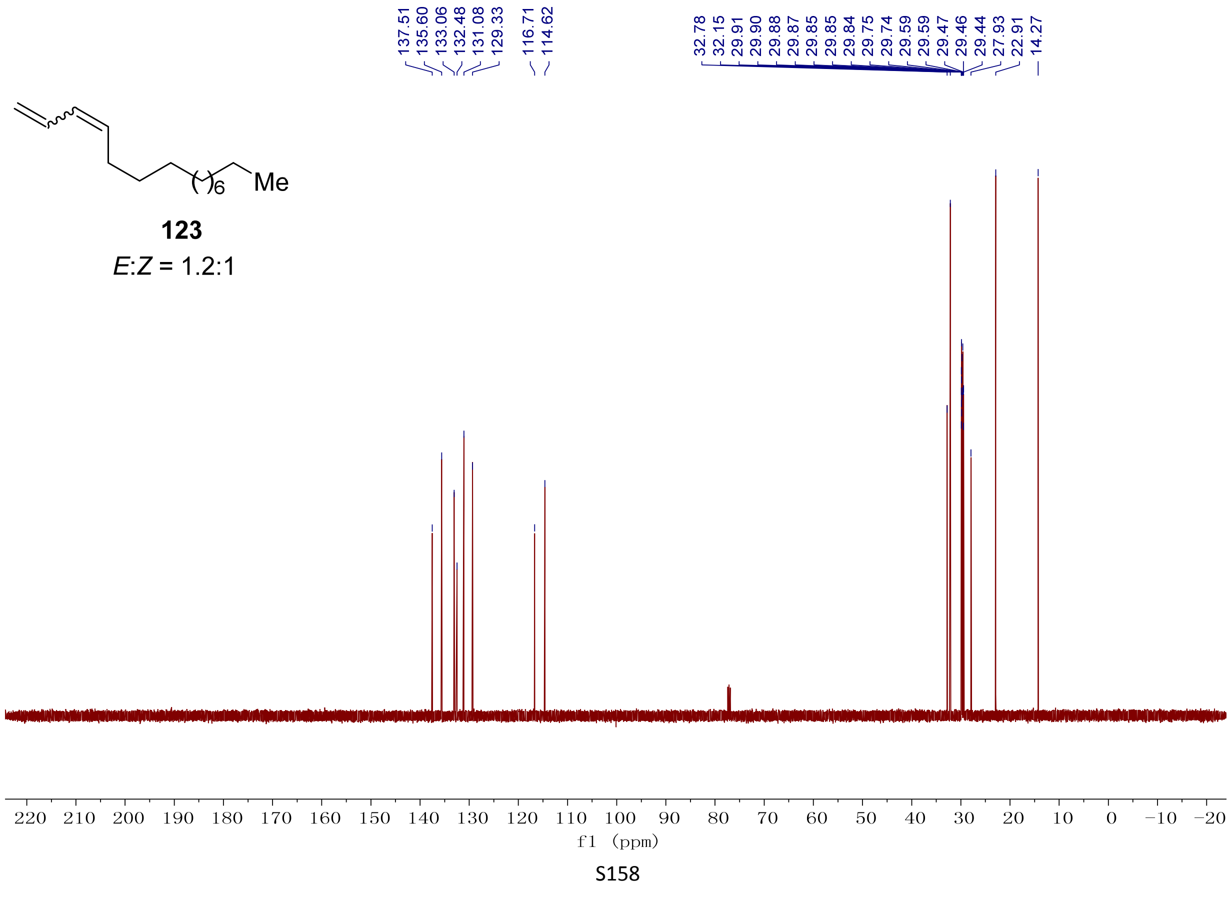

7.08
7.07
7.06
7.05
7.03
7.03
3.45
3.43
3.41
2.81
2.81
2.79
2.77
2.69
2.68
2.67
2.65
2.65
2.28
2.28
2.27
2.26
2.26
2.25
2.24
2.23
2.23
2.22
2.21
2.21
2.10
2.09
2.09
2.07
2.05
2.05
2.04
2.03
2.02
2.00
2.00
2.00
1.98
1.96
1.95
1.94
1.93
1.93
1.92
1.91
1.91
1.91
1.89
1.89
1.80
1.80
1.79
1.78
1.77
1.76
1.75
1.75
1.74
O
66
4.00
1.00
2.01
2.06
2.03
5.08
0.99
1.01
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)


208.24
144.21
138.36
128.22
126.57
45.44
40.15
30.21
29.97
29.47
18.38
O
66
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)



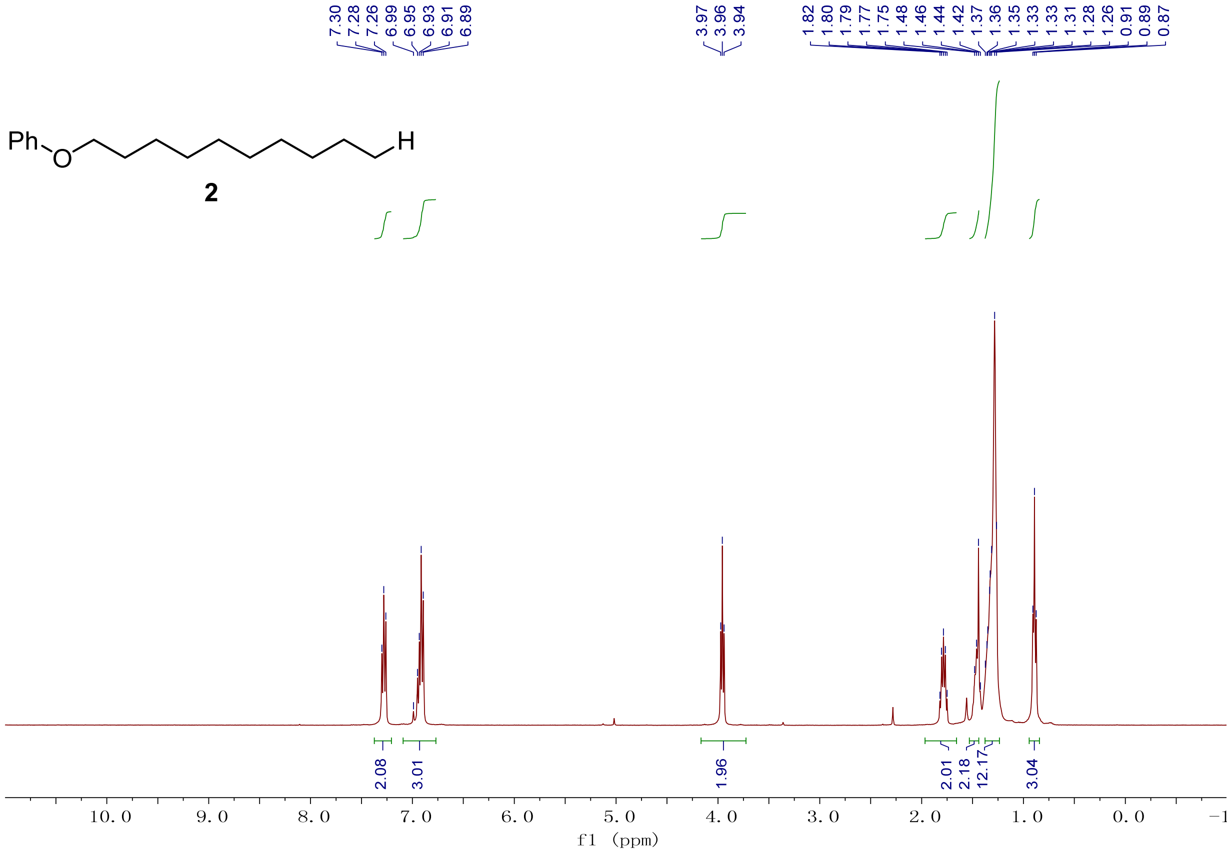
123

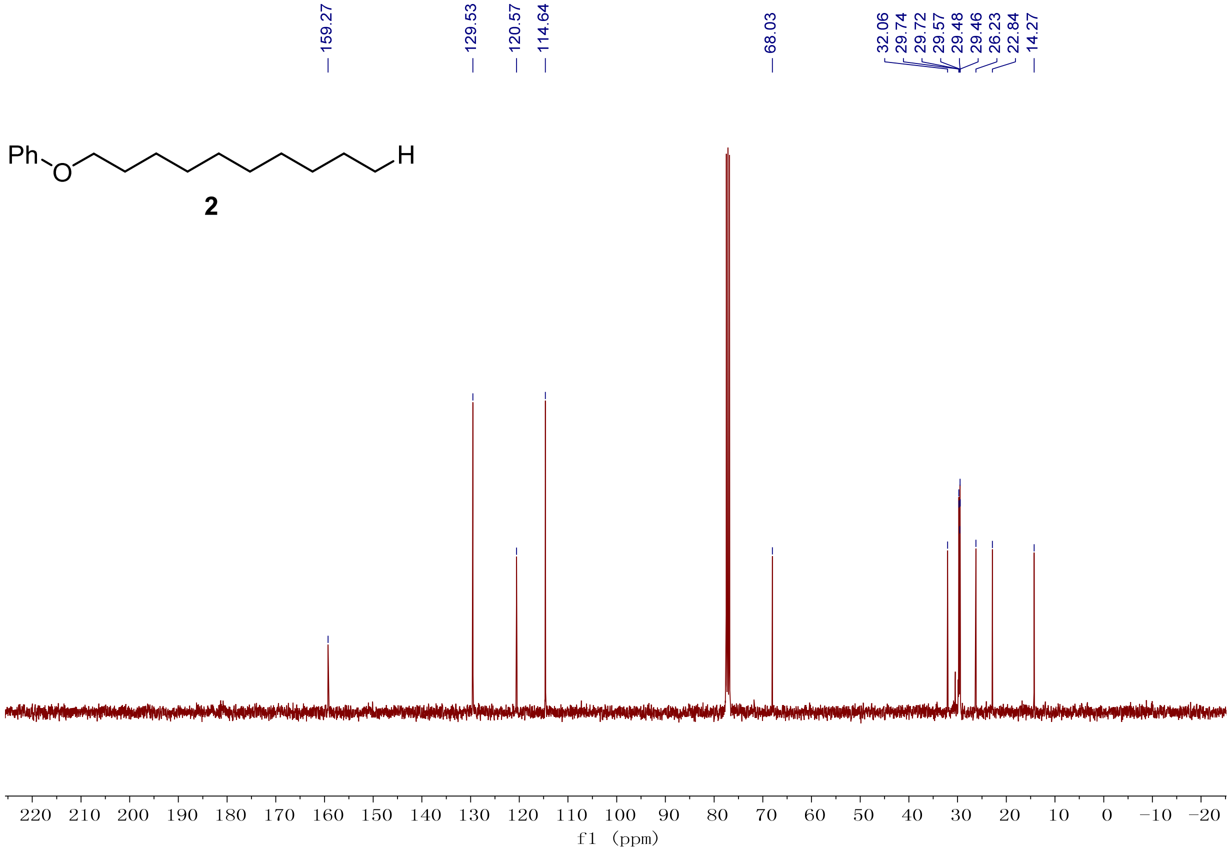
E:*Z* = 1.2:1

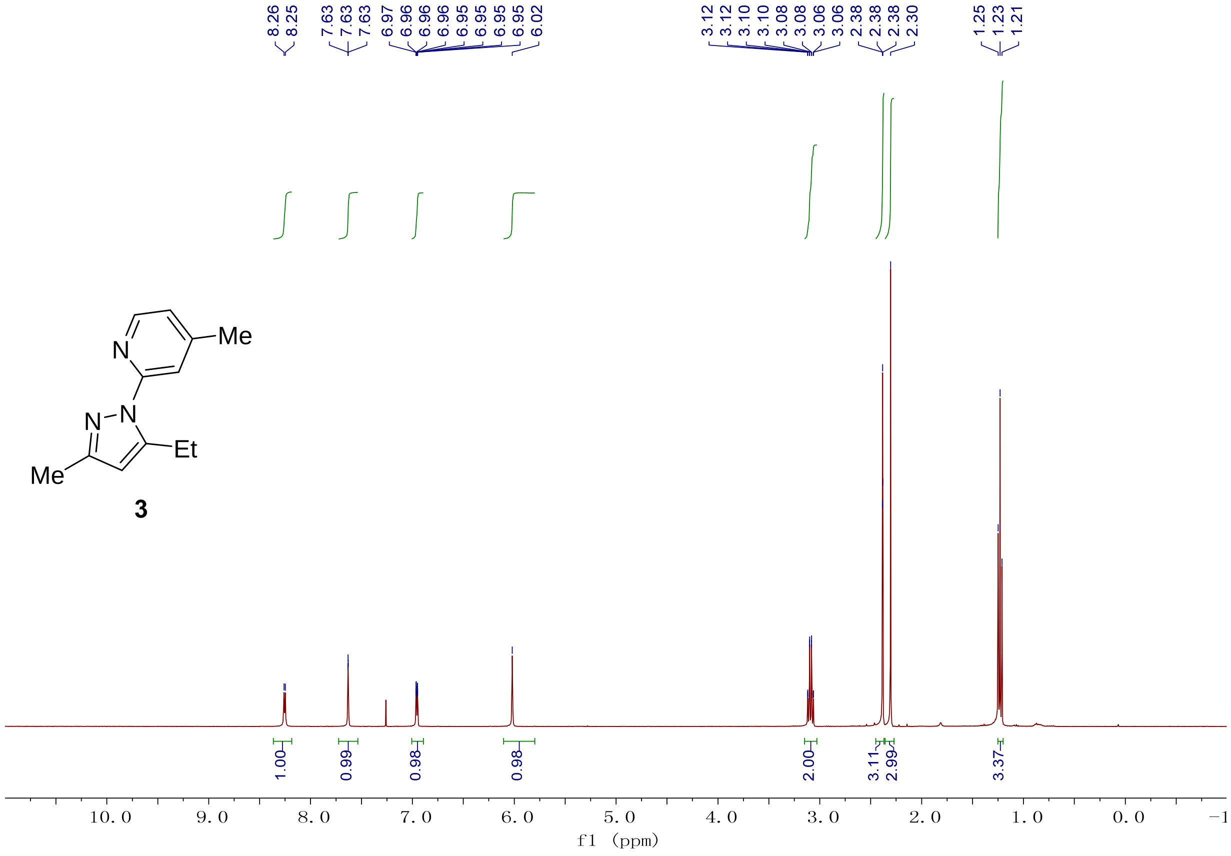


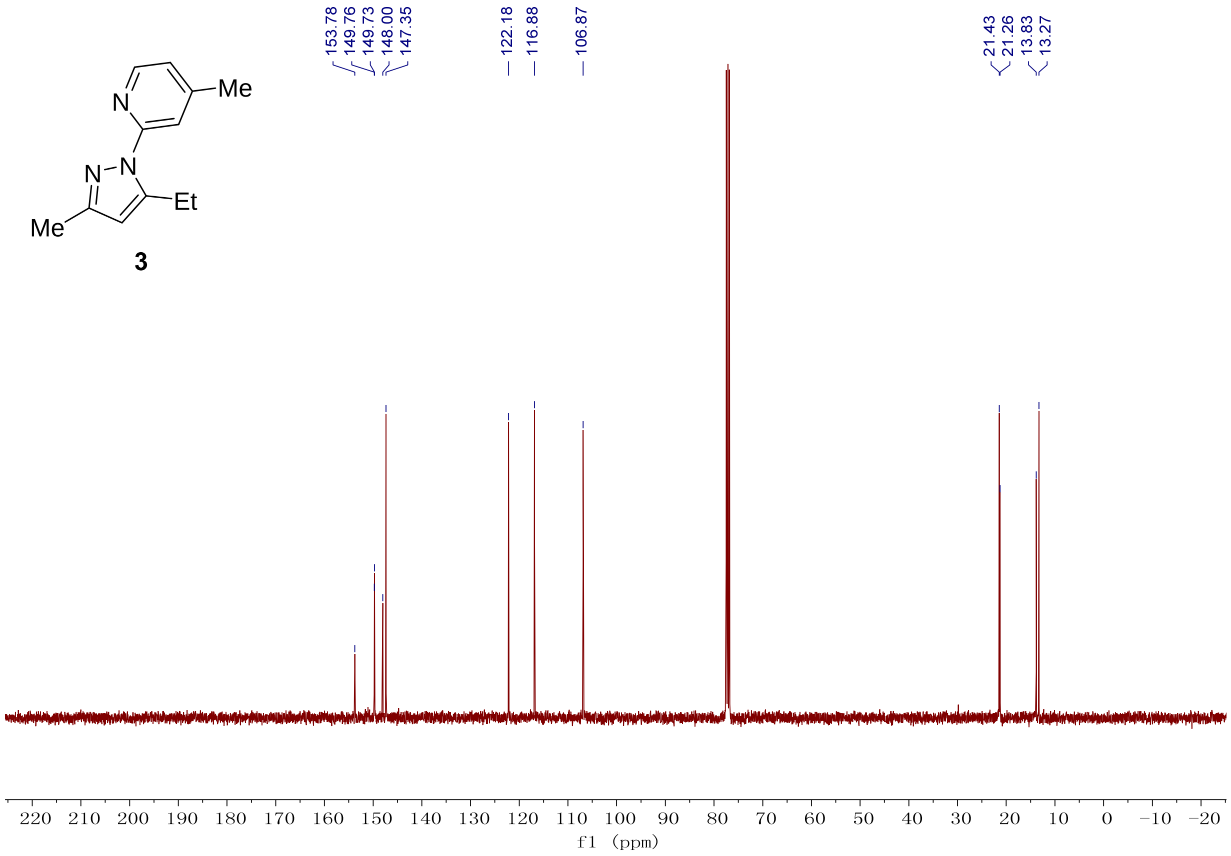
123

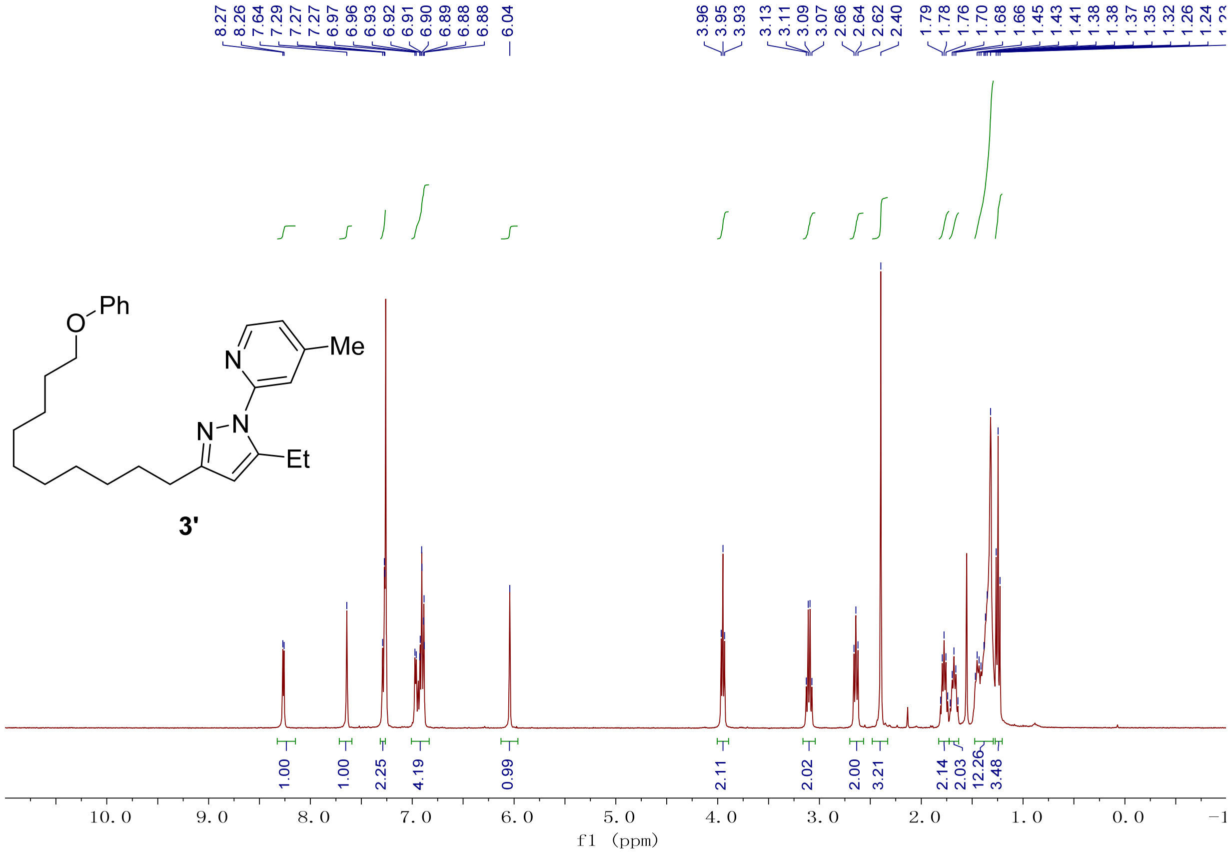
E:*Z* = 1.2:1

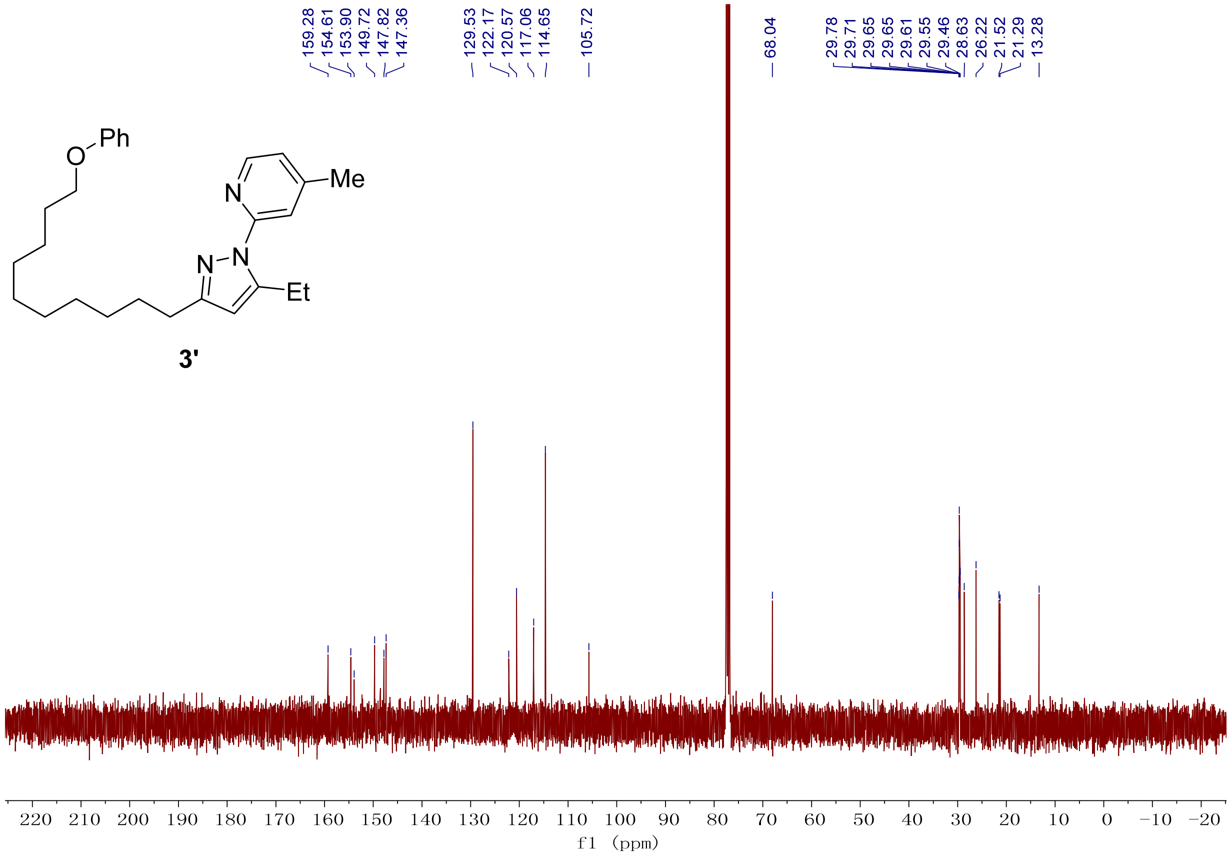

7.30
7.28
7.26
6.99
6.95
6.93
6.91
6.89
3.97
3.96
3.94
1.82
1.80
1.79
1.77
1.75
1.48
1.46
1.44
1.42
1.37
1.36
1.35
1.33
1.33
1.31
1.28
1.26
0.91
0.89
0.87
Ph
O
H
2
2.08
3.01
1.96
2.01
2.18
12.17
3.04
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

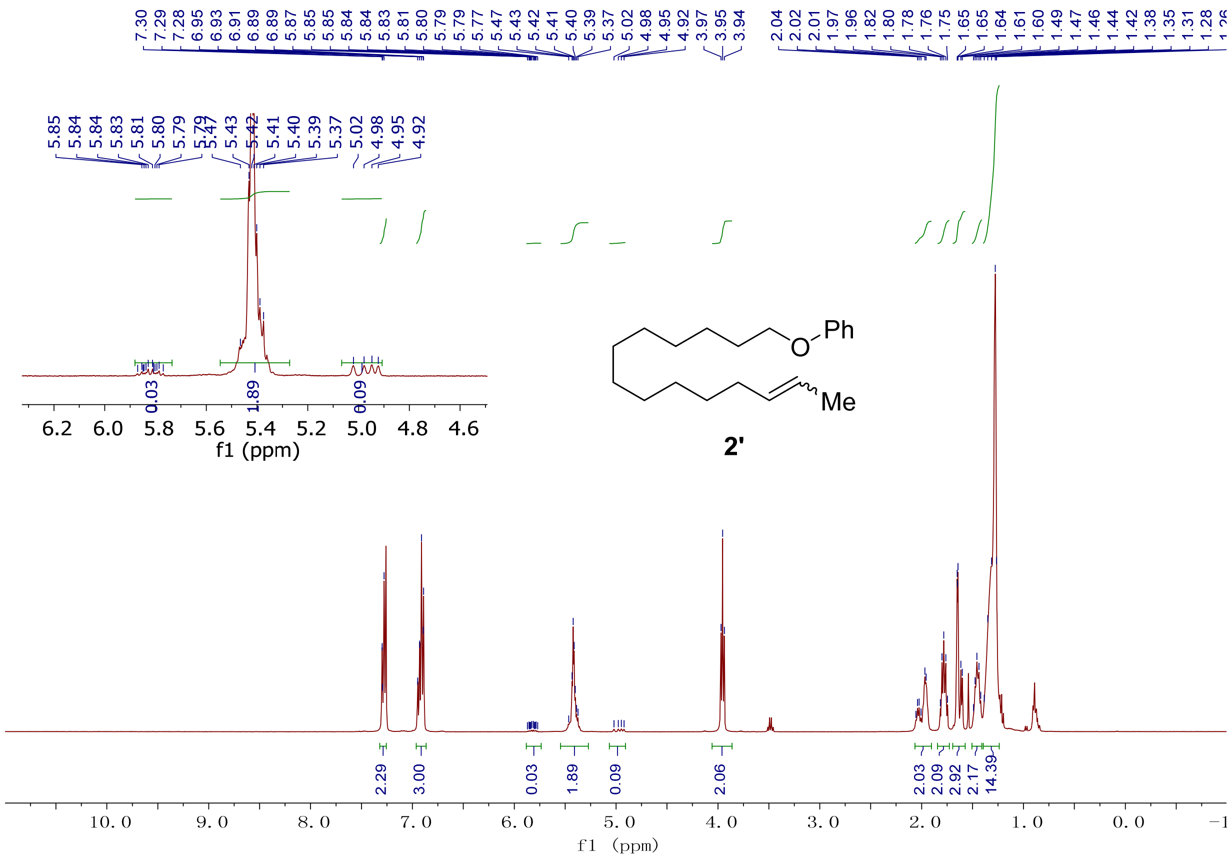

159.27
129.53
120.57
114.64
68.03
32.06
29.74
29.72
29.57
29.48
29.46
26.23
22.84
14.27
Ph
O
H
2
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
−10
−20
f1 (ppm)

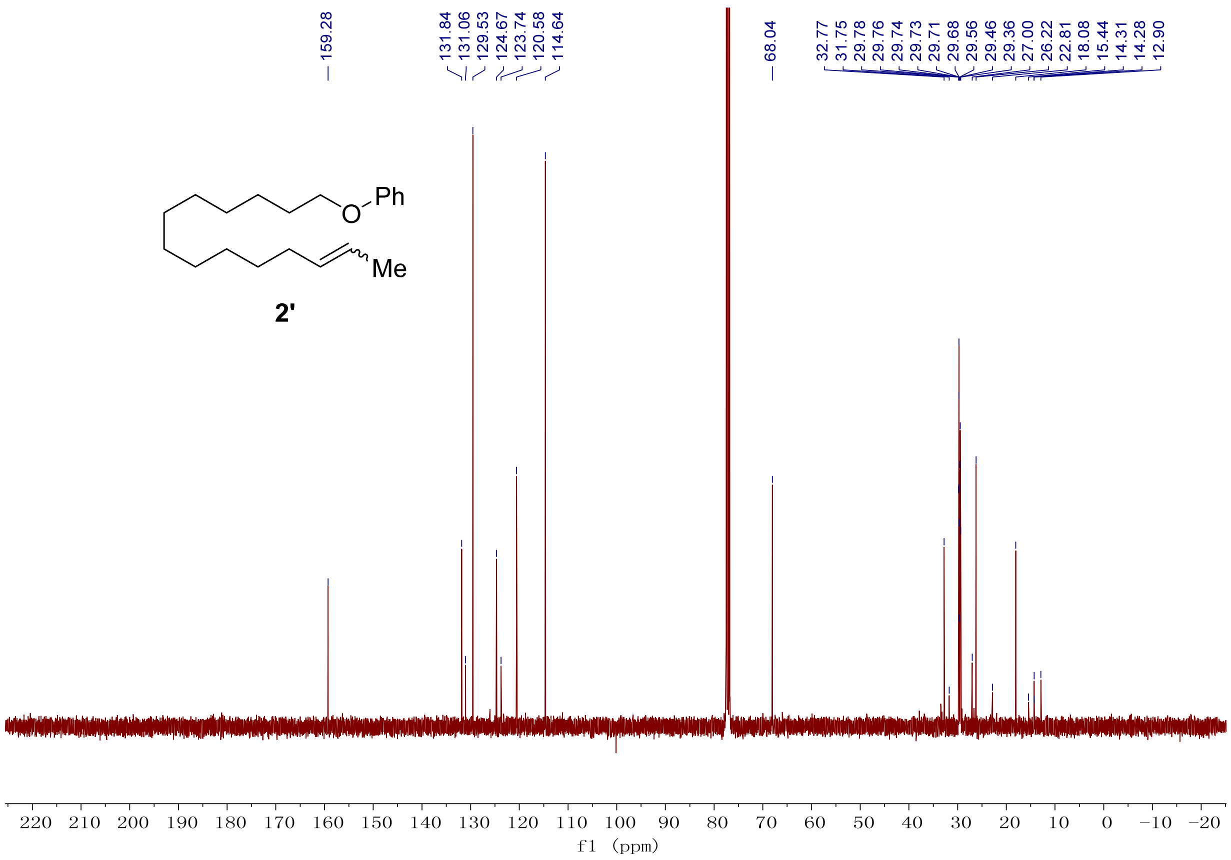

8.26
8.25
7.63
7.63
7.63
6.97
6.96
6.96
6.96
6.95
6.95
6.95
6.95
6.02
3.12
3.12
3.10
3.10
3.08
3.08
3.06
3.06
2.38
2.38
2.38
2.30
1.25
1.23
1.21
N
Me
N
N
Et
Me
3
1.00
0.99
0.98
0.98
2.00
3.11
2.99
3.37
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

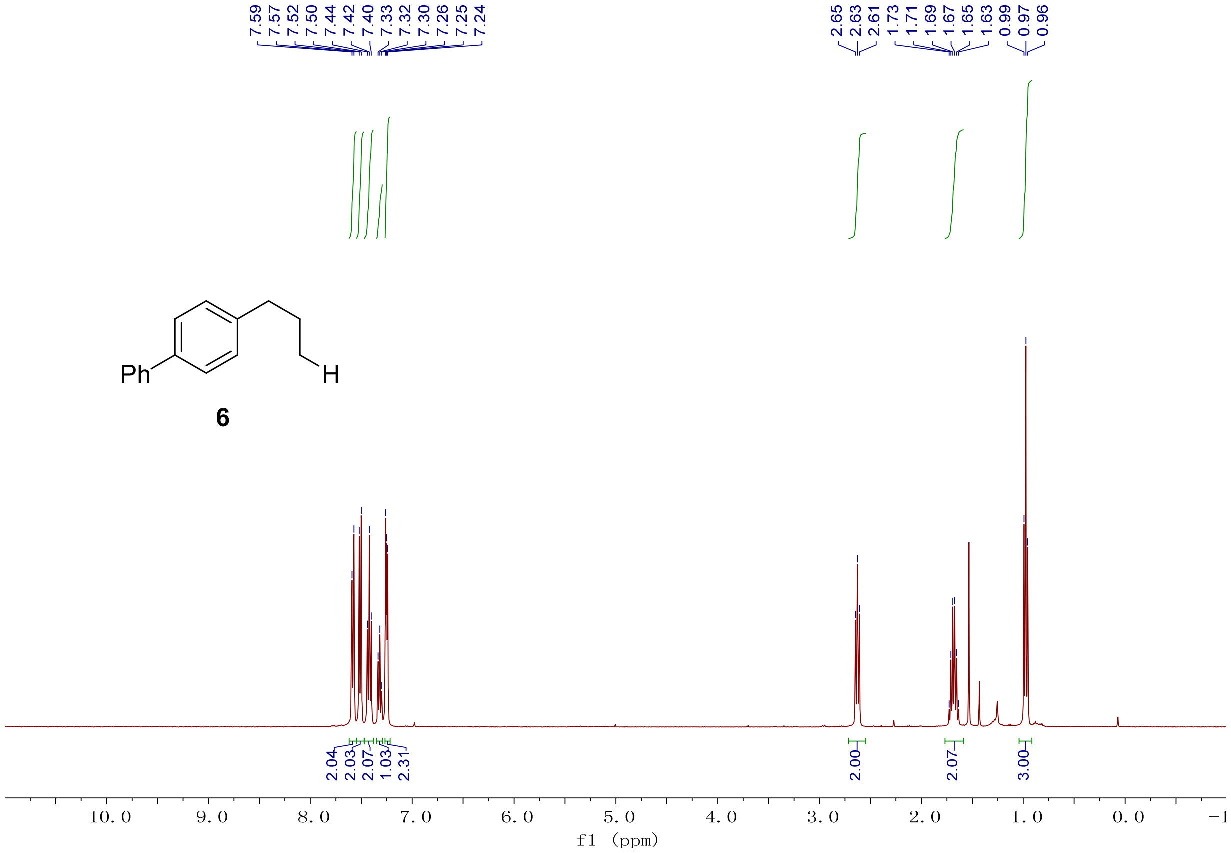

153.78
149.76
149.73
148.00
147.35
122.18
116.88
106.87
21.43
21.26
13.83
13.27
N
Me
N
N
Et
Me
3
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

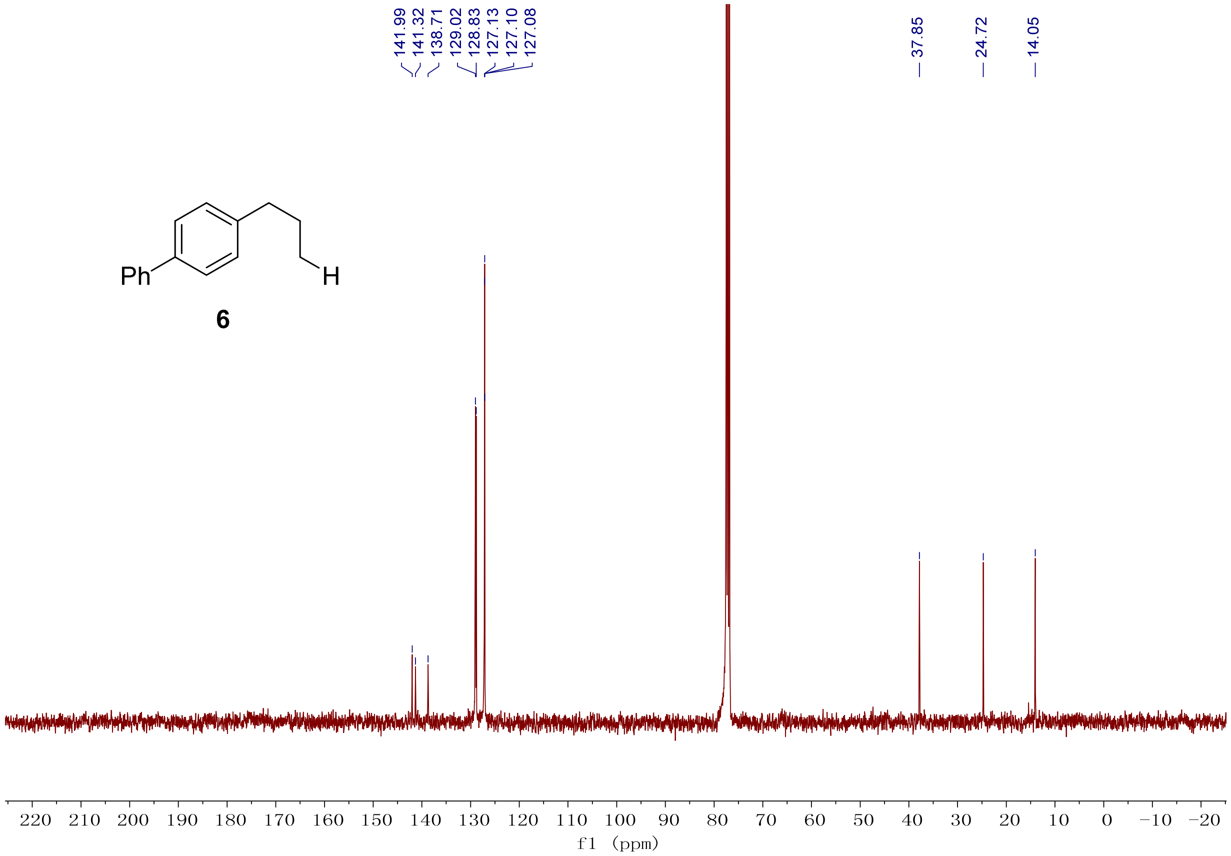

8.27
8.26
7.64
7.29
7.27
7.27
6.97
6.96
6.93
6.92
6.91
6.90
6.89
6.88
6.88
6.04
3.96
3.95
3.93
3.13
3.11
3.09
3.07
2.66
2.64
2.62
2.40
1.79
1.78
1.76
1.70
1.68
1.66
1.45
1.43
1.41
1.38
1.38
1.37
1.35
1.32
1.26
1.24
O
Ph
N
Me
N
N
Et
3'
1.00
1.00
2.25
4.19
0.99
2.11
2.02
2.00
3.21
2.14
2.03
12.26
3.48
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

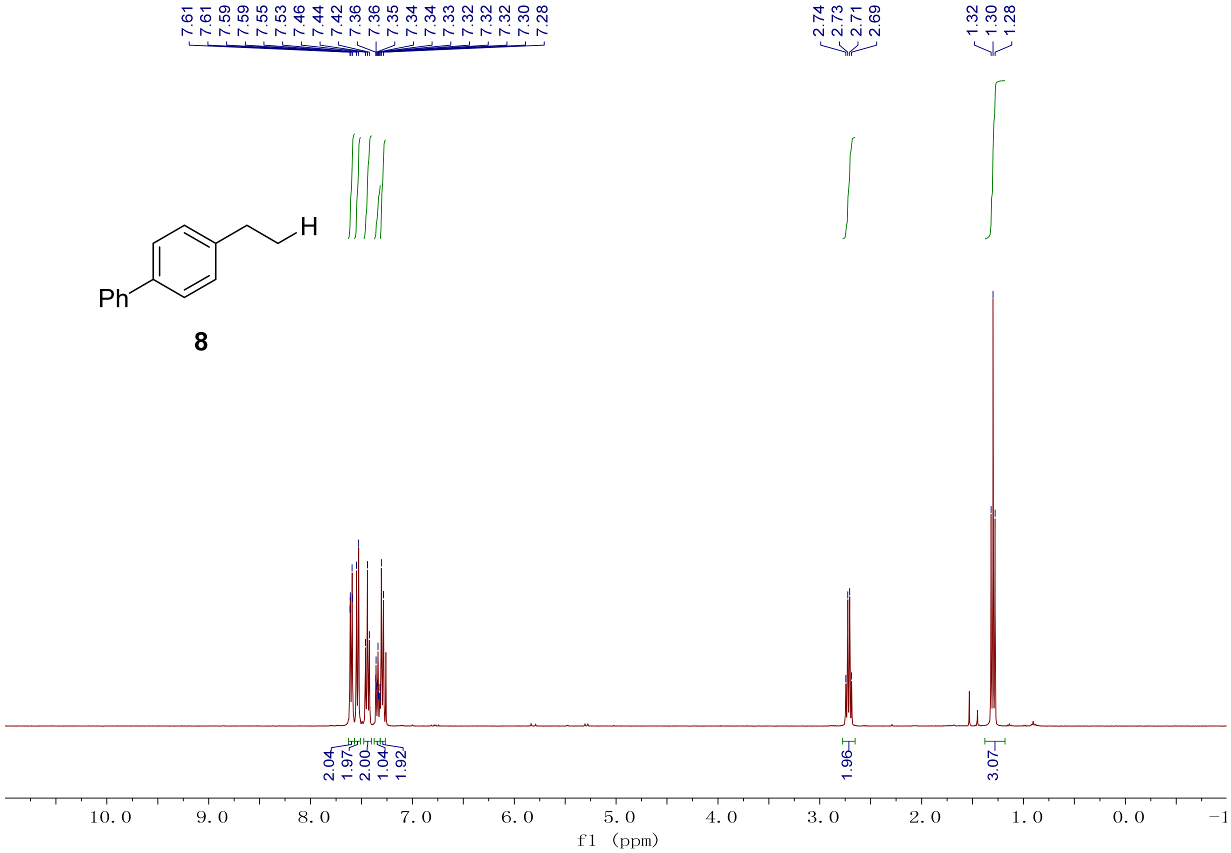

159.28
154.61
153.90
149.72
147.82
147.36
129.53
122.17
120.57
117.06
114.65
105.72
68.04
29.78
29.71
29.65
29.65
29.61
29.55
29.46
28.63
26.22
21.52
21.29
13.28
O
Ph
N
Me
N
N
Et
3'
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)


7.30
7.29
7.28
6.95
6.93
6.91
6.89
6.89
5.87
5.85
5.85
5.84
5.84
5.83
5.81
5.80
5.79
5.79
5.77
5.47
5.43
5.42
5.41
5.40
5.39
5.37
5.02
4.98
4.95
4.92
3.97
3.95
3.94
2.04
2.02
2.01
1.97
1.96
1.82
1.80
1.78
1.76
1.75
1.65
1.65
1.64
1.61
1.60
1.49
1.47
1.46
1.44
1.42
1.38
1.35
1.31
1.28
0.03
1.89
0.09
6.2
6.0
5.8
5.6
5.4
5.2
5.0
4.8
4.6
f1 (ppm)
O
Ph
Me
2'
2.29
3.00
0.03
1.89
0.09
2.06
2.03
2.09
2.92
2.17
14.39
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

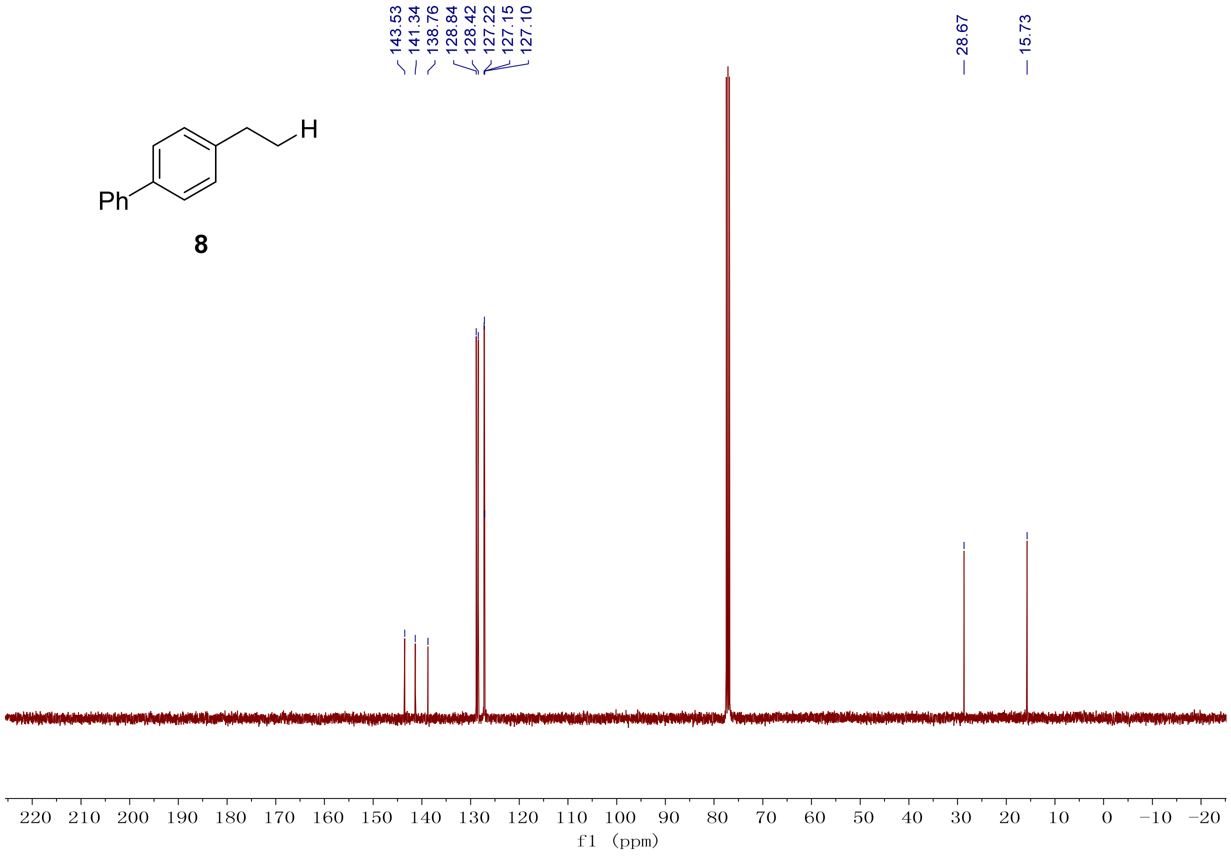

159.28
131.84
131.06
129.53
124.67
123.74
120.58
114.64
68.04
32.77
31.75
29.78
29.76
29.74
29.73
29.71
29.68
29.56
29.46
29.36
27.00
26.22
22.81
18.08
15.44
14.31
14.28
12.90
O
Ph
Me
2'
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)


7.59
7.57
7.52
7.50
7.44
7.42
7.40
7.33
7.32
7.30
7.26
7.25
7.24
2.65
2.63
2.61
1.73
1.71
1.69
1.67
1.65
1.63
0.99
0.97
0.96
Ph
H
6
2.04
2.03
2.07
1.03
2.31
2.00
2.07
3.00
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

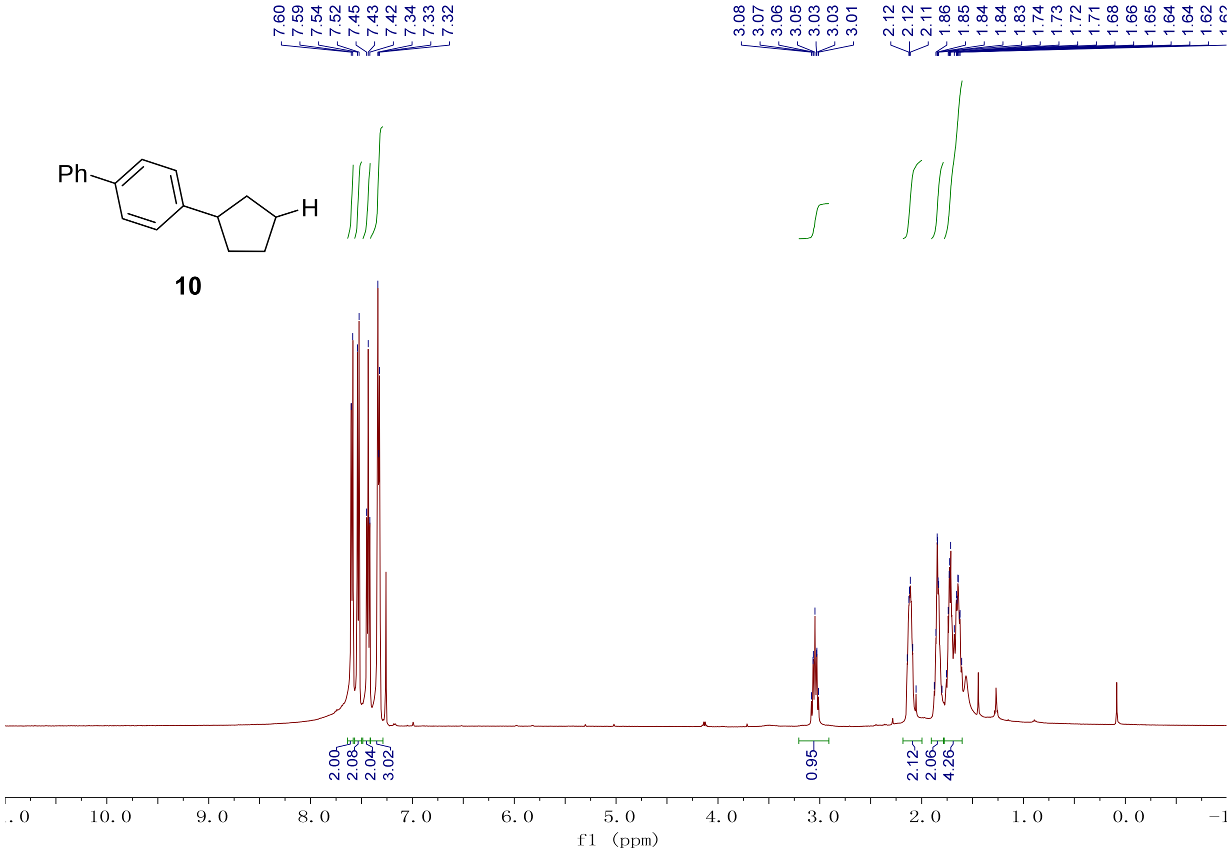

141.99
141.32
138.71
129.02
128.83
127.13
127.10
127.08
37.85
24.72
14.05
Ph
H
6
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

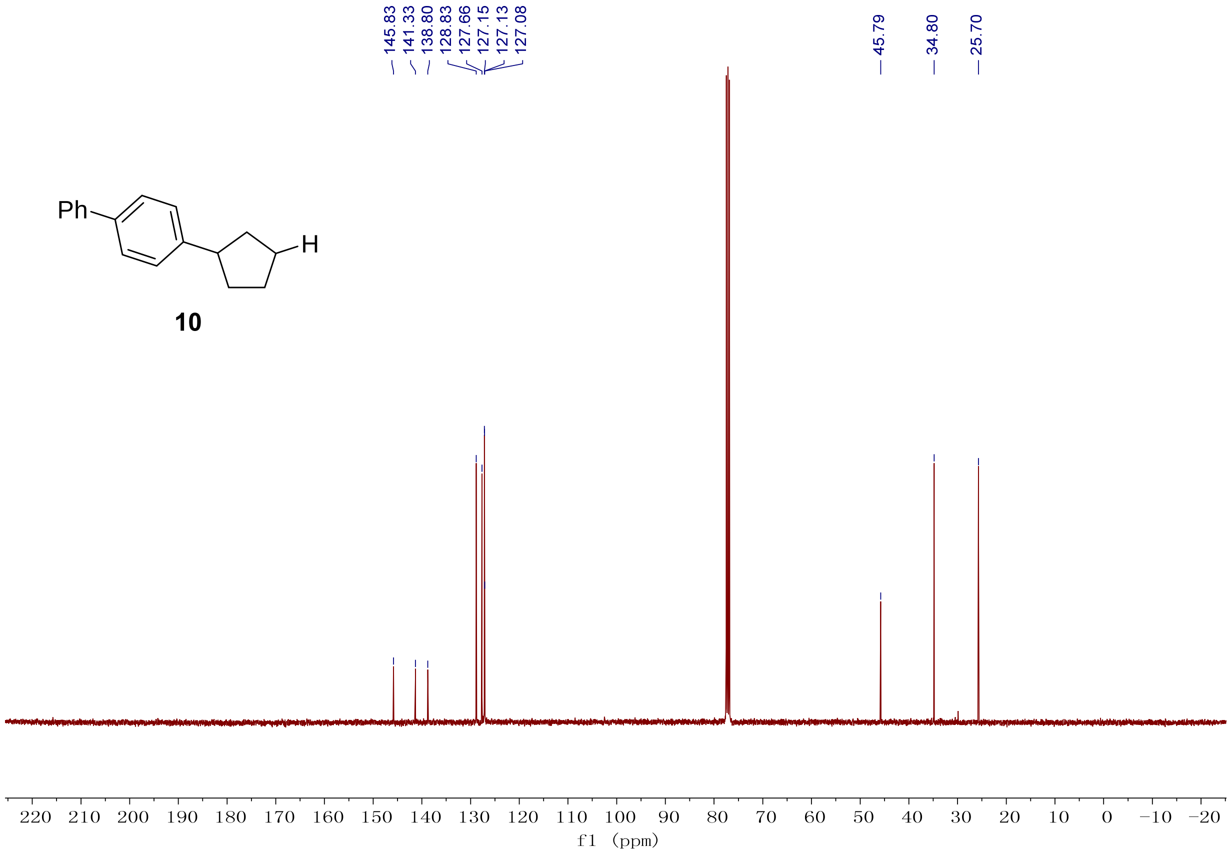

7.61
7.61
7.59
7.59
7.55
7.53
7.46
7.44
7.42
7.36
7.36
7.35
7.34
7.34
7.33
7.32
7.32
7.32
7.30
7.28
2.74
2.73
2.71
2.69
1.32
1.30
1.28
H
Ph
2.04
1.97
2.00
1.04
1.92
1.96
3.07
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

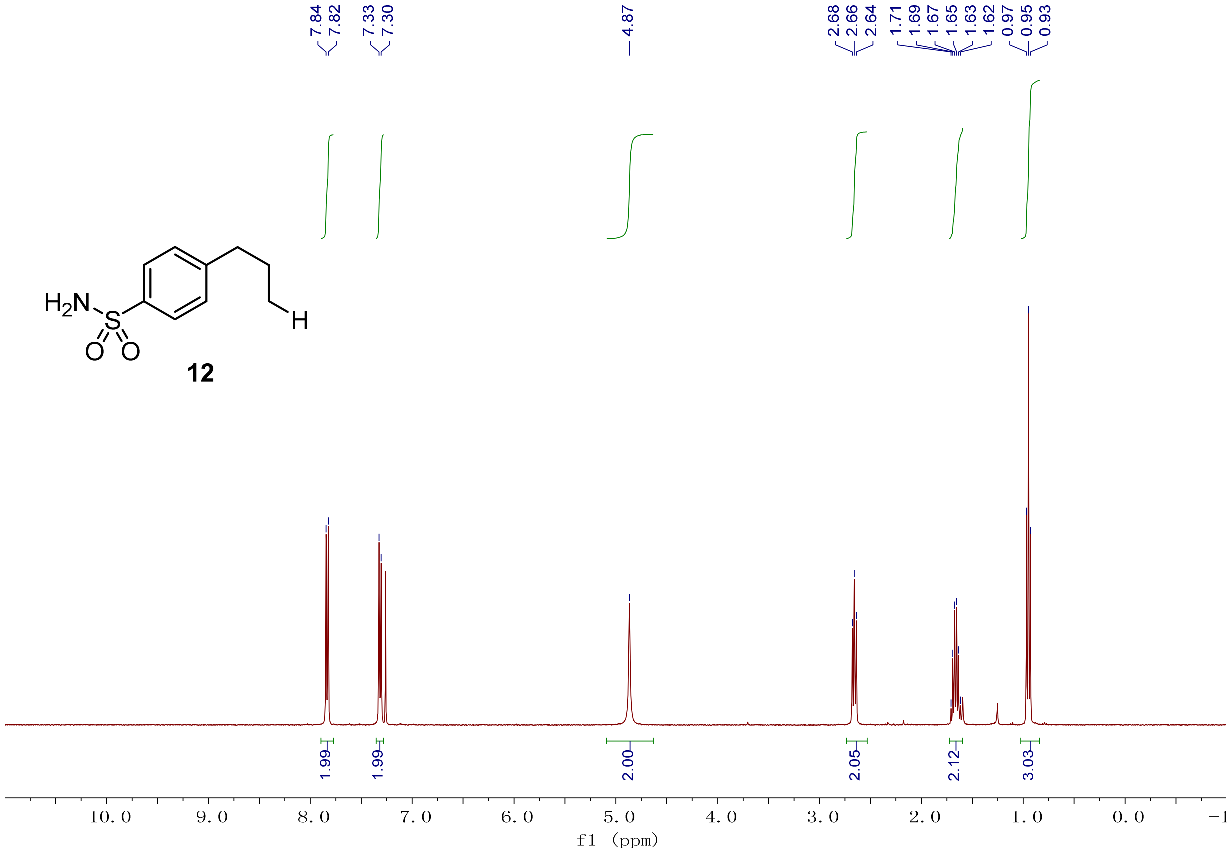
8


143.53
141.34
138.76
128.84
128.42
127.22
127.15
127.10
28.67
15.73
H
Ph
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

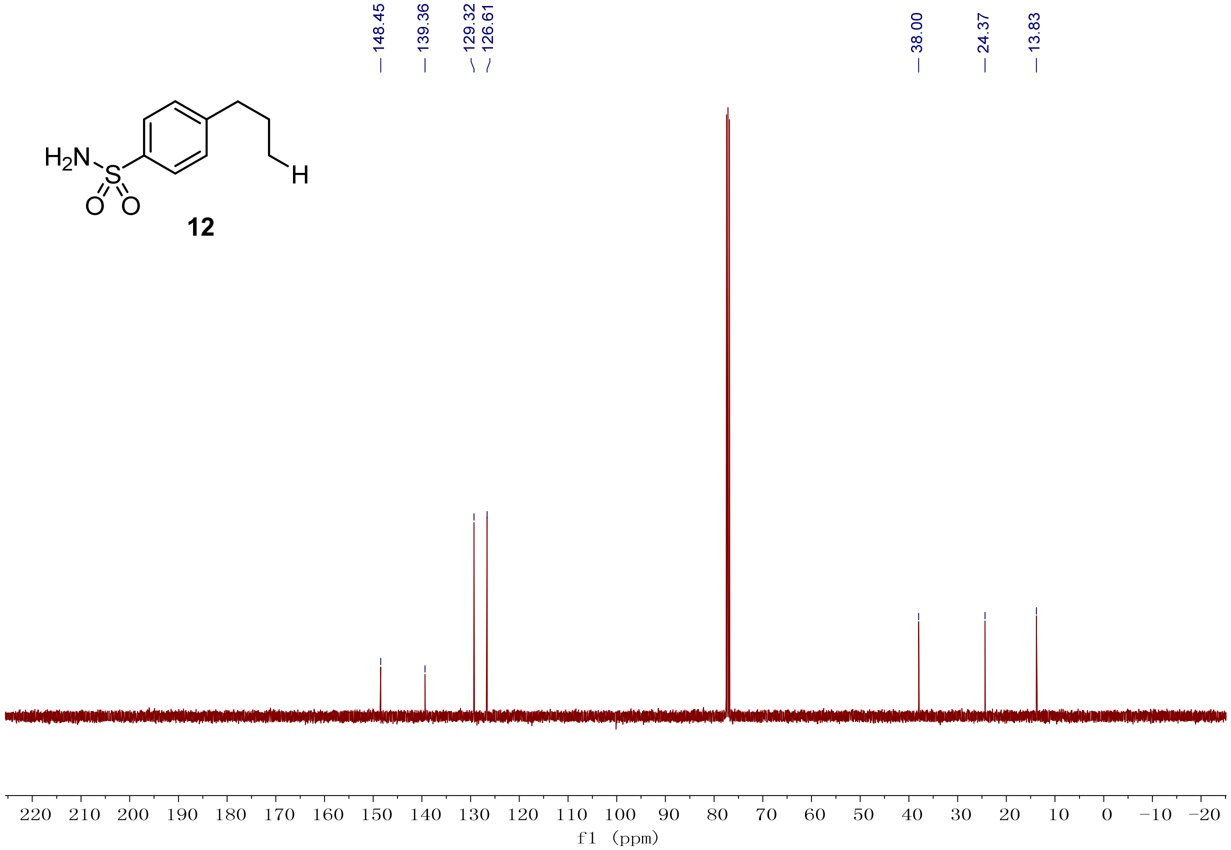
8


7.60
7.59
7.54
7.52
7.45
7.43
7.42
7.34
7.33
7.32
3.08
3.07
3.06
3.05
3.03
3.03
3.01
2.12
2.12
2.11
1.86
1.85
1.84
1.84
1.83
1.74
1.73
1.72
1.71
1.68
1.66
1.65
1.64
1.64
1.62
Ph
H
10
2.00
2.08
2.04
3.02
0.95
2.12
2.06
4.26
. 0
10. 0
9. 0
8. 0
7. 0
6. 0
5. 0
4. 0
3. 0
2. 0
1. 0
0. 0
−1
f1 (ppm)


145.83
141.33
138.80
128.83
127.66
127.15
127.13
127.08
45.79
34.80
25.70
Ph
H
10
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
−10
−20
f1 (ppm)


7.84
7.82
7.33
7.30
4.87
2.68
2.66
2.64
1.71
1.69
1.67
1.65
1.63
1.62
0.97
0.95
0.93
H$_2$N
S
O
O
H
1.99
1.99
2.00
2.05
2.12
3.03
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

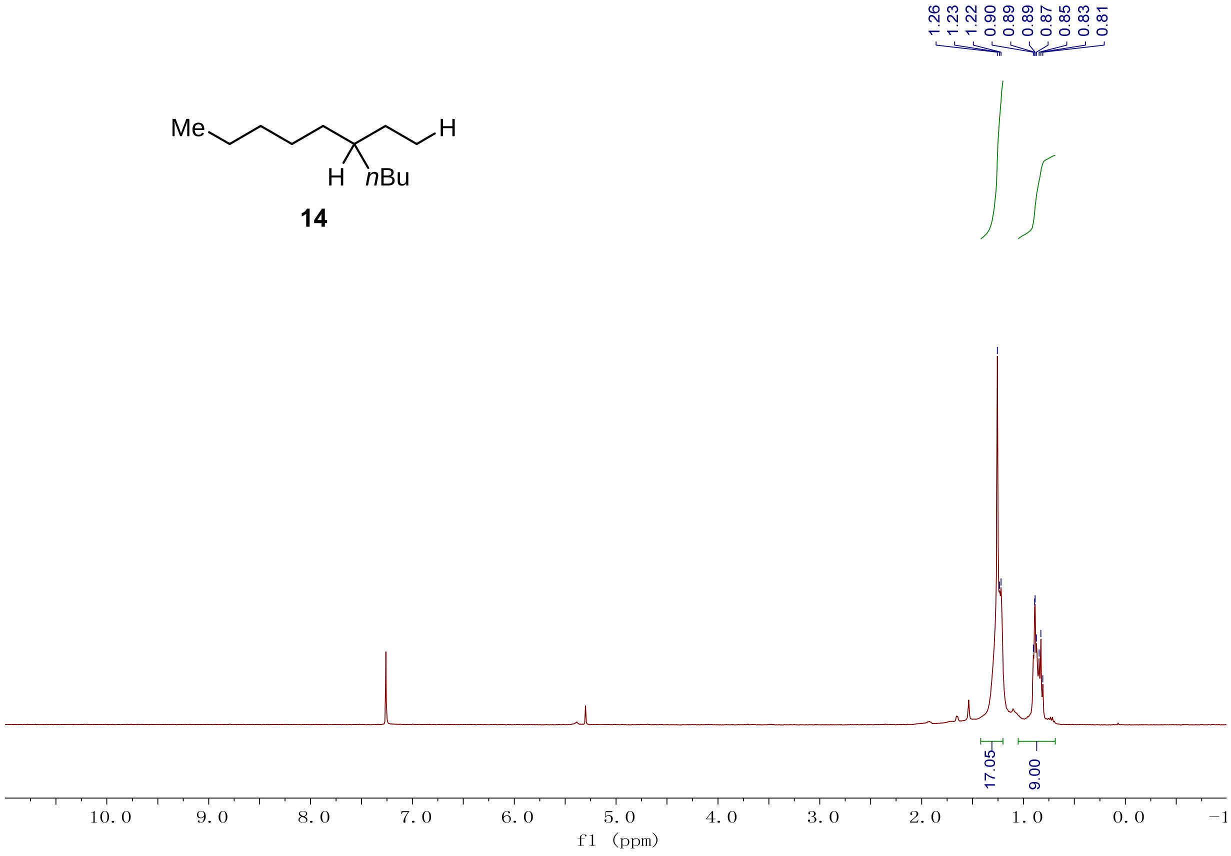
12


148.45
139.36
129.32
126.61
38.00
24.37
13.83
H$_2$N
S
O
O
H
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

12

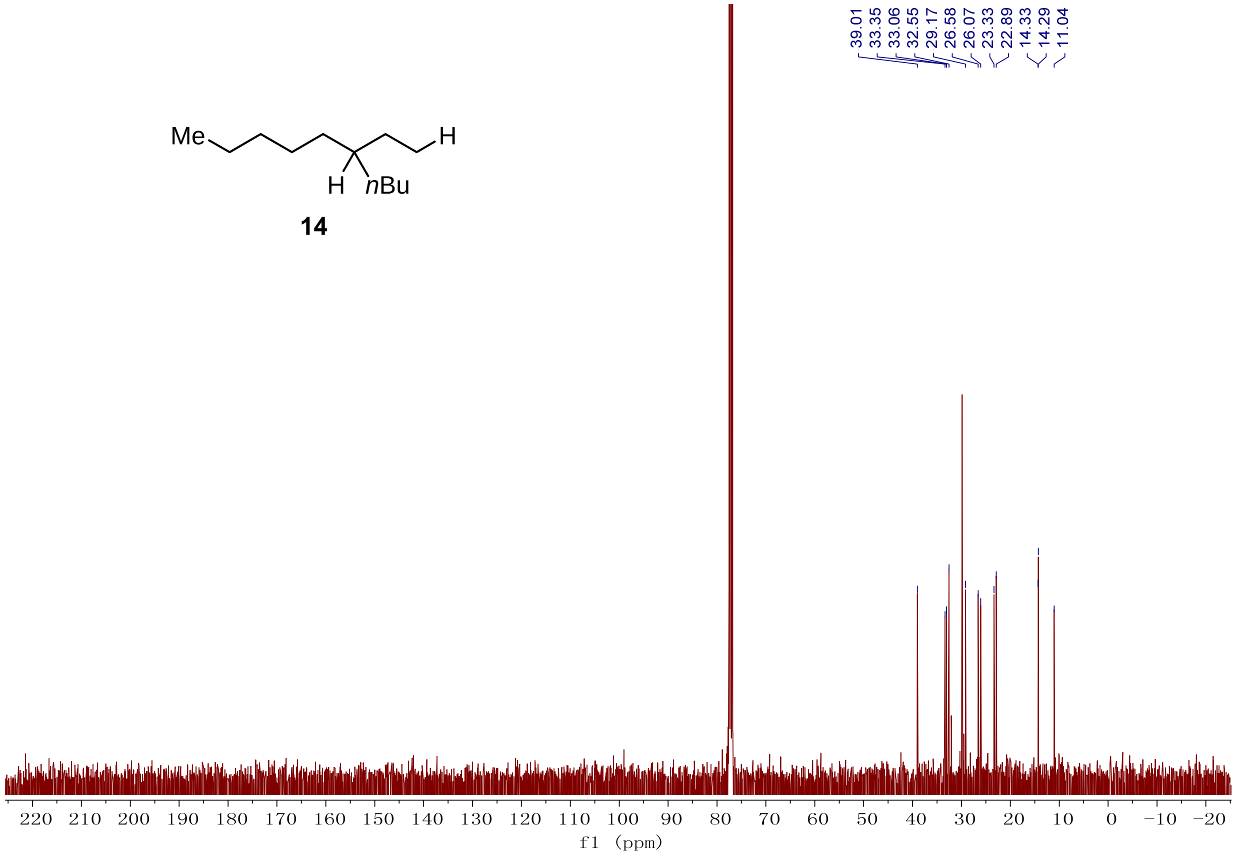
Me
H
H
nBu

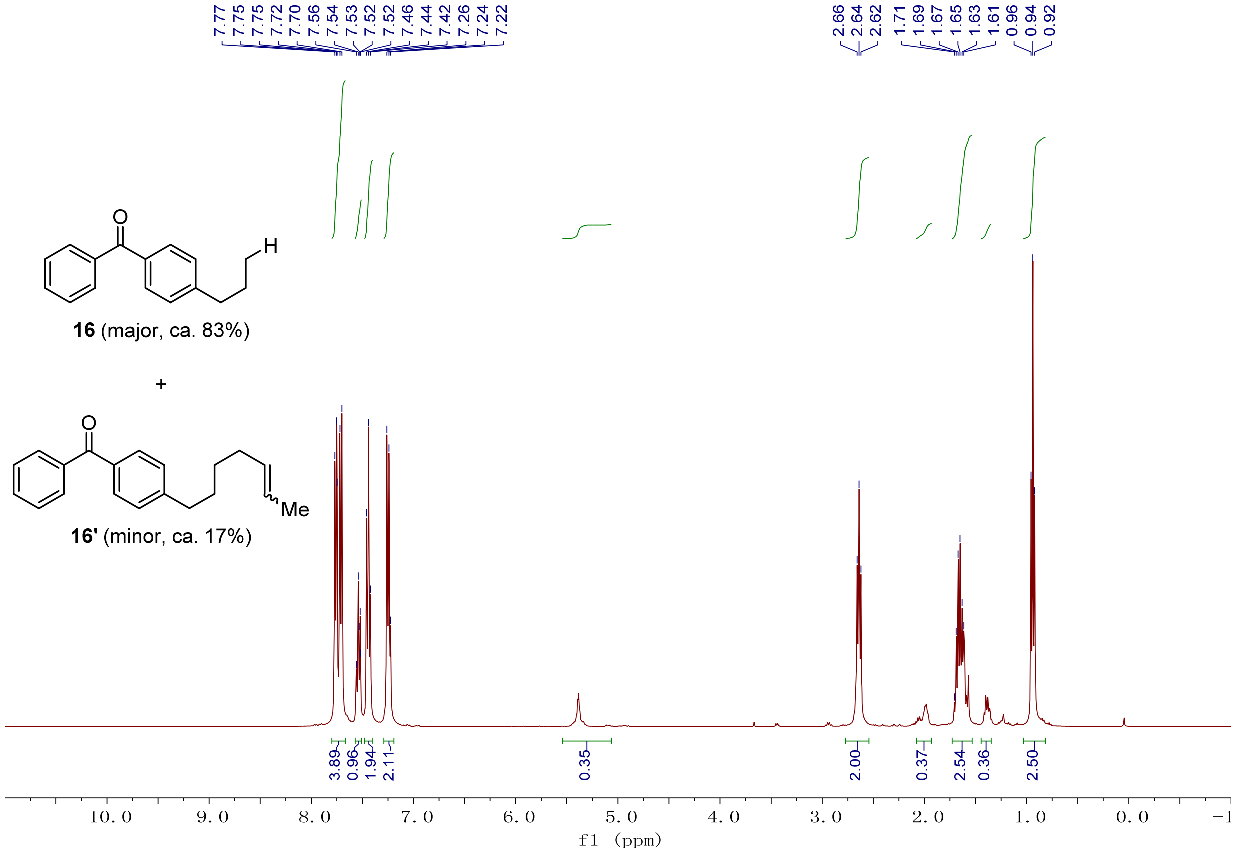
14

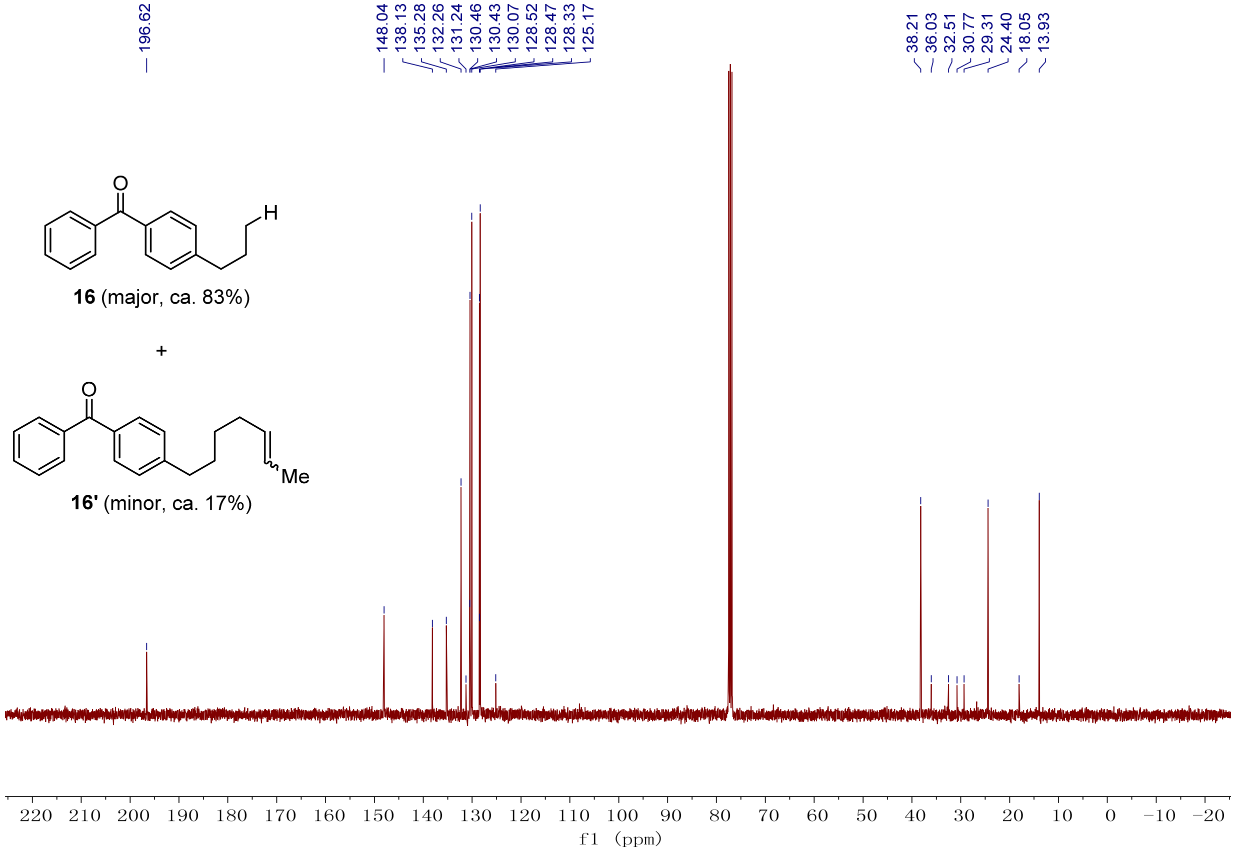

1.26
1.23
1.22
0.90
0.89
0.89
0.87
0.85
0.83
0.81
17.05
9.00
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

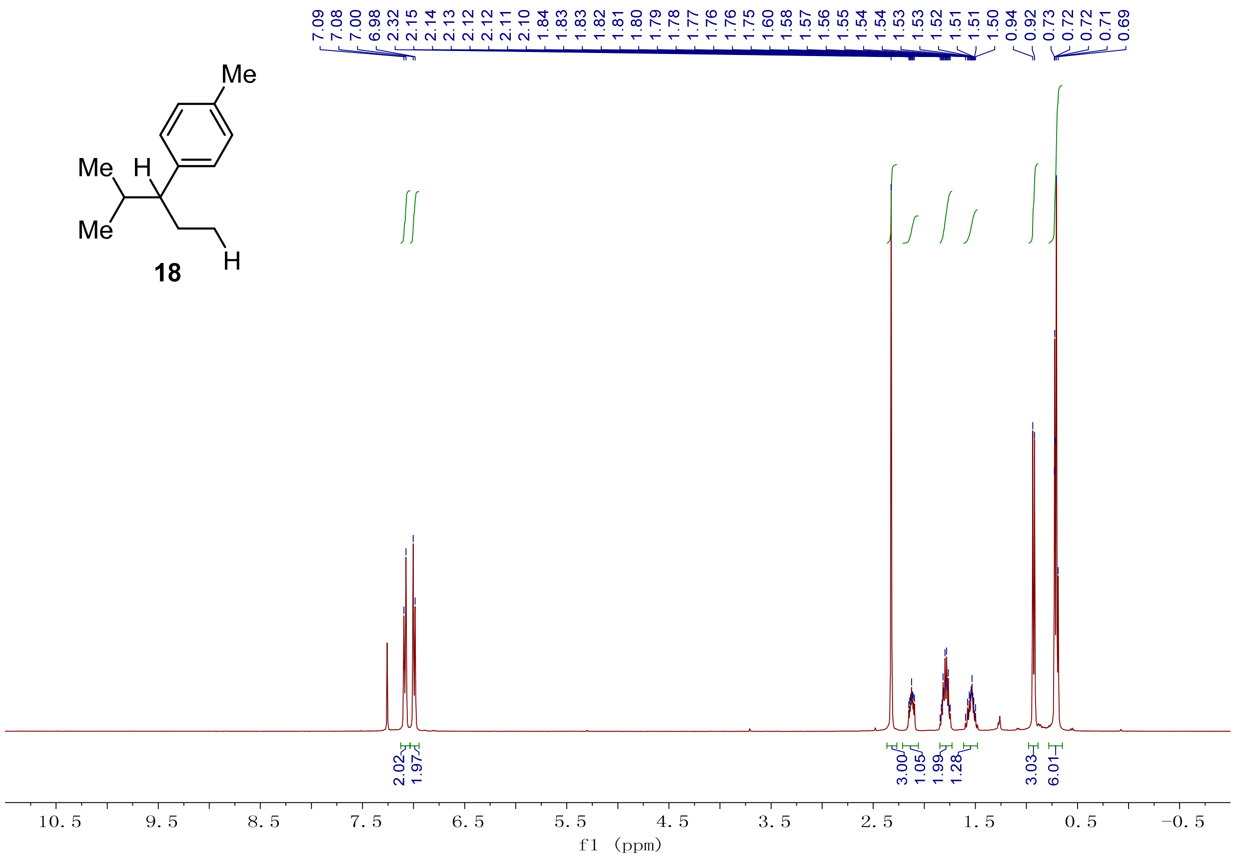
Me
H
H
nBu

14


39.01
33.35
33.06
32.55
29.17
26.58
26.07
23.33
22.89
14.33
14.29
11.04
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

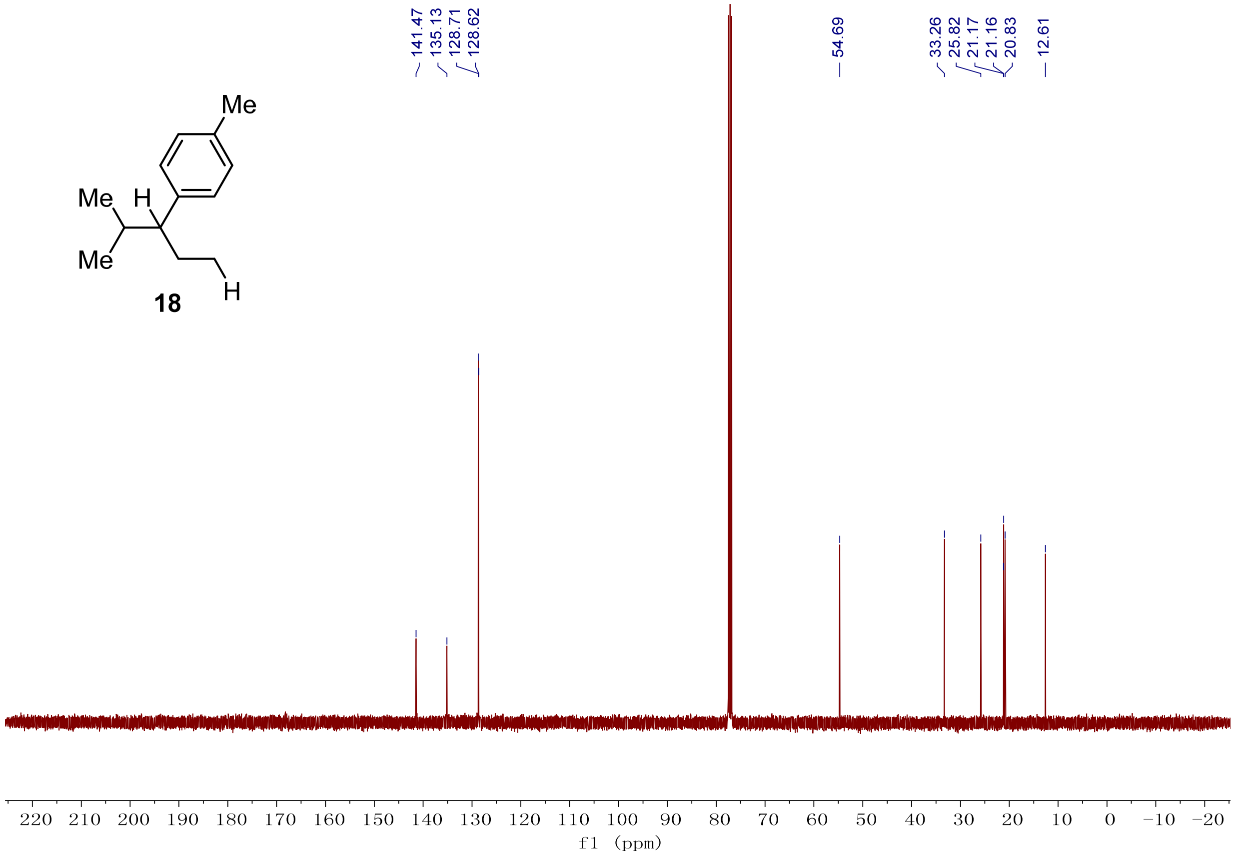

7.77
7.75
7.75
7.72
7.70
7.56
7.54
7.53
7.52
7.52
7.46
7.44
7.42
7.26
7.24
7.22
2.66
2.64
2.62
1.71
1.69
1.67
1.65
1.63
1.61
0.96
0.94
0.92
O
H
16 (major, ca. 83%)
+
O
Me
16' (minor, ca. 17%)
3.89
0.96
1.94
2.11
0.35
2.00
0.37
2.54
0.36
2.50
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)


196.62
148.04
138.13
135.28
132.26
131.24
130.46
130.43
130.07
128.52
128.47
128.33
125.17
38.21
36.03
32.51
30.77
29.31
24.40
18.05
13.93
O
H
16 (major, ca. 83%)
+
O
Me
16' (minor, ca. 17%)
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)



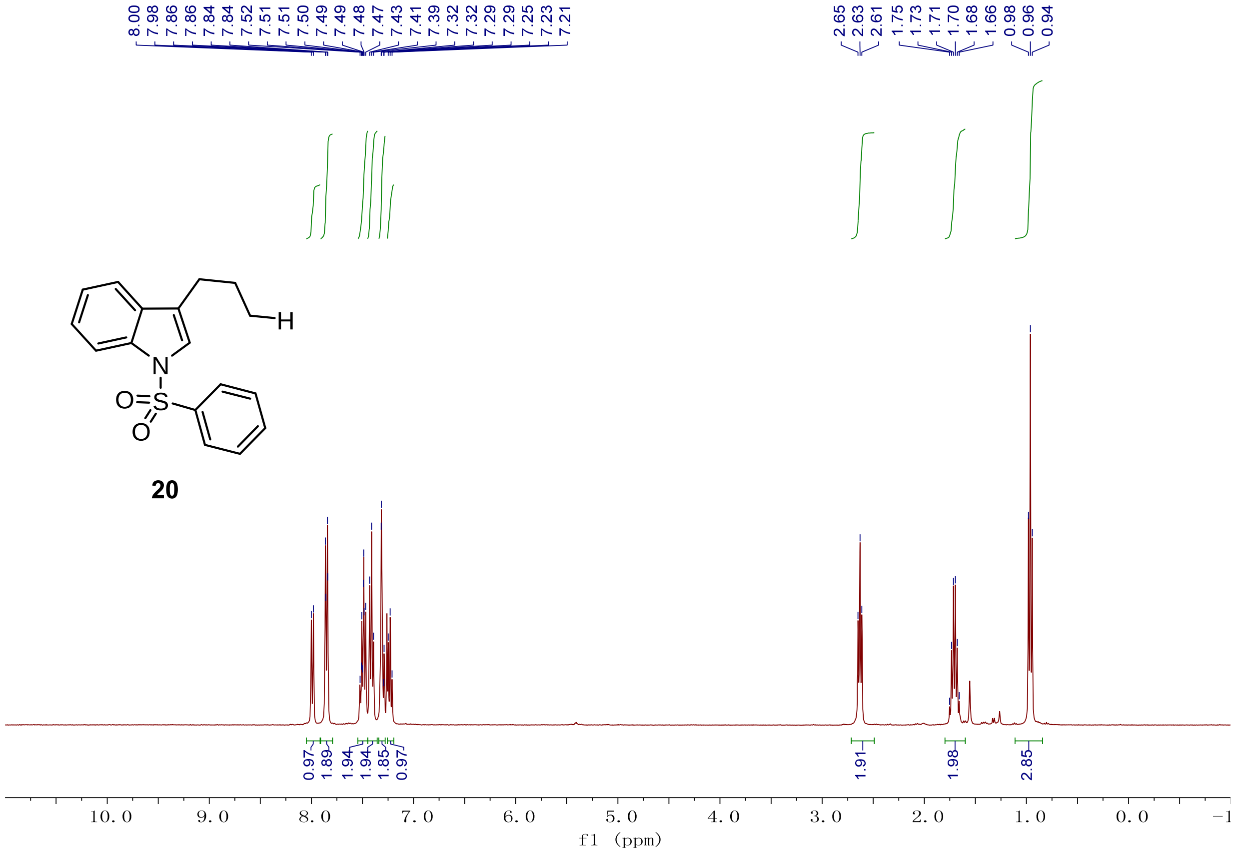
7.09
7.08
7.00
6.98
2.32
2.15
2.14
2.13
2.12
2.12
2.11
2.10
1.84
1.83
1.83
1.82
1.81
1.80
1.79
1.78
1.77
1.76
1.76
1.75
1.60
1.58
1.57
1.56
1.55
1.54
1.54
1.53
1.53
1.52
1.51
1.51
1.50
0.94
0.92
0.73
0.72
0.72
0.71
0.69
Me
Me
H
Me
H
2.02
1.97
3.00
1.05
1.99
1.28
3.03
6.01
10.5
9.5
8.5
7.5
6.5
5.5
4.5
3.5
2.5
1.5
0.5
-0.5
f1 (ppm)

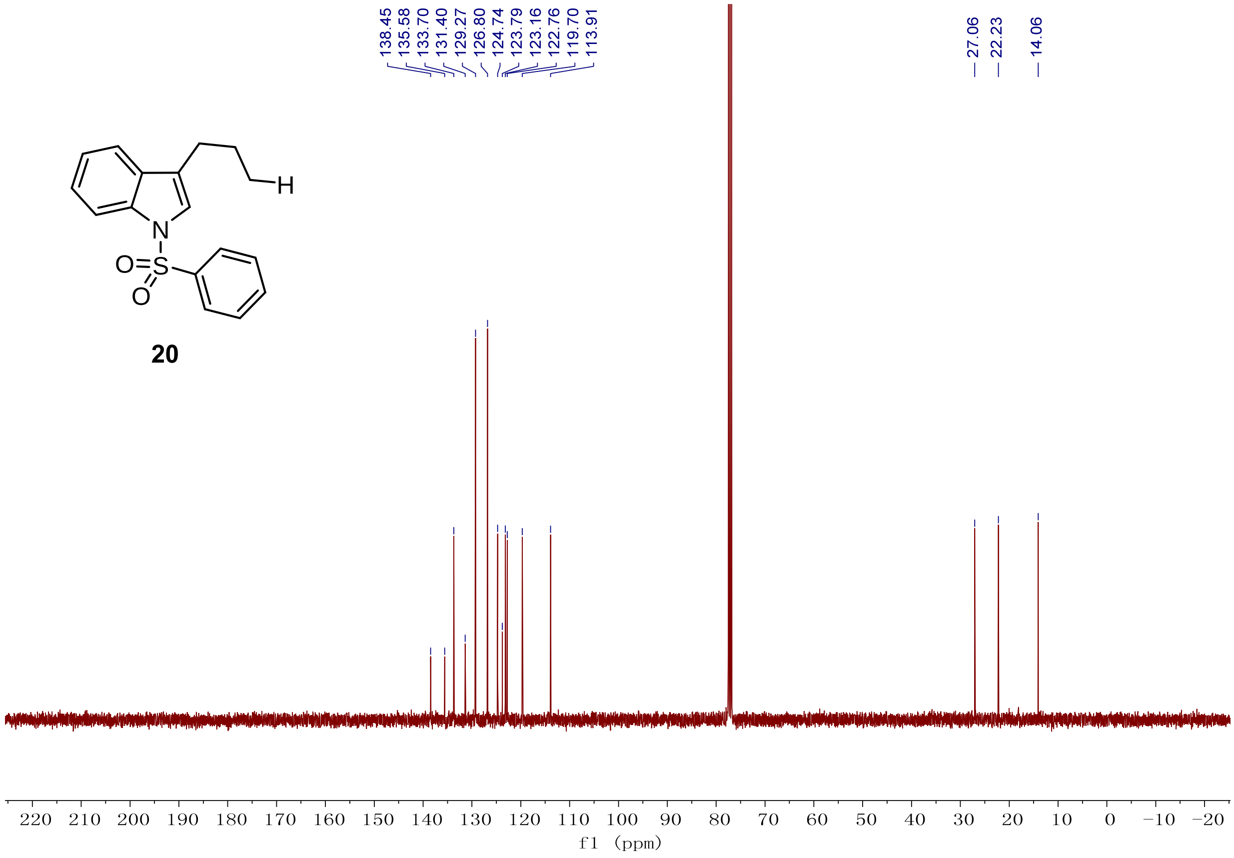
18

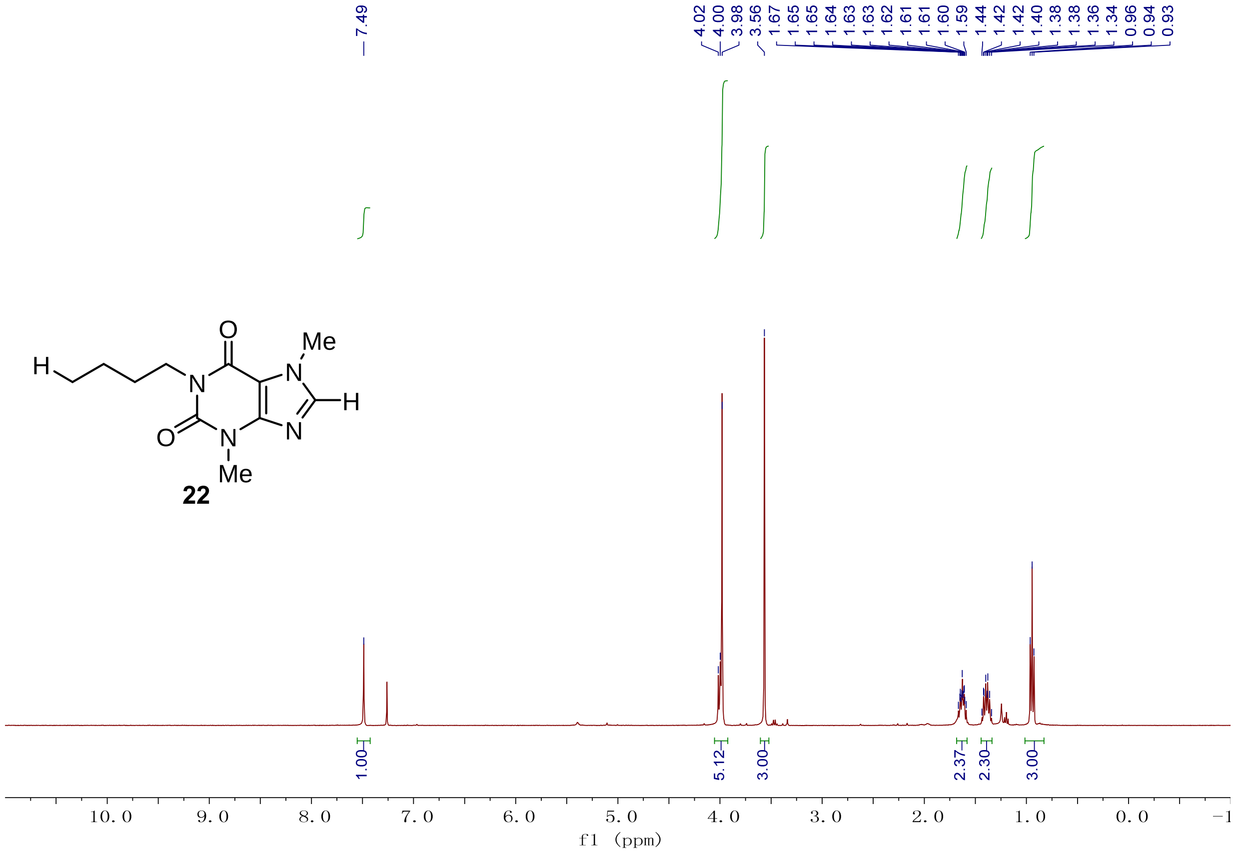


141.47
135.13
128.71
128.62
54.69
33.26
25.82
21.17
21.16
20.83
12.61
Me
Me
H
Me
H
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

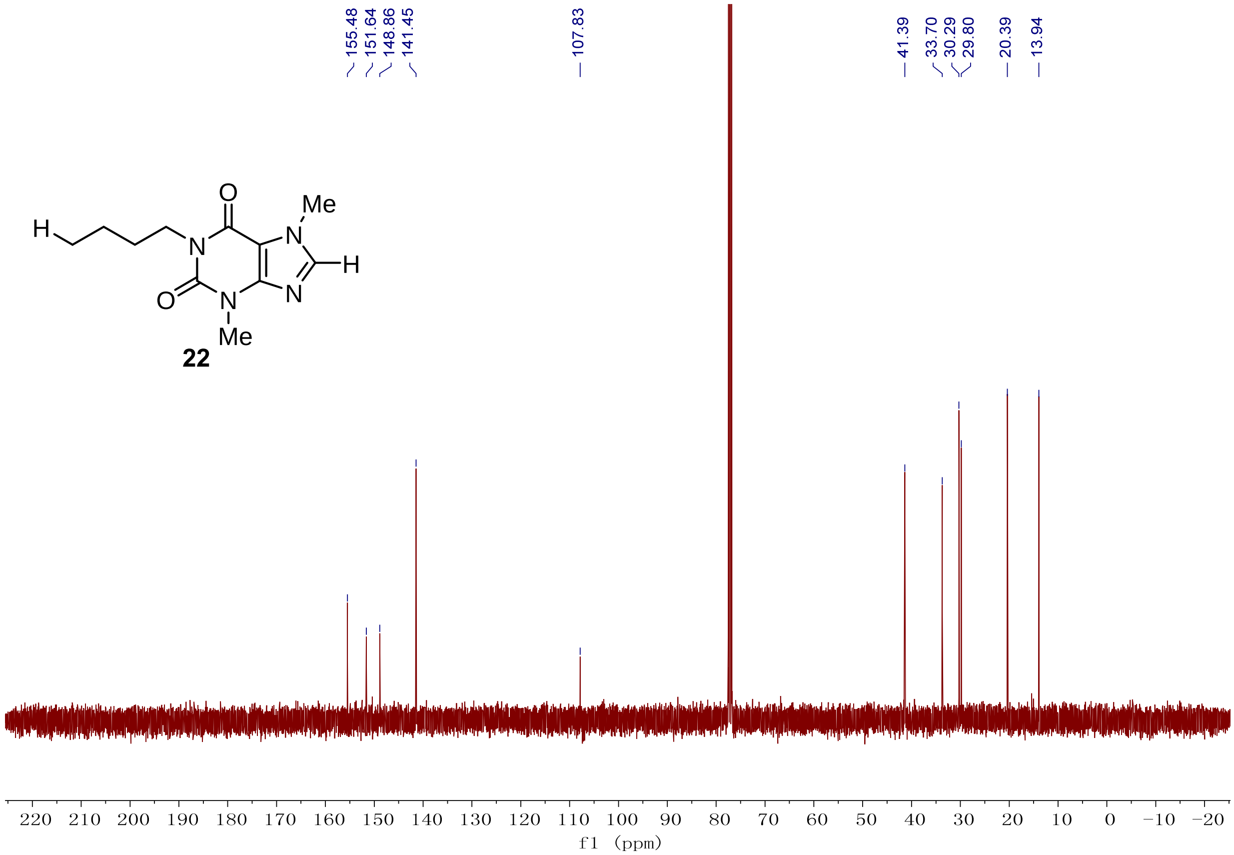
18


8.00
7.98
7.86
7.86
7.84
7.84
7.52
7.51
7.51
7.50
7.49
7.49
7.48
7.47
7.43
7.41
7.39
7.32
7.32
7.29
7.29
7.25
7.23
7.21
2.65
2.63
2.61
1.75
1.73
1.71
1.70
1.68
1.66
0.98
0.96
0.94
H
N
O
S
O
20
0.97
1.89
1.94
1.94
1.85
0.97
1.91
1.98
2.85
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

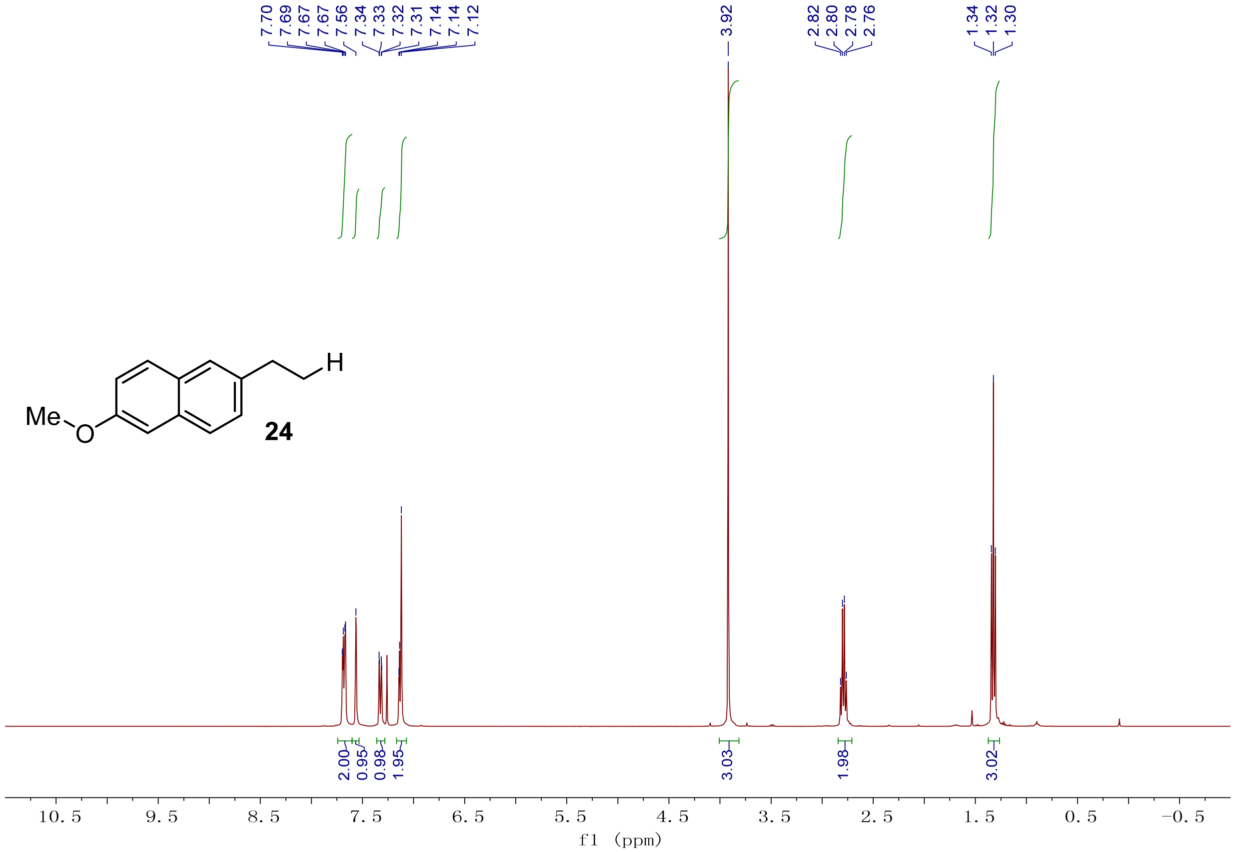

138.45
135.58
133.70
131.40
129.27
126.80
124.74
123.79
123.16
122.76
119.70
113.91
27.06
22.23
14.06
H
N
O
S
O
20
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

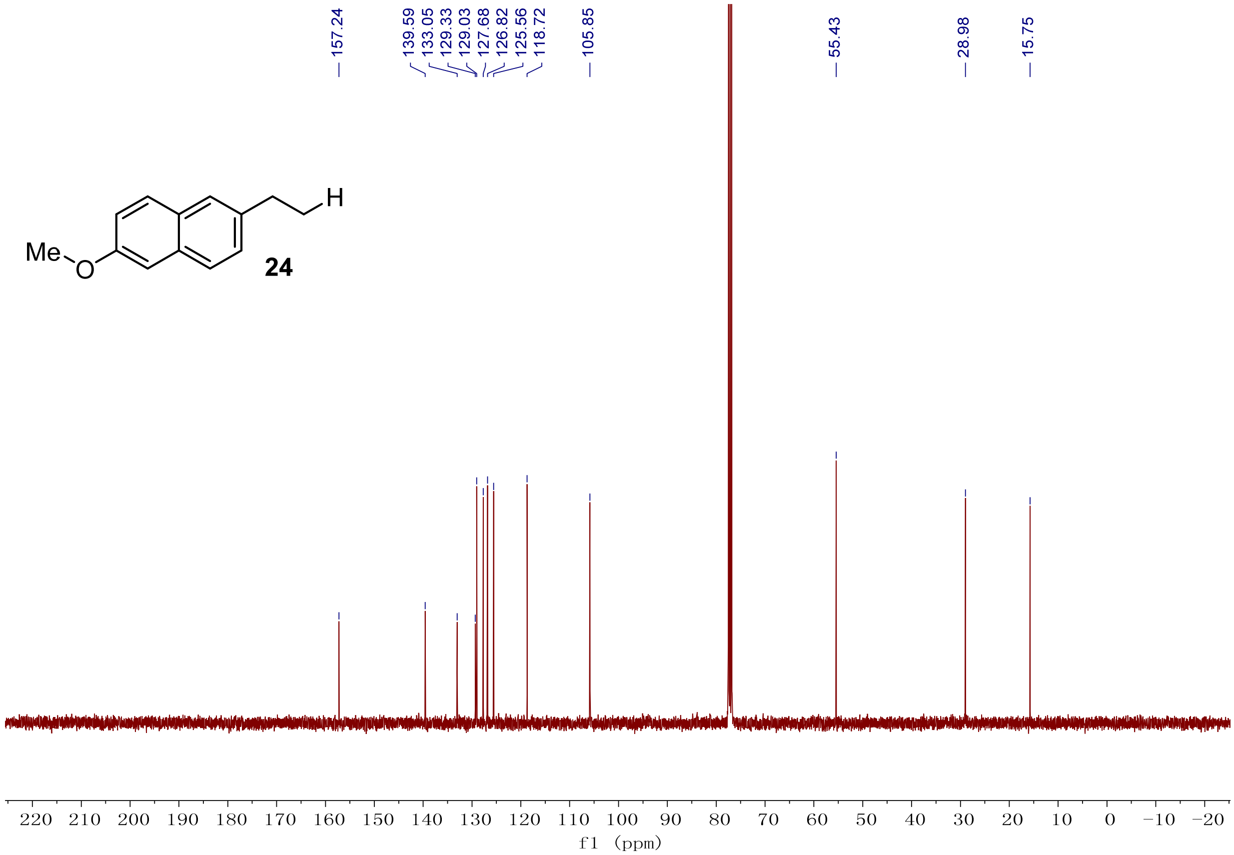

7.49
4.02
4.00
3.98
3.56
1.67
1.65
1.65
1.64
1.63
1.63
1.62
1.61
1.61
1.60
1.59
1.44
1.42
1.42
1.40
1.38
1.38
1.36
1.34
0.96
0.94
0.93
H
O
N
Me
N
H
O
N
N
Me
1.00
5.12
3.00
2.37
2.30
3.00
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

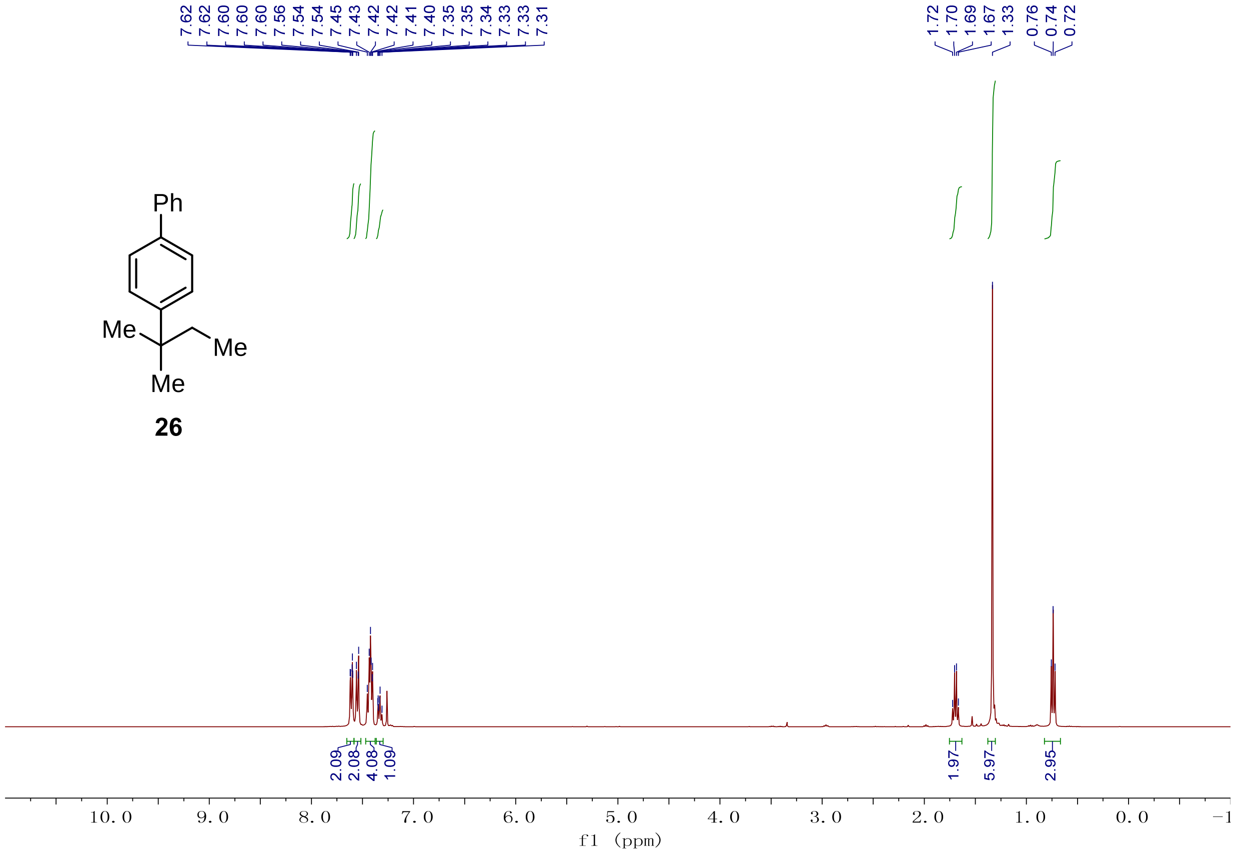
22

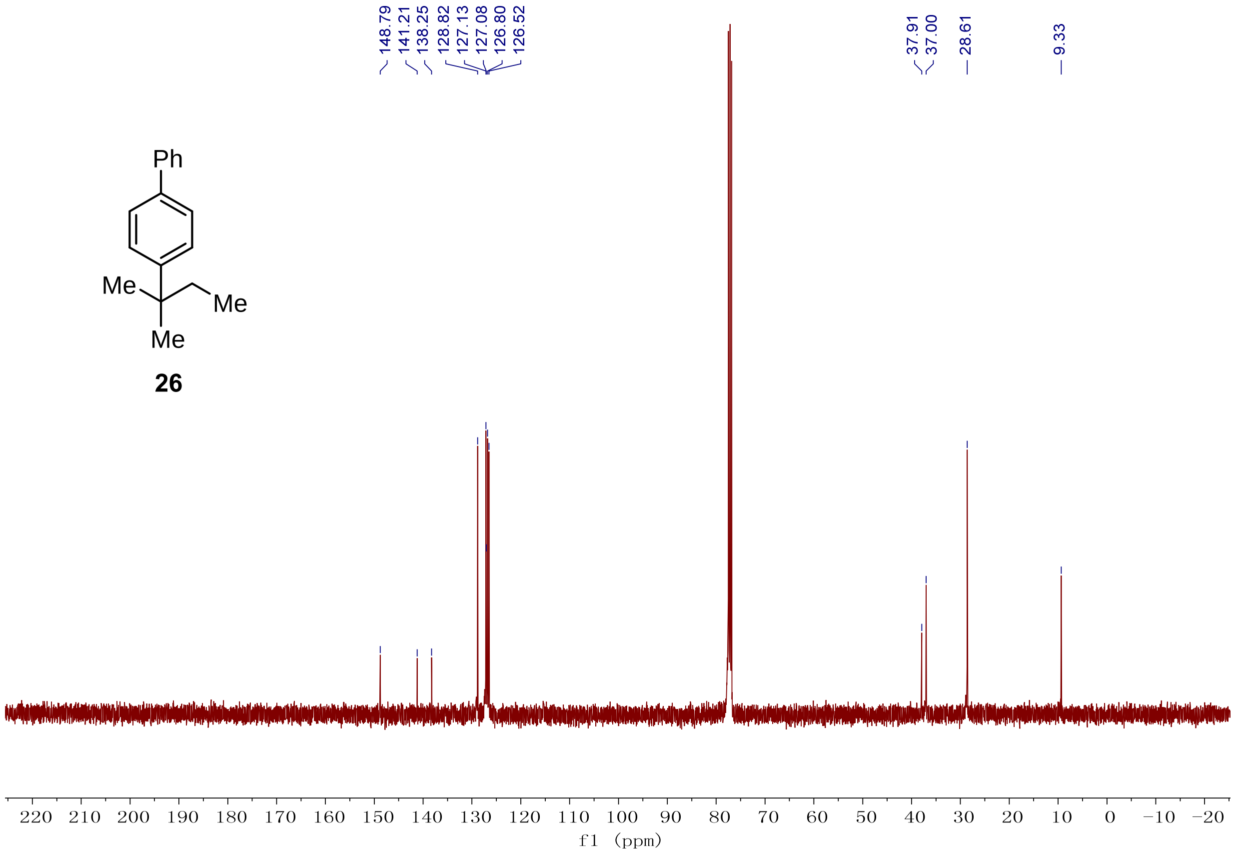

155.48
151.64
148.86
141.45
107.83
41.39
33.70
30.29
29.80
20.39
13.94
H
O
N
Me
N
H
O
N
N
Me
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

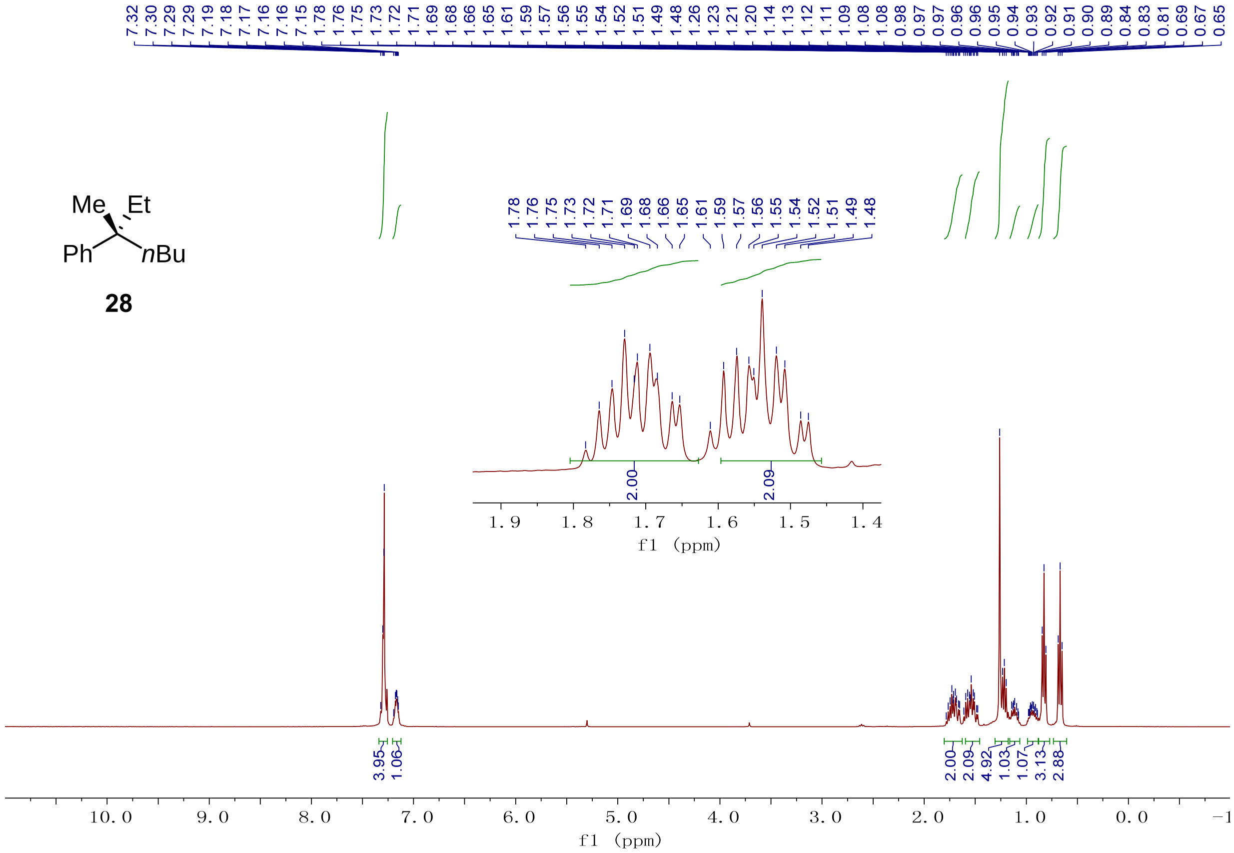
22

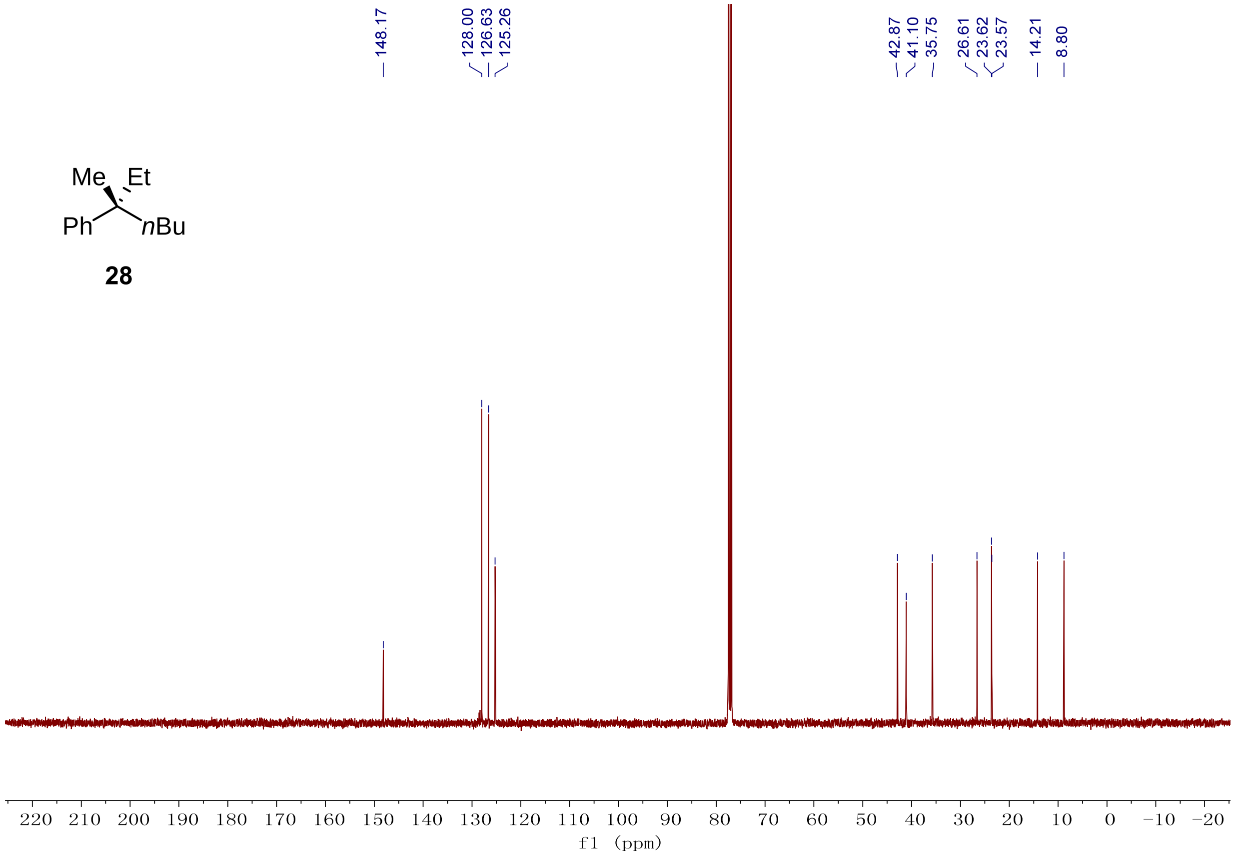

7.70
7.69
7.67
7.67
7.56
7.34
7.33
7.32
7.31
7.14
7.14
7.12
3.92
2.82
2.80
2.78
2.76
1.34
1.32
1.30
Me
O
H
24
2.00
0.95
0.98
1.95
3.03
1.98
3.02
10.5
9.5
8.5
7.5
6.5
5.5
4.5
3.5
2.5
1.5
0.5
-0.5
f1 (ppm)

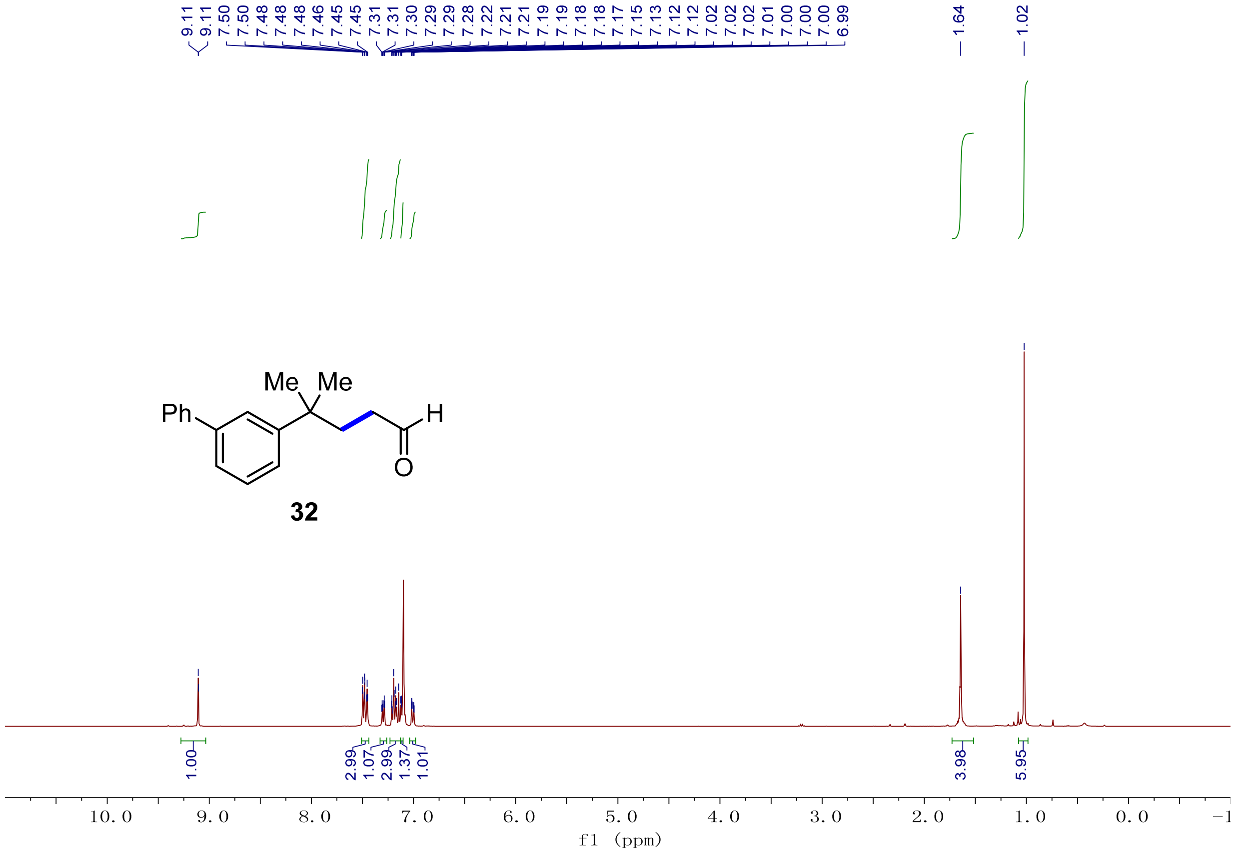

157.24
139.59
133.05
129.33
129.03
127.68
126.82
125.56
118.72
105.85
55.43
28.98
15.75
Me
O
H
24
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

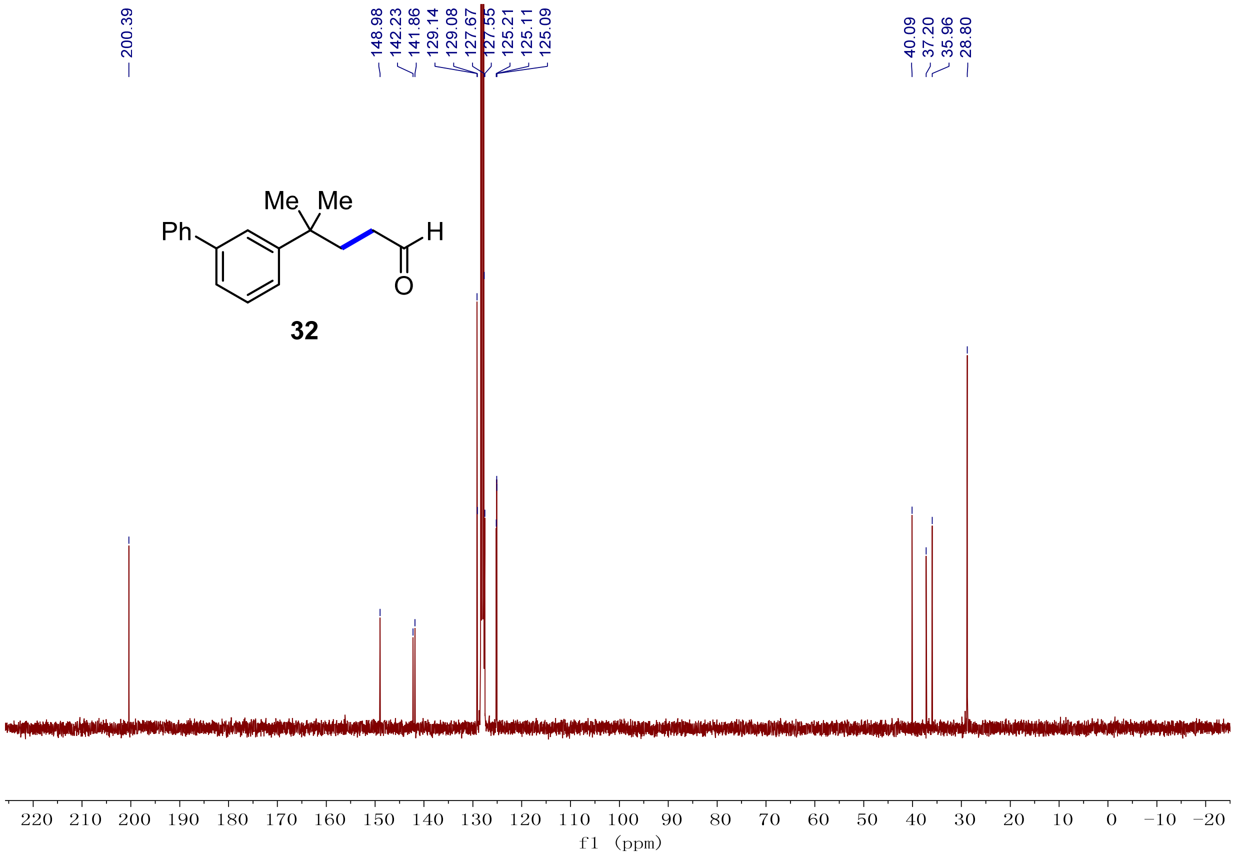

7.62
7.62
7.60
7.60
7.60
7.56
7.54
7.54
7.45
7.43
7.42
7.42
7.41
7.40
7.35
7.35
7.34
7.33
7.33
7.31
1.72
1.70
1.69
1.67
1.33
0.76
0.74
0.72
Ph
Me
Me
Me
26
2.09
2.08
4.08
1.09
1.97
5.97
2.95
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
−1
f1 (ppm)

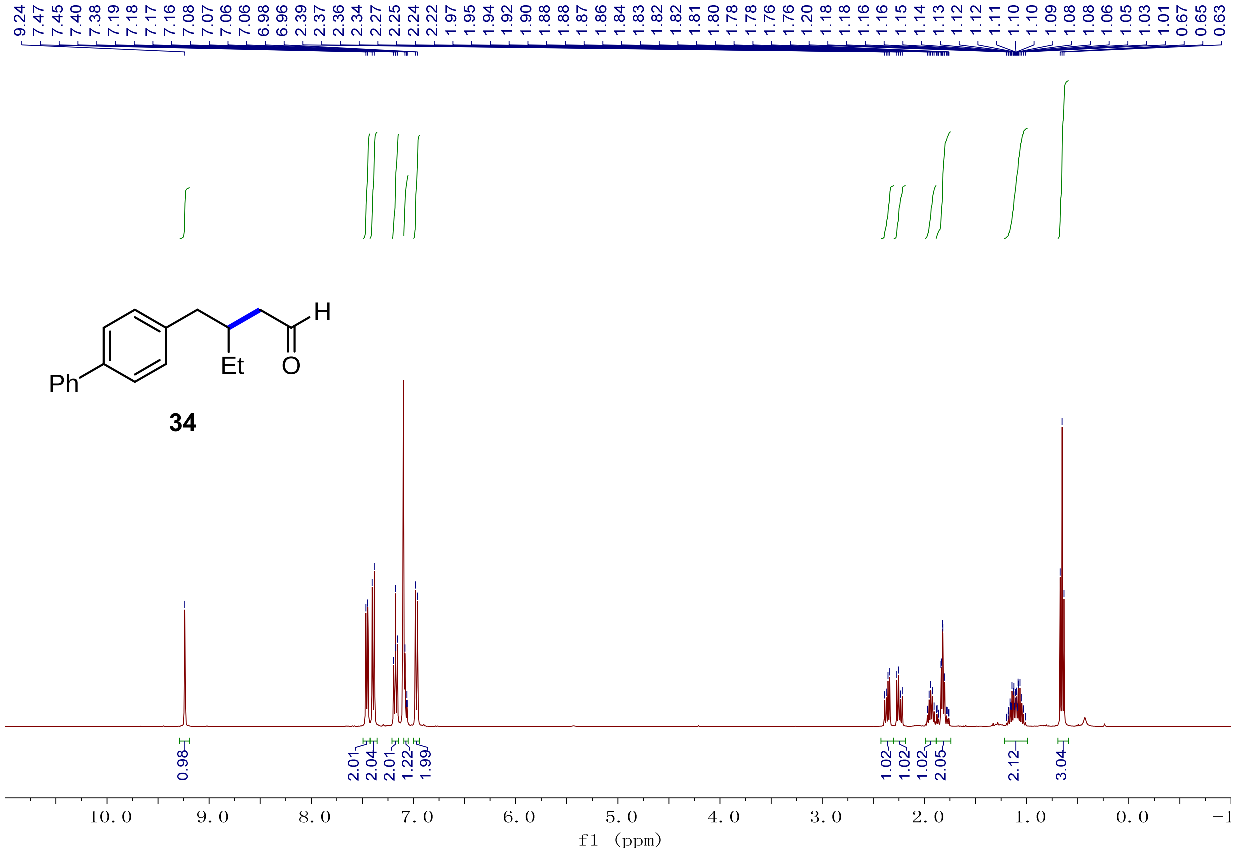

148.79
141.21
138.25
128.82
127.13
127.08
126.80
126.52
37.91
37.00
28.61
9.33
Ph
Me
Me
Me
26
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
−10
−20
f1 (ppm)

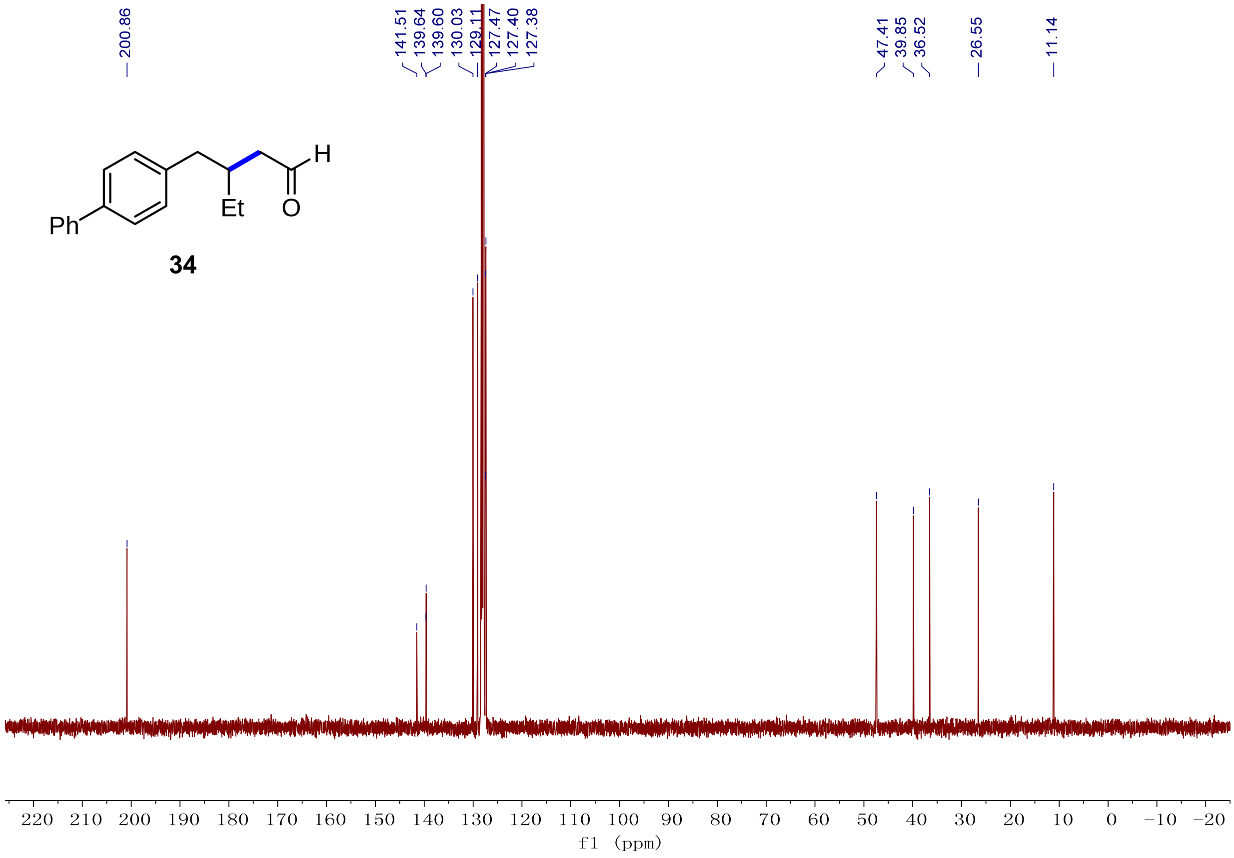

7.32 7.30 7.29 7.29 7.19 7.18 7.17 7.16 7.16 7.15 1.78 1.76 1.75 1.73 1.72 1.71 1.69 1.68 1.66 1.65 1.61 1.59 1.57 1.56 1.55 1.54 1.52 1.51 1.49 1.48 1.26 1.23 1.21 1.20 1.14 1.13 1.12 1.11 1.09 1.08 0.98 0.97 0.97 0.96 0.96 0.95 0.94 0.93 0.92 0.91 0.90 0.89 0.84 0.83 0.81 0.69 0.67 0.65
Me
Et
Ph
nBu
28
1.78 1.76 1.75 1.73 1.72 1.71 1.69 1.68 1.66 1.65 1.61 1.59 1.57 1.56 1.55 1.54 1.52 1.51 1.49 1.48
2.00
2.09
1.9 1.8 1.7 1.6 1.5 1.4
f1 (ppm)
3.95
1.06
2.00
2.09
4.92
1.03
1.07
3.13
2.88
10.0 9.0 8.0 7.0 6.0 5.0 4.0 3.0 2.0 1.0 0.0 −1
f1 (ppm)

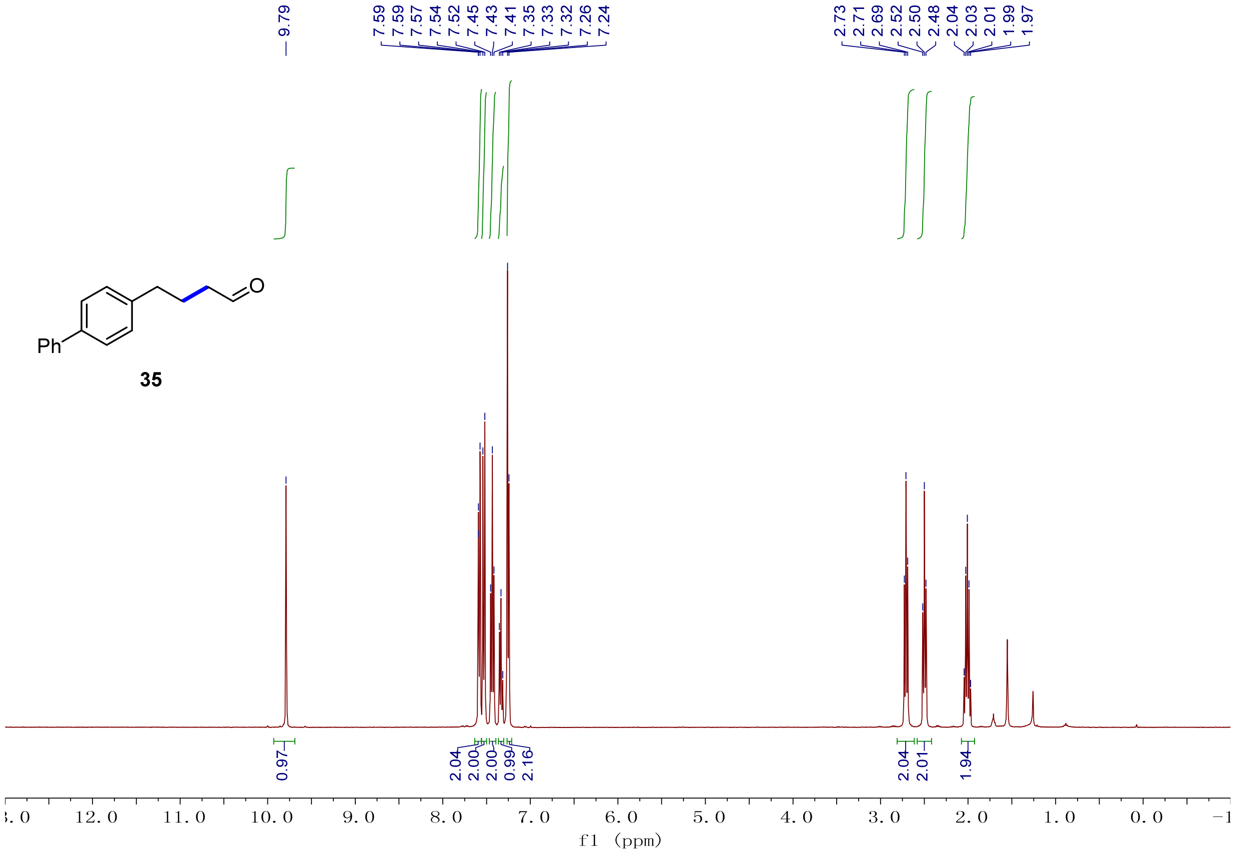

148.17
128.00 126.63 125.26
42.87 41.10 35.75 26.61 23.62 23.57 14.21 8.80
Me
Et
Ph
nBu
28
220 210 200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 −10 −20
f1 (ppm)


9.11
9.11
7.50
7.48
7.48
7.46
7.45
7.45
7.31
7.31
7.30
7.29
7.29
7.28
7.22
7.21
7.21
7.19
7.19
7.18
7.17
7.15
7.13
7.12
7.12
7.02
7.02
7.02
7.01
7.00
7.00
7.00
6.99
1.64
1.02
Me
Me
Ph
H
O
32
1.00
2.99
1.07
2.99
1.37
1.01
3.98
5.95
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)


200.39
148.98
142.23
141.86
129.14
129.08
127.67
127.55
125.21
125.11
125.09
40.09
37.20
35.96
28.80
Me
Me
Ph
H
O
32
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

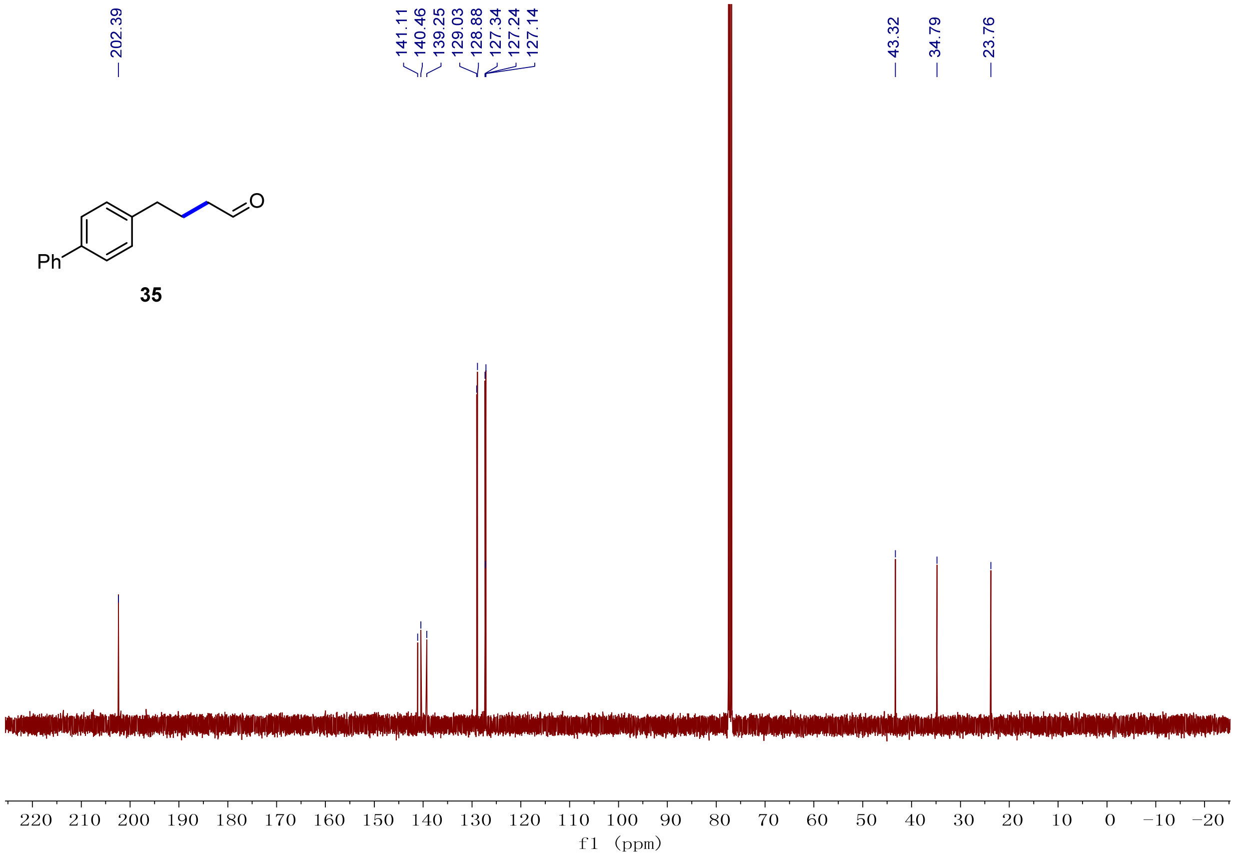

9.24
7.47
7.45
7.40
7.38
7.19
7.18
7.17
7.16
7.08
7.07
7.06
7.06
6.98
6.96
2.39
2.37
2.36
2.34
2.27
2.25
2.24
2.22
1.97
1.95
1.94
1.92
1.90
1.88
1.88
1.87
1.86
1.84
1.83
1.82
1.82
1.81
1.80
1.78
1.78
1.76
1.76
1.20
1.18
1.18
1.16
1.16
1.15
1.14
1.13
1.12
1.12
1.11
1.10
1.10
1.09
1.08
1.08
1.06
1.05
1.03
1.01
0.67
0.65
0.63
Ph
Et
O
H
34
0.98
2.01
2.04
2.01
1.22
1.99
1.02
1.02
1.02
2.05
2.12
3.04
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)


200.86
141.51
139.64
139.60
130.03
129.11
127.47
127.40
127.38
47.41
39.85
36.52
26.55
11.14
Ph
Et
O
H
34
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)



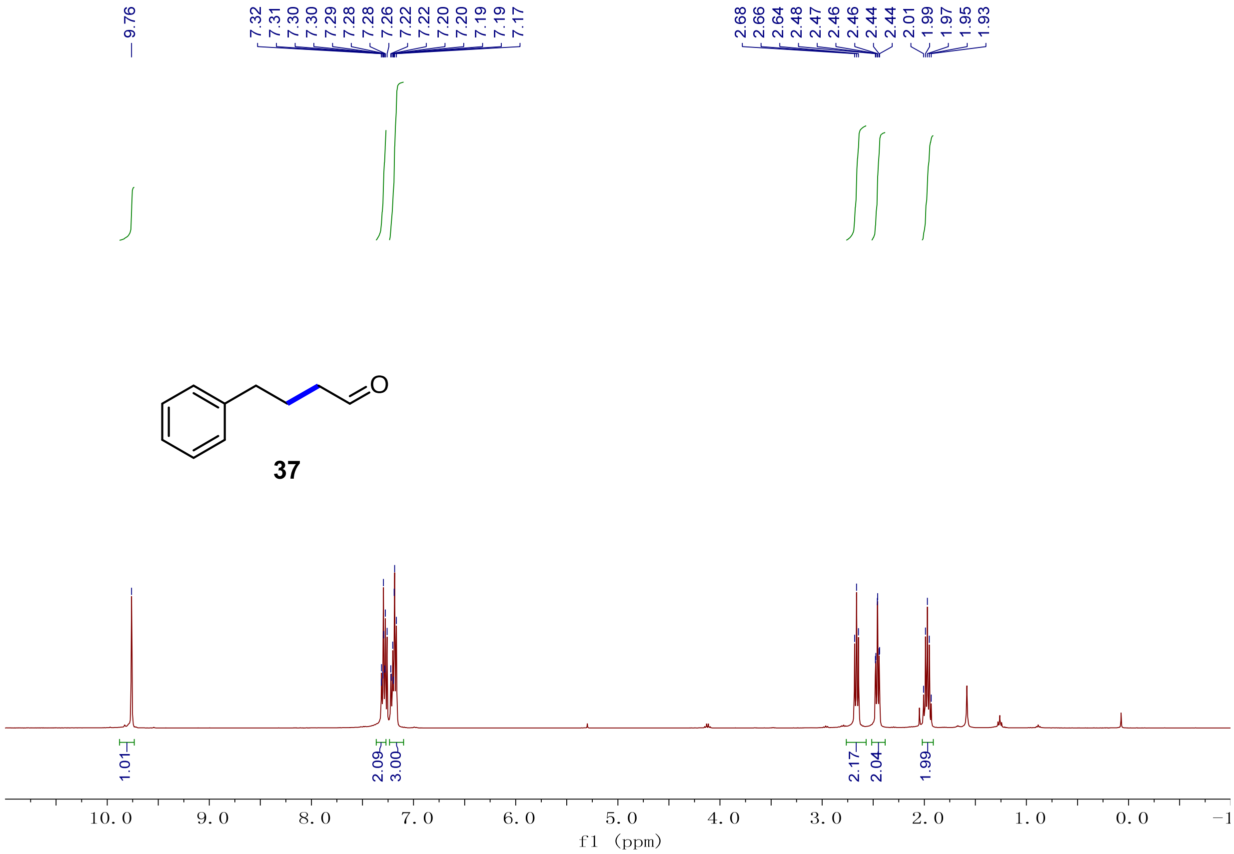
9.79
7.59
7.59
7.57
7.54
7.52
7.45
7.43
7.41
7.35
7.33
7.32
7.26
7.24
2.73
2.71
2.69
2.52
2.50
2.48
2.04
2.03
2.01
1.99
1.97
Ph
O
0.97
2.04
2.00
2.00
0.99
2.16
2.04
2.01
1.94
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

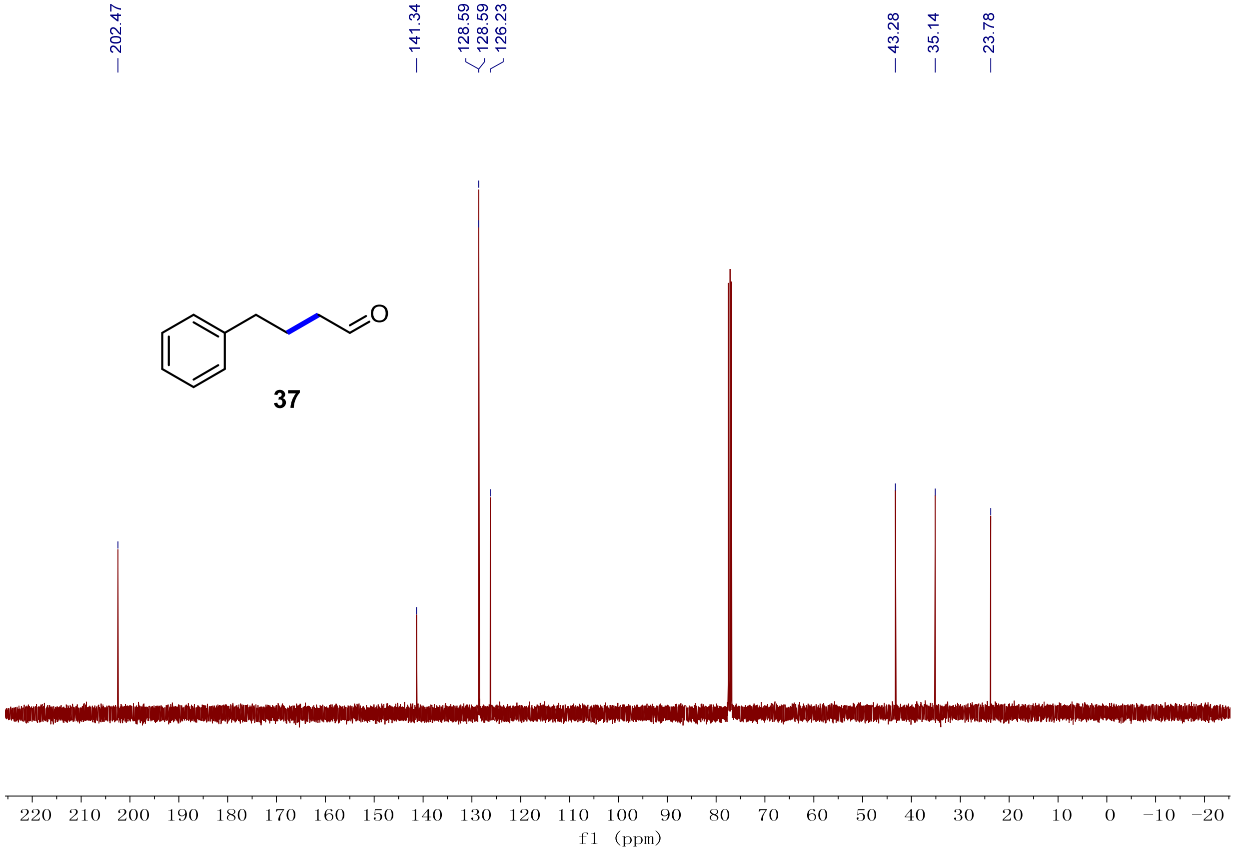
35

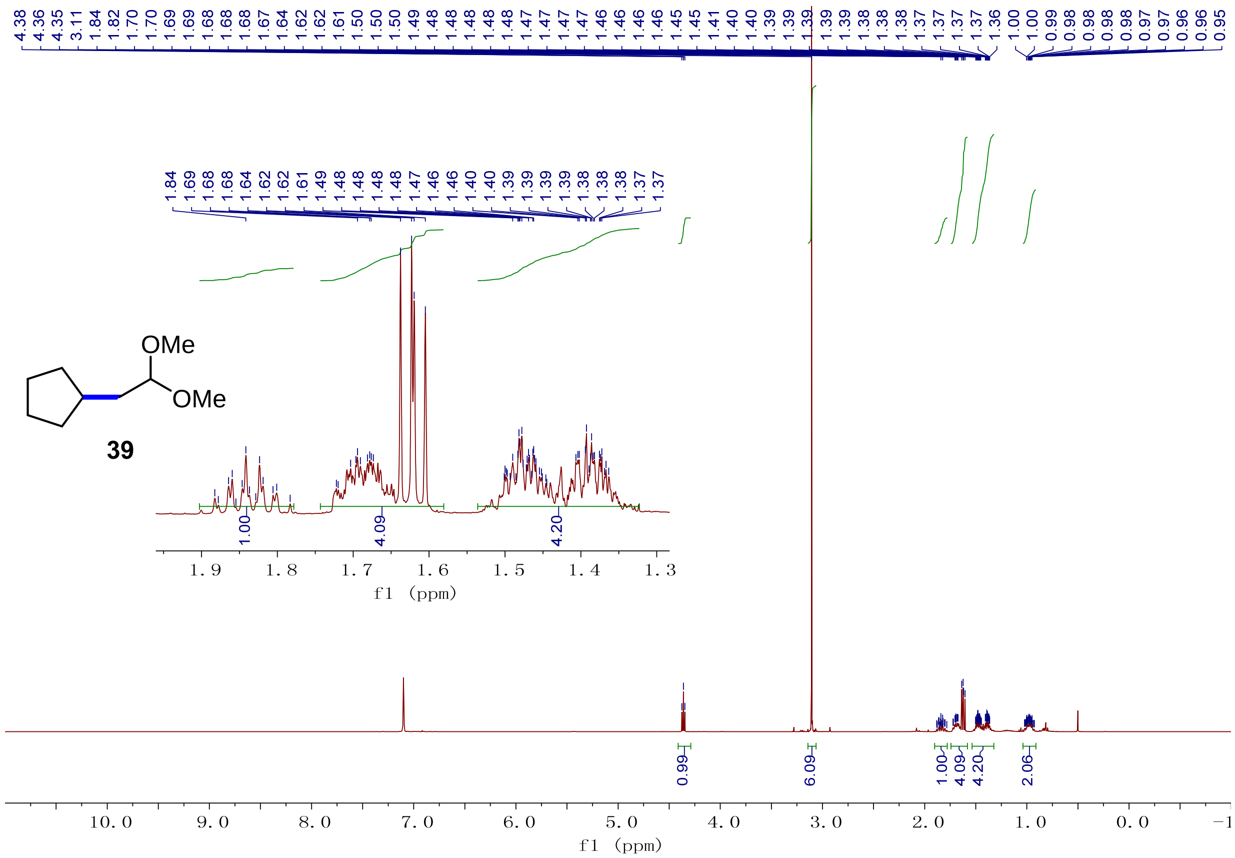


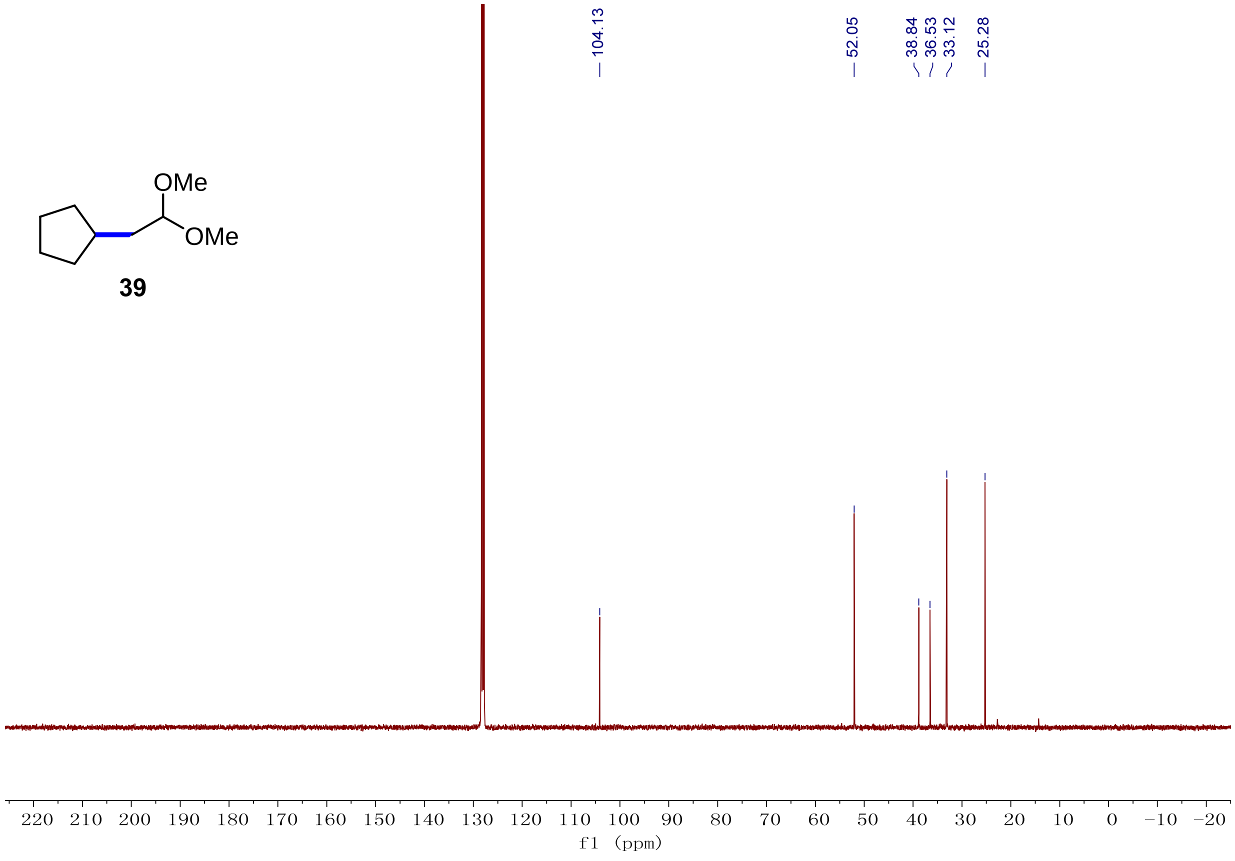
202.39
141.11
140.46
139.25
129.03
128.88
127.34
127.24
127.14
43.32
34.79
23.76
Ph
O
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

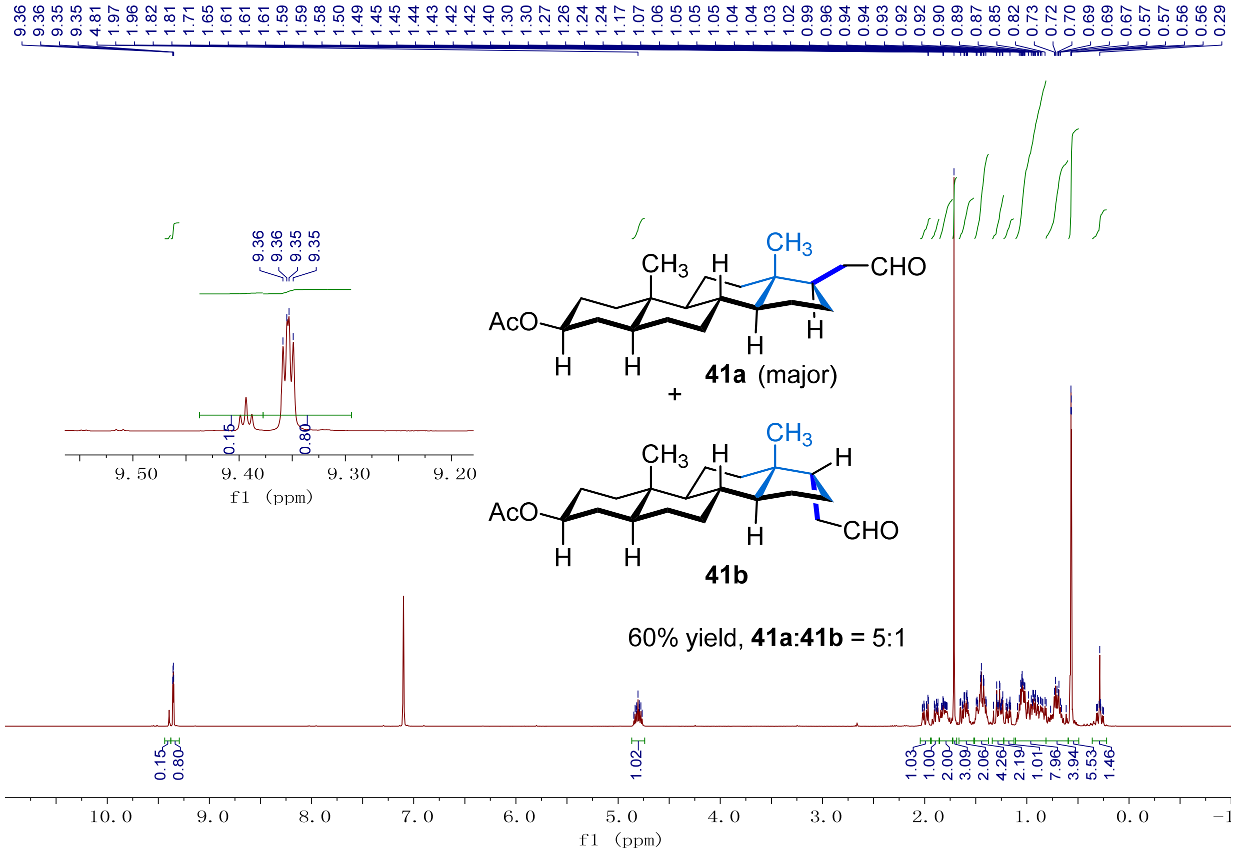
35


9.76
7.32
7.31
7.30
7.30
7.29
7.28
7.28
7.26
7.22
7.22
7.20
7.20
7.19
7.19
7.17
2.68
2.66
2.64
2.48
2.47
2.46
2.46
2.44
2.44
2.01
1.99
1.97
1.95
1.93
37
1.01
2.09
3.00
2.17
2.04
1.99
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

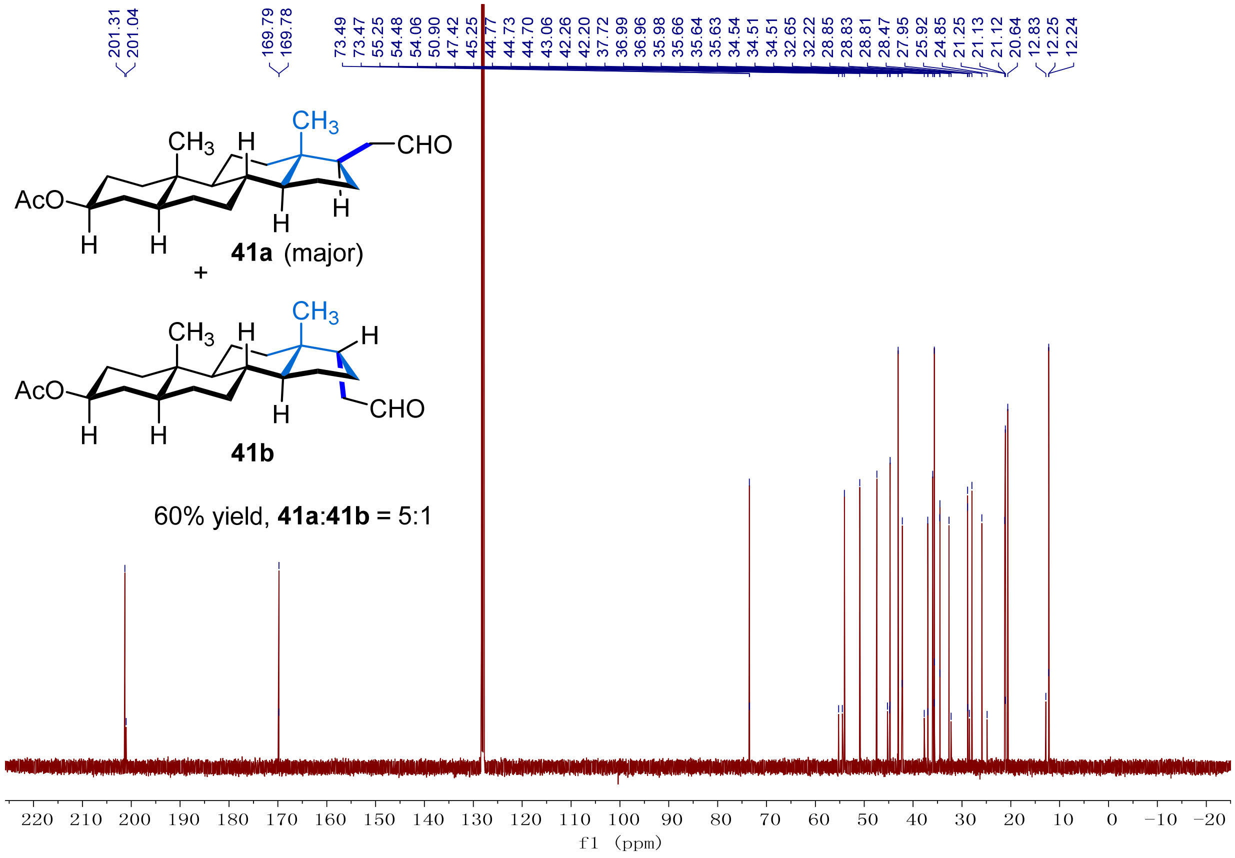

202.47
141.34
128.59
128.59
126.23
43.28
35.14
23.78
37
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)


4.38
4.36
4.35
3.11
1.84
1.82
1.70
1.69
1.69
1.68
1.68
1.68
1.67
1.64
1.62
1.62
1.61
1.50
1.50
1.49
1.48
1.48
1.48
1.48
1.47
1.47
1.47
1.46
1.46
1.46
1.45
1.45
1.41
1.40
1.40
1.39
1.39
1.39
1.39
1.38
1.38
1.38
1.37
1.37
1.37
1.36
1.00
1.00
0.99
0.98
0.98
0.98
0.98
0.97
0.97
0.96
0.95
1.84
1.69
1.68
1.68
1.64
1.62
1.62
1.61
1.49
1.48
1.48
1.48
1.48
1.47
1.46
1.46
1.40
1.40
1.39
1.39
1.39
1.39
1.38
1.38
1.38
1.37
1.37
OMe
OMe
39
1.00
4.09
4.20
1.9
1.8
1.7
1.6
1.5
1.4
1.3
f1 (ppm)
0.99
6.09
1.00
4.09
4.20
2.06
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

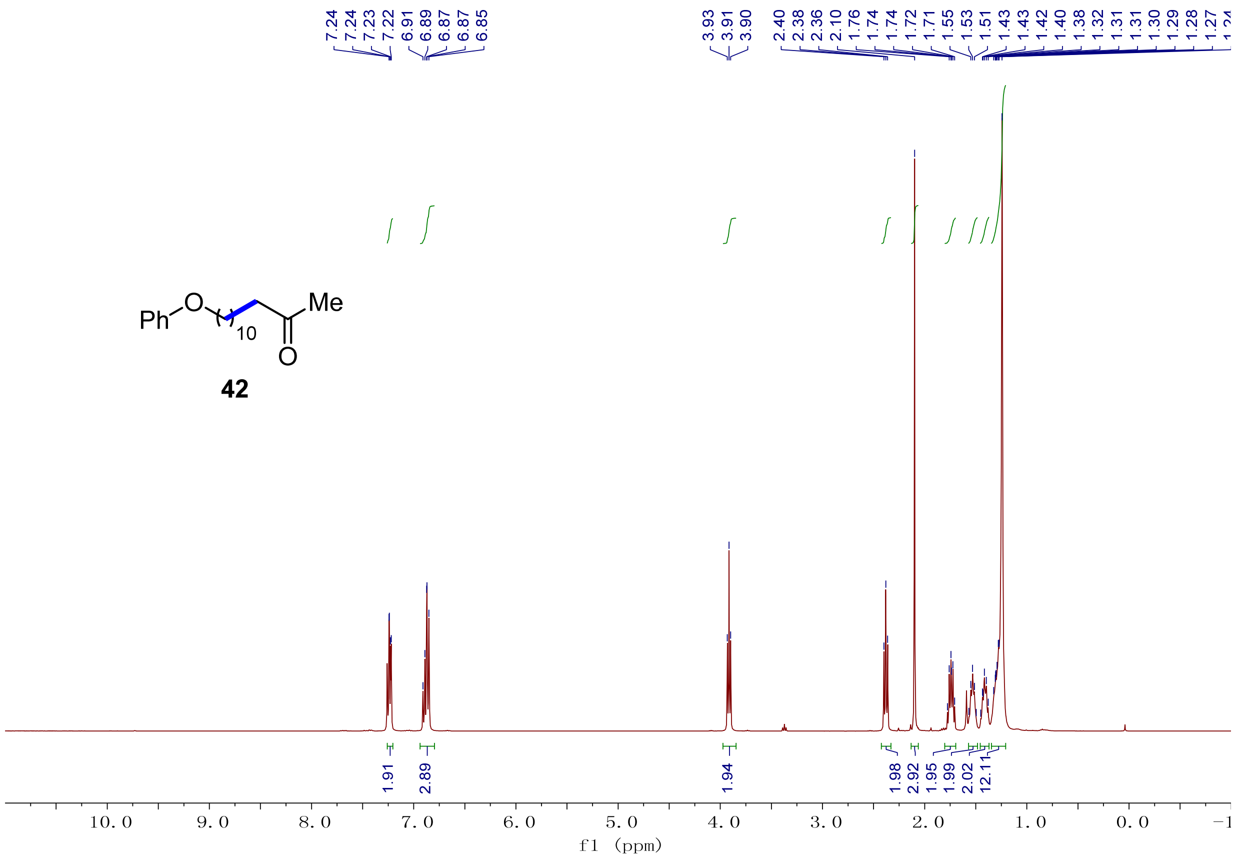

104.13
52.05
38.84
36.53
33.12
25.28
OMe
OMe
39
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

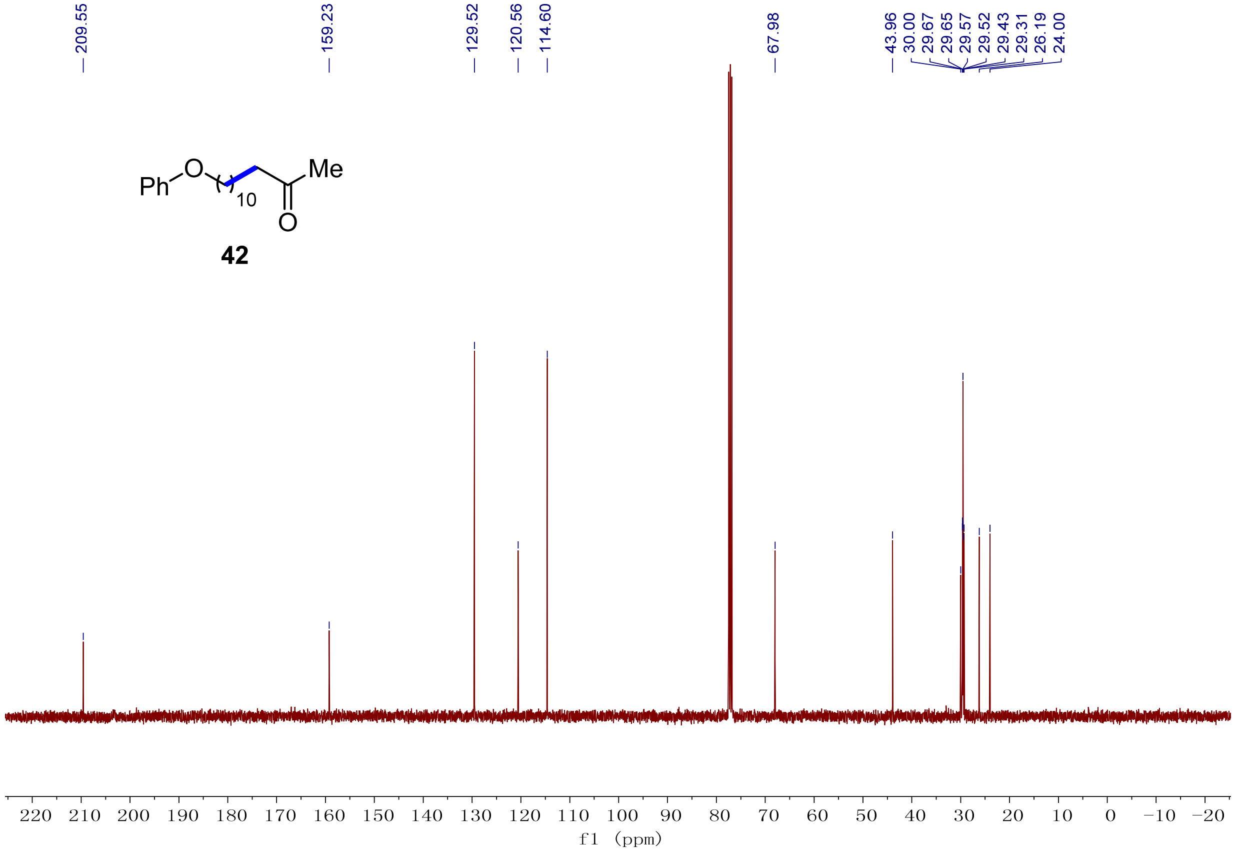

41a (major)
+
41b

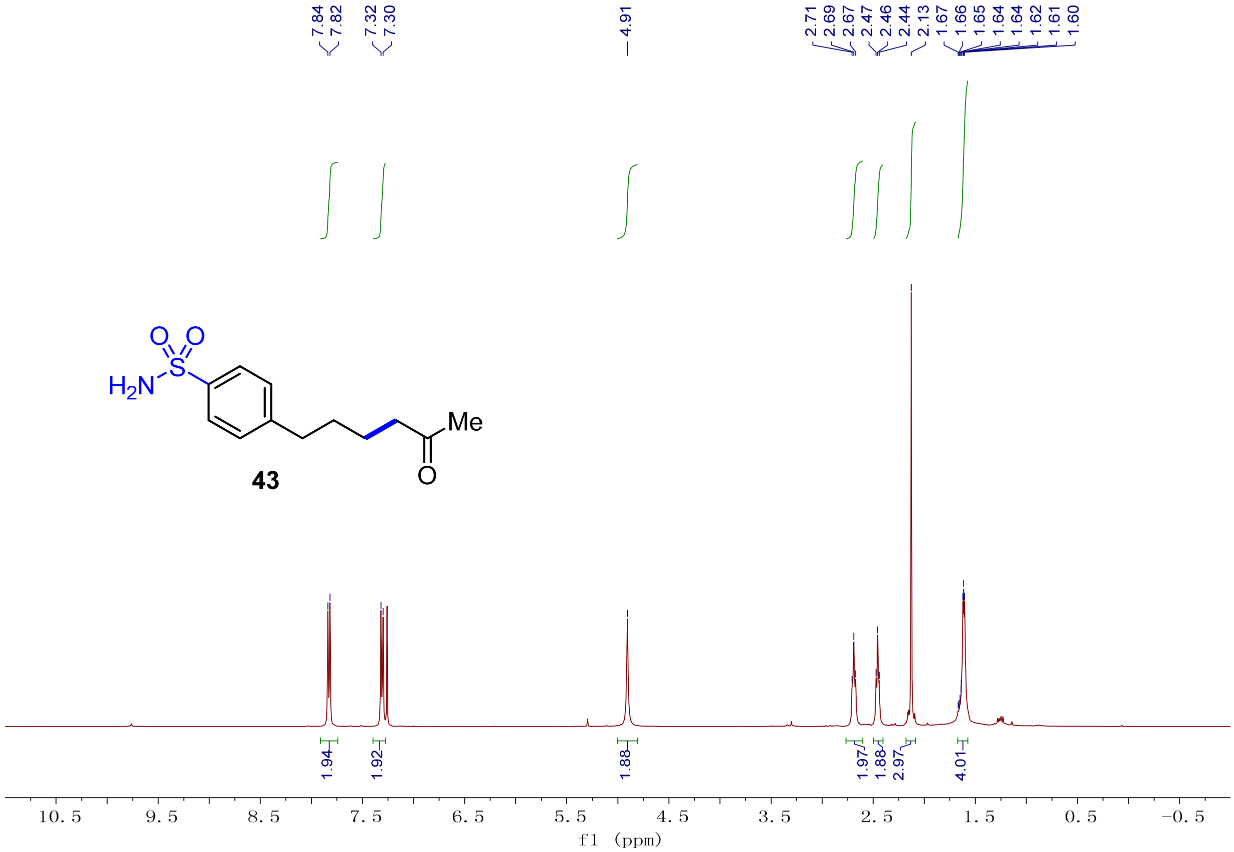
60% yield, **41a**:**41b** = 5:1


41a (major)
+
41b

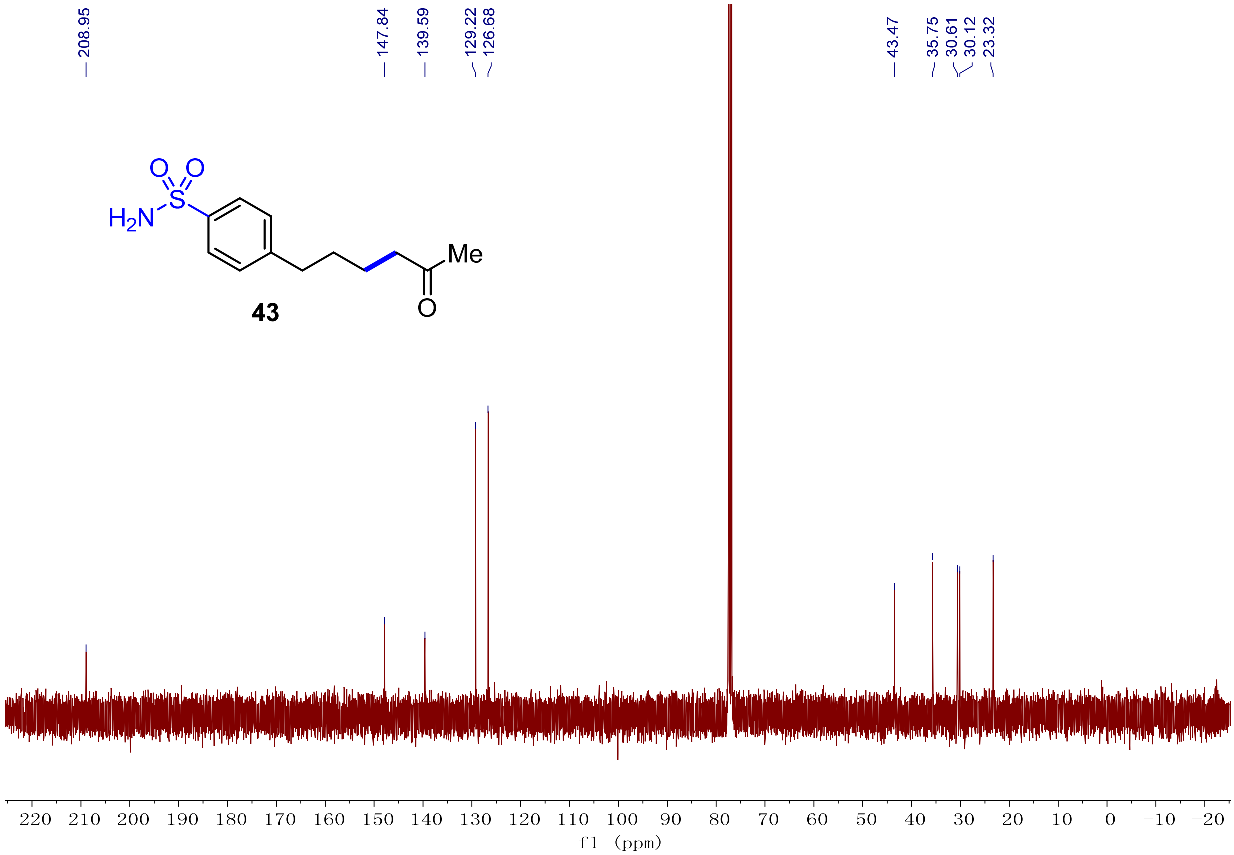
60% yield, **41a**:**41b** = 5:1


7.24
7.24
7.23
7.22
6.91
6.89
6.87
6.87
6.85
3.93
3.91
3.90
2.40
2.38
2.36
2.10
1.76
1.74
1.74
1.72
1.71
1.55
1.53
1.51
1.43
1.43
1.42
1.40
1.38
1.32
1.31
1.30
1.29
1.28
1.27
Ph
O
10
Me
O
42
1.91
2.89
1.94
1.98
2.92
1.95
1.99
2.02
12.11
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
f1 (ppm)

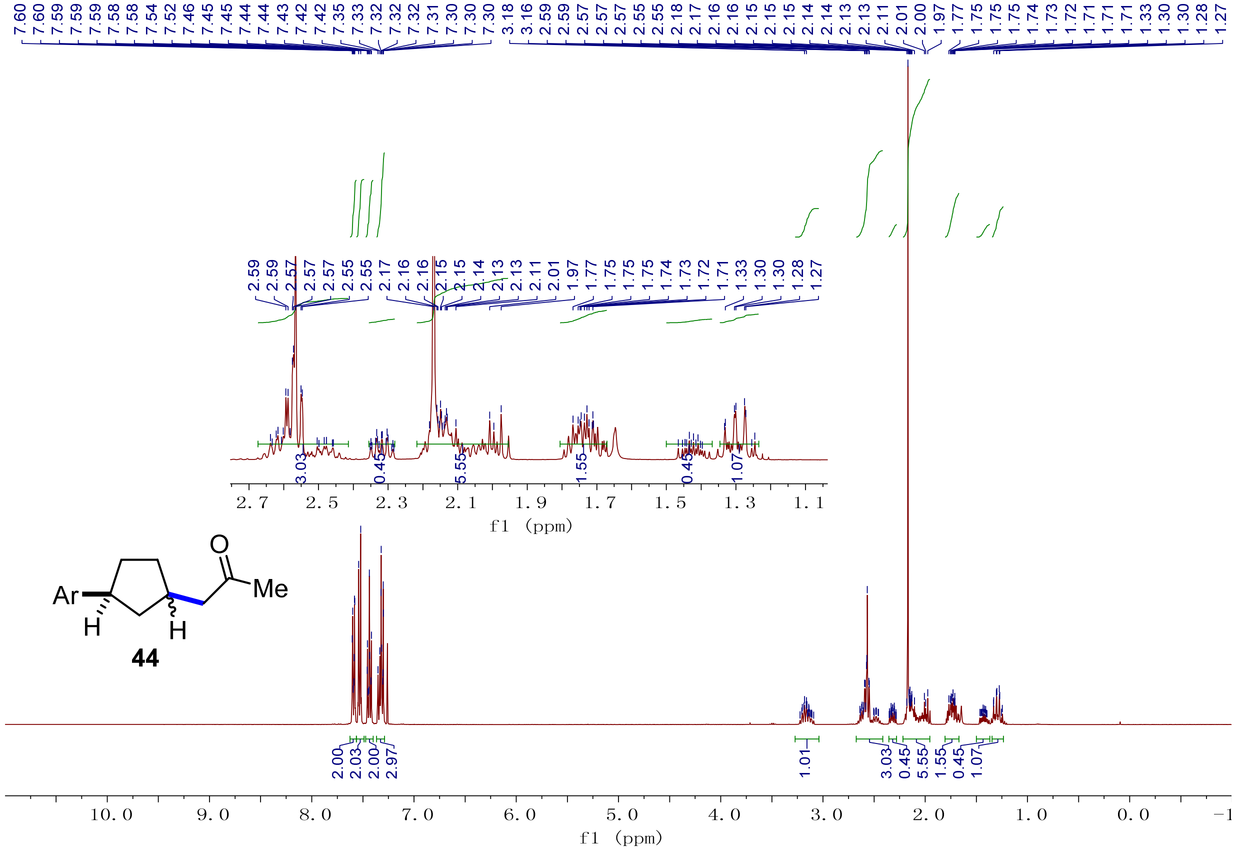

209.55
159.23
129.52
120.56
114.60
67.98
43.96
30.00
29.67
29.65
29.57
29.52
29.43
29.31
26.19
24.00
Ph
O
10
Me
O
42
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
−10
−20
f1 (ppm)

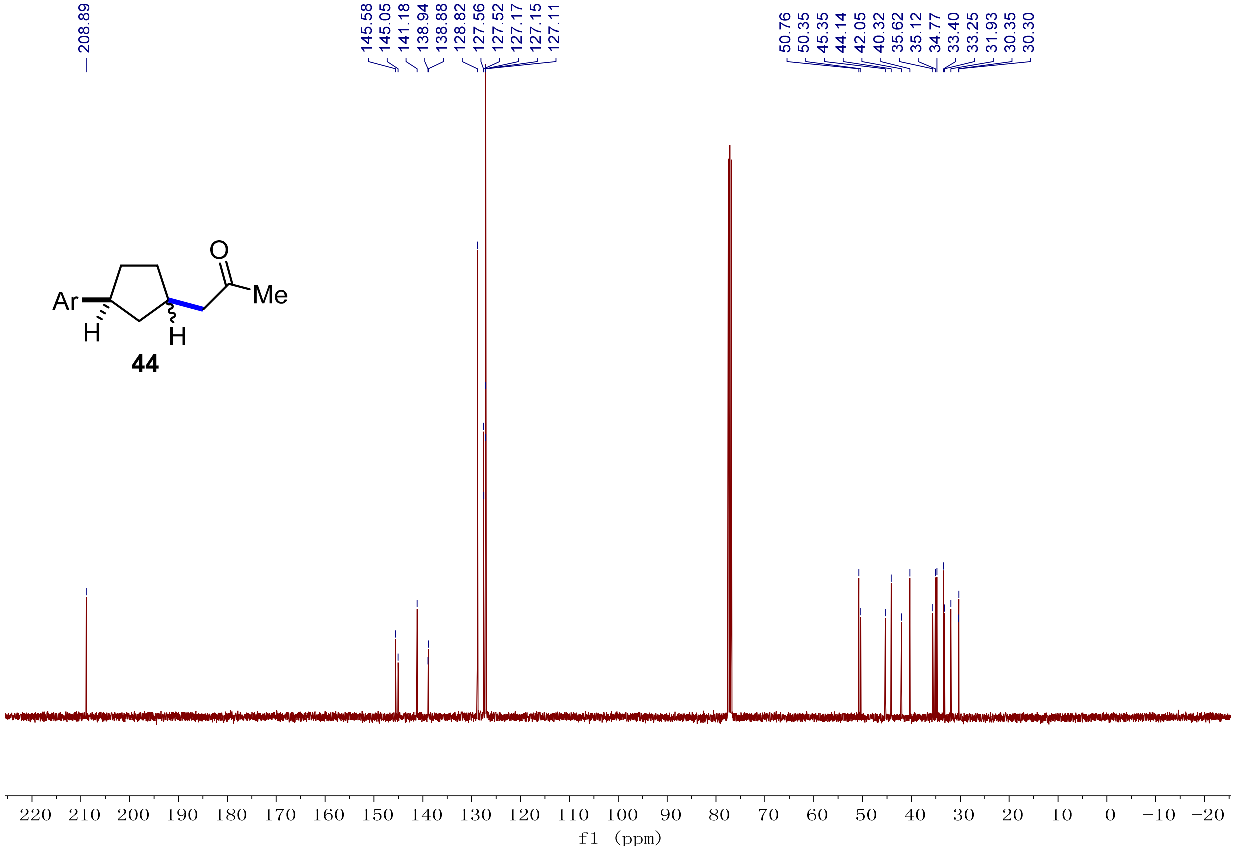

43

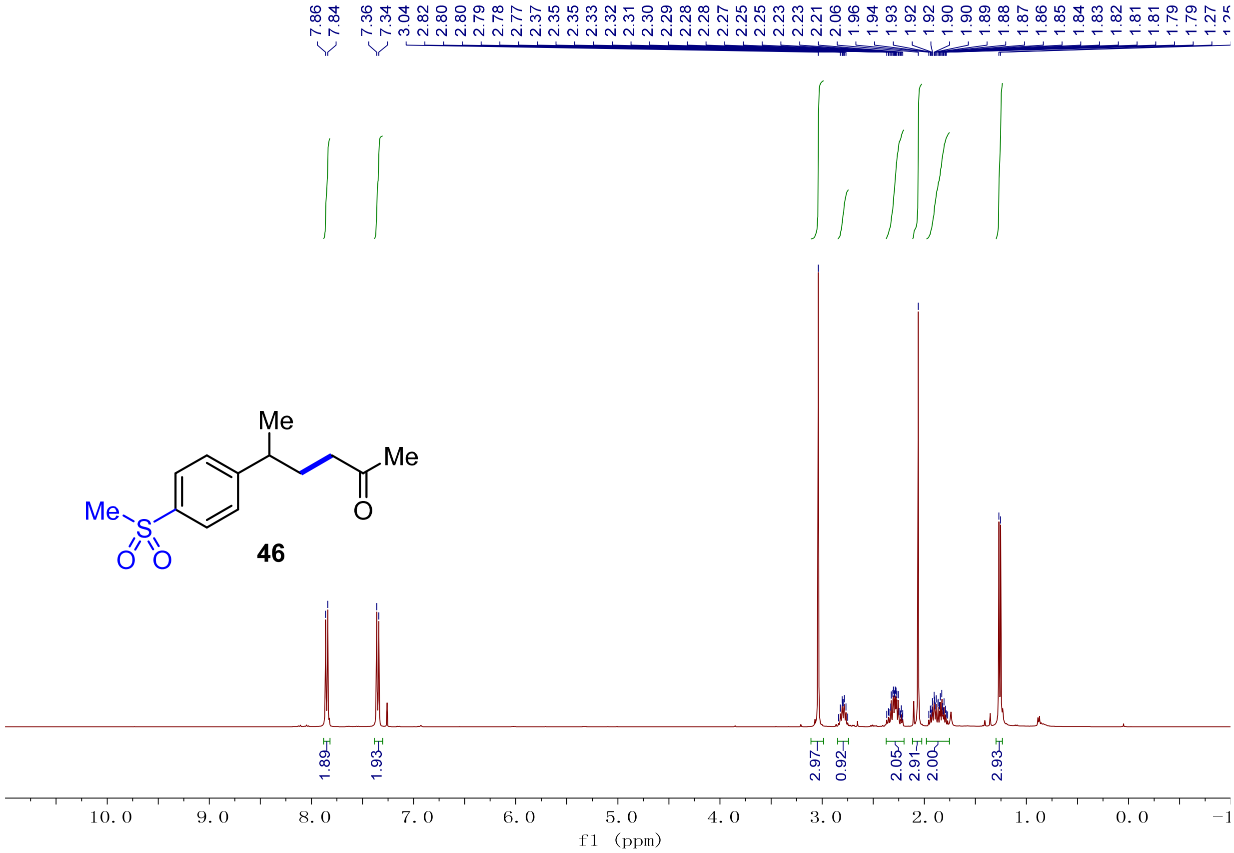
7.84
7.82
7.32
7.30
4.91
2.71
2.69
2.67
2.47
2.46
2.44
2.13
1.67
1.66
1.65
1.64
1.64
1.62
1.61
1.60
1.94
1.92
1.88
1.97
1.88
2.97
4.01
10.5
9.5
8.5
7.5
6.5
5.5
4.5
3.5
2.5
1.5
0.5
−0.5
f1 (ppm)
O
O
S
H_2N
Me
O

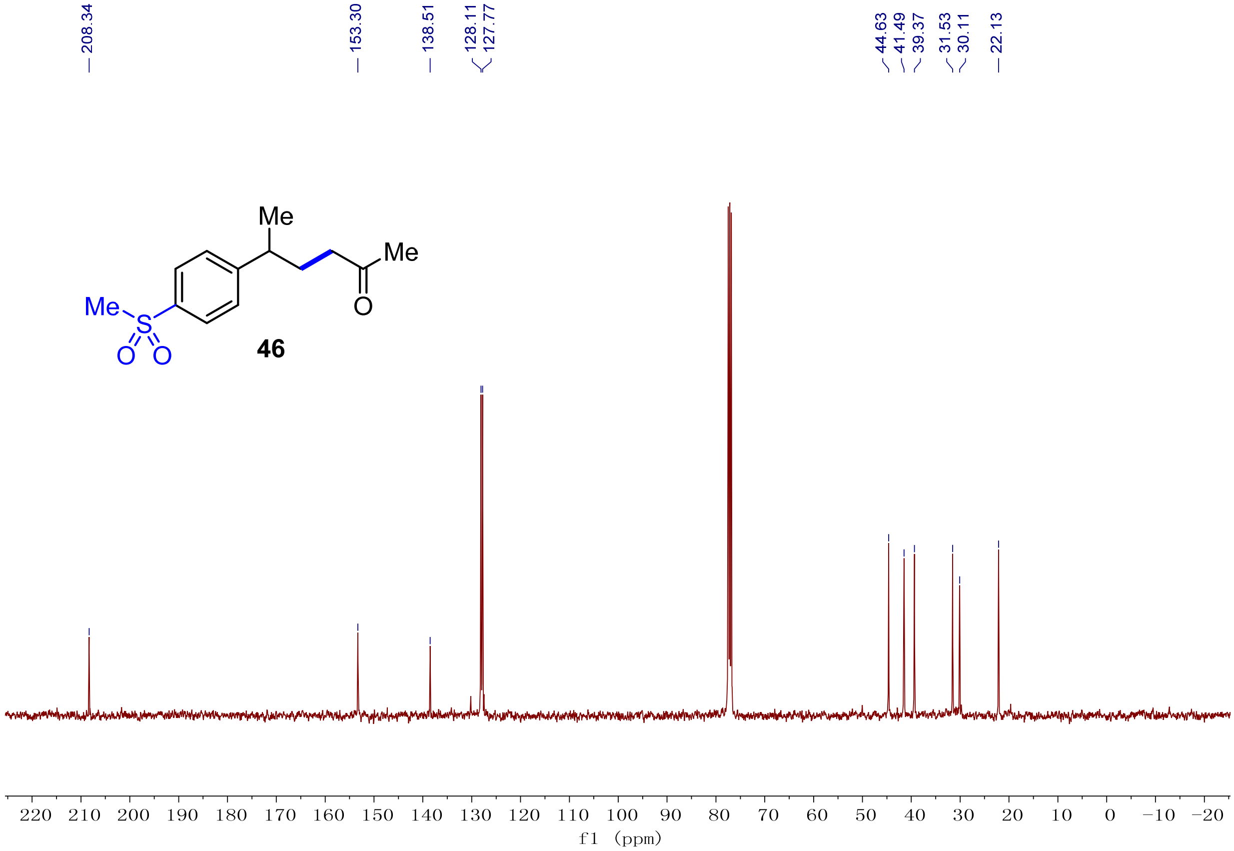

43

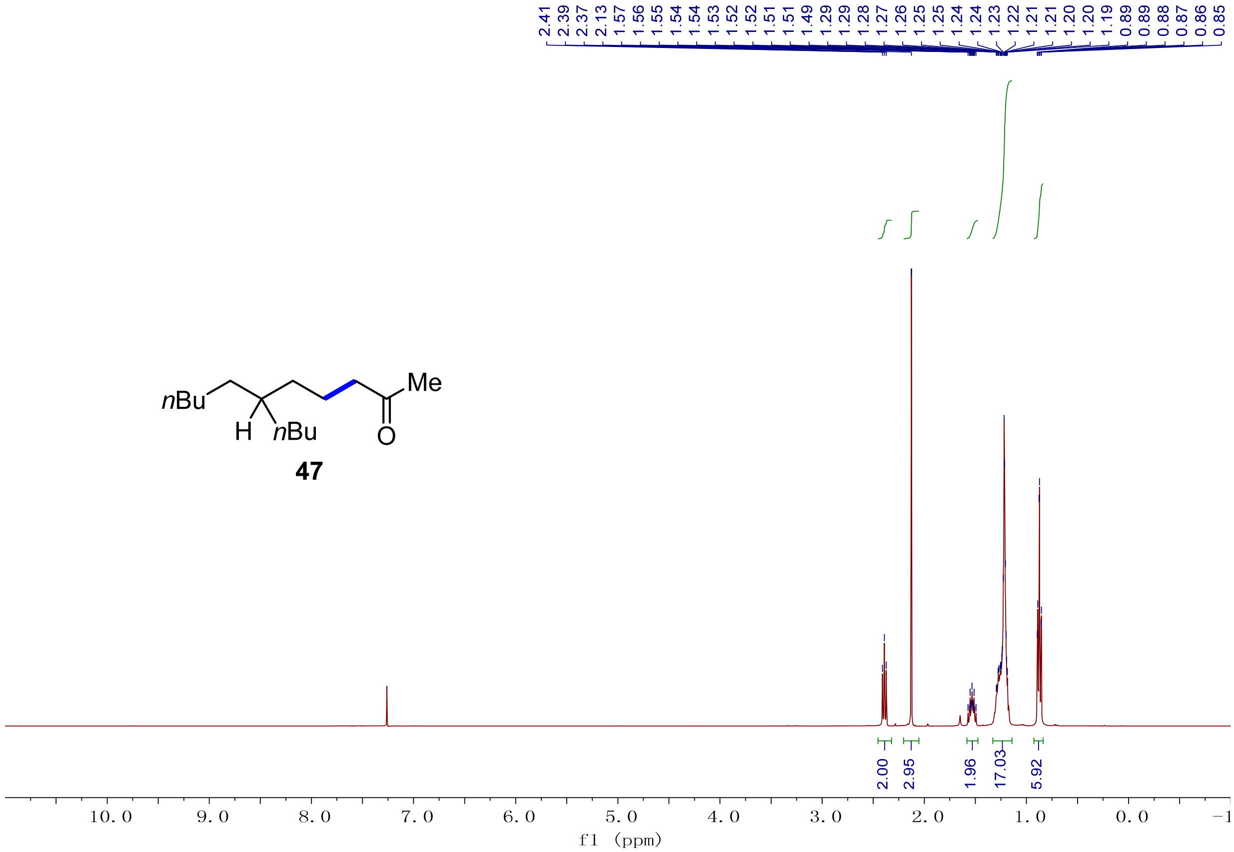
208.95
147.84
139.59
129.22
126.68
43.47
35.75
30.61
30.12
23.32
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
−10
−20
f1 (ppm)
O
O
S
H_2N
Me
O


7.60 7.60 7.59 7.59 7.58 7.58 7.54 7.52 7.46 7.45 7.44 7.44 7.43 7.42 7.42 7.35 7.33 7.32 7.32 7.31 7.30 7.30 3.18 3.16 2.59 2.59 2.57 2.57 2.57 2.55 2.55 2.18 2.17 2.16 2.16 2.15 2.15 2.15 2.14 2.14 2.13 2.13 2.11 2.01 2.00 1.97 1.77 1.75 1.75 1.75 1.74 1.73 1.72 1.71 1.71 1.71 1.33 1.30 1.30 1.28 1.27
2.59 2.59 2.57 2.57 2.57 2.55 2.55 2.17 2.16 2.16 2.15 2.15 2.14 2.13 2.13 2.11 2.01 1.97 1.77 1.75 1.75 1.75 1.74 1.73 1.72 1.71 1.33 1.30 1.30 1.28 1.27
3.03 0.45 5.55 1.55 0.45 1.07
2.7 2.5 2.3 2.1 1.9 1.7 1.5 1.3 1.1
f1 (ppm)
O
Ar
Me
H
H
44
2.00 2.03 2.00 2.97 1.01 3.03 0.45 5.55 1.55 0.45 1.07
10.0 9.0 8.0 7.0 6.0 5.0 4.0 3.0 2.0 1.0 0.0 −1
f1 (ppm)

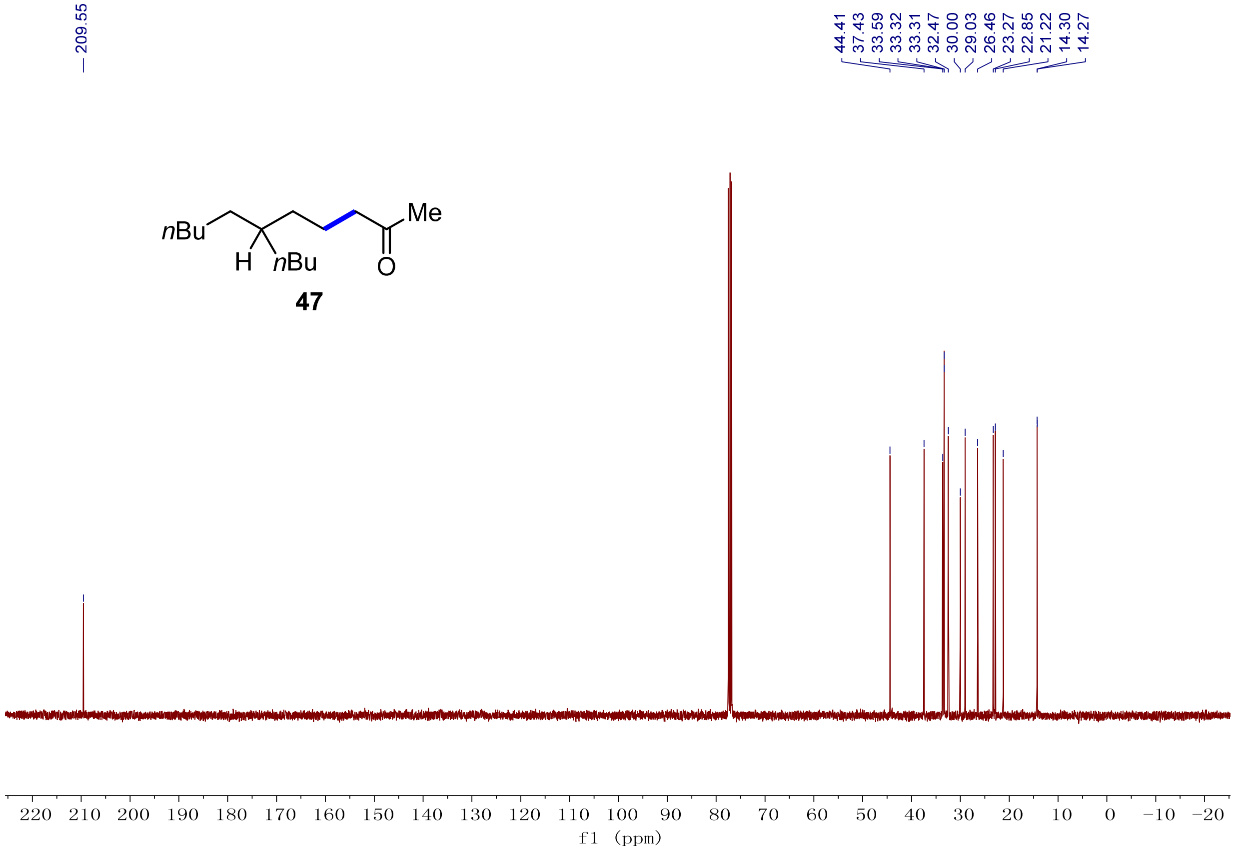

208.89
145.58 145.05 141.18 138.94 138.88 128.82 127.56 127.52 127.17 127.15 127.11
50.76 50.35 45.35 44.14 42.05 40.32 35.62 35.12 34.77 33.40 33.25 31.93 30.35 30.30
O
Ar
Me
H
H
44
220 210 200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 −10 −20
f1 (ppm)


7.86
7.84
7.36
7.34
3.04
2.82
2.80
2.80
2.79
2.78
2.77
2.37
2.35
2.33
2.32
2.31
2.30
2.29
2.28
2.28
2.27
2.25
2.25
2.23
2.23
2.21
2.06
1.96
1.94
1.93
1.92
1.92
1.90
1.89
1.88
1.87
1.86
1.85
1.84
1.83
1.82
1.81
1.81
1.79
1.27
Me
Me
Me
S
O
O
O
46
1.89
1.93
2.97
0.92
2.05
2.91
2.00
2.93
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
−1
f1 (ppm)

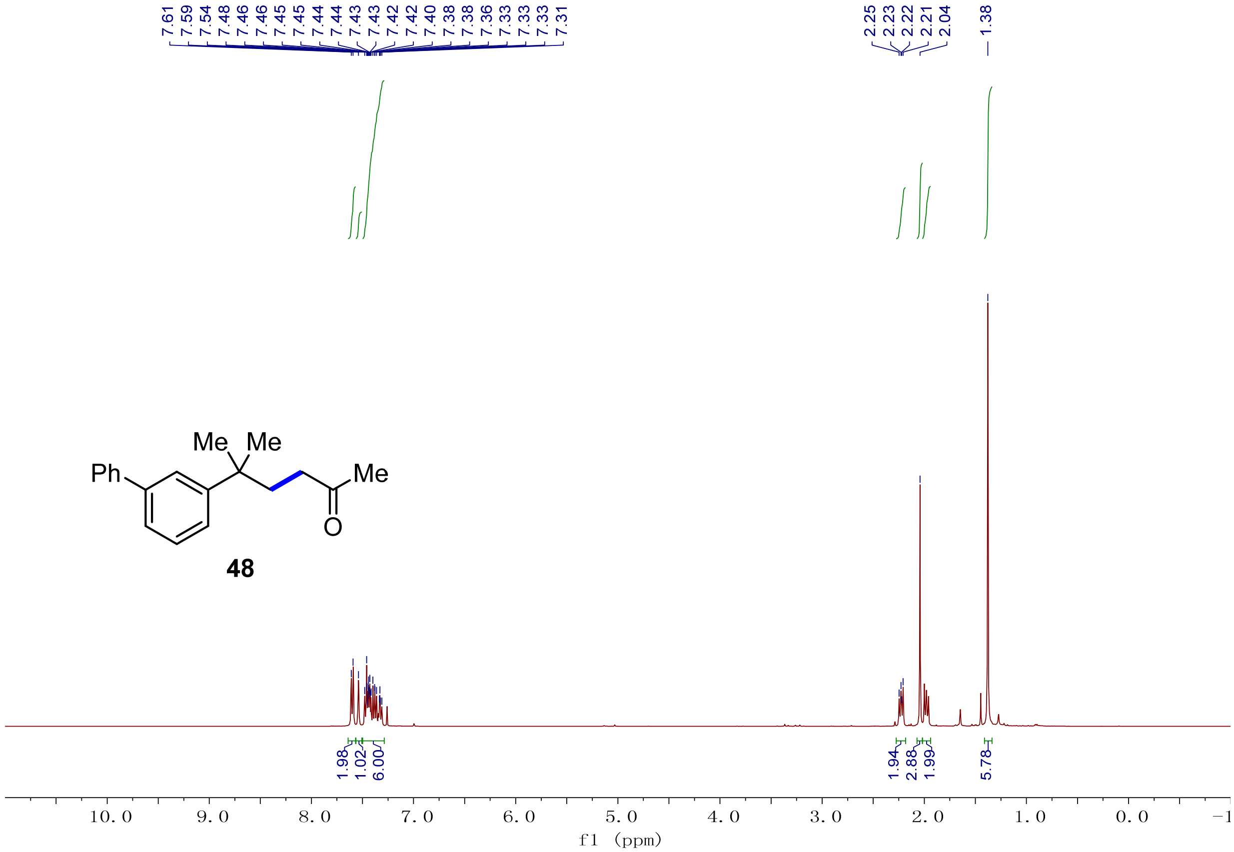

208.34
153.30
138.51
128.11
127.77
44.63
41.49
39.37
31.53
30.11
22.13
Me
Me
Me
S
O
O
O
46
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
−10
−20
f1 (ppm)

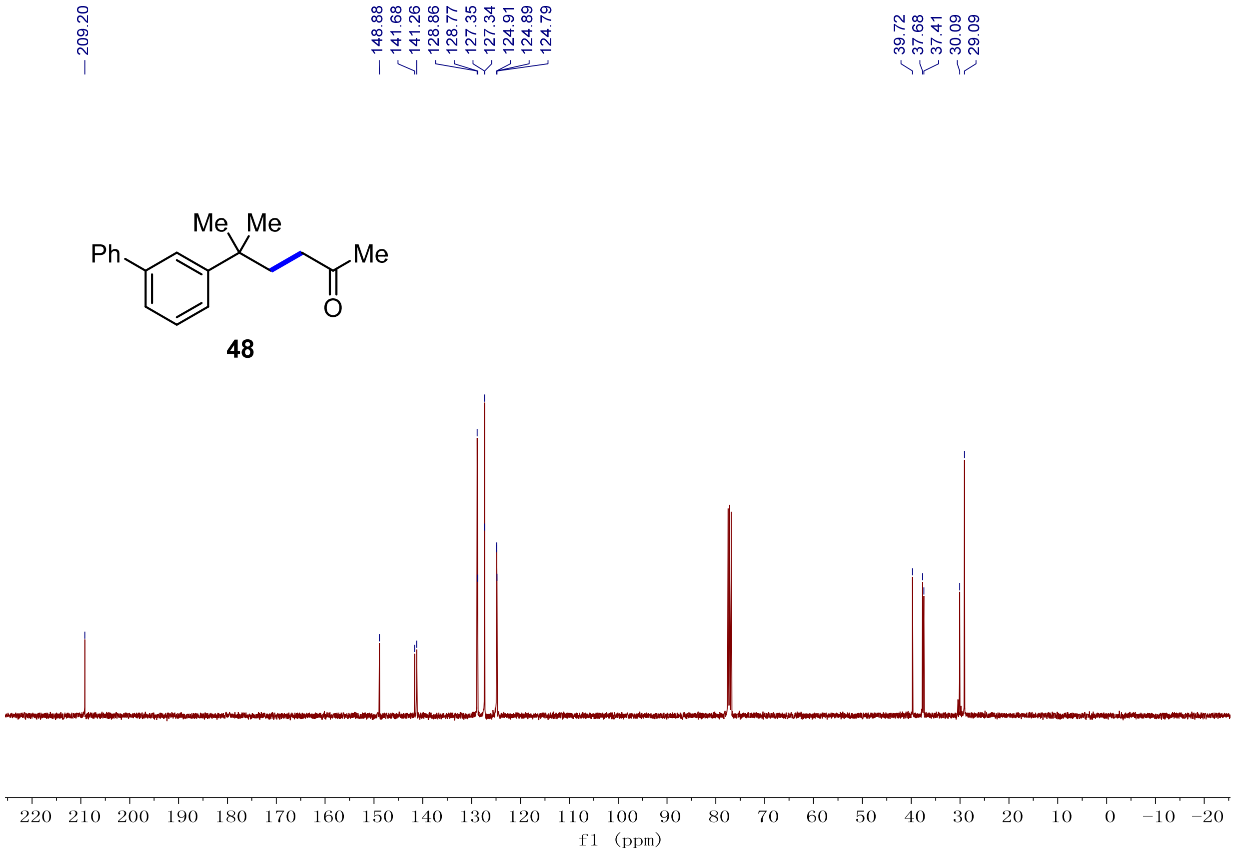

2.41
2.39
2.37
2.13
1.57
1.56
1.55
1.54
1.54
1.53
1.52
1.52
1.51
1.51
1.49
1.29
1.29
1.28
1.27
1.26
1.25
1.25
1.24
1.24
1.23
1.22
1.21
1.21
1.20
1.20
1.19
0.89
0.89
0.88
0.87
0.86
0.85
nBu
Me
H
nBu
O
2.00
2.95
1.96
17.03
5.92
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

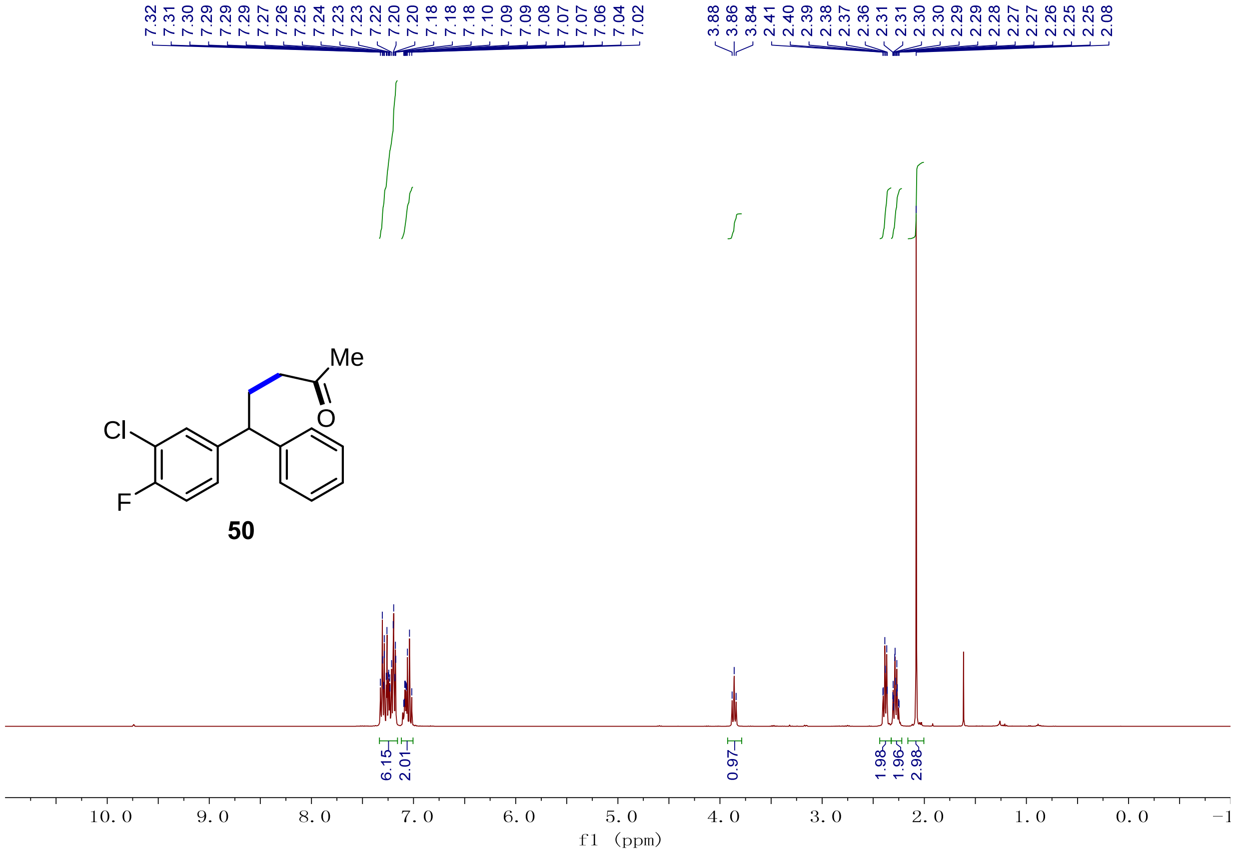
47

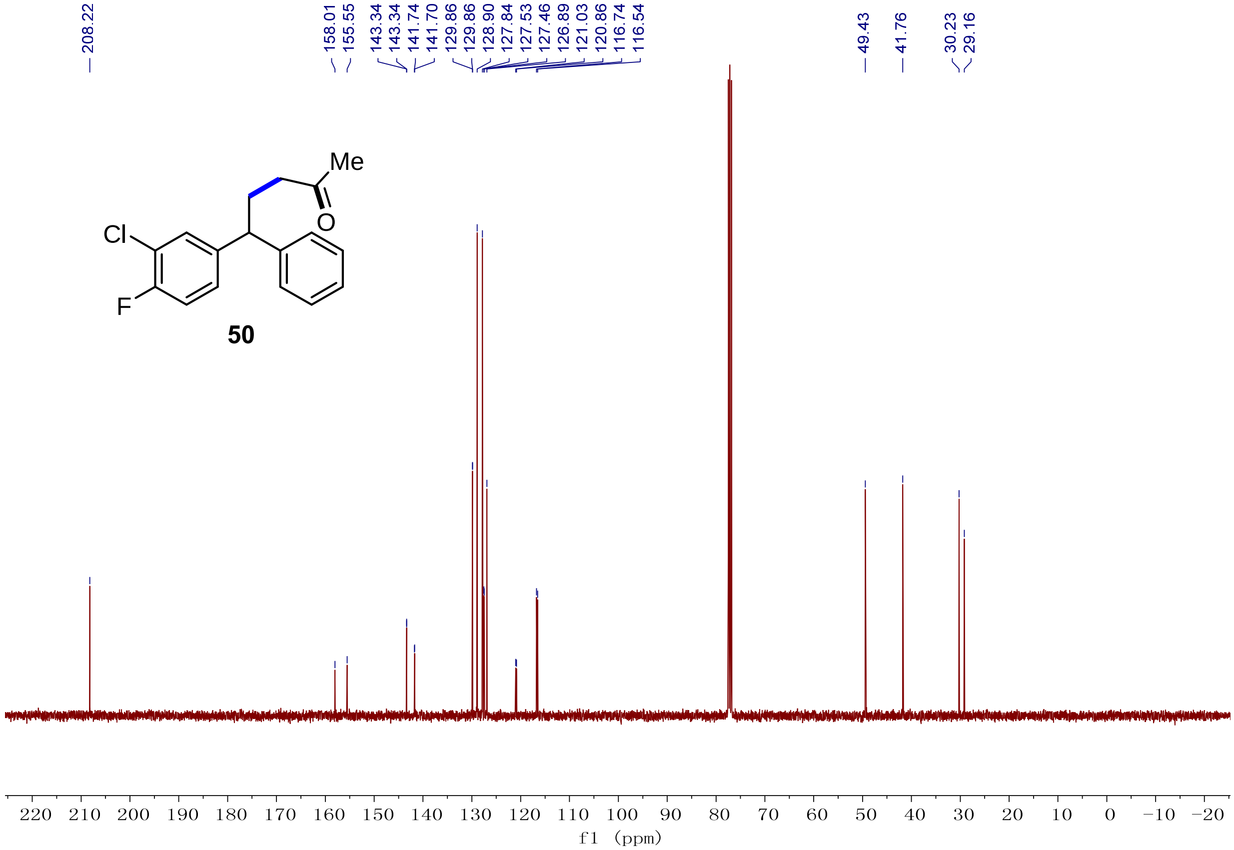

209.55
44.41
37.43
33.59
33.32
33.31
32.47
30.00
29.03
26.46
23.27
22.85
21.22
14.30
14.27
nBu
Me
H
nBu
O
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

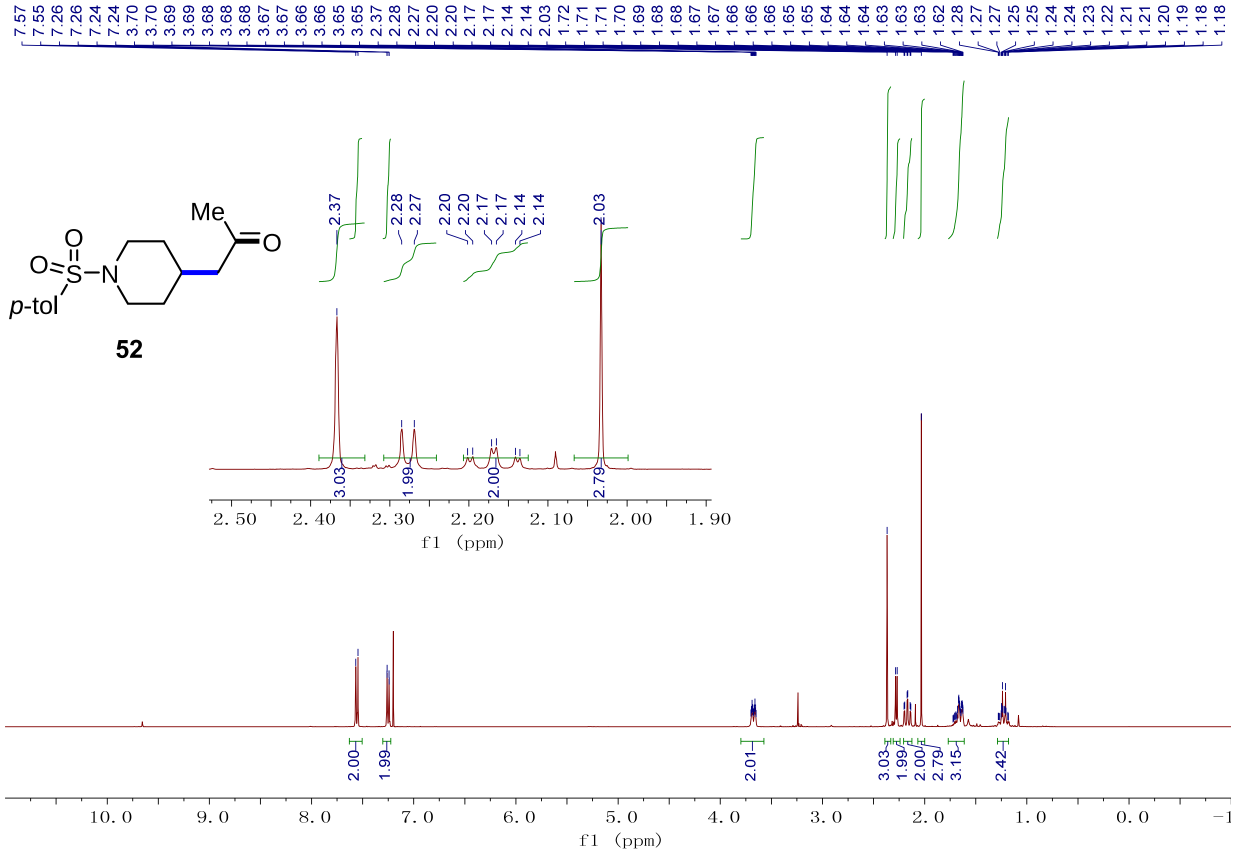
47


7.61 7.59 7.54 7.48 7.46 7.46 7.45 7.45 7.44 7.44 7.43 7.43 7.42 7.42 7.40 7.38 7.38 7.36 7.33 7.33 7.33 7.31
2.25 2.23 2.22 2.21 2.04
1.38
Ph
Me Me
Me
O
48
1.98
1.02
6.00
1.94
2.88
1.99
5.78
10.0 9.0 8.0 7.0 6.0 5.0 4.0 3.0 2.0 1.0 0.0 -1
f1 (ppm)

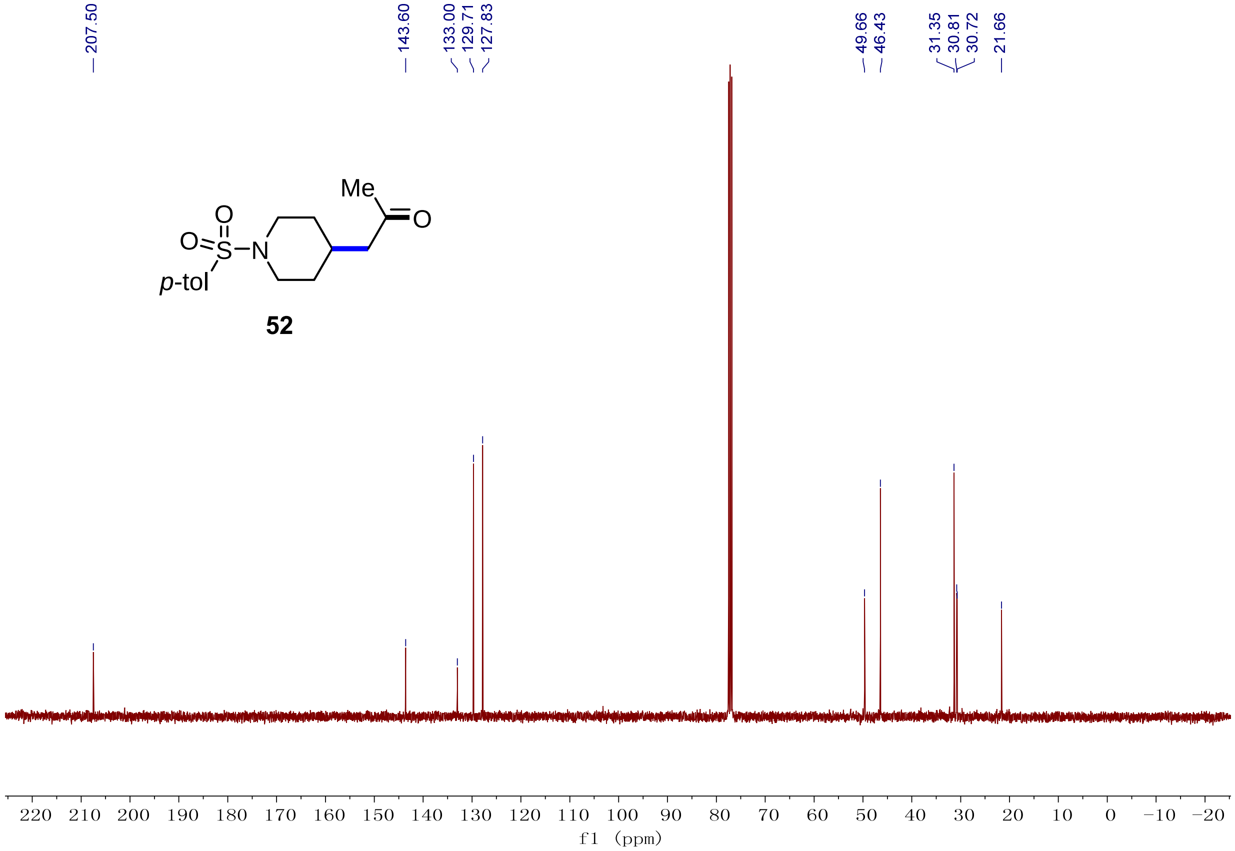

209.20
148.88 141.68 141.26 128.86 128.77 127.35 127.34 124.91 124.89 124.79
39.72 37.68 37.41 30.09 29.09
Ph
Me Me
Me
O
48
220 210 200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 -10 -20
f1 (ppm)


7.32
7.31
7.30
7.29
7.29
7.29
7.27
7.26
7.25
7.24
7.23
7.23
7.22
7.20
7.20
7.18
7.18
7.10
7.09
7.09
7.08
7.07
7.07
7.06
7.04
7.02
3.88
3.86
3.84
2.41
2.40
2.39
2.38
2.37
2.36
2.31
2.31
2.30
2.30
2.29
2.29
2.28
2.27
2.27
2.26
2.25
2.25
2.08
Me
O
Cl
F
50
6.15
2.01
0.97
1.98
1.96
2.98
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

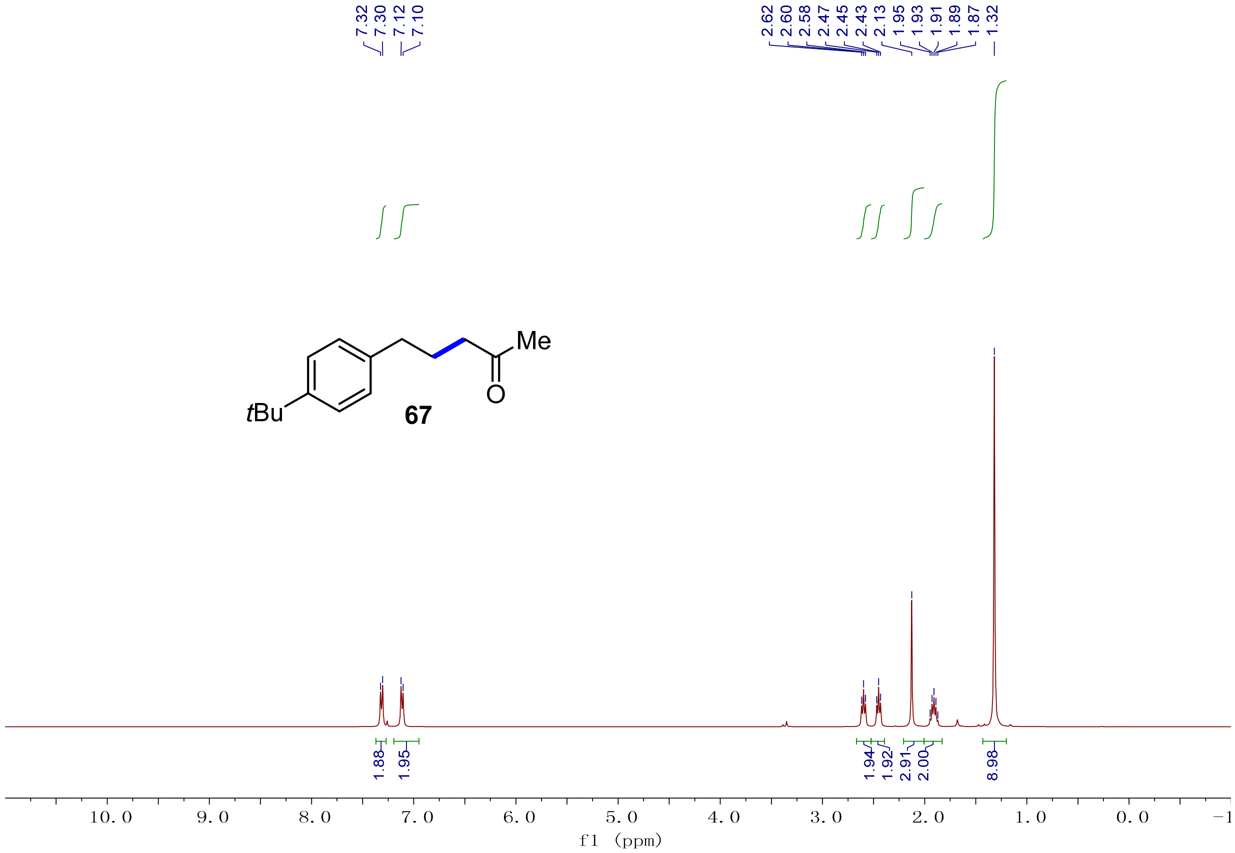

208.22
158.01
155.55
143.34
143.34
141.74
141.70
129.86
129.86
128.90
127.84
127.53
127.46
126.89
121.03
120.86
116.74
116.54
49.43
41.76
30.23
29.16
Me
O
Cl
F
50
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

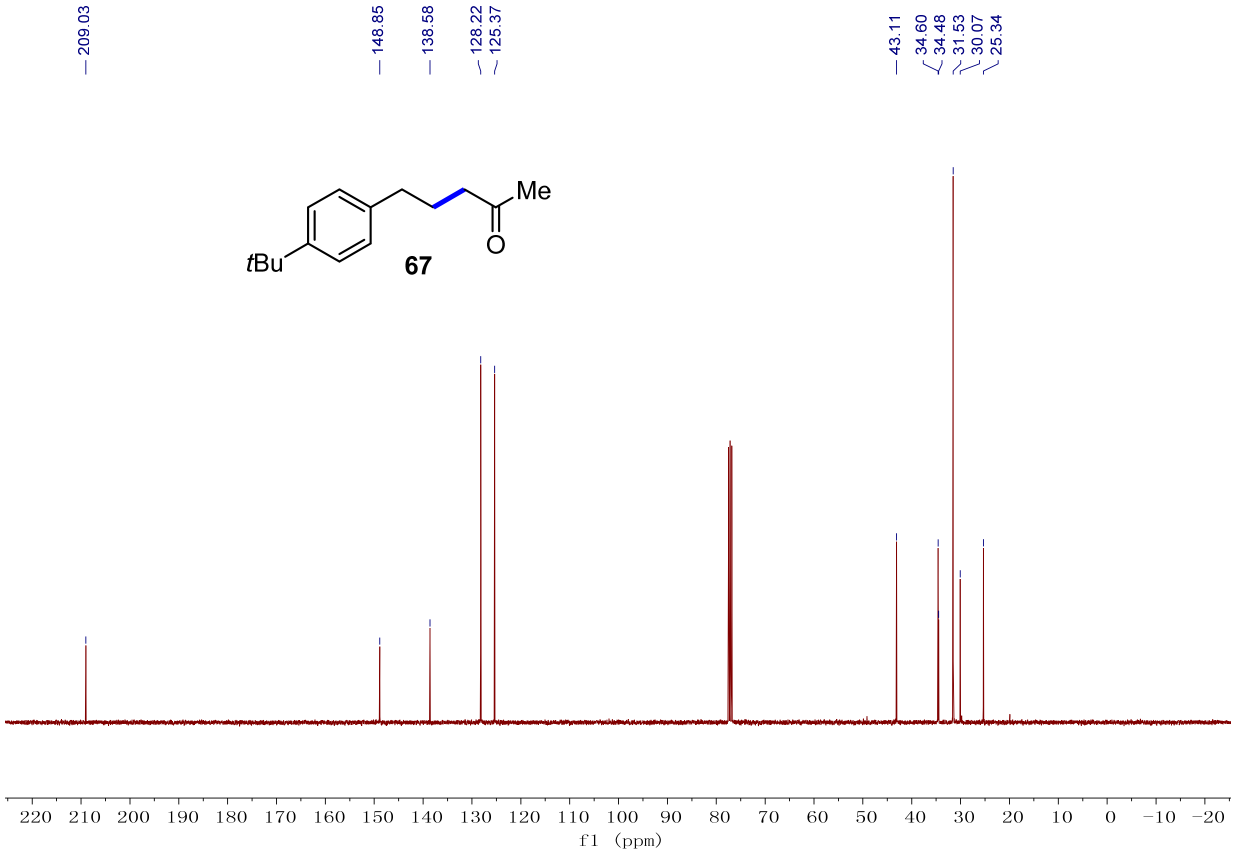

7.57
7.55
7.26
7.26
7.24
7.24
3.70
3.70
3.69
3.69
3.68
3.68
3.68
3.67
3.67
3.66
3.66
3.65
3.65
2.37
2.28
2.27
2.20
2.20
2.17
2.17
2.14
2.14
2.03
1.72
1.71
1.71
1.70
1.69
1.68
1.68
1.67
1.67
1.66
1.66
1.66
1.65
1.65
1.64
1.64
1.64
1.63
1.63
1.63
1.62
1.28
1.27
1.27
1.25
1.25
1.24
1.24
1.23
1.22
1.21
1.21
1.20
1.19
1.18
Me
O
O
S
N
O
p-tol
2.37
2.28
2.27
2.20
2.20
2.17
2.17
2.14
2.14
2.03
3.03
1.99
2.00
2.79
2. 50
2. 40
2. 30
2. 20
2. 10
2. 00
1. 90
f1 (ppm)
2.00
1.99
2.01
3.03
1.99
2.00
2.79
3.15
2.42
10. 0
9. 0
8. 0
7. 0
6. 0
5. 0
4. 0
3. 0
2. 0
1. 0
0. 0
-1
f1 (ppm)

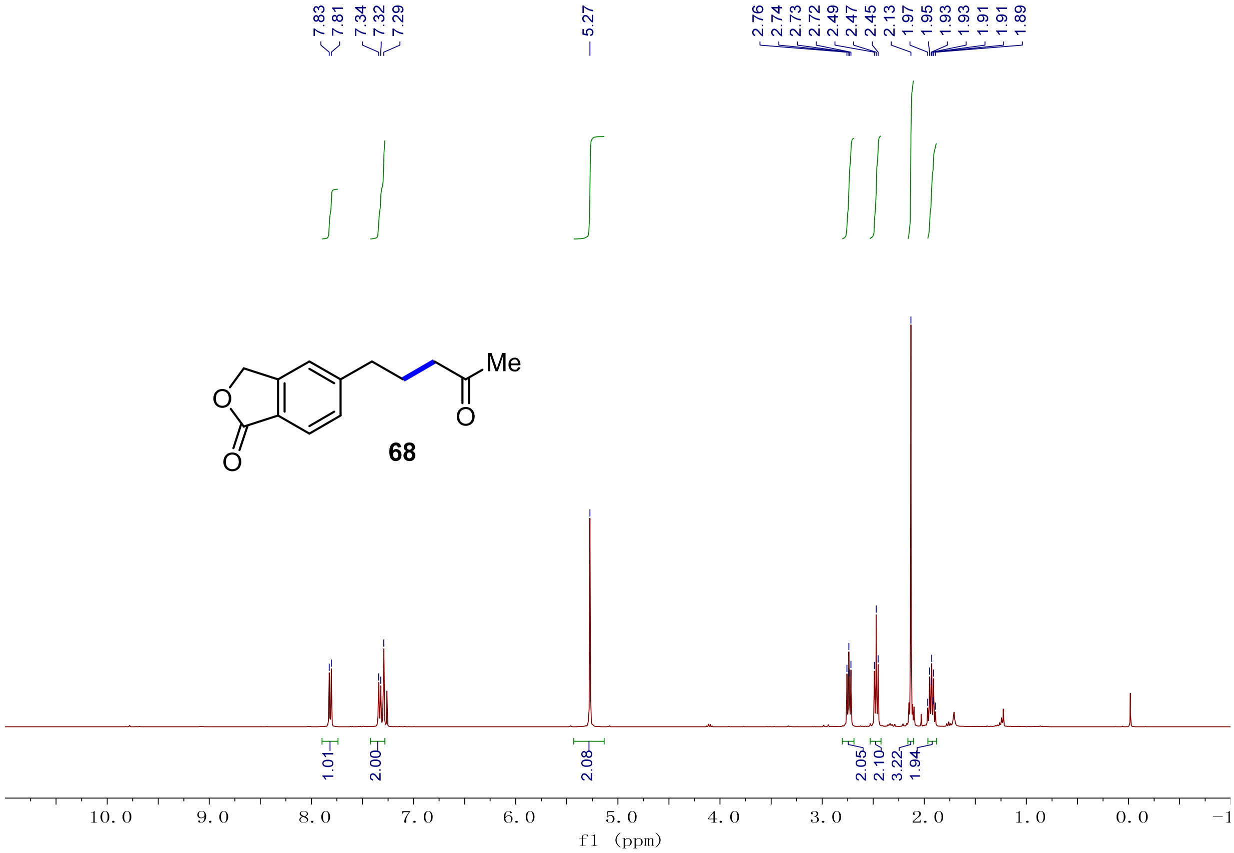
52


207.50
143.60
133.00
129.71
127.83
49.66
46.43
31.35
30.81
30.72
21.66
Me
O
O
S
N
O
p-tol
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

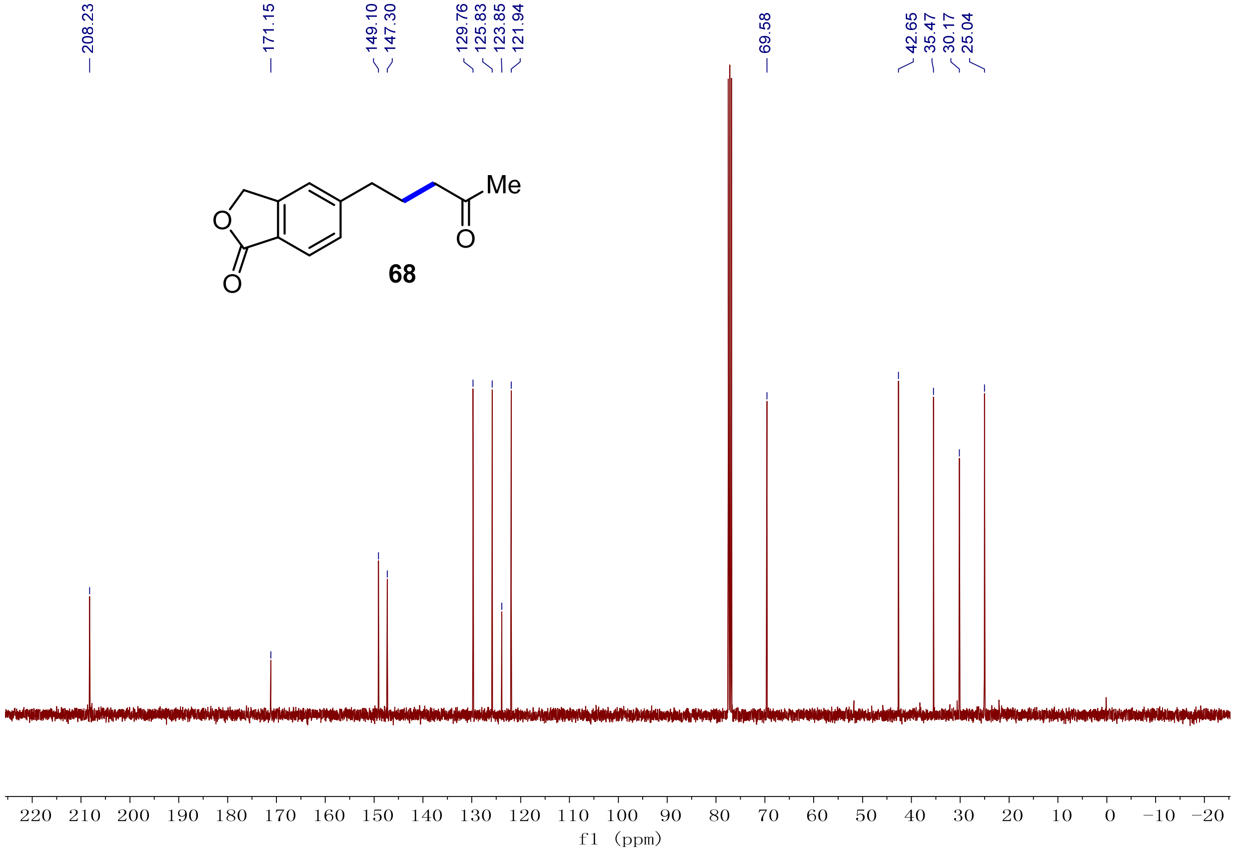
52


7.32
7.30
7.12
7.10
2.62
2.60
2.58
2.47
2.45
2.43
2.13
1.95
1.93
1.91
1.89
1.87
1.32
Me
O
tBu
67
1.88
1.95
1.94
1.92
2.91
2.00
8.98
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

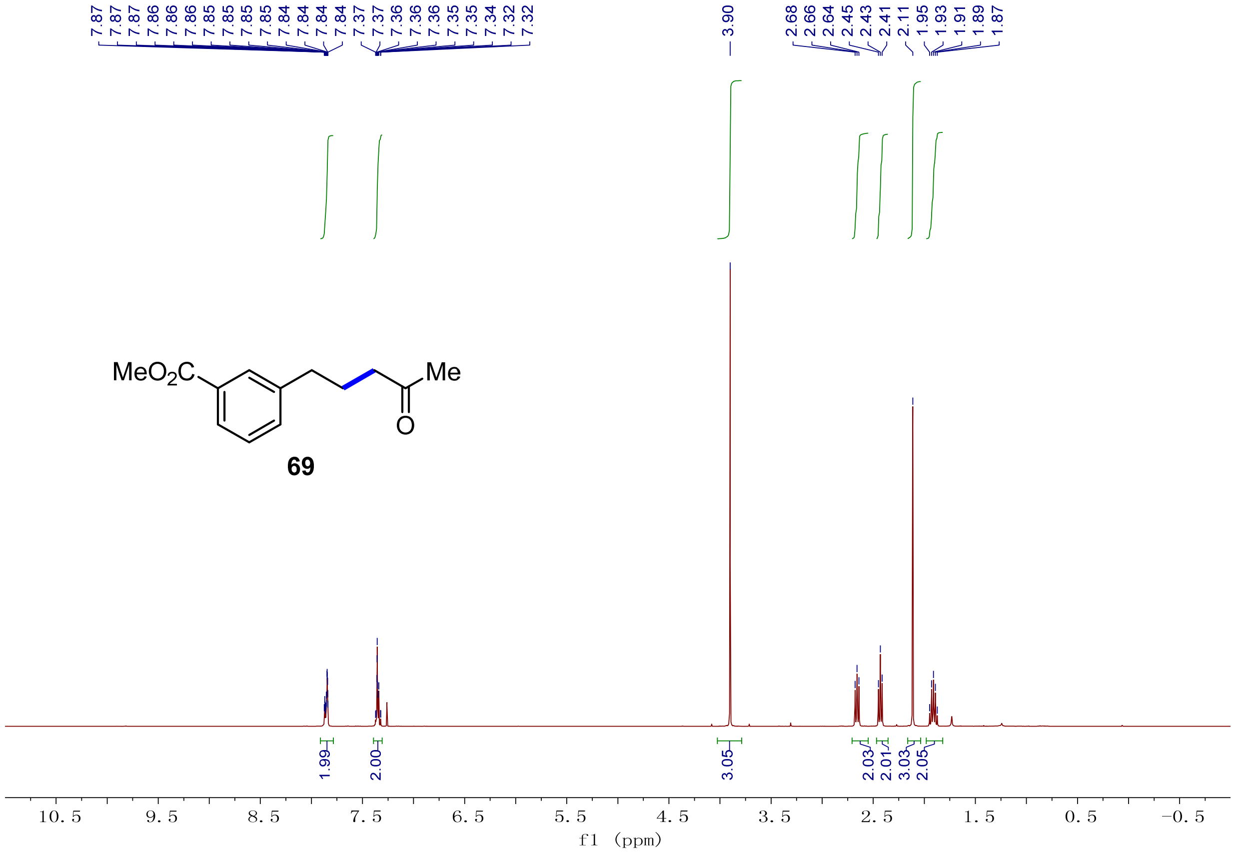

209.03
148.85
138.58
128.22
125.37
43.11
34.60
34.48
31.53
30.07
25.34
Me
O
tBu
67
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

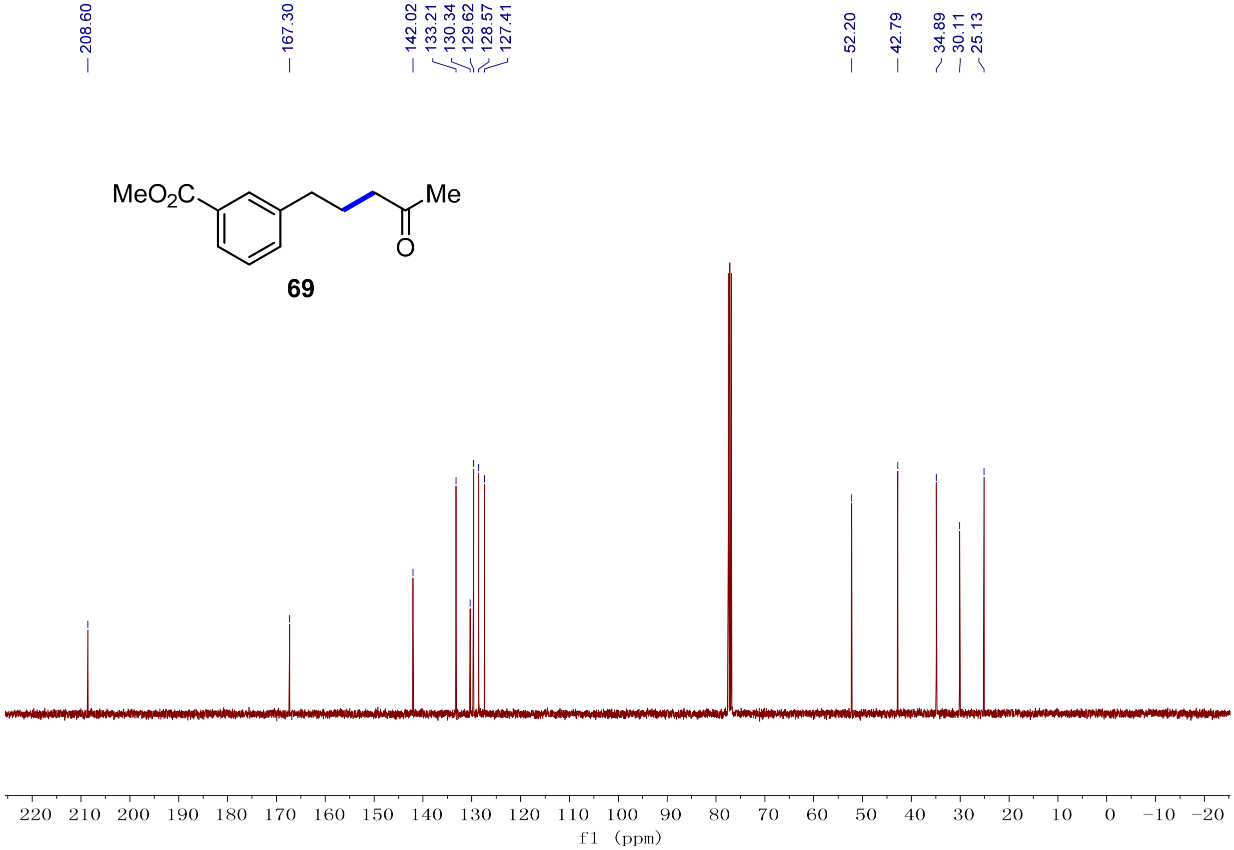

68

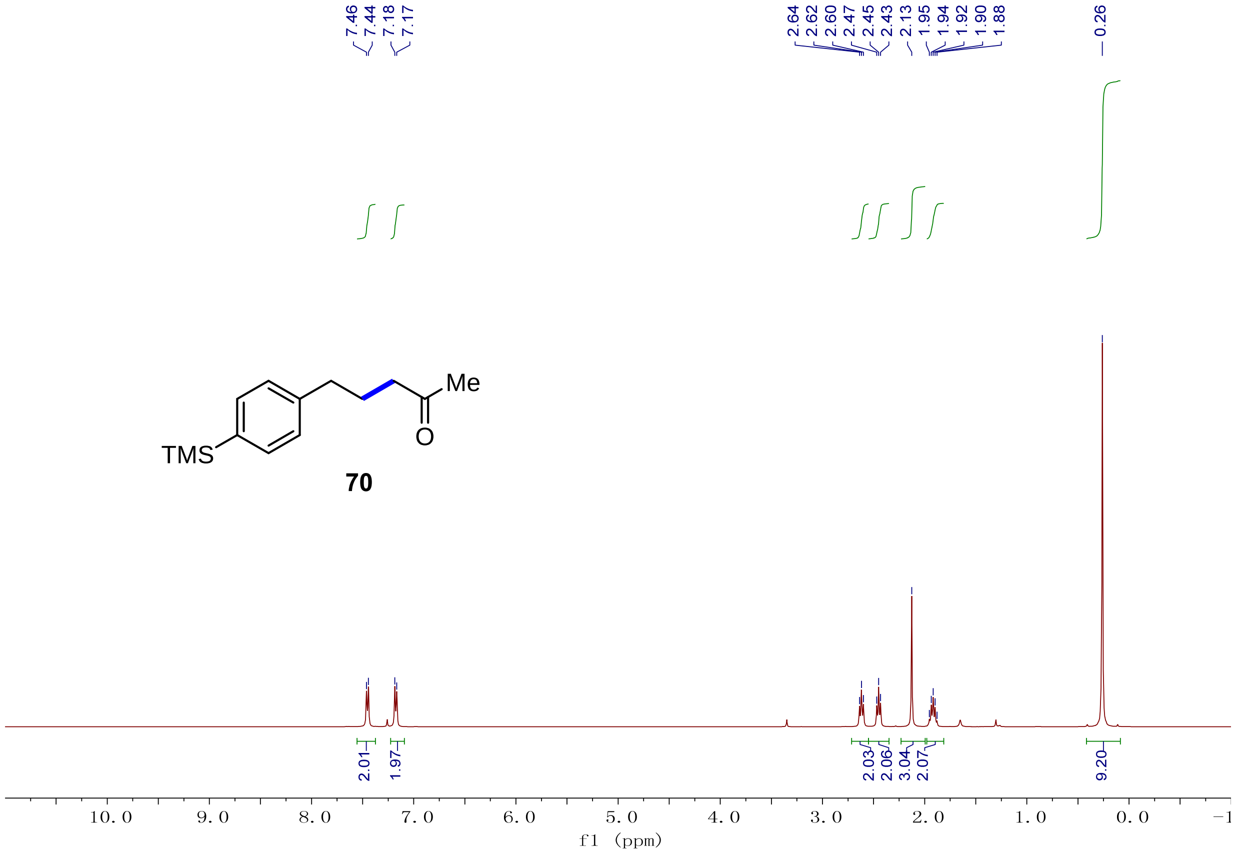
7.83
7.81
7.34
7.32
7.29
5.27
2.76
2.74
2.73
2.72
2.49
2.47
2.45
2.13
1.97
1.95
1.93
1.93
1.91
1.91
1.89
Me
O
O
O
1.01
2.00
2.08
2.05
2.10
3.22
1.94
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

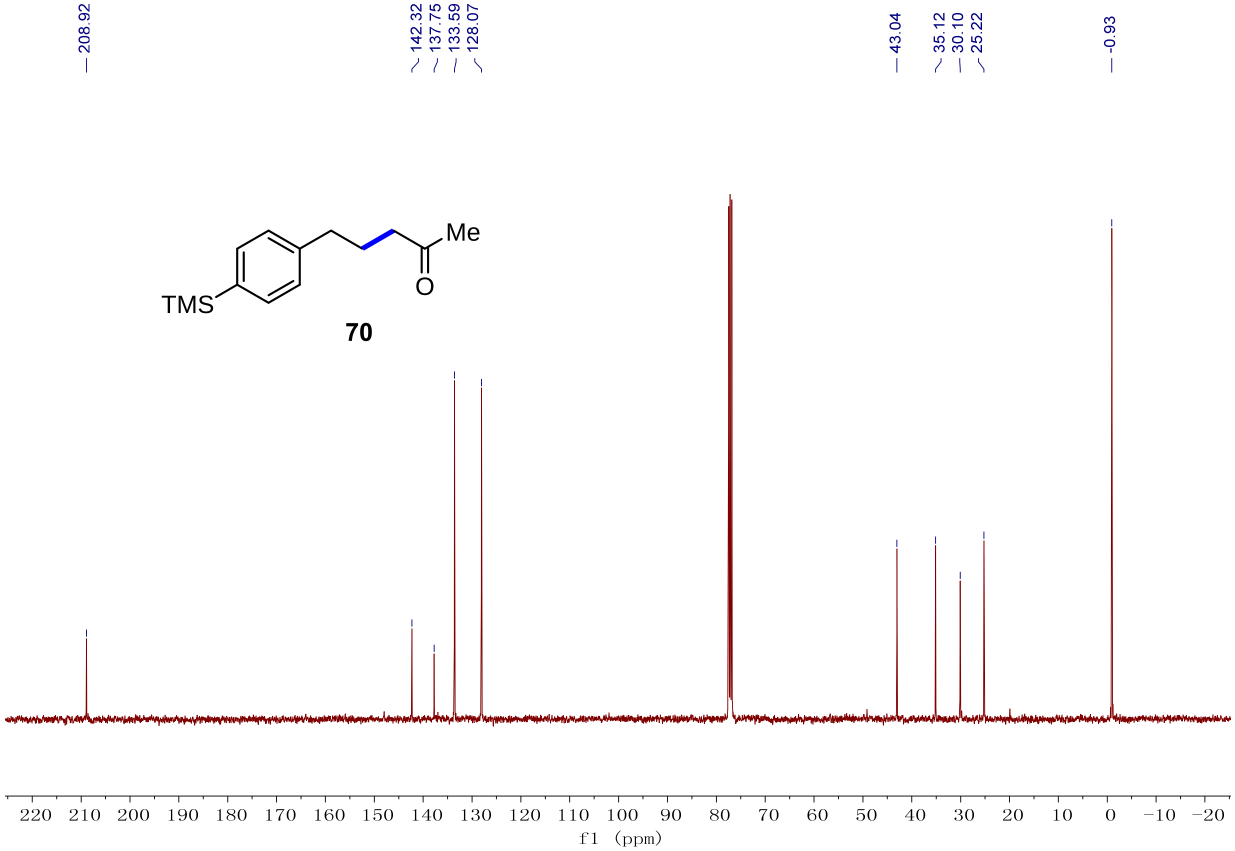

68

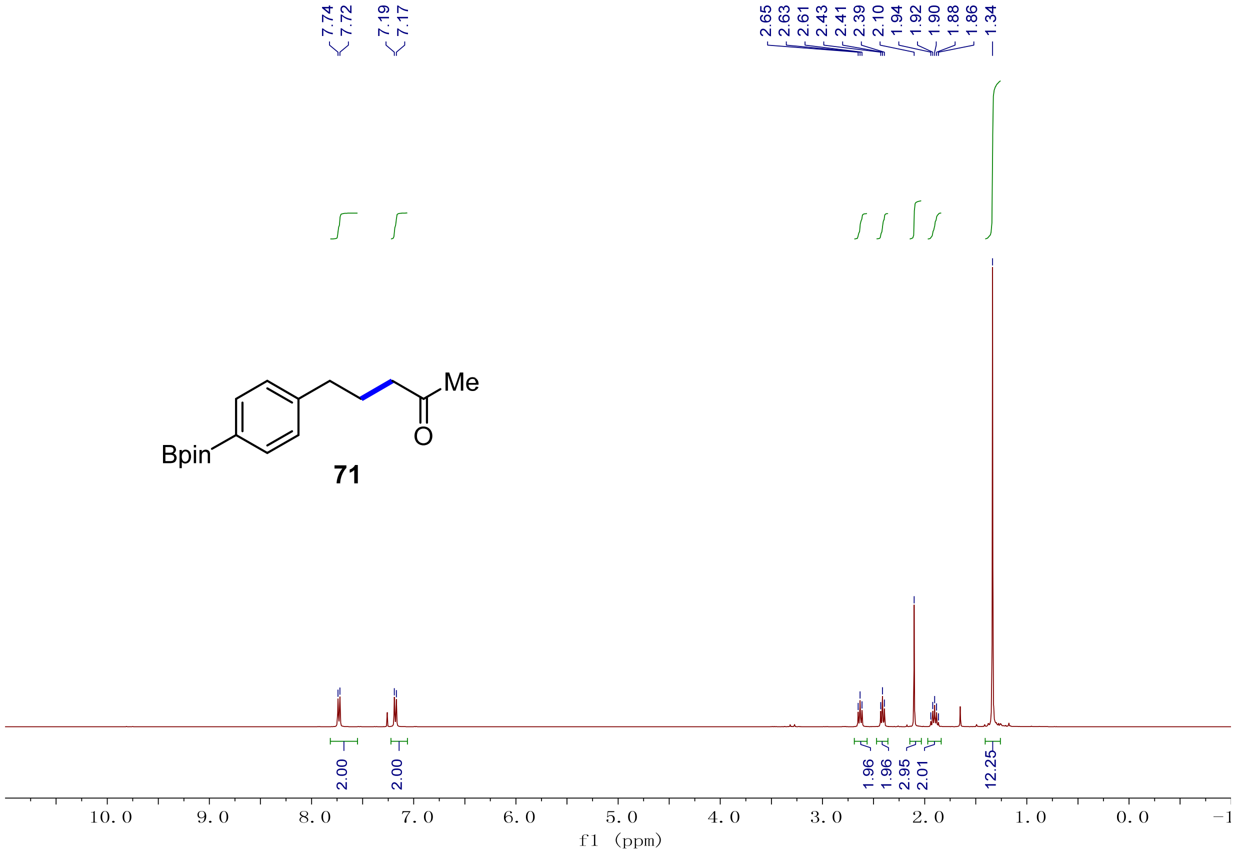
208.23
171.15
149.10
147.30
129.76
125.83
123.85
121.94
69.58
42.65
35.47
30.17
25.04
Me
O
O
O
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

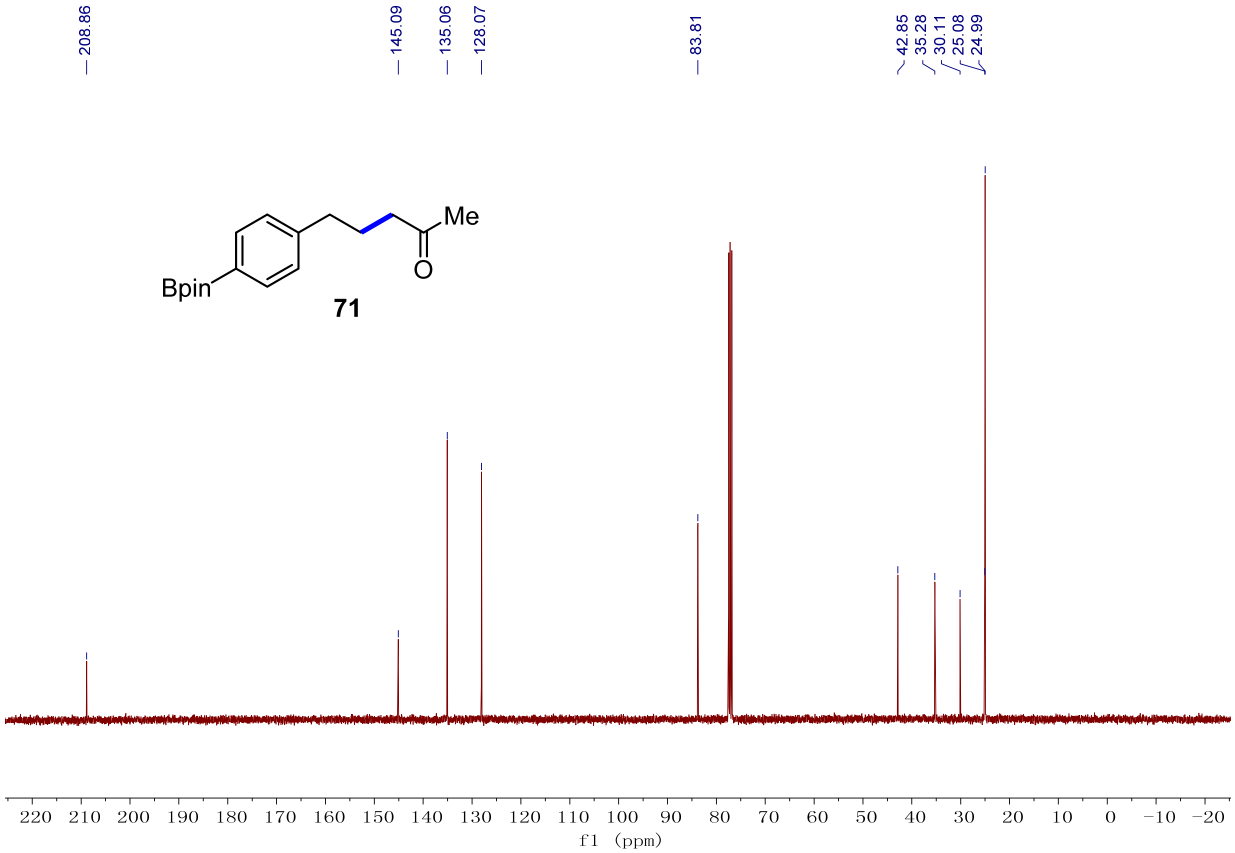

7.87
7.87
7.87
7.86
7.86
7.86
7.85
7.85
7.85
7.84
7.84
7.84
7.84
7.37
7.37
7.36
7.36
7.36
7.35
7.35
7.34
7.32
7.32
3.90
2.68
2.66
2.64
2.45
2.43
2.41
2.11
1.95
1.93
1.91
1.89
1.87
MeO2C
Me
O
69
1.99
2.00
3.05
2.03
2.01
3.03
2.05
10.5
9.5
8.5
7.5
6.5
5.5
4.5
3.5
2.5
1.5
0.5
-0.5
f1 (ppm)

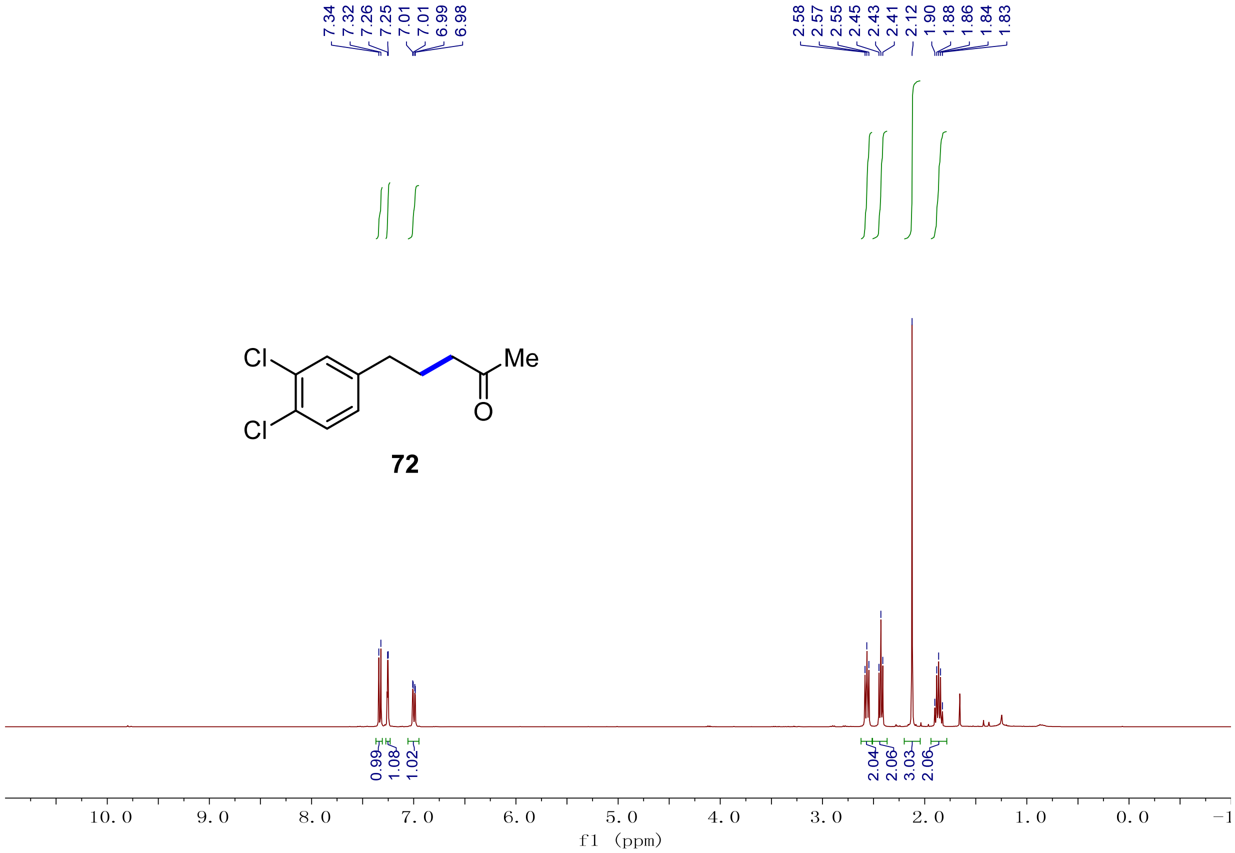

208.60
167.30
142.02
133.21
130.34
129.62
128.57
127.41
52.20
42.79
34.89
30.11
25.13
MeO2C
Me
O
69
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

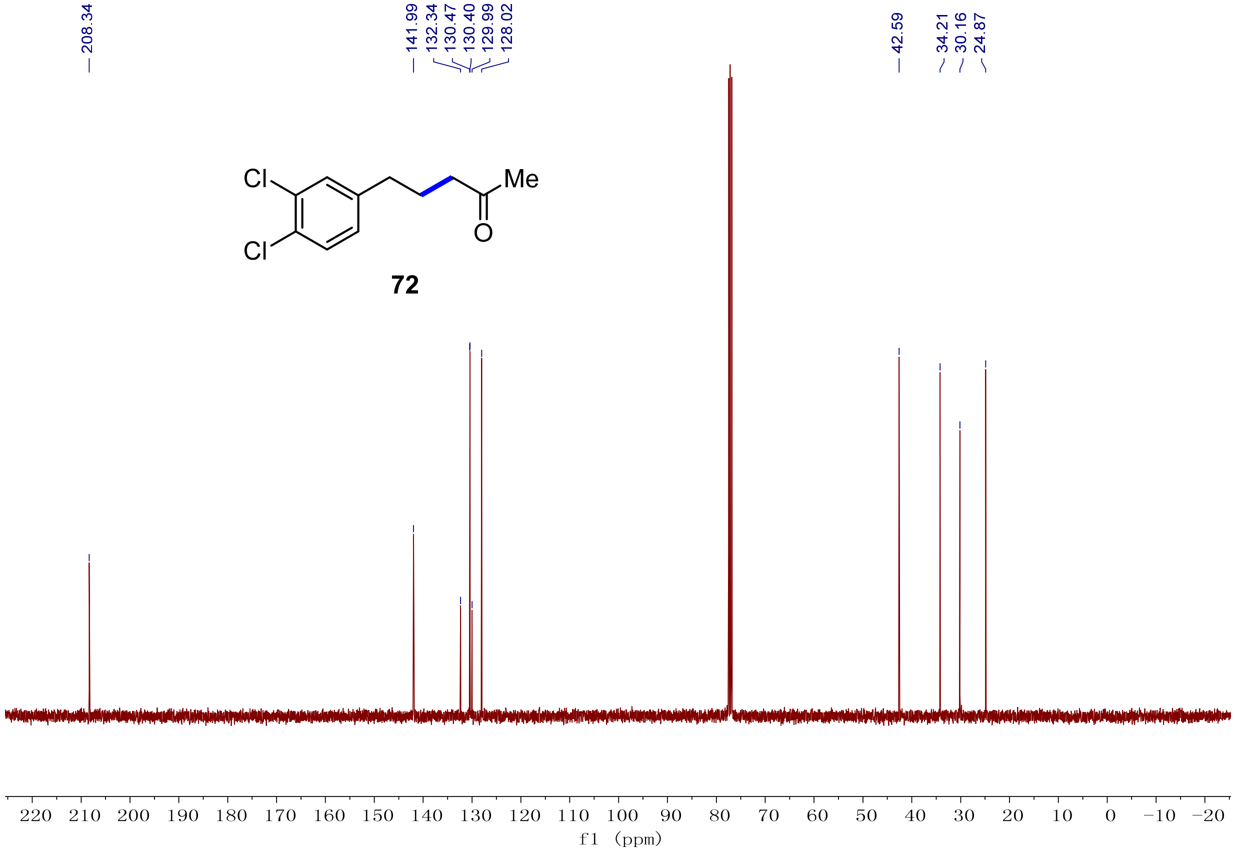

7.46
7.44
7.18
7.17
2.64
2.62
2.60
2.47
2.45
2.43
2.13
1.95
1.94
1.92
1.90
1.88
0.26
2.01
1.97
2.03
2.06
3.04
2.07
9.20
TMS
Me
O
70
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

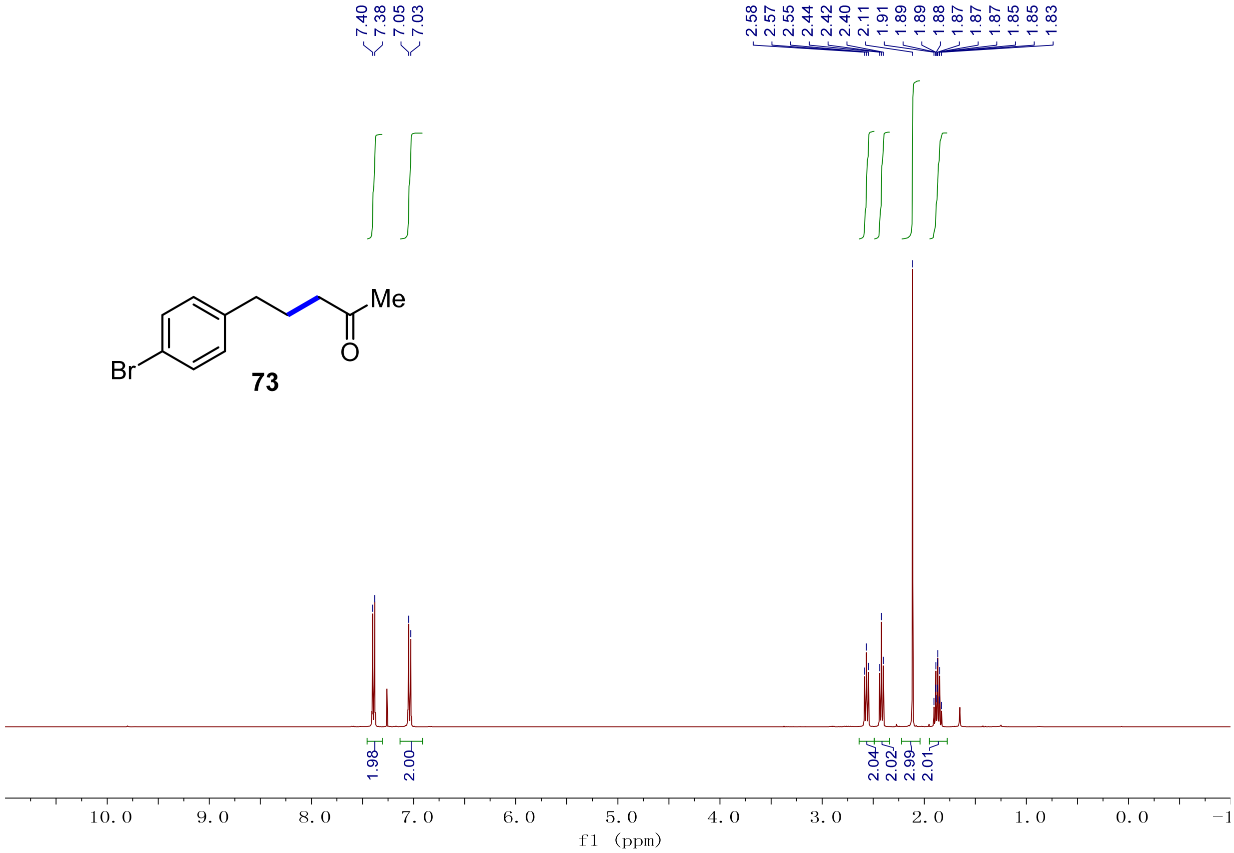

208.92
142.32
137.75
133.59
128.07
43.04
35.12
30.10
25.22
-0.93
TMS
Me
O
70
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)


7.74
7.72
7.19
7.17
2.65
2.63
2.61
2.43
2.41
2.39
2.10
1.94
1.92
1.90
1.88
1.86
1.34
Me
O
Bpin
71
2.00
2.00
1.96
1.96
2.95
2.01
12.25
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

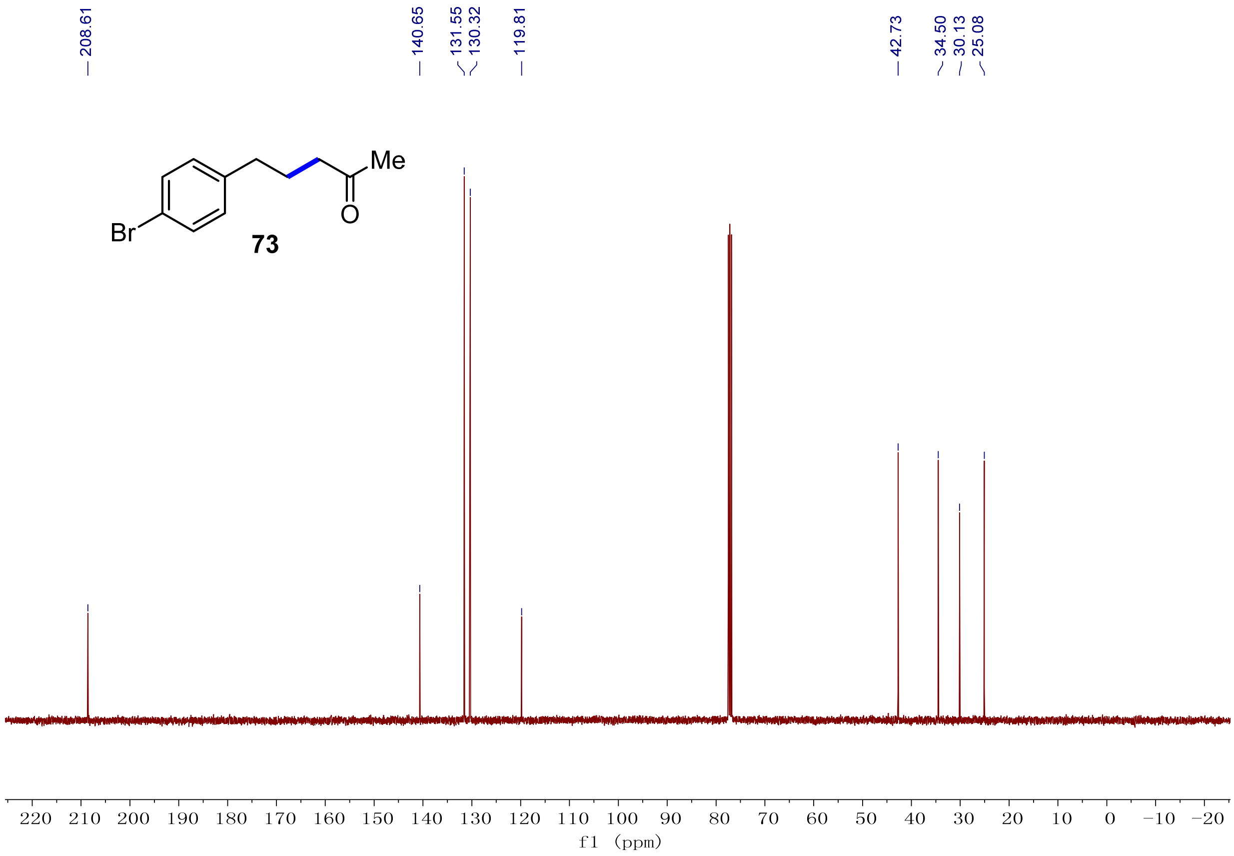

208.86
145.09
135.06
128.07
83.81
42.85
35.28
30.11
25.08
24.99
Me
O
Bpin
71
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)


7.34
7.32
7.26
7.25
7.01
7.01
6.99
6.98
2.58
2.57
2.55
2.45
2.43
2.41
2.12
1.90
1.88
1.86
1.84
1.83
Cl
Cl
Me
O
72
0.99
1.08
1.02
2.04
2.06
3.03
2.06
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

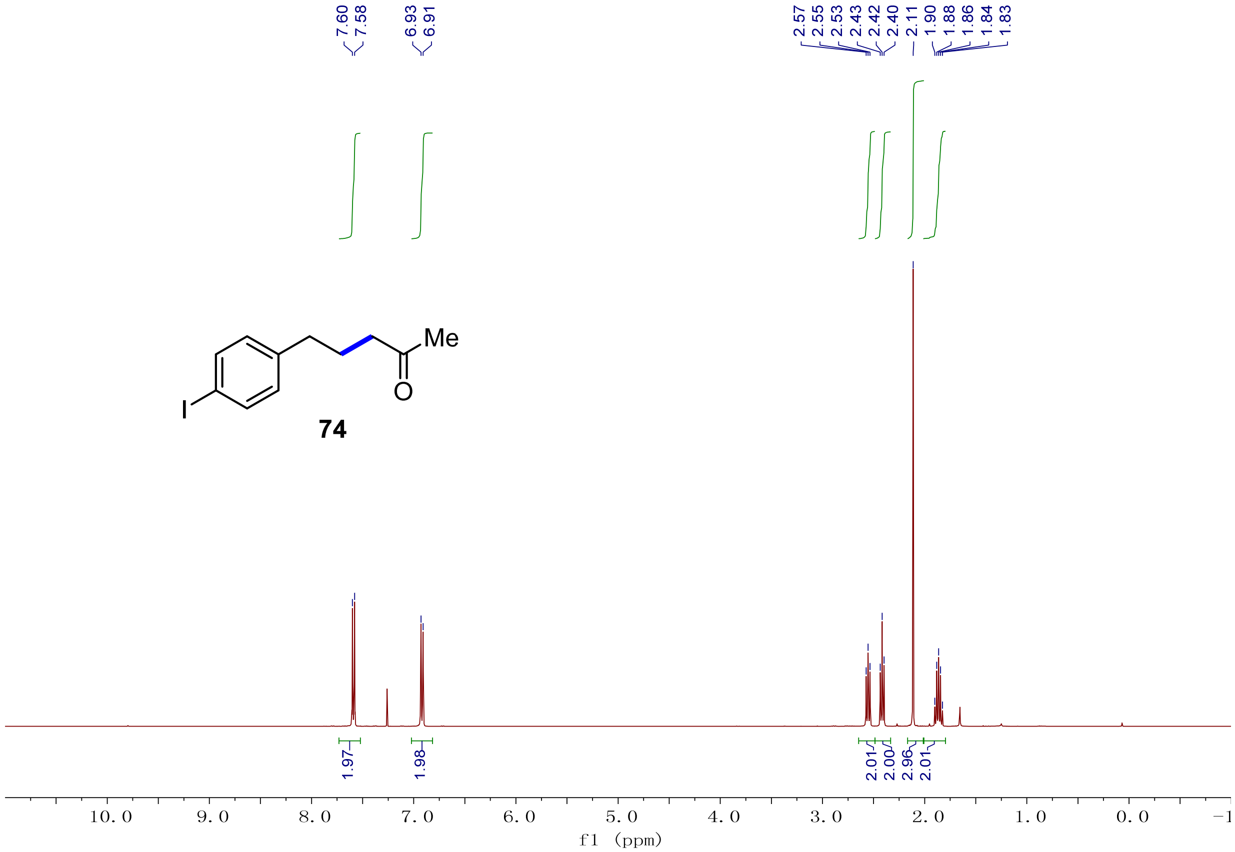

208.34
141.99
132.34
130.47
130.40
129.99
128.02
42.59
34.21
30.16
24.87
Cl
Cl
Me
O
72
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

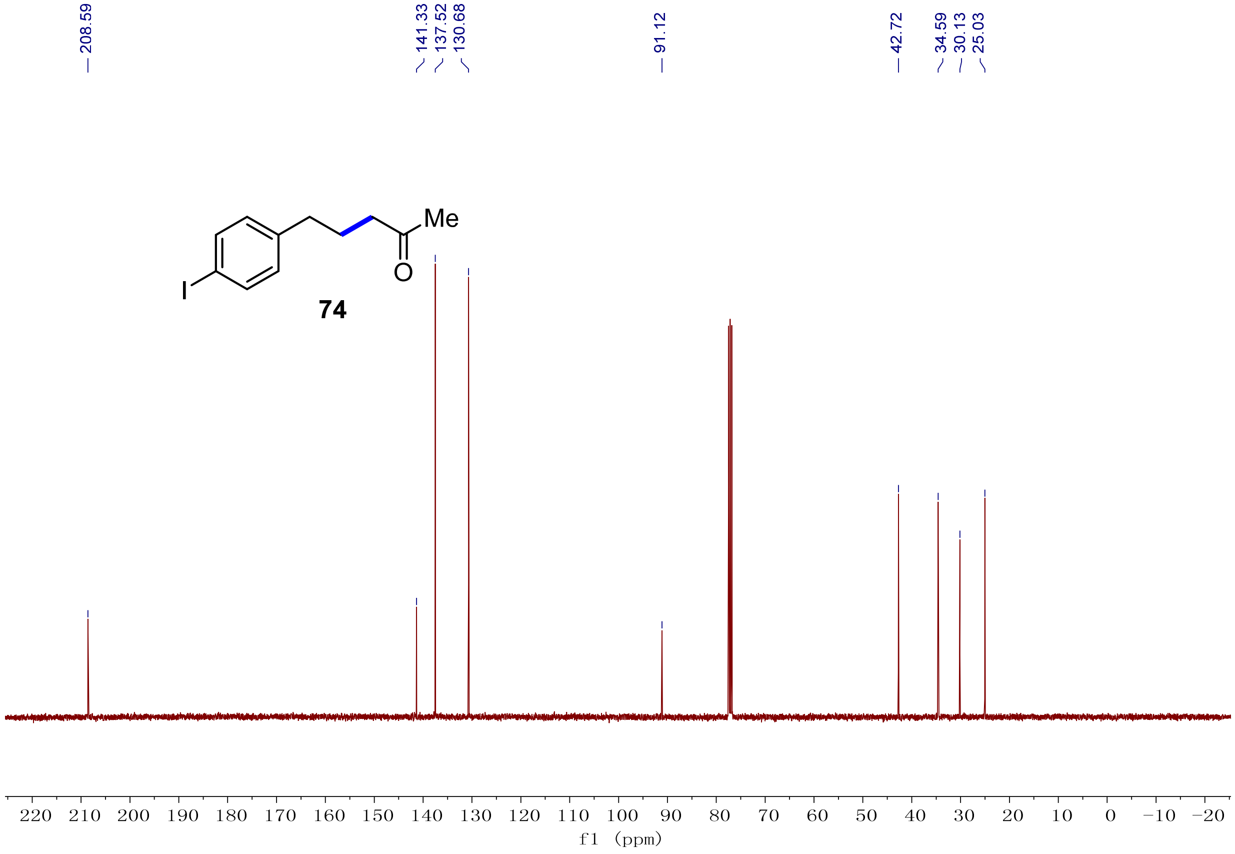


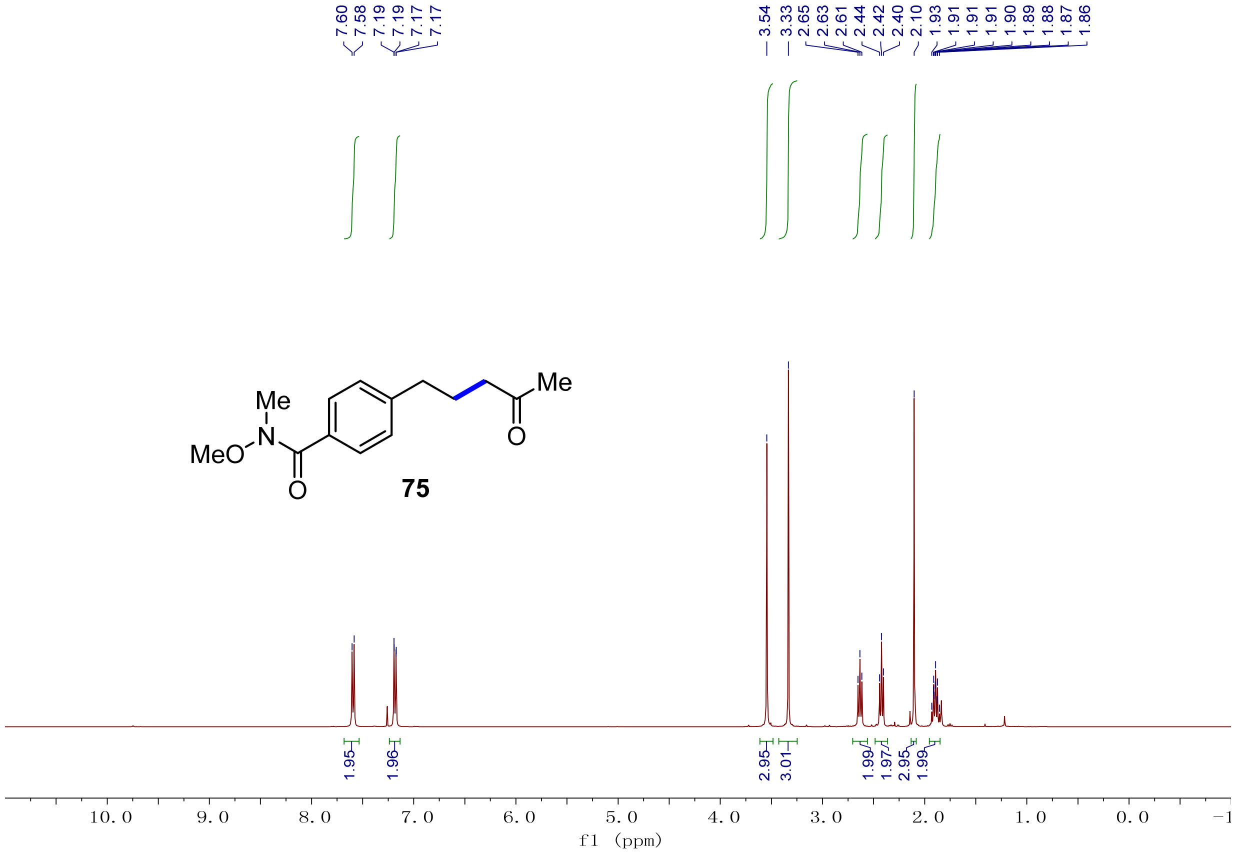
7.40
7.38
7.05
7.03
2.58
2.57
2.55
2.44
2.42
2.40
2.11
1.91
1.89
1.89
1.88
1.87
1.87
1.87
1.85
1.83
Me
O
Br
73
1.98
2.00
2.04
2.02
2.99
2.01
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

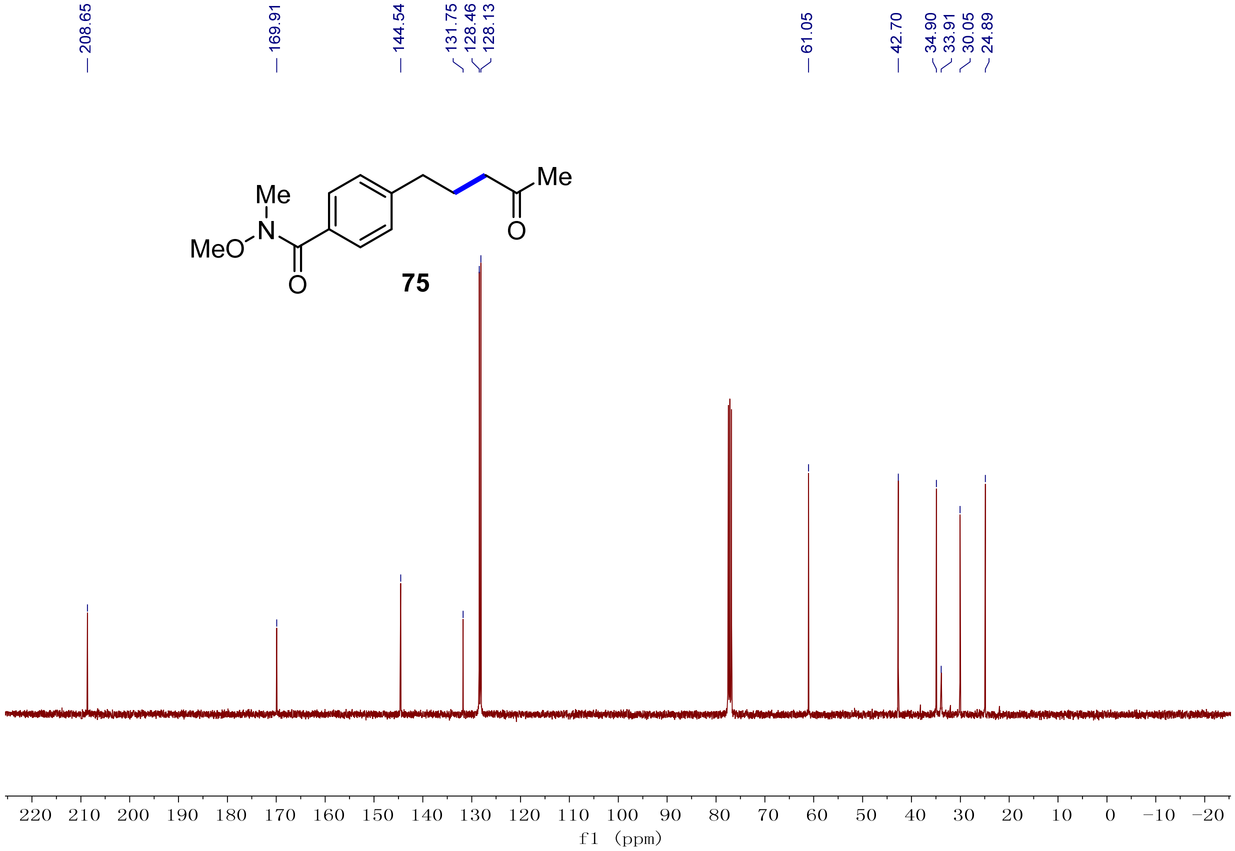


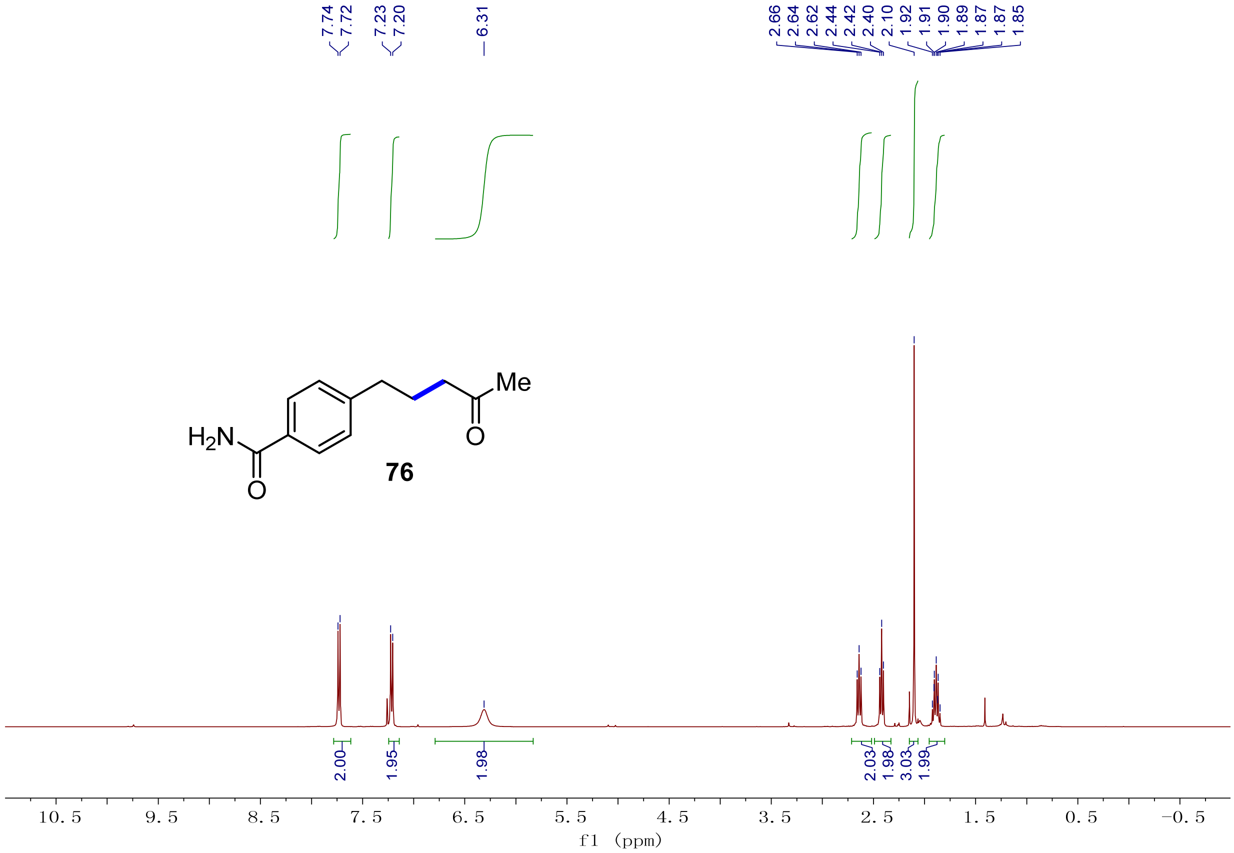
208.61
140.65
131.55
130.32
119.81
42.73
34.50
30.13
25.08
Me
O
Br
73
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

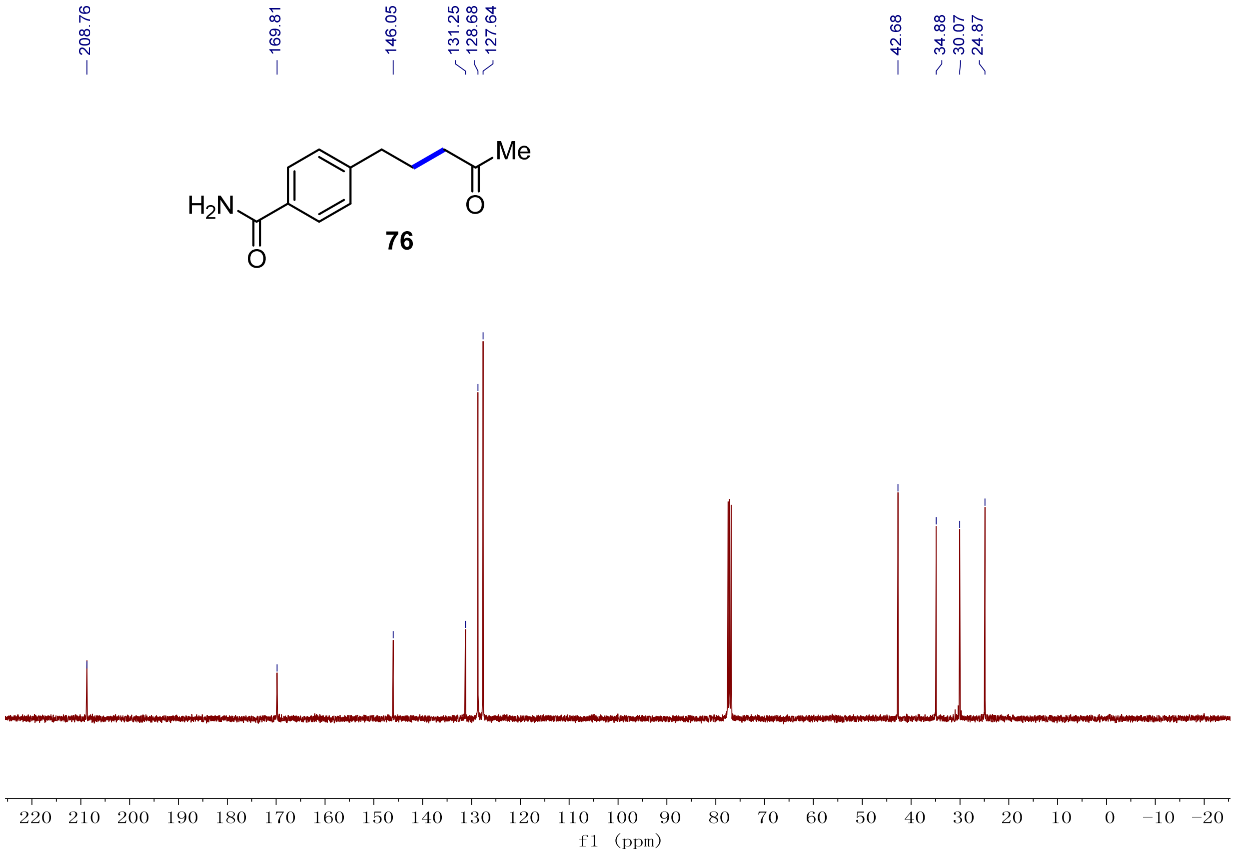

7.60
7.58
6.93
6.91
2.57
2.55
2.53
2.43
2.42
2.40
2.11
1.90
1.88
1.86
1.84
1.83
Me
O
I
74
1.97
1.98
2.01
2.00
2.96
2.01
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

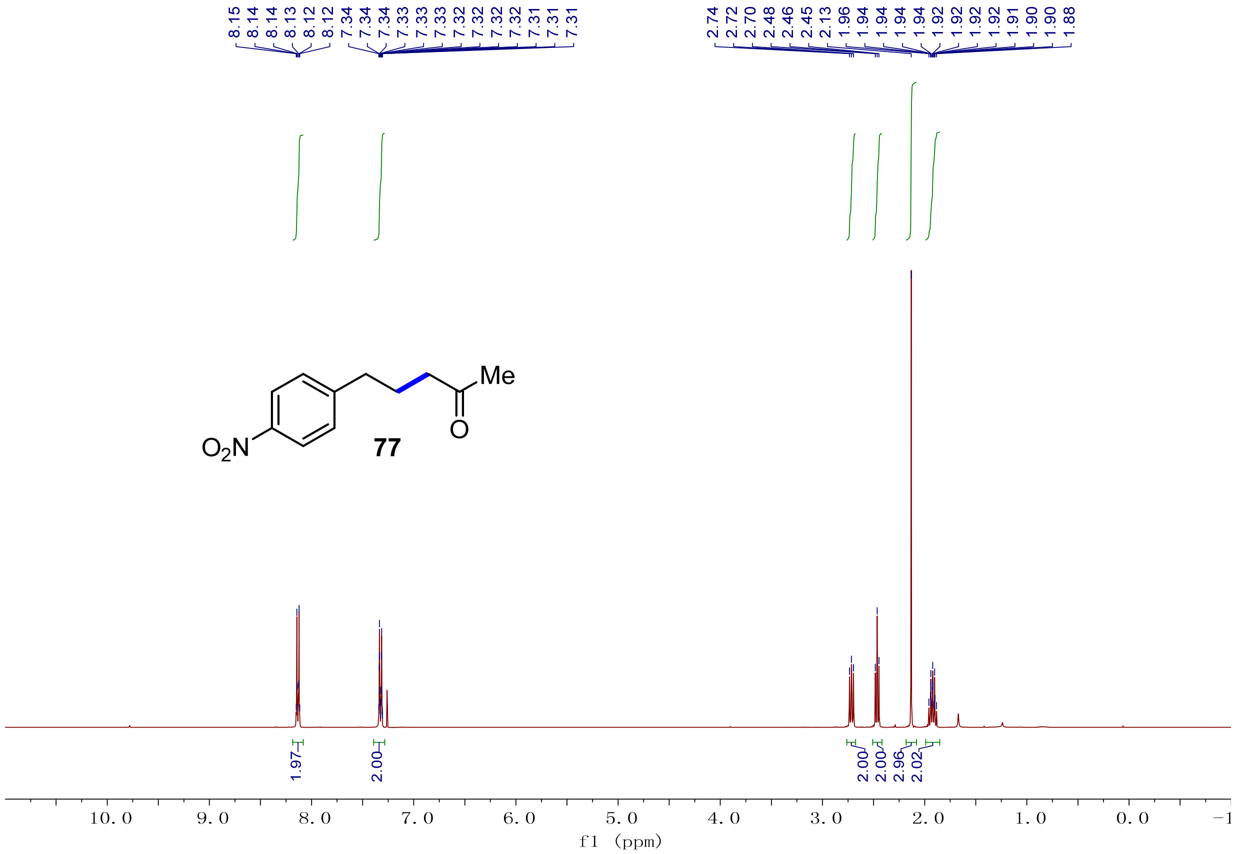

208.59
141.33
137.52
130.68
91.12
42.72
34.59
30.13
25.03
Me
O
I
74
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

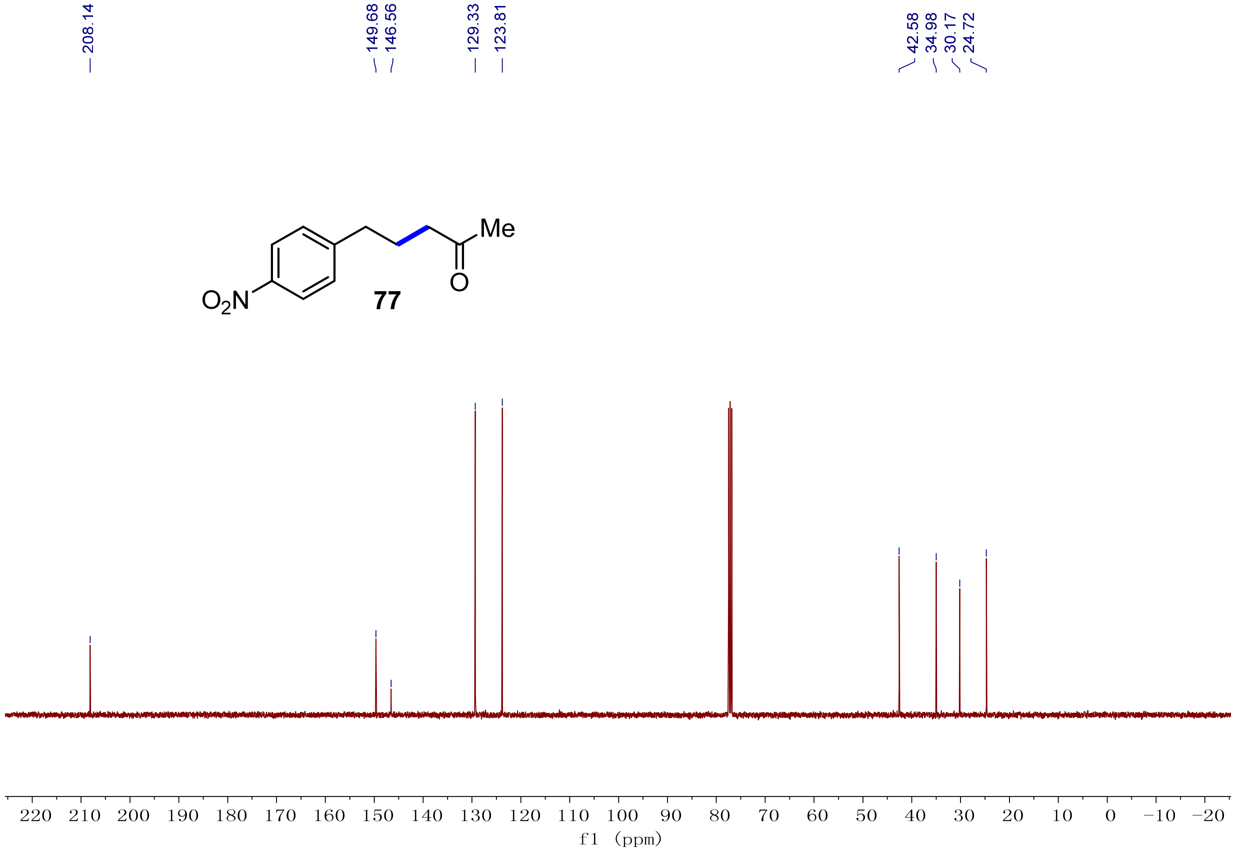

7.60
7.58
7.19
7.19
7.17
7.17
3.54
3.33
2.65
2.63
2.61
2.44
2.42
2.40
2.10
1.93
1.91
1.91
1.91
1.90
1.89
1.88
1.87
1.86
Me
MeO
N
O
O
Me
75
1.95
1.96
2.95
3.01
1.99
1.97
2.95
1.99
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

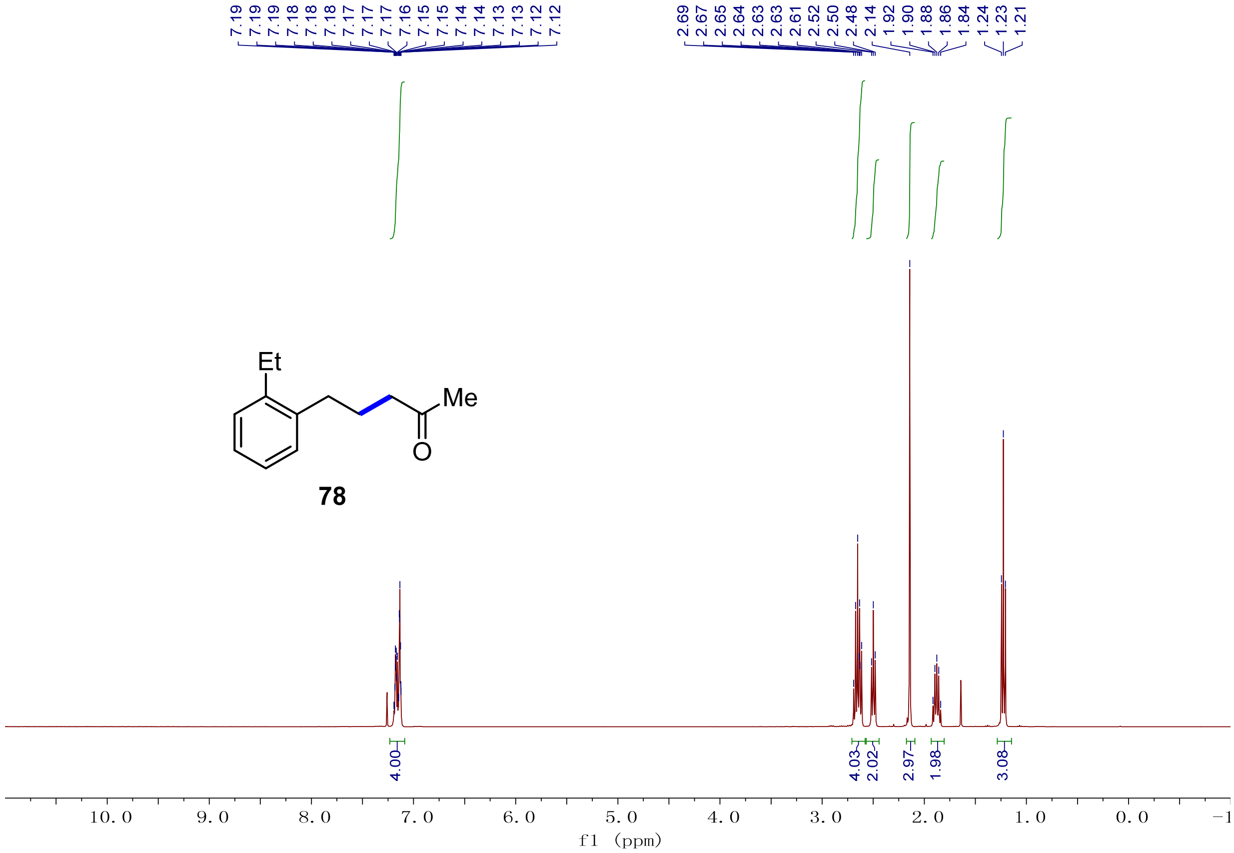

208.65
169.91
144.54
131.75
128.46
128.13
61.05
42.70
34.90
33.91
30.05
24.89
Me
MeO
N
O
O
Me
75
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

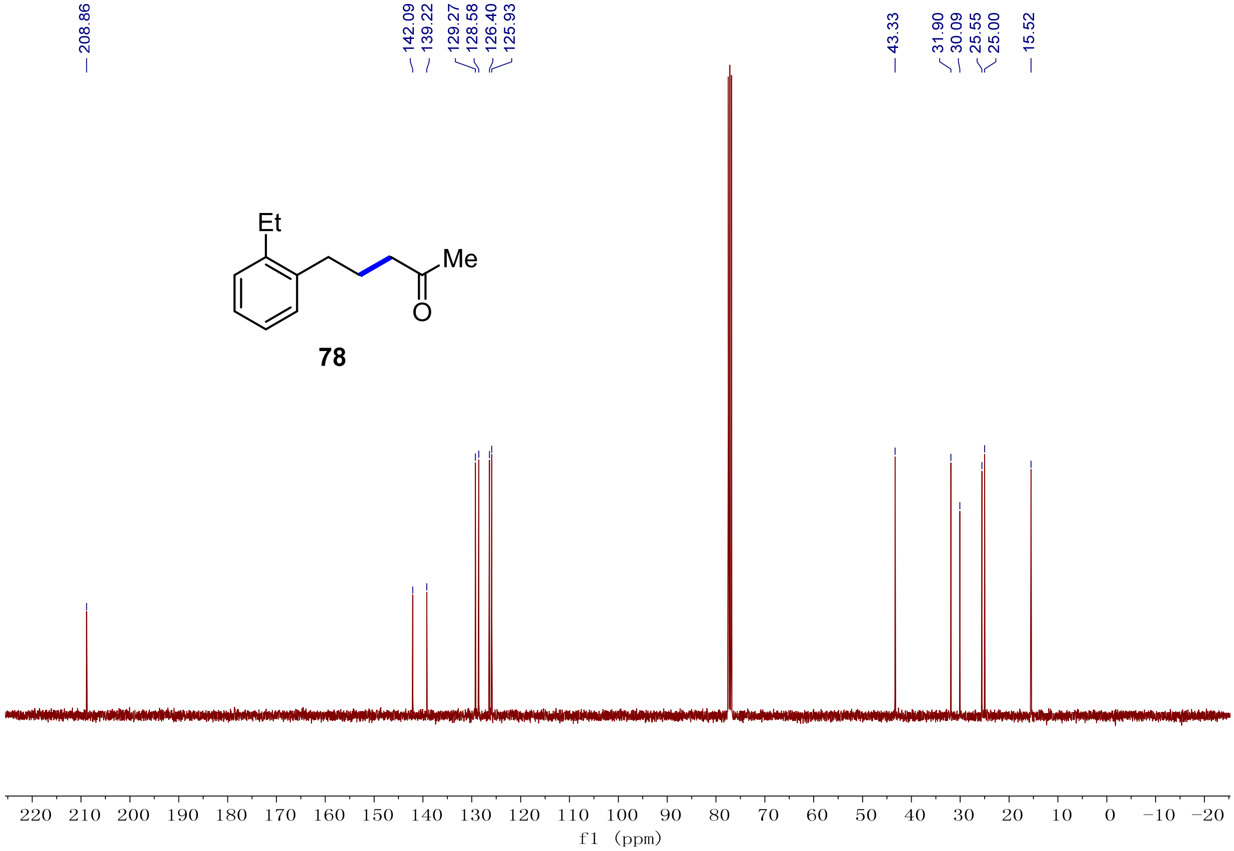

7.74
7.72
7.23
7.20
6.31
2.66
2.64
2.62
2.44
2.42
2.40
2.10
1.92
1.91
1.90
1.89
1.87
1.87
1.85
H_2N
O
Me
O
76
2.00
1.95
1.98
2.03
1.98
3.03
1.99
10.5
9.5
8.5
7.5
6.5
5.5
4.5
3.5
2.5
1.5
0.5
−0.5
f1 (ppm)

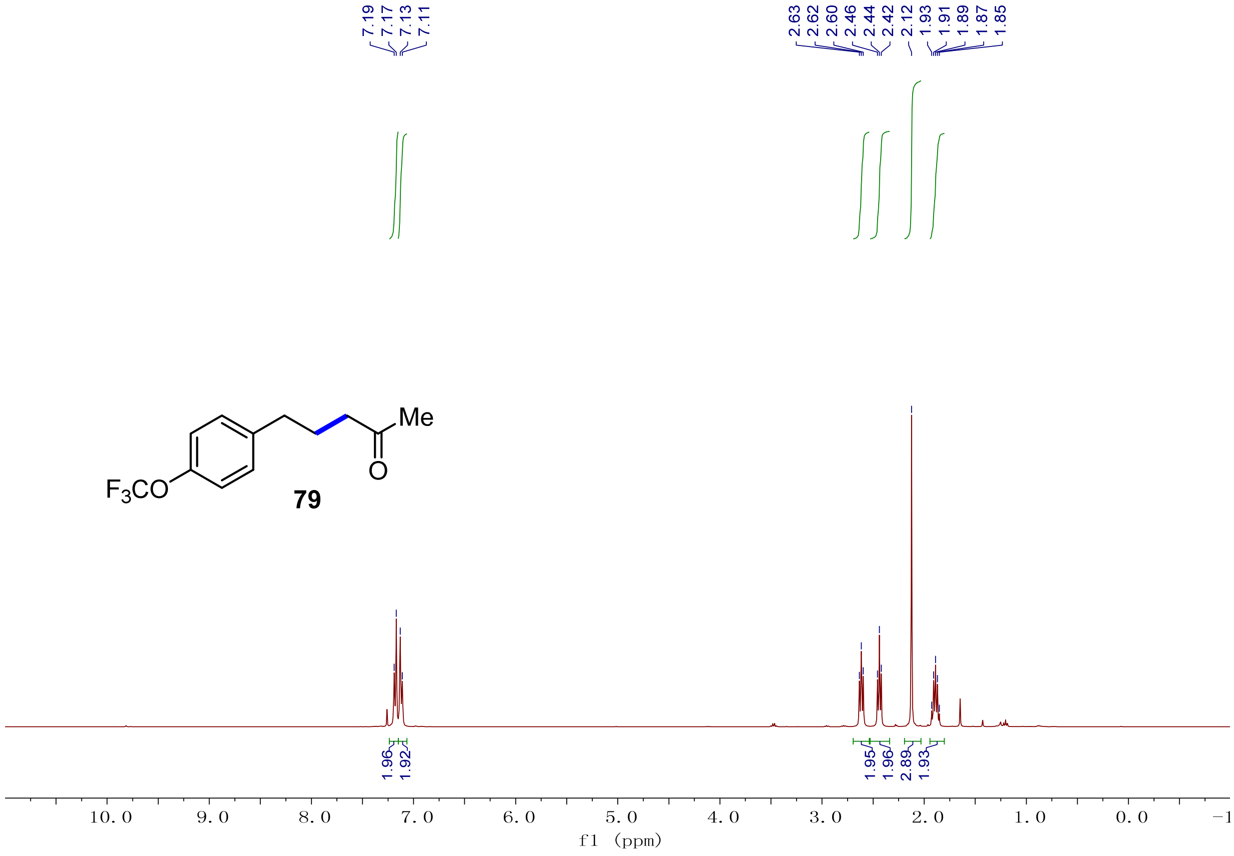

208.76
169.81
146.05
131.25
128.68
127.64
42.68
34.88
30.07
24.87
H_2N
O
Me
O
76
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
−10
−20
f1 (ppm)

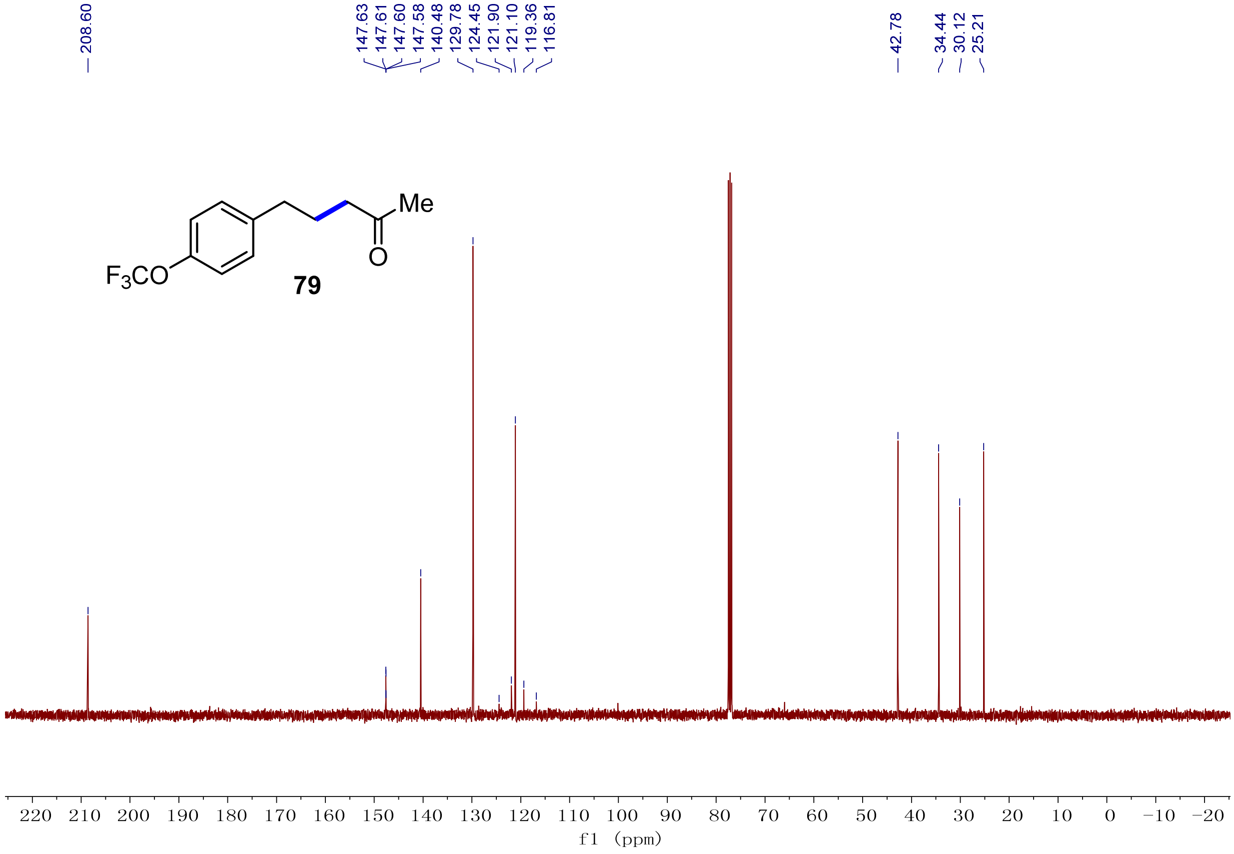

8.15
8.14
8.14
8.13
8.12
8.12
7.34
7.34
7.34
7.33
7.33
7.33
7.32
7.32
7.32
7.32
7.31
7.31
7.31
2.74
2.72
2.70
2.48
2.46
2.45
2.13
1.96
1.94
1.94
1.94
1.94
1.92
1.92
1.92
1.92
1.91
1.90
1.90
1.88
Me
O
O_2N
77
1.97
2.00
2.00
2.00
2.96
2.02
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

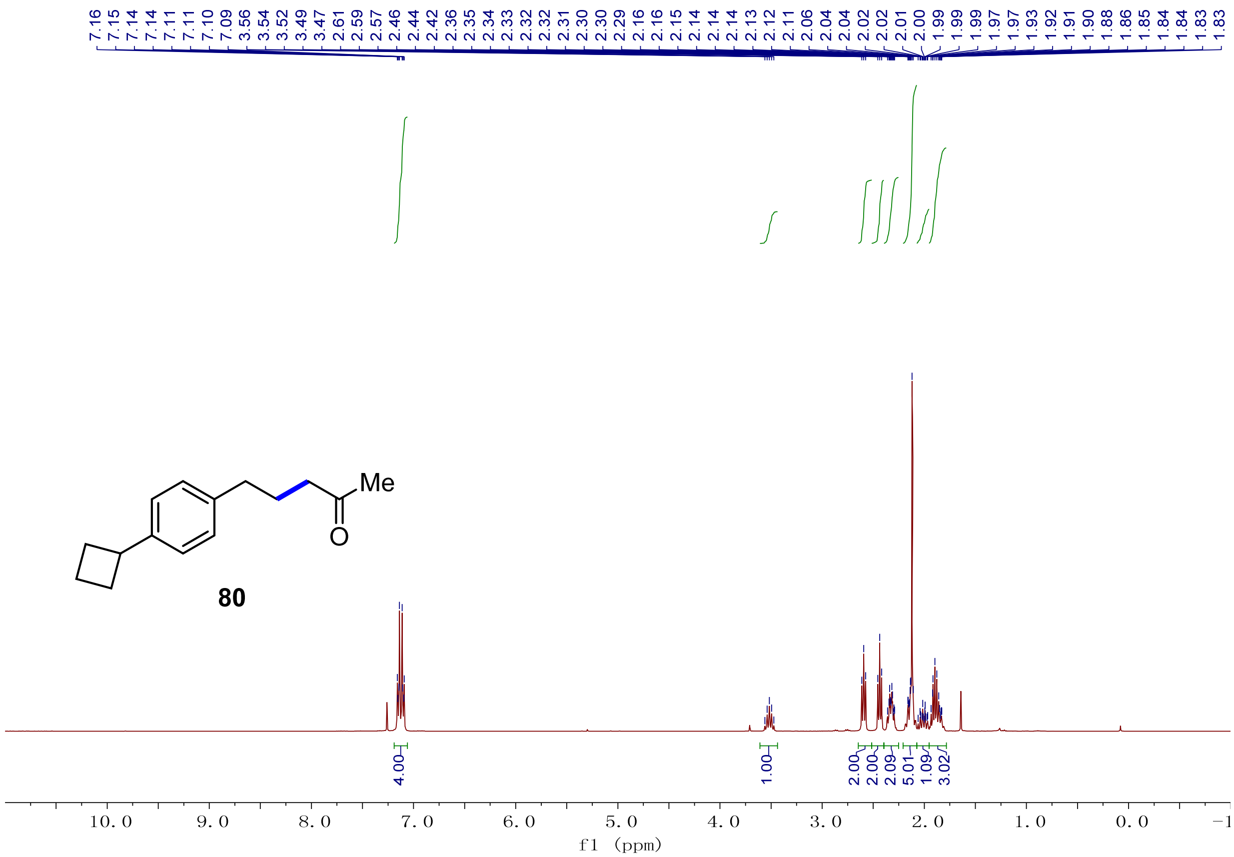

208.14
149.68
146.56
129.33
123.81
42.58
34.98
30.17
24.72
Me
O
O_2N
77
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

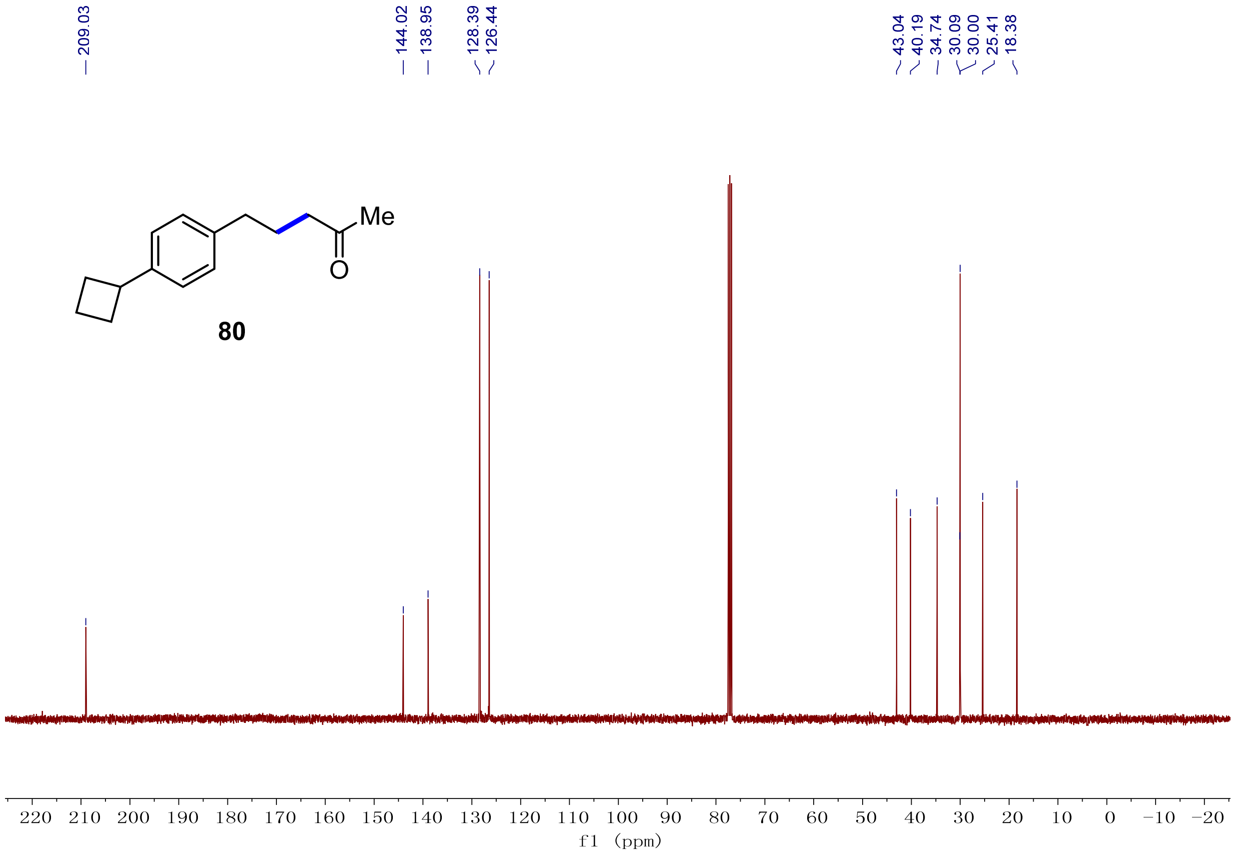

7.19
7.19
7.19
7.18
7.18
7.18
7.17
7.17
7.17
7.16
7.15
7.15
7.14
7.14
7.13
7.13
7.12
7.12
2.69
2.67
2.65
2.64
2.63
2.63
2.61
2.52
2.50
2.48
2.14
1.92
1.90
1.88
1.86
1.84
1.24
1.23
1.21
Et
Me
O
78
4.00
4.03
2.02
2.97
1.98
3.08
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

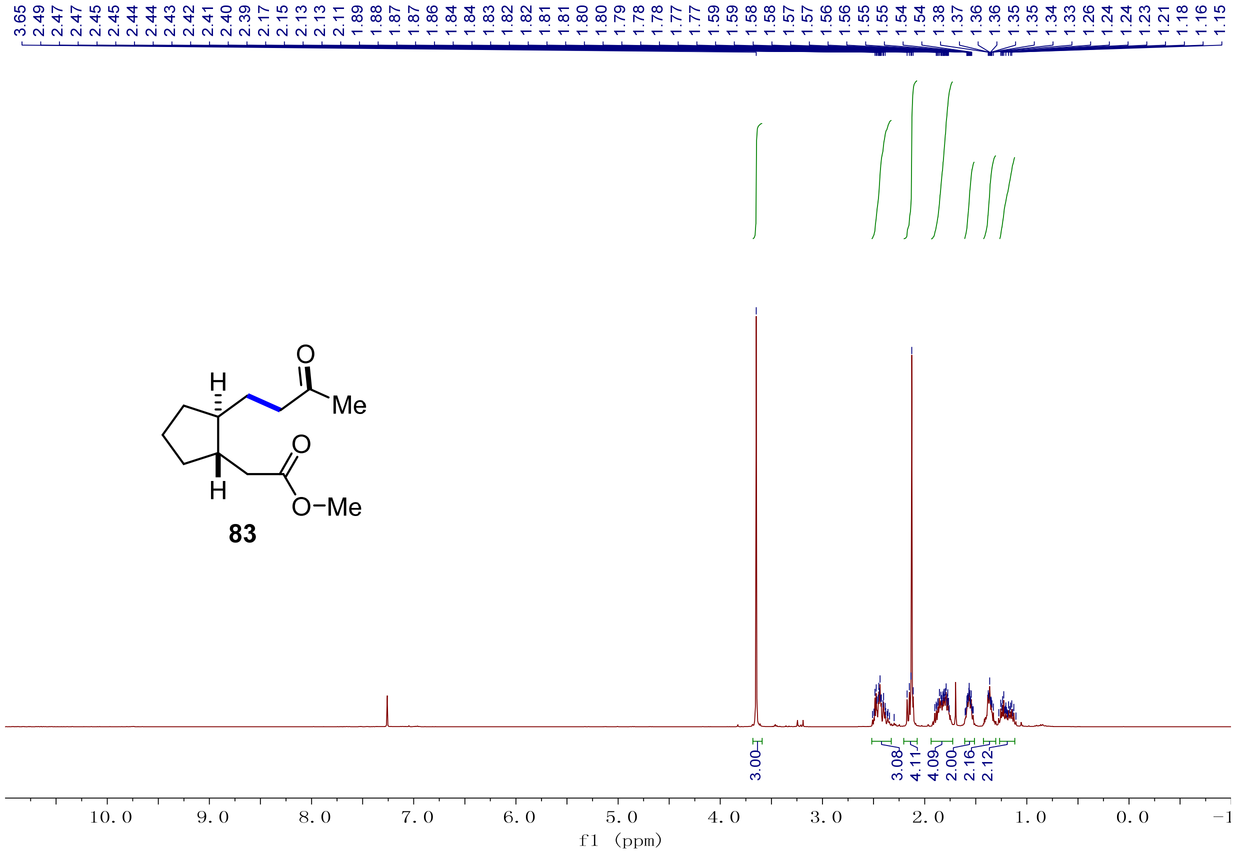

208.86
142.09
139.22
129.27
128.58
126.40
125.93
43.33
31.90
30.09
25.55
25.00
15.52
Et
Me
O
78
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

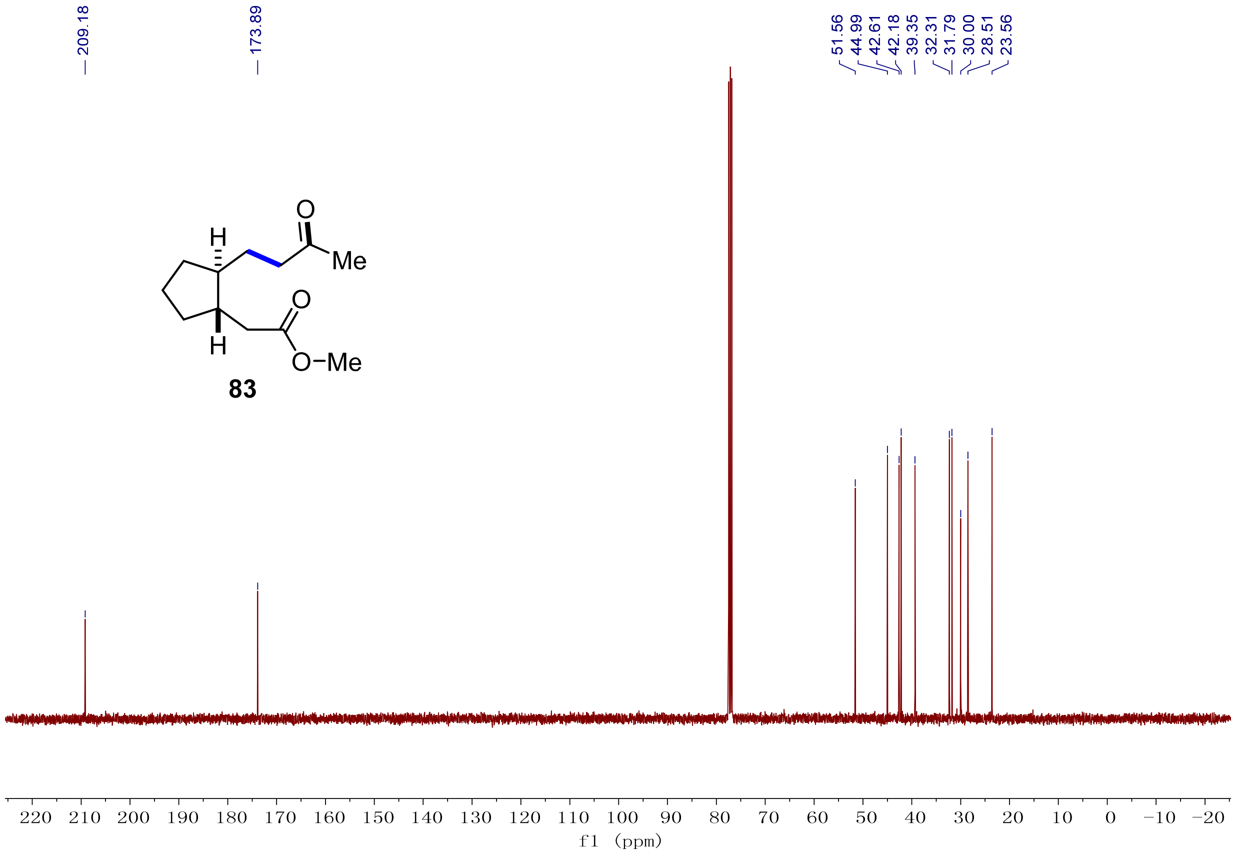

7.19
7.17
7.13
7.11
2.63
2.62
2.60
2.46
2.44
2.42
2.12
1.93
1.91
1.89
1.87
1.85
Me
O
F_3CO
79
1.96
1.92
1.95
1.96
2.89
1.93
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

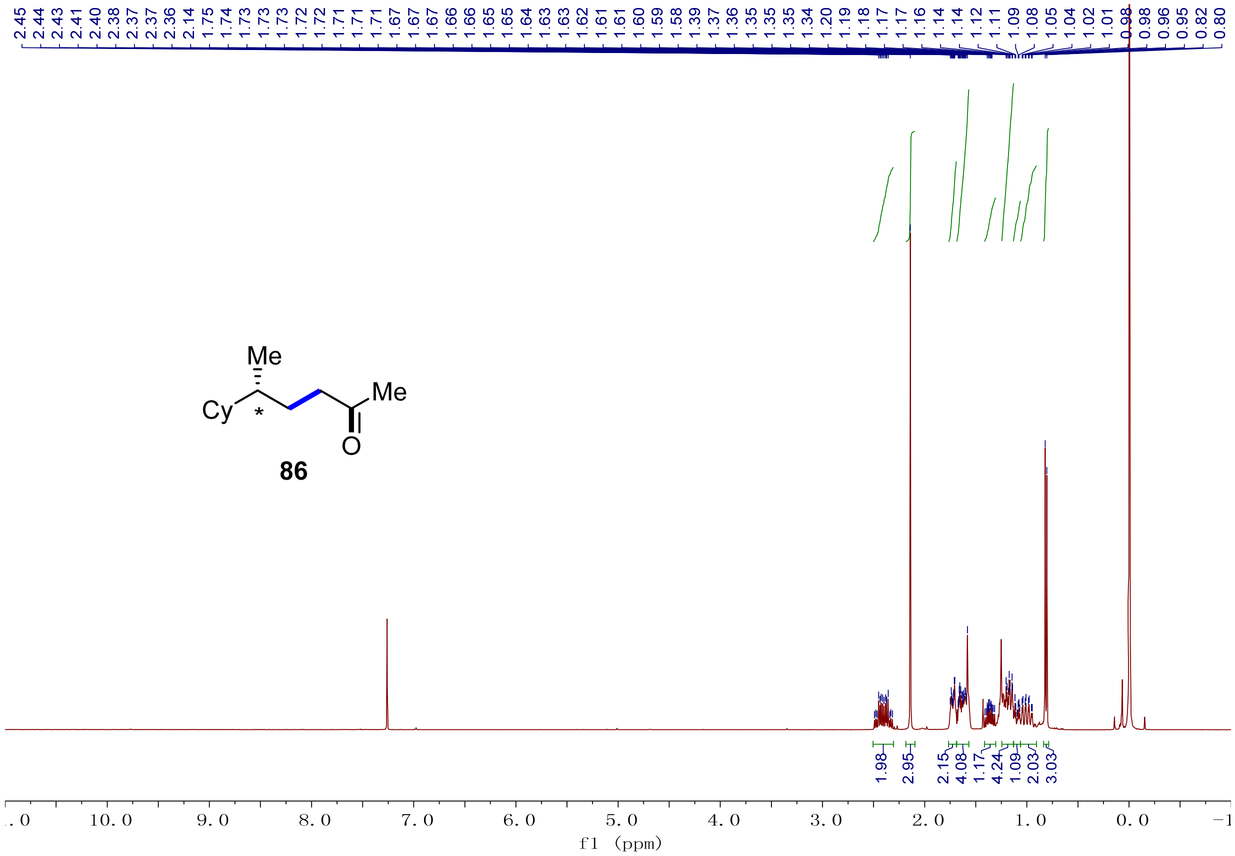

208.60
147.63
147.61
147.60
147.58
140.48
129.78
124.45
121.90
121.10
119.36
116.81
42.78
34.44
30.12
25.21
Me
O
F_3CO
79
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

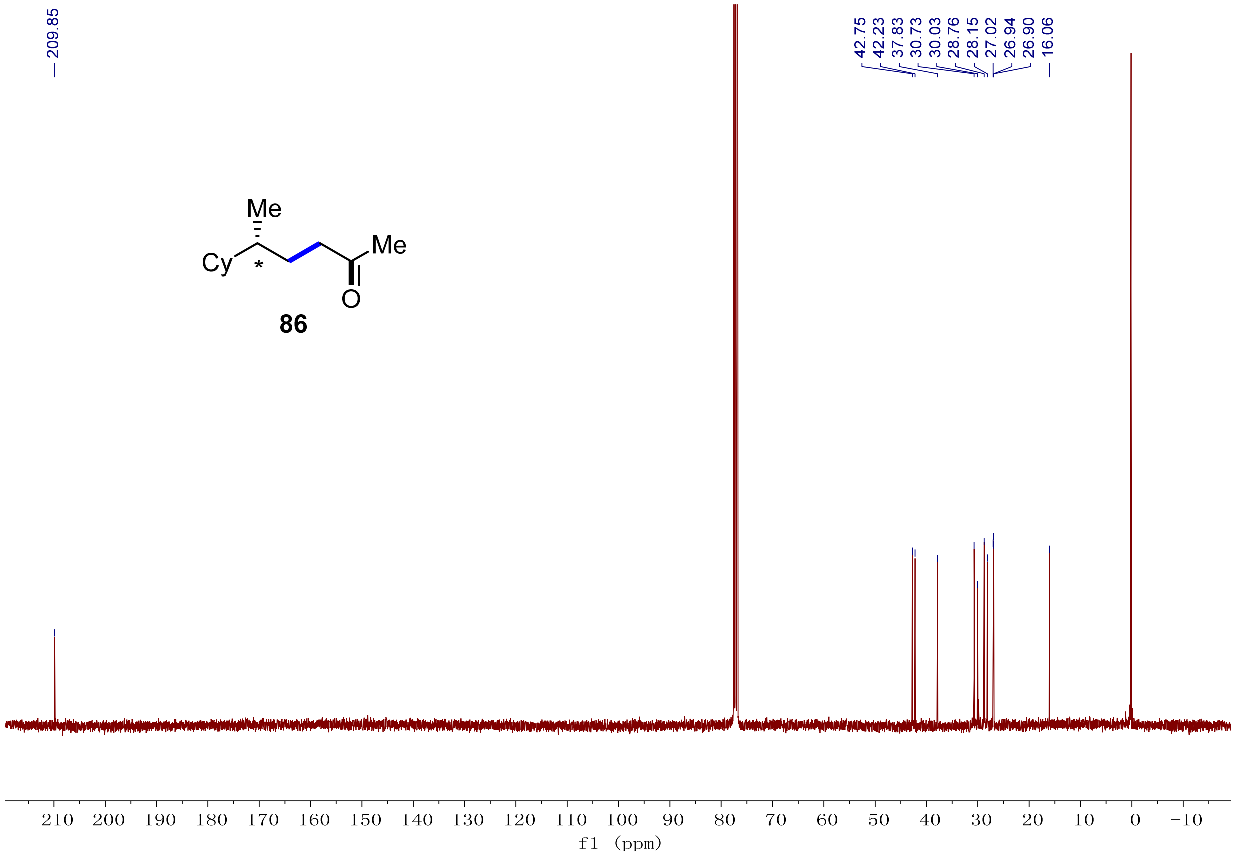

7.16
7.15
7.14
7.14
7.11
7.11
7.10
7.09
3.56
3.54
3.52
3.49
3.47
2.61
2.59
2.57
2.46
2.44
2.42
2.36
2.35
2.34
2.33
2.32
2.32
2.31
2.30
2.30
2.29
2.16
2.16
2.15
2.14
2.14
2.14
2.14
2.13
2.12
2.11
2.06
2.04
2.04
2.02
2.02
2.01
2.00
1.99
1.99
1.99
1.97
1.93
1.92
1.91
1.90
1.88
1.86
1.85
1.84
1.84
1.83
1.83
Me
O
80
4.00
1.00
2.00
2.00
2.09
5.01
1.09
3.02
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

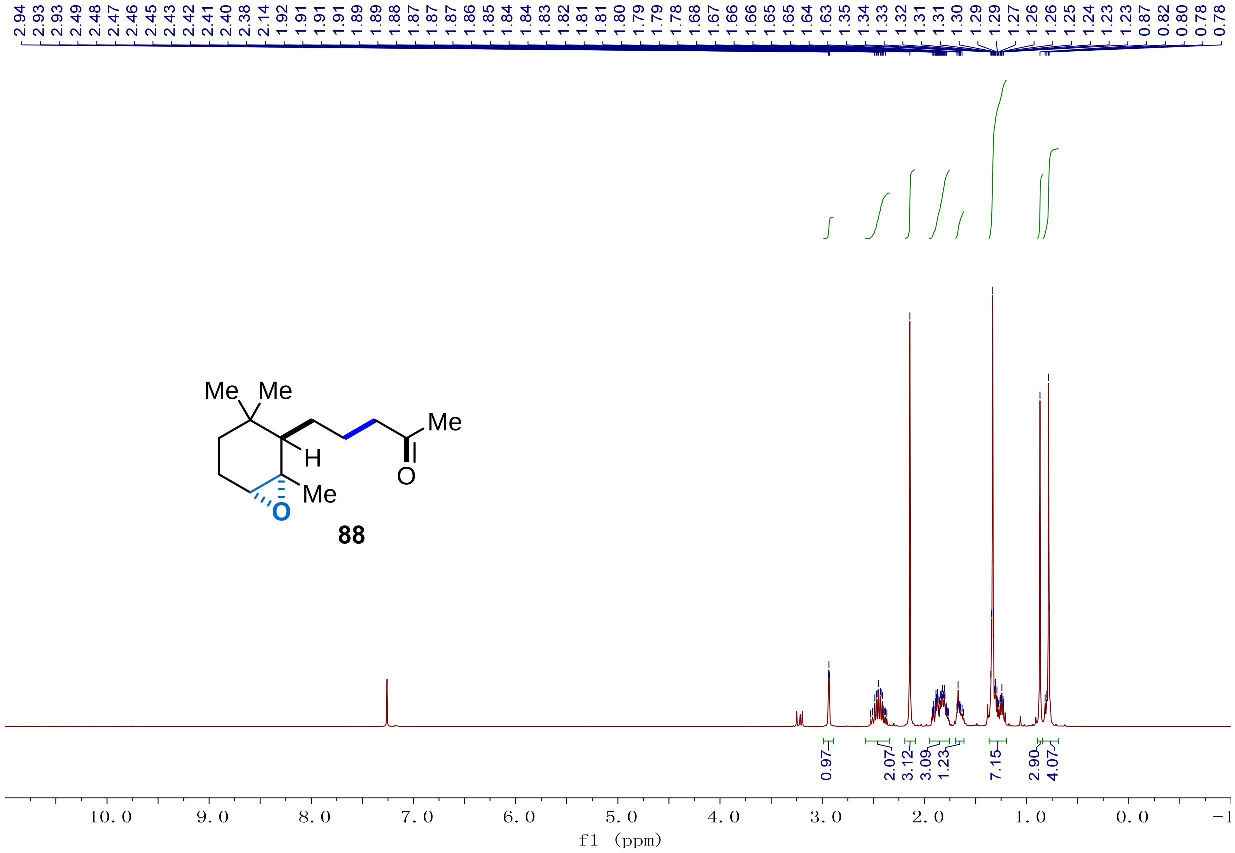

209.03
144.02
138.95
128.39
126.44
43.04
40.19
34.74
30.09
30.00
25.41
18.38
Me
O
80
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)


3.65 2.49 2.47 2.47 2.45 2.45 2.44 2.44 2.43 2.42 2.41 2.40 2.39 2.17 2.15 2.13 2.13 2.11 1.89 1.88 1.87 1.87 1.86 1.84 1.84 1.83 1.82 1.82 1.81 1.81 1.80 1.80 1.79 1.78 1.78 1.77 1.77 1.59 1.59 1.58 1.58 1.57 1.57 1.56 1.56 1.55 1.55 1.54 1.54 1.38 1.37 1.36 1.36 1.35 1.35 1.34 1.33 1.26 1.24 1.24 1.23 1.21 1.18 1.16 1.15
H
O
Me
O
H
O–Me
83
3.00
3.08
4.11
4.09
2.00
2.16
2.12
10.0 9.0 8.0 7.0 6.0 5.0 4.0 3.0 2.0 1.0 0.0 −1
f1 (ppm)

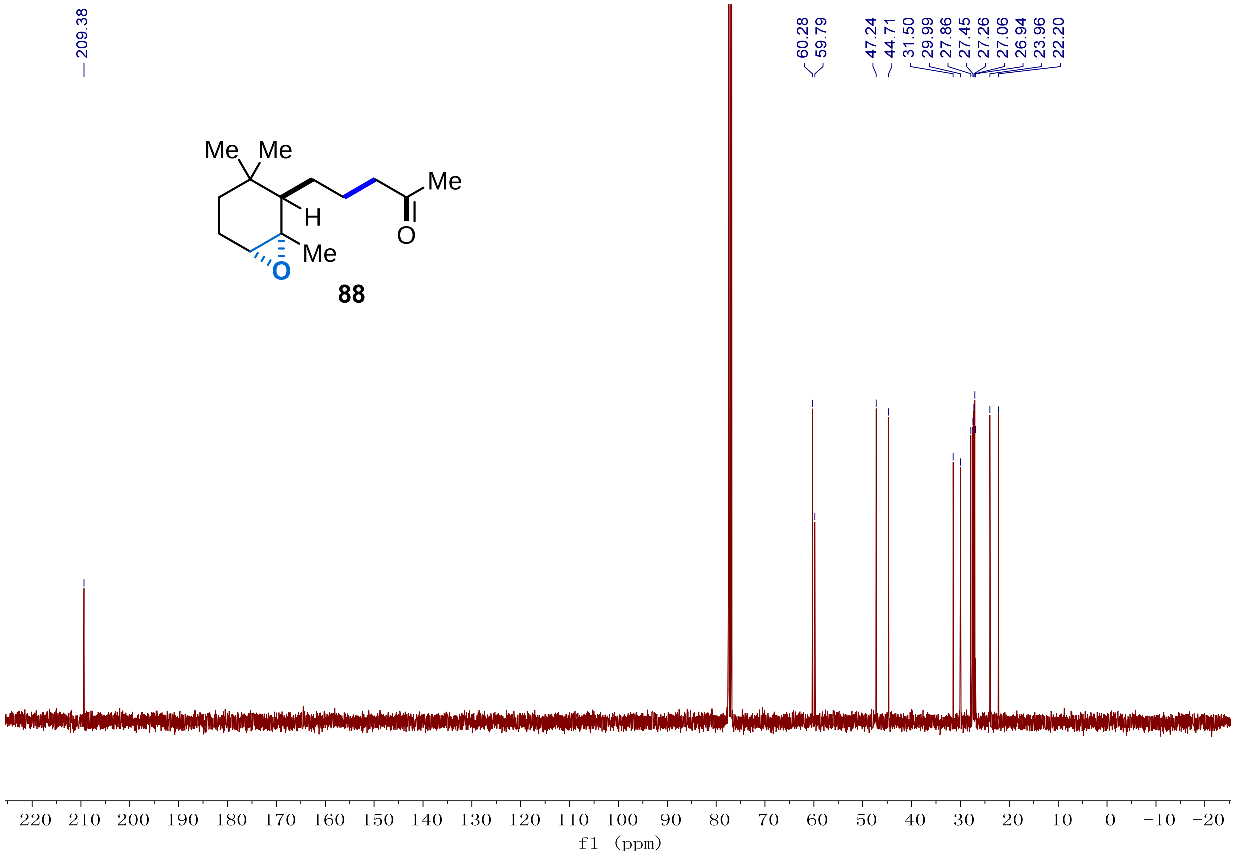

209.18
173.89
51.56
44.99
42.61
42.18
39.35
32.31
31.79
30.00
28.51
23.56
H
O
Me
O
H
O–Me
83
220 210 200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 −10 −20
f1 (ppm)


2.45
2.44
2.43
2.41
2.40
2.38
2.37
2.37
2.36
2.14
1.75
1.74
1.73
1.73
1.73
1.72
1.72
1.71
1.71
1.71
1.67
1.67
1.67
1.66
1.65
1.65
1.64
1.63
1.63
1.62
1.61
1.61
1.60
1.59
1.58
1.39
1.37
1.36
1.35
1.35
1.34
1.20
1.19
1.18
1.17
1.17
1.16
1.14
1.12
1.11
1.09
1.08
1.05
1.04
1.02
1.01
0.98
0.98
0.96
0.95
0.82
0.80
Me
Cy
*
Me
O
86
1.98
2.95
2.15
4.08
1.17
4.24
1.09
2.03
3.03
. 0
10. 0
9. 0
8. 0
7. 0
6. 0
5. 0
4. 0
3. 0
2. 0
1. 0
0. 0
-1
f1 (ppm)

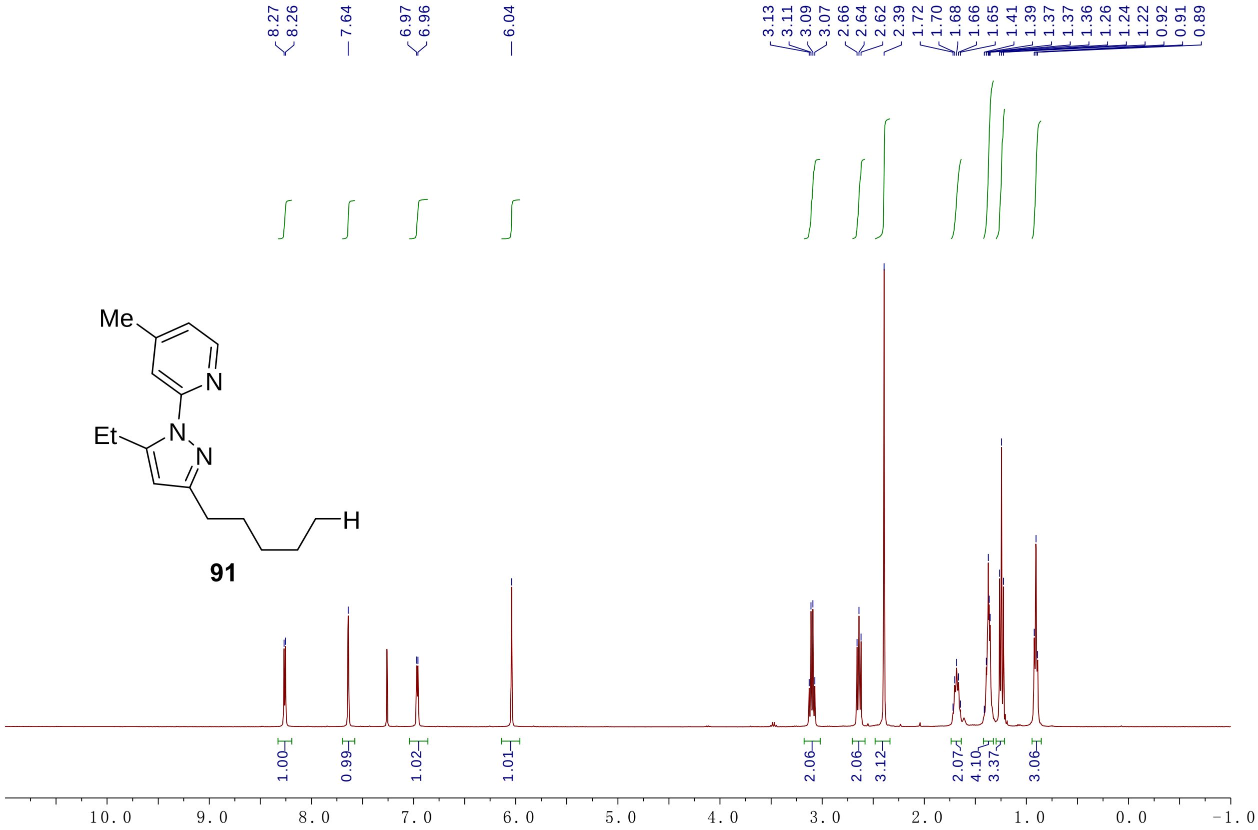

209.85
42.75
42.23
37.83
30.73
30.03
28.76
28.15
27.02
26.94
26.90
16.06
Me
Cy
*
Me
O
86
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
f1 (ppm)

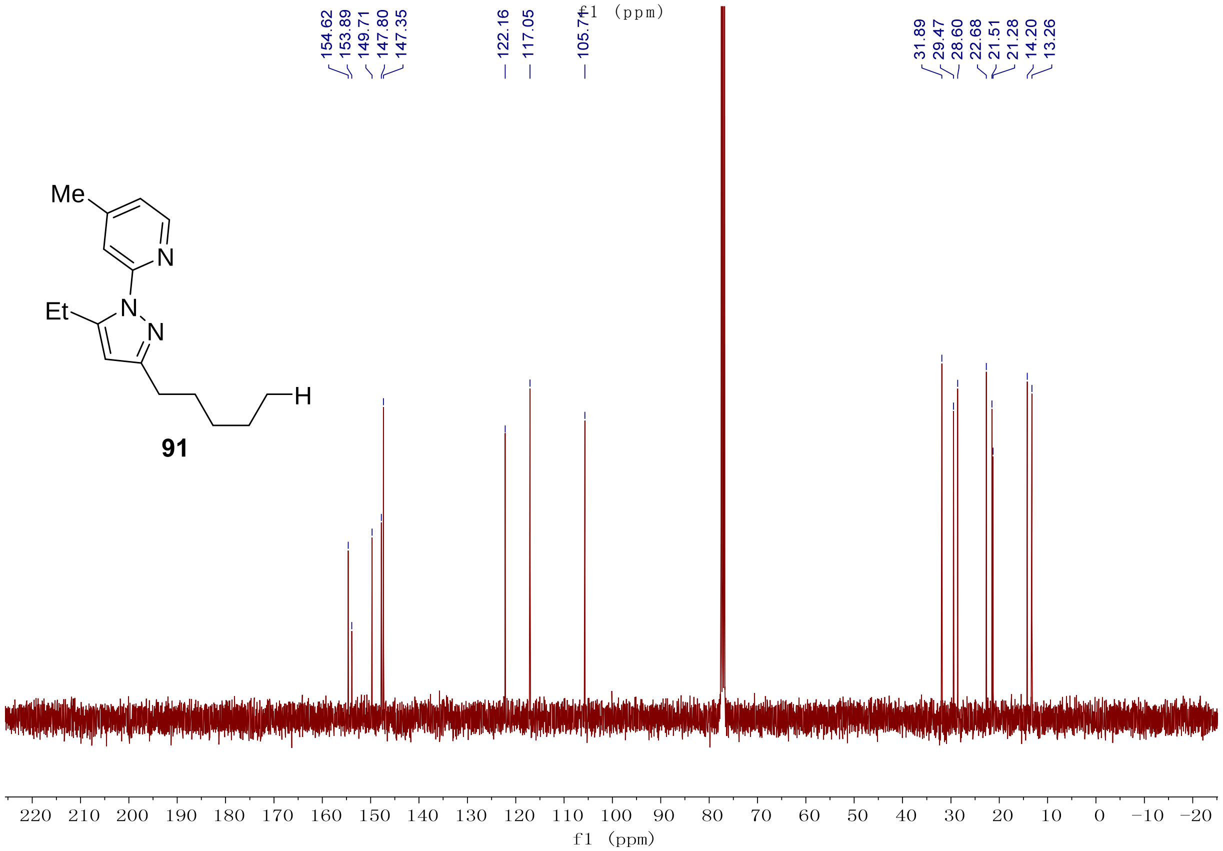

2.94
2.93
2.93
2.49
2.48
2.47
2.46
2.45
2.43
2.42
2.41
2.40
2.38
2.14
1.92
1.91
1.91
1.91
1.89
1.89
1.88
1.87
1.87
1.86
1.85
1.84
1.84
1.83
1.82
1.81
1.81
1.80
1.79
1.79
1.78
1.68
1.67
1.66
1.66
1.65
1.65
1.64
1.63
1.35
1.34
1.33
1.32
1.31
1.31
1.30
1.29
1.29
1.27
1.26
1.26
1.25
1.24
1.23
1.23
0.87
0.82
0.80
0.78
0.78
Me
Me
Me
H
Me
O
O
0.97
2.07
3.12
3.09
1.23
7.15
2.90
4.07
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

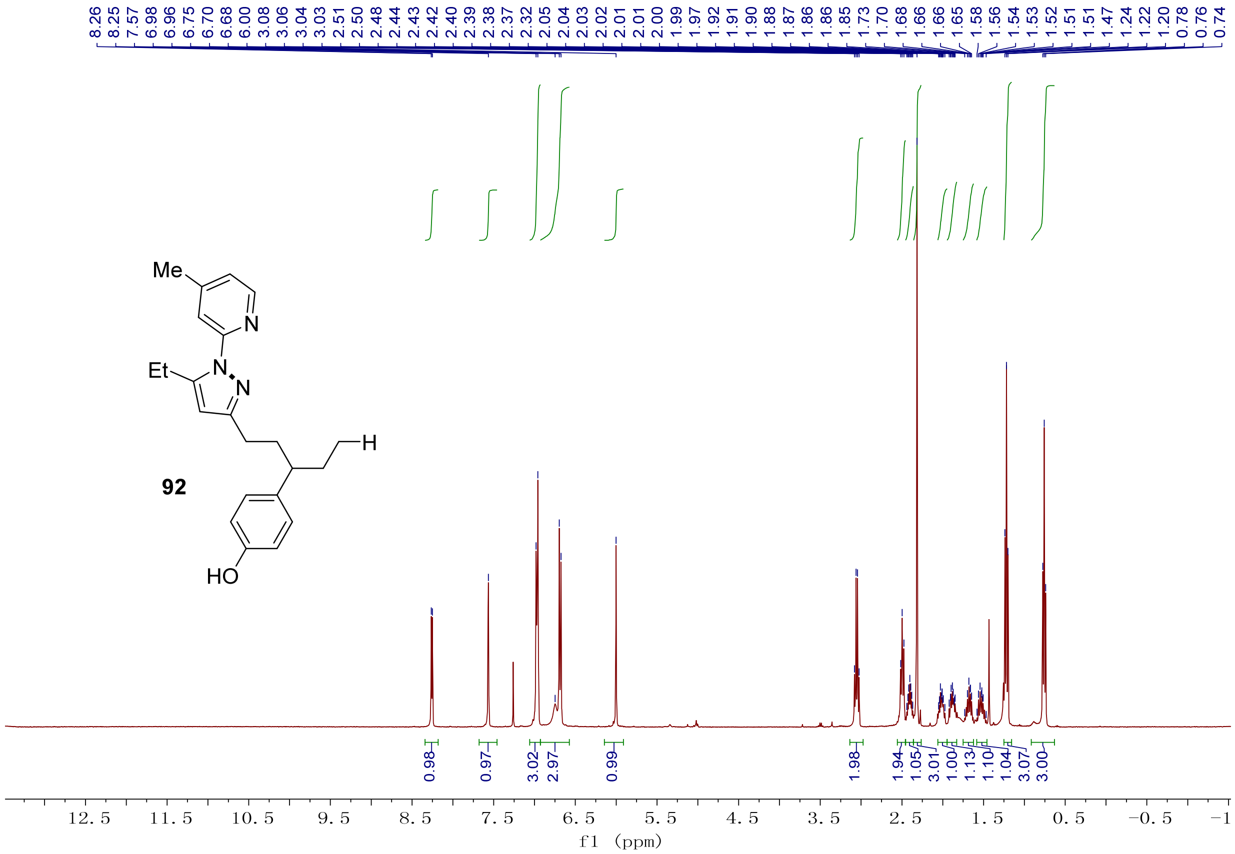
88


209.38
60.28
59.79
47.24
44.71
31.50
29.99
27.86
27.45
27.26
27.06
26.94
23.96
22.20
Me
Me
Me
H
Me
O
O
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

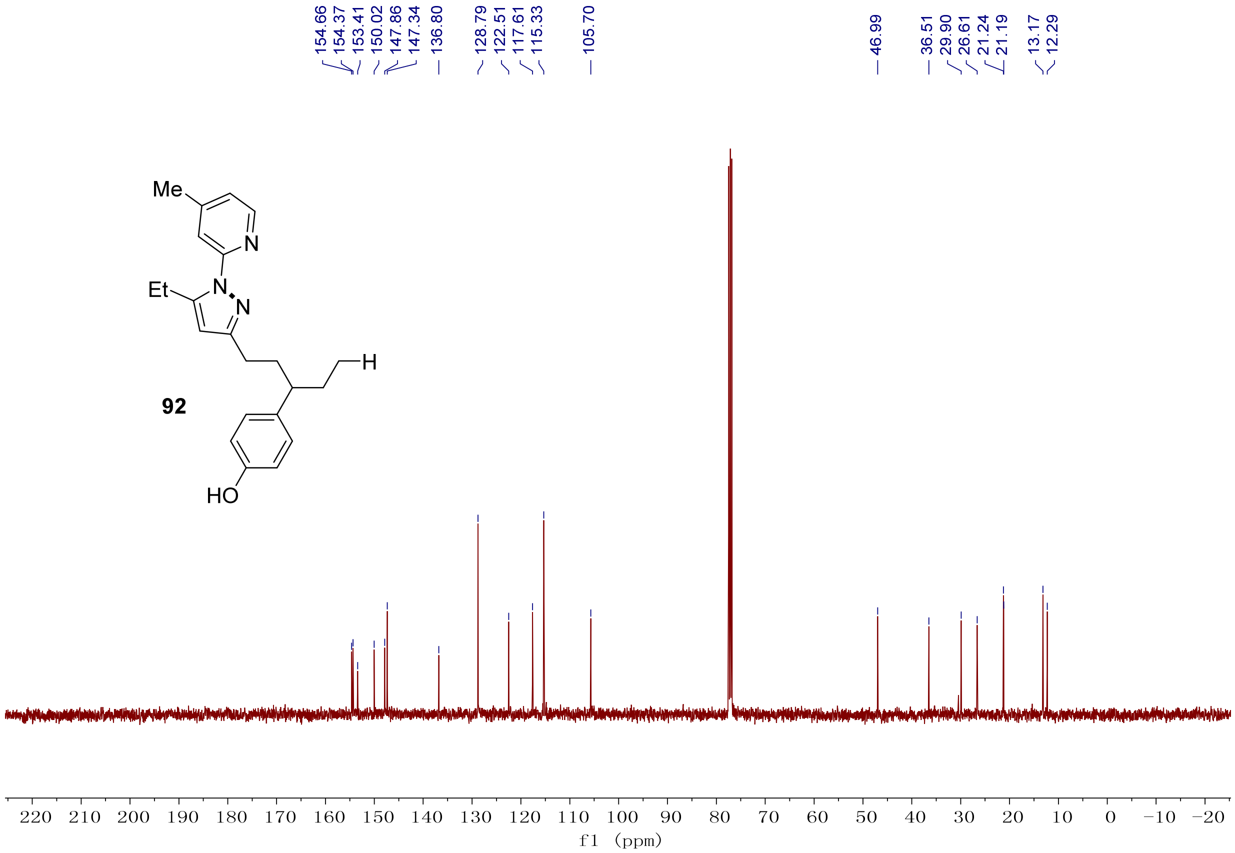
88


8.27
8.26
7.64
6.97
6.96
6.04
3.13
3.11
3.09
3.07
2.66
2.64
2.62
2.39
1.72
1.70
1.68
1.66
1.65
1.41
1.39
1.37
1.37
1.36
1.26
1.24
1.22
0.92
0.91
0.89
Me
N
Et
N
N
H
91
1.00
0.99
1.02
1.01
2.06
2.06
3.12
2.07
4.10
3.37
3.06
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
f1 (ppm)

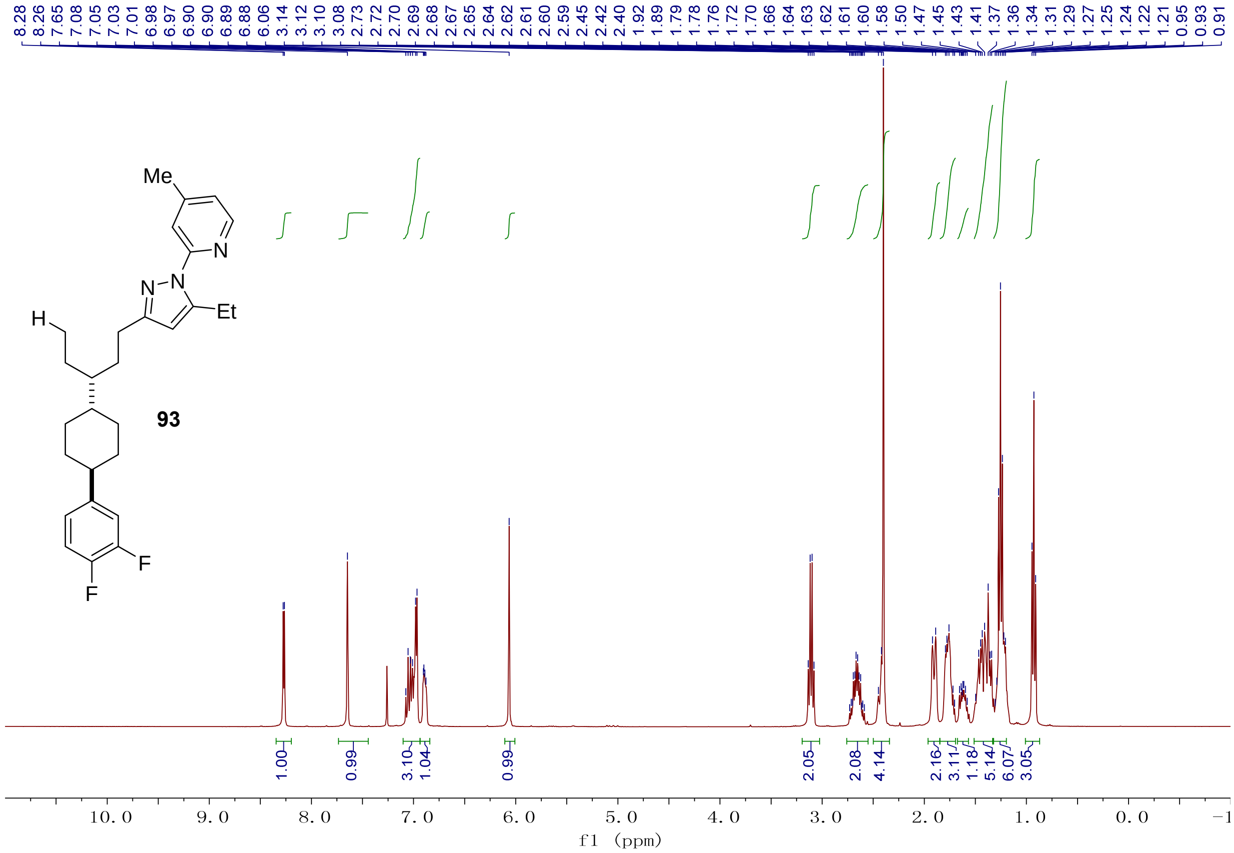

154.62
153.89
149.71
147.80
147.35
122.16
117.05
105.71
31.89
29.47
28.60
22.68
21.51
21.28
14.20
13.26
Me
N
Et
N
N
H
91
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

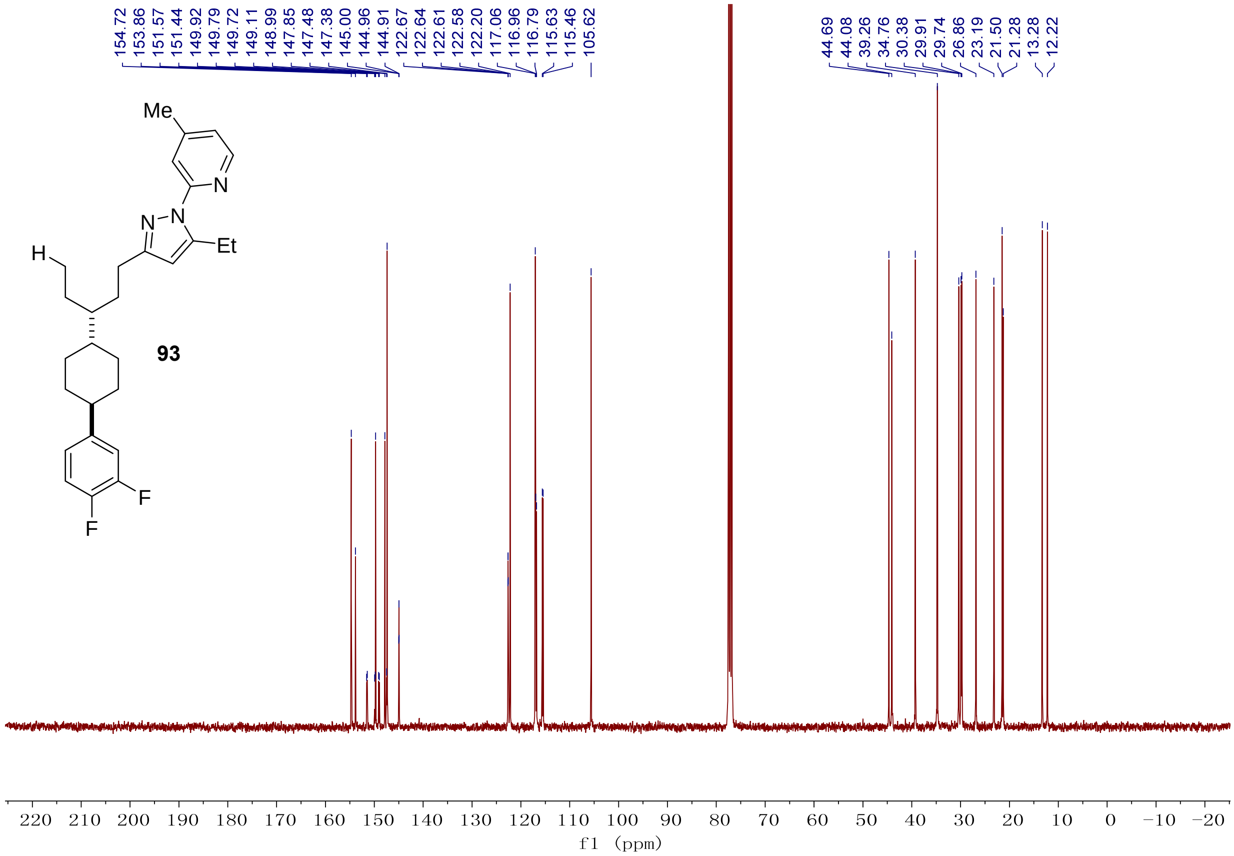

92

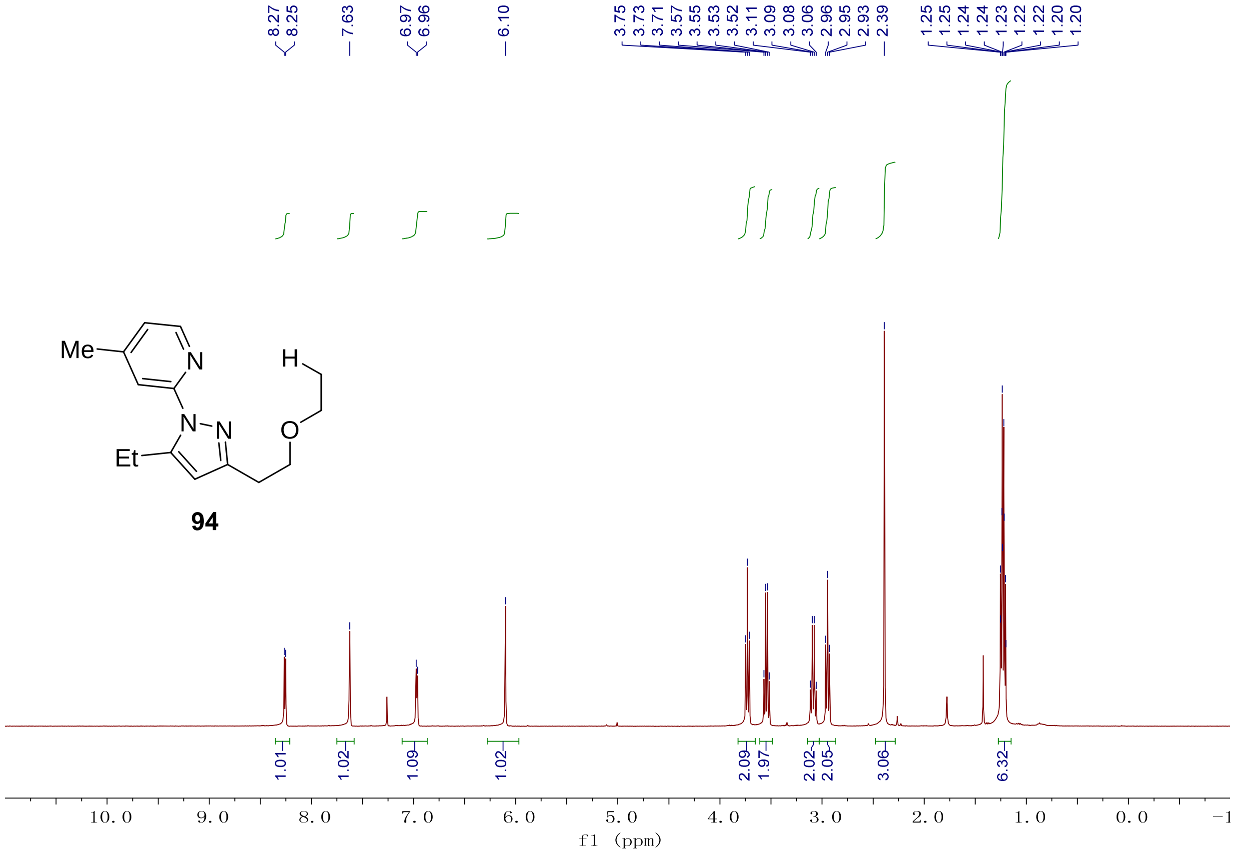
8.26
8.25
7.57
6.98
6.96
6.75
6.70
6.68
6.00
3.08
3.06
3.04
3.03
2.51
2.50
2.48
2.44
2.43
2.42
2.40
2.39
2.38
2.37
2.32
2.05
2.04
2.03
2.02
2.01
2.01
2.00
1.99
1.97
1.92
1.91
1.90
1.88
1.87
1.86
1.86
1.85
1.73
1.70
1.68
1.66
1.66
1.65
1.58
1.56
1.54
1.53
1.52
1.51
1.51
1.47
1.24
1.22
1.20
0.78
0.76
0.74
Me
N
Et
N
N
H
HO
0.98
0.97
3.02
2.97
0.99
1.98
1.94
1.05
3.01
1.00
1.13
1.10
1.04
3.07
3.00
12.5
11.5
10.5
9.5
8.5
7.5
6.5
5.5
4.5
3.5
2.5
1.5
0.5
−0.5
−1
f1 (ppm)


92

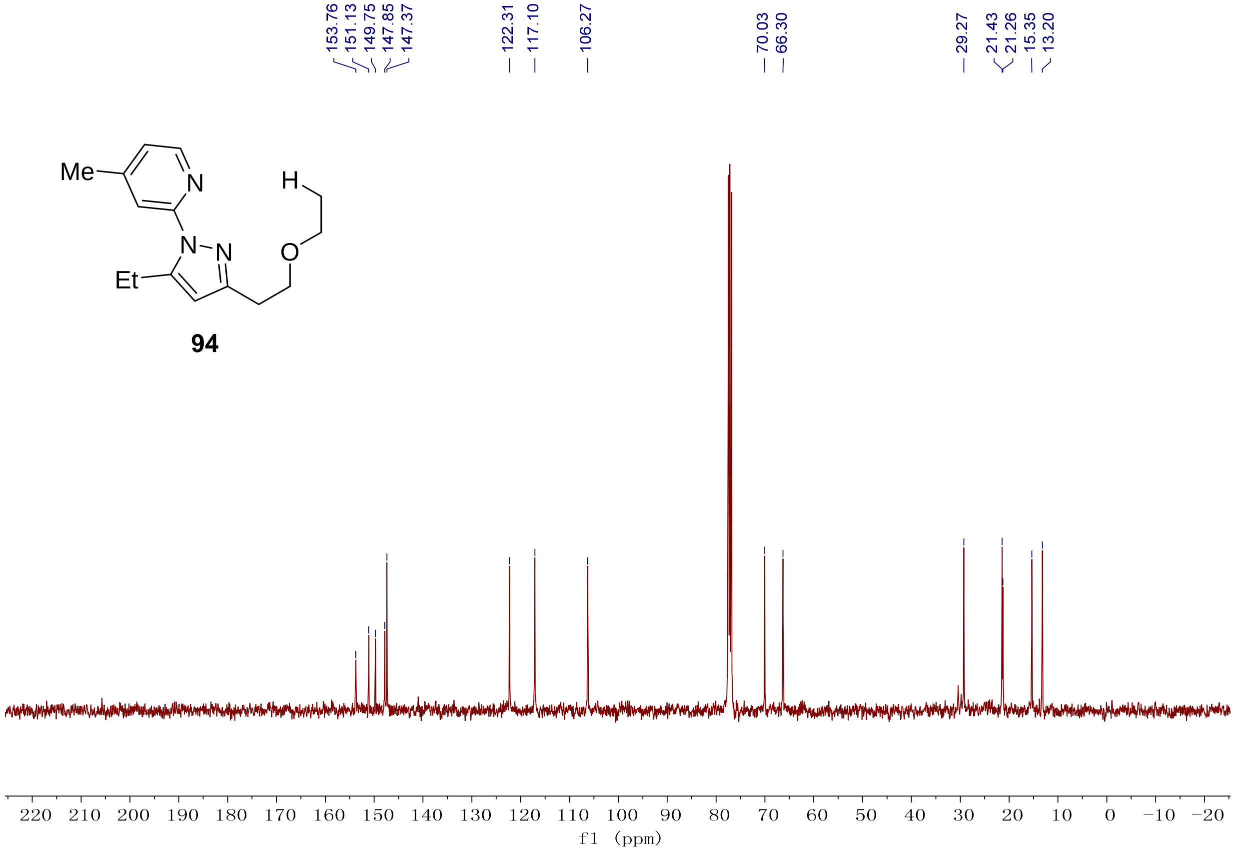
154.66
154.37
153.41
150.02
147.86
147.34
136.80
128.79
122.51
117.61
115.33
105.70
46.99
36.51
29.90
26.61
21.24
21.19
13.17
12.29
Me
N
Et
N
N
H
HO
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
−10
−20
f1 (ppm)


8.28
8.26
7.65
7.08
7.05
7.03
7.01
6.98
6.97
6.90
6.90
6.89
6.88
6.06
3.14
3.12
3.10
3.08
2.73
2.72
2.70
2.69
2.68
2.67
2.65
2.64
2.62
2.61
2.60
2.59
2.45
2.42
2.40
1.92
1.89
1.79
1.78
1.76
1.72
1.70
1.66
1.64
1.63
1.62
1.61
1.60
1.58
1.50
1.47
1.45
1.43
1.41
1.37
1.36
1.34
1.31
1.29
1.27
1.25
1.24
1.22
1.21
0.95
0.93
0.91
Me
N
N
N
Et
H
93
F
F
1.00
0.99
3.10
1.04
0.99
2.05
2.08
4.14
2.16
3.11
1.18
5.14
6.07
3.05
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

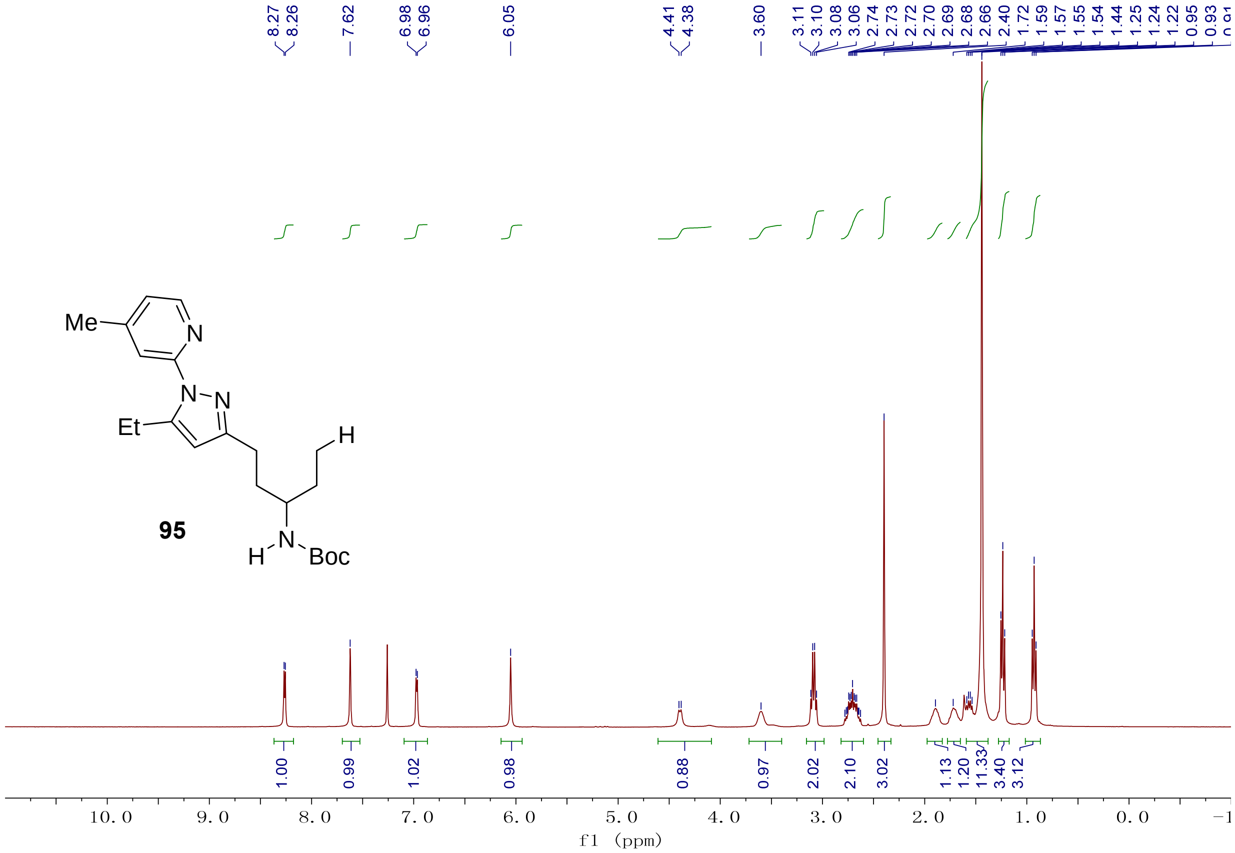

154.72
153.86
151.57
151.44
149.92
149.79
149.72
149.11
148.99
147.85
147.48
147.38
145.00
144.96
144.91
122.67
122.64
122.61
122.58
122.20
117.06
116.96
116.79
115.63
115.46
105.62
44.69
44.08
39.26
34.76
30.38
29.91
29.74
26.86
23.19
21.50
21.28
13.28
12.22
Me
N
N
N
Et
H
93
F
F
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)


94

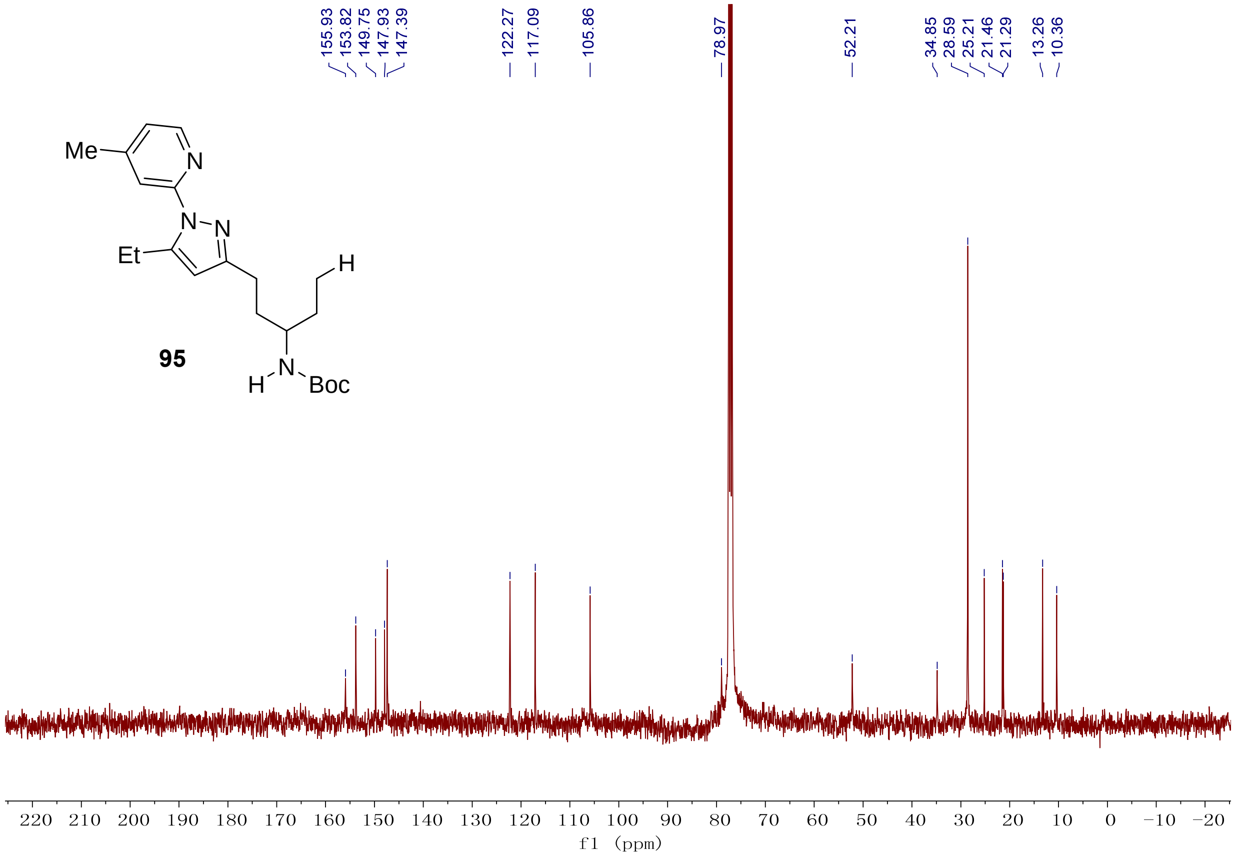
8.27
8.25
7.63
6.97
6.96
6.10
3.75
3.73
3.71
3.57
3.55
3.53
3.52
3.11
3.09
3.08
3.06
2.96
2.95
2.93
2.39
1.25
1.25
1.24
1.24
1.23
1.22
1.22
1.20
1.20
Me
N
H
N
N
O
Et
1.01
1.02
1.09
1.02
2.09
1.97
2.02
2.05
3.06
6.32
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)


94

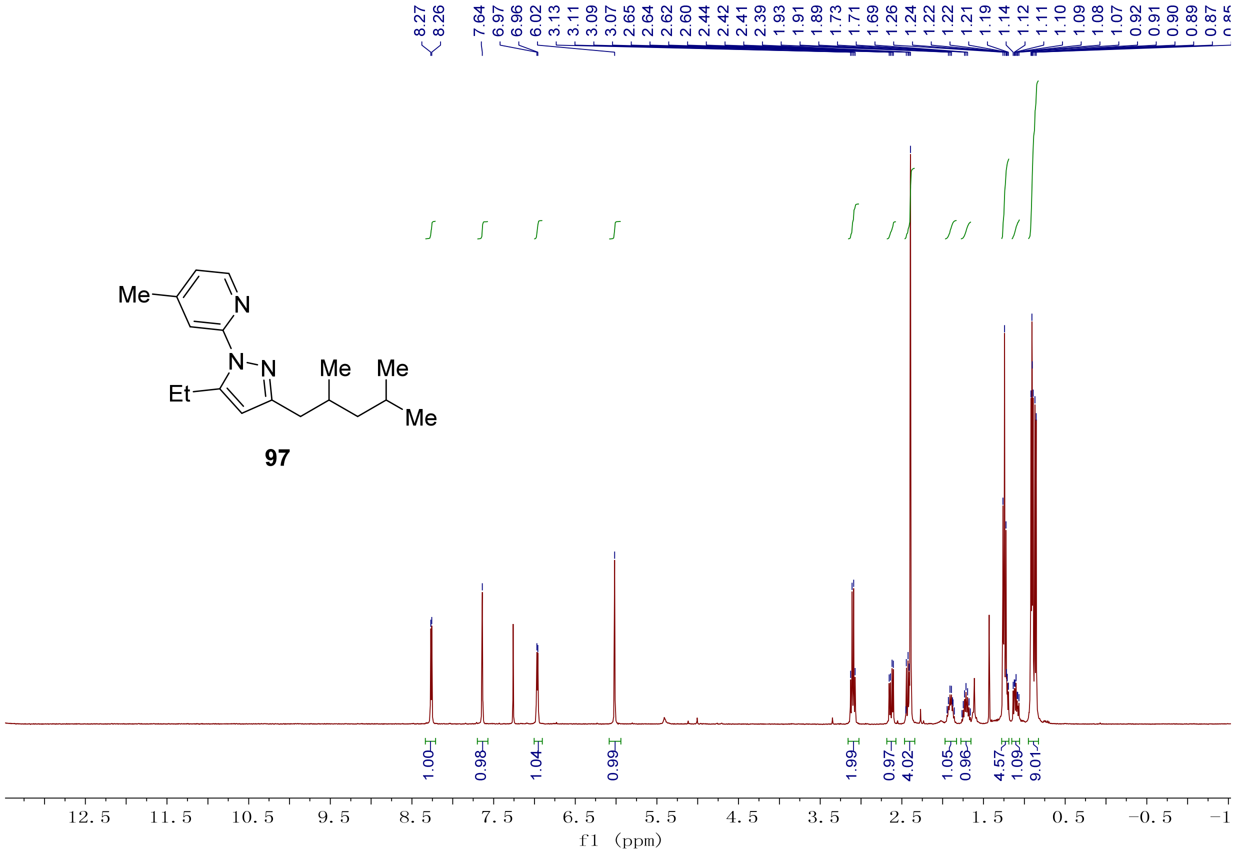
153.76
151.13
149.75
147.85
147.37
122.31
117.10
106.27
70.03
66.30
29.27
21.43
21.26
15.35
13.20
Me
N
H
N
N
O
Et
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

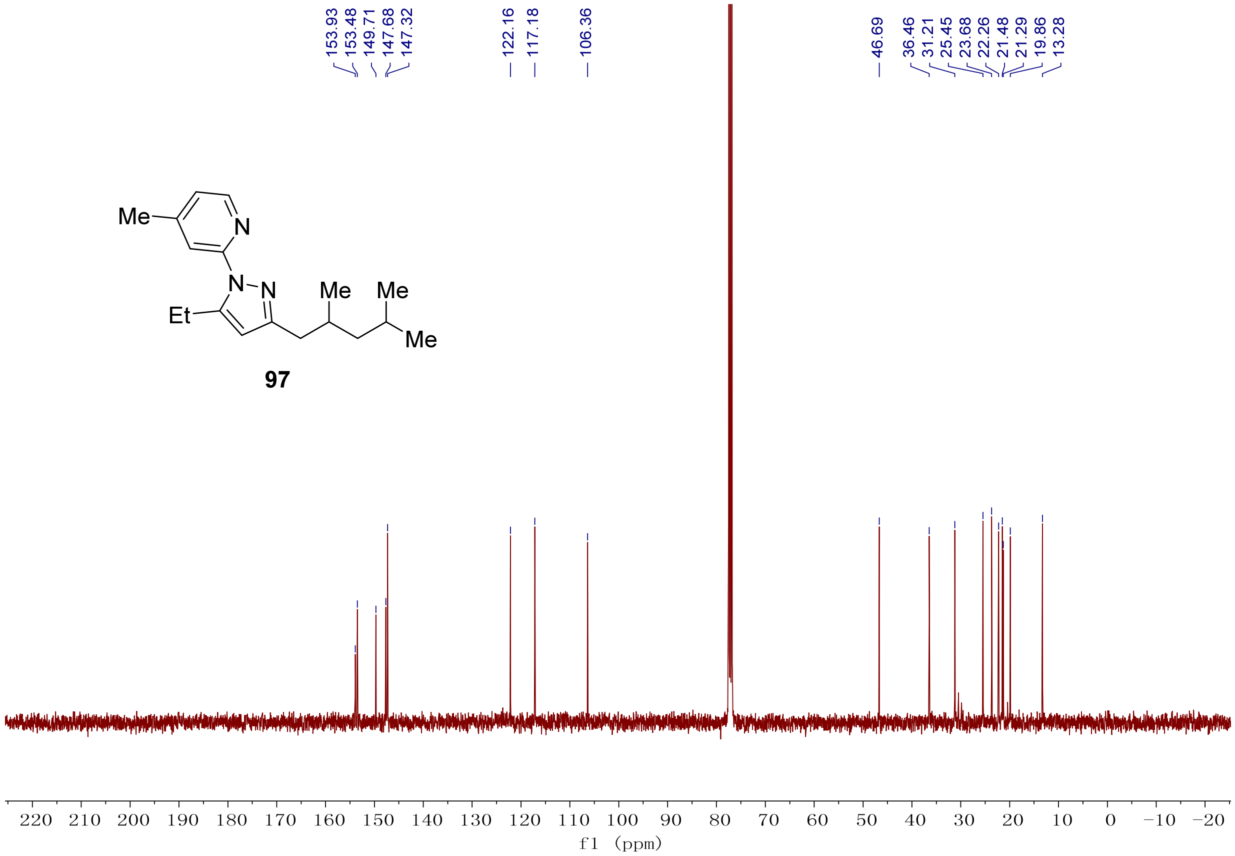

8.27
8.26
7.62
6.98
6.96
6.05
4.41
4.38
3.60
3.11
3.10
3.08
3.06
2.74
2.73
2.72
2.70
2.69
2.68
2.66
2.40
1.72
1.59
1.57
1.55
1.54
1.44
1.25
1.24
1.22
0.95
0.93
Me
N
N
N
Et
H
H
N
Boc
1.00
0.99
1.02
0.98
0.88
0.97
2.02
2.10
3.02
1.13
1.20
11.33
3.40
3.12
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

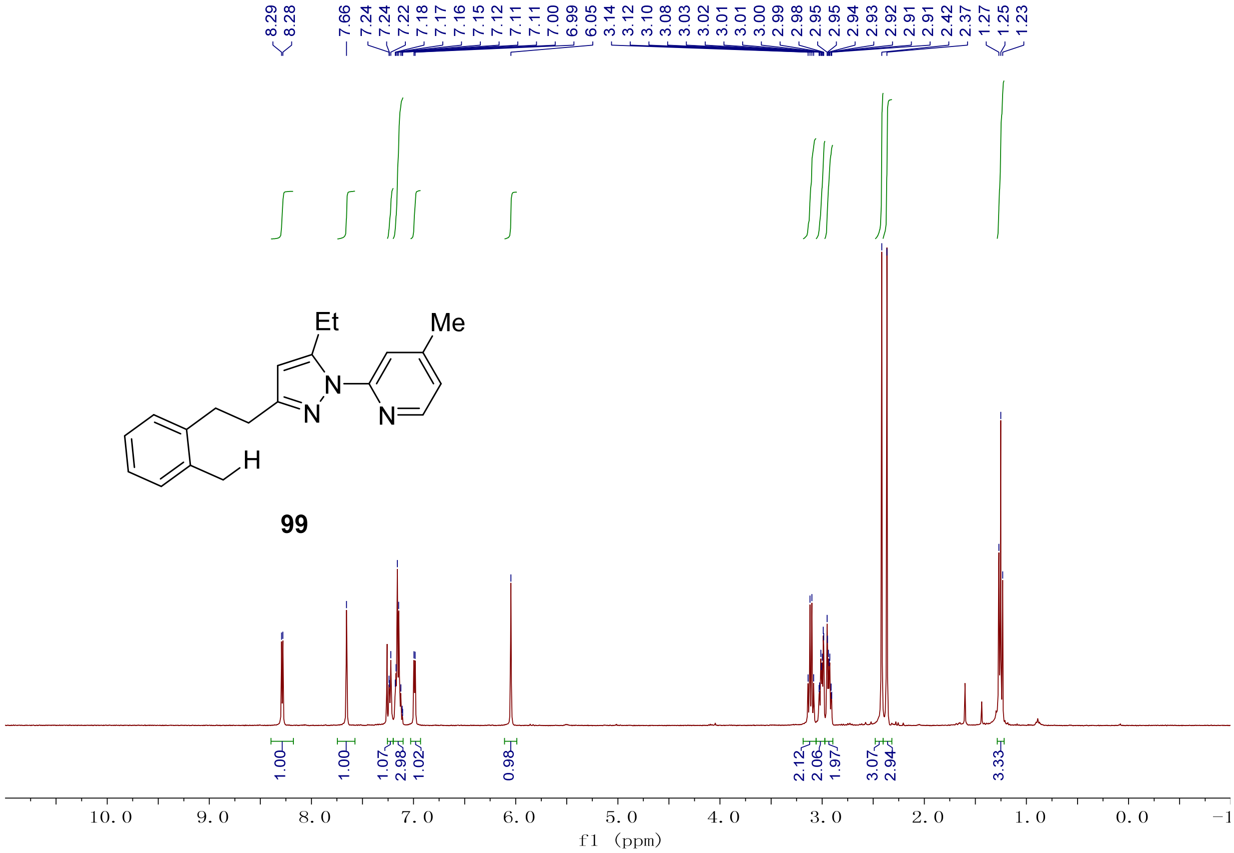
95


155.93
153.82
149.75
147.93
147.39
122.27
117.09
105.86
78.97
52.21
34.85
28.59
25.21
21.46
21.29
13.26
10.36
Me
N
N
N
Et
H
H
N
Boc
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

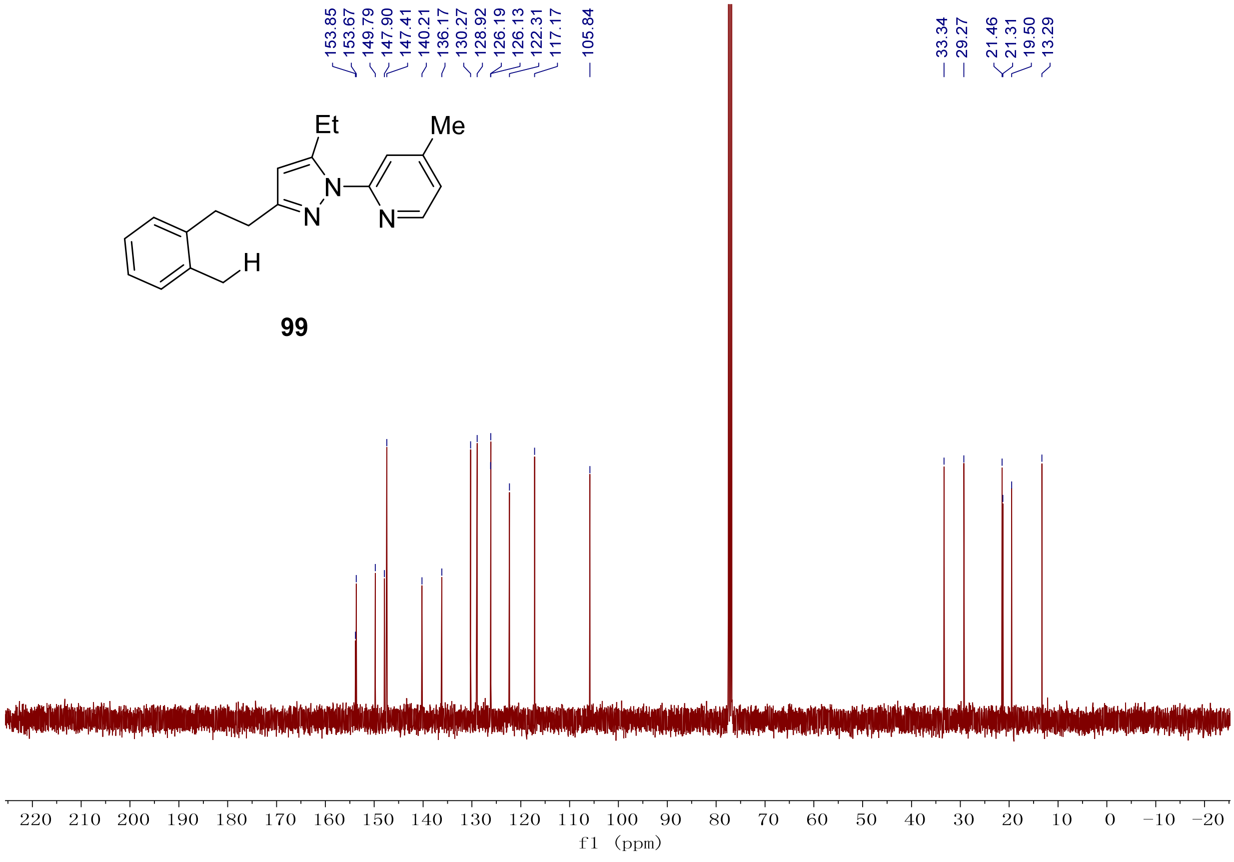
95


8.27
8.26
7.64
6.97
6.96
6.02
3.13
3.11
3.09
3.07
2.65
2.64
2.62
2.60
2.44
2.42
2.41
2.39
1.93
1.91
1.89
1.73
1.71
1.69
1.26
1.24
1.22
1.22
1.21
1.19
1.14
1.12
1.11
1.10
1.09
1.08
1.07
0.92
0.91
0.90
0.89
0.87
Me
N
N
N
Me
Me
Et
Me
97
1.00
0.98
1.04
0.99
1.99
0.97
4.02
1.05
0.96
4.57
1.09
9.01
12.5
11.5
10.5
9.5
8.5
7.5
6.5
5.5
4.5
3.5
2.5
1.5
0.5
−0.5
−1
f1 (ppm)

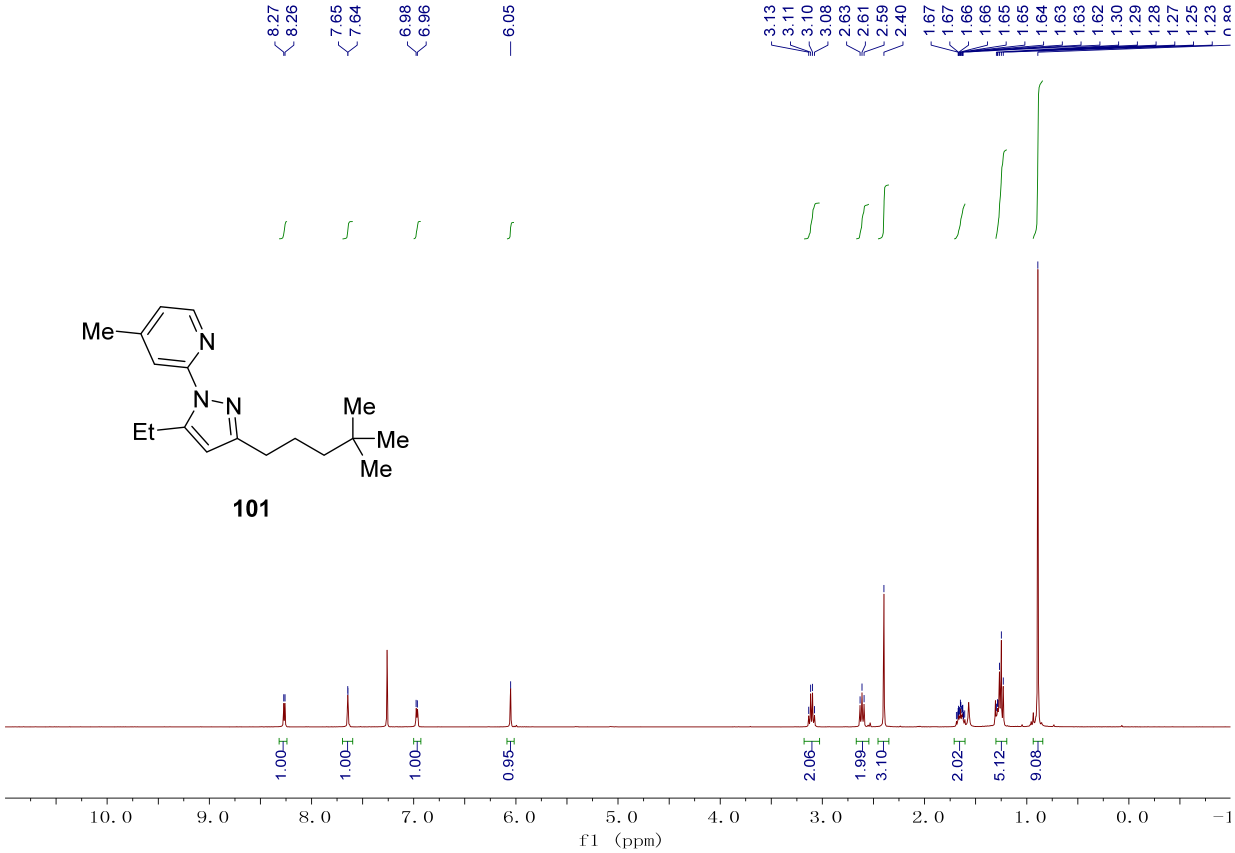

153.93
153.48
149.71
147.68
147.32
122.16
117.18
106.36
46.69
36.46
31.21
25.45
23.68
22.26
21.48
21.29
19.86
13.28
Me
N
N
N
Me
Me
Et
Me
97
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
−10
−20
f1 (ppm)

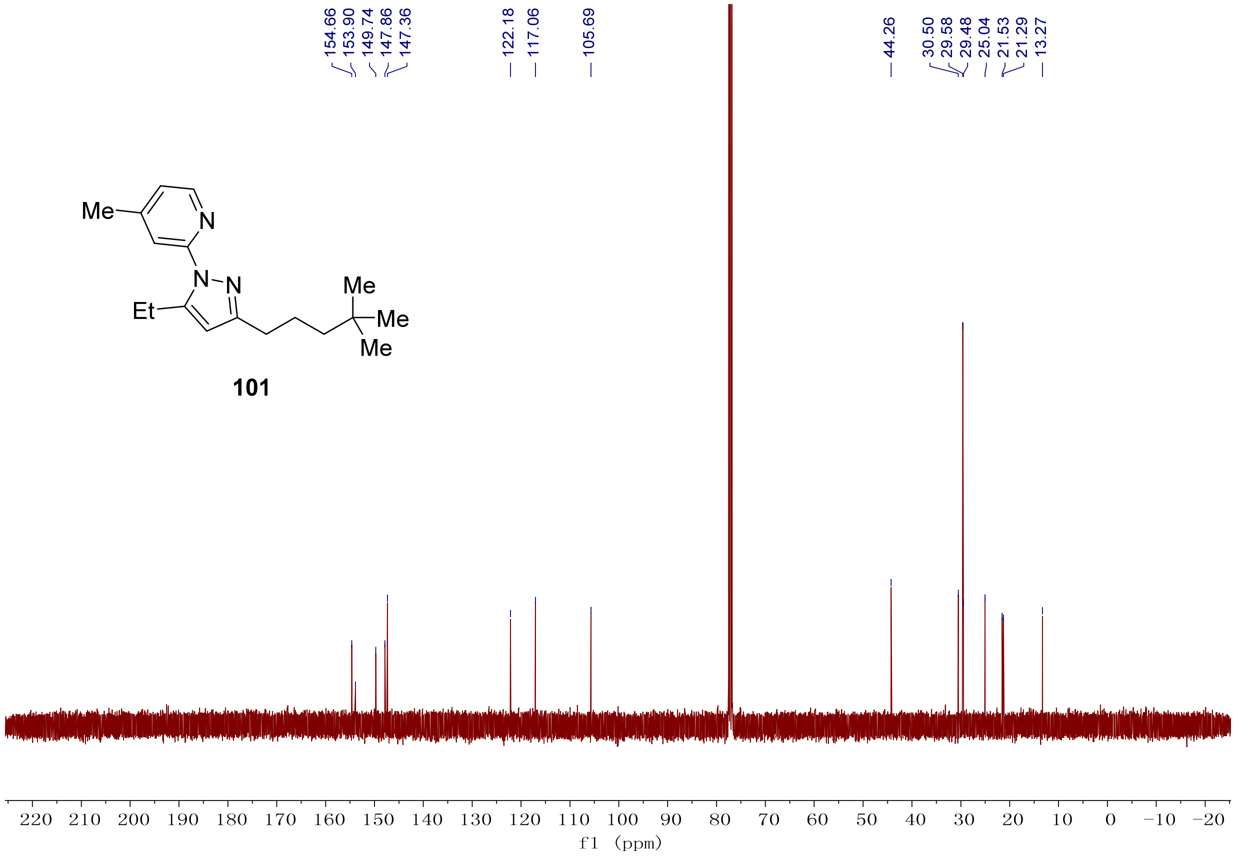

99

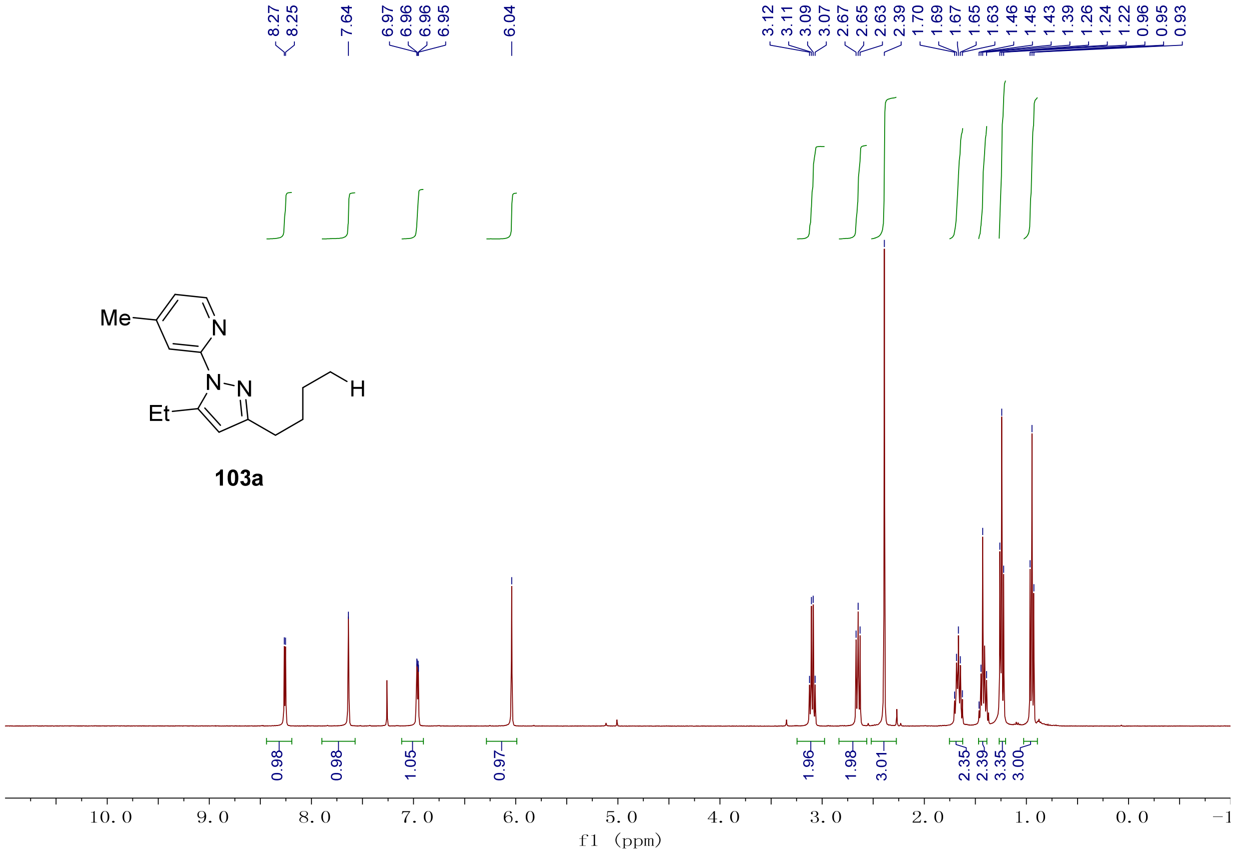
8.29
8.28
7.66
7.24
7.24
7.22
7.18
7.17
7.16
7.15
7.12
7.11
7.11
7.00
6.99
6.05
3.14
3.12
3.10
3.08
3.03
3.02
3.01
3.01
3.00
2.99
2.98
2.95
2.95
2.94
2.93
2.92
2.91
2.91
2.42
2.37
1.27
1.25
1.23
Et
Me
N
N
N
H
1.00
1.00
1.07
2.98
1.02
0.98
2.12
2.06
1.97
3.07
2.94
3.33
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

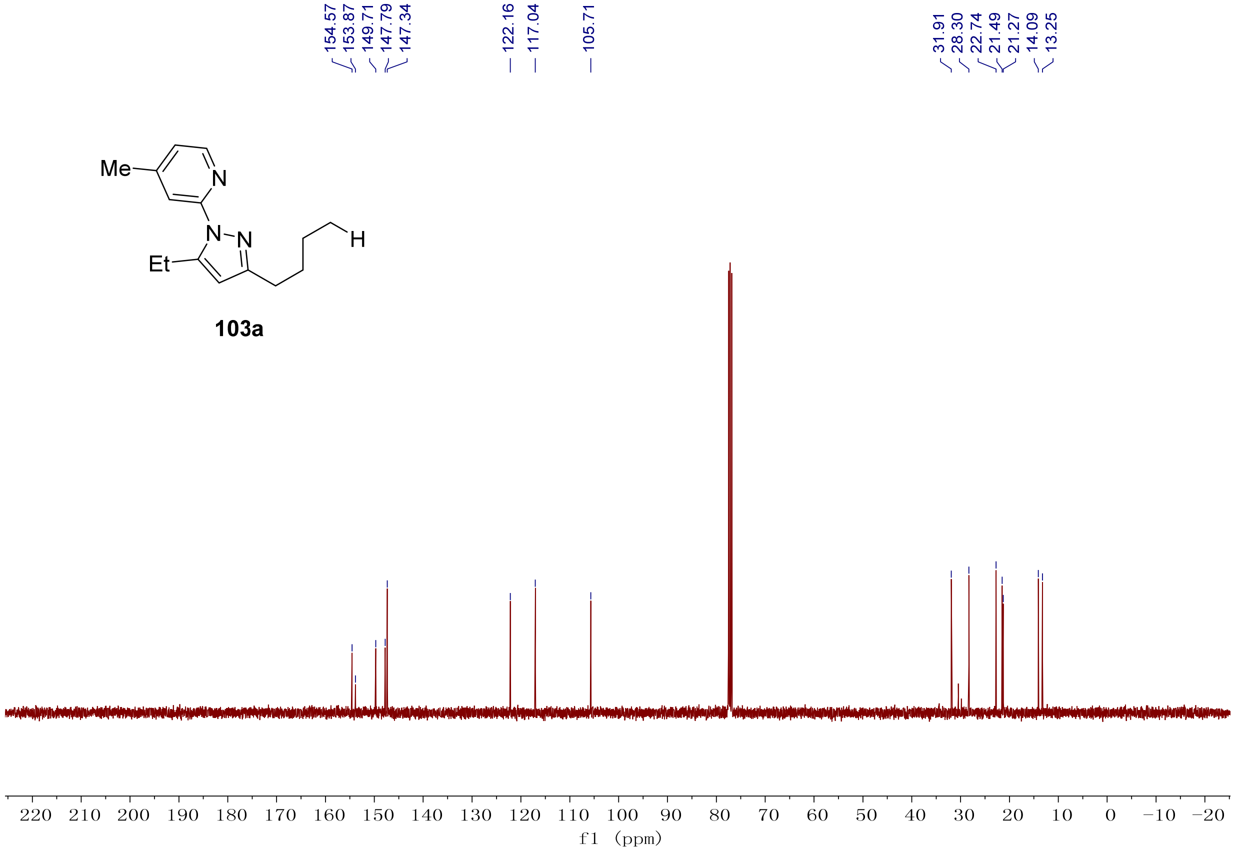

99

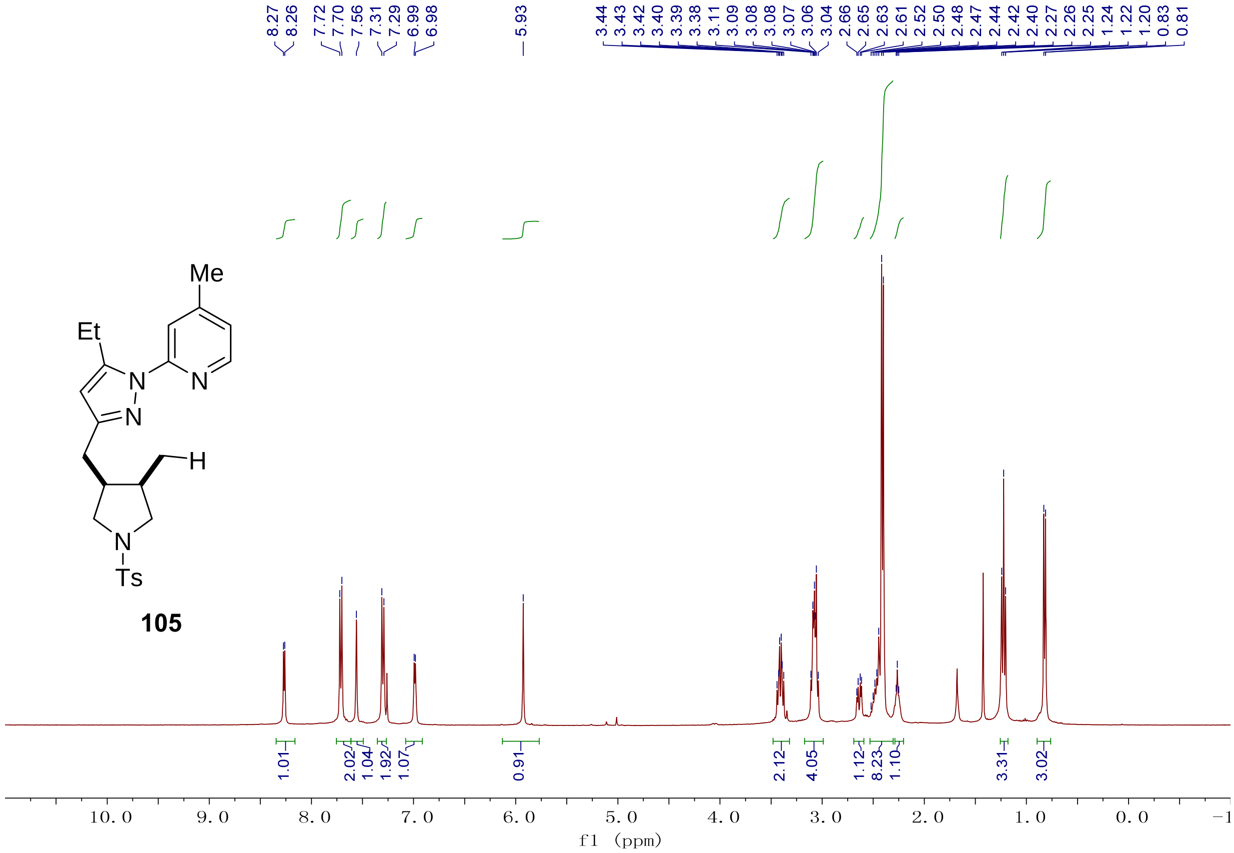
153.85
153.67
149.79
147.90
147.41
140.21
136.17
130.27
128.92
126.19
126.13
122.31
117.17
105.84
33.34
29.27
21.46
21.31
19.50
13.29
Et
Me
N
N
N
H
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)


8.27
8.26
7.65
7.64
6.98
6.96
6.05
3.13
3.11
3.10
3.08
2.63
2.61
2.59
2.40
1.67
1.67
1.66
1.66
1.65
1.65
1.64
1.63
1.63
1.62
1.30
1.29
1.28
1.27
1.25
1.23
Me
N
N
N
Et
Me
Me
Me
101
1.00
1.00
1.00
0.95
2.06
1.99
3.10
2.02
5.12
9.08
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

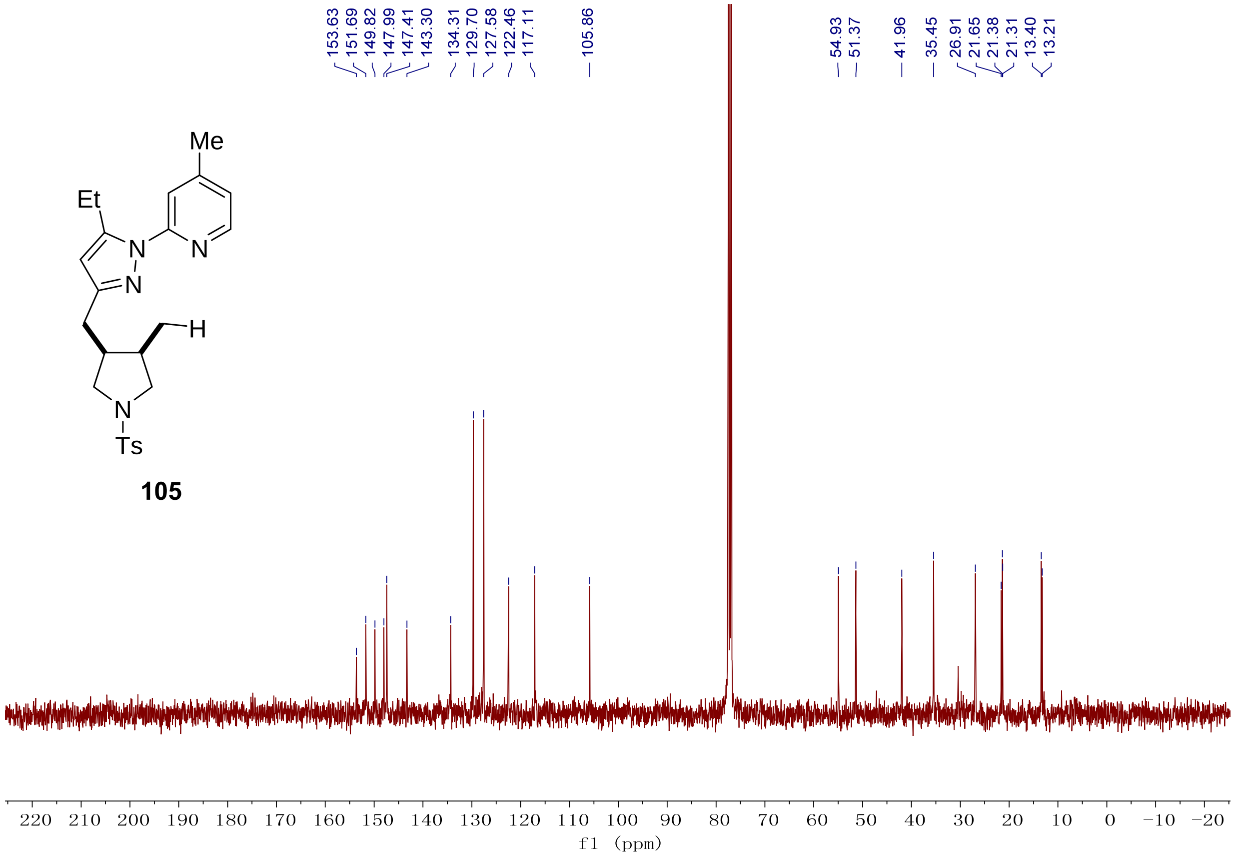

154.66
153.90
149.74
147.86
147.36
122.18
117.06
105.69
44.26
30.50
29.58
29.48
25.04
21.53
21.29
13.27
Me
N
N
N
Et
Me
Me
Me
101
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)


8.27
8.25
7.64
6.97
6.96
6.96
6.95
6.04
3.12
3.11
3.09
3.07
2.67
2.65
2.63
2.39
1.70
1.69
1.67
1.65
1.63
1.46
1.45
1.43
1.39
1.26
1.24
1.22
0.96
0.95
0.93
Me
N
N
N
H
Et
103a
0.98
0.98
1.05
0.97
1.96
1.98
3.01
2.35
2.39
3.35
3.00
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

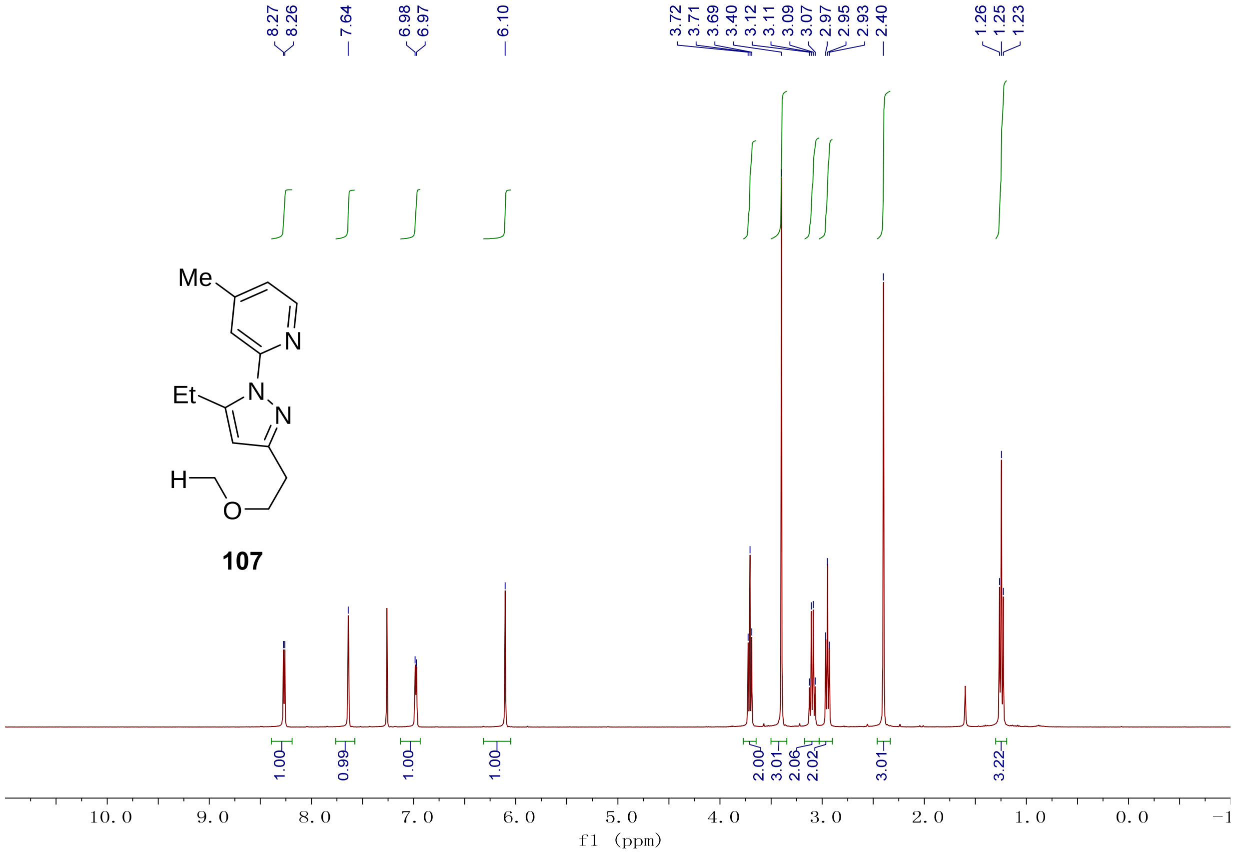

154.57
153.87
149.71
147.79
147.34
122.16
117.04
105.71
31.91
28.30
22.74
21.49
21.27
14.09
13.25
Me
N
N
N
H
Et
103a
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

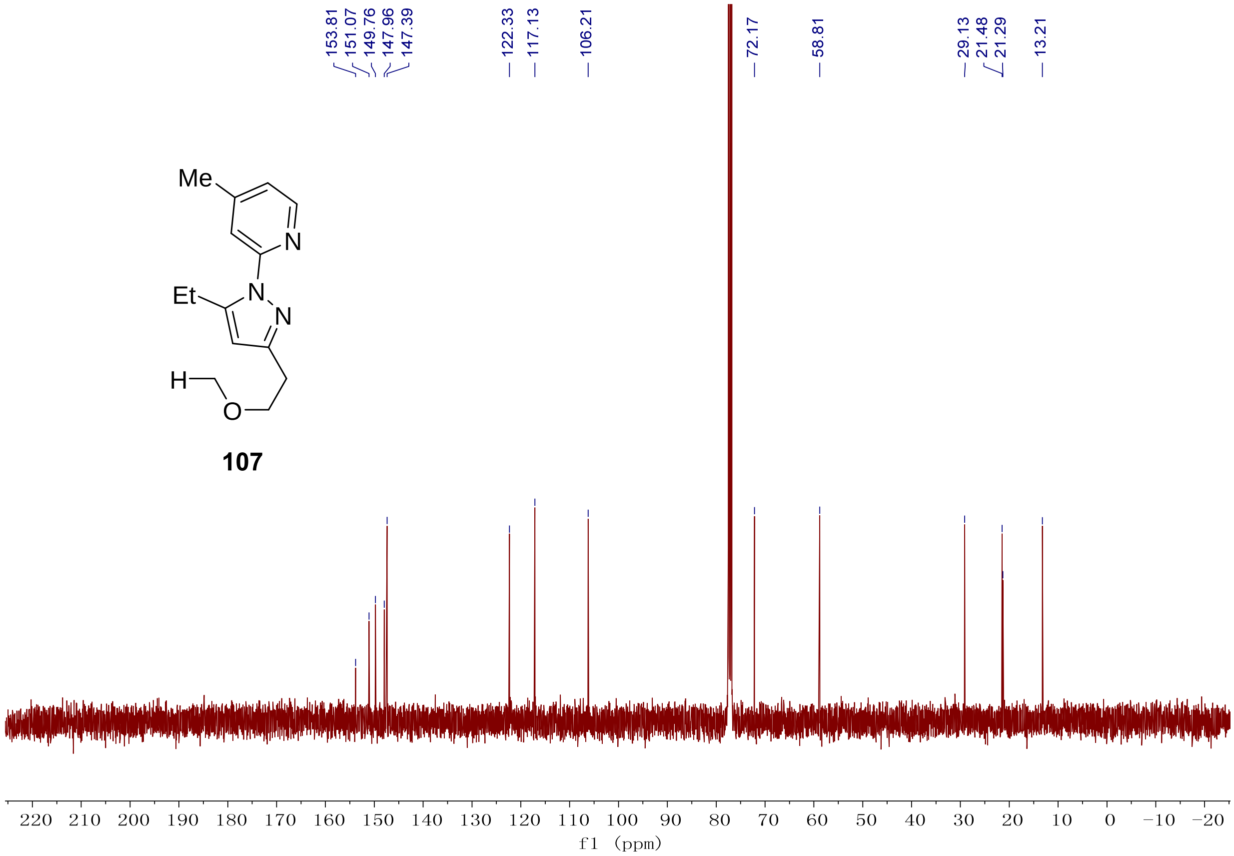

8.27
8.26
7.72
7.70
7.56
7.31
7.29
6.99
6.98
5.93
3.44
3.43
3.42
3.40
3.39
3.38
3.11
3.09
3.08
3.08
3.07
3.06
3.04
2.66
2.65
2.63
2.61
2.52
2.50
2.48
2.47
2.44
2.42
2.40
2.27
2.26
2.25
1.24
1.22
1.20
0.83
0.81
Me
Et
N
N
N
N
H
N
Ts
1.01
2.02
1.04
1.92
1.07
0.91
2.12
4.05
1.12
8.23
1.10
3.31
3.02
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

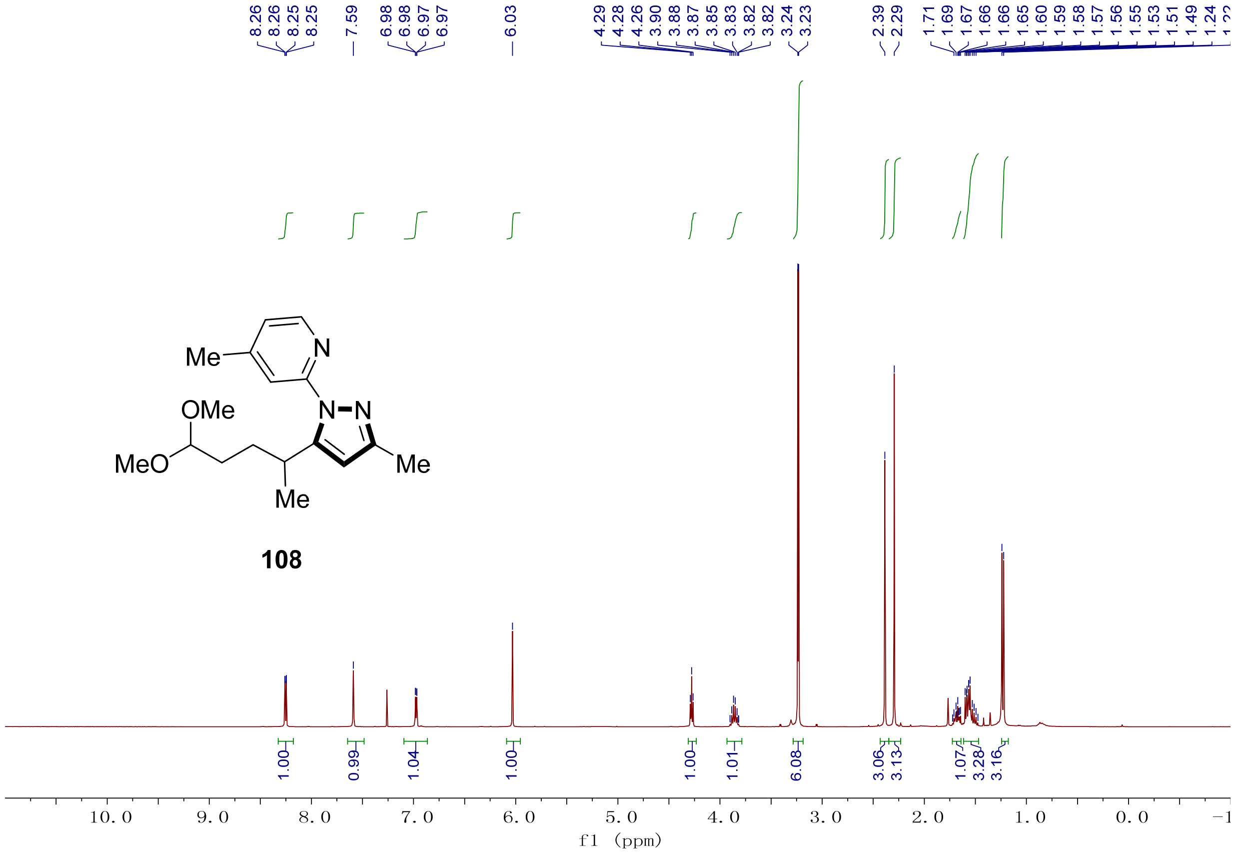
105

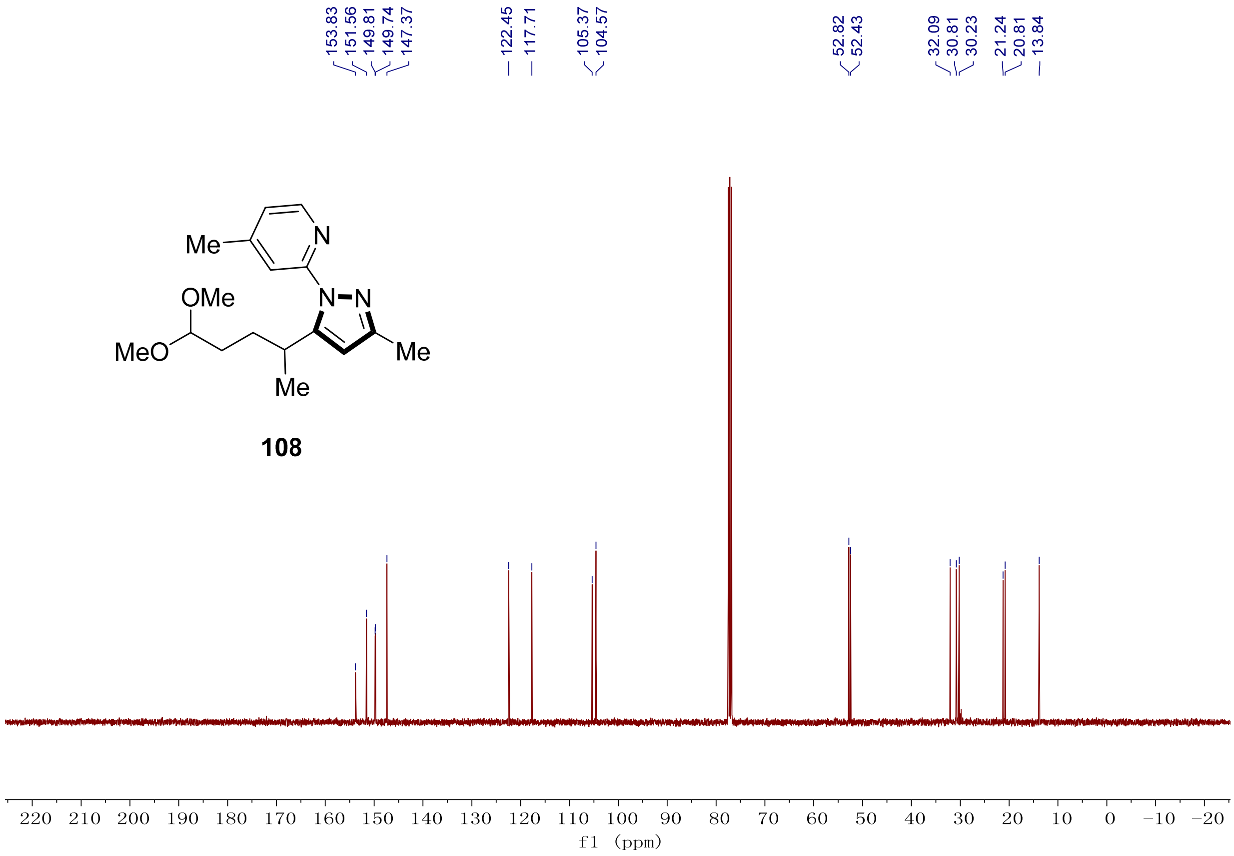

153.63
151.69
149.82
147.99
147.41
143.30
134.31
129.70
127.58
122.46
117.11
105.86
54.93
51.37
41.96
35.45
26.91
21.65
21.38
21.31
13.40
13.21
Me
Et
N
N
N
N
H
N
Ts
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

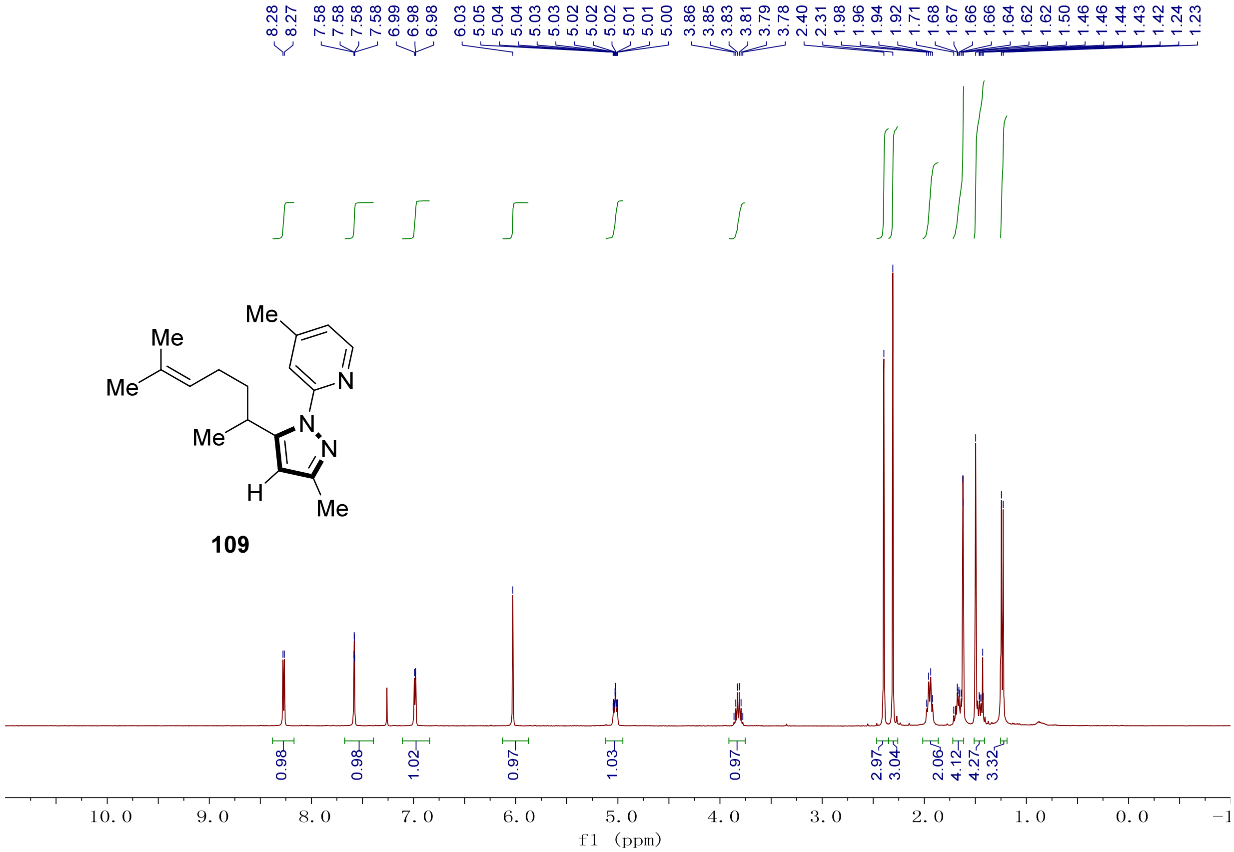
105


8.27
8.26
7.64
6.98
6.97
6.10
3.72
3.71
3.69
3.40
3.12
3.11
3.09
3.07
2.97
2.95
2.93
2.40
1.26
1.25
1.23
Me
N
Et
N
N
H
O
107
1.00
0.99
1.00
1.00
2.00
3.01
2.06
2.02
3.01
3.22
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

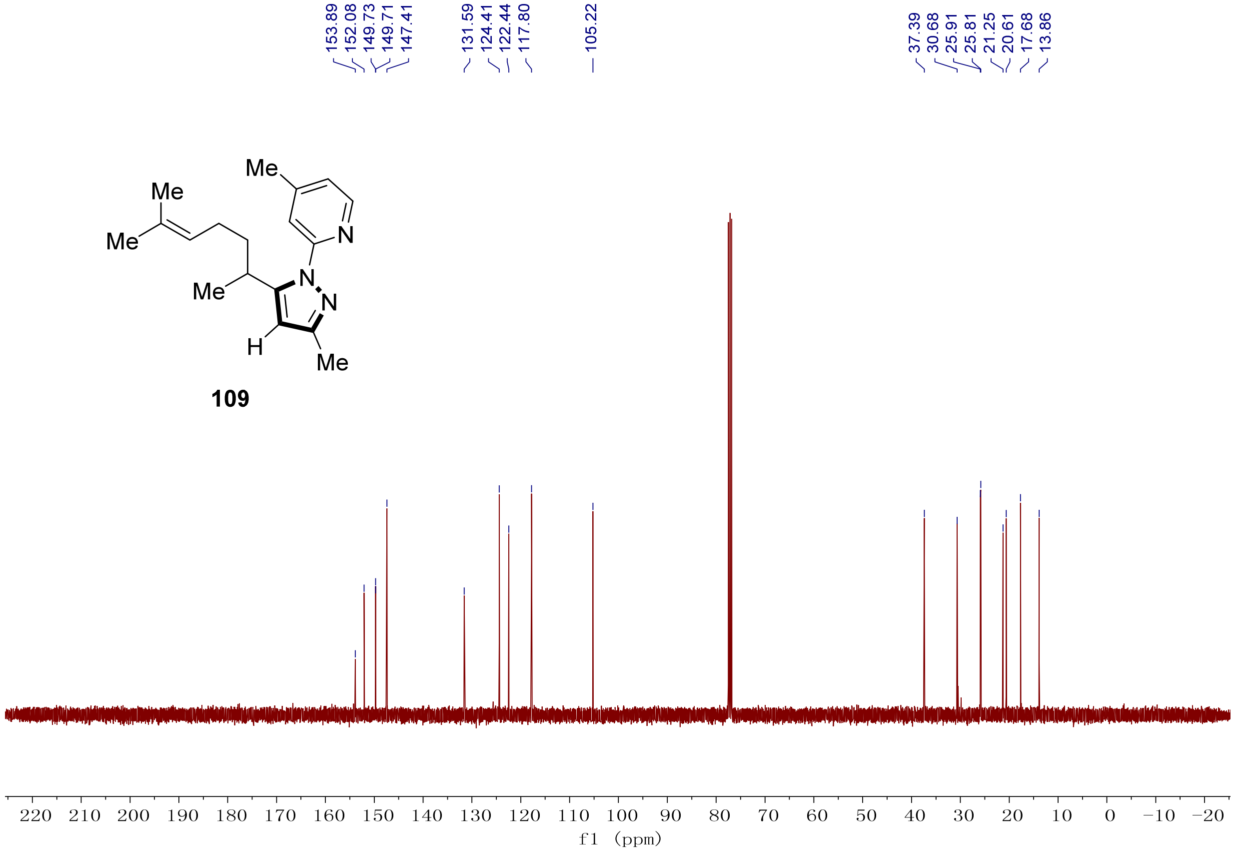

153.81
151.07
149.76
147.96
147.39
122.33
117.13
106.21
72.17
58.81
29.13
21.48
21.29
13.21
Me
N
Et
N
N
H
O
107
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)


8.26
8.26
8.25
8.25
7.59
6.98
6.98
6.97
6.97
6.03
4.29
4.28
4.26
3.90
3.88
3.87
3.85
3.83
3.82
3.82
3.24
3.23
2.39
2.29
1.71
1.69
1.67
1.66
1.66
1.65
1.60
1.59
1.58
1.57
1.56
1.55
1.53
1.51
1.49
1.24
Me
N
OMe
N
N
MeO
Me
Me
108
1.00
0.99
1.04
1.00
1.00
1.01
6.08
3.06
3.13
1.07
3.28
3.16
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
f1 (ppm)

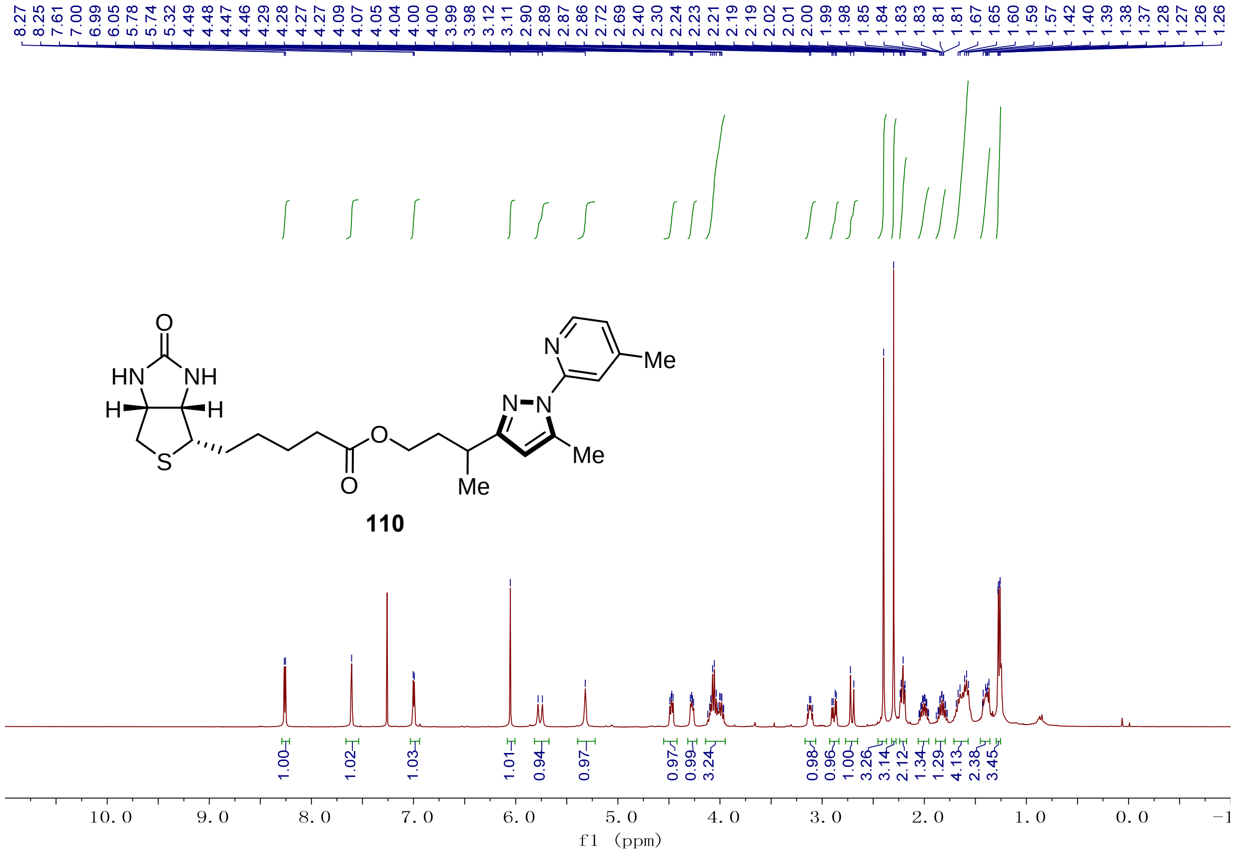

153.83
151.56
149.81
149.74
147.37
122.45
117.71
105.37
104.57
52.82
52.43
32.09
30.81
30.23
21.24
20.81
13.84
Me
N
OMe
N
N
MeO
Me
Me
108
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)


8.28
8.27
7.58
7.58
7.58
7.58
6.99
6.98
6.98
6.03
5.05
5.04
5.04
5.03
5.03
5.02
5.02
5.02
5.01
5.01
5.00
3.86
3.85
3.83
3.81
3.79
3.78
2.40
2.31
1.98
1.96
1.94
1.92
1.71
1.68
1.67
1.66
1.66
1.64
1.62
1.62
1.50
1.46
1.46
1.44
1.43
1.42
1.24
1.23
Me
Me
Me
N
N
N
Me
H
Me
0.98
0.98
1.02
0.97
1.03
0.97
2.97
3.04
2.06
4.12
4.27
3.32
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

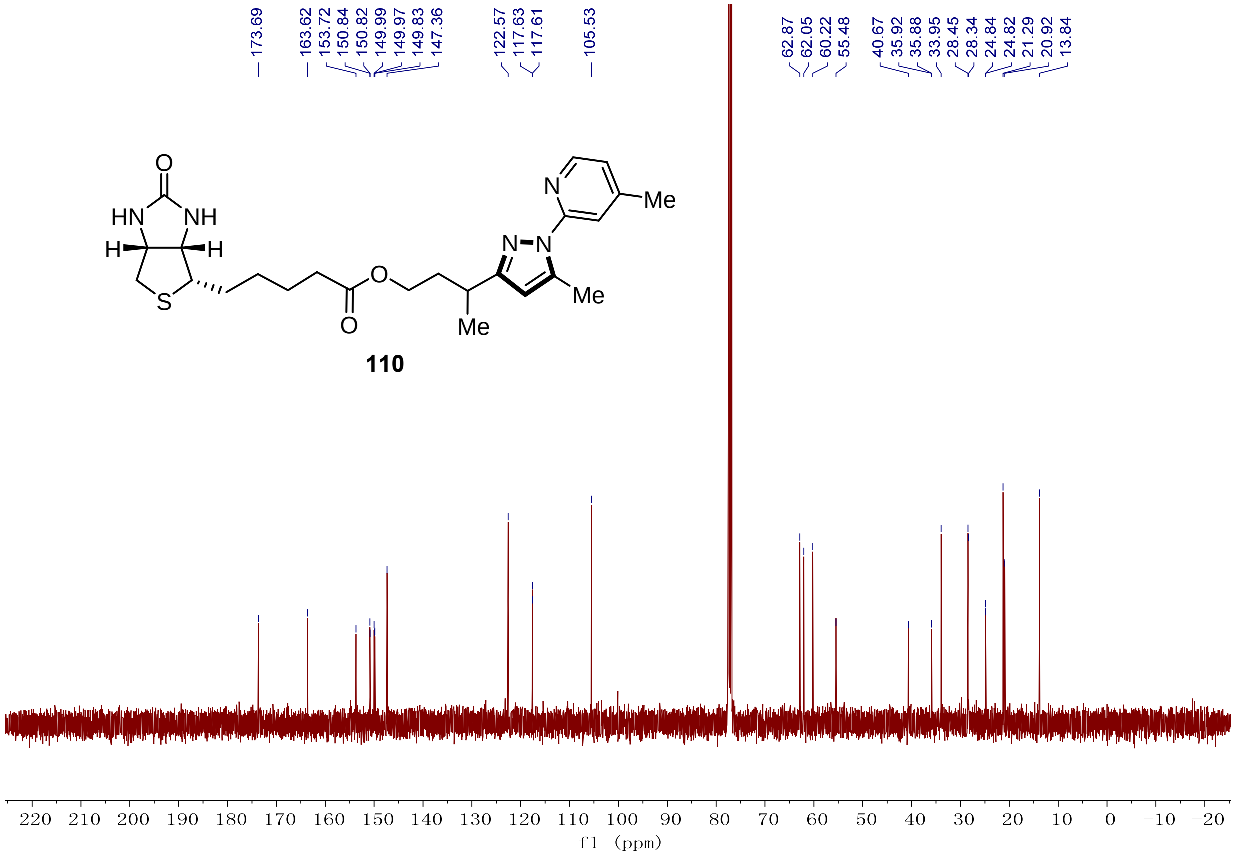
109


153.89
152.08
149.73
149.71
147.41
131.59
124.41
122.44
117.80
105.22
37.39
30.68
25.91
25.81
21.25
20.61
17.68
13.86
Me
Me
Me
N
N
N
Me
H
Me
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

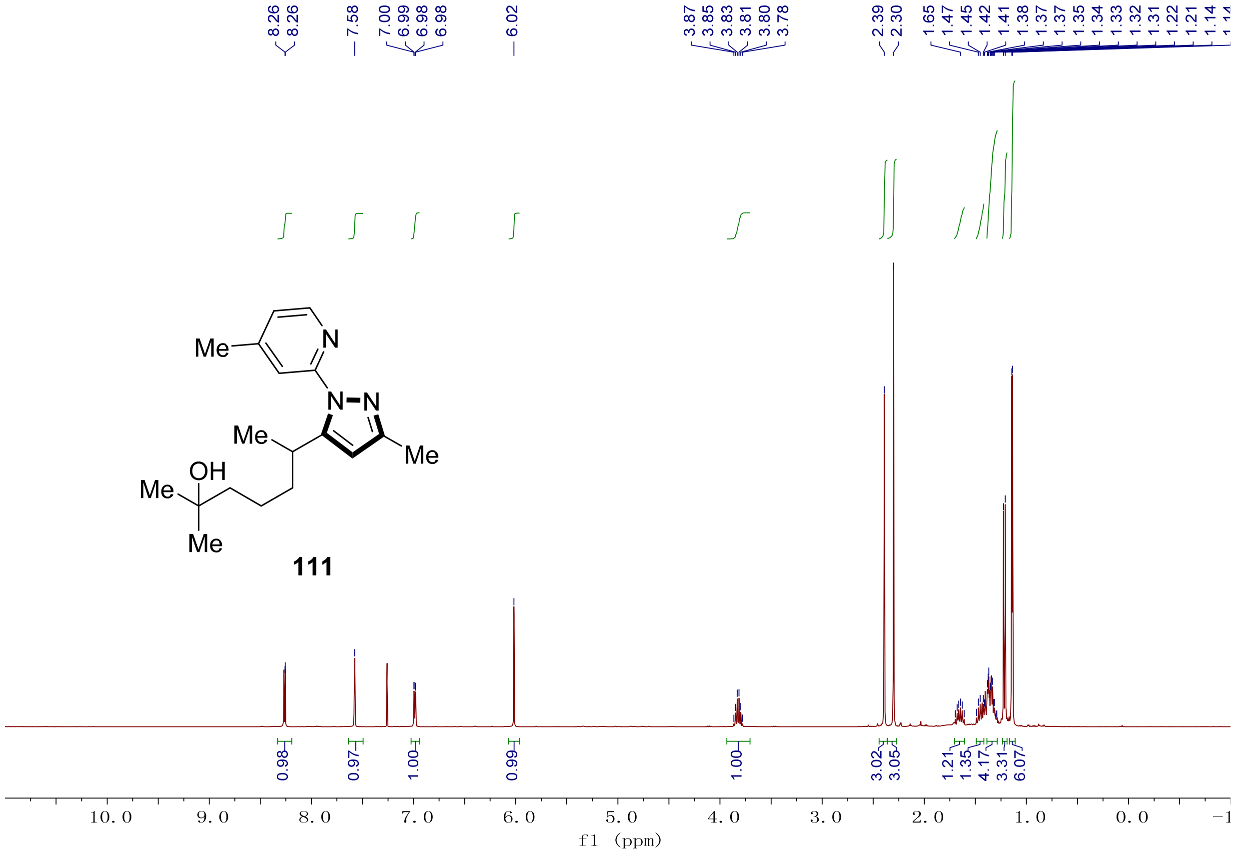
109

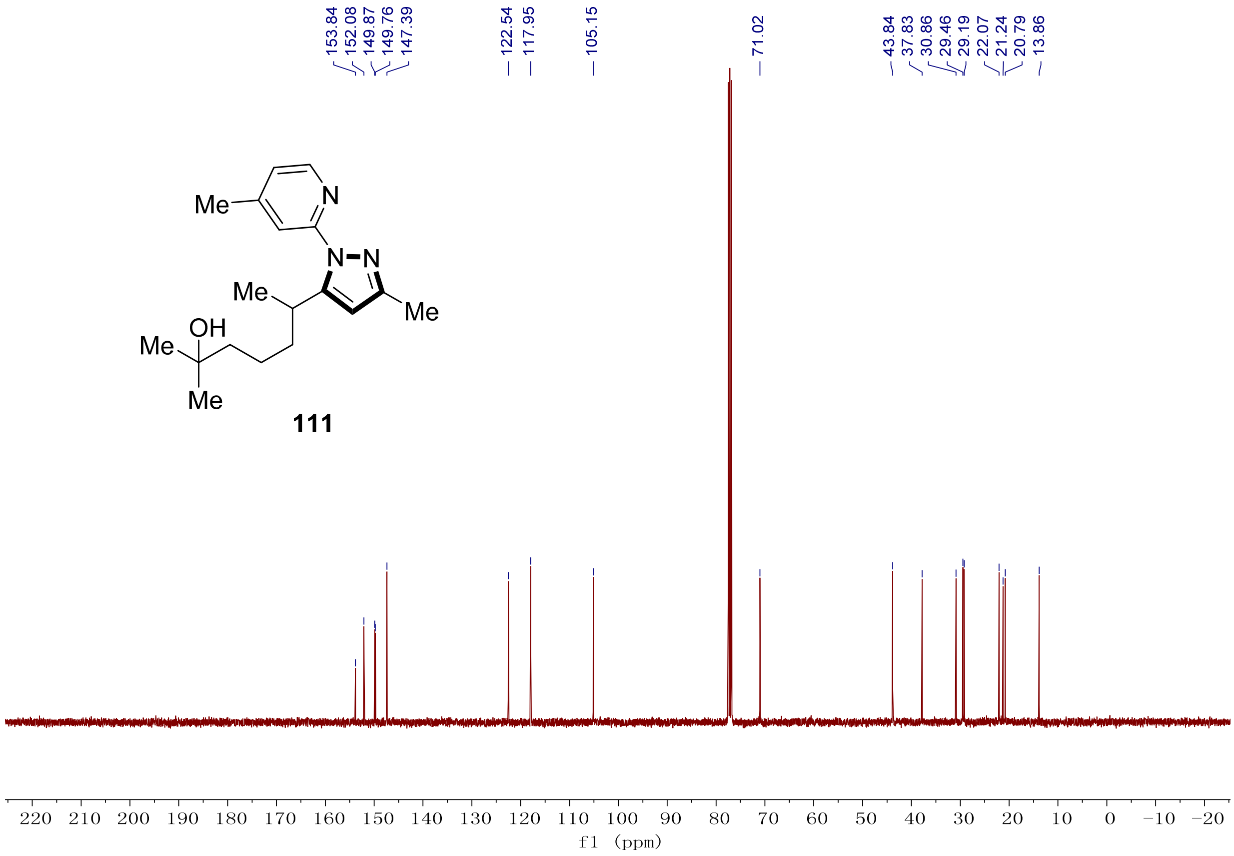

8.27
8.25
7.61
7.00
6.99
6.05
5.78
5.74
5.32
4.49
4.48
4.47
4.46
4.29
4.28
4.27
4.27
4.09
4.07
4.05
4.04
4.00
4.00
3.99
3.98
3.12
3.11
2.90
2.89
2.87
2.86
2.72
2.69
2.40
2.30
2.24
2.23
2.21
2.19
2.19
2.02
2.01
2.00
1.99
1.98
1.85
1.84
1.83
1.83
1.81
1.81
1.67
1.65
1.60
1.59
1.57
1.42
1.40
1.39
1.38
1.37
1.28
1.27
1.26
1.26
O
HN
NH
H
H
S
O
O
Me
N
N
N
Me
Me
1.00
1.02
1.03
1.01
0.94
0.97
0.97
0.99
3.24
0.98
0.96
1.00
3.26
3.14
2.12
1.34
1.29
4.13
2.38
3.45
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

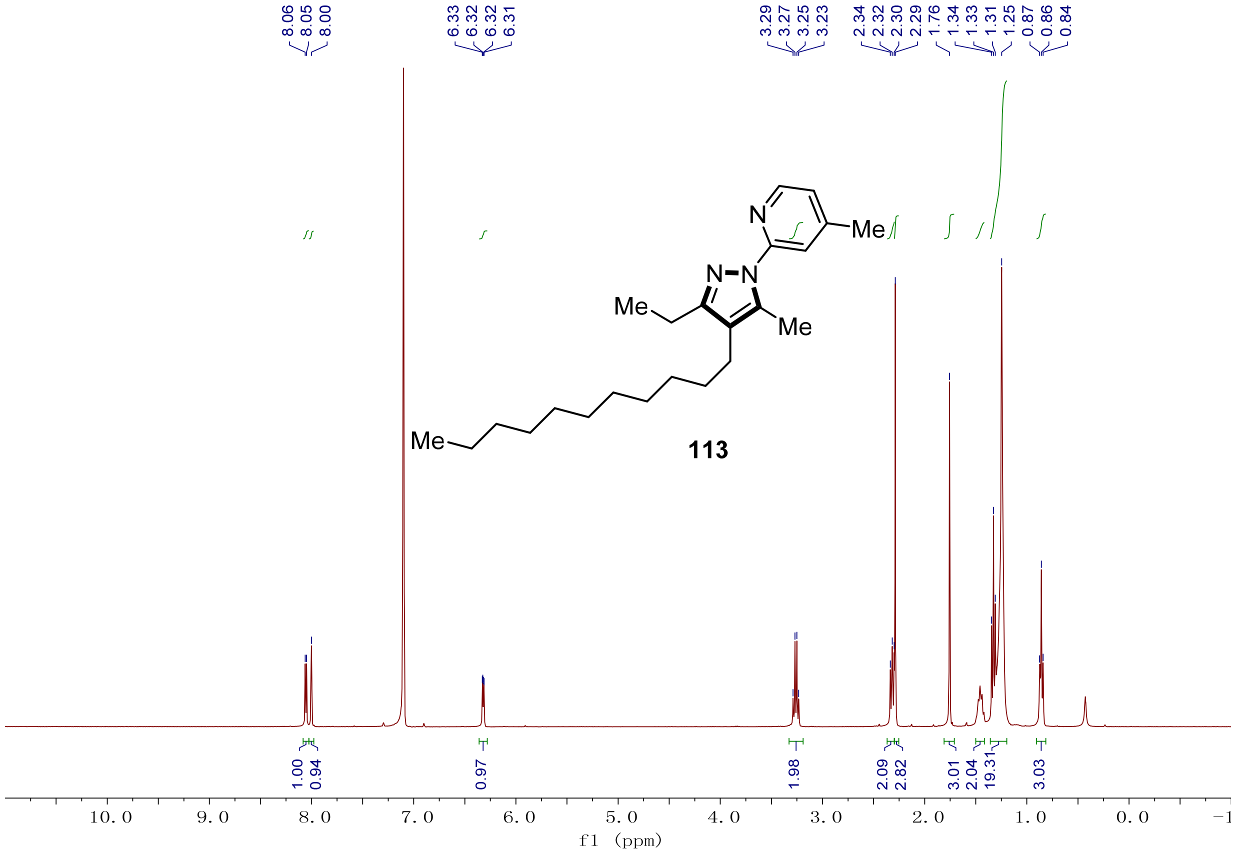
110

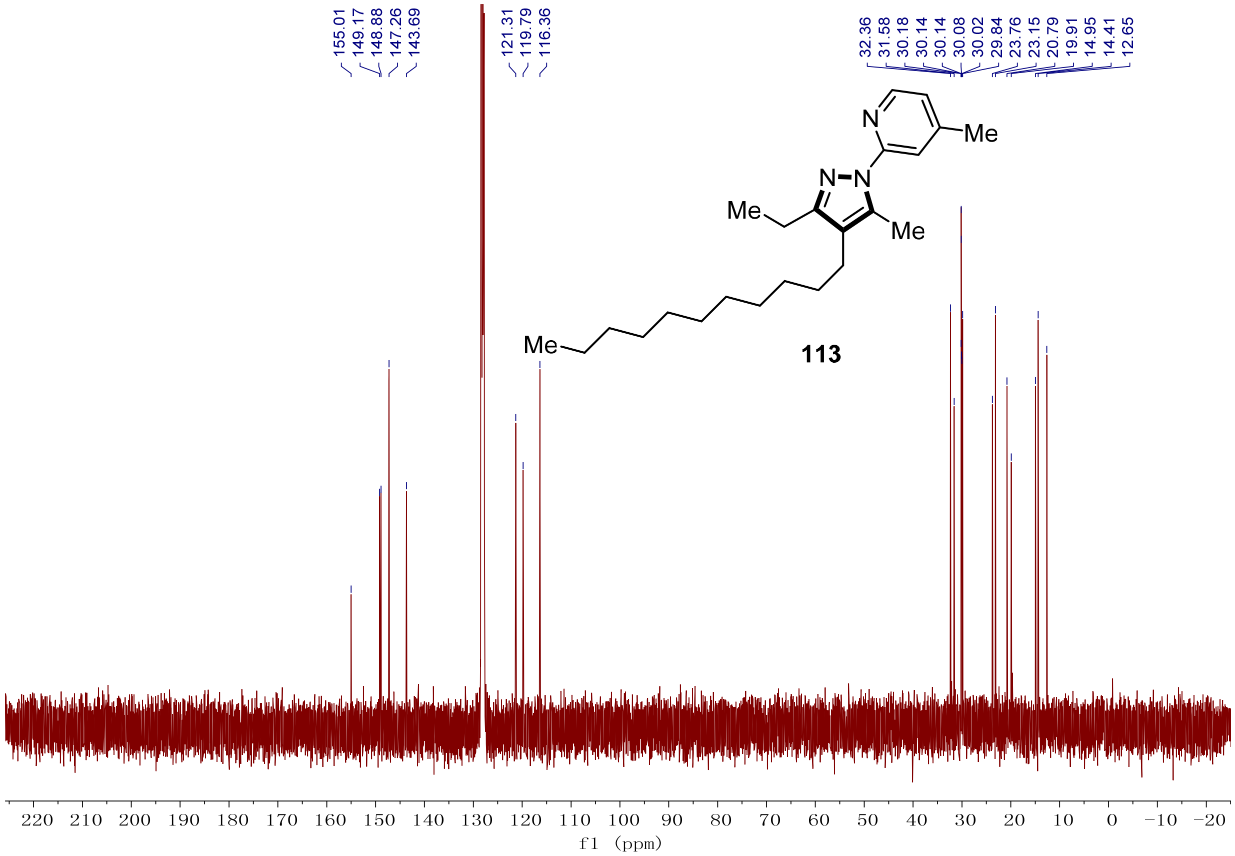

173.69
163.62
153.72
150.84
150.82
149.99
149.97
149.83
147.36
122.57
117.63
117.61
105.53
62.87
62.05
60.22
55.48
40.67
35.92
35.88
33.95
28.45
28.34
24.84
24.82
21.29
20.92
13.84
O
HN
NH
H
H
S
O
O
Me
N
N
N
Me
Me
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

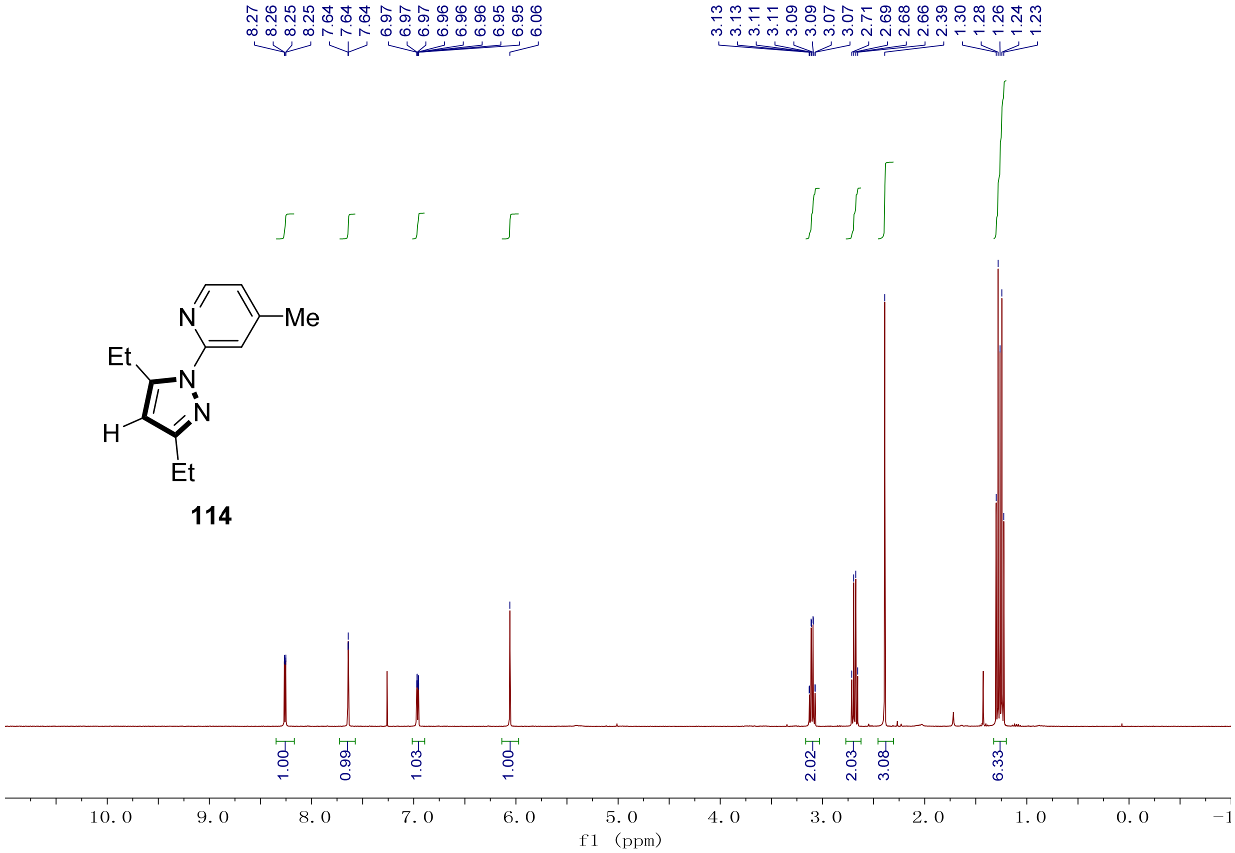
110


8.26
8.26
7.58
7.00
6.99
6.98
6.98
6.02
3.87
3.85
3.83
3.81
3.80
3.78
2.39
2.30
1.65
1.47
1.45
1.42
1.41
1.38
1.37
1.37
1.35
1.34
1.33
1.32
1.31
1.22
1.21
1.14
Me
N
N
N
Me
Me
OH
Me
Me
111
0.98
0.97
1.00
0.99
1.00
3.02
3.05
1.21
1.35
4.17
3.31
6.07
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
f1 (ppm)

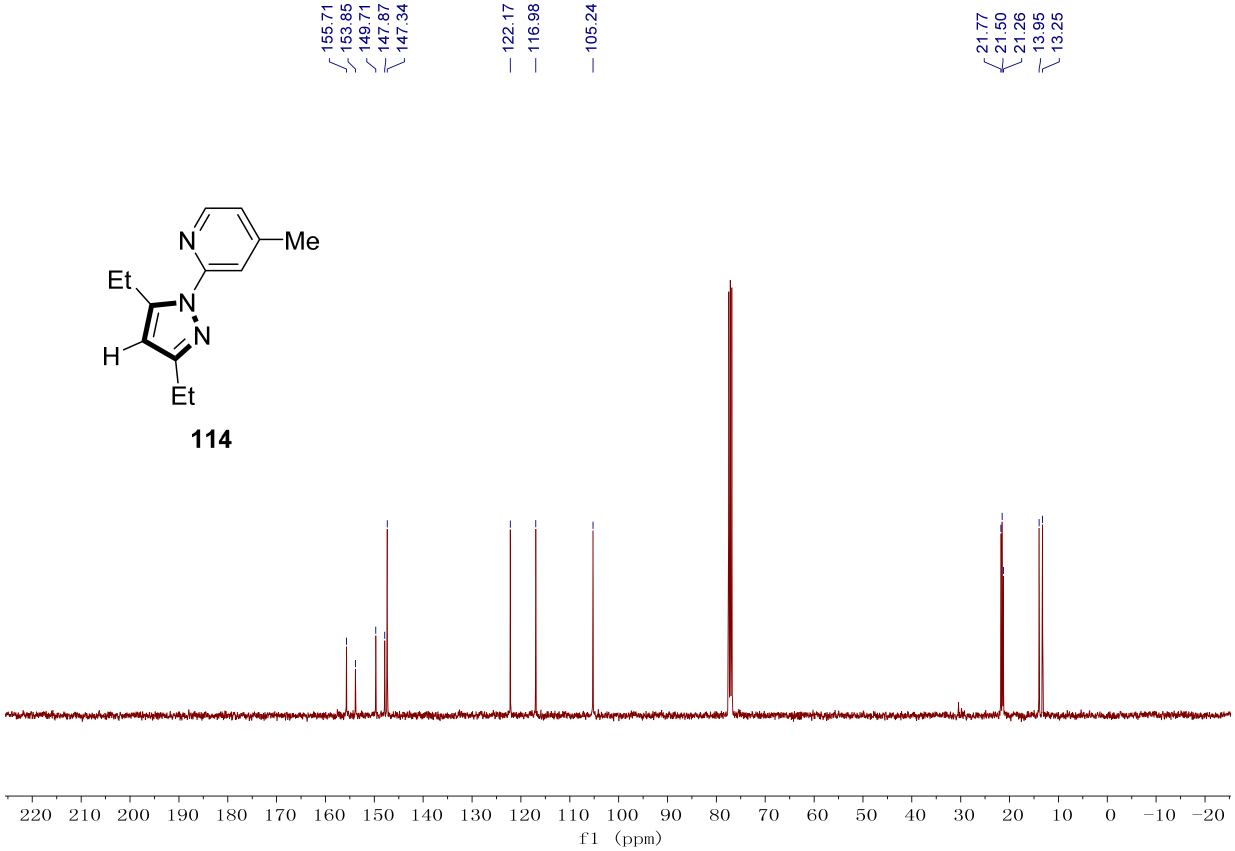

153.84
152.08
149.87
149.76
147.39
122.54
117.95
105.15
71.02
43.84
37.83
30.86
29.46
29.19
22.07
21.24
20.79
13.86
Me
N
N
N
Me
Me
OH
Me
Me
111
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
−10
−20
f1 (ppm)


8.06
8.05
8.00
6.33
6.32
6.32
6.31
3.29
3.27
3.25
3.23
2.34
2.32
2.30
2.29
1.76
1.34
1.33
1.31
1.25
0.87
0.86
0.84
N
Me
N
N
Me
Me
Me
113
1.00
0.94
0.97
1.98
2.09
2.82
3.01
2.04
19.31
3.03
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
−1
f1 (ppm)

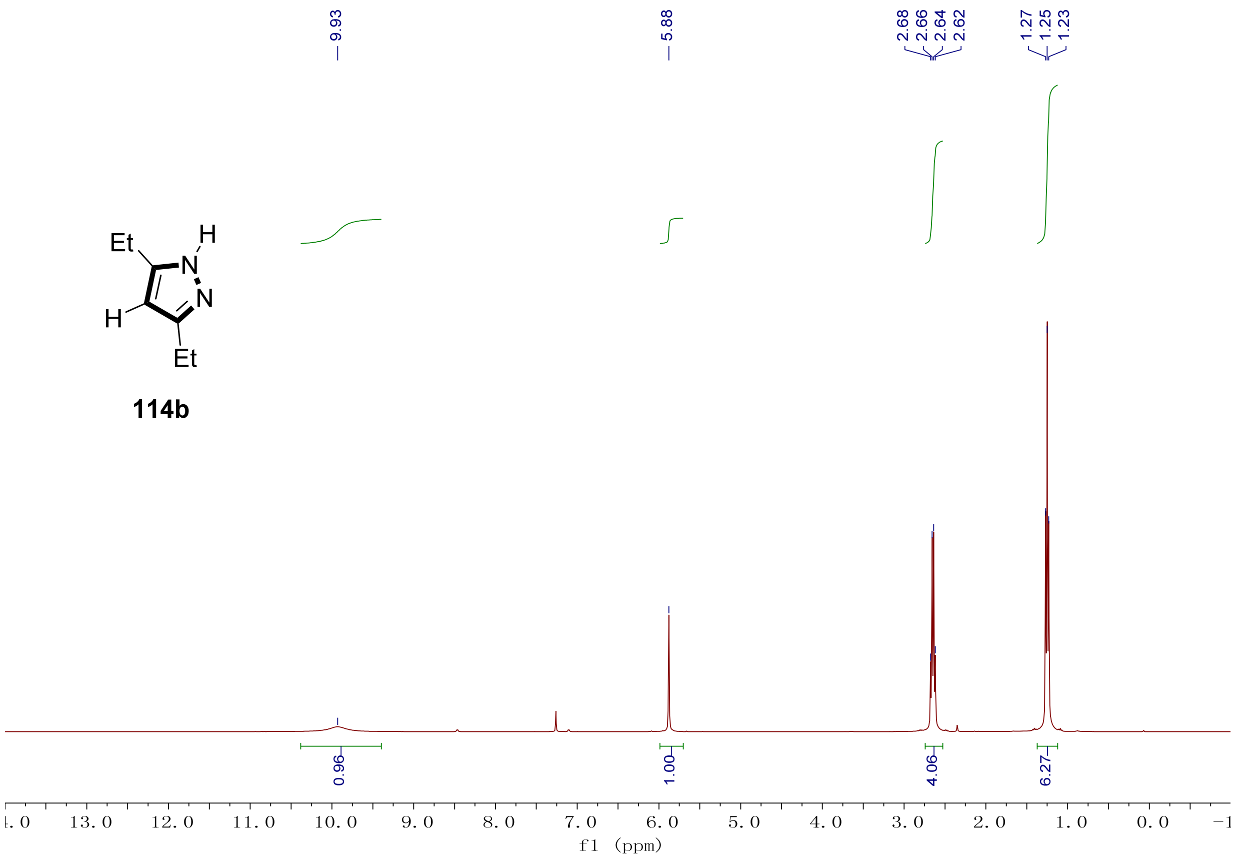

155.01
149.17
148.88
147.26
143.69
121.31
119.79
116.36
32.36
31.58
30.18
30.14
30.14
30.08
30.02
29.84
23.76
23.15
20.79
19.91
14.95
14.41
12.65
N
Me
N
N
Me
Me
Me
113
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
−10
−20
f1 (ppm)


8.27
8.26
8.25
8.25
7.64
7.64
7.64
6.97
6.97
6.97
6.96
6.96
6.96
6.95
6.06
3.13
3.13
3.11
3.11
3.09
3.09
3.07
3.07
2.71
2.69
2.68
2.66
2.39
1.30
1.28
1.26
1.24
1.23
N
Me
Et
N
N
H
Et
1.00
0.99
1.03
1.00
2.02
2.03
3.08
6.33
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

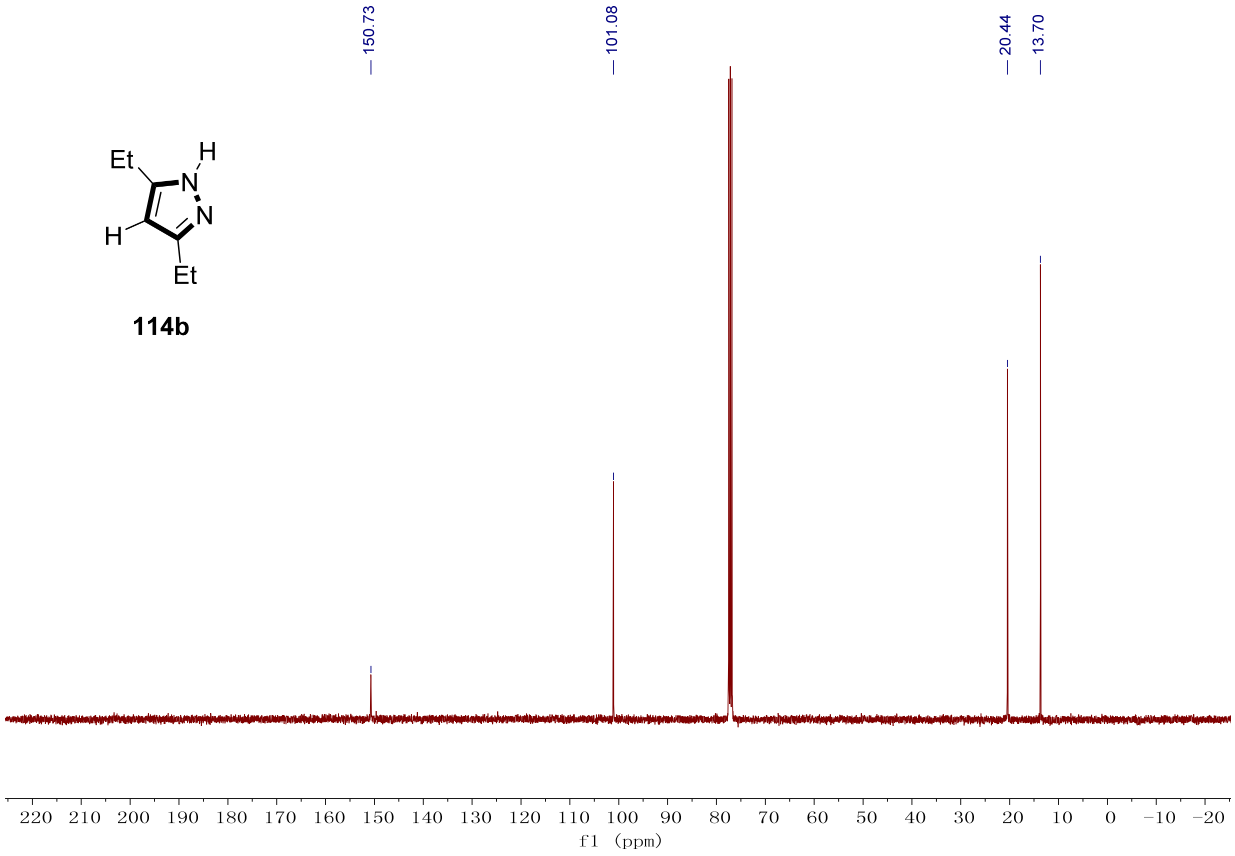
114


155.71
153.85
149.71
147.87
147.34
122.17
116.98
105.24
21.77
21.50
21.26
13.95
13.25
N
Me
Et
N
N
H
Et
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

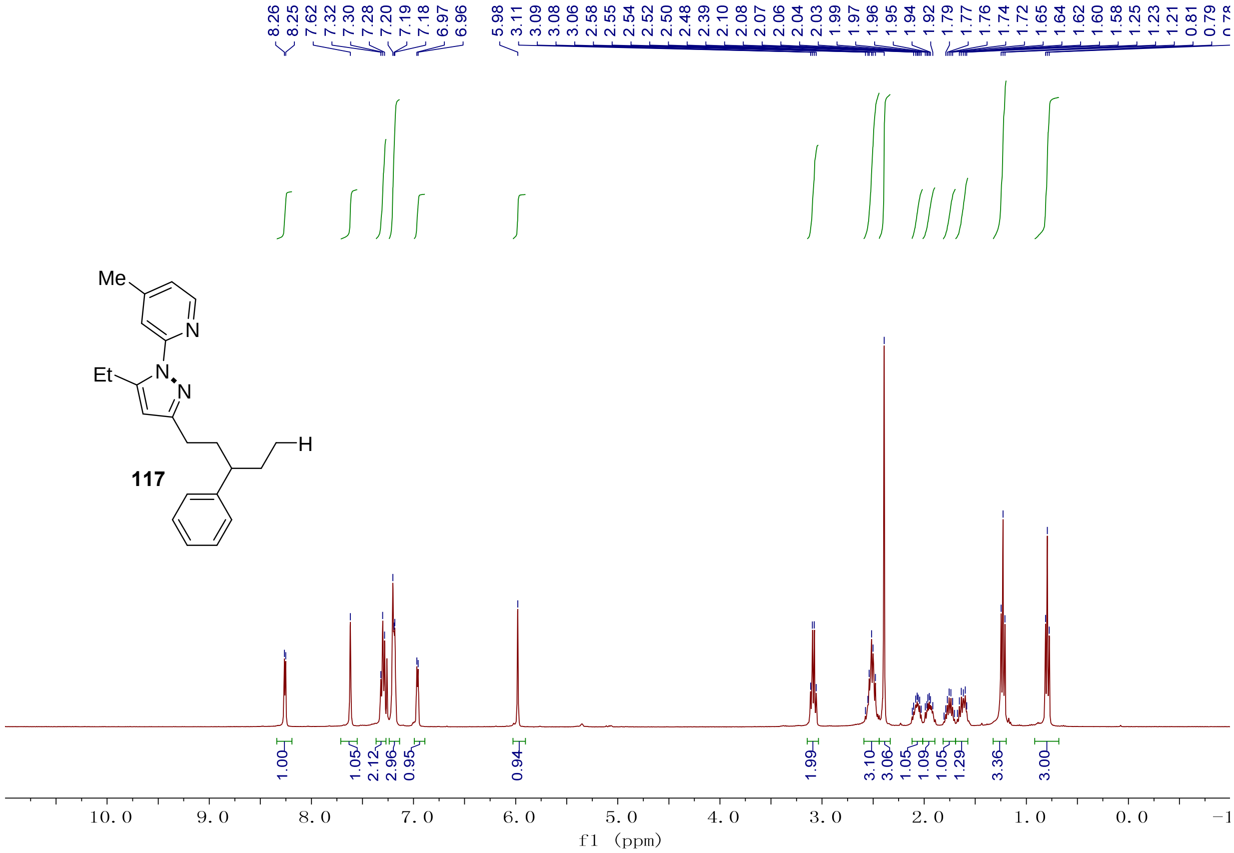
114


9.93
5.88
2.68
2.66
2.64
2.62
1.27
1.25
1.23
Et
H
N
N
H
Et
0.96
1.00
4.06
6.27
13.0
12.0
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
f1 (ppm)

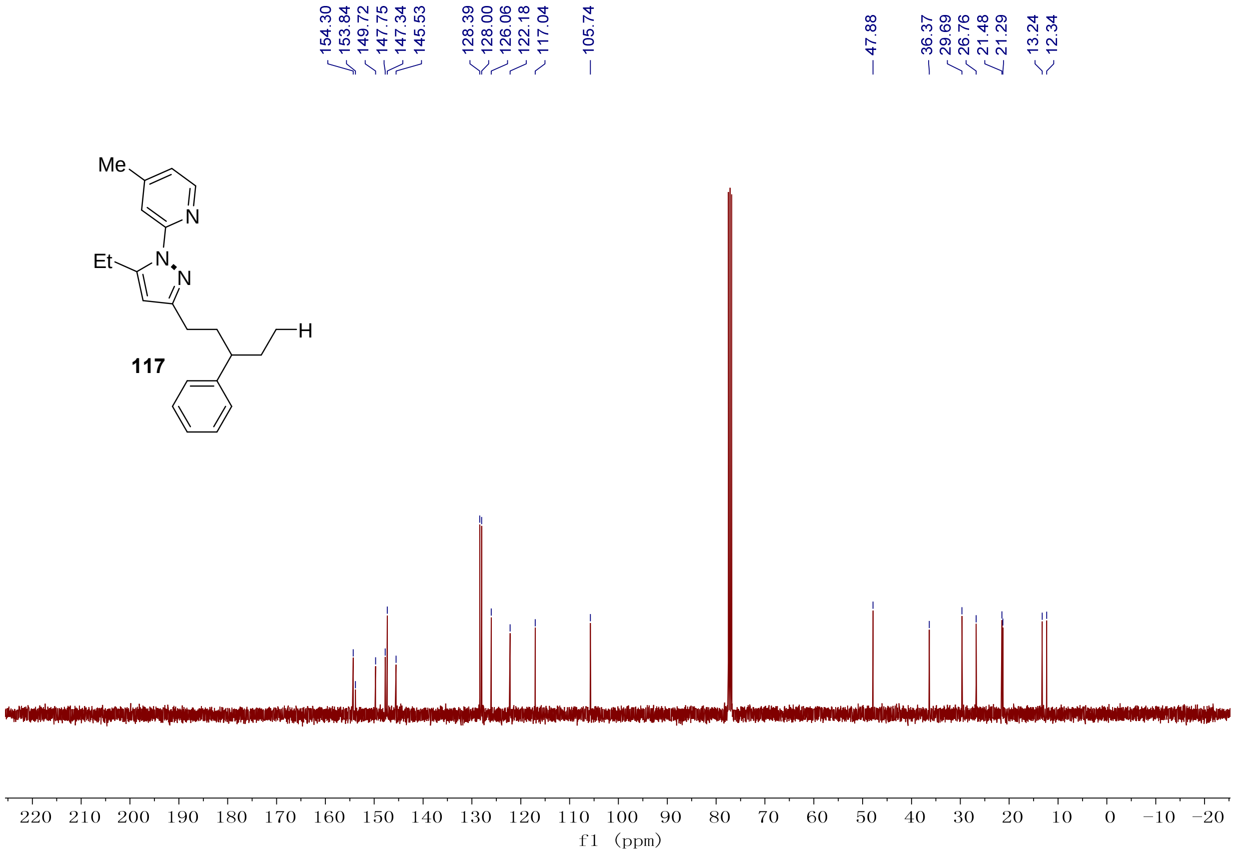
114b


150.73
101.08
20.44
13.70
Et
H
N
N
H
Et
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
−10
−20
f1 (ppm)

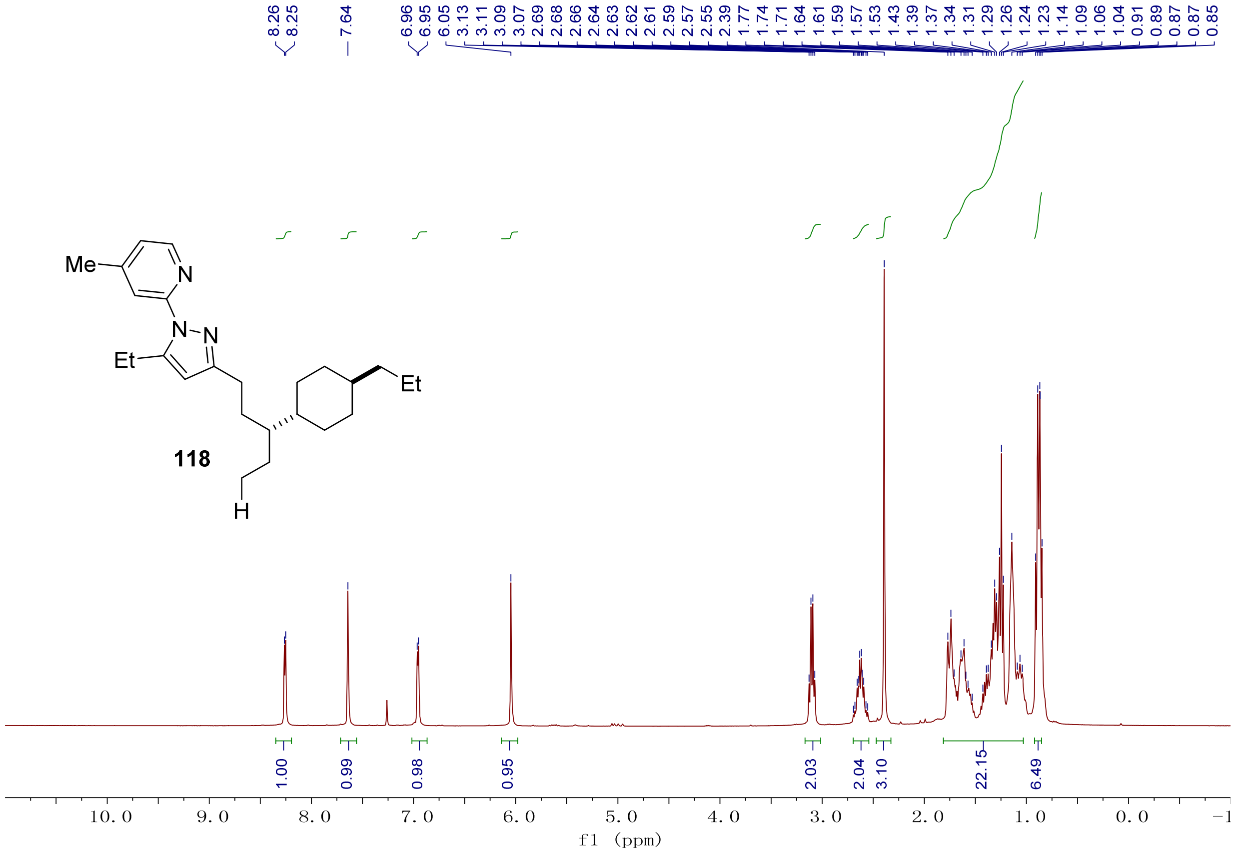
114b


8.26
8.25
7.62
7.32
7.30
7.28
7.20
7.19
7.18
6.97
6.96
5.98
3.11
3.09
3.08
3.06
2.58
2.55
2.54
2.52
2.50
2.48
2.39
2.10
2.08
2.07
2.06
2.04
2.03
1.99
1.97
1.96
1.95
1.94
1.92
1.79
1.77
1.76
1.74
1.72
1.65
1.64
1.62
1.60
1.58
1.25
1.23
1.21
0.81
0.79
Me
N
Et
N
N
H
1.00
1.05
2.12
2.96
0.95
0.94
1.99
3.10
3.06
1.05
1.09
1.05
1.29
3.36
3.00
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
f1 (ppm)

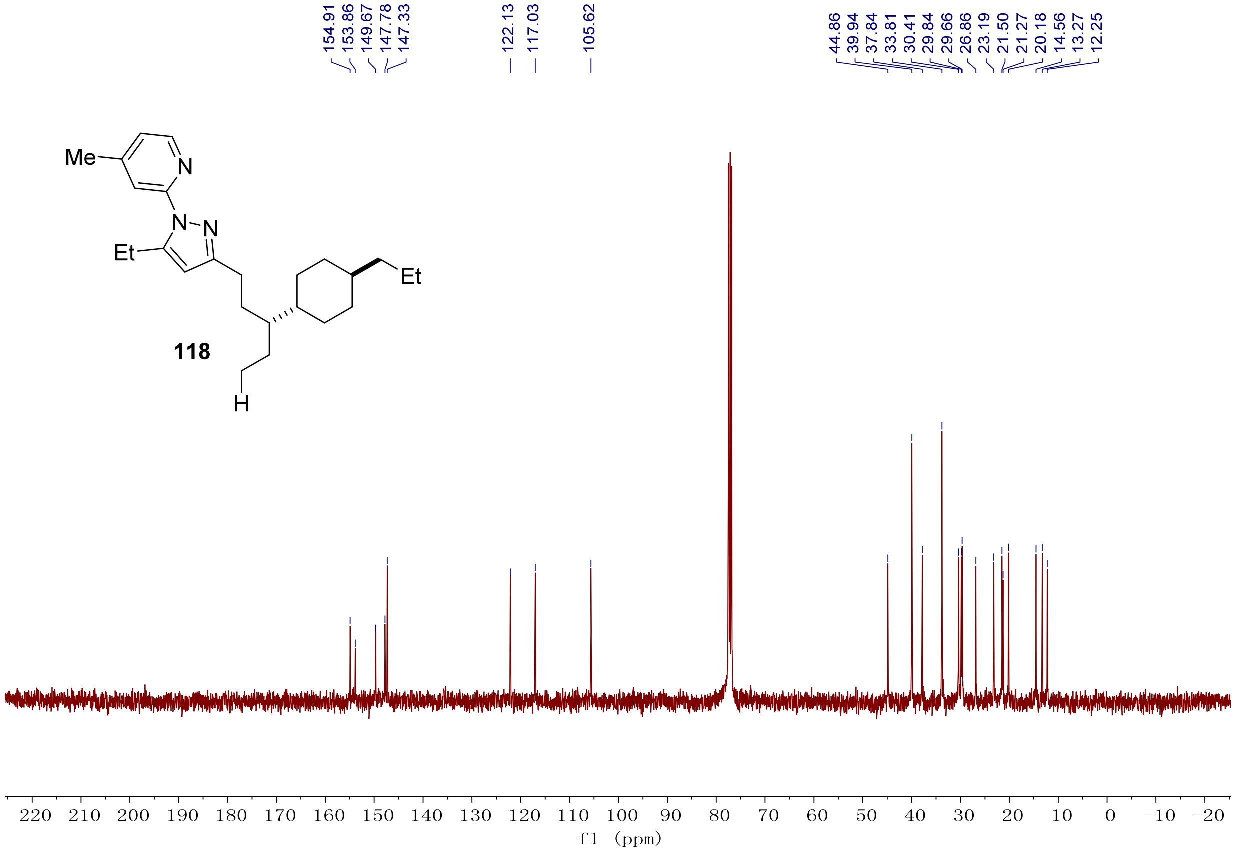
117


154.30
153.84
149.72
147.75
147.34
145.53
128.39
128.00
126.06
122.18
117.04
105.74
47.88
36.37
29.69
26.76
21.48
21.29
13.24
12.34
Me
N
Et
N
N
H
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
−10
−20
f1 (ppm)

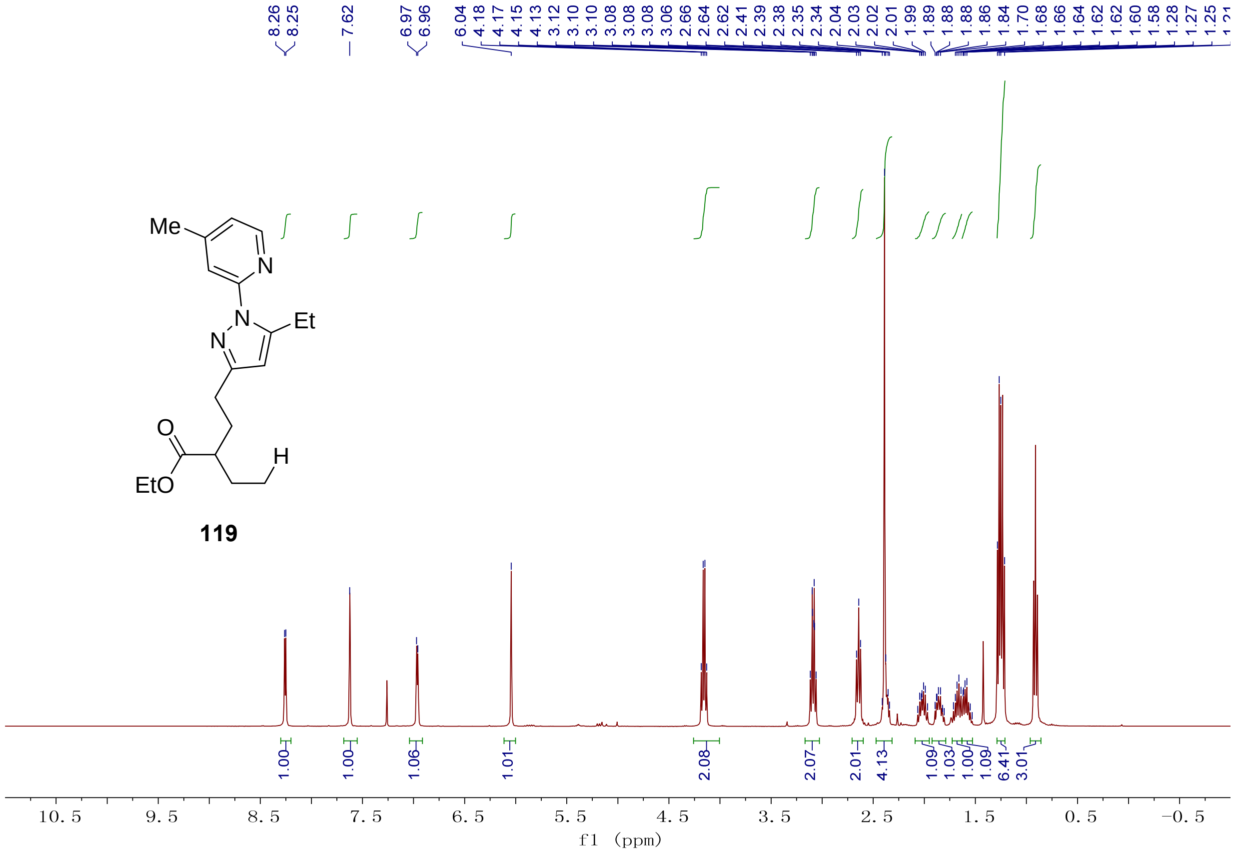
117


8.26
8.25
7.64
6.96
6.95
6.05
3.13
3.11
3.09
3.07
2.69
2.68
2.66
2.64
2.63
2.62
2.61
2.59
2.57
2.55
2.39
1.77
1.74
1.71
1.64
1.61
1.59
1.57
1.53
1.43
1.39
1.37
1.34
1.31
1.29
1.26
1.24
1.23
1.14
1.09
1.06
1.04
0.91
0.89
0.87
0.85
Me
N
N
N
Et
Et
H
1.00
0.99
0.98
0.95
2.03
2.04
3.10
22.15
6.49
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

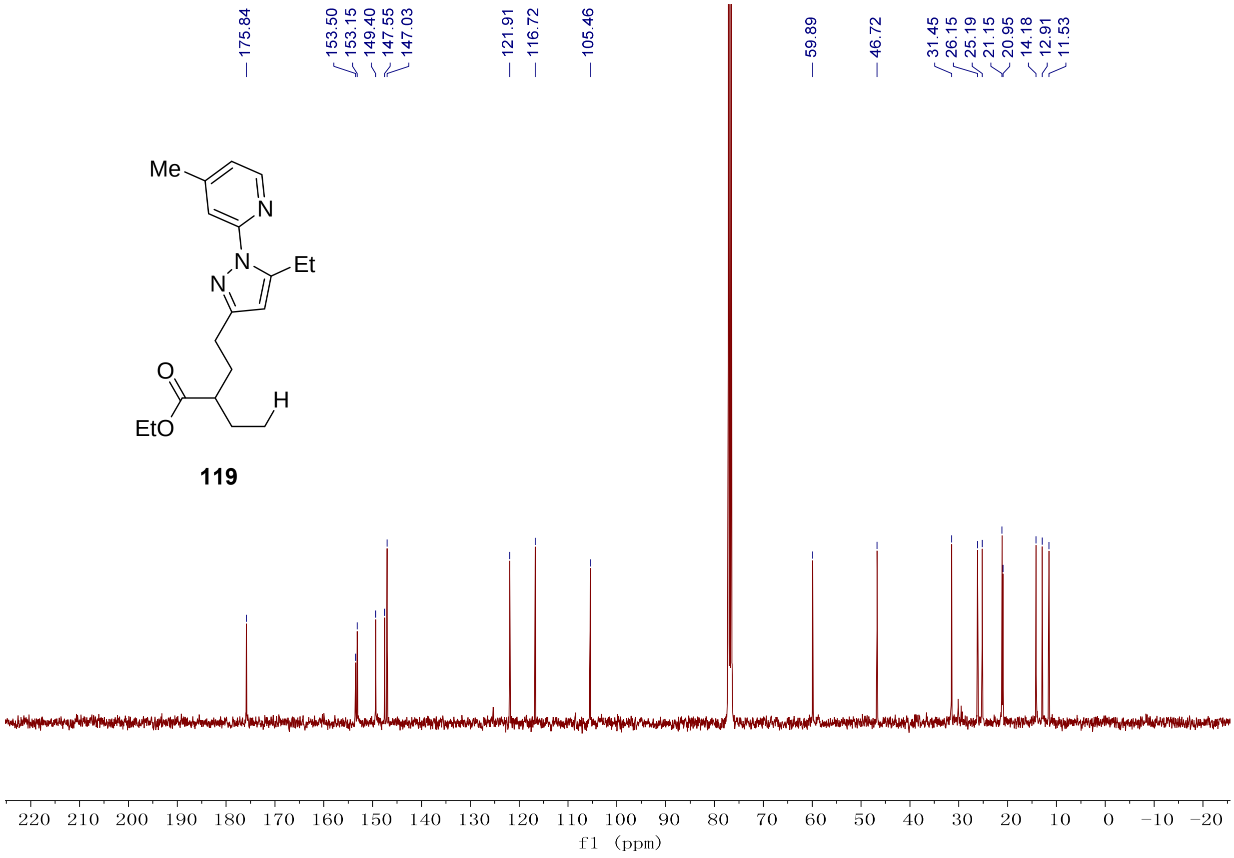
118


154.91
153.86
149.67
147.78
147.33
122.13
117.03
105.62
44.86
39.94
37.84
33.81
30.41
29.84
29.66
26.86
23.19
21.50
21.27
20.18
14.56
13.27
12.25
Me
N
N
N
Et
Et
H
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

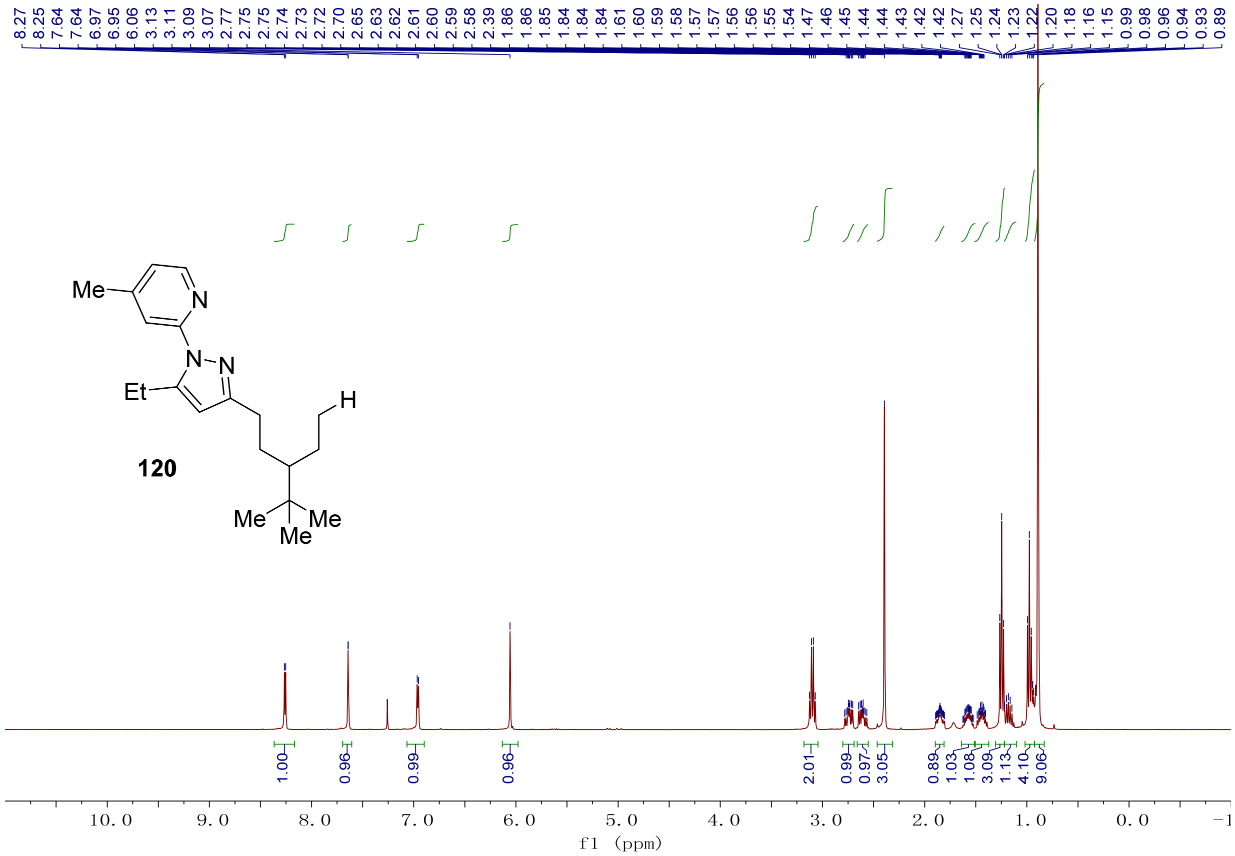
118

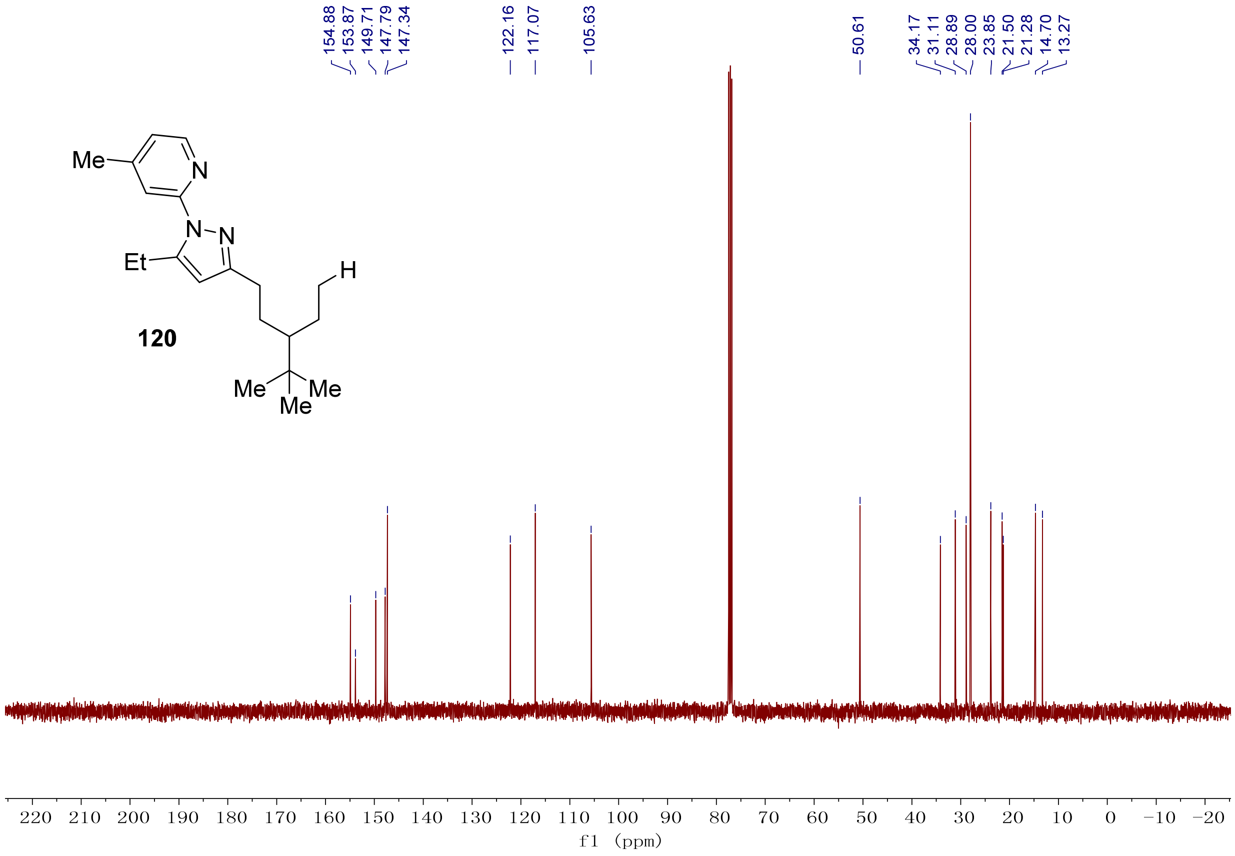

8.26
8.25
7.62
6.97
6.96
6.04
4.18
4.17
4.15
4.13
3.12
3.10
3.10
3.08
3.08
3.08
3.06
2.66
2.64
2.62
2.41
2.39
2.38
2.35
2.34
2.04
2.03
2.02
2.01
1.99
1.89
1.88
1.88
1.86
1.84
1.70
1.68
1.66
1.64
1.62
1.60
1.58
1.28
1.27
1.25
Me
N
N
N
Et
O
EtO
H
1.00
1.00
1.06
1.01
2.08
2.07
2.01
4.13
1.09
1.03
1.00
1.09
6.41
3.01
10.5
9.5
8.5
7.5
6.5
5.5
4.5
3.5
2.5
1.5
0.5
−0.5
f1 (ppm)

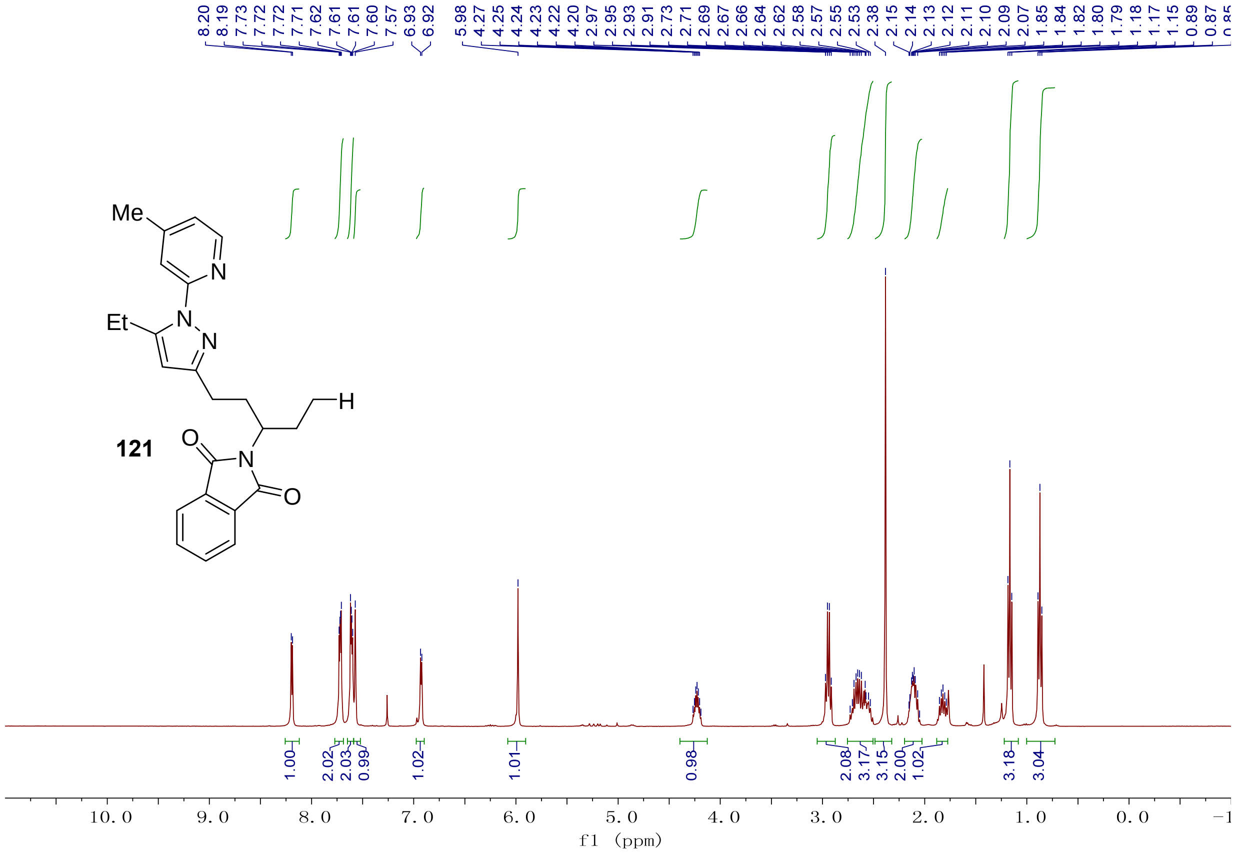
119

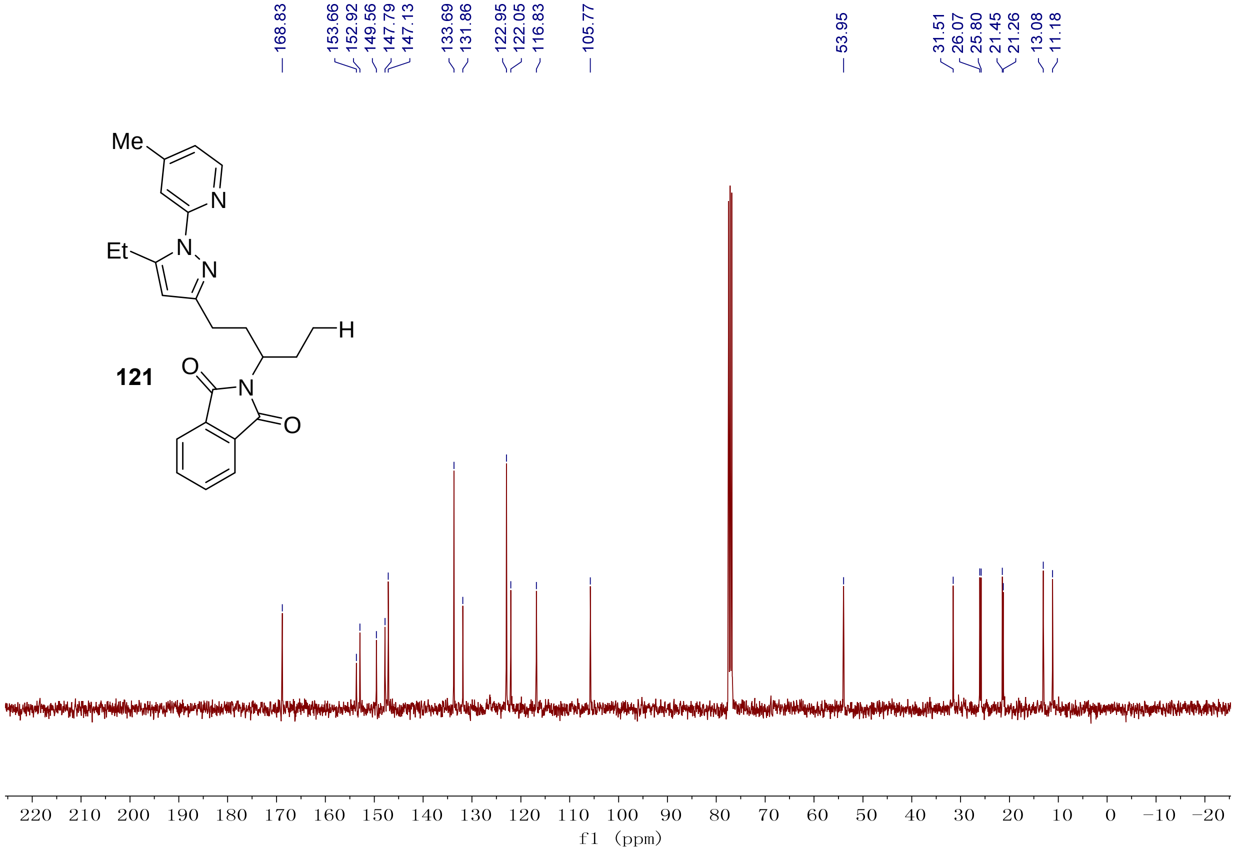

175.84
153.50
153.15
149.40
147.55
147.03
121.91
116.72
105.46
59.89
46.72
31.45
26.15
25.19
21.15
20.95
14.18
12.91
11.53
Me
N
N
N
Et
O
EtO
H
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
−10
−20
f1 (ppm)

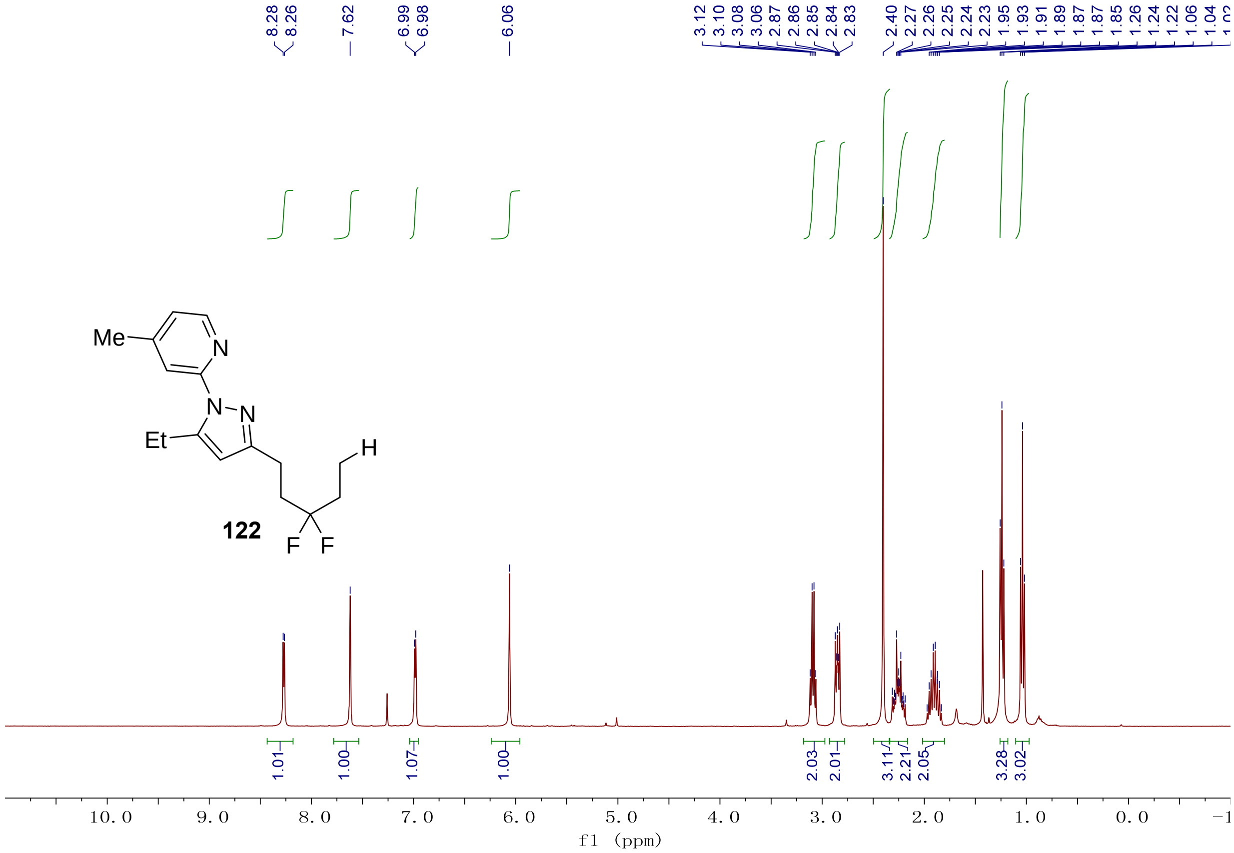
119

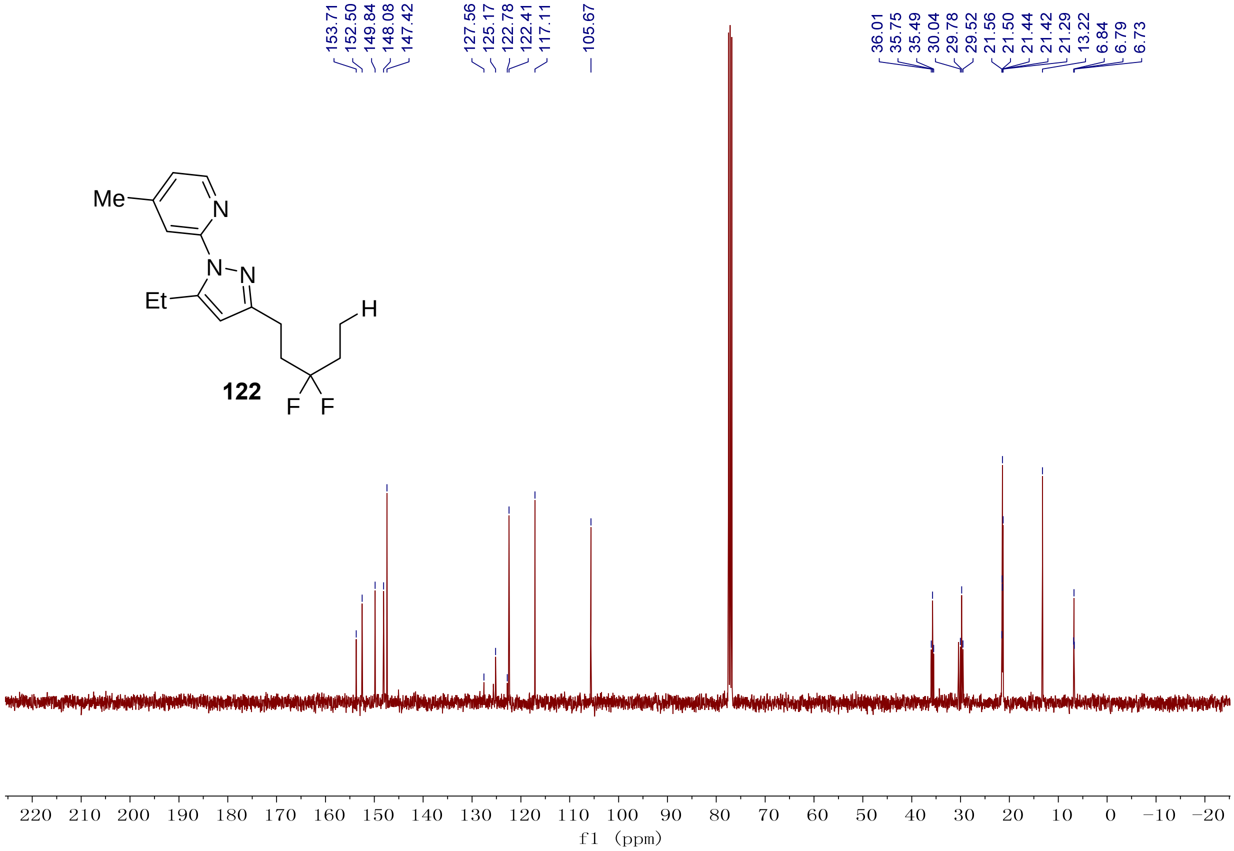

8.27
8.25
7.64
7.64
6.97
6.95
6.06
3.13
3.11
3.09
3.07
2.77
2.75
2.75
2.74
2.73
2.72
2.70
2.65
2.63
2.62
2.61
2.60
2.59
2.58
2.39
1.86
1.85
1.84
1.84
1.61
1.60
1.59
1.58
1.57
1.56
1.56
1.55
1.54
1.47
1.46
1.45
1.44
1.44
1.43
1.42
1.42
1.27
1.25
1.24
1.23
1.22
1.20
1.18
1.16
1.15
0.99
0.98
0.96
0.94
0.93
0.89
Me
N
N
N
Et
H
120
Me
Me
Me
1.00
0.96
0.99
0.96
2.01
0.99
0.97
3.05
0.89
1.03
1.08
3.09
1.13
4.10
9.06
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

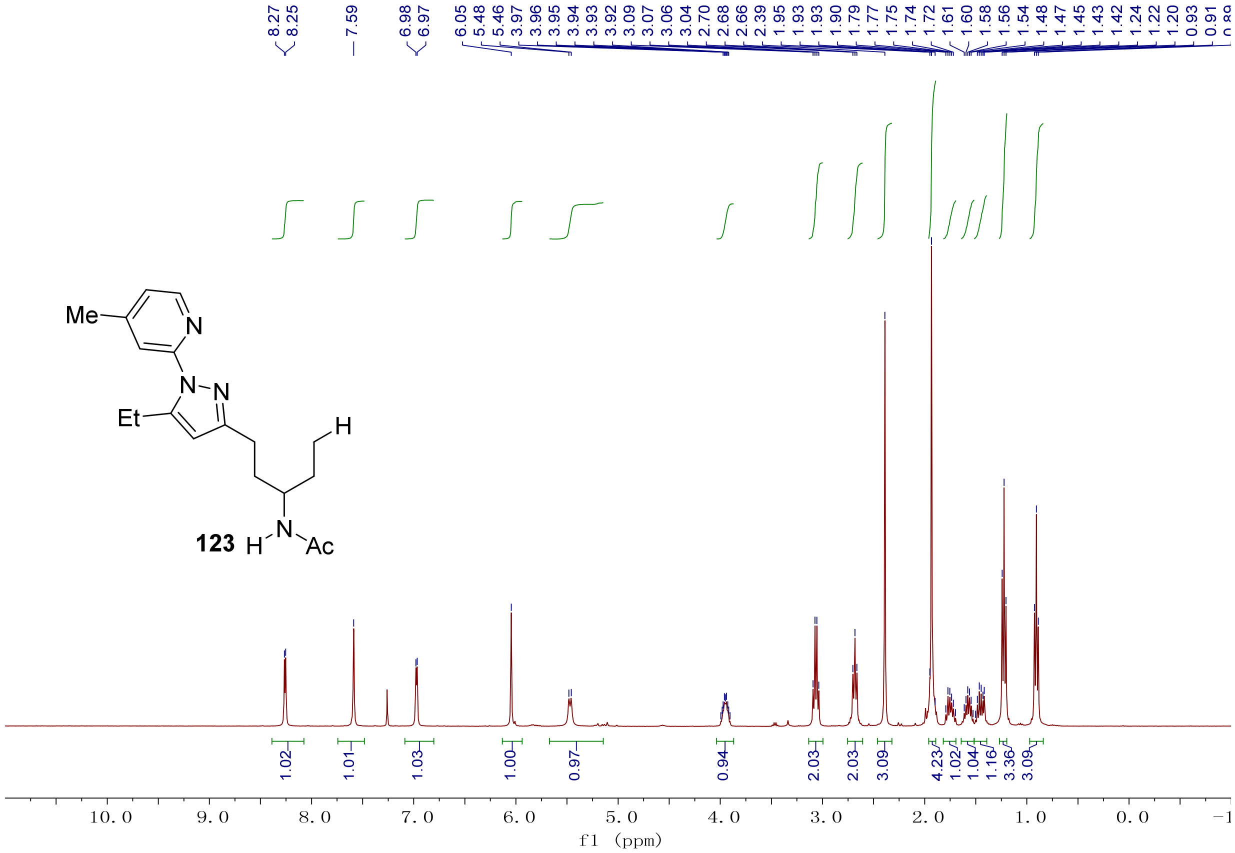

154.88
153.87
149.71
147.79
147.34
122.16
117.07
105.63
50.61
34.17
31.11
28.89
28.00
23.85
21.50
21.28
14.70
13.27
Me
N
N
N
Et
H
120
Me
Me
Me
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)


8.20 8.19 7.73 7.72 7.72 7.71 7.62 7.61 7.61 7.60 7.57 6.93 6.92 5.98 4.27 4.25 4.24 4.23 4.22 4.20 2.97 2.95 2.93 2.91 2.73 2.71 2.69 2.67 2.66 2.64 2.62 2.58 2.57 2.55 2.53 2.38 2.15 2.14 2.13 2.12 2.11 2.10 2.09 2.07 1.85 1.84 1.82 1.80 1.79 1.18 1.17 1.15 0.89 0.87
Me
N
Et
N
N
H
121
O
N
O
1.00
2.02
2.03
0.99
1.02
1.01
0.98
2.08
3.17
3.15
2.00
1.02
3.18
3.04
10.0 9.0 8.0 7.0 6.0 5.0 4.0 3.0 2.0 1.0 0.0 −1
f1 (ppm)

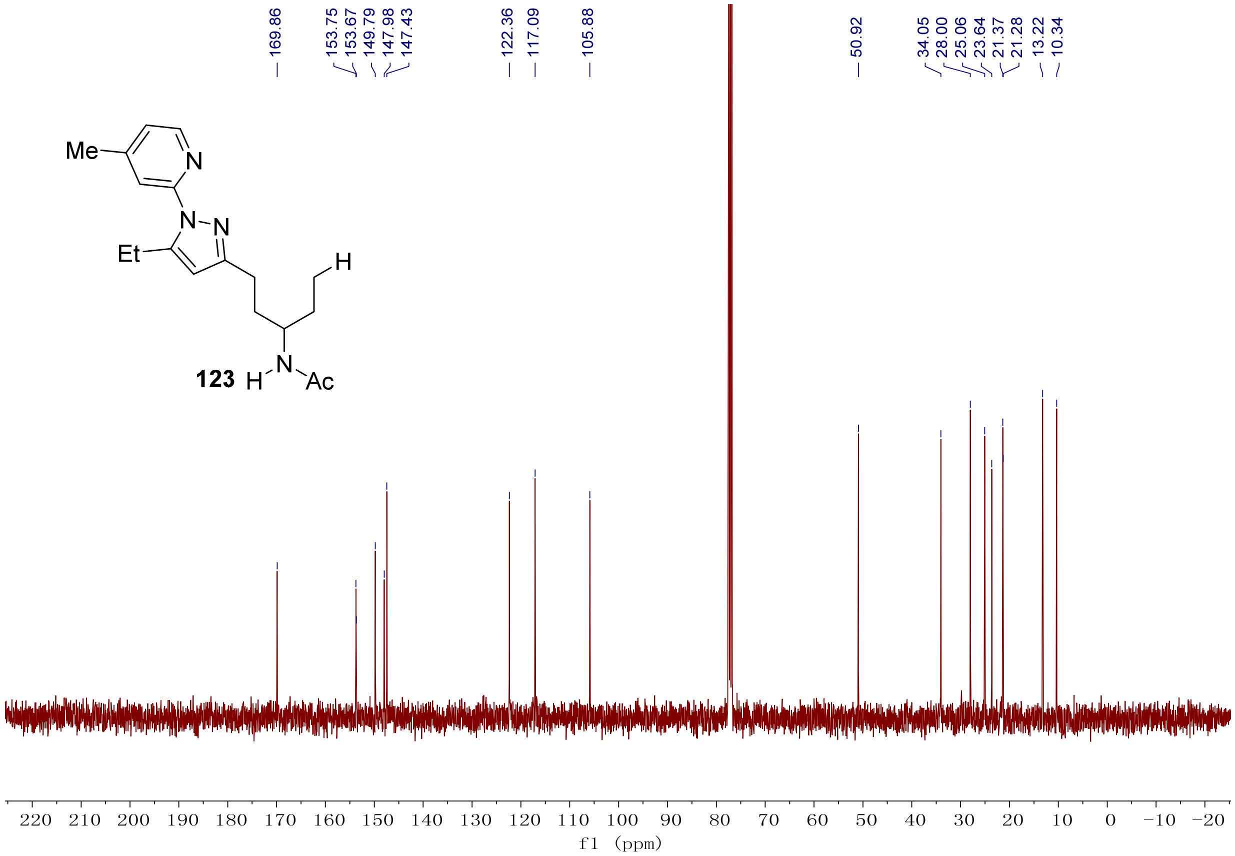

168.83
153.66 152.92 149.56 147.79 147.13
133.69 131.86
122.95 122.05 116.83
105.77
53.95
31.51 26.07 25.80 21.45 21.26 13.08 11.18
Me
N
Et
N
N
H
121
O
N
O
220 210 200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 −10 −20
f1 (ppm)


8.28
8.26
7.62
6.99
6.98
6.06
3.12
3.10
3.08
3.06
2.87
2.86
2.85
2.84
2.83
2.40
2.27
2.26
2.25
2.24
2.23
1.95
1.93
1.91
1.89
1.87
1.85
1.26
1.24
1.22
1.06
1.04
Me
N
N
N
Et
H
122
F
F
1.01
1.00
1.07
1.00
2.03
2.01
3.11
2.21
2.05
3.28
3.02
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
f1 (ppm)

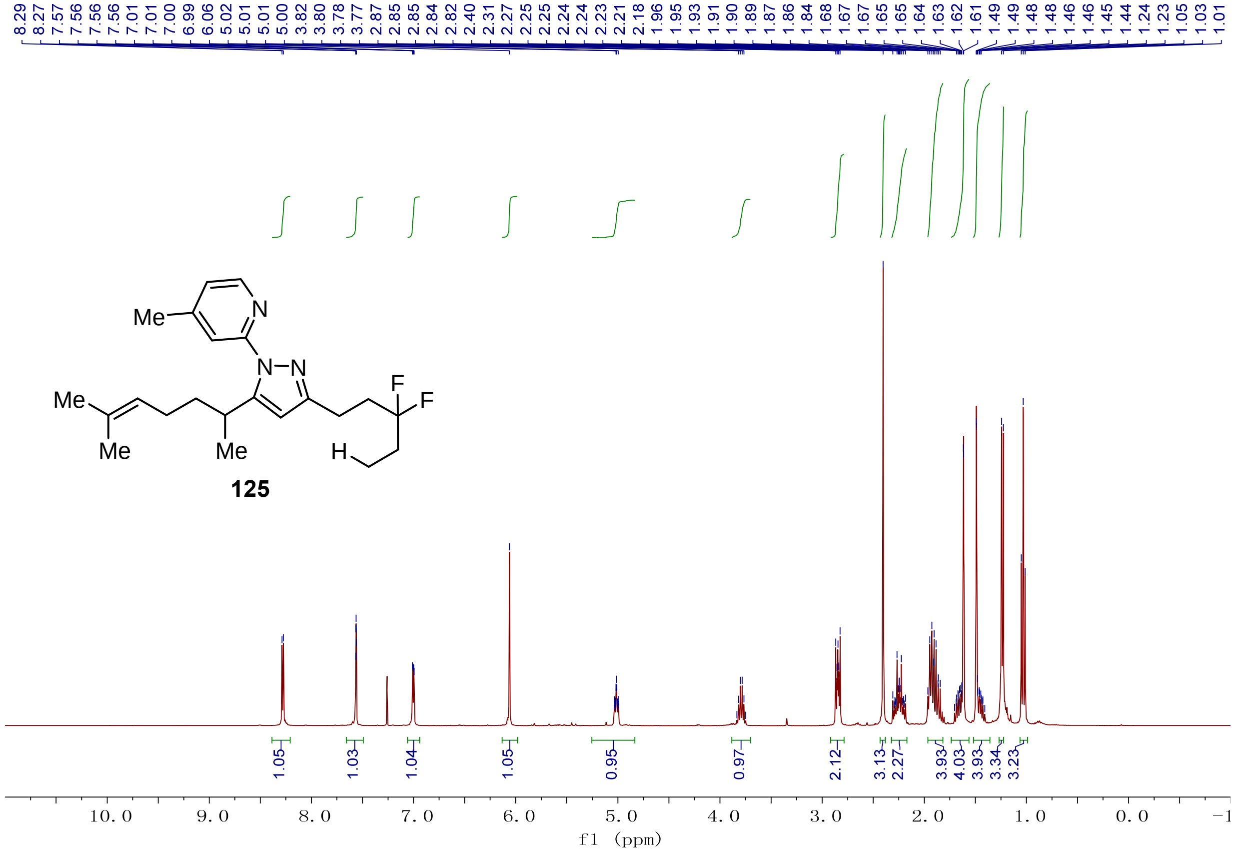

153.71
152.50
149.84
148.08
147.42
127.56
125.17
122.78
122.41
117.11
105.67
36.01
35.75
35.49
30.04
29.78
29.52
21.56
21.50
21.44
21.42
21.29
13.22
6.84
6.79
6.73
Me
N
N
N
Et
H
122
F
F
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
−10
−20
f1 (ppm)

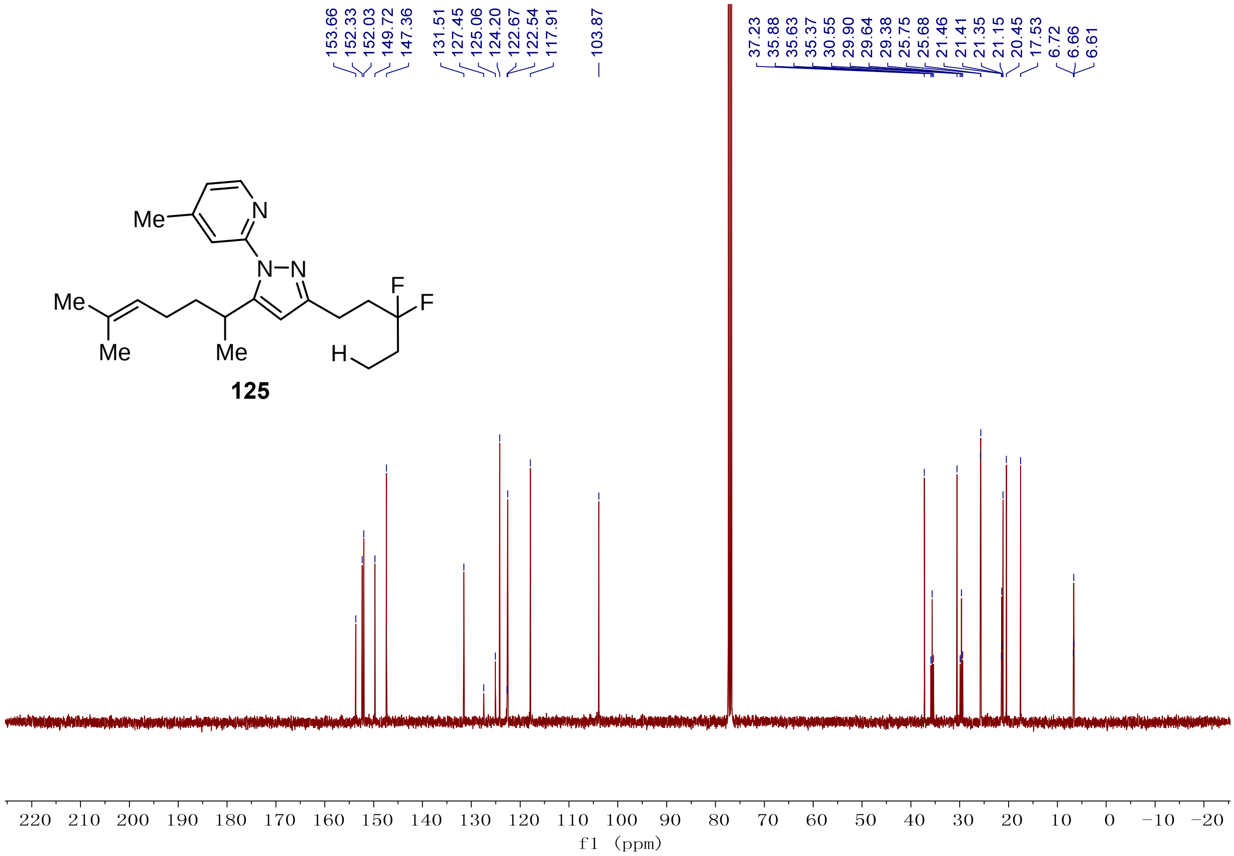

8.27
8.25
7.59
6.98
6.97
6.05
5.48
5.46
3.97
3.96
3.95
3.94
3.93
3.92
3.09
3.07
3.06
3.04
2.70
2.68
2.66
2.39
1.95
1.93
1.93
1.90
1.79
1.77
1.75
1.74
1.72
1.61
1.60
1.58
1.56
1.54
1.48
1.47
1.45
1.43
1.42
1.24
1.22
1.20
0.93
0.91
Me
N
N
N
Et
H
H
N
Ac
1.02
1.01
1.03
1.00
0.97
0.94
2.03
2.03
3.09
4.23
1.02
1.04
1.16
3.36
3.09
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
f1 (ppm)

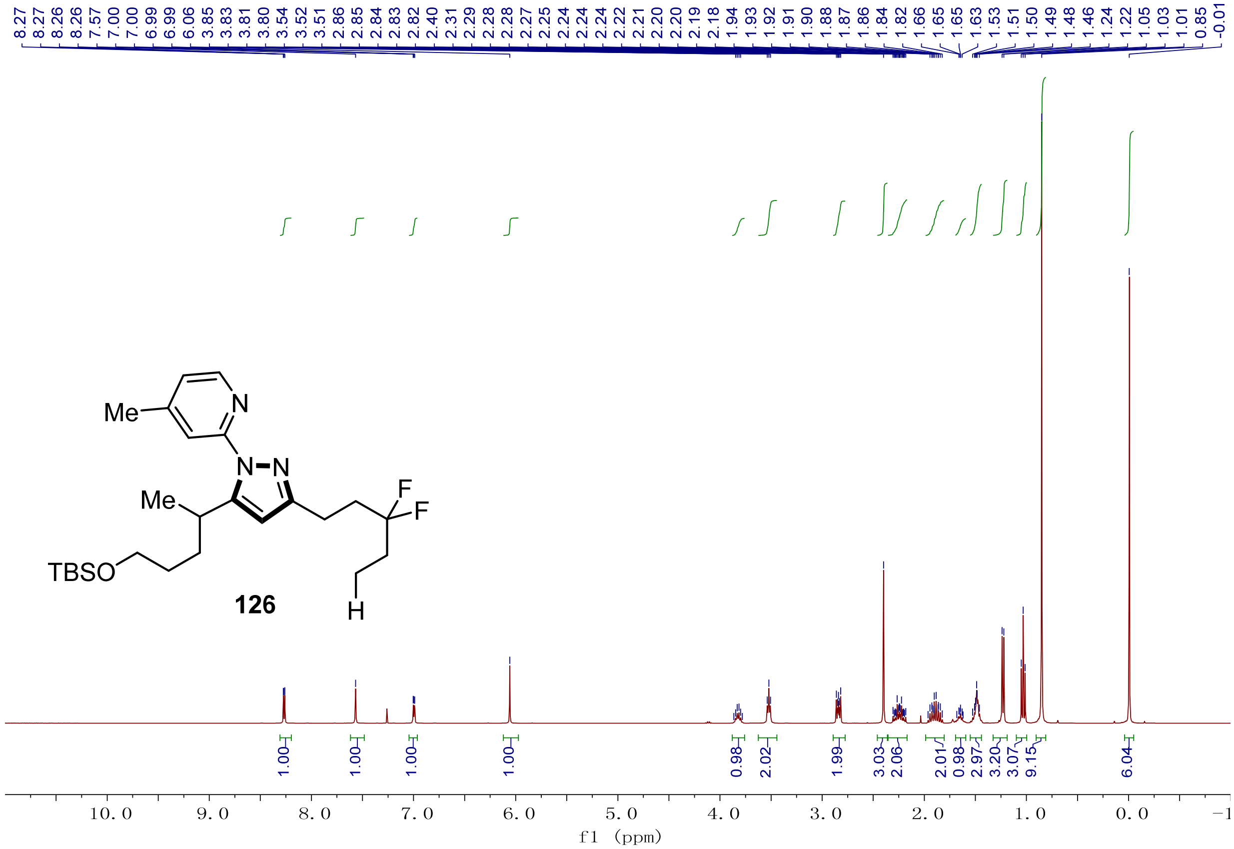
123


169.86
153.75
153.67
149.79
147.98
147.43
122.36
117.09
105.88
50.92
34.05
28.00
25.06
23.64
21.37
21.28
13.22
10.34
Me
N
N
N
Et
H
H
N
Ac
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
−10
−20
f1 (ppm)

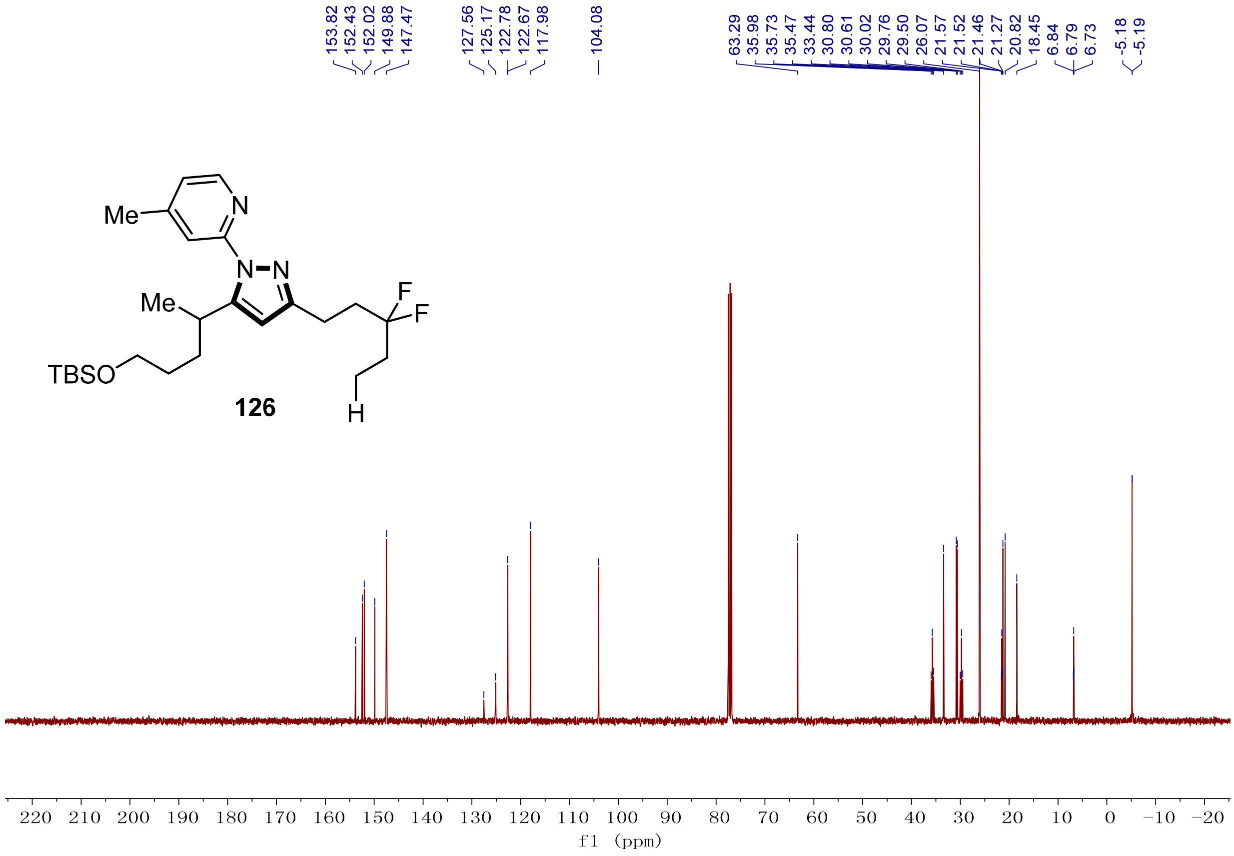
123


8.29
8.27
7.57
7.56
7.56
7.01
7.01
7.00
6.99
6.06
5.02
5.01
5.00
3.82
3.80
3.78
3.77
2.87
2.85
2.85
2.84
2.82
2.40
2.31
2.27
2.25
2.25
2.24
2.24
2.23
2.21
2.18
1.96
1.95
1.93
1.91
1.90
1.89
1.87
1.86
1.84
1.68
1.67
1.67
1.65
1.65
1.64
1.63
1.62
1.61
1.49
1.49
1.48
1.48
1.46
1.45
1.44
1.24
1.23
1.05
1.03
1.01
Me
N
N
N
Me
F
F
Me
Me
H
125
1.05
1.03
1.04
1.05
0.95
0.97
2.12
3.13
2.27
3.93
4.03
3.93
3.34
3.23
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

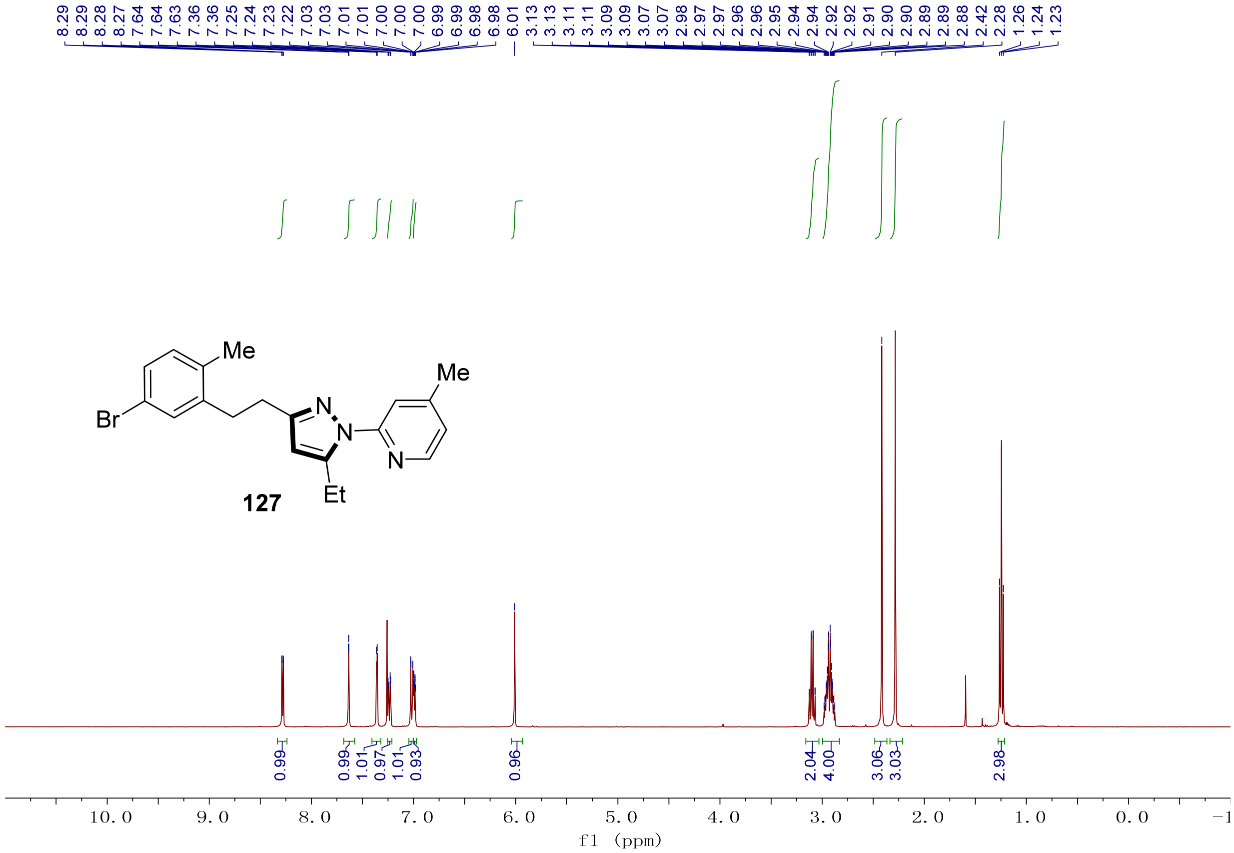

153.66
152.33
152.03
149.72
147.36
131.51
127.45
125.06
124.20
122.67
122.54
117.91
103.87
37.23
35.88
35.63
35.37
30.55
29.90
29.64
29.38
25.75
25.68
21.46
21.41
21.35
21.15
20.45
17.53
6.72
6.66
6.61
Me
N
N
N
Me
F
F
Me
Me
H
125
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

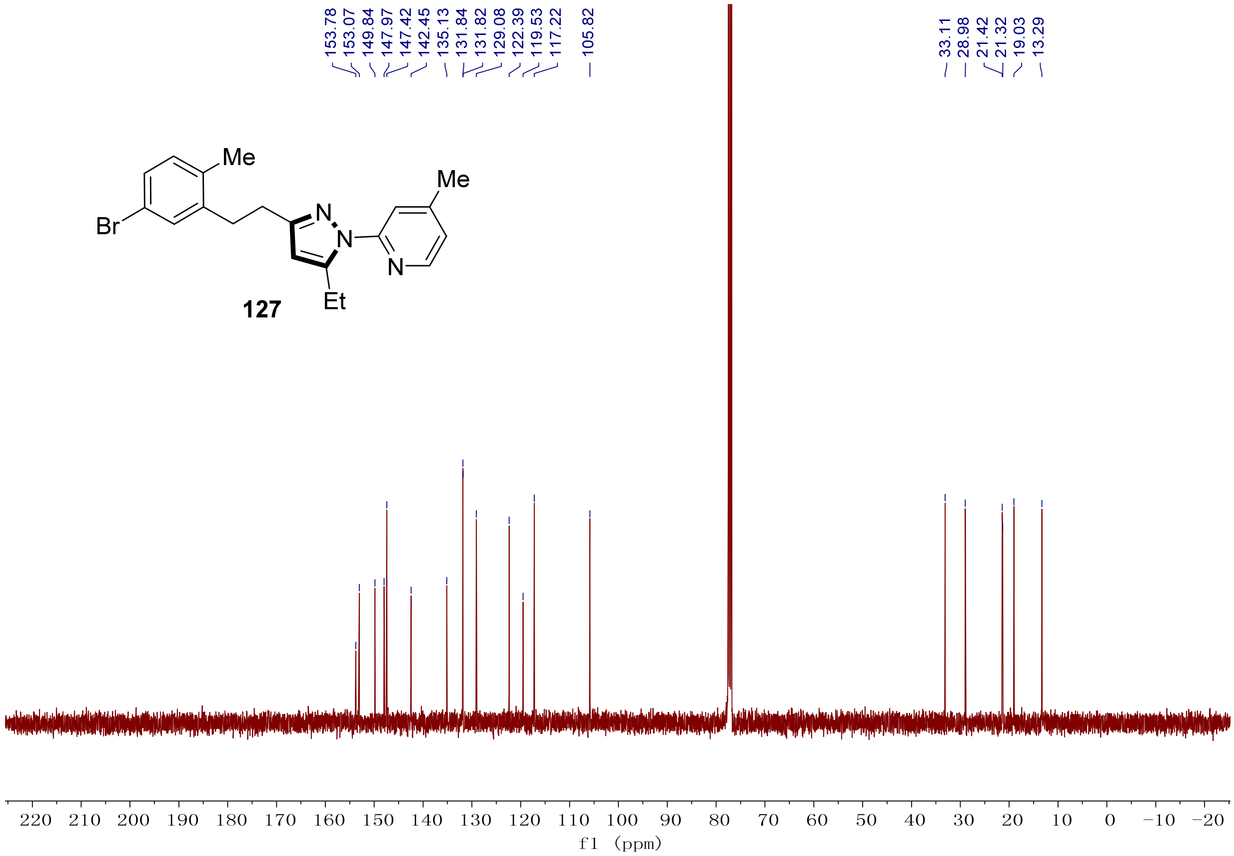

8.27
8.27
8.26
8.26
7.57
7.00
7.00
6.99
6.99
6.06
3.85
3.83
3.81
3.80
3.54
3.52
3.51
2.86
2.85
2.84
2.83
2.82
2.40
2.31
2.29
2.28
2.28
2.27
2.25
2.24
2.24
2.24
2.22
2.21
2.20
2.20
2.19
2.18
1.94
1.93
1.92
1.91
1.90
1.88
1.87
1.86
1.84
1.82
1.66
1.65
1.65
1.63
1.53
1.51
1.50
1.49
1.48
1.46
1.24
1.22
1.05
1.03
1.01
0.85
-0.01
Me
N
N
N
Me
F
F
TBSO
H
1.00
1.00
1.00
1.00
0.98
2.02
1.99
3.03
2.06
2.01
0.98
2.97
3.20
3.07
9.15
6.04
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

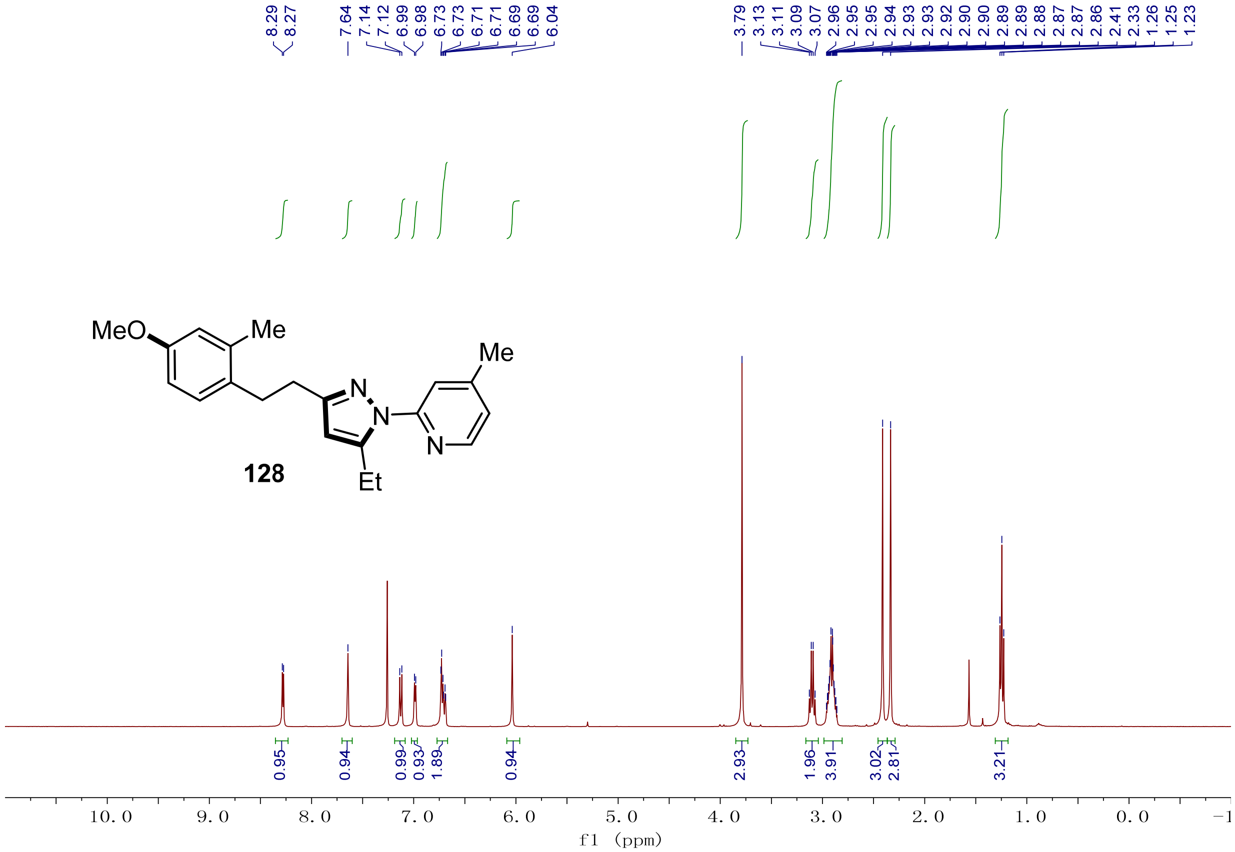
126


153.82
152.43
152.02
149.88
147.47
127.56
125.17
122.78
122.67
117.98
104.08
63.29
35.98
35.73
35.47
33.44
30.80
30.61
30.02
29.76
29.50
26.07
21.57
21.52
21.46
21.27
20.82
18.45
6.84
6.79
6.73
-5.18
-5.19
Me
N
N
N
Me
F
F
TBSO
H
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
−10
−20
f1 (ppm)

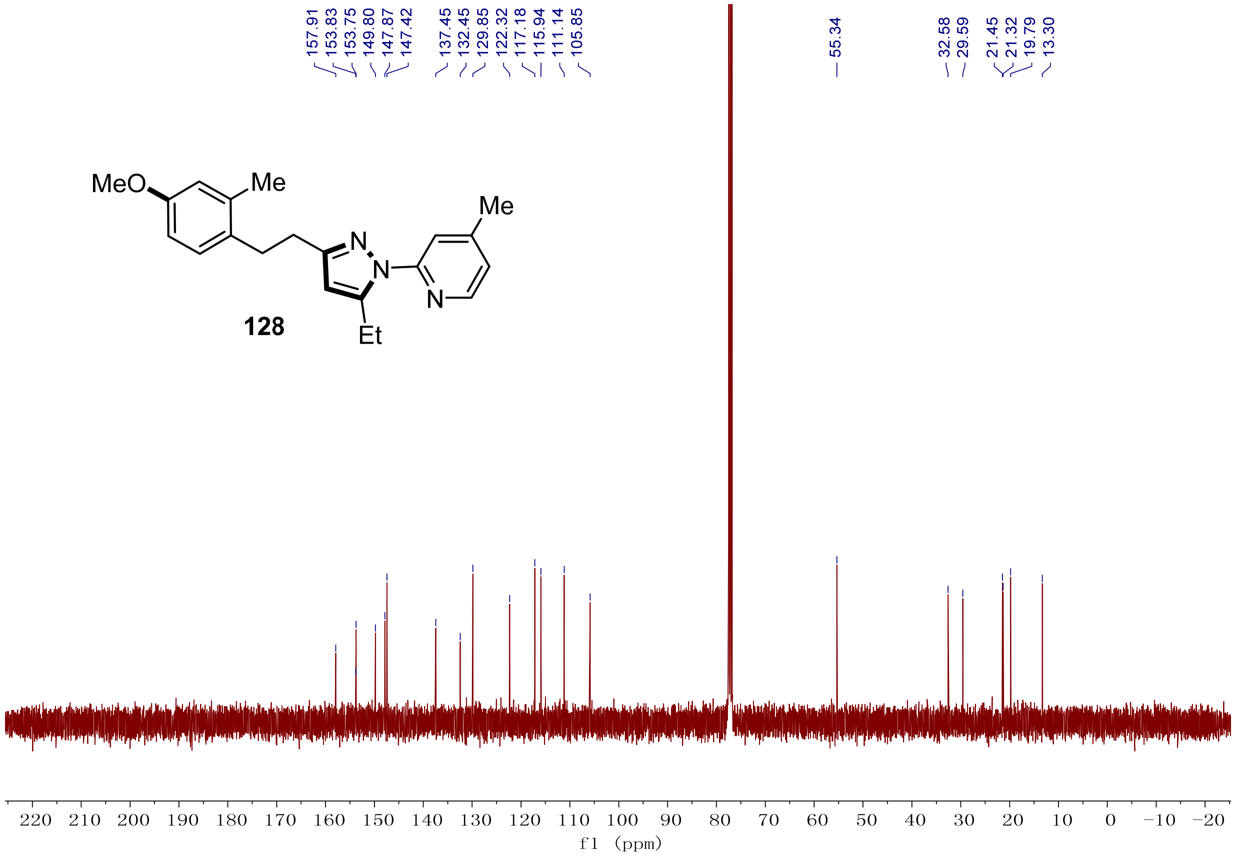
126


8.29 8.29 8.28 8.27 7.64 7.64 7.63 7.36 7.36 7.25 7.24 7.23 7.22 7.03 7.03 7.01 7.01 7.00 7.00 7.00 6.99 6.99 6.98 6.01 3.13 3.11 3.11 3.09 3.09 3.07 2.98 2.97 2.97 2.96 2.96 2.95 2.94 2.94 2.92 2.92 2.91 2.90 2.90 2.89 2.89 2.88 2.42 2.28 1.26 1.24 1.23
Me
Me
Br
N
N
N
Et
127
0.99
0.99
1.01
0.97
1.01
0.93
0.96
2.04
4.00
3.06
3.03
2.98
10.0 9.0 8.0 7.0 6.0 5.0 4.0 3.0 2.0 1.0 0.0 -1
f1 (ppm)

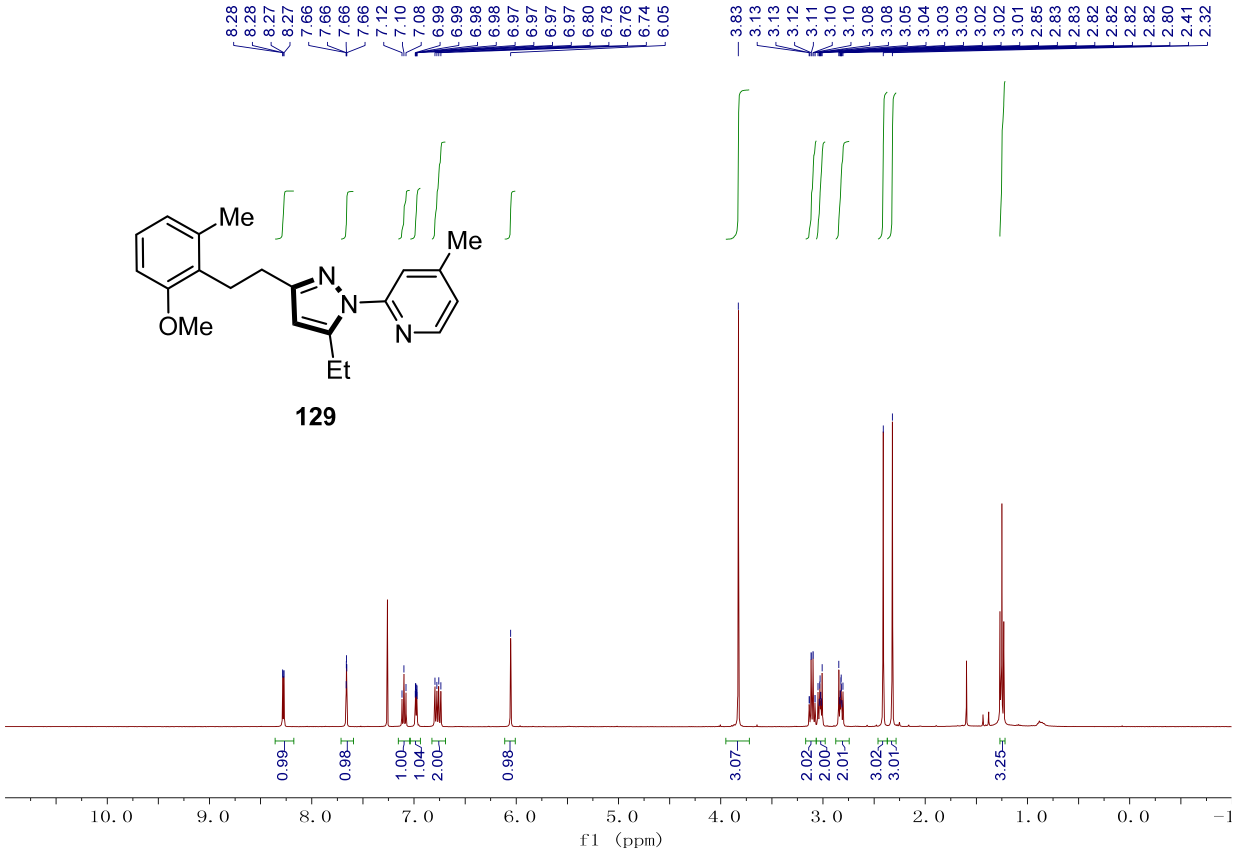

153.78 153.07 149.84 147.97 147.42 142.45 135.13 131.84 131.82 129.08 122.39 119.53 117.22 105.82
33.11 28.98 21.42 21.32 19.03 13.29
Me
Me
Br
N
N
N
Et
127
220 210 200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 -10 -20
f1 (ppm)


8.29
8.27
7.64
7.14
7.12
6.99
6.98
6.73
6.73
6.71
6.71
6.69
6.69
6.04
3.79
3.13
3.11
3.09
3.07
2.96
2.95
2.95
2.94
2.93
2.93
2.92
2.90
2.90
2.89
2.89
2.88
2.87
2.87
2.86
2.41
2.33
1.26
1.25
1.23
MeO
Me
Me
N
N
N
Et
0.95
0.94
0.99
0.93
1.89
0.94
2.93
1.96
3.91
3.02
2.81
3.21
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

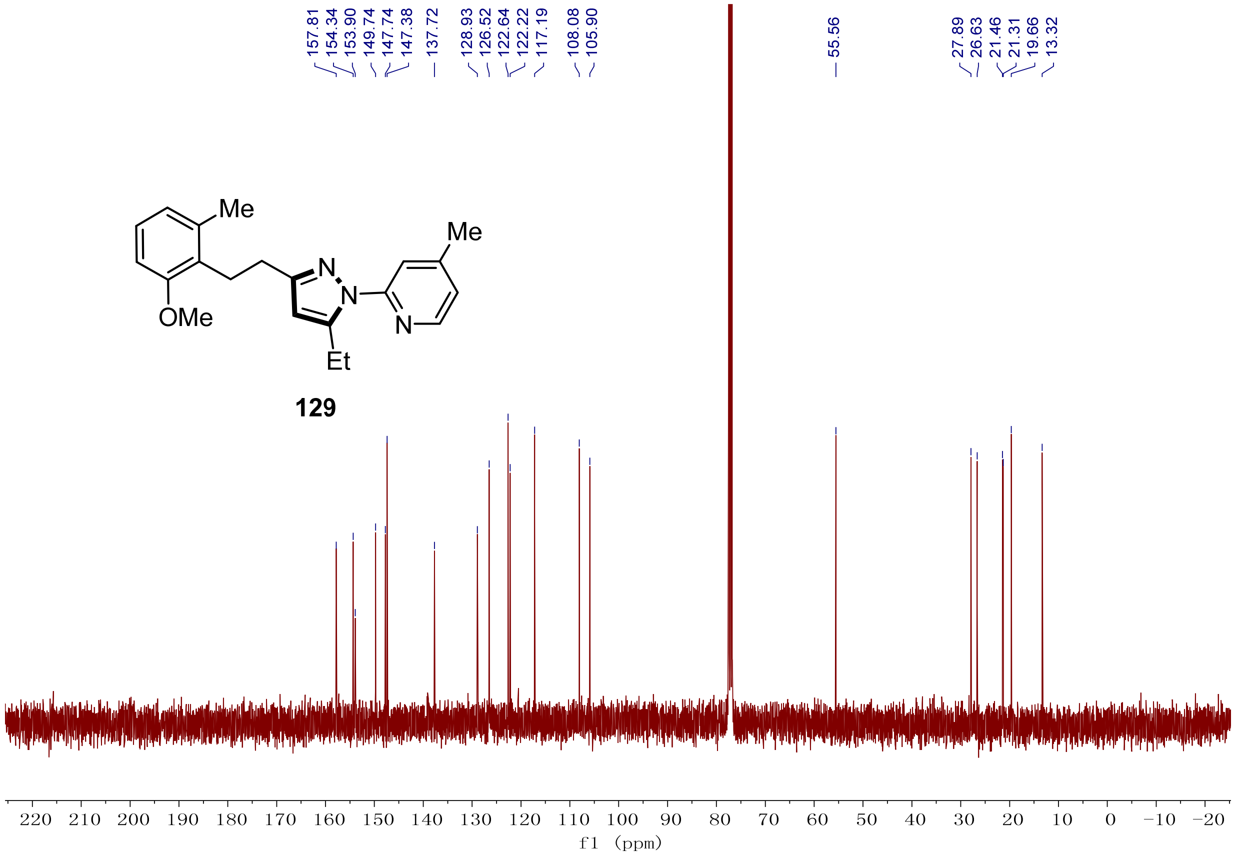
128


157.91
153.83
153.75
149.80
147.87
147.42
137.45
132.45
129.85
122.32
117.18
115.94
111.14
105.85
55.34
32.58
29.59
21.45
21.32
19.79
13.30
MeO
Me
Me
N
N
N
Et
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

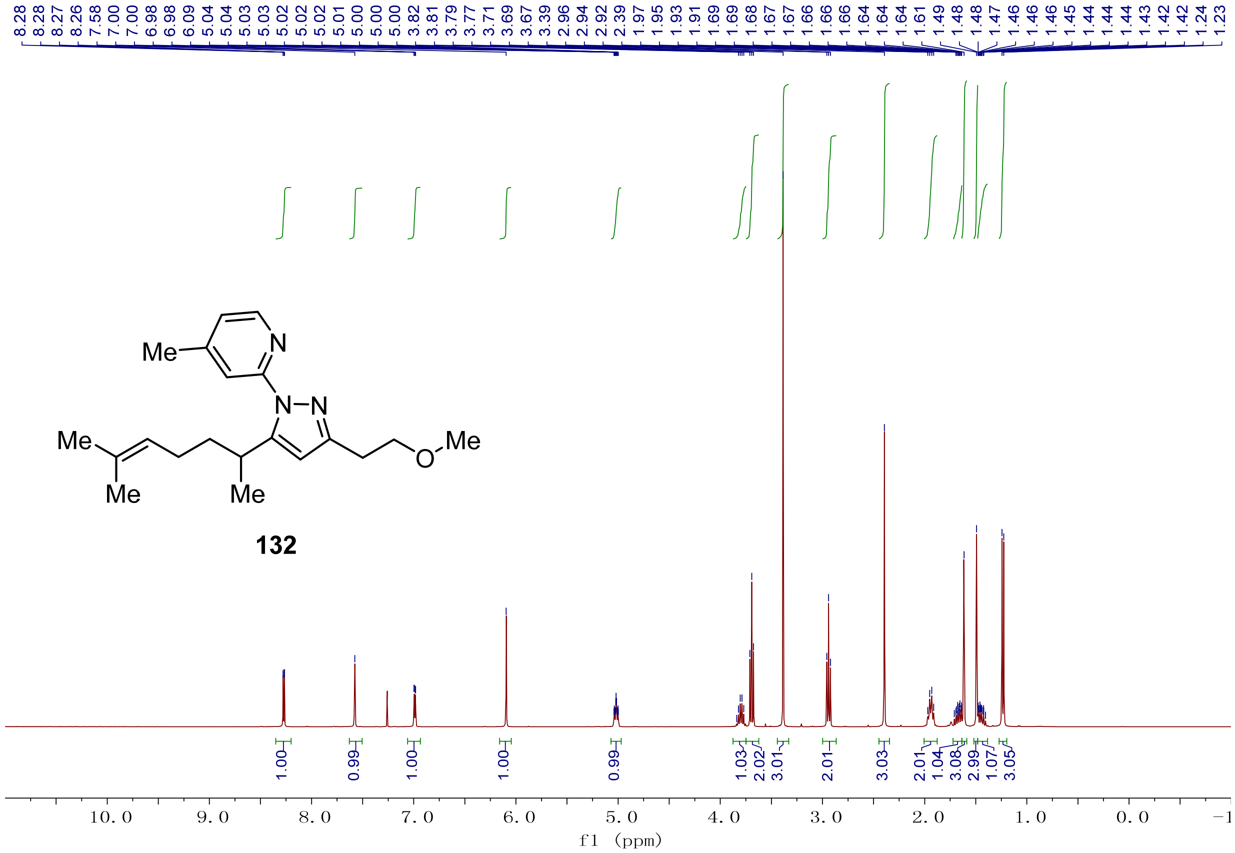
128


8.28
8.28
8.27
8.27
7.66
7.66
7.66
7.66
7.12
7.10
7.08
6.99
6.99
6.98
6.98
6.97
6.97
6.97
6.97
6.80
6.78
6.76
6.74
6.05
3.83
3.13
3.13
3.12
3.11
3.11
3.10
3.10
3.08
3.08
3.05
3.04
3.03
3.03
3.02
3.02
3.01
2.85
2.83
2.83
2.82
2.82
2.82
2.82
2.80
2.41
2.32
Me
Me
N
N
N
OMe
Et
0.99
0.98
1.00
1.04
2.00
0.98
3.07
2.02
2.00
2.01
3.02
3.01
3.25
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
−1
f1 (ppm)

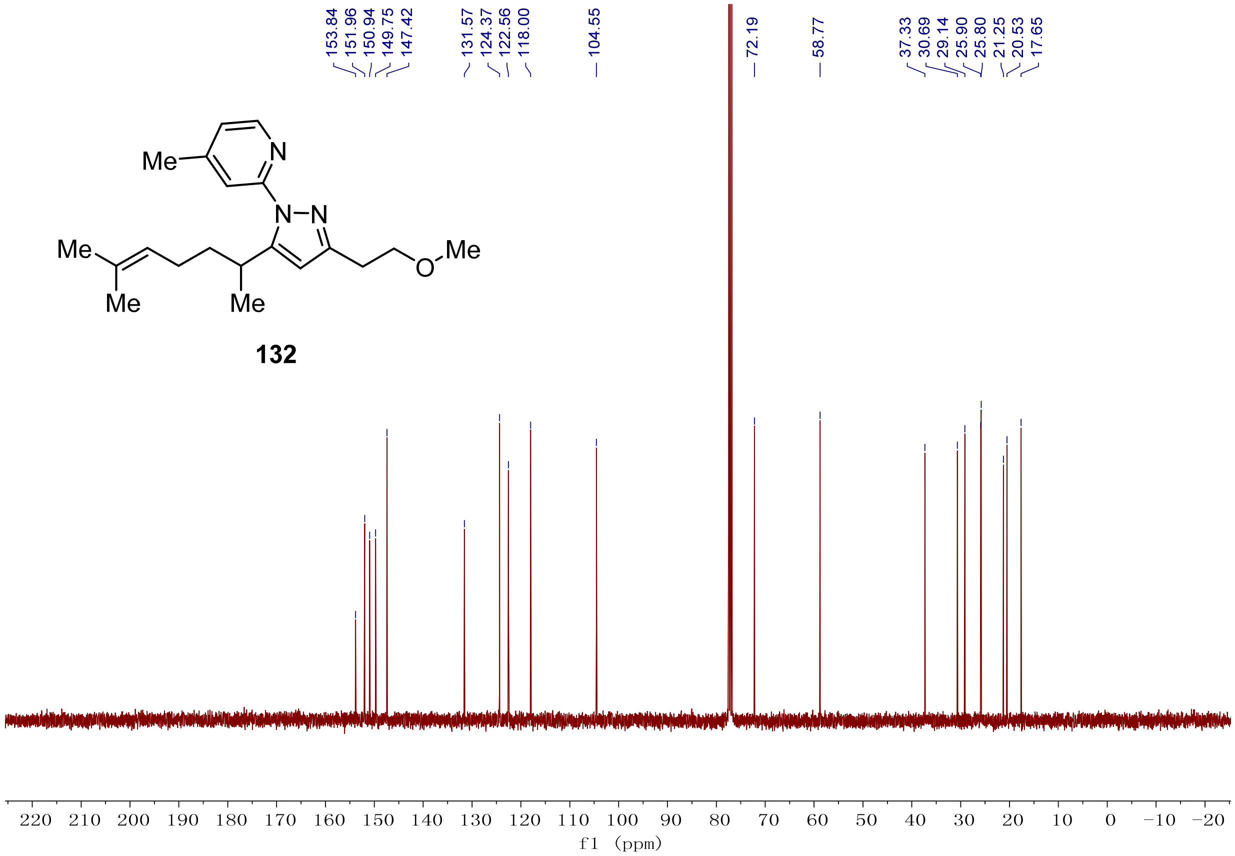
129


157.81
154.34
153.90
149.74
147.74
147.38
137.72
128.93
126.52
122.64
122.22
117.19
108.08
105.90
55.56
27.89
26.63
21.46
21.31
19.66
13.32
Me
Me
N
N
N
OMe
Et
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
−10
−20
f1 (ppm)

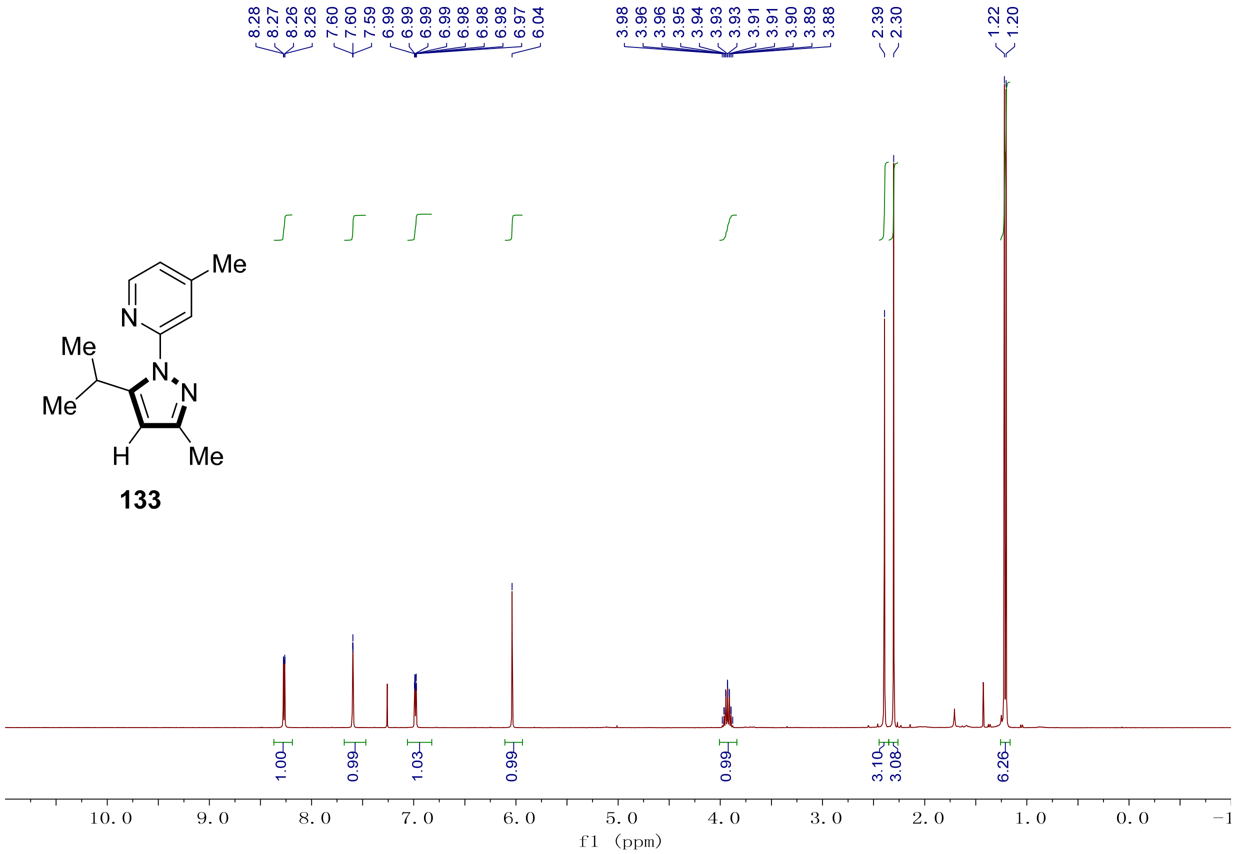
129


8.28
8.28
8.27
8.26
7.58
7.00
7.00
6.98
6.98
6.09
5.04
5.04
5.03
5.03
5.02
5.02
5.02
5.01
5.00
5.00
5.00
3.82
3.81
3.79
3.77
3.71
3.69
3.67
3.39
2.96
2.94
2.92
2.39
1.97
1.95
1.93
1.91
1.69
1.69
1.68
1.67
1.67
1.66
1.66
1.64
1.64
1.64
1.61
1.49
1.48
1.48
1.47
1.46
1.46
1.46
1.45
1.44
1.44
1.43
1.42
1.42
1.24
1.23
Me
N
N
N
Me
Me
Me
O
Me
1.00
0.99
1.00
1.00
0.99
1.03
2.02
3.01
2.01
3.03
2.01
1.04
3.08
2.99
1.07
3.05
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

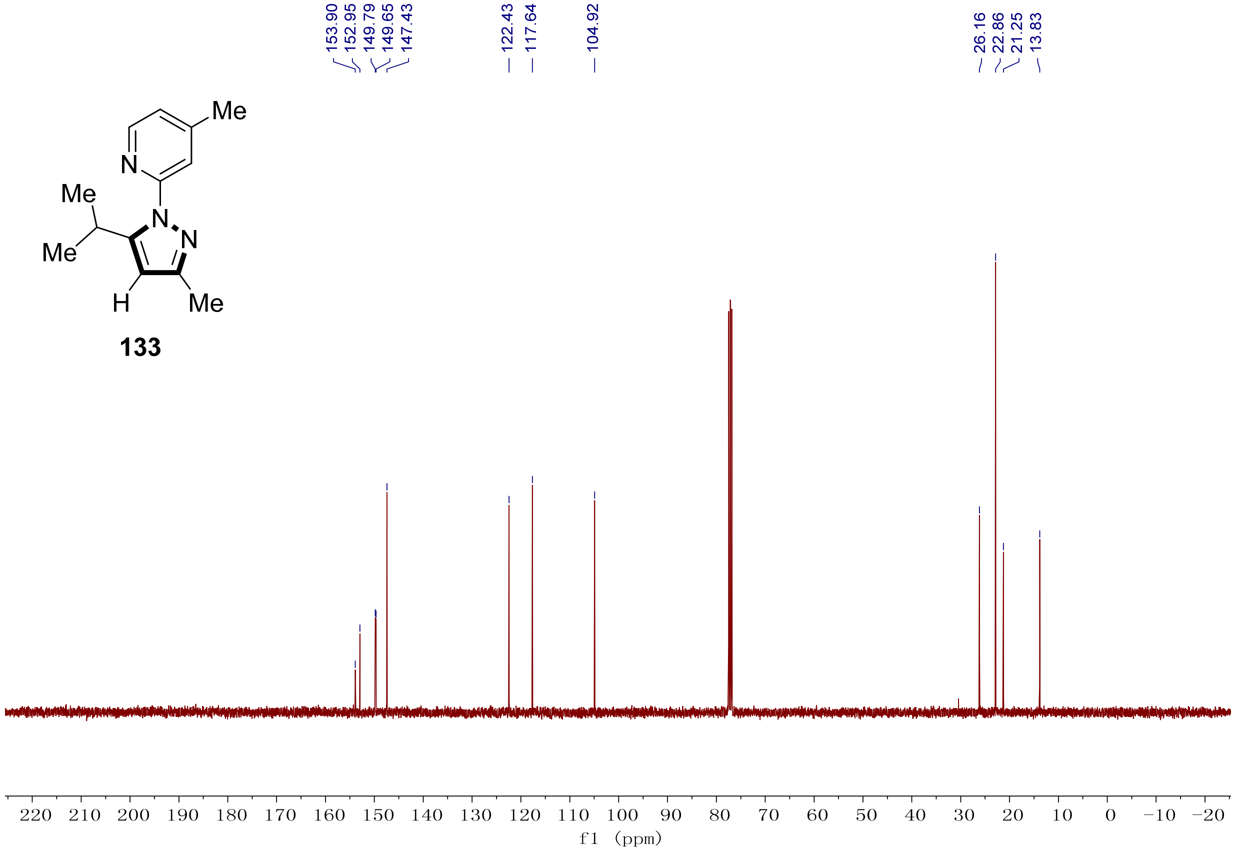
132


153.84
151.96
150.94
149.75
147.42
131.57
124.37
122.56
118.00
104.55
72.19
58.77
37.33
30.69
29.14
25.90
25.80
21.25
20.53
17.65
Me
N
N
N
Me
Me
Me
O
Me
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
−10
−20
f1 (ppm)

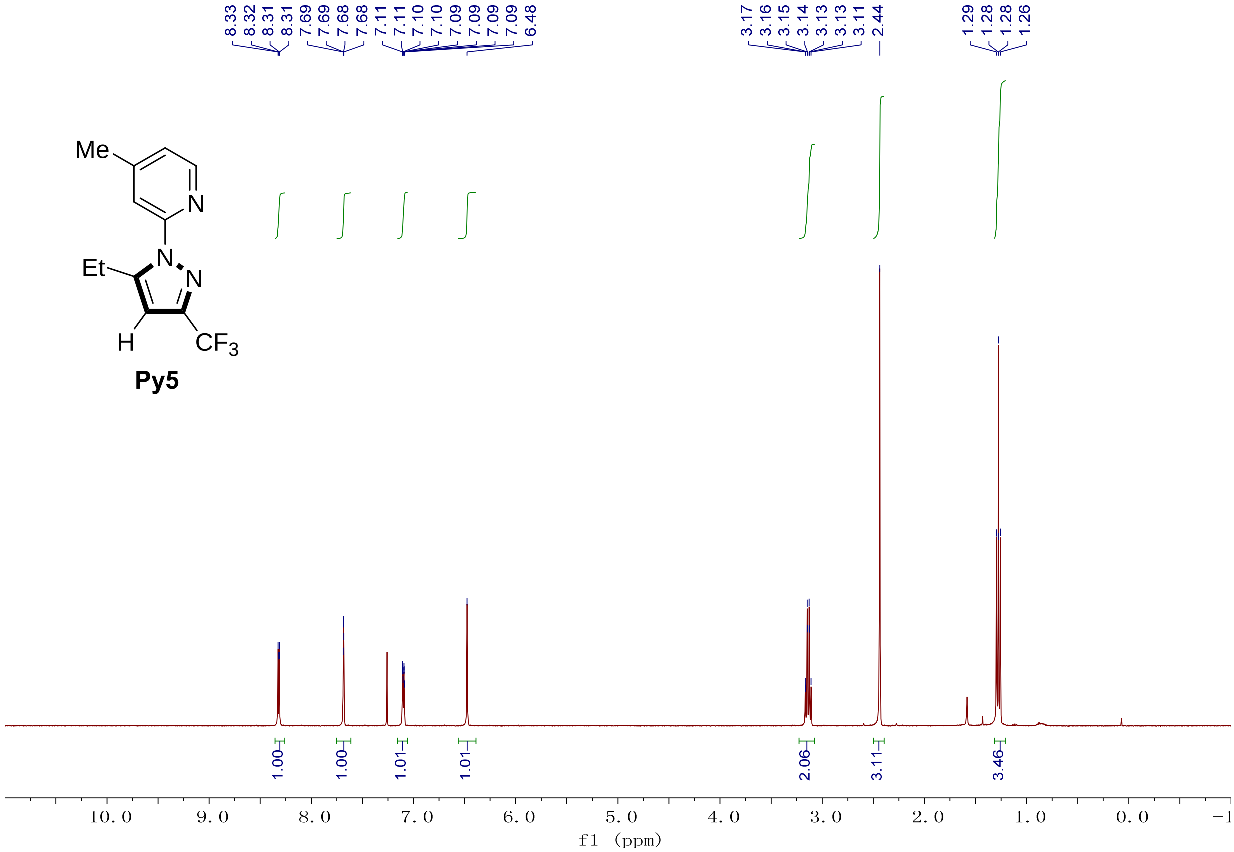
132

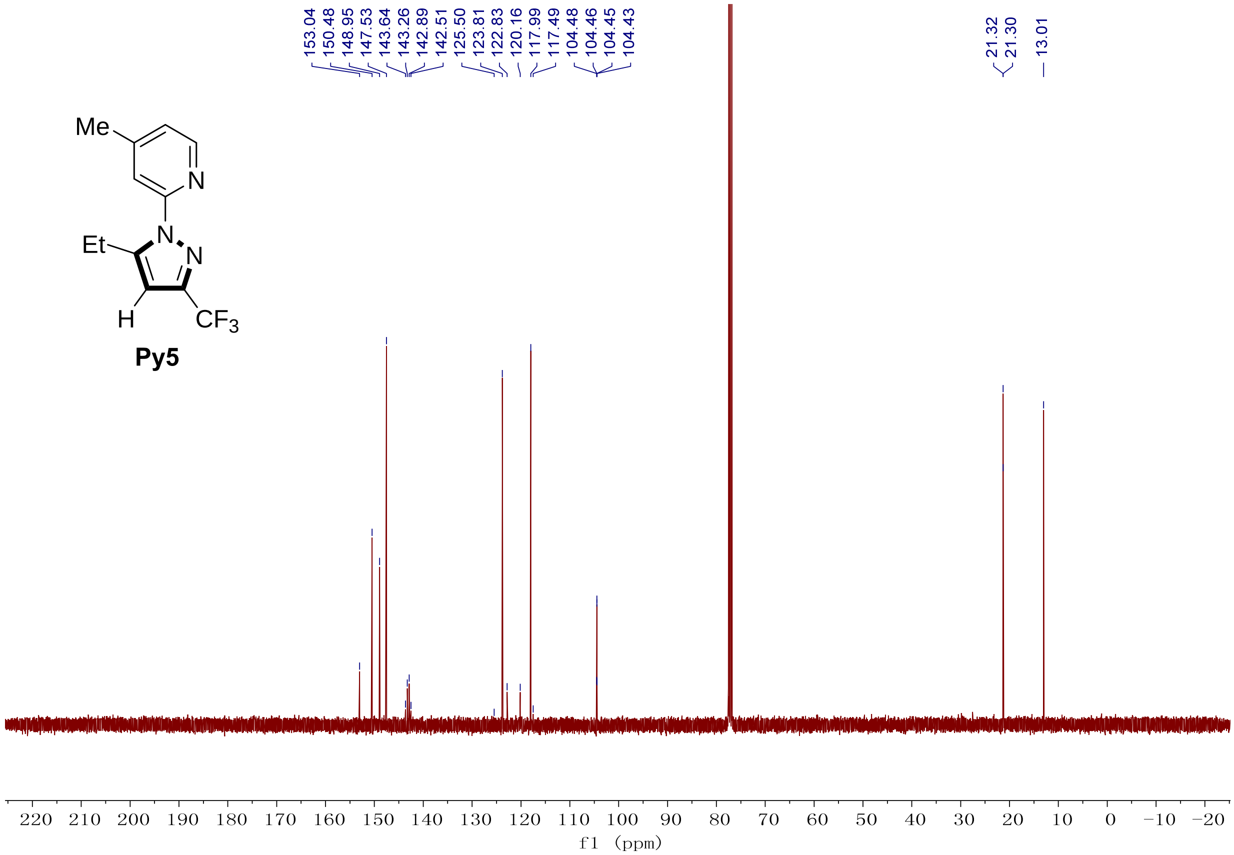

8.28
8.27
8.26
8.26
7.60
7.60
7.59
6.99
6.99
6.99
6.99
6.98
6.98
6.98
6.97
6.04
3.98
3.96
3.96
3.95
3.94
3.93
3.93
3.91
3.91
3.90
3.89
3.88
2.39
2.30
1.22
1.20
Me
N
Me
Me
N
N
H
Me
1.00
0.99
1.03
0.99
0.99
3.10
3.08
6.26
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

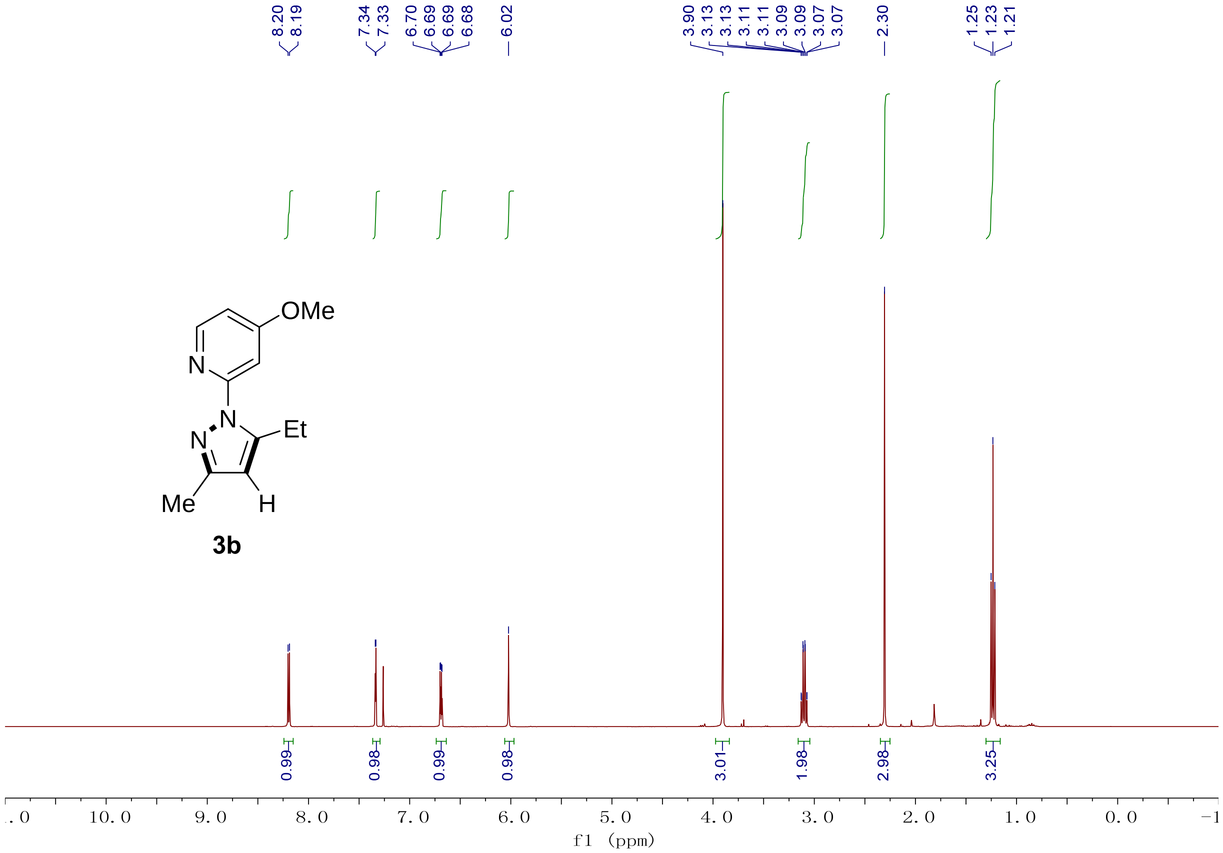
133

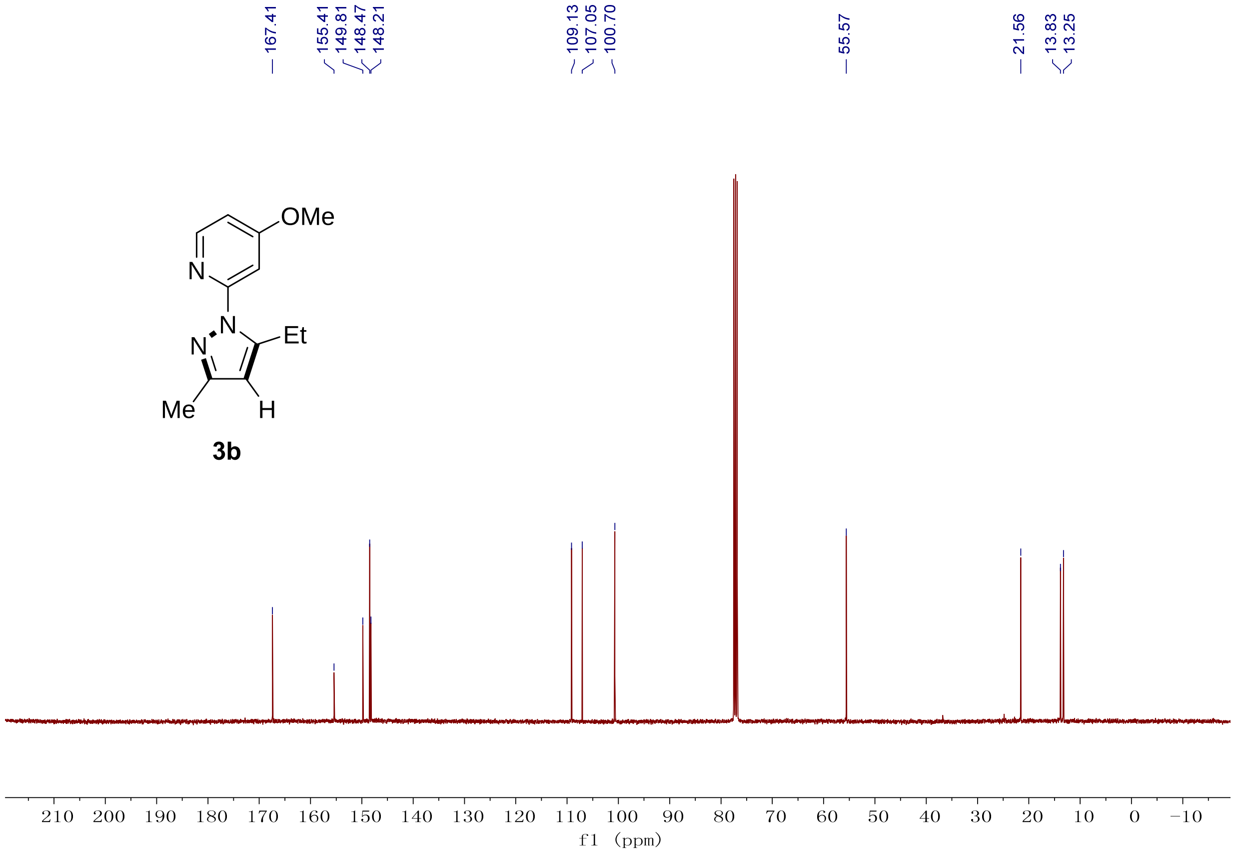

153.90
152.95
149.79
149.65
147.43
122.43
117.64
104.92
26.16
22.86
21.25
13.83
Me
N
Me
Me
N
N
H
Me
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

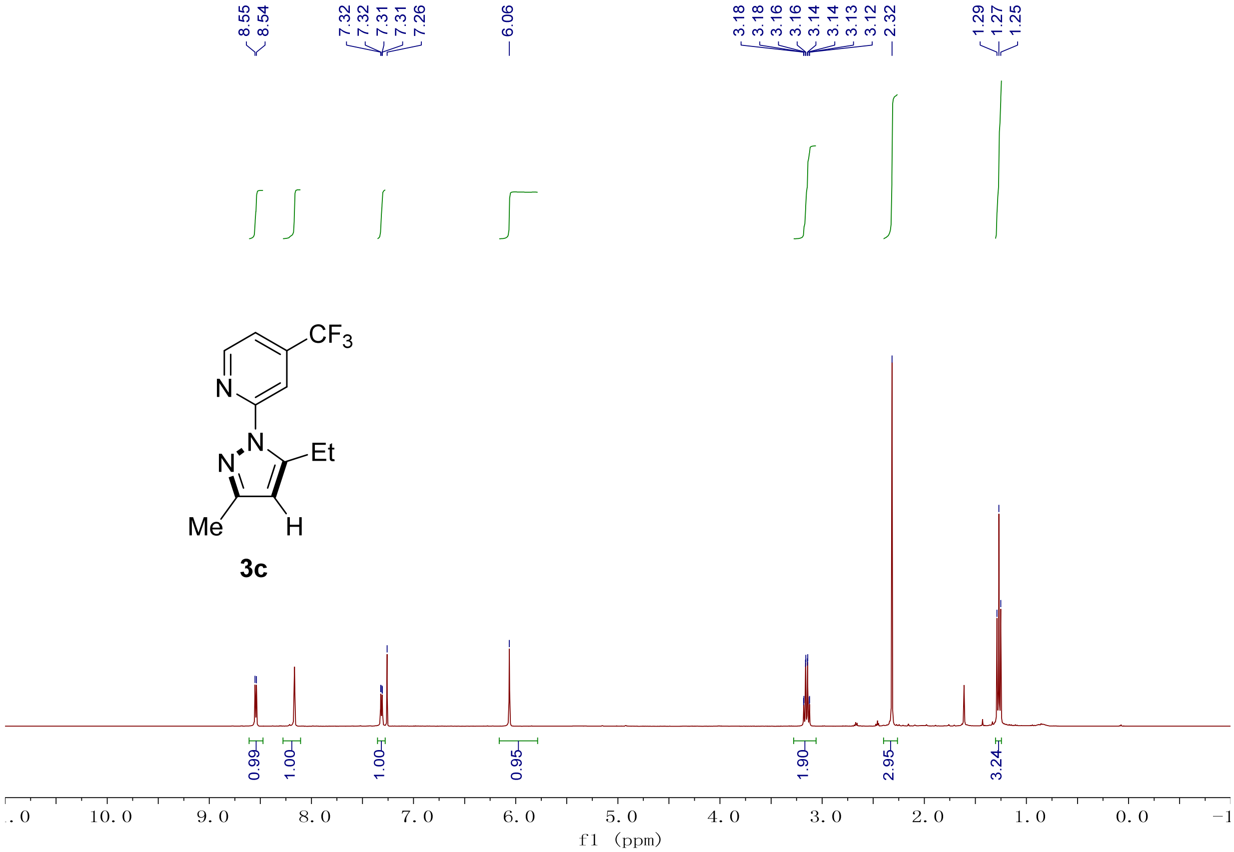
133

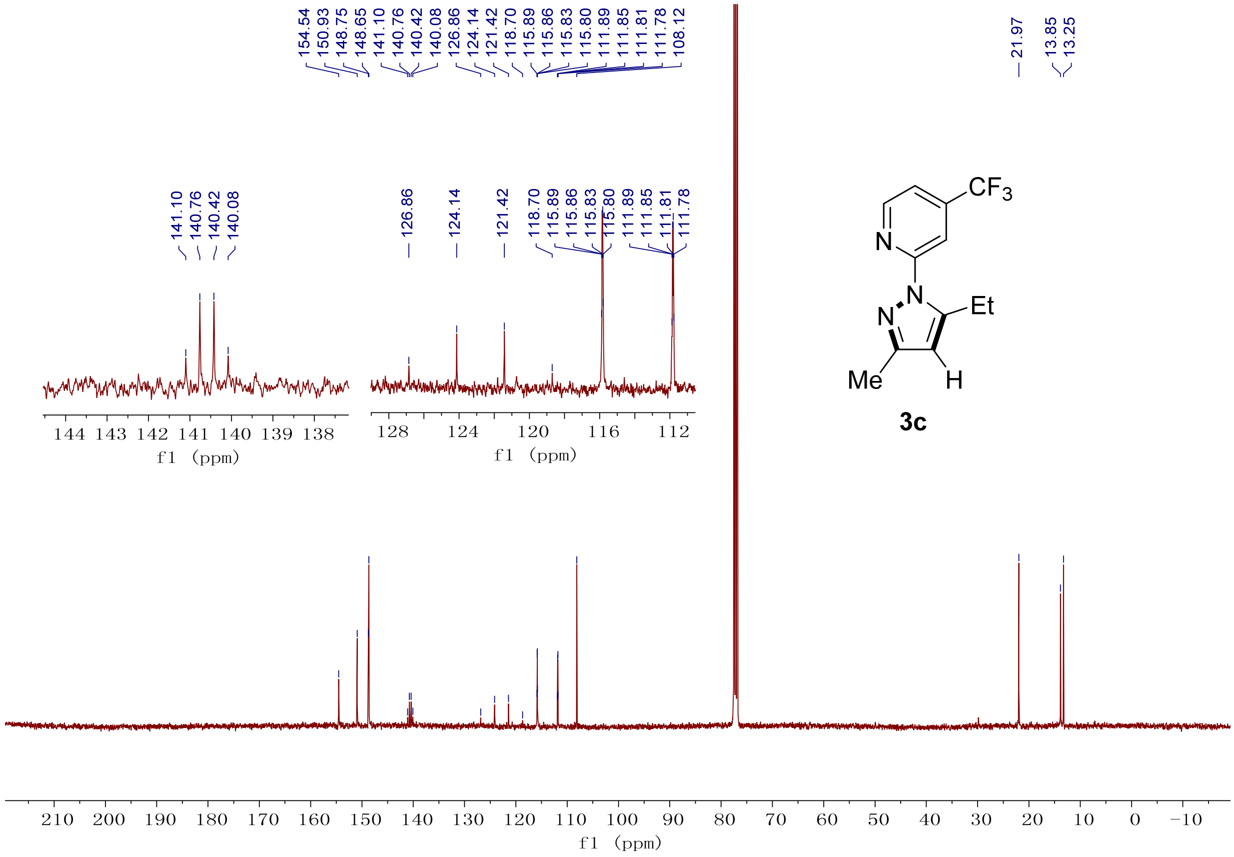

Py5
8.33
8.32
8.31
8.31
7.69
7.69
7.68
7.68
7.11
7.11
7.10
7.10
7.09
7.09
7.09
7.09
6.48
3.17
3.16
3.15
3.14
3.13
3.13
3.11
2.44
1.29
1.28
1.28
1.26
Me
N
Et
N
N
H
CF3
1.00
1.00
1.01
1.01
2.06
3.11
3.46
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

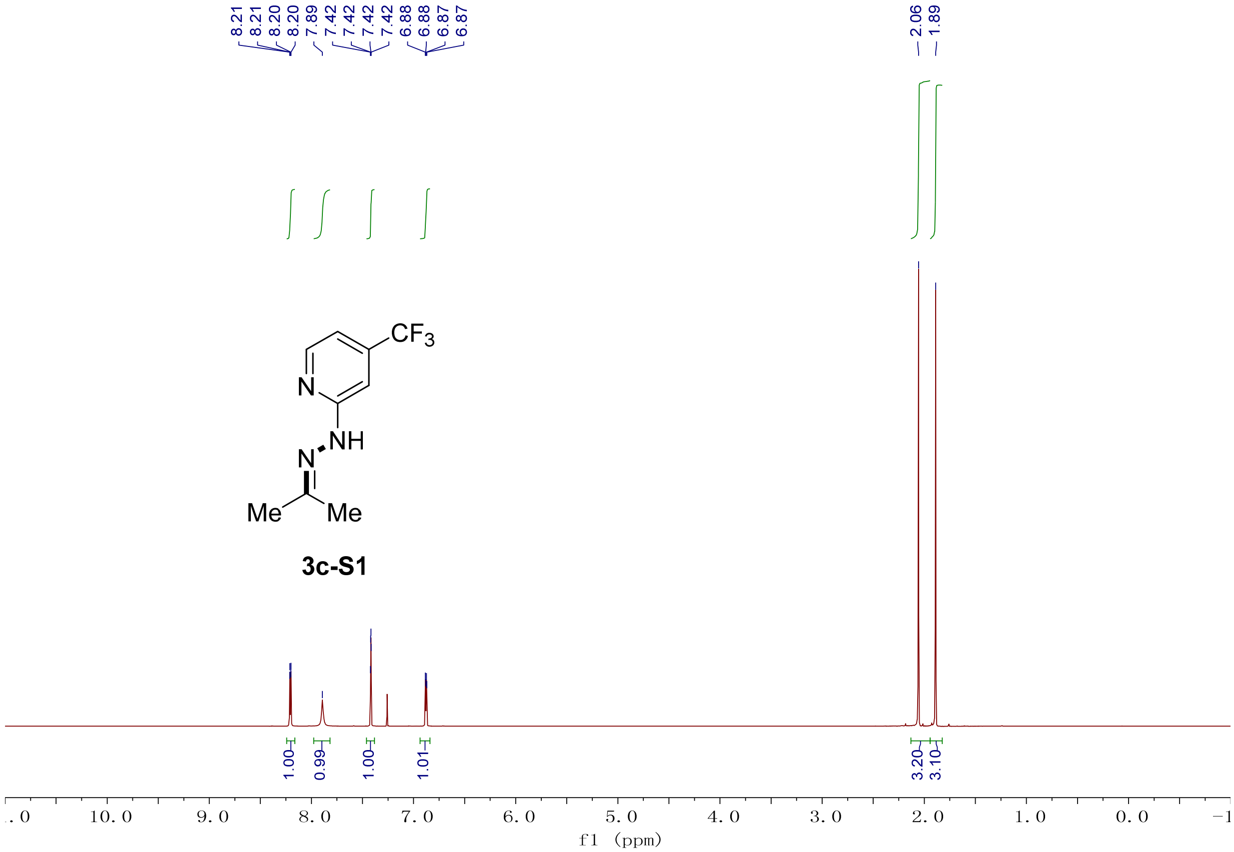

Py5
153.04
150.48
148.95
147.53
143.64
143.26
142.89
142.51
125.50
123.81
122.83
120.16
117.99
117.49
104.48
104.46
104.45
104.43
21.32
21.30
13.01
Me
N
Et
N
N
H
CF3
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

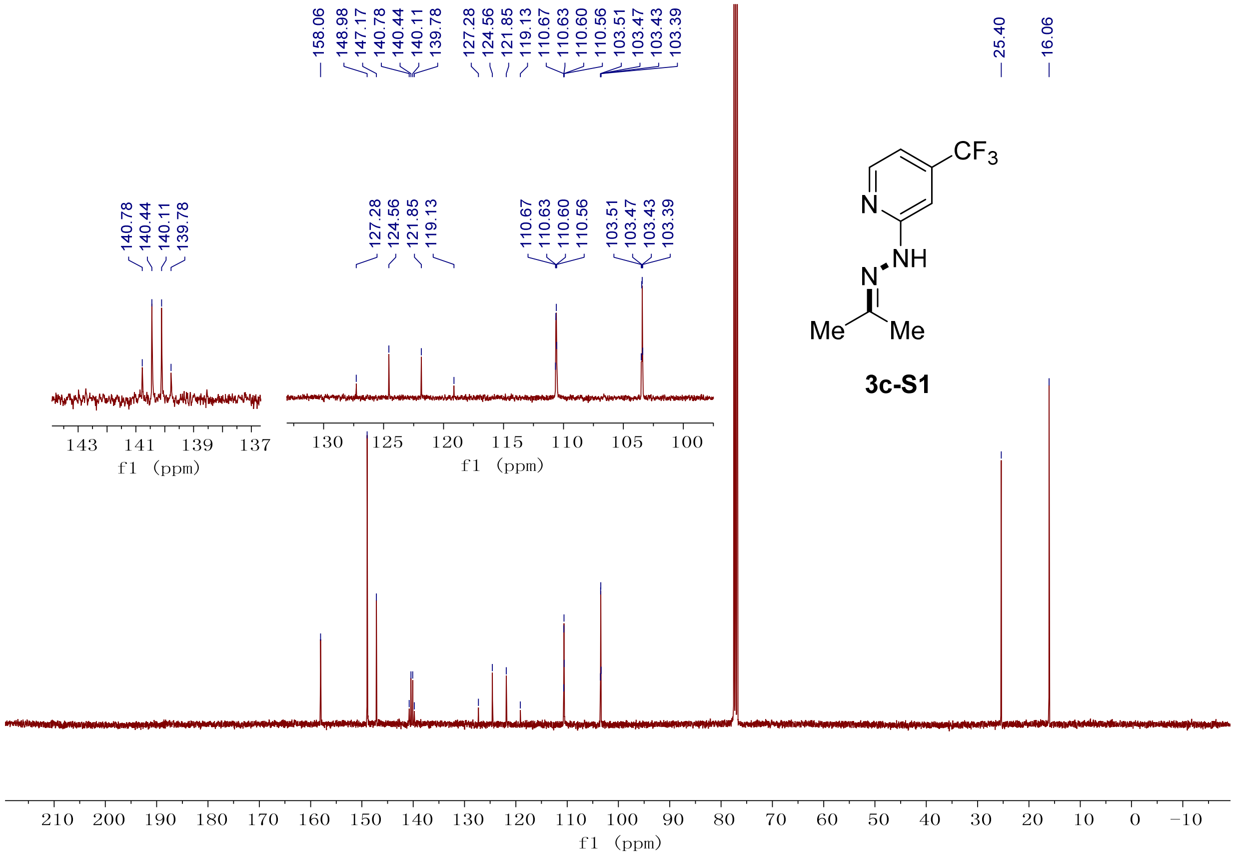

8.20
8.19
7.34
7.33
6.70
6.69
6.69
6.68
6.02
3.90
3.13
3.13
3.11
3.11
3.09
3.09
3.07
3.07
2.30
1.25
1.23
1.21
OMe
N
N
N
Et
Me
H
3b
0.99
0.98
0.99
0.98
3.01
1.98
2.98
3.25
. 0
10. 0
9. 0
8. 0
7. 0
6. 0
5. 0
4. 0
3. 0
2. 0
1. 0
0. 0
−1
f1 (ppm)

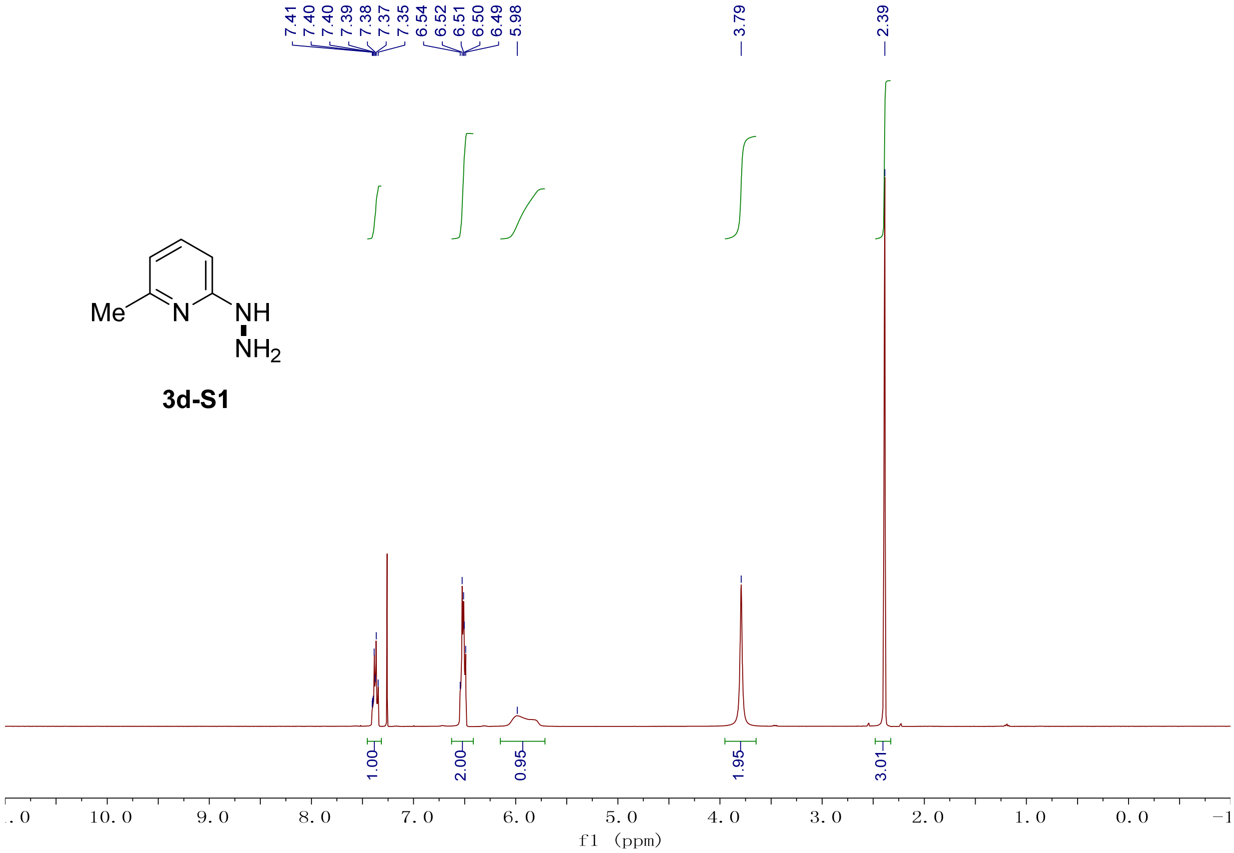

167.41
155.41
149.81
148.47
148.21
109.13
107.05
100.70
55.57
21.56
13.83
13.25
OMe
N
N
N
Et
Me
H
3b
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
−10
f1 (ppm)


3c
8.55
8.54
7.32
7.32
7.31
7.31
7.26
6.06
3.18
3.18
3.16
3.14
3.14
3.13
3.12
2.32
1.29
1.27
1.25
CF3
N
N
N
Et
Me
H
0.99
1.00
1.00
0.95
1.90
2.95
3.24
. 0
10. 0
9. 0
8. 0
7. 0
6. 0
5. 0
4. 0
3. 0
2. 0
1. 0
0. 0
−1
f1 (ppm)

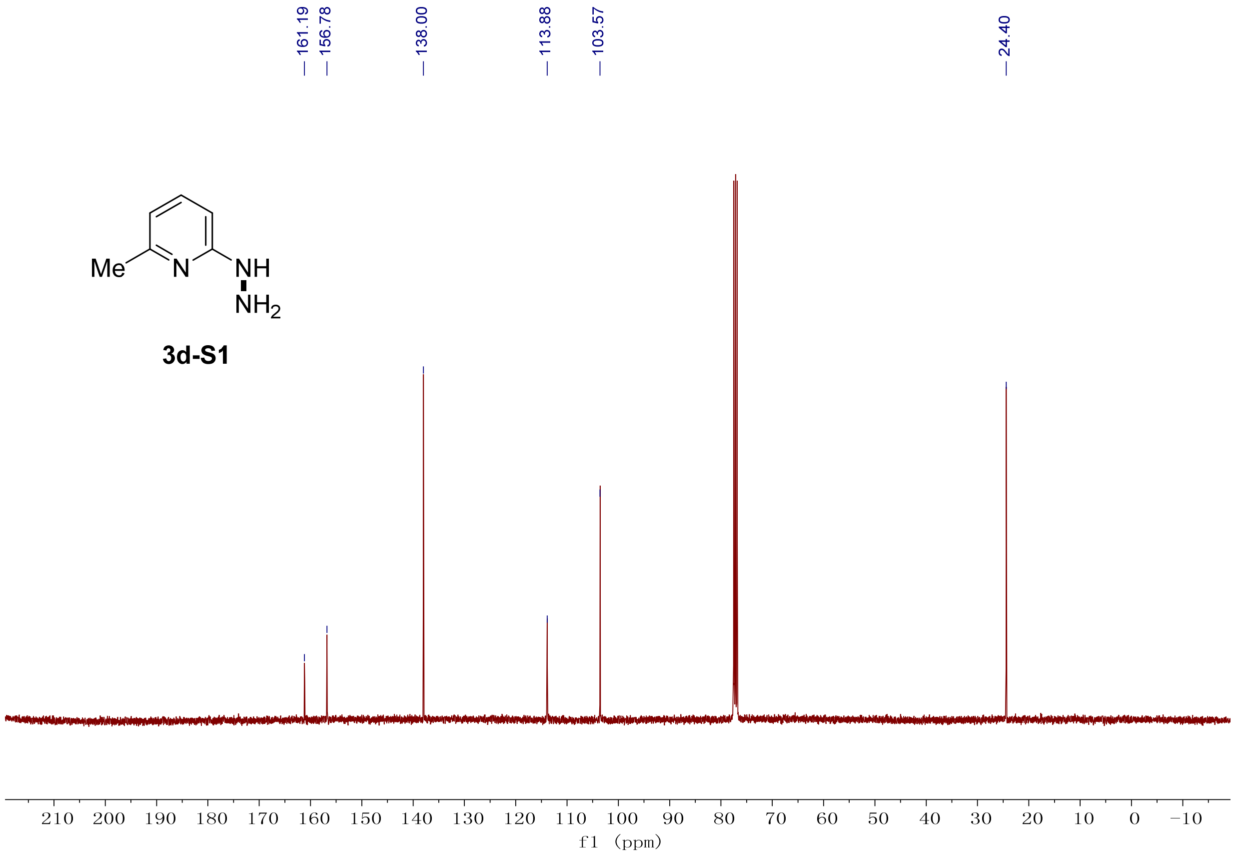

3c
154.54
150.93
148.75
148.65
141.10
140.76
140.42
140.08
126.86
124.14
121.42
118.70
115.89
115.86
115.83
115.80
111.89
111.85
111.81
111.78
108.12
21.97
13.85
13.25
141.10
140.76
140.42
140.08
144 143 142 141 140 139 138
f1 (ppm)
126.86
124.14
121.42
118.70
115.89
115.86
115.83
115.80
111.89
111.85
111.81
111.78
128 124 120 116 112
f1 (ppm)
CF3
N
N
N
Et
Me
H
210 200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 −10
f1 (ppm)


8.21
8.21
8.20
8.20
7.89
7.42
7.42
7.42
7.42
6.88
6.88
6.87
6.87
2.06
1.89
CF3
N
NH
N
Me
Me
3c-S1
1.00
0.99
1.00
1.01
3.20
3.10
.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
−1
f1 (ppm)

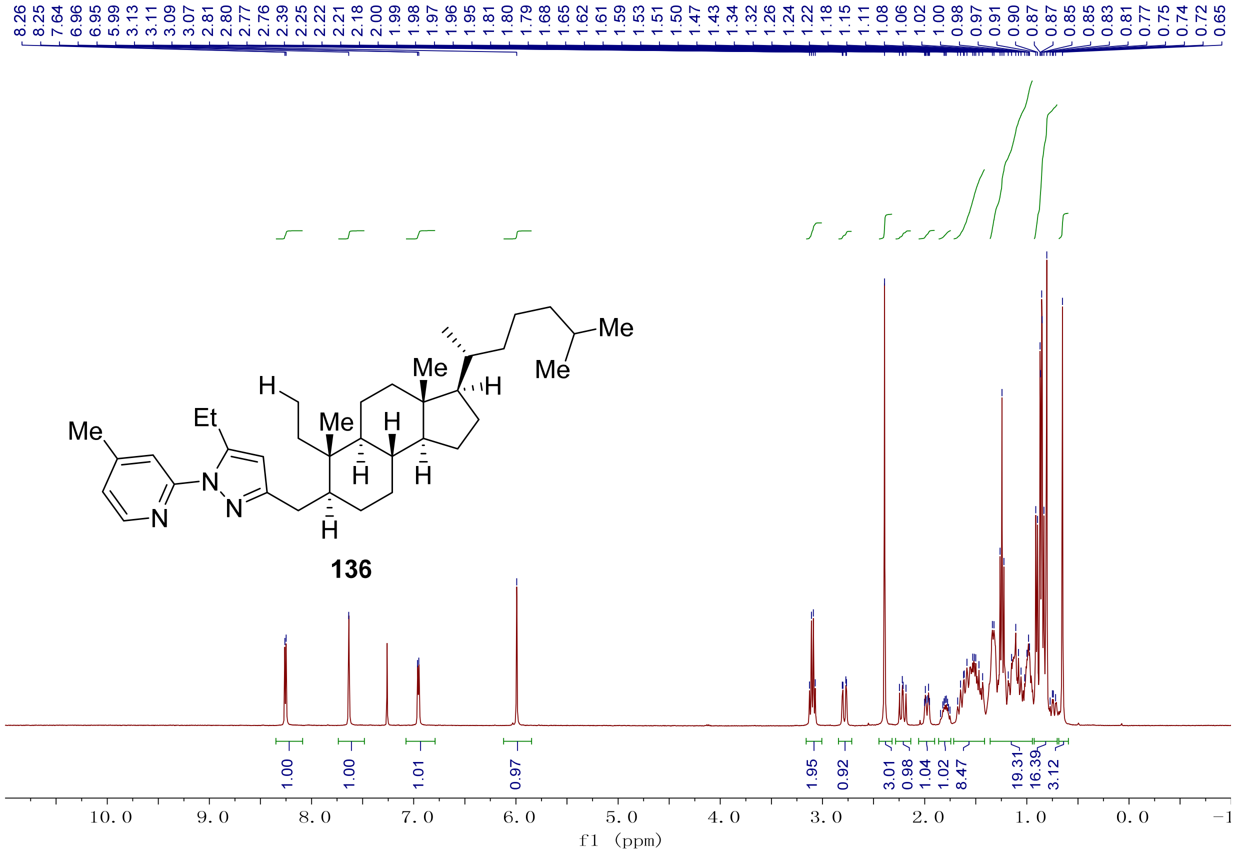

158.06
148.98
147.17
140.78
140.44
140.11
139.78
127.28
124.56
121.85
119.13
110.67
110.63
110.60
110.56
103.51
103.47
103.43
103.39
25.40
16.06
140.78
140.44
140.11
139.78
143
141
139
137
f1 (ppm)
127.28
124.56
121.85
119.13
110.67
110.63
110.60
110.56
103.51
103.47
103.43
103.39
130
125
120
115
110
105
100
f1 (ppm)
CF3
N
NH
N
Me
Me
3c-S1
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
−10
f1 (ppm)


3d-S1

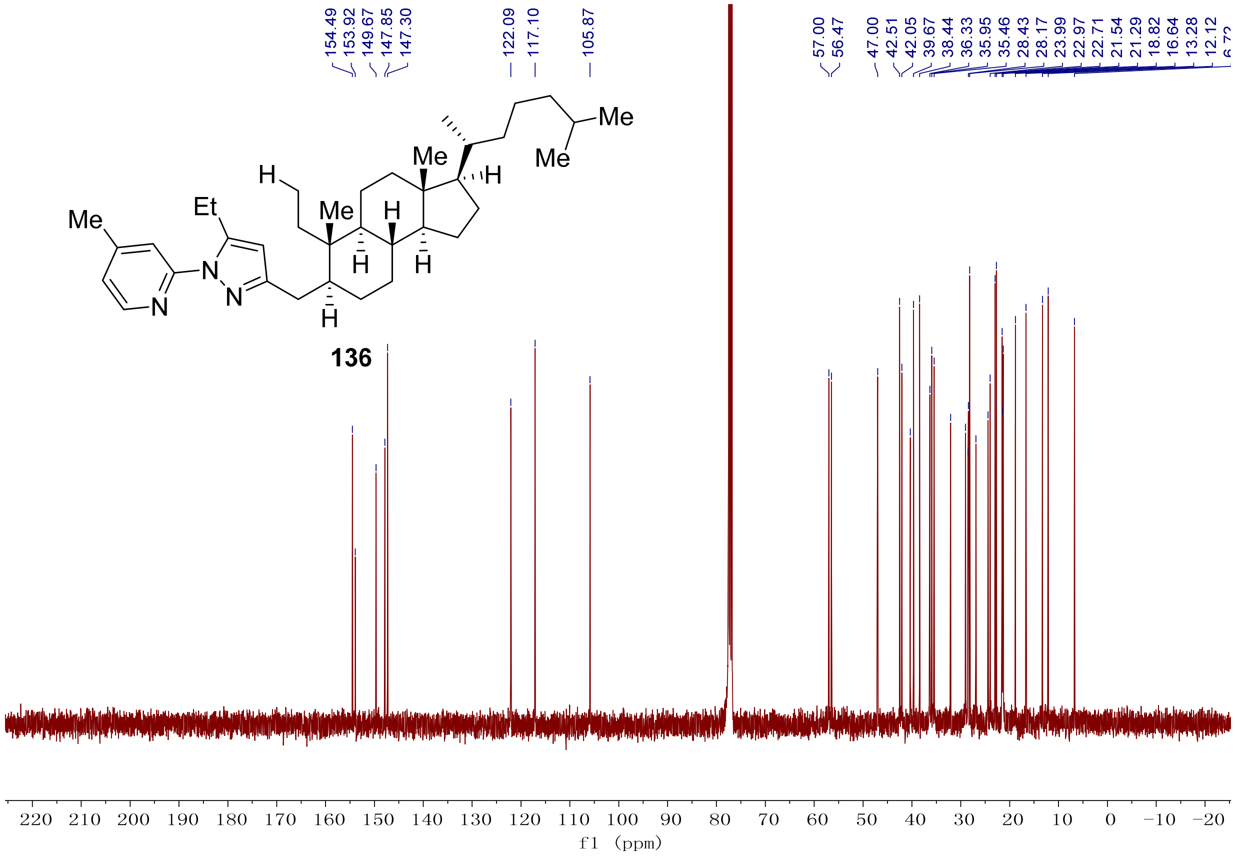
7.41
7.40
7.40
7.39
7.38
7.37
7.35
6.54
6.52
6.51
6.50
6.49
5.98
3.79
2.39
Me
N
NH
NH2
1.00
2.00
0.95
1.95
3.01
. 0
10. 0
9. 0
8. 0
7. 0
6. 0
5. 0
4. 0
3. 0
2. 0
1. 0
0. 0
−1
f1 (ppm)


3d-S1

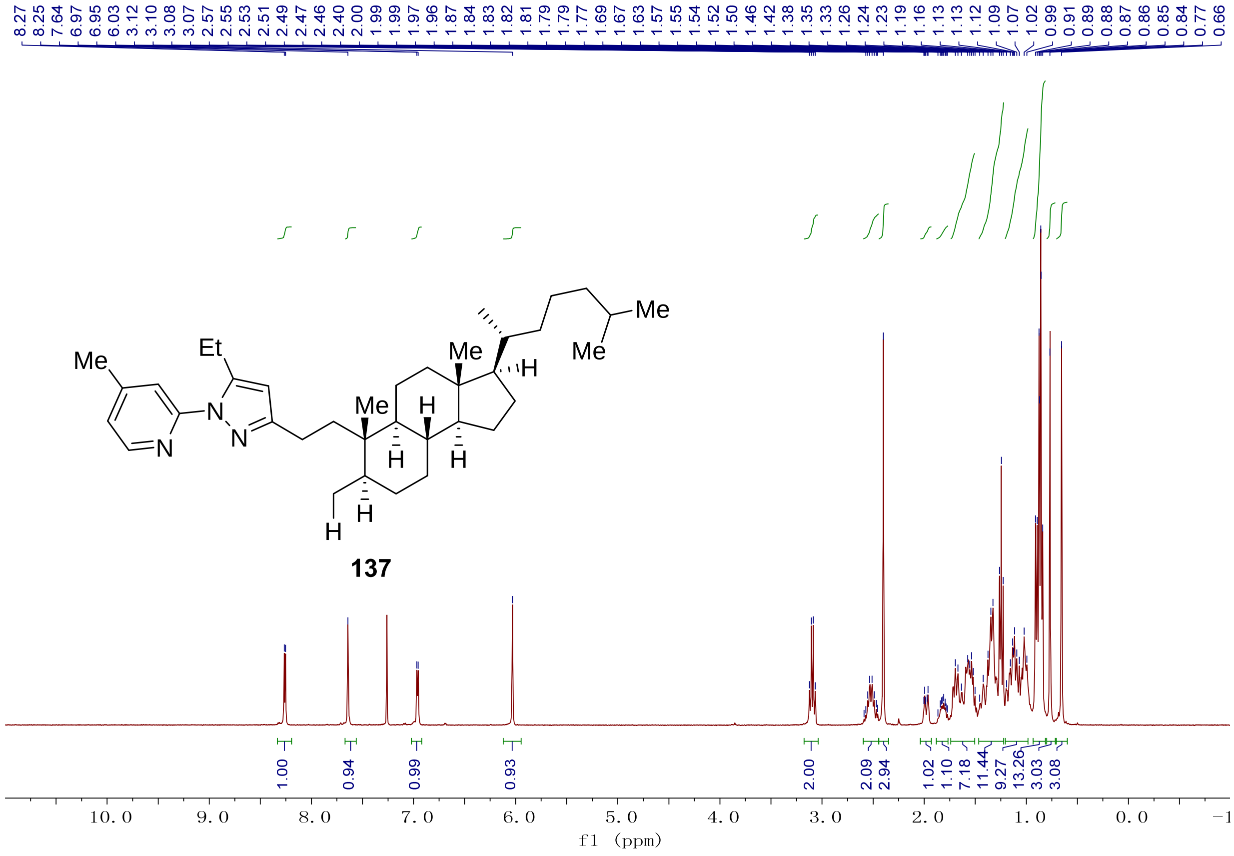
161.19
156.78
138.00
113.88
103.57
24.40
Me
N
NH
NH2
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
−10
f1 (ppm)


8.26
8.25
7.64
6.96
6.95
5.99
3.13
3.11
3.09
3.07
2.81
2.80
2.77
2.76
2.39
2.25
2.22
2.21
2.18
2.00
1.99
1.98
1.97
1.96
1.95
1.81
1.80
1.79
1.68
1.65
1.62
1.61
1.59
1.53
1.51
1.50
1.47
1.43
1.34
1.32
1.26
1.24
1.22
1.18
1.15
1.11
1.08
1.06
1.02
1.00
0.98
0.97
0.91
0.90
0.87
0.87
0.85
0.85
0.83
0.81
0.77
0.75
0.74
0.72
0.65
Me
Et
H
Me
H
Me
H
Me
Me
N
N
N
H
H
H
H
1.00
1.00
1.01
0.97
1.95
0.92
3.01
0.98
1.04
1.02
8.47
19.31
16.39
3.12
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

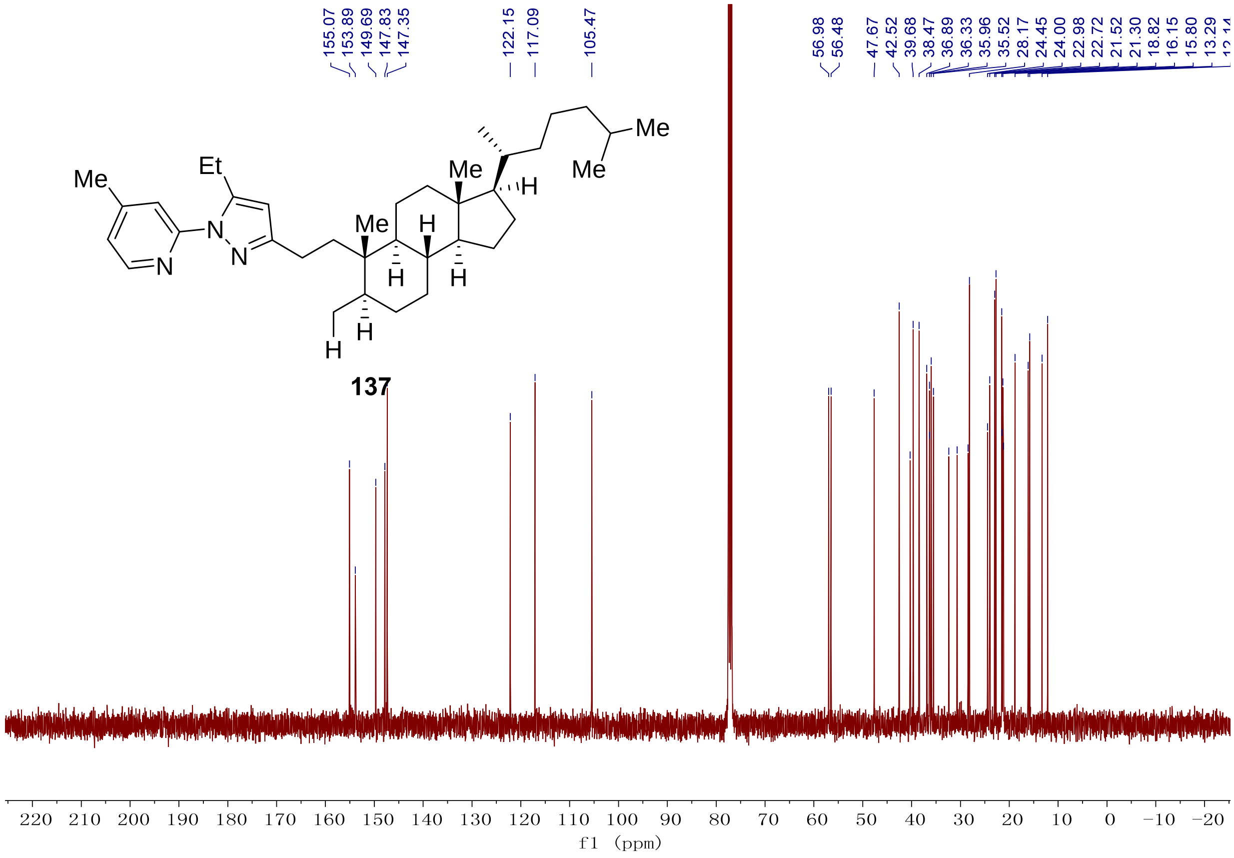
136


154.49
153.92
149.67
147.85
147.30
122.09
117.10
105.87
57.00
56.47
47.00
42.51
42.05
39.67
38.44
36.33
35.95
35.46
28.43
28.17
23.99
22.97
22.71
21.54
21.29
18.82
16.64
13.28
12.12
6.72
Me
Et
H
Me
H
Me
H
Me
Me
N
N
N
H
H
H
H
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

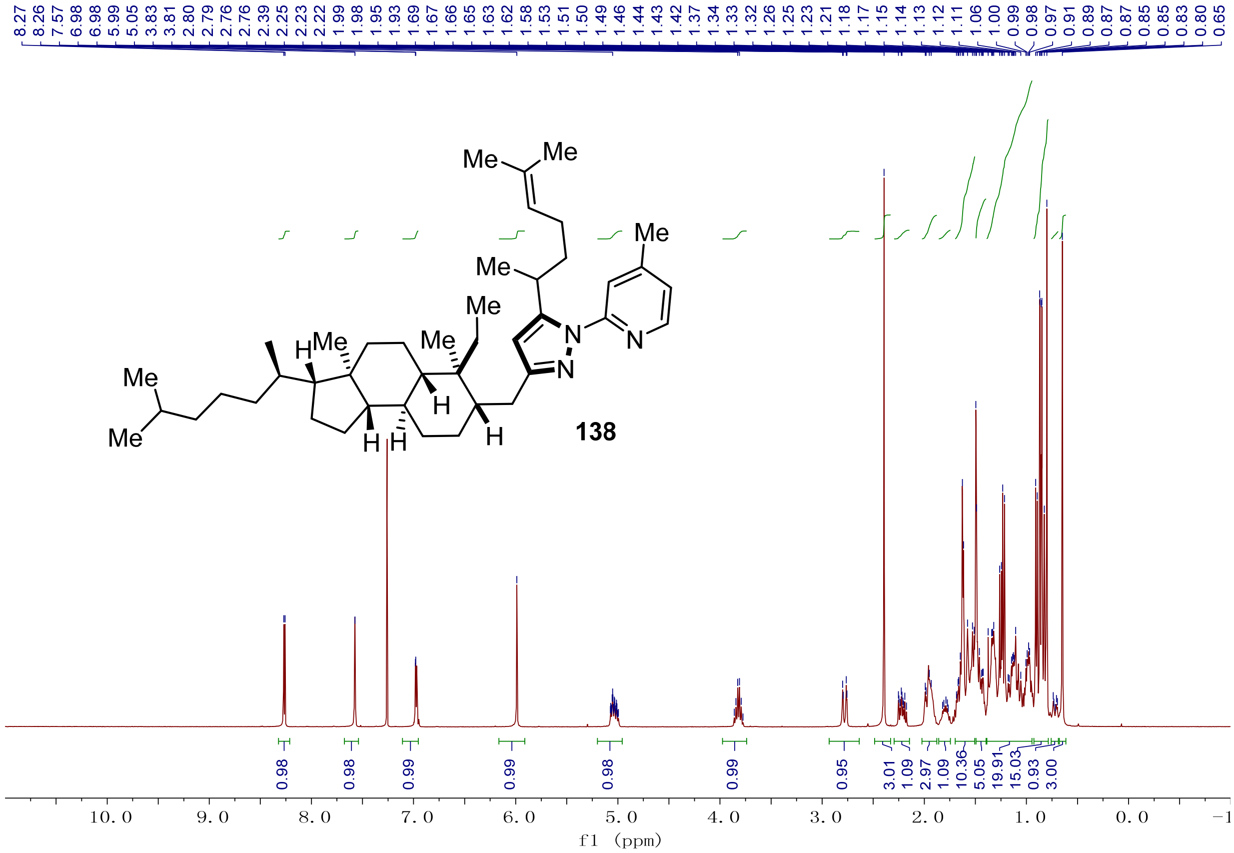
136

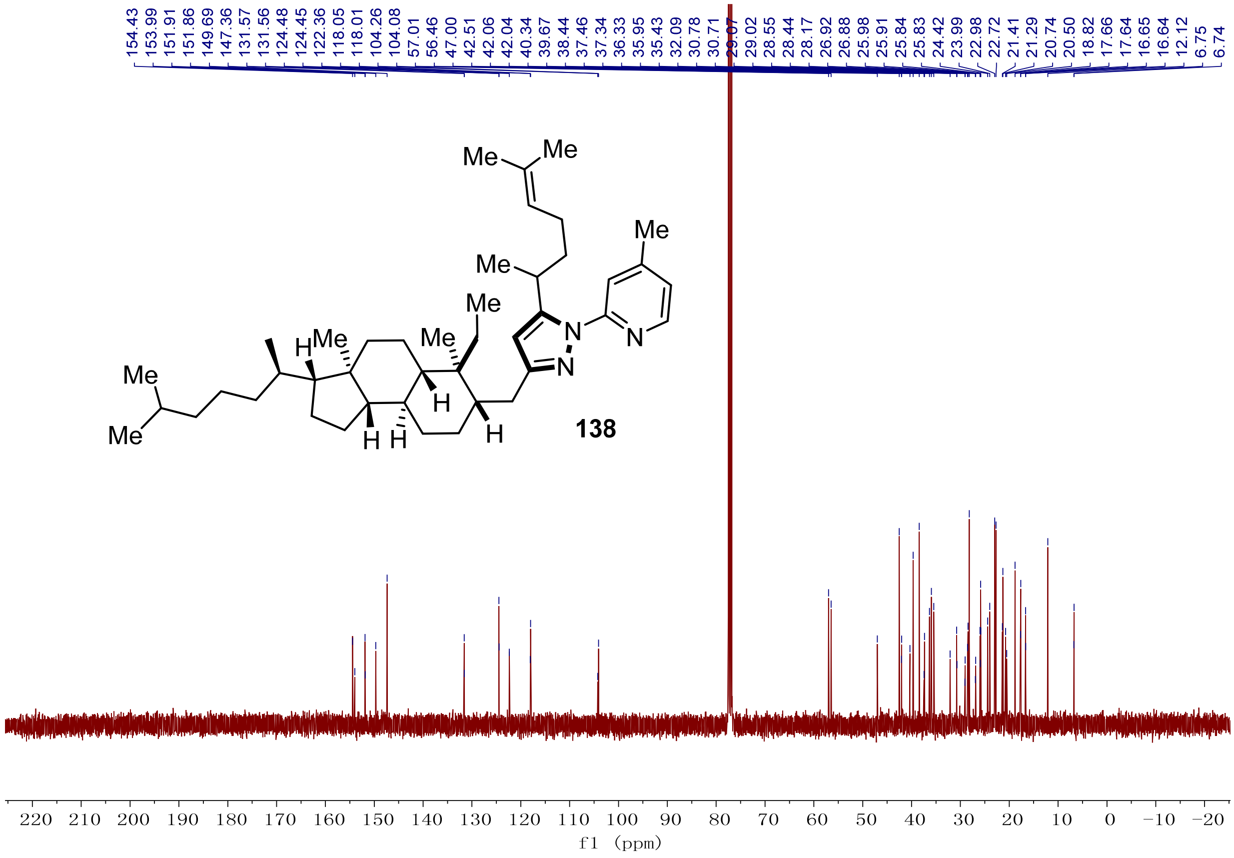

8.27 8.25 7.64 6.97 6.95 6.03 3.12 3.10 3.08 3.07 2.57 2.55 2.53 2.51 2.49 2.47 2.46 2.40 2.00 1.99 1.99 1.97 1.96 1.87 1.84 1.83 1.82 1.81 1.79 1.79 1.77 1.69 1.67 1.63 1.57 1.55 1.54 1.52 1.50 1.46 1.42 1.38 1.35 1.33 1.26 1.24 1.23 1.19 1.16 1.13 1.13 1.12 1.09 1.07 1.02 0.99 0.91 0.89 0.88 0.87 0.86 0.85 0.84 0.77 0.66
Me
Et
N
N
N
Me
Me
H
H
H
H
Me
Me
H
H
1.00 0.94 0.99 0.93 2.00 2.09 2.94 1.02 1.10 7.18 11.44 9.27 13.26 3.03 3.08
10.0 9.0 8.0 7.0 6.0 5.0 4.0 3.0 2.0 1.0 0.0 -1
f1 (ppm)

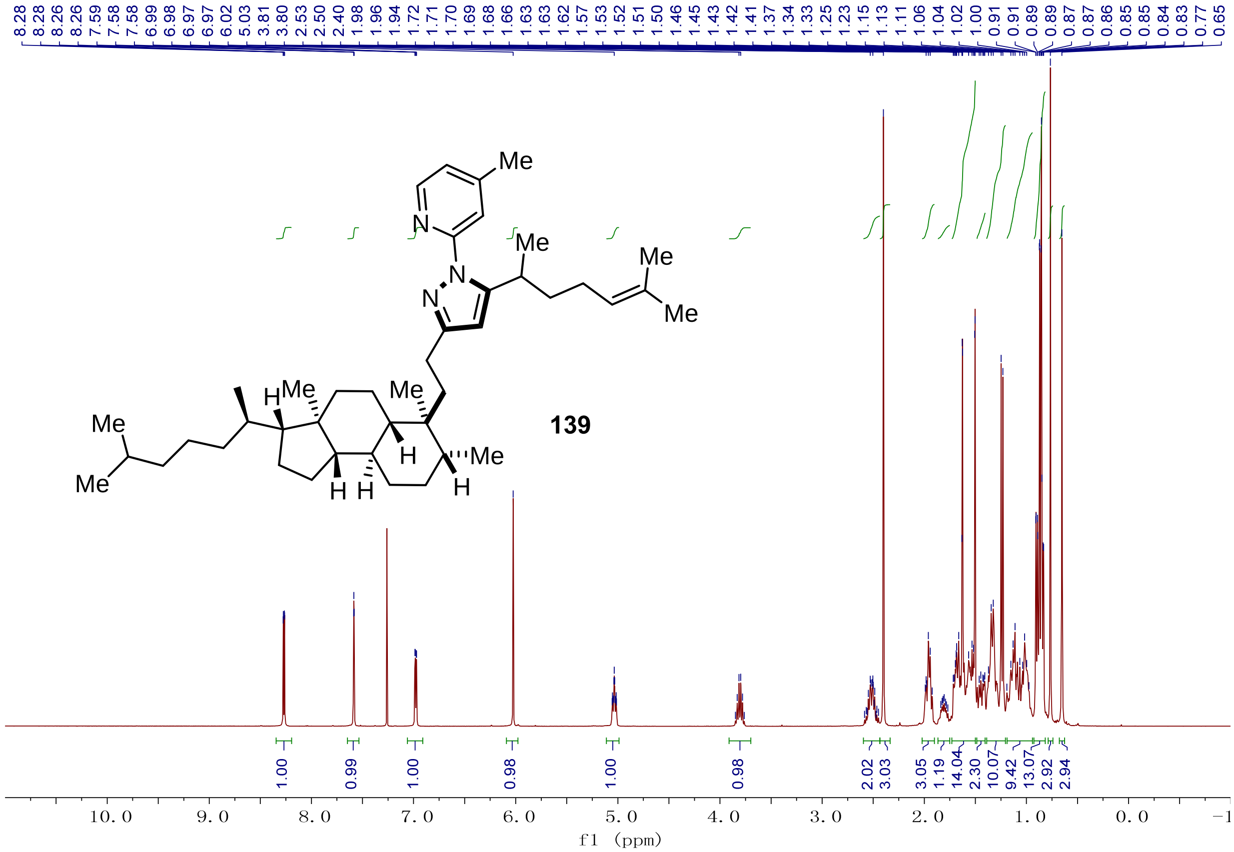
137


155.07 153.89 149.69 147.83 147.35 122.15 117.09 105.47 56.98 56.48 47.67 42.52 39.68 38.47 36.89 36.33 35.96 35.52 28.17 24.45 24.00 22.98 22.72 21.52 21.30 18.82 16.15 15.80 13.29
Me
Et
N
N
N
Me
Me
H
H
H
H
Me
Me
H
H
220 210 200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 -10 -20
f1 (ppm)

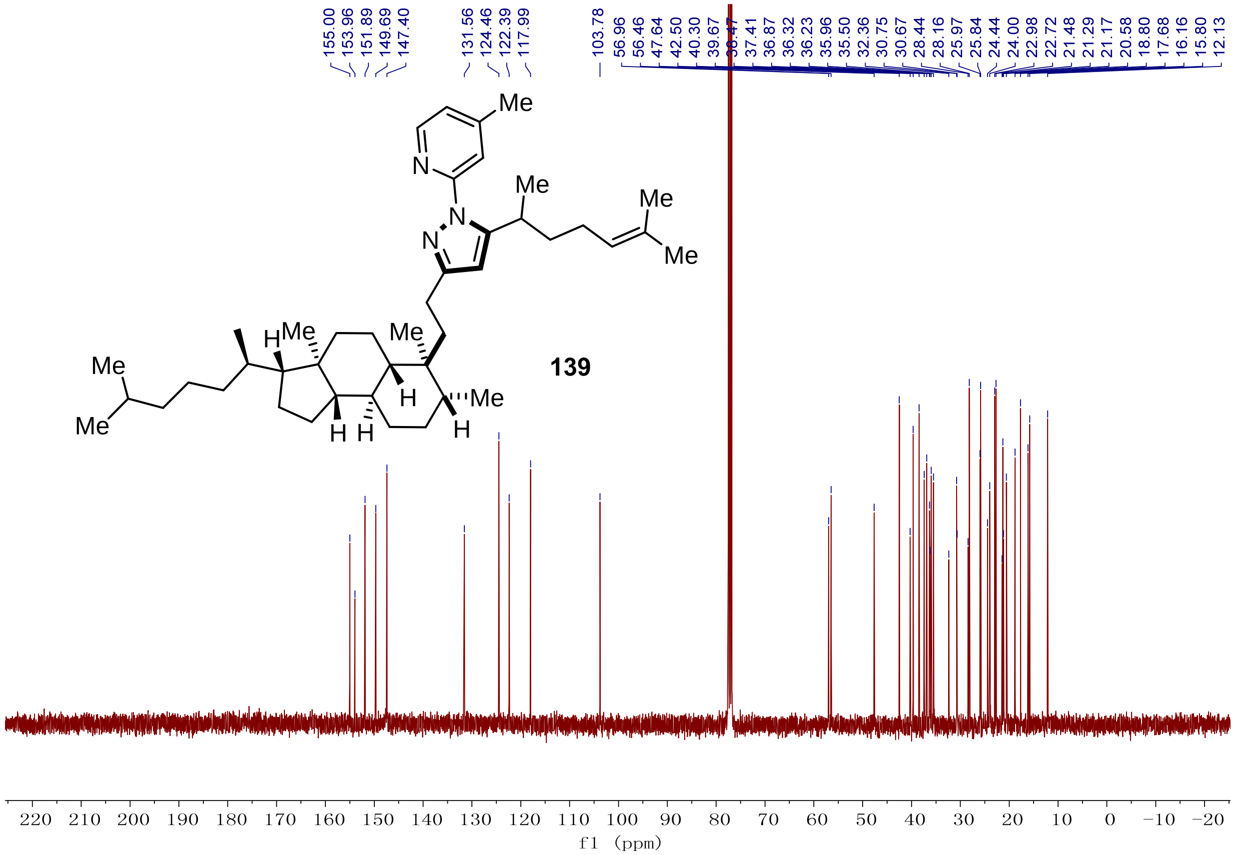
137


8.27
8.26
7.57
6.98
6.98
5.99
5.05
3.83
3.81
2.80
2.79
2.76
2.39
2.25
2.23
2.22
1.99
1.98
1.95
1.93
1.69
1.67
1.66
1.65
1.63
1.62
1.58
1.53
1.51
1.50
1.49
1.46
1.44
1.43
1.42
1.37
1.34
1.33
1.32
1.26
1.25
1.23
1.21
1.18
1.17
1.15
1.14
1.13
1.12
1.11
1.06
1.00
0.99
0.98
0.97
0.91
0.89
0.87
0.87
0.85
0.85
0.83
0.80
0.65
Me
Me
Me
Me
N
N
N
Me
H
Me
Me
Me
Me
H
H
H
H
138
0.98
0.98
0.99
0.99
0.98
0.99
0.95
3.01
1.09
2.97
1.09
10.36
5.05
19.91
15.03
0.93
3.00
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

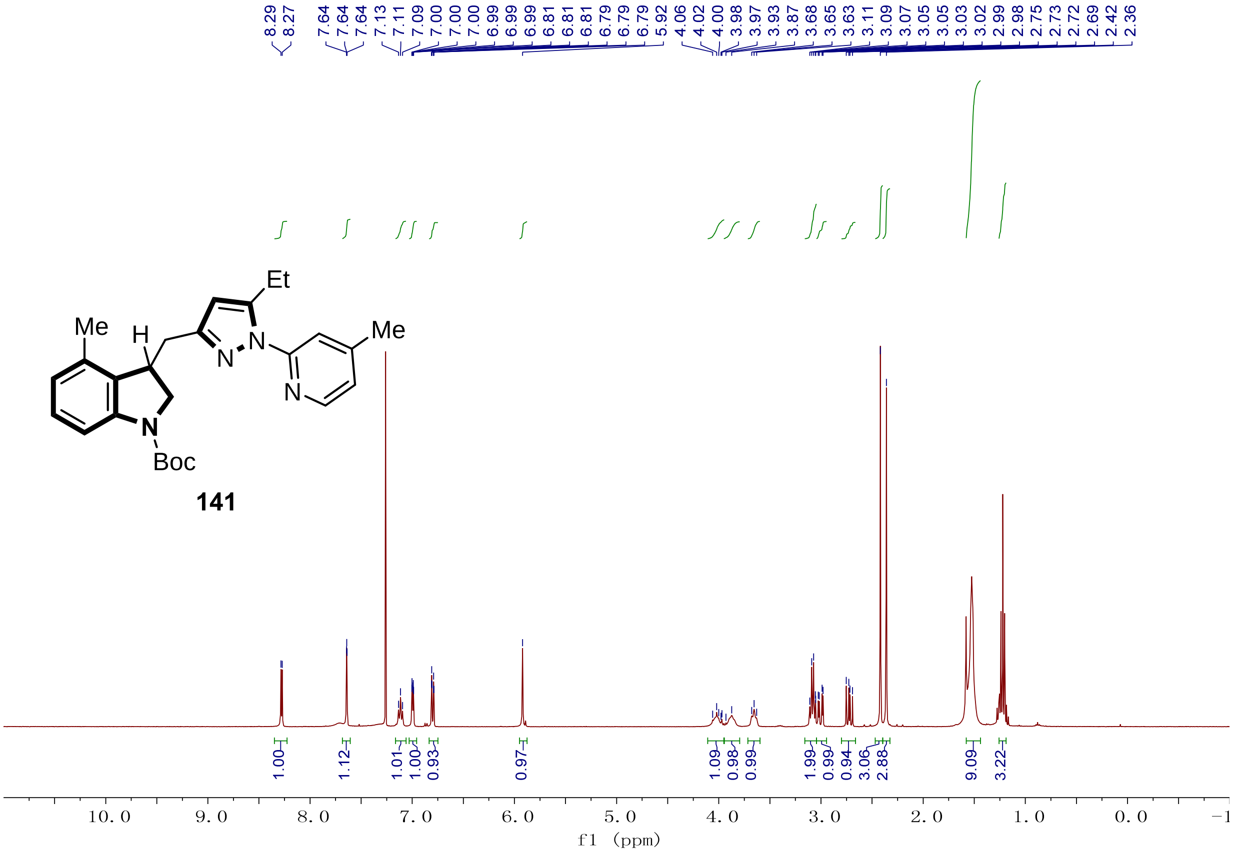

154.43
153.99
151.91
151.86
149.69
147.36
131.57
131.56
124.48
124.45
122.36
118.05
118.01
104.26
104.08
57.01
56.46
47.00
42.51
42.06
42.04
40.34
39.67
38.44
37.46
37.34
36.33
35.95
35.43
32.09
30.78
30.71
29.07
29.02
28.55
28.44
28.17
26.92
26.88
25.98
25.91
25.84
25.83
24.42
23.99
22.98
22.72
21.41
21.29
20.74
20.50
18.82
17.66
17.64
16.65
16.64
12.12
6.75
6.74
Me
Me
Me
Me
N
N
N
Me
H
Me
Me
Me
Me
H
H
H
H
138
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)


8.28
8.28
8.26
8.26
7.59
7.58
7.58
6.99
6.98
6.97
6.97
6.02
5.03
3.81
3.80
2.53
2.50
2.40
1.98
1.96
1.94
1.72
1.71
1.70
1.69
1.68
1.66
1.63
1.63
1.62
1.57
1.53
1.52
1.51
1.50
1.46
1.45
1.43
1.42
1.41
1.37
1.34
1.33
1.25
1.23
1.15
1.13
1.11
1.06
1.04
1.02
1.00
0.91
0.91
0.89
0.89
0.87
0.87
0.86
0.85
0.85
0.84
0.83
0.77
0.65
Me
N
N
N
Me
Me
Me
H
Me
Me
Me
Me
H
Me
H H
H
1.00
0.99
1.00
0.98
1.00
0.98
2.02
3.03
3.05
1.19
14.04
2.30
10.07
9.42
13.07
2.92
2.94
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

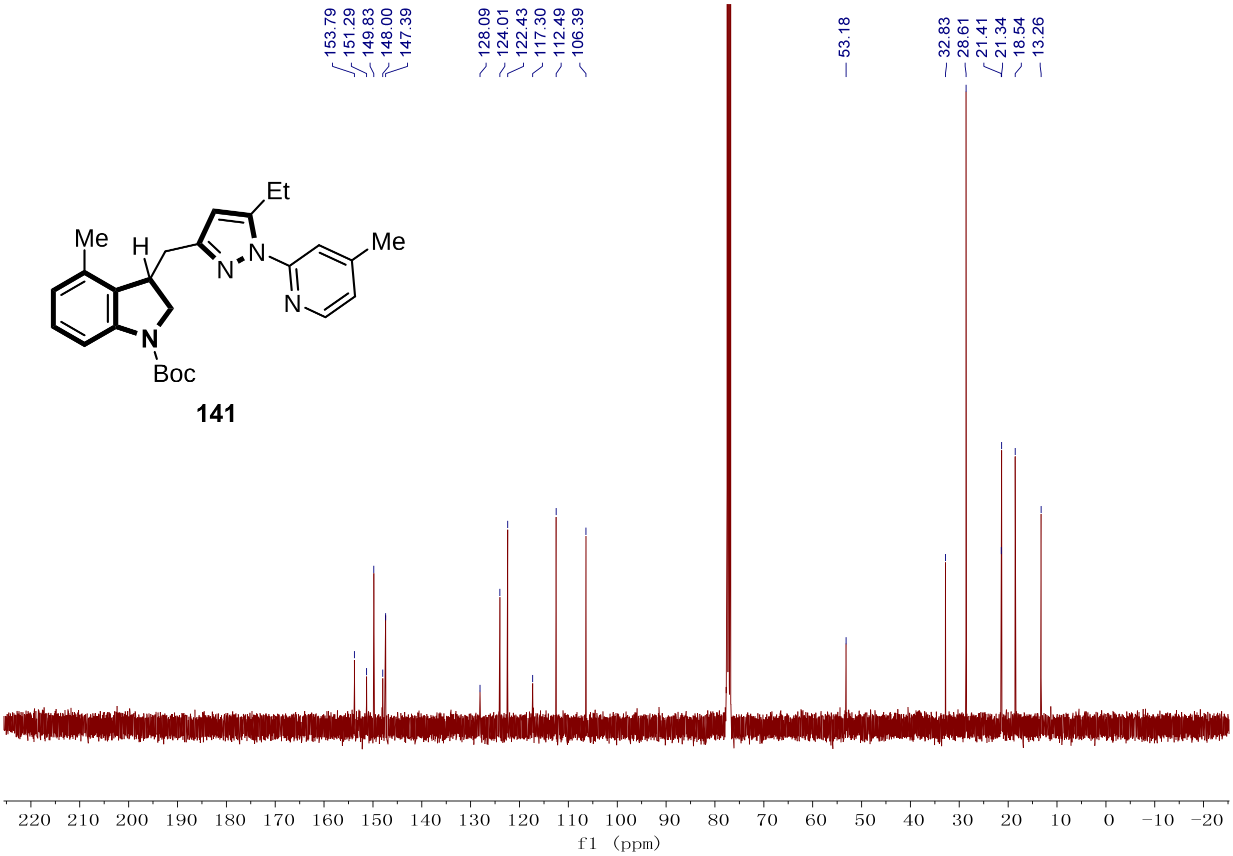
139


155.00
153.96
151.89
149.69
147.40
131.56
124.46
122.39
117.99
103.78
56.96
56.46
47.64
42.50
40.30
39.67
38.47
37.41
36.87
36.32
36.23
35.96
35.50
32.36
30.75
30.67
28.44
28.16
25.97
25.84
24.44
24.00
22.98
22.72
21.48
21.29
21.17
20.58
18.80
17.68
16.16
15.80
12.13
Me
N
N
N
Me
Me
Me
H
Me
Me
Me
Me
H
Me
H H
H
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

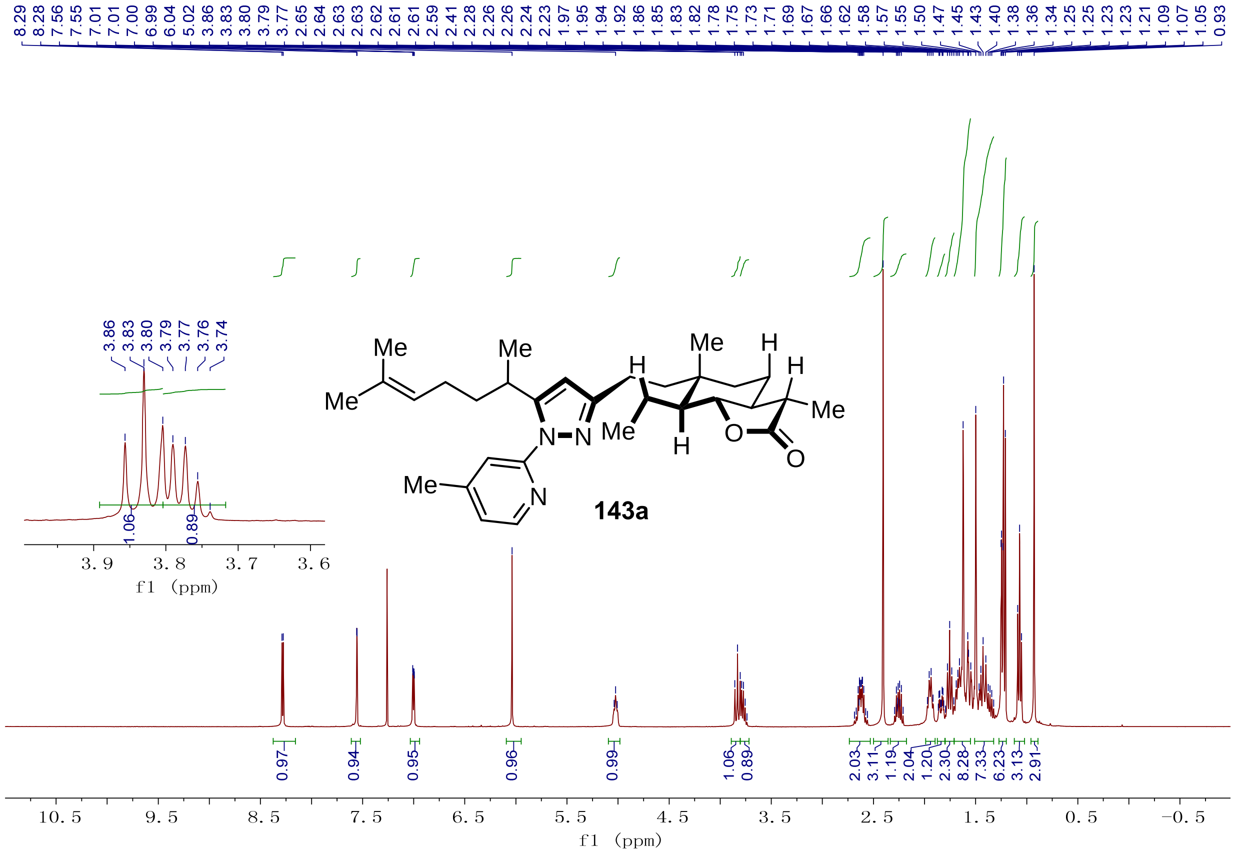
139


8.29
8.27
7.64
7.64
7.64
7.13
7.11
7.09
7.00
7.00
6.99
6.99
6.99
6.81
6.81
6.79
6.79
5.92
4.06
4.02
4.00
3.98
3.97
3.93
3.87
3.68
3.65
3.63
3.11
3.09
3.07
3.05
3.05
3.03
3.02
2.99
2.98
2.75
2.73
2.72
2.69
2.42
2.36
Me
H
Et
N
N
Me
N
N
Boc
1.00
1.12
1.01
1.00
0.93
0.97
1.09
0.98
0.99
1.99
0.99
0.94
3.06
2.88
9.09
3.22
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

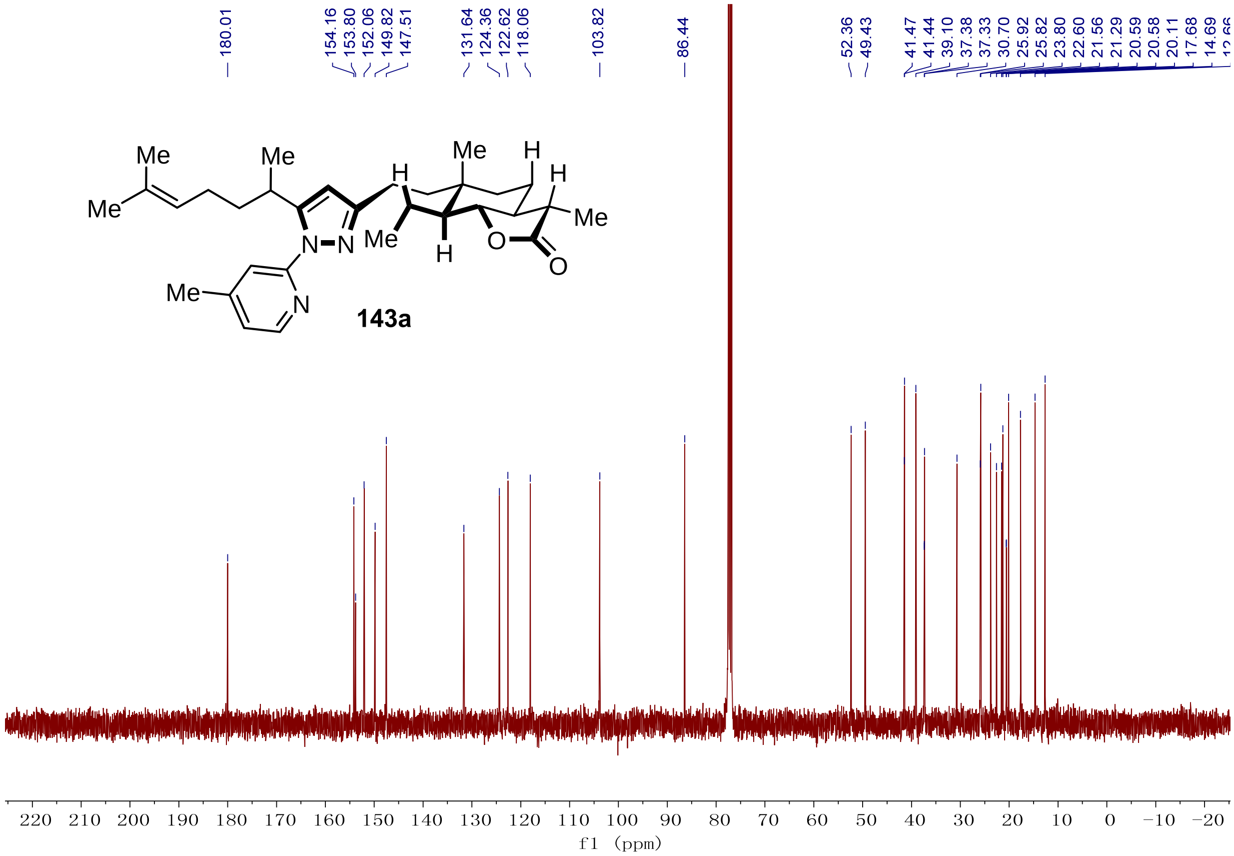
141


153.79
151.29
149.83
148.00
147.39
128.09
124.01
122.43
117.30
112.49
106.39
53.18
32.83
28.61
21.41
21.34
18.54
13.26
Me
H
Et
N
N
Me
N
N
Boc
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

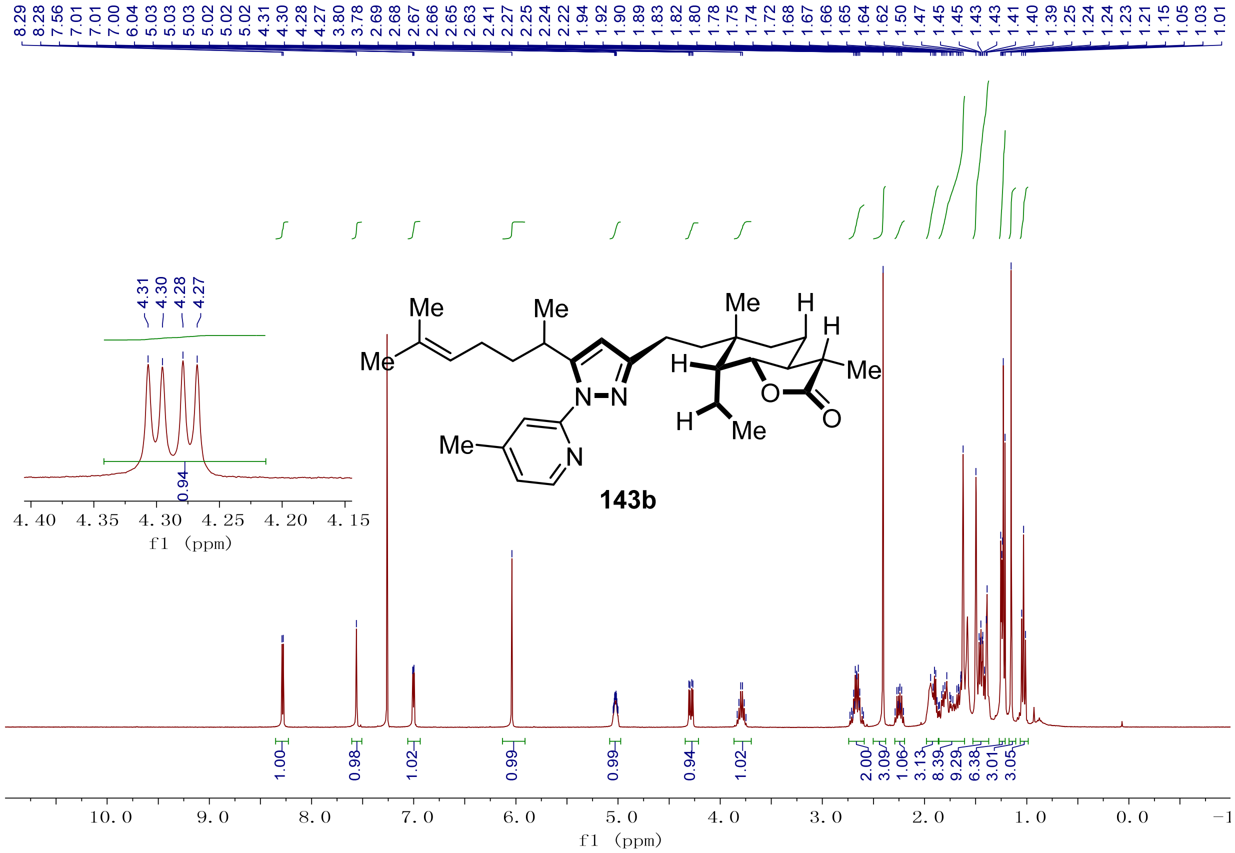
141


143a

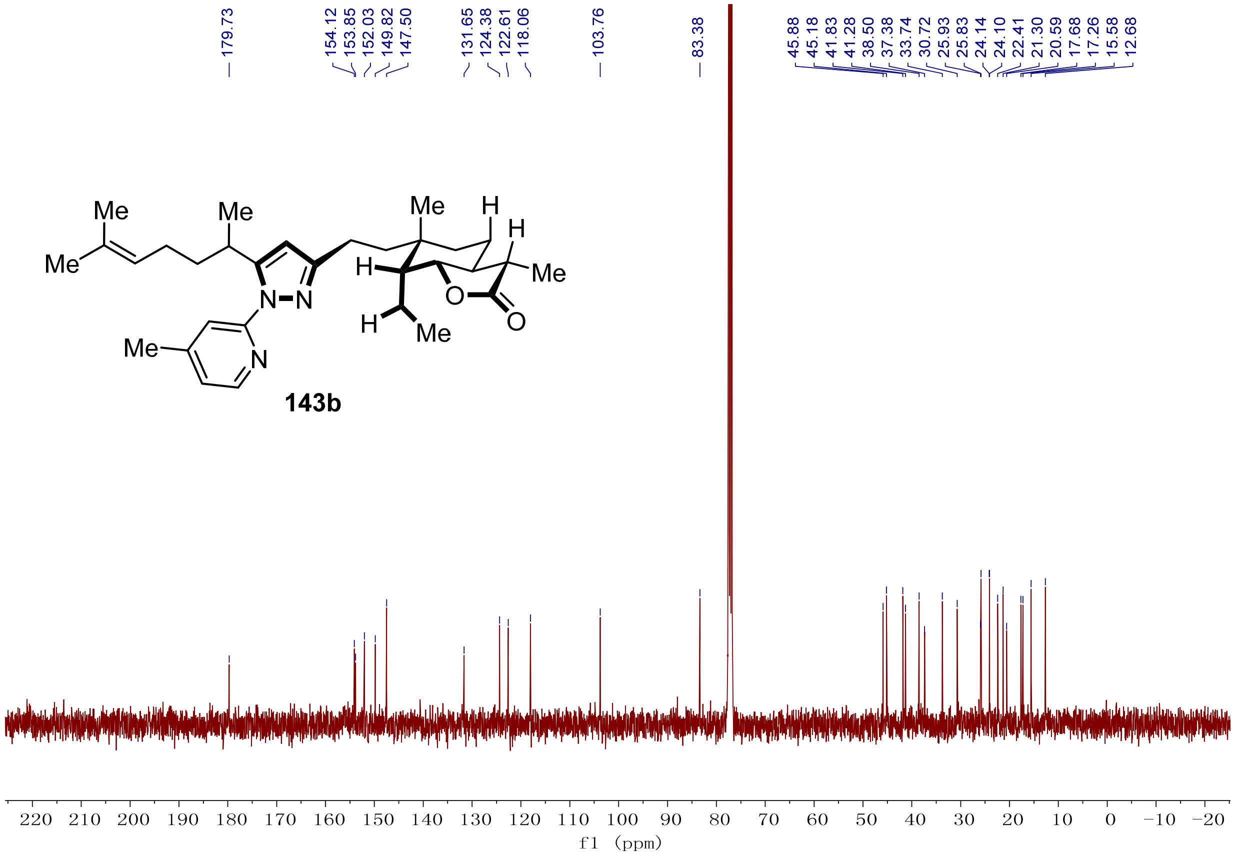
8.29 8.28 7.56 7.55 7.01 7.01 7.00 6.99 6.04 5.02 3.86 3.83 3.80 3.79 3.77 2.65 2.64 2.63 2.63 2.62 2.61 2.61 2.59 2.41 2.28 2.26 2.26 2.24 2.23 1.97 1.95 1.94 1.92 1.86 1.85 1.83 1.82 1.78 1.75 1.73 1.71 1.69 1.67 1.66 1.62 1.58 1.57 1.55 1.50 1.47 1.45 1.43 1.40 1.38 1.36 1.34 1.25 1.25 1.23 1.23 1.21 1.09 1.07 1.05 0.93
3.86 3.83 3.80 3.79 3.77 3.76 3.74
1.06 0.89
3.9 3.8 3.7 3.6
f1 (ppm)
Me
Me
Me
Me
H
H
H
Me
N
N
Me
H
O
O
Me
N
0.97 0.94 0.95 0.96 0.99 1.06 0.89 2.03 3.11 1.19 2.04 1.20 2.30 8.28 7.33 6.23 3.13 2.91
10.5 9.5 8.5 7.5 6.5 5.5 4.5 3.5 2.5 1.5 0.5 −0.5
f1 (ppm)


143a

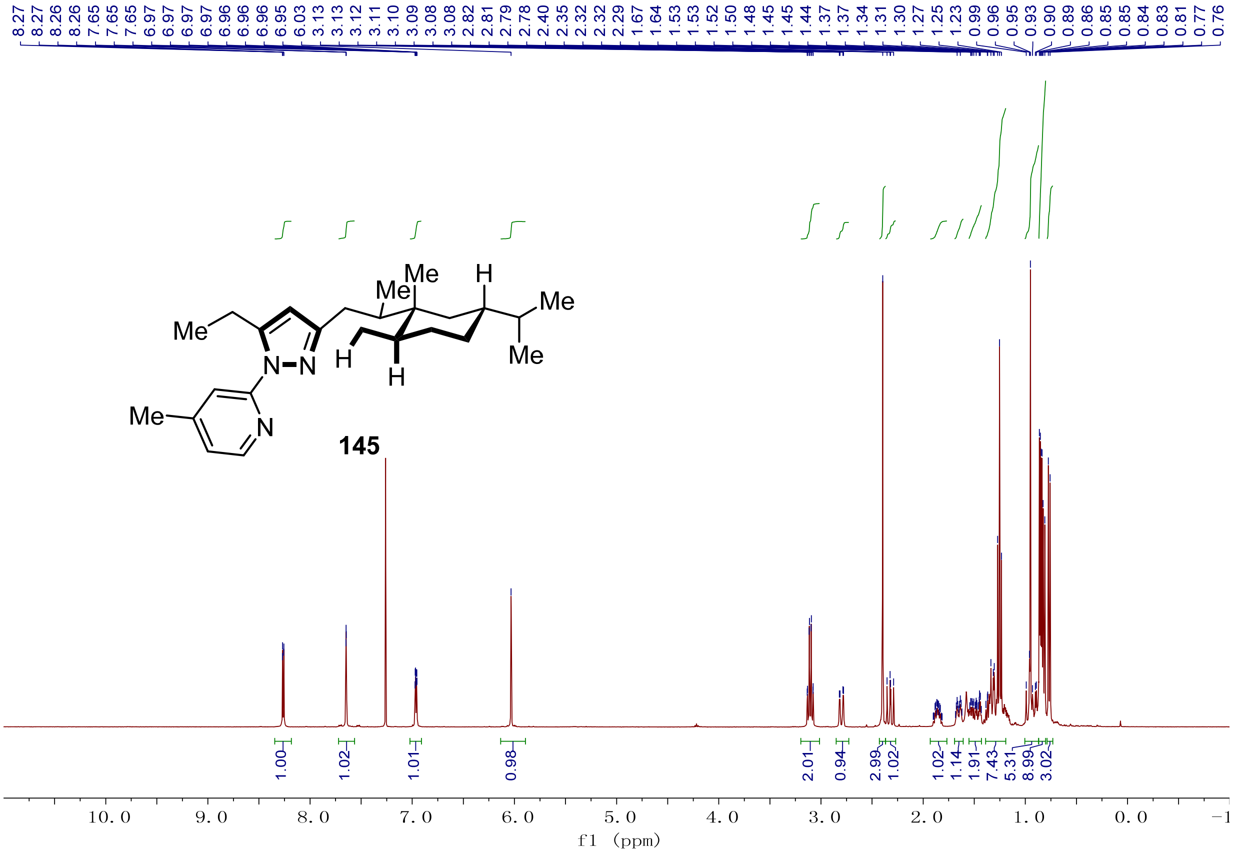
180.01
154.16 153.80 152.06 149.82 147.51
131.64 124.36 122.62 118.06
103.82
86.44
52.36 49.43
41.47 41.44 39.10 37.38 37.33 30.70 25.92 25.82 23.80 22.60 21.56 21.29 20.59 20.58 20.11 17.68 14.69 12.6
Me
Me
Me
Me
H
H
H
Me
N
N
Me
H
O
O
Me
N
220 210 200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 −10 −20
f1 (ppm)

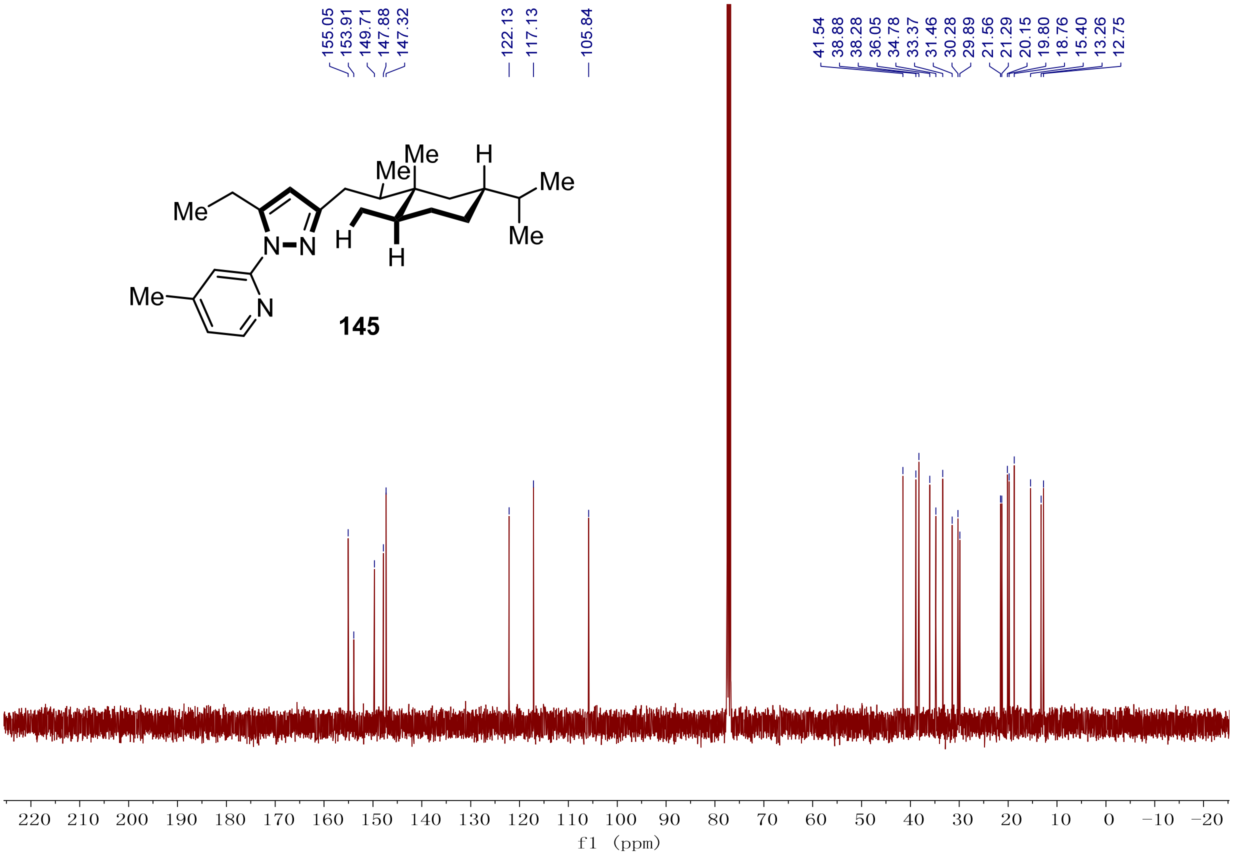


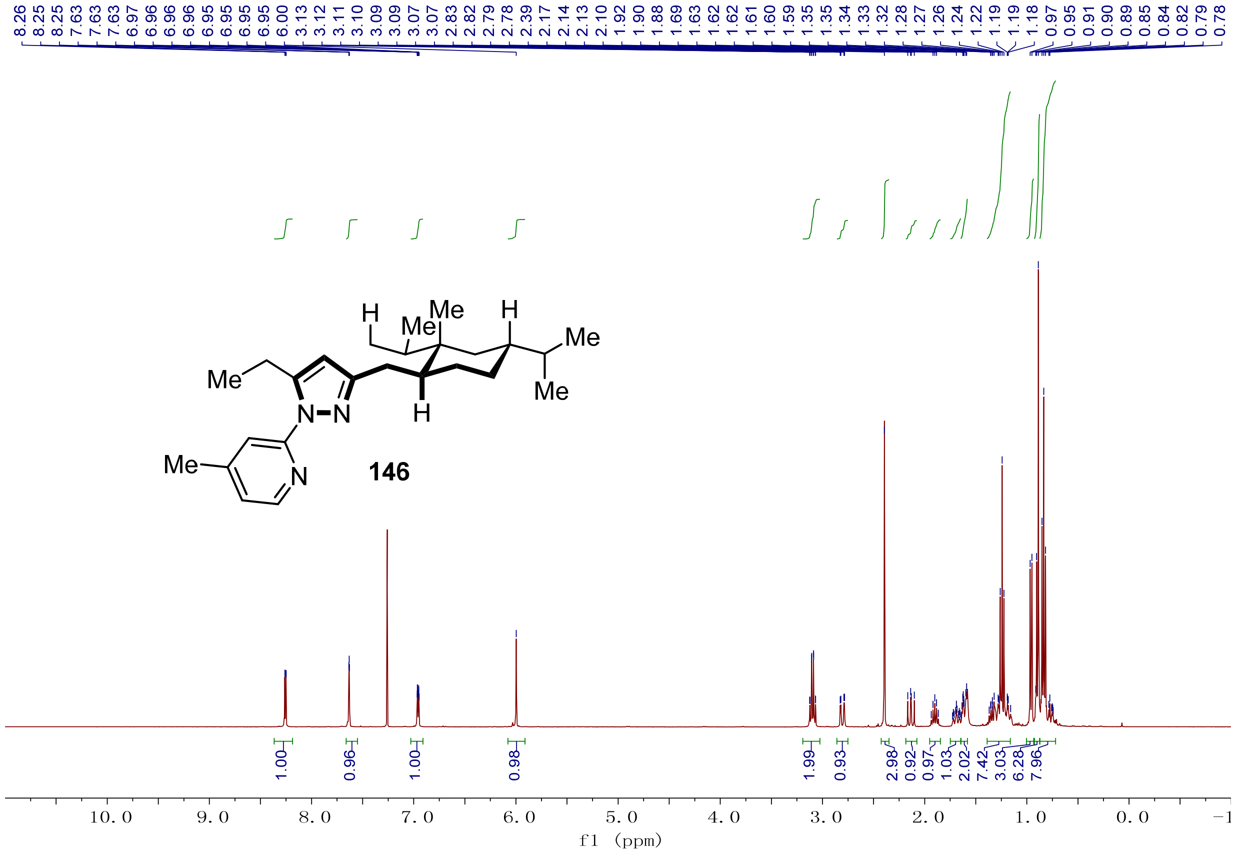
8.29
8.28
7.56
7.01
7.00
6.04
5.03
5.03
5.03
5.02
5.02
5.02
4.31
4.30
4.28
4.27
3.80
3.78
2.69
2.68
2.67
2.66
2.65
2.63
2.41
2.27
2.25
2.24
2.22
1.94
1.92
1.90
1.89
1.83
1.82
1.80
1.78
1.75
1.74
1.72
1.68
1.67
1.66
1.65
1.64
1.62
1.50
1.47
1.45
1.45
1.43
1.43
1.41
1.40
1.39
1.25
1.24
1.24
1.23
1.21
1.15
1.05
1.03
1.01
4.31
4.30
4.28
4.27
0.94
4.40
4.35
4.30
4.25
4.20
4.15
f1 (ppm)
Me
Me
Me
N
N
Me
N
Me
H
H
H
O
O
Me
H
Me
143b
1.00
0.98
1.02
0.99
0.99
0.94
1.02
2.00
3.09
1.06
3.13
8.39
9.29
6.38
3.01
3.05
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

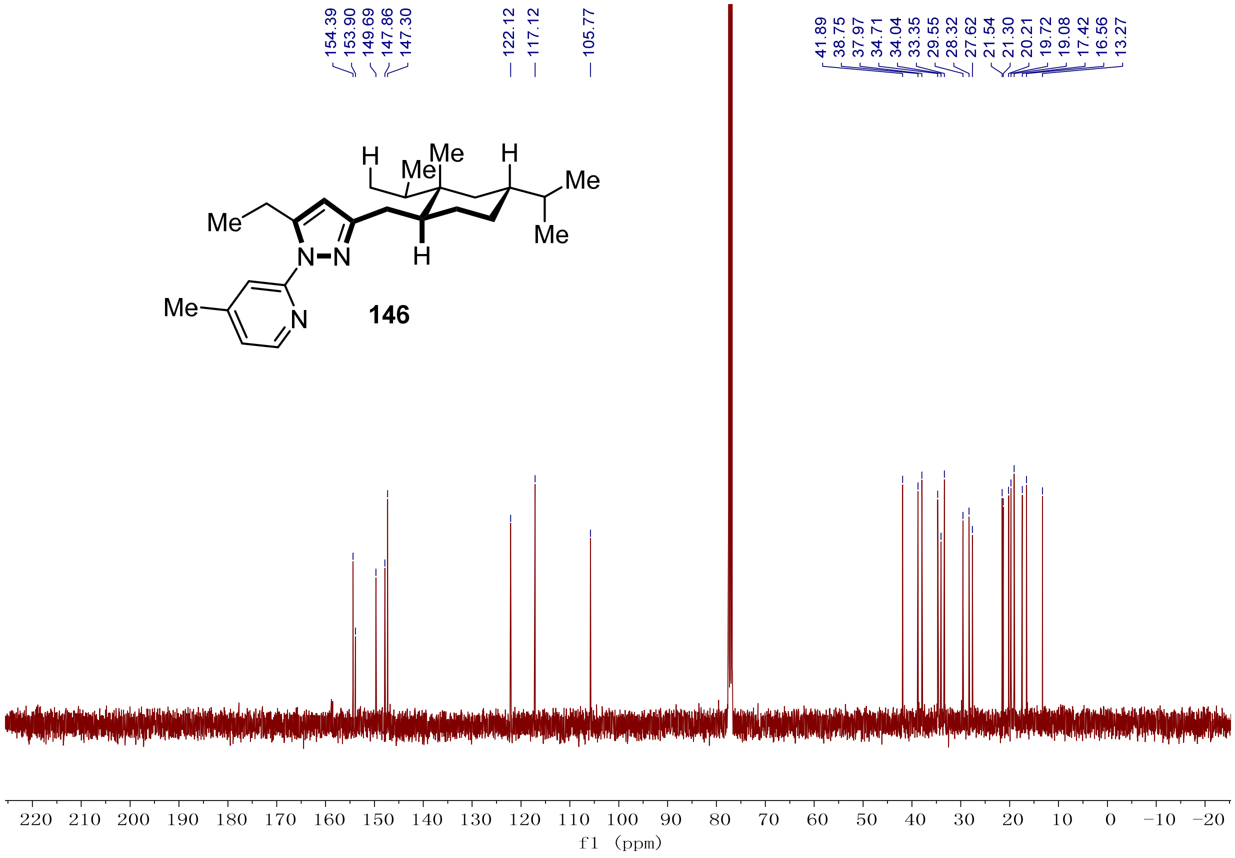


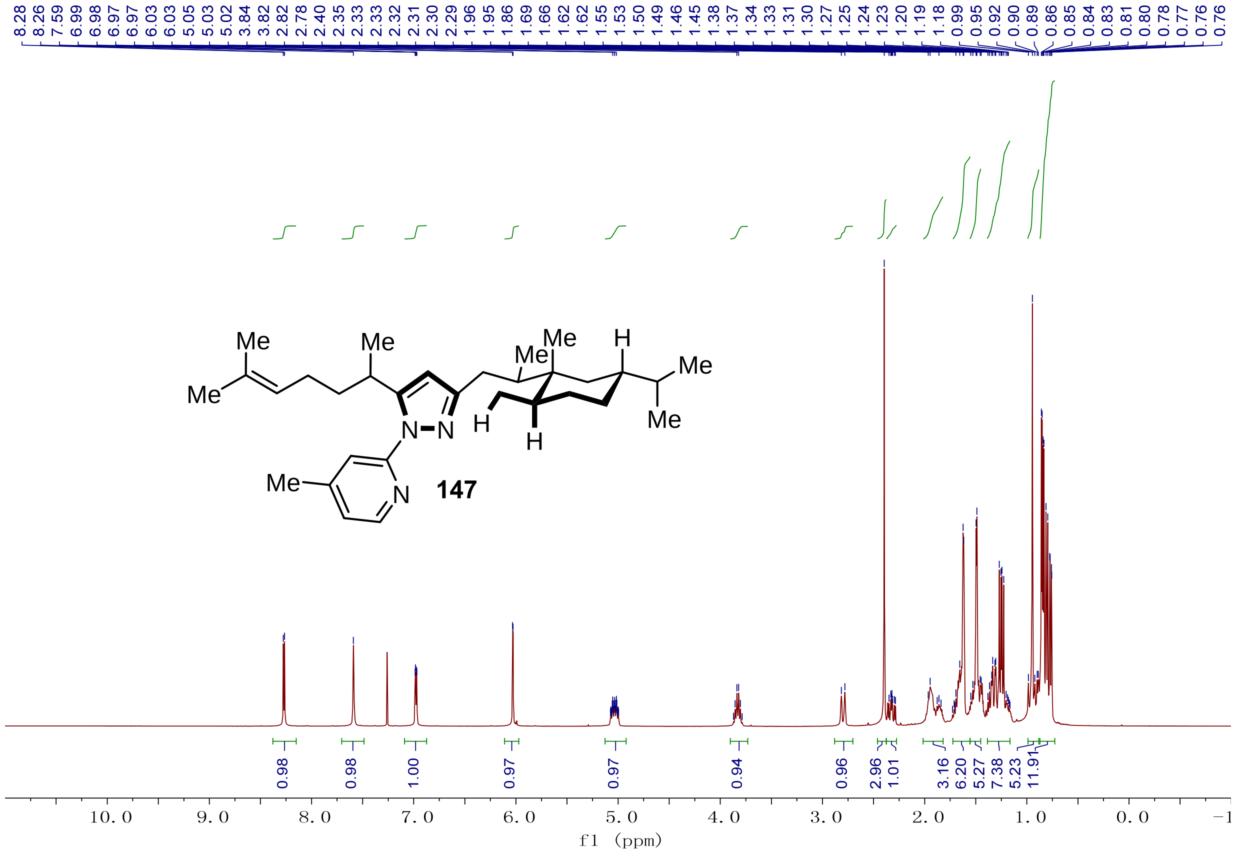
179.73
154.12
153.85
152.03
149.82
147.50
131.65
124.38
122.61
118.06
103.76
83.38
45.88
45.18
41.83
41.28
38.50
37.38
33.74
30.72
25.93
25.83
24.14
24.10
22.41
21.30
20.59
17.68
17.26
15.58
12.68
Me
Me
Me
N
N
Me
N
Me
H
H
H
O
O
Me
H
Me
143b
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)


8.27
8.27
8.26
8.26
7.65
7.65
6.97
6.97
6.97
6.97
6.96
6.96
6.96
6.95
6.03
3.13
3.13
3.12
3.11
3.10
3.09
3.08
3.08
2.82
2.81
2.79
2.78
2.40
2.35
2.32
2.32
2.29
1.67
1.64
1.53
1.53
1.52
1.50
1.48
1.45
1.45
1.44
1.37
1.37
1.34
1.31
1.30
1.27
1.25
1.23
0.99
0.96
0.95
0.93
0.90
0.89
0.86
0.85
0.85
0.84
0.83
0.81
0.77
0.76
Me
Me
H
Me
Me
N
N
H
H
Me
Me
N
145
1.00
1.02
1.01
0.98
2.01
0.94
2.99
1.02
1.02
1.14
1.91
7.43
5.31
8.99
3.02
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

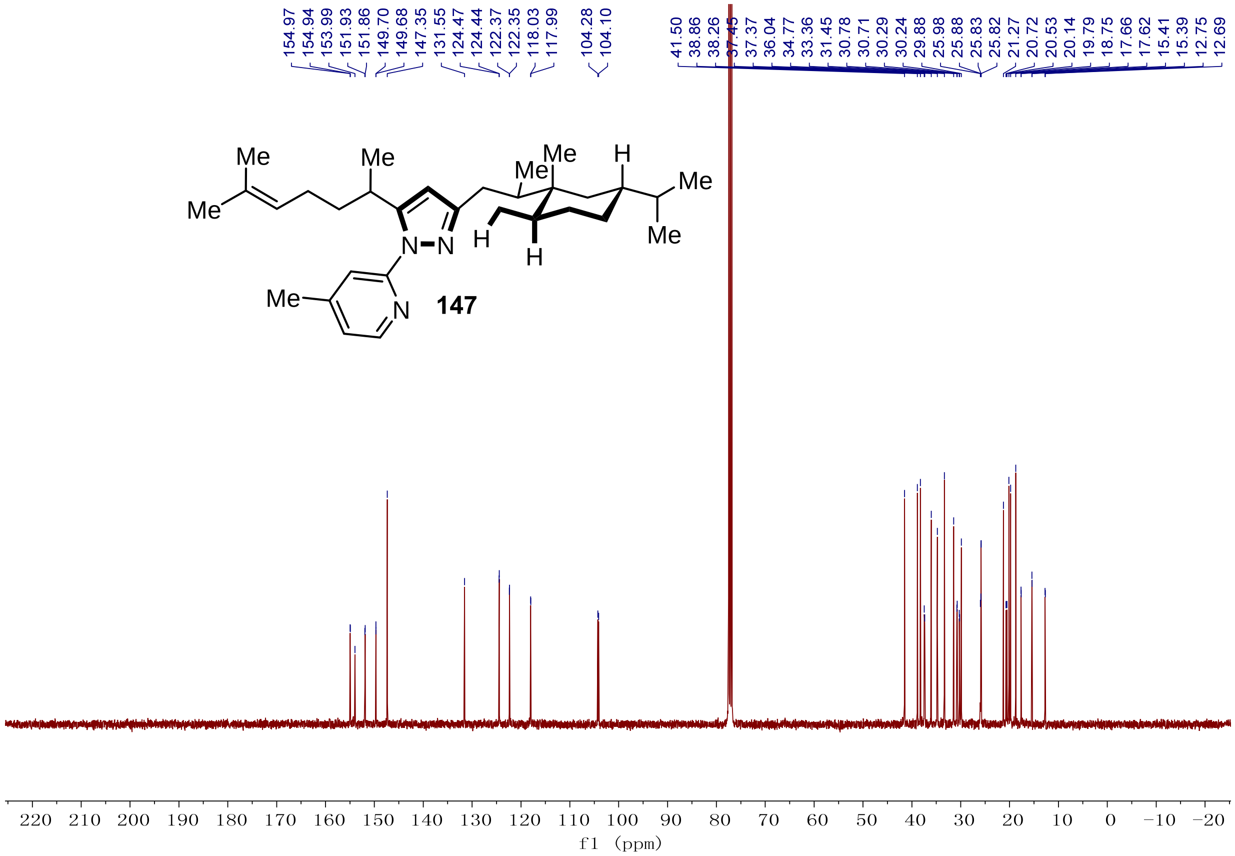

155.05
153.91
149.71
147.88
147.32
122.13
117.13
105.84
41.54
38.88
38.28
36.05
34.78
33.37
31.46
30.28
29.89
21.56
21.29
20.15
19.80
18.76
15.40
13.26
12.75
Me
Me
H
Me
Me
N
N
H
H
Me
Me
N
145
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)


8.26
8.25
8.25
7.63
7.63
6.97
6.96
6.96
6.96
6.95
6.95
6.95
6.95
6.00
3.13
3.12
3.11
3.10
3.09
3.09
3.07
3.07
2.83
2.82
2.79
2.78
2.39
2.17
2.14
2.13
2.10
1.92
1.90
1.88
1.69
1.63
1.62
1.62
1.61
1.60
1.59
1.35
1.35
1.34
1.33
1.32
1.28
1.27
1.26
1.24
1.22
1.19
1.19
1.18
0.97
0.95
0.91
0.90
0.89
0.85
0.84
0.82
0.79
0.78
H
Me
Me
H
Me
Me
Me
N
N
Me
N
146
1.00
0.96
1.00
0.98
1.99
0.93
2.98
0.92
0.97
1.03
2.02
7.42
3.03
6.28
7.96
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

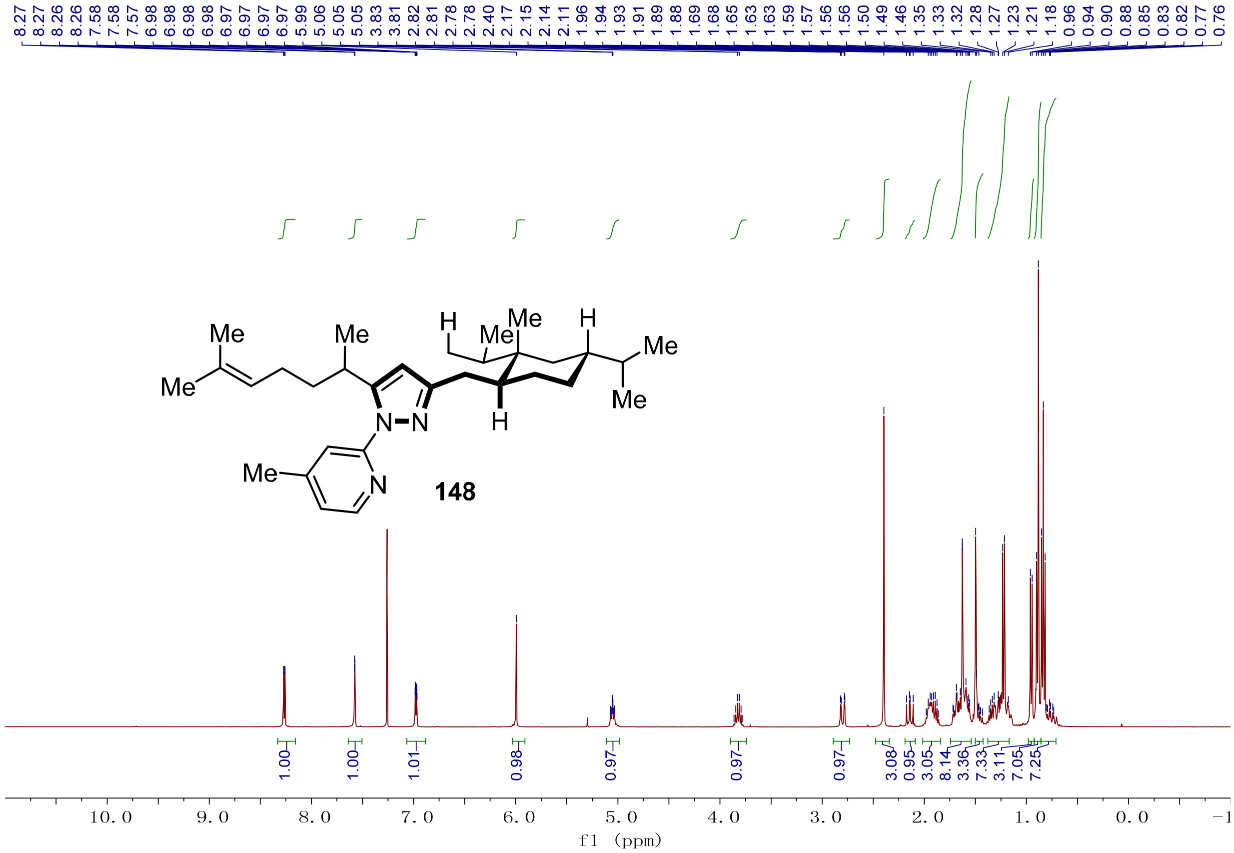

154.39
153.90
149.69
147.86
147.30
122.12
117.12
105.77
41.89
38.75
37.97
34.71
34.04
33.35
29.55
28.32
27.62
21.54
21.30
20.21
19.72
19.08
17.42
16.56
13.27
H
Me
Me
H
Me
Me
Me
N
N
Me
N
146
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

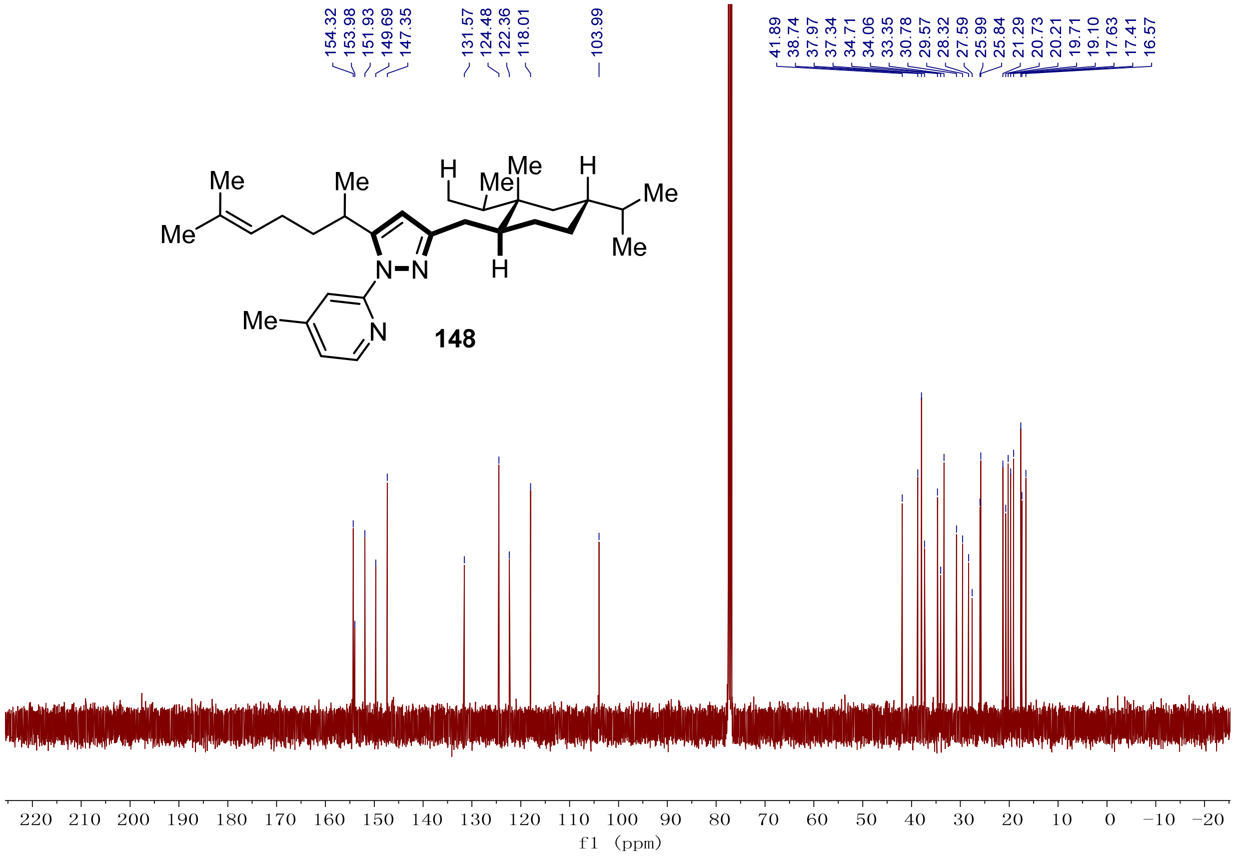

8.28
8.26
7.59
6.99
6.98
6.97
6.97
6.03
6.03
5.05
5.03
5.02
3.84
3.82
2.82
2.78
2.40
2.35
2.33
2.33
2.32
2.31
2.30
2.29
1.96
1.95
1.86
1.69
1.66
1.62
1.62
1.55
1.53
1.50
1.49
1.46
1.45
1.38
1.37
1.34
1.33
1.31
1.30
1.27
1.25
1.24
1.23
1.20
1.19
1.18
0.99
0.95
0.92
0.90
0.89
0.86
0.85
0.84
0.83
0.81
0.80
0.78
0.77
0.76
0.76
Me
Me
Me
Me
Me
H
Me
Me
N
N
H
H
Me
N
0.98
0.98
1.00
0.97
0.97
0.94
0.96
2.96
1.01
3.16
6.20
5.27
7.38
5.23
11.91
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

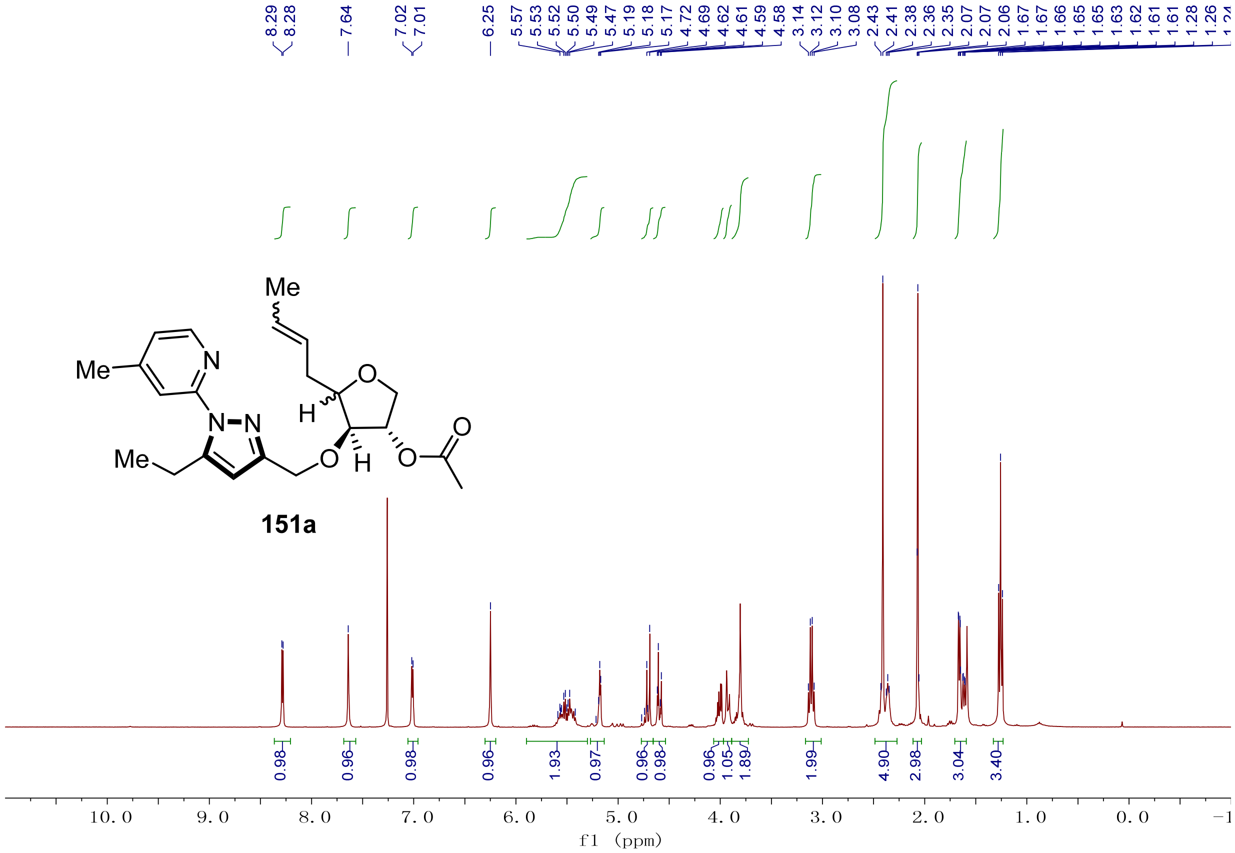
147


154.97
154.94
153.99
151.93
151.86
149.70
149.68
147.35
131.55
124.47
124.44
122.37
122.35
118.03
117.99
104.28
104.10
41.50
38.86
38.26
37.45
37.37
36.04
34.77
33.36
31.45
30.78
30.71
30.29
30.24
29.88
25.98
25.88
25.83
25.82
21.27
20.72
20.53
20.14
19.79
18.75
17.66
17.62
15.41
15.39
12.75
12.69
Me
Me
Me
Me
Me
H
Me
Me
N
N
H
H
Me
N
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

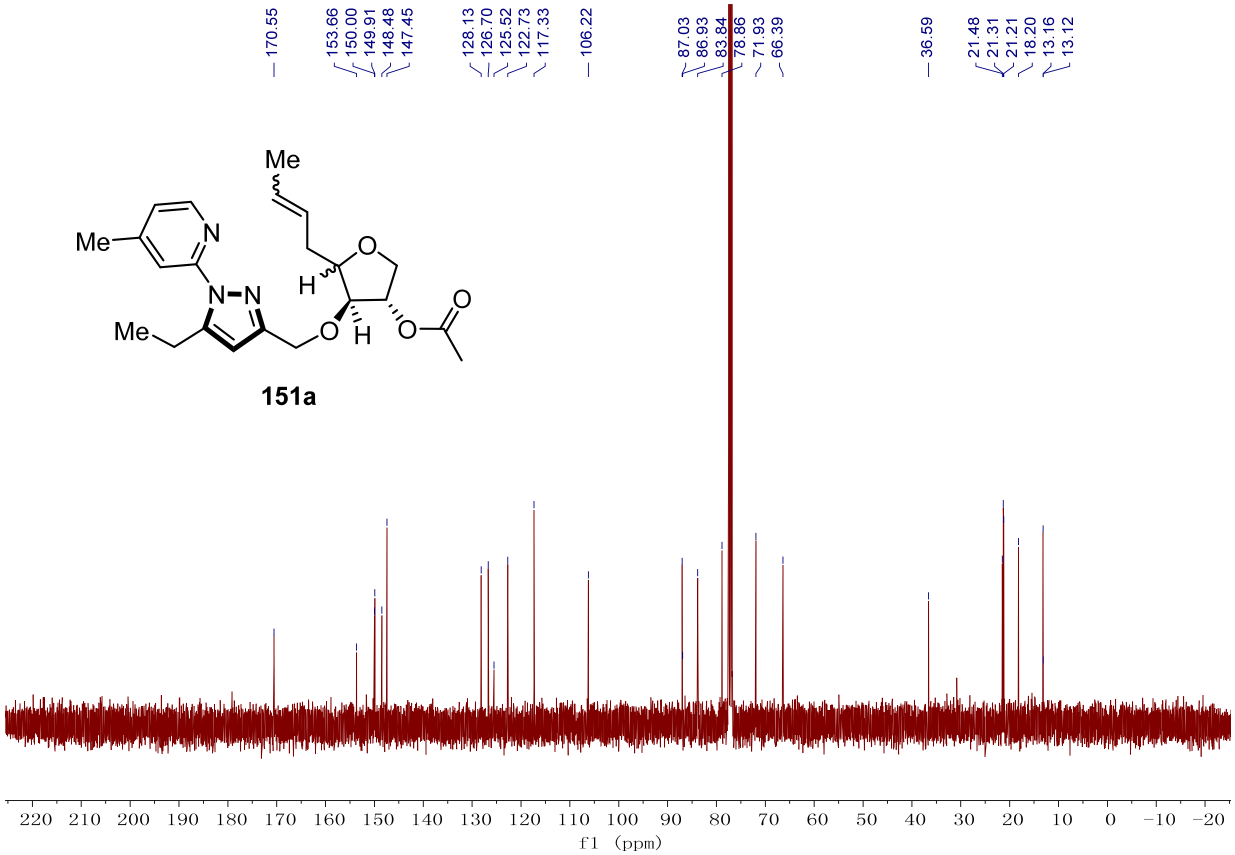
147


8.27
8.27
8.26
8.26
7.58
7.58
7.57
6.98
6.98
6.98
6.98
6.97
6.97
6.97
6.97
5.99
5.06
5.05
5.05
3.83
3.81
2.82
2.81
2.78
2.78
2.40
2.17
2.15
2.14
2.11
1.96
1.94
1.93
1.91
1.89
1.88
1.69
1.68
1.65
1.63
1.63
1.59
1.57
1.56
1.50
1.49
1.46
1.35
1.33
1.32
1.28
1.27
1.23
1.21
1.18
0.96
0.94
0.90
0.88
0.85
0.83
0.82
0.77
0.76
Me
Me
Me
H
Me
Me
H
Me
Me
N
N
H
Me
N
148
1.00
1.00
1.01
0.98
0.97
0.97
0.97
3.08
0.95
3.05
8.14
3.36
7.33
3.11
7.05
7.25
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

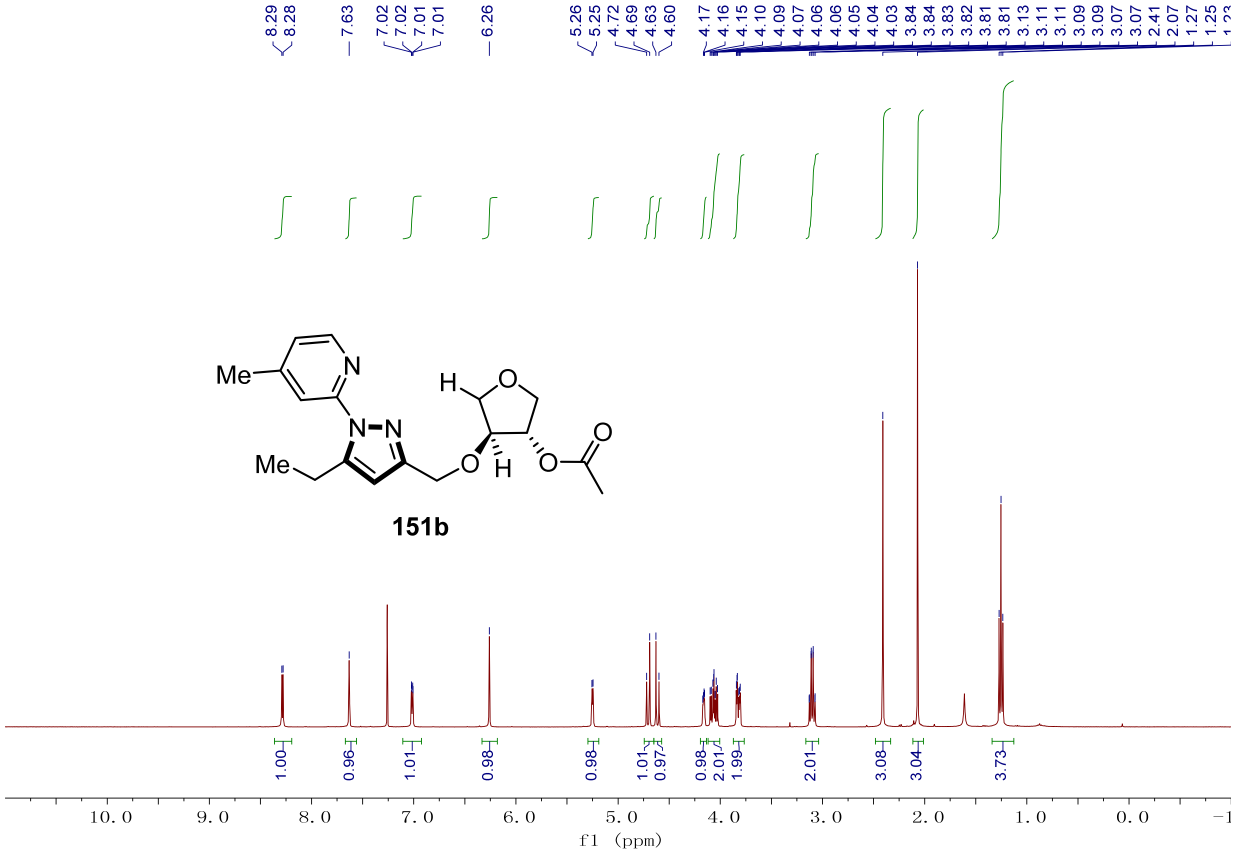

154.32
153.98
151.93
149.69
147.35
131.57
124.48
122.36
118.01
103.99
41.89
38.74
37.97
37.34
34.71
34.06
33.35
30.78
29.57
28.32
27.59
25.99
25.84
21.29
20.73
20.21
19.71
19.10
17.63
17.41
16.57
Me
Me
Me
H
Me
Me
H
Me
Me
N
N
H
Me
N
148
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)


8.29
8.28
7.64
7.02
7.01
6.25
5.57
5.53
5.52
5.50
5.49
5.47
5.19
5.18
5.17
4.72
4.69
4.62
4.61
4.59
4.58
3.14
3.12
3.10
3.08
2.43
2.41
2.38
2.36
2.35
2.07
2.07
2.06
1.67
1.67
1.66
1.65
1.65
1.63
1.62
1.61
1.61
1.28
1.26
Me
Me
N
N
N
O
H
H
O
O
O
Me
0.98
0.96
0.98
0.96
1.93
0.97
0.96
0.98
0.96
1.05
1.89
1.99
4.90
2.98
3.04
3.40
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

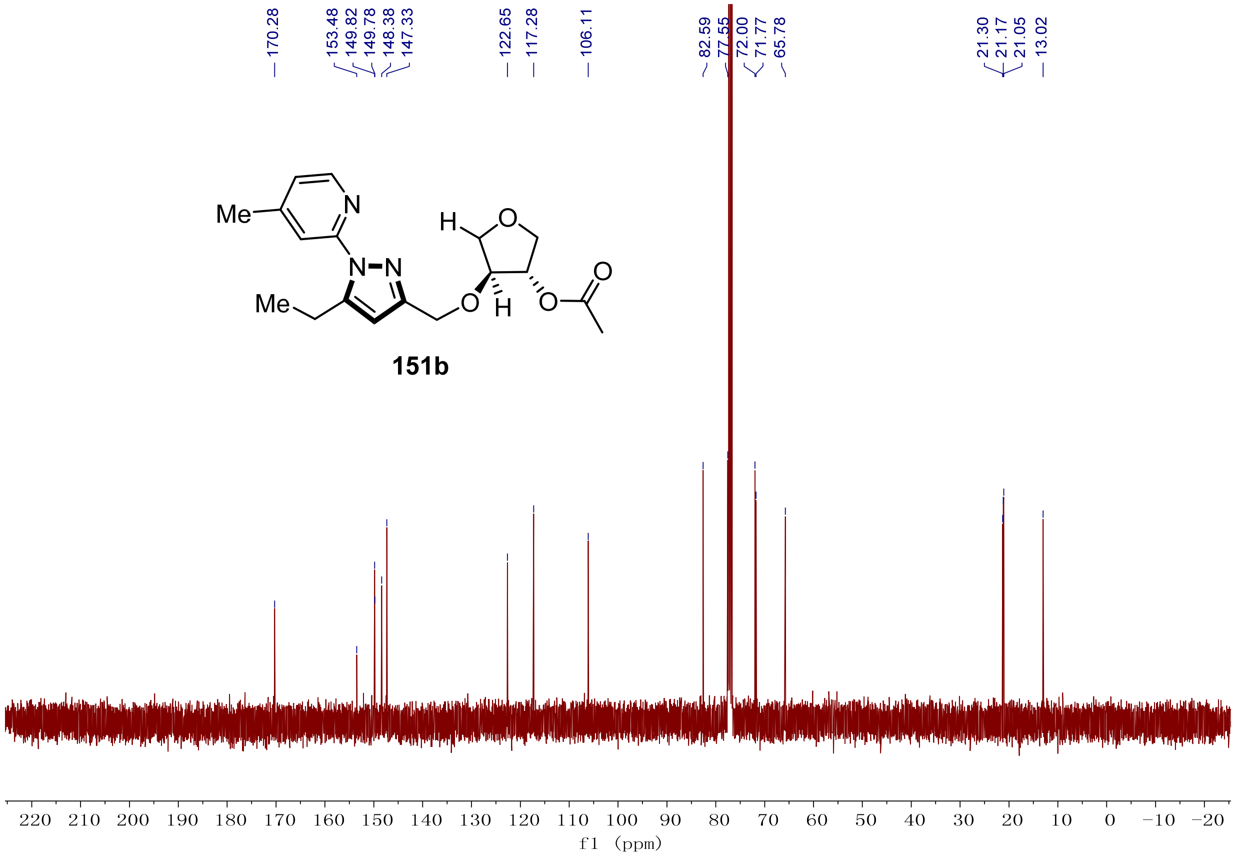
151a


170.55
153.66
150.00
149.91
148.48
147.45
128.13
126.70
125.52
122.73
117.33
106.22
87.03
86.93
83.84
78.86
71.93
66.39
36.59
21.48
21.31
21.21
18.20
13.16
13.12
Me
Me
N
N
N
O
H
H
O
O
O
Me
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

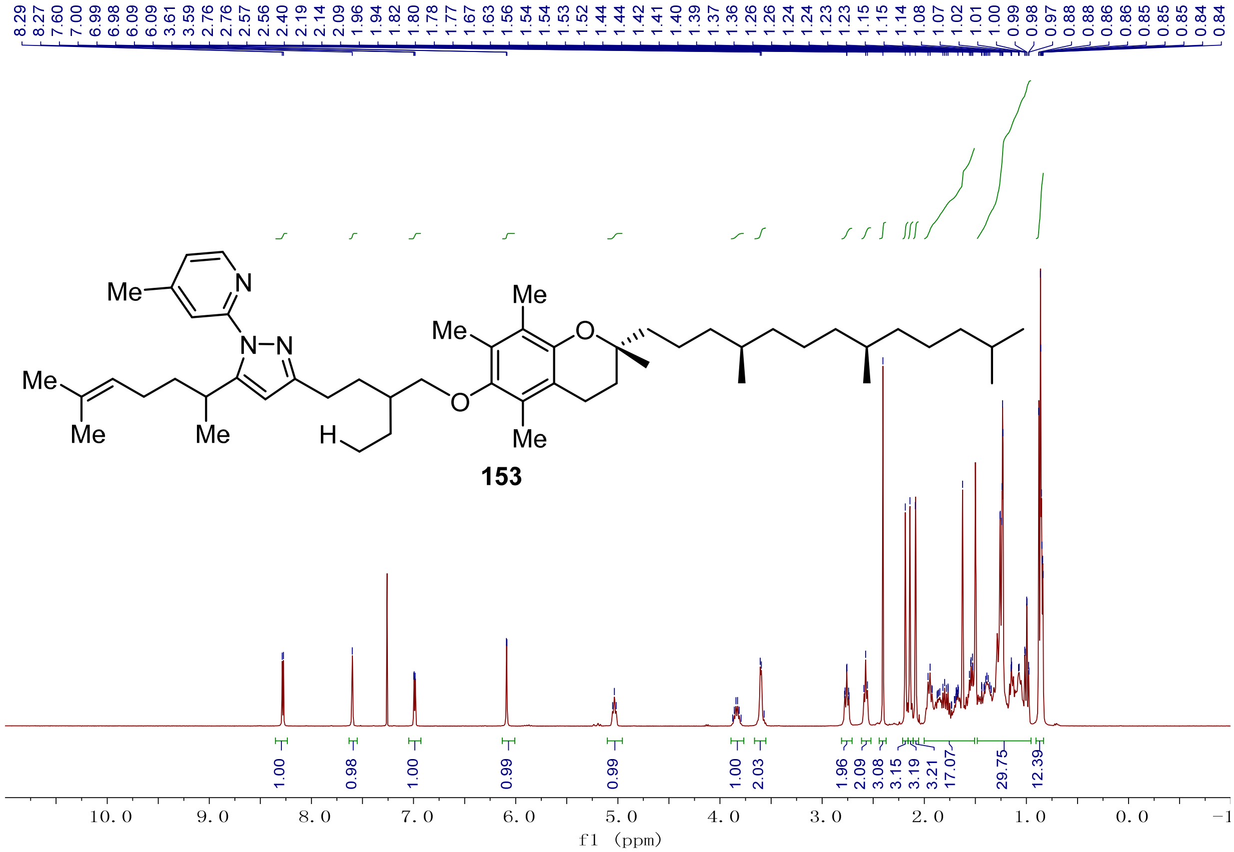
151a


8.29
8.28
7.63
7.02
7.02
7.01
7.01
6.26
5.26
5.25
4.72
4.69
4.63
4.60
4.17
4.16
4.15
4.10
4.09
4.07
4.06
4.06
4.05
4.04
4.03
3.84
3.84
3.83
3.82
3.81
3.81
3.13
3.11
3.11
3.09
3.09
3.07
3.07
2.41
2.07
1.27
1.25
1.2
Me
N
H
O
N
N
Me
O
H
O
O
1.00
0.96
1.01
0.98
0.98
1.01
0.97
0.98
2.01
1.99
2.01
3.08
3.04
3.73
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

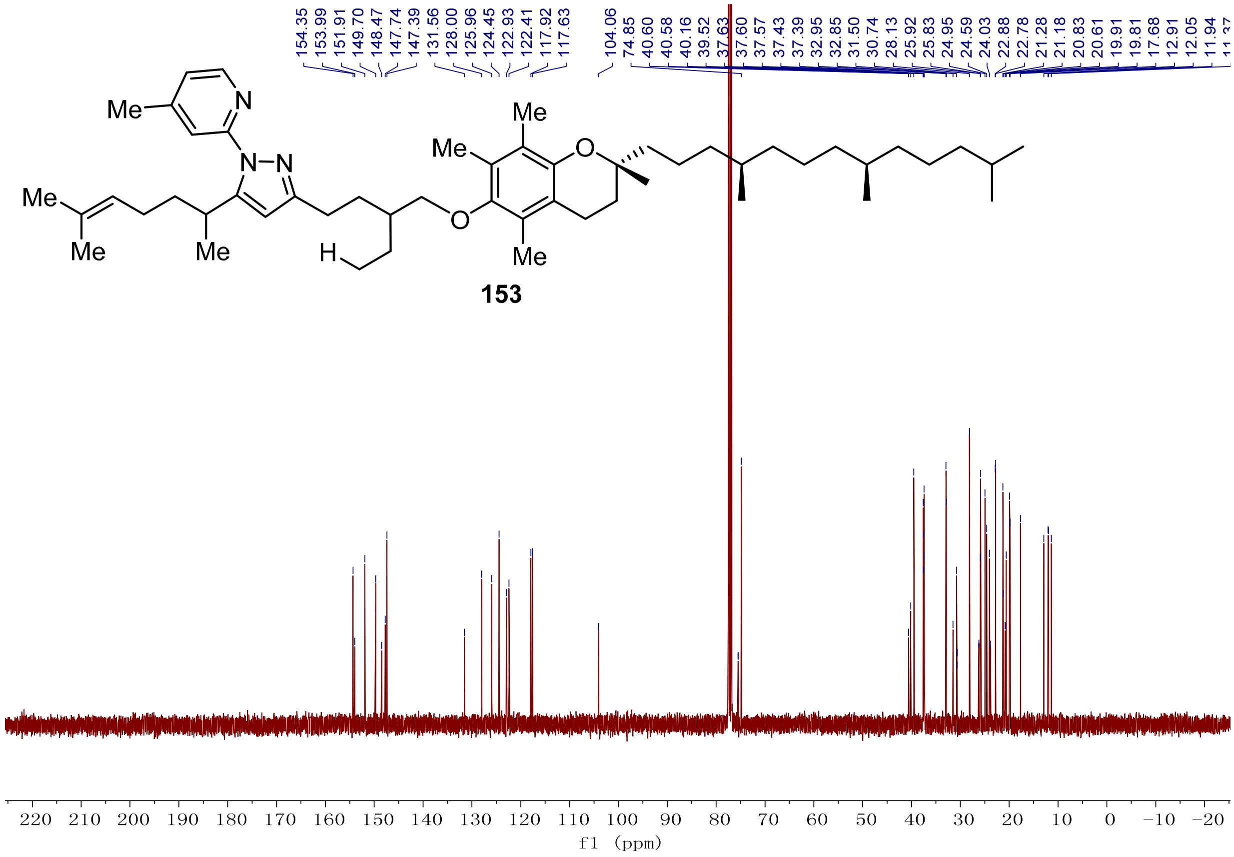
151b


170.28
153.48
149.82
149.78
148.38
147.33
122.65
117.28
106.11
82.59
77.55
72.00
71.77
65.78
21.30
21.17
21.05
13.02
Me
N
H
O
N
N
Me
O
H
O
O
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
−10
−20
f1 (ppm)

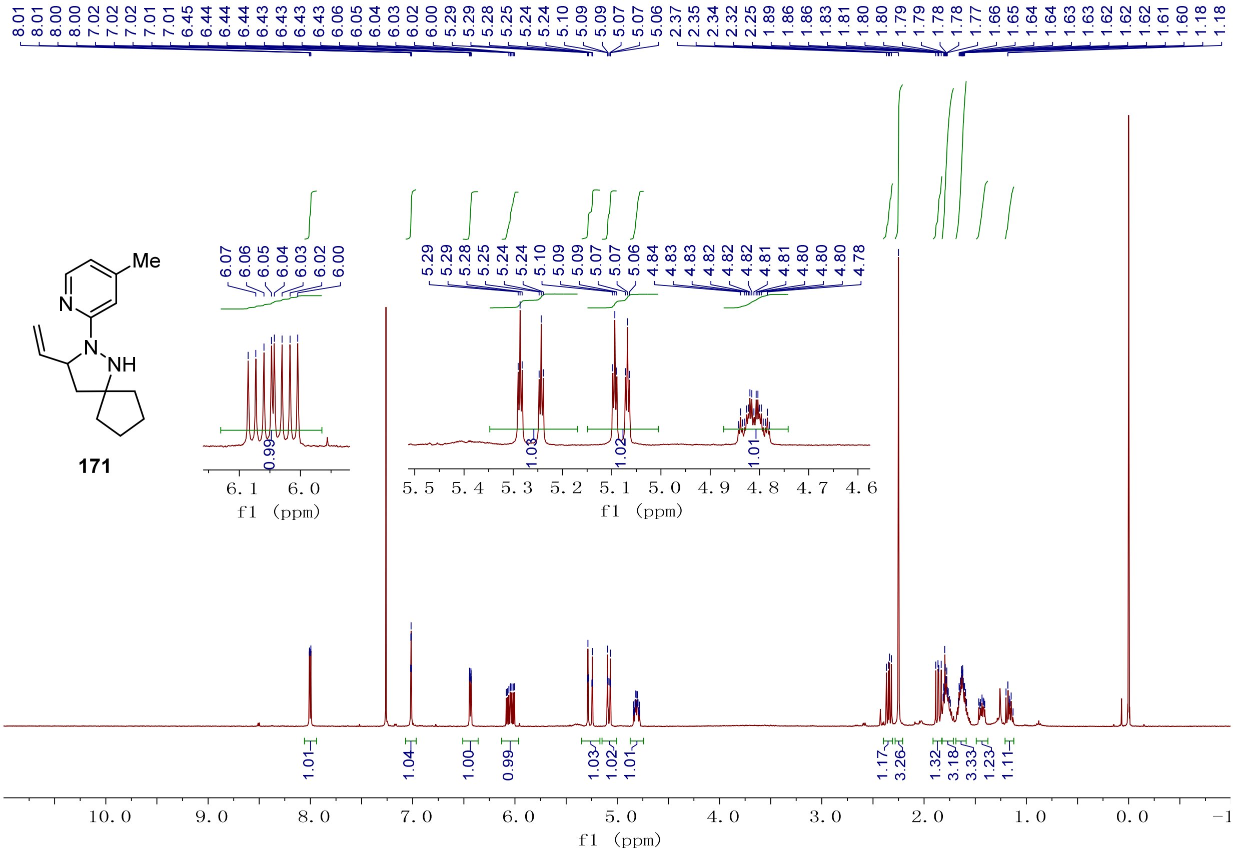
151b


8.29 8.27 7.60 7.00 6.99 6.98 6.09 6.09 3.61 3.59 2.76 2.76 2.57 2.56 2.40 2.19 2.14 2.09 1.96 1.94 1.82 1.80 1.78 1.77 1.67 1.63 1.56 1.54 1.54 1.53 1.52 1.44 1.42 1.41 1.40 1.39 1.37 1.36 1.26 1.26 1.24 1.24 1.23 1.23 1.15 1.15 1.14 1.08 1.07 1.02 1.01 1.00 0.99 0.98 0.97 0.88 0.88 0.86 0.86 0.85 0.85 0.84 0.84
Me
N
N–N
Me
Me
O
Me
Me
O
Me
Me
H
Me
1.00 0.98 1.00 0.99 0.99 1.00 2.03 1.96 2.09 3.08 3.15 3.19 3.21 17.07 29.75 12.39
10.0 9.0 8.0 7.0 6.0 5.0 4.0 3.0 2.0 1.0 0.0 −1
f1 (ppm)

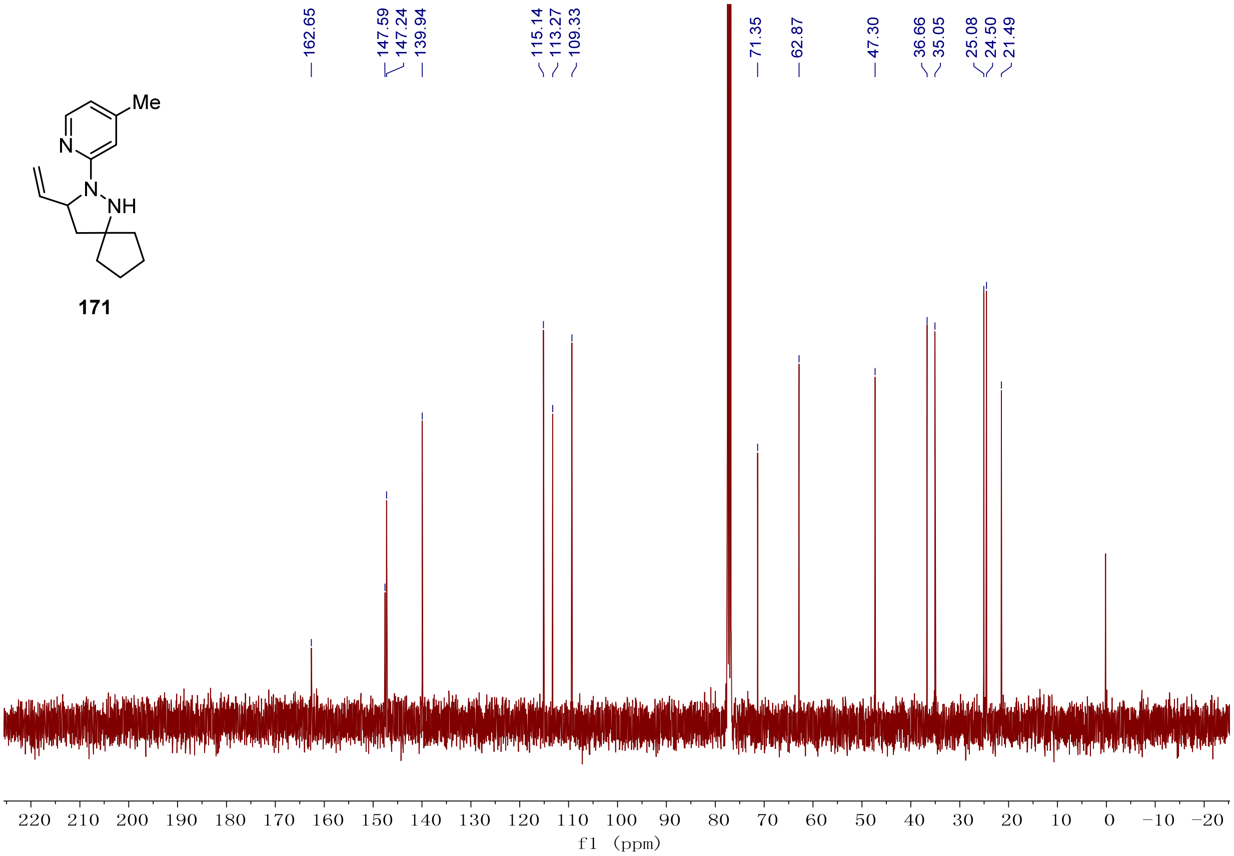
153


154.35 153.99 151.91 149.70 148.47 147.74 147.39 131.56 128.00 125.96 124.45 122.93 122.41 117.92 117.63 104.06 74.85 40.60 40.58 40.16 39.52 37.63 37.60 37.57 37.43 37.39 32.95 32.85 31.50 30.74 28.13 25.92 25.83 24.95 24.59 24.03 22.88 22.78 21.28 21.18 20.83 20.61 19.91 19.81 17.68 12.91 12.05 11.94
Me
N
N–N
Me
Me
O
Me
Me
O
Me
Me
H
Me
220 210 200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 −10 −20
f1 (ppm)

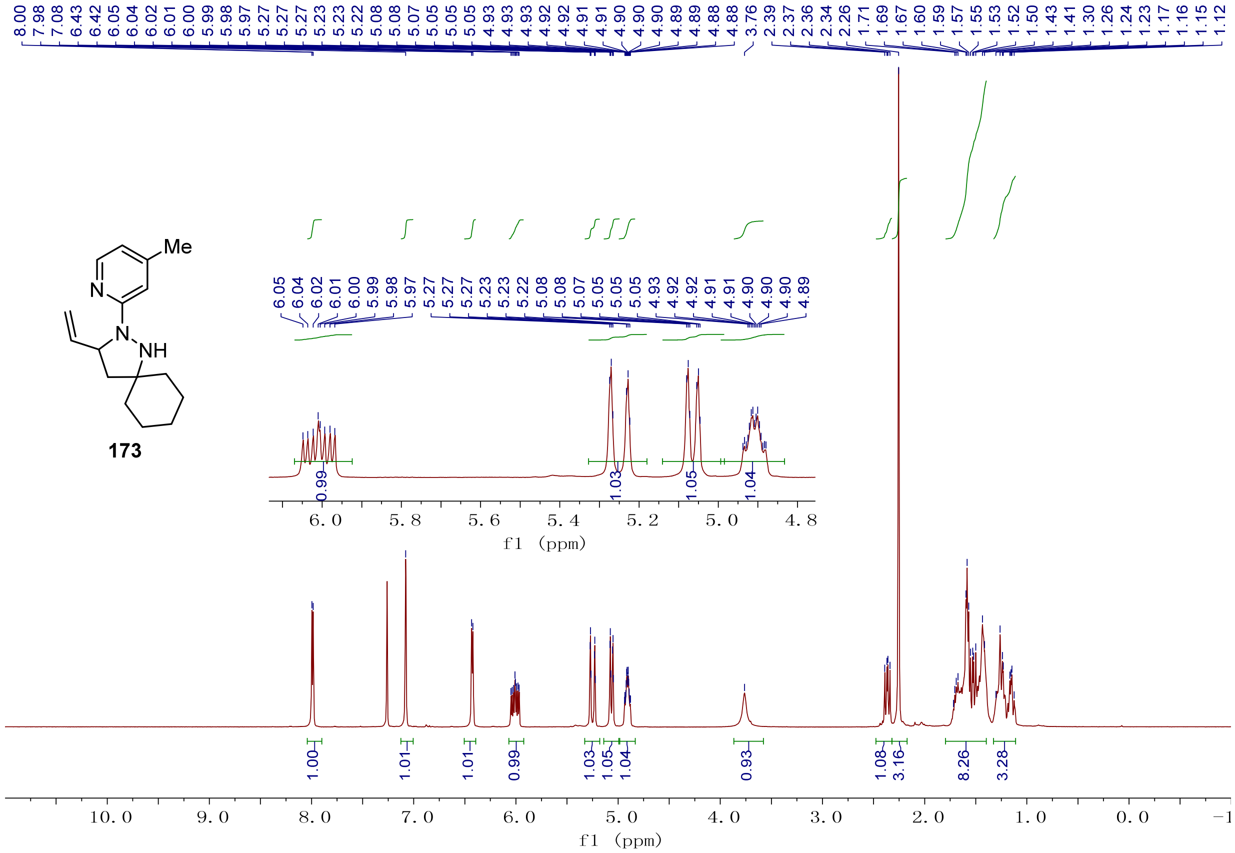
153


8.01
8.01
8.00
8.00
7.02
7.02
7.02
7.01
7.01
6.45
6.44
6.44
6.43
6.43
6.43
6.43
6.06
6.05
6.04
6.03
6.02
6.00
5.29
5.29
5.28
5.25
5.24
5.24
5.10
5.09
5.09
5.07
5.07
5.06
2.37
2.35
2.34
2.32
2.25
1.89
1.86
1.86
1.83
1.81
1.80
1.80
1.79
1.79
1.78
1.78
1.77
1.66
1.65
1.64
1.64
1.63
1.63
1.62
1.62
1.61
1.60
1.18
1.18
Me
N
N
NH
6.07
6.06
6.05
6.04
6.03
6.02
6.00
0.99
6.1
6.0
f1 (ppm)
5.29
5.29
5.28
5.25
5.24
5.24
5.10
5.09
5.09
5.07
5.07
5.06
4.84
4.83
4.82
4.82
4.82
4.81
4.81
4.80
4.80
4.80
4.78
1.03
1.02
1.01
5.5
5.4
5.3
5.2
5.1
5.0
4.9
4.8
4.7
4.6
f1 (ppm)
1.01
1.04
1.00
0.99
1.03
1.02
1.01
1.17
3.26
1.32
3.18
3.33
1.23
1.11
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

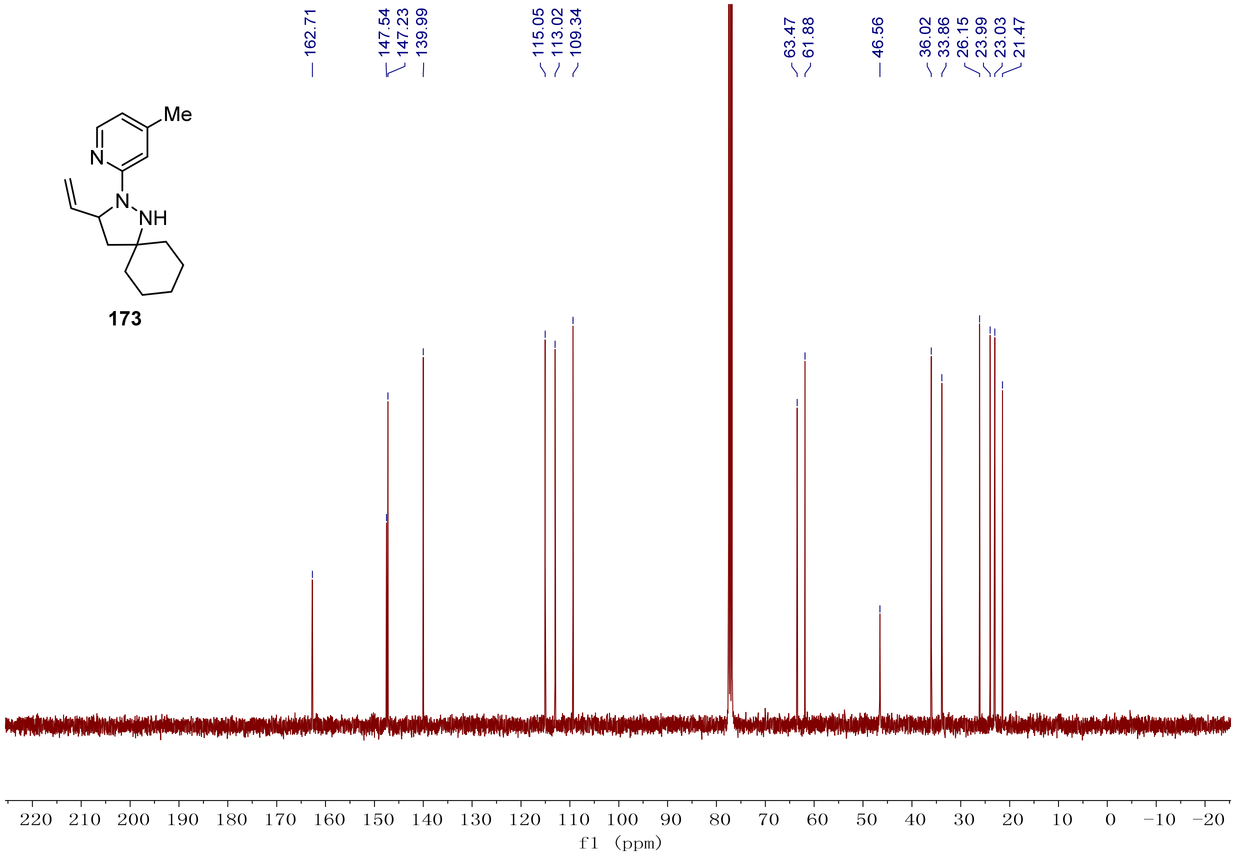
171


162.65
147.59
147.24
139.94
115.14
113.27
109.33
71.35
62.87
47.30
36.66
35.05
25.08
24.50
21.49
Me
N
N
NH
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
−10
−20
f1 (ppm)

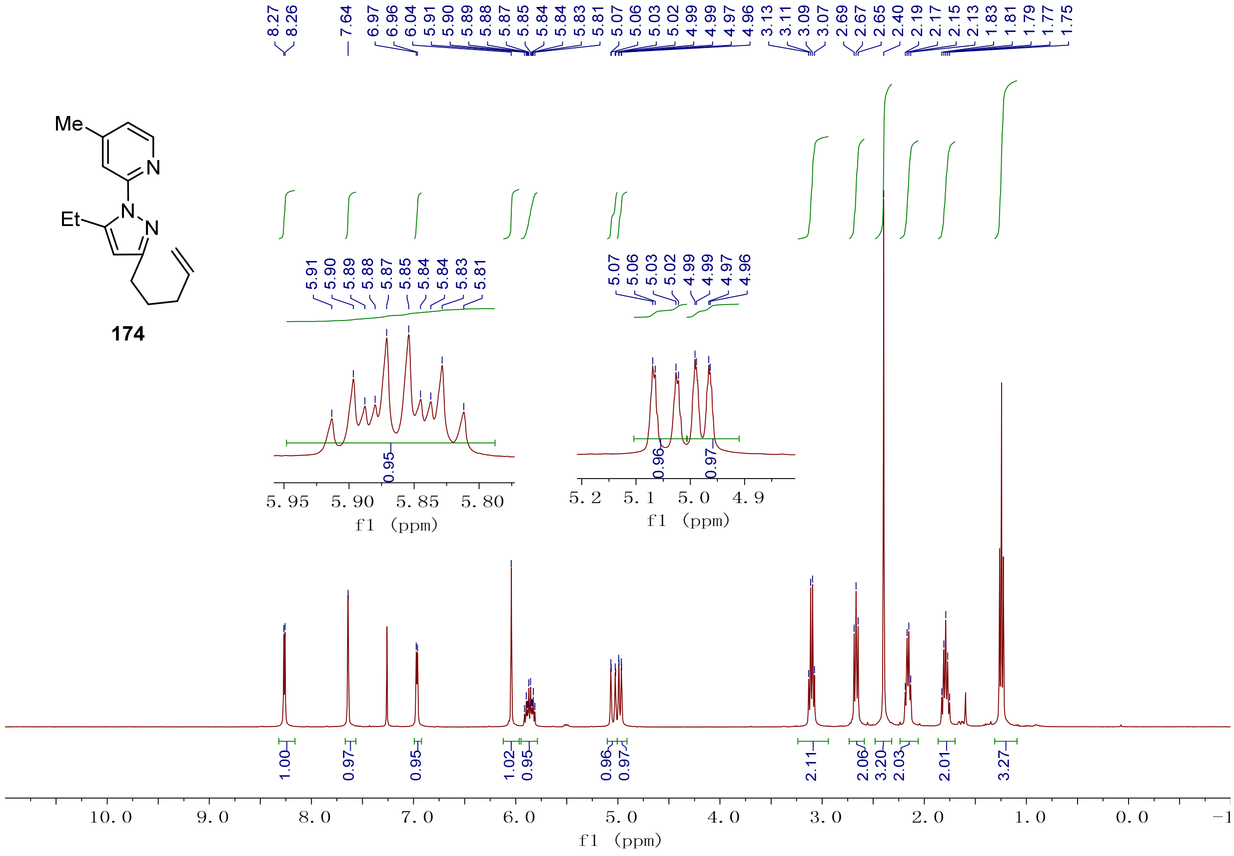
171


8.00 7.98 7.08 6.43 6.42 6.05 6.04 6.02 6.01 6.00 5.99 5.98 5.97 5.27 5.27 5.23 5.23 5.22 5.08 5.08 5.07 5.05 5.05 5.05 4.93 4.93 4.92 4.92 4.91 4.91 4.90 4.90 4.89 4.89 4.88 4.88 3.76 2.39 2.37 2.36 2.34 2.26 1.71 1.69 1.67 1.60 1.59 1.57 1.55 1.53 1.52 1.50 1.43 1.41 1.30 1.26 1.24 1.23 1.17 1.16 1.15 1.12
Me
N
N
NH
6.05 6.04 6.02 6.01 6.00 5.99 5.98 5.97 5.27 5.27 5.23 5.23 5.22 5.08 5.08 5.07 5.05 5.05 5.05 4.93 4.92 4.92 4.91 4.91 4.90 4.90 4.90 4.89
0.99 1.03 1.05 1.04
6.0 5.8 5.6 5.4 5.2 5.0 4.8
f1 (ppm)
1.00 1.01 1.01 0.99 1.03 1.05 1.04 0.93 1.08 3.16 8.26 3.28
10.0 9.0 8.0 7.0 6.0 5.0 4.0 3.0 2.0 1.0 0.0 -1
f1 (ppm)

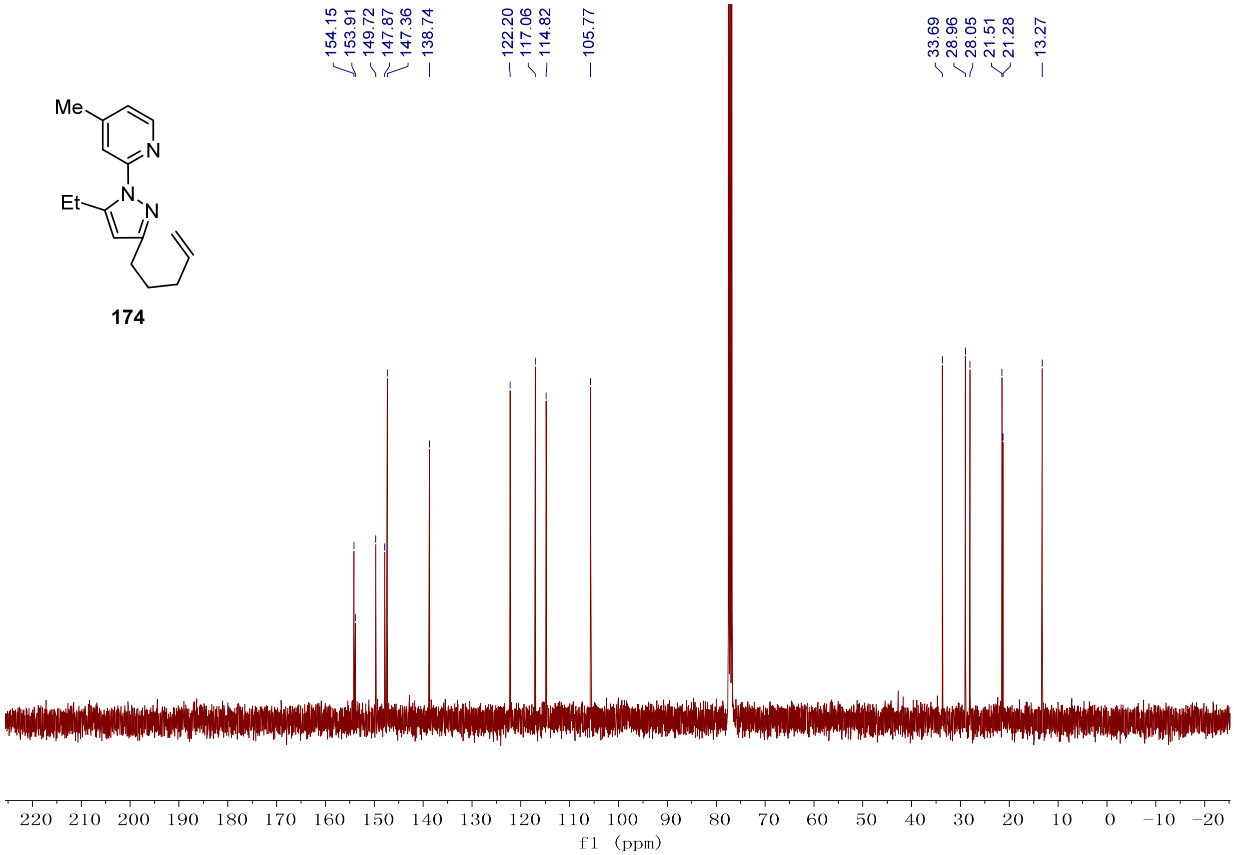
173


162.71
147.54 147.23 139.99
115.05 113.02 109.34
63.47 61.88
46.56
36.02 33.86 26.15 23.99 23.03 21.47
Me
N
N
NH
220 210 200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 -10 -20
f1 (ppm)

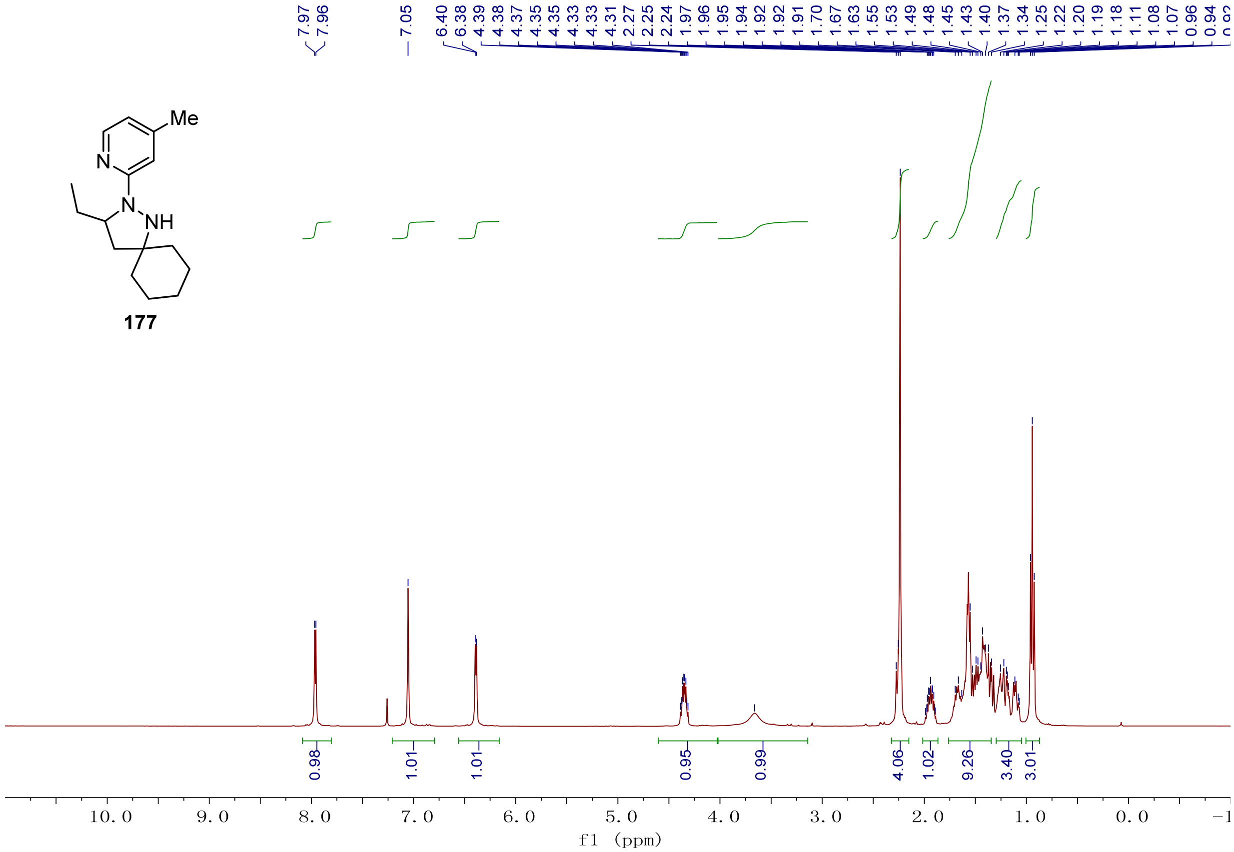
173

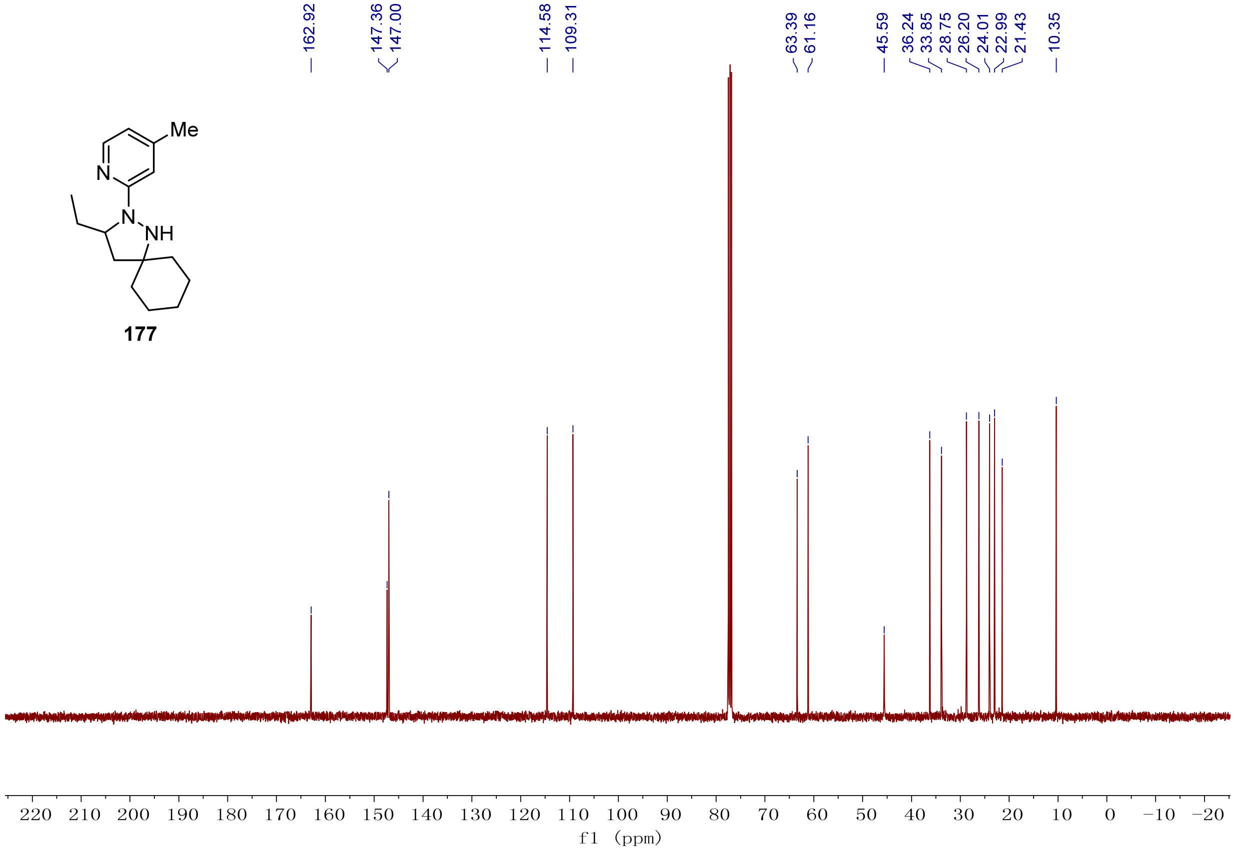

Me
N
Et
N
N
8.27
8.26
7.64
6.97
6.96
6.04
5.91
5.90
5.89
5.88
5.87
5.85
5.84
5.84
5.83
5.81
5.07
5.06
5.03
5.02
4.99
4.99
4.97
4.96
3.13
3.11
3.09
3.07
2.69
2.67
2.65
2.40
2.19
2.17
2.15
2.13
1.83
1.81
1.79
1.77
1.75
0.95
5.95 5.90 5.85 5.80
f1 (ppm)
0.96
0.97
5.2 5.1 5.0 4.9
f1 (ppm)
1.00
0.97
0.95
1.02
0.95
0.96
0.97
2.11
2.06
3.20
2.03
2.01
3.27
10.0 9.0 8.0 7.0 6.0 5.0 4.0 3.0 2.0 1.0 0.0 -1
f1 (ppm)

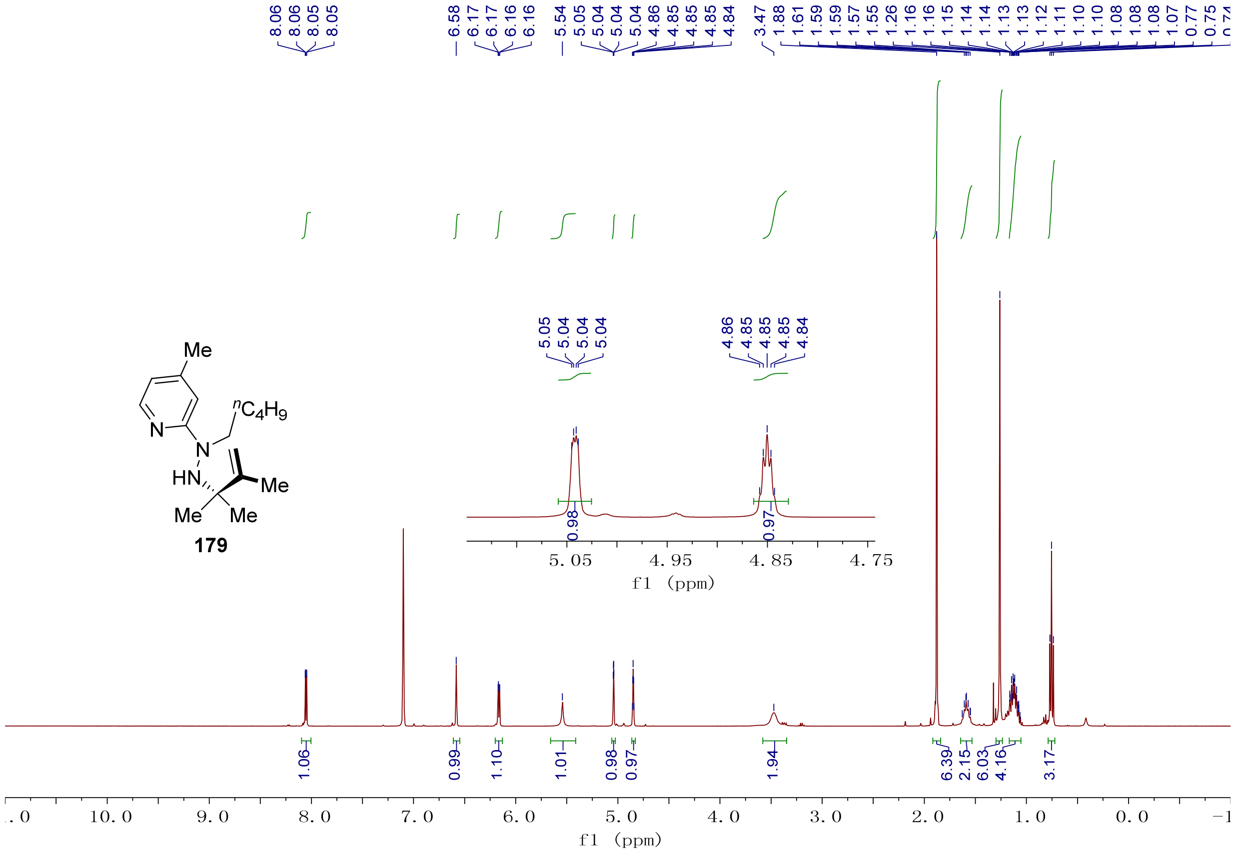
174

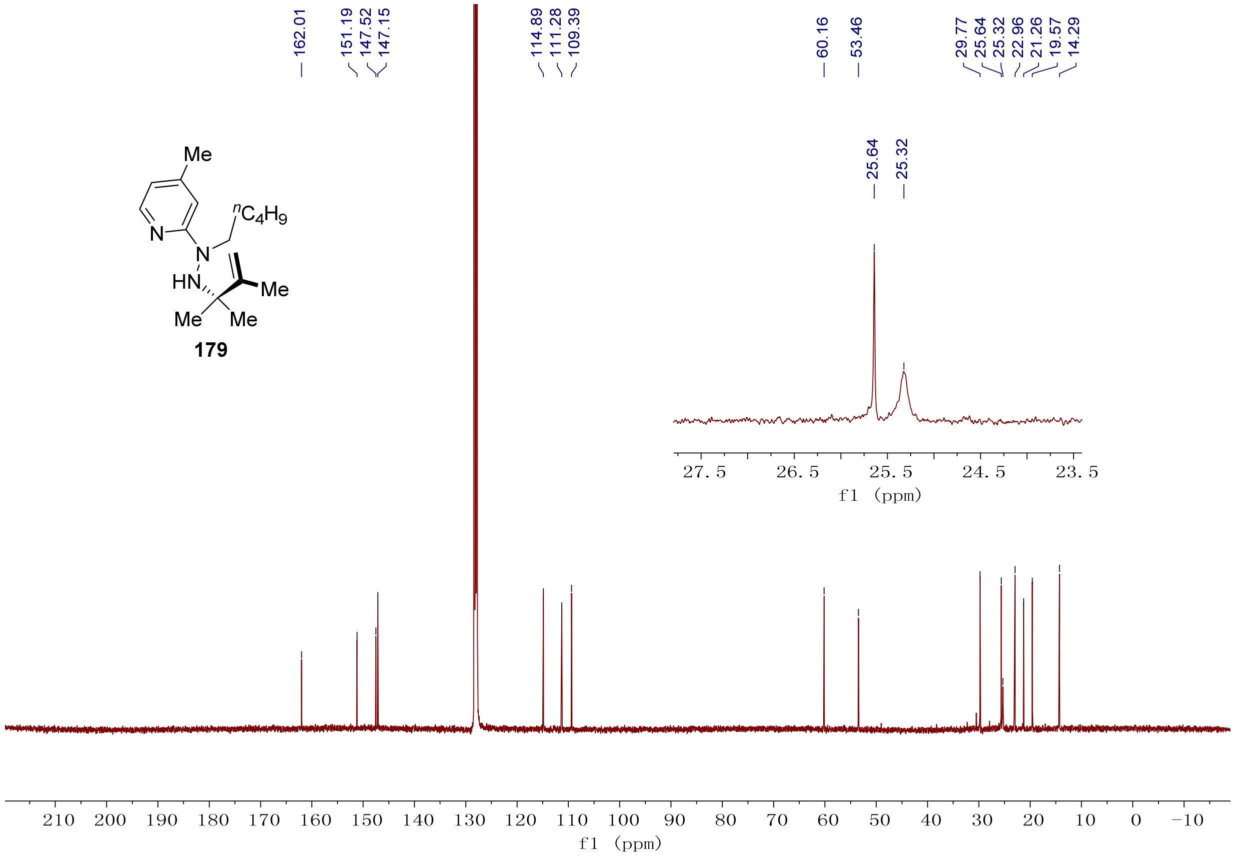

Me
N
Et
N
N
154.15
153.91
149.72
147.87
147.36
138.74
122.20
117.06
114.82
105.77
33.69
28.96
28.05
21.51
21.28
13.27
220 210 200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 -10 -20
f1 (ppm)

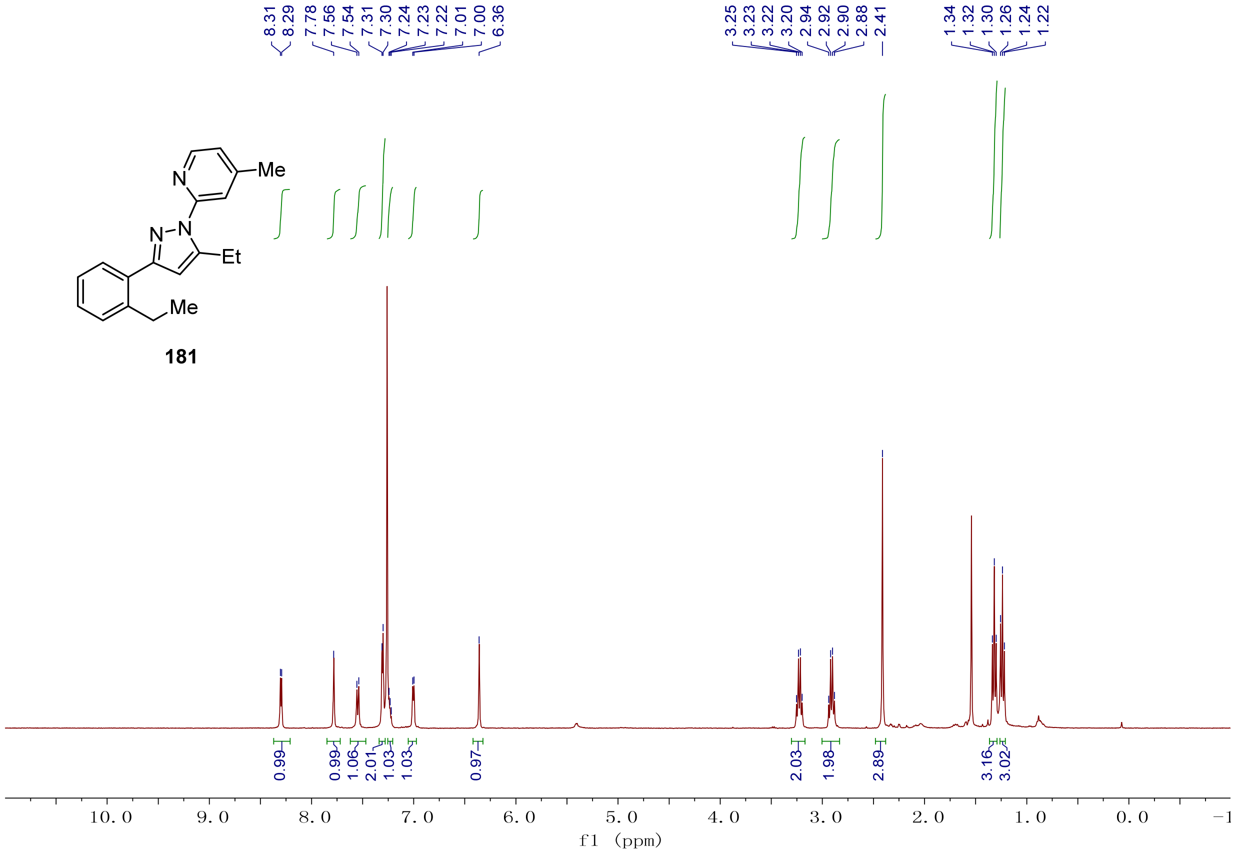
174

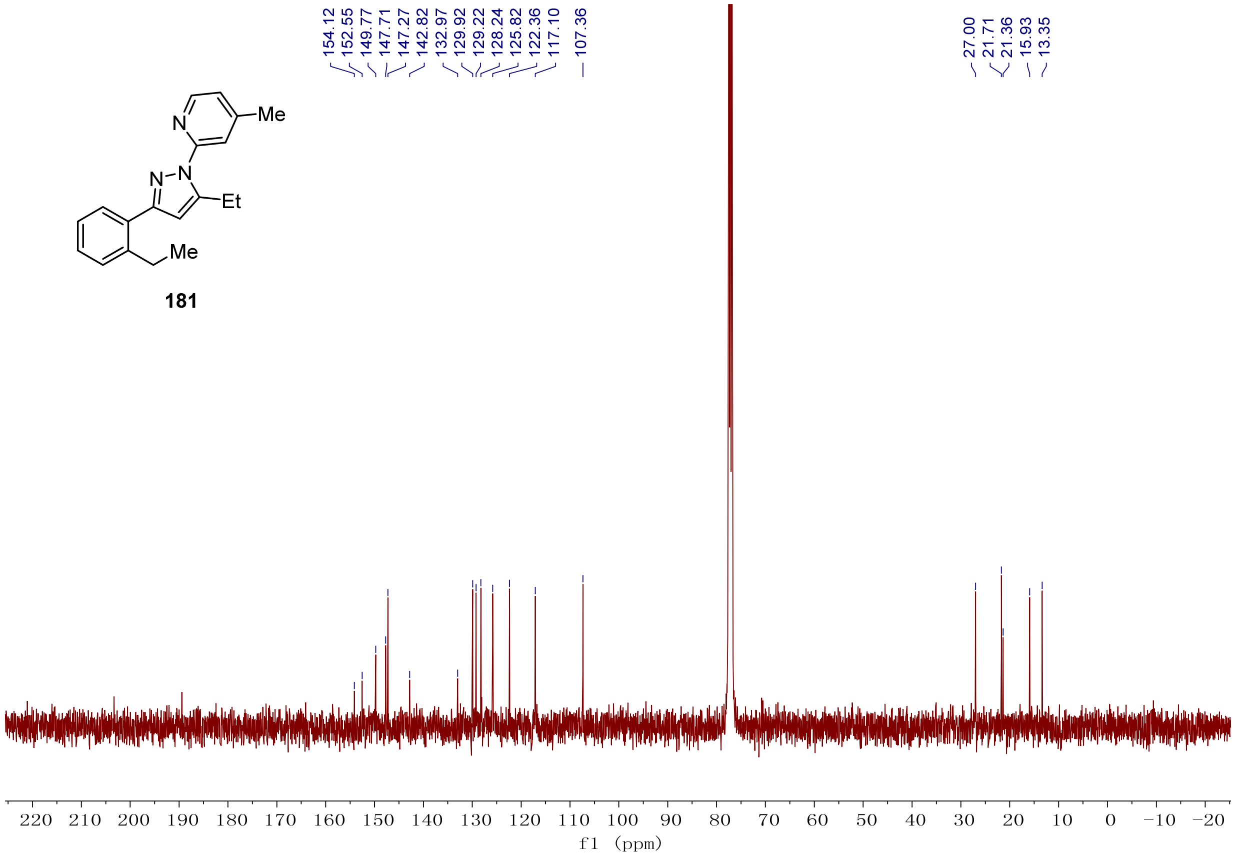

177
7.97
7.96
7.05
6.40
6.38
4.39
4.38
4.37
4.35
4.35
4.33
4.33
4.31
2.27
2.25
2.24
1.97
1.96
1.95
1.94
1.92
1.92
1.91
1.70
1.67
1.63
1.55
1.53
1.49
1.48
1.45
1.43
1.40
1.37
1.34
1.25
1.22
1.20
1.19
1.18
1.11
1.08
1.07
0.96
0.94
Me
N
N
NH
0.98
1.01
1.01
0.95
0.99
4.06
1.02
9.26
3.40
3.01
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

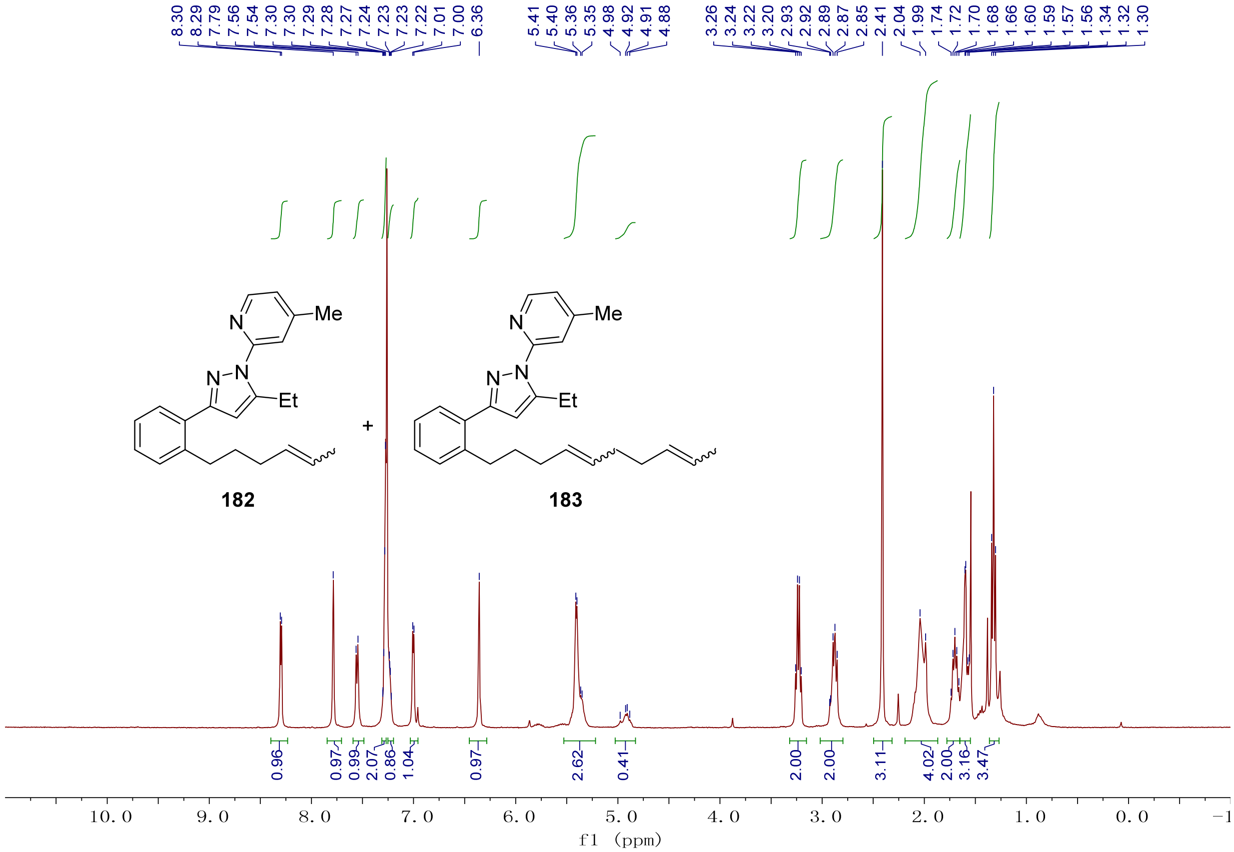

177
162.92
147.36
147.00
114.58
109.31
63.39
61.16
45.59
36.24
33.85
28.75
26.20
24.01
22.99
21.43
10.35
Me
N
N
NH
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

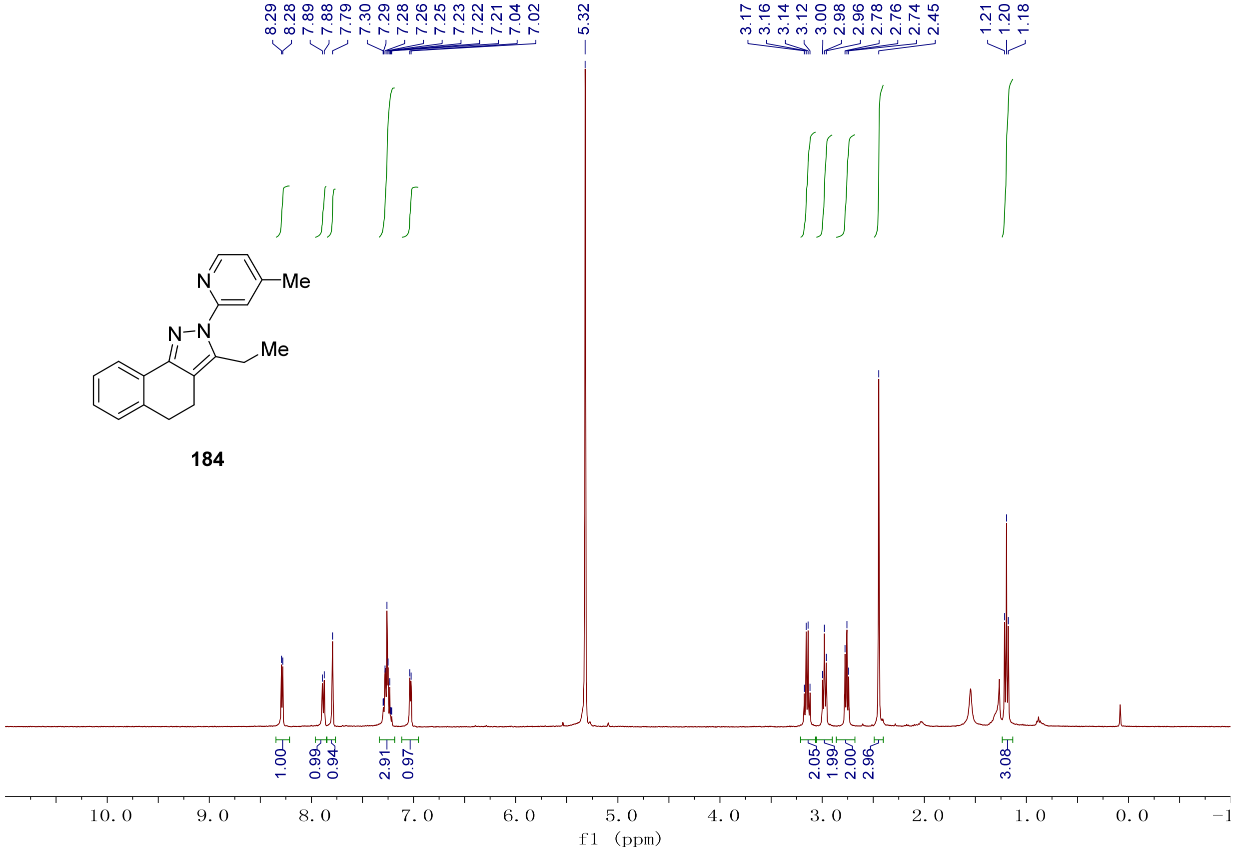

8.06
8.06
8.05
8.05
6.58
6.17
6.17
6.16
6.16
5.54
5.05
5.04
5.04
5.04
4.86
4.85
4.85
4.85
4.84
3.47
1.88
1.61
1.59
1.59
1.57
1.55
1.26
1.16
1.16
1.15
1.14
1.14
1.13
1.13
1.12
1.11
1.10
1.10
1.08
1.08
1.07
0.77
0.75
Me
^{n}C$_4$H$_9$
N
N
HN
Me
Me
Me
179
5.05
5.04
5.04
5.04
4.86
4.85
4.85
4.85
4.84
0.98
0.97
5.05
4.95
4.85
4.75
f1 (ppm)
1.06
0.99
1.10
1.01
0.98
0.97
1.94
6.39
2.15
6.03
4.16
3.17
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
f1 (ppm)

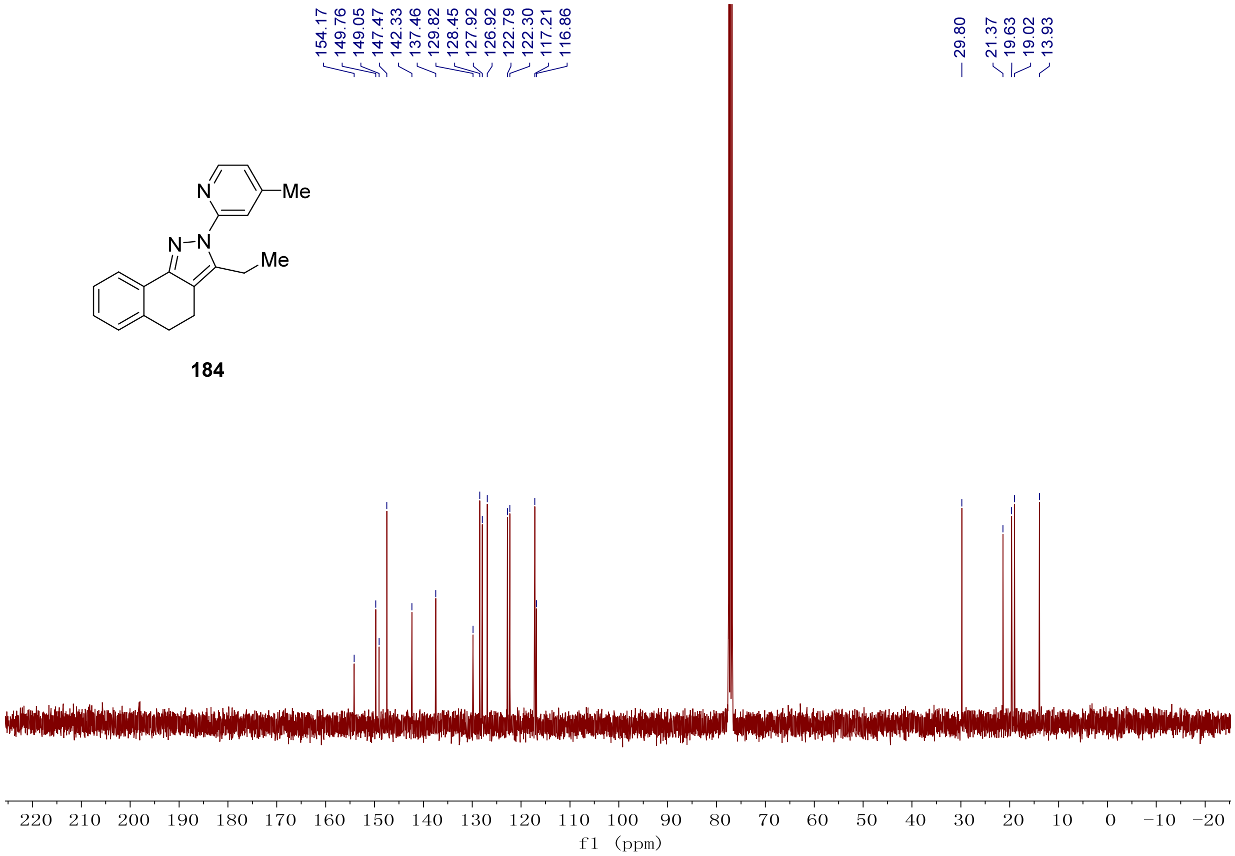

162.01
151.19
147.52
147.15
114.89
111.28
109.39
60.16
53.46
29.77
25.64
25.32
22.96
21.26
19.57
14.29
Me
^{n}C$_4$H$_9$
N
N
HN
Me
Me
Me
179
25.64
25.32
27.5
26.5
25.5
24.5
23.5
f1 (ppm)
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
−10
f1 (ppm)

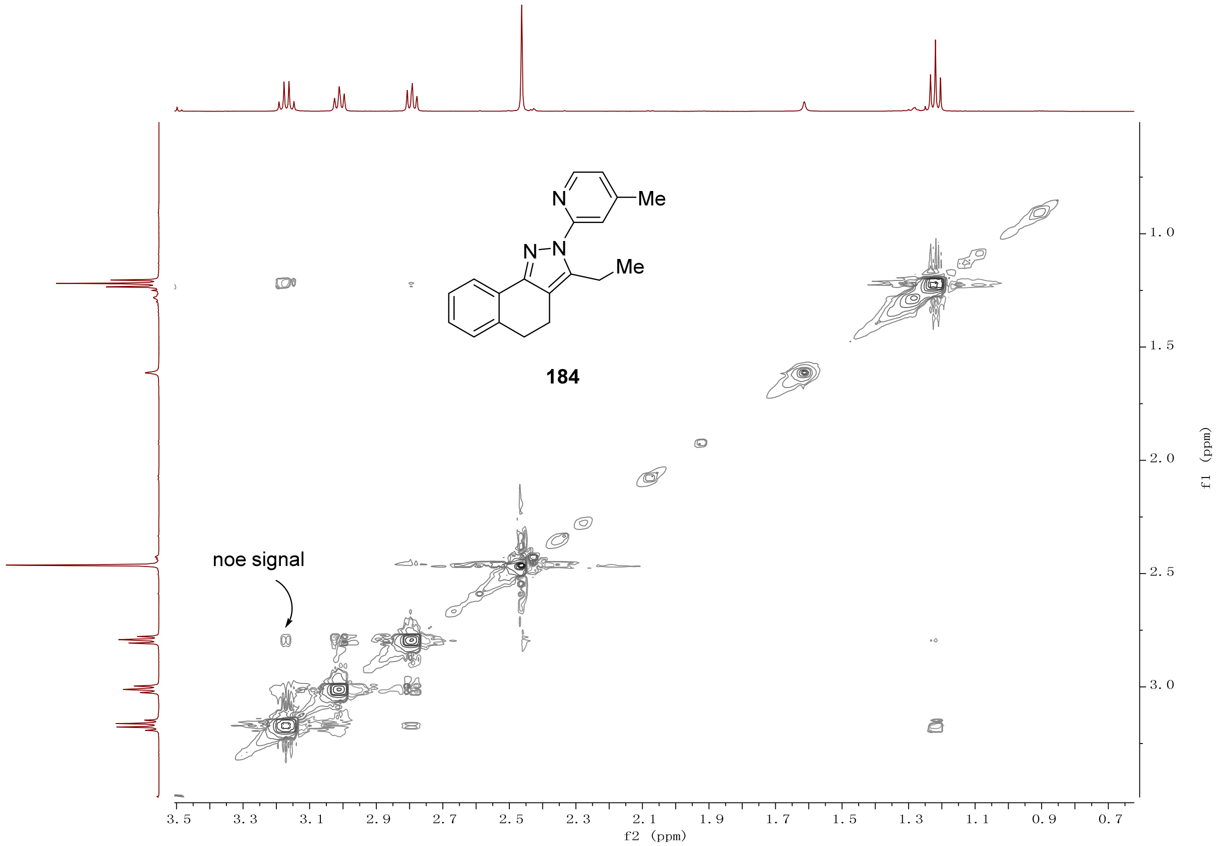

8.31
8.29
7.78
7.56
7.54
7.31
7.30
7.24
7.23
7.22
7.01
7.00
6.36
3.25
3.23
3.22
3.20
2.94
2.92
2.90
2.88
2.41
1.34
1.32
1.30
1.26
1.24
1.22
N
Me
N
N
Et
Me
181
0.99
0.99
1.06
2.01
1.03
1.03
0.97
2.03
1.98
2.89
3.16
3.02
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

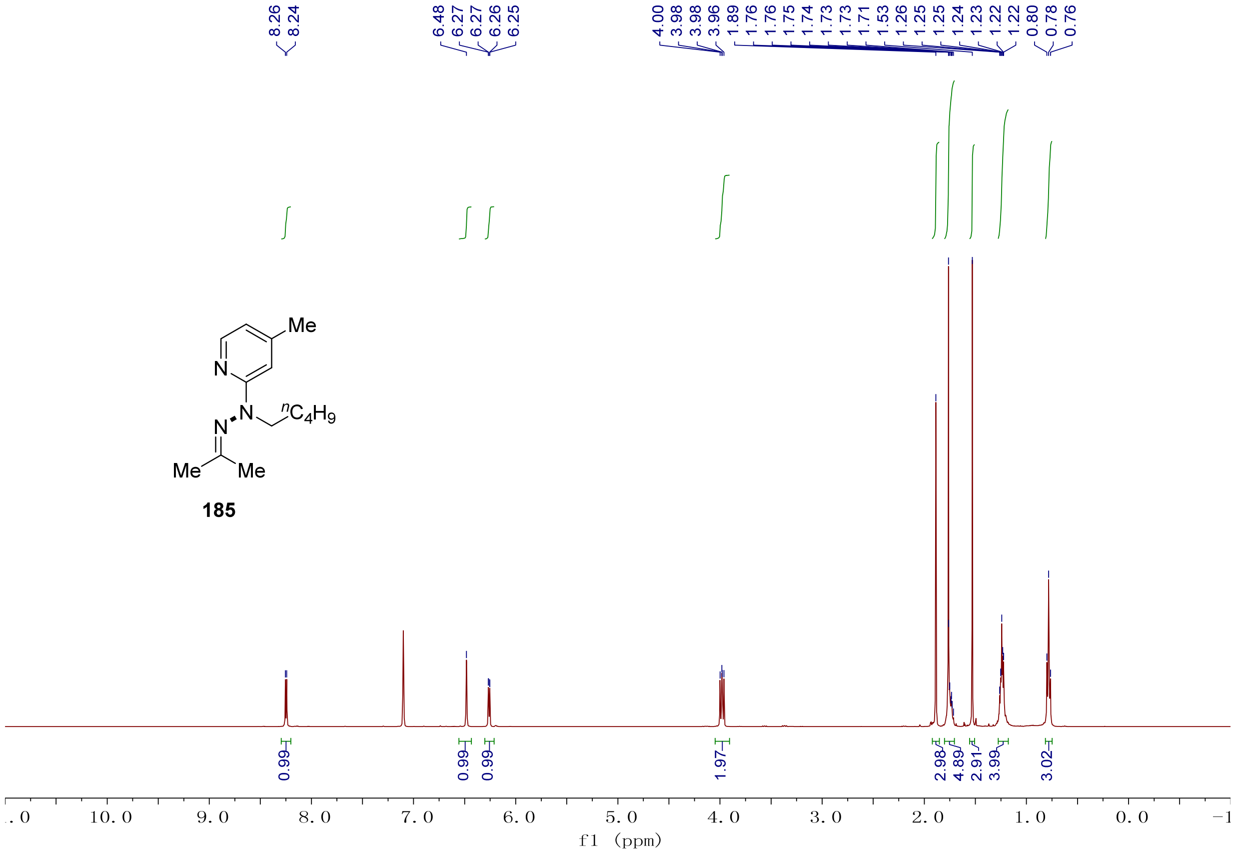

154.12
152.55
149.77
147.71
147.27
142.82
132.97
129.92
129.22
128.24
125.82
122.36
117.10
107.36
27.00
21.71
21.36
15.93
13.35
N
Me
N
N
Et
Me
181
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)

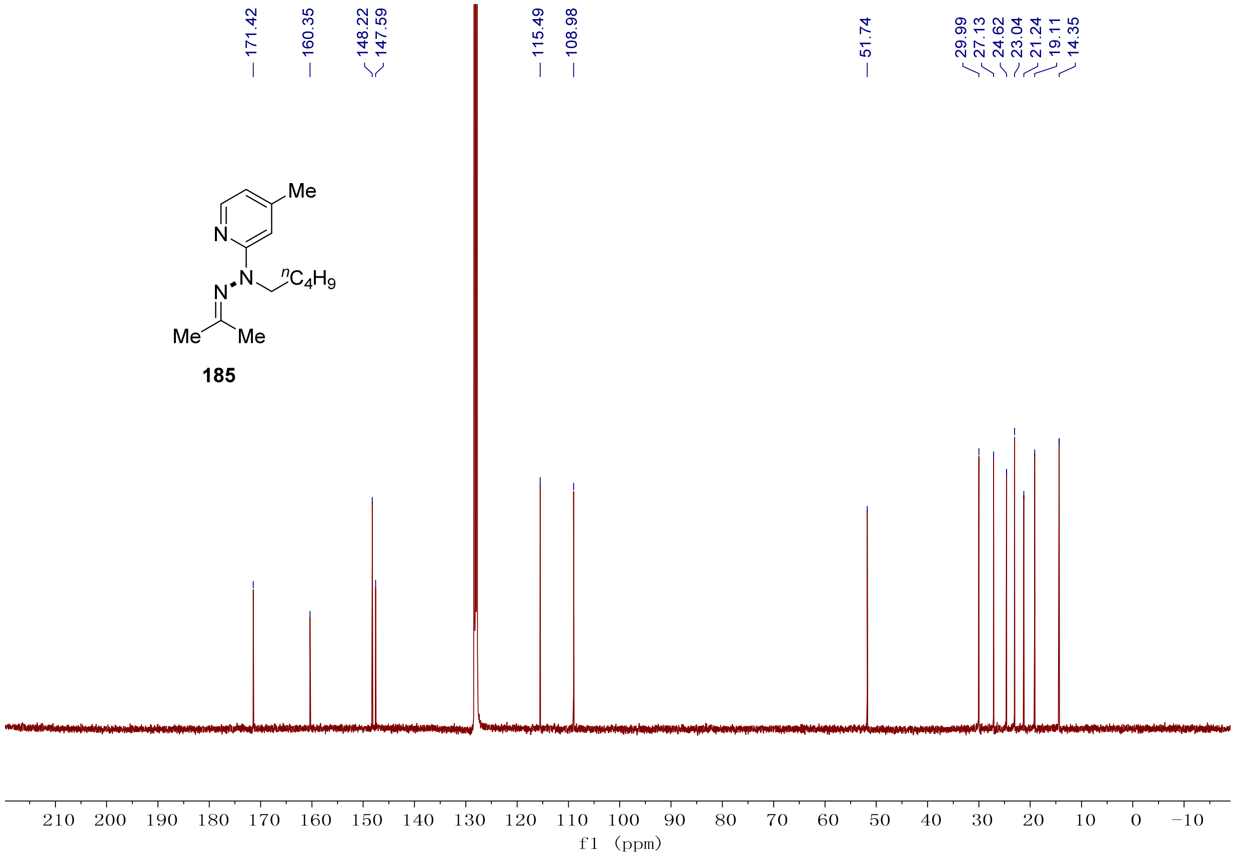

8.30
8.29
7.79
7.56
7.54
7.30
7.30
7.29
7.28
7.27
7.24
7.23
7.23
7.22
7.01
7.00
6.36
5.41
5.40
5.36
5.35
4.98
4.92
4.91
4.88
3.26
3.24
3.22
3.20
2.93
2.92
2.89
2.87
2.85
2.41
2.04
1.99
1.74
1.72
1.70
1.68
1.66
1.60
1.59
1.57
1.56
1.34
1.32
1.30
N
Me
N–N
Et
+
182
183
0.96
0.97
0.99
2.07
0.86
1.04
0.97
2.62
0.41
2.00
2.00
3.11
4.02
2.00
3.16
3.47
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

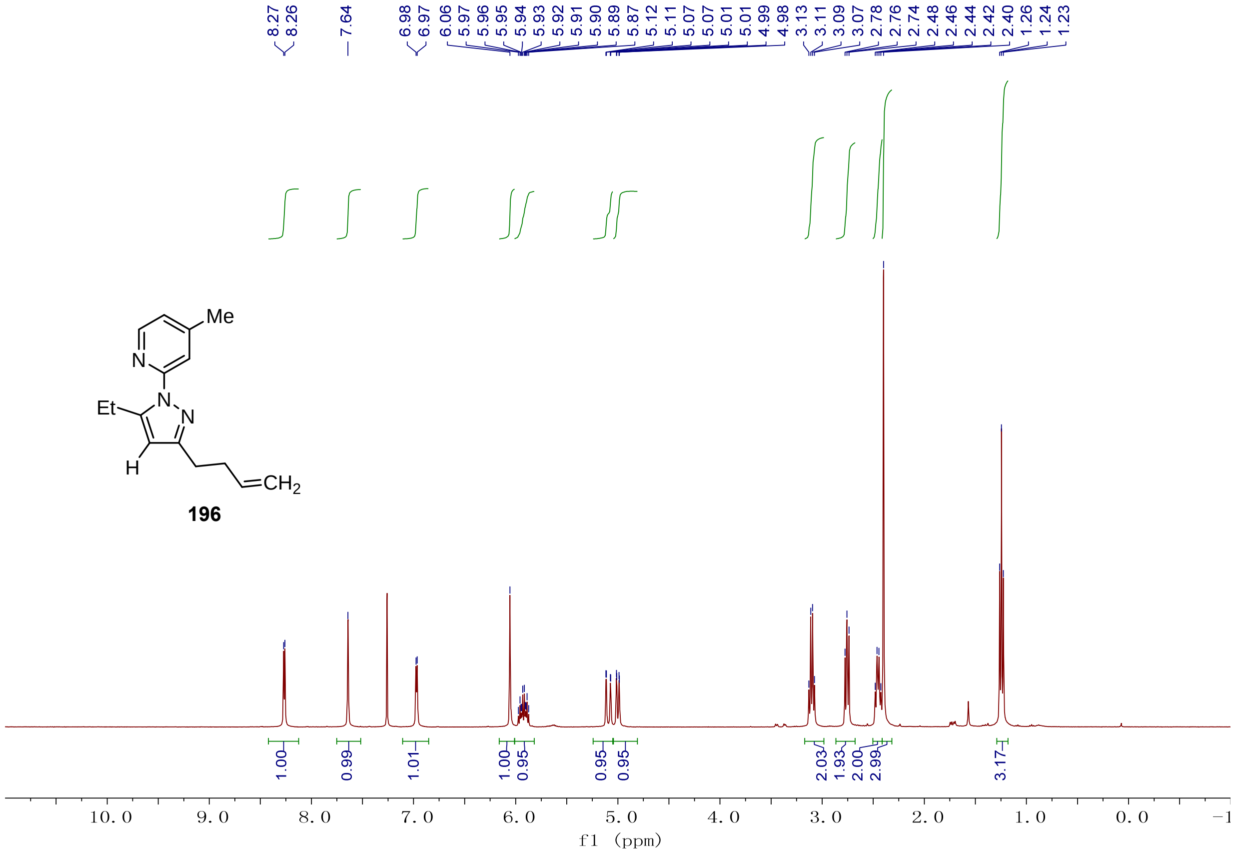

8.29
8.28
7.89
7.88
7.79
7.30
7.29
7.28
7.26
7.25
7.23
7.22
7.21
7.04
7.02
5.32
3.17
3.16
3.14
3.12
3.00
2.98
2.96
2.78
2.76
2.74
2.45
1.21
1.20
1.18
N
Me
N–N
Me
184
1.00
0.99
0.94
2.91
0.97
2.05
1.99
2.00
2.96
3.08
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)

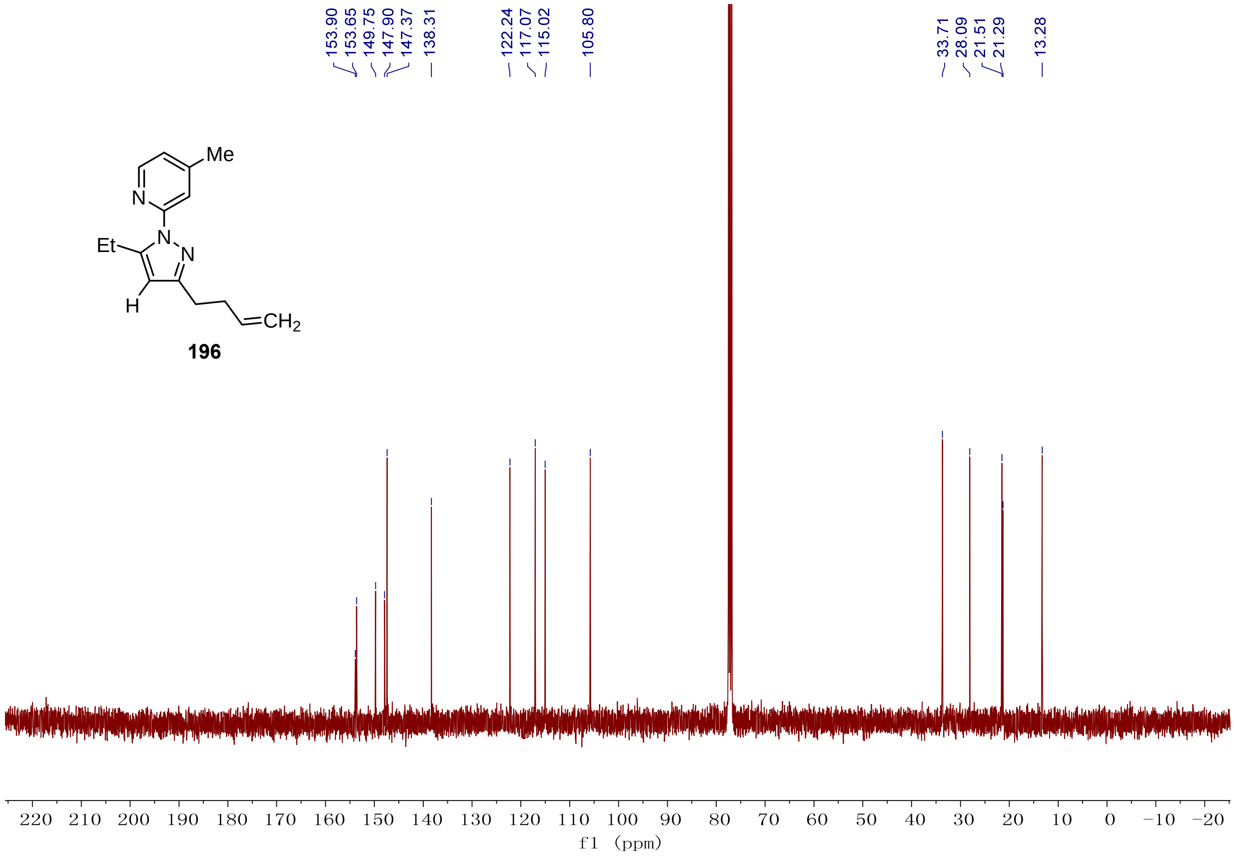

154.17
149.76
149.05
147.47
142.33
137.46
129.82
128.45
127.92
126.92
122.79
122.30
117.21
116.86
29.80
21.37
19.63
19.02
13.93
N
Me
N–N
Me
184
220 210 200 190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 −10 −20
f1 (ppm)


N
Me
N–N
Me
184
noe signal
1.0
1.5
2.0
2.5
3.0
f1 (ppm)
3.5 3.3 3.1 2.9 2.7 2.5 2.3 2.1 1.9 1.7 1.5 1.3 1.1 0.9 0.7
f2 (ppm)


8.26
8.24
6.48
6.27
6.27
6.26
6.25
4.00
3.98
3.98
3.96
1.89
1.76
1.76
1.75
1.74
1.73
1.73
1.71
1.53
1.26
1.25
1.25
1.24
1.23
1.22
1.22
0.80
0.78
0.76
Me
N
N
N
$^{n}C_4H_9$
Me
Me
185
0.99
0.99
0.99
1.97
2.98
4.89
2.91
3.99
3.02
. 0
10. 0
9. 0
8. 0
7. 0
6. 0
5. 0
4. 0
3. 0
2. 0
1. 0
0. 0
-1
f1 (ppm)


171.42
160.35
148.22
147.59
115.49
108.98
51.74
29.99
27.13
24.62
23.04
21.24
19.11
14.35
Me
N
N
N
$^{n}C_4H_9$
Me
Me
185
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
f1 (ppm)


8.27
8.26
7.64
6.98
6.97
6.06
5.97
5.96
5.95
5.94
5.93
5.92
5.91
5.90
5.89
5.87
5.12
5.11
5.07
5.07
5.01
4.99
4.98
3.13
3.11
3.09
3.07
2.78
2.76
2.74
2.48
2.46
2.44
2.42
2.40
1.26
1.24
1.23
Me
N
Et
N
N
H
CH2
196
1.00
0.99
1.01
1.00
0.95
0.95
0.95
2.03
1.93
2.00
2.99
3.17
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1
f1 (ppm)


153.90
153.65
149.75
147.90
147.37
138.31
122.24
117.07
115.02
105.80
33.71
28.09
21.51
21.29
13.28
Me
N
Et
N
N
H
CH2
196
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
f1 (ppm)