Asymmetric Synthesis of Methylenetetrahydrofurans by Palladium-Catalyzed [3+2] Cycloaddition of Trimethylenemethane with Aldehydes – A Novel Ligand Design

Barry M. Trost, Dustin A. Bringley and Steven M. Silverman
Department of Chemistry, Stanford University, Stanford, CA 94305-5080

Supporting Information

A. General Methods. All reactions were carried out under an argon atmosphere. All solvents were dried by passing through an Alumina column. All compounds were purchased from commercial sources unless listed. The following compounds were prepared according to known literature procedures: $Pd(dba)_2$[1], 3-acetoxy-2-trimethylsilylmethyl-1-propene[2], **L1-L4**[3], **L5**[4], (*E*)-2-benzylidene-3-methylbutanal[5]. Liquid aldehydes were purified by distillation immediately prior to use. 4-Chlorobenzaldehyde was purified by sublimation under reduced pressure. For TMM reactions at room temperature, toluene was degassed by bubbling argon through the solvent for 15 minutes.

Flash chromatography was performed with 0.040-0.063 μm Silica Gel. ^1H and ^{13}C NMR spectroscopy was performed on a Mercury NMR at 400 (^1H) or 100 (^{13}C) MHz and Unity NMR at 500 (^1H) or 125 (^{13}C) MHz. Chemical shifts are reported in ppm relative to tetramethylsilane or residual protiated solvent. All ^{13}C NMR spectra were proton decoupled. Infrared spectroscopic data was recorded on sodium chloride plates as thin films on a Perkin-Elmer Paragon 500 FT-IR spectrometer. Chiral HPLC analysis was performed on a Thermo Separation Products Spectra Series P-100 and on an Agilent Technologies 1200 Series using Chiralcel® columns. Optical rotations were measured on a Jasco DIP-1000 digital polarimeter using 5 cm glass cells with a Na 589 nm filter.

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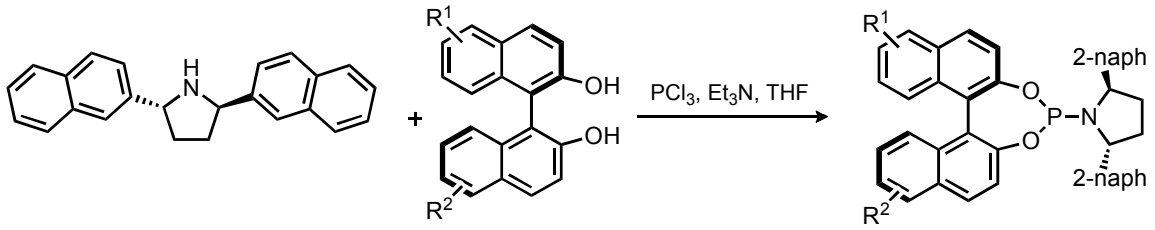
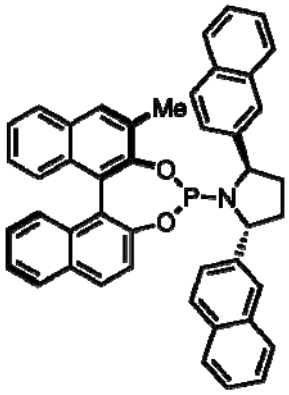
[1] Komiya, S. Synthesis of Organometallic Compounds. A Practical Guide; John Wiley & Sons: New York, 1997.
[2] Trost, B. M.; Chan, D. M. T. *J. Am. Chem. Soc.* **1979**, *101*, 6429.
[3] Trost, B. M.; Silverman, S. M.; Stambuli, J. P. *J. Am. Chem. Soc.* **2007**, *129*, 12398.
[4] Rimkus, A.; Sewald, N. *Org. Lett.* **2003**, *5*, 79.
[5] Nongkhlaw, R. L.; Nongrum, R.; Myrboh, B. *J. Chem. Soc., Perkin Trans. 1* **2001**, 1300.

B. Ligand Synthesis



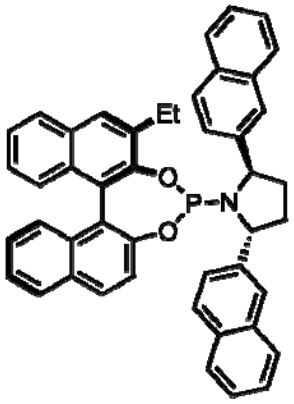
General procedure A for phosphoramidite synthesis. To a solution of PCl_3 (10.8 μL, 0.124 mmol) in THF (0.5 ml) at 0 ºC was added triethylamine (86 μL, 0.62 mmol) and the milky mixture was stirred for 20 minutes. To this suspension was added a solution of (2*R*,5*R*)-2,5-di(naphthalen-2-yl)pyrrolidine (40.0 mg, 0.124 mmol)[6] in THF (0.2 ml) by cannula, and the reaction was stirred for 3 hours, allowing for gradual warming to ambient temperature. It was then cooled to -78 ºC and a solution of the BINOL derivative (0.124 mmol) in THF (0.5 ml) was added dropwise by cannula over 2-3 minutes. The reaction was allowed to stir overnight with gradual warming to ambient temperature, concentrated and purified by flash chromatography. The purified products were concentrated from approximately 5:1 hexane/dichloromethane to yield a white powder.



Ligand L7: The reaction was performed according to general procedure A using (2*R*,5*R*)-2,5-di(naphthalen-2-yl)pyrrolidine (40.0 mg, 0.124 mmol) and (*R*)-3-methyl-1,1'-binaphthyl-2,2'-diol[7] (37.2 mg, 0.124 mmol) and purified by flash chromatography (25% dichloromethane in pet ether with 2% triethylamine) to yield the product as a white

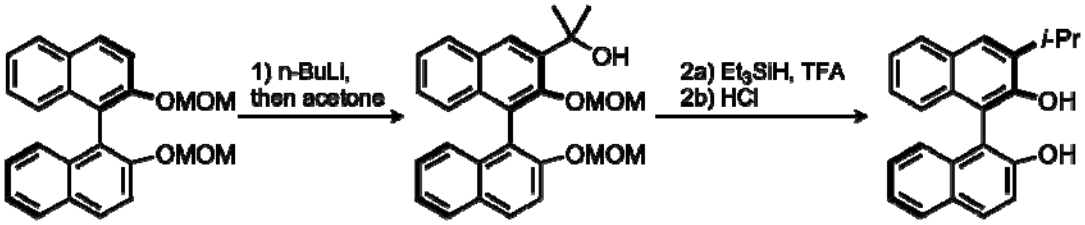
[6] Trost, B. M.; Silverman, S. M.; Stambuli, J. P. *J. Am. Chem. Soc.* **2007**, *129*, 12398.
[7] Graves, C. R.; Zhou, H.; Stern, C. L.; Nguyen, S. T. *J. Org. Chem.* **2007,** *72*, 9121.

powder (53.0 mg, 66% yield, dr 9:1 as determined by the methyl resonances at δ 2.26 and δ 1.95 in the ^{1}H spectrum). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.87-7.77 (m, 5H), 7.71-7.68 (m, 2H), 7.62 (bs, 2H), 7.54-7.41 (m, 8H), 7.32-6.94 (m, 10H), 6.47 (d, *J* = 8.4 Hz, 0.1 H, minor), 6.27 (s, 1H), 5.91 (d, *J* = 8.4 Hz, 0.1 H, minor), 5.42 (d, *J* = 6.8 Hz, 2H, major), 5.38 (d, *J* = 6.8 Hz, 0.3H, minor) 2.71-2.66 (m, 2H), 2.26 (s, 0.35 H, minor), 1.95 (s, 3H, major), 1.93-1.90 (m, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 149.6, 149.1 (d, *J* = 8.2 Hz), 143.3 (d, *J* = 3.7 Hz), 133.6, 133.2 (d, *J* = 1.5 Hz), 132.9, 131.62, 131.56 (d, *J* = 1.5 Hz), 130.5, 130.2, 129.6, 129.3, 128.8, 128.5, 128.3, 128.2, 127.9, 127.7, 127.4, 126.7, 126.4, 126.0, 125.8, 125.7 (d, *J* = 1.5 Hz), 125.6 (d, *J* = 1.5 Hz), 124.8, 124.7, 124.2, 122.2 (d, *J* = 1.6 Hz), 120.9 (d, *J* = 3.0 Hz), 63.5 (d, *J* = 12.6 Hz), 34.4 (d, *J* = 2.2 Hz), 18.4. ^{31}P NMR (162 MHz): δ 149.4 (major), 143.5 (minor). IR (thin film): 3052, 2966, 1591, 1505, 1237 cm^{-1}. $[\alpha]_{24}^{D}$ = -36.6 (c 0.52, $CHCl_3$). HRMS: calcd for ($M+H^+$) $C_{45}H_{35}NO_2P$ 652.2405; found 652.2375.



Ligand L8: The reaction was performed according to general procedure A using (2*R*,5*R*)-2,5-di(naphthalen-2-yl)pyrrolidine (40.0 mg, 0.124 mmol) and (*R*)-3-ethyl-1,1'-binaphthyl-2,2'-diol (38.9 mg, 0.124 mmol)[7] and purified by flash chromatography (25% dichloromethane in pet ether with 2% triethylamine) to yield the product as a white powder (70.1 mg, 85% yield, dr 11:1 as determined by ^{31}P NMR). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.89-7.78 (m, 5H), 7.69-7.41 (m, 13H), 7.32-6.97 (m, 9H), 6.50 (d, *J* = 8.8 Hz, 0.1H, minor), 6.30 (s, 1H), 5.89 (d, *J* = 8.8 Hz, 0.1H, minor), 5.41 (d, *J* = 7.2 Hz, 2H, major), 5.37 (d, *J* = 7.2 Hz, 0.26H, minor), 2.75-2.62 (m, 3H), 1.98 (apparent sextet, *J* = 7.6 Hz, 1H), 1.90-1.88 (m, 2H), 0.88 (t, *J* = 7.6 Hz, 3H). ^{13}C NMR (100 MHz, CD_2Cl_2):

δ 149.9, 149.0 (d, *J* = 7.5 Hz), 143.5 (d, *J* = 4.5 Hz), 135.6, 133.9, 133.4 (d, *J* = 1.5 Hz), 133.1, 131.9, 131.6 (d, *J* = 1.5 Hz), 131.0, 130.5, 128.8, 128.5, 128.3, 128.3, 128.0, 127.6, 127.4, 126.63, 126.58, 126.3, 126.1, 125.6, 125.95 (d, *J* = 1.5 Hz), 125.88 (1.5 Hz), 125.1, 125.0, 124.5, 122.3 (d, *J* = 1.5 Hz), 121.1 (d, *J* = 2.5 Hz), 63.8 (d, *J* = 14.1 Hz), 34.6 (d, *J* = 2.2 Hz), 25.2, 13.8. ^{31}P NMR (162 MHz, $CDCl_3$): δ 149.6 (major), 144.5 (minor). IR (thin film): 3052, 2965, 1506, 1460, 1234 cm^{-1}. $[\alpha]_{24}^{D}$ = -46.9 (c 0.42, $CHCl_3$). HRMS: calcd for ($M+H^+$) $C_{46}H_{37}NO_2P$ 666.2562; found 666.2533.

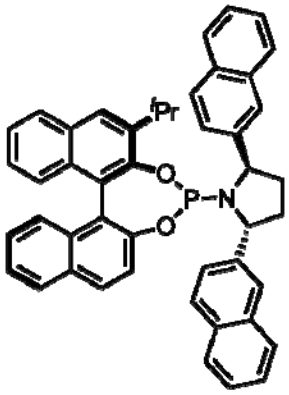


(*R*)-3-isopropyl-1,1'-binaphthyl-2,2'-diol:

1. A solution of (*R*)-2,2'-bis(methoxymethoxy)-1,1'-binaphthyl (1.0 g, 2.68 mmol) in THF (8 ml) was coooled to -78 ºC and *n*-butyl lithium (1.28 ml, 2.49 M in hexanes, 3.2 mmol) was added dropwise over 2 minutes. After 20 minutes at -78 ºC, the mixture was allowed to warm to 0 ºC and stirred for 3 hours. It was then recooled to -78 ºC and acetone (0.3 ml, 4.0 mmol) was added dropwise. The reaction was stirred overnight with gradual warming to RT, then quenched by the addition of saturated NH_4Cl (10 ml) and extracted with diethyl ether (2 x 10 ml). The combined organics were washed with brine (10 ml), dried over $MgSO_4$, concentrated, and purified by chromatography (15% ethyl acetate in hexanes) to yield a white foam (751 mg, 65% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.00 (d, *J* = 8.8 Hz, 1H), 7.95 (s, 1H), 7.88 (dd, *J* = 4.0, 8.0 Hz, 2H), 7.61 (d, *J* = 9.2 Hz, 1H), 7.41-7.35 (m, 2H), 7.31-7.11 (m, 4H), 5.12 (d, *J* = 7.2 Hz, 1H), 5.09 (d, *J* = 7.2 Hz, 1H), 4.79 (s, 1H), 4.60 (d, *J* = 5.2 Hz, 1H), 4.35 (d, *J* = 5.2 Hz, 1H), 3.24 (s, 3H), 3.18 (s, 3H), 1.84 (s, 3H), 1.84 (s, 3H).

2. To a solution of the above adduct (376 mg, 0.87 mmol) and triethylsilane (0.43 ml, 2.69 mmol) in DCM (5 ml) was added trifluoroacetic acid (0.17 ml, 2.22 mmol). After 25 minutes, the reaction was quenched with solid K_2CO_3, filtered, and purified by chromatography (25% ethyl acetate in hexanes) to yield 2 distinct products (385 mg combined) consisting of a mixture of partially deprotected and triethylsilylated products.

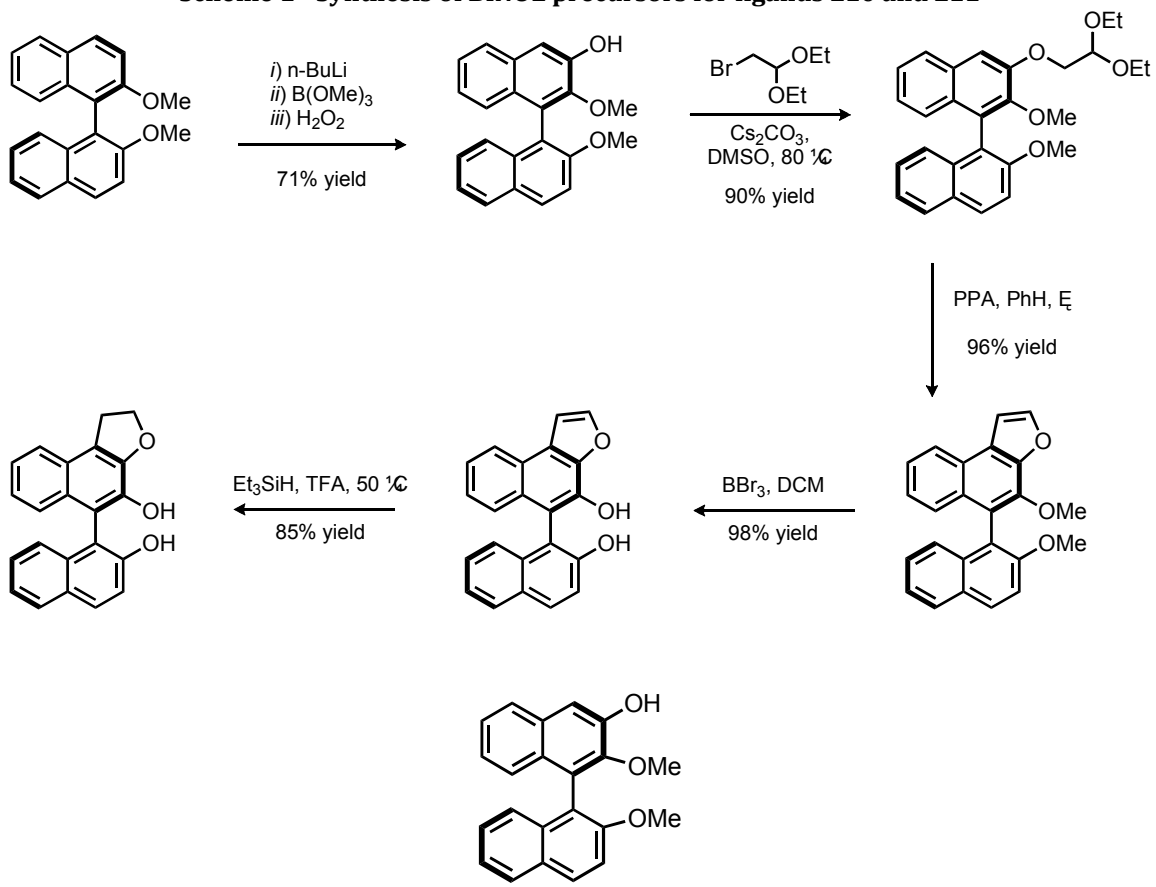
The combined mixture was then dissolved in benzene (4 ml) and methanol (1 ml), and anhydrous HCl (2.0 ml, 2.0 M in diethyl ether, 4.0 mmol) was added. After stirring for 16 hours, the reaction was concentrated and purified by chromatography (15% ethyl acetate in hexanes) to yield a white foam (206 mg, 76% over 2 steps). ^{1}H NMR (400 MHz, $CDCl_3$): 7.99 (d, J = 9.2 Hz, 1H), 7.92-7.85 (m, 3H), 7.41-7.06 (m, 7H), 5.1 (bs, 2H), 3.48 (apparent quintet, J = 6.8 Hz, 1H), 1.41 (d, J = 6.8 Hz, 3H), 1.40 (d, J = 6.8 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): 153.2, 151.7, 137.7, 133.8, 132.1, 131.7, 129.84, 129.82, 128.7, 128.3, 127.8, 127.1, 126.8, 124.6, 124.3, 124.23, 124.17, 118.1, 111.5, 110.7, 28.2, 22.99, 22.95 IR (thin film): 3517, 1960, 1619, 1596, 1384, 1211, 1144 cm^{-1}. $[\alpha]_{24}^{D}$ = +40.2 (c 0.73, $CHCl_3$).



Ligand L9: The reaction was performed according to general procedure A using (2*R*,5*R*)-2,5-di(naphthalen-2-yl)pyrrolidine (40.0 mg, 0.124 mmol) and (*R*)-3-isopropyl-1,1'-binaphthyl-2,2'-diol (40.6 mg, 0.124 mmol) and purified by flash chromatography on deactivated alumina oxide (10% dichloromethane in pet ether with 2% triethylamine) to yield the product as a white powder (71 mg, 84% yield, dr 5:1 as determined by ^{31}P NMR). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.93-7.72 (m, 5H), 7.68-7.63 (m, 4H), 7.56-7.53 (m, 2H), 7.74-6.92 (m, 13H), 6.76 (s, 0.82H, major), 6.54 (d, J = 8.8 Hz, 0.17H, minor), 5.88 (d, J = 8.8 Hz, 0.17H, minor), 5.33 (m, 2H), 3.10-2.97 (m, 1H), 2.64-2.52 (m, 2H), 1.99-1.82 (m, 2H), 1.01 (d, J = 6.8 Hz, 3H), 0.71 (d, J = 6.8 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 149.5, 148.8 (d, J = 8.7 Hz), 142.5 (d, J = 4.5 Hz), 139.7, 133.8, 133.6, 133.3, 133.1, 132.8, 131.6 (d, J = 9.0 Hz), 130.6, 130.3, 128.6, 128.5, 128.19, 128.16, 128.0, 127.5, 126.7, 126.5, 126.3, 126.0, 125.8, 125.7 (d, J = 1.4 Hz), 124.9, 124.8 (d, J = 4.4 Hz), 124.3, 122.2, 121.40 (d, J = 3.0 Hz), 63.5 (d, J = 11.9 Hz), 34.6 (d, J = 1.6 Hz),

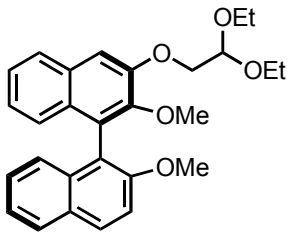
28.7, 24.6, 20.2. ^{31}P NMR (162 MHz, $CDCl_3$): δ 149.4 (major), 144.9 (minor). IR (thin film): 3052, 2961, 1232 cm^{-1}. $[\alpha]_{27}^{D}$ = -68.9 (c 0.84, $CHCl_3$).

Scheme 1 - Synthesis of BINOL precursors for ligands L10 and L11

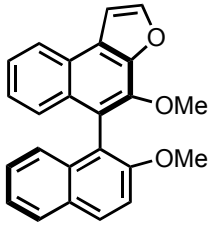


(*R*)-2,2'-dimethoxy-1,1'-binaphthyl-3-ol: A solution of (*R*)-2,2'-dimethoxy-1,1'-binaphthyl (2.00 g, 6.36 mmol) in THF (106 ml) was prepared by gentle heating until all solids had dissolved. It was then cooled to -78 ºC and *n*-butyl lithium (10.0 M in hexanes, 1.15 ml, 11.5 mmol) was added. The reaction was stirred for 30 minutes at -78 ºC before it was warmed to 0 ºC and stirred for 3 hours. The brown solution was then recooled to -78 ºC and trimethyl borate (1.4 ml, 12.7 mmol) was added dropwise, during which the solution became clear. After stirring overnight with gradual warming to room temperature, the reaction was concentrated, benzene (40 ml) and H_2O_2 (2.45 ml, 30% aq.) were added, and the mixture was refluxed for 2 hours. It was finally cooled, quenched with saturated aq. $NaHSO_3$ (15 ml) and the layers were separated. The aqueous phase was extracted with ethyl acetate (2 x 20 ml) and the combined organics were washed with

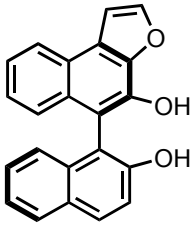
brine (20 ml), dried over $MgSO_4$, concentrated and purified by chromatography (30% ethyl acetate in hexanes) to yield a red and white foam (1.49 g, 71% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.00 (d, *J* = 9.2 Hz, 1H), 7.86 (d, *J* = 8.0 Hz, 1H), 7.73 (d, *J* = 8.4 Hz, 1H), 7.45-7.42 (m, 2H), 7.34-7.15 (m, 4H), 7.07-7.06 (m, 2H), 6.15 (s, 1H), 3.78 (s, 3H), 3.37 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 155.2, 147.9, 146.2, 134.1, 131.8, 130.4, 129.2, 129.0, 128.2, 127.1, 126.9, 125.6, 125.5, 125.4, 124.1, 124.0, 129.9, 118.5, 113.7, 110.0, 61.0, 56.8. IR (thin film): 3496, 3056, 2937, 1836, 1620, 1592, 1462 cm^{-1}. $[\alpha]_{26}^{D}$ = +20.2 (c 1.02, $CHCl_3$).



(*R*)-3-(2,2-diethoxyethoxy)-2,2'-dimethoxy-1,1'-binaphthalene: To a suspension of naphthol (3.46 g, 10.5 mmol) and Cs_2CO_3 (5.19 g, 15.9 mmol) in DMSO (49 ml) was added bromoacetaldehyde diethyl acetal (1.71 ml, 11.7 mmol). The suspension was stirred for 15 hours at 80 ºC then cooled, quenched with water (50 ml) and extracted with ethyl acetate (3 x 50 ml). The combined organics were washed with brine (50 ml), dried over $MgSO_4$, concentrated and purified by chromatography (20% ethyl acetate in hexanes) to yield a white solid (4.23 g, 90% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.99 (d, *J* = 9.2 Hz, 1H), 7.86 (d, *J* = 8.0 Hz, 1H), 7.76 (d, *J* = 8.0 Hz, 1H), 7.45 (d, *J* = 9.2 Hz, 1H), 7.36-7.28 (m, 3H), 7.23-7.19 (m, 1H), 7.13-7.09 (m, 2H), 7.02 (d, *J* = 8.0 Hz, 1H), 5.02 (t, *J* = 5.2 Hz, 1H), 4.25 (d, *J* = 5.2 Hz, 2H), 3.88-3.79 (m, 2H), 3.78 (s, 3H), 3.75-3.67 (m, 2H), 3.61 (s, 3H), 1.27 (t, *J* = 6.8 Hz, 3H), 1.26 (t, *J* = 6.8 Hz, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 155.0, 151.6, 147.7, 134.3, 131.4, 129.8, 129.3, 129.2, 128.1, 126.9, 126.7, 125.8, 125.5, 125.4, 124.3, 123.8, 119.2, 113.8, 108.4, 100.9, 69.2, 63.2, 63.1, 60.7, 56.8, 15.6. IR (thin film): 3056, 2973, 2933, 1593, 1507, 1463 cm^{-1}. $[\alpha]_{25}^{D}$ = +42.7 (c 0.66, $CHCl_3$).

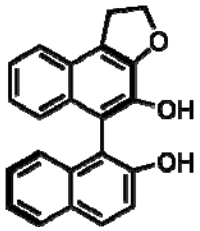


(*R*)-4-methoxy-5-(2-methoxynaphthalen-1-yl)naphtho[2,1-b]furan: A mixture of acetal (1.75 g, 3.92 mmol), polyphosphoric acid (approximately 0.9 g) and benzene (12 ml) was refluxed for 5 hours, then cooled, concentrated and purified by chromatography (15% ethyl acetate in hexanes) to yield a white solid (1.33 g, 96% yield). MP 206 ºC (crystallized from 15% ethyl acetate in hexanes). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.14 (d, *J* = 8.4 Hz, 1H), 7.98 (d, *J* = 9.2 Hz, 1H), 7.86 (d, *J* = 8.4 Hz, 1H), 7.80 (d, *J* = 2.1 Hz, 1H), 7.45 (d, *J* = 9.2 Hz, 1H), 7.44 (dt, *J* = 1.8, 7.6 Hz, 1H), 7.34 (d, *J* = 2.1 Hz, 1H), 7.30 (dt, *J* = 1.8, 7.6 Hz, 1H), 7.20-7.13 (m, 4H), 3.90 (s, 3H), 3.76 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 155.4, 146.3, 144.3, 143.6, 134.6, 131.4, 129.9, 129.4, 128.2, 126.74, 126.71, 125.5, 125.4, 125.2, 125.0, 124.8, 123.8, 123.6, 120.1, 119.3, 114.0, 106.3, 60.8, 56.9. IR (thin film): 2944, 1588, 1509, 1462, 1362 cm^{-1}. $[\alpha]_{25}^{D}$ = +86.7 (c 0.57, $CHCl_3$).

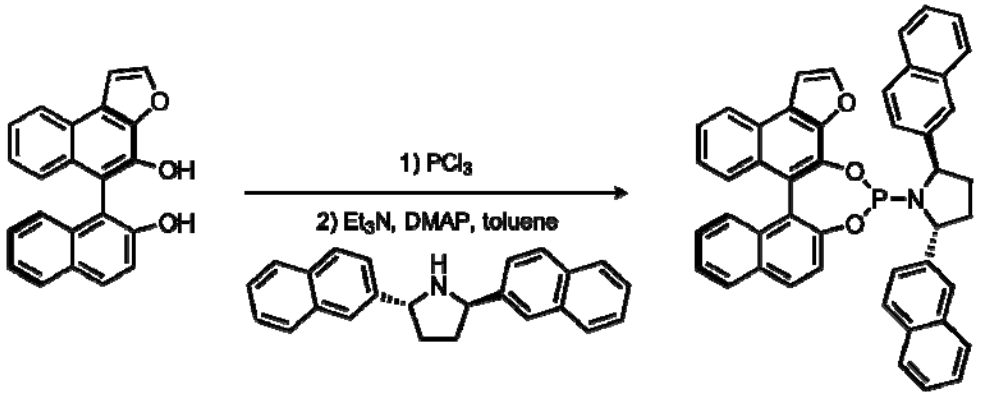


(*R*)-5-(2-hydroxynapthalen-1-yl)naphtho[2,1-*b*]furan-4-ol: To a room temperature solution of naphthofuran (2.87 g, 8.1 mmol) in dichloromethane (80 ml) was added BBr_3 (16.2 ml, 1.0 M in DCM, 16.2 mmol) and the dark green solution was stirred for 2.5 hours. It was carefully quenched with water (80 ml), the layers were separated, and the aqueous layer was washed with dichloromethane (80 ml). The combined organics were dried over Na_2SO_4, concentrated and purified by chromatography (15% ethyl acetate in hexanes) to yield a white foam (2.60 g, 98% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.17 (dm, *J* = 8.4 Hz, 1H), 7.95 (d, *J* = 8.8 Hz, 1H), 7.87 (d, *J* = 8.0 Hz, 1H), 7.86 (d, *J* = 2.0 Hz, 1H), 7.50-7.45 (m, 1H), 7.39-7.20 (m, 6H), 7.16 (d, *J* = 8.4 Hz, 1H), 4.99 (bs, 2H).

^{13}C NMR (100 MHz, $CDCl_3$): δ 153.3, 145.7, 143.3, 141.3, 134.0, 131.8, 130.8, 129.8, 128.7, 127.8, 126.4, 126.4, 125.7, 124.9, 124.6, 124.3, 124.3, 124.1, 118.1, 111.1, 108.4, 106.6. IR (thin film): 3496, 3056, 1619, 1594, 1513, 1389 cm^{-1}. Chiral HPLC: Chiralpak IA, 0.8 mL/min, 10% *i*-PrOH in heptane, λ = 254 nm, $t_{R,\ major}$ = 22.9 min, $t_{R,\ minor}$ = 34.7 min. $[\alpha]_{23}^{D}$ = +91.2 (c 1.05, $CHCl_3$). HRMS: calcd for ($M+H^+$) $C_{22}H_{15}O_3$ 327.1021; found 327.1007.



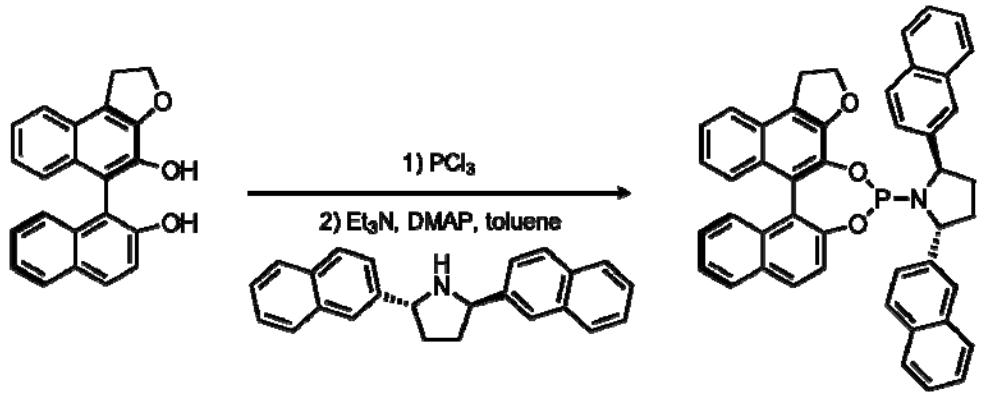
(*R*)-5-(2-hydroxynaphthalen-1-yl)-1,2-dihydronaphtho[2,1-b]furan-4-ol: To (*R*)-5-(2-hydroxynaphthalen-1-yl)naphtho[2,1-*b*]furan-4-ol (1.15 g, 3.52 mmol) was added trifluoroacetic acid (9.2 ml, 124 mmol) followed by triethylsilane (2.28 ml, 14.1 mmol). The reaction flask was sealed and the solution was stirred at 50 ºC for 18 hours. The resulting milky suspension was cooled, concentrated under vacuum and dissolved in ethyl acetate (30 ml). After washing with sat. $NaHCO_3$ (2 x 10 ml) and brine (10 ml), the organics were dried over $MgSO_4$, concentrated and purified by flash chromatography (30% ethyl acetate in hexanes) to give the product as a white solid (0.98 g, 85% yield). MP 234-236 ºC. ^1H NMR (400 MHz, $CDCl_3$): δ 7.96 (d, *J* = 9.0 Hz, 1H), 7.88 (d, *J* = 7.6 Hz, 1H), 7.67 (d, *J* = 7.6 Hz, 1H), 7.42-7.26 (m, 4H), 7.20-7.13 (m, 3H), 5.14 (bs, 2H), 4.92 (q, *J* = 8.8 Hz, 1H), 4.82 (q, *J* = 8.8 Hz, 1H), 3.73-3.59 (m, 2H). ^{13}C NMR (100 MHz, DMSO-d_6): δ 153.2, 148.4, 141.0, 134.3, 129.7, 128.8, 128.1, 127.9, 125.9, 125.3, 125.2, 124.4, 123.2, 122.88, 122.85, 122.3, 119.2, 118.5, 116.9, 115.0, 71.7, 28.9. IR (thin film): 3450, 3422, 3058, 2965, 2897, 1623, 1514, 1453 cm^{-1}. $[\alpha]_{26}^{D}$ = +67.7 (c 0.87, $CHCl_3$). HRMS: calcd for ($M+H^+$) $C_{22}H_{17}O_3$ 329.1177; found 329.1164.



Ligand L10:

1. Freshly distilled PCl_3 (3 ml, 34.0 mmol) was added to (*R*)-5-(2-hydroxynapthalen-1-yl)naphtho[2,1-*b*]furan-4-ol (282 mg, 0.86 mmol) followed by a single drop of N-Methyl-2-pyrrolidone. The mixture was stirred for 15 minutes at 60 ºC, cooled, concentrated, and concentrated from toluene (2 x 5 ml). The residue was then dissolved in toluene (1.7 ml) to give a 0.5 M solution (assuming full conversion) as a mixture of diastereomers. ^{31}P NMR (162 MHz, $CDCl_3$): δ 181.8, 181.7.

2. To a solution of (2*R*,5*R*)-2,5-di(naphthalen-2-yl)pyrrolidine (152 mg, 0.47 mmol), triethylamine (0.33 ml, 2.34 mmol) and 4-dimethylaminopyridine (11.5 mg, 0.09 mmol) in toluene (3 ml) at -40 ºC was added the above chlorophosphite solution (1.5 ml, 0.75 mmol) dropwise over 2 minutes. The solution was stirred for 16 hours with gradual warming to room temperature, then concentrated and purified by chromatography on deactivated alumina oxide (20% dichloromethane in pet ether with 1% triethylamine) to yield a white powder (309 mg, 97% yield, dr >20:1 as determined by ^{31}P NMR). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.09 (d, *J* = 8.4 Hz, 1H), 7.99-7.92 (m, 6H), 7.89 (d, *J* = 8.4 Hz, 2H), 7.60-7.39 (m, 9H), 7.32-7.28 (m, 2H), 7.24 (d, *J* = 2.2 Hz, 1H), 7.19-7.07 (m, 3H), 6.55 (d, *J* = 8.8 Hz, 1H), 5.89 (d, *J* = 8.8 Hz, 1H), 5.46 (d, *J* = 7.2 Hz, 2H), 2.62-2.51 (m, 2H), 1.89-1.77 (m, 2H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 149.7 (d, *J* = 10.5 Hz), 146.3 (d, *J* = 2.2 Hz), 145.3, 143.5 (d, *J* = 4.4 Hz), 137.4, 133.9, 133.2, 132.7 (d, *J* = 1.5 Hz), 130.3, 130.1 (d, *J* = 1.5 Hz), 128.71, 128.68, 128.53, 128.47, 128.3, 128.0, 127.5, 126.3, 126.0, 125.77, 125.75, 125.7, 125.6, 125.3, 124.7, 124.4, 124.0, 122.1, 121.23 (d, *J* = 3.7 Hz), 121.16 (d, *J* = 5.2 Hz), 106.3, 63.1 (d, *J* = 13.4 Hz), 35.5. ^{31}P NMR (162 MHz, $CDCl_3$): δ 146.7. IR (thin film): 3052, 2967, 1462, 1367 cm^{-1}. $[\alpha]_{24}^{D}$ = +113.7 (c 0.97, $CHCl_3$). HRMS: calcd for ($M+H^+$) $C_{46}H_{33}NO_3P$ 678.2198; found 678.2167.



Ligand L11:

1) Freshly distilled PCl_3 (1 ml, 11.3 mmol) was added to (R)-5-(2-hydroxynaphthalen-1-yl)-1,2-dihydronaphtho[2,1-b]furan-4-ol. (150 mg, 0.46 mmol) followed by N-methyl-2-pyrrolidone (5 μL). The mixture was stirred for 20 minutes at 60 ºC to give a pale yellow solution, then cooled and carefully concentrated under reduced pressure. The pale yellow foam was concentrated from toluene (2 x 1 ml) then dissolved in toluene (1.25 ml). ^{31}P NMR (162 MHz, $CDCl_3$): δ 181.6, 178.6.

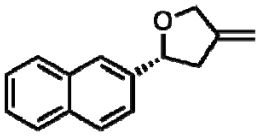
2) To a solution of (2*R*,5*R*)-2,5-di(naphthalen-2-yl)pyrrolidine (80.2 mg, 0.25 mmol), triethylamine (0.17 ml, 1.24 mmol) and 4-dimethylaminopyridine (6.1 mg, 0.05 mmol) in toluene (1.3 ml) at -40 ºC was added the above chlorophosphite solution dropwise by cannula over 3 minutes. The resulting reaction mixture was held at -40 ºC for 4 hours, then allowed to gradually warm to room temperature. After 16 hours at room temperature, the mixture was concentrated and purified by chromatography on deactivated alumina oxide (33% dichloromethane in pet ether with 1% triethylamine) to yield a white powder (110 mg, 66% yield, dr >20:1 as determined by ^{31}P NMR). ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.91-7.87 (m, 6H), 7.83 (d, *J* = 8.5 Hz, 2H), 7.55-7.49 (m, 5H), 7.45 (d, *J* = 8.5 Hz, 1H), 7.39 (dd, *J* = 1.5, 8.5 Hz, 2H), 7.31-7.25 (m, 3H), 7.15 (ddd, *J* = 1.2, 6.8, 8.2 Hz, 1H), 7.04 (d, *J* = 8.7 Hz, 1H), 6.93 (ddd, *J* = 1.2, 6.8, 8.2 Hz, 1H), 6.46 (d, *J* = 8.8 Hz, 1H), 5.89 (d, *J* = 8.8 Hz, 1H), 5.41 (d, *J* = 6.9 Hz, 2H), 4.88-4.82 (m, 1H), 4.64-4.58 (m, 1H), 3.60-3.53 (m, 1H), 3.48-3.41 (m, 1H), 2.56-2.46 (m, 2H), 1.80-1.73 (m, 2H). ^{13}C NMR (125 MHz, $CDCl_3$): δ 151.6, 149.9 (d, *J* = 10.1 Hz), 143.5 (d, *J* = 4.6 Hz), 137.2, 133.9, 133.1, 132.6, 130.2, 128.7, 128.64, 128.56, 128.42, 128.38, 128.2, 127.9, 127.4, 126.3, 125.9, 125.70, 125.67, 125.61, 125.59, 125.43,

125.39, 124.3, 123.3, 123.2, 122.1, 121.7, 121.2 (d, J = 2.5 Hz), 72.6, 63.0 (d, J = 13.3 Hz), 33.5, 29.7. ^{31}P NMR (162 MHz, $CDCl_3$): δ 144.4. IR (thin film): 3054, 2970, 1599, 1509, 1449, 1380, 1070 cm^{-1}. HRMS: calcd for ($M+H^+$) $C_{46}H_{35}NO_3P$ 680.2354; found 680.2324.

C. TMM Cycloadducts

General procedure A for the TMM cycloadditions of aldehydes with $In(acac)_3$. To an argon-purged vial of substrate (0.076 mmol), $In(acac)_3$ (3.1 mg, 0.0076 mmol), **L11** (5.2 mg, 0.0076 mmol) and $Pd(dba)_2$ (2.2 mg, 0.0038 mmol) was added toluene (0.5 ml) and the solution stirred for 2 minutes before 2-((trimethylsilyl)methyl)allyl acetate (25 μL, 0.12 mmol) was added (if the substrate was an oil, it was added immediately prior to the allyl acetate). After stirring for 3 or 24 hours (at 50ºC or room temperature, respectively), the solution was concentrated and purified by flash chromatography.

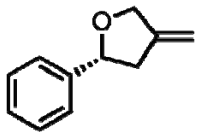
General procedure B for the TMM cycloadditions of aldehydes without $In(acac)_3$. To an argon-purged vial of substrate (0.076 mmol), **L11** (5.2 mg, 0.0076 mmol) and $Pd(dba)_2$ (2.2 mg, 0.0038 mmol) was added toluene (0.5 ml) and the solution stirred for 2 minutes before 2-((trimethylsilyl)methyl)allyl acetate (25 μL, 0.12 mmol) was added (if the substrate was an oil, it was added immediately prior to the allyl acetate). After stirring for 3 or 24 hours (at 50ºC or room temperature, respectively), the solution was concentrated and purified by flash chromatography.



(*R*)-4-methylene-2-(naphthalen-2-yl)tetrahydrofuran:

Small scale: The reaction was performed with 11.9 mg (0.076 mmol) of 2-naphthaldehyde according to general procedure B and purified by flash chromatography (4% ethyl acetate in hexanes) to give the product as a clear, colorless oil (11.5 mg, 72% yield).

Large scale: A mixture of 2-naphthaldehyde (154.0 mg, 1.0 mmol), $Pd(dba)_2$ (14.4 mg, 0.025 mmol) and ligand **L11** (34.0 mg, 0.05 mmol) was purged with argon for 15 minutes. Toluene (3.33 ml) was added and the solution was stirred for 2 minutes before 2-((trimethylsilyl)methyl)allyl acetate (0.33 mL, 1.6 mmol) was added. The solution was immersed in a 50 ºC oil bath and stirred for 3 hours. It was then cooled and purified directly by flash chromatography (4% ethyl acetate in hexanes) to give a clear, colorless oil (165.2 mg, 80% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.85-7.82 (m, 4H), 7.49-7.45 (m, 3H), 5.15 (dd, *J* = 2, 6.4 Hz, 1H), 5.05 (quintet, *J* = 2.2 Hz, 1H), 4.99 (quintet, *J* = 2.2 Hz, 1H), 4.67-4.64 (bd, *J* = 13.2 Hz, 1H), 4.49-4.44 (dm, *J* = 13.2 Hz, 1H), 3.06-3.00 (m, 1H), 2.68-2.61 (m, 1H). ^{13}C NMR: δ 148.2, 139.6, 133.6, 133.3, 128.6, 128.3, 128.0, 126.4, 126.2, 124.9, 124.4, 104.9, 81.6, 71.8, 41.5. IR (thin film): 3056, 2910, 2846, 1667, 1602, 1329, 1055 cm^{-1}. $[\alpha]_{24}^{D}$ = +13.2 (c 0.87, $CHCl_3$, 90% ee). Chiral HPLC: Chiralpak AD, 1.0 ml/min, 1% *i*-PrOH in heptane, λ = 254 nm, $t_{R, minor}$ = 9.1 min, $t_{R, major}$ = 10.1 min). HRMS: calcd for ($M+Na^+$) $C_{15}H_{14}ONa$ 233.0942; found 233.0941.



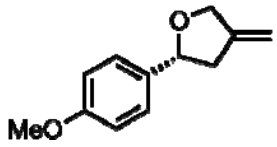
(*R*)-4-methylene-2-phenyltetrahydrofuran:

Small scale: The reaction was performed with 8.1 mg (0.076 mmol) of benzaldehyde according to general procedure A and purified by flash chromatography (4% ethyl acetate in hexanes) to give the product as a clear, colorless oil (9.7 mg, 80% yield).

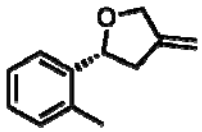
Large scale: A mixture of $Pd(dba)_2$ (14.4 mg, 0.025 mmol) and ligand **L11** (34.0 mg, 0.05 mmol) was purged with argon for 15 minutes. Toluene (3.33 ml) was added followed by benzaldehyde (102 μL, 1.0 mmol), and the solution was stirred for 2 minutes before 2-((trimethylsilyl)methyl)allyl acetate (0.33 mL, 1.6 mmol) was added. The solution stirred for 16 hours at room temperature then purified directly by flash chromatography (4% ethyl acetate in hexanes) to give a clear, colorless oil (111.7 mg, 70% yield). Matches known characterization.[8] ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.38-7.26

[8] Okuma, K.; Kamahori, Y.; Tsubakihara, K.; Yoshihara, K.; Tanaka, Y.; Shioji, K. *J. Org. Chem.* **2002**, *67*, 7355.

(m, 5H), 5.03 (quintet, J = 2.2 Hz, 1H), 4.99-4.94 (m, 2H), 4.61-4.56 (m, 1H), 4.43-4.38 (m, 1H), 2.99-2.94 (m 1H), 2.60-2.52 (m, 1H). $[\alpha]_{25}^{D}$ = +26.2 (c 0.27, $CHCl_3$, 77% ee). Chiral HPLC: Chiralcel OJ, 0.8 ml/min, 10% *i*-PrOH in heptane, λ = 220 nm, $t_{R,\ major}$ = 12.7 mins, $t_{R,\ minor}$ = 13.6 min.

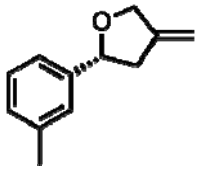


(*R*)-2-(4-methoxyphenyl)-4-methylenetetrahydrofuran: The reaction was performed with 10.3 mg (0.076 mmol) of *p*-anisaldehyde according to general procedure B and purified by flash chromatography (4% ethyl acetate in hexanes) to give the product as a clear, colorless oil (12.4 mg, 86% yield). Matches known characterization.[8] ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.30 (d, J = 9.2 Hz, 2H), 6.88 (d, J = 9.2 Hz, 2H), 5.03 (quintet, J = 2.3 Hz, 1H), 4.95 (quintet, J = 2.3 Hz, 1H), 4.91 (dd, J = 6, 8.8 Hz, 1H), 4.60-4.53 (m, 1H), 4.40-4.35 (m, 1H), 3.80 (s, 3H), 2.94-2.86 (m, 1H), 2.60-2.51 (m, 1H). $[\alpha]_{24}^{D}$ = +21.1 (c 1.10, $CHCl_3$, 88% ee). Chiral HPLC: Chiralpak AD, 1.0 ml/min, 1% *i*-PrOH in heptane, λ = 220 nm, $t_{R,\ major}$ = 11.4 mins, $t_{R,\ minor}$ = 12.4 min.

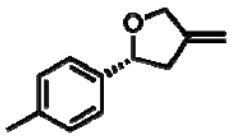


(*R*)-4-methylene-2-*o*-tolyltetrahydrofuran: The reaction was performed with 9.1 mg (0.076 mmol) of *o*-tolualdehyde according to general procedure B and purified by flash chromatography (4% ethyl acetate in hexanes) to give the product as a clear, colorless oil (12.3 mg, 93% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.48 (dd, J = 1.6, 7.2 Hz, 1H), 7.30-7.07 (m, 3H), 5.13 (dd, J = 6.4, 8.8 Hz, 1H), 5.02 (quintet, J = 2.2 Hz, 1H), 4.97 (quintet, J = 2.2 Hz, 1H), 4.65-4.59 (m, 1H), 4.44-4.38 (m, 1H), 3.02-2.95 (m, 1H), 2.48-2.39 (m, 1H), 2.32 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 148.4, 140.4, 134.9, 130.5, 127.6, 126.5, 125.2, 104.7, 78.7, 71.6, 40.2, 19.6. IR (thin film): 3074, 2921, 2851, 1667, 1461, 1058, 884, 753 cm^{-1}. $[\alpha]_{24}^{D}$ = +65.1 (c 0.78, $CHCl_3$, 88% ee). Chiral HPLC: Chiralcel OD, 0.8 ml/min, 0.1% *i*-PrOH in heptane, λ = 220 nm, $t_{R,\ major}$ = 31.2 mins, $t_{R,}$

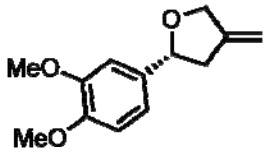
$_{minor}$ = 33.9 min. HRMS: calcd for ($M+H^+$) $C_{12}H_{15}O$ 175.1123; found 175.1112.



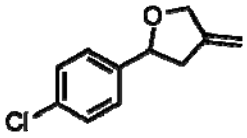
(*R*)-4-methylene-2-*m*-tolyltetrahydrofuran: The reaction was performed with 9.1 mg (0.076 mmol) of *m*-tolualdehyde according to general procedure A and purified by flash chromatography (4% ethyl acetate in hexanes) to give the product as a clear, colorless oil (10.1 mg, 76% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.30-7.07 (m, 4H), 5.02 (quintet, *J* = 2.4 Hz, 1H), 4.96 (quintet, *J* = 2.4 Hz, 1H), 4.93 (dd, *J* = 6.4, 8.4 Hz, 1H), 4.61-4.51 (m, 1H), 4.42-4.37 (m, 1H), 2.97-2.90 (m, 1H), 2.60-2.52 (m, 1H), 2.35 (s, 3H). ^{13}C NMR (100 MHz, $CDCl_3$): δ148.3, 142.0, 138.4, 128.7, 128.6, 126.9, 123.3, 104.7, 81.5, 71.7, 41.5, 21.8. IR (thin film): 2920, 2851, 1706, 1650, 1610, 1431, 1360, 1057, 884, 758, 700 cm^{-1}. $[\alpha]_{23}^{D}$ = +26.5 (c 0.95, $CHCl_3$, 81% ee). Chiral HPLC: Chiralpak AD, 1.0 ml/min, 1% *i*-PrOH in heptane, λ = 220 nm, $t_{R, minor}$ = 5.5 mins, $t_{R, major}$ = 6.2 min. HRMS: calcd for ($M+H^+$) $C_{12}H_{15}O$ 175.1123; found 175.1111.



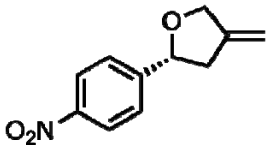
(*R*)-4-methylene-2-*p*-tolyltetrahydrofuran: The reaction was performed with 9.1 mg (0.076 mmol) of *p*-tolualdehyde according to general procedure A and purified by flash chromatography (4% ethyl acetate in hexanes) to give the product as a clear, colorless oil (9.1 mg, 69% yield). Matches known characterization.[8] ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.28-7.24 (m, 2H), 7.17-7.14 (m, 2H), 5.04-5.01 (m, 1H), 4.97-4.91 (m, 2H), 4.60-4.54 (m, 1H), 4.42-4.36 (m, 1H), 2.96-2.88 (m, 1H), 2.59-2.51 (m, 1H), 2.34 (s, 3H). $[\alpha]_{24}^{D}$ = +25.3 (c 0.81, $CHCl_3$, 84% ee). Chiral HPLC: Chiralcel OJ, 0.8 ml/min, 10% *i*-PrOH in heptane, λ = 220 nm, $t_{R, major}$ = 11.0 mins, $t_{R, minor}$ = 12.7 min.



(*R*)-2-(3,4-dimethoxyphenyl)-4-methylenetetrahydrofuran: The reaction was performed with 12.6 mg (0.076 mmol) of 3,4-dimethoxybenzaldehyde according to general procedure B and purified by flash chromatography (10% ethyl acetate in hexanes) to give a clear, colorless oil (16.7 mg, 100% yield). Matches known characterization.[8] ^{1}H-NMR (400 MHz, $CDCl_3$): 6.93 (d, J = 1.6 Hz, 1H), 6.88 (ddd, J = 8.2, 2.0, 0.6 Hz, 1H), 6.82 (d, J = 8.0 Hz, 1H), 5.02 (quint, J = 2.3 Hz, 1H), 4.95 (quint, J = 2.1 Hz, 1H), 4.89 (dd, J = 8.8, 6.0 Hz, 1H), 4.57 (d, J = 13.2 Hz, 1H), 4.40-4.35 (m, 1H), 3.88 (s, 3H), 3.86 (s, 3H), 2.94-2.87 (m, 1H), 2.59-2.51 (m, 1H). $[\alpha]_{23}^{D}$ = +17.1 (c 0.43, $CHCl_3$, 69% ee). Chiral HPLC: Chiralcel® AD column, 10% isopropanol in heptane, 1.0 mL/min, λ = 220 nm; t_R = 9.95 (major), 11.29 (minor).

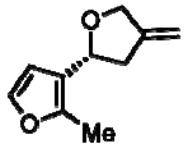


(*R*)-2-(4-chlorophenyl)-4-methylenetetrahydrofuran: The reaction was performed with 10.7 mg (0.076 mmol) of 4-chlorobenzaldehyde according to general procedure B and purified by flash chromatography (4% ethyl acetate in hexanes) to give the product as a clear, colorless oil (10.7 mg, 72% yield). Matches known characterization.[8] ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.33-7.28 (m, 4H), 5.03 (quintet, J = 2.4 Hz, 1H), 4.97 (quintet, J = 2.4 Hz, 1H), 4.94 (dd, J = 6.4, 8.4 Hz, 1H), 4.59-4.54 (m, 1H), 4.42-4.37 (m, 1H), 2.98-2.91 (m, 1H), 2.54-2.46 (m, 1H). $[\alpha]_{24}^{D}$ = +26.7 (c 0.78, $CHCl_3$, 83% ee). Chiral HPLC: Chiralpak OJ-H, 0.8 ml/min, 10% *i*-PrOH in heptane, λ = 220 nm, $t_{R,\ major}$ = 8.4 min, $t_{R,\ minor}$ = 9.4 min).



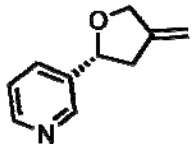
(*R*)-4-methylene-2-(4-nitrophenyl)tetrahydrofuran: The reaction was performed with

11.5 mg (0.076 mmol) of *p*-nitrobenzaldehyde according to general procedure A, but using ligand **L1** (4.8 mg, 0.0076 mmol). The reaction mixture was purified by flash chromatography (4% ethyl acetate in hexanes) to give the product as a pale yellow, waxy oil (9.6 mg, 62% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.20 (d, *J* = 8.4 Hz, 2H), 7.52 (d, *J* = 8.4 Hz, 2H), 5.08-5.04 (m, 2H), 5.00-4.98 (m, 1H), 4.63-4.57 (m, 1H), 4.46-4.41 (m, 1H), 3.07-2.99 (m, 1H), 2.53-2.45 (m, 1H). ^{13}C NMR (100 MHz, $CDCl_3$): δ 149.9, 147.6, 146.8, 126.8, 124.0, 105.7, 80.3, 71.9, 41.5. IR (thin film): 3080, 2920, 2852, 1669, 1605, 1520, 1347, 1559 cm^{-1}. $[\alpha]_{25}^{D}$ = +30.4 (c 0.42, $CHCl_3$, 78% ee). Chiral HPLC: Chiralcel OJ, 0.8 ml/min, 10% *i*-PrOH in heptane, λ = 220 nm, $t_{R,\ minor}$ = 20.4 mins, $t_{R,\ major}$ = 25.4 min. HRMS: calcd for ($M+Na^+$) $C_{11}H_{11}NO_3Na$ 228.0637; found 228.0648.

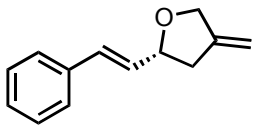


(*R*)-2-methyl-3-(4-methylenetetrahydrofuran-2-yl)furan: The reaction was performed with 8.4 mg (0.076 mmol) of 2-methyl-3-furaldehyde[9] according to general procedure A, but CpPd(η^3-C_3H_5) (0.8 mg, 0.0038 mmol) was used. The reaction mixture was purified by flash chromatography (4% ethyl acetate in hexanes) to give the product as a clear, colorless oil (7.8 mg, 63% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.25 (d, *J* = 1.9 Hz, 1H), 6.34 (d, *J* = 1.9 Hz, 1H), 5.05 (quintet, *J* = 2.3 Hz, 1H), 4.96 (quintet, *J* = 2.3 Hz, 1H), 4.85 (dd, *J* = 6.2, 8.7 Hz, 1H), 4.53-4.47 (m, 1H), 4.35-4.29 (m, 1H), 2.83-2.76 (m, 1H), 2.61-2.53 (m, 1H), 2.30 (s, 3H). ^{13}C NMR (125 MHz, $CDCl_3$): δ 149.4, 148.5, 140.8, 119.5, 109.2, 104.6, 74.1, 71.1, 39.9, 12.1. IR (thin film): 2921, 2853, 1665, 1631, 1515, 1050 cm^{-1}. $[\alpha]_{25}^{D}$ = +9.62 (c 0.61, $CHCl_3$, 83 % ee). Chiral HPLC: Chiralpak IC, 0.8 ml/min, 1% *i*-PrOH in heptane, λ = 220 nm, $t_{R,\ minor}$ = 7.7 mins, $t_{R,\ major}$ = 8.6 min. HRMS: calcd for ($M+H^+$) $C_{10}H_{13}O_2$ 165.0915; found 165.0904.

[9] Comins, D. L.; Killpack, M. O. *J. Org. Chem.* **1987**, *52*, 104.

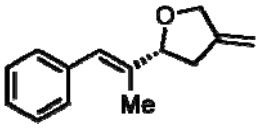


(*R*)-3-(4-methylenetetrahydrofuran-2-yl)pyridine: The reaction was performed with 8.1 mg (0.076 mmol) of 2-pyridinecarboxaldehyde according to general procedure A and purified by flash chromatography (66% ethyl acetate in hexanes) to give a clear, colorless oil (10.5 mg, 86% yield; contaminated with approximately 4% of 2-pyridinecarboxaldehyde as determined by ^{1}H NMR). ^{1}H NMR (400 MHz, $CDCl_3$): δ 8.61 (s, 1H), 8.55 (s, 1H), 7.73 (d, *J* = 8.0 Hz, 1H), 7.31 (dd, *J* = 4.8, 8.0 Hz, 1H), 5.06 (quintet, *J* = 2.1 Hz, 1H), 5.03-4.98 (m, 2H), 4.61-4.56 (m, 1H), 4.45-4.39 (m, 1H), 3.04-2.97 (m, 1H), 2.58-2.50 (m 1H). ^{13}C NMR (125 MHz, $CDCl_3$): δ 149.3, 148.1, 147.3, 137.6, 133.8, 123.7, 105.3, 79.1, 71.7, 41.2. IR (thin film): 2919, 2851, 1680, 1578, 1427, 1056 cm^{-1}. Chiral HPLC: Chiralpak IC, 0.8 ml/min, 10% *i*-PrOH in heptane, λ = 220 nm, $t_{R,\ minor}$ = 32.3 mins, $t_{R,\ major}$ = 36.4 min. RMS: calcd for ($M+H^+$) $C_{10}H_{12}NO$ 162.0919; found 162.0907.

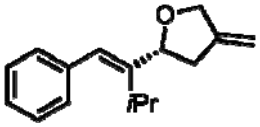


(*R,E*)-4-methylene-2-styryltetrahydrofuran: The reaction was performed with 9.6 μL (0.076 mmol) of cinnamaldehyde according to general procedure B and purified by flash chromatography (4% ethyl acetate in hexanes) to give a clear, colorless oil (11.0 mg, 78% yield) that was an approximately 3:1 mixture of carbonyl and olefin cycloadducts as determined by ^{1}H NMR. Tetrahydrofuran matches known characterization.[10] ^{1}H NMR (tetrahydrofuran only, 400 MHz, $CDCl_3$): δ 7.40-7.20 (m, 5H), 6.62 (d, *J* = 16.2 Hz, 1H), 6.24 (dd, *J* = 7.0, 15.9 Hz, 1H), 5.02 (quintet, *J* = 2.4 Hz, 1H), 4.94 (quintet, *J* = 2.4 Hz, 1H), 4.57 (q, *J* = 6.8 Hz, 1H), 4.47 (d, *J* = 12.8 Hz, 1H), 4.35 (m, 1H), 2.81-2.73 (m, 1H), 2.49-2.41 (m, 1H) . $[\alpha]_{24}^{D}$ = + 19.3 (c 1.10, $CHCl_3$, 70% ee). Chiral HPLC: Chiralpak IB, 0.8 ml/min, 1% *i*-PrOH in heptane, λ = 254 nm, $t_{R,\ major}$ = 8.7 mins, $t_{R,\ minor}$ = 10.0 min.

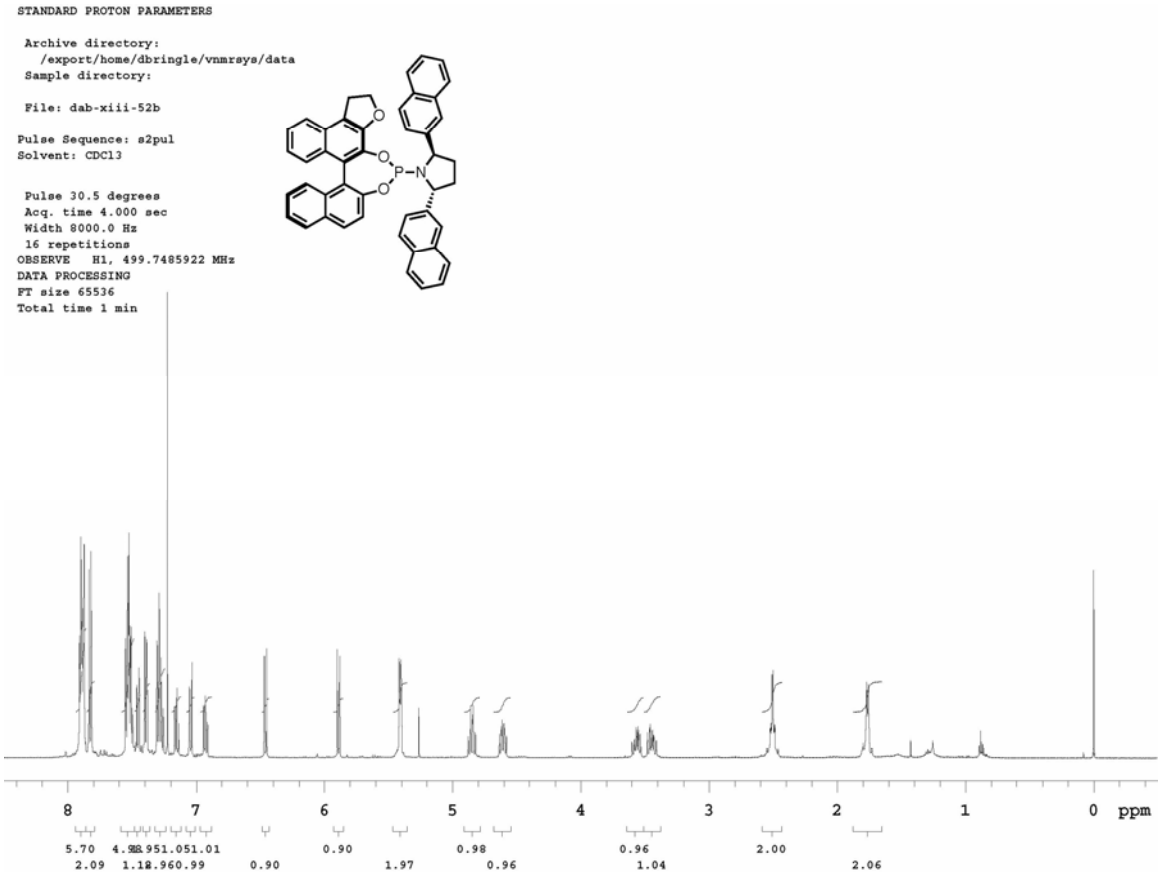
[10] Trost, B. M.; King, S. A.; Schmidt, T. *J. Am. Chem. Soc.* **1989**, *111*, 5902.



(*R,E*)-4-methylene-2-(1-phenylprop-1-en-2-yl)tetrahydrofuran: The reaction was performed with 10.6 μL (0.076 mmol) of alpha-methylcinnamaldehyde according to general procedure B and purified by flash chromatography (4% ethyl acetate in hexanes) to give a clear, colorless oil (10.5 mg, 69% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.35-7.19 (m, 5H), 6.57 (s, 1H), 5.02 (quintet, *J* = 2.4 Hz, 1H), 4.95 (quintet, *J* = 2.4 Hz, 1H), 4.54-4.46 (m, 2H), 4.38-4.42 (m, 1H), 2.79-2.71 (m, 1H), 2.56-2.47 (m, 1H), 1.87 (d, *J* = 1.3 Hz, 3H). ^{13}C NMR: δ 148.3, 137.9, 137.7, 129.3, 128.4, 126.7, 125.9, 104.7, 84.8, 71.7, 38.0, 14.1. IR (thin film): 3079, 2915, 2855, 1667, 1600, 1494, 1444, 1050 cm^{-1}. $[\alpha]_{24}^{D}$ = + 13.42 (c 1.01, $CHCl_3$, 72% ee). . HRMS: calcd for ($M+H^+$) $C_{11}H_{11}Cl_2O$ 201.1279; found 201.1267. Chiral HPLC: Chiralpak IB, 0.8 ml/min, 1% *i*-PrOH in heptane, λ = 254 nm, $t_{R, minor}$ = 6.2 mins, $t_{R, major}$ = 7.7 min.



(*R,E*)-2-(3-methyl-1-phenylbut-1-en-2-yl)-4-methylenetetrahydrofuran: The reaction was performed with 13.5 mg (13.5 μL, 0.076 mmol) of alpha-isopropylcinnamaldehyde according to general procedure B and purified by flash chromatography (4% ethyl acetate in hexanes) to give a clear, colorless oil (13.7 mg, 79% yield). ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.34-7.29 (m, 2H), 7.23-7.19 (m, 3H), 6.71 (s, 1H), 5.01 (bs, 1H), 4.94 (bs, 1H), 4.58-4.48 (m, 2H), 4.29 (d, *J* = 12.9 Hz, 1H), 3.10 (septet, *J* = 7.0 Hz, 1H), 2.83 (dd, *J* 5.8, 15.7 Hz, 1H), 2.50-2.41 (m, 1H), 1.12 (d, *J* = 7.0 Hz, 3H), 1.03 (d, *J* = 7.0 Hz, 3H). ^{13}C NMR: δ 148.9, 148.0, 138.4, 129.1, 128.4, 126.6, 124.1, 104.3, 78.0, 71.1, 42.2, 28.5, 22.01, 21.98. IR (thin film): 2962, 1691, 1494, 1362, 1051 cm^{-1}. $[\alpha]_{24}^{D}$ = + 39.415 (c 1.29, $CHCl_3$, 81% ee). HRMS: calcd for ($M+H^+$) $C_{11}H_{11}Cl_2O$ 229.1592; found 229.1580. Chiral HPLC: Chiralpak IB, 0.8 ml/min, 1% *i*-PrOH in heptane, λ = 254 nm, $t_{R, minor}$ = 5.0 mins, $t_{R, major}$ = 9.1 min.


STANDARD PROTON PARAMETERS
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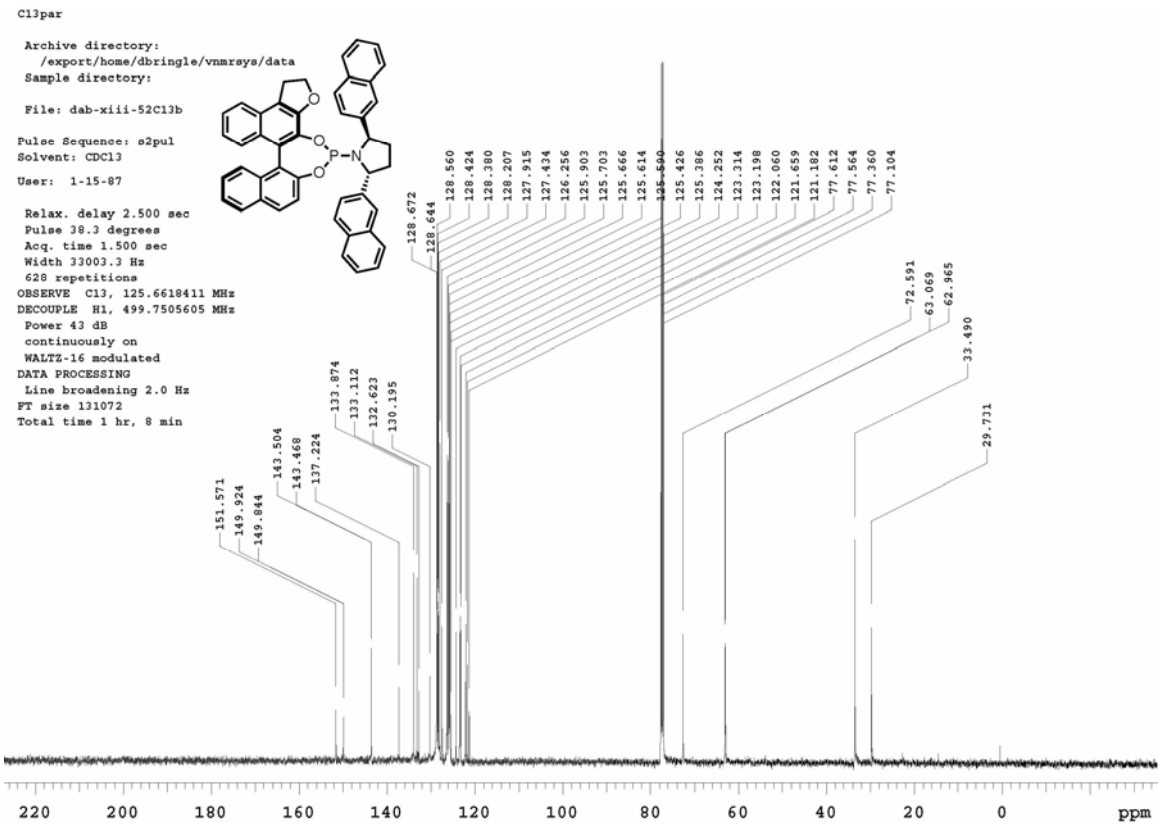
Pulse Sequence: s2pul
Solvent: CDCl3
Pulse 30.5 degrees
Acq. time 4.000 sec
Width 8000.0 Hz
16 repetitions
OBSERVE H1, 499.7485922 MHz
DATA PROCESSING
FT size 65536
Total time 1 min
8
7
6
5
4
3
2
1
0
ppm
5.70
4.98
951.05
1.01
0.90
0.98
0.96
2.00
2.09
1.18
960.99
0.90
1.97
0.96
1.04
2.06


C13par
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Sample directory:
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Solvent: CDCl3
User: 1-15-87
Relax. delay 2.500 sec
Pulse 38.3 degrees
Acq. time 1.500 sec
Width 33003.3 Hz
628 repetitions
OBSERVE C13, 125.6618411 MHz
DECOUPLE H1, 499.7505605 MHz
Power 43 dB
continuously on
WALTZ-16 modulated
DATA PROCESSING
Line broadening 2.0 Hz
FT size 131072
Total time 1 hr, 8 min
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128.644
128.560
128.424
128.380
128.207
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127.434
126.256
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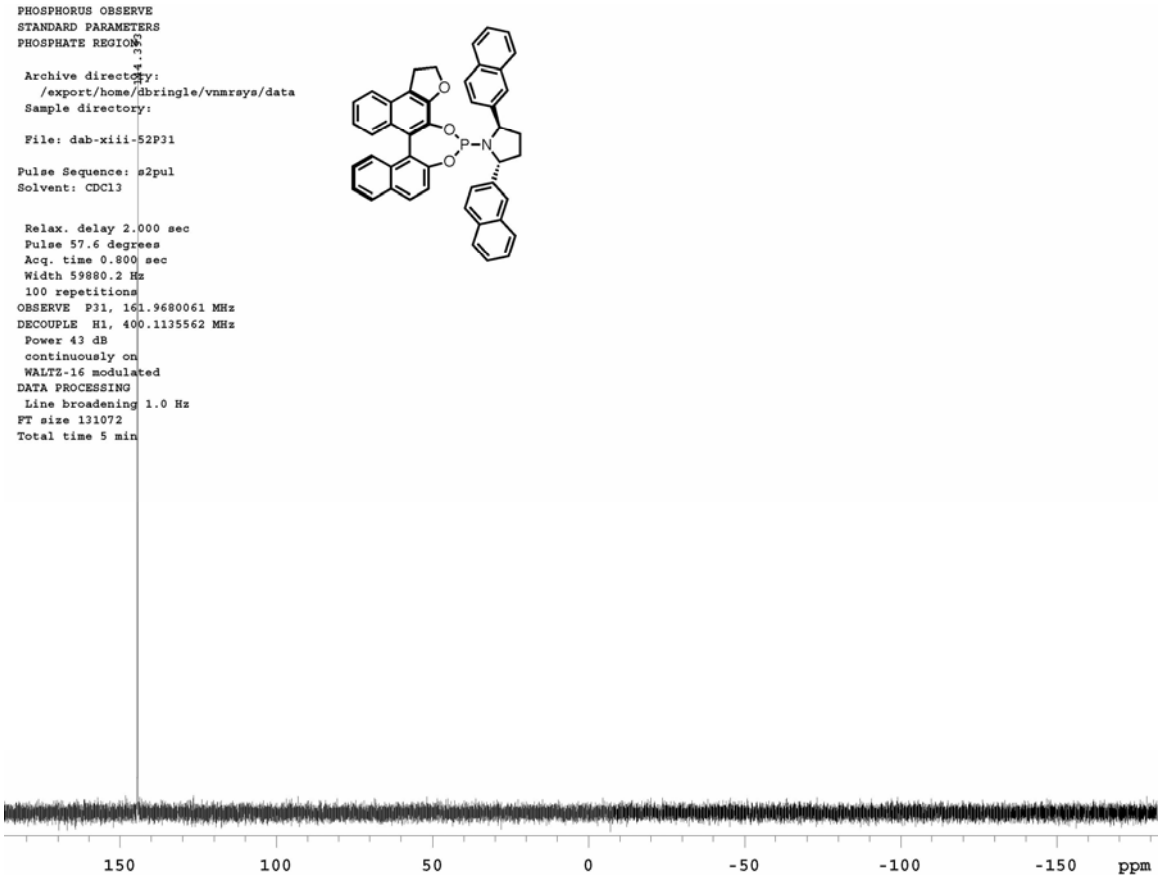
125.703
125.666
125.614
125.590
125.426
125.386
124.252
123.314
123.198
122.060
121.659
121.182
77.612
77.564
77.360
77.104
72.591
63.069
62.965
33.490
29.731
133.874
133.112
132.623
130.195
143.504
143.468
137.224
151.571
149.924
149.844
220
200
180
160
140
120
100
80
60
40
20
0
ppm


PHOSPHORUS OBSERVE
STANDARD PARAMETERS
PHOSPHATE REGION
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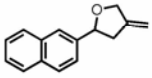
Solvent: CDCl3
Relax. delay 2.000 sec
Pulse 57.6 degrees
Acq. time 0.800 sec
Width 59880.2 Hz
100 repetitions
OBSERVE P31, 161.9680061 MHz
DECOUPLE H1, 400.1135562 MHz
Power 43 dB
continuously on
WALTZ-16 modulated
DATA PROCESSING
Line broadening 1.0 Hz
FT size 131072
Total time 5 min
O
O
P
N
150
100
50
0
-50
-100
-150
ppm

Std proton

Archive directory:

Sample directory:

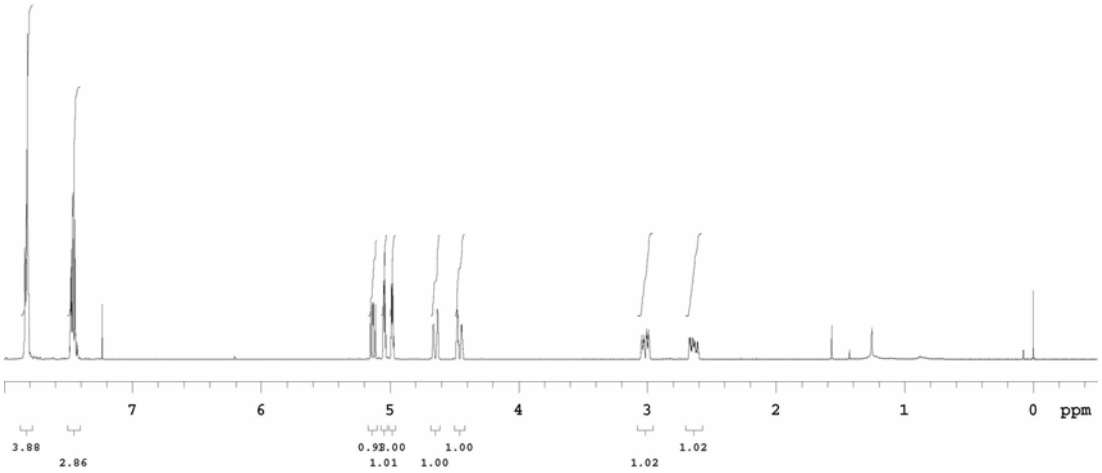
File: dab-iii-27



Pulse Sequence: s2pul
Solvent: cdcl3

Temp. 22.0 C / 295.1 K

Relax. delay 0.500 sec
Pulse 45.0 degrees
Acq. time 4.000 sec
Width 5605.4 Hz
16 repetitions
OBSERVE H1, 399.7291546 MHz
DATA PROCESSING
FT size 65536
Total time 1 min

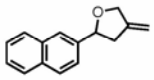


Std proton

Archive directory:

Sample directory:

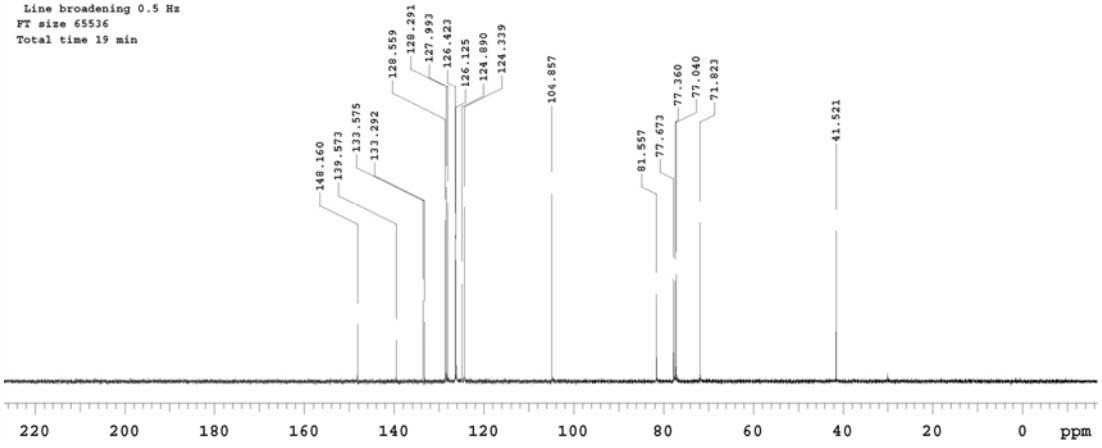
File: dab-iii-27C13

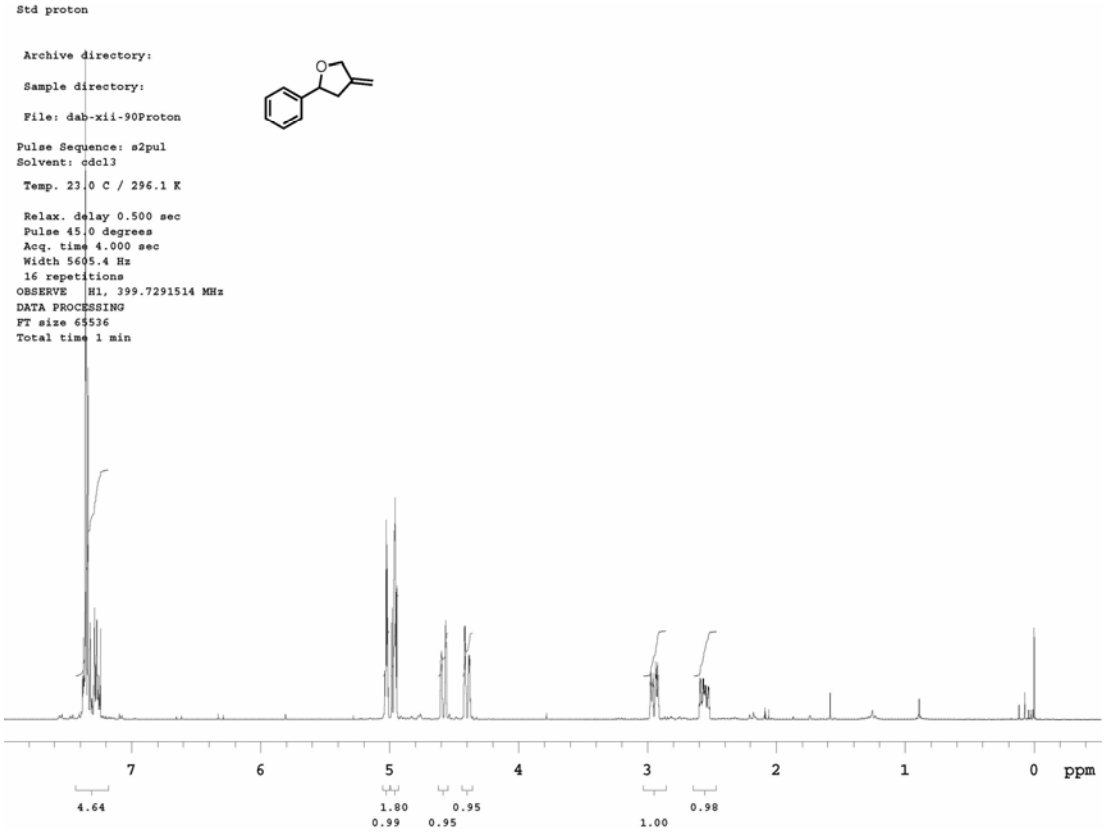


Pulse Sequence: s2pul
Solvent: cdcl3

Temp. 22.0 C / 295.1 K
User: 1-14-87

Relax. delay 1.000 sec
Pulse 40.0 degrees
Acq. time 1.300 sec
Width 24509.8 Hz
424 repetitions
OBSERVE C13, 100.5119421 MHz
DECOUPLE H1, 399.7311439 MHz
Power 43 dB
continuously on
WALTZ-16 modulated
DATA PROCESSING
Line broadening 0.5 Hz
FT size 65536
Total time 19 min




Std proton
Archive directory:
Sample directory:
File: dab-xii-90Proton
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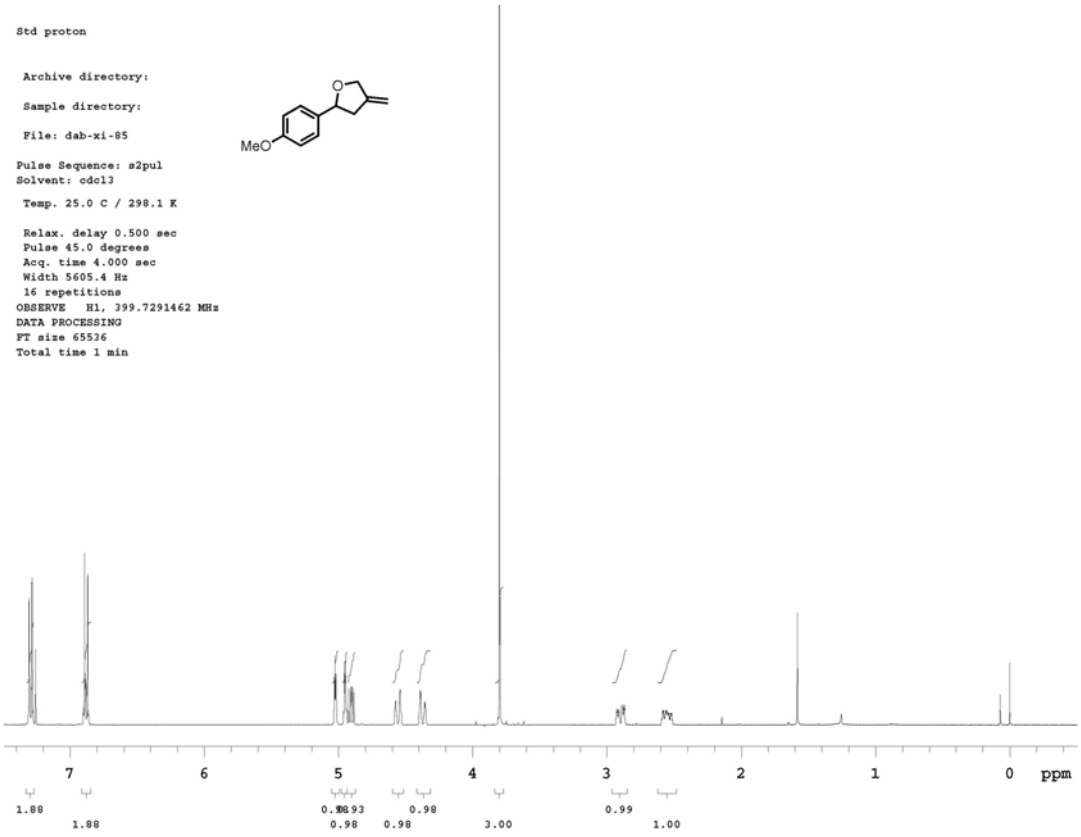
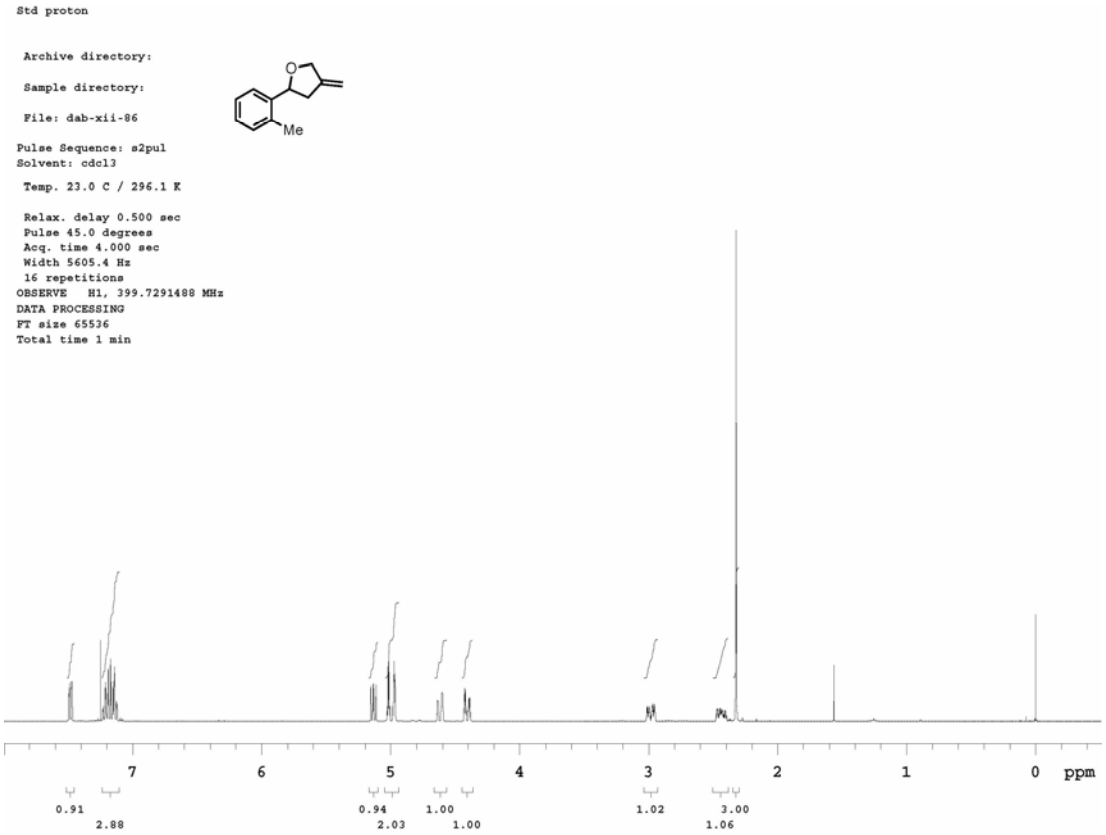
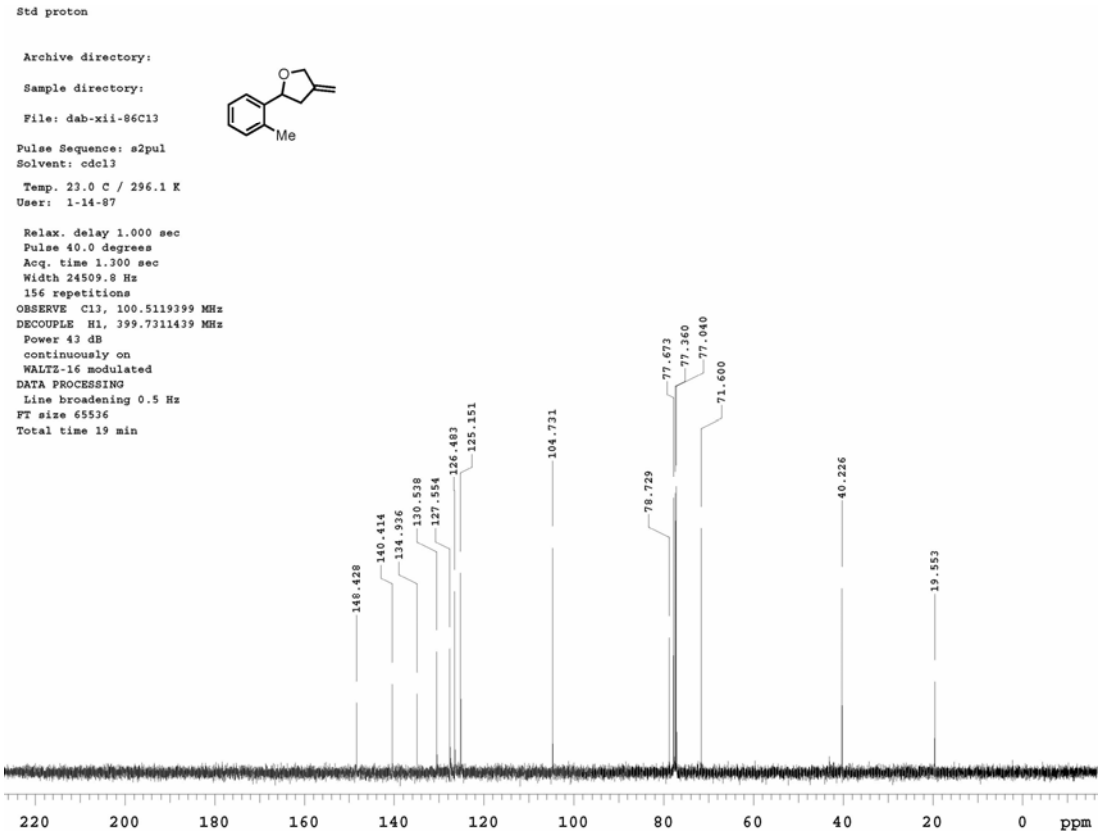
Solvent: cdcl3
Temp. 23.0 C / 296.1 K
Relax. delay 0.500 sec
Pulse 45.0 degrees
Acq. time 4.000 sec
Width 5605.4 Hz
16 repetitions
OBSERVE H1, 399.7291514 MHz
DATA PROCESSING
FT size 65536
Total time 1 min
O
7
6
5
4
3
2
1
0
ppm
4.64
1.80
0.99
0.95
0.95
1.00
0.98


Std proton
Archive directory:
Sample directory:
File: dab-xi-85
Pulse Sequence: s2pul
Solvent: cdcl3
Temp. 25.0 C / 298.1 K
Relax. delay 0.500 sec
Pulse 45.0 degrees
Acq. time 4.000 sec
Width 5605.4 Hz
16 repetitions
OBSERVE H1, 399.7291462 MHz
DATA PROCESSING
FT size 65536
Total time 1 min
O
MeO
7
6
5
4
3
2
1
0
ppm
1.88
1.88
0.98
0.98
0.98
3.00
0.99
1.00


Std proton
Archive directory:
Sample directory:
File: dab-xii-86
Me
Pulse Sequence: s2pul
Solvent: cdcl3
Temp. 23.0 C / 296.1 K
Relax. delay 0.500 sec
Pulse 45.0 degrees
Acq. time 4.000 sec
Width 5605.4 Hz
16 repetitions
OBSERVE H1, 399.7291488 MHz
DATA PROCESSING
FT size 65536
Total time 1 min
7
6
5
4
3
2
1
0
ppm
0.91
2.88
0.94
2.03
1.00
1.00
1.02
3.00
1.06


Std proton
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Sample directory:
File: dab-xii-86C13
Me
Pulse Sequence: s2pul
Solvent: cdcl3
Temp. 23.0 C / 296.1 K
User: 1-14-87
Relax. delay 1.000 sec
Pulse 40.0 degrees
Acq. time 1.300 sec
Width 24509.8 Hz
156 repetitions
OBSERVE C13, 100.5119399 MHz
DECOUPLE H1, 399.7311439 MHz
Power 43 dB
continuously on
WALTZ-16 modulated
DATA PROCESSING
Line broadening 0.5 Hz
FT size 65536
Total time 19 min
140.428
140.414
134.936
130.538
127.554
126.483
125.151
104.731
78.729
77.673
77.360
77.040
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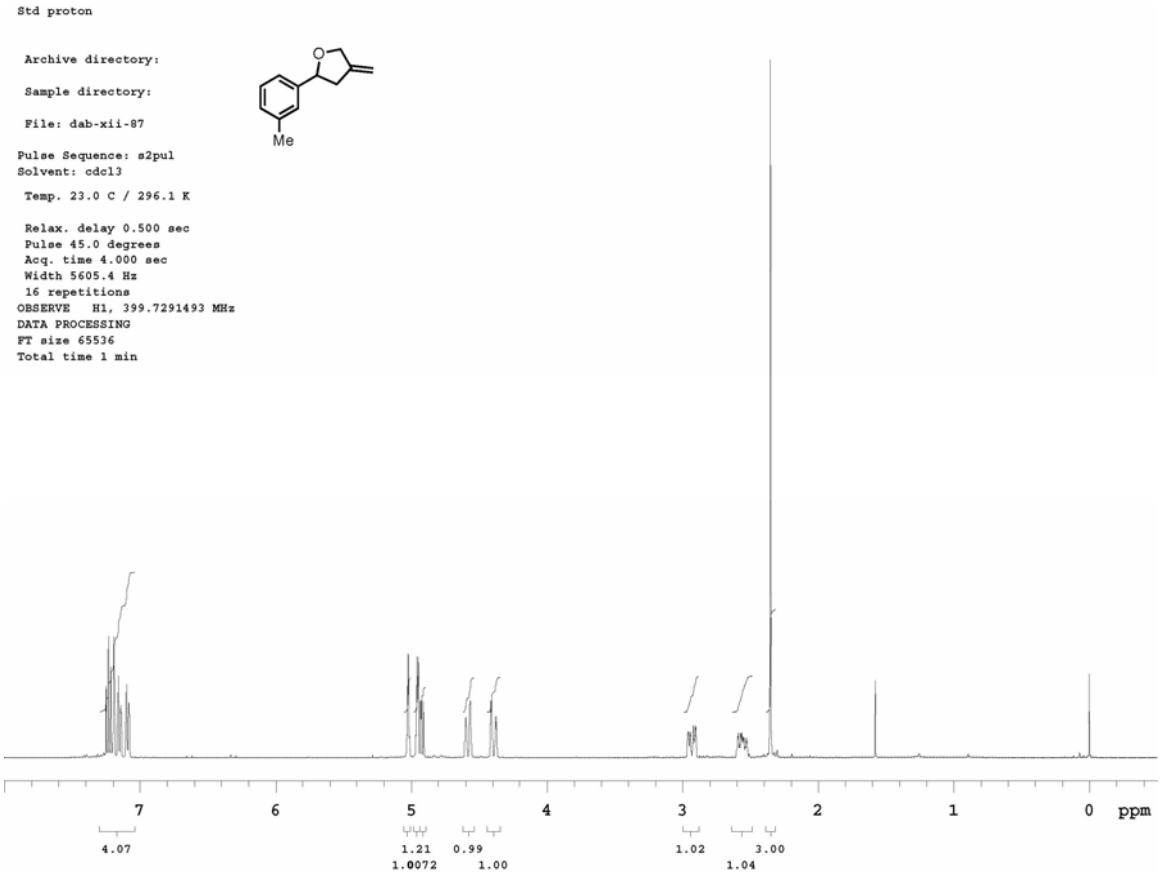
40.226
19.553
220
200
180
160
140
120
100
80
60
40
20
0
ppm


Std proton
Archive directory:
Sample directory:
File: dab-xii-87
Me
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Solvent: cdcl3
Temp. 23.0 C / 296.1 K
Relax. delay 0.500 sec
Pulse 45.0 degrees
Acq. time 4.000 sec
Width 5605.4 Hz
16 repetitions
OBSERVE H1, 399.7291493 MHz
DATA PROCESSING
FT size 65536
Total time 1 min
7
6
5
4
3
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1
0
ppm
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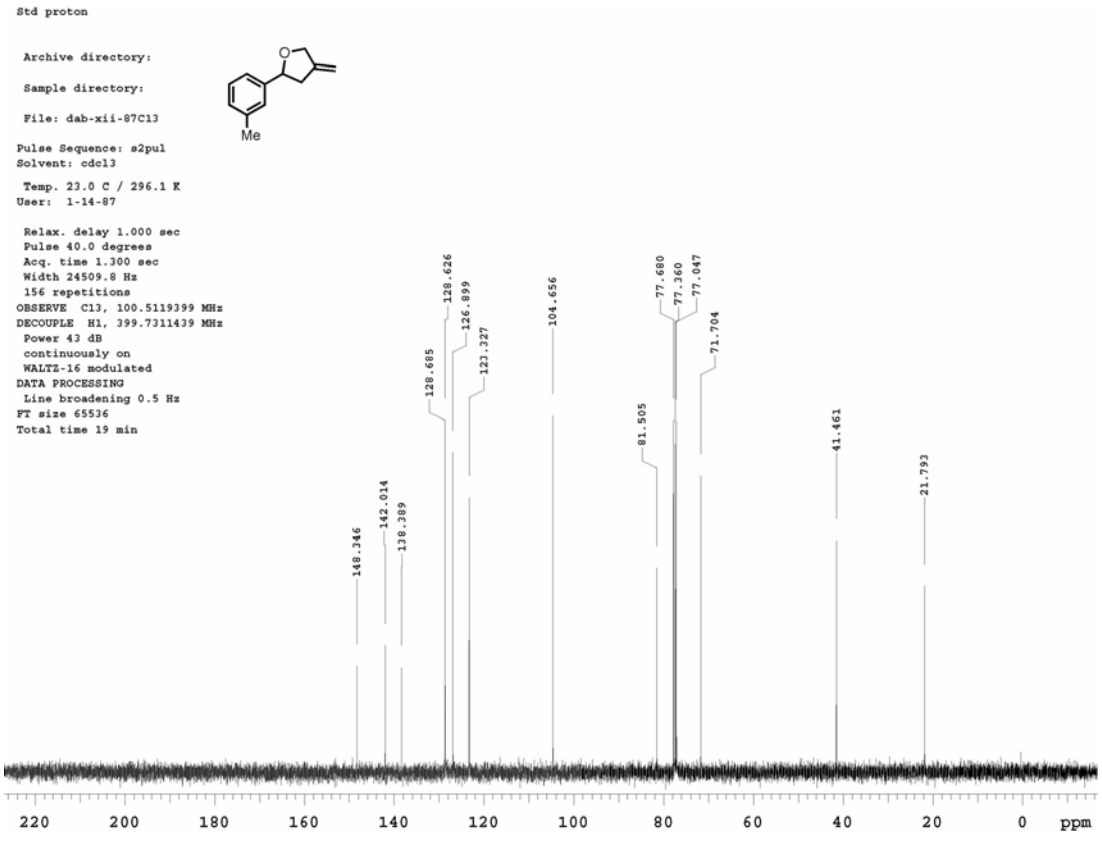
1.0072
0.99
1.00
1.02
1.04
3.00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Sample directory:
File: dab-xii-87C13
Me
Pulse Sequence: s2pul
Solvent: cdcl3
Temp. 23.0 C / 296.1 K
User: 1-14-87
Relax. delay 1.000 sec
Pulse 40.0 degrees
Acq. time 1.300 sec
Width 24509.8 Hz
156 repetitions
OBSERVE C13, 100.5119399 MHz
DECOUPLE H1, 399.7311439 MHz
Power 43 dB
continuously on
WALTZ-16 modulated
DATA PROCESSING
Line broadening 0.5 Hz
FT size 65536
Total time 19 min
148.346
142.014
138.389
128.685
128.626
126.899
123.327
104.656
81.505
77.680
77.360
77.047
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21.793
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200
180
160
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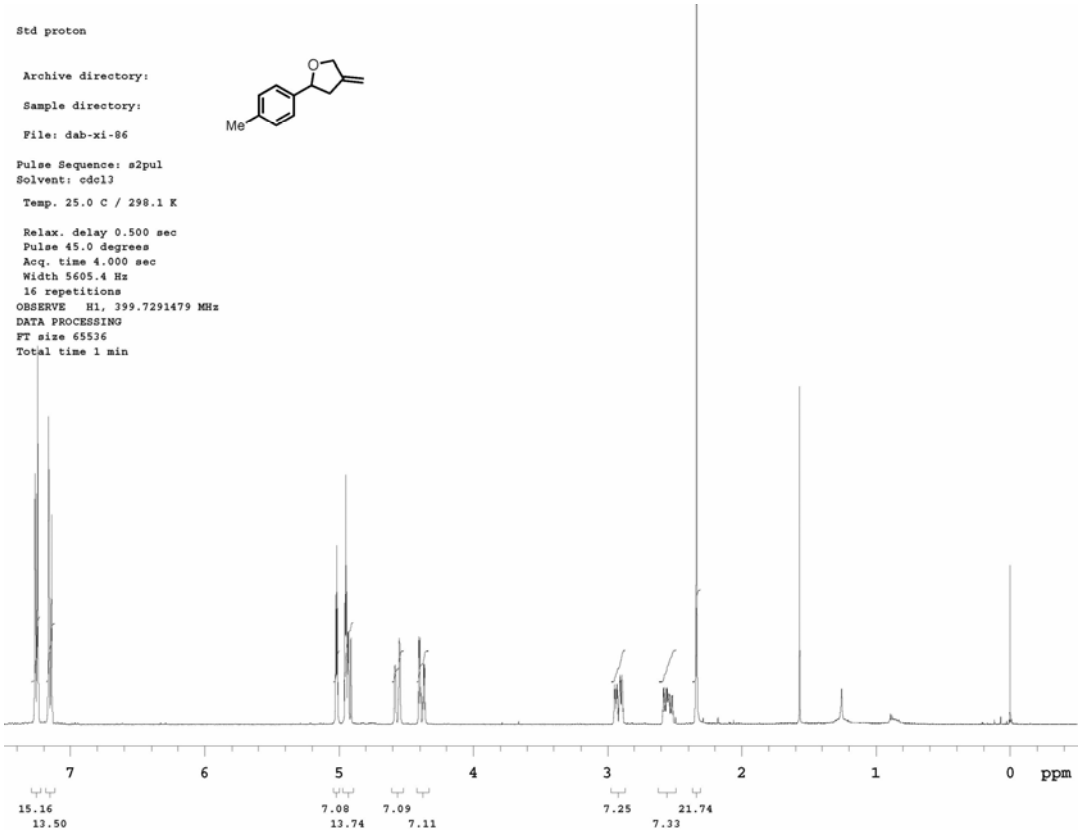
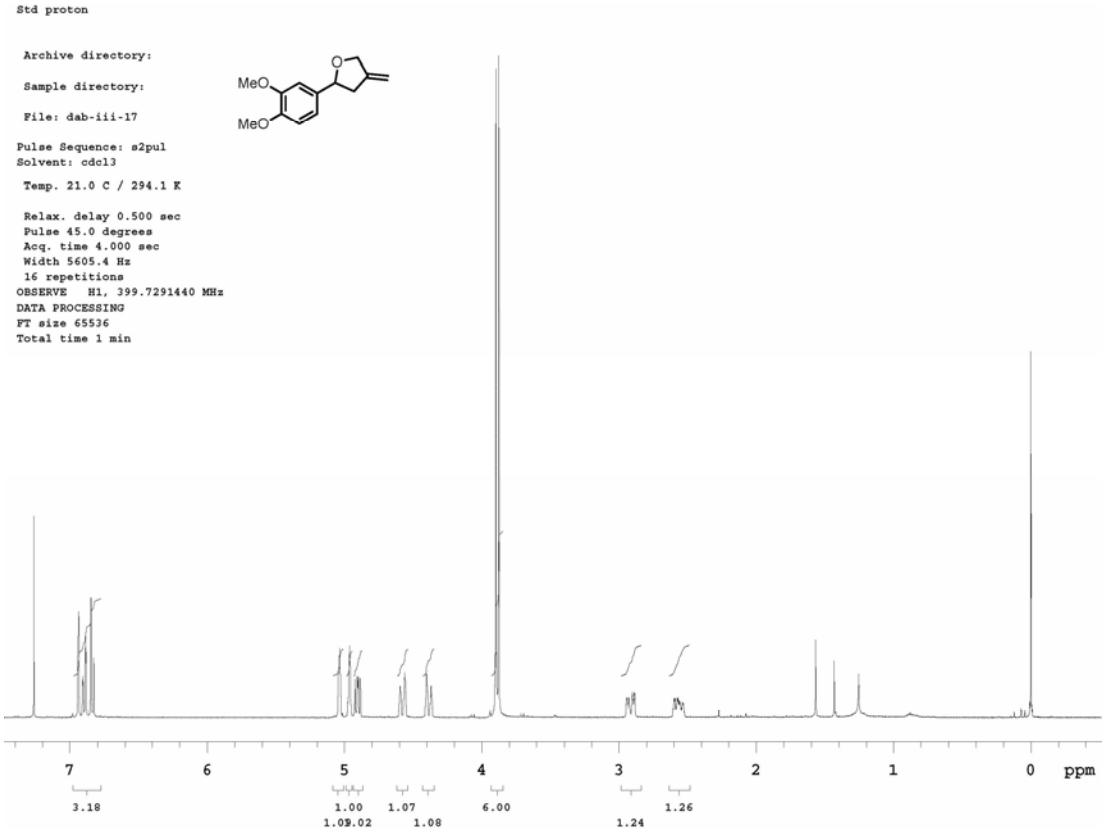
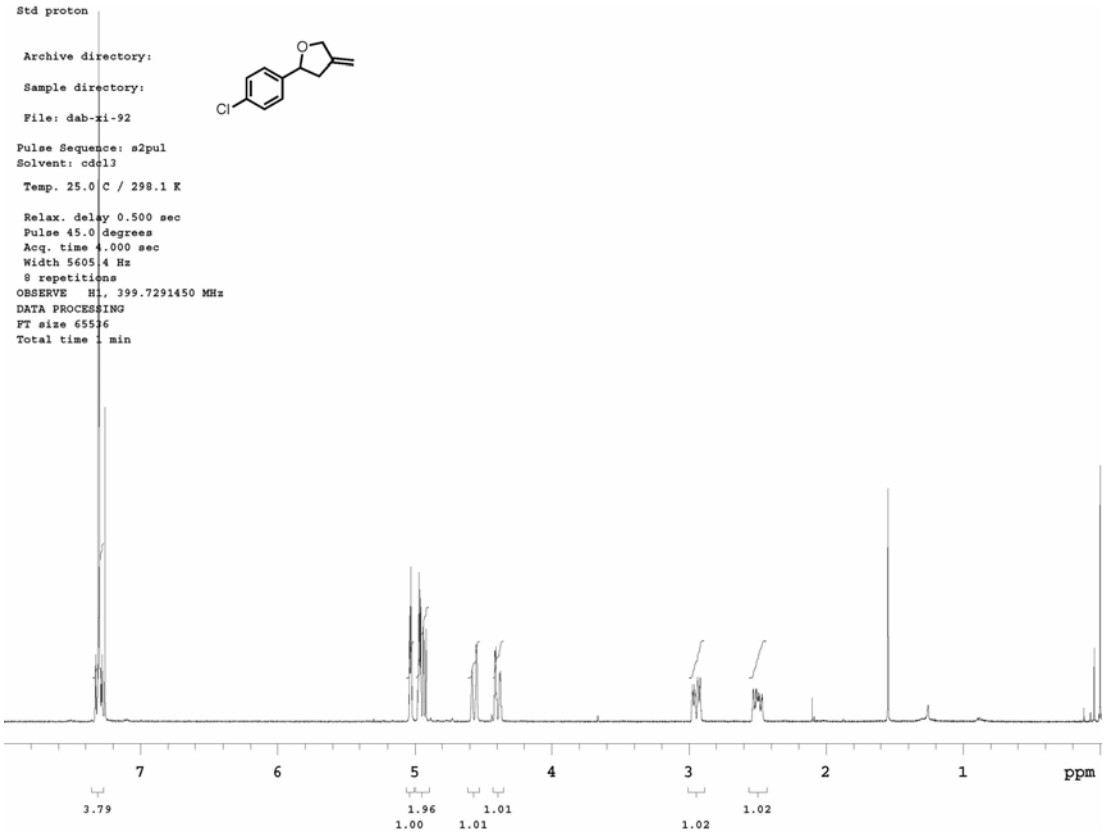
120
100
80
60
40
20
0
ppm


Std proton
Archive directory:
Sample directory:
File: dab-xi-86
Me
Pulse Sequence: s2pul
Solvent: cdcl3
Temp. 25.0 C / 298.1 K
Relax. delay 0.500 sec
Pulse 45.0 degrees
Acq. time 4.000 sec
Width 5605.4 Hz
16 repetitions
OBSERVE H1, 399.7291479 MHz
DATA PROCESSING
FT size 65536
Total time 1 min
7
6
5
4
3
2
1
0
ppm
15.16
13.50
7.08
13.74
7.09
7.11
7.25
7.33
21.74


Std proton
Archive directory:
Sample directory:
File: dab-iii-17
MeO
MeO
Pulse Sequence: s2pul
Solvent: cdcl3
Temp. 21.0 C / 294.1 K
Relax. delay 0.500 sec
Pulse 45.0 degrees
Acq. time 4.000 sec
Width 5605.4 Hz
16 repetitions
OBSERVE H1, 399.7291440 MHz
DATA PROCESSING
FT size 65536
Total time 1 min
7
6
5
4
3
2
1
0
ppm
3.18
1.00
1.07
6.00
1.26
1.24
1.08

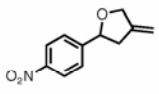

Std proton
Archive directory:
Sample directory:
File: dab-xi-92
Pulse Sequence: s2pul
Solvent: cdcl3
Temp. 25.0 C / 298.1 K
Relax. delay 0.500 sec
Pulse 45.0 degrees
Acq. time 4.000 sec
Width 5605.4 Hz
8 repetitions
OBSERVE H1, 399.7291450 MHz
DATA PROCESSING
FT size 65536
Total time 1 min
O
Cl
7
6
5
4
3
2
1
ppm
3.79
1.96
1.00
1.01
1.01
1.02
1.02

Std proton

Archive directory:

Sample directory:

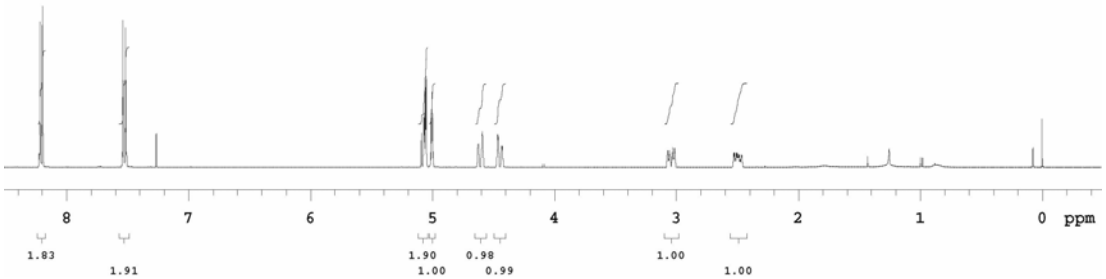
File: dab-xii-84



Pulse Sequence: s2pul
Solvent: cdcl3

Temp. 23.0 C / 296.1 K

Relax. delay 0.500 sec
Pulse 45.0 degrees
Acq. time 4.000 sec
Width 5605.4 Hz
4 repetitions
OBSERVE H1, 399.7291423 MHz
DATA PROCESSING
FT size 65536
Total time 1 min

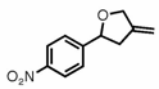


Std proton

Archive directory:

Sample directory:

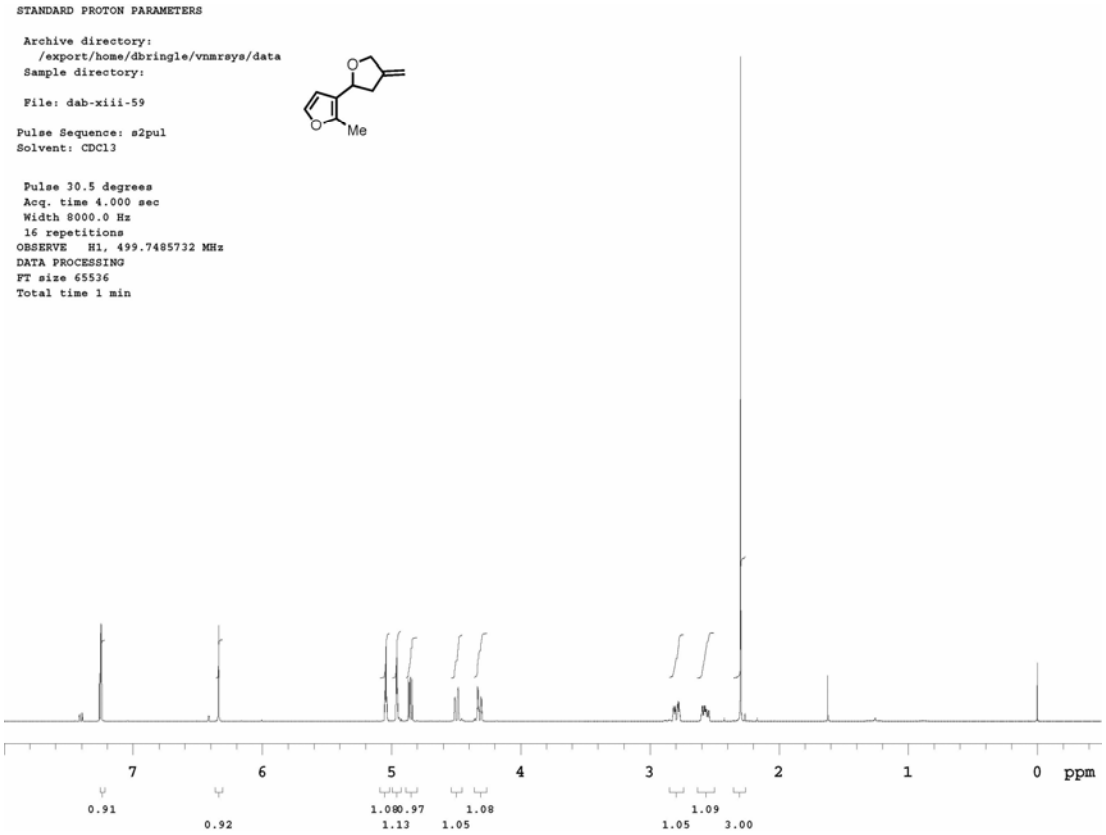
File: dab-xii-84C13

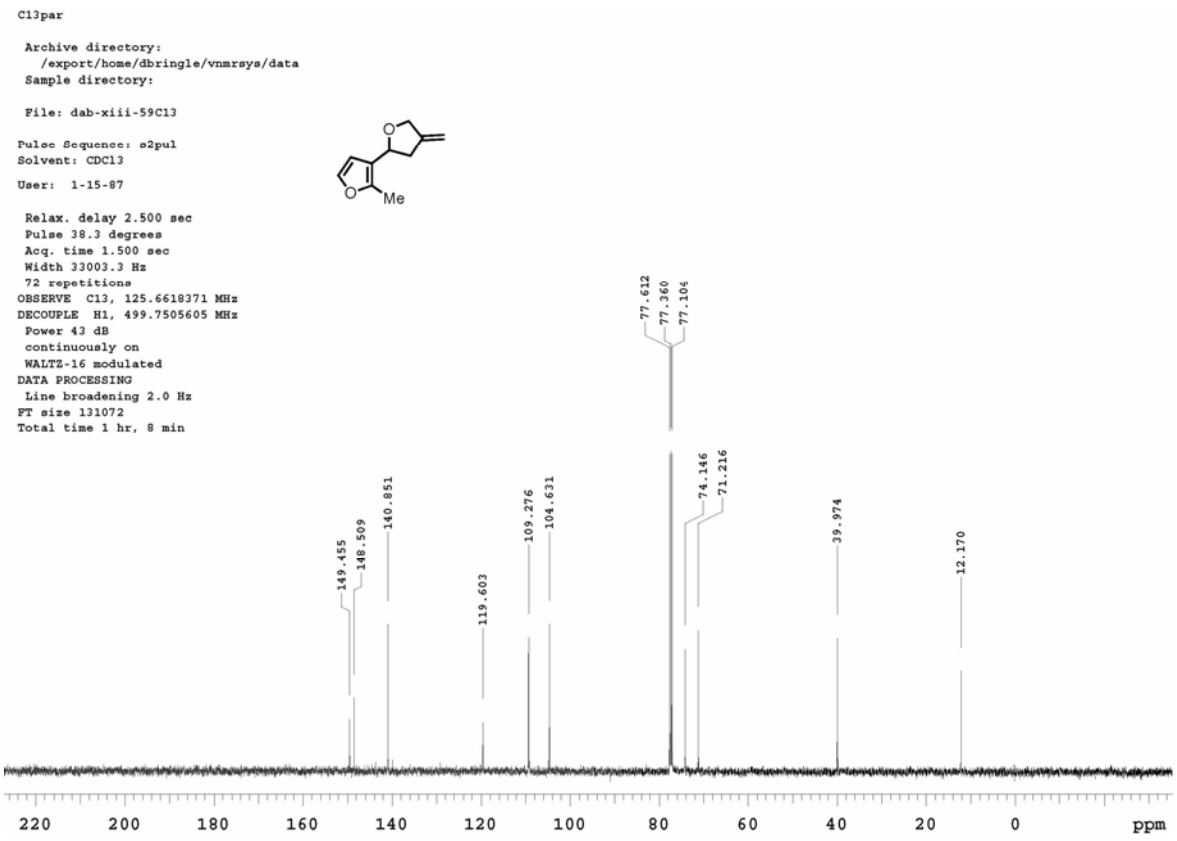


Pulse Sequence: s2pul
Solvent: cdcl3

Temp. 23.0 C / 296.1 K
User: 1-14-87

Relax. delay 1.000 sec
Pulse 40.0 degrees
Acq. time 1.300 sec
Width 24509.8 Hz
108 repetitions
OBSERVE C13, 100.5119399 MHz
DECOUPLE H1, 399.7311439 MHz
Power 43 dB
continuously on
WALTZ-16 modulated
DATA PROCESSING
Line broadening 0.5 Hz
FT size 65536
Total time 19 min

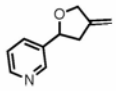

STANDARD PROTON PARAMETERS
Archive directory:
/export/home/dbringle/vnmrsys/data
Sample directory:
File: dab-xiii-59
Pulse Sequence: s2pul
Solvent: CDCl3
Pulse 30.5 degrees
Acq. time 4.000 sec
Width 8000.0 Hz
16 repetitions
OBSERVE H1, 499.7485732 MHz
DATA PROCESSING
FT size 65536
Total time 1 min
Me
7
6
5
4
3
2
1
0
ppm
0.91
0.92
1.08
0.97
1.13
1.08
1.05
1.09
1.05
3.00


C13par
Archive directory:
/export/home/dbringle/vnmrsys/data
Sample directory:
File: dab-xiii-59C13
Pulse Sequence: s2pul
Solvent: CDCl3
User: 1-15-87
Relax. delay 2.500 sec
Pulse 38.3 degrees
Acq. time 1.500 sec
Width 33003.3 Hz
72 repetitions
OBSERVE C13, 125.6618371 MHz
DECOUPLE H1, 499.7505605 MHz
Power 43 dB
continuously on
WALTZ-16 modulated
DATA PROCESSING
Line broadening 2.0 Hz
FT size 131072
Total time 1 hr, 8 min
Me
77.612
77.360
77.104
149.455
148.509
140.851
119.603
109.276
104.631
74.146
71.216
39.974
12.170
220
200
180
160
140
120
100
80
60
40
20
0
ppm

STANDARD 1H OBSERVE

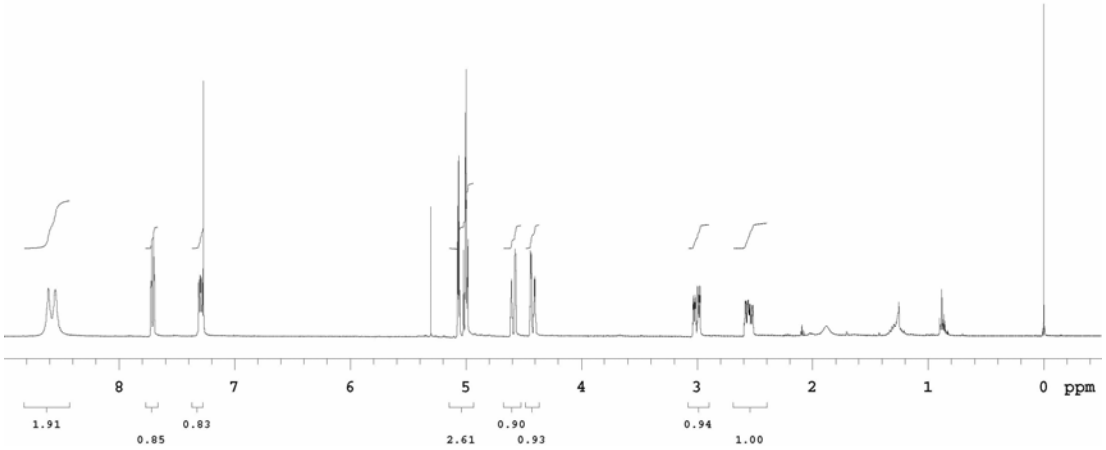
Archive directory:
/export/home/dbringle/vnmrsys/data
Sample directory:

File: dab-xiii-46Proton



Pulse Sequence: s2pul
Solvent: CDCl3

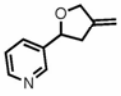
Relax. delay 0.500 sec
Pulse 52.1 degrees
Acq. time 4.002 sec
Width 4997.5 Hz
16 repetitions
OBSERVE H1, 400.1115332 MHz
DATA PROCESSING
FT size 65536
Total time 1 min



C13par

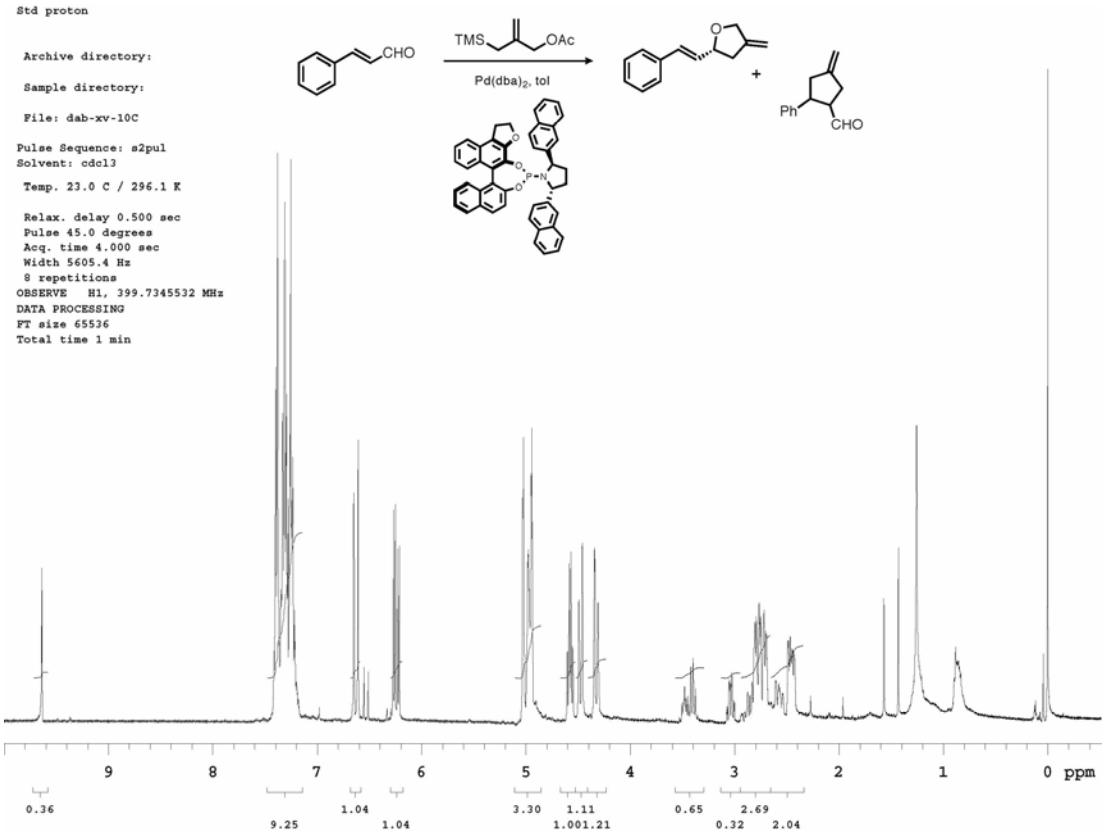
Archive directory:
/export/home/dbringle/vnmrsys/data
Sample directory:

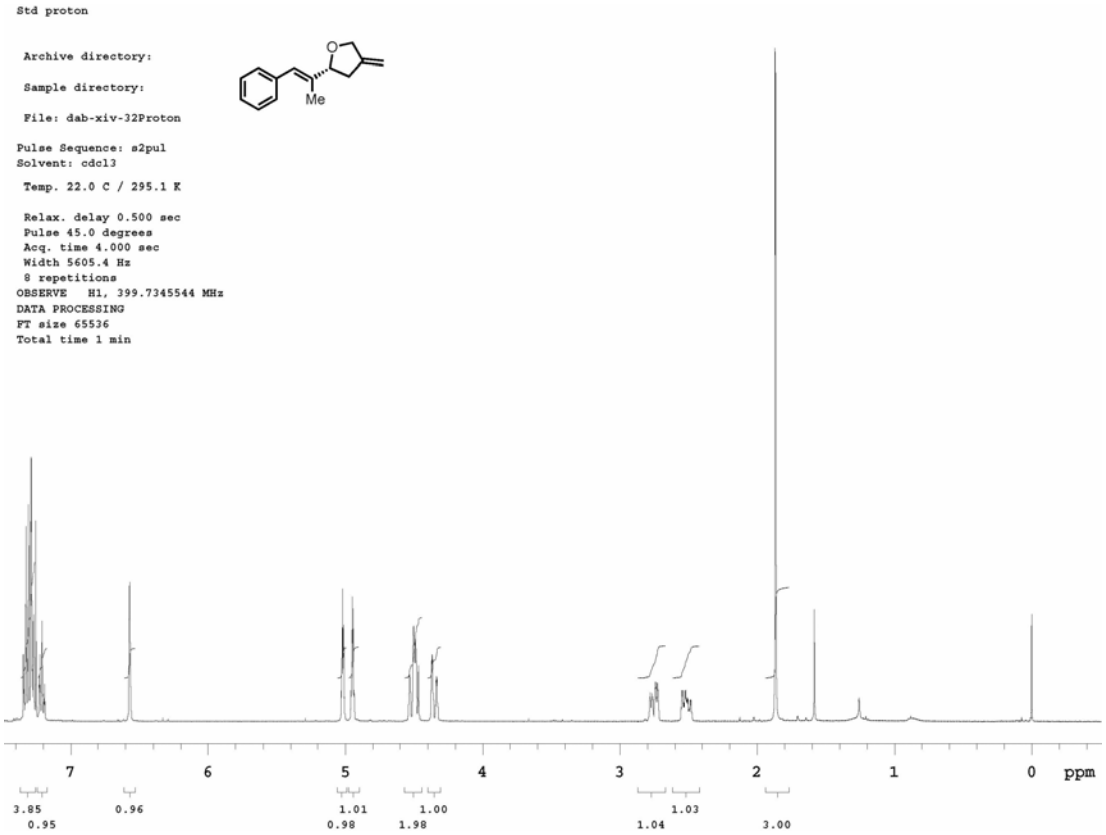
File: dab-xiii-46C13

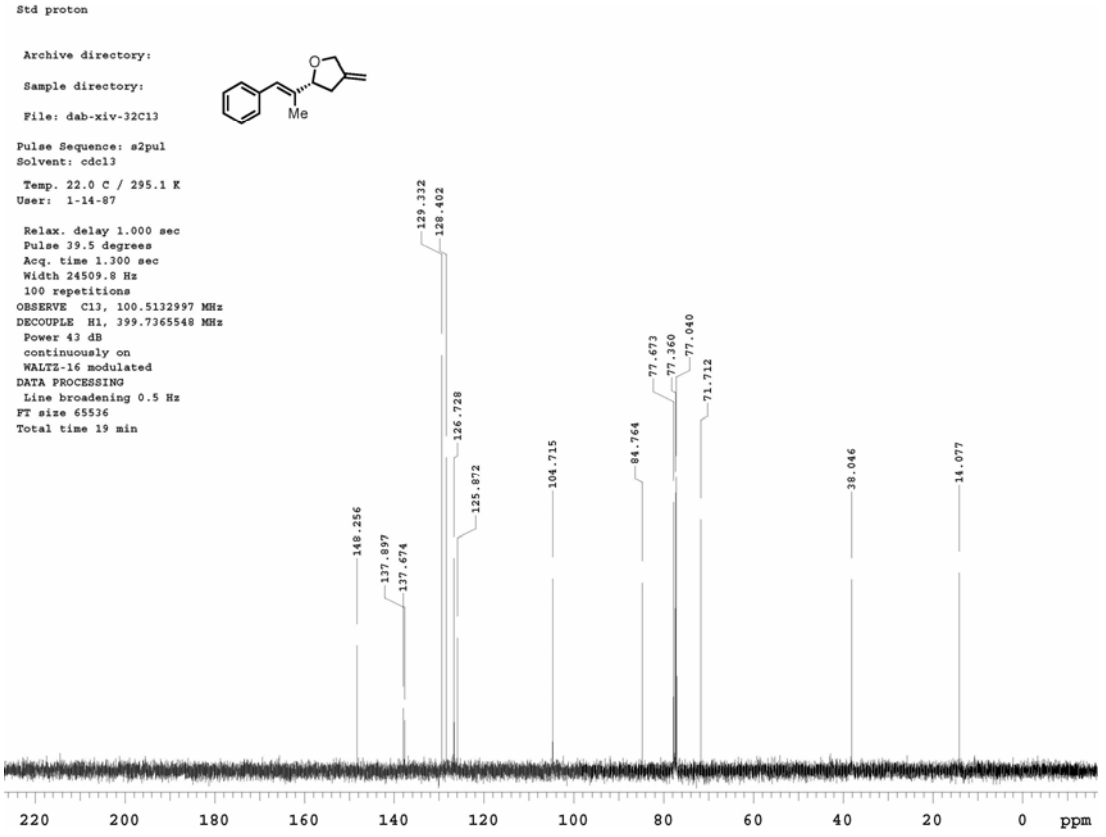


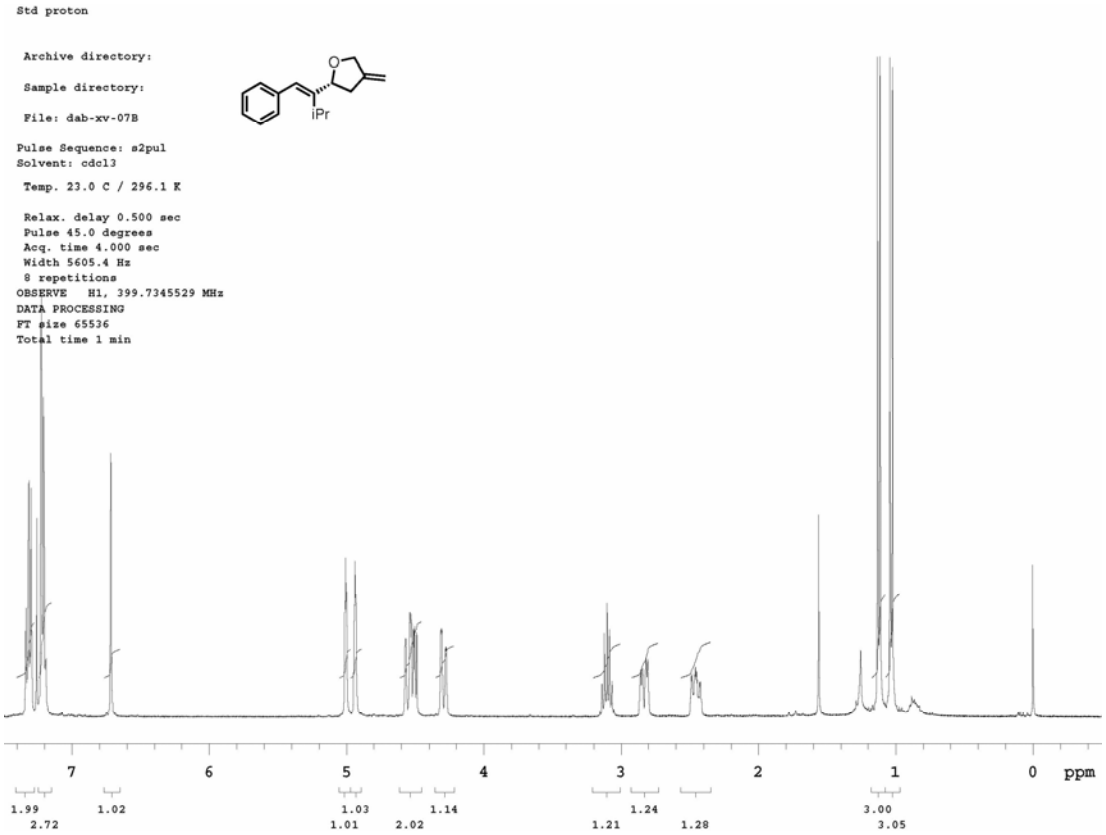
Pulse Sequence: s2pul
Solvent: CDCl3
User: 1-15-87

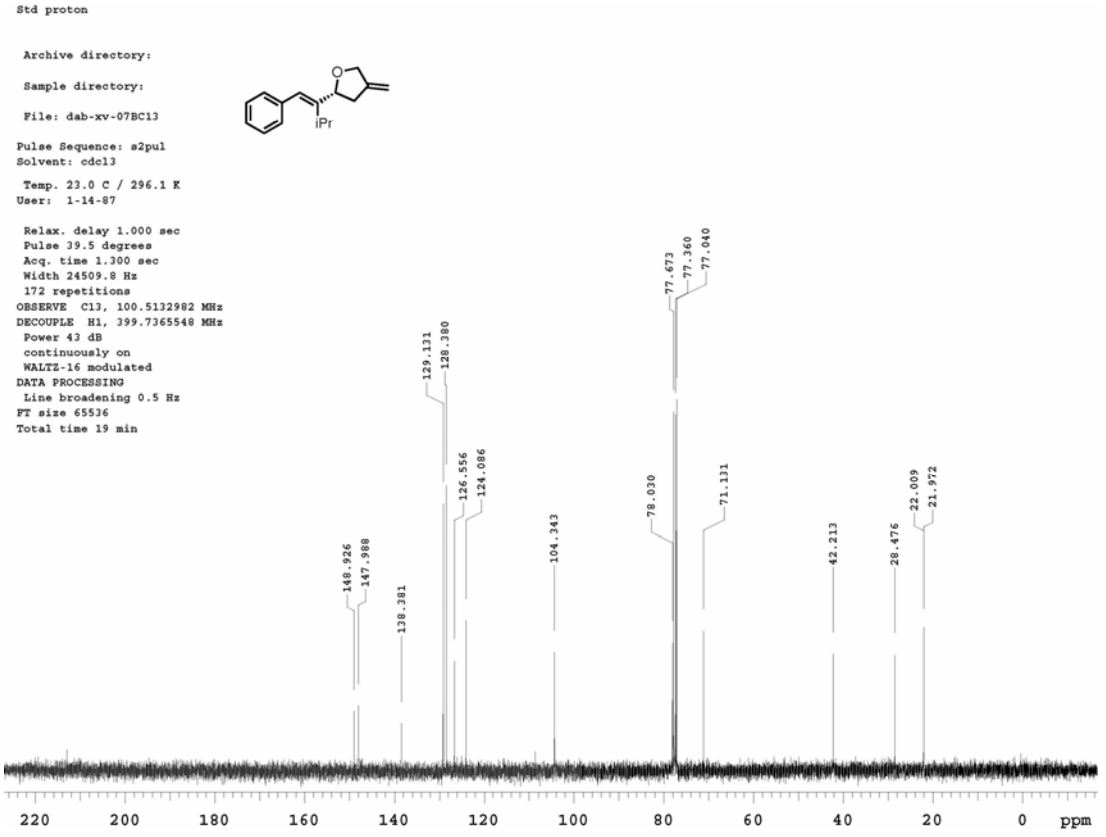
Relax. delay 2.500 sec
Pulse 38.3 degrees
Acq. time 1.500 sec
Width 33003.3 Hz
132 repetitions
OBSERVE C13, 125.6618455 MHz
DECOUPLE H1, 499.7505605 MHz
Power 43 dB
continuously on
WALTZ-16 modulated
DATA PROCESSING
Line broadening 2.0 Hz
FT size 131072
Total time 1 hr, 8 min


Std proton
Archive directory:
Sample directory:
File: dab-xv-10C
Pulse Sequence: s2pul
Solvent: cdcl3
Temp. 23.0 C / 296.1 K
Relax. delay 0.500 sec
Pulse 45.0 degrees
Acq. time 4.000 sec
Width 5605.4 Hz
8 repetitions
OBSERVE H1, 399.7345532 MHz
DATA PROCESSING
FT size 65536
Total time 1 min
CHO
TMS
OAc
Pd(dba)2, tol
Ph
CHO
9
8
7
6
5
4
3
2
1
0 ppm
0.36
9.25
1.04
1.04
3.30
1.11
1.001.21
0.65
0.32
2.69
2.04


Std proton
Archive directory:
Sample directory:
File: dab-xiv-32Proton
Pulse Sequence: s2pul
Solvent: cdcl3
Temp. 22.0 C / 295.1 K
Relax. delay 0.500 sec
Pulse 45.0 degrees
Acq. time 4.000 sec
Width 5605.4 Hz
8 repetitions
OBSERVE H1, 399.7345544 MHz
DATA PROCESSING
FT size 65536
Total time 1 min
Me
7
6
5
4
3
2
1
0
ppm
3.85
0.95
0.96
1.01
0.98
1.00
1.98
1.03
1.04
3.00


Std proton
Archive directory:
Sample directory:
File: dab-xiv-32C13
Pulse Sequence: s2pul
Solvent: cdcl3
Temp. 22.0 C / 295.1 K
User: 1-14-87
Relax. delay 1.000 sec
Pulse 39.5 degrees
Acq. time 1.300 sec
Width 24509.8 Hz
100 repetitions
OBSERVE C13, 100.5132997 MHz
DECOUPLE H1, 399.7365548 MHz
Power 43 dB
continuously on
WALTZ-16 modulated
DATA PROCESSING
Line broadening 0.5 Hz
FT size 65536
Total time 19 min
Me
129.332
128.402
126.728
125.872
104.715
84.764
77.673
77.360
77.040
71.712
38.046
14.077
148.256
137.897
137.674
220
200
180
160
140
120
100
80
60
40
20
0
ppm


Std proton
Archive directory:
Sample directory:
File: dab-xv-07B
iPr
Pulse Sequence: s2pul
Solvent: cdcl3
Temp. 23.0 C / 296.1 K
Relax. delay 0.500 sec
Pulse 45.0 degrees
Acq. time 4.000 sec
Width 5605.4 Hz
8 repetitions
OBSERVE H1, 399.7345529 MHz
DATA PROCESSING
FT size 65536
Total time 1 min
7
6
5
4
3
2
1
0
ppm
1.99
2.72
1.02
1.03
1.01
1.14
2.02
1.24
1.21
1.28
3.00
3.05


Std proton
Archive directory:
Sample directory:
File: dab-xv-07BC13
iPr
Pulse Sequence: s2pul
Solvent: cdcl3
Temp. 23.0 C / 296.1 K
User: 1-14-87
Relax. delay 1.000 sec
Pulse 39.5 degrees
Acq. time 1.300 sec
Width 24509.8 Hz
172 repetitions
OBSERVE C13, 100.5132982 MHz
DECOUPLE H1, 399.7365548 MHz
Power 43 dB
continuously on
WALTZ-16 modulated
DATA PROCESSING
Line broadening 0.5 Hz
FT size 65536
Total time 19 min
148.926
147.988
138.381
129.131
128.380
126.556
124.086
104.343
78.030
77.673
77.360
77.040
71.131
42.213
28.476
22.009
21.972
220
200
180
160
140
120
100
80
60
40
20
0
ppm