Supporting Information

A cyclopropenethione-phosphine ligation for rapid biomolecule labeling

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List of Figures and Schemes

I. General information

All reagents and solvents were used as received, unless specified otherwise. Anhydrous organic solvents were prepared by degassing with argon and passing through two 4 x 36 in. columns of anhydrous neutral A2 (8 x 12 mesh; LaRoche Chemicals; activated at 350 °C for 12 h under a flow of argon). Column chromatography was carried out using Silicycle 60 Å (32–64 mesh) silica gel. Thin layer chromatography (TLC) was carried out with Merck Millipore 250 mm silica gel F-254 plates. Plates were visualized using UV light or $KMnO_4$ stain. Organic solutions were concentrated under reduced pressure using a Büchi rotary evaporator. HPLC purifications were performed on a Varian ProStar equipped with 325 Dual Wavelength UV-Vis Detector, using an Agilent Prep-C18 Scalar column (9.4 x 150 mm, 5 µm) with a 4 mL/min flow rate.

^{1}H, ^{13}C, ^{19}F, and ^{31}P NMR spectra were obtained using either a Bruker DRX400 or a Bruker DRX500 instrument equipped with a cryo probe. ^{1}H NMR spectra were acquired at 400 MHz or 500 MHz, ^{13}C NMR spectra were acquired at 126 MHz, ^{19}F NMR spectra were obtained at 376 MHz, and ^{31}P NMR spectra were acquired at 162 MHz. Spectra were internally referenced to residual solvent signals ($CDCl_3$ was referenced to 7.27 ppm for ^{1}H and 77.16 ppm for ^{13}C, CD_3CN was referenced to 1.94 ppm for ^{1}H and 118.26 ppm for ^{13}C, D_2O was referenced to 4.79 ppm for ^{1}H, C_6D_6 was referenced to 7.16 ppm for ^{1}H and 128.06 for ^{13}C). ^{19}F and ^{31}P NMR spectra were referenced by indirect absolute chemical shift to residual protio solvent signals. All spectra were acquired at 298 K. Chemical shifts are reported in ppm, and coupling constants (*J*) are reported in Hz. Mass spectra were acquired at the University of California, Irvine Mass Spectrometry Facility. Protein mass spectra were acquired using a Waters Xevo G2-XS QTof mass spectrometer.

II. Stability experiments

Cyclopropenethione aqueous stabilities were assessed by dissolving compounds **3b**–**d** (final concentration 10 mM) in *d*-PBS (50 mM, pH 7.4). The solutions were incubated in an NMR tube at 37 °C. NMR spectra were acquired periodically over 0–7 d. For compound **3c**, a precipitate formed during the course of the experiment.

Cyclopropenethione stabilities to thiols were assessed by dissolving compounds **2b** or **2d** with L-glutathione (final concentration of 5 mM for each reagent) in *d*-PBS (50 mM, pH 7.4). The solutions were then incubated in an NMR tube at 37 °C. NMR spectra were acquired periodically over 0–24 h.

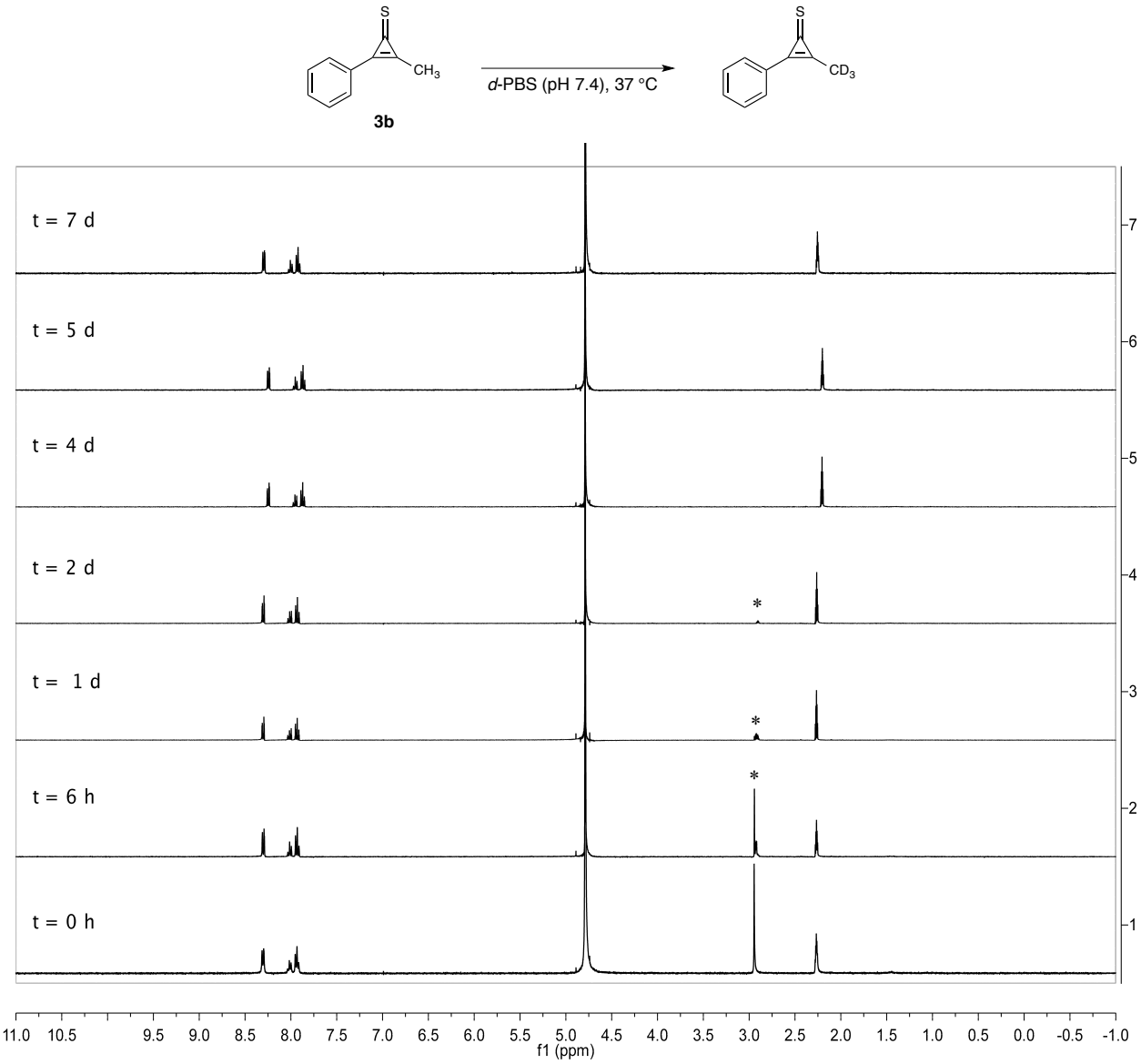


Figure S1. Cyclopropenethione **3b** is stable in *d*-PBS. Compound **3b** (10 mM) was incubated in *d*-PBS (50 mM, pH 7.4) at 37 °C and monitored via ^{1}H NMR spectroscopy.
*Allylic protons exchanged with deuterium.

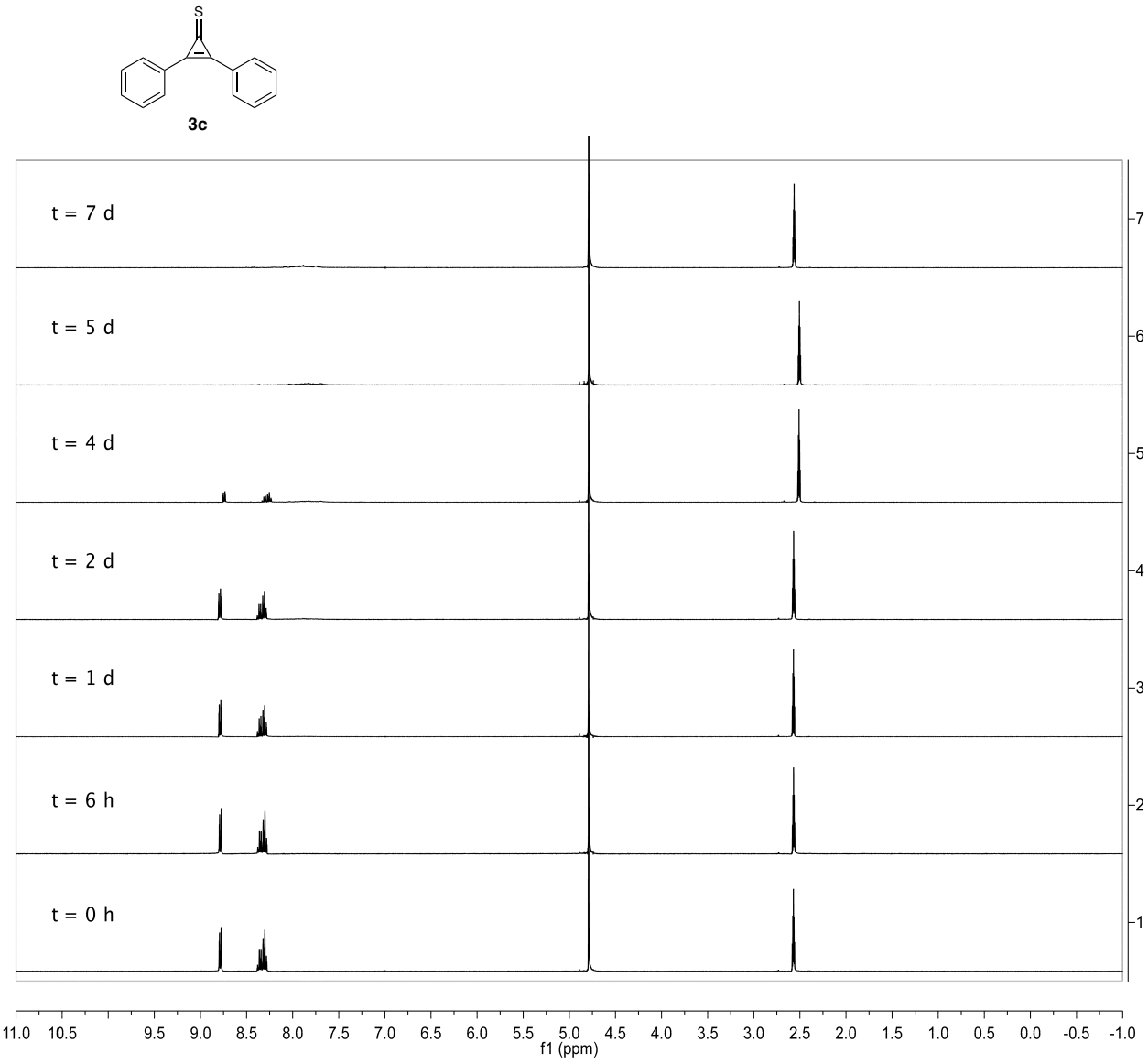


Figure S2. Cyclopropenethione **3c** is stable for ~24 h in *d*-PBS. Compound **3c** (10 mM) was incubated in *d*-PBS (50 mM, pH 7.4) at 37 °C and monitored via ^{1}H NMR spectroscopy.

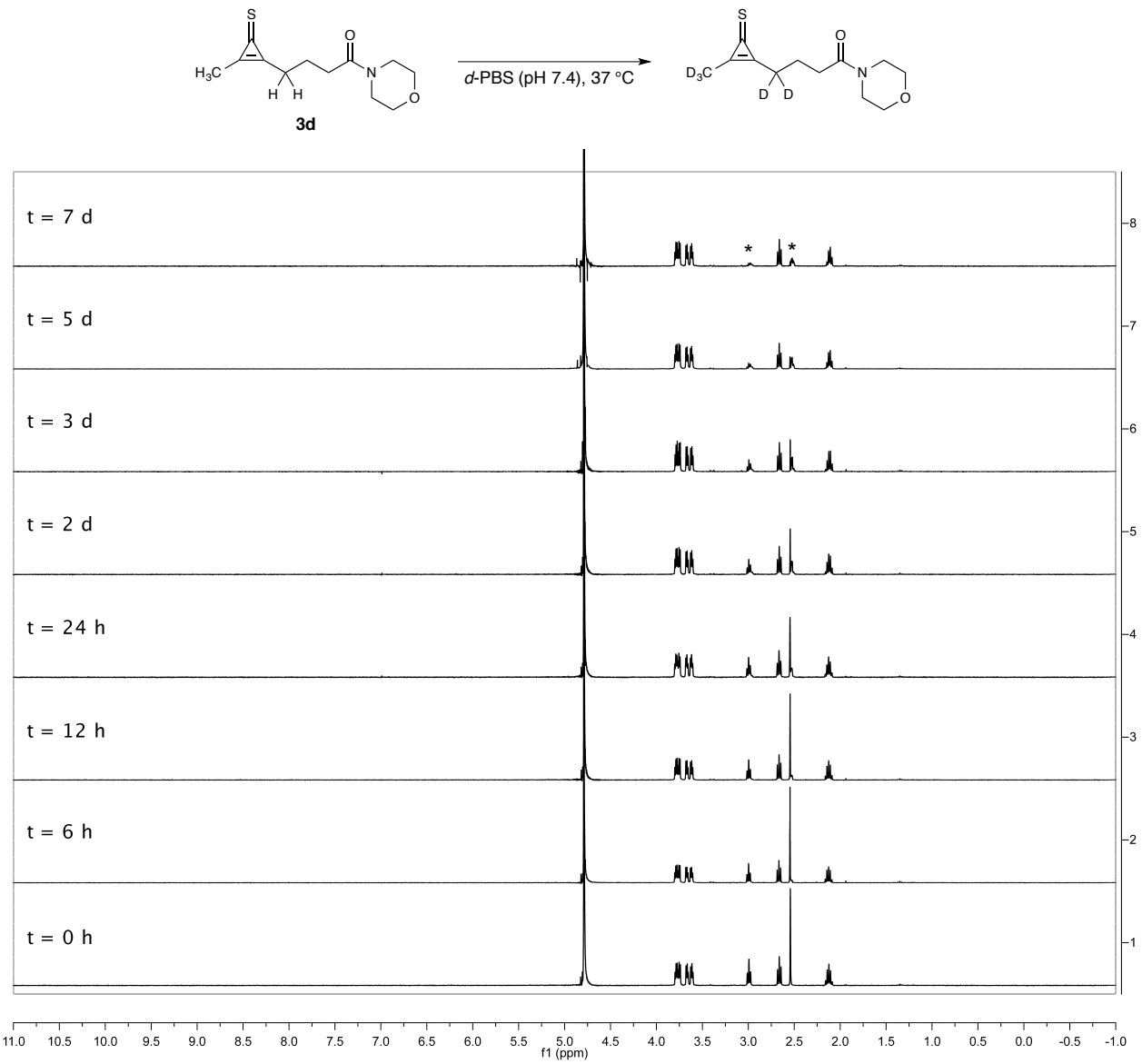


Figure S3. Cyclopropenethione **3d** is stable in *d*-PBS. Compound **3d** (10 mM) was incubated in *d*-PBS (pH 7.4) at 37 °C and monitored via ^{1}H NMR spectroscopy over 7d.
*Allylic protons exchanged with deuterium.

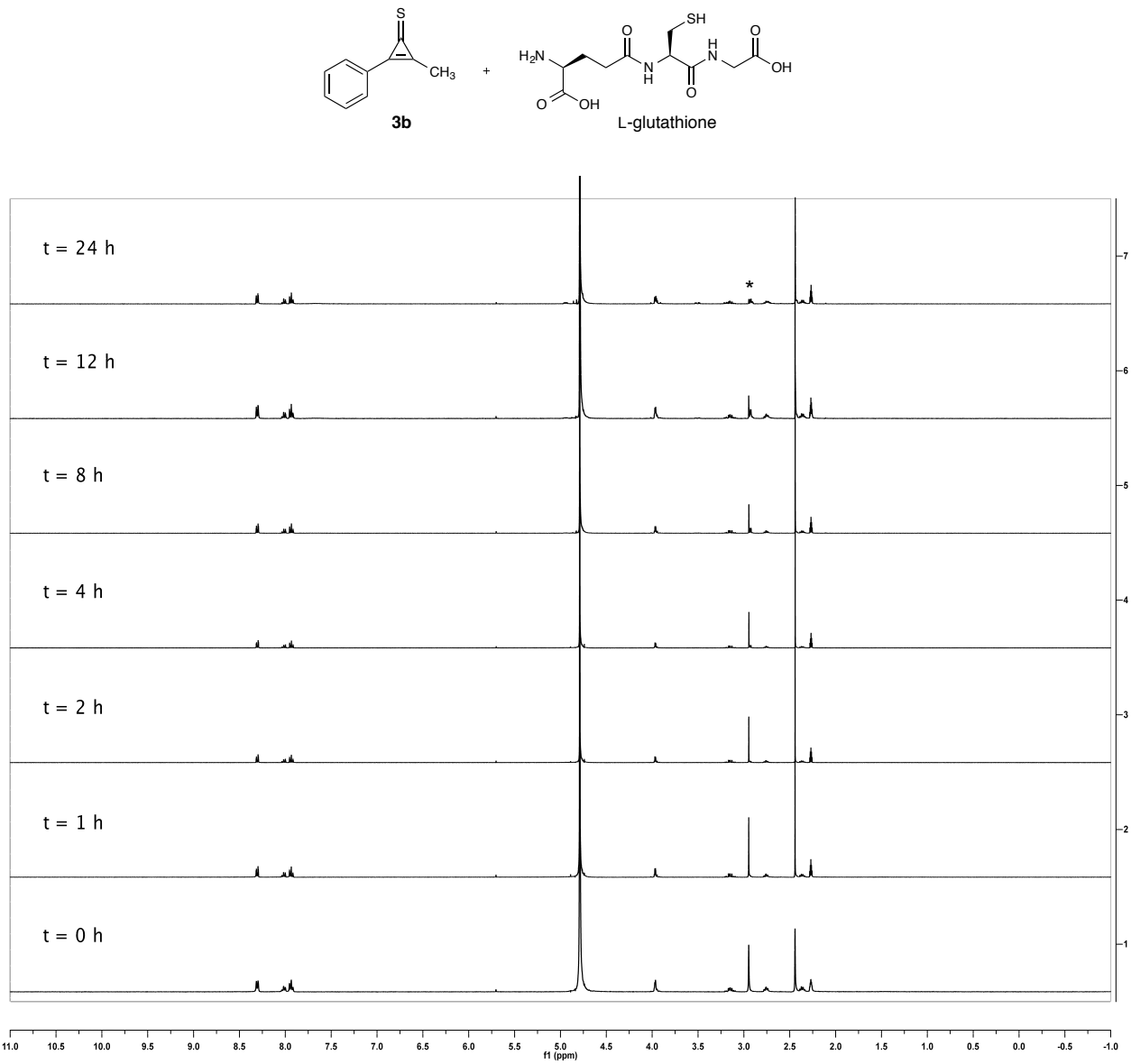


Figure S4. Cyclopropenethione **3b** is stable to L-glutathione. Compound **3b** (5 mM) and L-glutathione (5 mM) were incubated in *d*-PBS (50 mM, pH = 7.4) at 37 °C and monitored via ^{1}H NMR spectroscopy. *Allylic protons exchanged with deuterium.

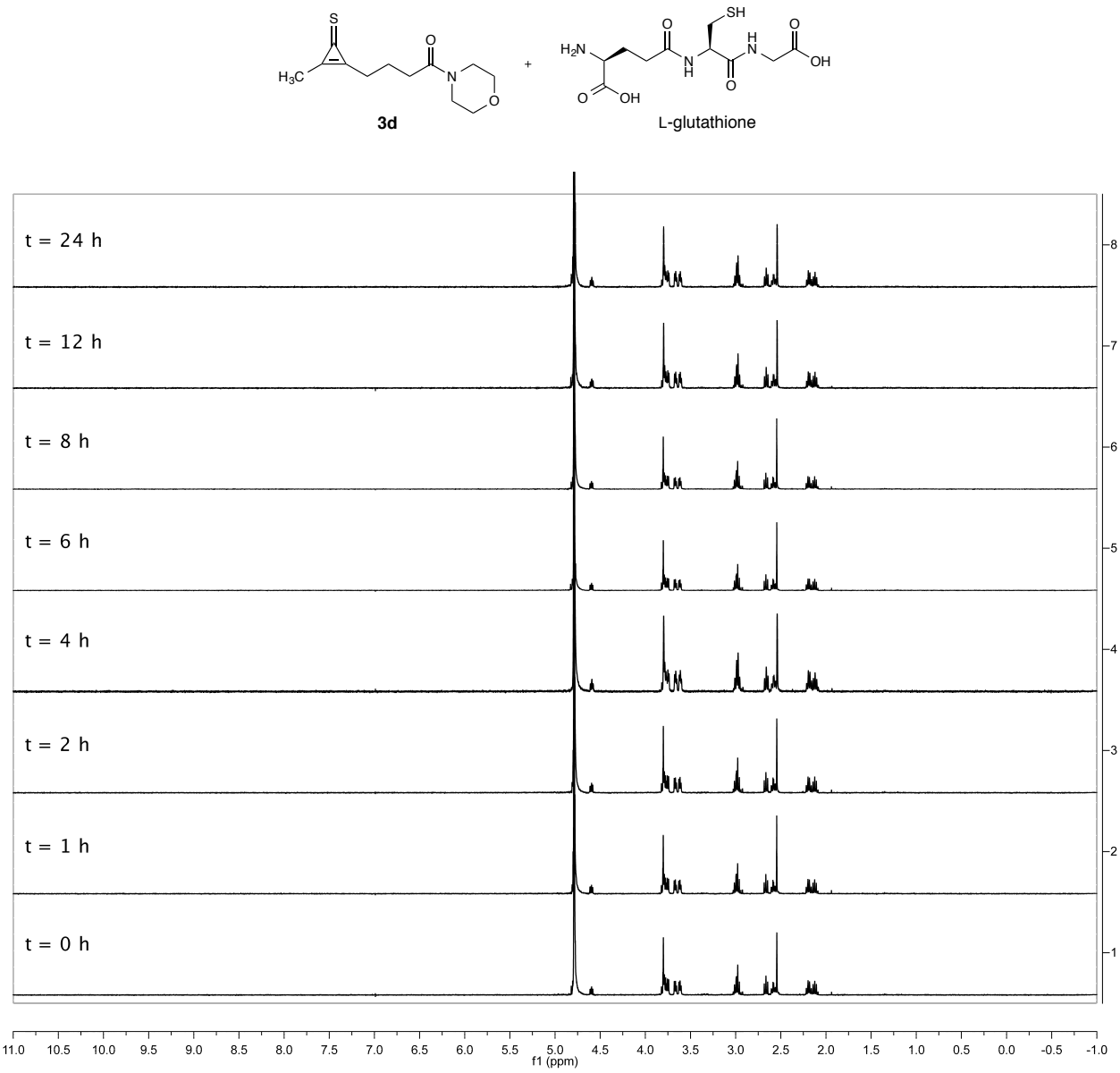


Figure S5. Cyclopropenethione **3d** is stable to L-glutathione. Compound **3d** (5 mM) and L-glutathione (5 mM) were incubated in *d*-PBS (50 mM, pH = 7.4) at 37 °C and monitored via ^{1}H NMR spectroscopy.

III. Kinetics experiments

All kinetics experiments were performed at room temperature. Reaction progress was monitored via ^{1}H NMR spectroscopy, using trimethylsilylacetylene as an internal standard. Phosphines and cyclopropenethiones or cyclopropenones were combined in equimolar ratios (final concentrations of 5 mM or 25 mM). Second order rate constants were calculated using the method of initial rates. Error values are the standard deviation of the mean for n = 3 independent experiments.

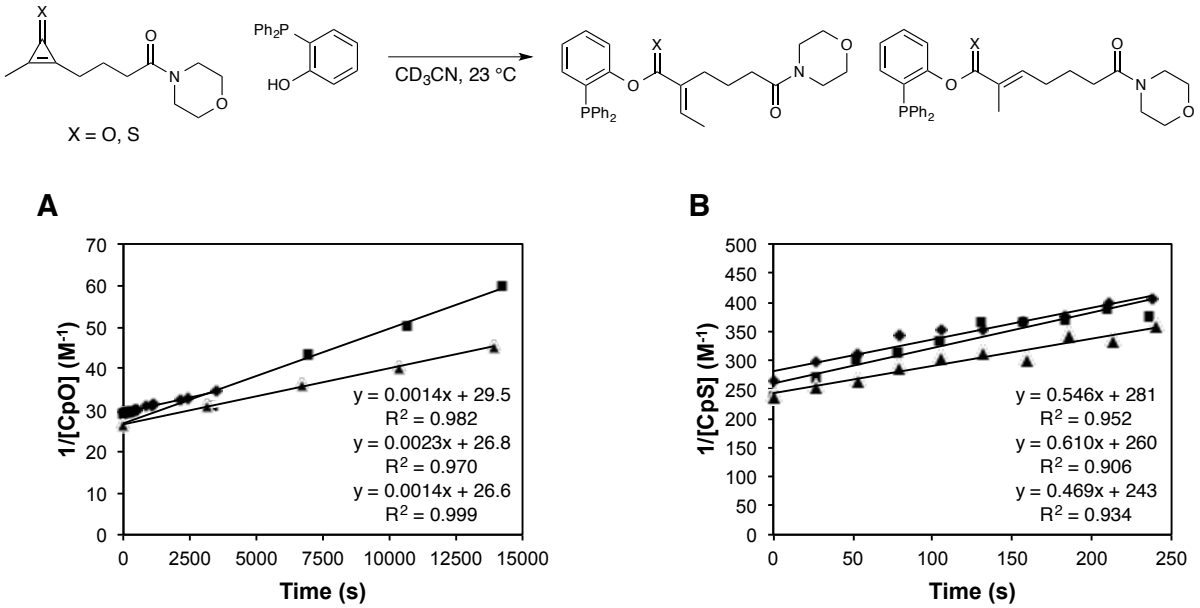


Figure S6. Rate comparison of compounds **2d** and **3d**. Second order rate constants were measured for reactions of phosphine **4** (5 or 25 mM) with A) cyclopropenone **2d** (25 mM) and B) cyclopropenethione **3d** (5 mM).

IV. CpS reactivity with model phosphines

NMR spectroscopy reaction analysis

Compound **3d** (25 mM final concentration) was treated with phosphines **4**–**8** (25 mM final concentration) in 650 µL of benzene-d_6. Reactions were incubated at room temperature and product formation was monitored over time via ^{1}H and ^{31}P NMR spectroscopy.

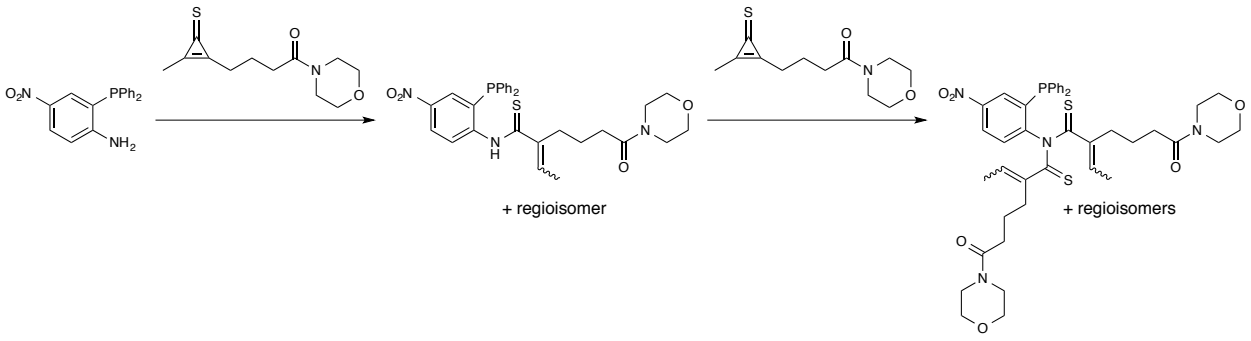


Figure S7. Phosphine double addition into cyclopropenethiones. Phosphine **7** can react with more than one equivalent of **3d** to form multiple products.

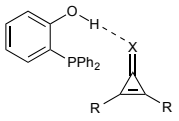
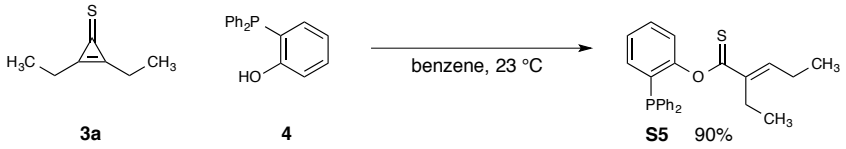


Figure S8. Hydrogen bond activation. Previously, we showed that cyclopropenones may be activated for attack via intermolecular hydrogen bonding in organic solvents.[4] Cyclopropenethiones may undergo similar activation.

Scheme 1. Thionoester product confirmation.



LC-MS reaction analysis

Reactions between **3d** and (1R,2R)-(-)-2-(diphenylphosphino)cyclohexylamine were analyzed via LC-MS. Compound **3d** (250 μM final concentration) and phosphine (500 μM final concentration) were mixed in PBS containing 50% MeCN and incubated at room temperature for 2 h. Reactions were analyzed on a Waters ACQUITY UPLC with an ACQUITY QDa Mass Detector, using a C18 column and eluting with a gradient of 10-90% MeCN/H_2O (containing 0.1% formic acid) over 3.5 min.

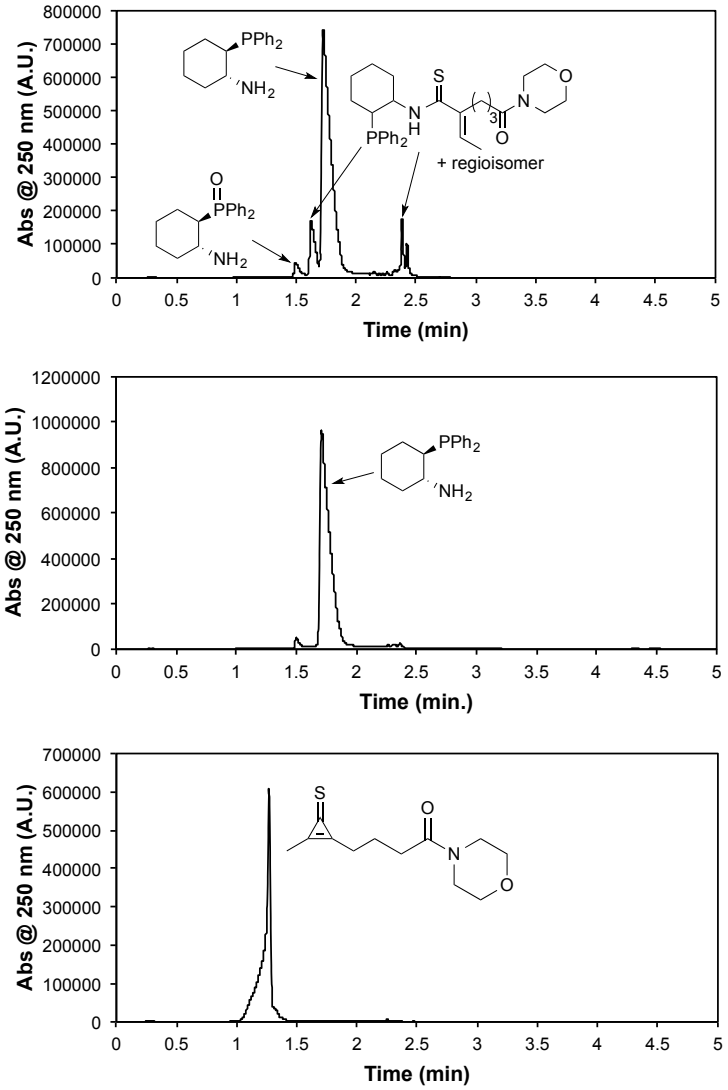


Figure S9. LC-MS plots of CpS-phosphine ligations. Compound **3d** (250 μM final concentration) and (1R,2R)-(-)-2-(Diphenylphosphino)cyclohexylamine (500 μM final concentration) were combined in PBS containing 50% MeCN and incubated at room temperature for 2h.

V. Protein functionalization and mass spectrometry

Lys-CpS and **Lys-CpO** were prepared by treating lysozyme with cyclopropenone **S3** or cyclopropenethione **S4** using previously reported conditions.[1] Hen egg-white lysozyme (Sigma Aldrich, 1 mL of a 10 mg/mL solution in 1:1 DMSO/PBS) was treated with 100 µL of either **S3** or **S4** (100 mM stock in DMSO). The solution was allowed to stand at room temperature for 3–5 h. The functionalized proteins were isolated using P-10 Biogel (BioRad), eluting with PBS (12 mM, pH 7.4). Protein-containing fractions were combined and concentrated to a volume of ~100 µL using a spin filter (3 kDa molecular weight cutoff). PBS (12 mM, pH 7.4) was then added to bring the volume to 400 µL, and the sample was concentrated again. This process was repeated 3 times to remove excess small molecules. Protein concentrations were measured with a Nanodrop® ND-1000 (Thermo Scientific), using absorbance readings at 280 nm and an extinction coefficient of 36 mM^{-1} cm^{-1}.[2]

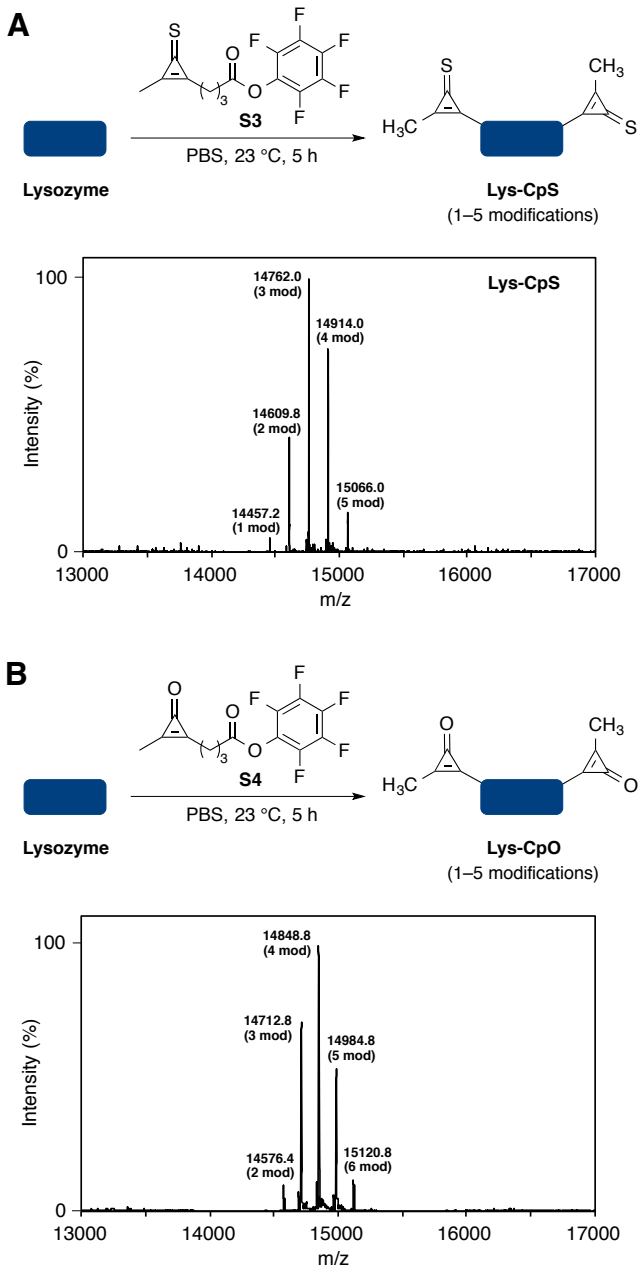


Figure S10. Mass spectrometry analysis of functionalized lysozyme. Lysozyme functionalization with A) cyclopropenethione **S4** and B) cyclopropenone **S3** was confirmed via mass spectrometry (ESI). The functionalized proteins comprised 1–6 modifications.

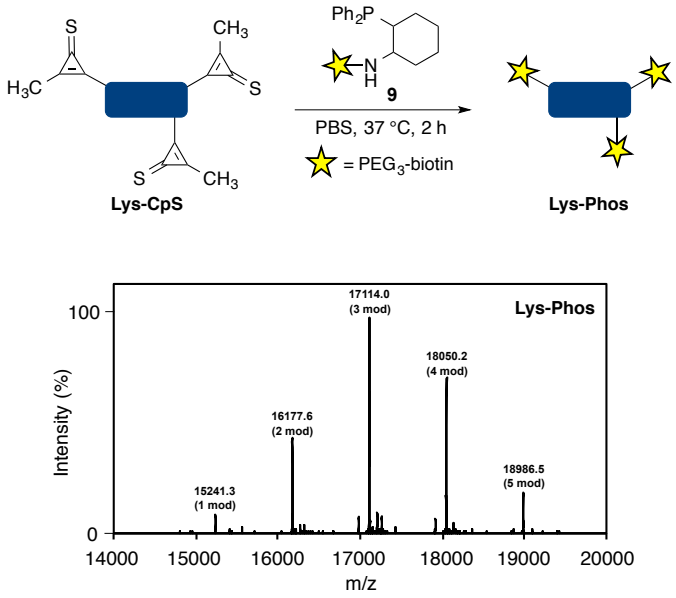


Figure S11. Mass spectrometry analysis of ligated proteins. **Lys-CpS** (20 μM) was treated with **9** (500 μM) in PBS (pH 7.4) at 37 °C for 2 h. The reaction products were confirmed via mass spectrometry.

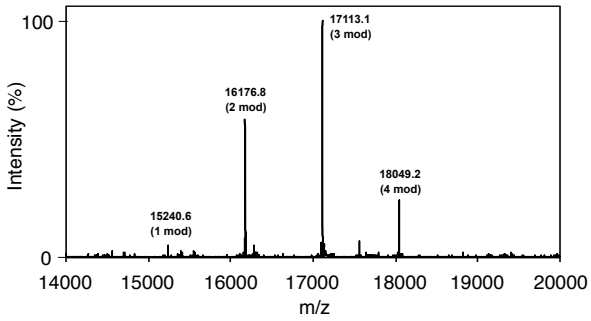


Figure S12. Lys-Phos is stable for up to 7 days. **Lys-Phos** (20 μM) was incubated in PBS (pH 7.4) at 37 °C for 1 week. The presence of **Lys-Phos** was confirmed via mass spectrometry.

VI. Western blot analysis of protein conjugates

Lys-CpS (2.7 µL of a 150 µM solution in PBS, 20 µM final concentration) and phosphine **9** (2 µL of a 1 or 10 mM stock in DMSO, 250 µM or 1 mM final concentration, respectively) were mixed with PBS (12 mM, pH 7.4) to total 20 µL. The reactions were incubated at 37 °C for 0–60 min. For time course experiments, reactions were quenched with 2-(4-morpholino-4-oxobutyl)cycloprop-2-en-1-one[3] (1 µL, 100 mM in DMSO) and stored at –20 °C until SDS-PAGE analysis. For cell lysate experiments, overnight cultures of *E. coli* XL1 cells were grown in Luria-Bertani broth containing tetracycline (10 µg/mL). Cultures were incubated at 37 °C with shaking (225 rpm). Cells were collected by centrifugation, resuspended in PBS (pH 7.4), sonicated, and centrifuged (14,500 rpm, 30 min). Total protein concentration was determined using UV-vis spectroscopy.

To prepare samples for SDS-PAGE and Western blot, 6.7 µL of 4X SDS-PAGE loading buffer (containing 8% βME) was added to each reaction mixture. For lysate labeling experiments, 5 µL of 8 M urea and 8.3 µL of 4X SDS-PAGE loading buffer (containing 8% βME) were added. Samples were then split evenly into 2 portions and subjected to SDS-PAGE using 4–20% polyacrylamide gels (BioRad). For each experiment, one gel was stained with Coomassie Blue, and the second was electroblotted to a nitrocellulose membrane (0.2 µm, BioRad). Membranes were stained with Ponceau C to assess transfer efficiency, then rinsed with H_2O and incubated with blocking buffer (7% BSA in PBS containing 1% Tween-20®, PBST) overnight at 4 °C. The membranes were then treated with IRDye® 800CW streptavadin (LI-COR Biosciences; 1:10,000 dilution in blocking buffer) for 2 h at room temperature. Membranes were then washed with PBST (6 x 10 min) and PBS (3 x 5 min). Blots were imaged using an Odyssey infrared imaging system (LI-COR, Odyssey® CLx).

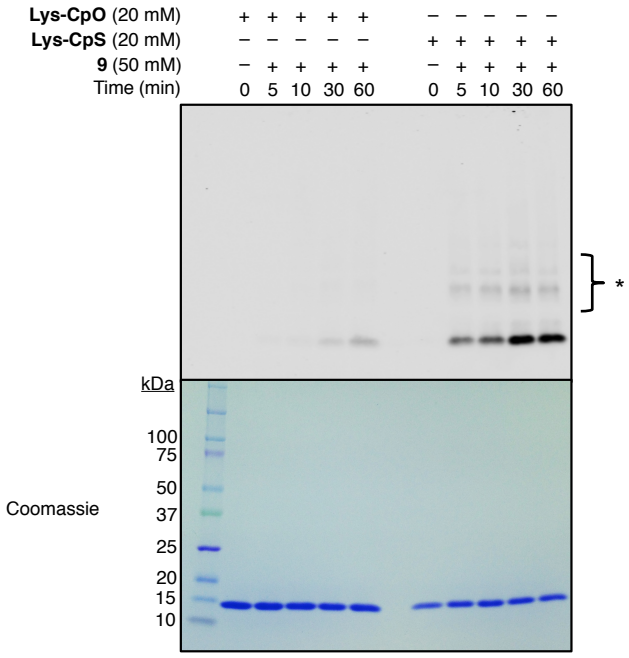
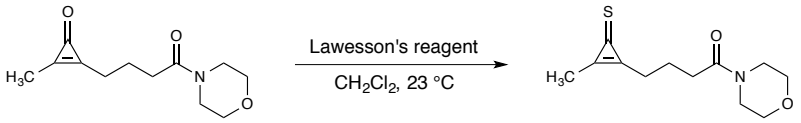


Figure S13. Western blot of **Lys-CpO** and **Lys-CpS** reaction time course. This image shows the full Western blot (above) and Coomassie-stained gel (below) shown in Figure 4C of the main text.
*Impurities present in commercial stock.

VII. Synthetic procedures

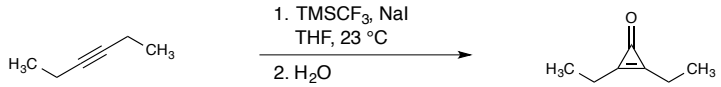
Compounds **S1**,[4] **3b–c,**[5] **4** and **6**,[3] **5**,[6] **7–8,**[4] and **9**[4] were prepared as previously reported.



2d **3d**

4-(2-Methyl-3-thioxocycloprop-1-en-1-yl)-1-morpholinobutan-1-one (3d)

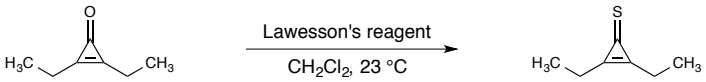
This compound was synthesized following the general procedure of Zhao, *et al.*[7] To a flame-dried 25 mL round-bottom flask was added **2d** (185 mg, 0.830 mmol). Anhydrous CH_2Cl_2 (10 mL) was added under an atmosphere of N_2. Lawesson's reagent (170 mg, 0.420 mmol) was then added, and the reaction was stirred at room temperature for 2 h. Approximately half of the solvent was removed *in vacuo*, and the crude reaction mixture was purified by flash column chromatography (eluting with 0–2% MeOH/CH_2Cl_2) to give **3d** as a pale yellow oil (132 mg, 0.552 mmol, 66.5%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 3.72–3.76 (m, 4H), 3.63–3.61 (m, 2H), 3.60–3.57 (m, 2H), 2.95 (tq, J = 6.7, 0.8 Hz, 2H), 2.72 (t, J = 7.1 Hz, 2H), 2.49 (t, J = 0.8 Hz, 3H), 2.13 (quin, J = 6.9 Hz, 2H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 186.4, 170.5, 168.6, 164.9, 67.0, 66.8, 46.1, 42.1, 31.9, 26.0, 21.2, 11.3. HRMS (ESI+) calculated for $C_{12}H_{17}NO_2SNa$ $[M+Na]^+$ 262.0878 *m*/*z*, found 262.0868.



2a

2,3-Diethylcycloprop-2-en-1-one (2a)

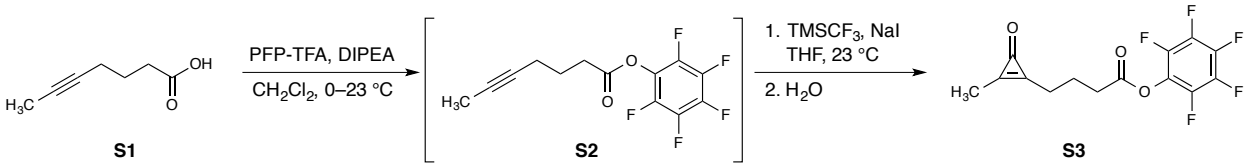
This compound was synthesized following the general procedure of Wang, *et al*.[8] with some modifications. To an oven-dried Schlenk tube containing a stir bar was added NaI (330 mg, 2.2 mmol). The NaI was gently flame-dried under vacuum. A solution of 3-hexyne (0.11 mL, 1.0 mmol) in anhydrous THF (3.0 mL) was then added against positive N_2 flow. Trifluoromethyltrimethylsilane (0.30 mL, 2.0 mmol) was added, and the Schlenk tube was sealed. The reaction was stirred vigorously at room temperature for ~14 h, then diluted with H_2O (20 mL) and extracted with CH_2Cl_2 (3 x 10 mL). The combined organic layers were dried over $MgSO_4$ and filtered. The filtrate was concentrated *in vacuo*, and the residue was purified by flash column chromatography (eluting with 0–10% acetone/CH_2Cl_2) to give **2a** as a yellow oil (65 mg, 0.59 mmol, 59%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.64 (qt, J = 7.6, 0.9 Hz, 4H), 1.31 (app t, J = 7.6 Hz, 6H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 161.5, 159.8, 20.0, 11.3. HRMS (ESI+) calculated for $C_7H_{10}ONa$ $[M+Na]^+$ 133.0629 *m*/*z*, found 133.0629.



2a **3a**

2,3-Diethylcycloprop-2-ene-1-thione (3a)

This compound was synthesized following the general procedure of Zhao, *et al.*[7] To a flame-dried 50 mL round-bottom flask was added **2a** (110 mg, 1.0 mmol). Anhydrous CH_2Cl_2 (10 mL) was added under an atmosphere of N_2. Lawesson's reagent (200 mg, 0.50 mmol) was then added, and the reaction was stirred at room temperature for 1 h. Approximately half of the solvent was removed *in vacuo*, and the crude reaction mixture was purified by flash column chromatography (eluting with 0–10% acetone/CH_2Cl_2) to give **3a** as a pale yellow oil (110 mg, 0.87 mmol, 87%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.85 (qt, J = 7.6, 0.9 Hz, 4H), 1.39 (app t, J = 7.5 Hz, 6H). ^{13}C NMR (126 MHz, $CDCl_3$) δ 186.2, 169.1, 19.9, 10.1. HRMS (ESI+) calculated for $C_7H_{10}SNa$ $[M+Na]^+$ 149.0401 m/z, found 149.0403.

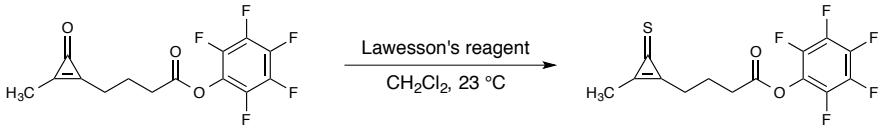


S1 **S2** **S3**

Perfluorophenyl 4-(2-methyl-3-oxocycloprop-1-en-1-yl)butanoate (S3)

To a flame-dried 50 mL round-bottom flask was added **S1** (2.00 g, 15.9 mmol), anhydrous CH_2Cl_2 (50 mL), and diisopropylethylamine (5.50 mL, 31.7 mmol). The solution was stirred under an atmosphere of N_2 and cooled in an ice bath. Pentafluorophenyl trifluoroacetate (4.10 mL, 23.8 mmol) was added dropwise over ~5 min. The reaction was warmed to room temperature and stirred for 45 min. Excess solvent was then removed *in vacuo*, and the crude reaction mixture was purified by flash column chromatography (eluting with 0–5% Et_2O/hexanes) to give **S2** as a pale yellow oil. This material was used directly in the next step.

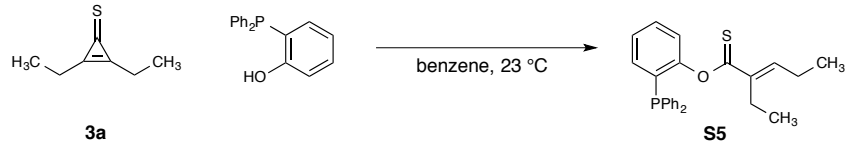
Compound **S3** was synthesized following the general procedure of Wang *et al.*[8] with some modifications. To an oven-dried Schlenk tube containing a stir bar was added NaI (4.15 g, 27.7 mmol). The NaI was gently flame-dried under vacuum. Compound **S2** was dissolved in anhydrous THF (38.0 mL) and added against positive N_2 flow. Trifluoromethyltrimethylsilane (3.70 mL, 25.1 mmol) was added, and the Schlenk tube was sealed. The reaction was stirred vigorously at room temperature for ~36 h, and then diluted with H_2O (100 mL) and extracted with CH_2Cl_2 (3 x 30 mL). The combined organic layers were dried over $MgSO_4$, then filtered. The filtrate was concentrated *in vacuo*, and the residue was purified by flash column chromatography (eluting with 50–100% EtOAc/hexanes) to give **S3** as a dark yellow solid (2.75 g, 8.59 mmol, 54.0% over 2 steps). ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.85 (t, J = 7.3 Hz, 2H), 2.77 (tq, J = 7.4, 0.9 Hz, 2H), 2.31 (t, J = 0.9 Hz, 3H), 2.20 (quin, J = 7.3 Hz, 2H). ^{19}F NMR (376 MHz, $CDCl_3$) δ -153.0 (d, J = 16.9 Hz, 2F), -157.9 (t, J = 21.8 Hz, 1F), -162.3 (dd, J =21.7, 17.2 Hz, 2F). ^{13}C NMR (126 MHz, $CDCl_3$) δ 168.6, 159.9, 159.2, 158.1, 141.1 (ddq, J = 251.4, 12.3, 4.1 Hz), 139.6 (dtt_{app}, J = 253.8, 13.8, 3.9 Hz), 137.9 (m), 124.9 (m), 32.4, 25.4, 21.3, 11.4. HRMS (ESI+) calculated for $C_{14}H_9F_5O_3Na$ $[M+Na]^+$ 343.0370 m/z, found 343.0378.



S3 **S4**

Perfluorophenyl 4-(2-methyl-3-thioxocycloprop-1-en-1-yl)butanoate (S4)

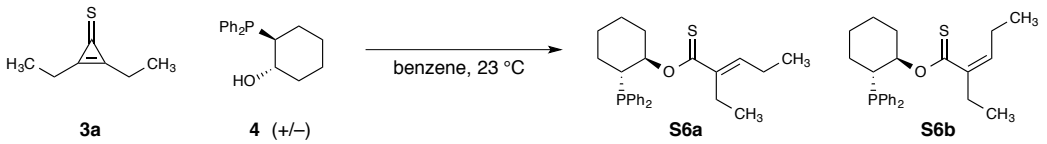
This compound was synthesized following the general procedure of Zhao, *et al.*[7] To a flame-dried 50 mL round-bottom flask was added **S3** (143 mg, 0.450 mmol). Anhydrous CH_2Cl_2 (6.0 mL) was added under an atmosphere of N_2. Lawesson's reagent (100 mg, 0.247 mmol) was then added, and the reaction was stirred at room temperature for 2 h. Approximately half of the solvent was removed *in vacuo*, and the crude reaction mixture was purified by flash column chromatography (eluting with 50–100% EtOAc/hexanes) to give **S4** as a pale yellow solid (121 mg, 0.360 mmol, 80.0%). ^{1}H NMR (400 MHz, $CDCl_3$) δ 2.99 (t, J = 7.2 Hz, 2H), 2.98 (tq, J = 7.2, 0.9 Hz, 2H), 2.52 (t, J = 0.9 Hz, 3H), 2.29 (quin, J = 7.2 Hz, 2H). ^{19}F NMR (376 MHz, $CDCl_3$) δ -153.0 (d, J = 17.1 Hz, 2F), -157.8 (t, J = 21.7 Hz, 1F), -162.3 (dd, J = 21.8, 17.2 Hz, 2F). ^{13}C NMR (126 MHz, $CDCl_3$) δ 186.1, 168.6, 167.2, 165.3, 141.1 (ddq, J = 251.2, 12.5, 4.0 Hz), 139.6 (dtt_{app}, J = 253.8, 13.9, 4.5 Hz), 137.9 (dtt_{app}, J = 252.5, 14.0, 4.3 Hz), 124.8 (m), 32.4, 25.3, 20.8, 11.3. HRMS (ESI+) calculated for $C_{14}H_9F_5O_2SNa$ $[M+Na]^+$ 359.0141 *m*/*z*, found 359.0145.



3a **S5**

***O*-(2-(Diphenylphosphanyl)phenyl) (*E*)-2-ethylpent-2-enethioate (S5)**

To a glass vial was added **3a** (6.3 mg, 0.050 mmol) and benzene (0.65 mL). Phosphine **4** (14 mg, 0.050 mmol) was added, and the reaction was stirred at room temperature for 10 min. The crude material was then passed through a small plug of neutral alumina, eluting with hexanes. The yellow fractions were collected, and the solvent was removed *in vacuo* to give **S5** (18 mg, 0.045 mmol, 90%) as a yellow solid. ^{1}H NMR (400 MHz, C_6D_6) δ 7.40–7.33 (m, 4H), 7.04–7.02 (m, 9H), 6.88 (t, J = 7.6 Hz, 1H), 6.85–6.82 (m, 1H), 2.64 (q, J = 7.5 Hz, 2H), 1.83 (quin, J = 7.5 Hz, 2H), 1.11 (t, J = 7.5 Hz, 3H), 0.75 (t, J = 7.5 Hz, 3H). ^{31}P NMR (162 MHz, C_6D_6) δ -15.31. ^{13}C NMR (126 MHz, C_6D_6) δ 211.0, 157.8 (d, J = 18.6 Hz), 141.98, 141.96, 136.8 (d, J = 12.1 Hz), 134.5, 134.4 (d, J = 20.5 Hz), 131.7 (d, J = 16.1 Hz), 130.1, 129.0, 128.8 (d, J = 7.0 Hz), 126.5, 123.9 (d, J = 2.2 Hz), 22.9, 22.7, 14.3, 13.2. HRMS (ESI+) calculated for $C_{25}H_{25}OPSH$ $[M+H]^+$ 405.1442 *m*/*z*, found 405.1451.



3a **4** (+/–) **S6a** **S6b**

***O*-((1*R*,2*R*)-2-(Diphenylphosphanyl)cyclohexyl) (*E*)-2-ethylpent-2-enethioate (S6a) and *O*-((1*R*,2*R*)-2-(diphenylphosphanyl)cyclohexyl) (*Z*)-2-ethylpent-2-enethioate (S6b).**

To a glass vial was added **3a** (6.3 mg, 0.050 mmol) and benzene (1.3 mL). Phosphine **8** (16 mg, 0.050 mmol) was added, and the reaction was stirred at room temperature for 2 h. The crude material was then passed through a small plug of neutral alumina, eluting with hexanes. The yellow fractions were collected, and the solvent was removed *in vacuo* to give **S6a** and **S6b** in a 2.1:1.0 ratio (12 mg, 0.029 mmol, 58%) as a yellow oil. ^{1}H NMR (400 MHz, C_6D_6) δ 7.59–7.51 (m, 4H), 7.12–7.01 (m, 6H), 6.85 (t, J = 7.5, 1.0 Hz, 1H), 5.93–5.88 (m, 1H), 5.87–5.83 (m, 1H), 2.87 (td, J = 8.4, 3.7 Hz, 1H), 2.80 (td, J = 8.7, 3.9 Hz, 1H), 2.62–2.54 (m, 2H), 2.48–2.26 (m, 2H), 1.92–1.78 (m, 2H), 1.78–1.72 (m, 2H), 1.62–1.40 (m, 3H), 1.24–1.11 (m, 2H), 1.09 (td, J = 7.5, 1.0 Hz, 3H), 1.04 (td, J = 7.5, 1.0 Hz, 3H), 0.96 (td, J = 7.5, 0.8 Hz, 3H), 0.81 (t, J = 7.6 Hz, 3H). ^{31}P NMR (162 MHz, C_6D_6) δ –7.75, –8.30. ^{13}C NMR (126 MHz, C_6D_6) δ 216.1, 212.3, 144.1, 143.0, 141.1, 137.4 (d, J = 14.4 Hz), 136.77 (d, J = 17.3 Hz), 136.71 (d, J = 17.3 Hz), 135.1, 135.0, 134.9, 133.6 (d, J = 19.3 Hz), 133.4 (d, J = 18.7), 132.4, 129.3, 129.2, 128.7, 128.63, 128.58, 128.5, 128.4, 81.0 (d, J = 17.4 Hz), 80.9 (d, J = 16.7 Hz), 39.6 (d, J = 16.7 Hz), 39.3 (d, J = 17.3 Hz), 30.56, 30.51, 30.4, 30.3, 30.2, 27.0, 26.91, 26.87, 24.8 (d, J = 5.3 Hz), 23.7, 23.6, 23.3, 22.5 (d, J = 7.0 Hz), 14.4, 14.3, 13.4, 13.4. HRMS calculated for $C_{25}H_{31}OPS$ $[M+H]^+$ 411.1912 m/z, found 411.1916.

References

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(2) Davies, R. C.; Neuberger, A.; Wilson, B. M. *Biochim. Biophys. Acta.* **1969**, *178*, 294.
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(4) Row, R. D.; Shih, H.-W.; Alexander, A. T.; Mehl, R. A.; Prescher, J. A. *J. Am. Chem. Soc.* **2017**, *139*, 7370.
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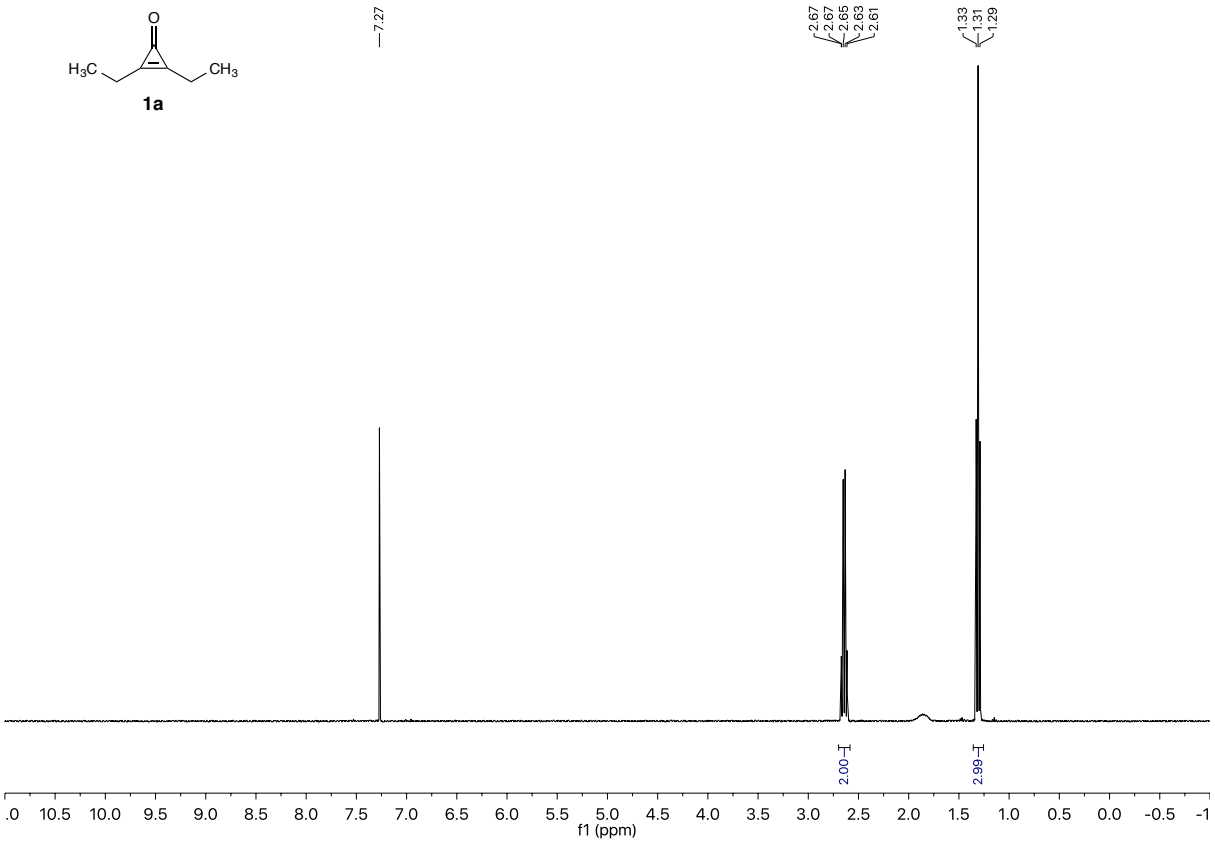
(8) Wang, F.; Luo, T.; Hu, J.; Wang, Y.; Krishnan, H. S.; Jog, P. V.; Ganesh, S. K.; Prakash, G. K. S.; Olah, G. A. *Angew. Chem. Int. Ed.* **2011**, *50*, 7153.

VIII. NMR Spectra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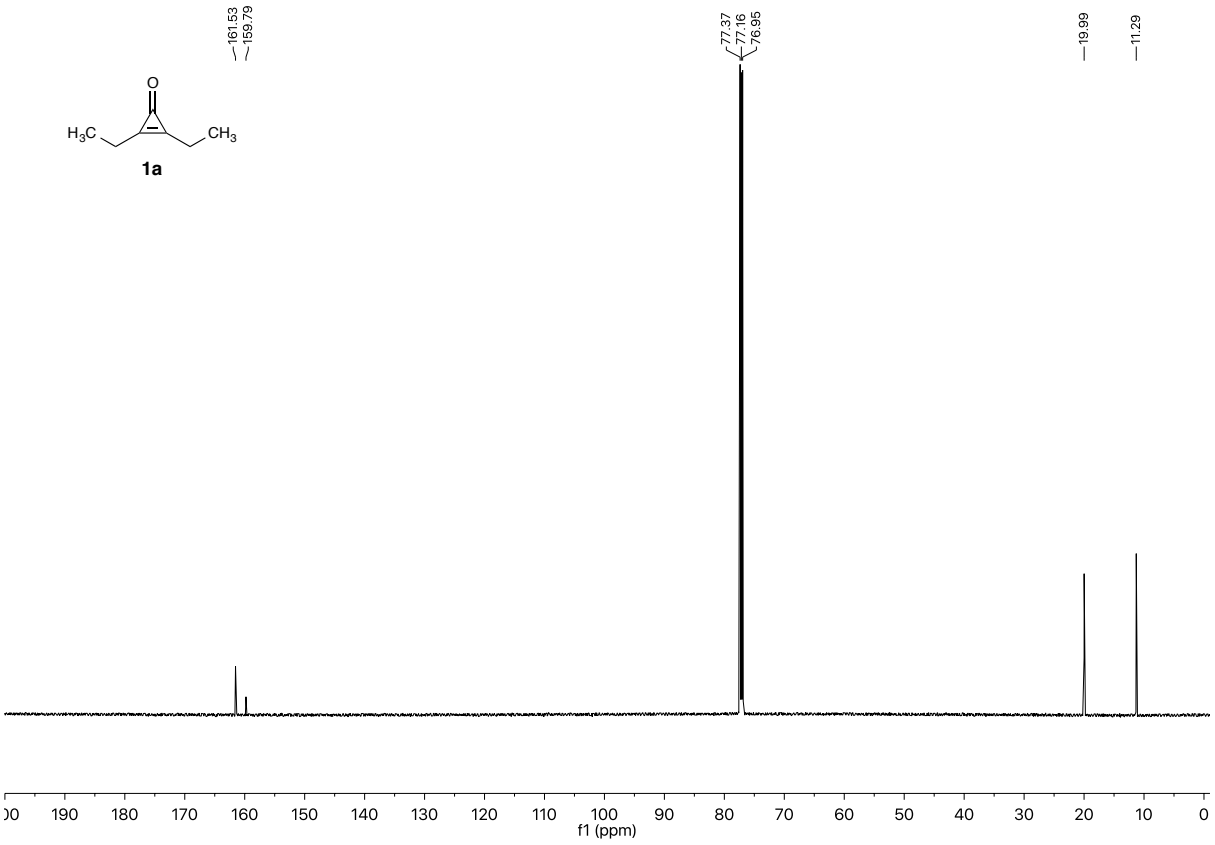
2.61
1.33
1.31
1.29
2.00
2.99
f1 (ppm)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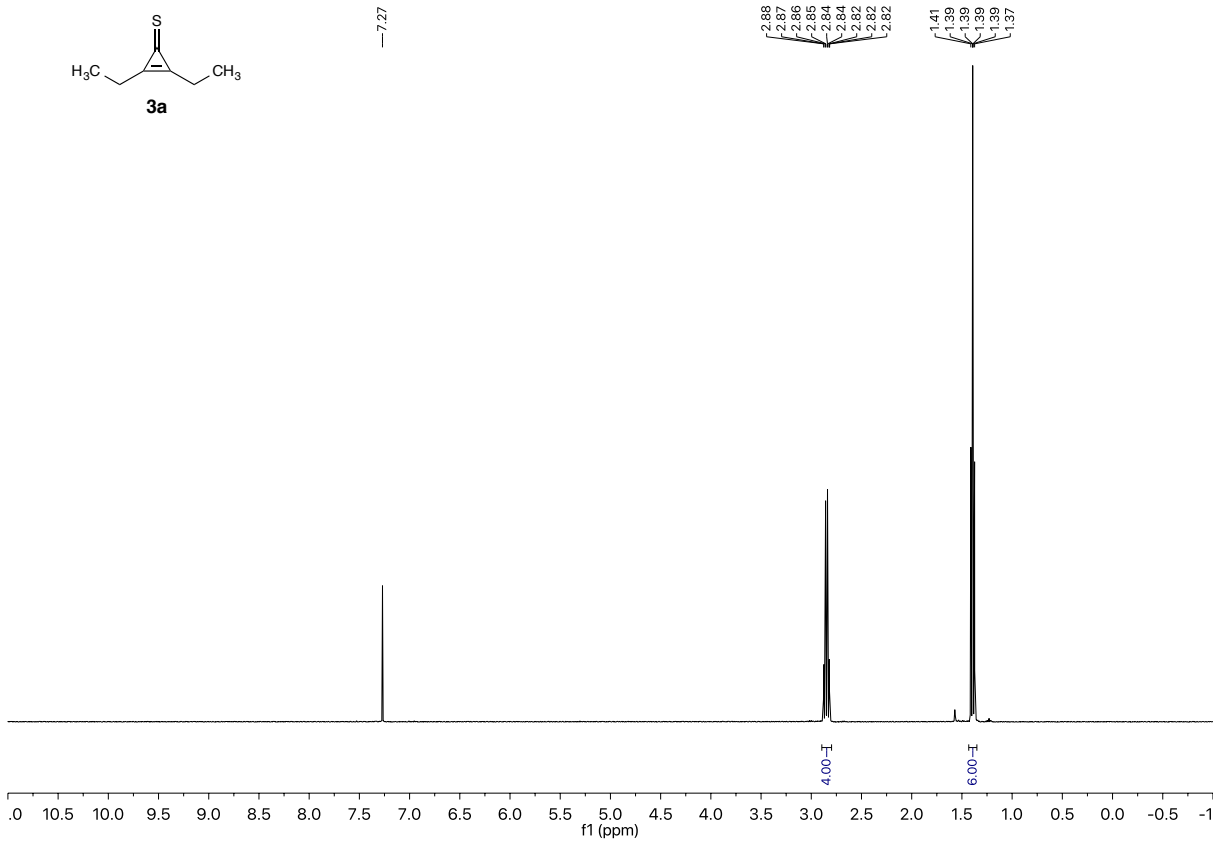
f1 (ppm)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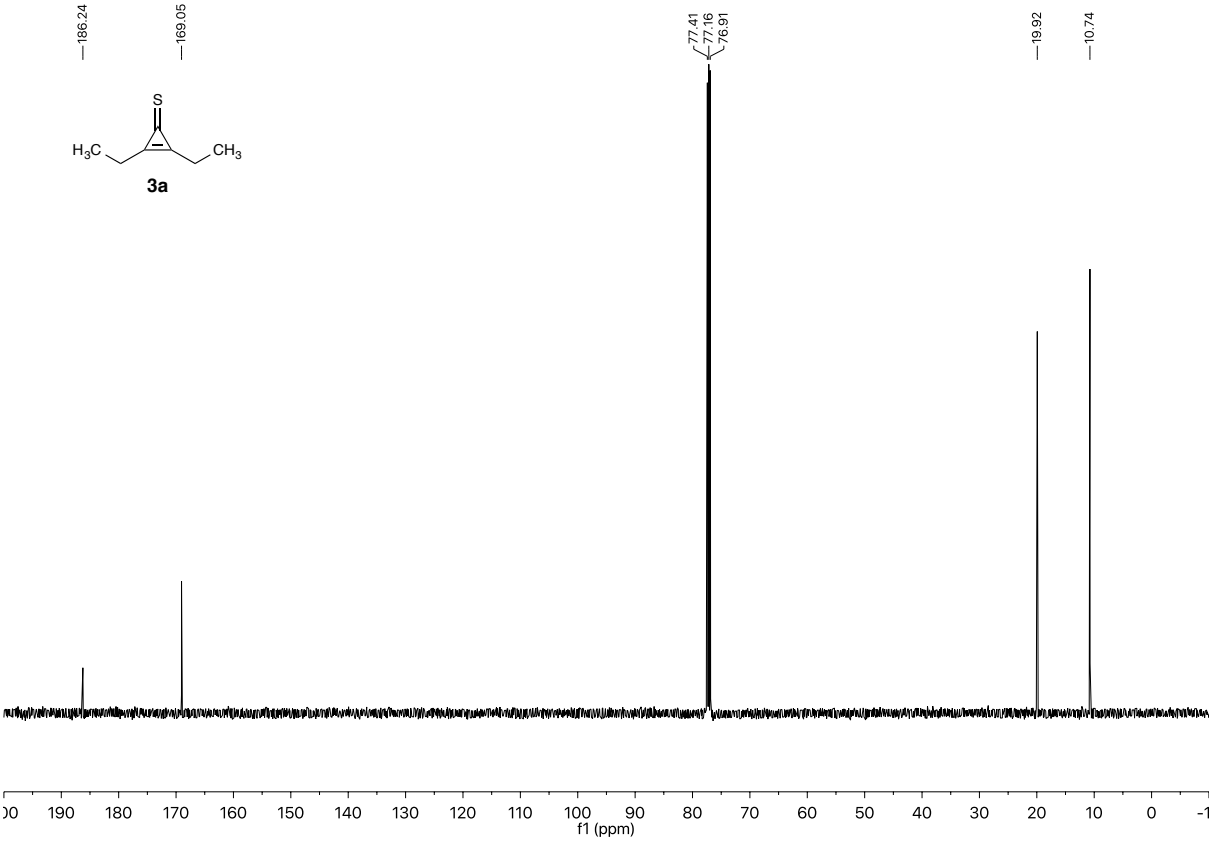
1.39
1.37
4.00
6.00
f1 (ppm)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19.92
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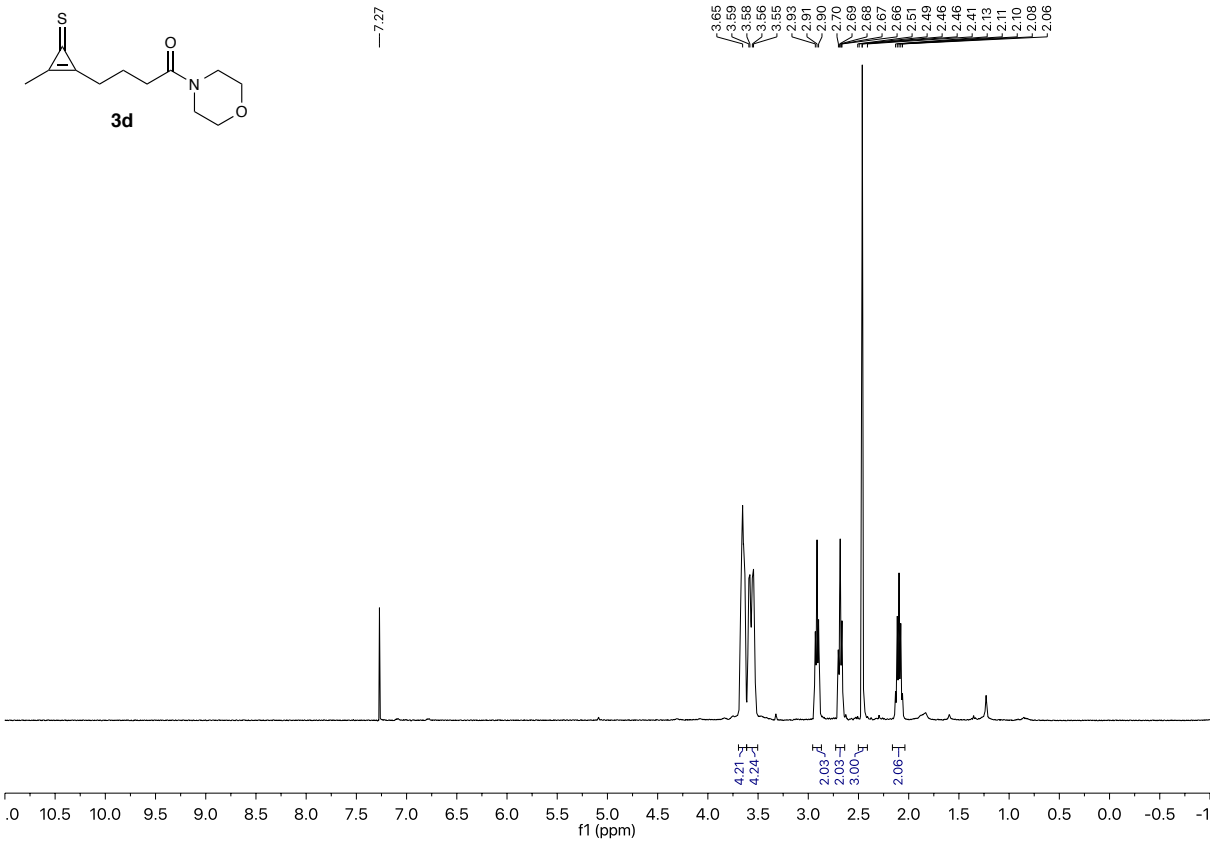
CH3
3a
f1 (ppm)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N
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3.56
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2.91
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2.69
2.68
2.67
2.66
2.51
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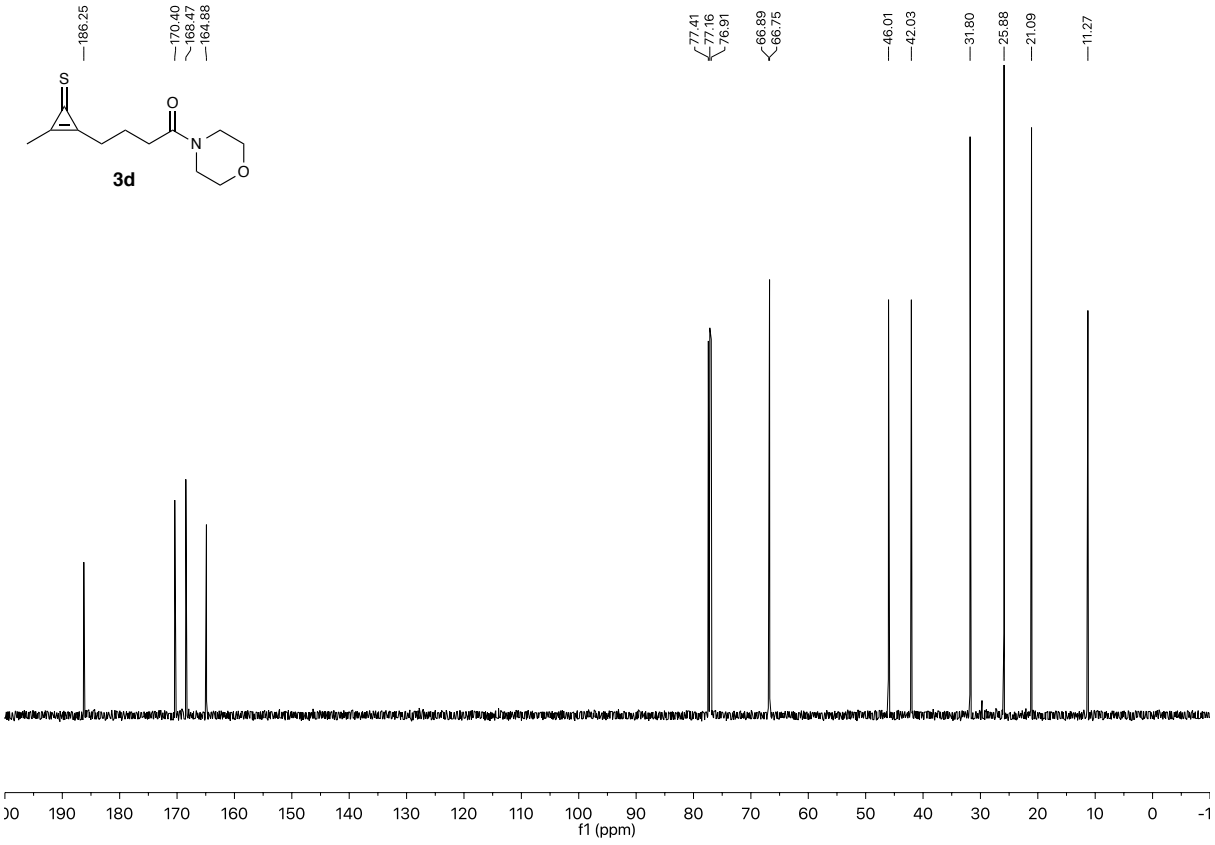
2.03
3.00
2.06
f1 (ppm)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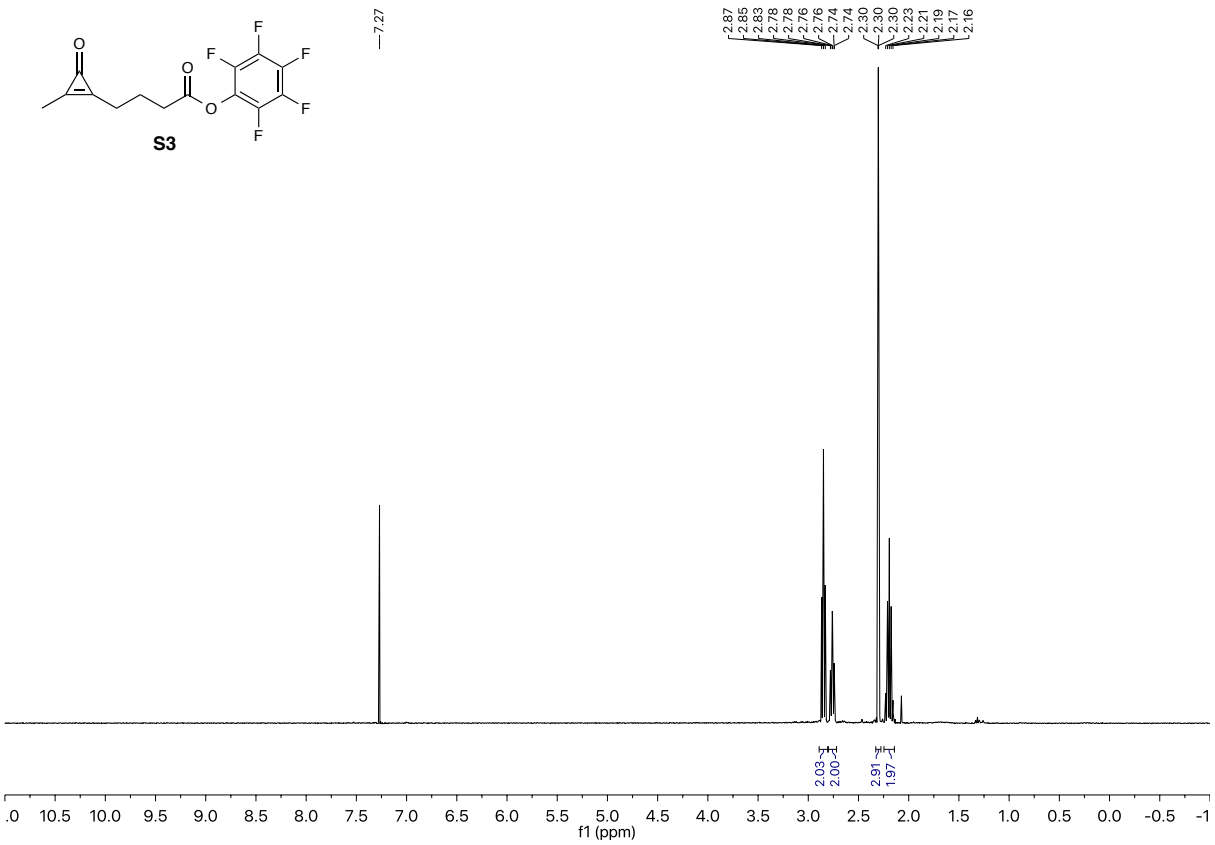
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2.30
2.30
2.23
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2.19
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2.16
2.03
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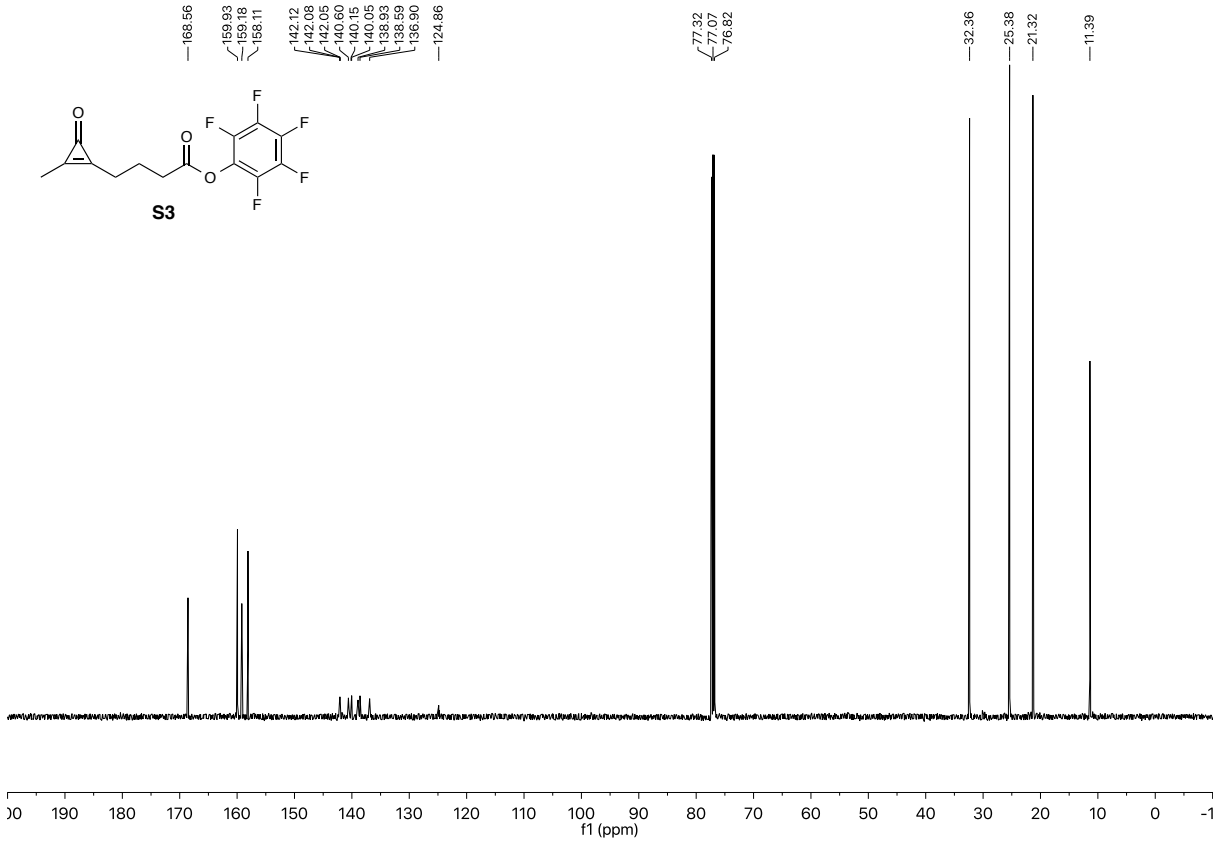
1.97
f1 (ppm)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142.08
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140.05
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77.07
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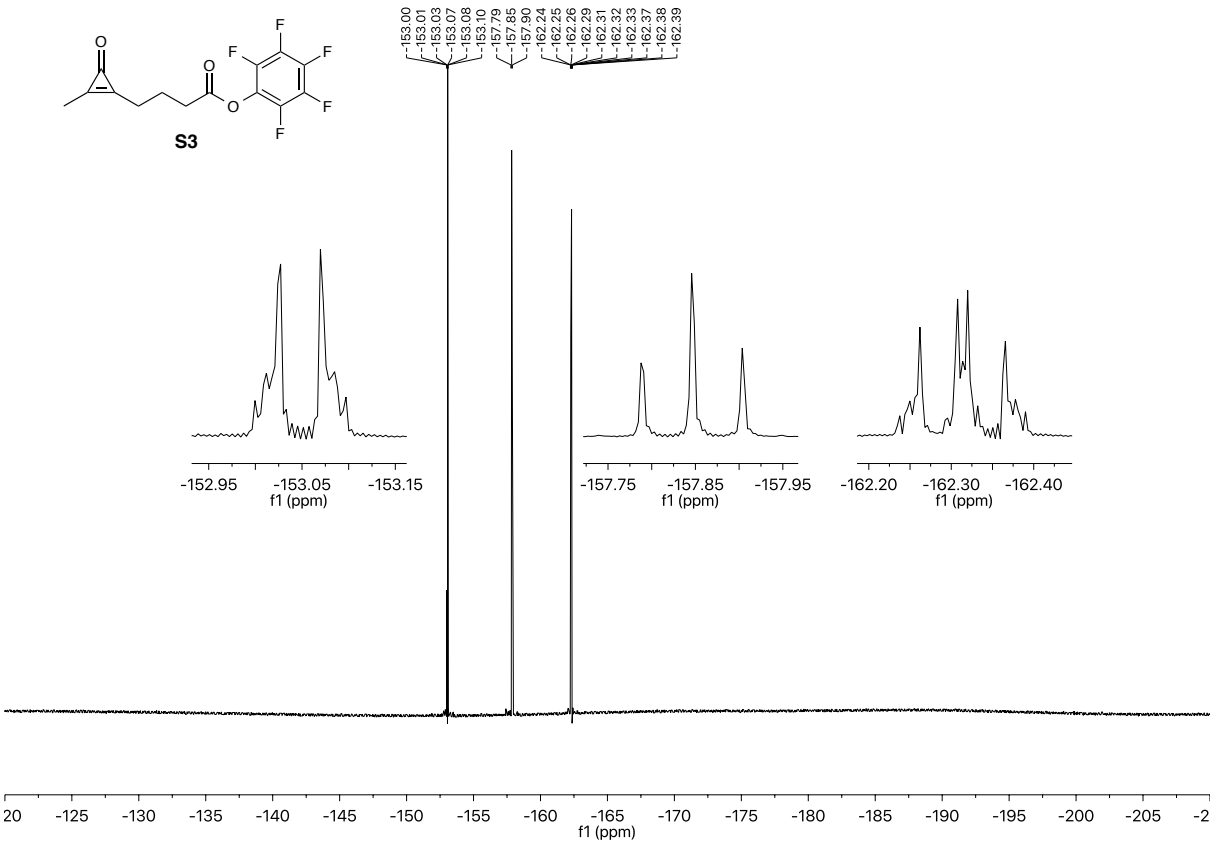
25.38
21.32
11.39
f1 (ppm)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-162.29
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-162.32
-162.33
-162.37
-162.38
-162.39
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-157.95
f1 (ppm)
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f1 (ppm)
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-130
-135
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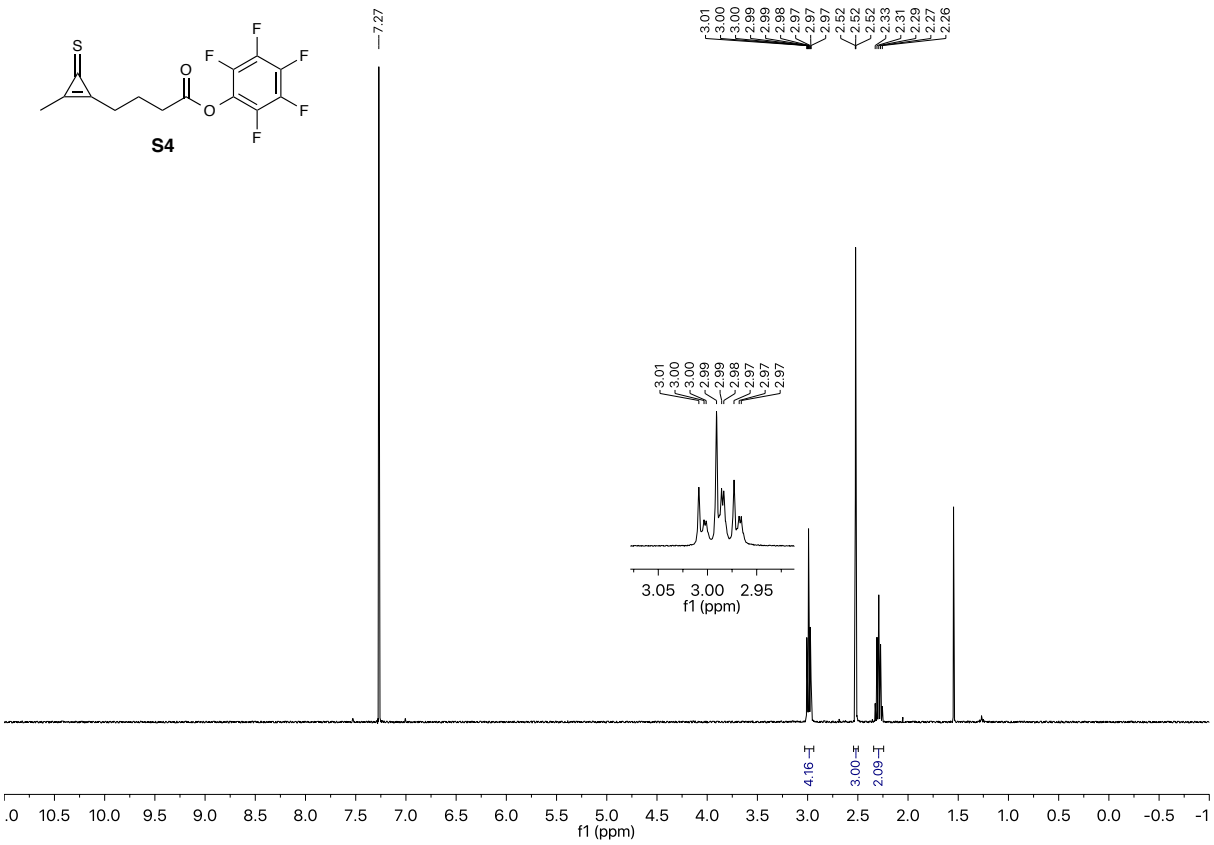
-190
-195
-200
-205
-2
f1 (ppm)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2.97
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2.52
2.52
2.33
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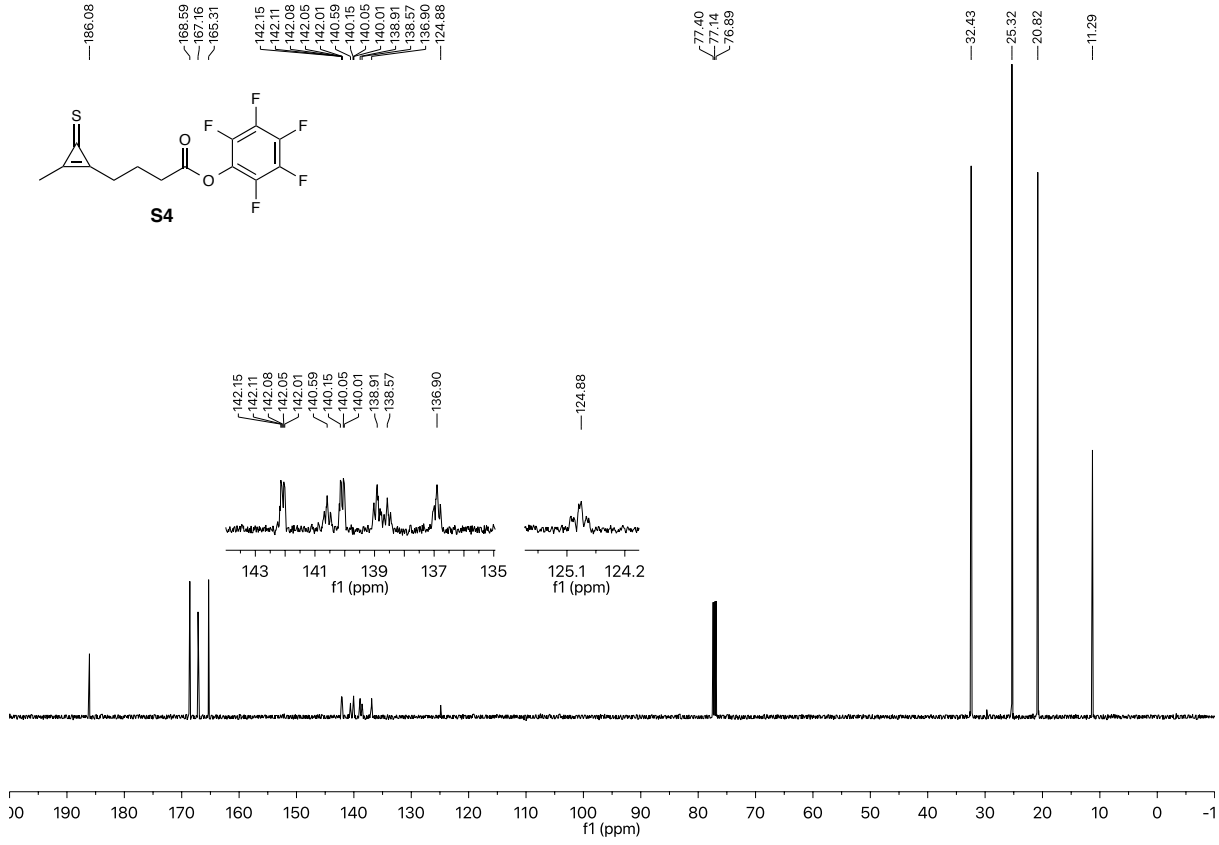
2.29
2.27
2.26
3.05 3.00 2.95
f1 (ppm)
4.16
3.00
2.09
f1 (ppm)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140.15
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140.01
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136.90
124.88
77.40
77.14
76.89
32.43
25.32
20.82
11.29
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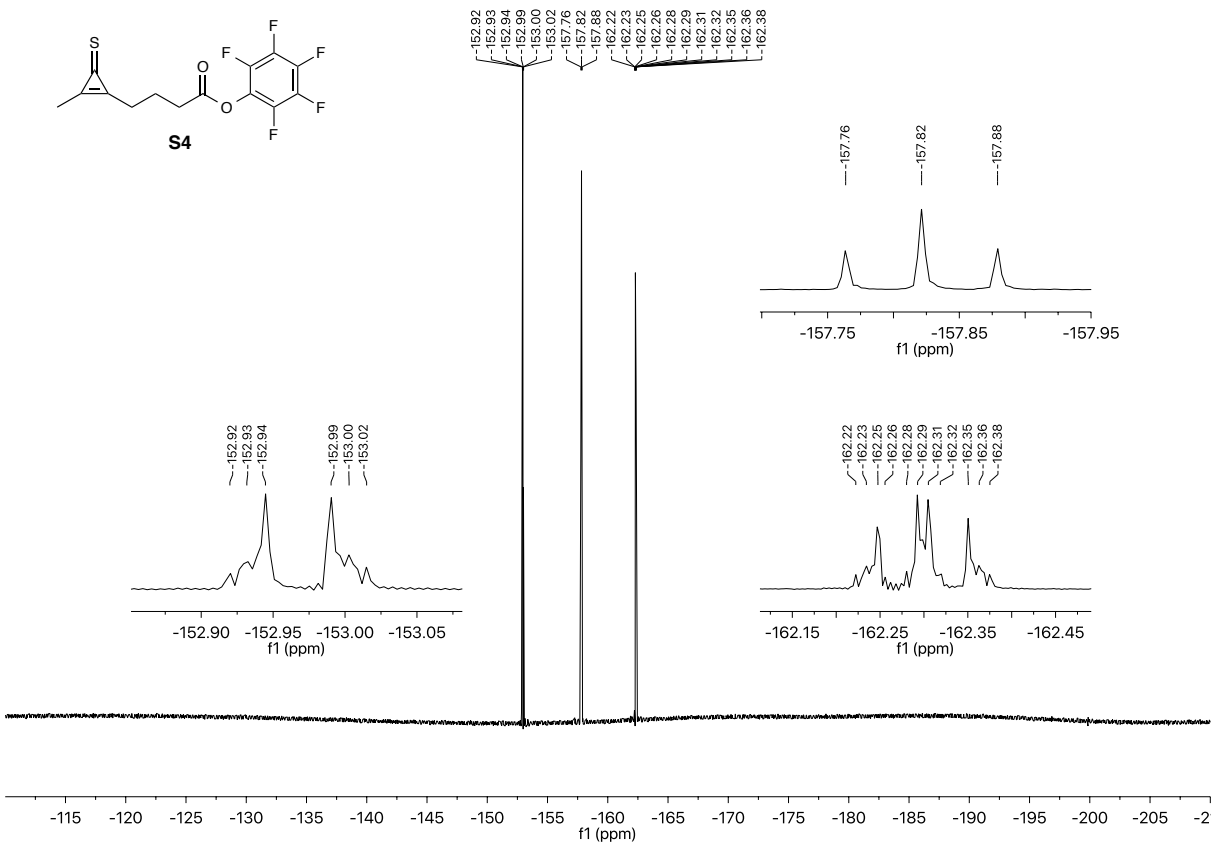
f1 (ppm)
125.1 124.2
f1 (ppm)
f1 (ppm)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O
F
F
F
F
F
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f1 (ppm)
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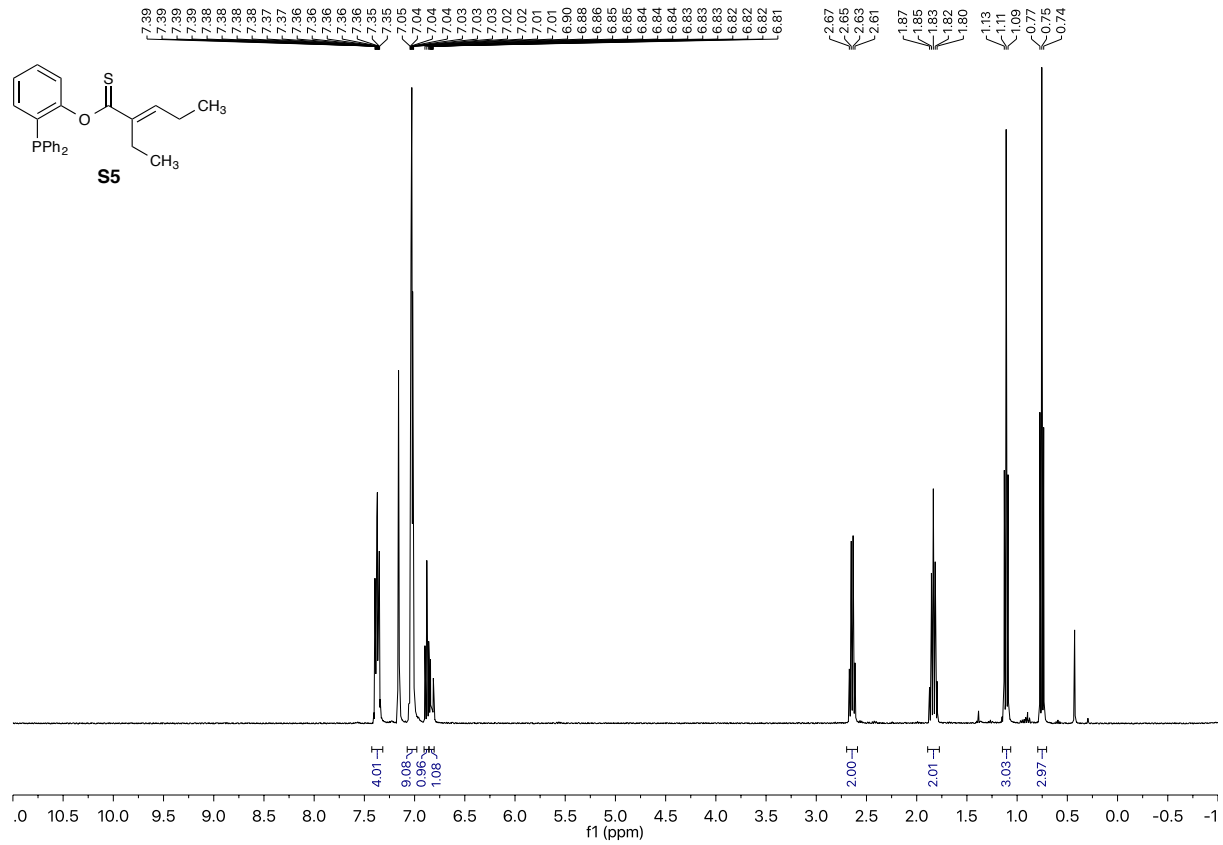
f1 (ppm)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CH3
CH3
S5
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7.05 7.04 7.04 7.04 7.03 7.03 7.03 7.02 7.02 7.01 7.01 6.90 6.88 6.86 6.85 6.85 6.84 6.84 6.83 6.83 6.82 6.82 6.82 6.81
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1.87 1.85 1.83 1.82 1.80
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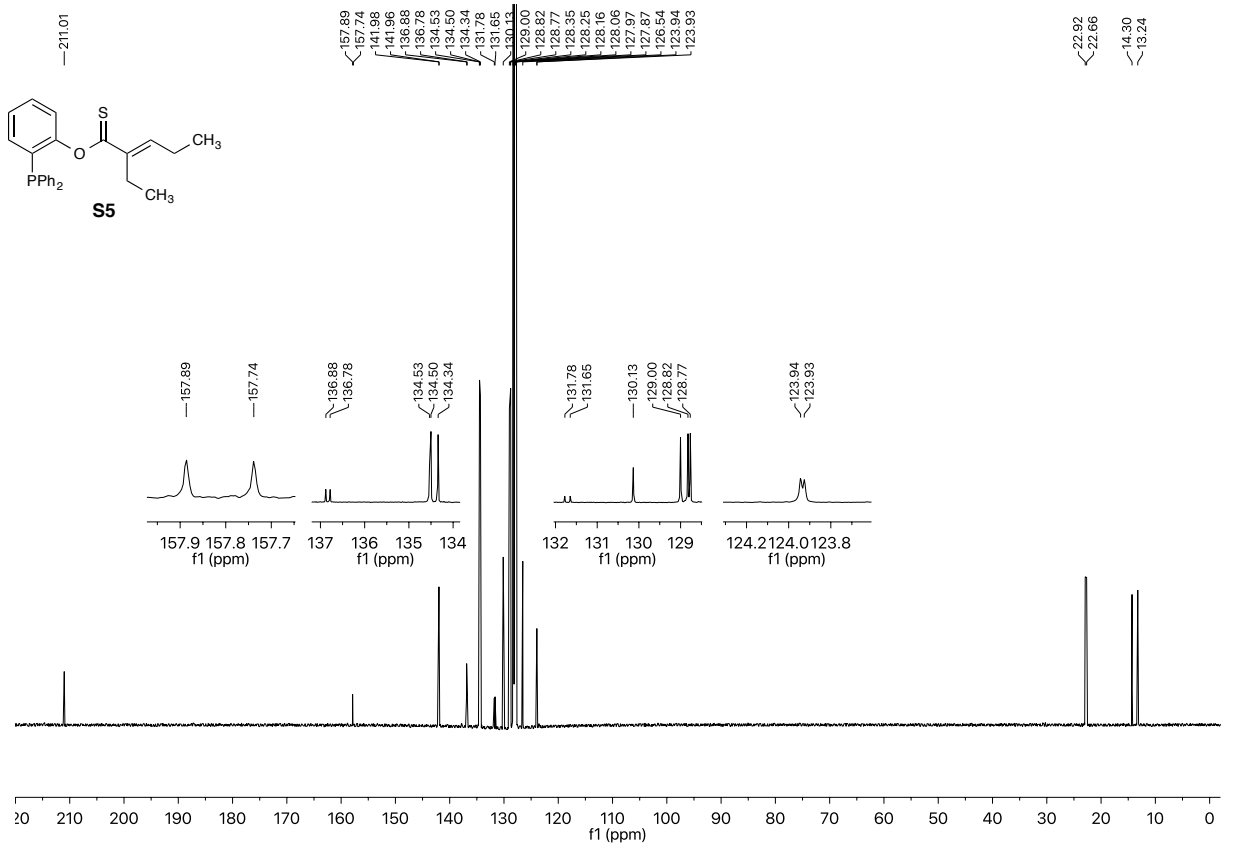
f1 (ppm)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CH3
S5
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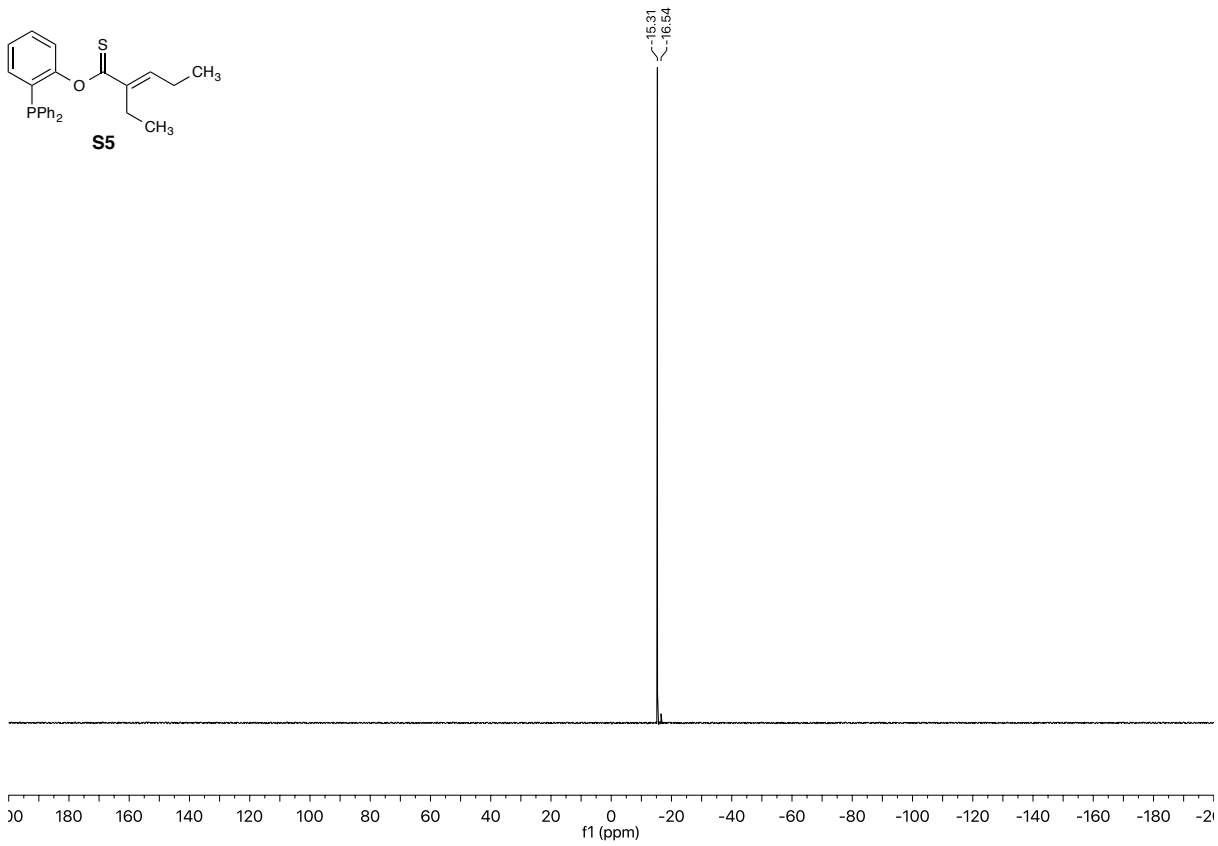
f1 (ppm)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CH3
S5
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160
140
120
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60
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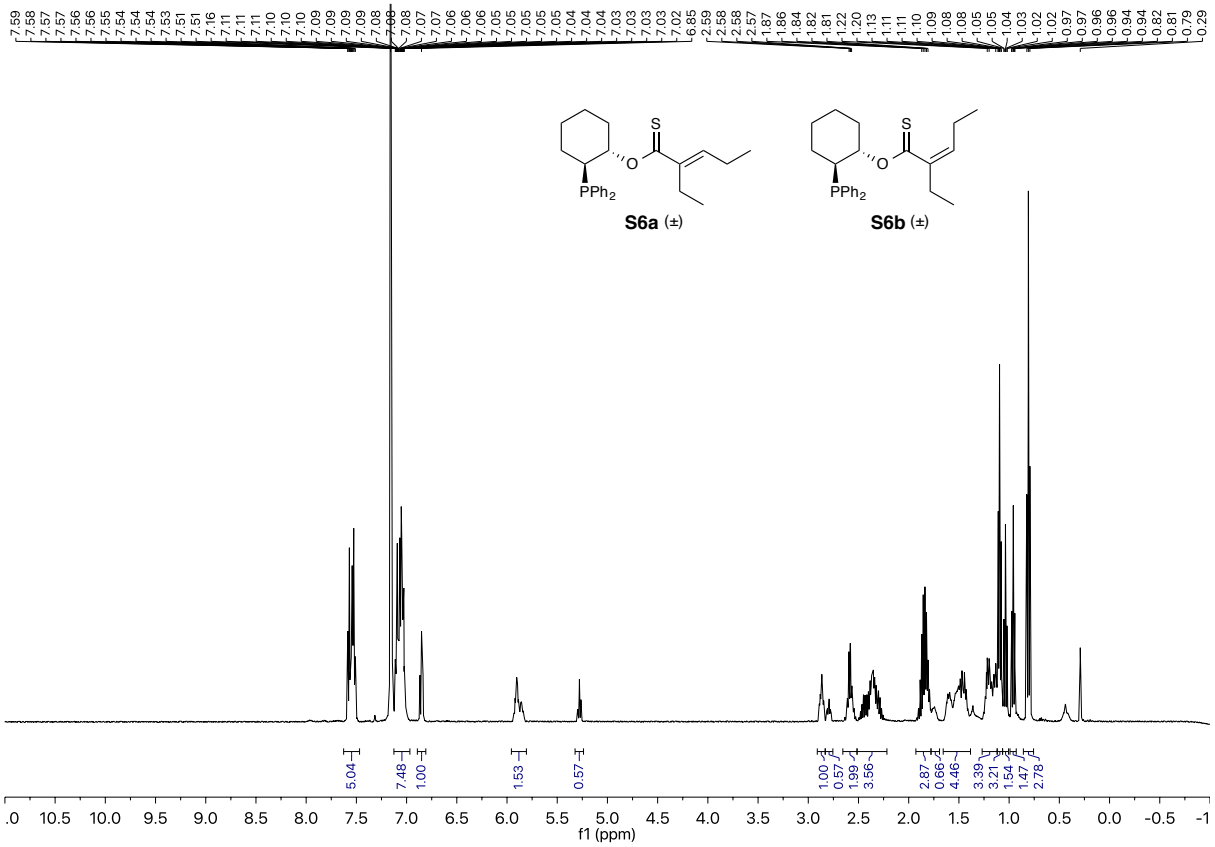
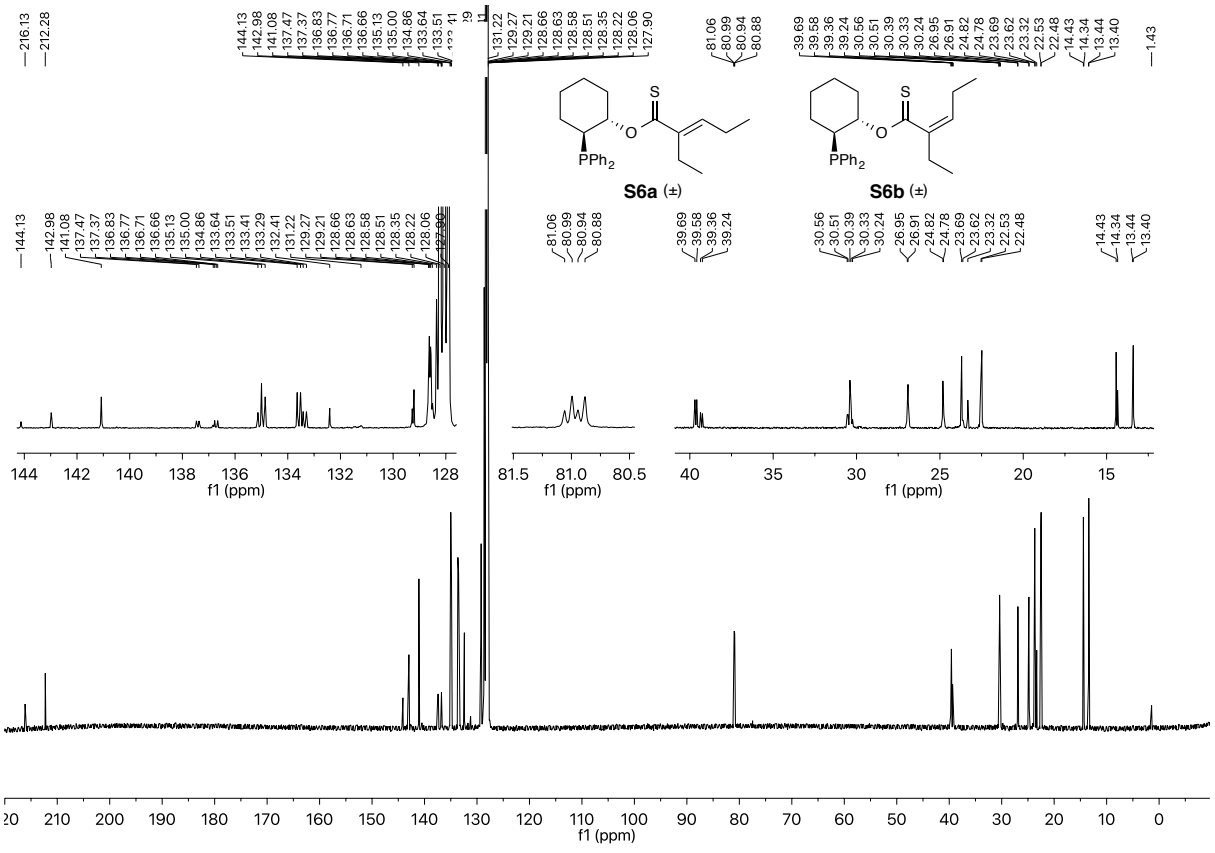
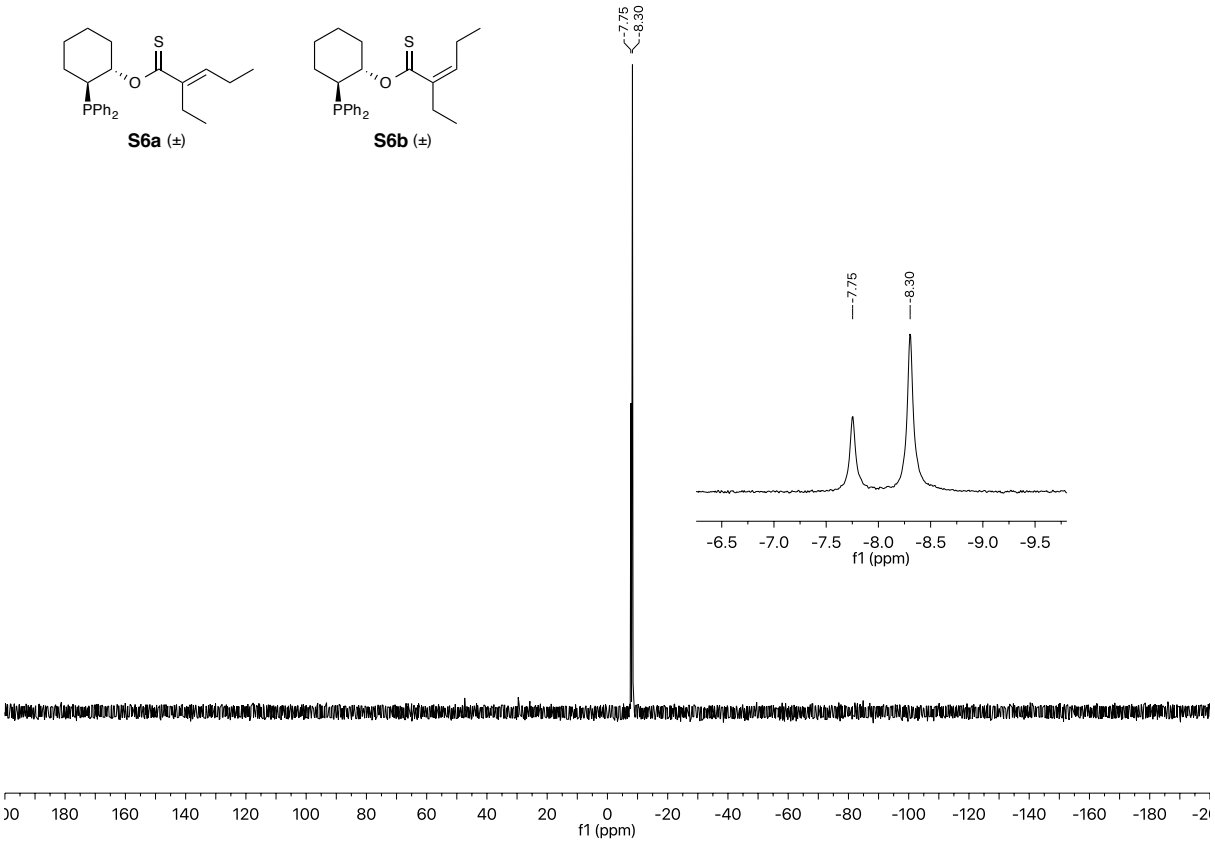
20
0
-20
-40
-60
-80
-100
-120
-140
-160
-180
f1 (ppm)


S6a (±)
S6b (±)
f1 (ppm)


S6a (±)
S6b (±)
f1 (ppm)


S
O
PPh2
S6a (±)
S6b (±)
7.75
8.30
-6.5 -7.0 -7.5 -8.0 -8.5 -9.0 -9.5
f1 (ppm)
180 160 140 120 100 80 60 40 20 0 -20 -40 -60 -80 -100 -120 -140 -160 -180
f1 (ppm)