Supporting Information

Understanding Hydrogen Sulfide Storage: Probing Conditions for Sulfide Release from Hydrodisulfides

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General experimental methods

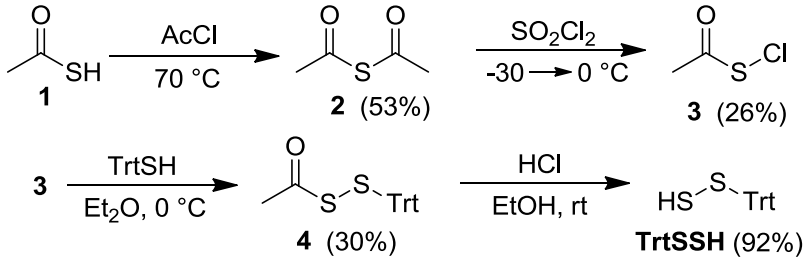
Materials and Methods. Thioacetic acid, acetyl chloride, sulfuryl chloride and trityl thiol were purchased from commercial suppliers and used as received. Triphenylphosphine, $[NBu_4^+][BH_4^-]$, $[NBu_4^+][CN^-]$, $[NBu_4^+][Cl^-]$, $[NEt_4^+][Br^-]$, $[NBu_4^+][I^-]$, $[NBu_4^+][OAc^-]$, and DMAP were handled in an inert atmosphere glove box and used at received. TrtSSH was prepared by a method modified from published procedures[1] and described in detail below. Dithiopropane, acetic acid, and benzyl thiol were degassed using three freeze-pump-thaw cycles and stored under nitrogen. TEA, DMEDA, and pyridine were distilled under vacuum prior to use and stored under nitrogen. Trityl thiolate was generated by deprotonation of trityl thiol with sodium hydride. $[NBu_4^+][TFA^-]$ was prepared by reaction of trifluoroacetic acid with $[NBu_4^+][OH^-]$. H_2S(g) was purchased from Sigma Aldrich and transferred through a custom-built stainless steel transfer line into a glass storage bulb prior to use. *Note*: Hydrogen sulfide and its salts are highly toxic and should be handled carefully to avoid exposure. Deuterated solvents were purchased from Cambridge Isotope Laboratories, degassed using three freeze-pump-thaw cycles and stored under nitrogen over 4Å molecular sieves. Diethyl ether and toluene degassed by sparging with argon followed by passage through a Pure Process Technologies solvent purification system. All air-free manipulations were performed using standard Schlenk techniques or by use of an Innovative Technology glove box.

Spectroscopic Methods. NMR spectra were acquired on a Brüker Avance-III-HD 600 spectrometer with a Prodigy multinuclear broadband CryoProbe or a Varian INVOA-500 spectrometer at 25.0 °C. Chemical shifts are reported in parts per million (δ) and are referenced to residual protic solvent resonances. The following abbreviations are used in describing NMR couplings: (s) singlet, (d) doublet, (b) broad, and (m) multiplet. UV-vis spectroscopic measurements were performed on either Cary 60 or Cary 100 spectrophotometers equipped with Quantum Northwest cuvette temperature controllers under anaerobic conditions in 1.0 cm path length septum-sealed cuvettes obtained from Starna Scientific. IR spectra were measured in the solid phase on a Thermo Scientific Nicolet 6700 RT-IR using an ATR attachment. Raman spectra were recorded in the solid phase on a WITEC alpha300 S scanning near-field optical microscope. High resolution mass spectrometry (HRMS) measurements were performed by the

Biomolecular Mass Spectrometry Core of the Environmental Health Sciences Core Center at Oregon State University.

X-Ray Crystallography. Single crystals of TrtSSH suitable for X-ray diffraction were grown from a mixed toluene/Et_2O solution. Diffraction data were collected on a Bruker Smart Apex diffractometer at 150(2) K using Mo K_α radiation (λ = 0.71073 Å). Data reduction was performed in SAINT, and absorption corrections were applied using SADABS. All refinements were performed using the SHELXTL software package.[2-4] All non-hydrogen atoms were refined anisotropically. Hydrogen atoms were found from the residual density map and were refined with isotropic thermal parameters. The terminal H atom in the SSH group was disordered over two positions, which were refined to a 60:40 ratio by iterative refinement of of different occupation factors. TrtSSH crystallized in the non-centrosymmetric space group $P2_12_12$ with an associated Flack parameter of 0.14(10).

Synthetic procedures



Diacetylsulfide (**2**): Acetyl chloride (12.15 mL, 170.3 mmol) was added dropwise to thioacetic acid (**1**, 6.0 mL, 85 mmol) under nitrogen. The reaction mixture was refluxed at 70 °C for 5 h, during which time the color changed from light yellow to deep red. After heating, the reaction mixture was allowed to cool to room temperature and vacuum distillation (40 °C bath temperature) afforded 5.31 g (53% yield) of **2** as a light pink to fuchsia liquid. Diacetylsulfide, **2**, can be stored at -20 °C without decomposition. ^{1}H NMR (600 MHz, $CDCl_3$) δ: 2.51 (s, 6H)

Acetyl sulfenylchloride (**3**): Sulfuryl chloride (3.73 mL, 46.2 mmol) was added dropwise to diacetylsulfide (5.3 g, 45 mmol) at -30 °C in a dry ice/methanol bath under nitrogen. The reaction mixture was warmed from -30 °C to 0 °C over the course of 3 h, during which time the color of the solution changed from pale yellow to orange. Vacuum distillation (30 °C bath temperature) of the reaction mixture yields 1.29 g (23% yield) of **3** as a yellow liquid. *Caution:* Sulfenyl chlorides decompose to the corresponding disulfide and chlorine gas at room temperature, but can be stored at -20 °C without decomposition. ^{1}H NMR (600 MHz, $CDCl_3$) δ: 2.41 (s, 3H). ^{13}C{^{1}H} NMR (150 MHz, $CDCl_3$) δ: 190.1, 26.5.

Tritylacetyldisulfide (**4**): Acetylsulfenyl chloride (1.07 g, 9.71 mmol) dissolved in 10 mL of Et_2O was added dropwise to a solution of tritylthiol (1.79 g, 6.48 mmol) in 25 mL of Et_2O in an ice bath under nitrogen. The reaction mixture was allowed to warm to room temperature and then stirred for 24 h. The solvent was removed under vacuum, and the remaining solids were suspended in concentrated aqueous bicarbonate and then stirred with ethyl acetate overnight. The organic layer was separated and washed twice with saturated aqueous bicarbonate, dried over

$MgSO_4$, filtered, and evaporated to dryness. Recrystallization from hot MeOH yields 660 mg (30% yield) of **4** as a white crystalline solid. ^{1}H NMR (600 MHz, CD_2Cl_2) δ: 7.33 (m, 15H), 2.03 (s, 3H). $^{13}C\{^1H\}$ NMR (150 MHz, $CDCl_3$) δ: 194.2, 143.3, 130.2, 128.0, 127.4, 73.38, 28.3.

Tritylhydrodisulfide (**TrtSSH**): Ethanolic HCl (5 N) was prepared by adding acetyl chloride to dry degassed ethanol in an ice bath. Tritylacetyldisulfide (120 mg, 0.342 mmol) was dissolved in 1.2 mL of 4:3 ethanol:toluene and cooled in an ice bath under nitrogen. Ethanolic HCl (5 N, 342 μL) was added to the solution dropwise, and the resultant reaction mixture was allowed to stir overnight under a gentle stream of nitrogen. After 3 h, the disulfide had dissolved fully, and after 12 h a white solid started to precipitate. After stirring for 24 h, the solvents were removed under vacuum, and the white precipitate was recrystallized from 1:1 ether:toluene under a gentle stream of nitrogen to afford **TrtSSH** 97.2 mg (92% yield) as a white crystalline solid. ^{1}H NMR (600 MHz, CD_2Cl_2) δ: 7.30 (m, 15H), 2.72 (s, 1H, SH). $^{13}C\{^1H\}$ NMR (150 MHz, CD_2Cl_2) δ: 143.5, 129.9, 128.0, 127.1, 70.4. IR (cm^{-1}): 3016, 2058, 1959, 1592, 1488, 1439, 1317, 1181, 1157, 1080, 1033, 1000, 924, 877. HRMS-ESI (m/z): $[M-H]^-$ calcd for $[C_{19}H_{15}S_2]^-$ 307.0621; found 307.0631.

General Procedure for NMR Reactions. A septum-sealed NMR tube was charged with TrtSSH (2.0 mg in 350 μL of CD_2Cl_2) under an N_2-atmosphere in a glove box. After measuring an initial NMR spectrum, reactants (1 equiv. in 200 μL CD_2Cl_2) were added and the reaction progress was monitored by ^{1}H NMR spectroscopy until completion.

NMR Spectra

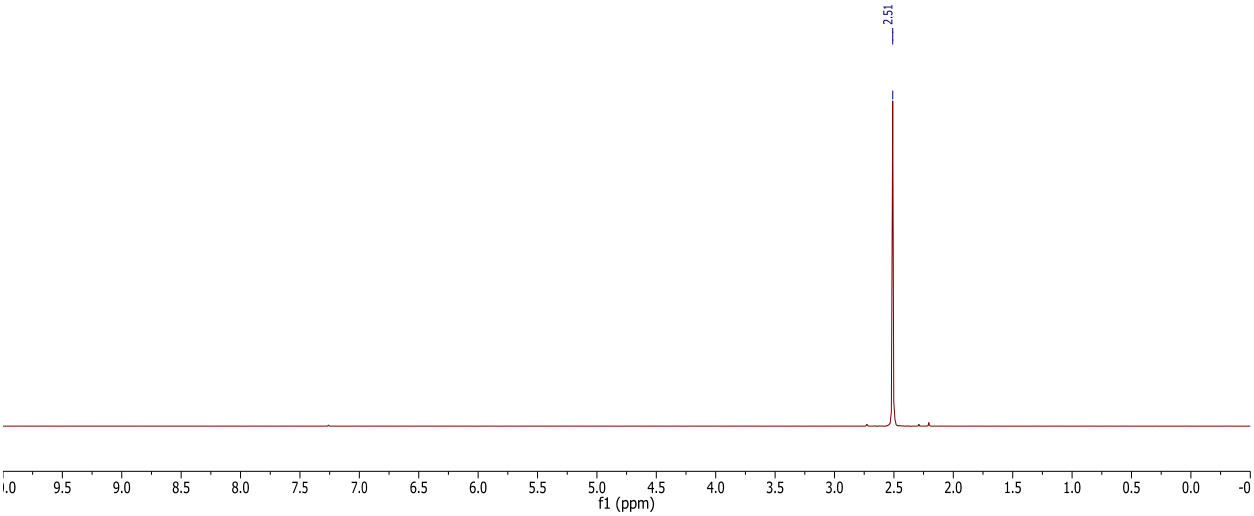


Figure S1: ^{1}H (600 MHz, $CDCl_3$) NMR spectrum of diacetylsulfide (**2**).

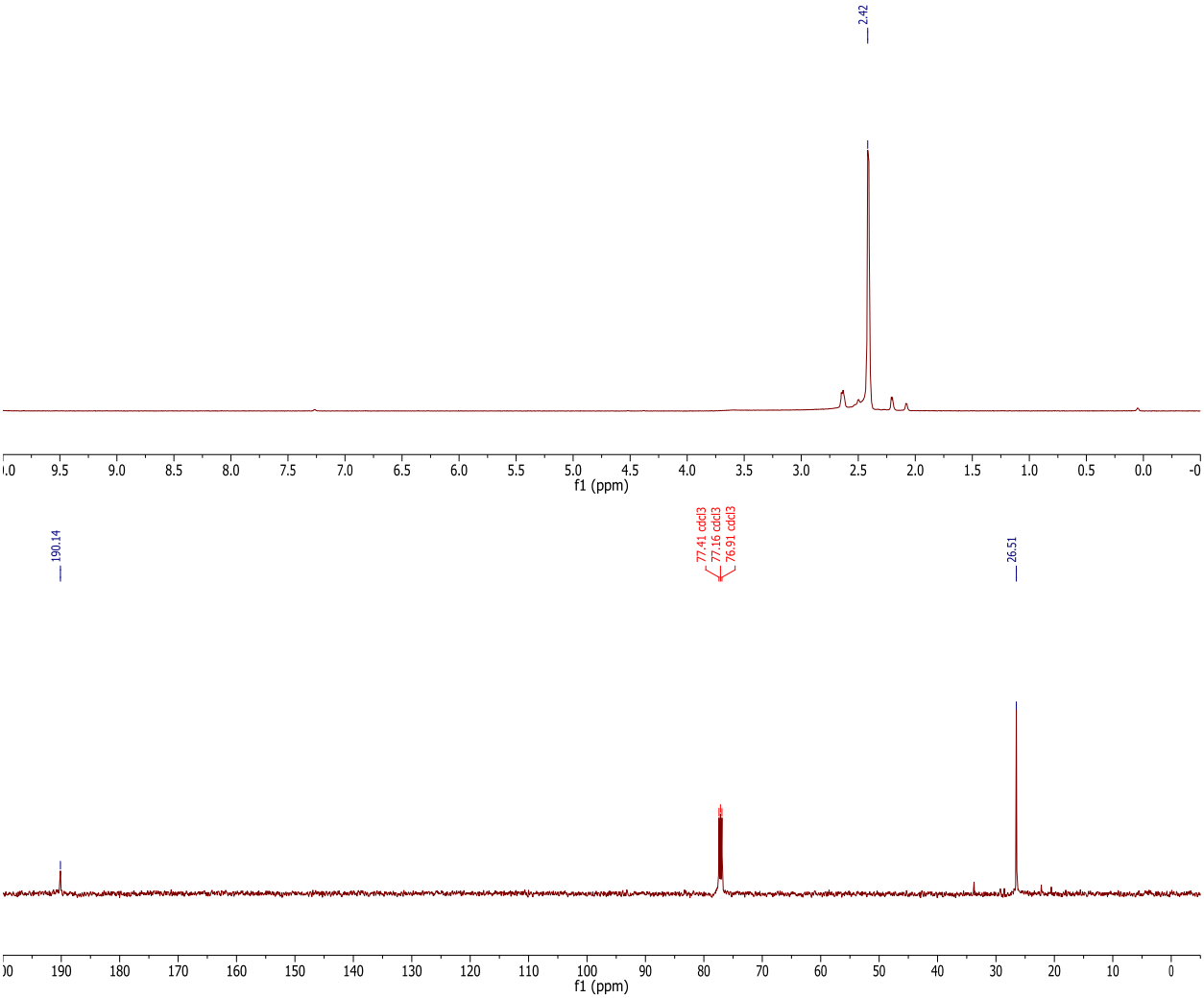


Figure S2: ^{1}H (600 MHz, $CDCl_3$) and $^{13}C\{^{1}H\}$ NMR spectra of acetyl sulfenylchloride (**3**).

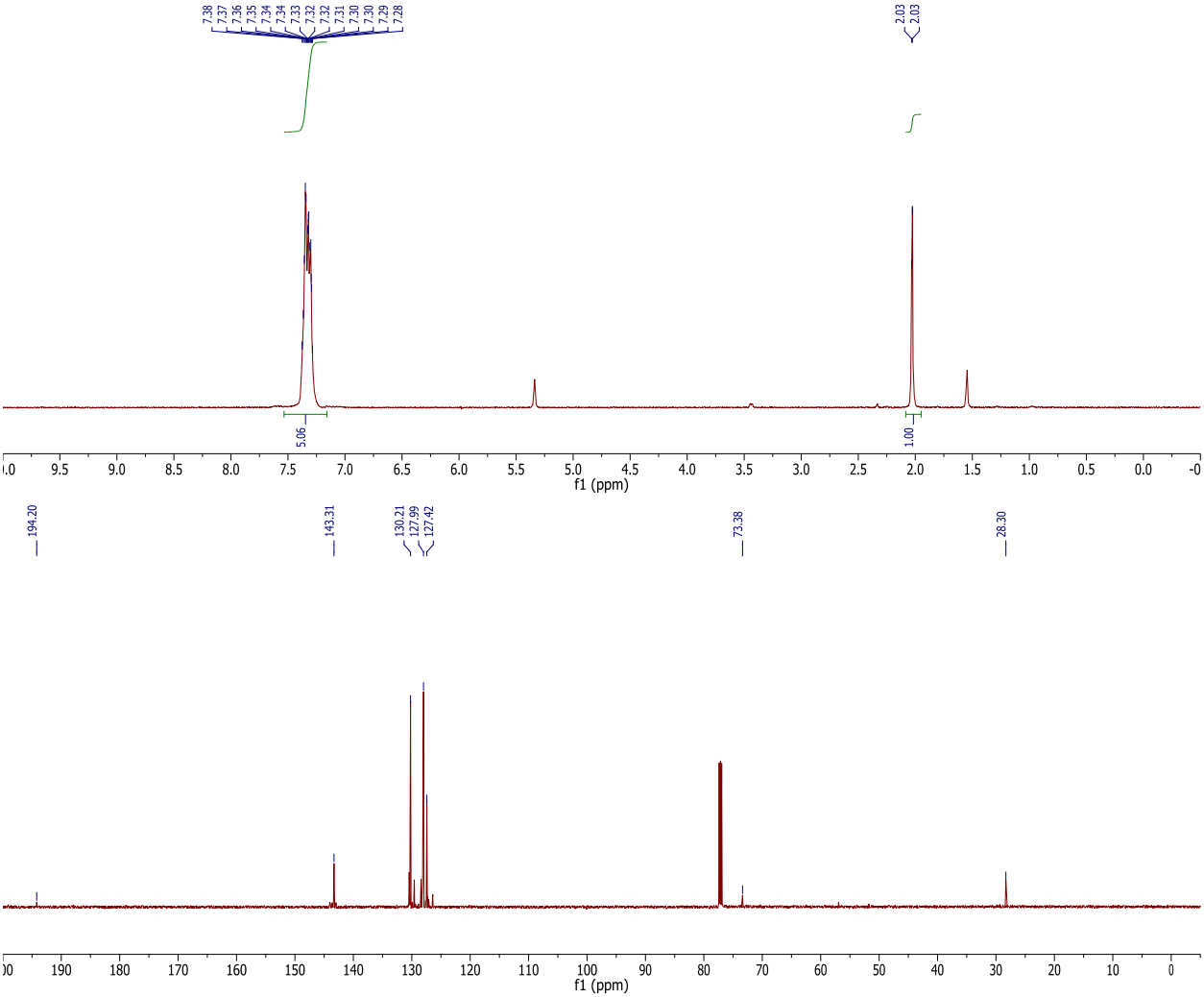


Figure S3: ^{1}H (600 MHz, CD_2Cl_2) and $^{13}C\{^{1}H\}$ (150 MHz, $CDCl_3$) NMR spectra of tritylacetyldisulfide (**4**).

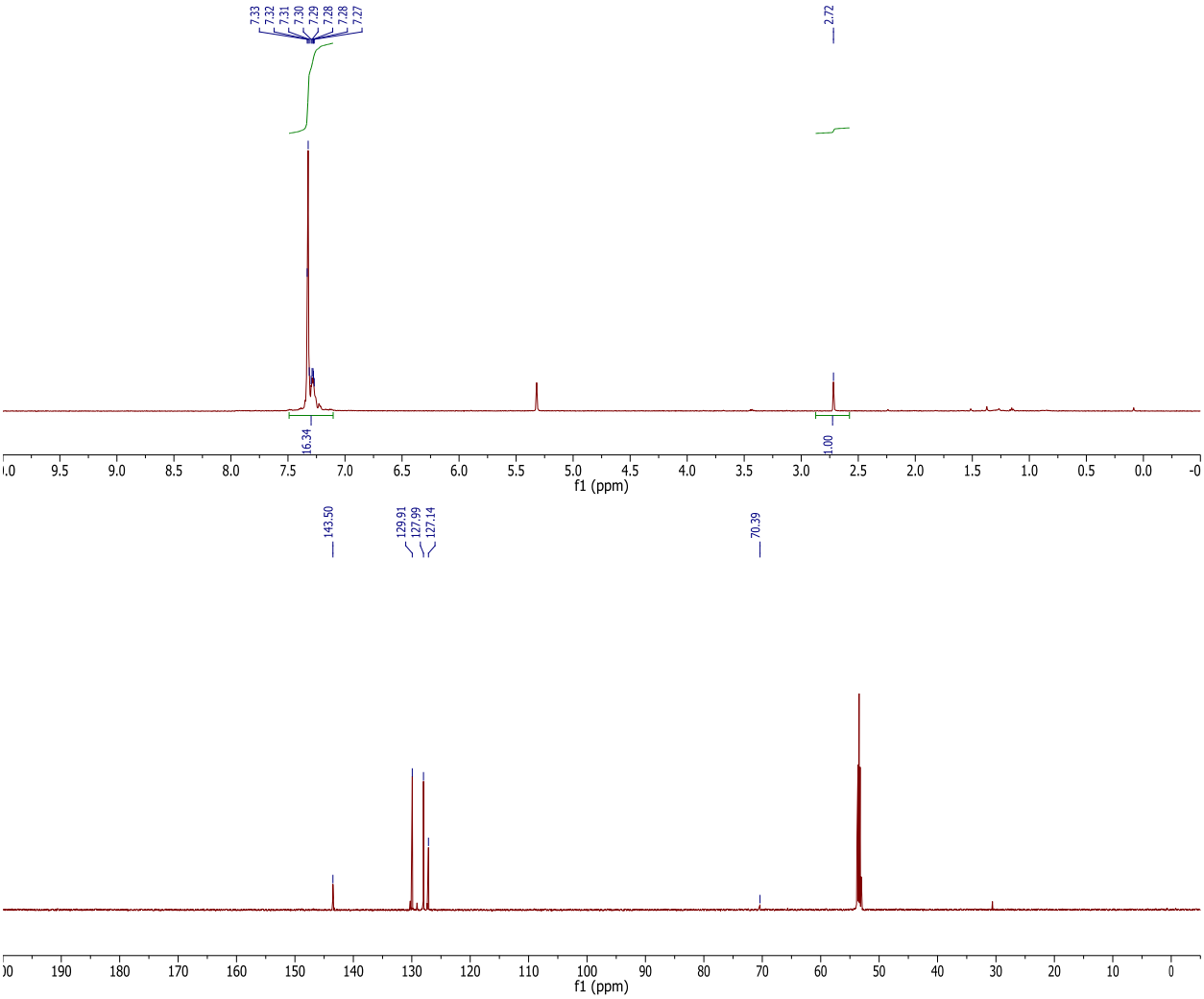


Figure S4: ^{1}H (600 MHz, CD_2Cl_2) and $^{13}C\{^{1}H\}$ NMR spectra of tritylhydrodisulfide (**TrtSSH**). δ (SS-H): 2.72 ppm.

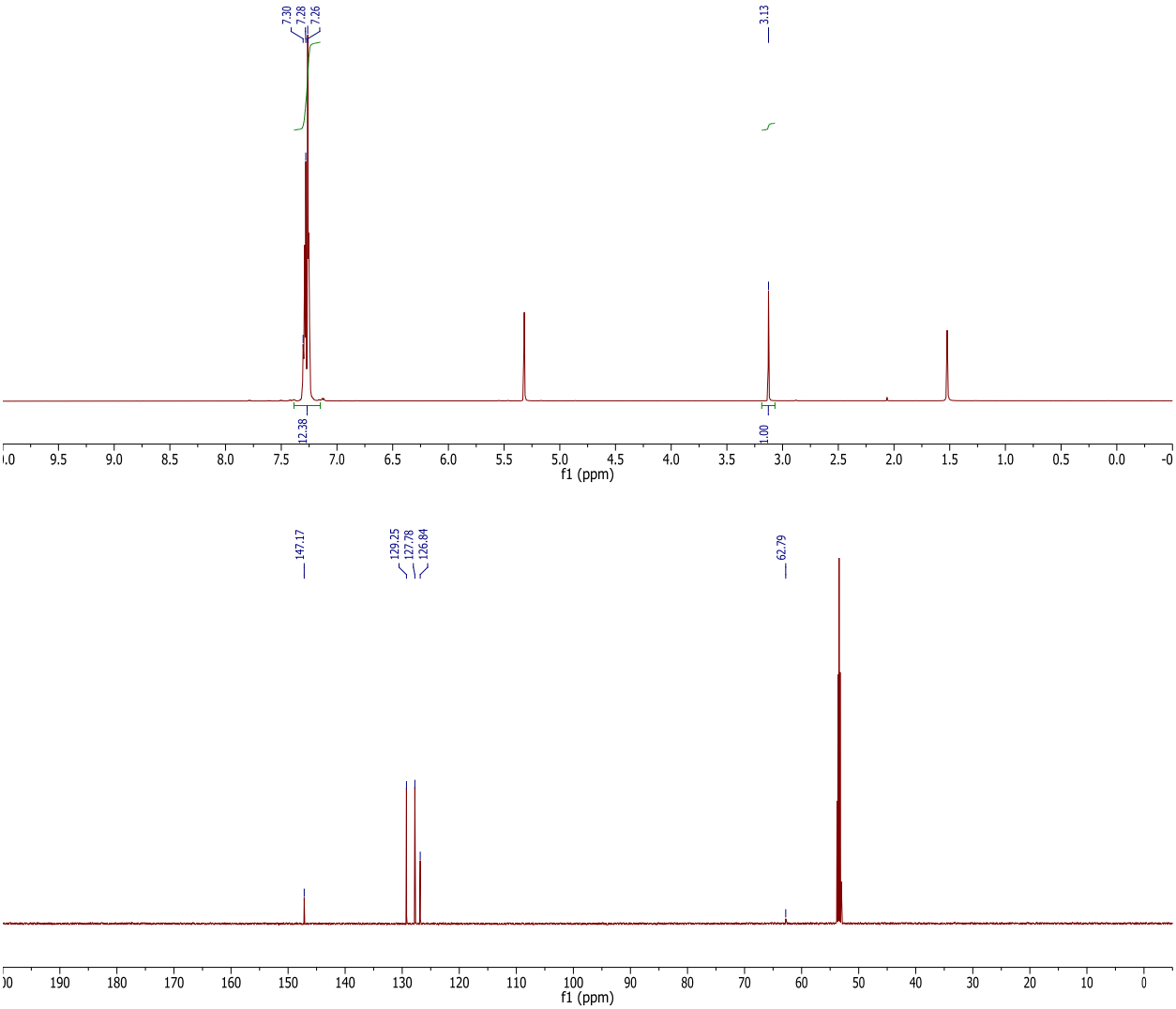


Figure S5: ^{1}H (600 MHz, CD_2Cl_2) and $^{13}C\{^{1}H\}$ NMR spectra of tritylthiol (**TrtSH**). δ (S-H): 3.13 ppm.

NMR Spectra of TrtSSH Reactivity Experiments

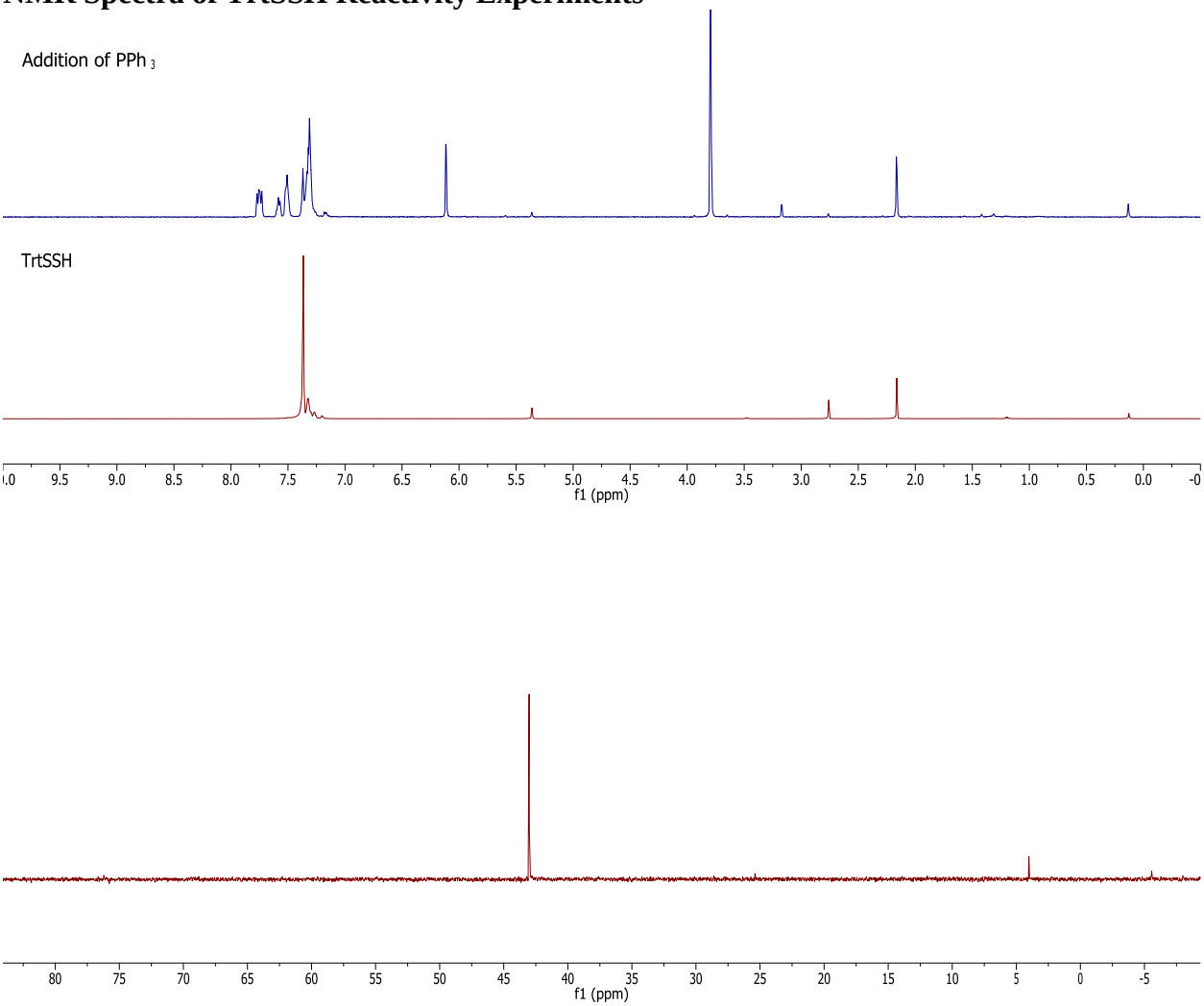


Figure S6: ^{1}H (500 MHz, CD_2Cl_2, top) and $^{31}P\{^{1}H\}$ (202 MHz, CD_2Cl_2, bottom) NMR spectra of TrtSSH upon addition of PPh_3. The ^{1}H NMR spectrum contains 1,3,5-trimethoxybenzene as an internal standard, which was used to quantify H_2S liberated. A minor acetone impurity is present at 2.1 ppm. Ph_3PO was added as an internal standard prior to acquisition of the $^{31}P\{^{1}H\}$ NMR spectrum. Ph_3PS is observed at 43 ppm in the $^{31}P\{^{1}H\}$ NMR spectrum.

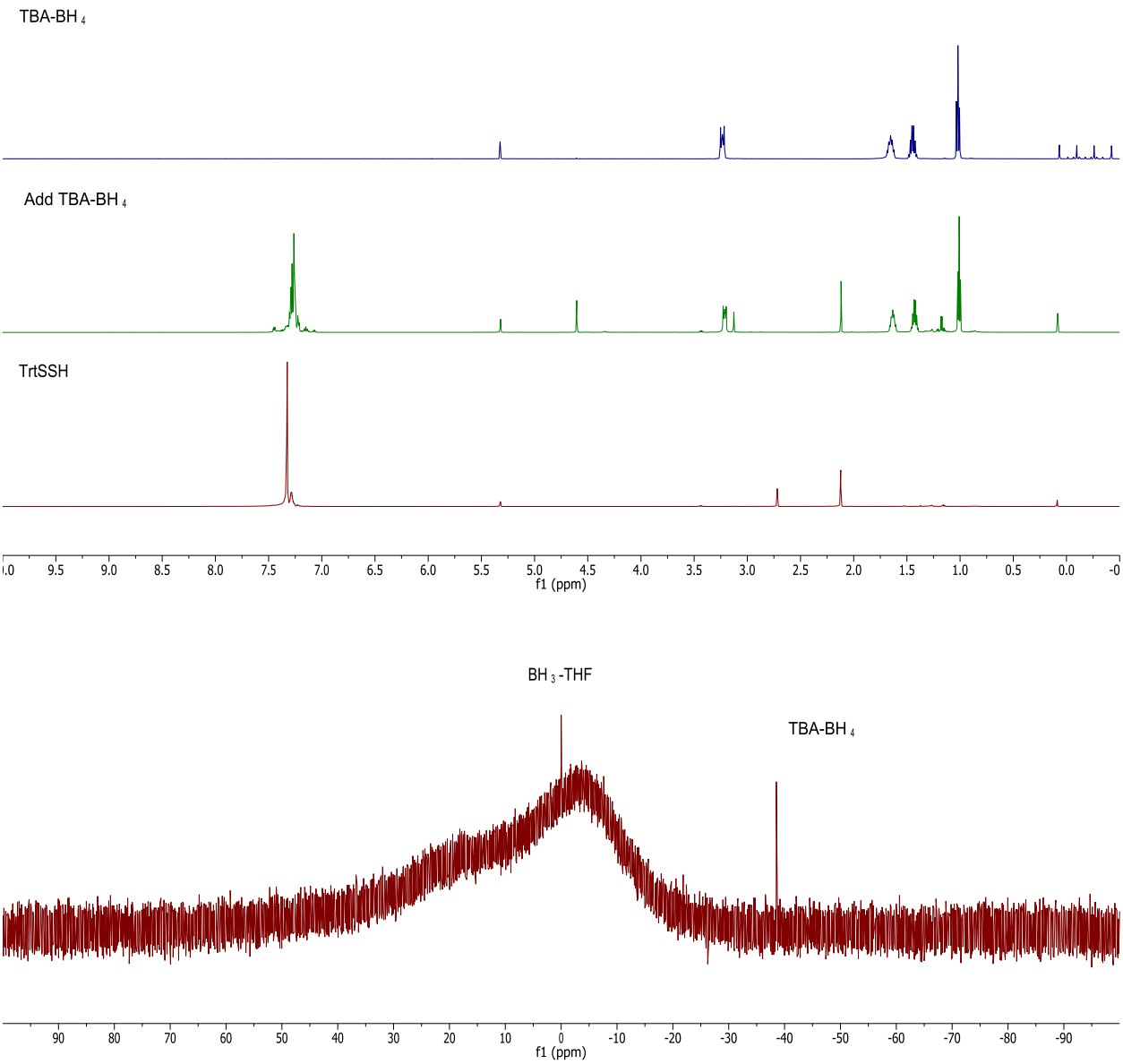


Figure S7: ^{1}H (500 MHz, CD_2Cl_2, top) and $^{11}B\{^{1}H\}$ (160 MHz, CD_2Cl_2, bottom) NMR spectra of TrtSSH upon addition of $[NBu_4^+][BH_4^-]$. The ^{1}H NMR spectrum contains a minor acetone impurity at 2.1 ppm. THF was added to the NMR sample prior to acquisition of the $^{11}B\{^{1}H\}$ NMR spectrum to complex any reduced BH_3 as BH_3THF. The ^{1}H NMR resonance at 4.53 ppm corresponding to liberated HS^- matched the resonance of HS^- generated from $[NBu_4][BH_4]$ reduction of S_8 in CD_2Cl_2 under anaerobic conditions.

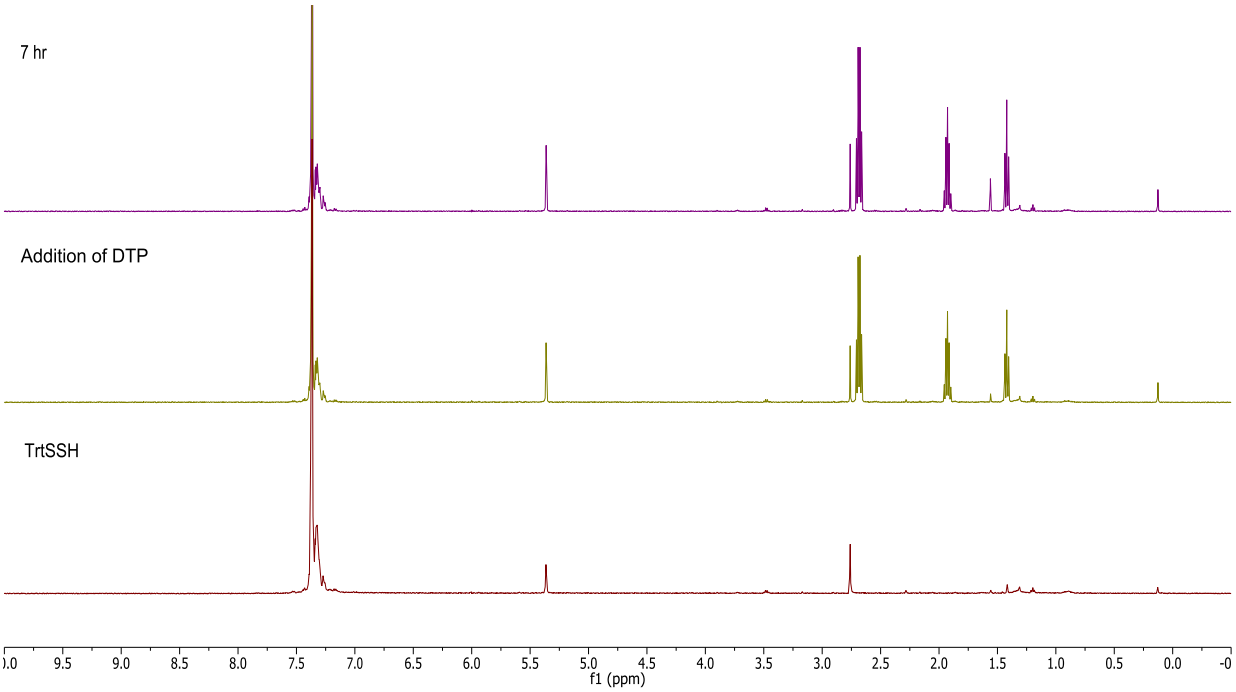


Figure S8: ^{1}H (500 MHz, CD_2Cl_2) NMR spectra of TrtSSH upon addition of DTP. No change to the TrtSSH ^{1}H NMR signal at 2.72 ppm was observed during the course of the reaction.

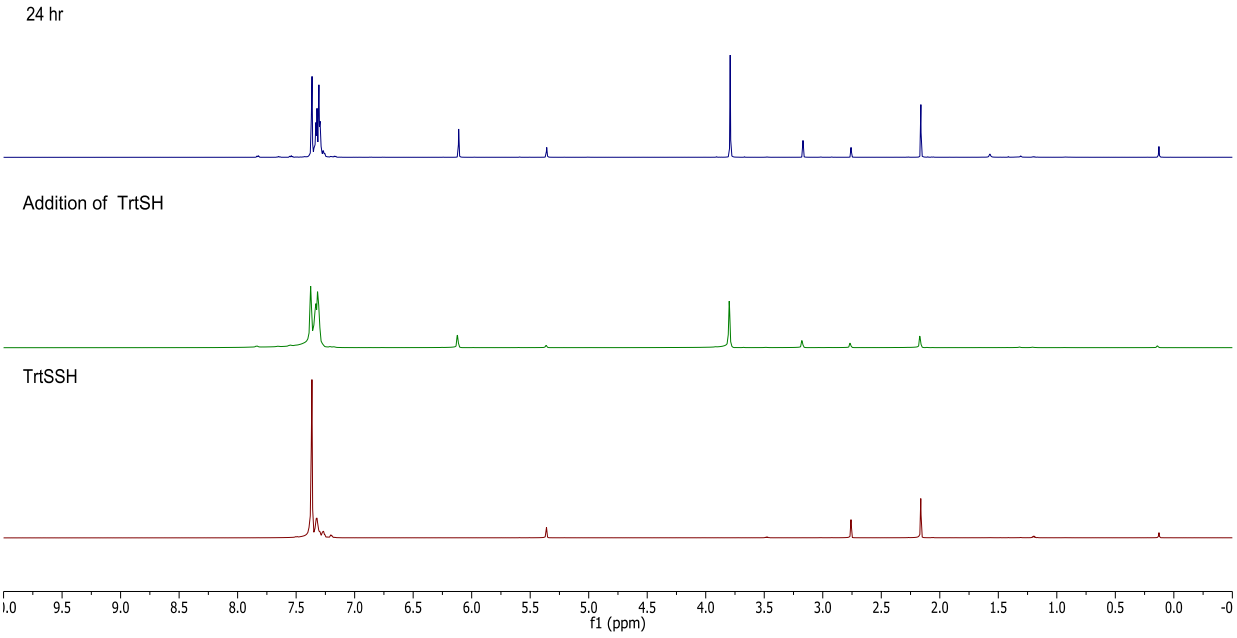


Figure S9: ^{1}H (500 MHz, CD_2Cl_2) NMR spectra of TrtSSH upon addition of TrtSH. The ^{1}H NMR spectra also show 1,3,5-trimethoxybenzene, which was used as an internal standard to quantify H_2S liberated. The ^{1}H NMR spectra also contain a minor acetone impurity at 2.1 ppm. No change to the TrtSSH ^{1}H NMR signal at 2.72 ppm was observed during the course of the reaction.

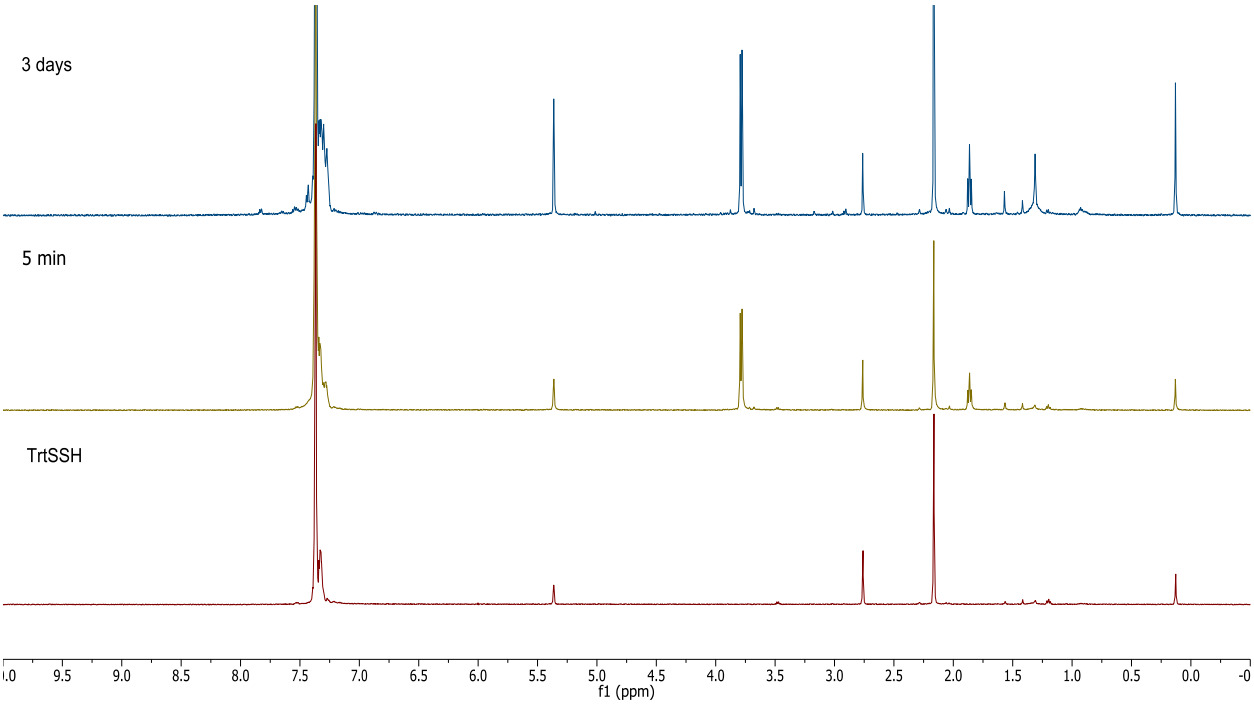


Figure S10: ^{1}H (500 MHz, CD_2Cl_2) NMR spectra of TrtSSH upon addition of BnSH. The ^{1}H NMR spectra contain a minor acetone impurity at 2.1 ppm. No change to the TrtSSH ^{1}H NMR signal at 2.72 ppm was observed during the course of the reaction.

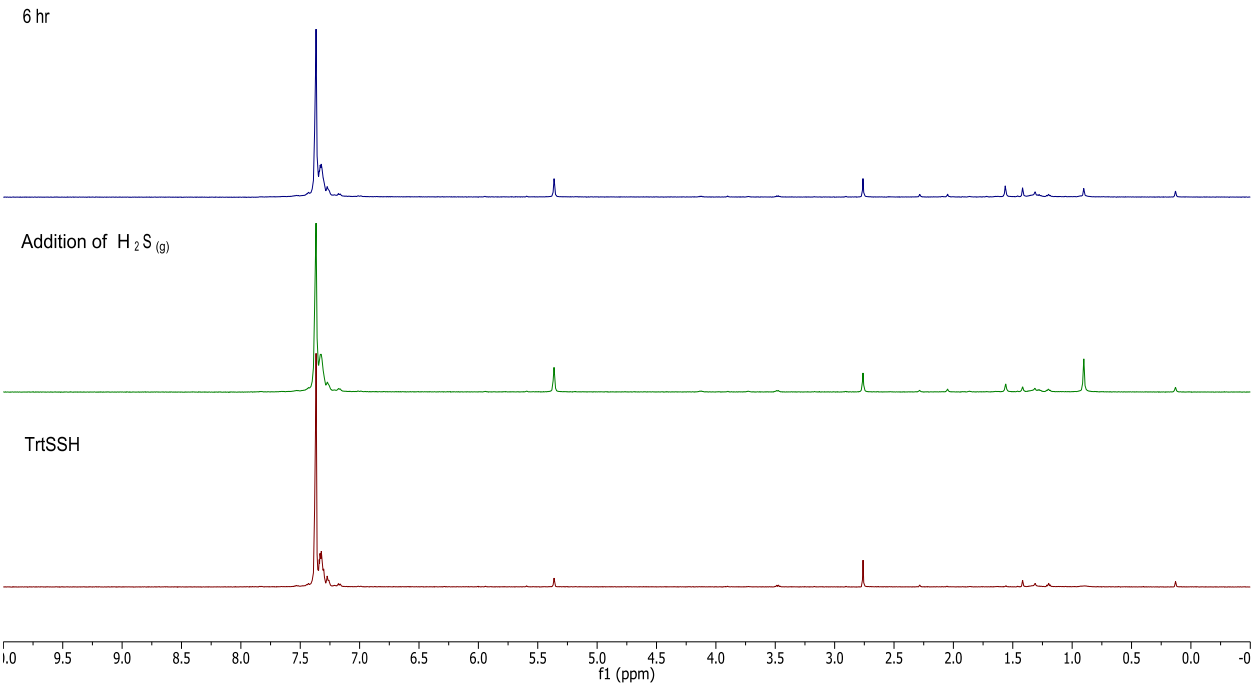


Figure S11: ^{1}H (500 MHz, CD_2Cl_2) NMR spectra of TrtSSH upon addition of $H_2S_{(g)}$. No change to the TrtSSH ^{1}H NMR signal at 2.72 ppm was observed during the course of the reaction.

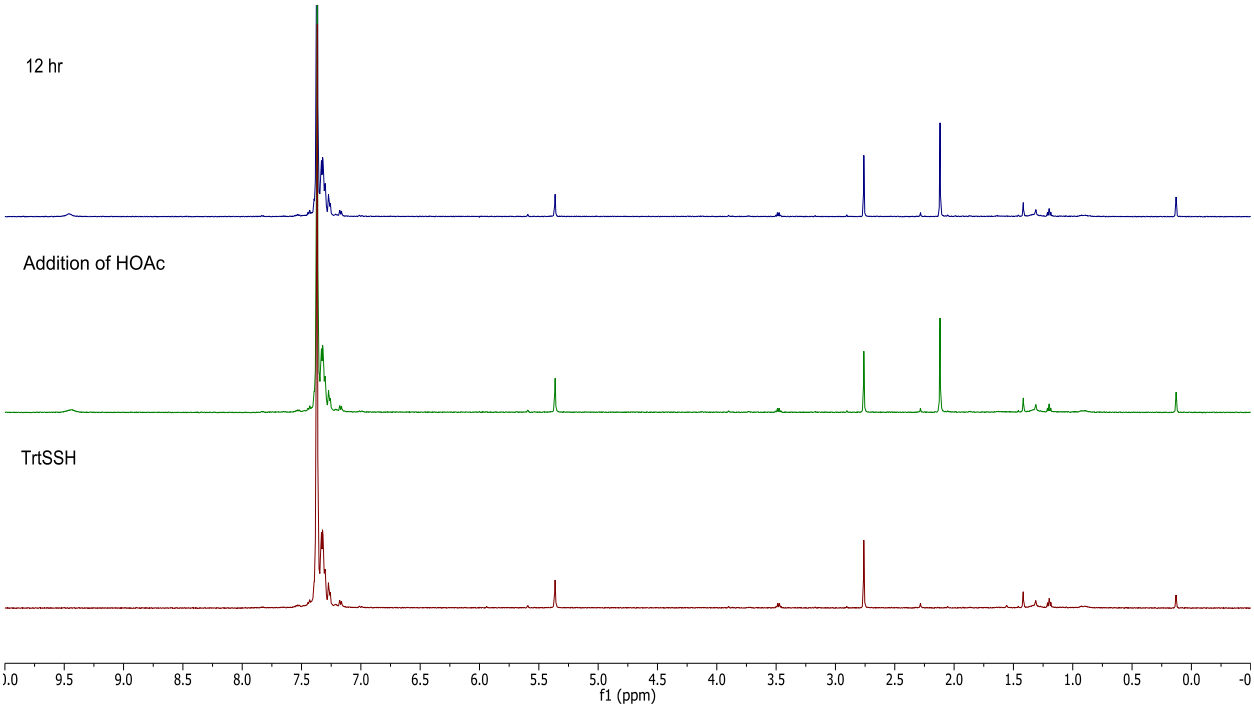


Figure S12: ^{1}H (500 MHz, CD_2Cl_2) spectra of TrtSSH upon addition of HOAc. No change to the TrtSSH ^{1}H NMR signal at 2.72 ppm was observed during the course of the reaction.

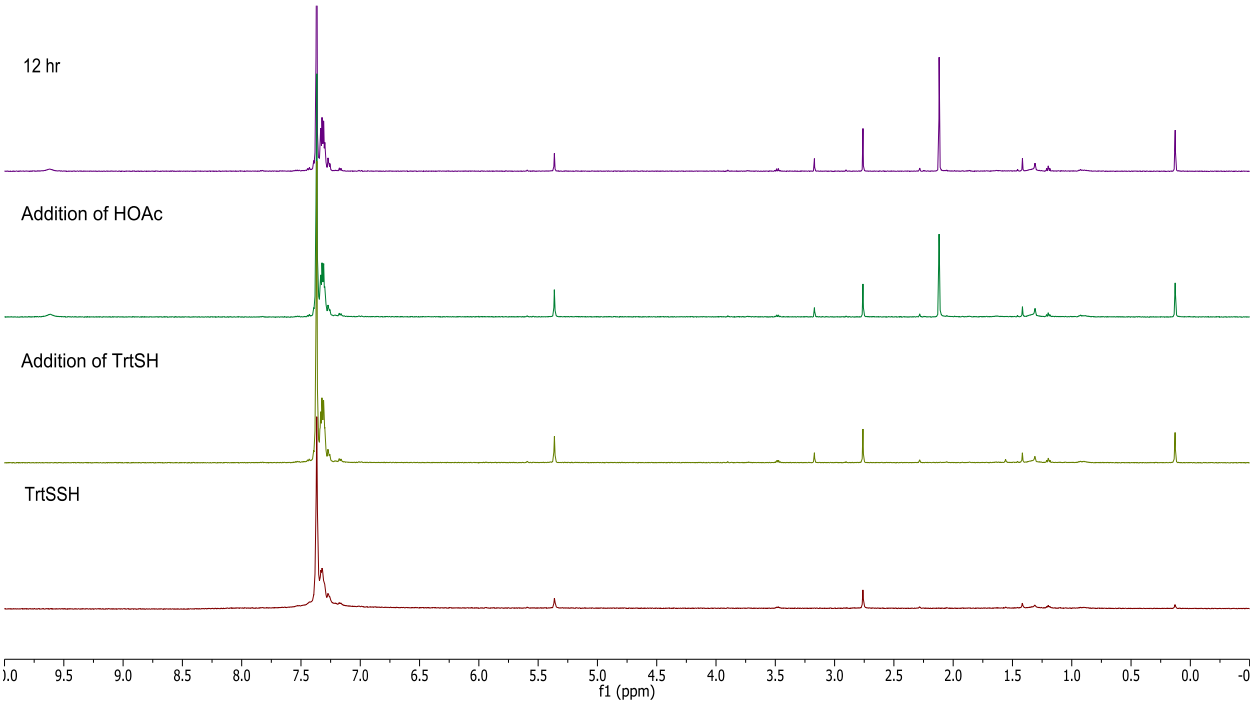


Figure S13: ^{1}H (500 MHz, CD_2Cl_2) NMR spectra of TrtSSH upon addition of HOAc and TrtSH. No change to the TrtSSH ^{1}H NMR signal at 2.72 ppm was observed during the course of the reaction.

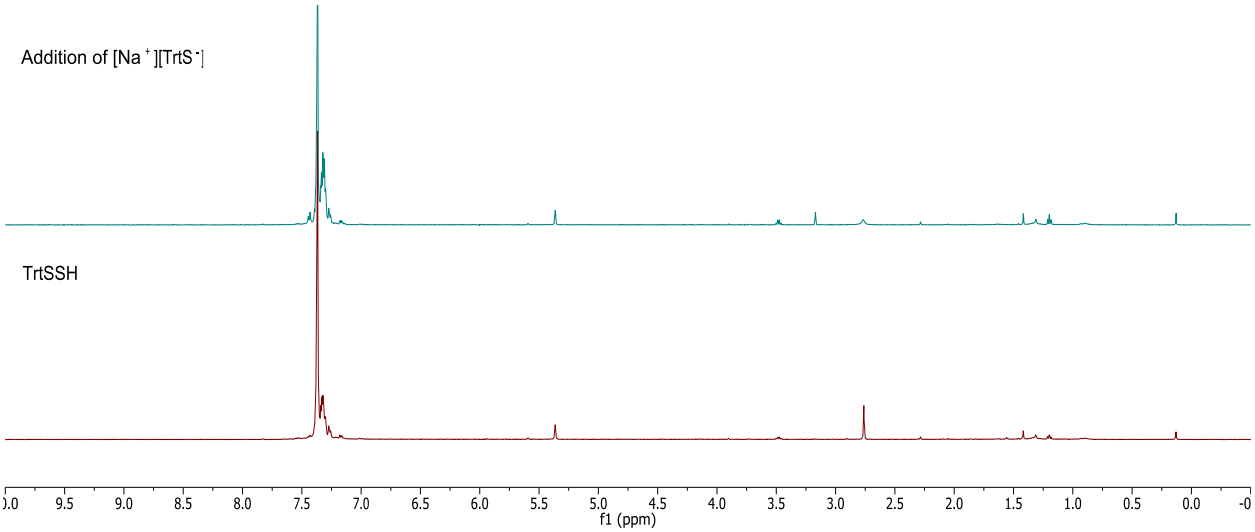


Figure S14: ^{1}H (500 MHz, CD_2Cl_2) NMR spectra of TrtSSH upon addition of $[Na^+][TrtS^-]$. A new peak at 3.1 ppm, corresponding to TrtSH, is observed during the course of the reaction.

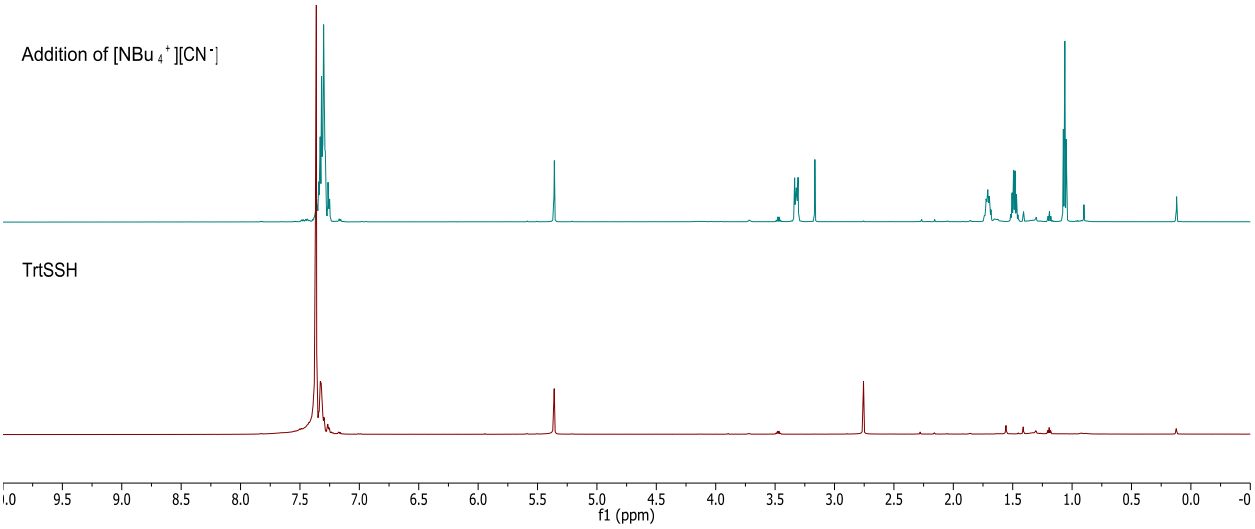


Figure S15: ^{1}H (500 MHz, CD_2Cl_2) NMR spectra of TrtSSH upon addition of of $[NBu_4^+][CN^-]$. A new peak at 3.1 ppm, corresponding to TrtSH, is observed during the course of the reaction.

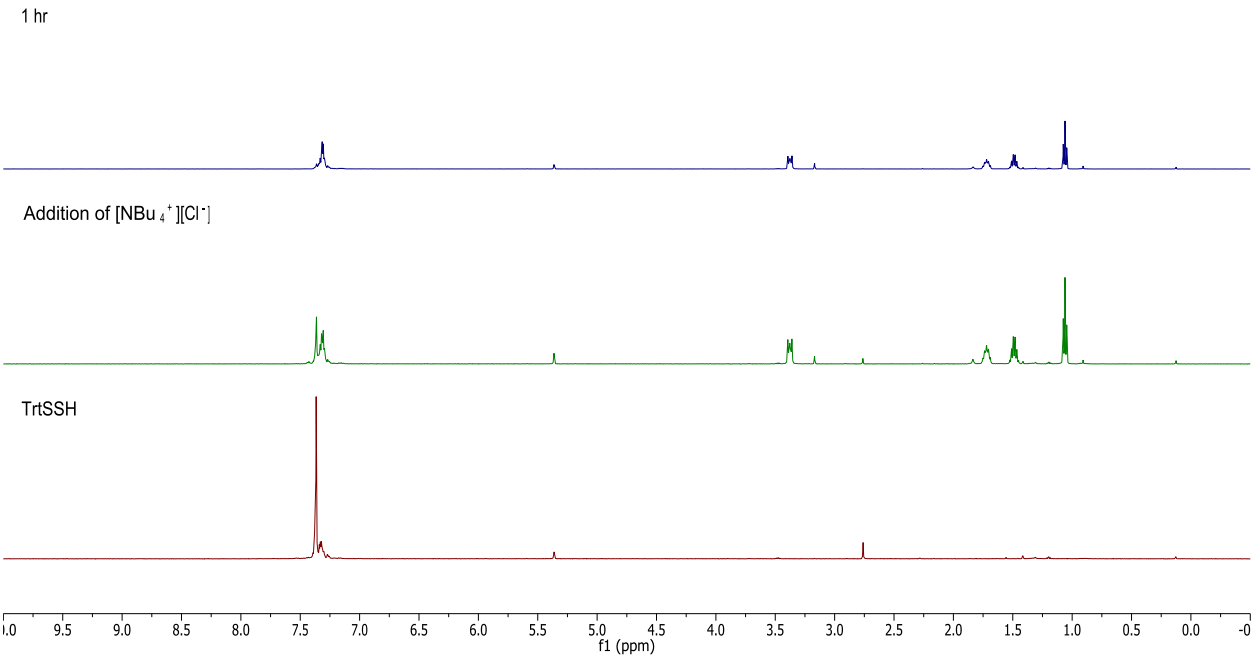


Figure S16: ^{1}H (500 MHz, CD_2Cl_2) NMR spectra of TrtSSH upon addition of of $[NBu_4^+][Cl^-]$. A new peak at 3.1 ppm, corresponding to TrtSH, is observed during the course of the reaction.

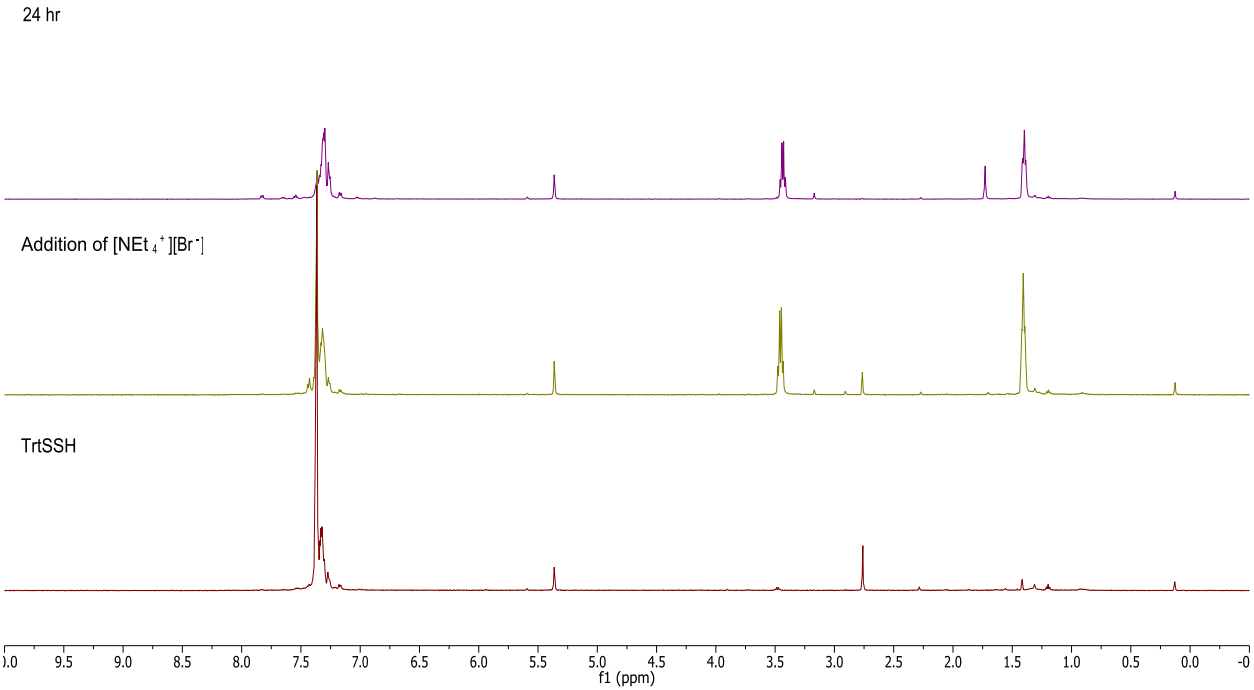


Figure S17: ^{1}H (500 MHz, CD_2Cl_2) NMR spectra of TrtSSH upon addition of of $[NEt_4^+][Br^-]$. A new peak at 3.1 ppm, corresponding to TrtSH, is observed during the course of the reaction.

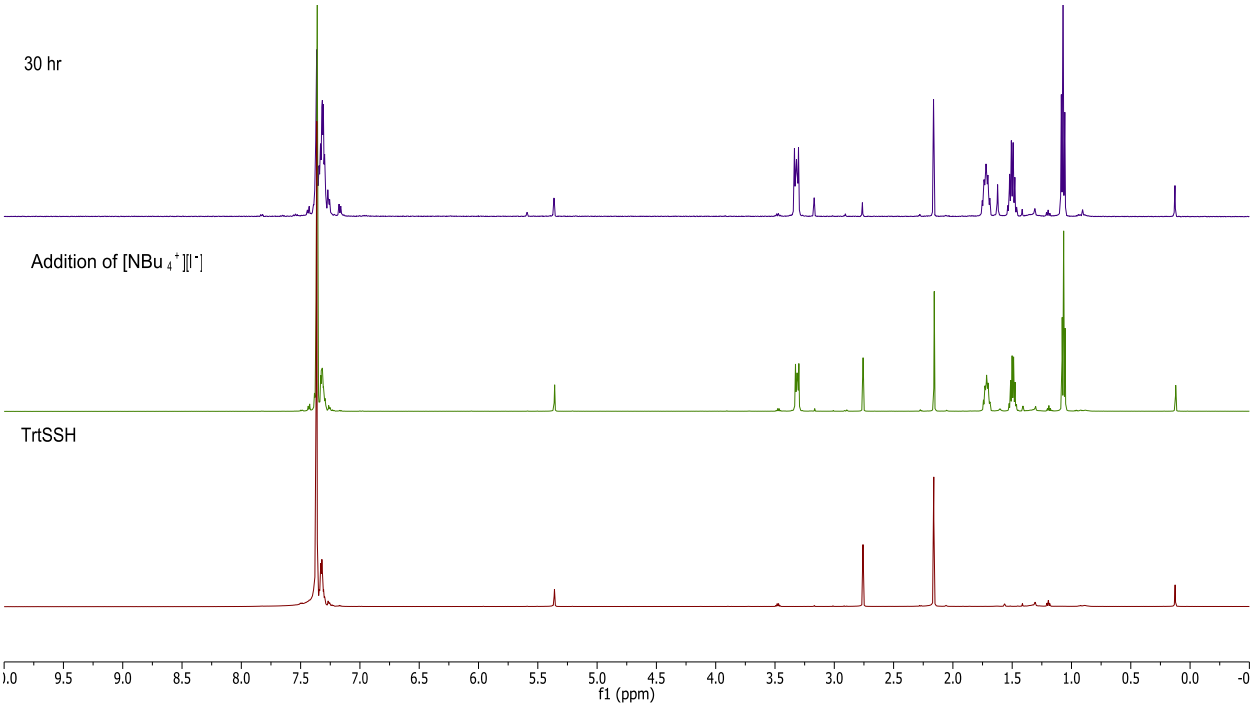


Figure S18: ^{1}H (500 MHz, CD_2Cl_2) NMR spectra of TrtSSH upon addition of of $[NBu_4^+][I^-]$. The ^{1}H NMR spectra contain a minor acetone impurity at 2.1 ppm. A new peak at 3.1 ppm, corresponding to TrtSH, is observed during the course of the reaction.

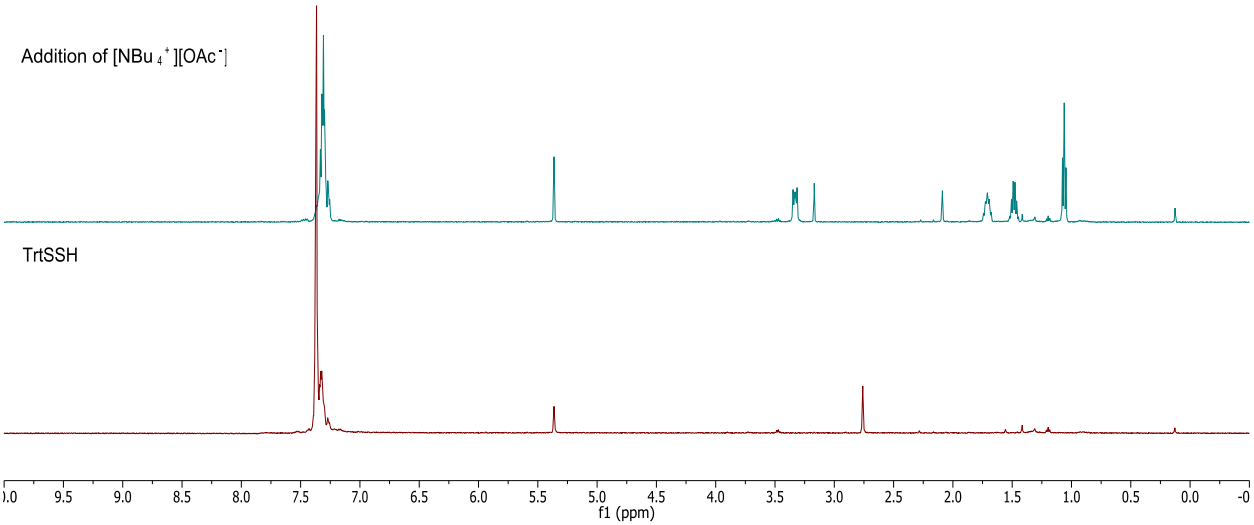


Figure S19: ^{1}H (500 MHz, CD_2Cl_2) spectra of TrtSSH upon addition of of $[NBu_4^+][OAc^-]$. A new peak at 3.1 ppm, corresponding to TrtSH, is observed during the course of the reaction.

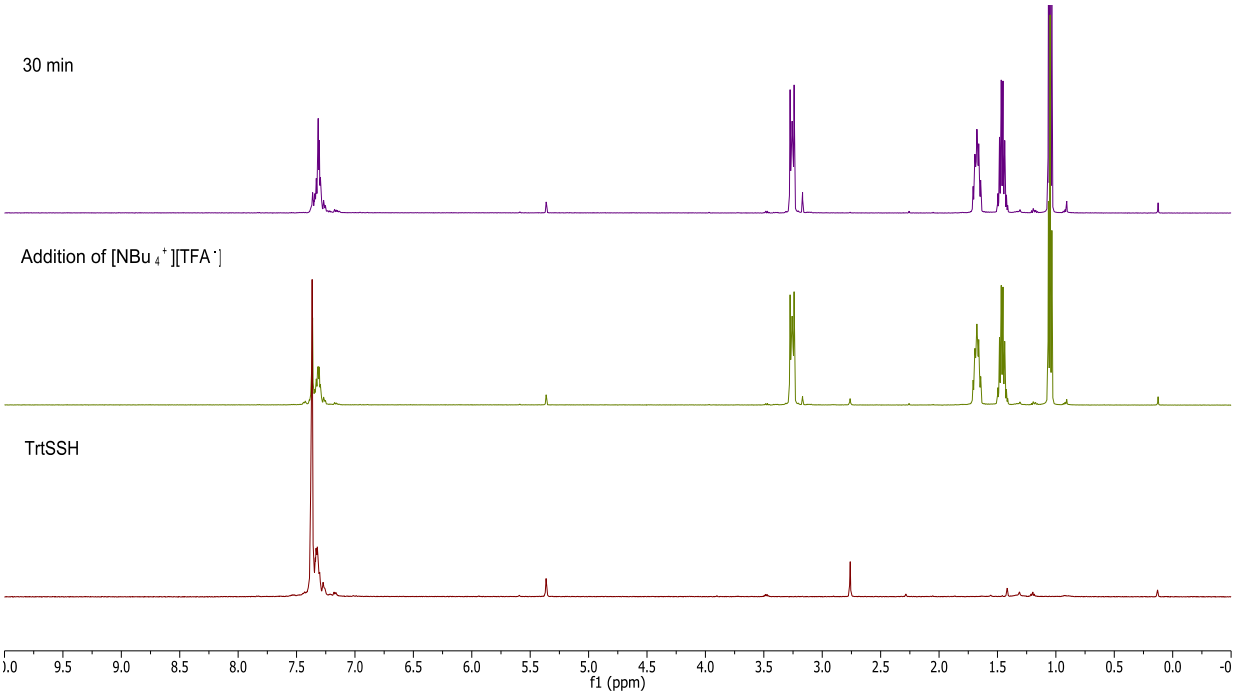


Figure S20: ^{1}H (500 MHz, CD_2Cl_2) NMR spectra of TrtSSH upon addition of [NBu_4^+][TFA^-]. A new peak at 3.1 ppm, corresponding to TrtSH, is observed during the course of the reaction.

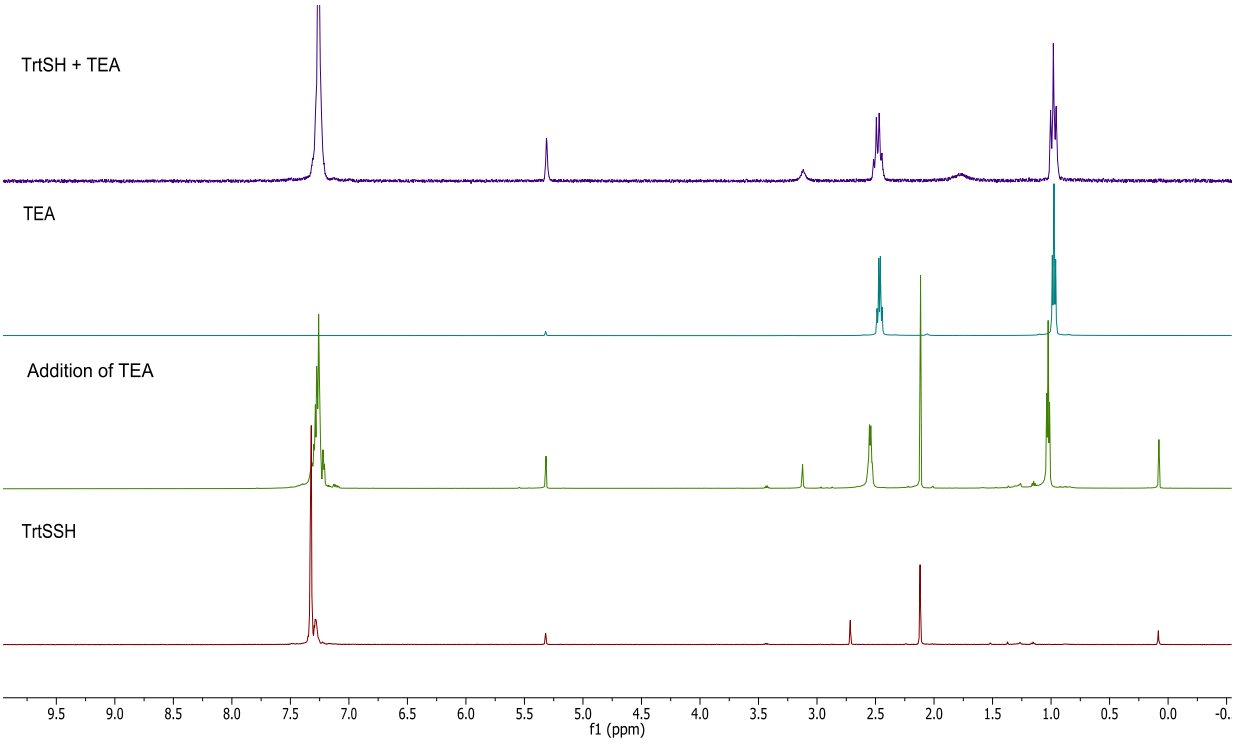


Figure S21: ^{1}H (500 MHz, CD_2Cl_2) NMR spectra of TrtSSH upon addition of NEt_3. The ^{1}H NMR spectra contain a minor acetone impurity at 2.1 ppm. A new peak at 3.1 ppm, corresponding to TrtSH, is observed during the course of the reaction.

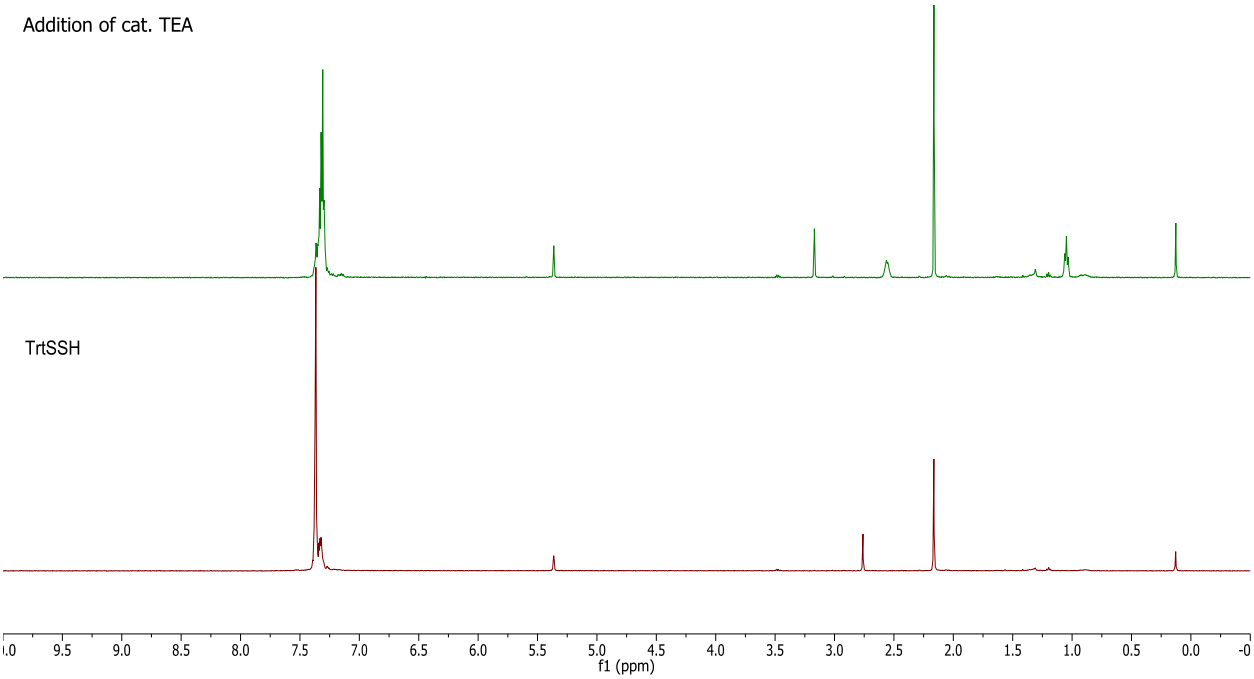


Figure S22: ^{1}H (500 MHz, CD_2Cl_2) NMR spectra of TrtSSH upon addition of 0.1 equiv. of NEt_3. The ^{1}H NMR spectra contains a minor acetone impurity at 2.1 ppm. A new peak at 3.1 ppm, corresponding to TrtSH, is observed during the course of the reaction.

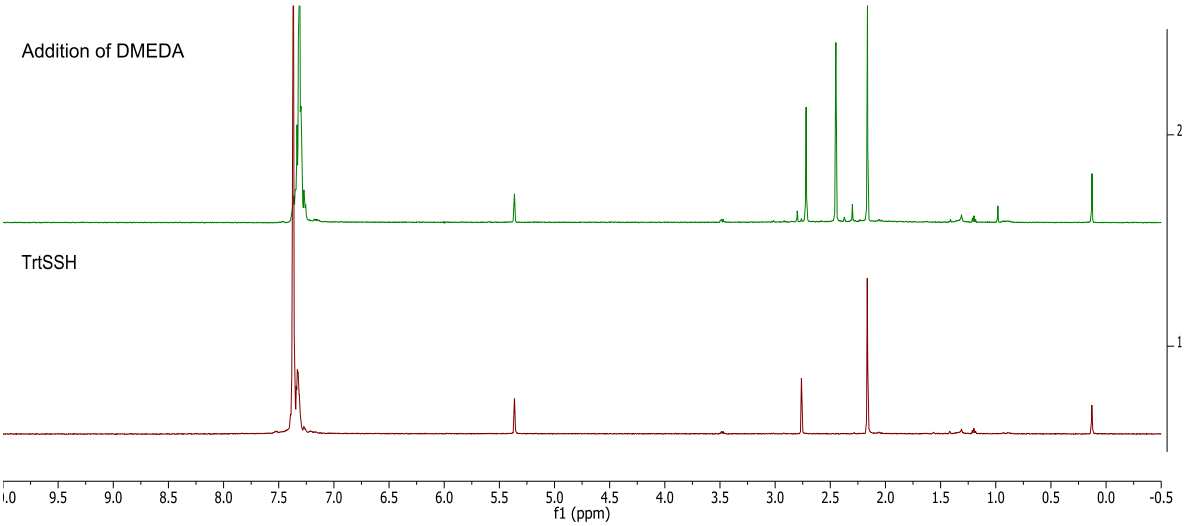


Figure S23: ^{1}H (500 MHz, CD_2Cl_2) NMR spectra of TrtSSH upon addition of DMEDA. The ^{1}H NMR spectra contain a minor acetone impurity at 2.1 ppm. The TrtSSH proton resonance disappears during the course of the reaction.

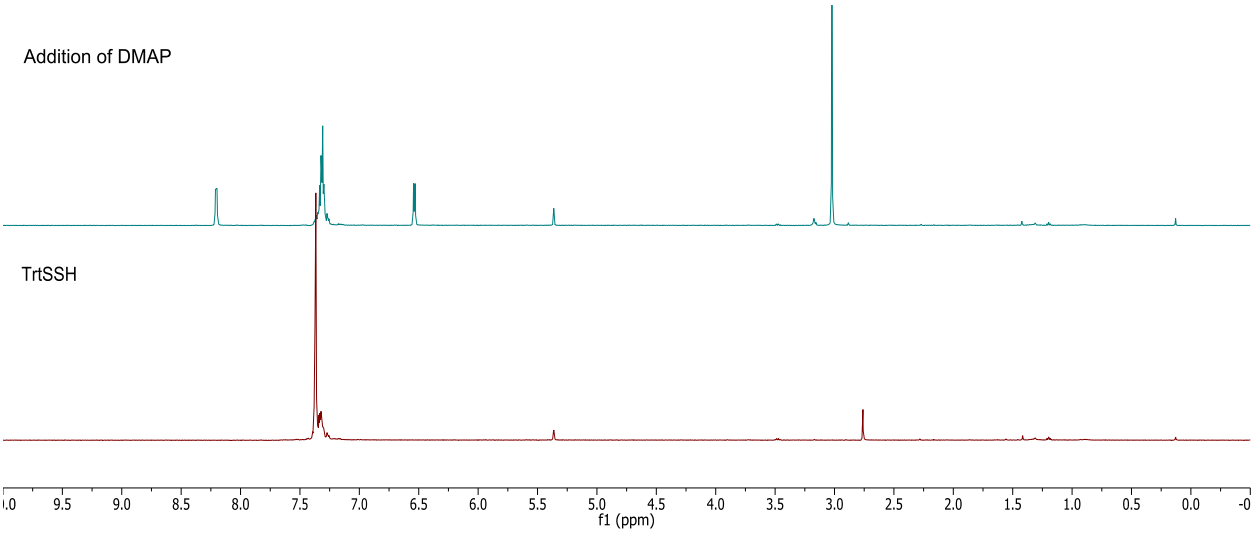


Figure S24: ^{1}H (500 MHz, CD_2Cl_2) NMR spectra of TrtSSH upon addition of DMAP. A new peak at 3.1 ppm, corresponding to TrtSH, is observed during the course of the reaction.

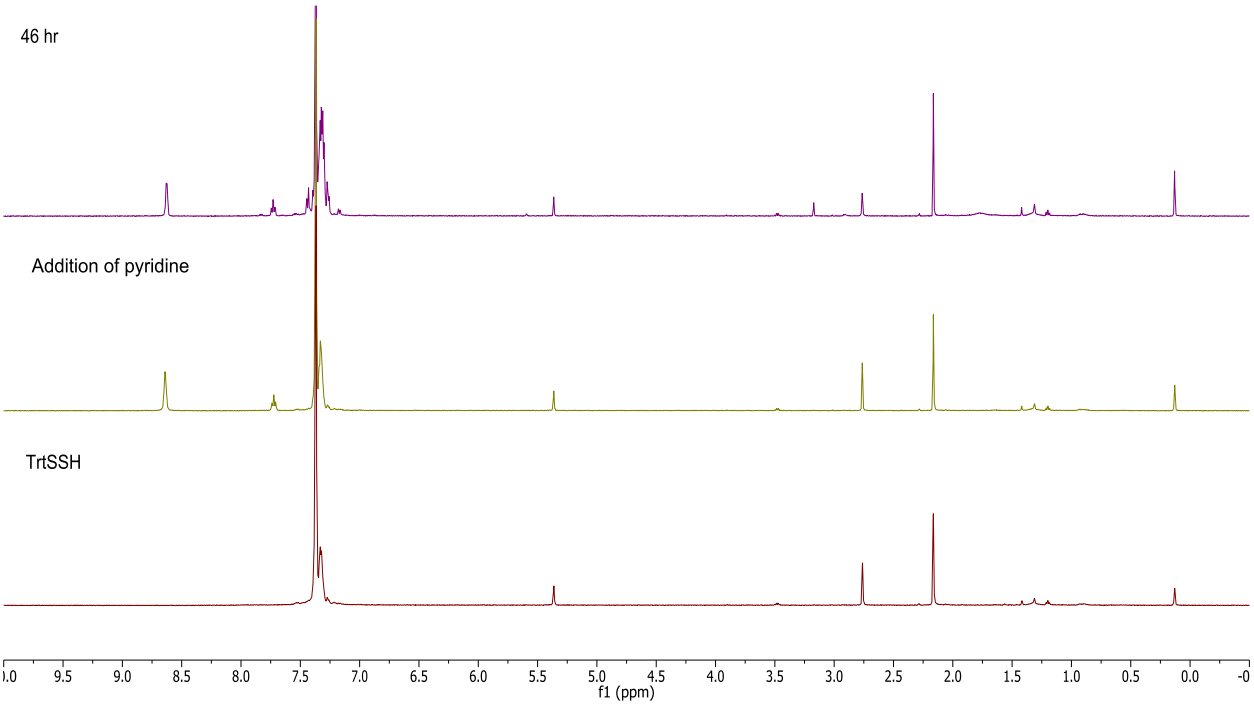


Figure S25: ^{1}H (500 MHz, CD_2Cl_2) NMR spectra of TrtSSH upon addition of pyridine. A new peak at 3.1 ppm, corresponding to TrtSH, is observed during the course of the reaction.

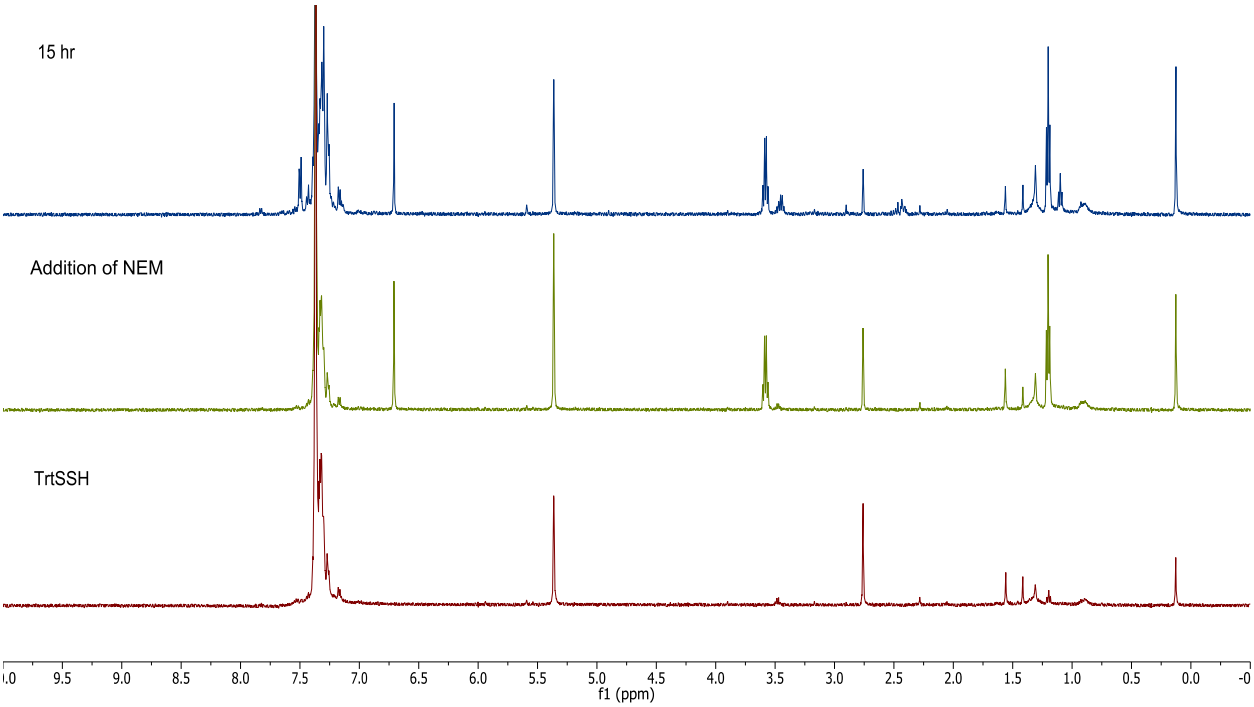


Figure S26: ^{1}H (500 MHz, CD_2Cl_2) NMR spectra of TrtSSH upon addition of *N*-ethyl-maleimide (NEM). The SSH peak at 2.7 ppm and the NEM alkene peak at 6.7 ppm decrease while muliplets at 3.1 ppm and 2.45 ppm begin to appear. The rate of reaction is slow because of proton transfer limitations in organic solvent.

UV-Vis Spectroscopic Data

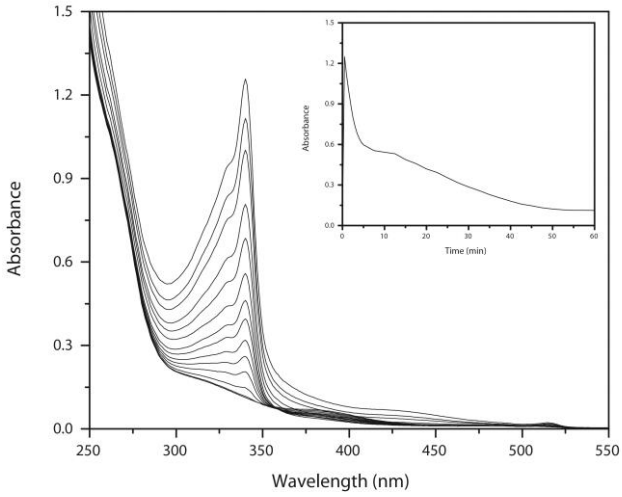


Figure S27: Reaction of TrtSSH with $[NBu_4^+][CN^-]$ monitored by UV-Vis spectroscopy. Condition: 1 mM TrtSSH, 1 mM $[NBu_4^+][CN^-]$, 25 °C in DCM under anaerobic conditions.

X-Ray crystallographic data

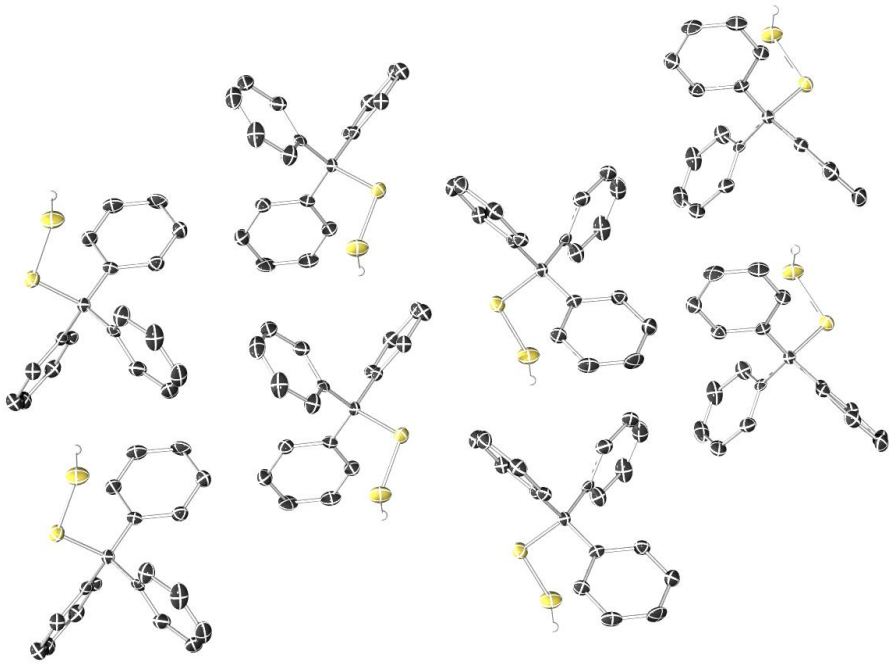


Figure S28: Packing diagram of the x-ray structure of TrtSSH.

Table S1. Crystal data and structure refinement for TrtSSH.

	TrtSSH
Empirical formula	$C_{19}H_{16}S_2$
Formula weight	308.44
Temperature (K)	150(2)
Wavelength (Å)	0.71073
Crystal system, space group	Orthorhombic, $P2_12_12_1$
Unit cell dimensions	a = 7.5037(16) Å; α= 90°
	b = 7.5470(16) Å; β= 90°
	c = 27.3474(6) Å; γ = 90°
Volume ($Å^3$)	1555.9(6)
Z	4
Calculated density (Mg/m^3)	1.317
Absorption coefficient (mm^{-1})	0.332
F(000)	648
Crystal size (mm)	0.19 x 0.13 x 0.04
Theta range for data collection	2.80 to 26.36°.
Index ranges	$-8 \leq h \leq 9$, $-9 \leq k \leq 9$, $-26 \leq l \leq 34$
Reflections collected	8185
Independent reflections	3154 [R_{int} = 0.0359]
Completeness to θ = 25.00° (%)	99.6
Absorption correction	Semi-empirical from equivalents
Max. and min. transmission	0.9868 and 0.9396
Refinement method	Full-matrix least-squares on F^2
Data / restraints / parameters	3154 / 56 / 259
Goodness-of-fit on F^2	1.025
Final R indices [I>2σ(I)]	R1 = 0.0446, wR2 = 0.1138
R indices (all data)	R1 = 0.0521, wR2 = 0.1179
Absolute structure parameter	0.14(10)
Largest diff. peak and hole ($e/Å^{-3}$)	0.330 and -0.258

References

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