UNIVERSITY OF CALIFORNIA,
IRVINE

Tandem Insertion/Rearrangements by Insertion of Rhodium Carbenes into Sulfur Bonds

and

Metal-Catalyzed Insertion into α–Diazocarbonyl Compounds

DISSERTATION

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DEDICATION

To my partner Kanoko

"In case signals cannot be seen, or perfectly understood,
no captain can do very wrong
if he places his ship alongside that of an enemy."

Lord Horatio Nelson
1805

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ABSTRACT OF THE DISSERTATION

Tandem Insertion/Sigmatropic Rearrangements by Insertion of Rhodium Carbenes into Sulfur Bonds

and

Metal-Catalyzed Halogen Insertion into α-Diazocarbonyl Compounds

By

Jason R. Combs

Doctor of Philosophy in Chemistry

University of California, Irvine, 2024

Professor David L. Van Vranken, Chair

This dissertation will focus on four main areas: The first aspect to be discussed will be reaction of allyl 2-diazo-2-phenylacetates with trimethylsilyl thioethers in the presence of rhodium(II) catalysts. These conditions generate α-allyl-α-thio silyl esters which undergo a spontaneous Ireland–Claisen rearrangement. Competing side-reactions, substrate scope and application will be explored.

The second aspect to be discussed will be metal-catalyzed halogen insertion into α-diazocarbonyl compounds. Attempts to optimize the reaction and efforts to obtain asymmetric induction will be explored.

The third aspect to be discussed will be rhodium(II)-catalyzed carbene transfer from trimethylsilyldiazomethane to arylmethyl thioethers, generating sulfonium ylides that undergo [2,3]-sigmatropic rearrangement, punching quaternary centers into aromatic rings. Substrate scope and competing side-reactions will be discussed.

The final aspect to be discussed will be rhodium(II)-catalyzed carbene transfer from trimethylsilyldiazomethane to allylic thioesters, generating *S*-acyl allylsulfonium ylides that undergo [2,3]-sigmatropic rearrangement. This is the first report of an *S*-acyl Doyle-Kirmse reaction.

Chapter 1

Tandem Insertion/[3,3]-Sigmatropic Rearrangement Involving the Formation of Silyl Ketene Acetals by Insertion of Rhodium Carbenes into S–Si Bonds

Introduction

Rhodium and copper carbenes derived from diazo precursors are powerful electrophiles that react with all categories of nucleophiles: lone pairs, pi bonds, and sigma bonds (Figure 1-1).[1a] Reaction of pi bonds leads to cyclopropanation of alkenes, alkynes and arene rings. Reaction of sigma bonds leads to C–H and Si–H insertions. Reaction of heteroatom lone pairs generates ylide intermediates that are not readily isolable but can react further in tandem processes such as sigmatropic rearrangements.[1b] Carbonyl ylides derived from diazo compounds can undergo 1,3-cycloaddition reactions which lead to oxygen heterocycles. 5-and 6-membered rings are typically favored.[1c-f]

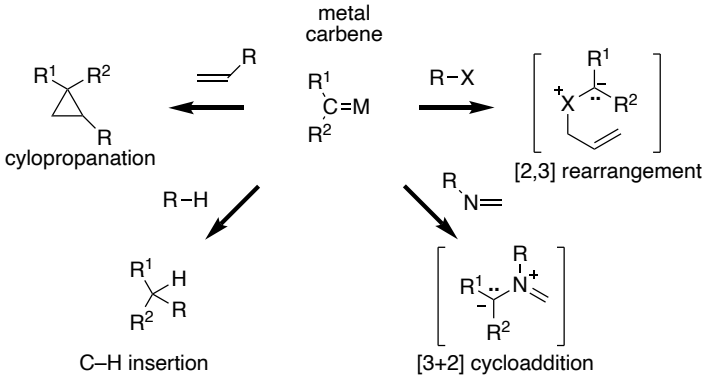


Figure 1-1. Common Reactions of Rhodium and Copper Carbenes

The overarching goal of my thesis was to develop new tandem reactions involving ylide intermediates generated from diazo compounds, as these processes are used extensively in the synthesis of natural products. Tandem reactions of ylides generated from diazo compounds are capable of constructing complex molecular scaffolds with stereochemical control. For example,

the construction of tigliane and daphnane structures have been generated by the formation of an oxonium ylide followed by a 1,2-Stevens rearrangement.[2a] (+/-)-Preussin has been synthesized by an ammonium ylide/Stevens rearrangement sequence.[2b] The thiolane subunit of *nuphar* sesquiterpene thioalkaloids has been synthesized by a Rh(II)-catalyzed sulfur ylide formation and Stevens rearrangement.[2c] [2,3]-sigmatropic rearrangements of ylides have been used extensively in natural product synthesis, including the synthesis of hyperolactone C *via* oxonium ylide/[2,3]-sigmatropic rearrangement.[2d] The tricyclic core of neoliacinic acid was assembled by a Rh(II)-catalyzed C–H insertion of an α-diazoketone followed by an oxonium ylide/[2,3]-sigmatropic rearrangement process of an α-diazoester.[2e] Marine diterpene (–)-cladiella-6, 11-dien-3-ol has been synthesized by an Rh(II)-catalyzed stereoselective [2,3]-sigmatropic rearrangement.[2f] The first reported synthesis of sclerophytin F relied on a Cu(II)-catalyzed ylide rearrangement.[2g]

When diazo compounds react with transition metal catalysts in the presence of heteroatom nucleophiles, ylide intermediates are generated[3] which can undergo reactions typical of the functional group. Diazo compounds react with sulfur compounds to generate allyl sulfonium intermediates that undergo [2,3]-sigmatropic rearrangement, forming new carbon–carbon bonds.[5] Asymmetric variants of the reaction have been reported.[6] Metal carbenes derived from α-diazoesters react with allyl thioethers to generate allyl sulfonium intermediates that undergo [2,3]-sigmatropic rearrangement[4] (Figure 1-2), but the latent enolate character of these intermediates is not used in the reaction. Likewise, metal carbenes derived from α-diazoesters react with carbonyl lone-pairs to generate 1,3-dipoles that undergo [3+2] cycloaddition, but the enolate carbonyl is not part of the 5-membered pericyclic transition state.

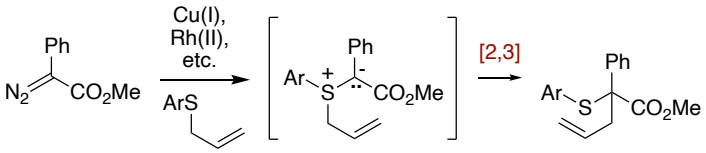


Figure 1-2. [2,3]-Sigmatropic rearrangement of allyl sulfonium intermediates

Enolates generated by insertion of metal carbene intermediates into X–H bonds have been shown to undergo 1,2-addition[7] (X = NR, Figures 1-3 and 1-5; X = O, Figures 1-4 and 1-6) or 1,4-addition[8] (Figures 1-7 and 1-8) with aldehydes, imines, and Michael acceptors, as well as with α-ketoesters and α-ketoamides.[9] Protonation of enolate intermediates generated from rhodium-catalyzed asymmetric X–H insertions have also been reported with α-diazoesters.[10-12] N–H insertion reactions between carbamates and arlydiazoacetates in the presence of a chiral protic acid are also proposed to go through a rhodium-bound enolate because the nature of the chiral acid impacts the level of asymmetric induction.[13]

In seminal work, Doyle and coworkers demonstrated the first example of an enolate, derived from X–H addition to a metal carbene, adding 1,2 to a pi-acceptor (Figure 1-3).[7a] Much of the subsequent related work in this area was published by Wenhao Hu and coworkers. Doyle's three-component reaction starts with selective addition of the aniline to the rhodium carbene to generate an α-ammonioenolate, which forms an intermolecular hydrogen bond to an imine, thus activating it for attack by the anionic enolate to stereoselectively generate an α, β-diaminoester in up to 96:4 dr. The main side reaction in this, and related processes, is tautomerization of the ylide/enolate. In later work,[7c] Hu and coworkers published an enantioselective variant of the three-component reaction utilizing a carbamate in place of the aniline. The reaction was catalyzed by chiral phosphoric acid to afford *anti* or *syn* diastereomers in up to 97:3 dr and up to 96% ee.

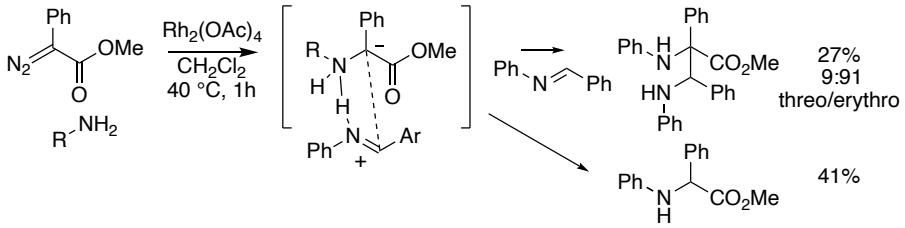


Figure 1-3. 1,2-Addition of an enolate generated from Rh(II) and a α-diazocarbonyl

In 2007, Hu and coworkers reported a similar 3-component reaction of an α-phenyl-α-diazoester with alcohols and salicylaldimines catalyzed by dirhodium tetraacetate (Figure 1-4).[7b] The reaction starts with preferential addition of the alcohol, rather than the imine, to the metal carbene. The internal hydrogen bond between the *ortho*-hydroxy group and imine likely prevents the addition of the imine to the carbene and generates an iminium electrophile. The following year Hu and coworkers published an asymmetric variant with benzyl alcohols, and not limited to salicylaldimines, employing a chiral phosphoric acid.[7d] The α-benzyloxy-β-aminoesters were obtained in good yields as a single diastereomer in up to 93% ee.

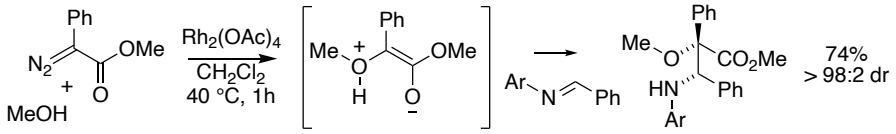


Figure 1-4. 3-Component reaction of an α-phenyl-α-diazoester with alcohols and salicylaldimines catalyzed by dirhodium tetraacetate

Hu and coworkers were able to generate β-hydroxy-α-amino acids via a three-component coupling of aryldiazoacetate, arylamine and arylaldehyde catalyzed by $Rh_2(OAc)_4$[7f] (Figure 1-5). The major competing pathway was N–H insertion followed by protonation of the enolate rather

than formation of the desired Aldol product. Hu solved this problem by adding an electron withdrawing nitro group to the arylaldehyde to increase electrophilicity, resulting in 74% yield of the desired product. The yield was then increased to 91% by adding three equivalents aldehyde to the reaction. In a related transformation, ammonium ylide/enolate intermediates were shown to add to isatins in good yields in up to 95:5 dr, favoring the erythro diastereomer.[7i]

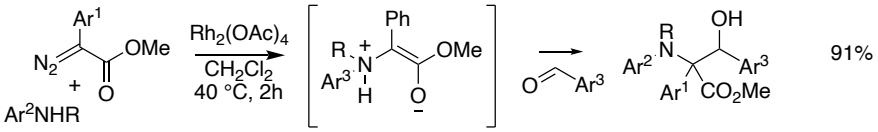


Figure 1-5. Tandem N–H insertion/Aldol reaction

Oxonium ylide/enolates generated from the reaction of diazo compounds with rhodium (II) also add to benzaldehydes to generate aldol products (Figure 1-6) with modest diastereoselectivity.[7e] $CuPF_6(MeCN)_4$ is also an effective catalyst for the reaction.[7j] The same transformation can also be accomplished using a titanium (IV) alkoxide in place of the alcohol.[7g] The titanium variant was shown to work with aliphatic aldehydes with dr up to 95:5 erythro/threo.

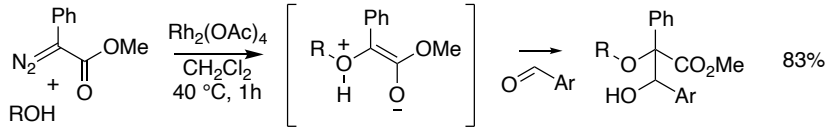


Figure 1-6. Oxonium ylide/enolates generated from the reaction of diazo compounds with rhodium (II) also add to benzaldehydes to generate aldol products

In a related transformation, oxonium ylide/enolate intermediates derived from a much larger range of diazo compounds, including ethyl diazoacetate, were shown to add to isatins in excellent yields in up to 99:1 dr, favoring the erythro diastereomer.[7h]

Enones can also be used as acceptors for the onium/enolate intermediates derived from diazo compounds, but the adducts cyclize to form 5-membered rings. Hu and coworkers synthesized 2,3-dihydropyrrole derivatives via a three-component coupling of aryldiazoacetate, anilines and unsaturated ketoesters catalyzed by $Rh_2(OAc)$ (Figure 1-7).[8b] The major competing pathway to this tandem Michael addition/cyclization reaction was again N-H insertion followed by protonation of the enolate. Yields up to 84% were achieved by adding a nitro group to the Michael acceptor.

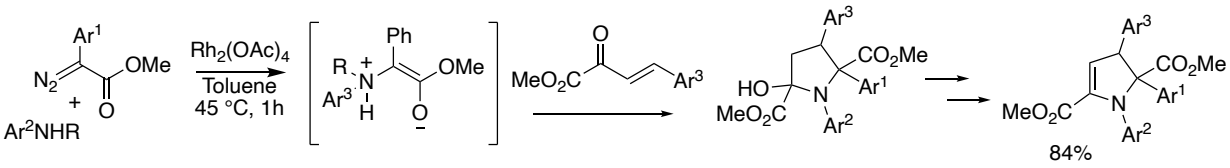


Figure 1-7. Tandem N–H insertion/Cyclization

Hu and coworkers have shown that allylic alcohols can add to rhodium carbene intermediates to generate oxonium ylides that undergo an intramolecular Michael addition of an enolate (Figure 1-8).[8a]

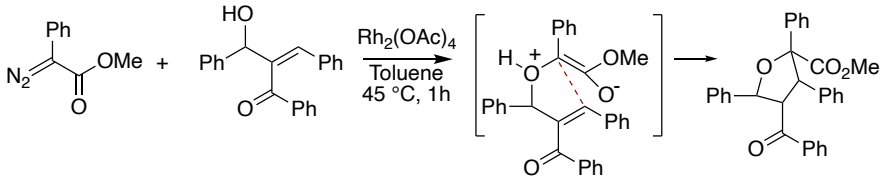


Figure 1-8. Michael reaction of an enolate generated from Rh(II) and an α-diazocarbonyl

Aldehydes can act as both nucleophiles and electrophiles toward rhodium carbenes. Muthasamy has shown that 3-diazoisatins undergo Darzens reactions with aldehydes (Figure 1-9). Addition of the carbonyl lone pair generates an oxacarbenium ion intermediate that cyclizes to form an epoxide.[7k] In a related transformation, Murarka and coworkers utilized the same intermediate in the presence of nitrostyrenes to afford spiro(tetrahydro-furanyl)oxindole

derivatives via a 1,3-dipolar cycloaddition of the carbonyl ylide,[7l] a process earlier popularized by Padwa and comprehensively reviewed.[7m,n]

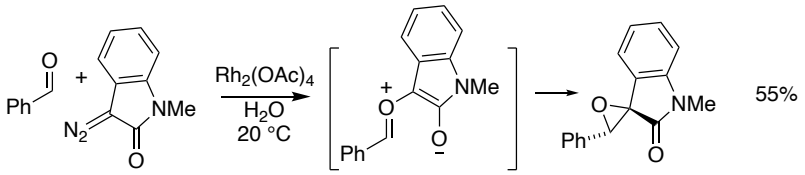


Figure 1-9. 3-Diazoisatins undergo Darzens reactions with aldehydes

Insertion of heteroatoms such as nitrogen, oxygen, sulfur, selenium, phosphorus or halogen atoms into metal carbenes generated from diazo compounds, followed by protonation of the enolate intermediate has been extensively explored and summarized in several review articles.[14] Modern research in the area has focused on catalytic asymmetric variants. Much of the state-of-the-art progress in this area has been published by the Zhou group, who reported the asymmetric N–H insertion of α-aryldiazoesters and Boc NH_2, catalyzed by $Rh_2(TPA)_4$ and a chiral phosphoric acid.[11a] The reaction generated products in excellent yield and high enantioselectivities and was later extended to include α-arylketones[11b] and vinyl diazoacetates.[11c] The Van Vranken group extended this work to carbazoles and other aromatic N–H substrates (Figure 1-10).[11d]

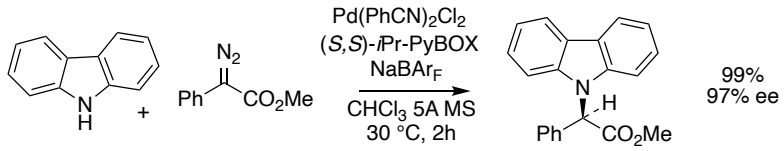


Figure 1-10. Enantioselective palladium-catalyzed carbene insertion into the N–H bonds of aromatic heterocycles

With spiro-bisoxazoline ligands, Zhou and coworkers were able to subject α-aryl-α-diazoesters to metal-catalyzed O–H insertion with high efficiency. The reaction is successful with water, alcohols and phenols, and works with Cu(I), Pd(II) and Fe(II) catalysts (Figure 1-11).[11e-h]

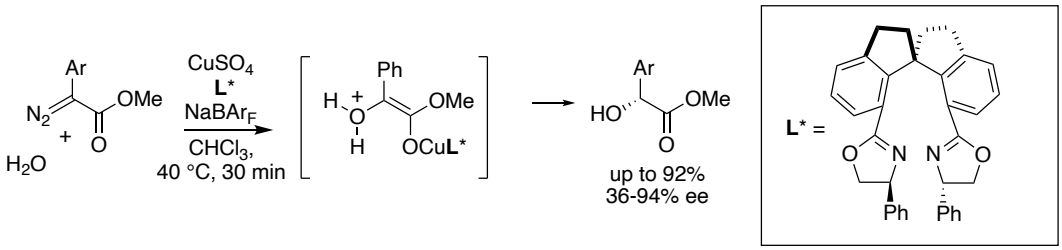


Figure 1-11. Asymmetric O–H insertion with chiral spiro-bisoxazoline ligands

The same spiro-bisoxazoline ligand was later employed by Zhou and coworkers to afford S–H insertion products with moderate success.[11i] However, α-mercaptoesters gave only moderate ee. By using the $Rh_2(TPA)_4$/chiral phosphoric acid system previously mentioned for N–H insertion, ee improved up to 98% (Figure 1-12).[11j] Halogen insertion processes will be discussed in chapter two.

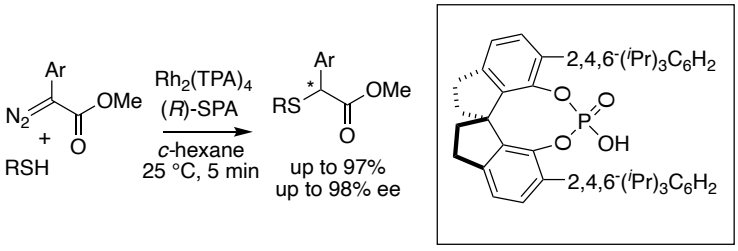


Figure 1-12. Asymmetric S–H insertion with chiral phosphoric acid

Tandem Insertion/[3,3]-Sigmatropic Rearrangement

We reasoned that enolates generated from heteroatom insertion into metal carbenes might form silylketene acetals in the presence of a silylating agent and in the absence of a proton source, which could undergo further rearrangement such as [3,3] sigmatropic rearrangements. (Figure 1-13). Nucleophilic heteroatoms are expected to add to α-carboxyallyl carbene intermediates to afford *C*-bound rhodium enolates which are expected to isomerize to *O*-bound rhodium enolates.[15] Silyl transfer, via a rhodium enolate or free enolate, is expected to favor the *O*-silyl ketene acetal.

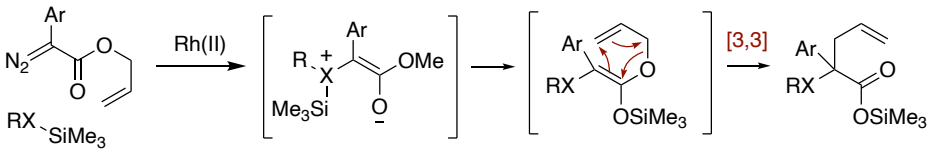


Figure 1-13. [3,3] sigmatropic rearrangement of silylketene acetals generated from heteroatom insertion into metal carbenes

A challenge foreseen with this approach is that α-diazo allyl esters are known to cyclopropanate in the presence of Rh(II) and Cu(I) catalysts.[16] Radosevich and coworkers had previously shown that cyclopropanation outpaces sulfonamide addition to rhodium carbenes derived from diazoesters,[17] leading to cyclopropanolactones **2**. We thus set out to explore this competition by experimenting with a variety of O–Si, N–Si, and S–Si nucleophiles (Figure 1-14).

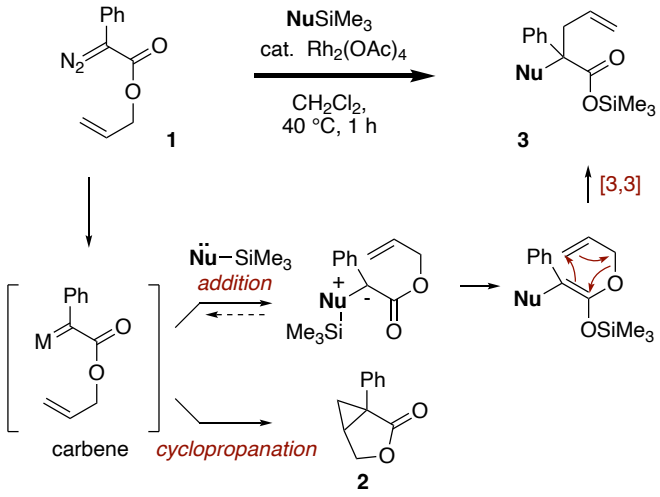


Figure 1-14. Intramolecular cyclopropanation is expected to compete with ylide formation

Using conditions developed by Cai and coworkers typical for O–H insertion[18] (1 mol % $Rh_2(OAc)_4$, CH_2Cl_2 solvent, 40 °C, 1 hour slow addition by syringe pump to reduce unwanted dimer formation[19]) we first attempted the reaction of PhO–$SiMe_3$ with allyl-α-phenyl-α-diazoacetate. Unfortunately, cyclopropanation was the major product at 44% yield, with other products consistent with addition of phenol and protonation of the enolate (Table 1-1).

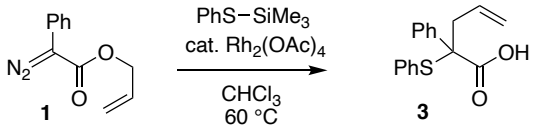
Table 1-1. O, N, S nucleophile screen

Nu−$SiMe_3$	cyclopropane **2**	adduct **3**
PhO-$SiMe_3$	44%	-
N_3-$SiMe_3$	78%	-
$CH_3C(OSiMe_3)$=N-$SiMe_3$	77%	-
$C_6H_{10}N$-$SiMe_3$	<15%	-
PhS-$SiMe_3$	-	56%

$Rh_2(hfb)_4$ and $Rh_2(cap)_4$ were also tried, but generated complex mixtures composed primarily of cyclopropane **2**.

Based on the competition shown in Figure 1-14, we reasoned that strengthening the nucleophile might increase the rate of nucleophilic attack leading to adduct **3** relative to intramolecular cyclopropanation, so multiple nitrogen nucleophiles were explored (trimethylsilyl azide, *O,N*-bis-trimethylsilyl acetamide, and *N*–trimethylsilylpiperidine) but these also generated either complex mixtures or predominately cyclopropane **2** (Table 1-1). We then further strengthened nucleophilicity with PhS–$SiMe_3$, and happily generated the product expected for S–Si insertion followed by Ireland-Claisen rearrangement (Figure 1-13, X = S). The carboxylic acid product **3** was isolated after hydrolysis of the silyl ester during aqueous work-up in 56% yield. We then set out to optimize the reaction conditions to improve the yield of product **3** (Table 1-2).

Table 1-2. Optimization table



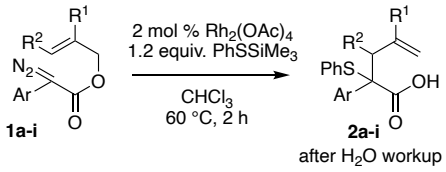
entry	equiv diazo **1**	mol% $Rh_2(OAc)_4$	equiv. PhS–SiMe3	time (h)	T(°C)	yield (%)
1	1.0	1	2.0	1+1	40	56
2	1.0	2	2.0	1	60	61
3	1.0	2	2.0	1+1	60	79
4	1.3	2	1.0	1+1	60	91
5	1.3	1	1.0	1+1	60	70
6	**1.0**	**2**	**1.2**	**1+1**	**60**	**92**

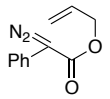
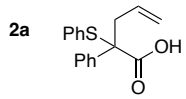
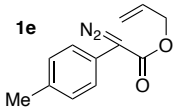
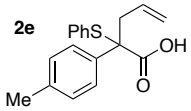
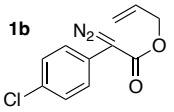
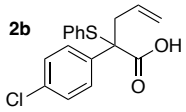
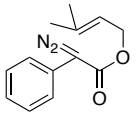
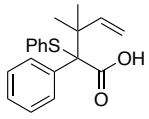
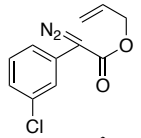
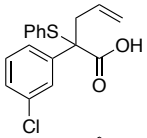
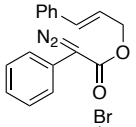
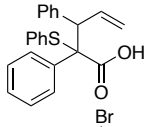
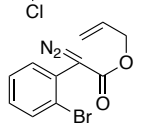
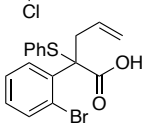
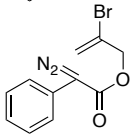
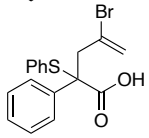
Following our initial positive result using standard conditions for O–H insertion, we next attempted conditions developed by Zhou and coworkers specific to S–H insertion[12] (2 mol % $Rh_2(OAc)_4$, 2 equiv. nucleophile, 60 °C over 1 h, followed immediately by workup). Under these conditions, yield improved slightly to 61% (Table 1-2, entry 2). When the reaction was allowed

to stir for an additional hour after syringe pump addition was complete, yield increased to 79% (Table 1-2, entry 3).

The presence of unreacted diazo compound in these reactions suggested deactivation of the catalyst. Strong nucleophiles complex with rhodium and reduce the amount of active catalyst on the cycle.[20] During sequestration, the catalyst can be deactivated by thiol(ate)[21] or by silylation of the acetate ligands[22] which generates $AcOSiMe_3$ and unreactive rhodium-sulfide complexes. When the concentration of $PhSSiMe_3$ was reduced from 2 to 1 equiv, yield improved to 91% (entry 4). We attempted to lower the catalyst loading to 1% (entry 5), but yield decreased. Finally, when 1 equiv. of the diazo compound was used with a slight excess of nucleophile (entry 6) yield of the desired product was 92%. Using these conditions, we next explored the scope of this addition/rearrangement process (Table 1-3).

Table 1-3. Substrate scope

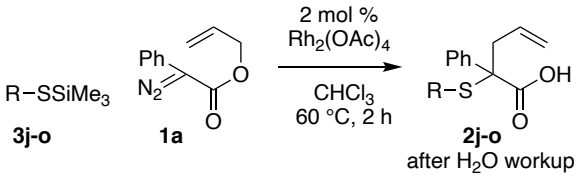


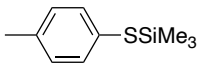
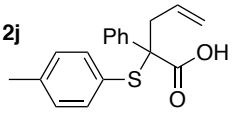
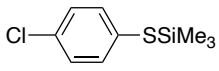
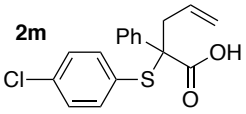
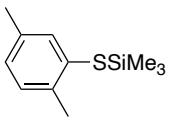
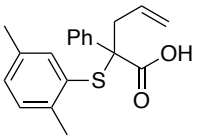
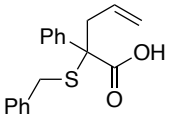
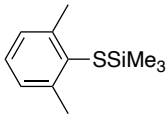
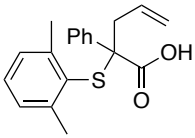
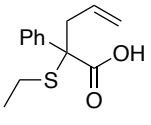
1a		**2a**		92%	**1e**		**2e**		92%
1b		**2b**		77%	**1f**		**2f**		-
1c		**2c**		90%	**1g**		**2g**		17%
1d		**2d**		89%	**1h**		**2h**		57%

Varying substitution at the *ortho*, *meta*, and *para* positions of the aryl group (Table 1-3, **2b-2d**) all gave good yields of addition/rearrangement product. Unfortunately, varying substitution on the allylic fragment was not as successful. Dimethylallyl substrate **1f** gave exclusive cyclopropanation. *E*-cinnamate ester **1g** gave 17% yield of the desired product in a 2.7:1 ratio of diastereomers (^{1}H NMR)[6b,6e,23] but the major product was again cyclopropanation. 2-Bromoallyl substrate **1h** gave 57% yield. As halogens are known to insert into metal-carbenes,[24] it is possible that bromine could be competing with the nucleophile, slowing the reaction and resulting in catalyst decomposition.

We then explored the scope of the reaction by varying the sulfur nucleophiles (Table 1-4), which were prepared by silylation of the lithium thiolates and purified through vacuum distillation.[25]

Table 1-4. Variance of sulfur nucleophile



3j		**2j**		86%	**3m**		**2m**		59%
3k		**2k**		84%	**3n**		**2n**		85%
3l		**2l**		43%	**3o**		**2o**		93%

Phenyl thioethers **3j** and **3k** both gave good yields, but yield decreased significantly when both *ortho* positions were blocked in bulky 2,5-dimethylphenyl thioether substrate **3l**. *p*-Chlorophenyl thioether **3m** also gave reduced yield (59%) due to competing cyclopropanation. Aliphatic nucleophiles **3n** and **3o**, however, both gave high yield.

We also experimented with propargyl ester **4** (Figure 1-15), which happily gave 82% of allene product **5** on a 1 mmol scale despite Ireland-Claisen rearrangements not being common with propargyl esters.[26]

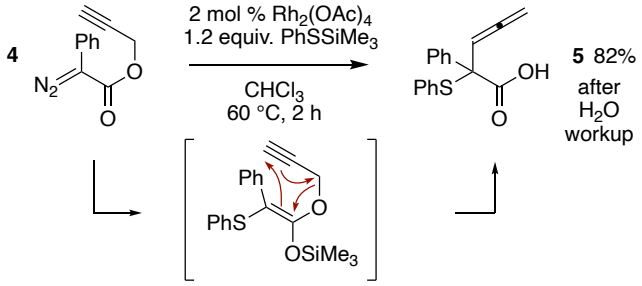


Figure 1-15. Ireland-Claisen rearrangement of propargyl ester

Reasoning that propargyl esters might be less prone to cyclopropenation than allyl esters, we then attempted the reaction of propargyl ester **4** with MeO–$SiMe_3$, N_3–$SiMe_3$, PhO–$SiMe_3$, AcO–$SiMe_3$, and Me_2NCOO–$SiMe_3$ in an effort to expand the scope to nucleophiles other than sulfur. Unfortunately, these substrates only gave complex mixtures with no or trace allene product. It is possible cyclopropenation does occur in preference to heteroatom insertion, followed by rearrangement and subsequent reaction as intramolecular cyclopropenation reactions typically do not form stable cyclopropene products.[27]

Although silyl ketene acetal intermediates were hypothesized mechanistically, we wanted to establish their intermediacy by experimentation as silyl ketene acetals are important

intermediates in a variety of synthetic transformations.[28] Therefore, we carried out the reaction in $CDCl_3$ with methyl 2-diazo-2-phenylacetate **6** (Figure 1-16), which lacks the allyl group needed for [3,3]-sigmatropic rearrangement. The presence of silyl ketene acetals of both *E* and *Z* isomers was detected by ^1H NMR and ^{13}C NMR.

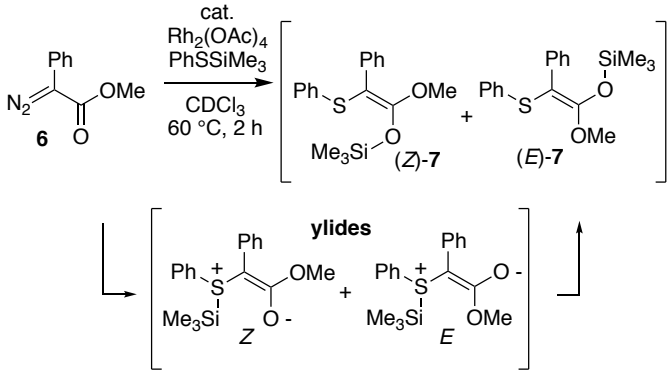


Figure 1-16. S–Si Insertion Reaction of $CDCl_3$ with methyl 2-diazo-2-phenylacetate

Silyl ketene acetal (*Z*)-**7** could in theory be generated intramolecularly from silyl transfer from sulfur to oxygen through a 5-membered transition state. If silyl ketene acetal (*E*)-**7** is formed stereospecifically from the *E*-ylide, transfer of the silyl group must have occurred intermolecularly.

In conclusion, silyl ketene acetals can be generated from reaction of trimethylsilyl thioethers with allyl diazoesters. Once generated, the silyl ketene acetals undergo [3,3]-sigmatropic rearrangement to produce tetrasubstituted carboxylic acid derivatives after aqueous workup. This process is potentially useful in the synthesis of bioactive molecules which possess the α-thiocarboxylic acid motif.[29]

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Chapter 1 Experimental

I. General methods: Reactions were run in oven-dried glassware. Reaction flasks were evacuated, backfilled with argon, and reactions were carried out under an atmosphere of argon. ^{1}H and ^{13}C NMR spectra were recorded at room temperature using a Bruker 500 MHz (^{1}H) spectrometer equipped with a cryoprobe and referenced to $CDCl_3$. NMR signals are reported as follows: chemical shift in ppm, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet, app = apparent), coupling constants in Hz if applicable, and proton integration. High Resolution Mass Spectrometry data was obtained on a MicroMass MS Technologies LCT Premier instrument using ESI-TOF. Infrared spectrometric data were recorded on Varian 640 IR FT-IR Spectrometer. (Ethylthio)trimethylsilane **(3e)** was obtained commercially and used without further purification. Catalysts were obtained commercially and used without further purification. All solvents used, unless specified otherwise, were dried and deoxygenated using activated alumina columns according to Grubb's procedure.[1] Column chromatography was performed under pressure using SiliCycle™ Silia*Flash*™ P60, 40-63 μm 60Å. Chloroform was purified prior to use by washing with aqueous bicarbonate and distillation. Unless otherwise indicated, compounds were purified to ≥99% purity as judged by ^{1}H NMR integrations, otherwise the purity was estimated based on the mole fraction of impurities. Molecular ions were not observable for the diazo compounds using ESI; but IR stretches around 2080 cm^{-1} provided convincing evidence of the diazo functionality.

II. Purification of Chloroform: Chloroform (200 mL) was washed with saturated aqueous sodium bicarbonate (2 × 100 mL) and dried over sodium sulfate. The solvent was decanted and purified by distillation under argon onto activated 3 Å molecular sieves. The chloroform was stored in a sealed flask over 3 Å molecular sieves under argon and kept in the dark prior to use. Chloroform was not kept for more than 30 days.

III. General Procedure for Synthesis of Diazo Compounds 1a-1h and 4: A round-bottom flask equipped with stir bar was charged with *p*-acetamidobenzenesulfonyl azide (4.91 g, 20.4 mmol, 120 mol %) and dry acetonitrile. To the stirred solution was added the α-phenyl ester (17.0 mmol, 100 mol %). The solution was cooled in an ice-water bath for 15 minutes. Separately, a 1 M solution of DBU (3.24 g, 21.3 mmol, 125 mol %) in dry acetonitrile was prepared, and then added to the reaction mixture dropwise over ca. 5 min. The solution was warmed gradually to room temperature and stirred for an additional 16 h. The resulting orange solution was diluted with 100 mL Et_2O and washed with half-saturated aq. ammonium chloride solution (2 ×), water and brine. The organic layer was dried over sodium sulfate, filtered, and concentrated by rotary evaporation. The α-phenyl-α-diazoester was purified by silica gel chromatography.

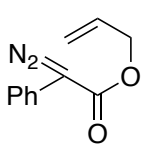
IV. Representative Procedure for Rhodium(II)-Catalyzed Formation of α-Thiocarboxylic Acids 2a-2o on 1.0 mmol Scale: In a round bottom flask was prepared a solution of rhodium tetraacetate (8.88 mg, 20.1 μmol, 2 mol %) in chloroform. The flask was lowered into a 60 °C oil bath. In a 5 mL pear-shaped flask was prepared a solution of diazo compound **4** (201 mg, 1.0 mmol, 100 mol%) in 1 mL chloroform. The solution was withdrawn by syringe and fitted into a syringe pump apparatus. To the solution of rhodium tetraacetate was added neat trimethyl(phenylthio)silane (203 μL , 1.20 mmol, 120 mol %) Within one minute after addition of trimethyl(phenylthio)silane was completed, syringe pump addition of the diazo compound was initiated at a rate of 0.016 mL/min over 1 h. After 1 h, an additional 0.3 mL chloroform was used to ensure complete transfer of the diazo compound from the 5 mL pear-shaped flask, and the reaction was stirred at 60 °C for an additional 1 h. The flask was then removed from the oil bath and extracted with dichloromethane, water, and brine. The organic layer was dried over sodium

sulfate, filtered, and concentrated by rotary evaporation. The α-thiocarboxylic acid **5** was purified by silica gel chromatography.

V. General Procedure for Synthesis of Trimethylsilyl Thioethers 3j-3o:

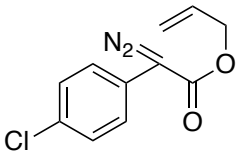
To a solution of thiol (20.0 mmol) in diethyl ether was added slowly 1.6 M *n*-butyl lithium in hexanes (22 mmol, 14 mL) at -78 °C. Chlorotrimethylsilane (22.0 mmol, 2.4 g) was added dropwise to the reaction mixture at -78 °C. The reaction mixture was stirred for 4 h at room temperature, then diluted with hexanes (13 mL). The mixture was evaporated, and the precipitated solids were filtered off. The organic layer was evaporated, and the residue purified by distillation under reduced pressure to give the product.

VI. Synthesis and Characterization of Diazo Compounds 1a-1h

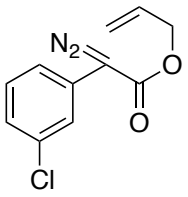


Allyl 2-diazo-2-phenylacetate (1a): A 250 mL round-bottom flask equipped with stir bar was charged with *p*-acetamidobenzenesulfonyl azide (4.91 g, 20.4 mmol, 120 mol %) and 60 mL dry acetonitrile. To the stirred solution was added the α-phenyl ester (3.00 g, 17.0 mmol, 100 mol %); the solution was cooled in an ice-water bath for 15 minutes. Separately, a 20 mL solution of DBU (3.24 g, 21.3 mmol, 125 mol %) in dry acetonitrile was prepared, and then added to the reaction mixture dropwise over 5 min. The solution was warmed gradually to room temperature and stirred for an additional 16 h. The resulting orange solution was diluted with 100 mL Et_2O and washed with half-saturated aq. ammonium chloride solution (2 × 100 mL), water (100 mL) and brine (100 mL). The organic layer was dried over sodium sulfate, filtered, and concentrated by rotary evaporation. The crude residue was purified by silica gel column chromatography using 92:8 hexanes/Et_2O to afford diazo compound **1a** as a red-orange oil (3.04 g, 15.2 mmol, 90.4%) in an estimated 98% purity (89% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.49 (d, J = 8.5 Hz, 2H), 7.39 (t, J = 8.16 Hz, 2H), 7.19 (t, J = 7.4 Hz, 1H), 5.99

(dddd, J = 17.1, 11.1, 5.6, 5.4 Hz, 1H), 5.37 (dd, J = 17.1, 1.3 Hz, 1H), 5.28 (dd, J = 10.4, 1.1 Hz, 1H), 4.78 (dt, J = 5.6, 1.3 Hz, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 164.9, 132.2, 129.0, 125.9, 124.1, 118.4, 65.5; HRMS (CI) m/z: [M – N_2 + NH_4]+ Calcd for $C_{11}H_{14}NO_2^+$ 192.1019; Found 192.1024; IR (ATR): 2079 (C=N_2), 1698 cm^{-1}. This is a known compound, and the spectral data is in agreement with the known data published.[2]

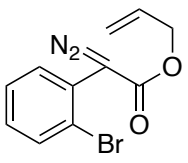


Allyl 2-(4-chlorophenyl)-2-diazoacetate (1b): Diazo compound **1b** was synthesized according to the general procedure using allyl 2-(4-chlorophenyl)acetate (1.50 g, 7.12 mmol, 100 mol %). The crude residue was purified by silica gel column chromatography using 92:8 hexanes/Et_2O to afford diazo compound **1b** as a red-orange oil (1.34 g, 5.65 mmol, 79.3%) in an estimated 98% purity (78% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.42 (d, J = 8.7 Hz, 2H), 7.35 (d, J = 8.5 Hz, 2H), 5.97 (dddd, J = 17.0, 10.7, 5.4, 5.4 Hz, 1H), 5.36 (dd, J = 17.2, 1.2 Hz, 1H), 5.28 (dd, J = 10.4, 1.1 Hz, 1H), 4.77 (dt, J = 1.2, 5.7 Hz, 2H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 172.7, 164.5, 132.0, 131.6, 129.1, 125.1, 124.2, 118.6, 65.6; IR (ATR): 2082 (C=N_2), 1695 cm^{-1}. This is a known compound, and the spectral data is in agreement with the known data published.[3]

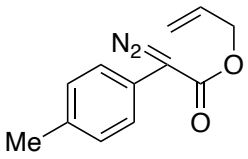


Allyl 2-(3-chlorophenyl)-2-diazoacetate (1c): Diazo compound **1c** was synthesized according to the general procedure using allyl 2-(3-chlorophenyl)acetate (1.80 g, 8.54 mmol, 100 mol %). The crude residue was purified by silica gel column chromatography using 92:8 hexanes/Et_2O to afford diazo compound **1c** as a red orange oil (1.59 g, 6.72 mmol, 78.7%) in an estimated 97% purity (77% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.55 (s, 1H), 7.34 -7.28 (m, 2H), 7.15 (dt, J = 7.7, 7.7, 1.2 Hz, 1H), 5.98 (dddd, J = 16.1, 10.7, 6.5, 5.7 Hz, 1H), 5.37 (dd, J = 17.1, 1.4 Hz, 1H), 5.29 (dd, J = 10.2, 1.0 Hz, 1H), 4.78 (dt, J = 5.7, 1.1, 1.1 Hz, 2H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 164.3, 135.1, 132.0,

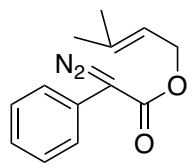
130.1, 127.7, 125.9, 123.8, 121.7, 118.7, 65.7; HRMS (CI) *m/z*: [M – N_2 + NH_4]+ Calcd for $C_{11}H_{13}ClNO_2^+$ 226.0629; Found 226.0635; IR (ATR): 2084 (C=N_2), 1699 cm^{-1}.



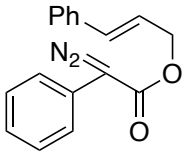
Allyl 2-(2-bromophenyl)-2-diazoacetate (1d): Diazo compound **1d** was synthesized according to the general procedure using allyl 2-(2-bromophenyl)acetate (1.80 g, 7.06 mmol, 100 mol %). The crude residue was purified by silica gel column chromatography using 92:8 hexanes/Et_2O to afford diazo compound **1d** as an orange oil (1.51 g, 5.42 mmol, 76.7%) in an estimated 98% purity (75% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.63 (dd, *J* = 7.7, 1.3 Hz, 1H), 7.53 (dd, *J* = 8.0, 1.7 Hz, 1H), 7.37 (td, *J* = 7.3, 7.3, 1.3 Hz, 1H), 7.21 (td, *J* = 7.5, 7.5, 1.7 Hz, 1H), 5.97 (dddd, *J* = 15.9, 10.8, 6.6, 5.6 Hz, 1H), 5.34 (dd, *J* = 17.0, 1.4 Hz, 1H), 5.26 (dd, *J* = 10.3, 1.4 Hz, 1H), 4.75 (dt, *J* = 5.7, 1.5, 1.5 Hz, 2H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 165.2, 133.4, 133.0, 132.2, 132.2, 130.2, 127.8, 125.8, 124.6, 118.3; HRMS (CI) *m/z*: [M – N_2 + NH_4]+ Calcd for $C_{11}H_{13}BrNO_2^+$ 270.0124; Found 270.0130; IR (ATR): 2091 (C=N_2), 1693 cm^{-1}.



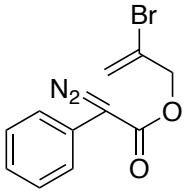
Allyl 2-diazo-2-(p-tolyl)acetate (1e): Diazo compound **1e** was synthesized according to the general procedure using allyl 2-(p-tolyl)acetate (2.50 g, 13.1 mmol, 100 mol %). The crude residue was purified by silica gel column chromatography using 92:8 hexanes/Et_2O, from which the pure fraction was isolated to afford diazo compound **1e** as a red orange solid (1.29 g, 5.95 mmol, 45.0%). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.37 (d, *J* = 7.5 Hz, 2H), 7.20 (d, *J* = 7.5, Hz, 2H), 6.02-5.94 (m, 1H), 5.36 (d, *J* = 17.1 Hz, 1H), 5.27 (d, *J* = 10.6, Hz, 1H), 4.77 (dd, *J* = 5.6, 1.1 Hz, 2H), 2.35 (s, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 165.1, 135.8, 132.3, 129.7, 124.2, 122.2, 118.3, 65.4, 21.1; HRMS (CI) *m/z*: [M – N_2 + NH_4]$^+$ Calcd for $C_{12}H_{16}NO_2^+$ 206.1176; Found 206.1181; IR (ATR): 2079 (C=N_2), 1699 cm^{-1}.



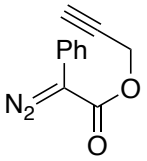
3-Methylbut-2-en-1-yl 2-diazo-2-phenylacetate (1f): Diazo compound **1f** was synthesized according to the general procedure using 3-methylbut-2-en-1-yl 2-phenylacetate (1.50 g, 7.34 mmol, 100 mol %). The crude residue was purified by silica gel column chromatography using 92:8 hexanes/Et_2O to afford diazo compound **1f** as a red orange oil (870 mg, 3.78 mmol, 51.5%) in an estimated 98% purity (50% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.49 (d, *J* = 8.3 Hz, 2H), 7.38 (t, *J* = 7.8 Hz, 2H), 7.18 (t, *J* = 7.3 Hz, 1H), 5.40 (td, *J* = 7.4, 1.2, 1.2 Hz, 1H), 4.78 (d, *J* = 6.9 Hz, 2H), 1.78 (s, 3H), 1.75 (s, 3H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 165.3, 139.4, 126.3, 129.0, 125.8, 124.0, 118.7, 61.9, 25.8, 18.2; IR (ATR): 2062 (C=N_2), 1695 cm^{-1}. This is a known compound, and the spectral data is in agreement with the known data published.[4]



Cinnamyl 2-diazo-2-phenylacetate (1g): Diazo compound **1g** was synthesized according to the general procedure using cinnamyl 2-phenylacetate (3.00 g, 11.9 mmol, 100 mol %). The crude residue was purified by silica gel column chromatography using 92:8 hexanes/Et_2O to afford diazo compound **1g** as an orange solid after discarding mixed fractions (1.86 g, 6.68 mmol, 56.2%) in an estimated 98% purity (55% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.50 (d, *J* = 8.5 Hz, 2H), 7.37-7.42 (m, 4H), 7.33 (t, *J* = 7.7 Hz, 2H), 7.27 (t, *J* = 7.4 Hz, 1H), 7.19 (t, *J* = 7.2 Hz, 1H), 6.70 (d, *J* = 16.2 Hz, 1H), 6.35 (dt, *J* = 16.0, 6.4, 6.4 Hz, 1H), 4.94 (d, *J* = 6.6 Hz, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 165.1, 136.2, 134.6, 129.0, 128.7, 128.2, 126.8, 126.0, 125.6, 124.1, 123.2, 65.5; IR (ATR): 2081 (C=N_2), 1694 cm^{-1}. This is a known compound, and the spectral data is in agreement with the known data published.[5]

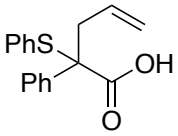


2-Bromoallyl 2-diazo-2-phenylacetate (1h): Diazo compound **1h** was synthesized according to the general procedure using 2-bromoallyl 2-phenylacetate (3.00 g, 11.8 mmol, 100 mol %). The crude residue was purified by silica gel column chromatography using 92:8 hexanes/Et_2O to afford diazo compound **1h** as a red orange oil (1.84 g, 6.52 mmol, 55.5%) in an estimated 95% purity (53% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.49 (d, *J* = 7.4 Hz, 2H), 7.40 (t, *J* = 7.9 Hz, 2H), 7.20 (t, *J* = 7.9 Hz, 1H), 5.94 (dt, *J* = 2.1, 0.7, 0.7 Hz, 1H), 5.69 (dt, *J* = 2.1, 0.8, 0.8 Hz, 1H), 4.90 (dd, *J* = 1.4, 0.6 Hz, 2H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 164.1, 129.1, 126.3, 126.1, 125.1, 124.1, 119.3, 67.7; HRMS (CI) *m/z*: $[M - N_2 + NH_4]^+$ Calcd for $C_{11}H_{13}BrNO_2^+$ 270.0124; Found 270.0130; IR (ATR): 2083 (C=N_2), 1700 cm^{-1}.

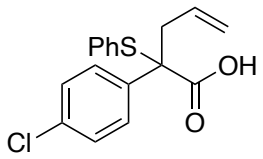


Prop-2-yn-1-yl 2-diazo-2-phenylacetate (4): Diazo compound **4** was synthesized according to the general procedure using prop-2-yn-1-yl 2-phenylacetate (1.50 g, 8.61 mmol, 100 mol %). The crude residue was purified by silica gel column chromatography using 92:8 hexanes/Et_2O to afford diazo compound **4** as a red orange oil (1.15 g, 5.78 mmol, 67.0%). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.49 (d, *J* = 10.0 Hz, 2H), 7.39 (t, *J* = 7.8 Hz, 2H), 7.20 (t, *J* = 7.8 Hz, 1H), 4.87 (d, *J* = 3.0 Hz, 2H), 2.54 (t, *J* = 3.1 Hz, 1H); ^{13}C NMR (125 MHz, $CDCl_3$) δ 164.3, 129.1, 126.1, 125.1, 124.0, 77.7, 75.3, 52.3; IR (ATR): 2088 (C=N_2), 1676 cm^{-1}. This is a known compound, and the spectral data is in agreement with the known data published.[6]

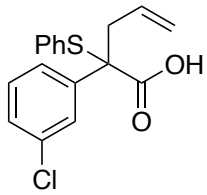
VII. Synthesis and Characterization of α-thiocarboxylic acids 2a-2o



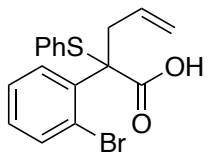
2-Phenyl-2-(phenylthio)pent-4-enoic acid (2a): In a 10 mL round bottom flask was prepared a solution of rhodium tetraacetate (6.34 mg, 14.3 μmol, 2 mol %) in 3 mL chloroform. The flask was lowered into a 60 °C oil bath. In a 5 mL pear-shaped flask was prepared a solution of the diazo compound (145 mg, 717 μmol, 100 mol %) in 1 mL chloroform. The solution was withdrawn by syringe and fitted into a syringe pump apparatus. To the solution of rhodium tetraacetate was added neat trimethyl(phenylthio)silane (163 μL, 860 μmol, 120 mol %). Within one minute after addition of trimethyl(phenylthio)silane was completed, syringe pump addition of the diazo compound was initiated at a rate of 0.016 mL/min over 1 h. After 1 h, an additional 0.3 mL chloroform was used to ensure complete transfer of the diazo compound from the 5 mL pear-shaped flask, and the reaction was stirred at 60 °C for an additional 1 h. The flask was then removed from the oil bath and extracted with dichloromethane, water, and brine. The organic layer was dried over sodium sulfate, filtered, and concentrated by rotary evaporation. The crude residue was purified by silica gel column chromatography using 5:1 hexanes/EtOAc with 1% AcOH to afford carboxylic acid **2a** as a transparent oil (193 mg, 679 μmol, 94.8%) in an estimated 97% purity (92% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.17-7.39 (m, 10H), 5.87 (dddd, J = 17.2, 10.1, 7.1, 6.7 Hz, 1H), 5.11 (dd, J = 9.8, 1.7 Hz, 1H), 5.06 (d, J = 16.9, 1.7 Hz, 1H), 2.87 (d, J = 7.1 Hz, 2H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 177.0, 138.7, 136.8, 132.8, 130.3, 129.5, 128.7, 128.3, 127.9, 119.2, 64.2, 40.6; HRMS (ESI) m/z: $[M + Na]^+$ Calcd for $C_{17}H_{16}O_2SNa$ 307.0769; Found 307.0761.



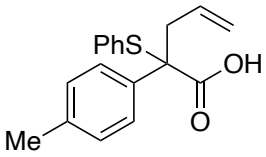
2-(4-Chlorophenyl)-2-(phenylthio)pent-4-enoic acid (2b): Carboxylic acid compound **2b** was synthesized according to the general procedure using diazo compound **1b** (150 mg, 634 μmol, 100 mol %). The crude residue was purified by silica gel column chromatography using 5:1 hexanes/EtOAc with 1% AcOH to afford carboxylic acid 2**b** as a transparent oil (160 mg, 501 μmol, 79.0%) in an estimated 97% purity (77% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.25-7.39 (m, 9H), 5.91 (ddt, *J* = 16.8, 10.3, 6.9, 6.9 Hz, 1H), 5.19 (d, *J* = 10.0 Hz, 1H), 5.14 (d, *J* = 17.0 Hz, 1H), 2.91 (d, *J* = 6.9 Hz, 2H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 177.1, 138.0, 136.8, 133.5, 132.7, 130.3, 129.6, 129.3, 128.8, 128.3, 119.4, 64.1, 40.4; HRMS (ESI) *m/z*: $[M - H + 2Na]^+$ Calcd for $C_{17}H_{15}ClO_2SNa$ 363.0198; Found 363.0182.



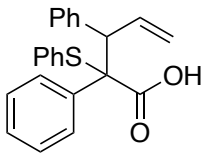
2-(3-Chlorophenyl)-2-(phenylthio)pent-4-enoic acid (2c): Carboxylic acid compound **2c** was synthesized according to the general procedure using diazo compound **1c** (150 mg, 634 μmol, 100 mol %). The crude residue was purified by silica gel column chromatography using 5:1 hexanes/EtOAc with 1% AcOH to afford carboxylic acid **2c** as a transparent oil (186 mg, 583 μmol, 92.0%) in an estimated 98% purity (90% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 9.10 (s, 1H) 7.37-7.21 (m, 9H), 5.87 (dddd, *J* = 16.9, 10.2, 7.3, 6.7 Hz, 1H), 5.15 (d, *J* = 10.2 Hz, 1H), 5.10 (d, *J* = 16.8 Hz, 1H), 2.86 (d, *J* = 5.6 Hz, 1H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 176.6, 141.0, 136.8, 134.2, 132.4, 130.0, 129.8, 129.4, 128.8, 128.1, 128.0, 126.1, 119.6, 63.8, 40.6; HRMS (ESI) *m/z*: $[M + Na]^+$ Calcd for $C_{17}H_{15}ClO_2SNa$ 341.0397; Found 341.0380.



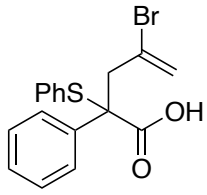
2-(2-Bromophenyl)-2-(phenylthio)pent-4-enoic acid (2d): Carboxylic acid compound **2d** was synthesized according to the general procedure using diazo compound **1d** (160 mg, 569 μmol, 100 mol %). The crude residue was purified by silica gel column chromatography using 5:1 hexanes/EtOAc with 1% AcOH to afford carboxylic acid **2d** as a transparent oil (192 mg, 529 μmol, 93.0%) in an estimated 96% purity (89% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.65 (dd, *J* = 8.0, 1.6 Hz, 1H), 7.44 (dd, *J* = 7.8, 1.4 Hz, 1H), 7.34 (t, *J* = 7.3 Hz, 1H), 7.30-7.21 (m, 6H), 7.15 (td, *J* = 7.6, 7.6, 1.8 Hz, 1H) 5.87 (dddd, *J* = 16.9, 10.4, 7.4, 6.3 Hz, 1H), 5.11-5.07 (m, 2H), 3.15 (dt, *J* = 6.2, 1.3, 1.3 Hz, 1H), 2.79 (dt, *J* = 7.5, 1.1, 1.1 Hz, 1H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 176.2, 137.5, 137.4, 134.7, 132.4, 130.1, 130.1, 129.9, 129.3, 128.8, 126.8, 124.1, 119.0, 64.6, 39.3; HRMS (ESI) *m/z*: $[M + Na]^+$ Calcd for $C_{17}H_{15}BrO_2SNa$ 384.9874; Found 384.9866



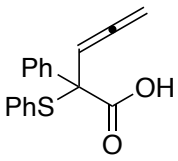
2-(Phenylthio)-2-(p-tolyl)pent-4-enoic acid (2e): Carboxylic acid compound **2e** was synthesized according to the general procedure using diazo compound **1e** (155 mg, 717 μmol, 100 mol %). The crude residue was purified by silica gel column chromatography using 5:1 hexanes/EtOAc with 1% AcOH to afford carboxylic acid **2e** as a transparent oil (200 mg, 673 μmol, 93.9%) in an estimated 98% purity (92% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.35- 7.29 (m, 5H), 7.21-7.24 (m, 2H), 7.16 (d, *J* = 8.2 Hz, 2H), 5.89 (dddd, *J* = 16.7, 10.1, 7.3, 6.1 Hz, 1H), 5.14 (dd, *J* = 10.7, 2.1 Hz, 1H), 5.09 (dd, *J* = 17.2, 1.7 Hz, 1H) 2.88 (d, *J* = 6.9 Hz, 2H), 2.37 (s, 3H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 177.6, 137.8, 136.9, 135.9, 133.2, 130.8, 129.6, 129.1, 128.8, 127.8, 119.2, 64.1, 40.8, 21.2; HRMS (ESI) *m/z*: $[M + Na]^+$ Calcd for $C_{17}H_{14}O_2S$ 321.0925; Found 321.0932



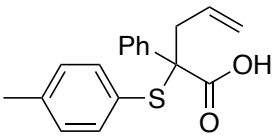
2,3-Diphenyl-2-(phenylthio)pent-4-enoic acid (2g): Carboxylic acid compound **2g** was synthesized according to the general procedure using diazo compound **1g** (155 mg, 557 μmol, 100 mol %). The crude residue was purified by silica gel column chromatography using 5:1 hexanes/EtOAc with 1% AcOH to afford carboxylic acid **2g** as a transparent oil (36 mg, 673 μmol, 17.9%) in an estimated 96% purity (17% yield) as a mixture of diastereomers in a 2.7 : 1 ratio. ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.50 (d, *J* = 7.0 Hz, 2.4H), 7.13-7.33 (m, 17.5H), 6.84 (d, *J* = 7.1 Hz, 0.85H), 6.75 (d, *J* = 8.0 Hz, 2H), 6.20 (dt, *J* = 16.5, 10.3 Hz, 0.4H), 6.06 (dt, *J* = 17.0, 9.4 Hz, 1H) 5.23 (m, 2.7H), 4.53 (d, *J* = 9.4 Hz 1.4H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 177.0, 175.4, 139.8, 137.6, 137.1, 136.1, 135.6, 134.7, 134.6, 132.1, 131.7, 131.1, 130.6, 129.7, 128.8, 128.7, 127.9, 127.6, 127.5, 127.4, 118.8, 70.0, 57.7, 55.8; HRMS (ESI) *m/z*: $[M + Na]^+$ Calcd for $C_{23}H_{20}O_2S$ 383.1082; Found 383.1076



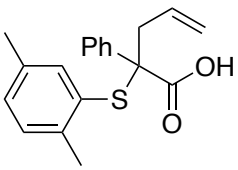
4-Bromo-2-phenyl-2-(phenylthio)pent-4-enoic acid (2h): Carboxylic acid compound **2h** was synthesized according to the general procedure using diazo compound **1h** (155 mg, 551 μmol, 100 mol %). The crude residue was purified by silica gel column chromatography using 5:1 hexanes/EtOAc with 1% AcOH to afford carboxylic acid **2h** as a transparent oil (118 mg, 324 μmol, 58.8%) in an estimated 97% purity (57% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.50 (d, *J* = 7.5 Hz, 2H), 7.36-7.30 (m, 6H), 7.22 (t, *J* = 7.4 Hz, 2H), 5.64 (s, 1H), 5.58 (d, *J* = 1.9 Hz 1H), 3.39 (d, *J* = 18.2 Hz, 1H), 3.30 (d, *J* = 51.6 Hz, 1H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 175.9, 137.5, 136.7, 130.2, 130.2, 129.8, 128.9, 128.3, 128.1, 127.0, 121.8, 63.1, 47.1; HRMS (ESI) *m/z*: $[M + Na]^+$ Calcd for $C_{17}H_{15}BrO_2SNa$ 384.9874; Found 384.9868



2-Phenyl-2-(phenylthio)penta-3,4-dienoic acid (5): Carboxylic acid compound **5** was synthesized according to the general procedure using diazo compound **4** (201 mg, 1.00 mmol, 100 mol %). The crude residue was purified by silica gel column chromatography using 5:1 hexanes/EtOAc with 1% AcOH to afford carboxylic acid **5** as a transparent oil (238 mg, 840 μmol, 84.0%) in an estimated 98% purity (82% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.53-7.51 (m, 2H), 7.40- 7.30 (m, 6H), 7.24-7.23 (m, 2H), 5.74 (t, J = 6.5 Hz, 1H), 4.80-4.71 (m, 2H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 208.5, 175.9, 138.3, 136.7, 131.3, 129.4, 128.6, 128.3, 128.1, 93.6, 79.2, 64.4; HRMS (ESI) m/z: $[M + Na]^+$ Calcd for $C_{17}H_{14}O_2SNa$ 305.0612; Found 305.0619.

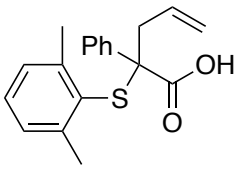


2-Phenyl-2-(p-tolylthio)pent-4-enoic acid (2j): Carboxylic acid compound **2j** was synthesized according to the general procedure using diazo compound **1a** (140 mg, 692 μmol, 100 mol %). The crude residue was purified by silica gel column chromatography using 5:1 hexanes/EtOAc with 1% AcOH to afford carboxylic acid **2j** as a transparent oil (184 mg, 617 μmol, 89.1%) in an estimated 97% purity (86% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.41 (d, J = 7.6 Hz, 2H), 7.29-7.35 (m, 3H) 7.16 (d, J = 8.4 Hz, 2H), 7.02 (d, J = 7.6 Hz, 2H) 5.88 (dddd, J = 16.9, 10.1, 7.0, 6.8 Hz, 1H), 5.12 (d, J = 10.1 Hz, 1H), 5.08 (d, J = 16.9 Hz, 1H), 2.86 (t, J = 5.0 Hz, 2H), 2.31 (s, 3H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 175.7, 139.9, 138.7, 136.8, 132.9, 129.6, 128.3, 127.7, 126.6, 119.1, 64.1, 40.6, 29.9, 21.3; HRMS (ESI) m/z: $[M]^+$ Calcd for $C_{18}H_{18}O_2S$ 298.1028; Found 298.1014.

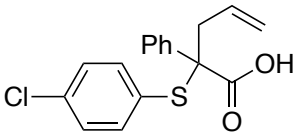


2-((2,5-Dimethylphenyl)thio)-2-phenylpent-4-enoic acid (2k): Carboxylic acid compound **2k** was synthesized according to the general procedure using diazo compound **1a** (140 mg, 692 μmol, 100 mol %). The crude residue was purified by silica gel column chromatography using 5:1 hexanes/EtOAc with

1% AcOH to afford carboxylic acid **2k** as a transparent oil (186 mg, 595 μmol, 86.0%) in an estimated 98% purity (84% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.27- 7.37 (m, 5H), 6.98- 7.05 (m, 3H) 5.87 (dddd, *J* = 17.0, 10.2, 6.9, 6.7 Hz, 1H), 5.08 (d, *J* = 10.0 Hz, 1H), 5.04 (d, *J* = 16.9 Hz, 1H), 2.96 (dd, *J* = 14.1, 6.1 Hz, 1H), 2.88 (dd, *J* = 14.5, 7.3 Hz, 1H), 2.22 (s, 3H), 2.16 (s, 3H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 177.2, 140.9, 138.9, 138.2, 135.5, 133.1, 130.4, 130.3, 129.4, 128.1, 127.9, 127.7, 119.1, 64.2, 41.1, 20.7, 20.4; HRMS (ESI) *m/z*: $[M + Na]^+$ Calcd for $C_{19}H_{20}O_2SNa$ 335.1082; Found 335.1084.

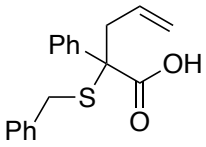


2-((2,6-Dimethylphenyl)thio)-2-phenylpent-4-enoic acid (2l): Carboxylic acid compound **2l** was synthesized according to the general procedure using diazo compound **1a** (140 mg, 692 μmol, 100 mol %). The crude residue was purified by silica gel column chromatography using 5:1 hexanes/EtOAc with 1% AcOH to afford carboxylic acid **2l** as a transparent oil (92.3 mg, 295 μmol, 42.7%). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.43 (dd, *J* = 8.3, 2.2 Hz, 3H) 7.27 (t, *J* = 5.8 Hz, 2H), 7.13 (t, *J* = 7.5 Hz, 1H), 7.05 (d, *J* = 7.4 Hz 2H), 5.69 (dddd, *J* = 17.1, 10.5, 6.8, 6.6 Hz, 1H), 5.01 (d, *J* = 10.3 Hz, 1H), 4.96 (d, *J* = 17.5 Hz, 1H), 3.00 (dd, *J* = 13.7, 6.0 Hz, 1H), 2.86 (dd, *J* = 14.1, 7.3 Hz 2H), 2.39 (s, 6H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 176.4, 146.4, 138.4, 133.0, 130.0, 129.7, 128.4, 128.2, 127.8, 127.7, 119.2, 63.7, 42.9, 22.7; HRMS (ESI) *m/z*: $[M + Na]^+$ Calcd for $C_{19}H_{20}O_2SNa$ 335.1082; Found 335.1093.

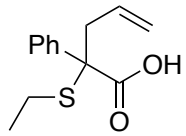


2-((4-Chlorophenyl)thio)-2-phenylpent-4-enoic acid (2m): Carboxylic acid compound **2m** was synthesized according to the general procedure using diazo compound **1a** (130 mg, 643 μmol, 100 mol %). The crude residue was purified by silica gel column chromatography using 5:1 hexanes/EtOAc with 1% AcOH to afford carboxylic acid **2m** as a transparent oil (121 mg, 380 μmol, 59.0%). ^{1}H NMR (500 MHz,

$CDCl_3$) δ 10.77 (s, 1H), 7.28-7.39 (m, 5H), 7.11-7.16 (m, 4H) 5.89 (dddd, *J* = 17.1, 10.3, 7.0, 6.8 Hz, 1H), 5.16 (dd, *J* = 10.3, 1.8 Hz, 1H), 5.12 (dd, *J* = 17.1, 1.6 Hz, 1H), 2.84-2.94 (m, 1H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 177.7, 138.6, 138.0, 136.1, 132.6, 129.0, 128.9, 128.4, 128.1, 127.7, 119.5, 64.4, 40.5; HRMS (ESI) *m/z*: $[M + Na]^+$ Calcd for $C_{17}H_{15}ClO_2SNa$ 341.0379; Found 341.0366.



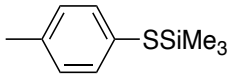
2-(Benzylthio)-2-phenylpent-4-enoic acid (2n): Carboxylic acid compound **2n** was synthesized according to the general procedure using diazo compound **1a** (140 mg, 692 μmol, 100 mol %). The crude residue was purified by silica gel column chromatography using 5:1 hexanes/EtOAc with 1% AcOH to afford carboxylic acid **2n** as a transparent oil (179 mg, 600 μmol, 86.6%) in an estimated 98% purity (85% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.59 (d, *J* = 8.7 Hz, 2H) 7.42 (t, *J* = 7.4 Hz, 2H), 7.34 (t, *J* = 7.8 Hz, 1H), 7.22-7.30 (m, 5H), 5.74 (dddd, *J* = 17.2, 10.2, 7.1, 6.9 Hz, 1H), 5.04 (t, *J* = 13.9 Hz, 2H), 3.80 (d, *J* = 12.2 Hz, 1H), 3.57 (d, *J* = 12.2 Hz, 1H), 2.94 (m, 2H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 178.5, 138.0, 136.6, 132.5, 129.3, 128.7, 128.5, 128.1, 127.9, 127.3, 119.3, 61.1, 43.4, 35.5; HRMS (ESI) *m/z*: $[M + Na]^+$ Calcd for $C_{18}H_{18}O_2SNa$ 321.0925; Found 321.0928.



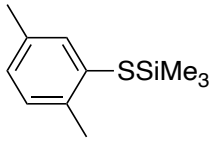
2-(Ethylthio)-2-phenylpent-4-enoic acid (2o): Carboxylic acid compound **2o** was synthesized according to the general procedure using diazo compound **1a** (175 mg, 865 μmol, 100 mol %). The crude residue was purified by silica gel column chromatography using 5:1 hexanes/EtOAc with 1% AcOH to afford carboxylic acid **2o** as a transparent oil (195 mg, 827 μmol, 95.5%) in an estimated 97% purity (93% yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.49 (d, *J* = 7.8 Hz, 2H), 7.36 (t, *J* = 7.8 Hz, 2H) 7.28 (t, *J* = 7.4 Hz, 1H), 5.67 (dddd, *J* = 17.2, 10.2, 7.1, 6.8 Hz, 1H), 4.98-5.03 (m, 2H), 2.93 (dd, *J* = 13.9, 6.2 Hz, 1H), 2.84 (dd, *J* = 14.5, 7.3 Hz, 1H), 2.57 (m, 1H), 2.40 (m, 1H), 1.17 (t, *J* = 7.7 Hz 3H). ^{13}C NMR (125

MHz, $CDCl_3$) δ 177.4, 138.2, 132.6, 128.3, 127.9, 127.6, 119.0, 60.4, 43.3, 24.4, 13.4; HRMS (ESI) *m/z*: [M +] Calcd for $C_{13}H_{16}O_2S$ 236.0871; Found 236.0865.

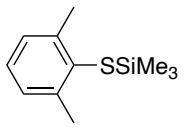
VIII. Synthesis and Characterization of Phenylthiotrimethylsilane Compounds 3j-3o



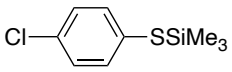
Trimethyl(*p*-tolylthio)silane (3j): To a solution of 4-methylbenzenethiol (24.2 mmol, 3.00 g) in diethyl ether (20 mL) was added slowly 1.6 M *n*-butyl lithium in hexanes (27 mmol, 17 mL) at -78 °C. Chlorotrimethylsilane (26.6 mmol, 3.37 mL) was added dropwise to the reaction mixture at -78 °C. The reaction was stirred for 4 hours at room temperature, then quenched with hexanes (13 mL). The mixture was evaporated, and the precipitated solids filtered off. The organic layer was evaporated, and the residue purified by distillation under reduced pressure to give the product (4.10 g, 20.9 mmol, 86.6%). bp: 85 °C/1.7 mm Hg. HRMS (ESI) m/*z*: $[M]^+$ Calcd for $C_{10}H_{10}SSi$ 196.0742; Found 196.0735. This is a known compound, and the spectral data is in agreement with the known data published.[7]



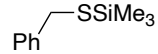
((2,5-Dimethylphenyl)thio)trimethylsilane (3k): To a solution of 2,5-dimethylbenzenethiol (21.7 mmol, 3.00 g) in diethyl ether (20 mL) was added slowly 1.6 M *n*-butyl lithium in hexanes (24 mmol, 15 mL) at -78 °C. Chlorotrimethylsilane (23.9 mmol, 3.03 mL) was added dropwise to the reaction mixture at -78 °C. The reaction was stirred for 4 hours at room temperature, then quenched with hexanes (13 mL). The mixture was evaporated, and the precipitated solids filtered off. The organic layer was evaporated, and the residue purified by distillation under reduced pressure to give the product (4.37 g, 20.8 mmol, 95.6%) in an estimated 98% purity (94% yield). bp: 90 °C/1.7 mm Hg. ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.23 (s, 1H), 7.09 (d, *J* = 7.8, 1H), 6.96 (d, *J* = 7.8 Hz, 1H), 2.38 (s, 3H), 2.28 (s, 3H), 0.27 (s, 9H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 138.70, 136.9, 135.5, 130.5, 130.2, 128.0, 21.6, 20.8, 1.0; HRMS (ESI) *m/z*: $[M + H]^+$ Calcd for $C_{11}H_{18}SSiNa$ 211.0977; Found 211.0983.



((2,6-Dimethylphenyl)thio)trimethylsilane (3l): To a solution of 2,6-dimethylbenzenethiol (14.5 mmol, 2.00 g) in diethyl ether (20 mL) was added slowly 1.6 M *n*-butyl lithium in hexanes (16 mmol, 10 mL) at -78 °C. Chlorotrimethylsilane (15.9 mmol, 1.73 g) was added dropwise to the reaction mixture at -78 °C. The reaction was stirred for 4 hours at room temperature, then quenched with hexanes (13 mL). The mixture was evaporated, and the precipitated solids filtered off. The organic layer was evaporated, and the residue purified by distillation under reduced pressure to give the product (2.55 g, 12.1 mmol, 83.9%). bp: 85 °C/1.7 mm Hg. HRMS (ESI) *m/z*: $[M]^+$ Calcd for $C_{11}H_{18}SSi$ 210.0898; Found 210.0888. This is a known compound, and the spectral data is in agreement with the known data published.[8]

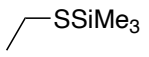


((4-Chlorophenyl)thio)trimethylsilane (3m): To a solution of 4-chlorobenzenethiol (20.0 mmol, 2.9 g) in diethyl ether (20 mL) was added slowly 1.6 M *n*-butyl lithium in hexanes (22 mmol, 14 mL) at -78 °C. Chlorotrimethylsilane (22.0 mmol, 2.4 g) was added dropwise to the reaction mixture at -78 °C. The reaction was stirred for 4 hours at room temperature, then quenched with hexanes (13 mL). The mixture was evaporated, and the precipitated solids filtered off. The organic layer was evaporated, and the residue purified by distillation under reduced pressure to give the product (525 mg, 2.40 mmol, 12.0%). bp: 85 °C/1.7 mm Hg. This is a known compound, and the spectral data is in agreement with the known data published.[9]



(Benzylthio)trimethylsilane (3n): To a solution of phenylmethanethiol (23.5 mmol, 2.92 g) in diethyl ether (20 mL) was added slowly 1.6 M *n*-butyl lithium in hexanes (26 mmol, 16 mL) at -78 °C. Chlorotrimethylsilane (25.9 mmol, 2.81 g) was added

dropwise to the reaction mixture at -78 °C. The reaction was stirred for 4 hours at room temperature, then quenched with hexanes (13 mL). The mixture was evaporated, and the precipitated solids filtered off. The organic layer was evaporated, and the residue purified by distillation under reduced pressure to give the product (2.50 g, 12.7 mmol, 54.2%). bp: 85 °C/1.7 mm Hg. HRMS (ESI) *m/z*: $[M]^+$ Calcd for $C_{10}H_{16}SSi$ 196.0742; Found 196.0732. This is a known compound, and the spectral data is in agreement with the known data published.[10]



(Ethylthio)trimethylsilane (3o): Compound **3o** was obtained commercially and used without further purification.

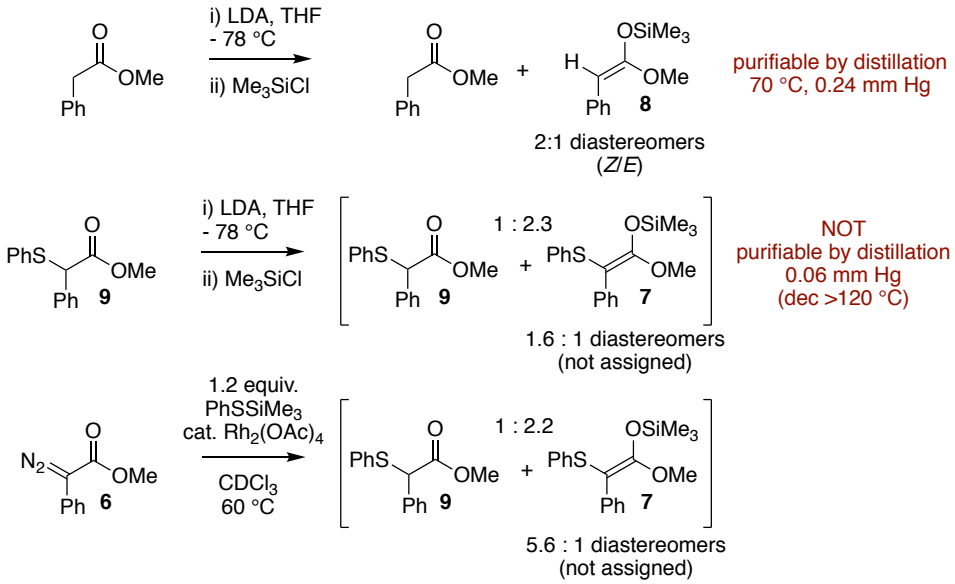
IX. Evidence for *O*-Silyl Ketene Acetals: Reaction of Methyl 2-diazo2-phenylacetate 6 with $PhSSiMe_3$ in $CDCl_3$

Traditional Silyl Ketene Acetals are Easily Distilled But Cpd 7 is Not Distillable ≥ 0.05 mm Hg

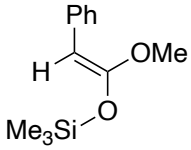
O-Silyl ketene acetals prepared from lithium enolates often contain starting material, even after non-aqueous workup. It is thought that the silyl ketene acetal is formed in quantitative yield (using LDA prepared from freshly titrated *n*-BuLi/hexanes and distilled *N*,*N*-diisopropylamine) but undergoes protodesilylation during workup. Traditional silyl ketene acetals such as **8** are readily purifiable by distillation (Scheme S1), and while unstable to GCMS (injector temp 250 °C), the molecular ion for silyl ketene acetal **8** (m/*z* 222) is present in the EI spectrum (70 eV). *In contrast*, the silyl ketene acetal **7** was not stable to distillation. Silyl ketene acetal **7** was also unstable to GCMS (injector temp 250 °C) but the EI mass spectrum (70 eV) did not present a molecular ion, nor did the corresponding GCMS with chemical ionization (NH_4^+). The broadened peak in the GC chromatogram that likely corresponds to the silyl ketene acetal **7**,

does give a parent ion at m/*z* 226 expected for fragmentation of silyl ketene acetals to ketene cation radical [Ph(PhS)C=C=O]$^{\bullet+}$.[11]

Scheme S1: *O*-Silyl ketene acetal 7 was not purifiable by distillation

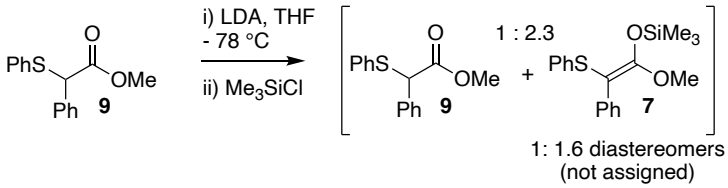


The inability to generate a pure sample of silyl ketene acetal **7**, led us to characterize the silylketene acetal **7** (generated from the lithium enolate) as a mixture with the protodesilylation product **9**. That mixture was used to identify the same two products in the rhodium reaction.



((1-Methoxy-2-phenylvinyl)oxy)trimethylsilane (*E*/*Z* = 2:1). *n*-BuLi (1.58 M in hexanes, 20.8 mL, 33.3 mmol) was added to a solution of diisopropylamine (4.70 mL, 33.3 mmol) in THF (25 mL) at 0 °C under an argon atmosphere, and the mixture was stirred at the same temperature for 10 min. After cooling to -78 °C, methyl phenylacetate (4.72 mL, 33.3 mmol) in THF (10 mL) was added to the mixture at the same temperature dropwise. After stirring for an additional 2 hours at -78 °C, TMSCl (10.6 mL, 82.2 mmol) was added dropwise to the mixture. The mixture was allowed to warm to room temperature and stirred overnight. Solvent was evaporated and the residue dissolved in 30 mL pentane, then

filtered through celite and washed with pentane. Solvent was evaporated and the crude product distilled by Vigreux column (b.p. 70 °C, 0.24 mm Hg) to afford the pure compound as a clear oil in a 2:1 mixture of *E* and *Z* diastereomers, respectively (2.35 g, 10.6 mmol, 38.1%). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.46 - 7.42 (m, 3.1H), 7.26 (t, *J* = 7 Hz, 3.4H), 7.05 (m, 1.5H), 4.71 (s, 1H), 4.62 (s, 0.5H), 3.71 (m, 4.7H), 0.35 (s, 9H), 0.31 (s, 5H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 158.0, 154.9, 137.2, 136.8, 128.2, 126.6, 126.4, 123.8, 123.6, 85.9, 78.8, 55.3, 53.9, 0.6, -0.1. This is a known compound, and the spectral data is in agreement with the published data.[12]

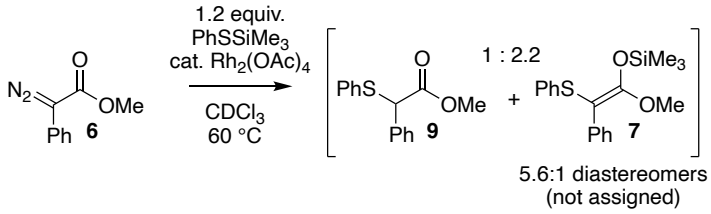


Generation of Methyl 2-phenyl-2-(phenylthio)acetate (9) + ((1-Methoxy-2-phenyl-2-(phenylthio)vinyl)oxy) trimethylsilane (7) from the Lithium Enolate

n-BuLi (1.58 M in hexanes, 12.1 mL, 19.4 mmol) was added to a solution of diisopropylamine (2.73 mL, 19.4 mmol) in THF (25 mL) at 0 °C under an argon atmosphere, and the mixture was stirred at the same temperature for 10 min. After cooling to -78 °C, methyl 2-phenyl-2-(phenylthio)acetate (5.0 g, 19.4 mmol) in THF (10 mL) was added to the mixture at the same temperature dropwise. After stirring for an additional 2 h at -78 °C, TMSCl (6.14 mL, 48.4 mmol) was added dropwise to the mixture. The mixture was allowed to warm to room temperature and stirred overnight. Solvent was evaporated and the residue dissolved in 30 mL pentane, then filtered through Celite and washed with pentane. Solvent was evaporated to afford the crude product as an olive oil (5.89 g, 17.8 mmol, 92.0%), consisting of a 1 : 2.3 mixture of methyl 2-phenyl-2-

(phenylthio)acetate and ((1-Methoxy-2-phenyl-2-(phenylthio)vinyl)oxy) trimethylsilane, the latter in a 1 : 1.7 ratio of diastereoisomers (not assigned).

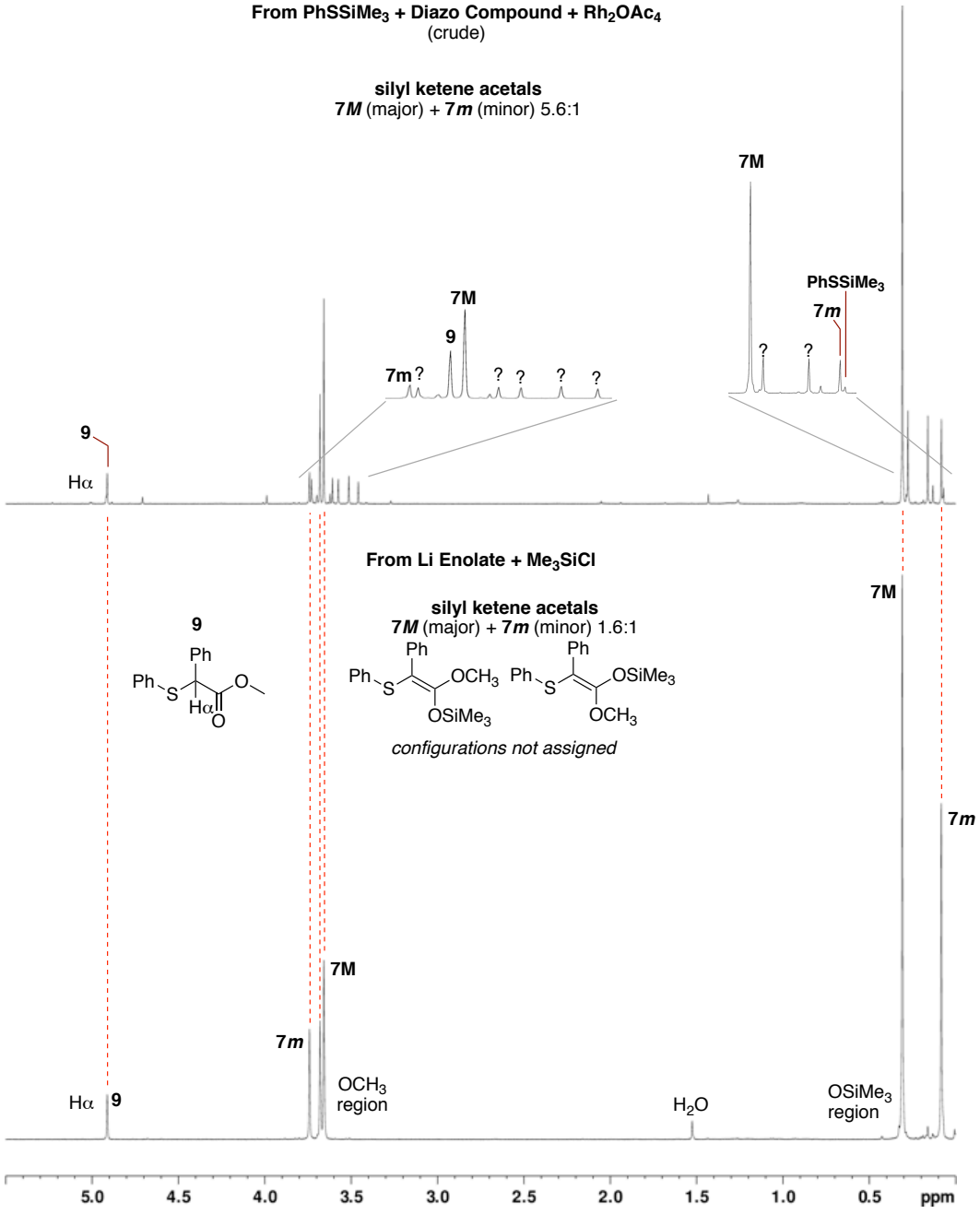
^{1}H NMR (500 MHz, $CDCl_3$) δ 7.61 - 7.05 (m, 38.1H), 7.26 (t, J = 7 Hz, 3.4H), 4.94 (s, 1.H), 3.77 (s, 2.7H), 3.70 (s, 3.2H), 3.68 (s, 4.6H), 0.33 (s, 13.8H), 0.11 (s, 8.1H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 170.9, 159.4, 159.3, 139.0, 138.9, 138.8, 138.7, 135.7, 133.8, 132.8, 129.8, 129.0, 128.7, 128.6, 128.4, 128.1, 127.8, 127.7, 126.0, 125.9, 125.5, 125.5, 124.5, 124.4, 87.4, 68.0, 56.6, 56.4, 55.7, 52.8, 25.7, 22.4, 14.1, 2.0, 0.5, 0.1.



The Presence of Methyl 2-phenyl-2-(phenylthio)acetate (9) + ((1-Methoxy-2-phenyl-2-(phenylthio)vinyl)oxy) trimethylsilane (7) in the Rhodium Reaction:

In a 10 mL round bottom flask was prepared a solution of rhodium tetraacetate (5.52 mg, 12.5 μmol, 2 mol %) in 3 mL $CDCl_3$. The flask was lowered into a 60 °C oil bath. In a 5 mL pear-shaped flask was prepared a solution of methyl 2-diazo-2-phenylacetate (110 mg, 624 μmol, 100 mol %) in 1 mL deuterated chloroform. The solution was withdrawn by syringe and fitted into a syringe pump apparatus. To the solution of rhodium tetraacetate was added neat trimethyl(phenylthio)silane (140 μL, 749 μmol, 120 mol %). Within one minute after addition of trimethyl(phenylthio)silane was completed, syringe pump addition of the diazo compound was initiated at a rate of 0.016 mL/min over 1 h. After 1 h, an additional 0.3 mL $CDCl_3$ was used to ensure complete transfer of the diazo compound from the 5 mL pear-shaped flask, and the reaction

was stirred at 60 °C for an additional 1 h. An aliquot was removed from the reaction flask by syringe for NMR analysis. Alignment with ^{1}H NMR spectrum of the silylketene acetal **7** obtained from silylation of the lithium enolate demonstrates the presence of the silyl ketene acetal in the rhodium reaction.



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Chapter 2

Enantioselective Halogen Insertion into α-Diazocarbonyl Compounds

Introduction

The chlorine atom is a good leaving group and can undergo S_N2 displacements with inversion of stereochemistry. Thus, chiral α-chloro carbonyl compounds are valuable chiral building blocks that can be used for a variety of transformations. Several pharmaceuticals also contain chiral α–carbon-halogen bonds, for example clindamycin for treatment of bacterial infections and clocortolone, a topical steroid used for treatment of various skin conditions.[1]

Several catalytic, asymmetric electrophilic α-halogenation of carbonyl compounds have been developed over the past few decades. In seminal work, Togni and coworkers reported in 2000 the first asymmetric α-halogenation of a β-ketoester. (Figure 2-1).[2a-b] The carbon–halogen bond is formed asymmetrically by selectively halogenating a single face of a chiral enolate derived from a chiral Lewis acid catalyst. α-Chlorination and α-fluorination proceeded with up to 90% ee, but α-bromination was less successful (23% ee). Later, late-transition metal Lewis acids with chiral ligands were used with 1,3-dicarbonyls, resulting in higher ee values for some substrates.[2c-g] In a different approach, Kim and coworkers used a chiral quaternary ammonium phase-transfer catalyst to direct fluorination to a single face of a prochiral enolate. The reaction gives excellent yields and moderate enantioselectivity.[3a] *N*-fluorobenzenesulfonimide was used as the fluorine source.

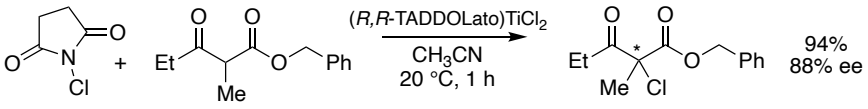


Figure 2-1. α-Halogenation of carbonyl compounds via titanium Lewis-acid catalysis

Chiral enolates generated through nucleophilic catalysis have also been used as nucleophiles in asymmetric halogenation. In 2005, Lectka and coworkers published a cinchona alkaloid catalyzed α-chlorination and α-bromination of carboxylic acid derivatives with up to 99% ee (Figure 2-2).[3b-e] Ketenes, generated from acyl chlorides, were used to generate chiral ammonium enolate intermediates in the presence of a nucleophilic cinchona catalyst. The chiral enolate undergoes selective α-halogenation on a single face in the presence of an electrophilic chlorine or bromine donor. The phenoxide leaving group from the halogenating agent is nucleophilic and generates an ester from the acyl ammonium intermediate.

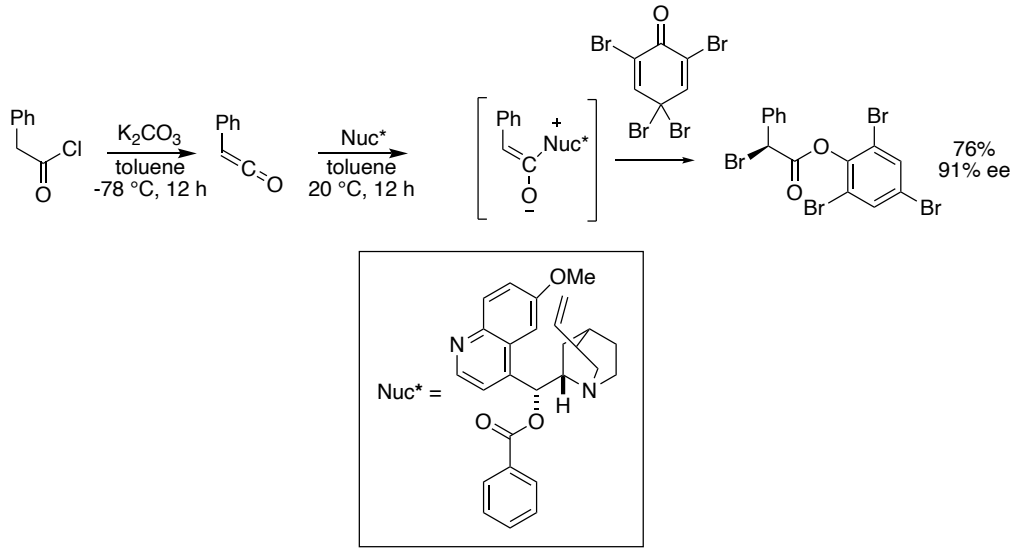


Figure 2-2. Cinchona alkaloid catalyzed α-chlorination

MacMillan and coworkers later reported the first organocatalytic α-chlorination of aldehydes employing an imidazolidinone organocatalyst to generate a chiral enamine (Figure 2-3).[3f] Jørgensen was able to extend this methodology to ketones with a different imidazolidinone catalyst.[3g]

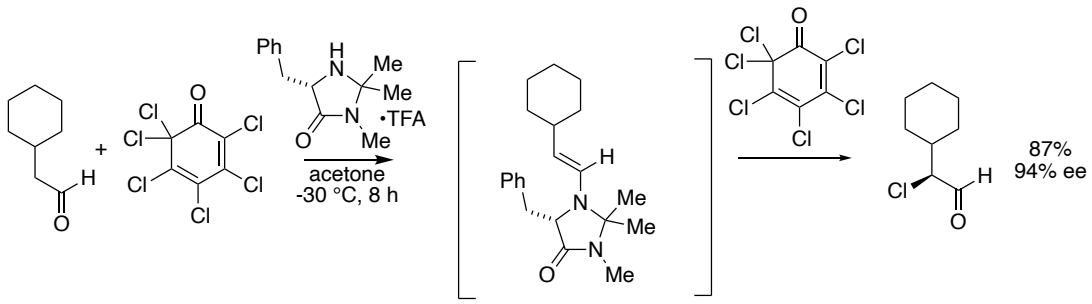


Figure 2-3. Organocatalytic α-halogenation of aldehydes

In a different approach, Yamamoto and coworkers then employed a stoichiometric chiral chlorinating agent to halogenate prochiral silyl enol ethers. A chiral 2,2-dichloro-1,3-dicarbonyl, activated by $ZrCl_4$, transfers electrophilic chlorine onto one face of the silyl enol ether (Figure 2-4).[3h] The enantioselectivity depends on the steric bulk of the silyl group, with ee values up to 98%.

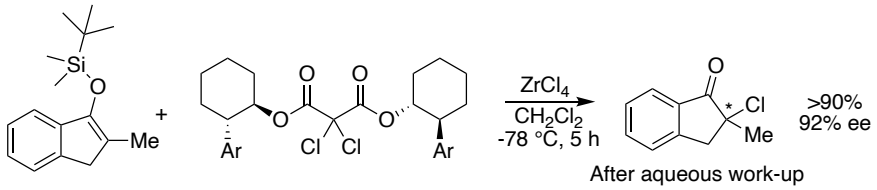


Figure 2-4. Asymmetric α-chlorination of silyl ketene acetals

In contrast to electrophilic halogenation to produce α-halocarbonyls, catalytic, asymmetric *nucleophilic* halogenation has been much less explored. Only two nucleophilic α-fluorination reactions of this type have been reported, with no corresponding α-chlorination or α-bromination. In 2016, a Cu(I)-catalyzed fluorination of α-diazocarbonyl compounds was reported using potassium fluoride with yields up to 81% (Figure 2-5).[4] Excess HFIP was used to solvate the KF. Although the reaction uses the chiral (*S,S*)-*t*-BuBOX ligand, enantioselectivity under the optimized conditions ($[Cu(MeCN)_4]PF_6$) was only 9%. Interestingly, when the pre-catalyst was replaced with $[Cu(OTf)]_2$•PhMe, modest asymmetric induction was achieved (31%

ee), although yields decreased to 62%. Reactions of this type correspond to formal insertion of a carbene into an X–H bond.

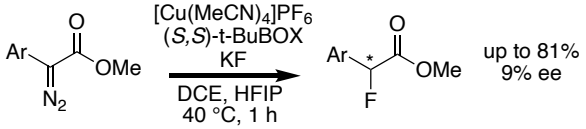


Figure 2-5. Cu(I)-catalyzed fluorination of α-diazocarbonyl compounds

Building on this work, Fürstner and coworkers were soon able to generate α-fluoroesters from α-diazoesters with *ee* values up to 96% using CsF in HFIP, $[Cu(OTf)]_2$•PhMe, and a novel indane-derived bis(oxazoline) ligand, "L19" (Figure 2-6).[5] High levels of asymmetric induction are dependent on the bulky benzyl substituents at the bridge and isopropyl groups at the core of the ligand. DFT calculations suggest the fluoride attacks the copper center of the catalyst rather than the electrophilic carbene carbon, followed by 1,2-migration of fluoride from copper to carbon to generate a fluoroenolate intermediate that is protonated selectively on one face.

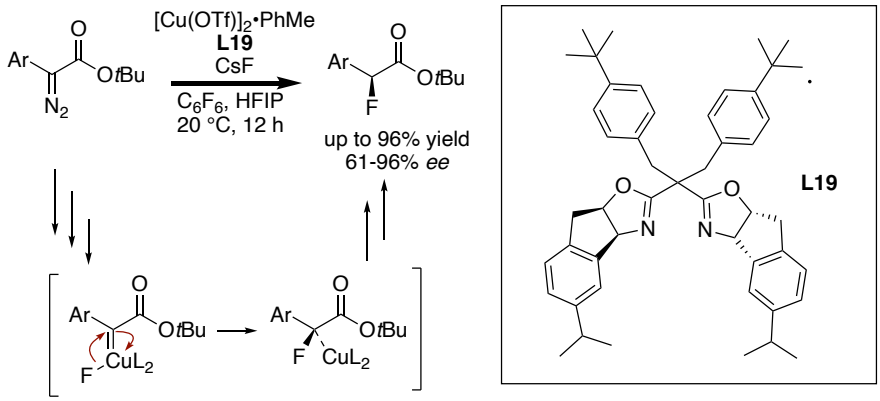


Figure 2-6. Generation α-fluoroesters from α-diazoesters using CsF in HFIP, $[Cu(OTf)]_2$•PhMe, and an indane-derived bis(oxazoline) ligand

There are no examples of formal asymmetric substitution of diazo compounds by H–Cl. Hsu, Chang and coworker have shown that copper triflate can catalyze substitution of diazo groups, in α-diazo-β-ketosulfones, with HCl using NH_4Cl. The authors did not invoke a metal carbene or chloroenolate intermediate.[6] We set out to develop an asymmetric metal-catalyzed insertion of carbene groups, derived from diazo compounds, into H–Cl bonds in two stages. First, we set out to demonstrate formation of chloroenolates from α-diazoesters. Second, we needed to overcome the competing protonation of diazo compounds by HCl or salts, to generate racemic insertion products, which occurs readily even in the absence of a transition metal catalyst.[7] To date, no catalytic asymmetric nucleophilic chlorination of α-diazoesters exists. Thus, we set out to demonstrate formation of chloroenolate intermediates from diazo compounds in high yield and explore asymmetric insertion of carbenes, generated from α-diazoesters, into H–Cl bonds.

Halogen Insertion into α-Diazocarbonyl Compounds

In principle, if a metal carbene was generated from an α-diazocarbonyl in the presence of a chiral ammonium chloride salt ($R_3N^*H^+ Cl^-$), chloride anion could add to the carbene, generating an enolate. The enolate, either free or associated with a chiral metal complex, could selectively protonate on one face, giving rise to asymmetric induction (Figure 2-7). Alternatively, in the presence of Me_3SiCl, the enolate could be *O*-silylated to form a silyl ketene acetal.

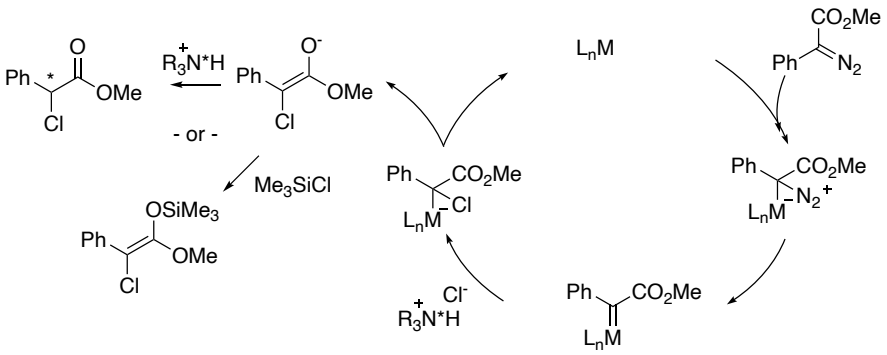
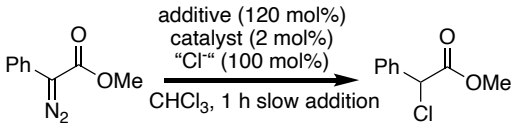


Figure 2-7. Possible mechanism for selective protonation of a chloroenolate generated from an α-diazocarbonyl compound in the presence of a metal catalyst

We explored the solubility of several amine•HCl salts in halogenated solvents typically used for rhodium catalyzed reactions of diazo compounds, but none of the amine•HCl salts had good solubility in halogenated solvents. Therefore, we abandoned the idea of using an ammonium counter-ion ($R_3N^*H^+$), as the chiral proton source. Tetraalkylammonium chloride salts are highly soluble in halogenated solvents but are prone to deprotonation at the α and β positions, leading to Stevens rearrangements and Hoffman eliminations, respectively. Instead, $Ph_4P^+Cl^-$ was selected as the chloride donor as it is known to be highly soluble in halogenated solvents and lacks protons at the α and β positions. As we had recent success in generating silyl ketene acetals from α-diazocarbonyl compounds, we decided to first generate silyl ketene acetals by addition of TMSCl to the enolate (Table 2-1), which carries the advantage of a second equivalent of chloride anion to the reaction, then to protonate the silyl ketene acetal using a chiral proton source.

Table 2-1. The role of metal and phosphonium salts in diazo substitution



entry	[diazo]	catalyst	"Cl⁻"	additive	T(°C)	yield
1	0.17 M	-	$Ph_4P^+Cl^-$	-	50	0%
2	0.17 M	$Rh_2(Oct)_4$	$Ph_4P^+Cl^-$	-	50	-
3	0.17 M	$Rh_2(Oct)_4$	-	TMSCl	50	-
4	0.17 M	$Rh_2(Oct)_4$	$Ph_4P^+Cl^-$	TMSCl	50	96%
5	0.17 M	-	$Ph_4P^+Cl^-$	TMSCl	50	96%
6	**0.17 M**	-	**$Ph_4P^+Cl^-$**	**TMSCl**	**20**	**96%**

α-Diazoesters do not react readily with Me_3SiCl at room temperature; alcohols can be readily silylated in the presence of α-diazoesters.[8] In the control experiment (entry 1), catalyst was omitted, and all of the starting material was recovered, showing that $Ph_4P^+Cl^-$ alone does not react with diazoesters. For these experiments we chose to use readily available $Rh_2(Oct)_4$ rather than $Rh_2(OAc)_4$. When $Rh_2(Oct)_4$ was added (entry 2), complete diazo consumption was observed (indicated by N_2 gas evolution), but the reaction only produced a complex mixture with no indication of the desired α-chloroester. With TMSCl as the source of chloride anion (entry 3), results were similar to entry 2. When both chloride sources were used (entry 4), a satisfying 96% yield of the α-chloroester was isolated after aqueous workup, supporting the formation of a chloro enolate intermediate, and ultimately a silyl ketene acetal (Figure 2-7). However, when the rhodium catalyst was omitted under these conditions, the yield of α-chloroester after aqueous workup remained excellent (entry 5), presumably by formation of a silyl ketene acetal, though the mechanism is unclear. As there were no proton sources prior to work-up, protonation must have occurred on addition of water. Notably, hygroscopic $Ph_4P^+Cl^-$ was presumed to be dry as it

was stored overnight over activated 3 Å mole sieves in dry $CHCl_3$. Me_3SiCl was purified by distillation and shown to be free of H_2O (^1H NMR). When the temperature was reduced to room temperature (entry 6), yield did not change. Tetraphenylphosphonium chloride seems to be catalyzing formation of silyl ketene acetals from α-diazoesters and Me_3SiCl. Inclusion of a chiral thiourea[9] and other chiral proton sources in the rhodium-free reaction directly afforded the racemic H–Cl insertion product.

We then decided to explore the use of HCl salts in a rhodium-catalyzed system (Figure 2-8). Methylphenyl diazoacetate was added by syringe pump over 4 hours to a solution of rhodium catalyst and HCl salt in $CHCl_3$ at room temperature. The HCl salt of MacMillan catalyst (**1**), gave a low yield of the HCl insertion product with statistically insignificant ee (< 2%, Chiralcel OD-H column). Cinchonidine•HBr salt (**2**) gave an even lower yield of the HBr insertion product with no asymmetric induction, so we chose to set aside HBr insertions (Figure 2-8).

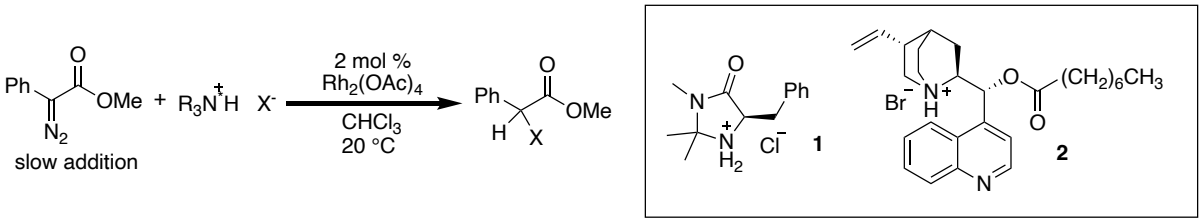
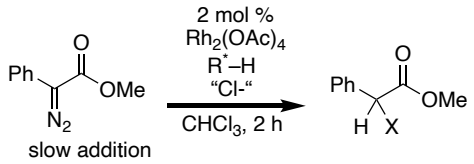


Figure 2-8. HCl salts in a rhodium-catalyzed system

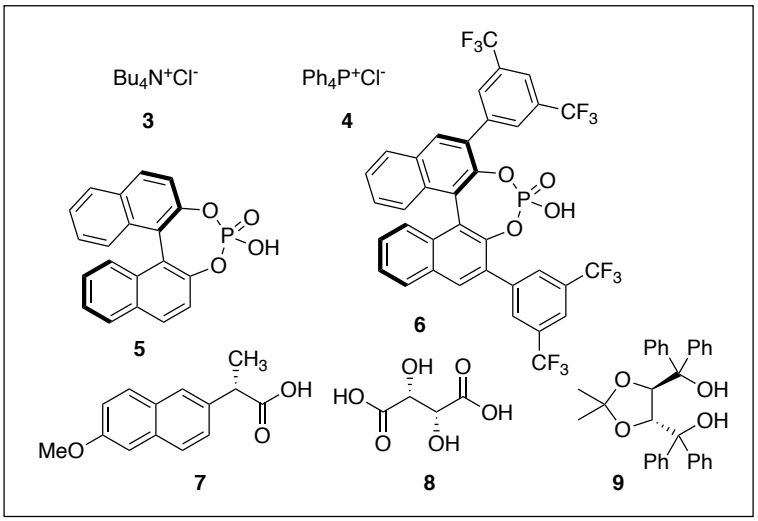
We reasoned that the low yield might be attributable to the generation of amine free base sequestering the catalyst. So, we next decided to employ tetrabutylammonium chloride with a chiral proton donor. Zhou and coworkers have employed chiral phosphoric acids with amine nucleophiles to achieve formal N–H insertion with diazo compounds with high yields and asymmetric induction.[10] Various combinations of tetrabutylammonium chloride (**3**) and tetraphenylphosphonium chloride (**4**) with chiral phosphoric acids (**5** and **6**), chiral carboxylic

acids (**7** and **8**) and other proton sources (TADDOL - **9**) failed to give appreciable yields (Table 2.2, entries 1-5) with the exception of $Ph_4P^+Cl^-$/binaphthyl phosphoric acid **5**, which gave a modest 30% yield of racemic product (entry 6).

Table 2-2. Achiral rhodium catalyst with chiral protic acid



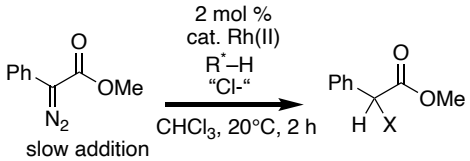
entry	"Cl⁻" (mol %)	R*–H (mol %)	T(°C)	yield	% ee
1	**3** (120)	**6** (120)	20	-	-
2	**3** (120)	**5** (120)	40	trace	-
3	**3** (120)	**9** (120)	40	trace	-
4	**3** (120)	**7** (120)	20	-	-
5	**4** (120)	**8** (120)	20	-	-
6	**4** (100)	**5** (120)	20	30%	-



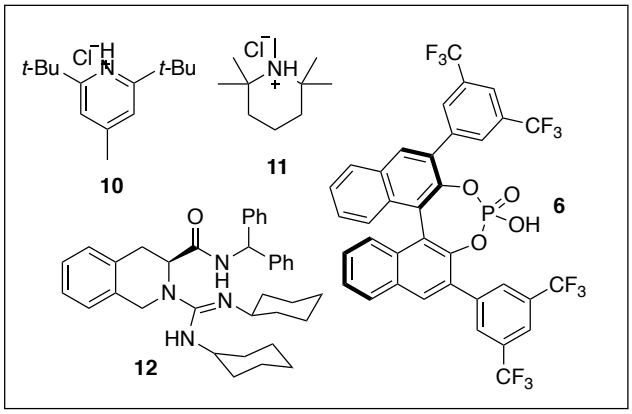
At this point we explored combinations of stoichiometric hindered pyridinium chloride salts (**10**) in combination with catalytic amounts of chiral proton donors **12** and **6** previously used for enantiotopic protonation of enolates. Both combinations gave promising yields above 70%

(Table 2-3, entries 1 and 2). To confirm the catalytic role of the rhodium catalyst, a control experiment was run without $Rh_2(Oct)_4$ and was shown to give no product (entry 3). Unfortunately, the products of these combinations were racemic. Combinations of chiral catalyst $Rh_2(R\text{-PTAD})_4$ and $Rh_2(R\text{-BTPCP})_4$[11] with DTBMP•HCl (**10**) and PMP•HCl (**11**), respectively, also gave promising amounts of HCl insertion product but with no asymmetric induction.

Table 2-3. Stoichiometric hindered pyridinium chloride salts with chiral proton donors or chiral catalyst



entry	cat. Rh(II)	"Cl^-" (mol %)	R^*–H (mol %)	yield	% ee
1	$Rh_2(Oct)_4$	**10** (150)	**12** (2)	70%	-
2	$Rh_2(Oct)_4$	**10** (150)	**6** (2)	76%	-
3	-	**10** (150)	**12** (2)	-	-
4	$Rh_2(R\text{-PTAD})_4$	**10** (150)	-	53%	-
5	$Rh_2(R\text{-BTPCP})_4$	**11** (150)	-	85%	-

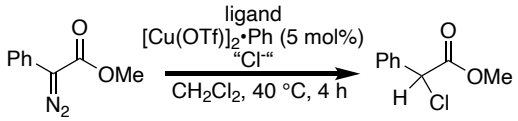


Most enantioselective insertions of carbene ligands into O–H and N–H bonds employ copper-catalyzed systems.[12-13] Huw Davies has proposed that the success of copper is attributable

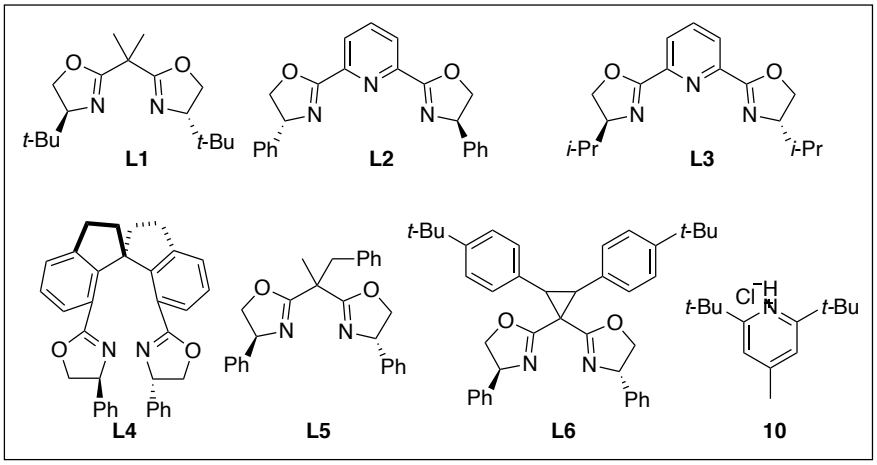
to a different mechanism involving formation of a chiral *C*-bound copper enolate in contrast with *O*-bound rhodium enolates.[14] Therefore, since the rhodium/chiral auxiliary strategy did not result in significant ee, we next decided to explore combinations of copper catalysts and chiral BOX ligands.

The promising conditions for chiral rhodium catalysis (Table 2-2) were extended to chiral copper catalyst systems. Methylphenyl diazoacetate was added by syringe pump over 4 hours to a solution of 5 mol % copper catalyst, prepared by pre-mixing the copper pre-catalyst with the BOX ligand and HCl salt in CH_2Cl_2. Reactions were monitored by TLC and worked up when diazo compound was consumed or when no further consumption of diazo was observed. Results with $[Cu(OTf)]_2$•Ph with BOX ligands gave promising yields of the HCl insertion product (Table 2-3). The highest yield (85%) was obtained with $[Cu(OTf)]_2$•Ph catalyst, three equivalents di-tert-butyl-methylpyridinium chloride source **10**, and Ph-PYBOX ligand **L2**. Unfortunately, this copper system did not result in significant asymmetric induction, much like the rhodium systems attempted previously.

Table 2-4. Results with $[Cu(OTf)]_2$•Ph and BOX ligands

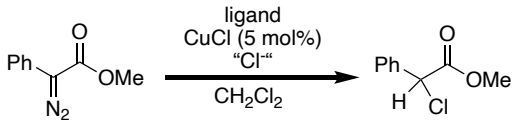


entry	catalyst	"Cl-" (mol %)	ligand (mol %)	yield	% ee
1	$[Cu(OTf)]_2$•Ph	**10** (150)	**L1** (8)	63%	-
2	$[Cu(OTf)]_2$•Ph	**10** (150)	**L4** (12)	48%	-
3	$[Cu(OTf)]_2$•Ph	**10** (300)	**L2** (12)	85%	-

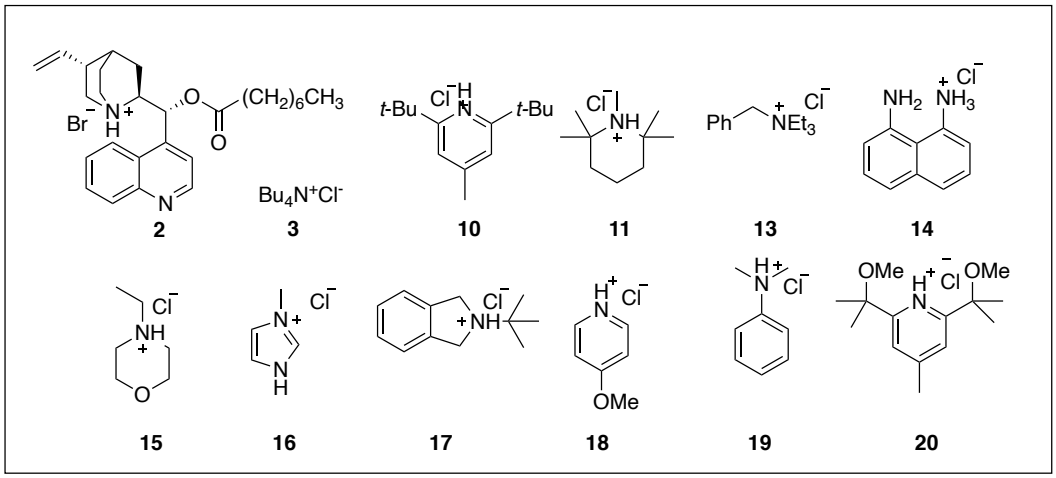


Zhou and coworkers successfully used a CuCl/$NaBAr^F_4$/SpiroBOX catalyst system for asymmetric N-H,[15] O-H,[16] S–H,[17] and B-H[18] insertion reactions. The Zhou catalyst gave similar results to the Cu(II) pre-catalyst system for H–Cl insertion (Table 2-5, entries 1 and 2). An experiment with PMP•HCl (**11**) gave no product (entry 3). Yields with other Cu(I)/BOX systems (entries 4-13) were significantly lower.

Table 2-5. Results with Cu(I)/BOX systems



entry	"Cl⁻" (mol %)	ligand (mol %)	additive (mol %)	T(°C)	t (hours)	yield	% ee
1	**10** (300)	**L4** (6)	$NaBAr_F$ (6)	20	3	72%	-
2	**10** (300)	**L4** (6)	$NaBAr_F$ (6)	0-20	24	74%	-
3	**11** (300)	**L4** (6)	$NaBAr_F$ (6)	20	4	0%	-
4	**10** (100)	**L4** (6)	-	20	3	25%	-
5	**2** (100)	**L5** (6)	-	40	19	0%	-
6	**3** (100)	**L5** (6)	-	40	4	0%	-
7	**14** (100)	**L5** (6)	-	40	4	0%	-
8	**15** (100)	**L5** (6)	-	20	20	59%	-
9	**16** (100)	**L5** (6)	-	40	20	0%	-
10	**17** (100)	**L4** (6)	-	20	24	trace	-
11	**18** (120)	**L5** (6)	-	20	4	0%	-
12	**19** (100)	**L6** (6)	-	20	20	38%	-
13	**20** (100)	**L4** (6)	-	20	3	50%	-



In conclusion, we observed that tetraphenylphosphonium chloride seems to be catalyzing formation of silyl ketene acetals from α-diazoesters and Me_3SiCl, which are protonated on work-up to give the corresponding α-chloroester in high yield. We developed rhodium and copper-catalyzed systems that give α-chloroester in yields up to 85%. Screening a variety of chiral

proton sources and chiral ligands did not result in significant asymmetric induction. As there are inexpensive methods already available to chlorinate the α-position of carbonyl compounds to give racemic products, we decided to pause research in this area and continue exploration of tandem sulfur-insertion/sigmatropic rearrangement processes.

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Chapter 2 Experimental

I. General methods: Reactions were run in oven-dried glassware. Reaction flasks were evacuated, backfilled with argon, and reactions were carried out under an atmosphere of argon. ^{1}H and ^{13}C NMR spectra were recorded at room temperature using a Bruker 500 MHz (^{1}H) spectrometer equipped with a cryoprobe and referenced to TMS. NMR signals are reported as follows: chemical shift in ppm, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet, app = apparent), coupling constants in Hz if applicable, and proton integration. High Resolution Mass Spectrometry data was obtained on a MicroMass MS Technologies LCT Premier instrument using ESI-TOF. Molecular sieves were activated with a flame *in vacuo*. Catalysts were obtained commercially and used without further purification. Chlorinated solvents were refluxed over CaH_2 (5% w/v), distilled and stored over 3 Å molecular sieves prior to use. Column chromatography was performed under pressure using SiliCycle™ Silia*Flash*™ P60, 40-63 μm 60Å. Eluant mixtures are listed as v/v ratios. Unless otherwise indicated, compounds were purified to ≥95% purity as judged by ^{1}H NMR integrations, otherwise the purity was estimated based on the mole fraction of impurities. Chloride salts were purchased commercially or generated by protonating the corresponding amine with a molar equivalent of 12 M HCl to form the precipitate, which was filtered, dried at 40 °C under high vacuum, then stored overnight over activated 3 Å mole sieves.

II. General Procedure for Metal-Free Synthesis of Methyl 2-Chloro-2-Phenylacetate:

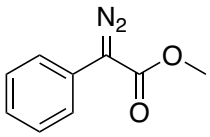
$Ph_4P^+Cl^-$ (100 mol %) was stored overnight over 3 Å molecular sieves in dichloromethane prior to use. TMSCl (120 mol %) was added to the solution of $Ph_4P^+Cl^-$. In a 5 mL pear-shaped flask was prepared a solution of diazo compound (100 mol%) in 1 mL dichloromethane. The solution was withdrawn by syringe and fitted into a syringe pump apparatus. Syringe pump addition of the diazo compound was initiated at a rate of 0.016 mL/min over 1 h. The reaction was then

extracted with dichloromethane, water, and brine. The organic layer was dried over sodium sulfate, filtered, and concentrated by rotary evaporation. The methyl 2-chloro-2-phenylacetate product was purified by silica gel chromatography.

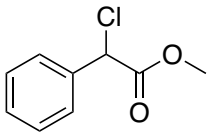
III. General Procedure for Rh(II)-Catalyzed Synthesis of Methyl 2-Chloro-2-Phenylacetate: Chloride salt (150 mol %) was stored overnight over 3 Å molecular sieves in chloroform prior to use. In a round bottom flask was prepared rhodium catalyst (2 mol %) and chiral additive (2 mol %). After backfilling with argon, the solution of chloride salt was transferred to the round-bottom flask. In a 5 mL pear-shaped flask was prepared a solution of diazo compound (100 mol%) in 1 mL chloroform. The solution was withdrawn by syringe and fitted into a syringe pump apparatus. Syringe pump addition of the diazo compound was initiated at a rate of 0.008 mL/min over 2 h. The reaction was then extracted with dichloromethane, water, and brine. The organic layer was dried over sodium sulfate, filtered, and concentrated by rotary evaporation. The methyl 2-chloro-2-phenylacetate product was purified by silica gel chromatography.

IV. General Procedure for Cu(I)-Catalyzed Synthesis of Methyl 2-Chloro-2-Phenylacetate: Chloride salt (150 mol %) was stored overnight over 3 Å molecular sieves in dichloromethane prior to use. In a round bottom flask was prepared copper catalyst (5 mol %) and ligand (12 mol %). After backfilling with argon, 2 mL dichloromethane was added, and the solution was stirred for 30 min. The solution of chloride salt was then transferred to the round-bottom flask, a condenser was fitted, and the solution brought to reflux. In a 5 mL pear-shaped flask was prepared a solution of diazo compound (100 mol%) in 1 mL dichloromethane. The solution was withdrawn by syringe and fitted into a syringe pump apparatus. Syringe pump addition of the diazo compound was initiated at a rate of 0.004 mL/min over 4 h. The reaction was then

extracted with dichloromethane, water, and brine. The organic layer was dried over sodium sulfate, filtered, and concentrated by rotary evaporation. The methyl 2-chloro-2-phenylacetate product was purified by silica gel chromatography.



Methyl 2-Diazo-2-Phenylacetate: A round-bottom flask equipped with stir bar was charged with p-acetamidobenzenesulfonyl azide (23.7 mmol, 120 mol %) and dry acetonitrile. To the stirred solution was added the α-phenyl ester (19.8 mmol, 100 mol %). The solution was cooled in an ice-water bath for 15 minutes. Separately, a 1 M solution of DBU (24.7 mmol, 125 mol %) in dry acetonitrile was prepared, and then added to the reaction mixture dropwise over ca. 5 min. The solution was warmed gradually to room temperature and stirred for an additional 16 h. The resulting orange solution was diluted with 100 mL Et_2O and washed with half-saturated aq. ammonium chloride solution (2 ×), water and brine. The organic layer was dried over sodium sulfate, filtered, and concentrated by rotary evaporation. The α-phenyl-α-diazoester was purified by silica gel chromatography (92 % hexanes, 8 % EtOAc) to give 2.60 g orange oil (14.8 mmol, 74.7 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.49 (d, J = 7.9 Hz, 2H), 7.39 (t, J = 7.4 Hz, 2H), 7.19 (t, J = 6.9 Hz, 1H), 3.87 (s, 3H). This is a known compound, and the spectral data is in agreement with the known data published.[1]



Methyl 2-chloro-2-phenylacetate: $Ph_4P^+Cl^-$ (1.14 mmol, 100 mol %) was stored overnight over 3 Å molecular sieves in dichloromethane prior to use. TMSCl (1.36 mmol, 120 mol %) was added to the solution of $Ph_4P^+Cl^-$. In a 5 mL pear-shaped flask was prepared a solution of diazo compound (1.14 mmol, 100 mol%) in 1 mL dichloromethane. The solution was withdrawn by syringe and fitted into a syringe pump apparatus. Syringe pump addition of the diazo compound was initiated at a rate of 0.016 mL/min

over 1 h. The reaction was then extracted with dichloromethane, water, and brine. The organic layer was dried over sodium sulfate, filtered, and concentrated by rotary evaporation. The methyl 2-chloro-2-phenylacetate product was purified by silica gel chromatography (90 % hexanes, 10 % EtOAc) to give 0.202g clear oil (1.10 mmol, 96.1 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.48-7.49 (m, 2H), 7.37-7.38 (m, 3H), 5.36 (s, 1H), 3.77 (s, 3H). This is a known compound, and the spectral data is in agreement with the known data published.[2]

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Chapter 3

Rhodium(II)-Catalyzed Hinsberg Dearomatization Using Trimethylsilyldiazomethane

Introduction

Oscar Hinsberg first reported the base-induced rearrangement of sulfonium ylides in 1931.[1] Later, Teresa and coworkers identified the reaction as a [2,3]-sigmatropic rearrangement[2] (Figure 3-1).

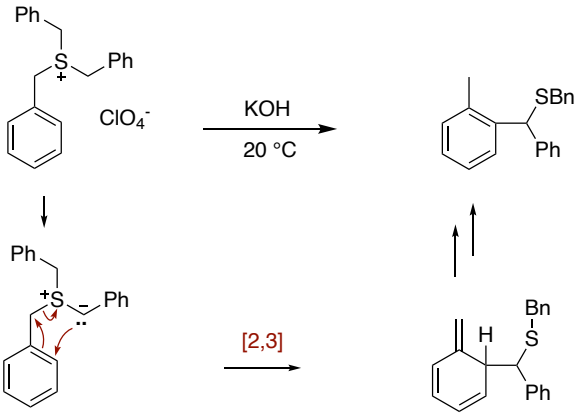


Figure 3-1. Base-induced rearrangement of sulfonium ylides

With the *ortho* positions blocked, Hayashi and coworkers attempted to generate dearomatized products in 1968 but found them thermally unstable. The triene products of the rearrangement underwent thermal isomerization to generate re-aromatized products.[3a] Van Vranken and coworkers reported a stereoselective [2,3] sigmatropic benzylsulfonium ylide dearomatization using lithium amide bases in 1998 (Figure 3-2). The sulfonium ylides used in this reaction generate products that are stable to silica gel and can be isolated by column chromatography.[3b] An enantioselective version was later reported using chiral lithium amide bases.[3c]

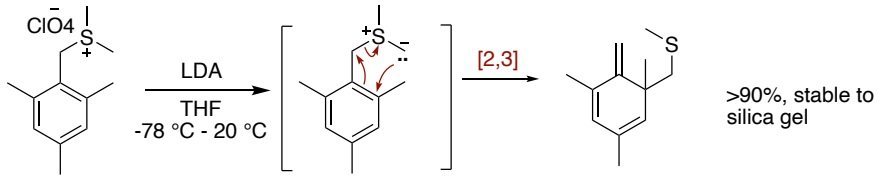


Figure 3-2. Stereoselective [2,3] sigmatropic benzylsulfonium ylide dearomatization

A fluoro-desilylation method for generating sulfonium ylides was reported by Padwa in 1986, which allows for greater regiocontrol by generating carbanions via desilylation rather than with strong base[3d] (Figure 3-3). Although the yield of dearomatized product was found to be 80% (^{1}H NMR), these products were unstable to silica gel, rearomatizing via an apparent 1,5 shift when placed on the silica-gel column.

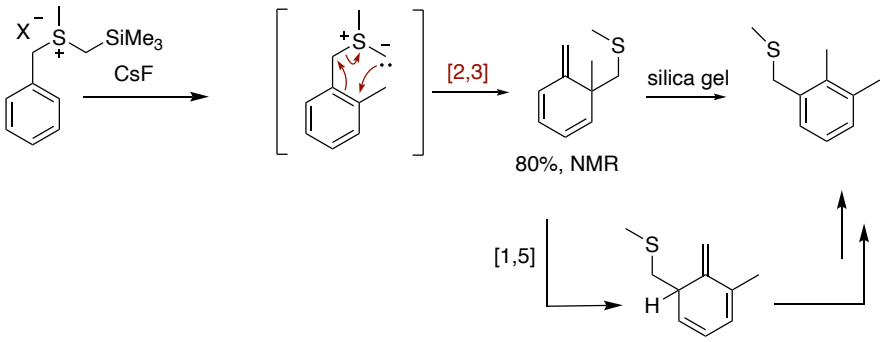


Figure 3-3. A fluoro-desilylation method for generating sulfonium ylides

Generation of oxa-sulfonium ylides from phenols and subsequent [2,3]- rearrangement is also a known process. In 1967, Moffatt was able to oxidize phenols to generate phenoxy-sulfonium ylides that undergo [2,3] sigmatropic dearomatization (Figure 3-4).[4a] Similar transformations were later reported using Parikh-Doering[4b] and Corey-Kim[4c] oxidation conditions.

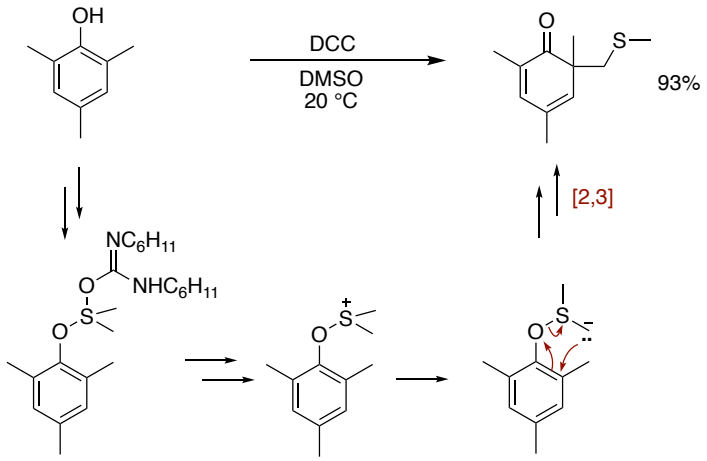


Figure 3-4. Oxidation of phenols to generate phenoxy-sulfonium ylides that undergo [2,3] sigmatropic dearomatization

In 1996, Barton and coworkers showed that the cyclohexadienone products are susceptible to photochemical electrocyclic ring opening with visible light to give ketenes (Figure 3-5), which were subsequently trapped with water, alcohols, or amines to give carboxylic acid derivatives.[4d] This could be a potential undesired side-reaction for this class of transformations. In a somewhat different approach, Casnati used a carbocation generated from *t*-butyl bromide and DMSO to generate phenoxy-sulfonium ylides that also undergo [2,3] sigmatropic dearomatization.[4e]

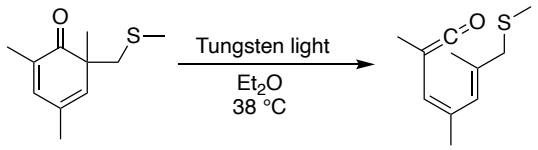


Figure 3-5. Cyclohexadienone products are susceptible to photochemical electrocyclic ring opening

Similar [2,3]-rearrangements of benzylammonium ylides were first reported by Sommelet in 1937[5a] and then by Hauser in 1951, who was able to demonstrate efficient [2,3]-rearrangement

of benzylammonium ylides with $NaNH_2$.[5b] Several years later, Hauser reported the first example of a [2,3]-dearomatization of benzylammonium ylides with $NaNH_2$.[5c-d] The *exo*-methylene cyclohexadiene products were shown to undergo thermal rearomatization or acid-catalyzed rearomatization with loss of *N*,*N*-dimethyliminium ion (Figure 3-6). Aggarwal has isolated an unexpected product of [2,3]-dearomatization without a quaternary center, but the product was unstable to tautomeric rearomatization at room temperature.[5e]

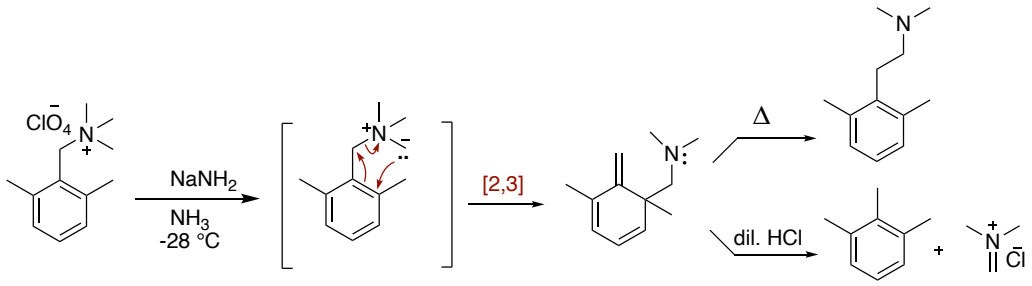


Figure 3-6. Cyclohexadiene products were shown to undergo thermal rearomatization and acid-catalyzed rearomatization

The regioselective fluoro-desilylation method discussed previously to generate sulfonium ylides was also used in 1992 to generate ammonium ylides by Saito and coworkers. However, yields of the [2,3]-dearomatization products were modest due to homolytic cleavage at the benzylic position and subsequent 1,2-Stevens rearrangement.[5f-g]

The preferred method of generating sulfonium ylides under *mild* conditions is via metal-catalyzed transfer of carbene groups to thioethers. A well-known reaction using allylsulfonium ylides which spontaneously undergo [2,3]-sigmatropic rearrangement is the Doyle-Kirmse reaction (Figure 3-7). Generally, copper[6] or rhodium[7] catalysts are used in the transformation, which also works for allylamines,[8] allylethers,[9] and allylhalides.[10] With weak nucleophiles such as halogens and oxygen, cyclopropanation is in competition with ylide formation.[11]

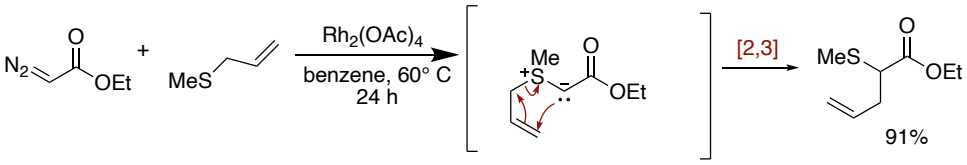


Figure 3-7. Doyle-Kirmse reaction

In the case of benzylic substrates, the reaction is more challenging due to competing Stevens rearrangement (homolytic cleavage followed by recombination). Typical diazo compounds contain pi acceptors (e.g., ethyl diazoacetate), which slow down the [2,3]-rearrangement by stabilizing the ylide and accelerate the Stevens process by captodative stabilization.[12,13] In spite of this, there are examples of benzyl thioethers reacting with rhodium[14] and copper[15] carbenes containing pi acceptors which undergo the Hinsberg reaction (Figure 3-8).

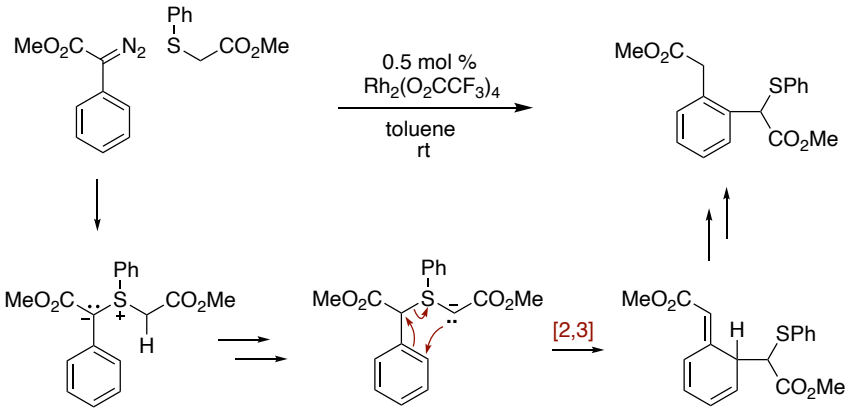


Figure 3-8. Benzyl thioethers undergo the Hinsberg reaction

The [2,3]-sigmatropic rearrangement occurs after proton transfer and the dearomatized intermediate isomerizes to give aromatic products. This reaction has also been carried out using sulfoxonium ylides instead of diazo precursors (Figure 3-9).[16]

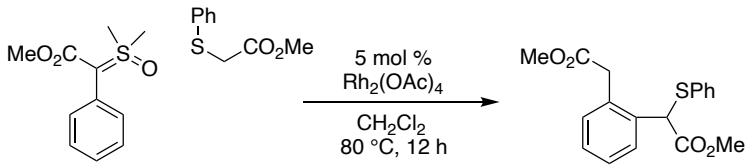


Figure 3-9. Sulfoxonium ylides instead of diazo precursors

In a recent development, a copper-catalyzed dearomatization of tetrahydroisoquinolines with α-diazoesters was reported,[17] wherein spirocyclic triene products of a Sommelet-Hauser reaction were stable to silica gel (Figure 3-10). The copper catalyst reacts with ethyl diazoacetate to generate a copper carbene which is attacked the amine starting material to generate an ammonium ylide. A rapid intramolecular reaction to generate spirocyclic compounds follows. Interestingly, steric repulsion between the two *ortho* substituents increases the distortion in the biaryl structure, enhancing its reactivity. Without the *ortho* substituents, yields decrease significantly due to competing Stevens rearrangement.

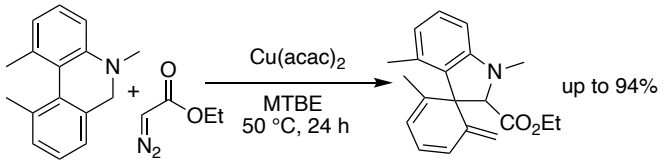


Figure 3-10. Copper-catalyzed dearomatization of tetrahydroisoquinolines

As there is increasing interest in metal-catalyzed dearomatization reactions involving various rearrangements,[18] we decided to investigate the first metal-catalyzed Hinsberg dearomatization of benzylsulfonium ylides generated from thioethers and a diazo compound.

Hinsberg Dearomatization Using Trimethylsilyldiazomethane

We chose to avoid α-diazoesters as carbene precursors in order to mitigate competing Stevens rearrangement, as pi-acceptors stabilize the ylide, slowing down the desired process and increasing the likelihood of homolytic cleavage. Thus, we began our experiment with trimethylsilyldiazomethane (TMSD)[19]. As substrate, we chose aryl benzyl thioether **1** (Figure 3-11) and selected conditions typical for Doyle-Kirmse reaction of allyl thioethers.[20] Unfortunately, the reaction generated thioether **2** resulting from Stevens rearrangement in 73% yield with no trace of the desired [2,3]-rearrangement product.

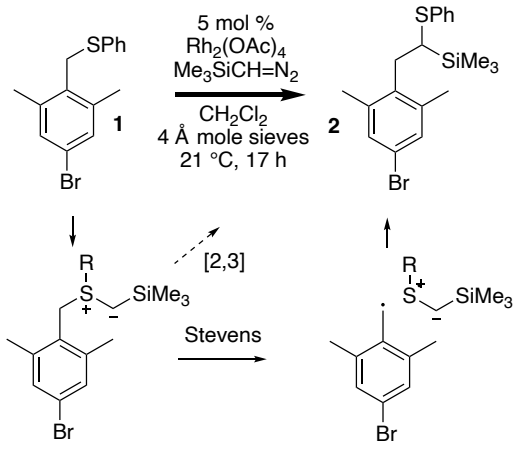
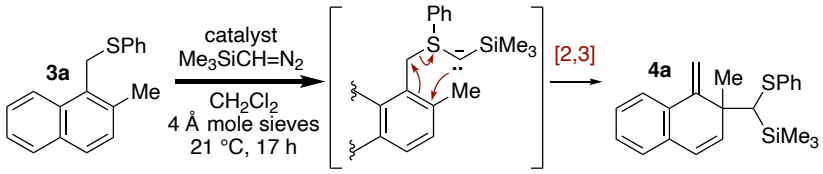


Figure 3-11. Aryl benzyl thioether **1** and trimethylsilyldiazomethane under conditions typical for Doyle-Kirmse reaction of allyl thioethers

Reasoning that the reaction might be successful on a substrate with lower resonance energy than benzene, we decided to attempt the reaction on naphthalene substrate **3a** (Table 3-1). The second ring in the naphthalene system is around 10 kcal/mol lower in resonance energy than benzene,[21] and should facilitate the [2.3]-rearrangement. On the other hand, there was a concern cyclopropanation might be a problem.[22] Happily, we obtained the Hinsberg dearomatization product in 80% yield along with unreacted starting material, which suggests the diazo was being

consumed by dimerization. Aggarwal and coworkers had previously shown TMSD undergoes dimerization under rhodium catalysis to give the azine dimer.[23] Dilution to 0.08M thus increased the yield to 91% (entry 2), and it was then discovered additional TMSD was not necessary for good yield (entry 3). We were able to reduce catalyst loading to 4% (entry 4) without sacrificing yield, but further reduction had a detrimental effect (entry 5). Concerned about catalyst stability, we screened the reaction with the more robust Du Bois catalyst, $Rh_2(esp)_2$ but results were similar to that expected for $Rh_2(OAc)_4$ (entry 6). We also tried heating the reaction (entry 7), and 2% mol $Rh_2(OAc)_4$ yielded 83% of product at 40 °C.

Table 3-1. Optimization table



entry	[thioether]	catalyst	mol % cat	equiv. diazo	yield **4a**
1	0.17 M	$Rh_2(OAc)_4$	5 mol %	3	80%
2	0.08 M	$Rh_2(OAc)_4$	5 mol %	3	91%
3	0.08 M	$Rh_2(OAc)_4$	5 mol %	1	91%
4	**0.08 M**	**$Rh_2(OAc)_4$**	**4 mol %**	**1**	**91%**
5	0.08 M	$Rh_2(OAc)_4$	3 mol %	1	70%
6	0.08 M	$Rh_2(esp)_2$	2 mol %	1	63%
7	0.08 M	$Rh_2(OAc)_4$	2 mol %	1	83%*
8	0.08 M	$Cu(acac)_2$	10 mol %	1	21%
9	0.08 M	$Cu(acac)_2$	15 mol %	1	30%
10	0.08 M	$Cu(acac)_2$	100 mol %	1	100%
11	0.08 M	CuI+BiPy	10 mol %	1	0%
12	0.17 M	none	-	3	0%

* 40 °C

Reasoning we had optimized to reaction for $Rh_4(OAc)_4$, we decided also to experiment with inexpensive $Cu(acac)_2$ under the same conditions. At first, the copper catalyst gave low yield, but increasing the loading from 10% to 15% increased yield to 30% (entry 9). Using

stoichiometric $Cu(acac)_2$ the yield was quantitative. Therefore, there is an inexpensive method of carrying out the reaction non-catalytically using cheap Cu(II), if the cost of rhodium is a concern to the user. We also ran a control experiment (entry 12), which confirmed the reaction is metal-catalyzed.

Product **4a** was formed as an 8:1 mixture of diastereomers regardless of the catalyst used or the conditions employed. Both *syn* and *anti* products are expected from 4 diastereotopic transition states (Figure 3-12, PBE0/def2-TZVP (gas phase), R = H).

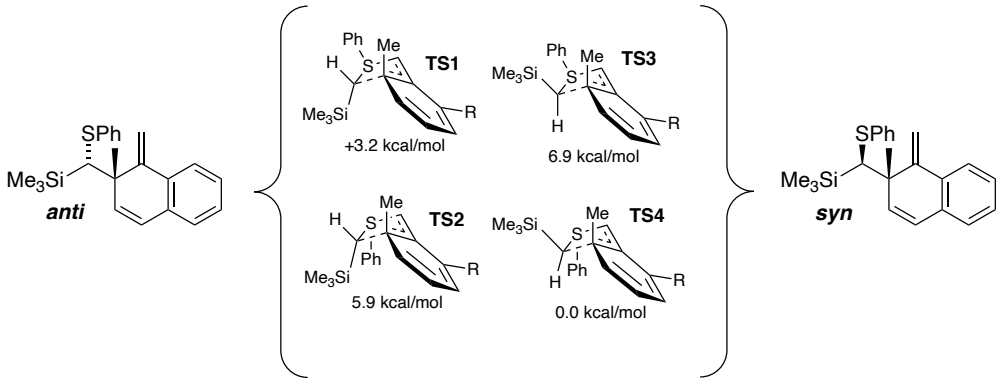


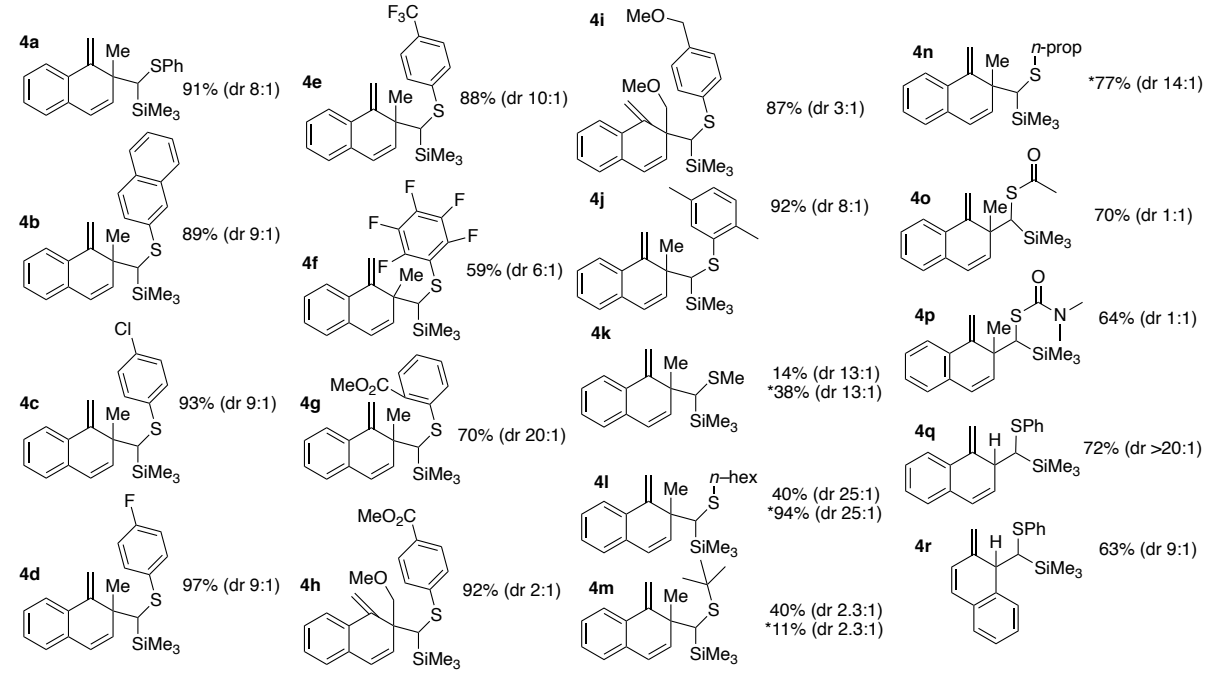
Figure 3-12. Products expected from 4 diastereotopic transition states

The lowest energy transition states are **TS1** and **TS4** which avoid steric clash between the bulky Ph and $SiMe_3$ groups. **TS4**, which has the lowest transition state energy, leads to the *syn* product, whereas **TS1** leads to the *anti* product. This suggests the major product of the reaction generating **4a** is the *syn* diastereomer. With optimized conditions in-hand (Table 3-1, entry 4), we then set out to explore the scope of the reaction.

We began by varying substituents on the thiophenyl group (Table 3-2, substrates **3a**-**3g**). *S*-Naphthyl substrate **3b** gave results similar to optimized substrate **3a**. *Para*-substituted compounds **3c-3e** all gave excellent yields. Pentafluorophenyl substrate **3f** generated an inseparable mixture of Hinsberg product and Stevens rearrangement in a 2:1 ratio. Studies have

shown the acidity of arylsulfonium salts is influenced by electron-withdrawing groups on the aromatic ring.[24] The C_6F_5 group likely stabilizes the ylide, slowing the [2,3]-rearrangement and increasing the amount of homolytic cleavage and thus Stevens rearrangement. With an ester group in the *ortho* position (substrate **3g**), yield decreased to 70%, likely due to steric hindrance. Notably, the diastereomeric ratio improved to 20:1. Moving the ester to the *para* position (substrate **3h**) increased the yield back to 92% but saw the d.r. drop to 2:1. Xylyl substrate **3j** did not lower the yield of the reaction.

Table 3-2. Naphthyl substrate table



*with $Rh_2(cap)_4$

We next tried a series of alkyl thioethers (substrates **4k**-**4n**). In general, yields were lower than aryl thioether substrates with $Rh_2(OAc)_4$, but notably diastereoselectivity was greater than 10:1 In the case of methyl thioether **4k**, yield was only 14%, with substantial recovery of starting material. As alkyl thioethers are less sterically hindering and more basic than aryl thioethers, we suspected the thiomethyl substrate was strongly binding to the catalyst and sequestering the reaction, leading to unreacted starting material. Another possibility was that the reaction product, now less hindered than in the case of aryl thioethers, might further react with the rhodium carbene to generate sulfonium ylides which could not be isolated, leading to low mass balance.

S-Hexyl substrate **3l** led to 40% product yield, but unreacted starting material was still present at the end of the reaction, consistent with catalyst sequestration. *t*-Butyl thioether **3m** gave similar yield, with 36% unreacted starting material and 18% Stevens product. As the mass balance was higher in this case than for the less hindered alkyl substrates, it is reasonable to assume the less hindered substrates were forming non-isolable ylides and depleting the diazo compound, resulting in unreacted starting material.

Reasoning that alkyl thioethers might bind less strongly to $Rh_2(cap)_4$ and generate less reactive carbenes that might be more selective for starting material than the more hindered products, we re-ran alkyl thioether substrates with this catalyst. Happily, yields improved significantly for substrates **3k** and **3l**, but not for hindered *t*-butyl thioether **3m.** We used dirhodium caprolactamate exclusively for *n*-propyl substrate **3n** and isolated a good yield of 77%.

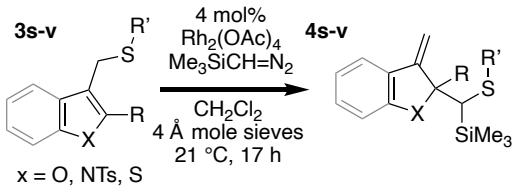
We also attempted the reaction on less reactive *S*-acyl thioethers and discovered they were also competent substrates for the reaction. *S*-Acetal substrate **3o** generated product in 70%

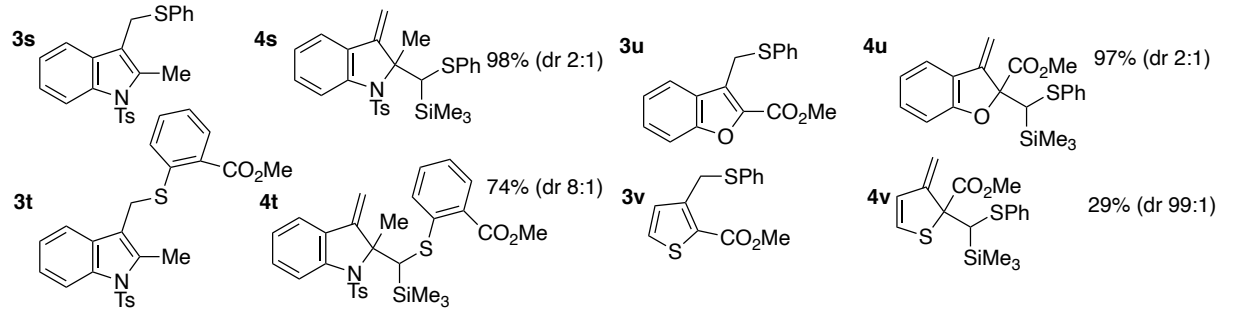
yield (as an inseparable 94% yield of dearomatized product and Stevens rearrangement in a 3:1 ratio). *S*-Benzyl thiocarbamate substrate **3p** produced a more favorable 6:1 mixture, albeit in a lower 75% combined yield (64% yield of Hinsberg product).

Naphthalene substrates **3q** and **3r** generated isolable dearomatized products, which is remarkable considering how easily such products should tautomerize.[25] This highlights the mild conditions of the reaction.

To complete our substrate scope, we next explored the reaction with heterocycles (Table 3-3). Tosylindole product **4s** was isolated in a superb 98% yield. When a carboxymethyl group was installed *ortho* to sulfur, yield dropped to 74%. This result was similar to carbocyclic product **4g**, as expected. Benzofuran substrate **3u**, on the other hand, gave product in 97% yield, despite the ester group installed at the site of C–C bond formation. Monocyclic thiophene **3v** gave dearomatized product in only 29% yield. Byproducts of the reaction contained multiple trimethylsilylmethylene groups and CI-MS masses were consistent with a second addition of TMS, likely from cyclopropanation. We chose not to explore simple furan and pyrrole substrates, as they would generate enol and enamine products which would not be isolable using silica chromatography.

Table 3-3. Heterocycle substrate table





In addition to reactions available directly from α-silyl thioethers, such as Peterson olefination[26], sila-Pummerer reaction,[27] and others,[28] we reasoned that oxidation of the dearomatized products to sulfone would open up further synthetic avenues. To this end, we were able to oxidize substrate **4a** to α-silyl sulfone **7** (Figure 3-13) in 85% yield as a single diastereomer with no trace of sila-Pummerer rearrangement. α-Silyl sulfones have been used in Peterson olefinations to generate vinylsulfones.[29]

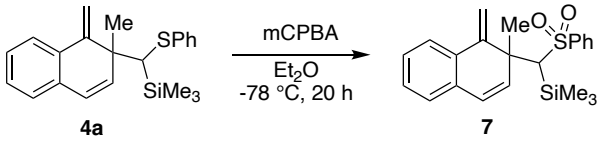


Figure 3-13. Oxidation of substrate **4a** to α-silyl sulfone **7**

In conclusion, Rh(II) catalyzes carbene transfer from TMSD to generate sulfonium ylides that undergo [2,3]-sigmatropic dearomatization. The reaction works well for naphthyl and heterocyclic substrates to generate highly congested quaternary centers. Stevens rearrangement competes with the desired reaction. Yields for *S*-alkyl substrates can be improved by using $Rh_2(cap)_4$ and *S*-acyl substrates are surprisingly also competent for the reaction.

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Chapter 3 Experimental

I. General methods: Reactions were run in oven-dried glassware. Reaction flasks were evacuated, backfilled with argon, and reactions were carried out under an atmosphere of argon. ^{1}H and ^{13}C NMR spectra were recorded at room temperature using a Bruker 500 MHz (^{1}H) spectrometer

equipped with a cryoprobe and referenced to TMS. NMR signals are reported as follows: chemical shift in ppm, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet, app = apparent), coupling constants in Hz if applicable, and proton integration. High Resolution Mass Spectrometry data was obtained on a MicroMass MS Technologies LCT Premier instrument using ESI-TOF. Molecular sieves were activated with a flame *in vacuo*. Catalysts were obtained commercially and used without further purification. Trimethylsilyldiazomethane (0.6 M in hexanes) was purchased from TCI America and used without further purification (purity was determined to be 99 mol% by ^{1}H NMR integration). CH_2Cl_2 was refluxed over CaH_2 (5% w/v), distilled and stored over 3 Å molecular sieves prior to use.[1] Column chromatography was performed under pressure using SiliCycle™ Silia*Flash*™ P60, 40-63 μm 60Å. Preparative Thin-Layer chromatography was performed using PLC Silica gel 60 F_{254}, 0.5 mm glass plates (20 x 20 cm). Eluant mixtures are listed as v/v ratios. Unless otherwise indicated, compounds were purified to ≥95% purity as judged by ^{1}H NMR integrations, otherwise the purity was estimated based on the mole fraction of impurities.

II. General Procedure for Rhodium(II)-Catalyzed Hinsberg Dearomatization Using Trimethylsilyldiazomethane

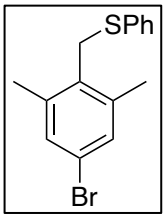
To a flame-dried round bottom flask equipped with a magnetic stir bar under argon was added $Rh_2(OAc)_4$ (0.0202 mmol), thioether (0.500 mmol) and 4 Å molecular sieves (0.13 g), 6.0 mL CH_2Cl_2 and the mixture was stirred to dissolve the solutes. Trimethylsilyldiazomethane (0.840 mL, 0.6 M in hexanes, 0.500 mmol) was added dropwise via syringe pump over 17 h at a rate of 0.001 mL/min. The solution was filtered through a pad of Celite and washed with CH_2Cl_2 until the filtrate was colorless. The solvent was removed in vacuo and the crude product was purified by chromatography on silica gel.

Reaction on 1.0 mmol scale: To a flame-dried round bottom flask equipped with a magnetic stir bar under argon was added $Rh_2(OAc)_4$ (17.8 mg, 0.0402 mmol), naphthalene **3b** (0.316 g, 1.00 mmol) and 4 Å molecular sieves (0.316 g). 12.0 mL CH_2Cl_2 was added by syringe and the mixture was stirred to dissolve the solutes. Trimethylsilyldiazomethane (1.68 mL, 0.6 M in hexanes) was added dropwise via syringe pump using dual syringes over 17 h at a rate of 0.002 mL/min. The solution was filtered through a pad of Celite, which was washed with CH_2Cl_2 until the filtrate was colorless. The solvent was removed *in vacuo* and the crude product was purified by column chromatography (95:5 hexanes/CH_2Cl_2) to give compound **4b** (0.354 g, 0.879 mmol, 87.9 %).

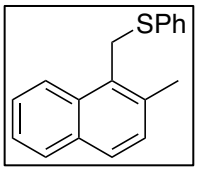
III. General Procedure for Synthesis of Thioether Substrates

Naphthylmethyl thioethers **3a-p** were prepared from benzylic bromides under biphasic conditions using a slightly modified procedure of Renaud and coworkers.[2] The benzylic bromide (6.4 mmol) and thiophenol (0.69 mL, 6.4 mmol) were dissolved in 10 mL benzene. NaOH (380 mg, 9.6 mmol) and tetra-*n*-butylammonium iodide (71 mg, 0.19 mmol) were dissolved in 10 mL DI water and added to the benzyl halide solution. The reaction was stirred for 12 h at RT, then extracted with ether, washed with 1 M NaOH, then brine. The organic layer was dried with sodium sulfate, filtered, and concentrated *in vacuo*. The crude solid was taken up in a minimal amount boiling CH_2Cl_2 and boiling hexanes was added until saturation was reached. A small amount of hot CH_2Cl_2 was added until the solution became clear. The solution was allowed to cool to room temperature and then placed in a -4 °C freezer to complete the crystallization. Crystals were filtered, rinsed with cold hexanes and dried under vacuum.

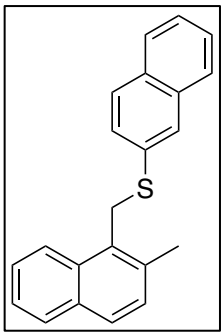
IV. Synthesis and Characterization of Thioether Substrates



(4-Bromo-2,6-dimethylbenzyl)(phenyl)sulfane (1). Benzyl thioether **1** was synthesized according to the general procedure using 5-bromo-2-(bromomethyl)-1,3-dimethylbenzene (4.00 g, 14.4 mmol). The crude residue was purified by recrystallization using CH_2Cl_2/hexanes to afford **1** as a white solid (2.55 g, 8.30 mmol, 57.7 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.34-7.37 (m, 2H), 7.26-7.31 (m, 2H), 7.20-7.24 (m, 1H), 7.16 (bs, 2H), 4.07 (s, 2H), 2.31 (s, 6H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 139.7, 136.9, 132.6, 131.2, 130.6, 129.2, 126.9, 121.1, 33.9, 19.7; HRMS (CI) *m*/*z*: [M]+ Calcd for $C_{15}H_{15}BrS$ 306.0078; Found 306.0070.



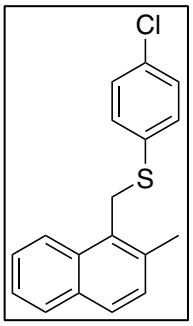
((2-Methylnaphthalen-1-yl)methyl)(phenyl)sulfane (3a). Naphthalene **3a** was synthesized according to the general procedure using 1-(bromomethyl)-2-methylnaphthalene (3.21 g, 13.7 mmol). The crude residue was purified by recrystallization using CH_2Cl_2/hexanes to afford **3a** as a white solid (2.64 g, 9.99 mmol, 73.2 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.09 (d, *J* = 8.7 Hz, 1H), 7.81 (d, *J* = 8.2 Hz, 1H), 7.70 (d, *J* = 8.2 Hz, 1H), 7.51 (td, *J* = 7.2, 1.4 Hz, 1H), 7.41-7.44 (m, 3H), 7.28-7.32 (m, 3H), 7.21-7.24 (m, 1H), 4.58 (s, 2H), 2.49 (s, 3H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 137.3, 135.0, 132.6, 132.2, 130.0, 129.2, 129.1, 129.0, 128.6, 127.9, 126.47, 126.45, 125.0, 123.6, 32.9, 20.1; HRMS (CI) *m*/*z*: [M]+ Calcd for $C_{18}H_{16}S$ 264.0973; Found 264.0971.



((2-Methylnaphthalen-1-yl)methyl)(naphthalen-2-yl)sulfane (3b).

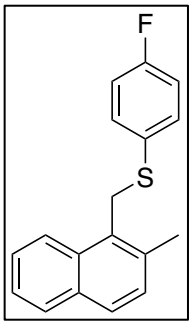
Naphthalene **3b** was synthesized according to the general procedure using 1-(bromomethyl)-2-methylnaphthalene (1.70 g, 7.23 mmol) and naphthalene-2-thiol (1.16 g, 7.23 mmol). The crude residue was purified by recrystallization using CH_2Cl_2/hexanes to afford **3b** as a white solid (1.66 g, 5.28 mmol, 73.0 %).

^{1}H NMR (500 MHz, $CDCl_3$) δ 8.11 (d, *J* = 9.0 Hz, 1H), 7.67-7.82 (m, 6H), 7.39-7.50 (m, 5H), 7.27 (d, *J* = 8.6 Hz, 1H), 4.65 (s, 2H), 2.49 (s, 3H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 135.21, 135.17, 134.0, 132.7, 132.3, 132.0, 129.2, 129.1, 128.7, 128.5, 128.1, 127.9, 127.8, 127.3, 127.2, 126.7, 126.6, 125.9, 125.1, 123.7, 32.7, 20.2; HRMS (CI) *m/z*: [M]+ Calcd for $C_{22}H_{18}S$ 314.1129; Found 314.1124.



(4-Chlorophenyl)((2-methylnaphthalen-1-yl)methyl)sulfane (3c).

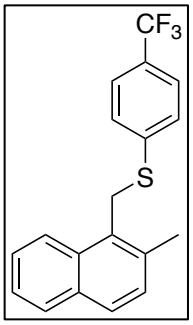
Naphthalene **3c** was synthesized according to the general procedure using 1-(bromomethyl)-2-methylnaphthalene (0.840 g, 3.57 mmol) and 4-chlorobenzenethiol (0.517 g, 3.57 mmol). The crude residue was purified by recrystallization using CH_2Cl_2/hexanes to afford **3c** as a white solid (0.761 g, 2.53 mmol, 70.9 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.03 (d, *J* = 8.5 Hz, 1H), 7.79 (d, *J* = 8.5 Hz, 1H), 7.68 (d, *J* = 8.5 Hz, 1H), 7.49 (td, *J* = 6.8, 1.4 Hz, 1H), 7.41 (t, *J* = 7.6 Hz, 1H), 7.22-7.30 (m, 5H), 4.52 (s, 2H), 2.45 (s, 3H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 135.6, 135.1, 132.62, 132.57, 132.1, 131.6, 129.09, 129.06, 128.9, 128.7, 128.1, 126.5, 125.0, 123.5, 33.1, 20.1; HRMS (CI) *m/z*: [M]+ Calcd for $C_{18}H_{15}ClS$ 298.0583; Found 298.0579.



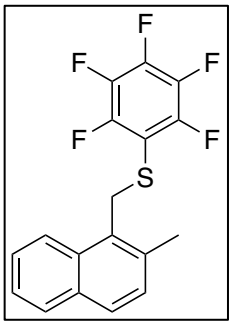
(4-Fluorophenyl)((2-methylnaphthalen-1-yl)methyl)sulfane (3d).

Naphthalene **3d** was synthesized according to the general procedure using 1-(bromomethyl)-2-methylnaphthalene (1.70 g, 7.23 mmol) and 4-fluorobenzenethiol (0.770 mL, 7.23 mmol) The crude residue was purified by recrystallization using CH_2Cl_2/hexanes to afford **3d** as a white solid (1.41 g, 4.98 mmol, 68.9 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.04 (d, *J* = 8.7 Hz, 1H), 7.80 (d, *J* = 8.2 Hz, 1H), 7.68 (d, *J* = 8.2 Hz, 1H), 7.50 (td, *J* = 6.8, 1.5 Hz, 1H), 7.42 (t, *J* = 7.5 Hz, 1H), 7.33-7.36 (m, 2H), 7.26 (d, *J* = 8.4 Hz, 1H), 6.94-6.98 (m, 2H), 4.51 (s, 2H), 2.41 (s, 3H). ^{13}C NMR (125 MHz,

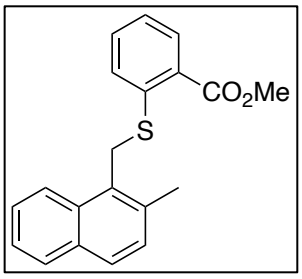
$CDCl_3$) δ 162.3 (d, *J* = 246.6 Hz), 135.0, 133.7 (d, *J* = 8.2 Hz), 132.6, 132.0, 131.5 (d, *J* = 3.3 Hz), 129.5, 129.1, 128.6, 127.9, 126.4, 125.0, 123.6, 116.0 (d, *J* = 21.9 Hz), 34.1, 20.0; HRMS (CI) *m*/*z*: [M]+ Calcd for $C_{18}H_{15}FS$ 282.0879; Found 282.0877.



((2-Methylnaphthalen-1-yl)methyl)(4-(trifluoromethyl)phenyl)sulfane (3e). Naphthalene **3e** was synthesized according to the general procedure using 1-(bromomethyl)-2-methylnaphthalene (3.50 g, 15.1 mmol) and 4-(trifluoromethyl)benzenethiol (1.70 mL, 15.1 mmol). The crude residue was purified by recrystallization using CH_2Cl_2/hexanes to afford **3e** as a white solid (3.95 g, 11.9 mmol, 79.0 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.04 (d, *J* = 9.0 Hz, 1H), 7.82 (d, *J* = 8.2 Hz, 1H), 7.72 (d, *J* = 8.2 Hz, 1H), 7.42-7.56 (m, 6H), 7.31 (d, *J* = 9.0 Hz, 1H), 4.62 (s, 2H), 2.53 (s, 3H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 143.2, 135.3, 132.6, 132.1, 129.1, 128.7, 128.3, 128.0, 128.0, 126.7, 125.80, 125.77, 125.74, 125.71, 125.1, 123.3, 31.6, 20.1; HRMS (CI) *m*/*z*: [M]+ Calcd for $C_{19}H_{15}F_3S$ 322.0847; Found 322.0861.

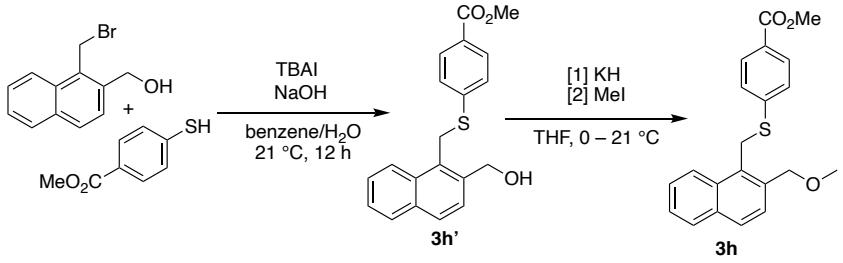


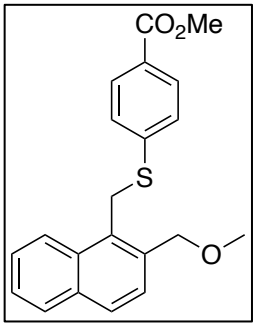
((2-Methylnaphthalen-1-yl)methyl)(perfluorophenyl)sulfane (3f). Naphthalene **3f** was synthesized according to the general procedure using 1-(bromomethyl)-2-methylnaphthalene (1.80 g, 7.66 mmol) and 2,3,4,5,6-pentafluorobenzenethiol (1.02 mL, 7.66 mmol). The crude residue was purified by recrystallization using CH_2Cl_2/hexanes to afford **3f** as a white solid (1.63 g, 4.61 mmol, 60.1 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.08 (d, *J* = 9.2 Hz, 1H), 7.80 (d, *J* = 8.2 Hz, 1H), 7.71 (d, *J* = 8.7 Hz, 1H), 7.54 (td, *J* = 6.8, 1.3 Hz, 1H), 7.43 (t, *J* = 7.5 Hz, 1H), 7.32 (d, *J* = 8.2 Hz, 1H), 4.56 (s, 2H), 2.60 (s, 3H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 148.9 (m), 146.9 (m), 142.6 (m), 140.6 (m), 138.7 (m), 136.7 (m), 135.7, 132.5, 132.1, 129.1, 128.7, 128.6, 128.0, 126.7, 125.1, 123.0, 33.4, 19.9; HRMS (CI) *m*/*z*: [M]+ Calcd for $C_{18}H_{11}F_5S$ 354.0502; Found 354.0501.



Methyl 2-(((2-methylnaphthalen-1-yl)methyl)thio)benzoate (3g). Naphthalene **3g** was synthesized according to the general procedure using 1-(bromomethyl)-2-methylnaphthalene (1.35 g, 5.74 mmol) and methyl 2-mercaptobenzoate (0.966 g, 5.74 mmol). The crude residue was purified by recrystallization using CH_2Cl_2/hexanes to afford **3g** as a white solid (1.30 g, 4.04 mmol, 70.3 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.06 (d, *J* = 8.7 Hz, 1H), 8.01 (d, *J* = 7.7 Hz, 1H), 7.80 (d, *J* = 8.2 Hz, 1H), 7.71 (d, *J* = 8.7 Hz, 1H), 7.52-7.57 (m, 2H), 7.48 (td, *J* = 7.2, 1.3 Hz, 1H), 7.41 (t, *J* = 7.7 Hz 1H), 7.31 (d, *J* = 8.4 Hz, 1H), 7.21-7.24 (m, 1H), 4.55 (s, 2H), 3.83 (s, 3H), 2.56 (s, 3H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 167.0, 143.0, 135.6, 132.6, 132.53, 132.48, 131.4, 129.1, 128.5, 128.1, 128.0, 127.7, 126.6, 126.1, 124.9, 124.1, 123.7, 52.2, 31.2, 20.1; HRMS (CI) *m*/*z*: [M]+ Calcd for $C_{20}H_{18}O_2S$ 322.1028; Found 322.1028.

Scheme S1. Two-step Synthesis of 2-methoxymethylnaphthyl Substrate 3h

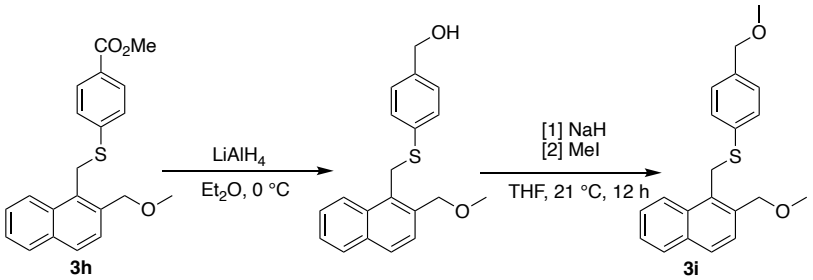


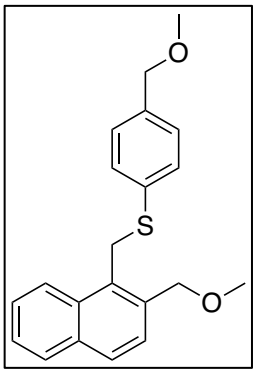


Methyl 4-(((2-(methoxymethyl)naphthalen-1-yl)methyl)thio)benzoate (3h). Thioether **3h'** was synthesized according to the general procedure using (1-(bromomethyl)naphthalen-2-yl)methanol (2.00 g, 8.04 mmol). The crude residue was purified by recrystallization using CH_2Cl_2/hexanes to afford crude thioether **3h'** as a white solid (2.21 g, 6.54 mmol, 81.4 %).

A solution of the crude alcohol **3h'** (1.60 g, 4.73 mmol) in 5 mL THF was then added dropwise to KH (0.379 g, 5.67 mmol) at 0 °C. After 30 min., MeI (0.400 mL, 5.67 mmol) was added, and the reaction was monitored by TLC until the naphthalene starting material was consumed. The reaction was quenched with sat. NH_4Cl, extracted with EtOAc and rinsed with H_2O and brine. The organic layer was dried with sodium sulfate and solvent removed *in vacuo* to afford Naphthalene **3h** after recrystallization in CH_2Cl_2/hexanes and column chromatography (1:9 EtOAc/Hexanes) as a white solid (0.423 g, 1.20 mmol, 25. 3%). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.12 (d, J = 8.4 Hz, 1H), 8.00 (s, 1H), 7.99 (s, 1H), 7.86 (d, J = 8.4 Hz, 1H), 7.82 (d, J = 8.4 Hz, 1H), 7.55 (td, J = 6.9, 1.4 Hz, 1H), 7.48-7.51 (m, 2H), 7.43 (s, 1H), 7.41 (s, 1H), 4.74 (s, 2H), 4.68 (s, 2H), 3.93 (s, 3H), 3.41 (s, 3H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 166.8, 144.7, 134.9, 133.6, 132.1, 130.1, 129.6, 128.8, 128.6, 127.23, 127.18, 126.9, 126.8, 126.0, 123.8, 72.8, 58.5, 52.2, 30.3; HRMS (ES) *m*/*z*: [M + Na]+ Calcd for $C_{21}H_{20}O_3SNa^+$ 375.1031; Found 375.1026.

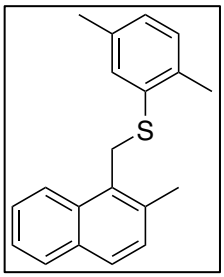
Scheme S2. Two-step Synthesis of 2-methoxymethylnaphthyl Substrate 3i



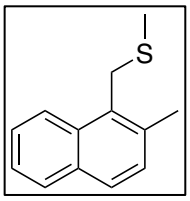


((2-(Methoxymethyl)naphthalen-1-yl)methyl)(4-(methoxymethyl)-phenyl)sulfane (3i). Under argon, naphthalene **3h**, (0.300 g, 0.850 mmol) in 10 mL ether was added to a suspension of $LiAlH_4$ (81.0 mg, 2.13 mmol) in 10 mL ether at 0 °C and stirred until complete by TLC. The reaction was quenched with 6.0 ml H_2O and extracted with ether and Rochelle salt. The

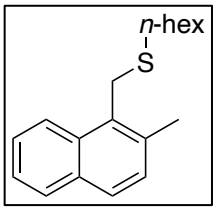
organic layer was dried with sodium sulfate and solvent removed *in vacuo.* The crude product (0.276 g, 0.850 mmol) was dissolved in THF, then NaH (0.136 g, 3.40 mmol) was added, followed by MeI (0.220 mL, 3.40 mmol). The reaction was stirred overnight, quenched with sat. NH_4Cl and extracted with CH_2Cl_2. The organic layer was dried with sodium sulfate and solvent removed *in vacuo,* followed by column chromatography (1:5 EtOAc/hexanes) to yield **3i** as a white solid (0.211 g, 0.620 mmol, 73.0 % yield). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.14 (d, *J* = 8.7 Hz, 1H), 7.84 (d, *J* = 8.2 Hz, 1H), 7.79 (d, *J* = 8.4 Hz, 1H), 7.53 (td, *J* = 7.2, 1.3 Hz, 1H), 7.47-7.49 (m, 2H), 7.41 (s, 1H), 7.39 (s, 1H), 7.30 (s, 1H), 7.28 (s, 1H), 4.65 (s, 2H), 4.61 (s, 2H), 4.45 (s, 2H), 3.40 (s, 6H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 136.8, 136.4, 134.6, 133.6, 132.1, 130.7, 130.2, 128.7, 128.4, 128.2, 127.0, 126.6, 125.9, 124.1, 74.3, 72.6, 58.4, 58.2, 32.1; HRMS (CI) *m*/*z*: [M]+ Calcd for $C_{21}H_{22}O_2S$ 338.1341; Found 338.1338.



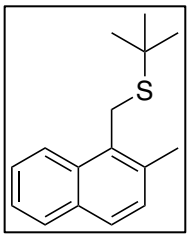
(2,5-Dimethylphenyl)((2-methylnaphthalen-1-yl)methyl)sulfane (3j). Naphthalene **3j** was synthesized according to the general procedure using 1-(bromomethyl)-2-methylnaphthalene (1.70 g, 7.23 mmol) and 2,5-dimethylbenzenethiol (0.980 mL, 7.23 mmol). The crude residue was purified by recrystallization using CH_2Cl_2/hexanes to afford **3j** as a white solid (1.70 g, 5.83 mmol, 80.7 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.09 (d, *J* = 8.7 Hz, 1H), 7.81 (d, *J* = 8.2 Hz, 1H), 7.70 (d, *J* = 8.2 Hz, 1H), 7.50 (t, *J* = 7.2 Hz, 1H), 7.43 (t, *J* = 7.7 Hz, 1H), 7.31 (d, *J* = 7.7 Hz, 1H), 7.25 (s, 1H), 7.08 (d, *J* = 7.7 Hz, 1H), 6.96 (d, *J* = 8.2 Hz, 1H), 4.52 (s, 2H), 2.52 (s, 3H), 2.35 (s, 3H), 2.30 (s, 3H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 136.5, 136.1, 135.1, 134.7, 132.6, 132.3, 130.0, 129.4, 129.3, 129.1, 128.6, 127.9, 126.9, 126.4, 124.9, 123.7, 32.0, 21.1, 20.0, 19.9; HRMS (CI) *m*/*z*: [M]+ Calcd for $C_{20}H_{20}S$ 292.1286; Found 292.1289.



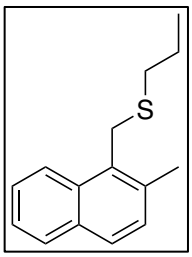
Methyl((2-methylnaphthalen-1-yl)methyl)sulfane (3k). Naphthalene **3k** was synthesized by adding a solution of sodium methanethiolate (1.19 g, 7.23 mmol) dissolved in 5 mL H_2O to a solution of 1-(bromomethyl)-2-methylnaphthalene (2.00 g, 8.51 mmol) dissolved in 25 mL MeCN. The reaction was stirred overnight at 60 °C, cooled to RT and solvent removed *in vacuo.* The residue was diluted with CH_2Cl_2 and extracted with H_2O, dried with sodium sulfate and solvent removed *in vacuo.* The crude compound was purified by column chromatography (100:0 – 95:5 hexanes/EtOAc gradient) to afford **3k** as an amber oil (1.16 g, 5.74 mmol, 67.4 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.15 (d, *J* = 8.7 Hz, 1H), 7.82 (d, *J* = 8.2 Hz, 1H), 7.69 (d, *J* = 8.7 Hz, 1H), 7.54 (td, *J* = 6.6, 1.3 Hz, 1H), 7.44 (t, *J* = 7.7 Hz, 1H), 7.32 (d, *J* = 8.4 Hz, 1H), 4.22 (s, 2H), 2.59 (s, 3H), 2.16 (s, 3H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 134.5, 132.6, 132.2, 130.6, 129.1, 128.6, 127.5, 126.3, 124.9, 123.8, 31.5, 20.3, 15.6; HRMS (CI) *m*/*z*: [M]+ Calcd for $C_{13}H_{14}S$ 202.0816; Found 202.0825.



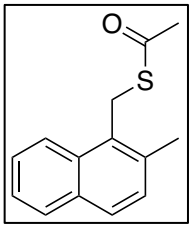
Hexyl((2-methylnaphthalen-1-yl)methyl)sulfane (3l). Naphthalene **3l** was synthesized according to the general procedure using 1-(bromomethyl)-2-methylnaphthalene (3.30 g, 14.0 mmol) and hexane-1-thiol (2.00 mL, 14.0 mmol). The crude residue was purified by column chromatography (100:0 – 95:5 hexanes/EtOAc gradient) to afford **3l** as a clear oil (1.91 g, 7.02 mmol, 50.0 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.12 (d, *J* = 8.2 Hz, 1H), 7.79 (d, *J* = 8.2 Hz, 1H), 7.66 (d, *J* = 9.2 Hz, 1H), 7.51 (t, *J* = 7.7 Hz, 1H), 7.41 (t, *J* = 7.7 Hz, 1H), 7.29 (d, *J* = 8.7 Hz, 1H), 4.19 (s, 2H), 2.62 (t, *J* = 7.6 Hz, 2H), 2.57 (s, 3H), 1.66 (quint, *J* = 7.2 Hz, 2H), 1.40 (quint, *J* = 7.5 Hz, 2H), 1.26-1.33 (m, 4H), 0.89 (t, *J* = 7.2 Hz, 3H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 134.3, 132.6, 132.2, 131.0, 129.2, 128.6, 127.4, 126.2, 124.8, 123.8, 33.1, 31.5, 30.0, 29.9, 28.7, 22.6, 20.2, 14.1; HRMS (CI) *m*/*z*: [M]+ Calcd for $C_{18}H_{24}S$ 272.1599; Found 272.1592.



***tert*-Butyl((2-methylnaphthalen-1-yl)methyl)sulfane (3m)**. Naphthalene **3m** was synthesized according to the general procedure using 1-(bromomethyl)-2-methylnaphthalene (1.90 g, 8.08 mmol) and 2-methylpropane-2-thiol (0.910 mL, 8.08 mmol). The crude residue was purified by column chromatography (99:1 hexanes/EtOAc) to afford **3m** as a white solid (1.69 g, 6.92 mmol, 85.7 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.12 (d, *J* = 8.7 Hz, 1H), 7.77 (d, *J* = 8.2 Hz, 1H), 7.65 (d, *J* = 8.2 Hz, 1H), 7.52 (t, *J* = 7.9 Hz, 1H), 7.40 (t, *J* = 7.4 Hz, 1H), 7.28 (d, *J* = 8.4 Hz, 1H), 4.17 (s, 2H), 2.58 (s, 3H), 1.50 (s, 9H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 134.4, 132.6, 132.3, 129.9, 129.2, 128.5, 127.4, 126.4, 124.8, 123.7, 42.9, 30.7, 26.6, 19.9; HRMS (CI) *m*/*z*: [M]+ Calcd for $C_{16}H_{20}S$ 244.1286; Found 244.1283.

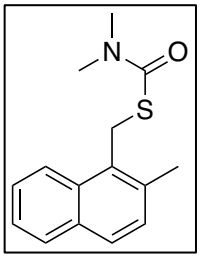


((2-Methylnaphthalen-1-yl)methyl)(propyl)sulfane (3n). Naphthalene **3n** was synthesized according to the general procedure using 1-(bromomethyl)-2-methylnaphthalene (1.70 g, 7.23 mmol) and propane-1-thiol (0.820 mL, 7.23 mmol). The crude residue was purified by column chromatography (100:0 – 99:1 hexanes/EtOAc gradient) to afford **3n** as a clear oil (1.29 g, 5.58 mmol, 77.2 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.12 (d, *J* = 8.7 Hz, 1H), 7.78 (d, *J* = 8.7 Hz, 1H), 7.66 (d, *J* = 8.2 Hz, 1H), 7.51 (t, *J* = 7.7 Hz, 1H), 7.41 (t, *J* = 7.7 Hz, 1H), 7.28 (d, *J* = 8.7 Hz, 1H), 4.19 (s, 2H), 2.57-2.62 (m, 5H), 1.70 (m, 2H), 1.01 (t, *J* = 7.4 Hz, 3H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 134.3, 132.6, 131.0, 129.2, 128.6, 127.5, 126.3, 124.8, 123.8, 35.2, 30.0, 23.2, 20.2, 13.7; HRMS (CI) *m*/*z*: [M]+ Calcd for $C_{15}H_{18}S$ 230.1129; Found 230.1121.



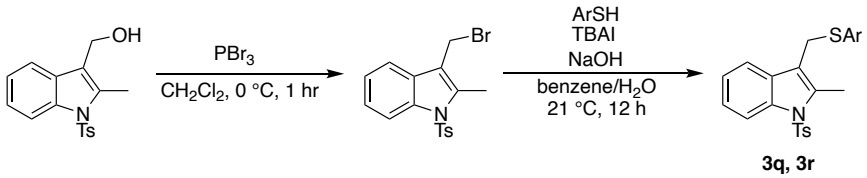
***S*-((2-methylnaphthalen-1-yl)methyl) ethanethioate (3o)**. Naphthalene **3o** was synthesized according to the general procedure using 1-(bromomethyl)-2-methylnaphthalene (1.70 g, 7.23 mmol, 100 mol %) and potassium ethanethiolate (0.830 g, 7.23 mmol 100 mol %). The crude residue was purified by column chromatography (99:1

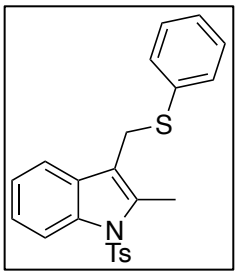
hexanes/ EtOAc) to afford **3o** as a white solid (0.920 g, 3.98 mmol, 55.0 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.94 (d, *J* = 8.6 Hz, 1H), 7.80 (d, *J* = 8.0 Hz, 1H), 7.68 (d, *J* = 8.0 Hz, 1H), 7.51 (td, *J* = 6.9, 1.4 Hz, 1H), 7.43 (t, *J* = 7.7 Hz, 1H), 7.29 (d, *J* = 8.6 Hz, 1H), 4.64 (s, 2H), 2.52 (s, 3H), 2.37 (s, 3H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 196.1, 135.0, 132.6, 132.1, 129.1, 129.0, 128.7, 128.0, 126.7, 125.1, 123.3, 30.4, 27.5, 20.3; HRMS (CI) *m*/*z*: [M]+ Calcd for $C_{14}H_{14}OS$ 230.0765; Found 230.0771.



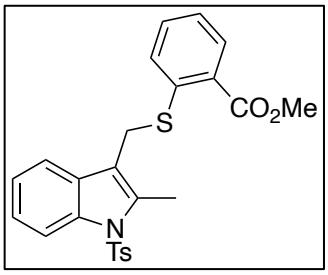
***S*-((2-Methylnaphthalen-1-yl)methyl) dimethylcarbamothioate (3p)**. Naphthalene **3p** was synthesized by dissolving (2-methylnaphthalen-1-yl)methanethiol (1.60 g, 8.50 mmol) and Et_3N (3.60 mL, 25.5 mmol) in 25 mL MeCN. The mixture was brought to 0 °C and dimethylcarbamyl chloride (2.40 mL, 25.5 mmol) was added dropwise. The reaction mixture was stirred for 6 hours at 0 °C. Solvent was removed *in vacuo*, and the residue was extracted with ether and H_2O. The crude residue was purified by column chromatography (95:5 hexanes/EtOAc) to afford **3p** as a white solid (1.50 g, 5.78 mmol, 68.0 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.07 (d, *J* = 8.7 Hz, 1H), 7.79 (d, *J* = 8.3 Hz, 1H), 7.68 (d, *J* = 8.7 Hz, 1H), 7.52 (td, *J* = 6.9, 1.4 Hz, 1H), 7.43 (td, *J* = 7.1, 1.2 Hz, 1H), 7.29 (d, *J* = 8.3 Hz, 1H), 4.67 (s, 2H), 3.05 (bs, 3H), 2.94 (bs, 3H), 2.56 (s, 3H). ^{13}C NMR (125 MHz, CD_3CN, 50 °C) δ 168.4, 136.3, 133.8, 133.3, 131.4, 130.3, 129.7, 128.9, 127.6, 126.2, 124.8, 37.2, 29.6, 20.5; HRMS (ES) *m*/*z*: [M + Na]+ Calcd for $C_{15}H_{17}NOSNa^{+}$ 282.0929; Found 282.0932.

Scheme S3. Two-step Synthesis of 2-methylindole Substrate 3s and 3t



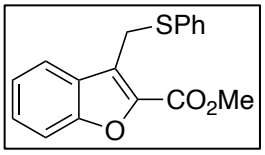


2-Methyl-3-((phenylthio)methyl)-1-tosyl-1*H*-indole (3s). Indole **3s** was synthesized by slowly adding PBr_3 (0.300 mL, 3.17 mmol) to a solution of (2-methyl-1-tosyl-1*H*-indol-3-yl)methanol (1.00 g, 3.17 mmol) in CH_2Cl_2 at 0 °C. The reaction was stirred for 1.0 h, quenched with excess sat. sodium bicarbonate and extracted with CH_2Cl_2. The resulting solution was dried with sodium sulfate, filtered, and concentrated *in vacuo*. The crude residue was then treated according to the general procedure with benzenethiol (0.303 mL, 3.17 mmol) and purified by recrystallization in CH_2Cl_2/hexanes to afford **3s** as a white solid (0.970 g, 2.37 mmol, 74.8 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.18 (d, *J* = 8.4 Hz, 1H), 7.59 (d, *J* = 8.4 Hz, 2H), 7.49 (d, *J* = 7.7 Hz, 1H), 7.13-7.30 (m, 9H), 4.06 (s, 2H), 2.35 (s, 3H), 2.24 (s, 3H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 144.8, 136.4, 136.3, 135.4, 134.7, 132.3, 129.3, 128.8, 127.3, 126.4, 124.3, 123.5, 118.8, 115.8, 114.6, 29.7, 21.6, 12.5; HRMS (CI) *m/z*: [M]+ Calcd for $C_{23}H_{21}NO_2S_2$ 407.1014; Found 407.1022.

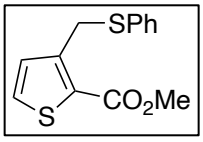


Methyl 2-(((2-methyl-1-tosyl-1*H*-indol-3-yl)methyl)thio)benzoate (3t). Indole **3t** was synthesized by slowly adding PBr_3 (0.450 mL, 4.76 mmol) to a solution of (2-methyl-1-tosyl-1*H*-indol-3-yl)methanol (1.50 g, 4.76 mmol) in CH_2Cl_2 at 0 °C. The reaction was stirred for 1.0 h, quenched with excess sodium bicarbonate and extracted with CH_2Cl_2. The resulting solution was dried with sodium sulfate, filtered, and concentrated *in vacuo*. The crude residue was then treated according to the general procedure with methyl 2-mercaptobenzoate (0.800 g, 4.76 mmol) and purified by recrystallization in CH_2Cl_2/hexanes to afford **3t** as a white solid (1.39 g, 2.99 mmol, 62.9 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.18 (d, *J* = 8.4 Hz, 1H), 7.91 (dd, *J* = 7.8, 1.6 Hz, 1H), 7.65 (dt, *J* = 8.5, 1.8 Hz, 2H), 7.52 (d, *J* = 7.7 Hz, 1H), 7.34-7.41 (m, 2H), 7.19-7.29 (m, 5H), 4.16 (s, 2H), 3.83 (s, 3H), 2.50 (s, 3H), 2.36 (s, 3H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 167.1, 144.9, 141.0,

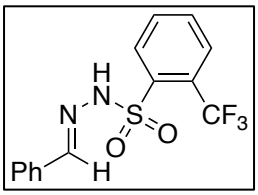
136.30, 136.28, 135.2, 132.2, 131.0, 130.0, 129.5, 129.1, 127.6, 126.5, 124.8, 124.3, 123.5, 118.8, 114.5, 114.1, 52.2, 27.5, 21.6, 12.8; HRMS (ES) *m/z*: [M + Na]+ Calcd for $C_{25}H_{23}NO_4S_2Na^+$ 488.0966; Found 488.0951.



Methyl 3-((phenylthio)methyl)benzofuran-2-carboxylate (3u). Benzofuran **3u** was synthesized according to the general procedure using methyl 3-(bromomethyl)benzofuran-2-carboxylate (1.00 g, 3.72 mmol) and benzenethiol (0.380 mL, 3.72 mmol). The crude residue was purified by column chromatography (100:0 – 97:3 hexanes/EtOAc gradient) to afford **3u** as a white solid (0.900 g, 3.02 mmol, 81.1 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.68 (d, *J* = 7.9 Hz, 1H), 7.53 (d, *J* = 8.4 Hz, 1H), 7.45 (td, *J* = 7.2, 1.2 Hz, 1H), 7.32-7.34 (m, 2H), 7.28 (t, *J* = 7.2 Hz, 1H), 7.21-7.25 (m, 3H), 4.59 (s, 2H), 3.86 (s, 3H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 160.3, 154.5, 141.1, 134.8, 132.3, 128.9, 128.1, 127.5, 127.3, 125.9, 123.5, 121.9, 112.3, 52.2, 28.8; HRMS (CI) *m/z*: [M]+ Calcd for $C_{17}H_{14}O_3S$ 298.0664; Found 298.0662.

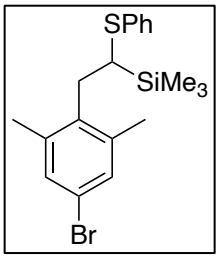


Methyl 3-((phenylthio)methyl)thiophene-2-carboxylate (3v). Thiophene **3v** was synthesized according to the general procedure using methyl 3-(chloromethyl)thiophene-2-carboxylate (1.50 g, 7.87 mmol) and benzenethiol (0.800 mL, 7.87 mmol). The crude residue was purified by column chromatography (100:0 – 98:2 hexanes/EtOAc gradient) followed by recrystallization in CH_2Cl_2 to afford **3v** as a white solid (0.570 g, 2.16 mmol, 27.4 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.36 (d, *J* = 5.4 Hz, 1H), 7.31 (d, *J* = 7.7 Hz, 2H), 7.23 (t, *J* = 7.3, Hz, 2H), 7.16-7.19 (m, 1H), 7.03 (d, *J* = 5.4 Hz, 1H), 4.53 (s, 2H), 3.82 (s, 3H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 162.7, 146.0, 135.6, 130.72, 130.70, 130.4, 128.9, 127.6, 126.7, 52.0, 32.3; HRMS (CI) *m/z*: [M]+ Calcd for $C_{13}H_{12}O_2S_2$ 264.0279; Found 264.0271.

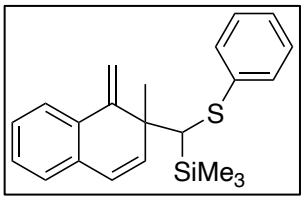


(*E*)-*N*'-Benzylidene-2-(trifluoromethyl)benzenesulfonohydrazide (5). *N*-Triftosylhydrazone **5** was synthesized by adding benzaldehyde (1.60 mL, 15.7 mmol) to a stirred suspension of 2-(trifluoromethyl)benzenesulfonohydrazide (3.77 g, 15.7 mmol) in 100 mL EtOH at RT. The reaction was stirred for 5 h and the solvent removed *in vacuo*. The crude solid was purified by recrystallization in boiling MeOH to give **5** as a white solid (2.71 g, 8.25 mmol, 52.6 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.43 (d, *J* = 7.7 Hz, 1H), 8.09 (bs, 1H), 7.88 (dd, *J* = 7.6, 1.4Hz, 1H), 7.81 (s, 1H), 7.70-7.79 (m, 2H), 7.52-7.55 (m, 2H), 7.31-7.39 (m, 3H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 148.6, 137.1, 133.7, 133.6, 133.1, 132.7, 130.9, 128.9, 128.5 (q), 127.7, 124.4, 121.7; HRMS (CI) *m*/*z*: [ES+]+ Calcd for $C_{14}H_{11}F_3N_2O_2SNa^+$ 351.0391; Found 351.0374.

V. Synthesis and Characterization of Products

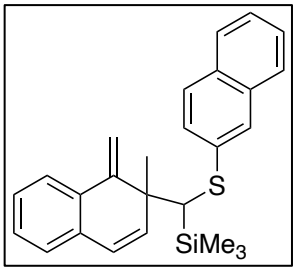


(2-(4-Bromo-2,6-dimethylphenyl)-1-(phenylthio)ethyl)trimethylsilane (2). Compound **2** was synthesized according to the general procedure using substrate **1** (0.175 g, 0.570 mmol). The crude residue was purified by column chromatography (95:5 hexanes/CH_2Cl_2), followed by PTLC (98:2 hexanes/ EtOAc) to afford compound **2** as a clear oil (0.164 g, 0.420 mmol, 73.2%). ^{1}H NMR (500 MHz, $CDCl_3$) δ 6.81-7.14 (m, 7H), 2.92-2.94 (m, 2H), 2.68-2.74 (m, 1H), 2.24 (s, 6H), 0.21 (s, 9H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 139.2, 138.3, 137.0, 130.8, 130.4, 128.4, 126.0, 119.6, 36.4, 31.2, 20.7, -2.4; HRMS (CI) *m*/*z*: [M]+ Calcd for $C_{19}H_{25}BrSSi$ 392.0630; Found 392.0615.

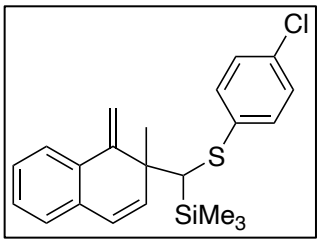


Trimethyl((2-methyl-1-methylene-1,2-dihydronaphthalen-2-yl) (phenylthio)methyl)silane (4a). Compound **4a** was synthesized according to the general procedure using naphthalene **3a** (0.133 g, 0.500 mmol). The crude residue was purified by PTLC (hexanes) to afford **4a** as a white solid (0.160 g,

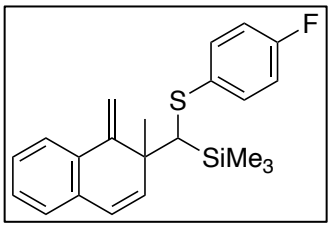
0.456 mmol, 90.7 %) as an 8 : 1 mixture of diastereomers. ^{1}H NMR major diastereomer (500 MHz, $CDCl_3$) δ 7.05-7.14 (m, 6H), 6.97 (d, *J* = 7.2 Hz, 1H), 7.68 (d, *J* = 8.0 Hz, 1H), 7.86 (td, *J* = 7.8, 1.4 Hz, 1H), 6.58 (d, *J* = 8.1 Hz, 1H), 6.38 (d, *J* = 9.6 Hz, 1H), 5.98 (d, *J* = 9.6 Hz, 1H), 5.33 (s, 1H), 5.20 (s, 1H), 2.50 (s, 1H), 1.40 (s, 3H), 0.19 (s, 9H). ^{13}C NMR major diastereomer (125 MHz, $CDCl_3$) δ 148.9, 140.2, 139.2, 138.4, 133.4, 131.6, 130.2, 128.4, 127.5, 127.0, 125.8, 125.6, 125.5, 125.1, 114.0, 45.5, 44.8, 24.8, 0.8; HRMS (FAB) *m*/*z*: [M]+ Calcd for $C_{22}H_{26}SSi$ 350.1524; Found 350.1526.



Trimethyl((2-methyl-1-methylene-1,2-dihydronaphthalen-2-yl)-(naphthalen-2-ylthio)methyl)silane (4b). Compound **4b** was synthesized according to the general procedure using naphthalene **3b** (0.158 g, 0.500 mmol). The crude residue was purified by column chromatography (92:8 hexanes/CH_2Cl_2) followed by PTLC (hexanes) to afford **4b** as a white solid (0.180 g, 0.447 mmol, 89.4 %) as a 9 : 1 mixture of diastereomers. ^{1}H NMR major diastereomer (500 MHz, $CDCl_3$) δ 7.74-7.76 (m, 1H), 7.54 (d, *J* = 8.4 Hz 1H), 7.37-7.47 (m, 4H), 7.20 (dd, *J* = 8.7, 1.8 Hz, 1H), 7.03 (t, *J* = 7.4 Hz, 1H), 6.98 (d, *J* = 7.4 Hz, 1H), 6.49 (t, *J* = 7.7 Hz, 1H), 6.40 (d, *J* = 9.7 Hz, 1H), 6.36 (d, *J* = 7.9 Hz, 1H), 6.01 (d, *J* = 9.7 Hz, 1H), 5.30 (s, 1H), 5.21 (s, 1H), 2.63 (s, 1H), 1.43 (s, 3H), 0.22 (s, 9H). ^{13}C NMR major diastereomer (125 MHz, $CDCl_3$) δ 150.7, 148.9, 140.1, 138.4, 136.5, 133.6, 133.4, 131.6, 131.5, 128.0, 127.7, 127.64, 127.61, 127.1, 127.0, 126.2, 125.80, 125.75, 125.3, 114.1, 45.5, 44.3, 24.8, 0.8; HRMS (CI) *m*/*z*: [M]+ Calcd for $C_{26}H_{28}SSi$ 400.1681; Found 400.1696.

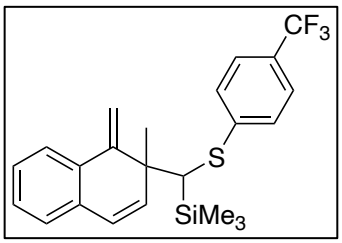


(((4-Chlorophenyl)thio)(2-methyl-1-methylene-1,2-dihydro-naphthalen-2-yl)methyl)trimethylsilane (4c). Compound **4c** was synthesized according to the general procedure using naphthalene **3c** (0.150 g, 0.500 mmol). The crude residue was purified by column chromatography (100:0 – 98:2 hexanes/EtOAc gradient) followed by PTLC (hexanes) to afford **4c** as a white solid (0.181 g, 0.469 mmol, 93.7 %) as a 9 : 1 mixture of diastereomers. ^{1}H NMR major diastereomer (500 MHz, $CDCl_3$) δ 7.12 (td, *J* = 7.4, 1.2 Hz, 1H), 6.96-7.03 (m, 5H), 6.90 (td, *J* = 7.6, 1.3 Hz, 1H), 6.57 (d, *J* = 7.8 Hz, 1H), 6.37 (d, *J* = 9.6 Hz, 1H), 5.96 (d, *J* = 9.7 Hz, 1H), 5.31 (s, 1H), 5.18 (s, 1H), 2.40 (s, 1H), 1.39 (s, 3H), 0.19 (s, 9H). ^{13}C NMR major diastereomer (125 MHz, $CDCl_3$) δ 148.9, 138.3, 137.8, 133.4, 131.54, 131.46, 129.4, 128.4, 127.7, 127.2, 125.9, 125.8, 125.0, 114.3, 45.4, 45.2, 24.4, 0.8; HRMS (CI) *m/z*: [M]+ Calcd for $C_{22}H_{25}ClSSi$ 384.1135; Found 384.1120.

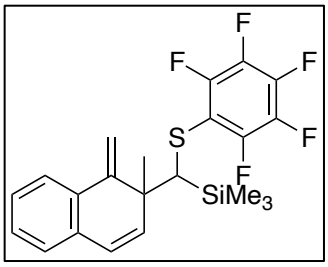


(((4-Fluorophenyl)thio)(2-methyl-1-methylene-1,2-dihydro-naphthalen-2-yl)methyl)trimethylsilane (4d). Compound **4d** was synthesized according to the general procedure using naphthalene **3d** (0.142 g, 0.500 mmol). The crude residue was purified by column chromatography (100:0 – 99:1 hexanes/EtOAc gradient) followed by PTLC (hexanes) to afford **4d** as a white solid (0.181 g, 0.489 mmol, 97.7 %) as a 9 : 1 mixture of diastereomers. ^{1}H NMR major diastereomer (500 MHz, $CDCl_3$) δ 7.10 (t, *J* = 7.1 Hz, 1H), 7.05 (m, 2H), 6.97 (d, *J* = 7.4 Hz, 1H), 6.88 (t, *J* = 7.7 Hz, 1H), 6.77 (t, *J* = 8.4 Hz, 2H), 6.55 (d, *J* = 8.2 Hz, 1H), 6.37 (d, *J* = 9.7 Hz, 1H), 5.96 (d, *J* = 9.4 Hz, 1H), 5.30 (s, 1H), 5.19 (s, 1H), 2.35 (s, 1H), 1.39 (s, 3H), 0.20 (s, 9H). ^{13}C NMR major diastereomer (125 MHz, $CDCl_3$) δ 162.5, 160.6, 149.0, 138.4, 133.4, 132.5, 132.4, 127.6, 127.1, 125.8, 124.9, 115.4,

115.2, 114.1, 45.9, 45.4, 24.4, 0.8; HRMS (CI) *m/z*: [M]+ Calcd for $C_{22}H_{25}FSSi$ 368.1430; Found 368.1421.

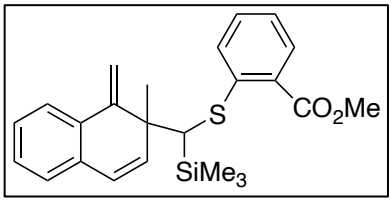


Trimethyl((2-methyl-1-methylene-1,2-dihydronaphthalen-2-yl)-((4-(trifluoromethyl)phenyl)thio)methyl)silane (4e). Compound **4e** was synthesized according to the general procedure using naphthalene **3e** (0.167 g, 0.500 mmol). The crude residue was purified by column chromatography (hexanes) to afford **4e** as a white solid (0.186 g, 0.442 mmol, 88.4 %) as a 10 : 1 mixture of diastereomers. ^{1}H NMR major diastereomer (500 MHz, $CDCl_3$) δ 7.26 (s, 2H), 7.11 (m, 3H), 6.99 (d, *J* = 7.4 Hz, 1H), 6.83 (t, *J* = 7.4 Hz, 1H), 6.46 (d, *J* = 7.9 Hz, 1H), 6.39 (d, *J* = 9.5 Hz, 1H), 5.97 (d, *J* = 9.2 Hz, 1H), 5.30 (s, 1H), 5.19 (s, 1H), 2.51 (s, 1H), 1.41 (s, 3H), 0.21 (s, 9H). ^{13}C NMR major diastereomer (125 MHz, $CDCl_3$) δ 148.8, 144.4, 138.3, 133.3, 131.5, 129.5, 127.8, 127.6, 127.1, 127.0, 126.0, 125.9, 125.1(q), 125.0, 114.6, 45.5, 44.2, 24..2, 0.7; HRMS (CI) *m/z*: [M]+ Calcd for $C_{23}H_{25}F_3SSi$ 418.1398; Found 418.1391.

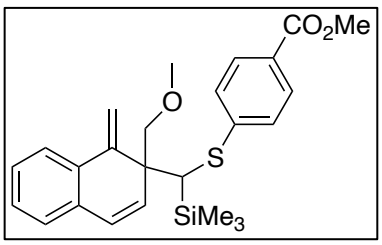


Trimethyl((2-methyl-1-methylene-1,2-dihydronaphthalen-2-yl)-((perfluorophenyl)thio)methyl)silane (4f). Compound **4f** was synthesized according to the general procedure using naphthalene **3f** (0.180 g, 0.510 mmol). The crude residue was purified by column chromatography (100:0 – 99:1 hexanes/EtOAc gradient) followed by PTLC (hexanes) to afford as a white solid an inseparable mixture of **4f** (6:1 d.r.) and isomeric Stevens rearrangement product in a 2 : 1 ratio. (0.198 g, 0.451 mmol, 88.5 %). ^{1}H NMR major diastereomer (500 MHz, $CDCl_3$) δ 7.16 (t, *J* = 7.5 Hz, 1H), 7.02 (d, *J* = 8.0 Hz, 1H), 6.94 (t, *J* = 8.0 Hz, 1H), 6.40 (d, *J* = 9.5 Hz, 1H), 6.35 (d, *J* = 8.0 Hz, 1H), 5.98 (d, *J* = 9.5 Hz, 1H), 5.26 (s, 1H), 5.24 (s, 1H), 2.76 (s, 1H), 1.46 (s, 3H), 0.26 (s, 9H). ^{13}C NMR major diastereomer (125 MHz, $CDCl_3$) δ 148.4, 138.5, 132.9, 131.7,

129.1, 128.1, 126.8, 126.5, 126.3, 125.9, 125.3, 124.6, 123.4, 114.3, 45.1, 43.0, 22.9, 0.7; ^{1}H NMR Stevens rearrangement product (500 MHz, $CDCl_3$), δ 7.78 (bs, 1H), 7.59 (d, *J* = 8.0 Hz, 1H), 7.40-7.43 (m, 2H), 7.33 (d, *J* = 7.4 Hz, 1H), 7.21 (d, *J* = 8.2 Hz 1H), 3.60-3.63 (m, 1H), 3.39-3.49 (m, 2H), 2.63 (s, 3H), 0.36 (s, 9H). HRMS (CI) *m/z*: [M]+ Calcd for $C_{22}H_{21}F_5SSi$ 440.1053; Found 440.1055.

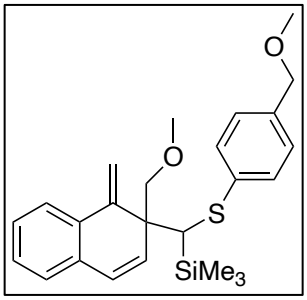


Methyl 2-(((2-methyl-1-methylene-1,2-dihydronaphthalen-2-yl)(trimethylsilyl)methyl)thio)benzoate (4g). Compound **4g** was synthesized according to the general procedure using naphthalene **3g** (0.162 g, 0.500 mmol). The crude residue was purified by column chromatography (100:0 – 99.5:0.5 hexanes/EtOAc gradient) to afford **4g** as a white solid (0.144 g, 0.351 mmol, 70.1 %) as a 20 : 1 mixture of diastereomers. ^{1}H NMR major diastereomer (500 MHz, $CDCl_3$) δ 7.72 (d, *J* = 8.2 Hz, 1H), 7.11 (d, *J* = 7.4 Hz, 1H), 7.08 (d, *J* = 7.7 Hz, 1H), 6.97 (d, *J* = 7.4 Hz, 1H), 6.92 (t, *J* = 8.2 Hz, 1H), 6.82 (m, 2H), 6.47 (d, *J* = 8.2 Hz, 1H), 6.38 (d, *J* = 9.7 Hz, 1H), 5.98 (d, *J* = 9.7 Hz, 1H), 5.24 (s, 1H), 5.06 (s, 1H), 3.96 (s, 3H), 2.51 (s, 1H), 1.39 (s, 3H), 0.23 (s, 9H). ^{13}C NMR major diastereomer (125 MHz, $CDCl_3$) δ 167.5, 148.5, 141.7, 138.7, 133.4, 132.2, 131.3, 129.9, 129.6, 127.4, 126.9, 125.7, 125.0, 124.4, 114.1, 52.2, 45.7, 44.2, 24.4, 0.9; HRMS (CI) *m/z*: [M]+ Calcd for $C_{24}H_{28}O_2SSi$ 408.1579; Found 408.1599.

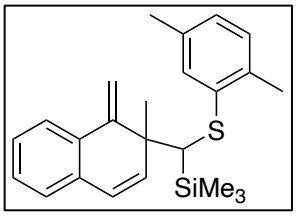


Methyl 4-(((2-(methoxymethyl)-1-methylene-1,2-dihydro-naphthalen-2-yl)(trimethylsilyl)methyl)thio)benzoate (4h). Compound **4h** was synthesized according to the general procedure using naphthalene **3h** (0.177 g, 0.500 mmol). The crude residue was purified by column chromatography (100:0 – 97:3 hexanes/EtOAc gradient) to afford **4h** as a

white solid (0.202 g, 0.459 mmol, 91.7 %) as a 2 : 1 mixture of diastereomers. ^{1}H NMR major diastereomer (500 MHz, $CDCl_3$) δ 7.74 (d, *J* = 8.7 Hz, 2H), 7.14 (d, *J* = 8.7 Hz, 3H), 7.00 (m, 1H), 6.93 (t, *J* = 7.7 Hz, 1H), 6.77 (d, *J* = 8.2 Hz, 1H), 6.48 (d, *J* = 9.7 Hz, 1H), 6.18 (d, *J* = 9.7 Hz, 1H), 5.46 (s, 1H), 5.13 (s, 1H), 3.91 (s, 3H), 3.68 (d, *J* = 8.7 Hz, 1H), 3.51 (d, *J* = 8.4 Hz, 1H), 3.22 (s, 3H), 2.71 (s, 1H), 0.15 (s, 9H). ^{13}C NMR major diastereomer (125 MHz, $CDCl_3$) δ 167.0, 146.1, 144.7, 134.2, 133.3, 131.3, 129.5, 128.2, 128.0, 127.4, 126.9, 126.7, 126.3, 125.1, 114.4, 75.3, 58.7, 52.1, 49.2, 41.2, 0.8; HRMS (CI) *m*/*z*: [M]+ Calcd for $C_{25}H_{30}O_3SSi$ 438.1685; Found 438.1706.

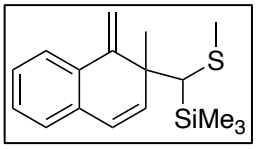


((2-(Methoxymethyl)-1-methylene-1,2-dihydronaphthalen-2-yl)((4-(methoxymethyl)phenyl)thio)methyl)trimethylsilane (4i). Compound **4i** was synthesized according to the general procedure using naphthalene **3i** (0.200 g, 0.590 mmol). The crude residue was purified by column chromatography (100:0 – 97:3 hexanes/EtOAc gradient) to afford **4i** as a white solid (0.220 g, 0.517 mmol, 87.7 %) as a 3 : 1 mixture of diastereomers. ^{1}H NMR major diastereomer (500 MHz, $CDCl_3$) δ 7.07-7.14 (m, 5H), 6.99 (d, *J* = 7.6 Hz, 1H), 6.90 (t, *J* = 7.9 Hz, 1H), 6.73 (d, *J* = 7.9 Hz, 1H), 6.47 (d, *J* = 9.9 Hz, 1H), 6.19 (d, *J* = 9.9 Hz, 1H), 5.46 (s, 1H), 5.14 (s, 1H), 4.42 (s, 2H), 3.72 (d, *J* = 8.6 Hz, 1H), 3.52 (d, *J* = 9.2 Hz, 1H), 3.39 (s, 3H), 3.22 (s, 3H), 2.59 (s, 1H), 0.15 (s, 9H). ^{13}C NMR major diastereomer (125 MHz, $CDCl_3$) δ 144.8, 138.5, 135.7, 133.6, 133.1, 129.9, 128.3, 127.9, 127.7, 127.2, 126.7, 126.1, 125.0, 114.2, 75.7, 74.4, 58.7, 58.0, 49.3, 42.4, 0.8; HRMS (CI) *m*/*z*: [M]+ Calcd for $C_{25}H_{32}O_2SSi$ 424.1892; Found 424.1879.

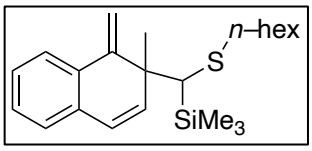


(((2,5-Dimethylphenyl)thio)(2-methyl-1-methylene-1,2-dihydro-naphthalen-2-yl)methyl)trimethylsilane (4j). Compound **4j** was synthesized according to the general procedure using naphthalene **3j**

(0.147 g, 0.500 mmol). The crude residue was purified by column chromatography (95:5 hexanes/CH_2Cl_2) followed by PTLC (95:5 hexanes/CH_2Cl_2) to afford **4j** as a white solid (0.175 g, 0.460 mmol, 91.9 %) as an 8 : 1 mixture of diastereomers. ^{1}H NMR major diastereomer (500 MHz, $CDCl_3$) δ 7.10 (td, *J* = 7.4, 1.2 Hz, 1H), 6.96-6.99 (m, 2H), 6.84 (td, *J* = 7.6, 1.4 Hz, 1H), 6.81 (d, *J* = 7.5 Hz, 1H), 6.39-6.41 (m, 2H), 6.35 (d, *J* = 7.8 Hz, 1H), 6.01 (d, *J* = 9.7 Hz, 1H), 5.16 (s, 2H), 2.59 (s, 1H), 2.35 (s, 3H), 1.92 (s, 3H), 1.42 (s, 3H), 0.22 (s, 9H). ^{13}C NMR major diastereomer (125 MHz, $CDCl_3$) δ 149.3, 138.9, 137.5, 135.5, 134.5, 133.6, 131.2, 129.5, 129.1, 127.4, 126.8, 126.0, 125.8, 125.6, 125.3, 113.6, 45.5, 44.5, 24.0, 20.9, 20.6, 0.9; HRMS (CI) *m*/*z*: [M]+ Calcd for $C_{24}H_{30}SSi$ 378.1837; Found 378.1855.

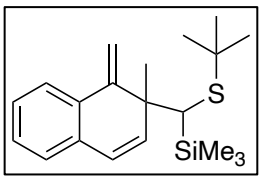


Trimethyl((2-methyl-1-methylene-1,2-dihydronaphthalen-2-yl)-(methylthio)methyl)silane (4k). Compound **4k** was synthesized according to the general procedure using naphthalene **3k** (0.102 g, 0.500 mmol) and $Rh_2(cap)_4$ (13.2 mg, 0.0202 mmol). The crude residue was purified by column chromatography (100:0 – 99:1 hexanes/EtOAc gradient) followed by PTLC (hexanes) to afford **4k** as a clear oil (0.055 g, 0.189 mmol, 37.8 %) as a 13 : 1 mixture of diastereomers. ^{1}H NMR major diastereomer (500 MHz, $CDCl_3$) δ 7.58 (d, *J* = 7.4 Hz, 1H), 7.17-7.25 (m, 2H), 7.05 (d, *J* = 7.4 Hz, 1H), 6.38 (d, *J* = 9.5 Hz, 1H), 5.98 (d, *J* = 9.5 Hz, 1H), 5.62 (s, 1H), 5.24 (s, 1H), 1.95 (s, 3H), 1.65 (s, 1H), 1.35 (s, 3H), 0.11 (s, 9H). ^{13}C NMR major diastereomer (125 MHz, $CDCl_3$) δ 149.7, 139.4, 133.8, 132.3, 128.0, 127.6, 126.3, 125.4, 125.2, 113.6, 46.1, 45.5, 24.9, 20.5, 0.7; HRMS (CI) *m*/*z*: [M]+ Calcd for $C_{17}H_{24}SSi$ 288.1368; Found 288.1371.



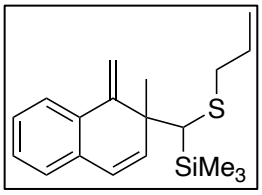
((Hexylthio)(2-methyl-1-methylene-1,2-dihydronaphthalen-2-yl)-methyl)trimethylsilane (4l). Compound **4l** was synthesized according to the general procedure using naphthalene **3l** (0.137 g, 0.500 mmol) and $Rh_2(cap)_4$ (13.2 mg,

0.0202 mmol). The crude residue was purified by column chromatography(100:0 – 99:1 hexanes/EtOAc gradient) followed by PTLC (hexanes) to afford **4l** as a clear oil (0.170 g, 0.472 mmol, 94.3 %) as a 25 : 1 mixture of diastereomers. ^{1}H NMR major diastereomer (500 MHz, $CDCl_3$) δ 7.55 (d, *J* = 7.7 Hz, 1H), 7.17-7.23 (m, 2H), 7.05 (d, *J* = 7.4 Hz, 1H), 6.37 (d, *J* = 9.8 Hz, 1H), 5.99 (d, *J* = 9.5 Hz, 1H), 5.61 (s, 1H), 5.23 (s, 1H), 2.38-2.43 (m, 1H), 2.25-2.30 (m, 1H), 1.15-1.35 (m, 11H), 0.87 (t, *J* = 7.3 Hz, 3H), 0.11 (s, 9H). ^{13}C NMR major diastereomer (125 MHz, $CDCl_3$) δ 149.6, 139.6, 133.8, 132.2, 128.0, 127.5, 126.3, 125.3, 125.1, 113.6, 45.4, 36.1, 31.5, 29.8, 28.8, 25.0, 22.6, 14.1, 0.9; HRMS (CI) *m*/*z*: [M]+ Calcd for $C_{22}H_{34}SSi$ 358.2151; Found 358.2155.

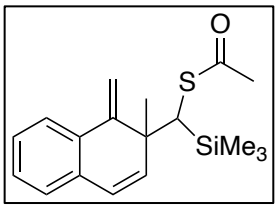


((*tert*-Butylthio)(2-methyl-1-methylene-1,2-dihydronaphthalen-2-yl)-methyl)trimethylsilane (4m). Compound **4m** was synthesized according to the general procedure using naphthalene **3m** (0.123 g, 0.500 mmol) and $Rh_2(cap)_4$ (13.2 mg, 0.0202 mmol). The crude residue was purified by column chromatography (100:0 – 98:2 hexanes/EtOAc gradient) followed by PTLC (hexanes) to afford **4m** as a clear oil as a 5 : 1 ratio of compound **4m** : Stevens rearrangement product (0.018 g, 0.054 mmol, 10.8 %) as an 11 : 1 mixture of diastereomers. ^{1}H NMR major diastereomer (500 MHz, $CDCl_3$) δ 7.62 (d, *J* = 7.7 Hz, 1H), 7.17-7.23 (m, 2H), 7.04 (d, *J* = 6.6 Hz, 1H), 6.32 (d, *J* = 9.7 Hz, 1H), 5.87 (d, *J* = 9.7 Hz, 1H), 5.78 (s, 1H), 5.23 (s, 1H), 2.23 (s, 1H), 1.35 (s, 3H), 1.29 (s, 9H), 0.03 (s, 9H). ^{13}C NMR major diastereomer (125 MHz, $CDCl_3$) δ 150.0, 138.1, 132.5, 131.8, 128.0, 127.5, 127.0, 124.4, 123.9, 111.2, 44.3, 40.2, 32.6, 31.0, 30.3, 1.3; ^{1}H NMR Stevens rearrangement product (500 MHz, $CDCl_3$), δ 7.99 (d, *J* = 8.7 Hz, 1H), 7.78 (d, *J* = 8.2 Hz, 1H), 7.61 (d, *J* = 8.4 Hz, 1H), 7.49 (m, 1H), 7.39 (m, 1H), 3.48 (dd, *J* = 14.5, 3.3 Hz 1H), 3.20 (dd, *J* = 14.7, 12.3 Hz, 1H), 2.63 (s, 3H), 1.47 (s, 1H), 0.64 (s, 9H), 0.22 (s, 9H). ^{13}C NMR Stevens rearrangement product (125 MHz,

$CDCl_3$) δ 135.2, 134.8, 133.0, 132.7, 129.3, 128.7, 126.3, 125.8, 125.7, 124.2, 43.4, 43.1, 38.7, 24.6, 21.6, -2.3; HRMS (CI) *m*/*z*: [M]+ Calcd for $C_{20}H_{30}SSi$ 330.1837; Found 330.1825.

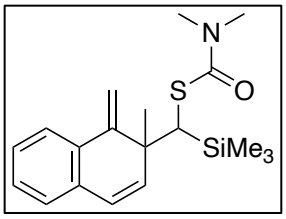


Trimethyl((2-methyl-1-methylene-1,2-dihydronaphthalen-2-yl)-(propylthio)methyl)silane (4n). Compound **4n** was synthesized according to the general procedure using naphthalene **3n** (0.116 g, 0.500 mmol) and $Rh_2(cap)_4$ (13.20 mg, 0.0202 mmol). The crude residue was purified by column chromatography (95:5 hexanes/CH_2Cl_2) to afford **4n** as a clear oil (0.123 g, 0.386 mmol, 77.2 %) as a 14 : 1 mixture of diastereomers. ^{1}H NMR major diastereomer (500 MHz, $CDCl_3$) δ 7.56 (d, *J* = 7.3 Hz, 1H), 7.17-7.23 (m, 2H), 7.05 (d, *J* = 7.7 Hz, 1H), 6.37 (d, *J* = 9.8 Hz, 1H), 5.99 (d, *J* = 9.4 Hz, 1H), 5.61 (s, 1H), 5.23 (s, 1H), 2.34-2.40 (m, 1H), 2.27-2.32 (m, 1H), 1.81 (s, 1H), 1.33-1.40 (m, 5H), 0.86 (t, *J* = 7.7 Hz, 3H), 0.11 (s, 9H). ^{13}C NMR major diastereomer (125 MHz, $CDCl_3$) δ 139.6, 133.8, 132.3, 128.0, 127.5, 126.3, 125.3, 125.1, 113.6, 45.5, 42.8, 38.1, 25.0, 23.2, 13.7, 0.9; HRMS (CI) *m*/*z*: [M]+ Calcd for $C_{19}H_{28}SSi$ 316.1681; Found 316.1683.



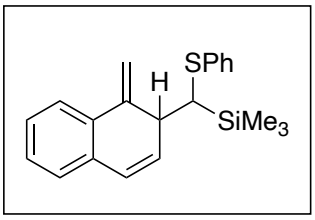
***S*-((2-Methyl-1-methylene-1,2-dihydronaphthalen-2-yl)-(trimethylsilyl)methyl) ethanethioate (4o)**. Compound **4o** was synthesized according to the general procedure using naphthalene **3o** (0.150 g, 0.650 mmol). The crude residue was purified by column chromatography (100:0 – 99.5:0.5 hexanes/ EtOAc gradient) to afford **4o** as a white solid in a 3 :1 molar ratio of compound **4o** : Stevens rearrangement product (0.146 g, 0.458 mmol, 70.5 %) as a 1.3 : 1 mixture of diastereomers. ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.50 (d, *J* = 7.5, 2H), 7.17-7.24 (m, 4H), 7.04 (d, *J* = 7.5, 2H), 6.31 (6.37) (d, *J* = 9.7 Hz, 1H), 5.83 (5.78) (d, *J* = 9.3 Hz, 1H), 5.55 (5.68) (s, 1H), 5.33 (5.28) (s, 1H), 3.29 (3.22) (s, 1H), 2.29 (2.35) (s, 3H), 1.39 (1.28) (s, 3H), 0.01 (0.0) (s, 9H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 195.2 (195.2), 149.6 (149.2), 137.7 (136.9), 129.0 (128.6), 128.3

(128.1), 127.7 (127.7), 126.6 (126.5), 125.7 (125.4), 124.8 (124.6), 124.4 (124.1), 113.0 (112.3), 44.1 (43.7), 40.3 (39.7), 30.4 (30.2), 27.4 (27.1), 0.4 (0.3); ^{1}H NMR Stevens Rearrangement Product ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.07 (d, *J* = 8.9 Hz, 1H), 7.77 (d, *J* = 7.9 Hz, 1H), 7.61 (d, *J* = 8.5 Hz, 1H), 7.49-7.52 (m, 1H), 7.40 (q, *J* = 7.8, 14.3 Hz, 1H), 7.26 (m, 1H), 3.39-3.47 (m, 2H), 2.78 (s, 1H), 2.54 (s, 3H), 1.97 (s, 3H), 0.14 (s, 9H); ^{13}C NMR Stevens Rearrangement Product (125 MHz, $CDCl_3$) δ 195.2, 134.1, 133.8, 133.3, 133.0, 132.8, 132.4, 132.4, 132.4, 131.6, 128.4, 126.7, 30.2, 30.0, 28.7, 21.0, -2.5; HRMS (CI) *m*/*z*: [M]+ Calcd for $C_{18}H_{24}OSSi$ 316.1317; Found 316.1323.

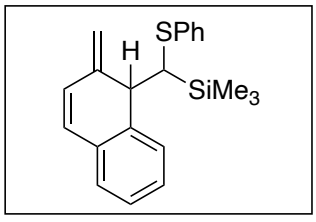


***S*-((2-Methyl-1-methylene-1,2-dihydronaphthalen-2-yl)-(trimethylsilyl)methyl) dimethylcarbamothioate (4p)**. Compound **4p** was synthesized according to the general procedure using naphthalene **3p** (0.130 g, 0.500 mmol). The crude residue was purified by column chromatography (100:0 – 90:10 hexanes/EtOAc gradient) to afford **4p** as a white solid in a 6 :1 molar ratio of compound **4p** : Stevens rearrangement product (0.113 g, 0.322 mmol, 64.3 %) as a 1 : 1 mixture of diastereomers. ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.47-7.59 (m, 2H), 7.14-7.21 (m, 4H), 7.01-7.03 (m, 2H), 6.34 (6.33) (d, *J* = 9.5 Hz, 1H), 5.84 (5.80) (d, *J* = 9.5 Hz, 1H), 5.79 (5.59) (s, 1H), 5.40 (5.38) (s, 1H), 3.37 (3.27) (s, 1H), 3.05 (2.97) (s, 6H), 1.42 (1.29) (s, 3H), 0.01 (0.0) (s, 9H). ^{13}C NMR (125 MHz, CD_3CN, 50 °C) δ 168.2 (168.1), 150.2 (149.8), 138.7 (137.6), 133.2 (132.8), 128.3 (128.2), 127.8 (127.7), 126.7 (126.5), 125.3 (124.7), 124.9 (124.8), 124.6 (124.5), 113.1 (111.9), 44.4 (44.0), 41.7 (41.6), 36.4 (36.3), 27.5 (27.0), -0.1 (-0.2); ^{1}H NMR Stevens Rearrangement Product (500 MHz, $CDCl_3$) δ 8.23 (d, *J* = 8.5 Hz, 1H), 7.75 (d, *J* = 8.5 Hz, 1H), 7.61 (s, 2H), 7.37 (t, *J* = 7.6 Hz, 1H), 7.24 (s, 1H), 3.40-3.42 (m, 2H), 2.90 (s, 1H), 2.71 (s, 6H), 2.57 (s, 3H), 0.08 (s, 9H). ^{13}C NMR Stevens Rearrangement Product (125 MHz, CD_3CN, 50 °C) δ 134.6, 134.2, 134.1, 133.2, 132.8,

131.9, 129.2, 128.4, 126.5, 125.6, 36.0, 31.4, 29.4, 20.3, -3.0; HRMS (ES) *m/z*: [M + Na]+ Calcd for $C_{19}H_{27}NOSSiNa^+$ 368.1480; Found 368.1473.

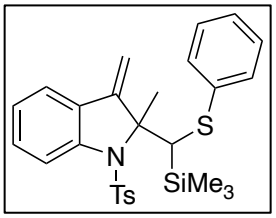


Trimethyl((1-methylene-1,2-dihydronaphthalen-2-yl)(phenylthio)methyl)silane (4q). Compound **4q** was synthesized according to the general procedure using naphthalene **3q** (0.161 g, 0.640 mmol). The crude residue was purified by preparative TLC (hexanes) to afford **4q** as a pale yellow solid (0.156 g, 72.0 %). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.13-7.34 (m, 7H), 7.10 (td, *J* = 7.6, 1.3 Hz, 1H), 7.00 (d, *J* = 7.4 Hz, 1H), 6.42 (d, *J* = 9.8 Hz, 1H), 6.24 (dd, *J* = 9.7, 4.7 Hz, 1H), 5.55 (s, 1H), 5.02 (d, *J* = 1.6 Hz, 1H), 3.48 (ddd, *J* = 6.1, 4.6, 1.6 Hz, 1H), 2.68 (d, *J* = 4.6 Hz, 1H), 0.13 (s, 9H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 144..6, 137.8, 133.1, 132.3, 130.6, 130.0, 128.7, 128.1, 127.5, 126.7, 126.6, 126.0, 124.1, 114.5, 44.7, 43.0, -0.5; HRMS (FAB) *m/z*: [M]+ Calcd for $C_{21}H_{24}SSi$ 336.1368; Found 336.1361; Anal calcd for $C_{21}H_{24}$ SSi C, 74.94; H, 7.19; Found C, 74.58, H, 7.13

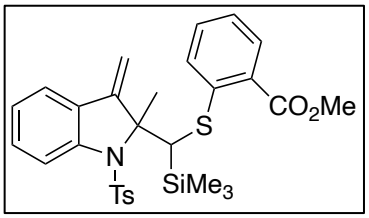


Trimethyl((2-methylene-1,2-dihydronaphthalen-1-yl)(phenylthio)methyl)silane (4r). Compound **4r** was synthesized according to the general procedure using naphthalene **3r** (0.153 g, 0.610 mmol). The crude residue was purified by preparative TLC (hexanes) to afford **4r** as a clear oil (0.130 g, 63.2 %) in a 9 : 1 mixture of diastereomers. ^{1}H NMR major diastereomer (500 MHz, $CDCl_3$) δ 7.54 (dd, *J* = 5.4, 3.5 Hz, 1H), 7.29-7.34 (m, 2H), 7.17-7.25 (m, 2H), 7.10-7.15 (m, 3H), 6.97 (dd, *J* = 5.2, 3.7 Hz, 1H), 6.33 (d, *J* = 9.8Hz, 1H), 6.25 (d, *J* = 9.8 Hz, 1H), 5.10 (s, 1H), 4.92 (s, 1H), 4.03 (d, *J* = 1.7 Hz, 1H), 2.74 (d, *J* = 3.5 Hz, 1H), -0.05

(s, 9H). ^{13}C NMR major diastereomer (125 MHz, $CDCl_3$) δ 146.2, 137.8, 133.0, 130.3, 130.2, 129.1, 129.0, 128.8, 127.7, 127.0, 126.8, 126.0, 118.5, 116.6, 49.9, 45.3, -0.8; HRMS (CI) *m/z*: [M]+ Calcd for $C_{21}H_{24}SSi$ 336.1368; Found 336.1368; Anal calcd for $C_{21}H_{24}SSi$ C, 74.94; H, 7.19; Found C, 74.67, H, 7.26

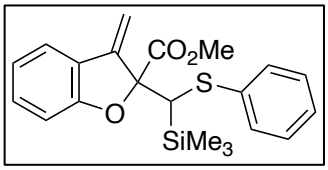


2-Methyl-3-methylene-2-((phenylthio)(trimethylsilyl)methyl)-1-tosylindoline (4s). Compound **4s** was synthesized according to the general procedure using indole **3s** (0.204 g, 0.500 mmol). The crude residue was purified by column chromatography (100:0 – 97:3 hexanes/ EtOAc gradient) to afford **4s** as a white solid (0.244 g, 0.494 mmol, 98.7 %) as a 1 : 1 mixture of diastereomers, characterized as a mixture. ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.84 (d, *J* = 8.7 Hz, 1H), 7.76 (d, *J* = 8.3 Hz, 2H), 7.72 (d, *J* = 8.6 Hz, 1H), 7.63 (d, *J* = 8.3 Hz, 2H), 7.56 (d, *J* = 8.1 Hz, 2H), 7.43 (t, *J* = 8.0 Hz, 2H), 7.35 (t, *J* = 7.7 Hz, 2H), 7.29-7.33 (m, 2H), 7.25 (s, 2H), 7.17-7.20 (m, 4H), 7.12 (d, *J* = 8.5 Hz, 2H), 7.04-7.09 (m, 2H), 5.59 (s, 1H), 5.52 (s, 1H), 5.46 (s, 1H), 4.89 (s, 1H), 4.01, (s, 1H), 3.52 (s, 1H), 2.34 (s, 3H), 2.31 (s, 3H), 1.69 (s, 3H), 1.68 (s, 3H), 0.28 (s, 9H), 0.01 (s, 9H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 151.2, 149.0, 143.9, 143.8, 143.4, 143.1, 139.8, 139.4, 139.0, 130.4, 130.1, 130.0, 129.6, 129.5, 129.14, 129.06, 128.6, 127.8, 127.7, 126.8, 126.6, 126.1, 125.4, 123.49, 123.47, 120.8, 120.5, 115.2, 114.9, 104.2, 102.8, 78.5, 76.9, 50.4, 42.9, 27.02, 26.99, 21.53, 21.49, 0.7, 0.5; HRMS (CI) *m/z*: [M]+ Calcd for $C_{27}H_{31}NO_2S_2Si$ 493.1565; Found 493.1573.

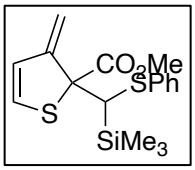


Methyl 2-(((2-methyl-3-methylene-1-tosylindolin-2-yl)-(trimethylsilyl)methyl)thio)benzoate (4t). Compound **4t** was synthesized according to the general procedure using indole **3t** (0.235 g, 0.500 mmol). The crude residue was purified by column chromatography (90:10 hexanes/

EtOAc) to afford **4t** as a white solid (0.207 g, 0.372 mmol, 74.3 %) in an 8 : 1 mixture of diastereomers. ^{1}H NMR major diastereomer (500 MHz, $CDCl_3$) δ 7.75 (dd, *J* = 7.8, 1.5 Hz, 1H), 7.50-7.58 (m, 4H), 7.43 (dd, *J* = 7.4, 1.6 Hz, 1H), 7.34 (d, *J* = 7.5 Hz, 1H), 7.21 (td, *J* = 7.6, 1.5 Hz, 1H), 7.16 (td, *J* = 7.6, 1.0 Hz, 1H), 7.08 (d, *J* = 8.3 Hz, 2H), 7.01 (td, *J* = 7.5, 1.0 Hz, 1H), 5.46 (s, 1H), 4.88 (s, 1H), 3.75 (s, 1H), 3.66 (s, 3H), 2.28 (s, 3H), 1.69 (s, 3H), 0.33 (s, 9H). ^{13}C NMR major diastereomer (125 MHz, $CDCl_3$) δ 166.7, 150.2, 143.6, 143.3, 141.8, 139.2, 131.7, 130.5, 130.4, 129.9, 129.7, 129.6, 129.4, 126.5, 124.5, 123.3, 120.4, 115.0, 103.4, 78.5, 51.8, 48.6, 26.2, 21.5, 0.9; HRMS (ES+) *m*/*z*: [M + Na]+ Calcd for $C_{29}H_{33}NO_4S_2SiNa^+$ 574.1518; Found 574.1492.

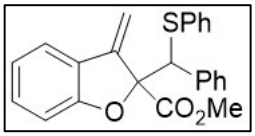


Methyl 3-methylene-2-((phenylthio)(trimethylsilyl)methyl)-2,3-dihydrobenzofuran-2-carboxylate (4u). Compound **4u** was synthesized according to the general procedure using benzofuran **3u** (0.150 g, 0.500 mmol). The crude residue was purified by column chromatography (100:0 – 97:3 hexanes/ EtOAc gradient) to afford **4u** as a clear oil (0.189 g, 0.489 mmol, 97.8 %) as a 2 : 1 mixture of diastereomers. ^{1}H NMR major diastereomer (500 MHz, $CDCl_3$) δ 7.47 (d, *J* = 7.7 Hz, 1H), 7.26-7.32 (m, 5H), 7.03 (d, *J* = 8.4 Hz, 1H), 6.96 (d, *J* = 7.0 Hz, 1H), 5.57 (s, 1H), 5.41 (s, 1H), 3.36 (s, 3H), 3.23 (s, 1H), 0.02 (s, 9H). ^{13}C NMR major diastereomer (125 MHz, $CDCl_3$) δ 170.5, 160.9, 145.5, 137.8, 131.3, 129.8, 128.9, 126.4, 125.0, 121.7, 121.1, 111.1, 105.3, 95.2, 52.4, 44.7, 0.5; HRMS (CI) *m*/*z*: [M]+ Calcd for $C_{21}H_{24}O_3SSi$ 384.1216; Found 384.1226.

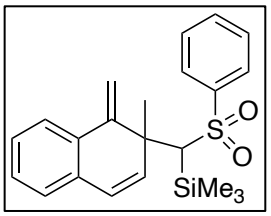


Methyl 3-methylene-2-((phenylthio)(trimethylsilyl)methyl)-2,3-dihydrothiophene-2-carboxylate (4v). Compound **4v** was synthesized according to the general procedure using thiophene **3v** (0.133 g, 0.500 mmol). The crude residue was purified by column chromatography (100:0 – 97:3 hexanes/ EtOAc gradient) to

afford **4v** as an amber oil (0.051 g, 0.146 mmol, 28.9 %) as a 99 : 1 mixture of diastereomers. ^{1}H NMR major diastereomer (500 MHz, $CDCl_3$) δ 7.41 (d, *J* = 7.4 Hz, 1H), 7.26-7.29 (m, 2H), 7.18 (t, *J* = 7.4 Hz, 1H), 6.55 (d, *J* = 6.1 Hz, 1H), 5.96 (d, *J* = 6.2 Hz, 1H), 5.26 (s, 1H), 5.20 (s, 1H), 3.39 (s, 1H), 3.26 (s, 3H), 0.21 (s, 9H). ^{13}C NMR major diastereomer (125 MHz, $CDCl_3$) δ 171.1, 152.8, 137.7, 132.2, 130.3, 128.7, 126.5, 124.5, 111.1, 73.9, 52.8, 46.3, 0.3; HRMS (CI) *m*/*z*: [M]+ Calcd for $C_{17}H_{22}O_2S_2Si$ 350.0830; Found 350.0839.



Methyl 3-methylene-2-(phenyl(phenylthio)methyl)-2,3-dihydrobenzofuran-2-carboxylate (6). Compound **6** was synthesized by suspending *N*-Triftosylhydrazone **5** (0.165 g, 0.503 mmol), cesium carbonate (0.246 g, 0.754 mmol), and $Rh_2(OAc)_4$ (8.90 mg, 0.0202 mmol) in 5 mL dry dioxane under argon. Benzofuran **3s** (0.150 g, 0.503 mmol) was dissolved in 5 mL dioxane and added dropwise to the reaction and the reaction was stirred for 18 hr. The solution was filtered through a pad of Celite and washed with CH_2Cl_2 and MeOH until the filtrate was colorless. The solvent was removed *in vacuo* and the crude product was purified by column chromatography (20:1 hexanes/EtOAc) followed by PTLC (3:1 hexanes/EtOAc) to give compound **7** (0.0541 g, 0.139 mmol, 27.7% yield) as a white solid as a 1.6 :1.0 ratio of diastereomers. ^{1}H NMR major diastereomer (500 MHz, $CDCl_3$) δ 7.48-7.49 (m, 1H), 7.30-7.32 (m, 2H), 7.11-7.27 (m, 6H), 6.98-7.03 (m, 4H), 6.74 (td, *J* = 7.4, 0.8 Hz, 1H), 5.43 (d, *J* = 0.9 Hz, 1H), 5.35 (d, *J* = 0.8 Hz, 1H), 4.81 (s, 1H), 3.79 (s, 3H). ^{13}C NMR major diastereomer (125 MHz, $CDCl_3$) δ 170.9, 162.0, 144.6, 137.4, 135.4, 132.9, 131.3, 130.5, 129.3, 128.6, 128.03, 127.95, 125.0, 121.8, 121.3, 110.9, 105.3, 94.7, 61.6, 53.7. HRMS (ES+) *m*/*z* [M+Na]+ Calcd for $C_{24}H_{20}O_3SNa$ 411.1031; Found 411.1038.



Trimethyl((2-methyl-1-methylene-1,2-dihydronaphthalen-2-yl)-(phenylsulfonyl)methyl)silane (7). *m*-CPBA was enriched by washing with pH 7-8 phosphate buffer and drying overnight under high vacuum. *m*-CPBA (0.561 g, 3.26 mmol) was dissolved in 15 mL anhydrous diethyl ether and brought to –78 °C. Compound **4b** (0.190 g, 0.540 mmol, 8:1 dr) was dissolved in 5 mL anhydrous ether and slowly added to the *m*-CPBA solution over one hour. The reaction was then placed in a -20 °C freezer overnight. After 20 h, the reaction mixture was extracted with 1 M NaOH, sat. sodium bicarbonate and brine. The organic layer was dried with sodium sulfate anhydrous, and solvent removed *in vacuo*. The crude residue was purified by column chromatography (19:1 hexanes/ EtOAc) to afford **7** as a white solid (0.176 g, 0.458 mmol, 84.8 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.74 (d, *J* = 8.2 Hz, 2H), 7.54 (t, *J* = 7.7 Hz, 1H), 7.45 (t, *J* = 8.2 Hz, 2H), 7.14 (t, *J* = 7.4 Hz, 1H), 6.93-6.99 (m, 2H), 6.81 (d, *J* = 7.7 Hz, 1H) 6.37 (d, *J* = 9.9 Hz, 1H), 6.33 (d, *J* = 9.7 Hz, 1H), 5.41 (s, 1H), 5.12 (s, 1H), 3.53 (s, 1H), 1.37 (s, 3H), 0.36 (s, 9H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 148.3, 144.9, 136.1, 132.3, 131.0, 128.9, 128.3, 127.7, 127.5, 126.6, 125.4, 124.4, 112.3, 63.5, 42.9, 26.9, 2.8; HRMS (ES+) *m/z*: [M + Na]+ Calcd for $C_{22}H_{26}O_2SSiNa^+$ 405.1320; Found 405.1338.

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Chapter 4

S-Acyl Doyle-Kirmse Reaction with Trimethylsilyldiazomethane

Introduction

Thiols are biologically active and there are multiple thiol-based drugs on the market. These include *N*-acetylcysteine (Nac), for treatment of acetaminophen poisoning, 2-mercaptoethane sulfonate (Mesna), for treatment of bladder conditions resulting from certain chemotherapeutic medications. Also tiopronin, for treatment of the disease cystinuria, amifostine (whose active metabolite contains the free thiol) for prevention of kidney damage during cisplatin therapy, and erdosteine for chronic bronchitis, among others.[1] Additionally, there are over 4.6 million thiol containing compounds that have been tested for biological activity on PubChem, 1.6 million of which were found to be biologically active.

α-Silylthiols have not yet been tested for biological activity. Routes to α-silylthiols are limited, and include thia-Brook rearrangement of benzyl anions,[2a-b] addition of silyllithium reagents to thiobenzaldehydes,[2c] metalation of protected thioethers, silylation, and deprotection[2d], photochemical addition of thiols to vinylsilanes,[2e] and S_N2 reactions of α-chlorosilanes.[2f] Having demonstrated that sigmatropic dearomatization via *S*-acylsulfonium ylide intermediates can construct α-silylthioesters in modest yields, we sought to explore the applicability of this process to allyl substrates.

Reactions in the literature of *S*-acylsulfonium ylides generated from metal carbenes are scarce. Two early examples reported by Stuetz and Moody show intramolecular ring closure of S-acyl nucleophiles onto metal carbenes derived from a diazo moiety to generate *S*-acylsulfonium ylides that undergo [1,2] S-to-C acyl shift (Figure 4-1).[3a-b] However, yields in both cases were low.

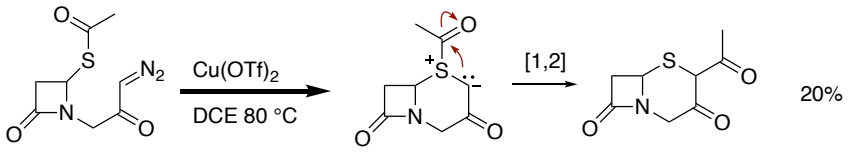


Figure 4-1. Early example of *S*-acylsulfonium ylide generated from a metal carbene

A more common example is the Danheiser ketene synthesis (Figure 1-2), whereby diazoethanethioates are used to form cyclopropenone intermediates. These intermediates undergo a [1,2] S-to-C shift-like process to open the ring and form ketene intermediates which are subsequently used for [2+2] cycloaddition processes.[3c]

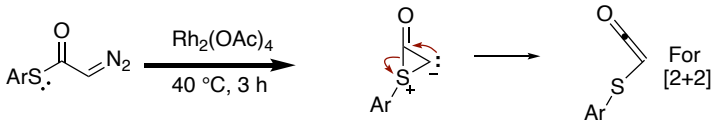


Figure 4-2. Danheiser ketene synthesis

In a more recent example, Wang and coworkers were able to substitute indoles by reaction of 3-diazoindol-2-imines with thioesters catalyzed by $Rh_2(TFA)_4$. The *S*-acylsulfonium ylide intermediate undergoes [1,4] S-to-N acyl shift to generate aza enolates in moderate yields (Figure 4-3).[3d] A single example of a cyclization that seems to involve an acyl sulfonium and S-to-O acyl shift was recently reported, although the yield was only 22% and the authors did not provide any mechanistic insight.[3e]

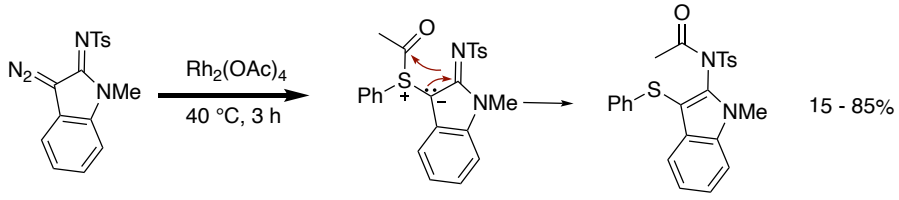
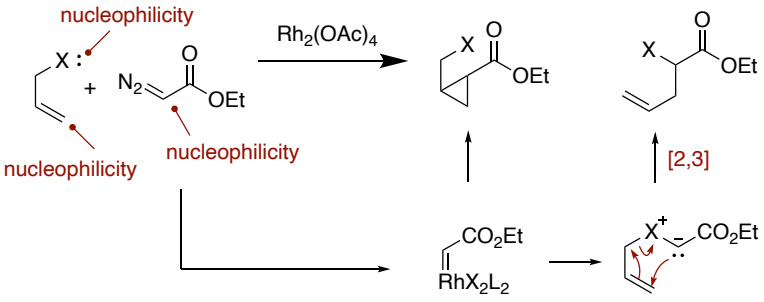


Figure 4-3. [1,4] S-to-N acyl shift to generate aza enolates

In our previous work *S*-acylsulfonium ylide intermediates were used to construct α-silylthioesters via sigmatropic dearomatization (Table 3-2, compounds 4o and 4p) – a more complex pattern of reactivity than the simple acyl shifts shown in Figures 4-1 through 4-3. By applying this procedure to allyl substrates we might expect higher yields, as the energy barrier to dearomatization is no longer a factor. However, we questioned whether the deactivated sulfur could compete with more nucleophilic alkenes. Previously, Doyle and coworkers had explored the competition between lone pairs on allylic heteroatoms and the attached olefin for addition to the carbene center.[4] Reaction of the π-bond leads to cyclopropane products, whereas reaction of the lone pairs generates onium-ylide intermediates that undergo [2,3]-sigmatropic rearrangement (Figure 4-4). Doyle found that nucleophilic lone pairs on MeS, Me_2N and iodide generated products from onium ylides exclusively, whereas the same reaction with less nucleophilic lone pairs on MeO, Br and Cl gave increasingly more cyclopropane products. We wondered where *S*-acyl nucleophiles would fit in this series and sought to test this competition.



X	[2,3]	:	cyclopropane
MeS	91%		0%
Me_2N	79%		0%
MeO	73%		27%
I	98%		0%
Br	21%		55%
Cl	5%		90%

Figure 4-4. Competition between heteroatoms and alkenes

A wide variety of transition metals and diazo compounds have been used to access allylonium ylides that undergo [2,3]-sigmatropic rearrangements. These metal-catalyzed reactions of allylonium ylides are a powerful strategy for generating quaternary centers. Sulfonium ylides generally undergo either [2,3]-rearrangements or [1,2]-shifts. The [2,3]-rearrangement of allyl sulfides, named the Doyle-Kirmse reaction,[4-5] is a common rearrangement process (Figure 4-5). The reaction produces thioethers rather than thiols, but if Me were replaced with an acyl group, thiol esters could be generated which would give the free thiol after hydrolysis.

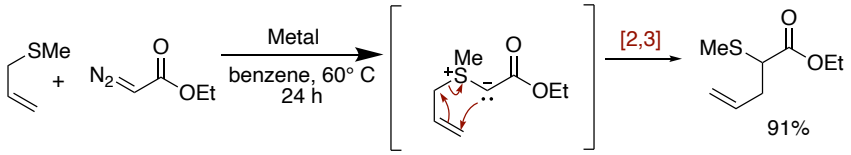


Figure 4-5. The Doyle-Kirmse reaction

The [2,3]-rearrangement typically proceeds with significant diastereoselectivity and has been used in the synthesis of trisubstituted alkenes,[7] stereoselective formation of quaternary centers,[8] ring enlargement,[9] conversion of cephalosporins into penicillans,[10] and ring closures.[11] Traditionally, copper-stabilized carbenes were used for the generation of sulfonium ylides and their subsequent [2,3]-rearrangement.[6] Rhodium catalysts have been shown to have broader applicability.

Vedejs reported the superiority of dirhodium catalysts for the procedure, as the reaction can occur under milder conditions than with copper and results in higher product yields.[12] Since the early studies by Doyle on the rhodium-catalyzed process,[13] enantioselective versions of the reaction have been developed,[14] as well as variants for amino-acid and peptide modification,[15]

reactions in aqueous solvents,[16] and reactions of propargyl sulfides to generate allenyl products which can undergo further tandem processes.[17]

There is no instance in the literature of an *S*-acyl substituted Doyle-Kirmse reaction of a thioester. Presumably this is because the acyl group would delocalize the sulfur lone-pairs, slowing ylide formation and favoring competitive pathways such as diazo dimerization and cyclopropanation, as in the case of allyl halonium ylides and oxonium ylides. Extending the reaction to *S*-acyl substrates, followed by hydrolysis of the resulting thiol esters would provide a new methodology for accessing α-silylthiols. Thus, we decided to attempt the first [2,3]-rearrangement of allyl thioesters.

[2,3]-Rearrangement of Allyl Thioesters

We began our investigation using conditions developed previously by our group for [2,3] sigmatropic rearrangement of allyl sulfides ($Rh_2(OAc)_4$, CH_2Cl_2, 20 °C, 17 h slow addition of excess TMSD, mole sieves).[18] Happily, we were able to isolate 85% product yield, with no evidence of cyclopropanation and many byproducts in low concentration that we were not able to isolate. Monitoring the reaction hourly revealed that the byproducts were forming from the beginning of the reaction and building up over time. Running a control experiment with no sulfur compound did not result in the same byproduct formation. Running the reaction over 50 hours (slow addition of TMSD) resulted in no byproduct formation but only gave 76% yield with 23% recovery of starting material, possibly due to catalyst degradation.

Opting to install a phenyl handle on the carbonyl in order to better monitor the reaction gave 73% product and surprisingly 19% cyclopropanation of the product alkene (Figure 4-6). Reducing the amount of TMSD to 1.0 equiv. reduced the product yield. Attempts to slow down

further reaction of the product by using bulky catalysts $Rh_2(5S\text{-MEPY})_4$ and $Rh_2(4R\text{-PHOX})_4$ were also unsuccessful, returning mostly starting material with minimal product formation.

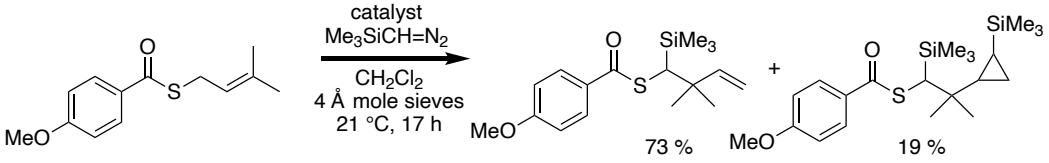


Figure 4-6. Reaction with methoxy group *para* to the carbonyl

We next attempted to halt cyclopropanation by installing an electron-withdrawing group in the substrate to deactivate the product alkene. The thioester was prepared from the known allyl bromide methyl 2-(bromomethyl)-3-methylbut-2-enoate, available in three steps from methyl propinoate. Alkylation of thiobenzoic acid afforded the substrate in 82% yield (Figure 4-7). When used in the Doyle-Kirmse reaction the sterically demanding substrate gave 67% yield, 15% recovery of starting material and 4% side-product suggesting Stevens rearrangement.

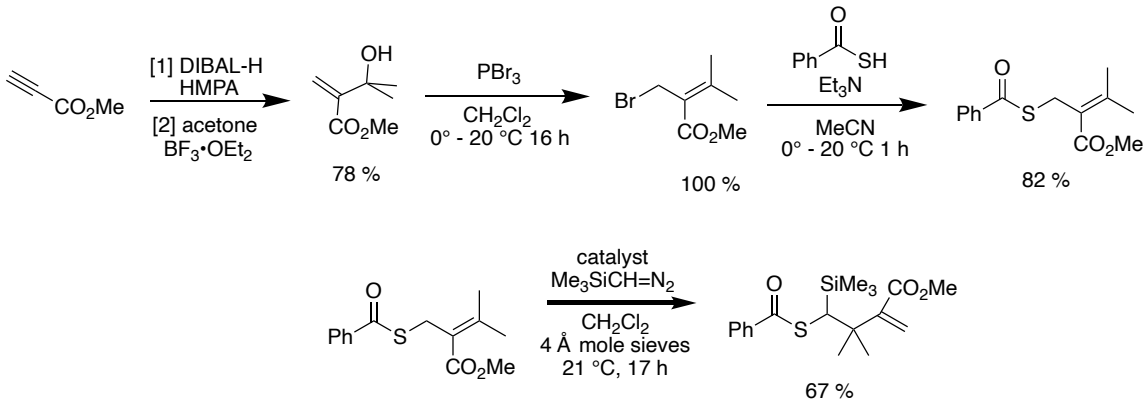
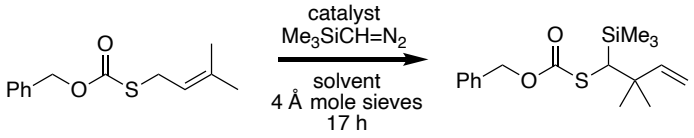


Figure 4-7. Deactivating the alkene by installing an electron-withdrawing group

Finally, we decided to attempt a carbonothiolate substrate in order to reduce steric hindrance while still leaving the carbonyl tied-up in resonance with the oxygen atom (thereby

increasing the nucleophilicity of the starting material relative to product alkene). Happily, we were able to isolate 96% of the desired product with no evidence of cyclopropanation (Table 4-1, entry 1). As we were using excess TMSD and relatively high catalyst loading of 5%, we decided to next optimize the reaction for efficiency.

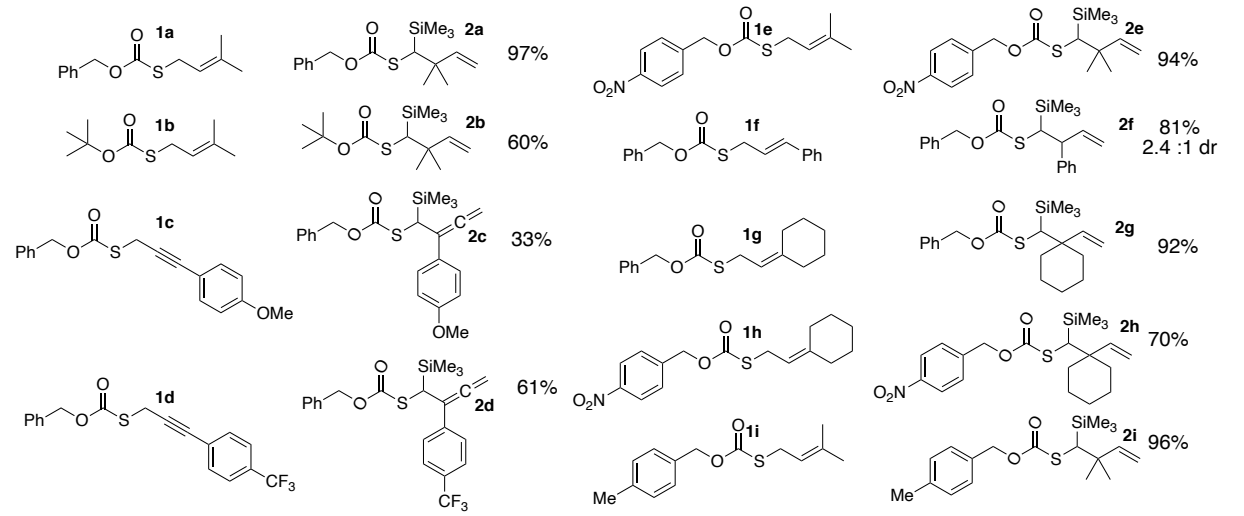
Table 4-1. Optimization table



entry	solvent	equiv TMSD	catalyst	mol% catalyst	T(°C)	yield (%)
1	DCM	1.7	$Rh_2(OAc)_4$	5	20	96
2	DCM	1.7	$Rh_2(OAc)_4$	3	20	90
3	DCE	1.7	$Rh_2(OAc)_4$	3	60	95
4	DCE	1.7	$Rh_2(OAc)_4$	1	60	92
5	DCE	1.7	$Rh_2(esp)_2$	1	60	97
6	DCE	1.7	$Rh_2(esp)_2$	0.5	60	83
7	**DCE**	**1.5**	**$Rh_2(esp)_2$**	**1**	**60**	**97**
8	DCE	1.0	$Rh_2(esp)_2$	1	60	80

Reducing the catalyst loading to 3 mol % reduced the yield, but when the temperature was increased to 60 °C, the high yield was restored (entry 3). With 1 mol % $Rh_2(OAc)_4$ at 60 °C, yield dropped to 92%, but with 1 mol % of the more robust $Rh_2(esp)_4$ the yield again rose to 97% (entry 5). $Rh_2(esp)_4$ loadings lower than 1 mol % reduced the yield (entry 6). Lowering the amount of TMSD to 1.5 equiv. did not affect the yield, but reduction to one equivalent of diazo compound led to a significant decrease in yield (entry 8). With optimized conditions thus in hand (Table 4-1, entry 7), we next began to explore the substrate scope (Table 4-2).

Table 4-2. Substrate scope



The electron rich *Para*-methyl substrate **1i** of homoallyl thioester **2i** gave a satisfying 96% yield. Happily, an electron deficient nitro-substituted ring (substrate **1e**) also gave excellent yield (94%), suggesting the reaction is tolerant to a variety of ring substituents. We then constructed cyclohexylidene substrates **1g** and **1h** from the known bromide (2-bromoethylidene)cyclohexane.[19] Cyclohexyl product **2g** was isolated in an excellent 92% yield, although nitro-substituted product **2h** was isolated in 70% yield along with significant starting material. As both nitro-containing product **2e** and cyclohexyl compound **2g** both exhibited slightly lower yields than the optimized substrate **2a**, it is possible the combination of these features in substrate **1h** slow the reaction sufficiently to allow for either azine-dimerization of TMSD or sequestration of the catalyst. *tert*-Butyl mono thiocarbonate substrate **1b** gave a modest 60% yield along with a complex mixture of products containing mostly silyl and up-field aliphatic peaks (^{1}H

NMR). Although yields were modest, the Boc group can be easily cleaved under acidic conditions. We next explored the reaction of cinnamyl-substrate **1f** in order to explore the diastereoselectivity of the rearrangement, which gave 2.4:1 dr in 81% yield. We also constructed cyclohexyl derivates **1g** and **1h**, which if successful would potentially open-up the reaction to a wider variety of substrates than prenyl, propargyl, and cinnamyl thus far explored.

We next attempted the Doyle-Kirmse reaction on propargyl substrates to give the corresponding allenes. The unsubstituted propargyl gave low mass balance. The corresponding phenyl acetylenes **1c** and **1d** were prepared through Sonagashira coupling. When used in the Doyle-Kirmse reaction electron rich phenylacetylene substrate **1c** only gave 33% yield with 43% recovery of starting material along with a complex mixture of byproducts. The methoxy substituent raises the HOMO of the π-system. As alkynes are known to undergo metathesis reactions with rhodium catalysts, deactivating the π-system should decrease competing metathesis processes . The conditions improved with CF_3-substituted phenylacetlyene **1d**, giving a 60% yield of the desired product. Byproducts were consistent with a second addition of silyl group (^{1}H NMR). We attempted to improve the yield of allene **2d** by reducing the amount of TMSD to 1.0 equiv., but the yield only slightly improved from 60% to 65%.

The reaction appears to be efficient with allyl monothiocarbonates, but not with allyl thioesters. Based on prior work with Hinsberg dearomatizations, good yields might also be expected with thiocarbamates. Substrate scope and synthetic applications of this transformation are still being explored in our laboratory. Results have been promising thus far.

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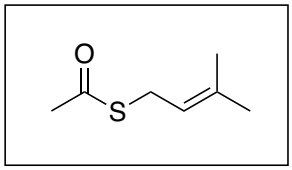
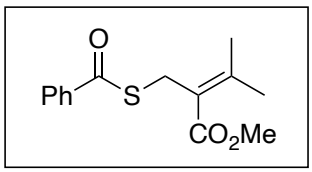
Chapter 4 Experimental

I. General methods: Reactions were run in oven-dried glassware. Reaction flasks were evacuated, backfilled with argon, and reactions were carried out under an atmosphere of argon. ^{1}H and ^{13}C NMR spectra were recorded at room temperature using a Bruker 500 MHz (^{1}H) spectrometer equipped with a cryoprobe and referenced to TMS. NMR signals are reported as follows: chemical shift in ppm, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet, app = apparent), coupling constants in Hz if applicable, and proton integration. High Resolution Mass Spectrometry data was obtained on a MicroMass MS Technologies LCT Premier instrument using ESI-TOF. Molecular sieves were activated with a flame *in vacuo*. Catalysts were obtained commercially and used without further purification. Trimethylsilyldiazomethane (0.6 M in hexanes) was purchased from TCI America and used without further purification (purity was determined to be 99 mol% by ^{1}H NMR integration). 1,2-Dichloroethane was refluxed over CaH_2 (5% w/v), distilled and stored over 3 Å molecular sieves prior to use. Column chromatography was performed under pressure using SiliCycle™ Silia*Flash*™ P60, 40-63 μm 60Å. Preparative Thin-Layer chromatography was performed using PLC Silica gel 60 F_{254}, 0.5mm glass plates (20 x 20 cm). Eluant mixtures are listed as v/v ratios. Unless otherwise indicated, compounds were purified to ≥95% purity as judged by ^{1}H NMR integrations, otherwise the purity was estimated based on the mole fraction of impurities.

II. General Procedure for Synthesis of Allyl Thioesters



***S*-(3-Methylbut-2-en-1-yl) ethanethioate.** *S*-(3-Methylbut-2-en-1-yl) ethanethioate was synthesized by dissolving prenyl bromide (2.33 mL, 19.9 mmol) in 50 mL THF. Thioacetate (2.49 g, 21.8 mmol) was added, and the reaction was stirred overnight. The reaction mixture was passed through a pad of diatomaceous earth and solvent removed *in vacuo,* then purified by column chromatography (EtOAc/hexanes 1:40) to give the product as a clear oil (1.94 g, 13.5 mmol, 67.8 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 5.18-5.23 (m, 1H), 3.52 (d, *J* = 7.7 Hz, 2H), 2.31 (s, 3H), 1.71 (s, 3H), 1.68 (s, 3H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 196.1, 136.7, 118.9, 30.6, 27.6, 25.8, 17.9; HRMS (CI) *m*/*z*: [M]+ Calcd for $C_7H_{12}OS$ 144.0609; Found 144.0610.



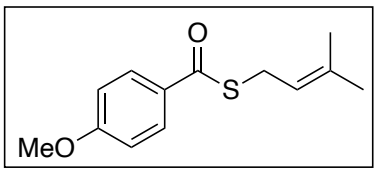
Methyl 2-((benzoylthio)methyl)-3-methylbut-2-enoate. Thiobenzoic acid (1.05 mL, 7.96 mmol) was dissolved in 200 mL MeCN and brought to 0 °C. Et_3N (2.22 mL, 15.9 mmol) was added, and the reaction stirred for 15 min. In a separate flask, methyl 2-(bromomethyl)-3-methylbut-2-enoate (1.65 g, 7.97 mmol) was dissolved in 100 mL MeCN and brought to 0 °C. The thiobenzoate solution was then added slowly by cannula to the bromide solution. The reaction was brought to room temperature and stirred for 30 min. The solvent was evaporated, and the thioester was purified by silica gel chromatography (hexanes/EtOAc 20:1) to give the product as a clear oil (1.74g, 6.57 mmol, 82.4 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.94-7.96 (m, 2H), 7.55 (tt, *J* = 7.4, 1.9 Hz, 1H), 7.41-7.45 (m, 2H), 4.09 (s, 2H), 3.76 (s, 3H), 2.12 (s, 3H), 2.01 (s, 3H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 192.1, 168.3, 150.9, 137.1, 133.5, 128.8, 127.5, 122.8, 51.8, 28.9, 23.7, 23.4; HRMS (ES) *m*/*z*: [M+Na]+ Calcd for $C_{14}H_{16}O_3SNa$ 287.0718; Found 287.0724.

III. Synthesis of Other *S*-Acyl Substrates

General Two-Step Procedure For Synthesis of *S*-Acyl Derivatives from Alkyl Bromides

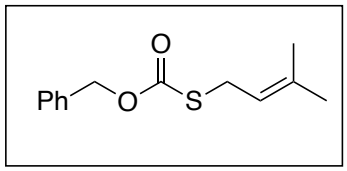
Thiourea (26.8 mmol) was dissolved in ethanol. Prenyl bromide (26.8 mmol) was added, and the solution was refluxed for 30 min. Solvent was then removed *in vacuo* until almost dry. 3M NaOH solution was then added, and a precipitate formed. The reaction was refluxed an additional hour and cooled to room temperature. The solution was extracted with CH_2Cl_2, dried under Na_2SO_4 and concentrated to give prenyl thiol (40 - 60%) as an amber oil which was used without further purification.

Prenyl thiol (17.6 mmol) was dissolved in 25 mL ether and DIPEA (17.6 mmol) was then added. Benzyl chloroformate (14.1 mmol) was dissolved in 100 mL ether and brough to 0 °C. The thiol solution was added to the benzyl chloroformate solution dropwise, then stirred overnight at room temperature. The reaction was extracted with ether and sat. $NaHCO_3$, dried over Na_2SO_4 and concentrated, then purified by column chromatography (Et_2O/hexanes 1:40) to give the carbonothiolate product as a clear oil (6.21 mmol, 44.1 %).

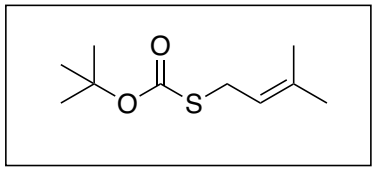


***S*-(3-Methylbut-2-en-1-yl) 4-methoxybenzothioate**. Prenyl thiol was synthesized according to the general protocol. *S*-(3-Methylbut-2-en-1-yl) 4-methoxybenzothioate was synthesized by dissolving 4-methoxybenzoyl chloride (1.31 mL, 9.67 mmol) in dry CH_2Cl_2 and adding Et_3N (2.70 mL, 19.3 mmol). The reaction was brought to 0 °C and prenyl thiol (1.24 g, 12.1 mmol) was added. After 15 min., the reaction was brought to room temperature and stirred overnight. The reaction was then extracted with CH_2Cl_2 and sat. $NaHCO_3$ and solvent removed *in vacuo*. The compound was purified by column chromatography (hexanes/EtOAc 98:2) to give *S*-(3-Methylbut-2-en-1-yl) 4-methoxybenzothioate as a colorless oil (1.48 g, 6.24 mmol, 64.6 %). ^{1}H NMR (500 MHz, $CDCl_3$)

δ 7.94 (d, *J* = 9.0 Hz, 2H), 6.91 (d, *J* = 9.0 Hz, 2H), 5.31 (m, 1H), 3.85 (s, 3H), 3.70 (d, *J* = 8.1 Hz, 2H), 1.74 (s, 6H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 190.1, 163.9, 136.9, 130.3, 129.6, 119.1, 113.9, 55.7, 27.4, 25.9, 18.1; HRMS (ES) *m*/*z*: [M+Na]+ Calcd for $C_{13}H_{16}O_2SNa$ 259.0769; Found 259.0773.

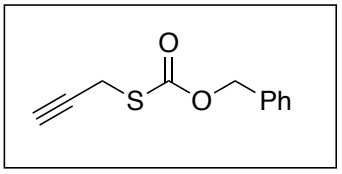


***O*-benzyl *S*-(3-methylbut-2-en-1-yl) carbonothioate (1a).** *O*-benzyl *S*-(3-methylbut-2-en-1-yl) carbonothioate was synthesized according to the general procedure using benzyl chloroformate (14.1 mmol) which was vacuum distilled before use. The reaction mixture was purified by column chromatography (Et_2O/hexanes 1:40) to give *O*-benzyl *S*-(3-methylbut-2-en-1-yl) carbonothioate (1.47 g, 6.21 mmol, 44.1 %) as a clear oil. ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.31-7.38 (m, 5H), 5.24-5.28 (m, 1H), 5.23 (s, 2H), 3.54 (d, *J* = 7.3 Hz, 2H), 1.72 (s, 3H), 1.68 (s, 3H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 171.3, 137.2, 135.4, 128.6, 128.5, 128.4, 118.5, 68.8, 29.3, 25.7, 17.8; HRMS (ES) *m*/*z*: [M+Na]+ Calcd for $C_{13}H_{16}O_2SNa$ 259.0769; Found 259.0780.

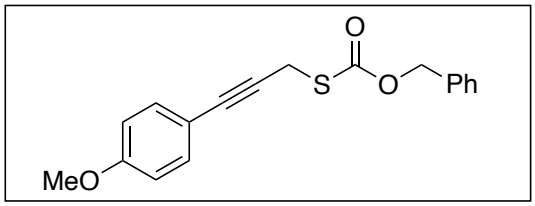


***O*-(Tert-butyl) *S*-(3-methylbut-2-en-1-yl) carbonothioate (1b)**. Prenyl thiol was synthesized according to the general protocol. *O*-(*tert*-butyl) *S*-(3-methylbut-2-en-1-yl) carbonothioate was synthesized by dissolving prenyl thiol (4.16 mmol) in 100 mL MeCN. Potassium carbonate was added (10.8 mmol), followed by Boc_2O (5.41 mmol). The reaction was stirred for 48 h at room temperature, then filtered through a pad of Celite, concentrated, and purified by column chromatography (hexanes/EtOAc 40:1) followed by PTLC (hexanes/Et_2O 90:10) to give *O*-(tert-butyl) *S*-(3-methylbut-2-en-1-yl) carbonothioate as a colorless oil (0.105 g, 0.52 mmol, 12.5 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 5.25 (t, *J* = 7.8 Hz, 1H), 3.46 (d, *J* = 7.8 Hz, 2H), 1.72 (s, 3H), 1.68

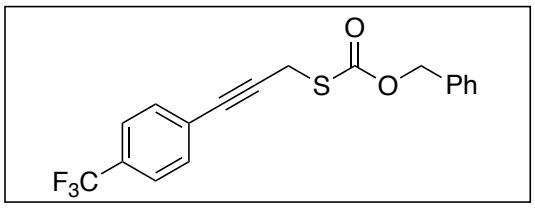
(s, 3H), 1.49 (s, 9H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 169.5, 136.7, 118.9, 84.5, 29.1, 28.3, 25.7, 17.8; HRMS (CI) *m/z*: [M]+ Calcd for $C_{10}H_{18}O_2S$ 202.1028; Found 202.1030.



***O*-Benzyl *S*-(prop-2-yn-1-yl) carbonothioate** was synthesized by suspending potassium thioacetate (121 mmol) in 100 mL acetone. Propargyl bromide (100 mmol) was then dissolved in 50 mL acetone and added dropwise to the thioacetate suspension. The reaction was stirred for 3 hours, then the acetone was removed *in vacuo*. The reaction mixture was then reconstituted in ether, extracted with H_2O and brine, dried over Na_2SO_4, and solvent removed *in vacuo*. The resulting reddish oil was purified by vacuum distillation (30 °C at 0.8 Torr) to give 49.9 mmol (49.9 %) S-(prop-2-yn-1-yl) ethanethioate as a light yellow oil, which was then added dropwise to a solution of $LiAlH_4$ (50.4 mmol) in 70 mL ether at -30 °C. The reaction was warmed to 20 °C and stirred for 1.0 hour, then cooled again to -30 °C and quenched with 5 mL sat. NH_4Cl. The solution was then diluted with 200 mL dry DCE, dried over Na_2SO_4 and filtered to remove solids. DIPEA (50.2 mmol) was then added to the filtrate. Benzyl chloroformate (40.2 mmol) was dissolved in 150 mL DCE and brought to 0 °C. The thiolate solution was added by cannula and the reaction stirred overnight at room temperature, then extracted with DCM and $NaHCO_3$ dried over Na_2SO_4, and solvent removed *in vacuo*. The resulting oil was purified by chromatography on silica gel (Et_2O / hexanes 1:40) to give 30.8 mmol (76.8 %) *O*-benzyl *S*-(prop-2-yn-1-yl) carbonothioate as a clear oil. ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.37 (s, 5H), 5.28 (s, 2H), 3.64 (m, 2H), 2.24 (m, 1H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 169.6, 134.9, 128.8, 128.7, 128.6, 78.6, 71.6, 69.6, 19.6; HRMS (CI) *m/z*: [M]+ Calcd for $C_{11}H_{10}O_2S$ 206.0401; Found 206.0408.

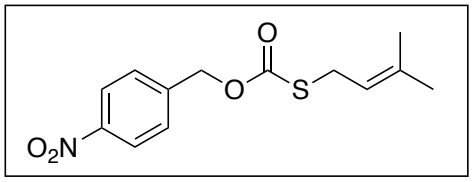


***O*-Benzyl *S*-(3-(4-methoxyphenyl)prop-2-yn-1-yl) carbonothioate** (**1c**) was synthesized by suspending $PdCl_2(PPh_3)_2$ (0.41 mmol) in 5.0 mL THF. 4-iodoanisole (2.04 mmol) and *O*-benzyl *S*-(prop-2-yn-1-yl) carbonothioate (2.04 mmol) were added, followed by Et_3N (6.11 mmol), and the reaction was stirred for 5 min. at room temperature. Then, CuI (0.20 mmol) was added, and the reaction stirred overnight at room temperature. The reaction was extracted with ether, dried over Na_2SO_4, passed through a pad of celite and solvent removed *in vacuo*. The resulting oil was purified by chromatography on silica gel (EtOAc / hexanes 1:40) to give 0.61 mmol (29.9 %) *O*-benzyl *S*-(3-(4-methoxyphenyl)prop-2-yn-1-yl) carbonothioate as an orange oil. ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.31-7.38 (m, 7H), 6.82 (d, J = 8.4 Hz, 2H), 5.28 (s, 2H), 3.89 (s, 2H), 3.80 (s, 3H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 170.0, 159.7, 135.0, 133.3, 128.70, 128.68, 128.5, 114.8, 113.9, 83.4, 82.3, 69.4, 55.3, 20.9; HRMS (CI) *m*/*z*: [M]+ Calcd for $C_{18}H_{16}O_3S$ 312.0820; Found 312.0811.

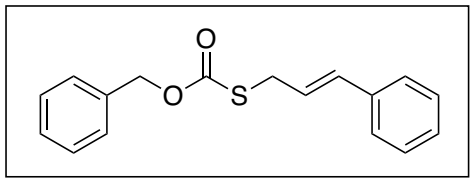


***O*-Benzyl *S*-(3-(4-(trifluoromethyl)phenyl)prop-2-yn-1-yl) carbonothioate** (**1d**) was synthesized by suspending $PdCl_2(PPh_3)_2$ (0.97 mmol) in 20.0 mL THF. 4-iodobenzotrifluoride (4.85 mmol) and *O*-benzyl *S*-(prop-2-yn-1-yl) carbonothioate (4.85 mmol) were added, followed by Et_3N (14.54 mmol), and the reaction was stirred for 5 min. at room temperature. Then, CuI (0.97 mmol) was added, and the reaction stirred two hours at room temperature. The reaction was extracted with ether, dried over Na_2SO_4, passed through a pad of celite and solvent removed *in vacuo*. The resulting oil was purified by chromatography on silica gel (EtOAc / hexanes 1:40) followed by PTLC (hexanes / 10% Et_2O) to give 2.54 mmol (52.3 %) *O*-benzyl *S*-(3-(4-(trifluoromethyl)phenyl)prop-2-yn-1-yl) carbonothioate as a white solid. ^{1}H

NMR (500 MHz, $CDCl_3$) δ 7.55 (d, *J* = 7.9 Hz, 2H), 7.51 (d, *J* = 7.9 Hz, 2H), 7.35-7.39 (m, 5H), 5.30 (s, 2H), 3.90 (s, 2H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 169.6, 134.9, 132.1, 130.2 (q, *J* = 33.5 Hz), 128.8, 128.7, 128.6, 126.6, 125.2 (q, *J* = 3.9 Hz), 125.0, 122.8, 86.7, 82.0, 69.7, 20.6; HRMS (CI) *m*/*z*: [M]+ Calcd for $C_{18}H_{13}F_3O_2S$ 350.0588; Found 350.0596.

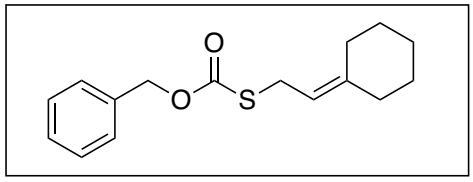


***S*-(3-Methylbut-2-en-1-yl) *O*-(4-nitrobenzyl) carbonothioate** (**1e**). Prenyl thiol was synthesized according to the general protocol. *S*-(3-methylbut-2-en-1-yl) *O*-(4-nitrobenzyl) carbonothioate was synthesized according to the general procedure using 4-nitrobenzyl chloroformate (10.7 mmol). The reaction mixture was purified by column chromatography (Et_2O/hexanes 2:98) to give *S*-(3-methylbut-2-en-1-yl) *O*-(4-nitrobenzyl) carbonothioate as a clear oil after mixed fractions were discarded (1.13 g, 4.01 mmol, 37.6 %). ^1H NMR (500 MHz, $CDCl_3$) δ 8.21 (d, *J* = 8.4 Hz, 2H), 7.51 (d, *J* = 8.6 Hz, 2H), 5.25 (m, 1H), 3.54 (d, *J* = 7.9 Hz, 2H), 1.72 (s, 3H), 1.68 (s, 3H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 171.2, 147.9, 142.6, 137.6, 128.5, 123.9, 118.2, 67.0, 29.4, 25.7, 17.9.

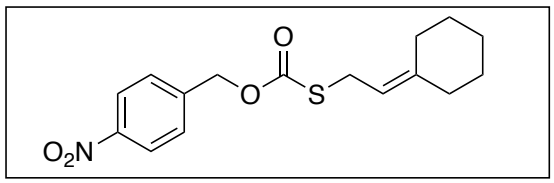


***O*-Benzyl *S*-cinnamyl carbonothioate** (**1f**). (E)-3-phenylprop-2-ene-1-thiol was synthesized according to the general protocol from cinnamyl bromide. *O*-benzyl *S*-cinnamyl carbonothioate was synthesized according to the general procedure using benzyl chloroformate (23.5 mmol). The reaction mixture was purified by column chromatography (Et_2O/hexanes 1:99) to give *O*-benzyl *S*-cinnamyl carbonothioate as a clear oil after mixed fractions were discarded (2.94 g, 10.3 mmol, 44.1 %), which turned into a white solid after refrigeration. ^1H NMR (500 MHz, $CDCl_3$) δ 7.31-7.40 (m, 9H), 7.25-7.27 (m, 1H), 6.61 (d, *J* =

15.4 Hz, 1H), 6.23-6.29 (m, 1H), 5.28 (s, 2H), 3.73 (dd, J = 7.5, 0.9 Hz, 2H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 170.7, 136.6, 135.2, 133.5, 128.7, 128.6, 128.5, 127.9, 126.5, 124.3, 69.2, 33.8.

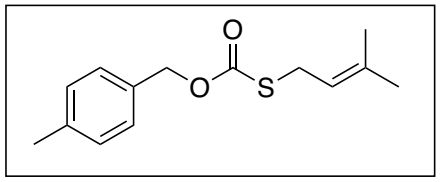


***O*-Benzyl *S*-(2-cyclohexylideneethyl) carbonothioate (1g)** was synthesized according to the general procedure using benzyl chloroformate (6.74 mmol). The reaction mixture was purified by column chromatography (Et_2O/hexanes 1:99) followed by PTLC (Et_2O/hexanes 10:90) to give *O*-benzyl *S*-(2-cyclohexylideneethyl) carbonothioate as a clear oil (0.298 g, 1.08 mmol, 16.0 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.36 (s, 5H), 5.21-5.24 (m, 3H), 3.56 (d, J = 7.8 Hz, 2H), 2.18 (s, 2H), 2.09 (s, 2H), 1.54 (s, 6H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 171.3, 145.3, 135.4, 128.6, 128.5, 128.4, 115.0, 68.9, 37.0, 28.9, 28.5, 28.4, 27.8, 26.7.



***S*-(2-Cyclohexylideneethyl) *O*-(4-nitrobenzyl) carbonothioate (1h)** was synthesized by dissolving 2-cyclohexylideneethane-1-thiol in dry THF and adding *n*-BuLi (6.67 mmol, 1.5 M in hexanes) dropwise at 0 °C. After 10 minutes, 4-nitrobenzyl benzyl chloroformate (6.67 mmol) in THF was added dropwise over 5 minutes and the reaction was stirred for two hours at 0 °C. The reaction mixture was quenched with H_2O and extracted with ether, then dried over Na_2SO_4, solvent removed *in vacuo* and purified by column chromatography (EtOAc/hexanes 2:98) followed by PTLC (EtOAc/hexanes 20:80) to give *S*-(2-cyclohexylideneethyl) *O*-(4-nitrobenzyl) carbonothioate as an amber oil (0.602 g, 1.88 mmol, 28.1 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.23 (d, J = 8.6 Hz, 2H), 7.53 (d, J = 8.2 Hz, 2H), 5.32 (s, 2H), 5.21 (t, J = 8.2 Hz, 1H), 3.57 (d, J = 7.8 Hz, 2H), 2.18 (s, 2H), 2.09 (s, 2H), 1.54 (s, 6H). ^{13}C

NMR (125 MHz, $CDCl_3$) δ 171.2, 147.9, 145.7, 142.7, 128.5, 123.9, 114.6, 67.0, 37.0, 28.9, 28.6, 28.4, 27.8, 26.7.



***O*-(4-methylbenzyl) *S*-(3-methylbut-2-en-1-yl) carbonothioate** (**1i**) was synthesized according to the general procedure using 4-methylbenzyl carbonochloridate (15.7 mmol). The reaction mixture was purified by column chromatography (Et_2O/hexanes 1:99) to give *O*-(4-methylbenzyl) *S*-(3-methylbut-2-en-1-yl) carbonothioate (1.94 g, 7.76 mmol, 49.4 %) as a clear oil. ^1H NMR (500 MHz, $CDCl_3$) δ 7.24 (d, J = 8.2 Hz, 2H), 7.16 (d, J = 7.8 Hz, 2H), 5.25 (t, J = 7.8 Hz, 1H), 5.18 (s, 2H), 3.52 (d, J = 7.8 Hz, 2H), 2.34 (s, 3H), 1.71 (s, 3H), 1.67 (s, 3H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 171.3, 138.4, 137.1, 132.4, 129.3, 128.6, 118.6, 68.9, 29.3, 25.7, 21.3 17.8.

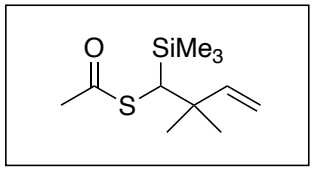
IV. General Procedure for S-Acyl Doyle-Kirmse Reaction Using Trimethylsilyldiazomethane

To a flame-dried round bottom flask equipped with a magnetic stir bar under argon was added $Rh_2(esp)_2$ (0.006 mmol), thioether (0.630 mmol) and 4 Å molecular sieves (0.13 g), 6.0 mL DCE and the mixture was stirred to dissolve the solutes. The reaction vessel was brought to 60 °C and trimethylsilyldiazomethane (0.950 mL, 0.6 M in hexanes, 0.950 mmol) was added dropwise via syringe pump over 17 h at a rate of 0.001 mL/min. The solution was cooled to room temperature, filtered through a pad of Celite and washed with CH_2Cl_2 until the filtrate was colorless. The solvent was removed in vacuo and the crude product was purified by chromatography on silica gel.

V. Synthesis and Characterization of Products

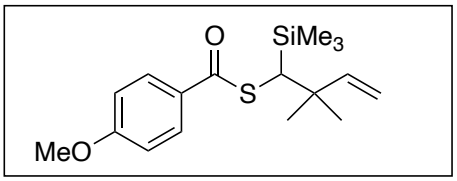
General Procedure for *S*-Acyl Doyle-Kirmse Reaction Using Trimethylsilyldiazomethane

To a flame-dried round bottom flask equipped with a magnetic stir bar under argon was added $Rh_2(esp)_2$ (0.006 mmol), thioether (0.630 mmol) and 4 Å molecular sieves (0.13 g), 6.0 mL DCE and the mixture was stirred to dissolve the solutes. The reaction vessel was brought to 60 °C and trimethylsilyldiazomethane (0.950 mL, 0.6 M in hexanes, 0.950 mmol) was added dropwise via syringe pump over 17 h at a rate of 0.001 mL/min. The solution was cooled to room temperature, filtered through a pad of Celite and washed with CH_2Cl_2 until the filtrate was colorless. The solvent was removed in vacuo and the crude product was purified by chromatography on silica gel.

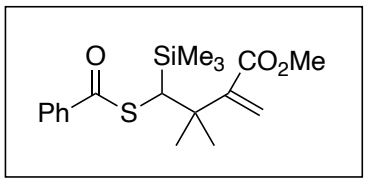


***S*-(2,2-dimethyl-1-(trimethylsilyl)but-3-en-1-yl) ethanethioate.** To a flame-dried round bottom flask equipped with a magnetic stir bar under argon was added $Rh_2(OAc)_4$ (0.045 mmol), thioether (0.900 mmol) and 4 Å molecular sieves (0.13 g), 6.0 mL CH_2Cl_2 and the mixture was stirred to dissolve the solutes. Trimethylsilyldiazomethane (1.50 mL, 0.6 M in hexanes, 0.900 mmol) was added dropwise via syringe pump over 17 h. The solution was filtered through a pad of Celite and washed with CH_2Cl_2 until the filtrate was colorless. The solvent was removed in vacuo and the crude product was purified by chromatography on silica gel (hexanes/EtOAc 1:40), followed by PTLC (hexanes/EtOAc 95:5) to give *S*-(2,2-dimethyl-1-(trimethylsilyl)but-3-en-1-yl) ethanethioate as a clear oil (0.177 g, 0.767 mmol, 85.2 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 5.90 (dd, *J* = 17.6, 10.8 Hz, 1H), 5.01 (dd, *J* = 17.3, 1.3 Hz, 1H), 4.99 (dd, *J* = 10.8, 1.3 Hz, 1H), 3.04 (s, 1H), 2.42 (s, 3H), 1.14 (s, 6H), 0.15 (s, 9H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 196.0, 147.6,

111.3, 41.1, 41.0, 30.5, 27.4, 26.6, 0.71; HRMS (CI) *m/z*: [M+H]+ Calcd for $C_{11}H_{22}OSSiH$ 231.1239; Found 231.1236.

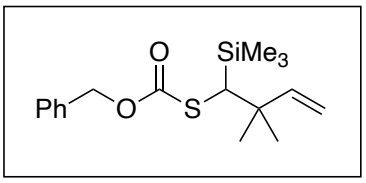


***S*-(2,2-Dimethyl-1-(trimethylsilyl)but-3-en-1-yl) 4-methoxybenzothioate**. To a flame-dried round bottom flask equipped with a magnetic stir bar under argon was added $Rh_2(OAc)_4$ (0.032 mmol), thioether (0.630 mmol) and 4 Å molecular sieves (0.15 g), 6.0 mL CH_2Cl_2 and the mixture was stirred to dissolve the solutes. Trimethylsilyldiazomethane (1.06 mL, 1.0 M in hexanes, 1.06 mmol) was added dropwise via syringe pump over 17 h. The solution was filtered through a pad of Celite and washed with CH_2Cl_2 until the filtrate was colorless. The solvent was removed in vacuo and the crude product was purified by chromatography on silica gel (hexanes/EtOAc 1:40), followed by PTLC (hexanes/EtOAc 95:5) to give *S*-(2,2-Dimethyl-1-(trimethylsilyl)but-3-en-1-yl) 4-methoxybenzothioate as a clear oil (0.151 g, 0.464 mmol, 73.6 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.01 (d, *J* = 8.9 Hz, 2H), 6.92 (d, *J* = 8.8 Hz, 2H), 5.92 (dd, *J* = 17.5, 10.6 Hz, 1H), 4.98 (dd, *J* = 17.5, 1.1 Hz, 1H), 4.94 (dd, *J* = 10.8, 1.1 Hz, 1H), 3.85 (s, 3H), 3.27 (s, 1H), 1.14 (s, 6H), 0.13 (s, 9H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 190.8, 163.8, 147.8, 130.3, 129.7, 113.9, 111.3, 55.7, 41.3, 40.3, 27.7, 26.7, 0.85; HRMS (CI) *m/z*: [M]+ Calcd for $C_{17}H_{26}O_2SSi$ 322.1423; Found 322.1412.

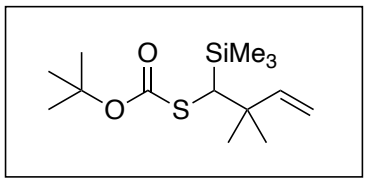


Methyl 4-(benzoylthio)-3,3-dimethyl-2-methylene-4-(trimethylsilyl)butanoate. To a flame-dried round bottom flask equipped with a magnetic stir bar under argon was added $Rh_2(OAc)_4$ (0.028 mmol), thioether (0.570 mmol) and 4 Å molecular sieves (0.15 g), 6.0 mL CH_2Cl_2 and the mixture was stirred to dissolve the solutes. Trimethylsilyldiazomethane (0.85

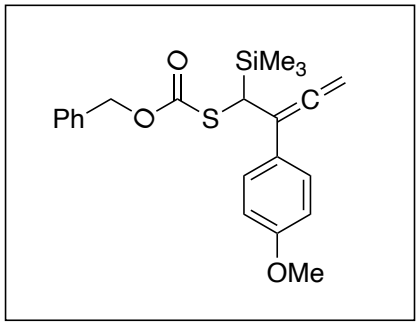
mL, 1.0 M in hexanes, 0.85 mmol) was added dropwise via syringe pump over 17 h. The solution was filtered through a pad of Celite and washed with CH_2Cl_2 until the filtrate was colorless. The solvent was removed in vacuo and the crude product was purified by chromatography on silica gel (hexanes/EtOAc 1:40), followed by PTLC (hexanes/EtOAc 95:5) to give methyl 4-(benzoylthio)-3,3-dimethyl-2-methylene-4-(trimethylsilyl)butanoate as a clear oil (0.134 g, 0.384 mmol, 67.4 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.01 (d, *J* = 7.2 Hz, 2H), 7.54 (t, *J* = 7.3 Hz, 1H), 7.43 (t, *J* = 7.9 Hz, 2H), 6.08 (s, 1H), 5.58 (s, 1H), 4.21 (s, 1H), 3.78 (s, 3H), 1.38 (s, 3H), 1.25 (s, 3H), 0.12 (s, 9H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 191.3, 168.5, 148.3, 138.0, 133.0, 128.5, 127.4, 123.6, 51.7, 42.3, 37.5, 27.7, 27.6, 0.51; HRMS (ES) *m/z*: [M+Na]+ Calcd for $C_{18}H_{26}O_3SSiNa$ 373.1270; Found 373.1263.



***O*-Benzyl S-(2,2-dimethyl-1-(trimethylsilyl)but-3-en-1-yl) carbonothioate** (**2a**) was synthesized according to the general procedure using *O*-benzyl S-(3-methylbut-2-en-1-yl) carbonothioate (0.630 mmol). The crude product was purified by chromatography on silica gel (hexanes/EtOAc 99:1) to give *O*-benzyl S-(2,2-dimethyl-1-(trimethylsilyl)but-3-en-1-yl) carbonothioate as a clear oil (0.199 g, 0.612 mmol, 97.2 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.35 (s, 5H), 5.85 (dd, *J* = 17.5, 10.5 Hz, 1H), 5.24 (s, 2H), 4.97 (dd, *J* = 17.5, 0.8 Hz, 1H), 4.93 (dd, *J* = 10.7, 0.8 Hz, 1H), 2.75 (s, 1H), 1.12 (s, 3H), 1.11 (s, 3H), 0.12 (s, 9H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 172.7, 147.2, 135.5, 128.6, 128.4, 128.2, 111.5, 69.1, 43.8, 41.1, 27.2, 26.2, 0.57; HRMS (CI) *m/z*: [M–$C_8H_7O_2$]+ Calcd for $C_9H_{19}O_3SSi$ 187.0977; Found 187.0969.

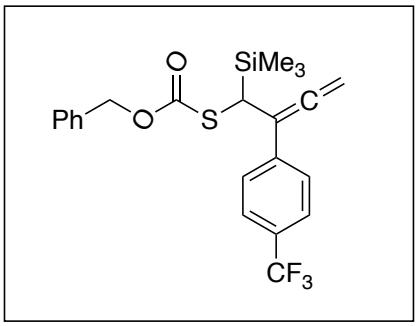


***O*-(Tert-butyl) *S*-(2,2-dimethyl-1-(trimethylsilyl)but-3-en-1-yl) carbonothioate** (**2b**) was synthesized according to the general procedure using *O*-(tert-butyl) *S*-(3-methylbut-2-en-1-yl) carbonothioate (0.370 mmol). The crude product was purified by PTLC (hexanes/EtOAc 90:10) to give *O*-(tert-butyl) *S*-(2,2-dimethyl-1-(trimethylsilyl)but-3-en-1-yl) carbonothioate as a clear oil (0.064 g, 0.222 mmol, 59.8 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 5.85 (dd, *J* = 17.4, 10.8 Hz, 1H), 4.96 (dd, *J* = 17.4, 1.1 Hz, 1H), 4.92 (dd, *J* = 10.7, 1.1 Hz, 1H), 2.63 (s, 1H), 1.48 (s, 9H), 1.11 (s, 3H), 1.10 (s, 3H), 0.11 (s, 9H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 170.8, 147.6, 111.1, 84.2, 43.6, 41.0, 28.2, 27.2, 26.3, 0.54; HRMS (CI) *m/z*: [M–$C_5H_{15}O_2$]+ Calcd for $C_9H_{19}SSi$ 187.0977; Found 187.0973.

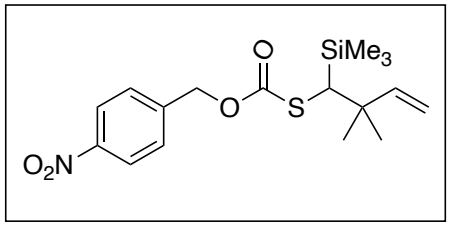


***O*-Benzyl *S*-(2-(4-methoxyphenyl)-1-(trimethylsilyl)buta-2,3-dien-1-yl) carbonothioate** (**2c**) was synthesized according to the general procedure using *O*-benzyl S-(3-(4-methoxyphenyl)prop-2-yn-1-yl) carbonothioate (0.510 mmol). The crude product was purified by chromatography on silica gel (hexanes/EtOAc 99:1) followed by PTLC (hexanes/EtOAc 90:10) to give *O*-benzyl *S*-(2-(4-methoxyphenyl)-1-(trimethylsilyl)buta-2,3-dien-1-yl) carbonothioate as a clear oil (0.067 g, 0.167 mmol, 32.8 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.43 (d, *J* = 8.5 Hz, 2H), 7.31-7.38 (m, 5H), 6.86 (d, *J* = 8.9 Hz, 2H), 5.28 (d, *J* = 12.0 Hz, 1H), 5.23 (d, *J* = 12.0 Hz, 1H), 5.20 (dd, *J* = 11.6, 1.4 Hz, 1H), 5.09 (d, *J* = 11.4 Hz, 1H), 3.81 (s, 3H), 3.72 (s, 1H), 0.07 (s, 9H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 209.5, 172.0, 158.8, 135.4, 128.7, 128.6, 128.5, 128.4, 128.0, 113.9, 107.7,

80.5, 69.2, 55.3, 31.6, 2.10; HRMS (CI) *m/z*: [M]+ Calcd for $C_{22}H_{26}O_3SSi$ 398.1372; Found 398.1378.

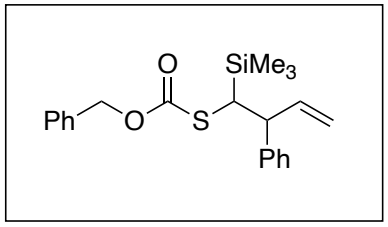


***O*-Benzyl *S*-(2-(4-(trifluoromethyl)phenyl)-1-(trimethylsilyl)buta-2,3-dien-1-yl) carbonothioate** (**2d**) was synthesized according to the general procedure using *O*-benzyl *S*-(3-(4-(trifluoromethyl)phenyl)prop-2-yn-1-yl) carbonothioate (0.510 mmol). The crude product was purified by chromatography on silica gel (hexanes/Et_2O 40:1) followed by PTLC (hexanes/ Et_2O 90:10, then hexanes, 100%) to give *O*-benzyl *S*-(2-(4-(trifluoromethyl)phenyl)-1-(trimethylsilyl)buta-2,3-dien-1-yl) carbonothioate as a clear oil (0.136 g, 0.309 mmol, 60.6 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.62 (d, *J* = 8.2 Hz, 2H), 7.56 (d, *J* = 8.2 Hz, 2H), 7.33-7.38 (m, 5H), 5.18-5.30 (m, 4H), 3.74 (s, 1H), 0.09 (s, 9H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 210.2, 171.8, 140.4, 135.2, 129.1, 128.9, 128.7, 128.6, 128.4, 127.0, 125.4 (q, *J* = 3.9 Hz), 123.2, 107.7, 81.3, 69.4, 31.2, -2.1.

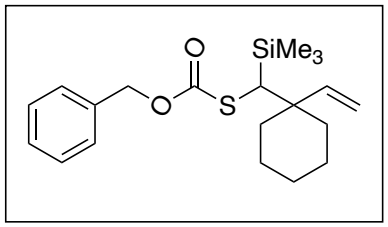


***S*-(2,2-Dimethyl-1-(trimethylsilyl)but-3-en-1-yl) O-(4-nitrobenzyl) carbonothioate** (**2e**) was synthesized according to the general procedure using *S*-(3-methylbut-2-en-1-yl) *O*-(4-nitrobenzyl) carbonothioate (0.570 mmol). The crude product was purified by chromatography on silica gel (hexanes/EtOAc 98:2) followed by PTLC (hexanes/ Et_2O 90:10to give S-(2,2-Dimethyl-1-(trimethylsilyl)but-3-en-1-yl) *O*-(4-nitrobenzyl) carbonothioate as a clear oil (0.196 g, 0.535 mmol, 93.8 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.22 (d, *J* = 8.8 Hz, 2H), 7.51 (d, *J* = 8.6 Hz, 2H), 5.83 (dd, *J* = 17.7, 10.3 Hz 1H), 5.32

(s, 2H), 4.97 (d, J = 17.2 Hz, 1H), 4.93 (d, J = 10.8 Hz, 1H), 2.74, (s, 1H), 1.11 (s, 6H), 0.12 (s, 9H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 172.8, 147.8, 147.0, 142.8, 128.2, 123.9, 111.6, 67.3, 44.0, 41.1, 27.1, 26.3, 0.6.

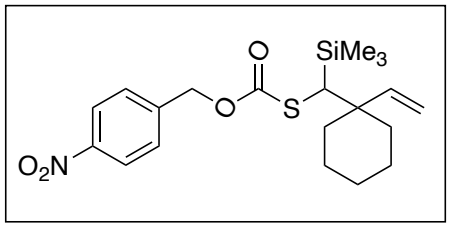


***O*-Benzyl *S*-(2-phenyl-1-(trimethylsilyl)but-3-en-1-yl) carbonothioate** (**2f**) was synthesized according to the general procedure using *O*-benzyl *S*-cinnamyl carbonothioate (0.560 mmol). The crude product was purified by chromatography on silica gel (hexanes/EtOAc 99:1) followed by PTLC (hexanes/ Et_2O 90:10) to give *O*-benzyl *S*-(2-phenyl-1-(trimethylsilyl)but-3-en-1-yl) carbonothioate as a clear oil (0.168 g, 0.451 mmol, 80.6 %) in a 2.4 :1 mixture of diastereomers. ^{1}H NMR major diastereomer (500 MHz, $CDCl_3$) δ 7.19-7.39 (m, 10H), 6.05 (dt, J = 17.0, 9.8 Hz, 1H), 5.05-5.29 (m, 4H), 3.63 (t, J = 8.4 Hz, 1H), 3.12 (d, J = 8.4 Hz, 1H), -0.02 (s, 9H). ^{13}C NMR major diastereomer (125 MHz, $CDCl_3$) δ 171.9, 143.4, 142.5, 140.0, 135.5, 128.6, 128.5, 128.2, 128.1, 126.7, 116.3, 69.1, 52.3, 37.8, -1.69.

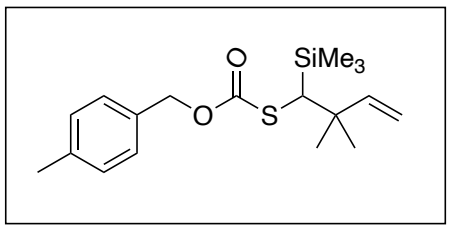


***O*-Benzyl S-((trimethylsilyl)(1-vinylcyclohexyl)methyl) carbonothioate** (**2g**) was synthesized according to the general procedure using *O*-benzyl S-(2-cyclohexylideneethyl) carbonothioate (0.580 mmol). The crude product was purified by chromatography on silica gel (hexanes/Et_2O 99:1) to give *O*-benzyl *S*-((trimethylsilyl)(1-vinylcyclohexyl)methyl) carbonothioate as a clear oil (0.193 g, 0.533 mmol, 92.0 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.31-7.38 (m, 5H), 5.63 (dd, J = 17.9, 10.9 Hz, 1H), 5.25 (d, J = 12.1 Hz, 1H), 5.21 (d, J = 12.1 Hz, 1H), 5.14 (dd, J = 10.9, 1.3 Hz, 1H), 5.05 (dd, J = 17.7, 1.3 Hz, 1H),

2.80 (s, 1H), 1.16-1.79 (m, 10 H), 0.12 (s, 9H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 172.9, 144.2, 135.6, 128.6, 128.4, 128.2, 115.3, 69.1, 44.8, 44.1, 35.6, 34.6, 26.1, 22.5, 22.4, 0.9.

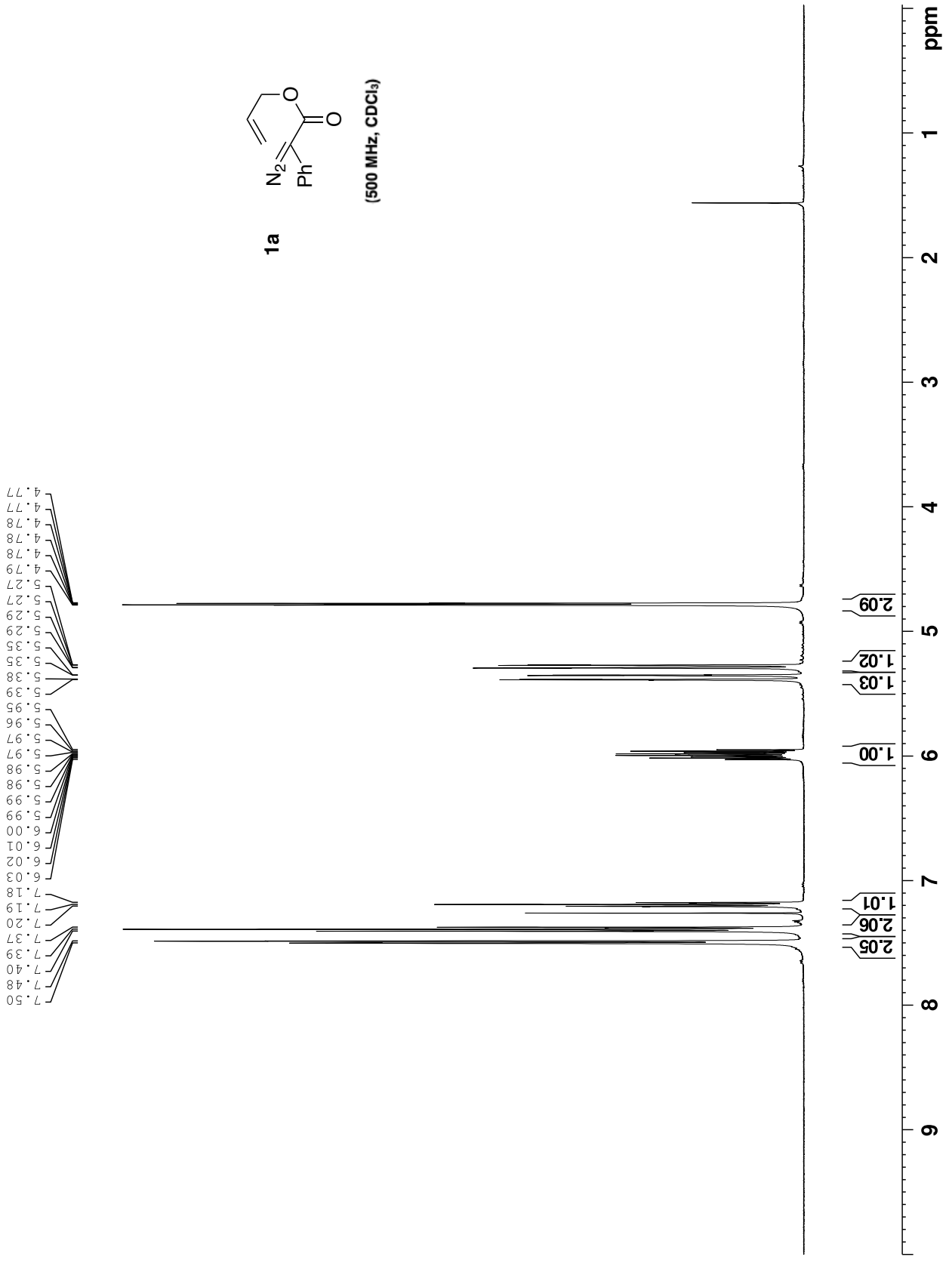


***O*-(4-nitrobenzyl) *S*-((trimethylsilyl)(1-vinylcyclohexyl)methyl) carbonothioate** (**2h**) was synthesized according to the general procedure using *S*-(2-cyclohexylideneethyl) *O*-(4-nitrobenzyl) carbonothioate (0.500 mmol). The crude product was purified by chromatography on silica gel (hexanes/EtOAc 98:2), followed by PTLC (hexanes/Et_2O 90:10) to give *O*-(4-nitrobenzyl) *S*-((trimethylsilyl)(1-vinylcyclohexyl)methyl) carbonothioate as an amber oil (0.142 g, 0.350 mmol, 70.0 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 8.23 (d, *J* = 8.2 Hz, 2H), 7.52 (d, *J* = 8.2 Hz, 2H), 5.63 (dd, *J* = 17.7, 10.8 Hz, 1H), 5.34 (d, *J* = 13.4 Hz, 1H), 5.29 (d, *J* = 12.9 Hz, 1H), 5.16 (d, *J* = 11.2 Hz, 1H), 5.06 (d, *J* = 17.7 Hz, 1H), 2.79 (s, 1H), 1.17-1.80 (m, 10 H), 0.13 (s, 9H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 172.9, 147.8, 144.0, 142.9, 128.3, 123.9, 115.4, 67.3, 45.0, 44.1, 35.7, 34.6, 26.1, 22.5, 22.4, 0.9.



***S*-(2,2-Dimethyl-1-(trimethylsilyl)but-3-en-1-yl) *O*-(4-methylbenzyl) carbonothioate** (**2i**) was synthesized according to the general procedure using *O*-(4-methylbenzyl) *S*-(3-methylbut-2-en-1-yl) carbonothioate (0.600 mmol). The crude product was purified by chromatography on silica gel (hexanes/Et_2O 98:2) to give *S*-(2,2-dimethyl-1-(trimethylsilyl)but-3-en-1-yl) *O*-(4-methylbenzyl) carbonothioate (**2i**) as a clear oil (0.194 g, 0.577 mmol, 96.2 %). ^{1}H NMR (500 MHz, $CDCl_3$) δ 7.24 (d, *J* = 8.2

Hz, 2H), 7.16 (d, J = 7.8 Hz, 2H), 5.85 (dd, J = 18.1, 10.8 Hz, 1H), 5.19 (s, 2H), 4.97 (d, J = 17.2 Hz, 1H), 4.93 (d, J = 10.6 Hz, 1H), 2.75 (s, 1H), 2.35 (s, 3H), 1.12 (s, 3H), 1.11 (s, 3H), 0.12 (s, 9H). ^{13}C NMR (125 MHz, $CDCl_3$) δ 172.7, 147.2, 138.3, 132.5, 129.3, 128.3, 111.4, 69.1, 43.7, 41.1, 27.2, 26.2, 0.59.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(500 MHz, CDCl3)
N2
Ph
O
O
ppm
1
2
3
4
5
6
7
8
9
2.09
1.02
1.03
1.00
1.01
2.06
2.05
4.77
4.77
4.78
4.78
4.78
4.79
5.27
5.27
5.29
5.29
5.35
5.35
5.38
5.39
5.95
5.96
5.97
5.97
5.98
5.98
5.99
5.99
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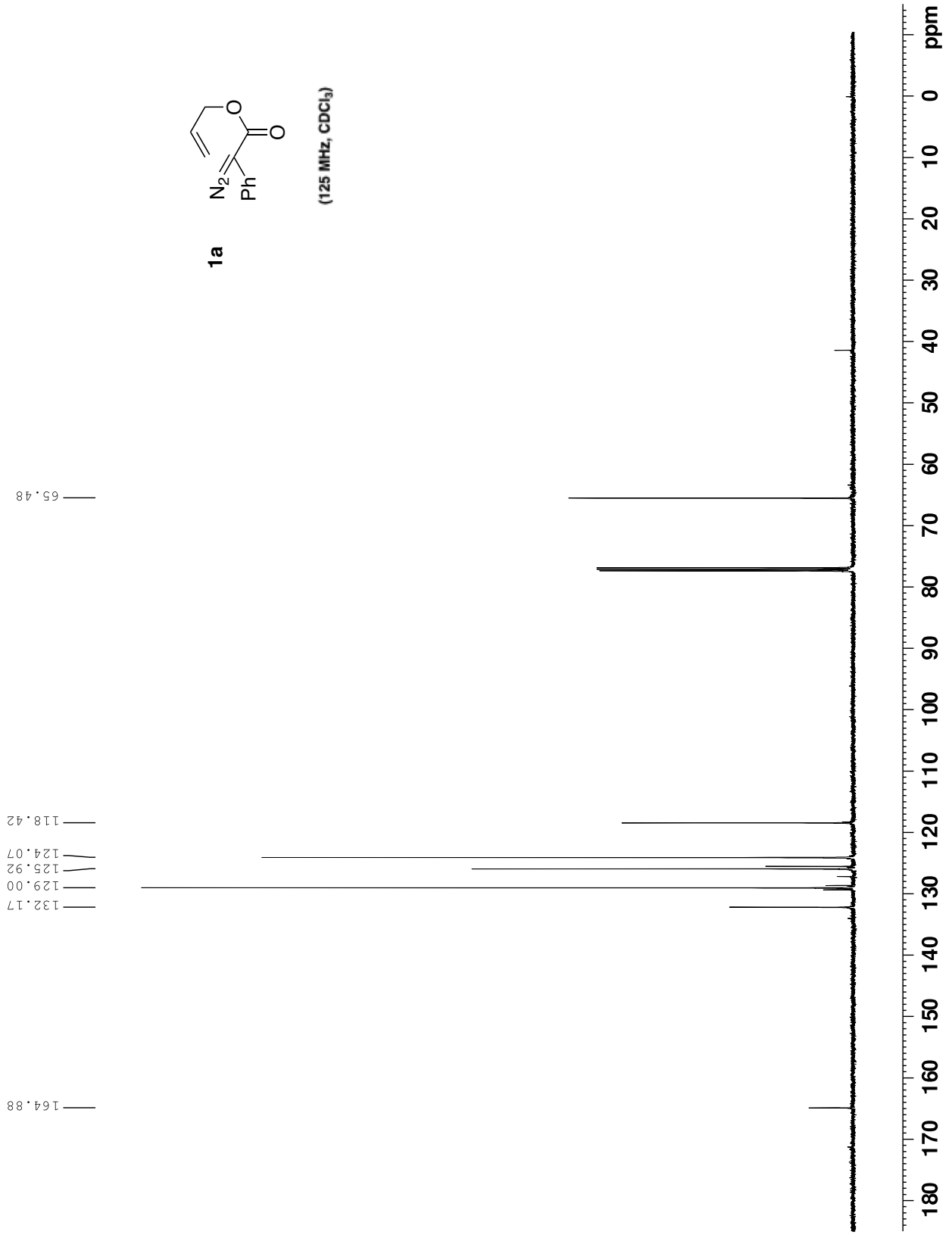
7.20
7.37
7.39
7.40
7.48
7.50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(125 MHz, CDCl3)
N2
Ph
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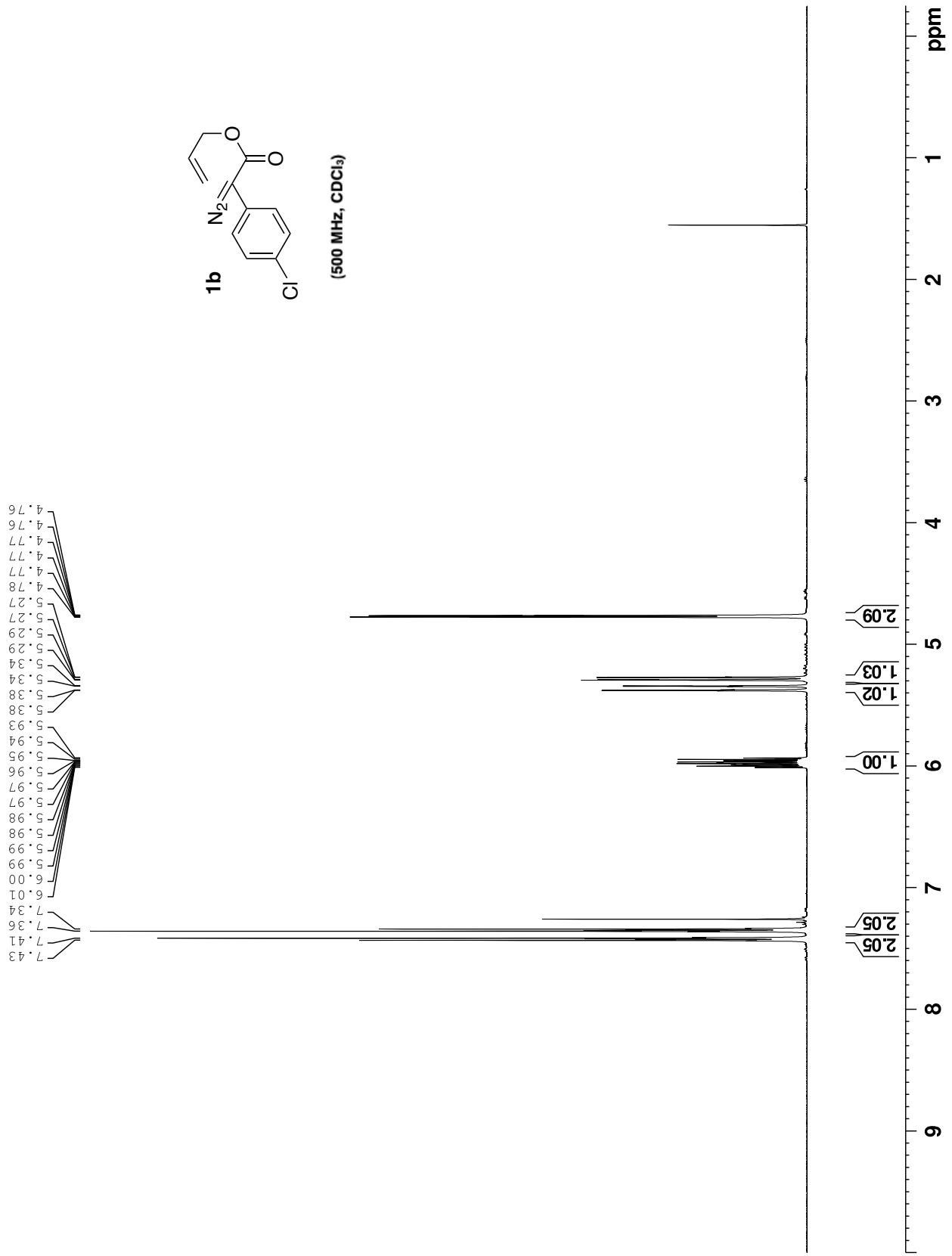
O
65.48
118.42
124.07
125.92
129.00
132.17
164.88
ppm
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180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(500 MHz, CDCl3)
ppm
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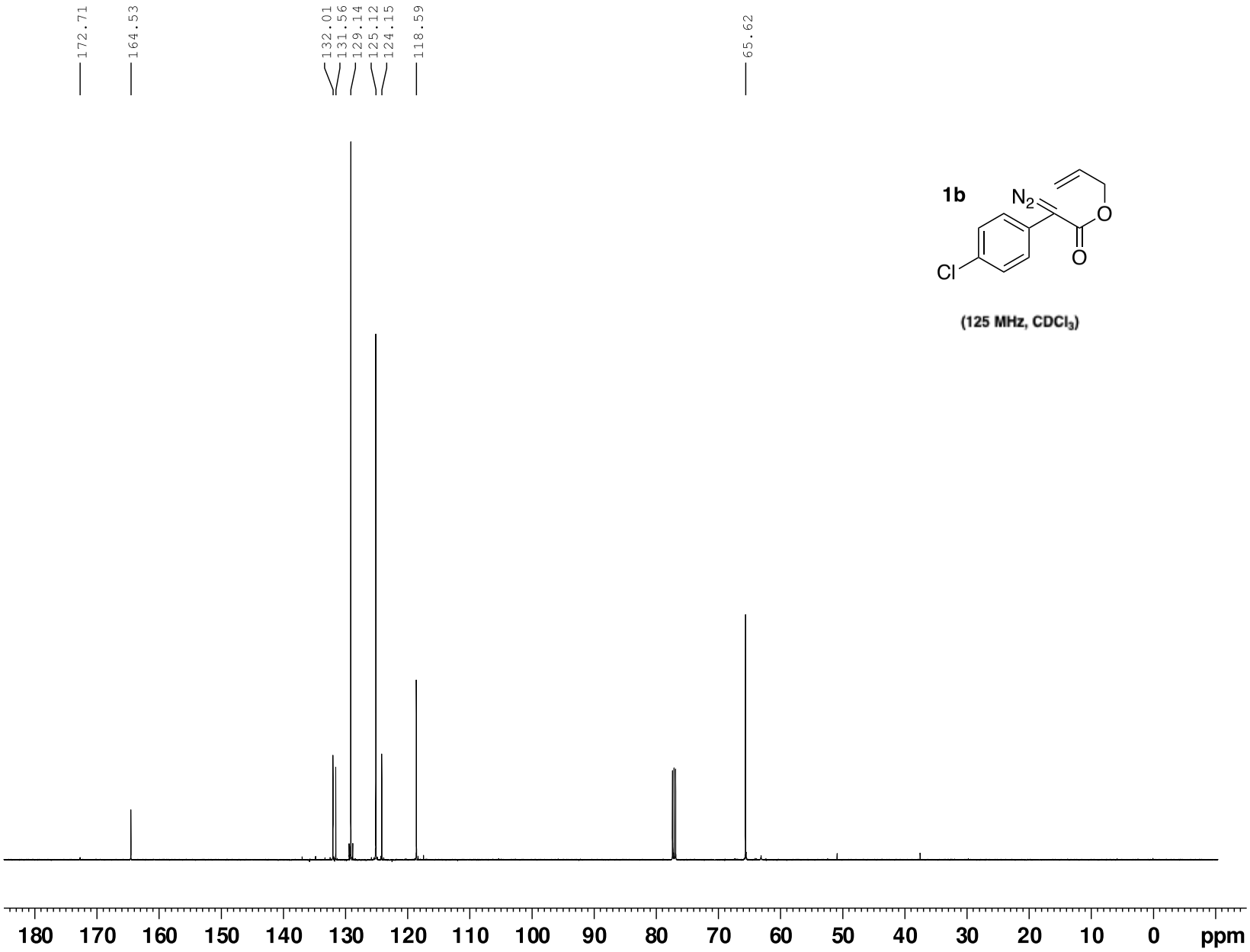
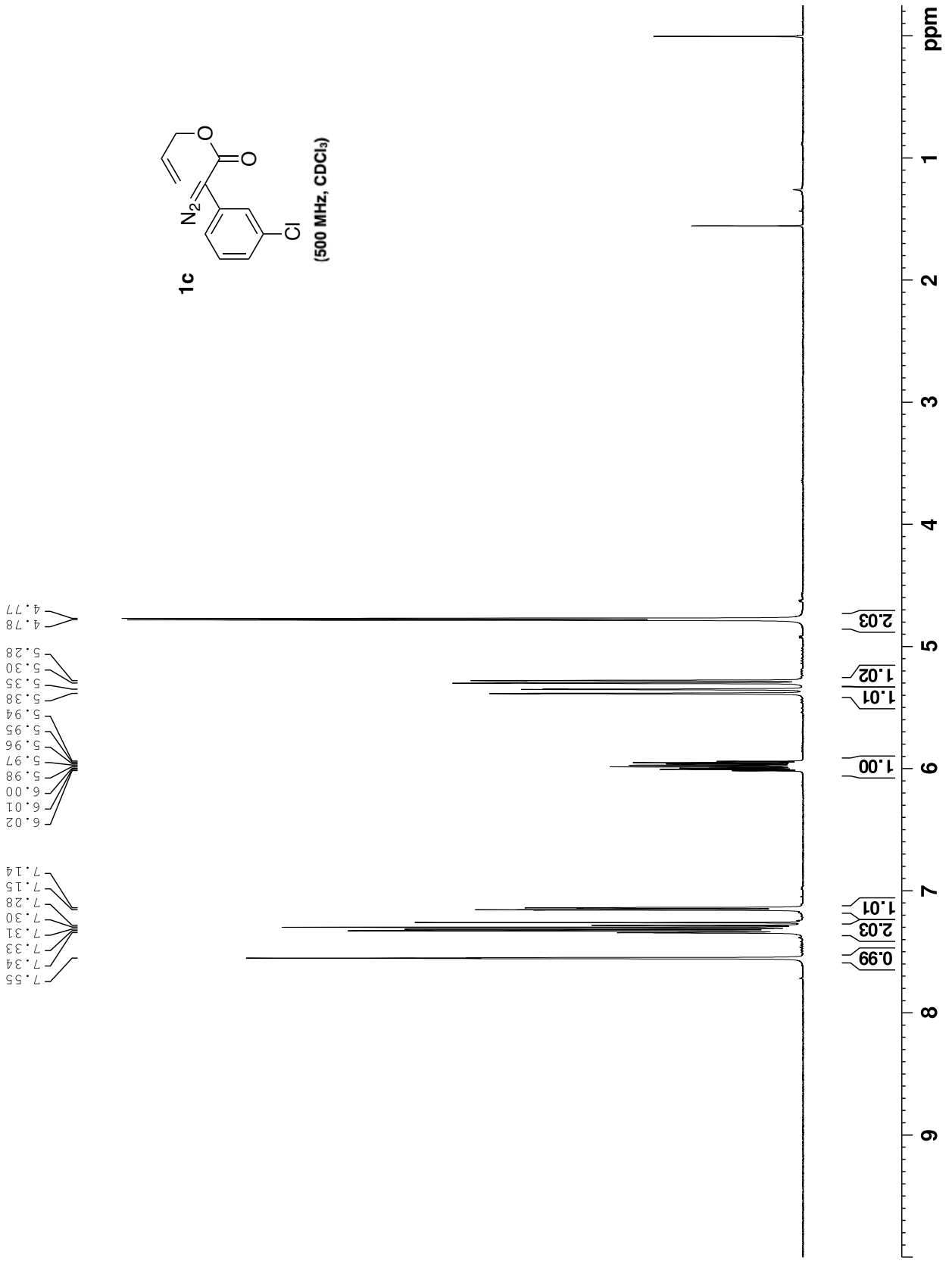
1.03
1.02
1.00
2.05
2.05


172.71
164.53
132.01
131.56
129.14
125.12
124.15
118.59
65.62
1b
N2
O
O
Cl
(125 MHz, CDCl3)
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
ppm


1c
(500 MHz, CDCl3)
ppm
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1.02
1.01
1.00
1.01
2.03
0.99
4.78
4.77
5.28
5.30
5.35
5.38
5.94
5.95
5.96
5.97
5.98
6.00
6.01
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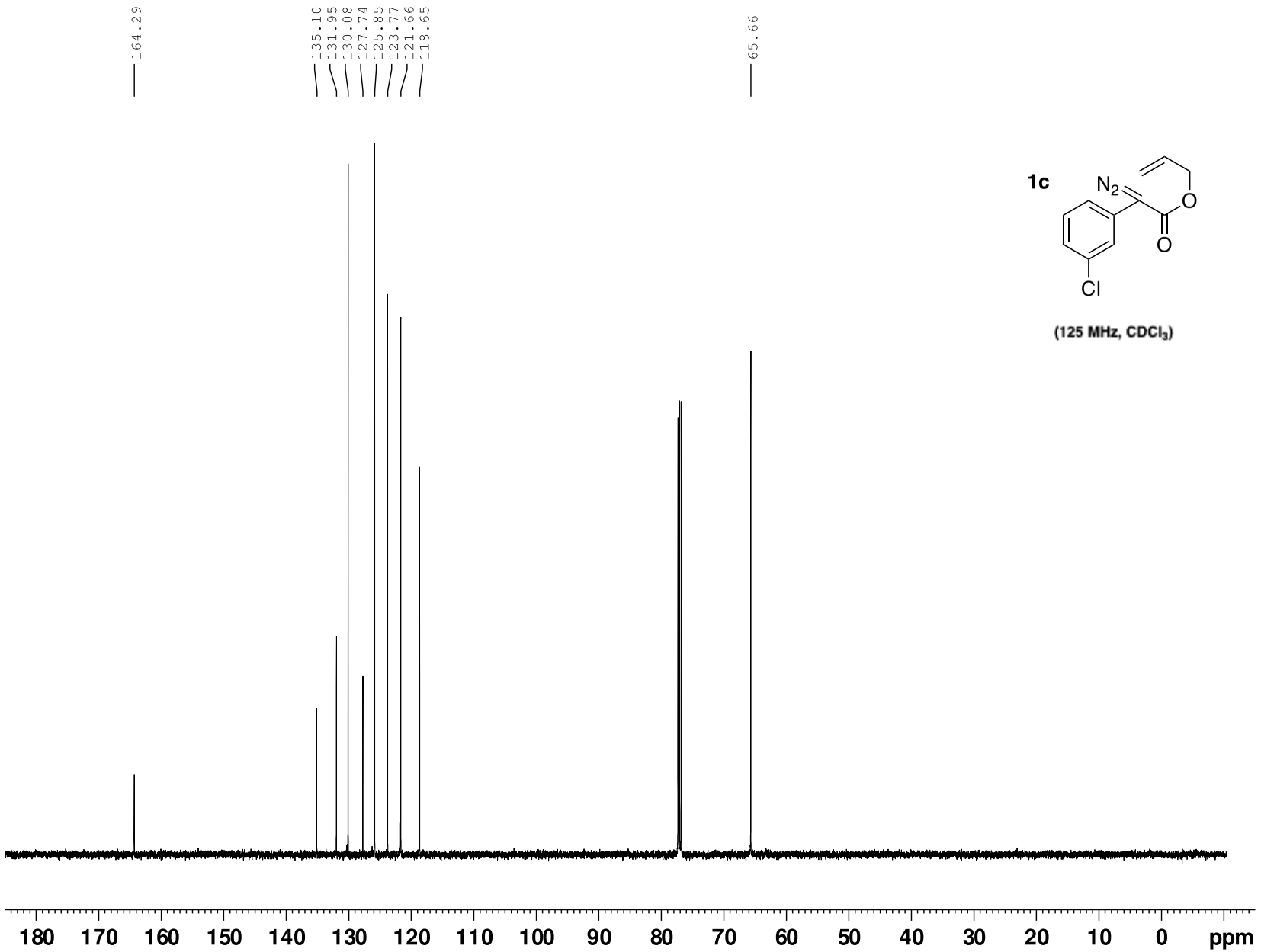
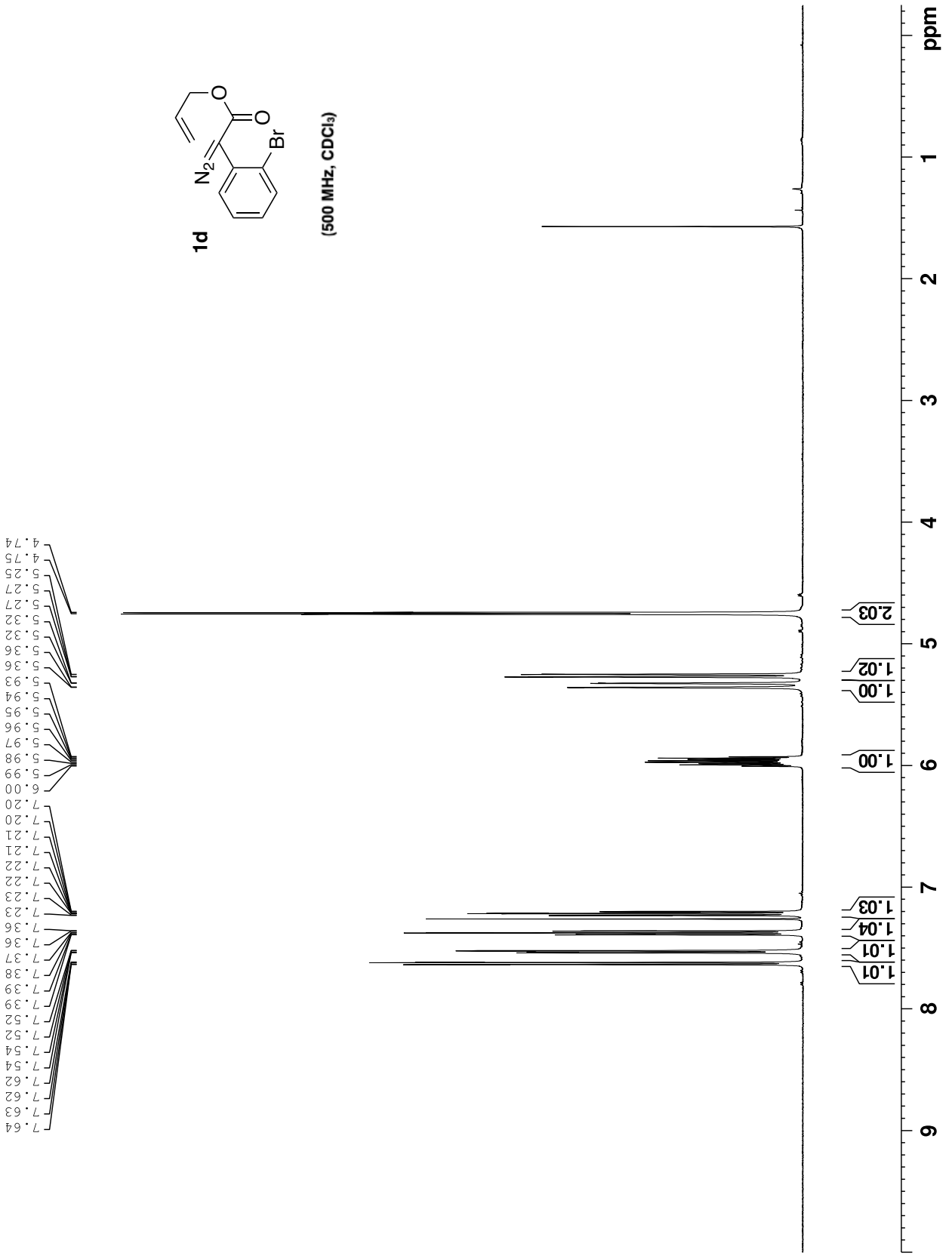
7.28
7.30
7.31
7.33
7.34
7.55


164.29
135.10
131.95
130.08
127.74
125.85
123.77
121.66
118.65
65.66
1c
N2
O
O
Cl
(125 MHz, CDCl3)
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
ppm


1d
(500 MHz, CDCl3)
N2
O
O
Br
ppm
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2
3
4
5
6
7
8
9
2.03
1.02
1.00
1.00
1.03
1.04
1.01
1.01
4.74
4.75
5.25
5.27
5.27
5.32
5.32
5.36
5.36
5.93
5.94
5.95
5.96
5.97
5.98
5.99
6.00
7.20
7.20
7.21
7.21
7.22
7.22
7.23
7.23
7.36
7.36
7.37
7.38
7.39
7.39
7.52
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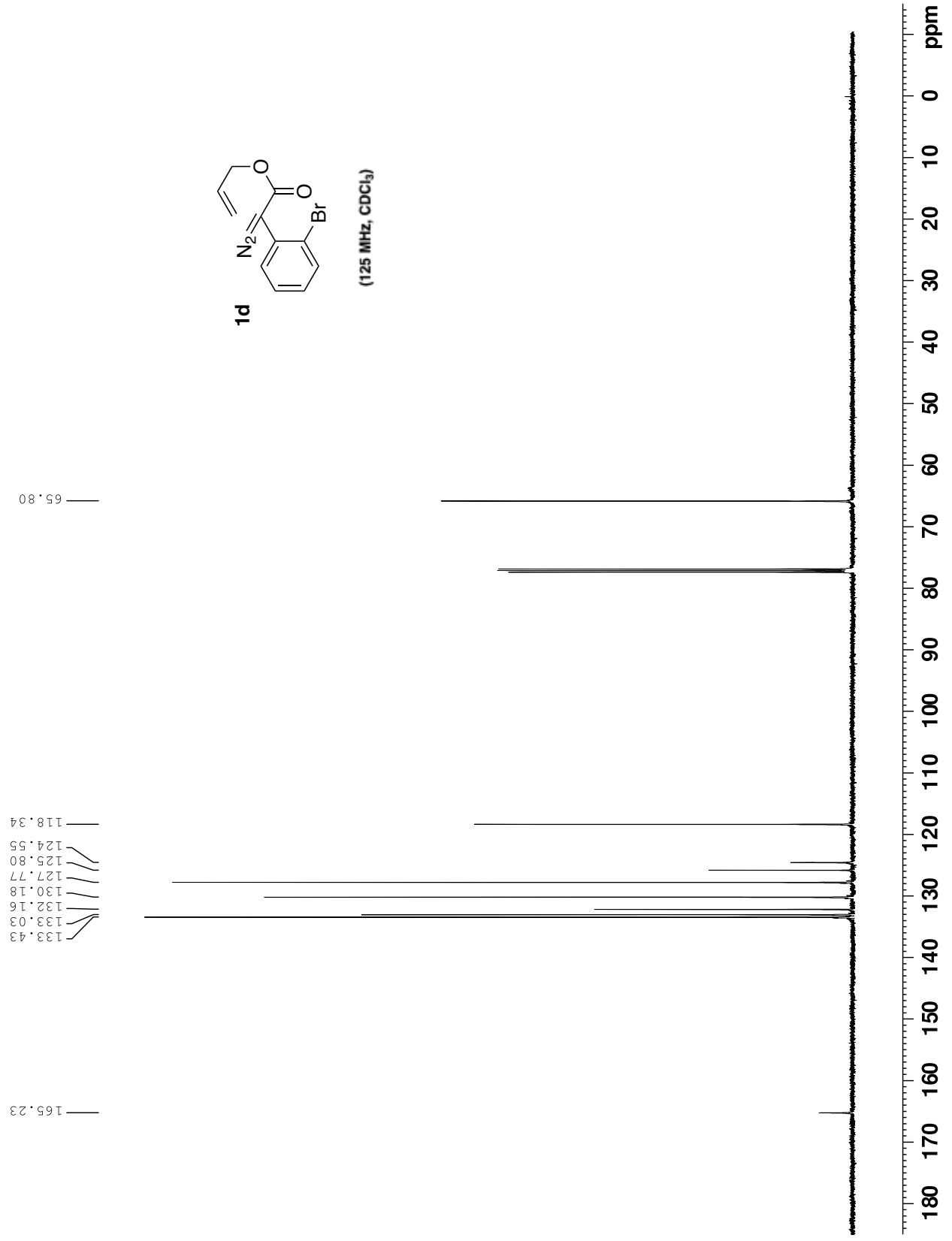
7.54
7.54
7.62
7.62
7.63
7.64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124.55
125.80
127.77
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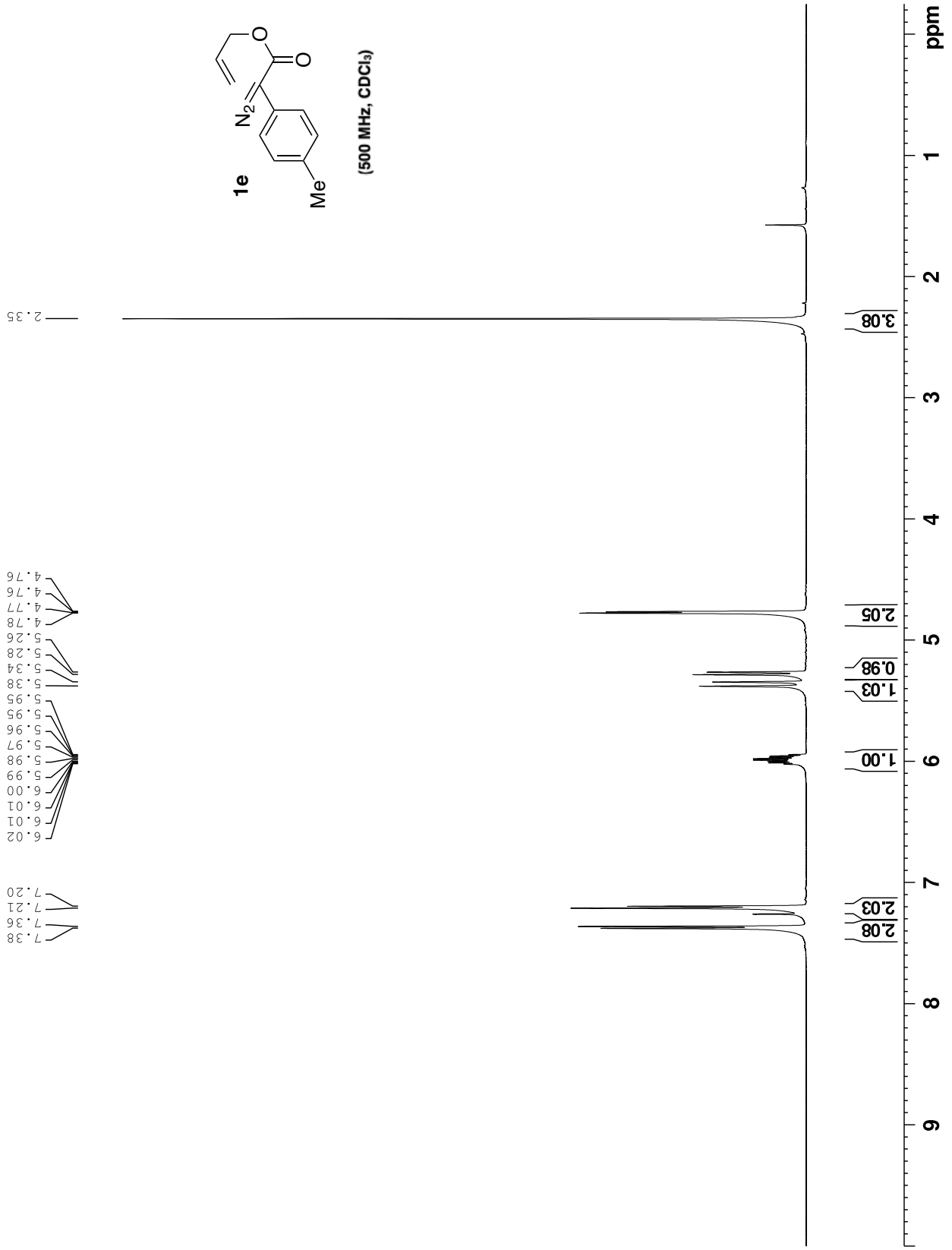
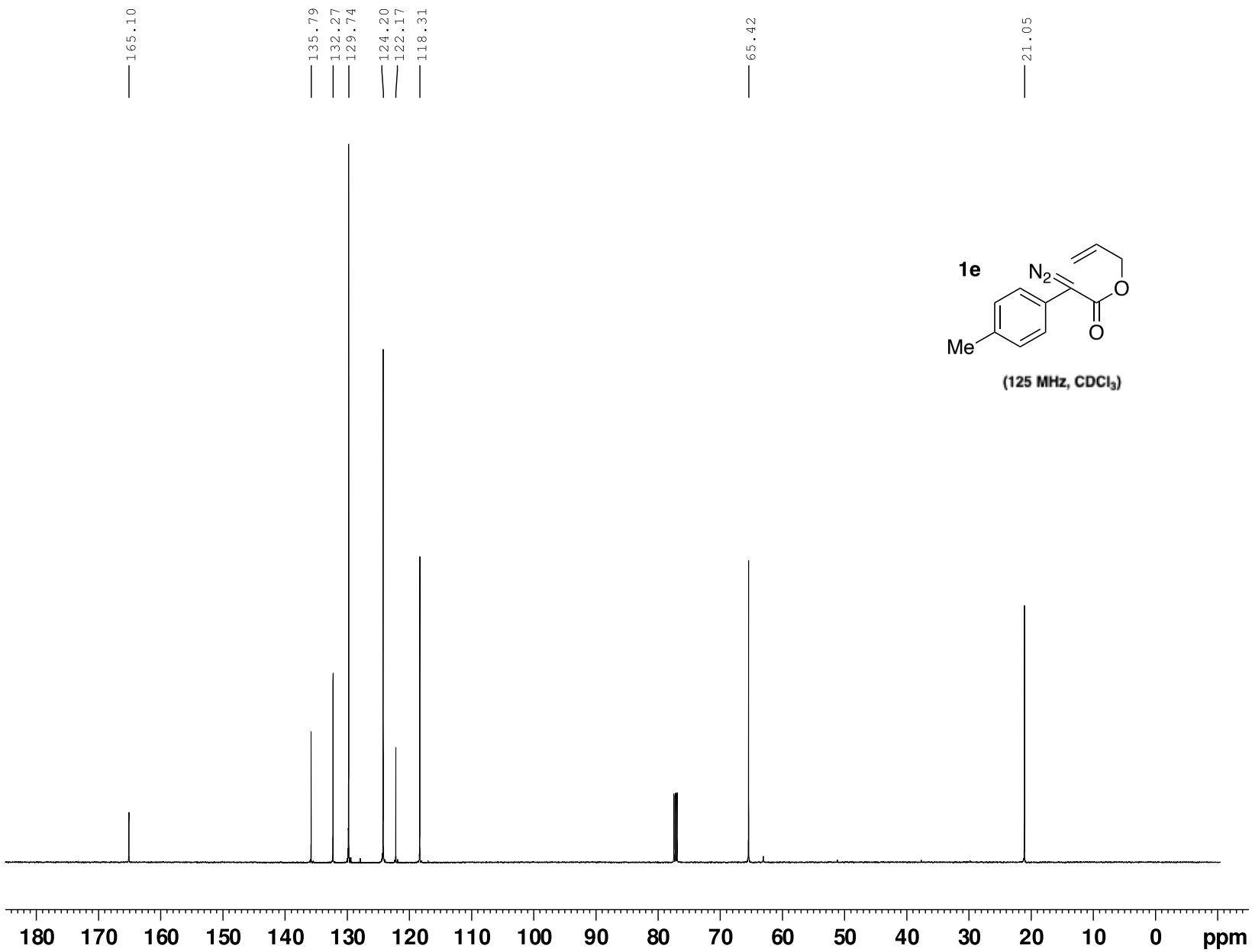
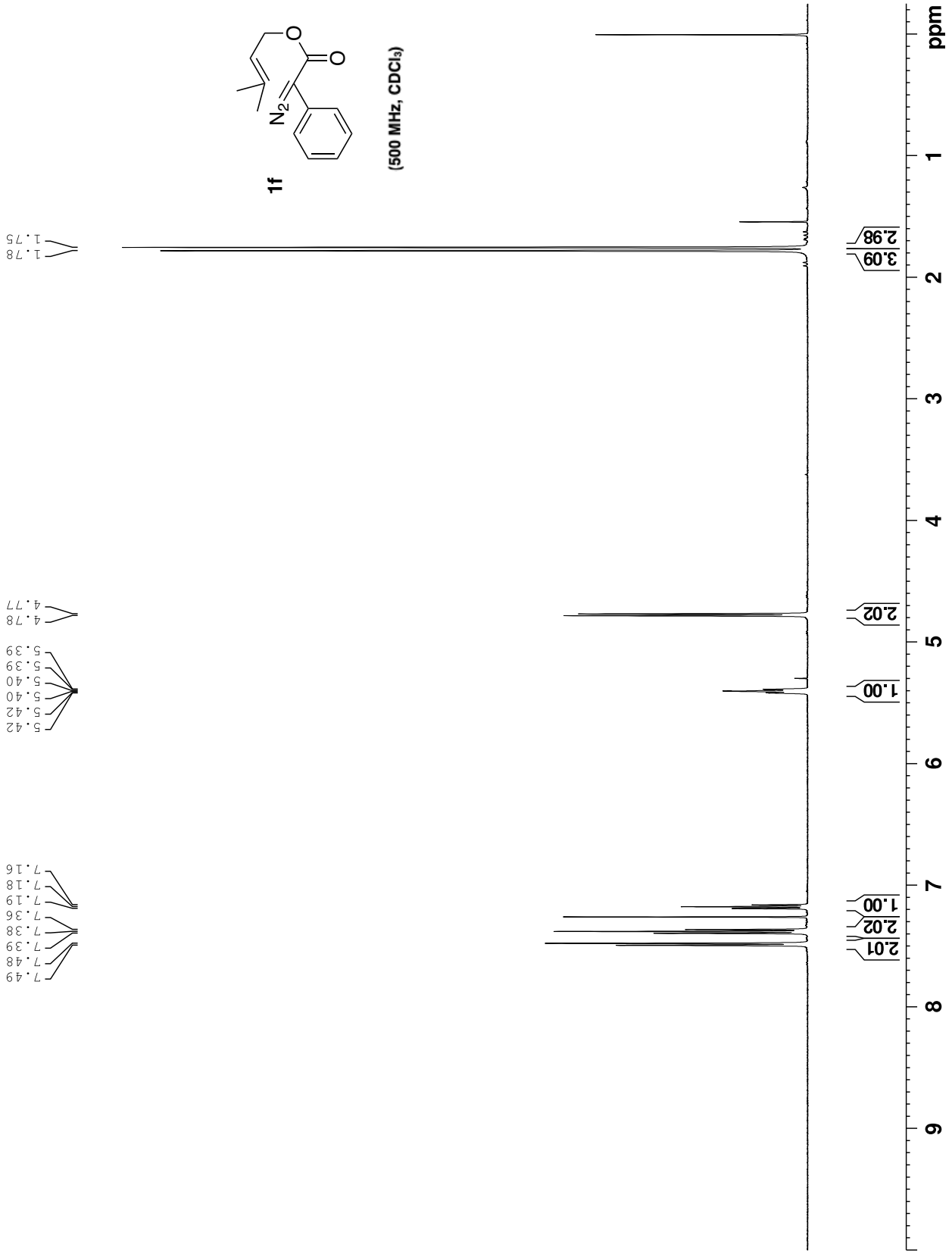
132.16
133.03
133.43
165.23
ppm


1e
(500 MHz, CDCl3)
Me
N2
O
O
ppm
1
2
3
4
5
6
7
8
9
2.35
4.76
4.76
4.77
4.78
5.26
5.28
5.34
5.38
5.95
5.95
5.96
5.97
5.98
5.99
6.00
6.01
6.01
6.02
7.20
7.21
7.36
7.38
3.08
2.05
0.98
1.03
1.00
2.03
2.08


165.10
135.79
132.27
129.74
124.20
122.17
118.31
65.42
21.05
1e
N2
O
O
Me
(125 MHz, CDCl3)
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
ppm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(500 MHz, CDCl3)
ppm
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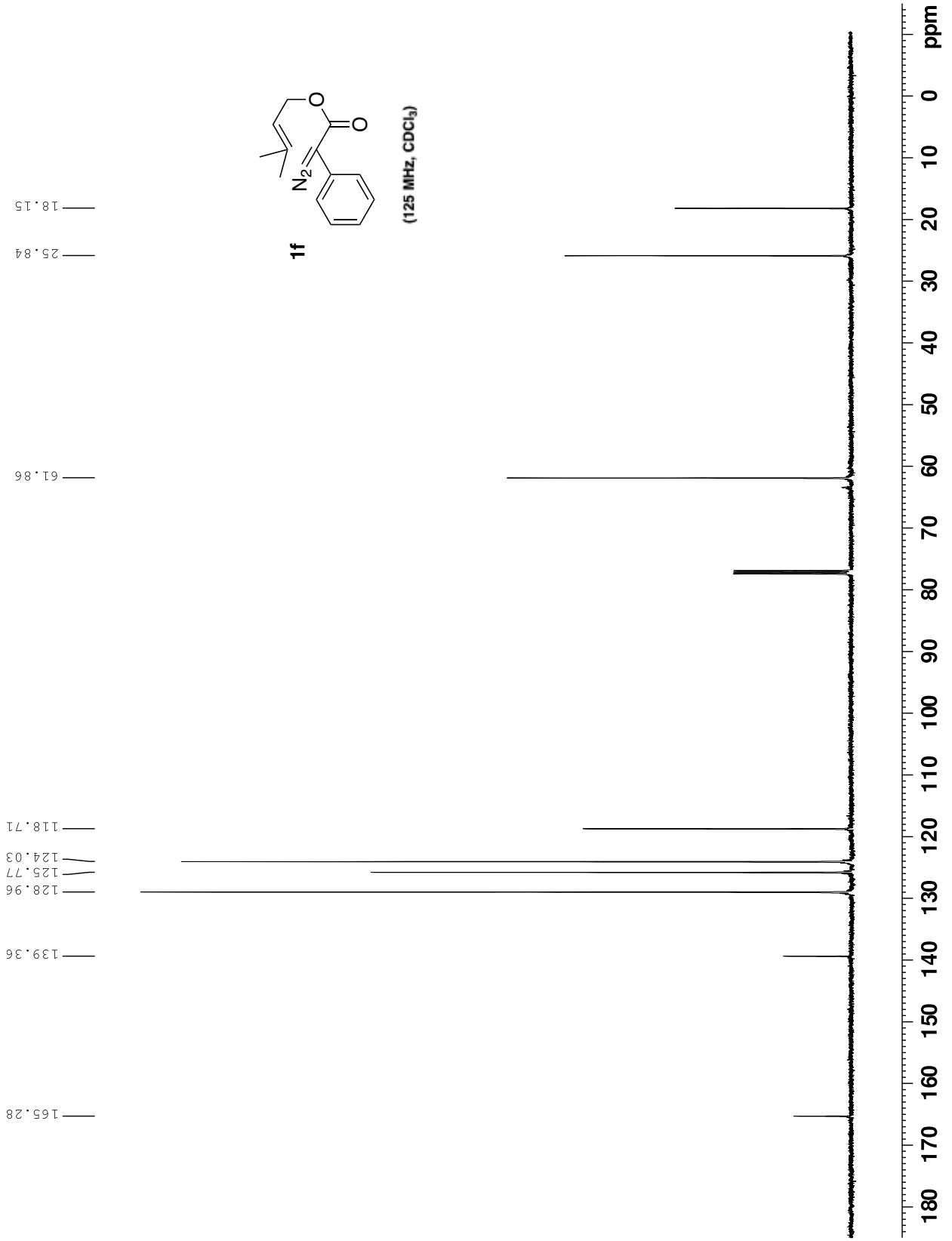
4.77
4.78
5.39
5.39
5.40
5.40
5.42
5.42
7.16
7.18
7.19
7.36
7.38
7.39
7.48
7.49
2.98
3.09
2.02
1.00
1.00
2.02
2.01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25.84
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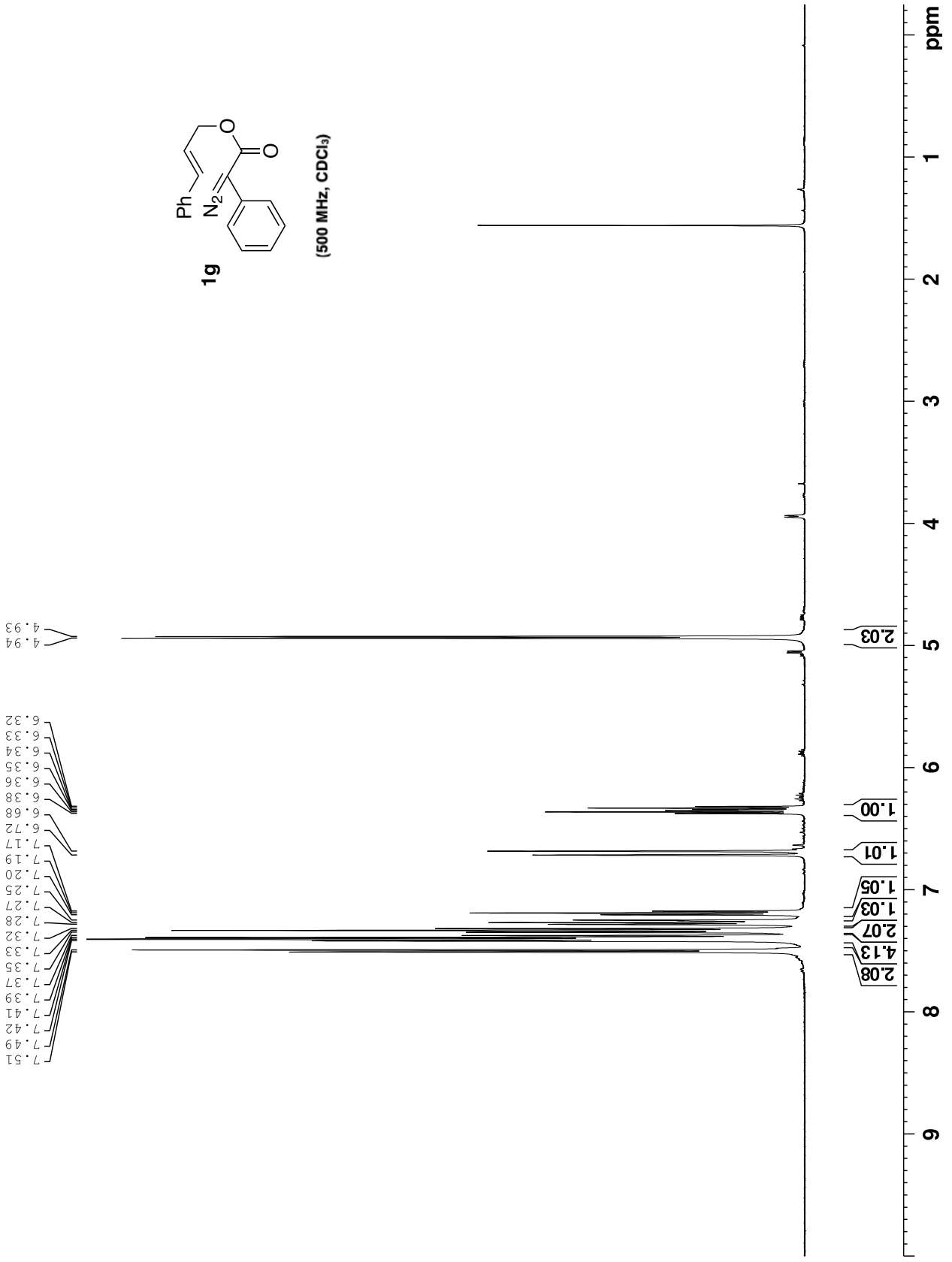
124.03
125.77
128.96
139.36
165.28
1f
(125 MHz, CDCl3)
ppm


1g
(500 MHz, CDCl3)
Ph
N2
O
O
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4.93
6.32
6.33
6.34
6.35
6.36
6.38
6.68
6.72
7.17
7.19
7.20
7.25
7.27
7.28
7.32
7.33
7.35
7.37
7.39
7.41
7.42
7.49
7.51
2.03
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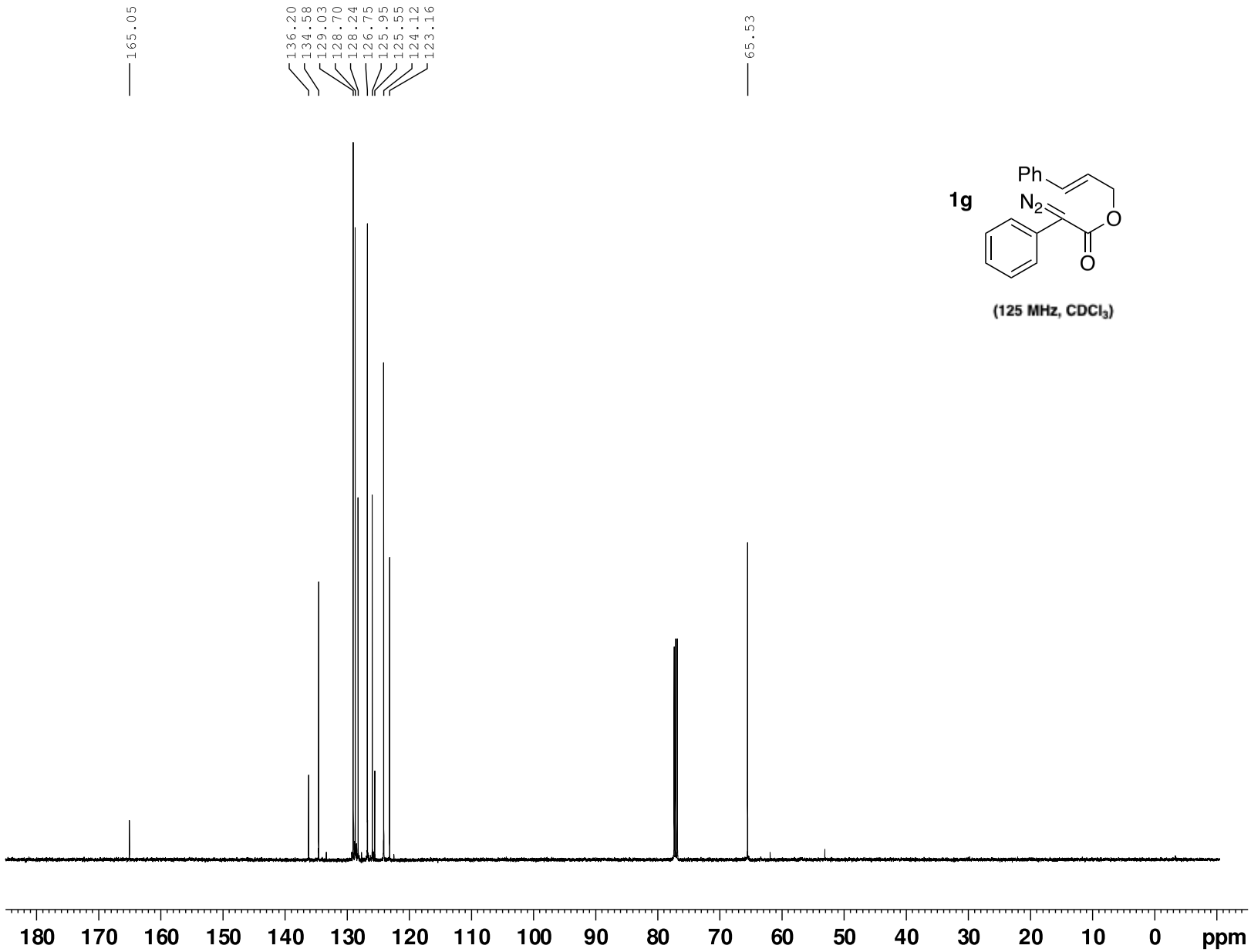
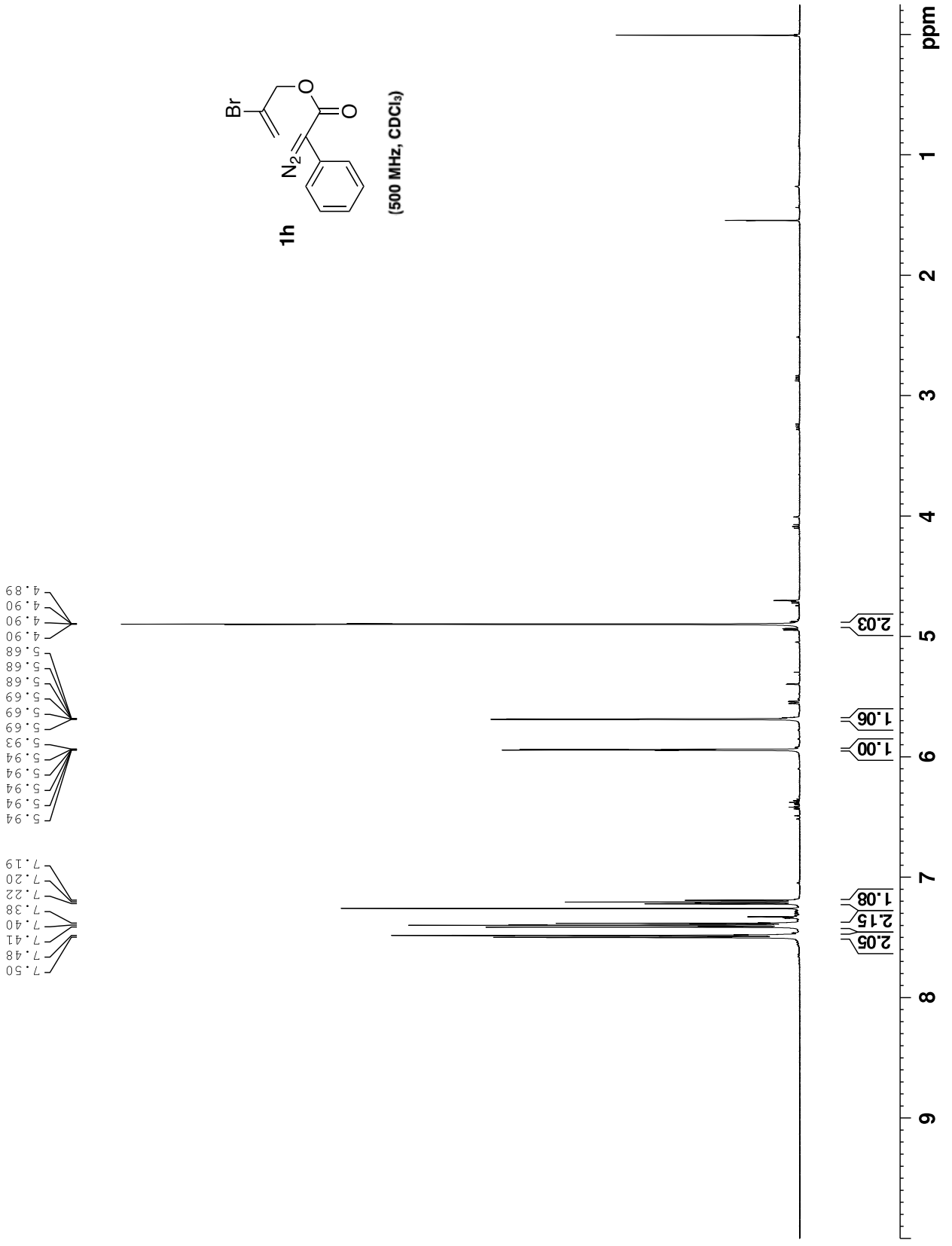
1.01
1.05
1.03
2.07
4.13
2.08
ppm


165.05
136.20
134.58
129.03
128.70
128.24
126.75
125.95
125.55
124.12
123.16
65.53
1g
Ph
N2
O
O
(125 MHz, CDCl3)
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
ppm


1h
(500 MHz, CDCl3)
Br
O
O
N2
ppm
1
2
3
4
5
6
7
8
9
2.03
1.06
1.00
1.08
2.15
2.05
4.89
4.90
4.90
4.90
5.68
5.68
5.68
5.69
5.69
5.69
5.93
5.94
5.94
5.94
5.94
5.94
7.19
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7.22
7.38
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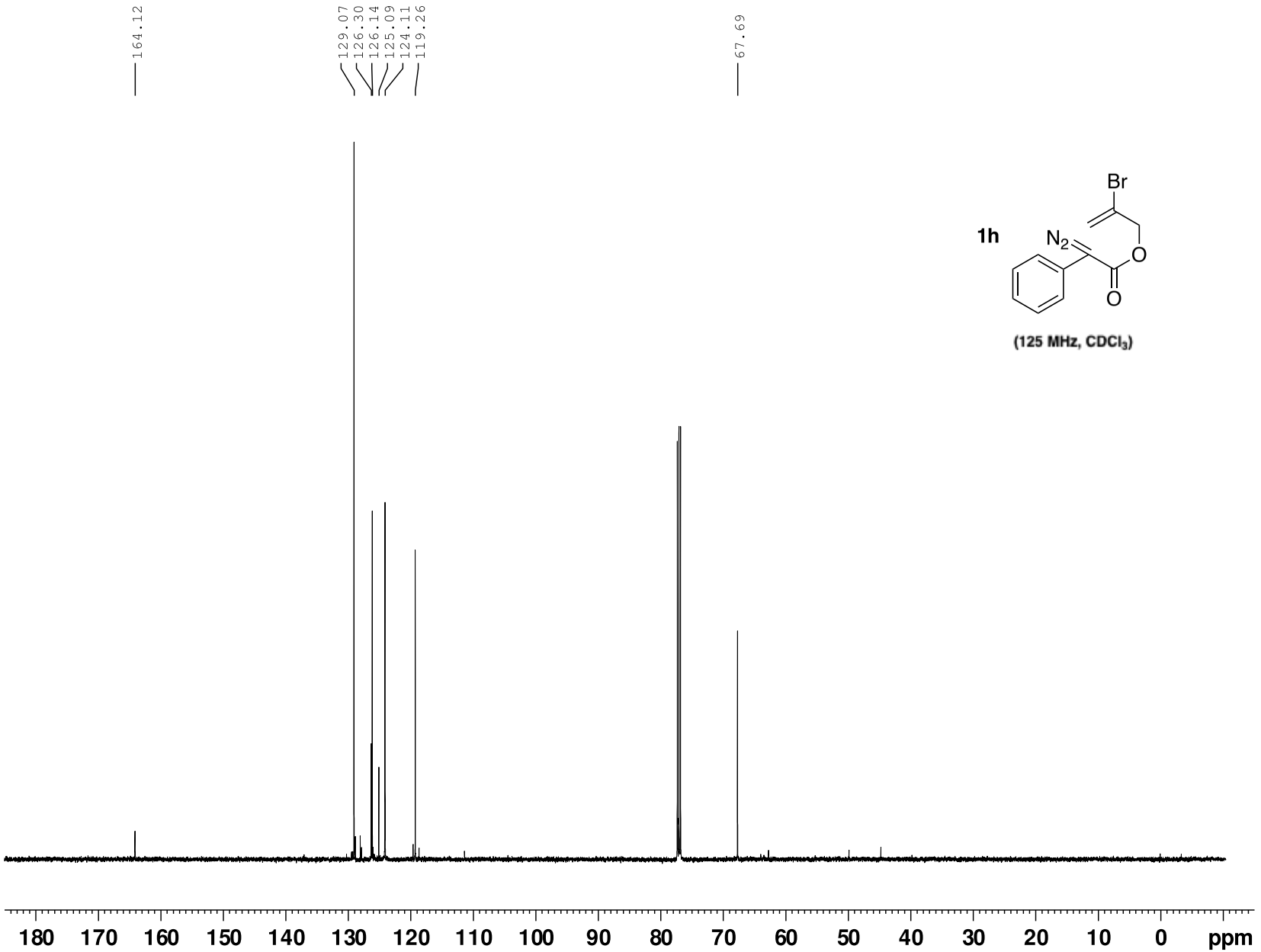
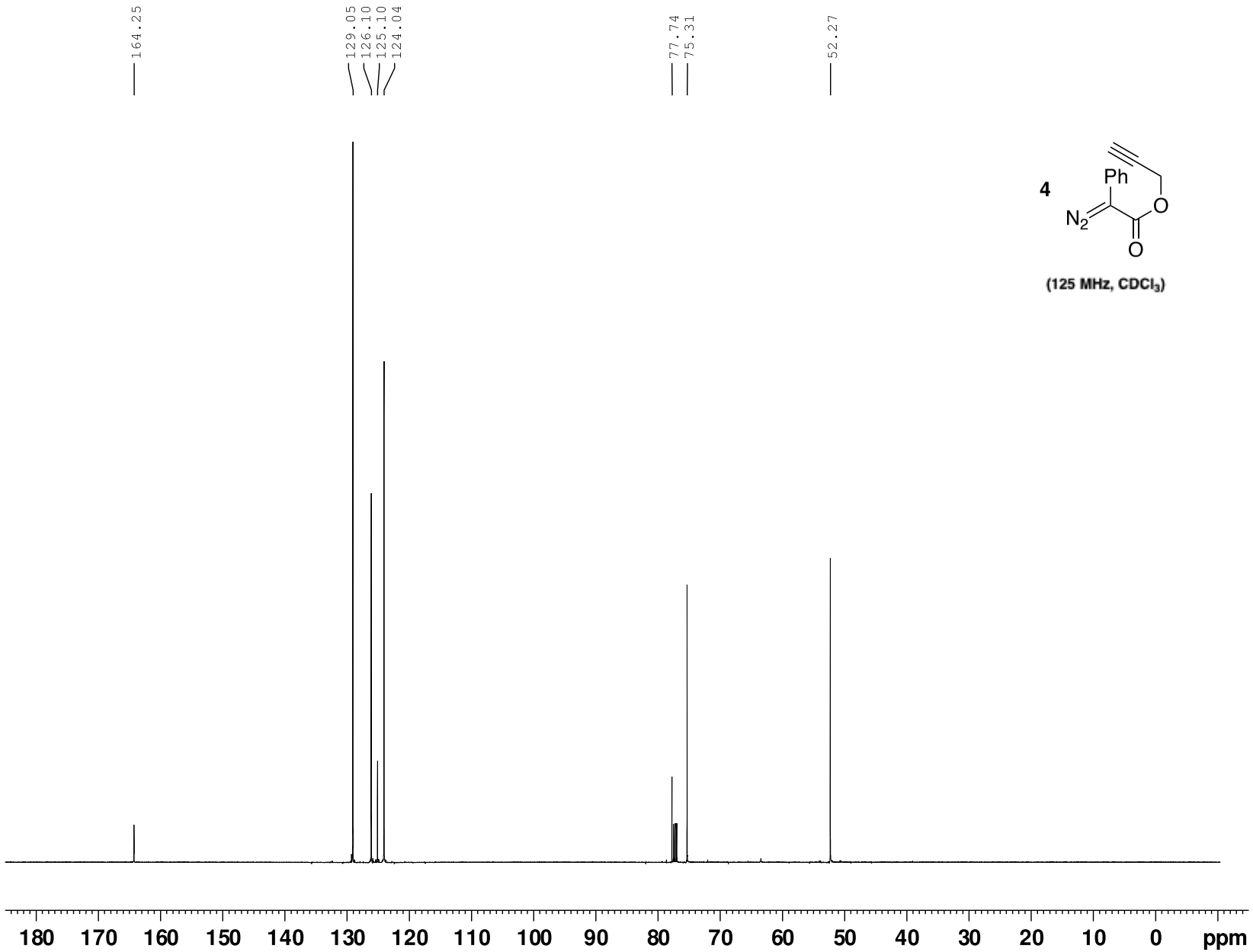
7.41
7.48
7.50


164.12
129.07
126.30
126.14
125.09
124.11
119.26
67.69
1h
Br
N2
O
O
(125 MHz, CDCl3)
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
ppm

4
(500 MHz, CDCl3)
Ph
O
O
N2
2.55
2.54
2.54
4.87
4.87
7.50
7.48
7.41
7.39
7.38
7.22
7.20
7.19
1.00
2.07
1.06
2.04
1.97
ppm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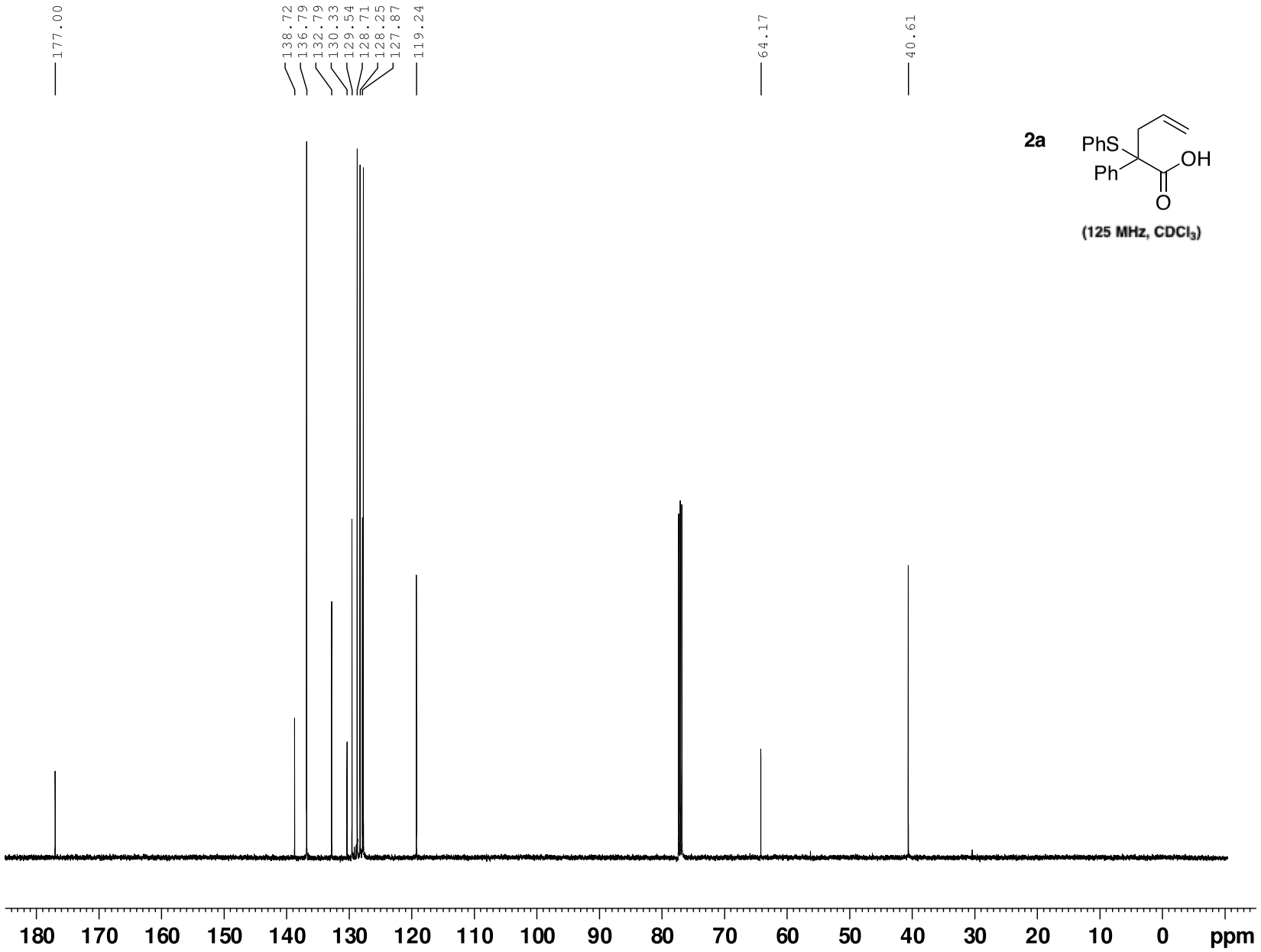
129.05
126.10
125.10
124.04
77.74
75.31
52.27
Ph
4
N2
O
O
(125 MHz, CDCl3)
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
ppm

2a
(500 MHz, CDCl3)
PhS
Ph
OH
O
ppm
2.08
3.54
2.49
2.03
1.00
2.02
2.01
7.39
7.39
7.37
7.33
7.33
7.31
7.31
7.30
7.28
7.25
7.25
7.23
7.23
7.20
7.18
7.17
5.91
5.90
5.89
5.88
5.88
5.86
5.86
5.85
5.84
5.83
5.12
5.12
5.10
5.08
5.08
5.05
5.05
2.87
2.86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138.72
136.79
132.79
130.33
129.54
128.71
128.25
127.87
119.24
64.17
40.61
2a
PhS
Ph
OH
O
(125 MHz, CDCl3)
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
ppm

2b
(500 MHz, CDCl3)
PhS
OH
O
Cl
ppm
1
2
3
4
5
6
7
8
9
2.01
1.00
1.01
1.00
4.05
5.17
2.90
2.91
5.12
5.15
5.18
5.20
5.86
5.88
5.88
5.89
5.90
5.91
5.92
5.92
5.93
5.94
7.25
7.27
7.28
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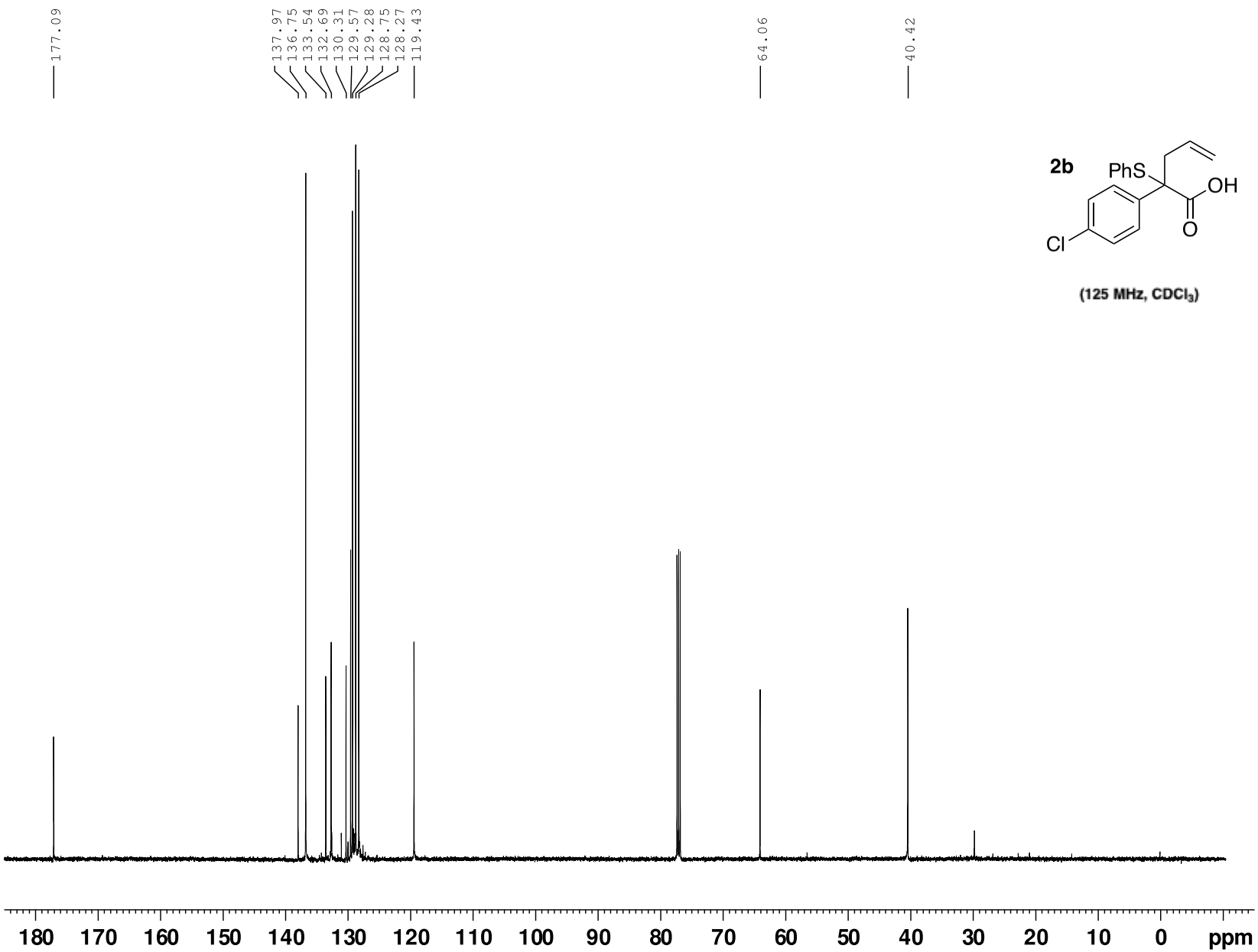
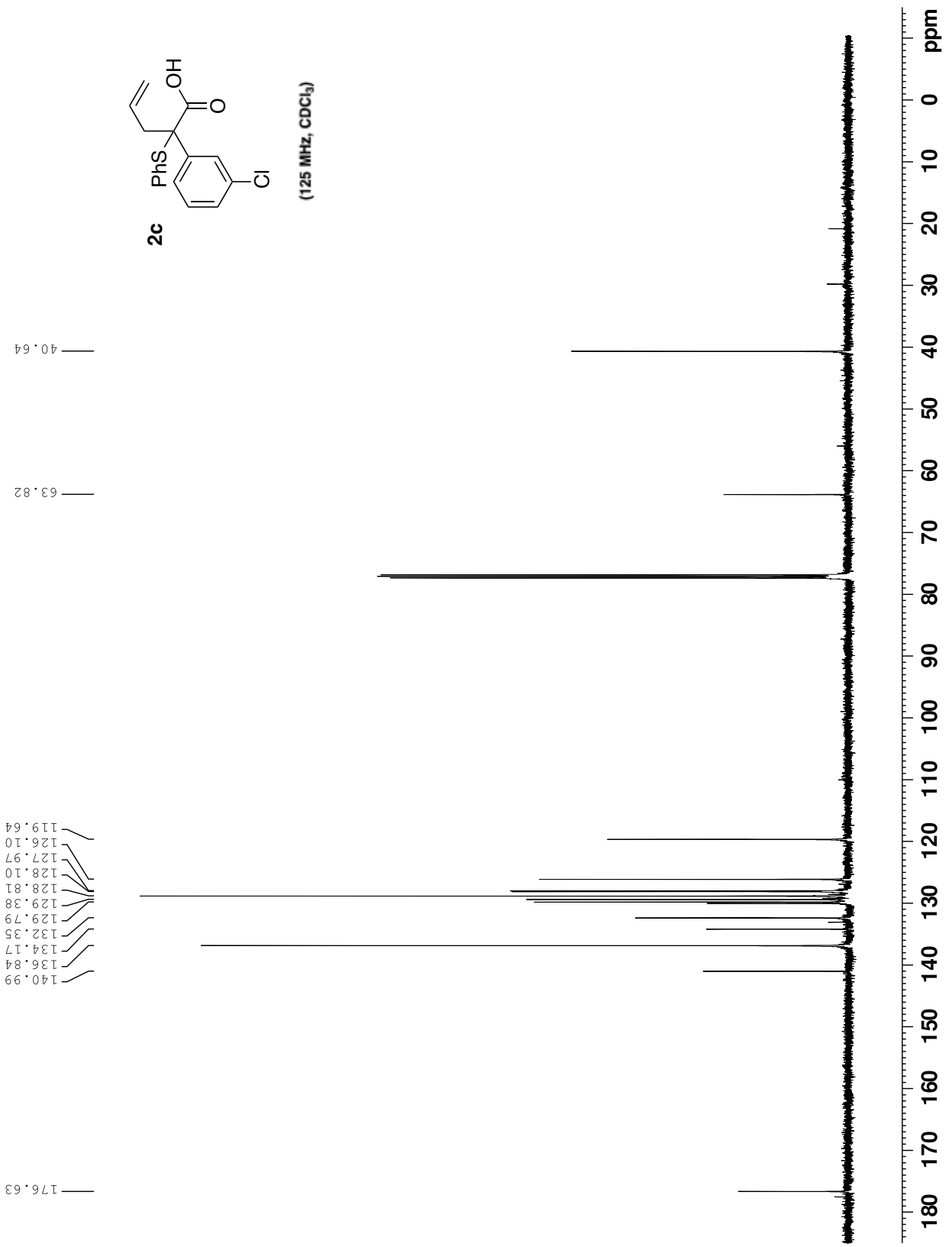
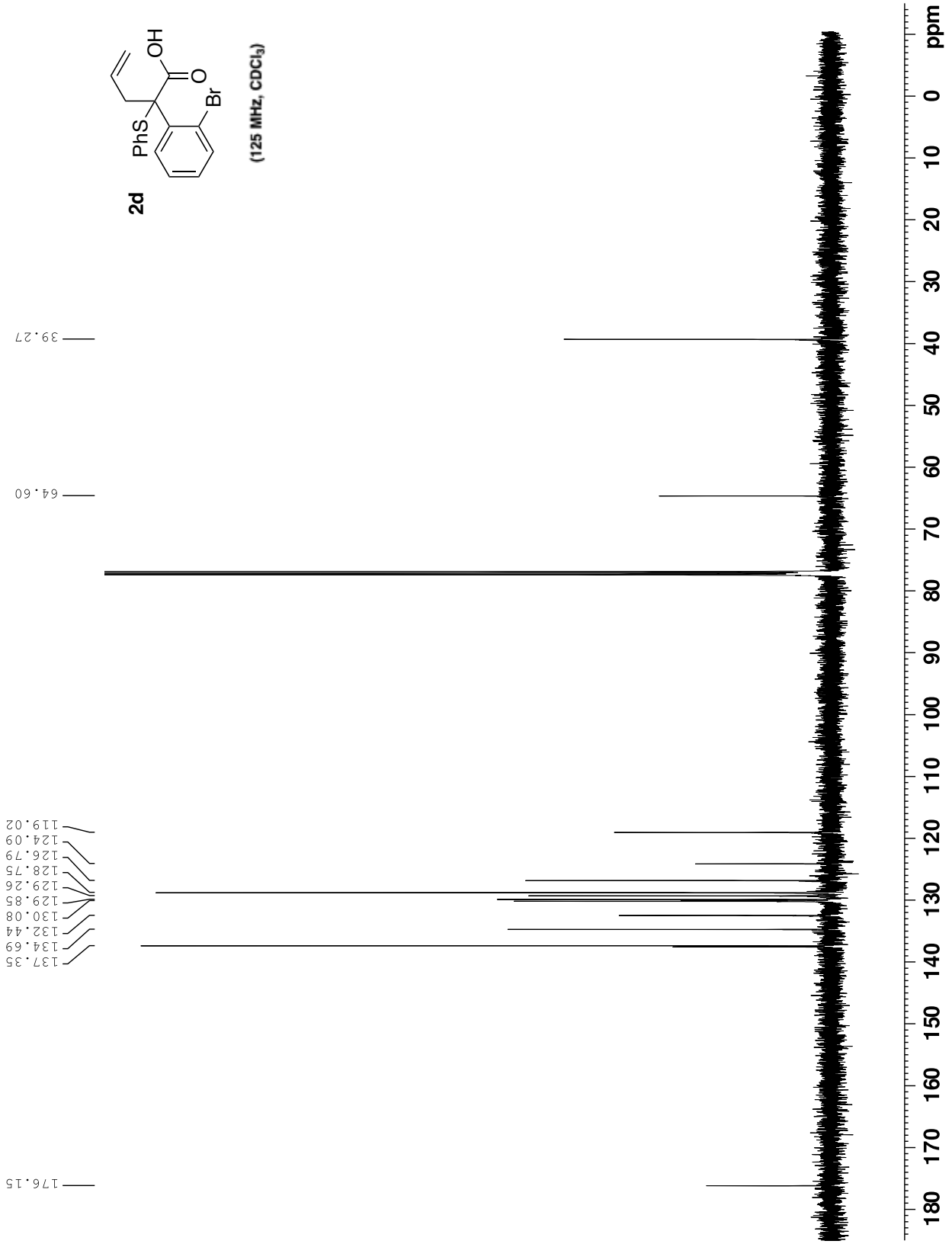
7.31
7.31
7.34
7.35
7.38
7.39


177.09
137.97
136.75
133.54
132.69
130.31
129.57
129.28
128.75
128.27
119.43
64.06
40.42
2b
PhS
OH
O
Cl
(125 MHz, CDCl3)
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
ppm

2c
(500 MHz, CDCl3)
OH
O
PhS
Cl
7.39
7.36
7.35
7.29
7.28
7.26
7.24
5.93
5.92
5.90
5.89
5.87
5.85
5.18
5.16
5.13
5.10
2.88
7.93
1.06
1.00
2.05
1.99
ppm


2c
(125 MHz, $CDCl_3$)
OH
O
PhS
Cl
ppm
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
40.64
63.82
119.64
126.10
127.97
128.10
128.81
129.38
129.79
132.35
134.17
136.84
140.99
176.63

2d
(500 MHz, CDCl3)
PhS
OH
O
Br
ppm
1
2
3
4
5
6
7
8
9
0.99
0.98
2.00
1.00
1.05
4.08
2.08
1.05
1.04
1.03
3.17
3.16
3.14
3.13
2.81
2.80
2.78
2.77
5.11
5.10
5.09
5.07
5.91
5.90
5.89
5.88
5.86
5.85
5.85
5.84
5.83
7.66
7.64
7.44
7.43
7.35
7.34
7.32
7.30
7.28
7.24
7.23
7.21
7.21
7.18
7.17
7.16
7.14
7.14


2d
(125 MHz, $CDCl_3$)
OH
O
Br
PhS
39.27
64.60
119.02
124.09
126.79
128.75
129.26
129.85
130.08
132.44
134.69
137.35
176.15
ppm

2e
(500 MHz, CDCl3)
PhS
OH
O
Me
ppm
1
2
3
4
5
6
7
8
9
3.10
2.02
2.04
1.00
2.01
2.00
5.06
2.37
2.88
2.87
5.07
5.08
5.11
5.11
5.13
5.13
5.13
5.15
5.15
5.85
5.86
5.87
5.88
5.88
5.90
5.90
5.91
5.92
5.93
7.15
7.16
7.21
7.22
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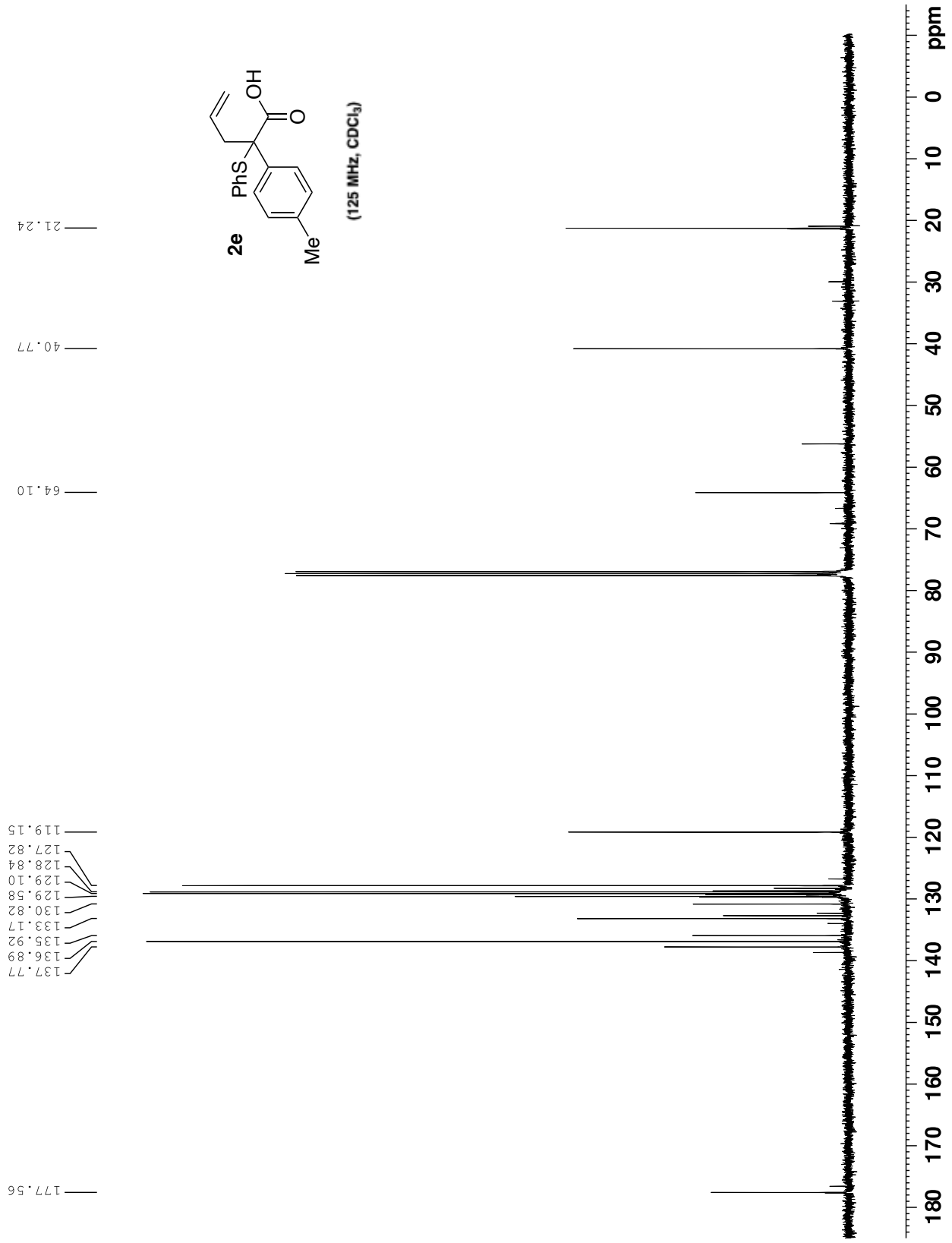
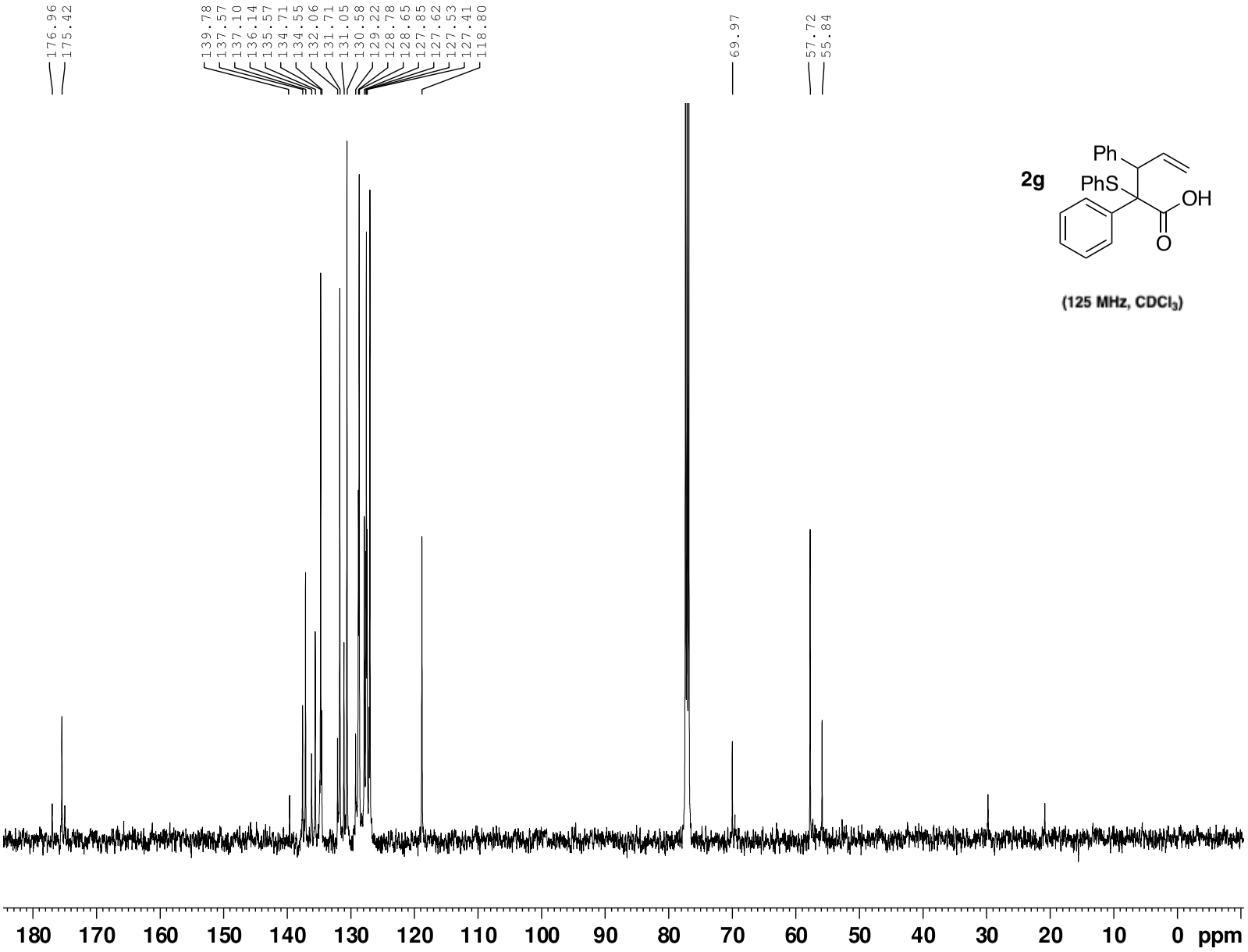
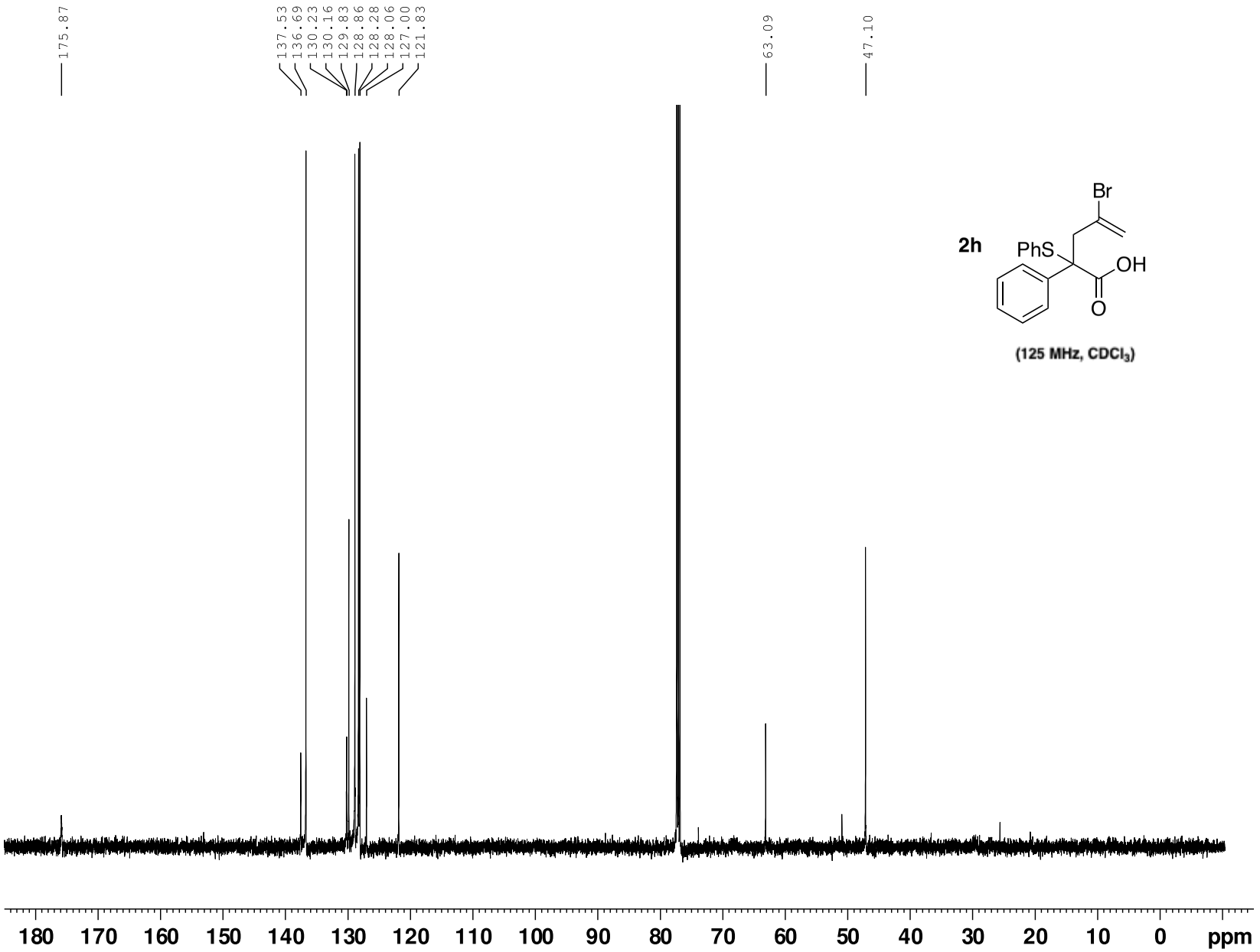
7.29
7.29
7.30
7.32
7.32
7.33
7.35
7.35
7.35

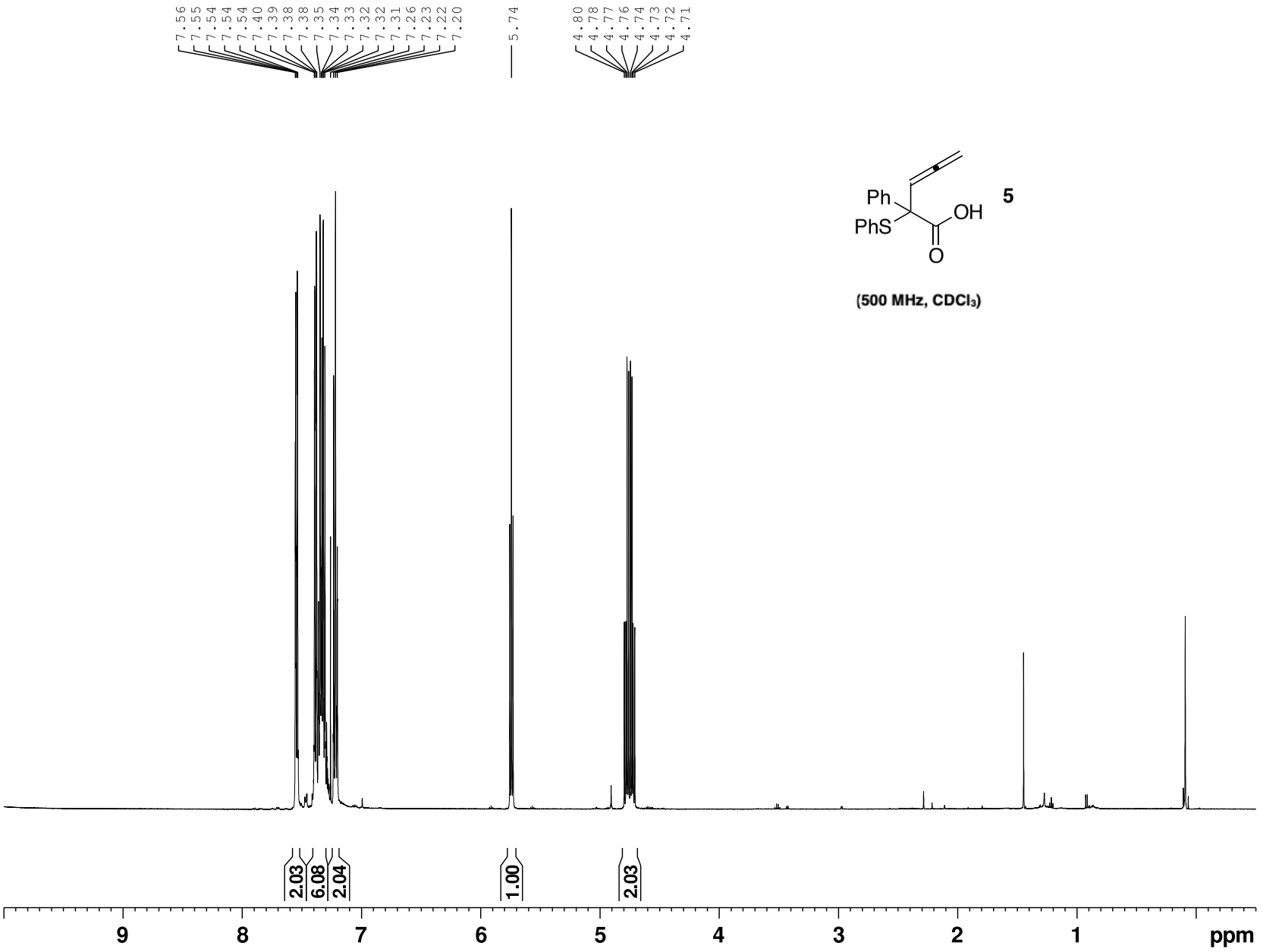

2e
(125 MHz, CDCl3)
OH
O
PhS
Me
21.24
40.77
64.10
119.15
127.82
128.84
129.10
129.58
130.82
133.17
135.92
136.89
137.77
177.56
ppm
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180

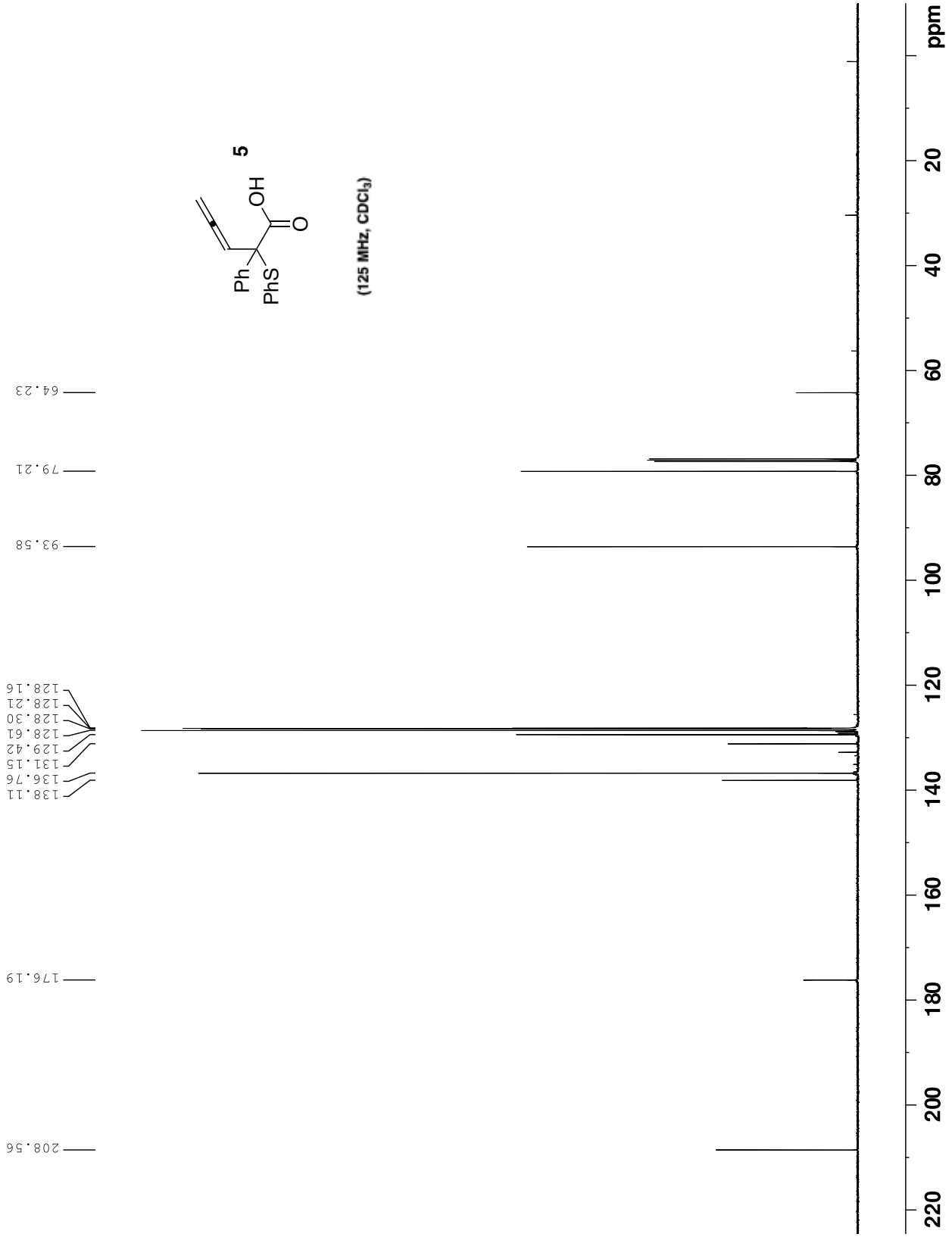
2g
(500 MHz, CDCl3)
Ph
PhS
OH
O
7.50
7.49
7.33
7.31
7.31
7.29
7.28
7.26
7.24
7.23
7.22
7.21
7.18
7.16
7.15
7.13
7.10
7.08
7.07
6.84
6.83
6.75
6.74
6.24
6.22
6.20
6.20
6.18
6.16
6.10
6.08
6.06
6.06
6.04
6.02
5.28
5.24
5.23
5.22
5.20
5.18
4.54
4.52
2.37
7.50
2.79
5.08
2.10
0.85
2.00
0.37
1.00
2.73
1.37
ppm


176.96
175.42
139.78
137.57
137.10
136.14
135.57
134.71
134.55
132.06
131.71
131.05
130.58
129.22
128.78
128.65
127.85
127.62
127.53
127.41
118.80
69.97
57.72
55.84
2g
Ph
PhS
OH
O
(125 MHz, CDCl3)
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
ppm

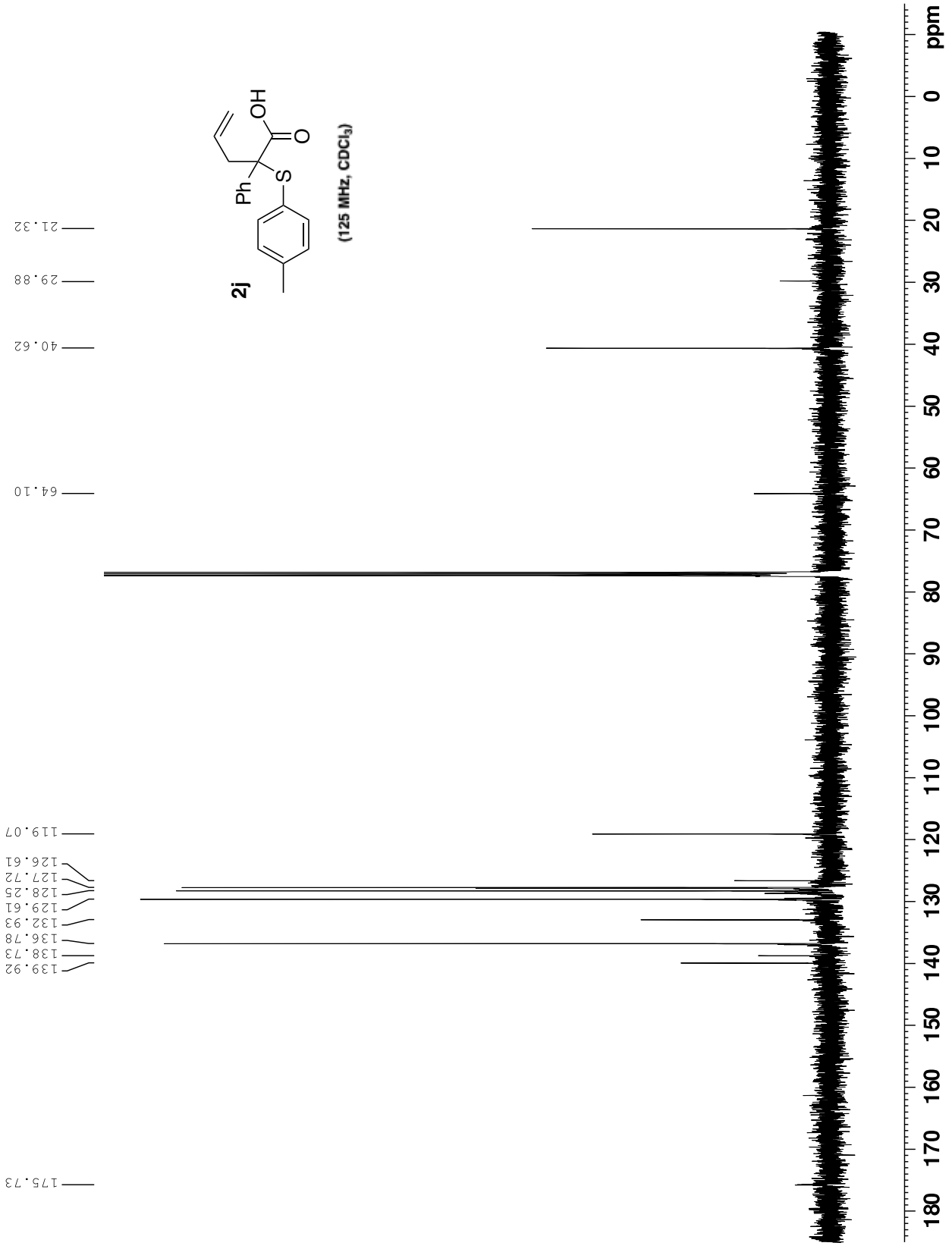
Br
OH
O
PhS
2h
(500 MHz, CDCl3)
ppm
1
2
3
4
5
6
7
8
9
2.03
6.14
2.04
1.00
1.01
0.99
1.01
7.50
7.49
7.36
7.35
7.34
7.34
7.33
7.32
7.31
7.30
7.30
7.23
7.22
7.20
5.64
5.58
5.58
3.41
3.37
3.31
3.28


175.87
137.53
136.69
130.23
130.16
129.83
128.86
128.28
128.06
127.00
121.83
63.09
47.10
2h
Br
PhS
OH
O
(125 MHz, CDCl3)
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
ppm

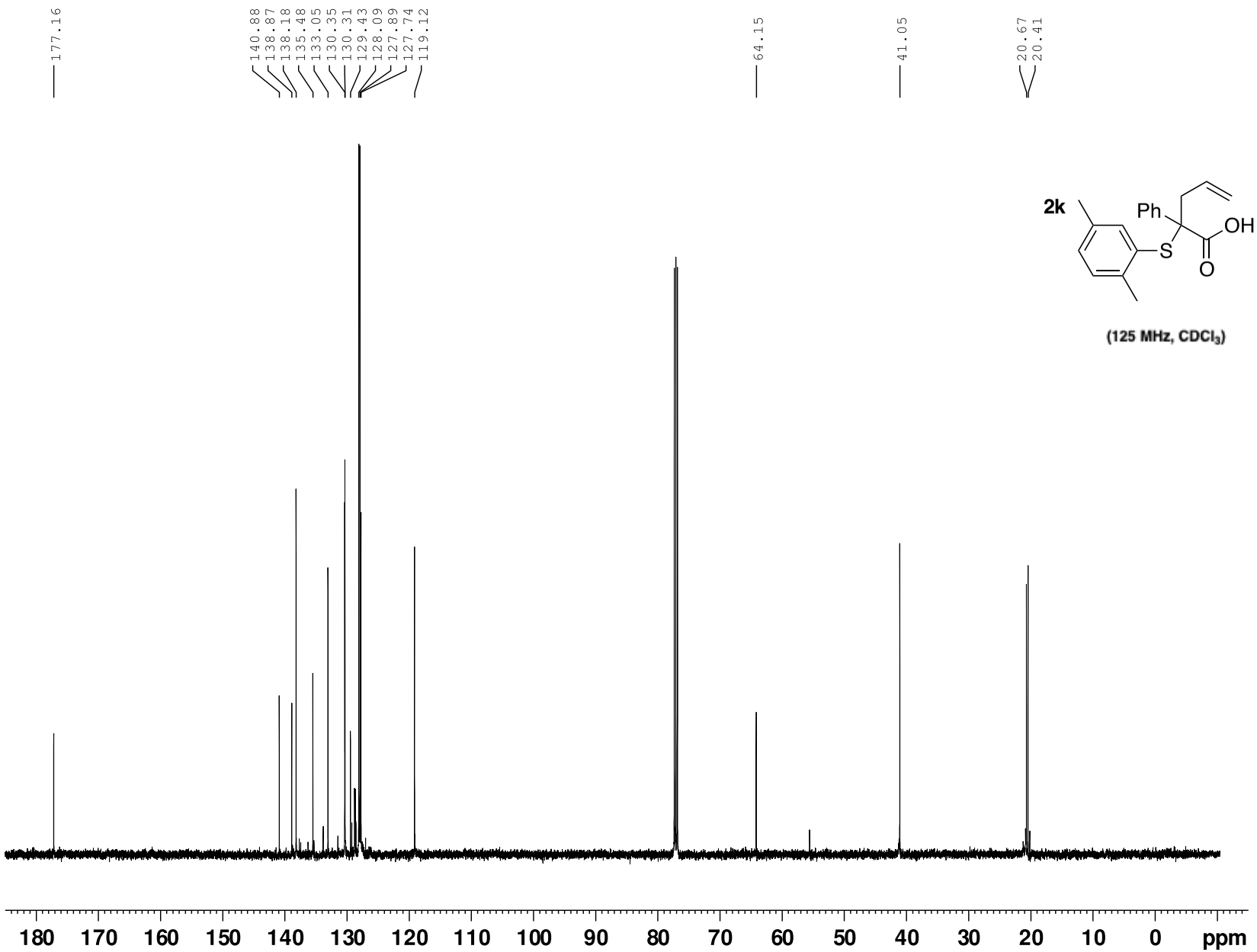

7.56
7.55
7.54
7.54
7.54
7.40
7.39
7.38
7.38
7.35
7.34
7.33
7.32
7.32
7.31
7.26
7.23
7.22
7.20
5.74
4.80
4.78
4.77
4.76
4.74
4.73
4.72
4.71
Ph
PhS
OH
O
5
(500 MHz, CDCl3)
2.03
6.08
2.04
1.00
2.03
9
8
7
6
5
4
3
2
1
ppm


5
OH
O
Ph
PhS
(125 MHz, CDCl3)
64.23
79.21
93.58
128.16
128.21
128.30
128.61
129.42
131.15
136.76
138.11
176.19
208.56
ppm
20
40
60
80
100
120
140
160
180
200
220

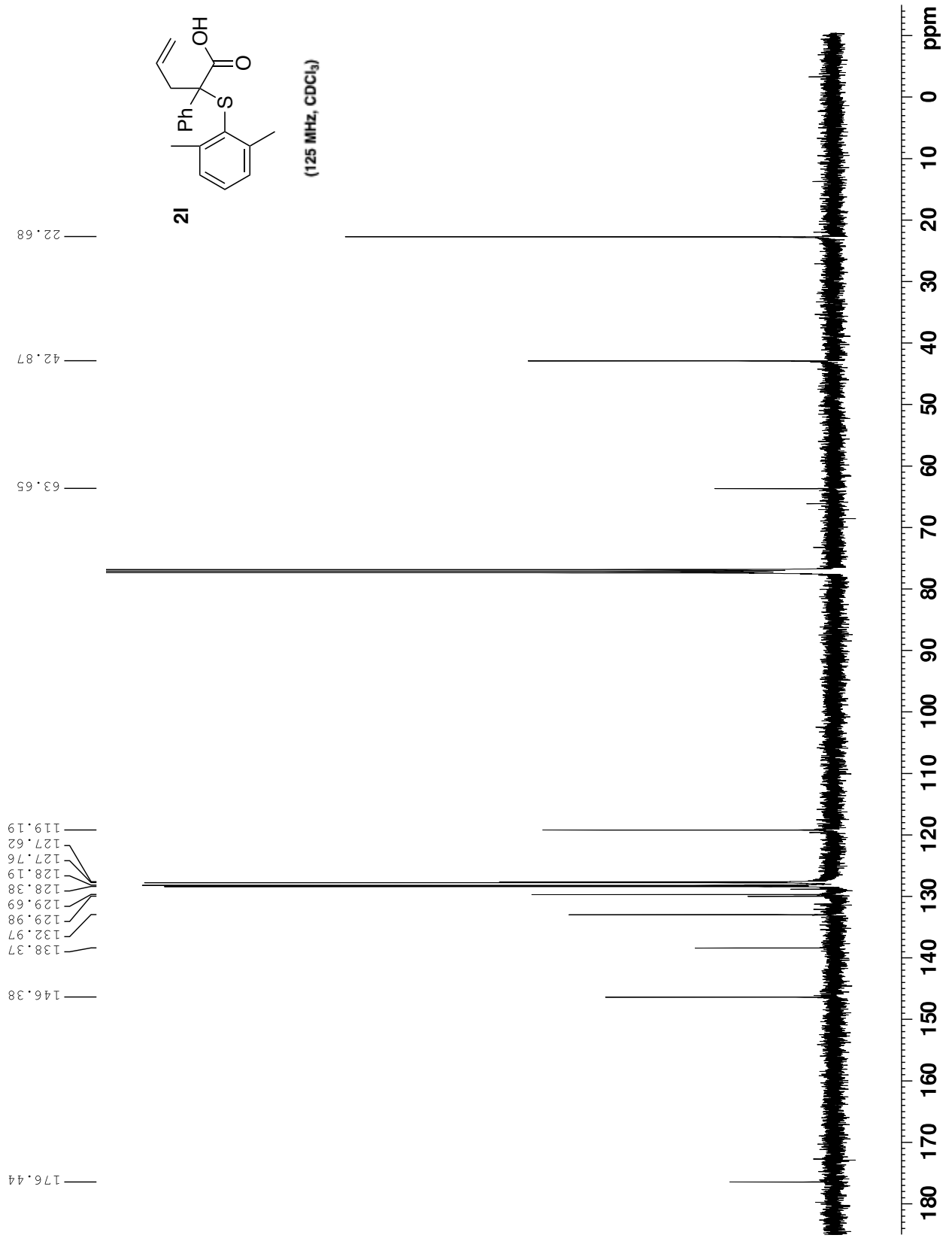
2j
(500 MHz, CDCl3)
OH
O
S
Ph
ppm
1
2
3
4
5
6
7
8
9
3.05
2.00
1.01
0.99
1.00
2.07
2.05
3.18
2.01
2.31
2.87
2.86
2.86
5.06
5.09
5.11
5.13
5.84
5.85
5.86
5.86
5.87
5.88
5.89
5.90
5.90
5.92
7.01
7.02
7.15
7.17
7.29
7.30
7.32
7.34
7.35
7.41
7.41
7.42

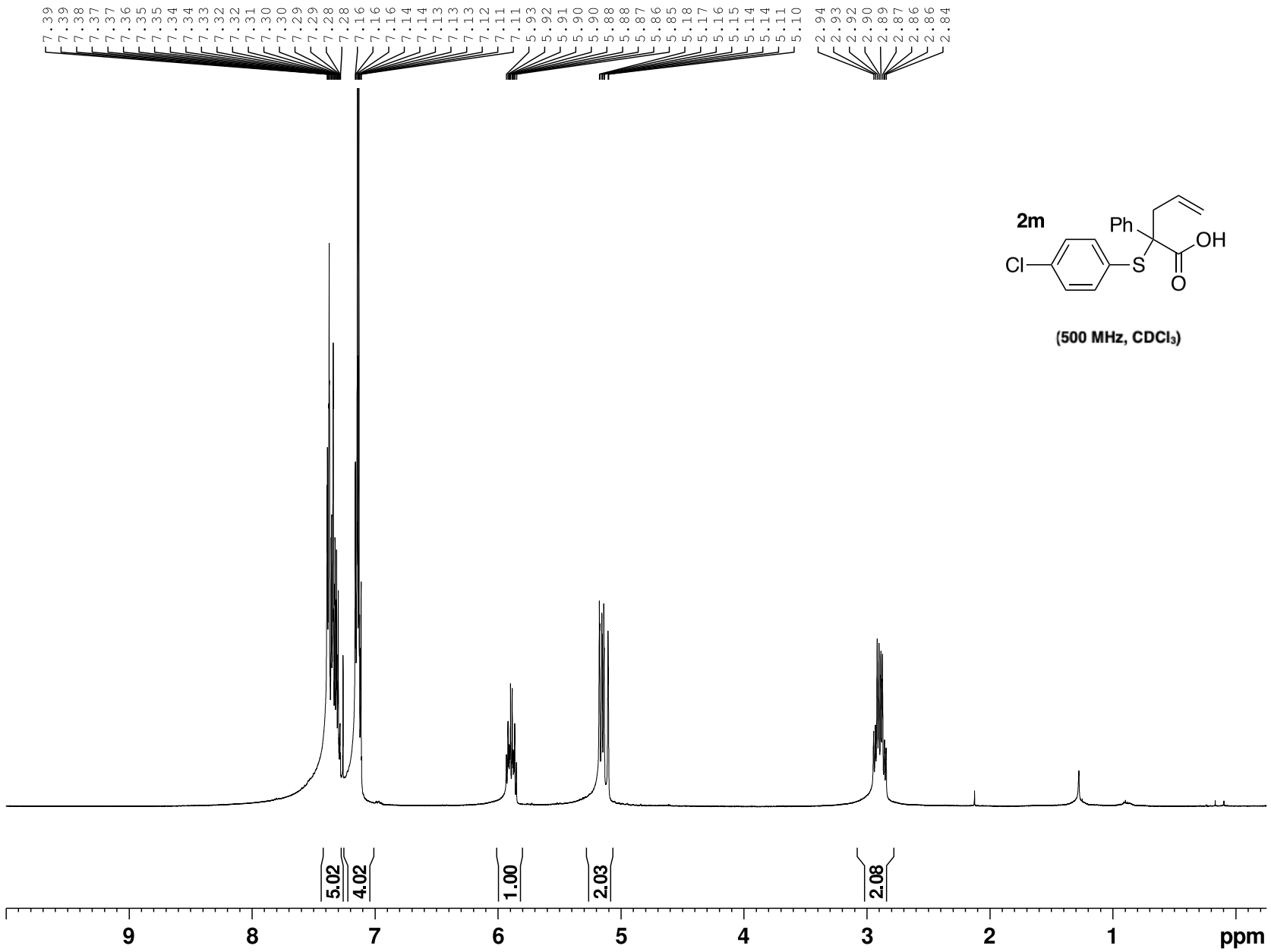

2j
(125 MHz, CDCl3)
OH
O
S
Ph
21.32
29.88
40.62
64.10
119.07
126.61
127.72
128.25
129.61
132.93
136.78
138.73
139.92
175.73
ppm

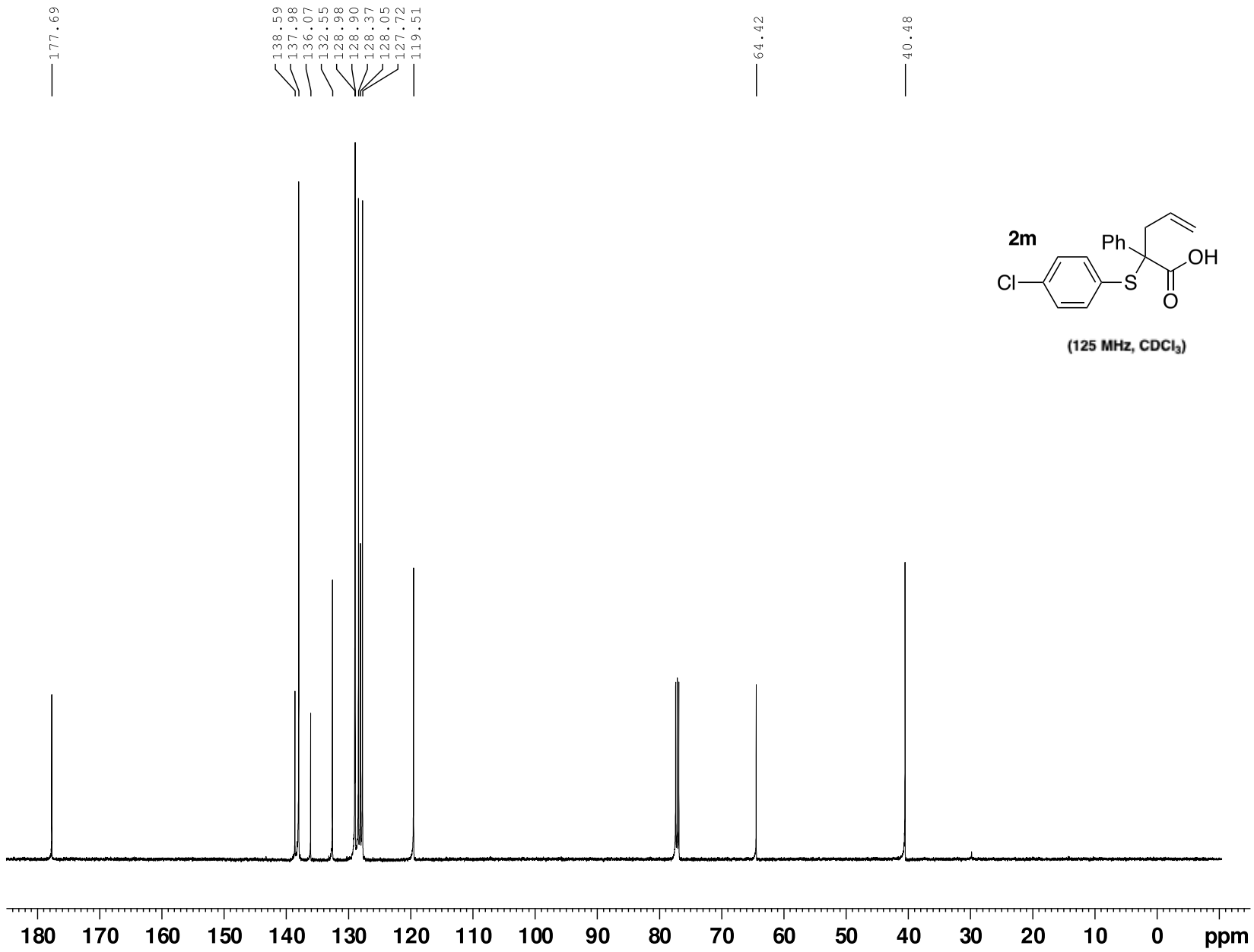
2k
(500 MHz, CDCl3)
OH
O
S
Ph
2.16
2.22
2.85
2.87
2.88
2.90
2.93
2.95
2.96
2.97
5.02
5.06
5.07
5.09
5.83
5.84
5.85
5.85
5.86
5.87
5.88
5.89
5.89
5.91
6.98
7.00
7.01
7.04
7.05
7.27
7.29
7.31
7.32
7.32
7.36
7.36
7.37
3.08
3.02
1.00
1.01
2.08
1.00
3.07
5.01
ppm

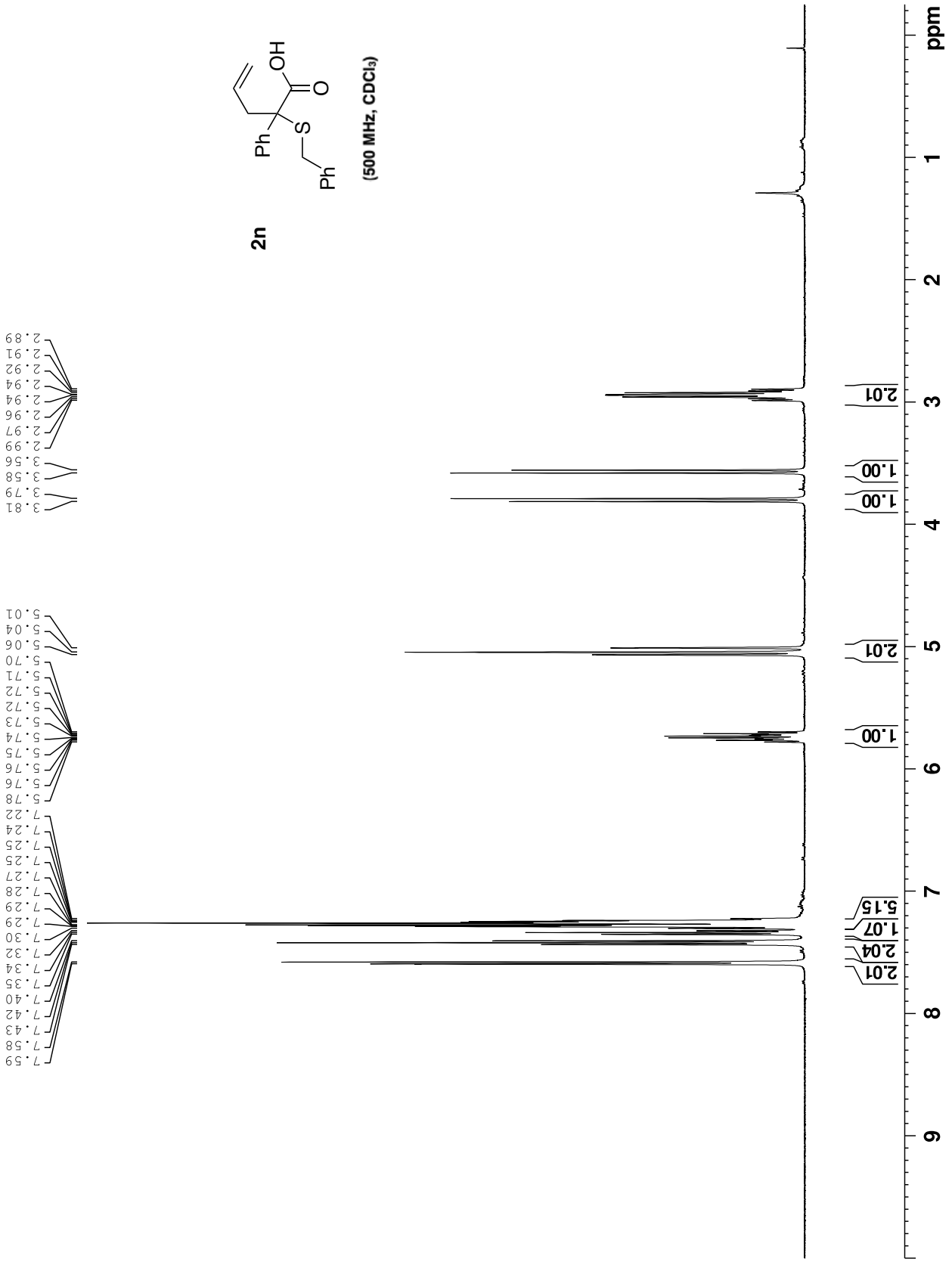

177.16
140.88
138.87
138.18
135.48
133.05
130.35
130.31
129.43
128.09
127.89
127.74
119.12
64.15
41.05
20.67
20.41
2k
Ph
OH
S
O
(125 MHz, CDCl3)
180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 ppm

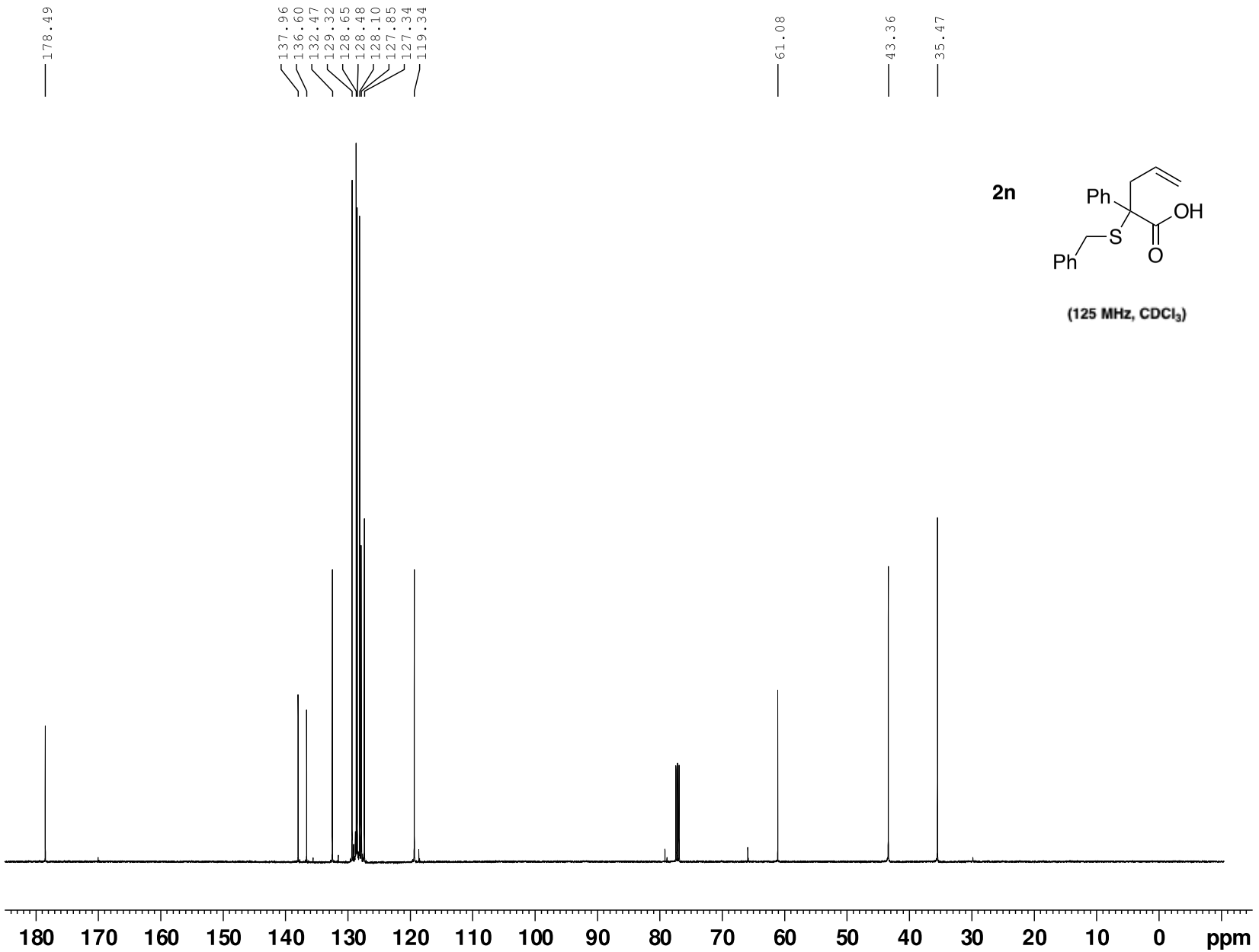
2l
(500 MHz, CDCl3)
OH
O
S
Ph
ppm
1
2
3
4
5
6
7
8
9
6.05
1.05
1.03
1.08
1.02
1.00
2.07
1.09
3.06
2.09
2.39
2.83
2.85
2.86
2.88
2.97
2.98
3.00
3.01
4.93
4.97
4.99
5.01
5.64
5.65
5.66
5.67
5.67
5.69
5.69
5.70
5.71
5.72
7.03
7.05
7.11
7.13
7.14
7.26
7.26
7.27
7.28
7.42
7.42
7.43
7.43


2l
(125 MHz, CDCl3)
OH
O
S
Ph
22.68
42.87
63.65
119.19
127.62
127.76
128.19
128.38
129.69
129.98
132.97
138.37
146.38
176.44
ppm

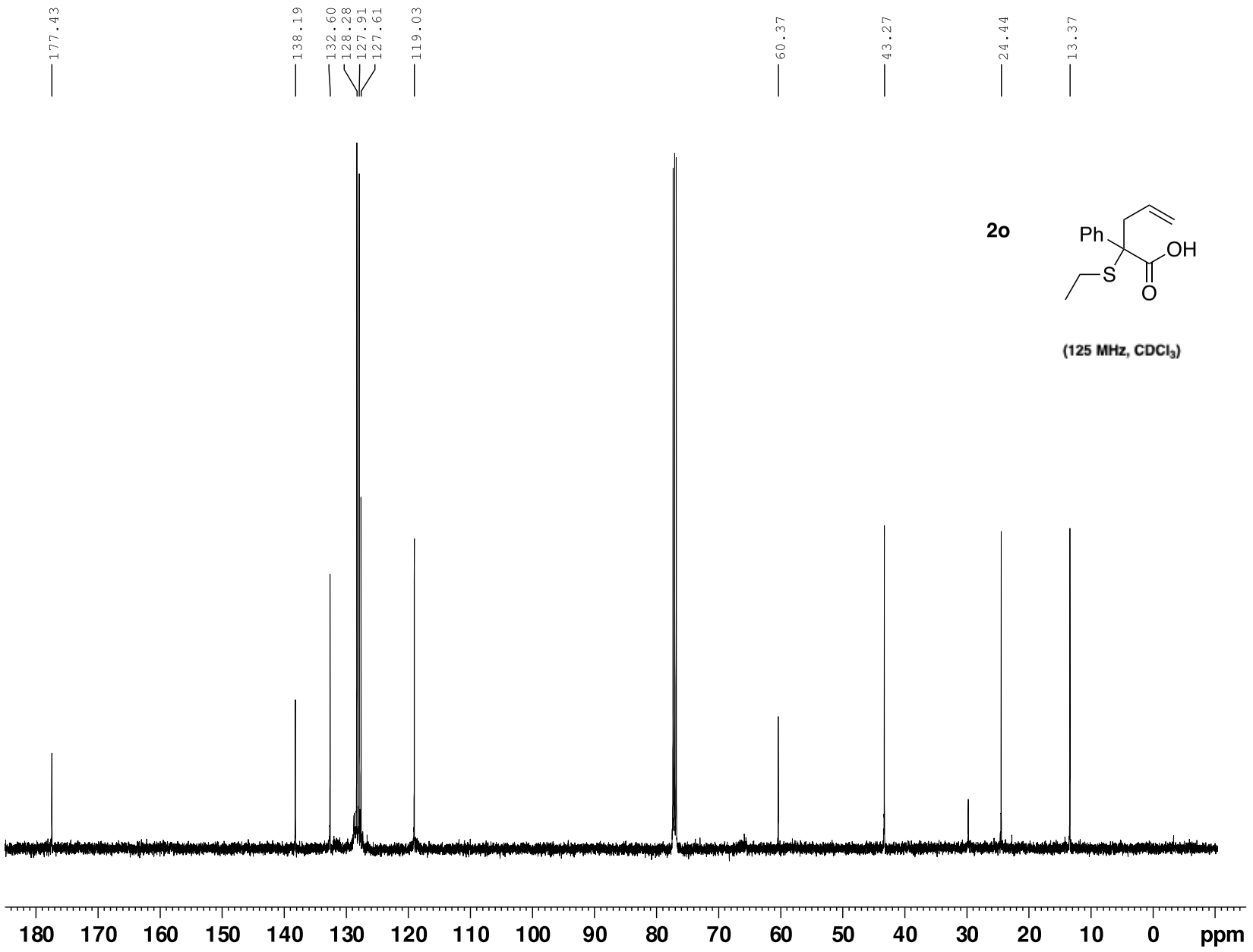

7.39
7.39
7.38
7.37
7.37
7.36
7.35
7.35
7.34
7.34
7.33
7.32
7.32
7.31
7.30
7.30
7.29
7.29
7.28
7.28
7.16
7.16
7.14
7.14
7.13
7.13
7.12
7.11
7.11
5.93
5.92
5.91
5.90
5.90
5.88
5.88
5.87
5.86
5.85
5.18
5.17
5.16
5.15
5.14
5.14
5.11
5.10
2.94
2.93
2.92
2.90
2.89
2.87
2.86
2.86
2.84
2m
Ph
OH
Cl
S
O
(500 MHz, CDCl3)
5.02
4.02
1.00
2.03
2.08
9
8
7
6
5
4
3
2
1
ppm


177.69
138.59
137.98
136.07
132.55
128.98
128.90
128.37
128.05
127.72
119.51
64.42
40.48
2m
Ph
OH
Cl
S
O
(125 MHz, CDCl3)
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
ppm

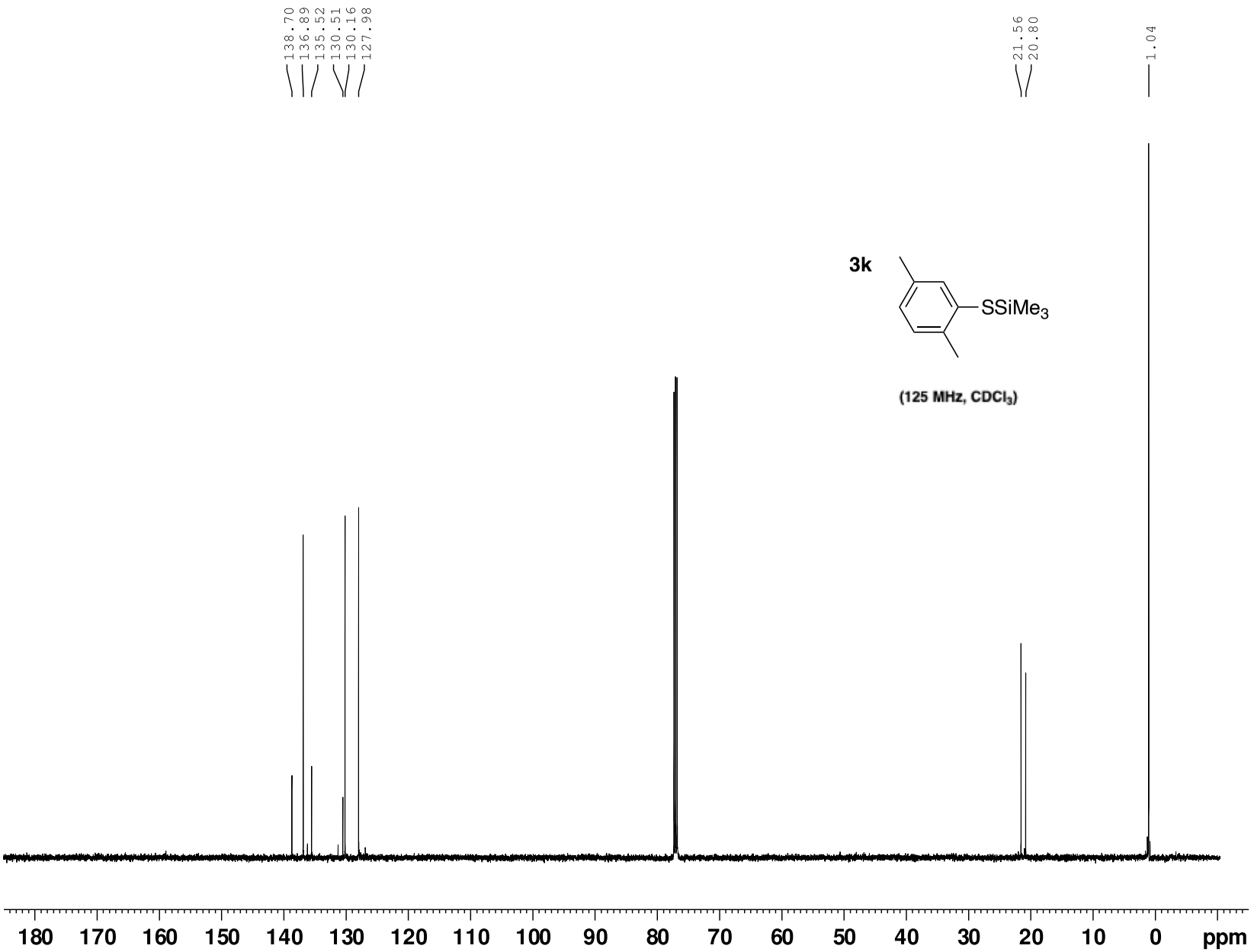

2n
(500 MHz, CDCl3)
OH
O
S
Ph
Ph
ppm
2.01
2.04
1.07
5.15
1.00
2.01
1.00
1.00
2.01

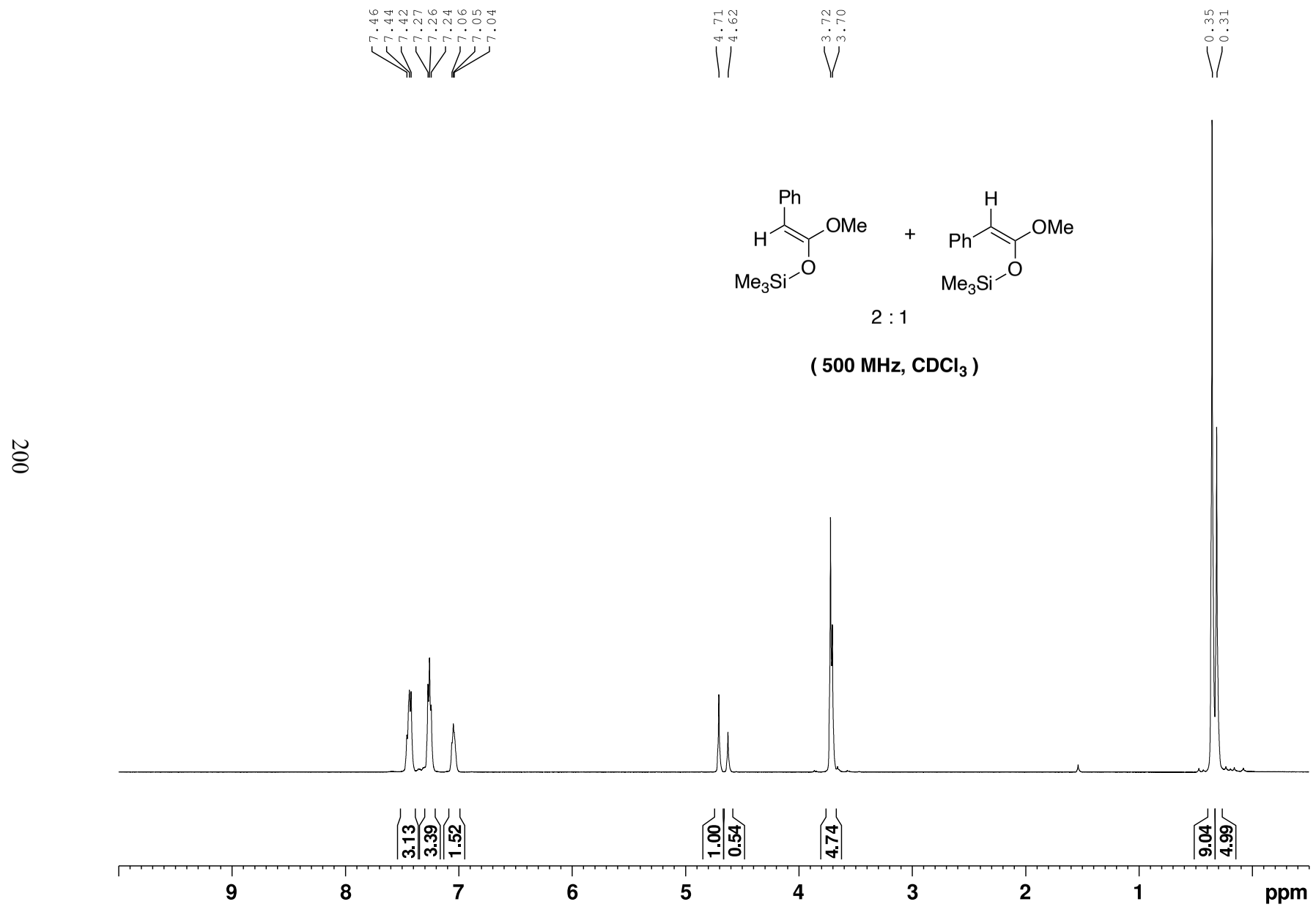

178.49
137.96
136.60
132.47
129.32
128.65
128.48
128.10
127.85
127.34
119.34
61.08
43.36
35.47
2n
Ph
OH
S
Ph
O
(125 MHz, CDCl3)
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
ppm

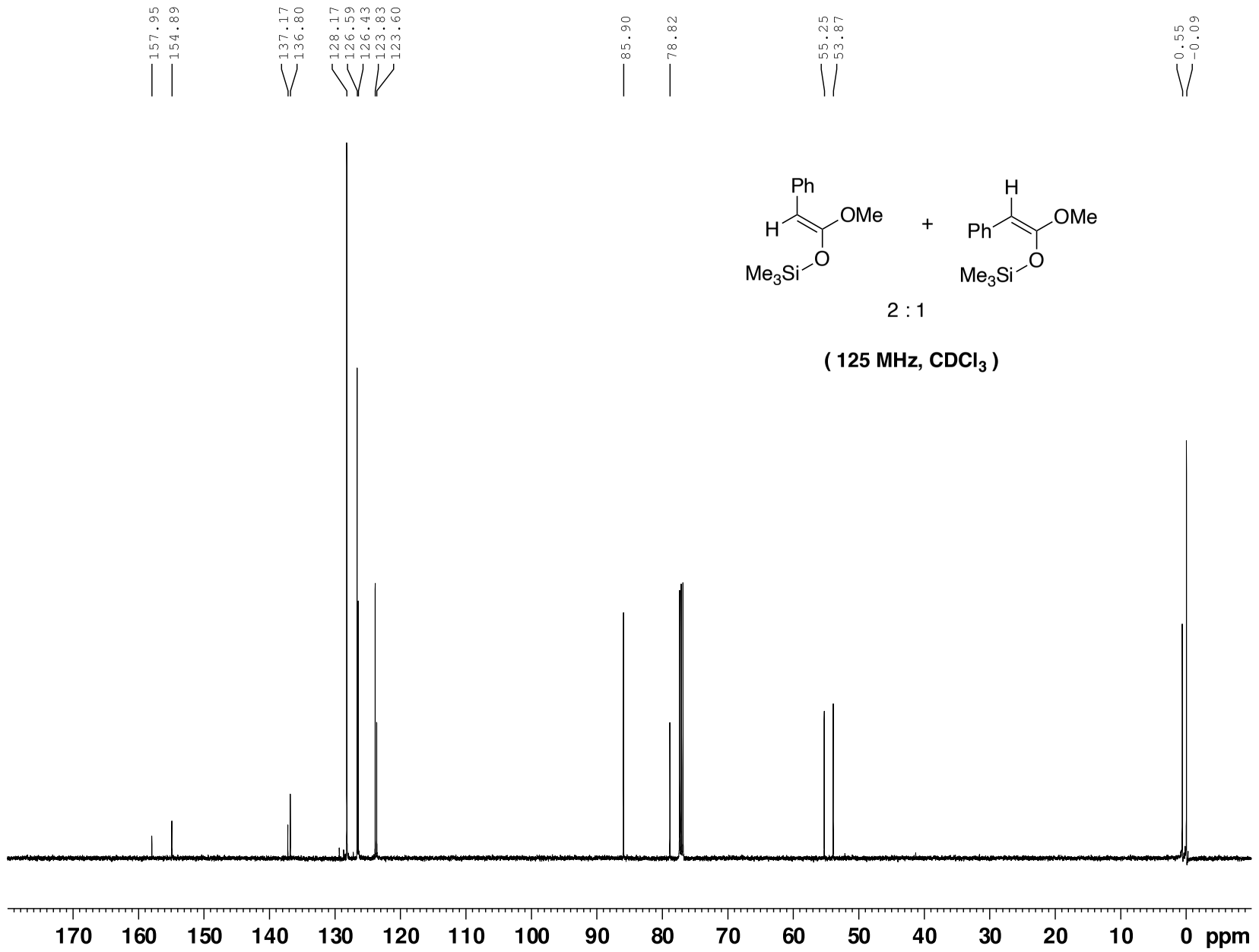
1.15
1.17
1.18
2.37
2.38
2.39
2.40
2.40
2.41
2.42
2.43
2.53
2.54
2.55
2.56
2.57
2.57
2.58
2.60
2.82
2.83
2.85
2.86
2.90
2.92
2.93
2.95
4.98
5.01
5.03
5.63
5.64
5.65
5.66
5.66
5.68
5.68
5.69
5.70
5.71
7.27
7.28
7.30
7.35
7.36
7.38
7.48
7.50
2o
(500 MHz, CDCl3)
OH
O
S
Ph
3.04
1.01
1.01
1.00
1.02
2.00
1.00
1.00
2.00
2.01
ppm

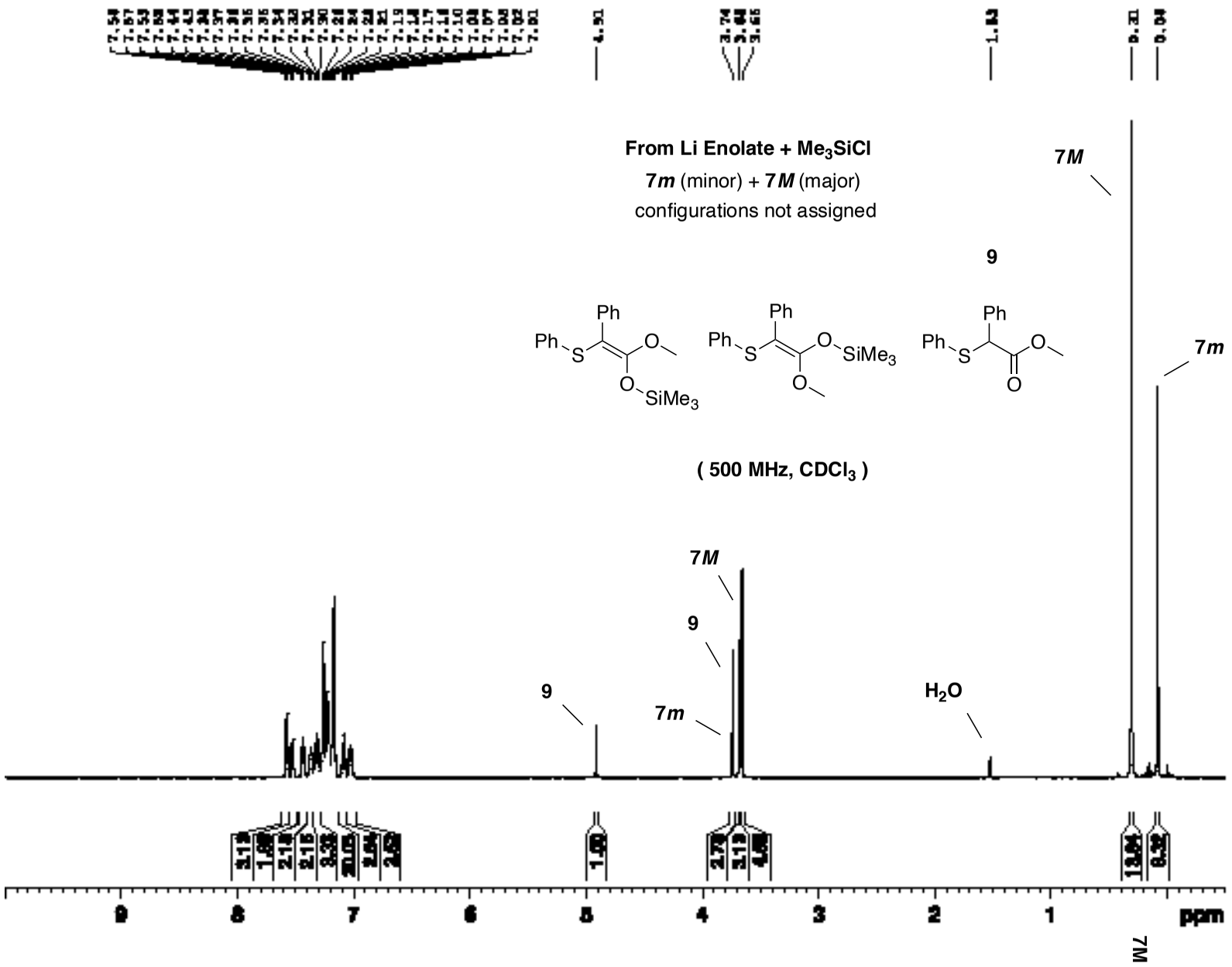

177.43
138.19
132.60
128.28
127.91
127.61
119.03
60.37
43.27
24.44
13.37
2o
Ph
OH
S
O
(125 MHz, CDCl3)
180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 ppm

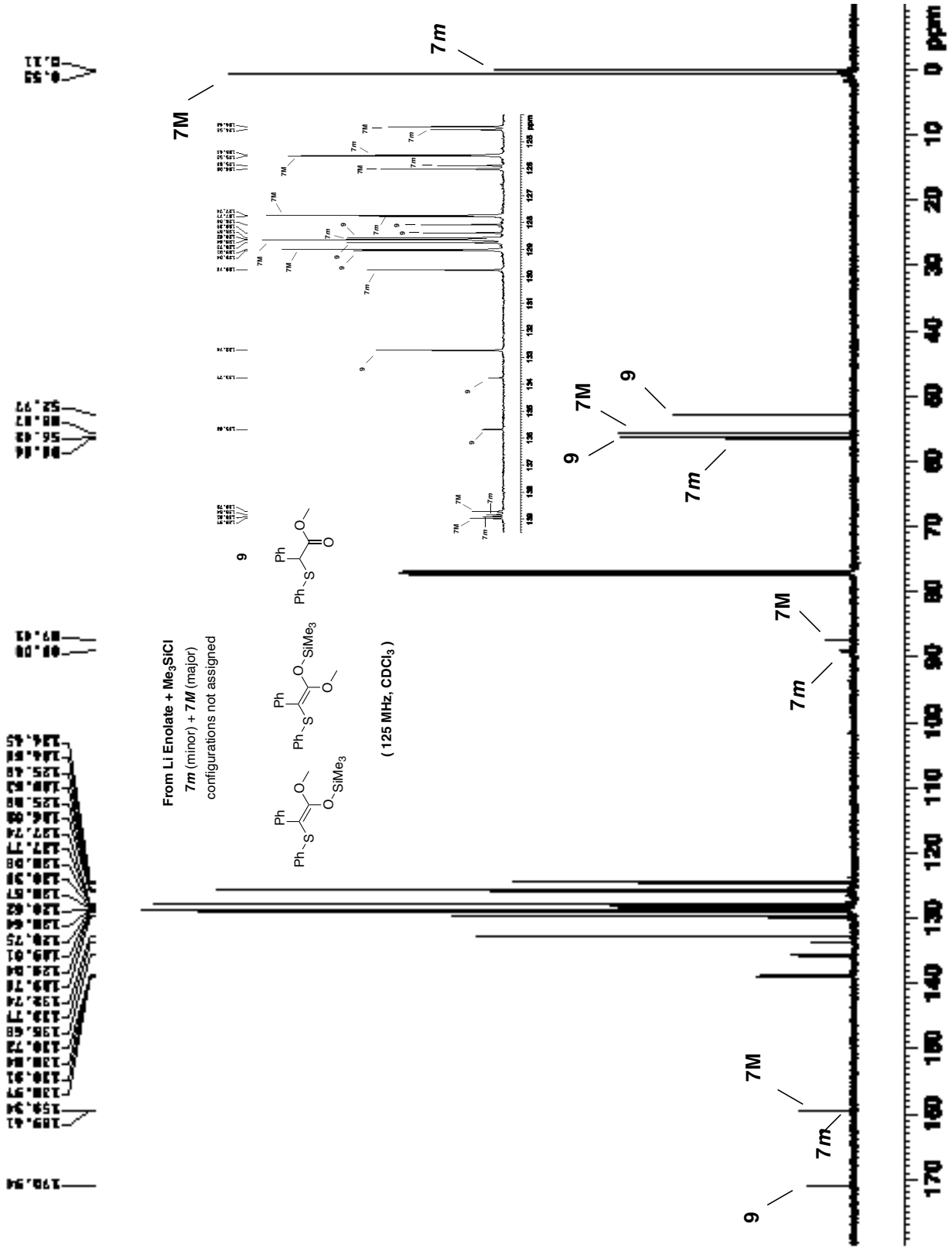
0.27
2.38
2.28
7.23
7.10
7.08
6.96
6.95
SSiMe3
3k
(500 MHz, CDCl3)
9.04
3.03
3.01
1.00
1.03
1.01
ppm
1
2
3
4
5
6
7
8
9

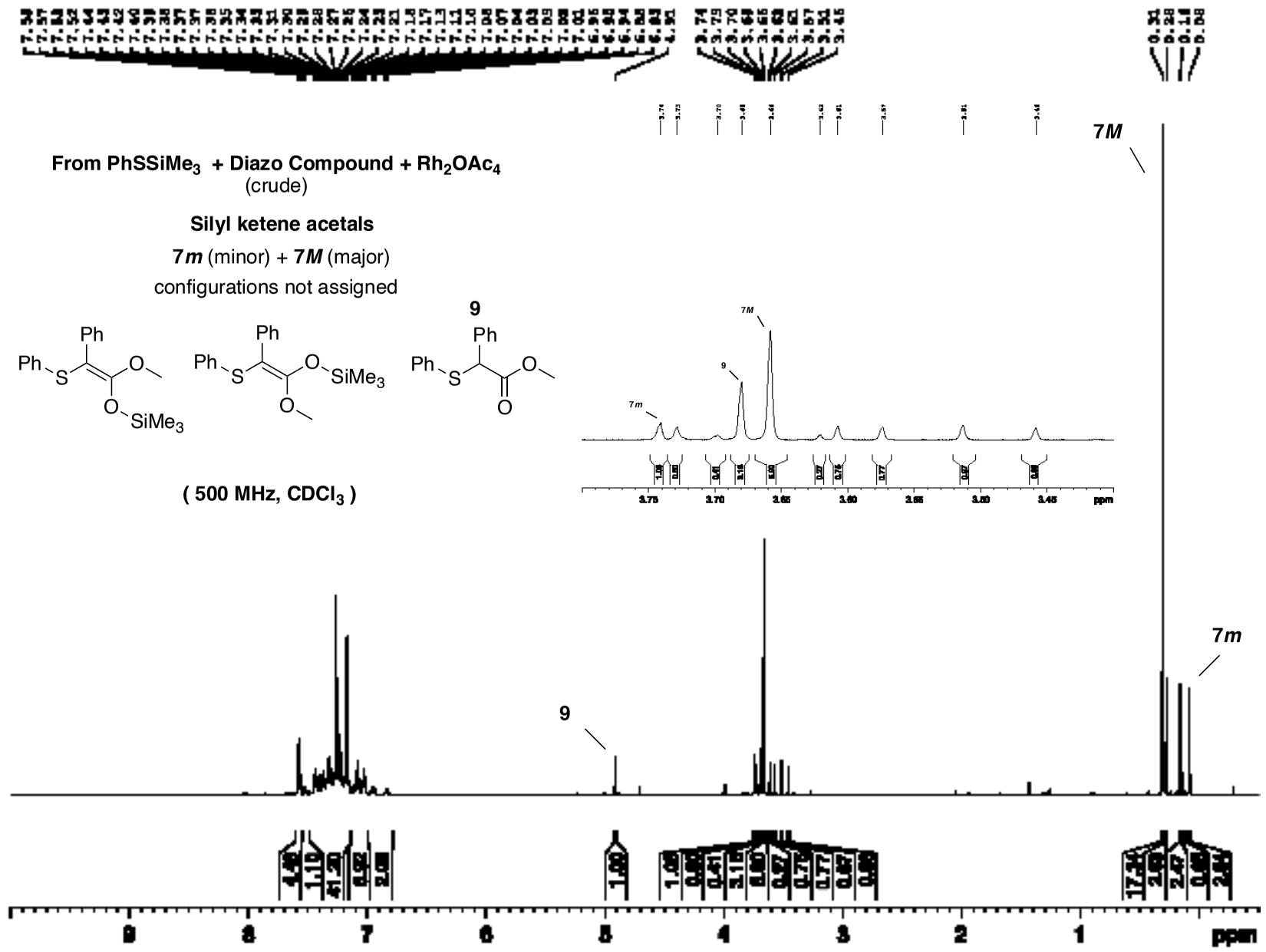

138.70
136.89
135.52
130.51
130.16
127.98
21.56
20.80
1.04
3k
SSiMe3
(125 MHz, CDCl3)
180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 ppm

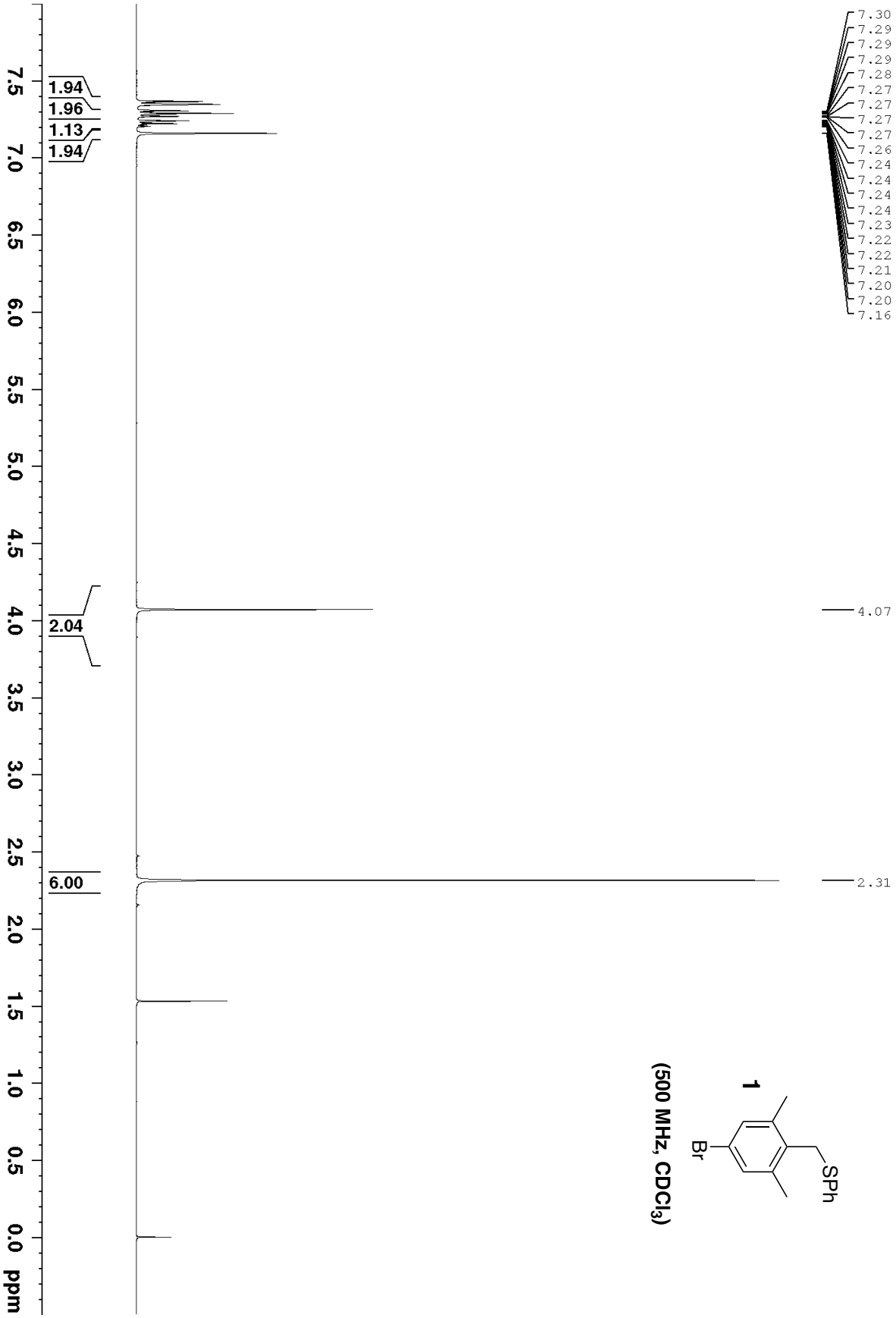

7.46
7.44
7.42
7.27
7.26
7.24
7.06
7.05
7.04
4.71
4.62
3.72
3.70
0.35
0.31
Ph
H
OMe
Me3Si
O
+
H
Ph
OMe
Me3Si
O
2 : 1
(500 MHz, CDCl3)
3.13
3.39
1.52
1.00
0.54
4.74
9.04
4.99
9
8
7
6
5
4
3
2
1
ppm

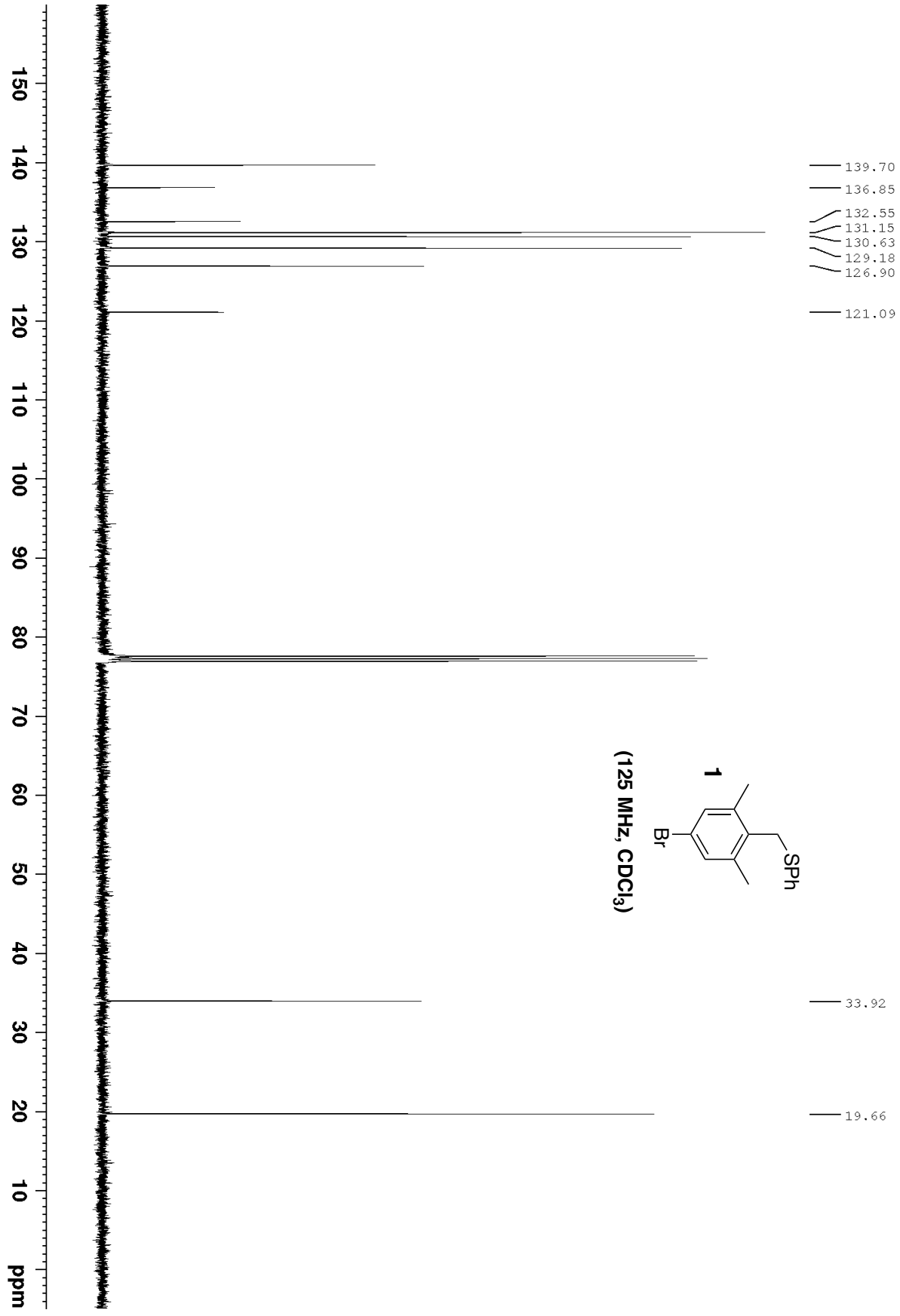

157.95
154.89
137.17
136.80
128.17
126.59
126.43
123.83
123.60
85.90
78.82
55.25
53.87
0.55
-0.09
Ph
H
OMe
Me3Si
O
+
H
Ph
OMe
Me3Si
O
2 : 1
(125 MHz, CDCl3)
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0 ppm

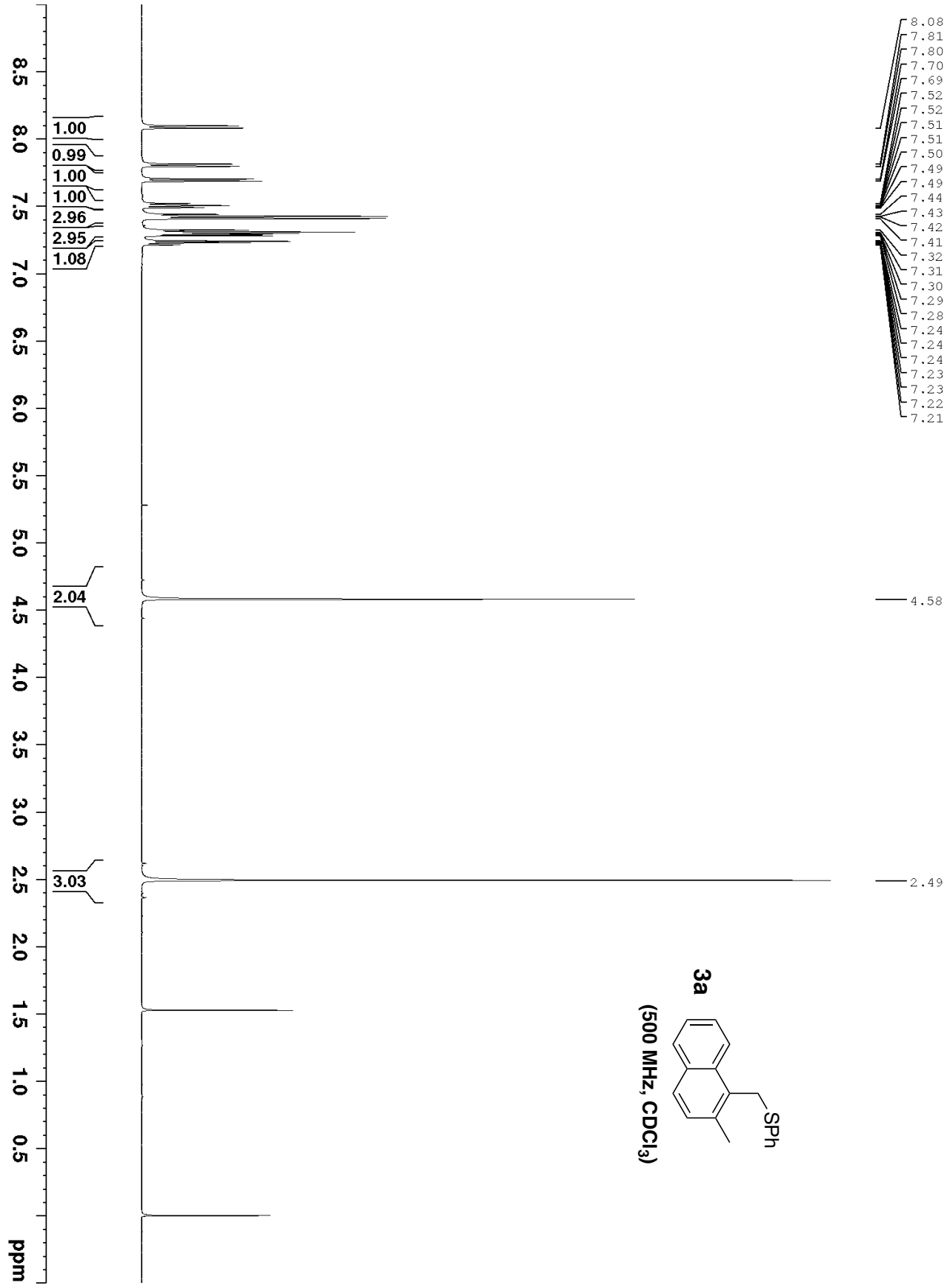

From Li Enolate + Me3SiCl
7m (minor) + 7M (major)
configurations not assigned
9
7M
7m
(500 MHz, CDCl3)
7M
9
9
7m
H2O
ppm
7M

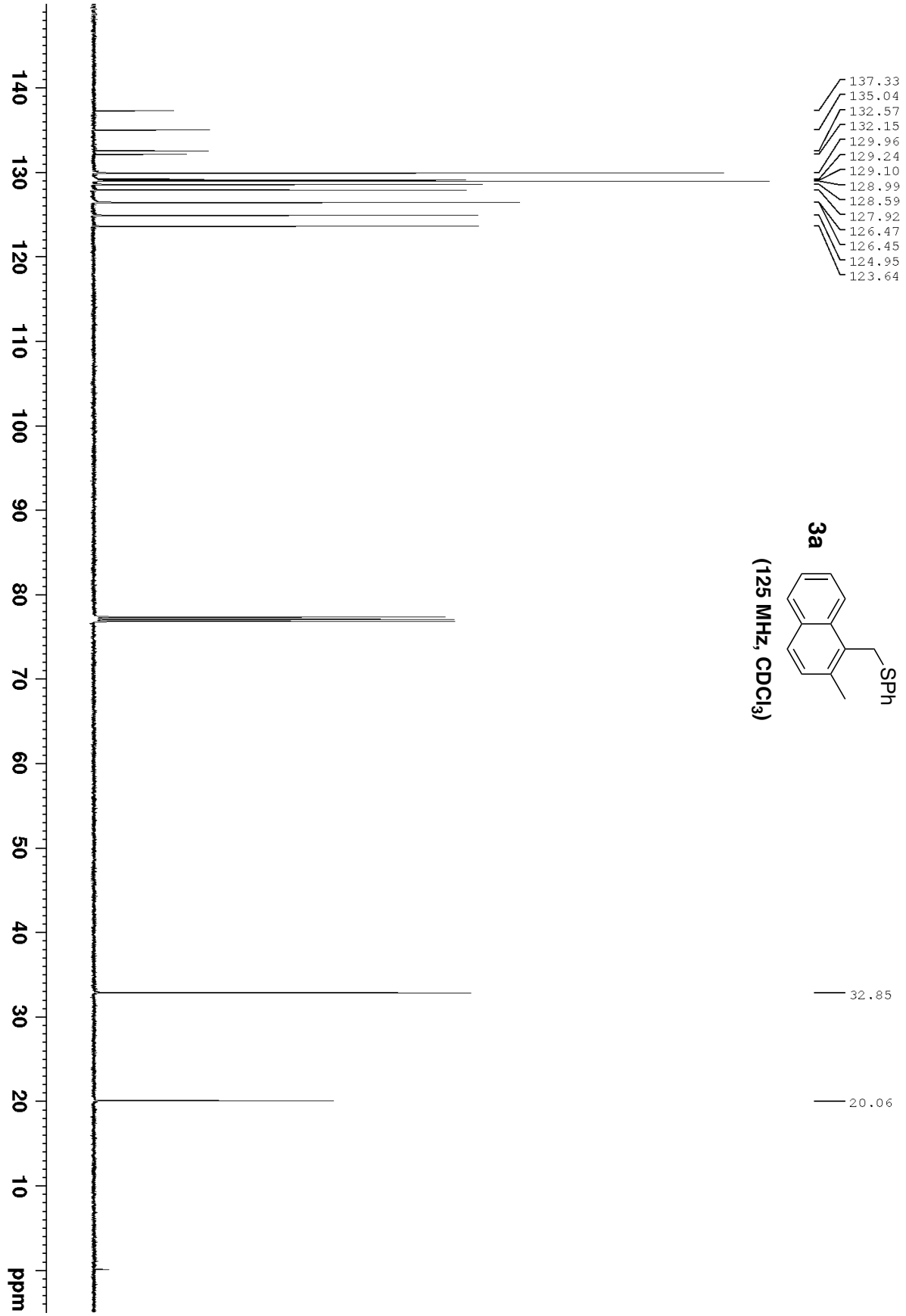

From Li Enolate + Me3SiCl
7m (minor) + 7M (major)
configurations not assigned
(125 MHz, CDCl3)
7M
7m
9
Ph
S
O
SiMe3

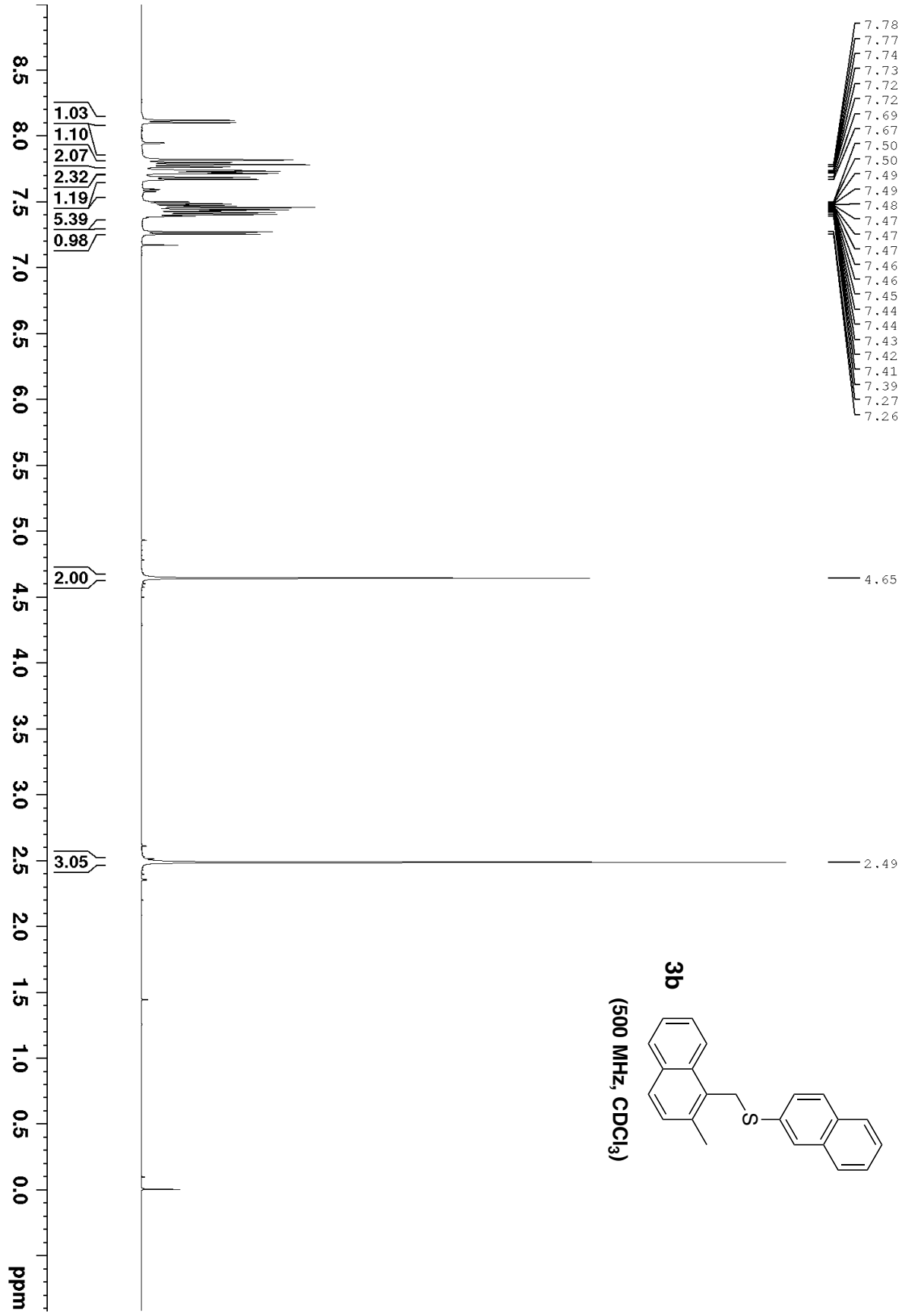

From PhSSiMe3 + Diazo Compound + Rh2OAc4
(crude)
Silyl ketene acetals
7m (minor) + 7M (major)
configurations not assigned
9
(500 MHz, CDCl3)
7M
7m
9
ppm

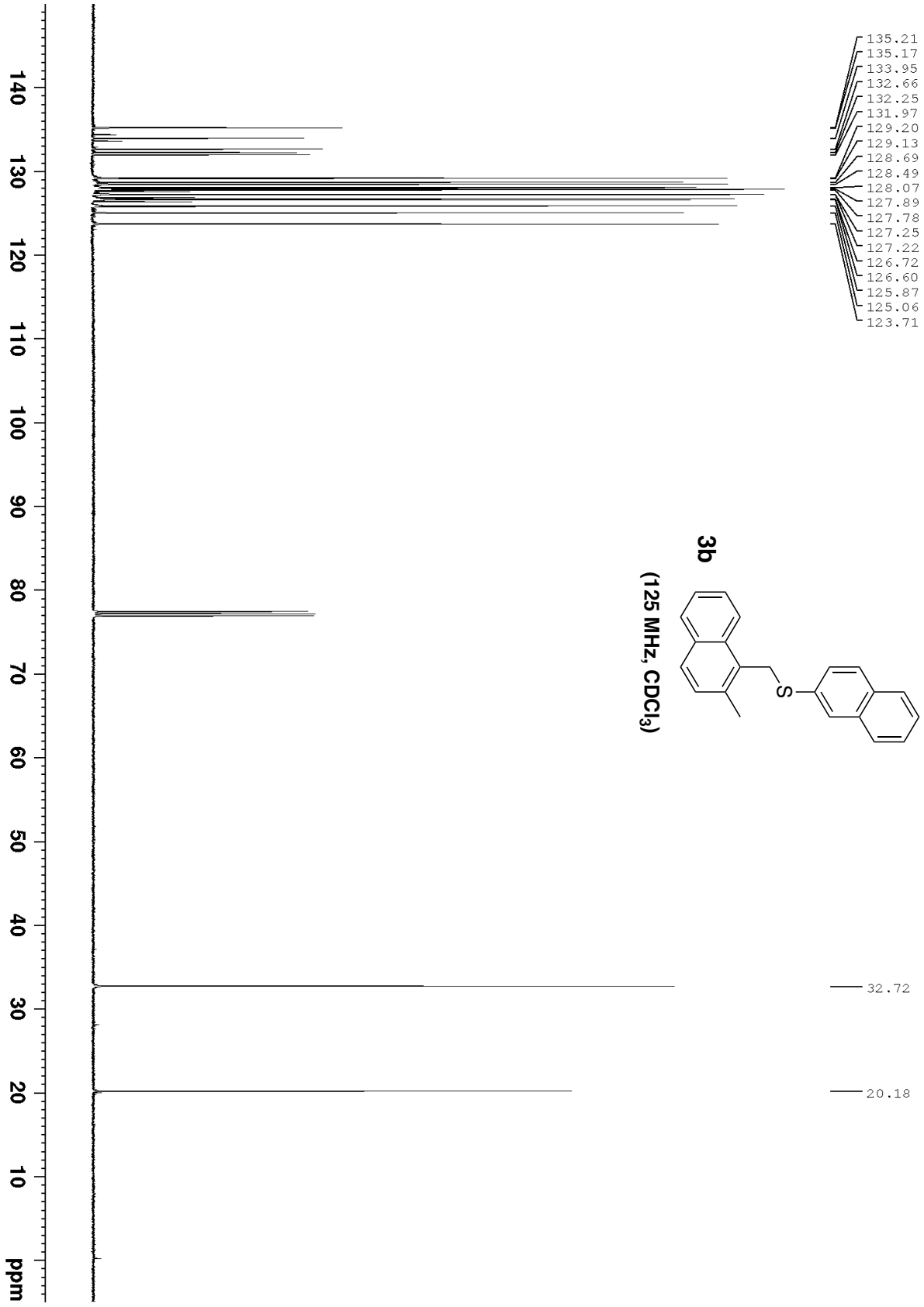

7.30
7.29
7.29
7.29
7.28
7.27
7.27
7.27
7.27
7.26
7.24
7.24
7.24
7.24
7.23
7.22
7.22
7.21
7.20
7.20
7.16
1.94
1.96
1.13
1.94
2.04
6.00
4.07
2.31
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ppm
1
Br
SPh
(500 MHz, CDCl3)

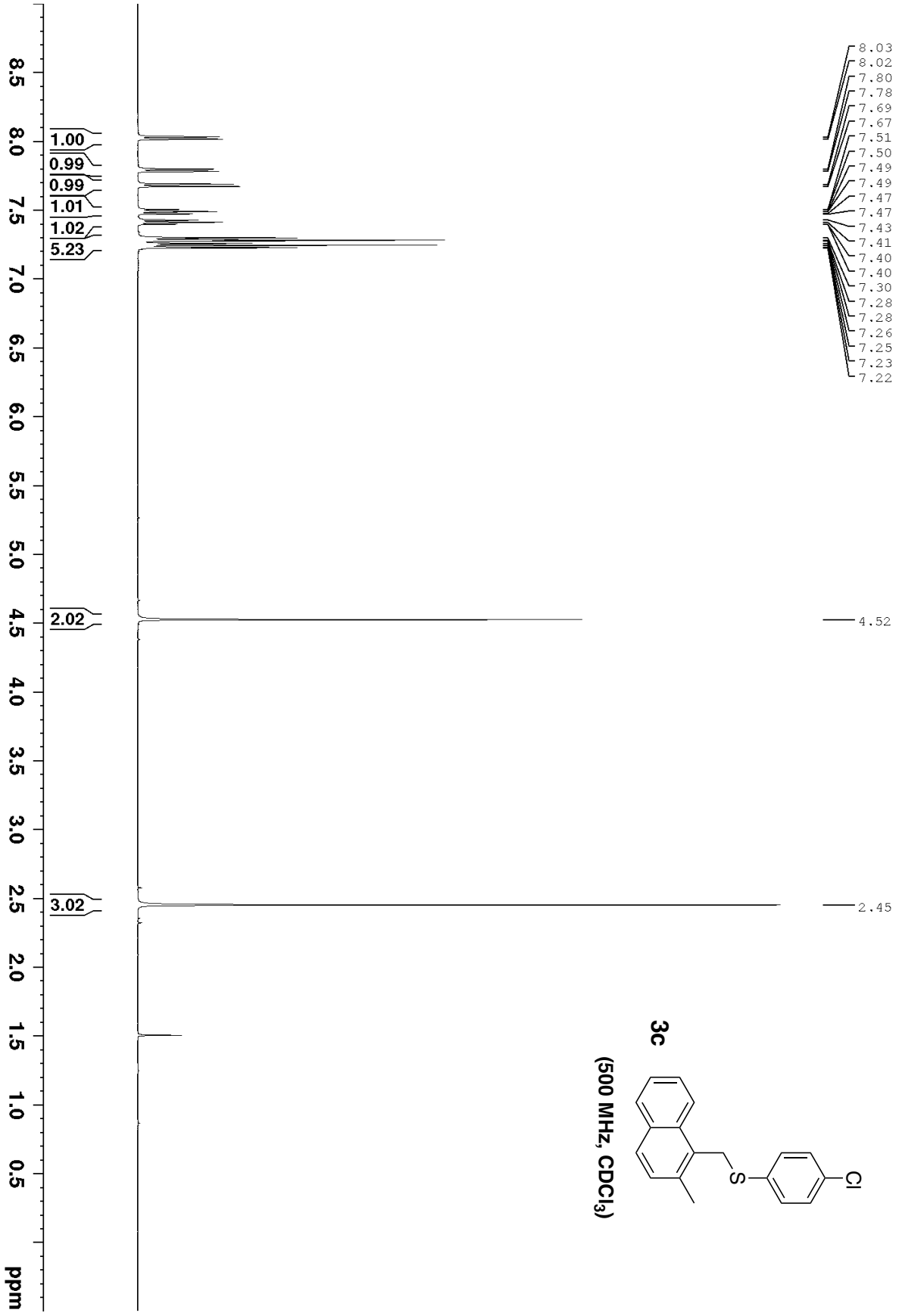

139.70
136.85
132.55
131.15
130.63
129.18
126.90
121.09
33.92
19.66
1
Br
SPh
(125 MHz, CDCl3)
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm

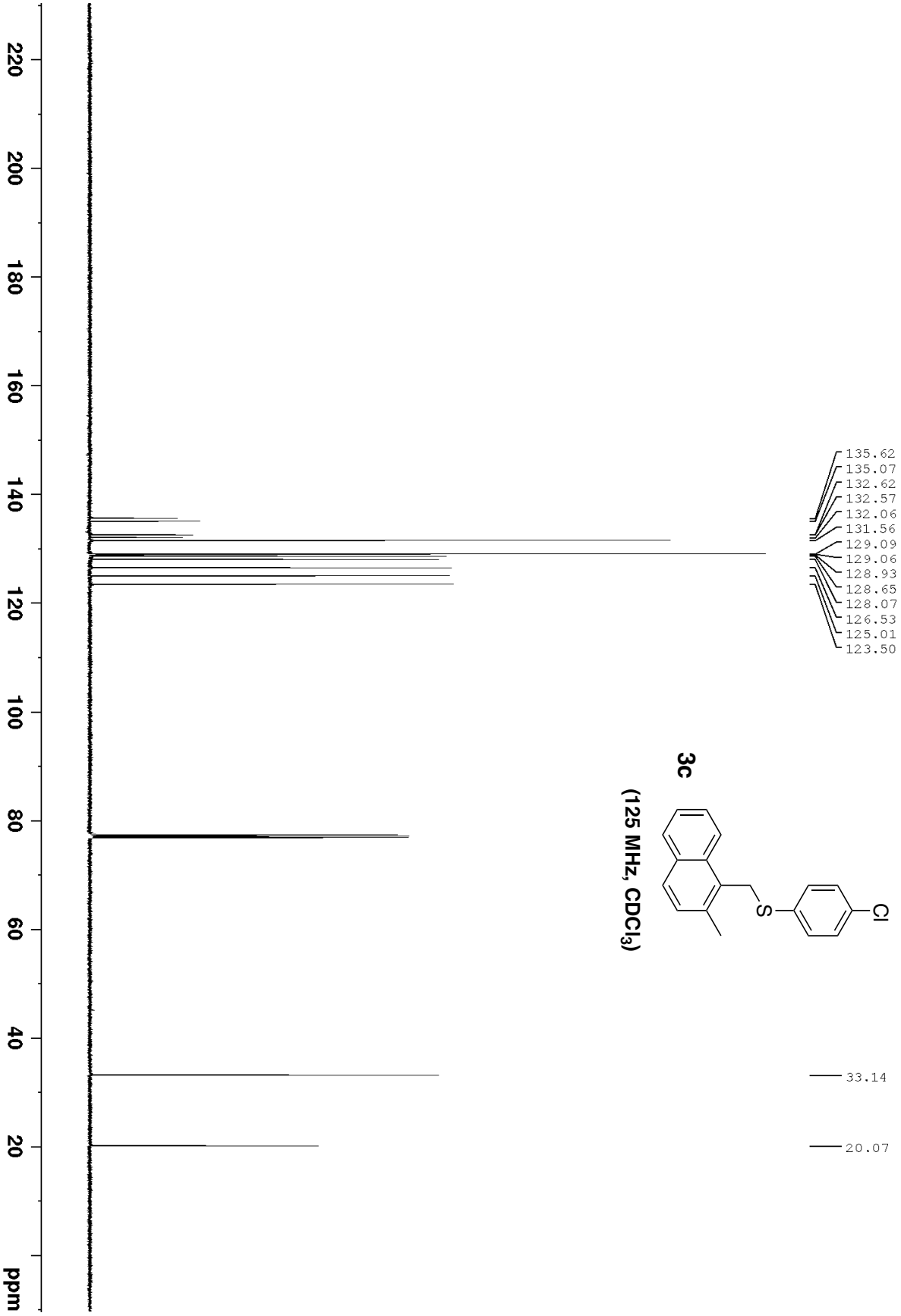

8.08
7.81
7.80
7.70
7.69
7.52
7.52
7.51
7.51
7.50
7.49
7.49
7.44
7.43
7.42
7.41
7.32
7.31
7.30
7.29
7.28
7.24
7.24
7.24
7.23
7.23
7.22
7.21
1.00
0.99
1.00
1.00
2.96
2.95
1.08
2.04
3.03
4.58
2.49
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
ppm
3a
(500 MHz, CDCl3)
SPh

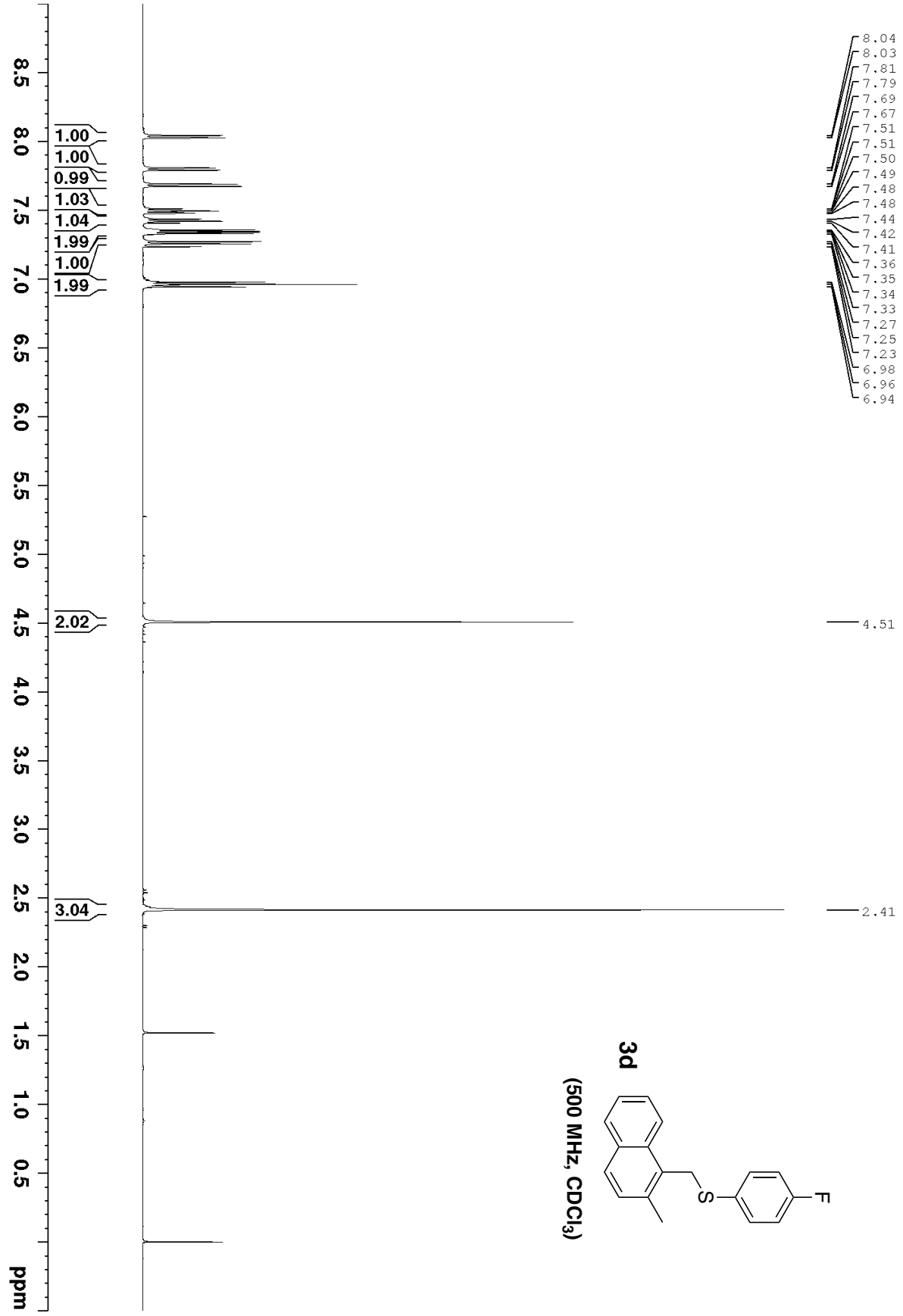

137.33
135.04
132.57
132.15
129.96
129.24
129.10
128.99
128.59
127.92
126.47
126.45
124.95
123.64
3a
(125 MHz, CDCl3)
SPh
32.85
20.06
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm

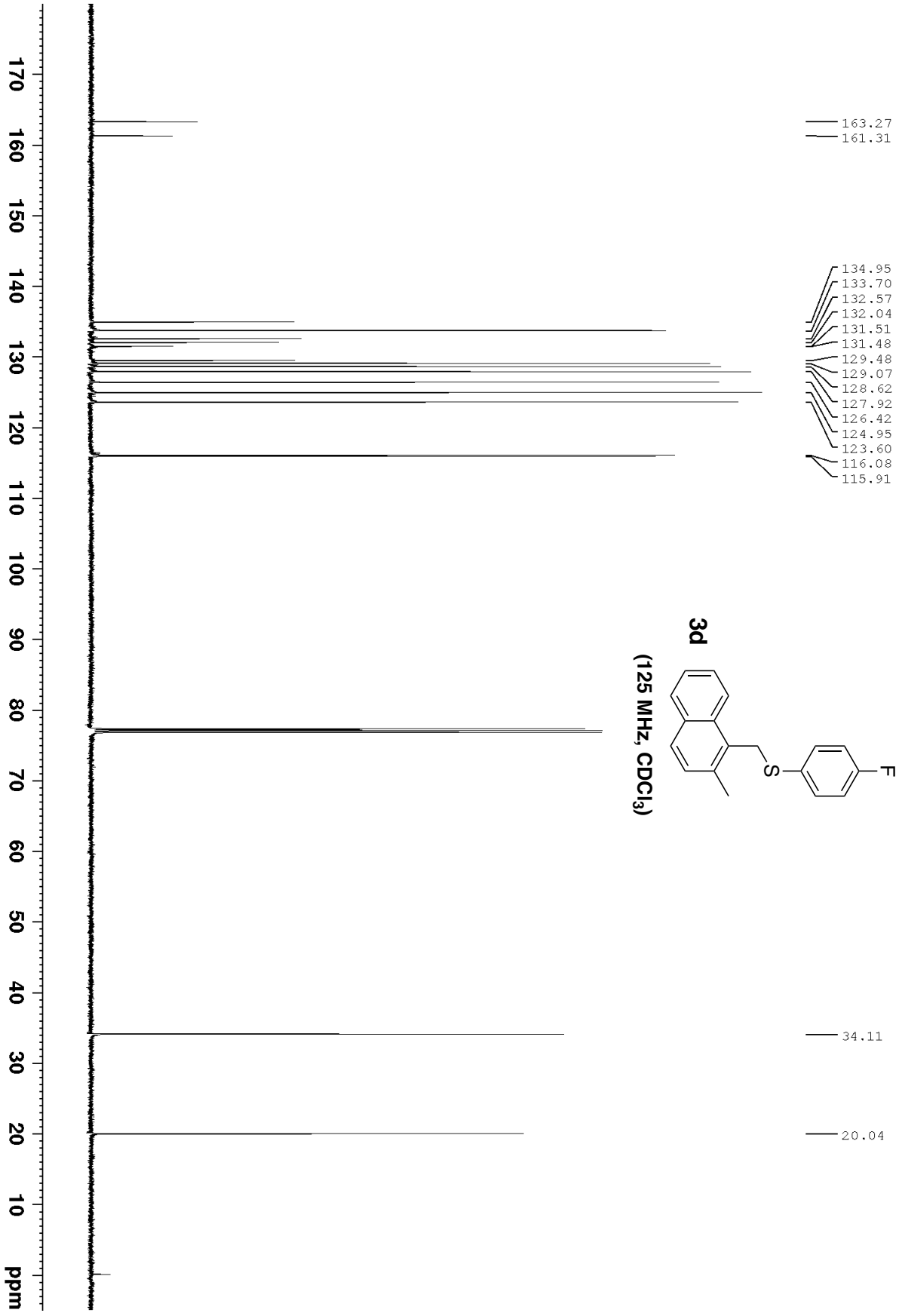

8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ppm
1.03
1.10
2.07
2.32
1.19
5.39
0.98
2.00
3.05
7.78
7.77
7.74
7.73
7.72
7.72
7.69
7.67
7.50
7.50
7.49
7.49
7.48
7.47
7.47
7.47
7.46
7.46
7.45
7.44
7.44
7.43
7.42
7.41
7.39
7.27
7.26
4.65
2.49
3b
(500 MHz, CDCl3)
S

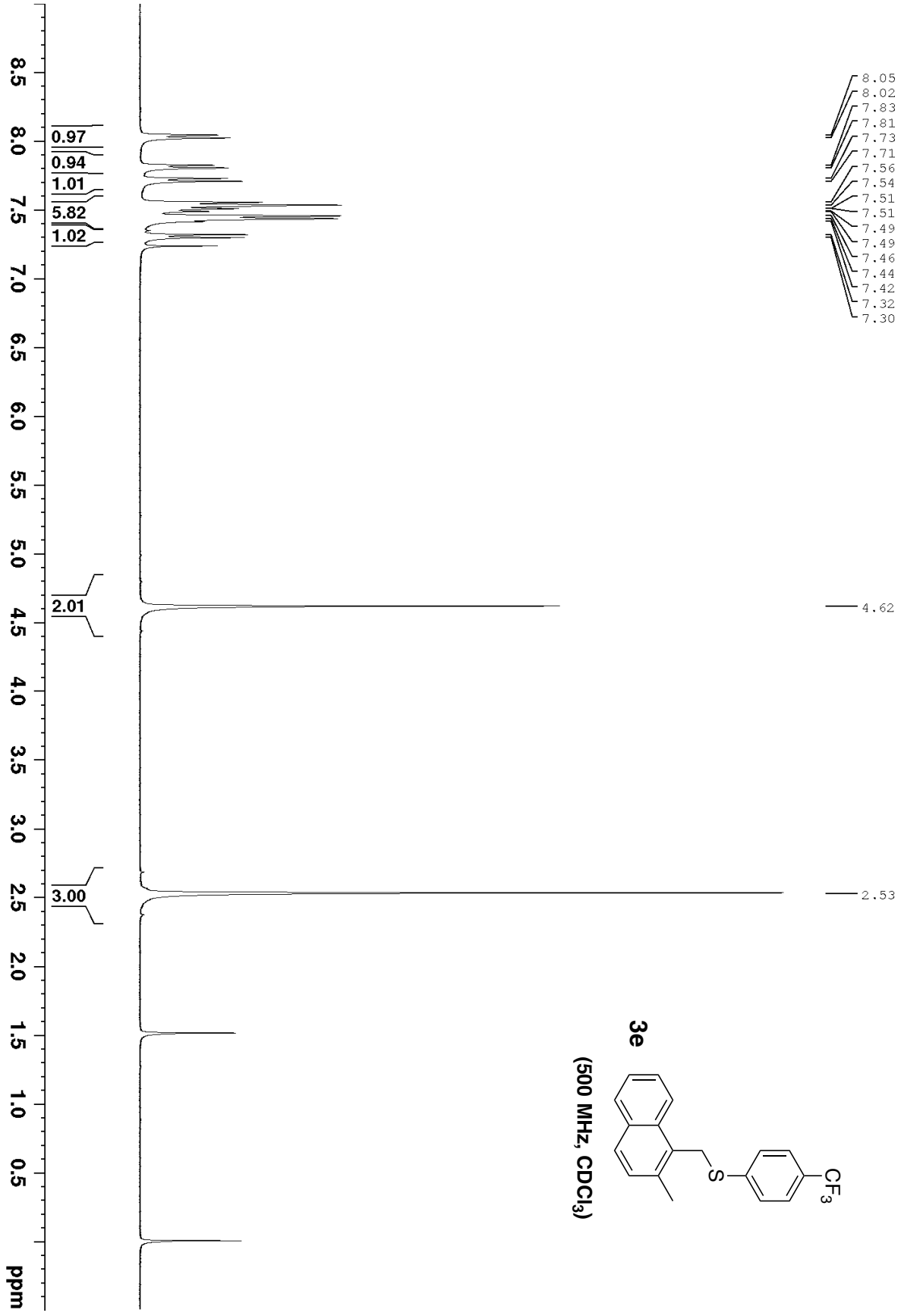

135.21
135.17
133.95
132.66
132.25
131.97
129.20
129.13
128.69
128.49
128.07
127.89
127.78
127.25
127.22
126.72
126.60
125.87
125.06
123.71
32.72
20.18
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm
3b
(125 MHz, CDCl3)
S

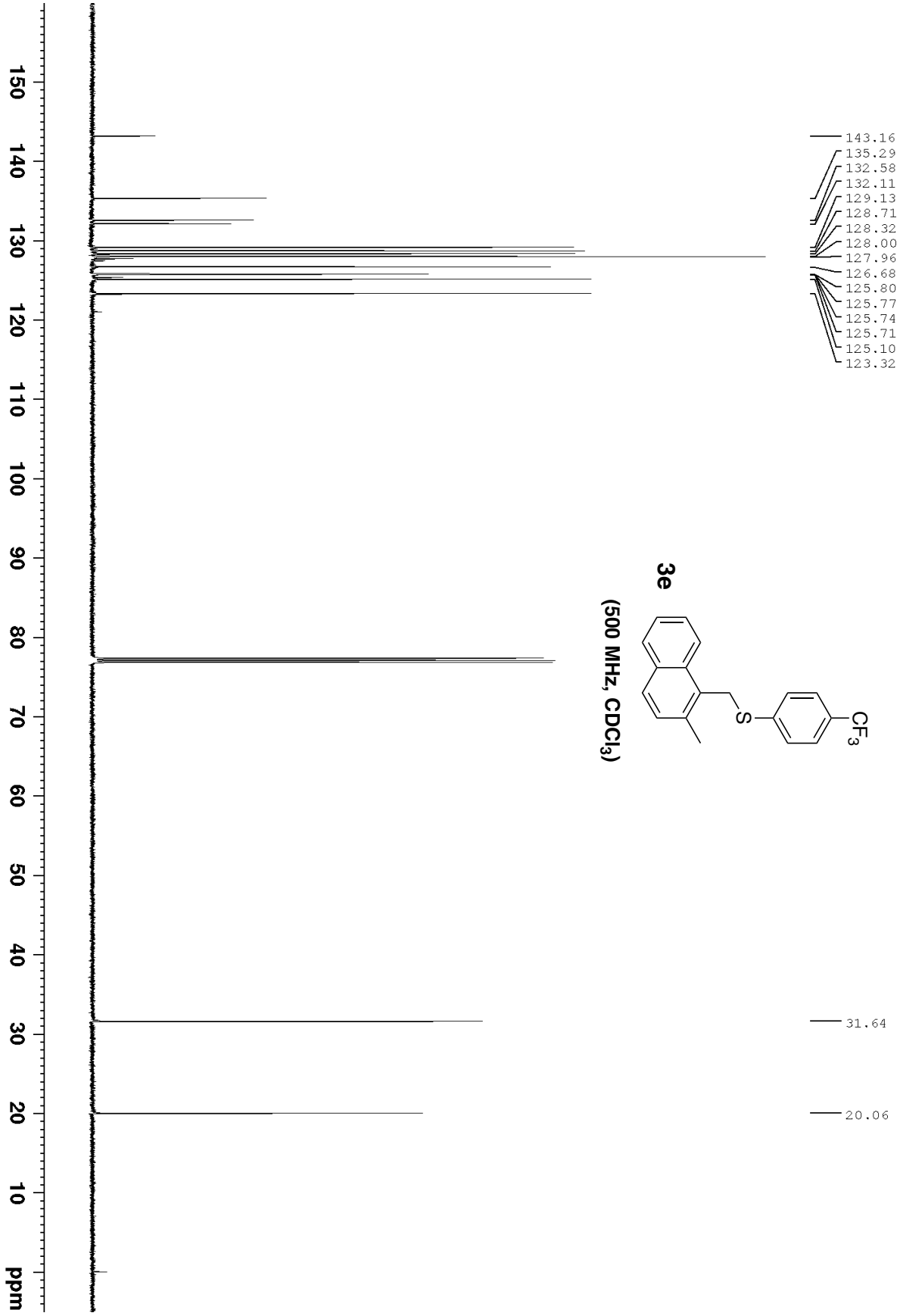

8.03
8.02
7.80
7.78
7.69
7.67
7.51
7.50
7.49
7.49
7.47
7.47
7.43
7.41
7.40
7.40
7.30
7.28
7.28
7.26
7.25
7.23
7.22
1.00
0.99
0.99
1.01
1.02
5.23
2.02
3.02
4.52
2.45
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
ppm
3c
(500 MHz, CDCl3)
S
Cl

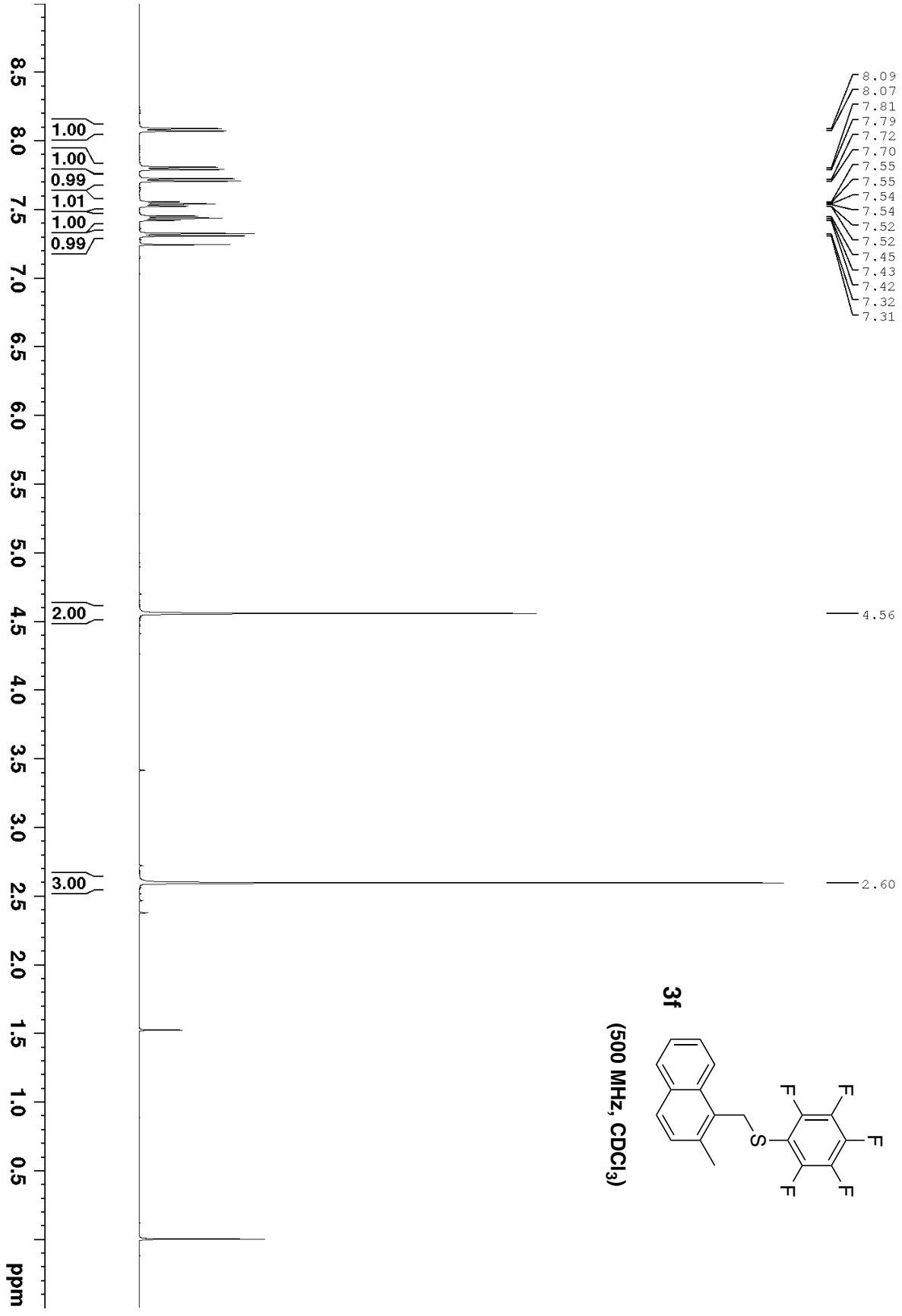

220
200
180
160
140
120
100
80
60
40
20
ppm
135.62
135.07
132.62
132.57
132.06
131.56
129.09
129.06
128.93
128.65
128.07
126.53
125.01
123.50
33.14
20.07
3c
(125 MHz, CDCl3)
S
Cl

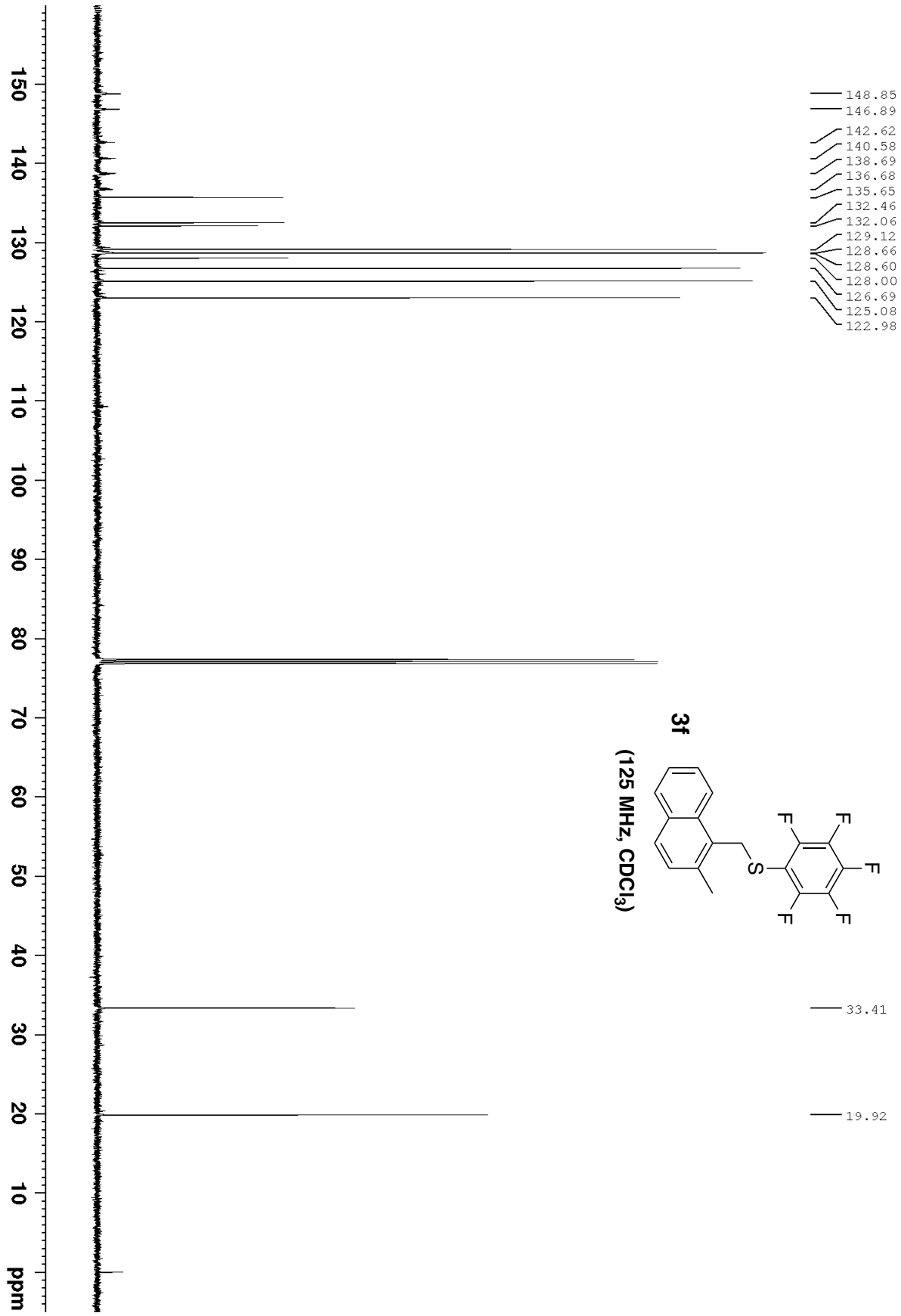

8.04
8.03
7.81
7.79
7.69
7.67
7.51
7.51
7.50
7.49
7.48
7.48
7.44
7.42
7.41
7.36
7.35
7.34
7.33
7.27
7.25
7.23
6.98
6.96
6.94
1.00
1.00
0.99
1.03
1.04
1.99
1.00
1.99
2.02
3.04
4.51
2.41
ppm
3d
(500 MHz, CDCl3)
S
F

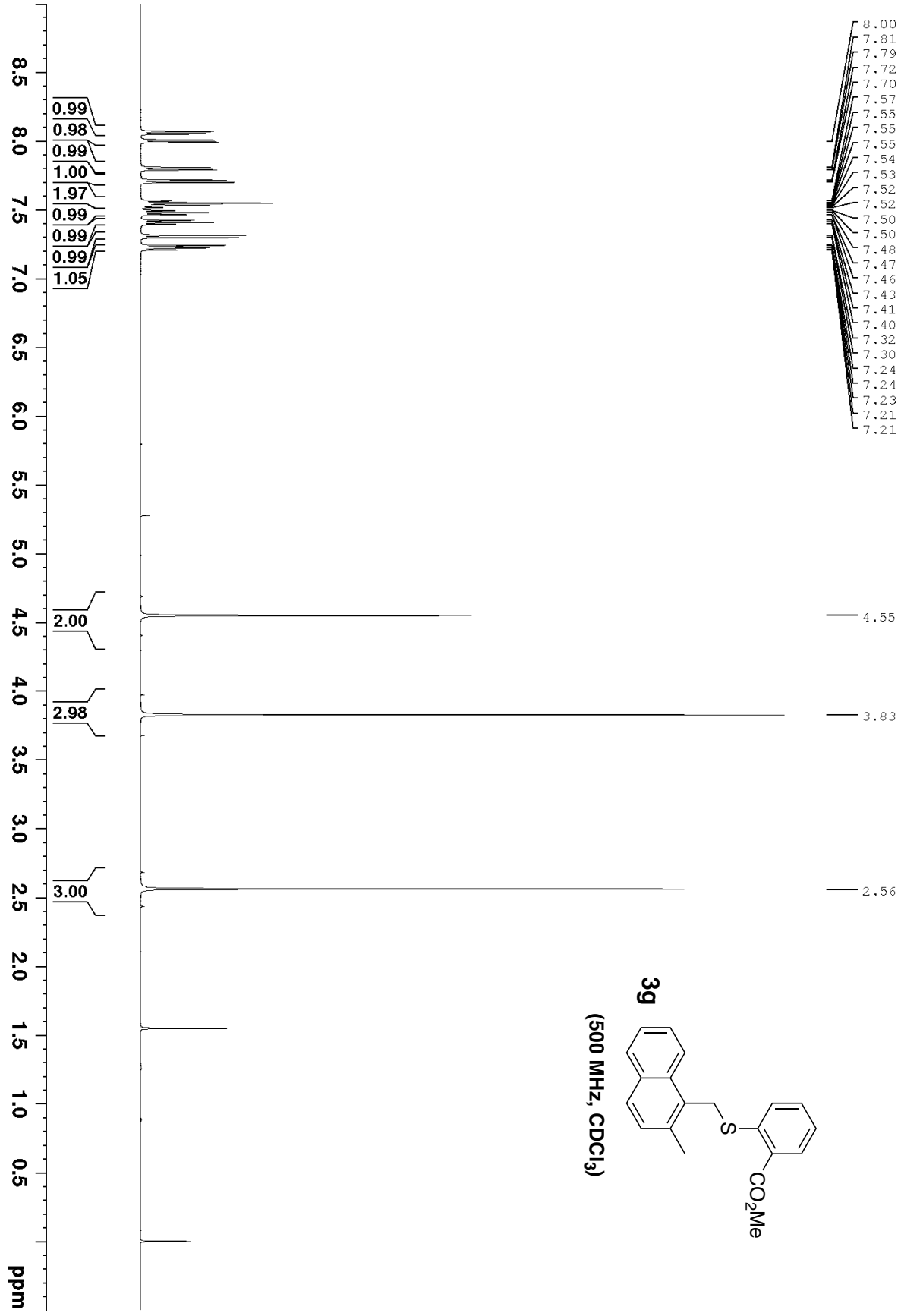

163.27
161.31
134.95
133.70
132.57
132.04
131.51
131.48
129.48
129.07
128.62
127.92
126.42
124.95
123.60
116.08
115.91
34.11
20.04
3d
(125 MHz, CDCl3)
S
F
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm

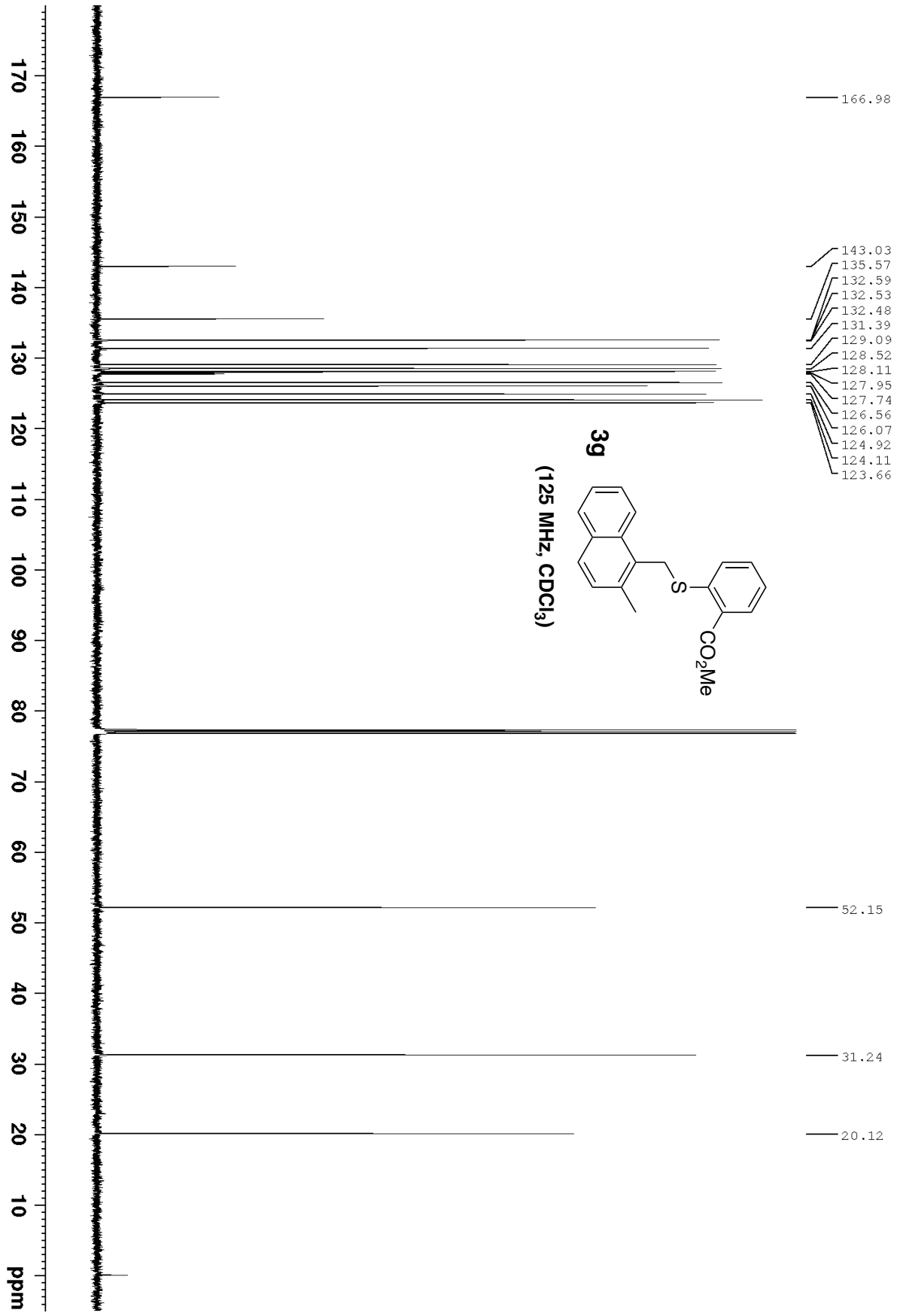

8.05
8.02
7.83
7.81
7.73
7.71
7.56
7.54
7.51
7.51
7.49
7.49
7.46
7.44
7.42
7.32
7.30
4.62
2.53
0.97
0.94
1.01
5.82
1.02
2.01
3.00
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
ppm
3e
(500 MHz, CDCl3)
S
CF3

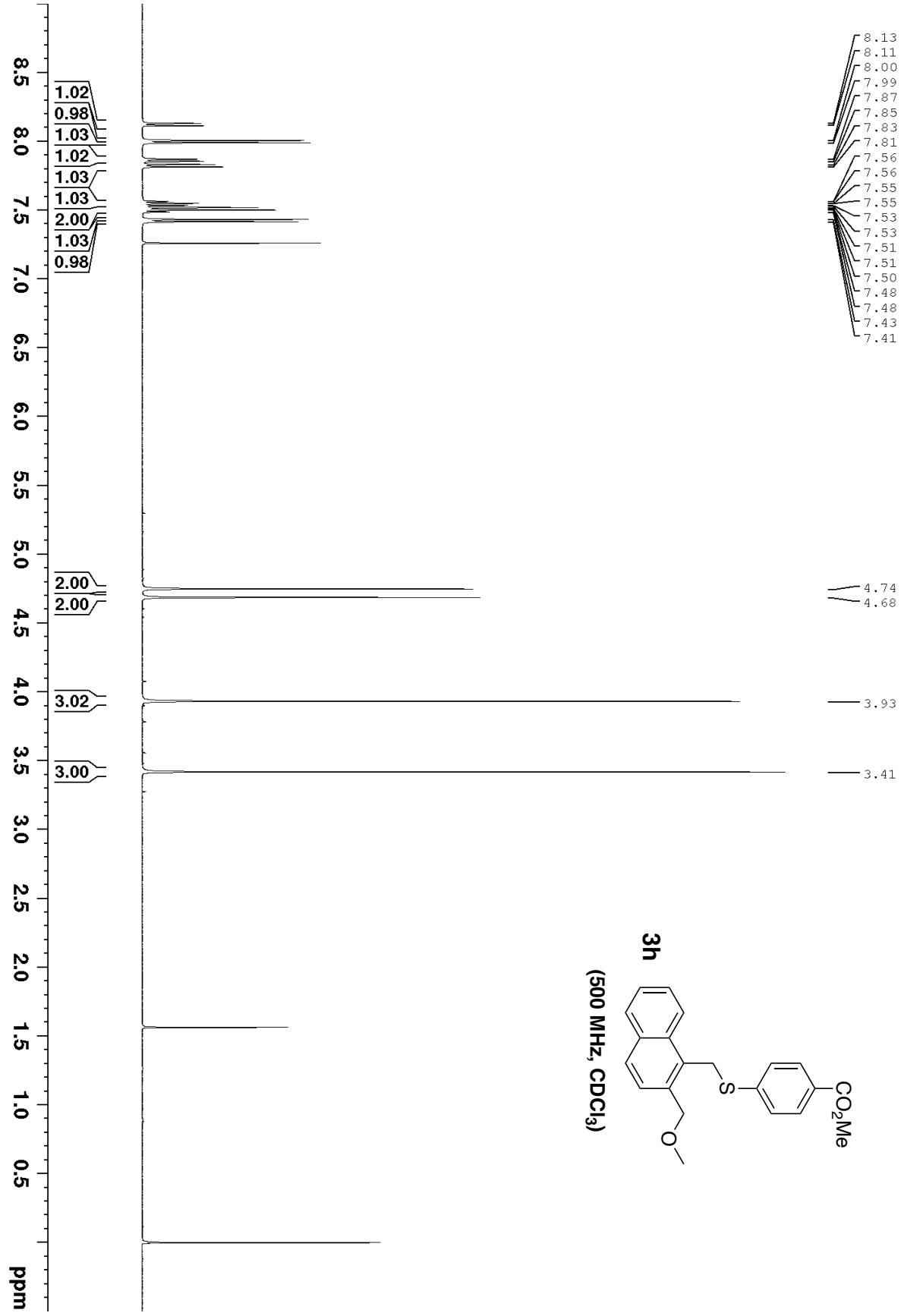

143.16
135.29
132.58
132.11
129.13
128.71
128.32
128.00
127.96
126.68
125.80
125.77
125.74
125.71
125.10
123.32
31.64
20.06
3e
(500 MHz, CDCl3)
S
CF3
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm

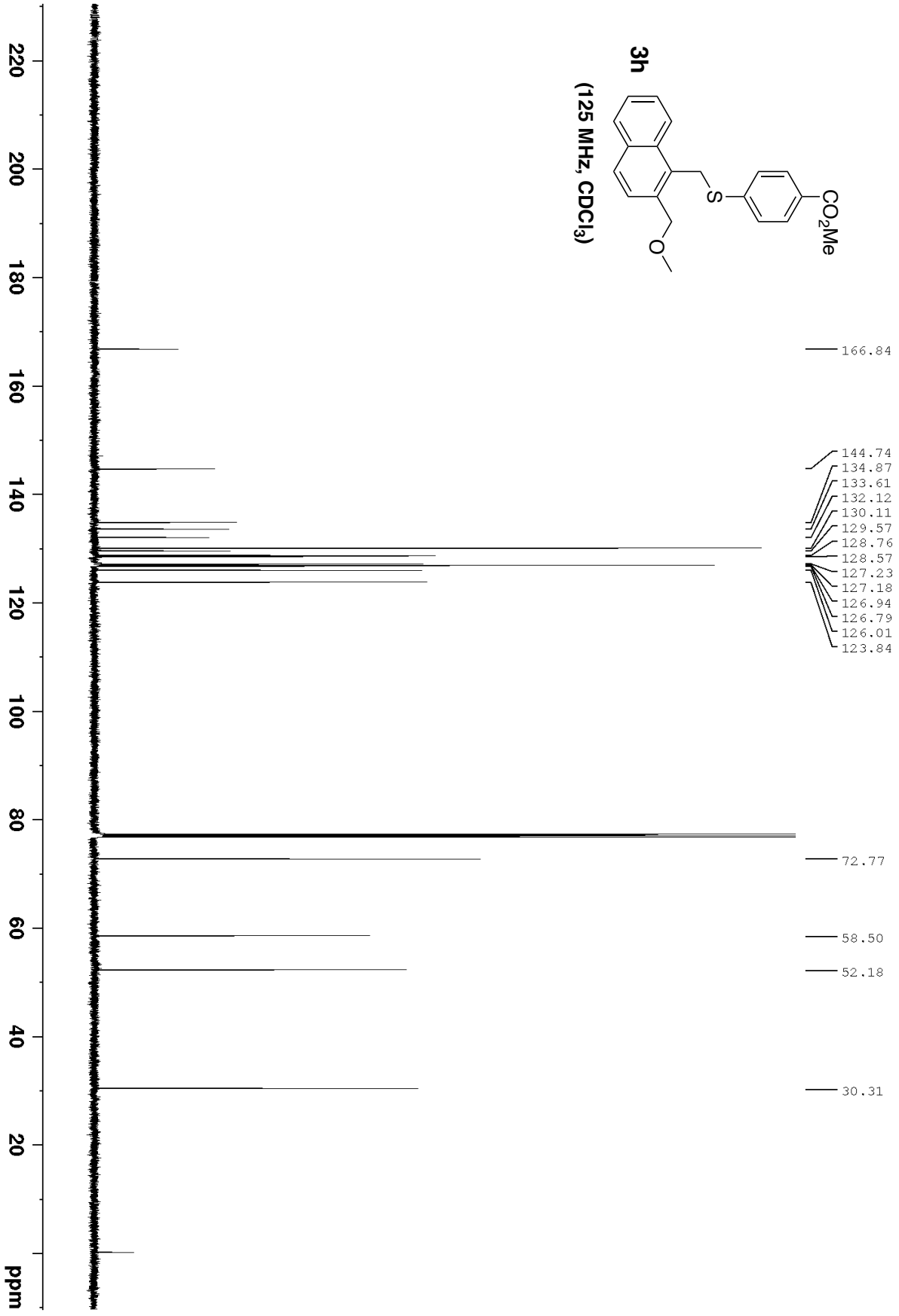

8.09
8.07
7.81
7.79
7.72
7.70
7.55
7.55
7.54
7.54
7.52
7.52
7.45
7.43
7.42
7.32
7.31
1.00
1.00
0.99
1.01
1.00
0.99
2.00
3.00
4.56
2.60
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
ppm
3f
(500 MHz, CDCl3)
S
F
F
F
F
F

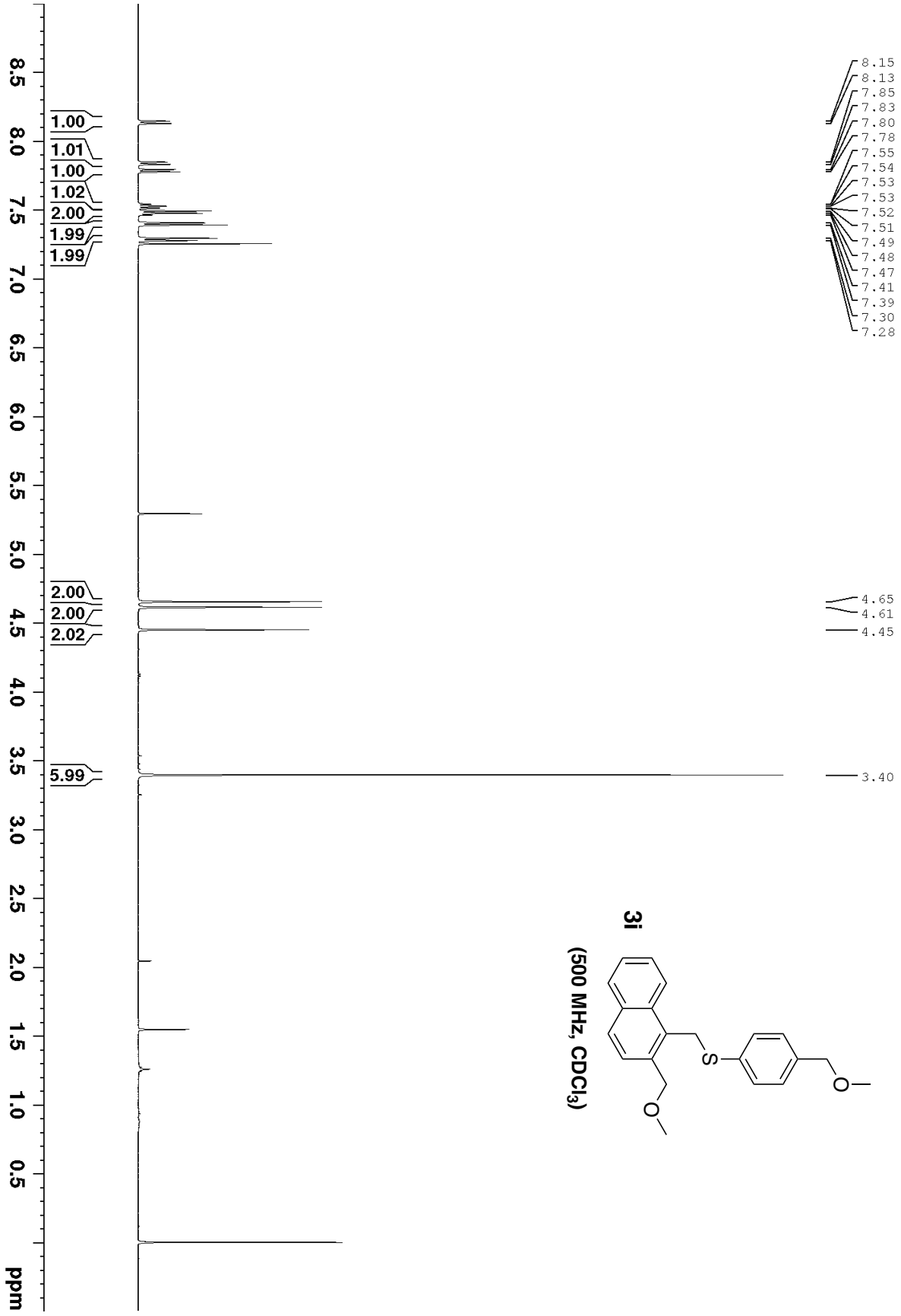

148.85
146.89
142.62
140.58
138.69
136.68
135.65
132.46
132.06
129.12
128.66
128.60
128.00
126.69
125.08
122.98
33.41
19.92
3f
(125 MHz, CDCl3)
F
F
F
F
F
S
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm

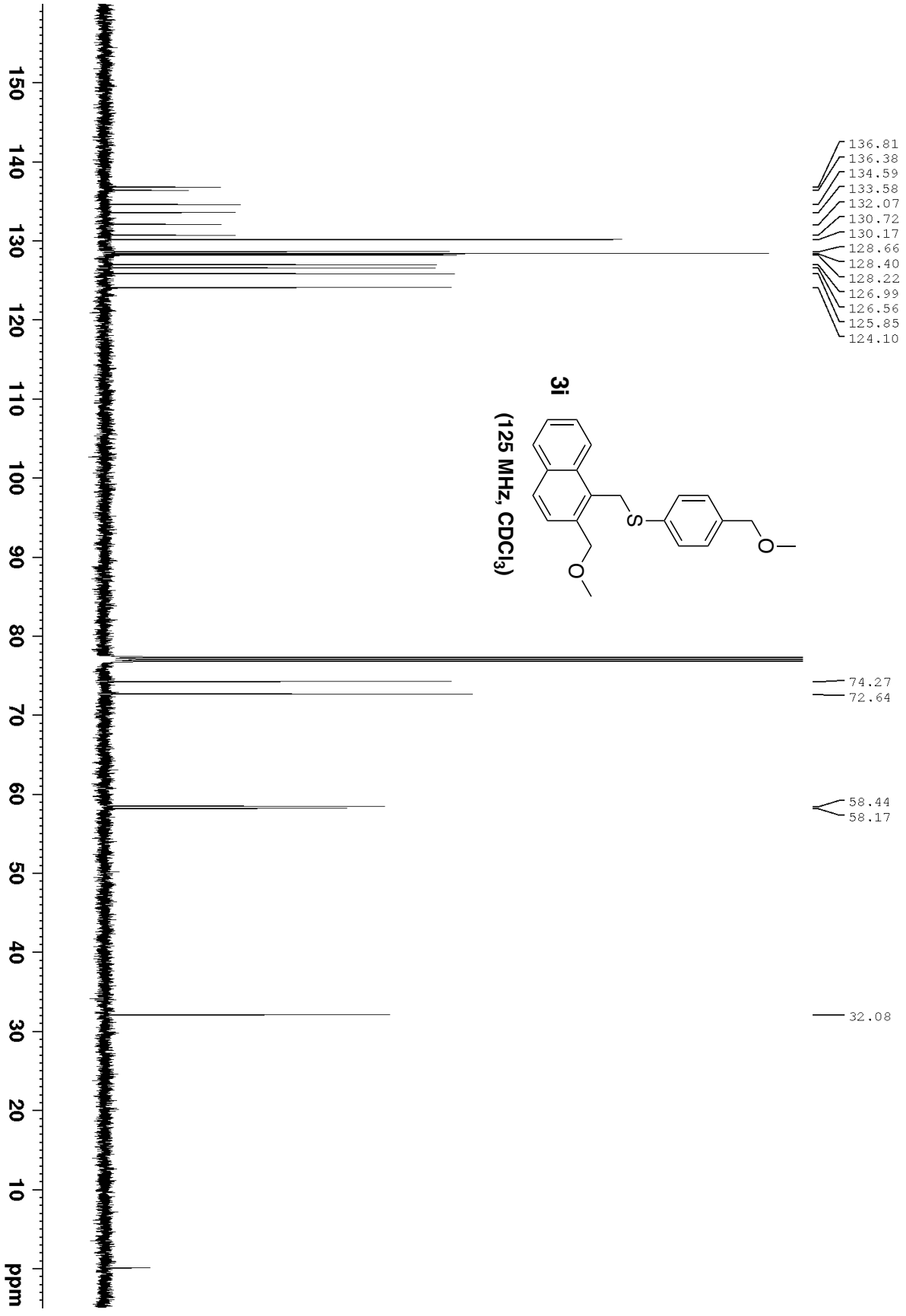

3g
(500 MHz, CDCl3)
S
CO2Me
8.00
7.81
7.79
7.72
7.70
7.57
7.55
7.55
7.55
7.54
7.53
7.52
7.52
7.50
7.50
7.48
7.47
7.46
7.43
7.41
7.40
7.32
7.30
7.24
7.24
7.23
7.21
7.21
4.55
3.83
2.56
0.99
0.98
0.99
1.00
1.97
0.99
0.99
0.99
1.05
2.00
2.98
3.00
ppm

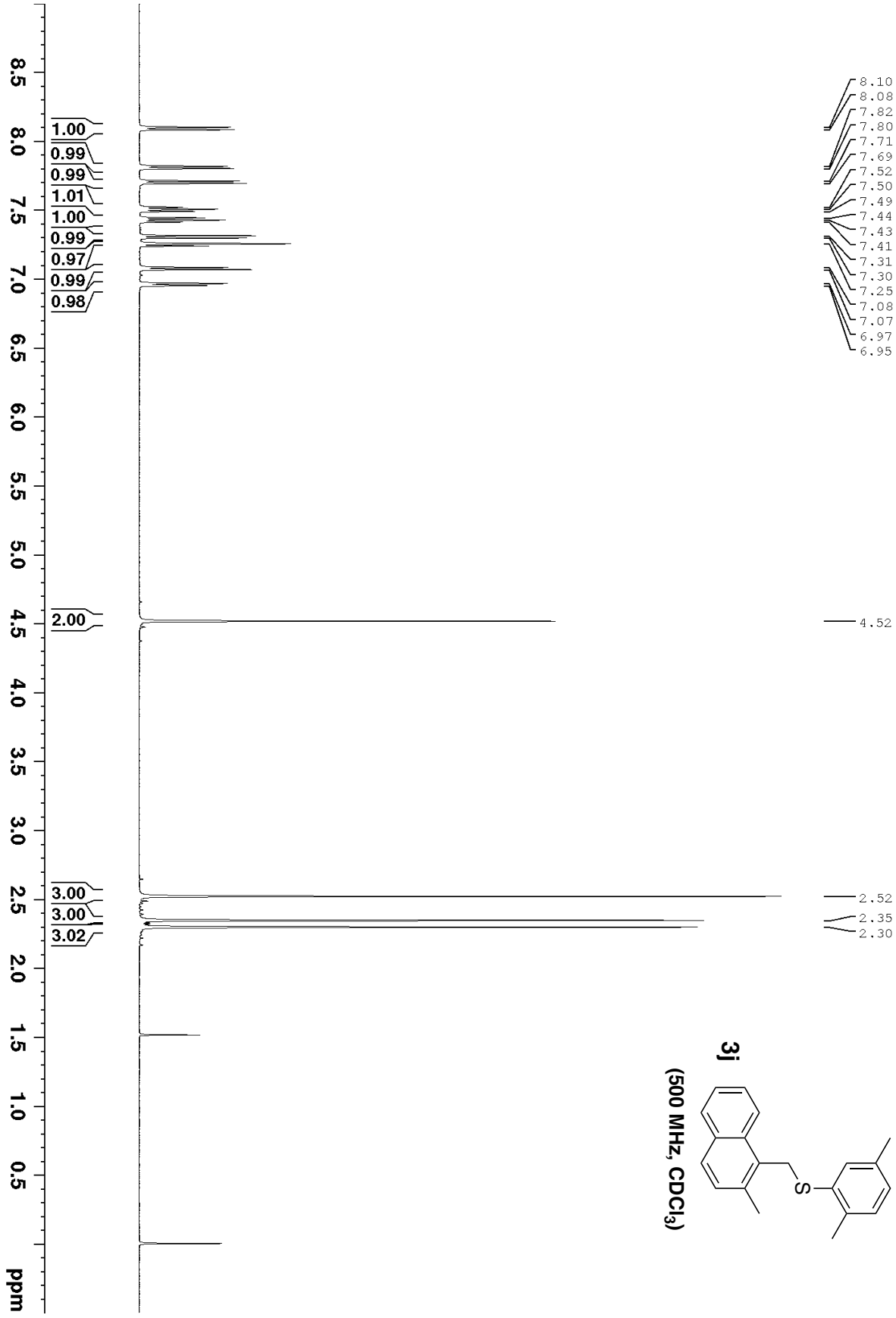

166.98
143.03
135.57
132.59
132.53
132.48
131.39
129.09
128.52
128.11
127.95
127.74
126.56
126.07
124.92
124.11
123.66
52.15
31.24
20.12
3g
(125 MHz, CDCl3)
S
CO2Me
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm

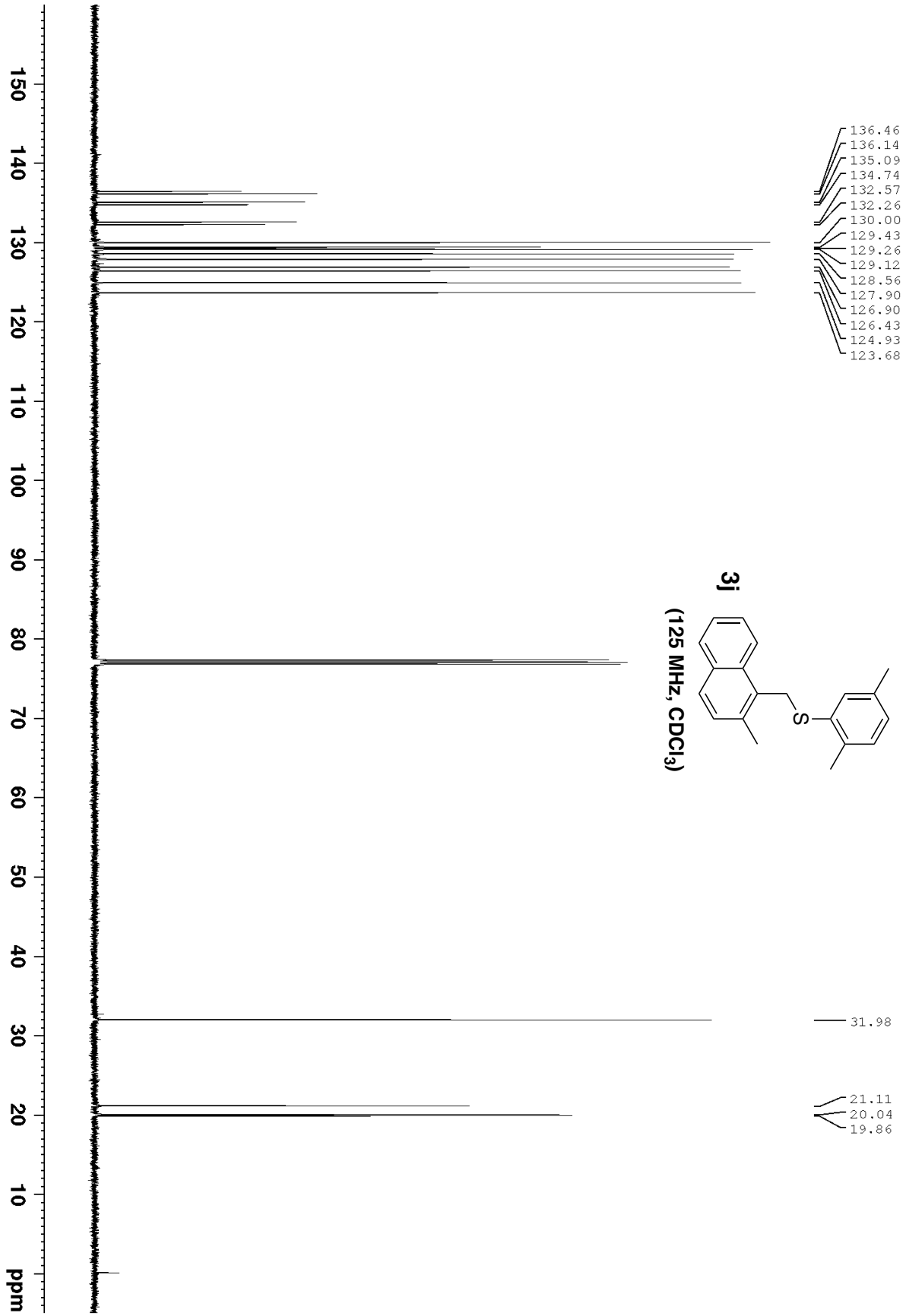

8.13
8.11
8.00
7.99
7.87
7.85
7.83
7.81
7.56
7.56
7.55
7.55
7.53
7.53
7.51
7.51
7.50
7.48
7.48
7.43
7.41
4.74
4.68
3.93
3.41
1.02
0.98
1.03
1.02
1.03
1.03
2.00
1.03
0.98
2.00
2.00
3.02
3.00
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
ppm
3h
(500 MHz, CDCl3)
S
O
CO2Me

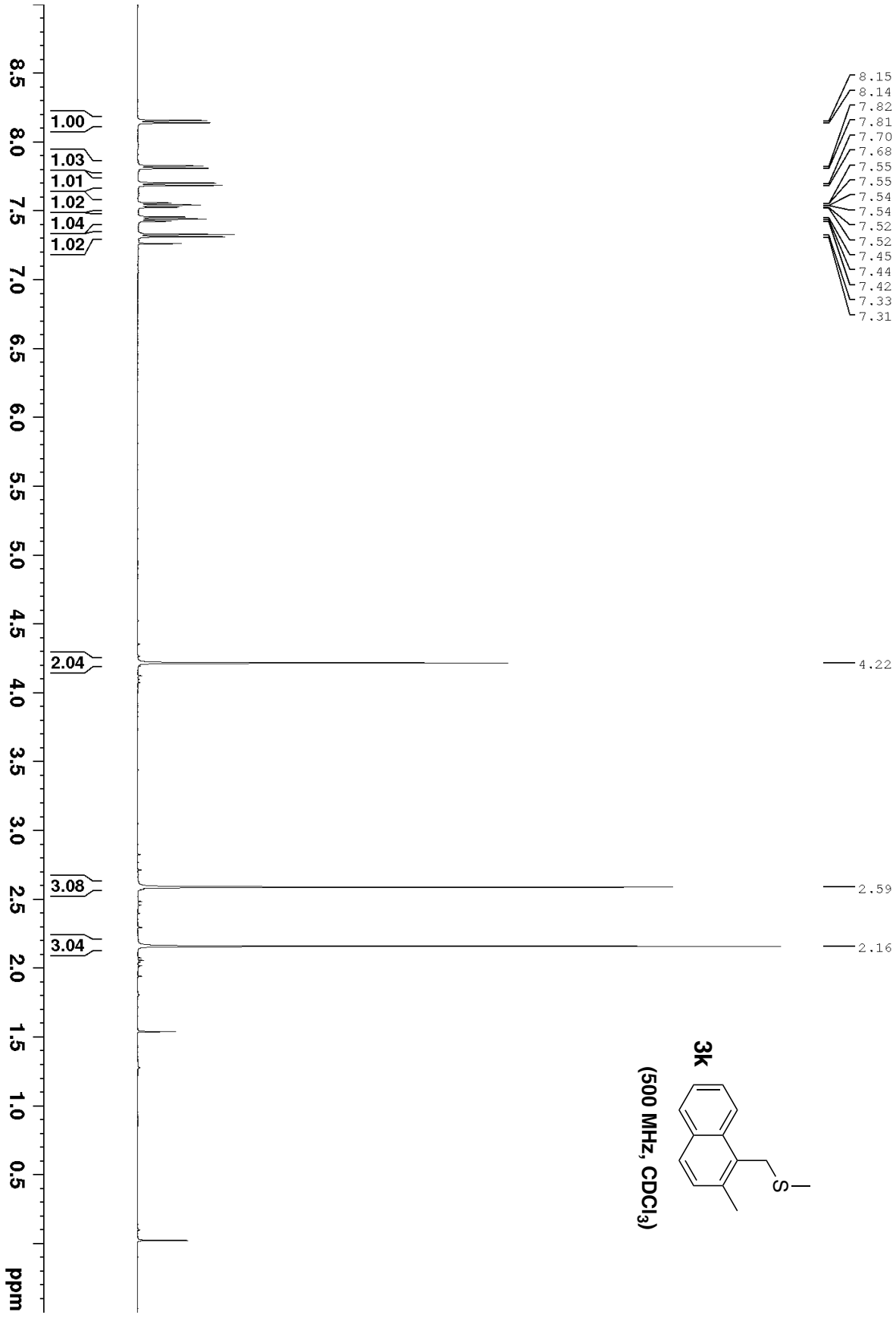

3h
(125 MHz, CDCl3)
S
O
CO2Me
166.84
144.74
134.87
133.61
132.12
130.11
129.57
128.76
128.57
127.23
127.18
126.94
126.79
126.01
123.84
72.77
58.50
52.18
30.31
220
200
180
160
140
120
100
80
60
40
20
ppm

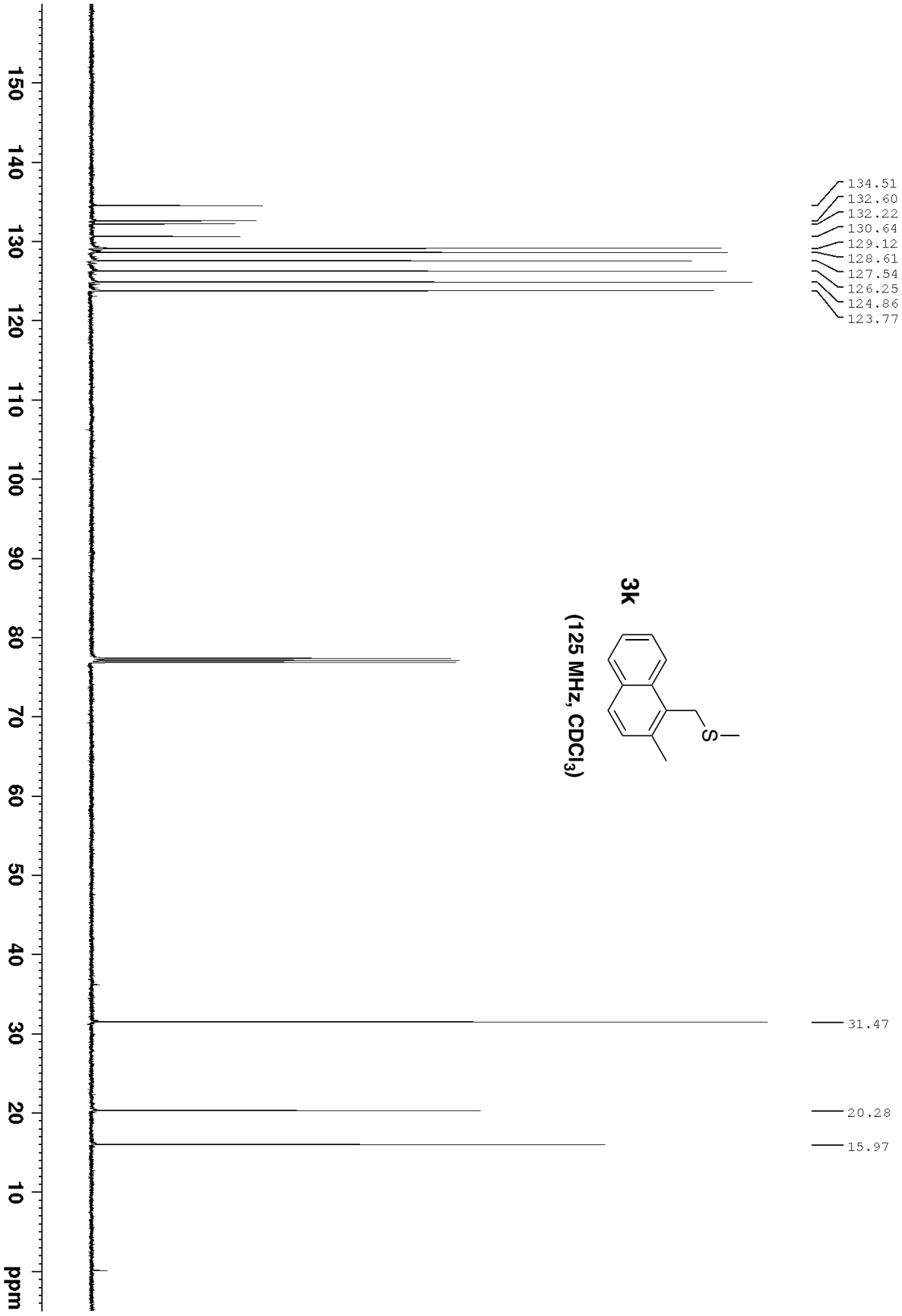

8.15
8.13
7.85
7.83
7.80
7.78
7.55
7.54
7.53
7.53
7.52
7.51
7.49
7.48
7.47
7.41
7.39
7.30
7.28
4.65
4.61
4.45
3.40
1.00
1.01
1.00
1.02
2.00
1.99
1.99
2.00
2.00
2.02
5.99
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
ppm
3i
(500 MHz, CDCl3)
S
O
O

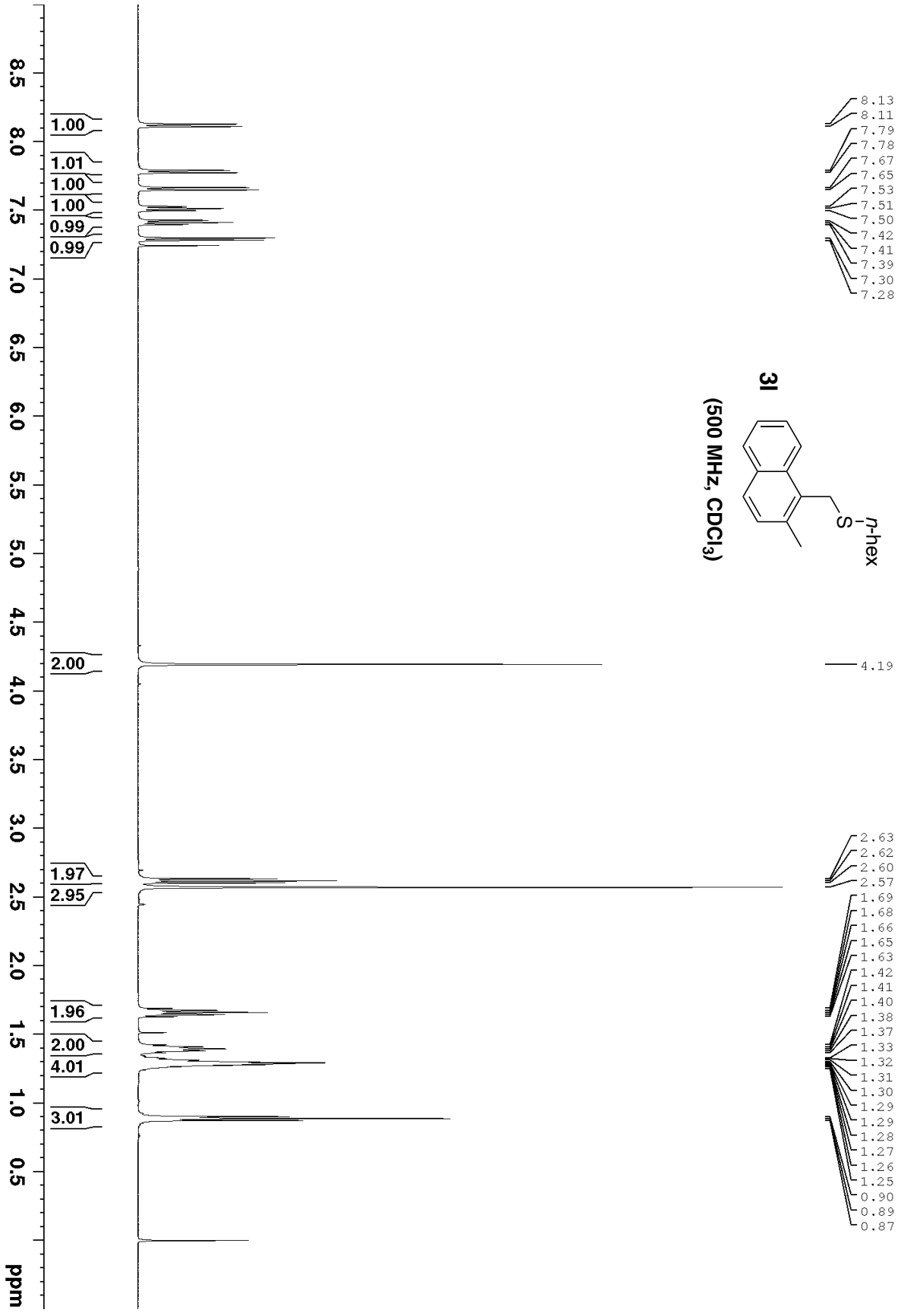

136.81
136.38
134.59
133.58
132.07
130.72
130.17
128.66
128.40
128.22
126.99
126.56
125.85
124.10
74.27
72.64
58.44
58.17
32.08
3i
(125 MHz, CDCl3)
S
O
O
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm

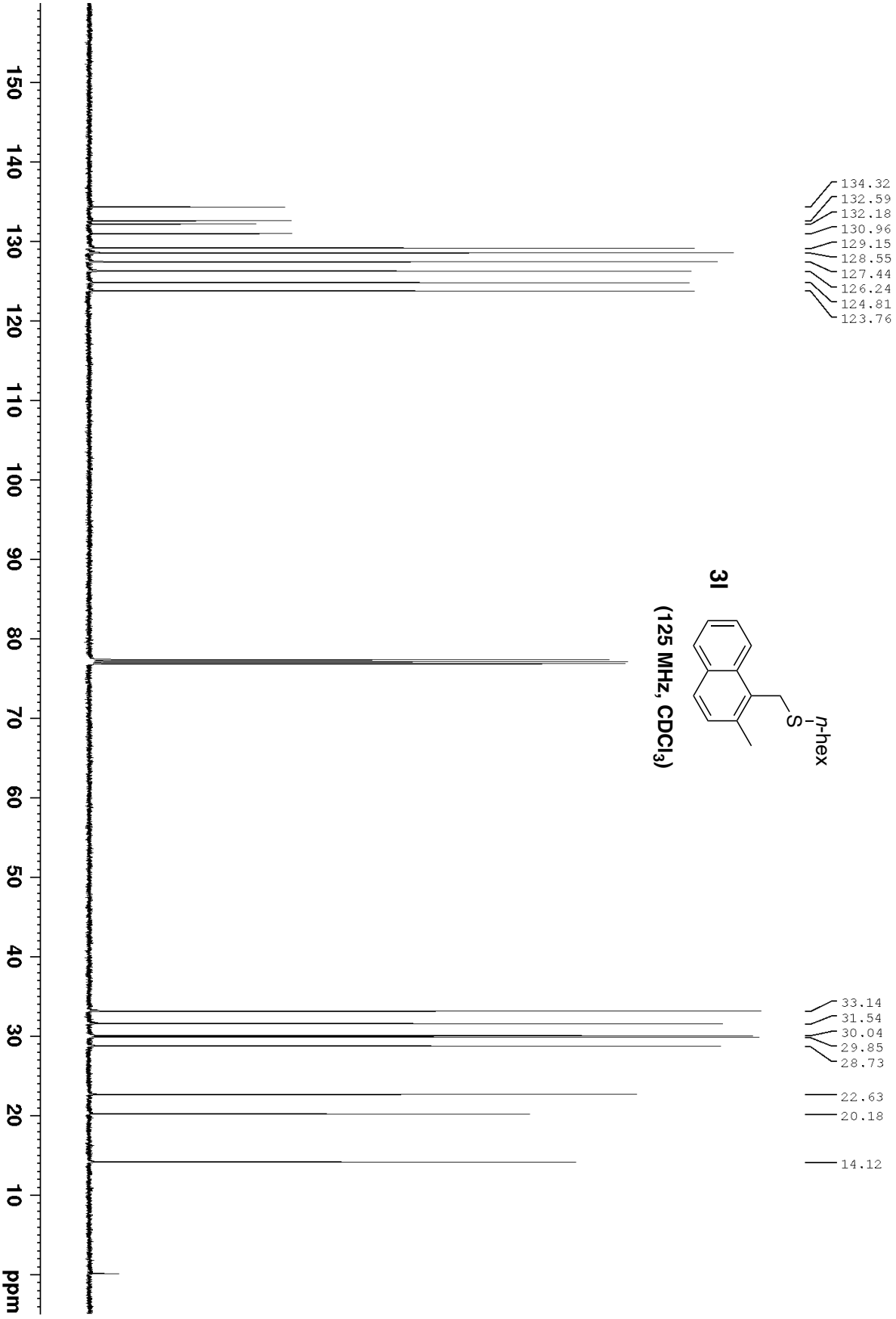

8.10
8.08
7.82
7.80
7.71
7.69
7.52
7.50
7.49
7.44
7.43
7.41
7.31
7.30
7.25
7.08
7.07
6.97
6.95
4.52
2.52
2.35
2.30
1.00
0.99
0.99
1.01
1.00
0.99
0.97
0.99
0.98
2.00
3.00
3.00
3.02
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
ppm
3j
(500 MHz, CDCl3)
S

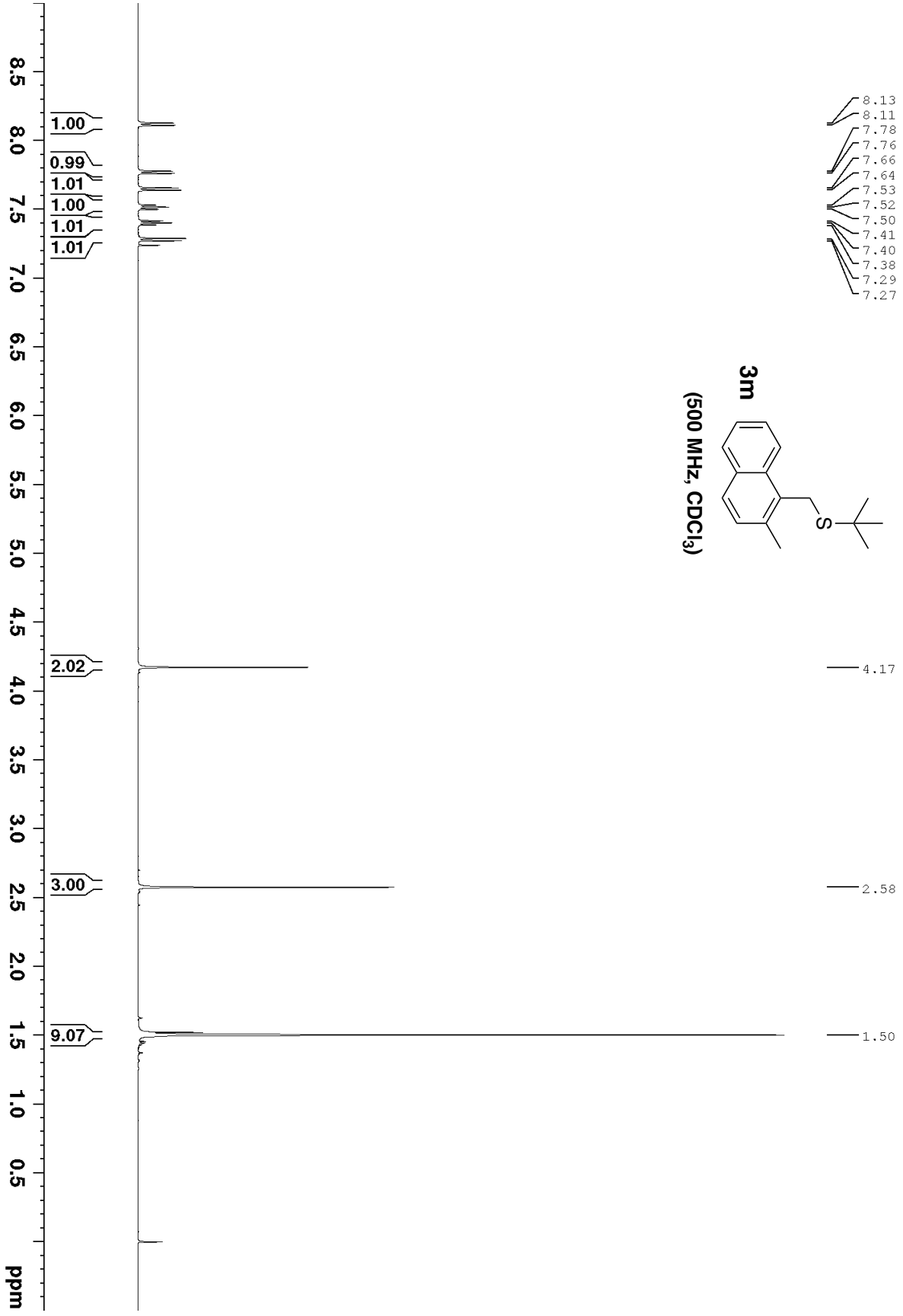

136.46
136.14
135.09
134.74
132.57
132.26
130.00
129.43
129.26
129.12
128.56
127.90
126.90
126.43
124.93
123.68
31.98
21.11
20.04
19.86
3j
(125 MHz, CDCl3)
S
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm

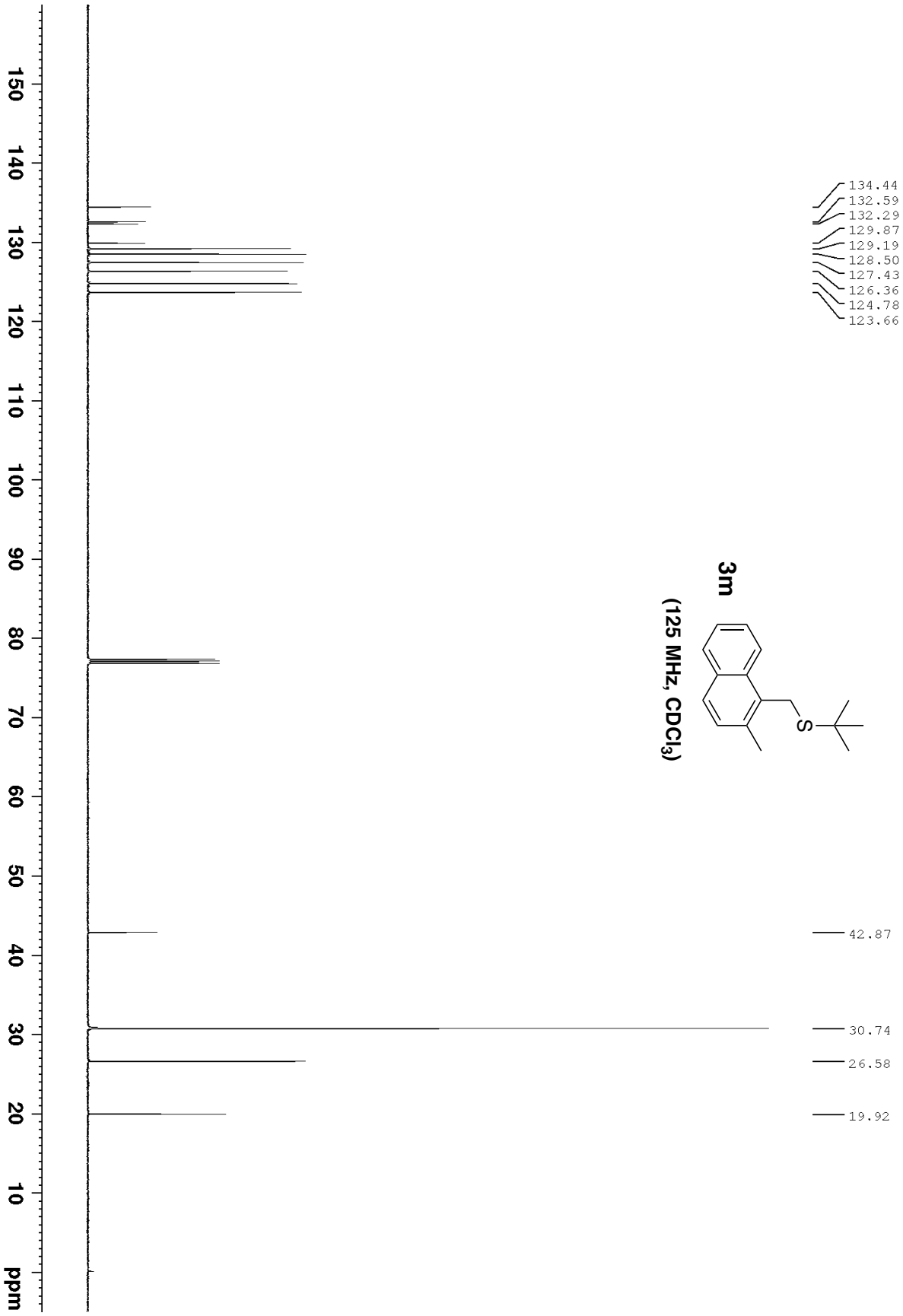

8.15
8.14
7.82
7.81
7.70
7.68
7.55
7.55
7.54
7.54
7.52
7.52
7.45
7.44
7.42
7.33
7.31
1.00
1.03
1.01
1.02
1.04
1.02
2.04
3.08
3.04
4.22
2.59
2.16
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
ppm
3k
(500 MHz, CDCl3)
S

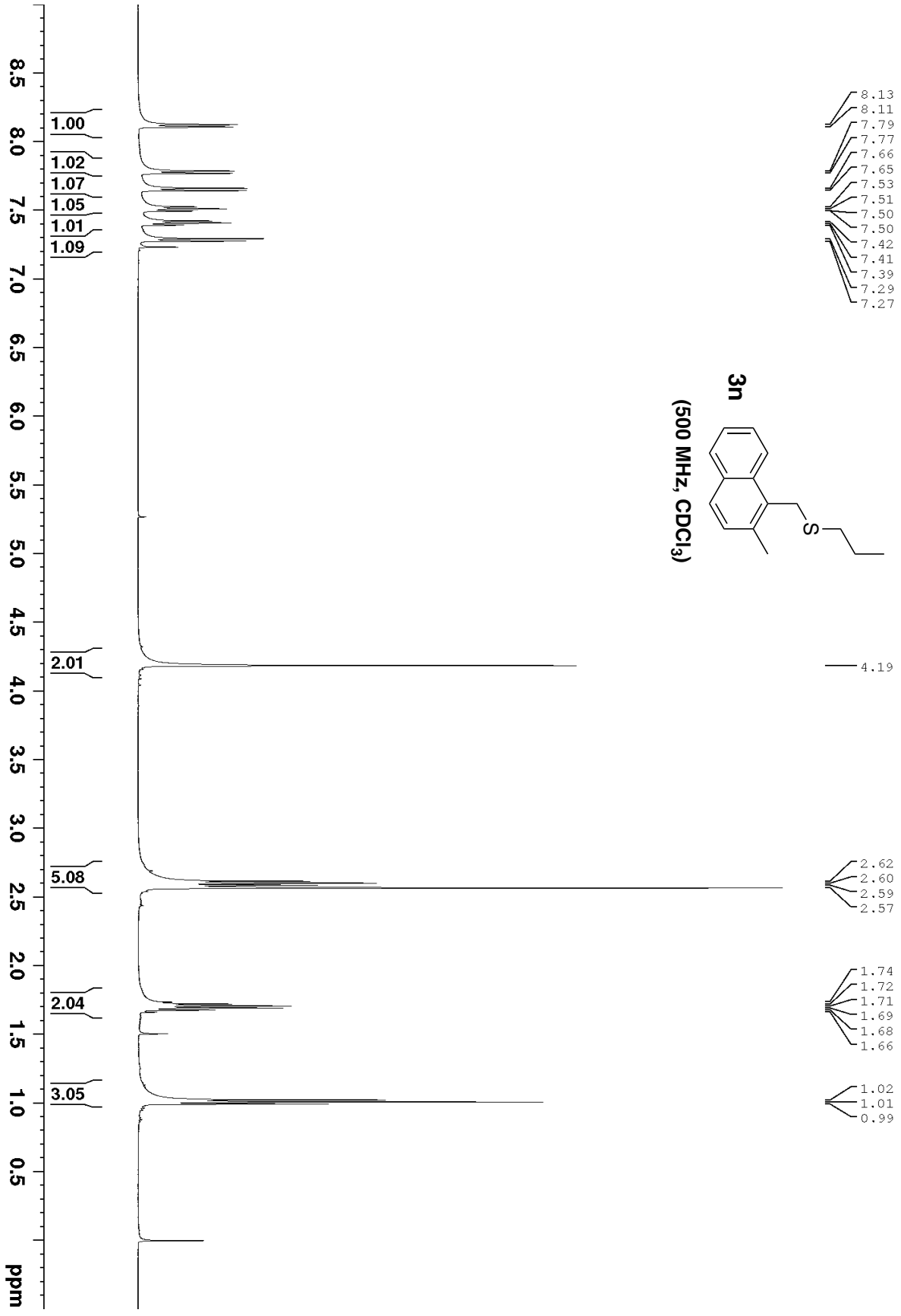

3k
(125 MHz, CDCl3)
S
134.51
132.60
132.22
130.64
129.12
128.61
127.54
126.25
124.86
123.77
31.47
20.28
15.97
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm

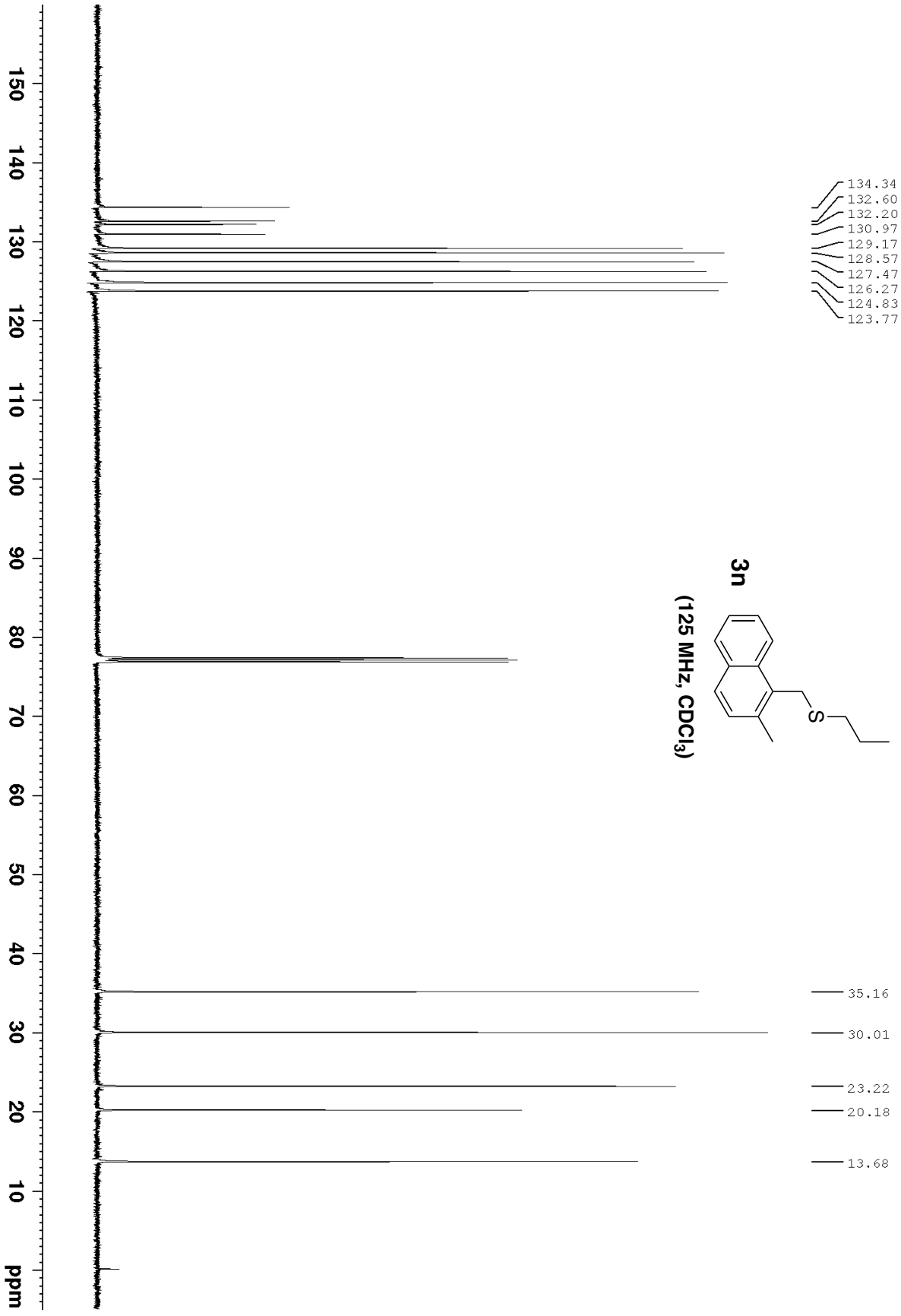

3l
(500 MHz, CDCl3)
n-hex
S
8.13
8.11
7.79
7.78
7.67
7.65
7.53
7.51
7.50
7.42
7.41
7.39
7.30
7.28
4.19
2.63
2.62
2.60
2.57
1.69
1.68
1.66
1.65
1.63
1.42
1.41
1.40
1.38
1.37
1.33
1.32
1.31
1.30
1.29
1.29
1.28
1.27
1.26
1.25
0.90
0.89
0.87
1.00
1.01
1.00
1.00
0.99
0.99
2.00
1.97
2.95
1.96
2.00
4.01
3.01
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
ppm

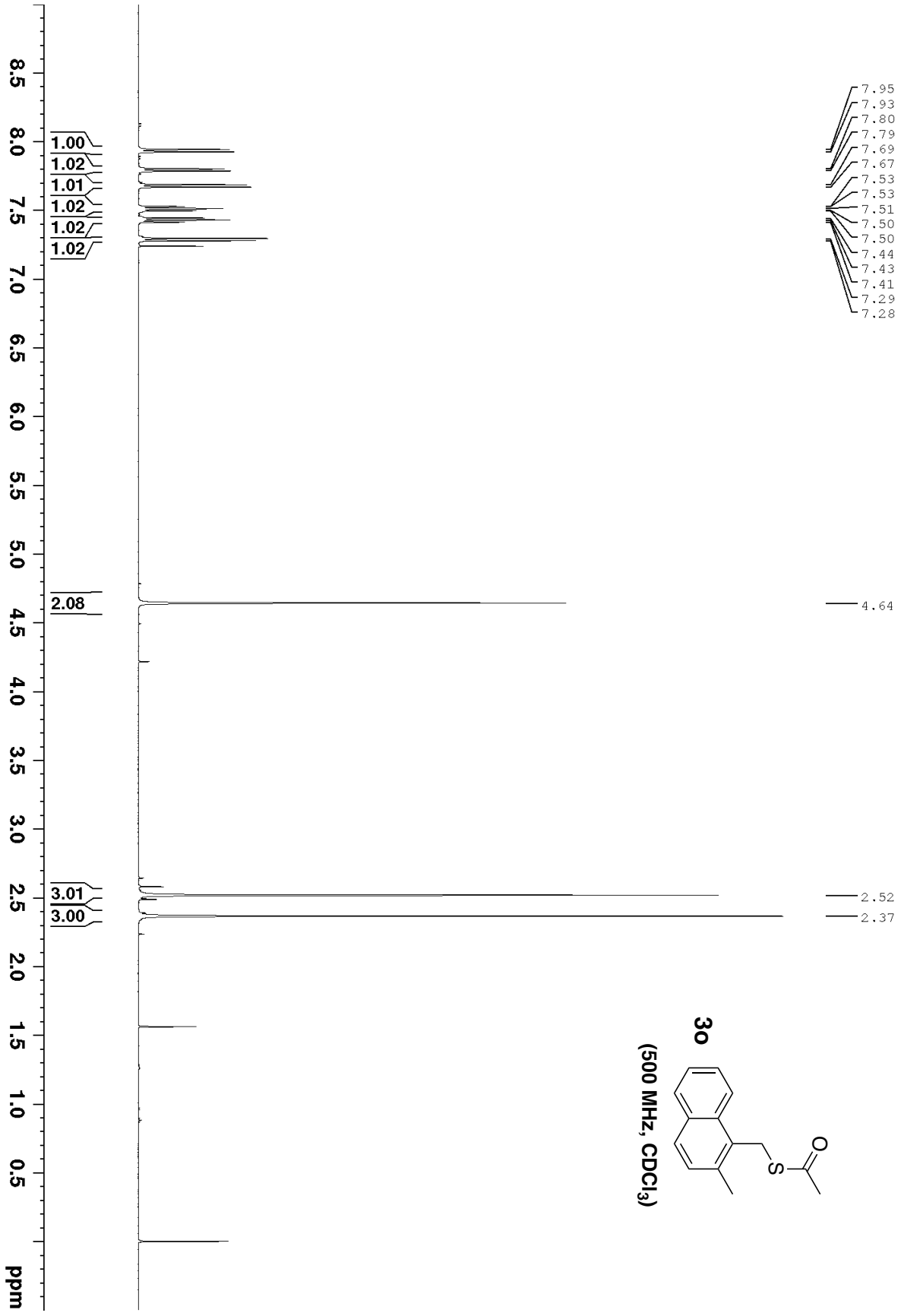

3l
(125 MHz, CDCl3)
n-hex
S
134.32
132.59
132.18
130.96
129.15
128.55
127.44
126.24
124.81
123.76
33.14
31.54
30.04
29.85
28.73
22.63
20.18
14.12
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm

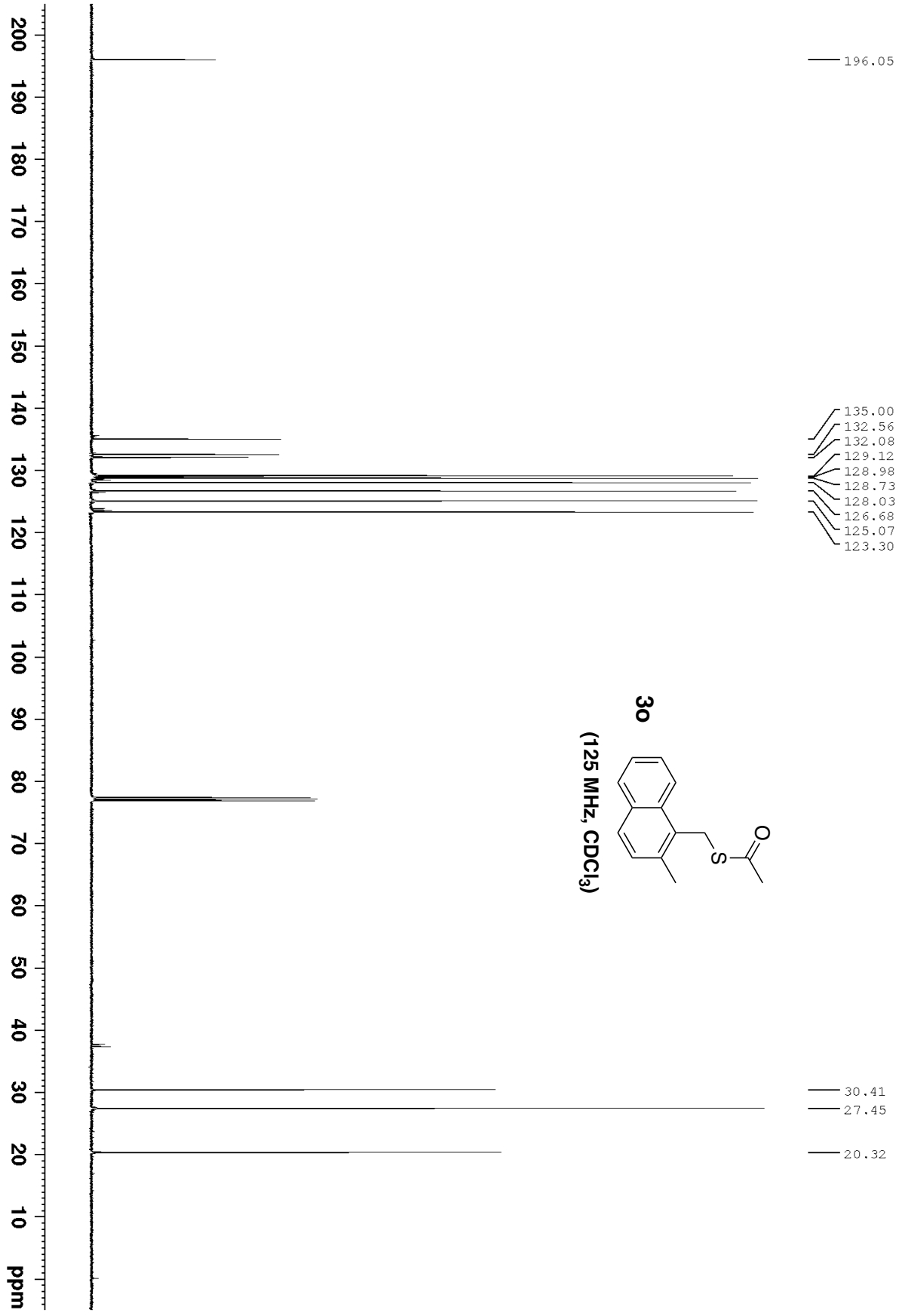

3m
(500 MHz, CDCl3)
8.13
8.11
7.78
7.76
7.66
7.64
7.53
7.52
7.50
7.41
7.40
7.38
7.29
7.27
4.17
2.58
1.50
1.00
0.99
1.01
1.00
1.01
1.01
2.02
3.00
9.07
S
ppm

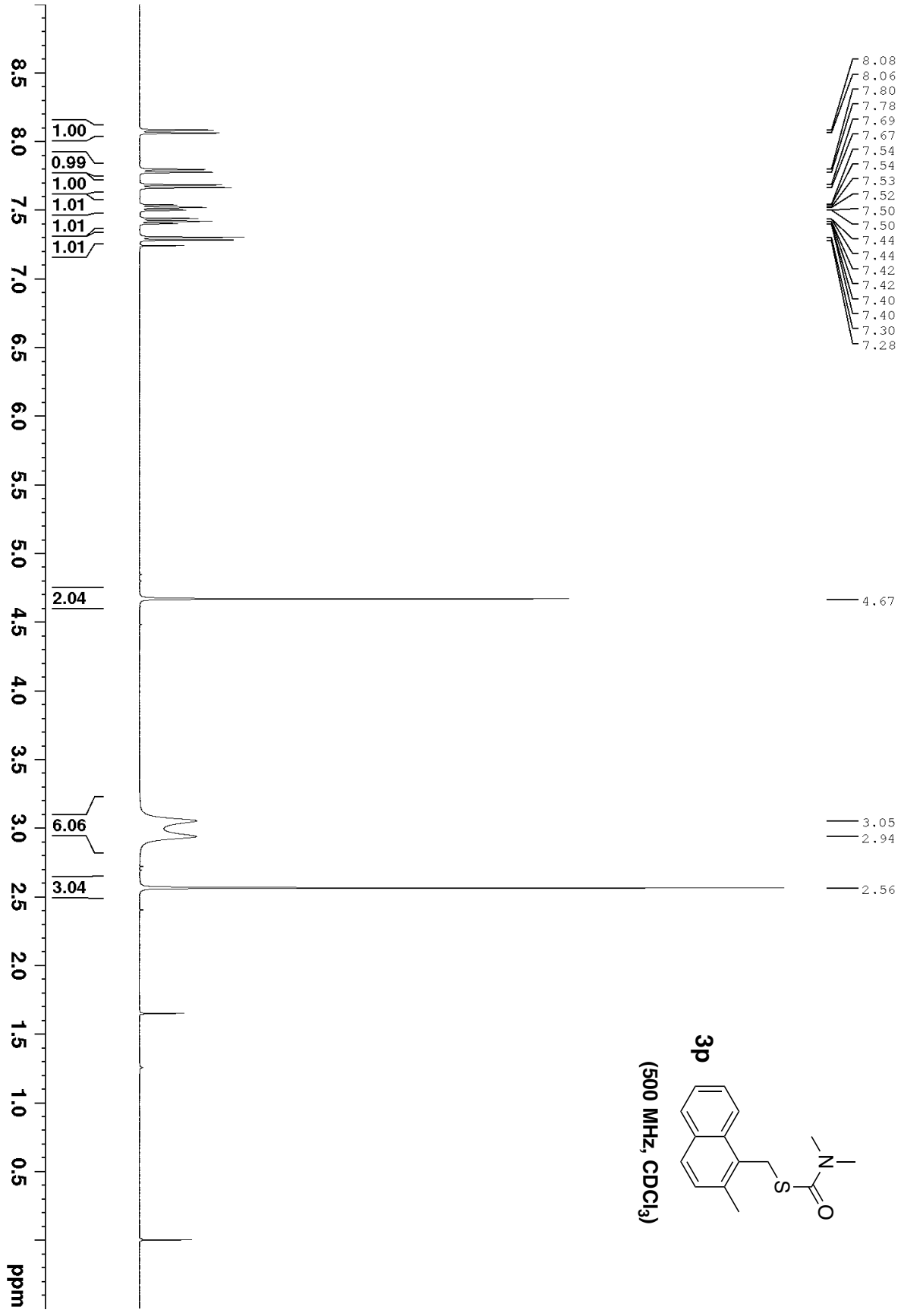

3m
(125 MHz, CDCl3)
S
134.44
132.59
132.29
129.87
129.19
128.50
127.43
126.36
124.78
123.66
42.87
30.74
26.58
19.92
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm

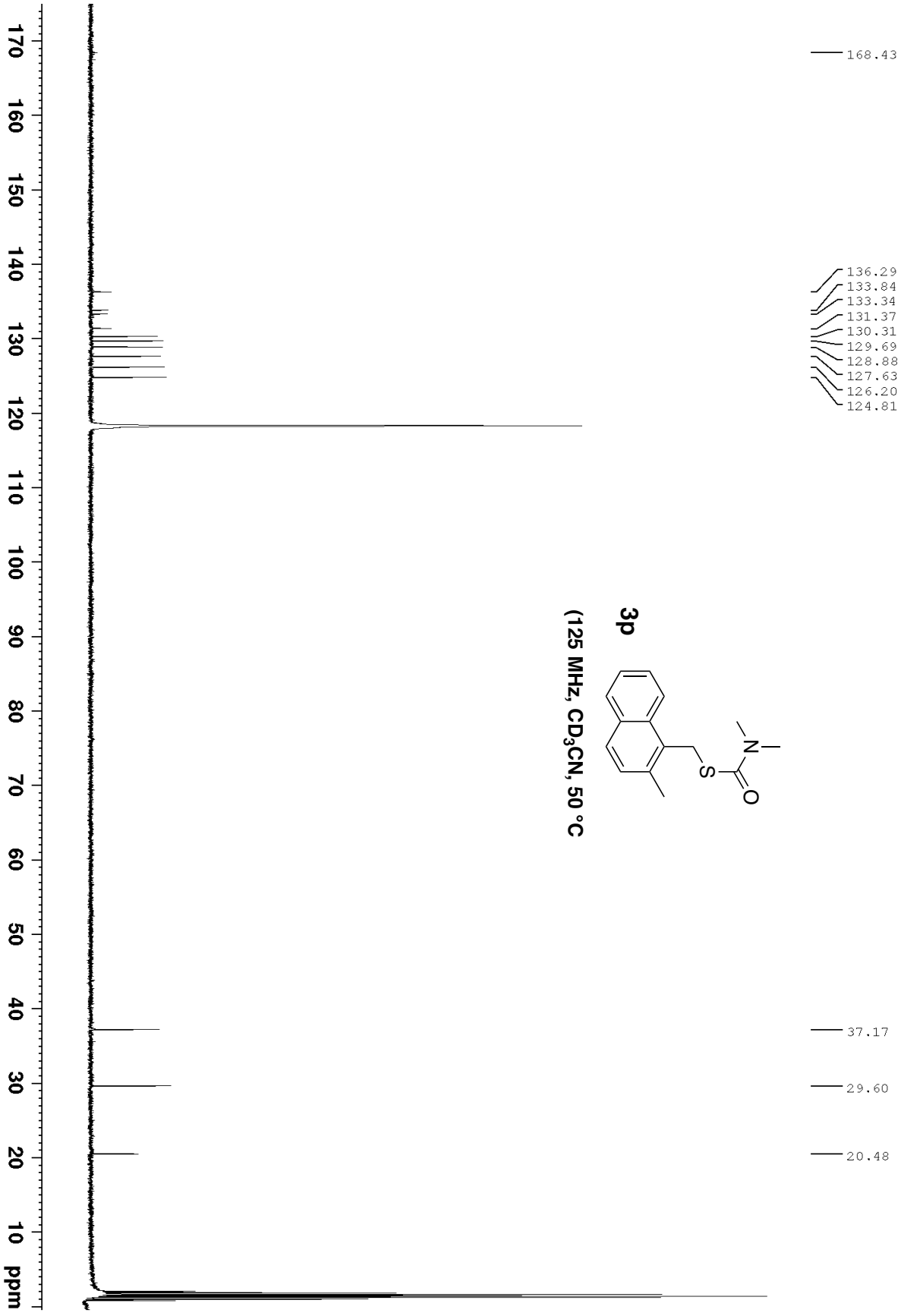

3n
(500 MHz, CDCl3)
8.13
8.11
7.79
7.77
7.66
7.65
7.53
7.51
7.50
7.50
7.42
7.41
7.39
7.29
7.27
4.19
2.62
2.60
2.59
2.57
1.74
1.72
1.71
1.69
1.68
1.66
1.02
1.01
0.99
1.00
1.02
1.07
1.05
1.01
1.09
2.01
5.08
2.04
3.05
S
ppm

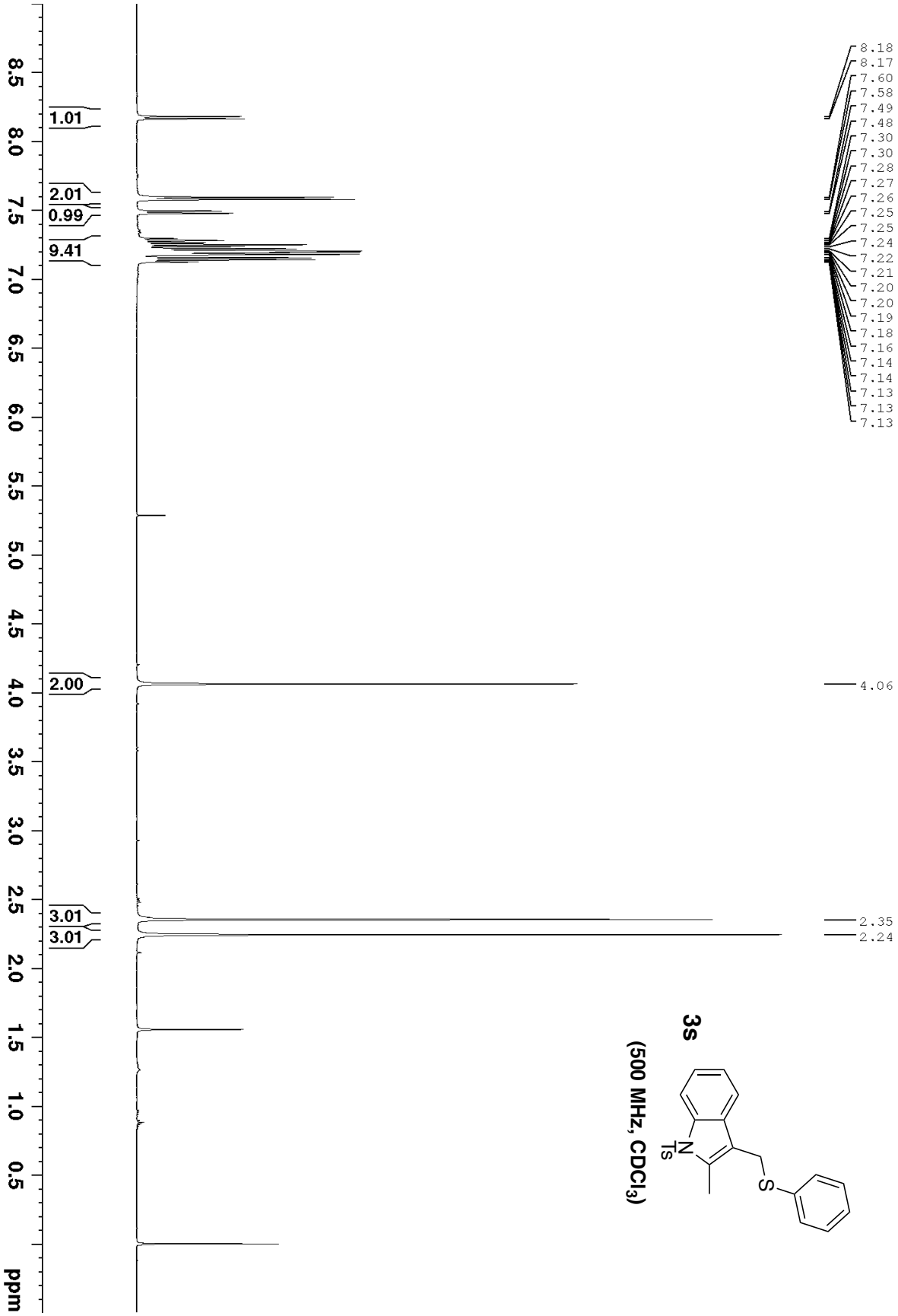

3n
(125 MHz, CDCl3)
134.34
132.60
132.20
130.97
129.17
128.57
127.47
126.27
124.83
123.77
35.16
30.01
23.22
20.18
13.68
S
ppm

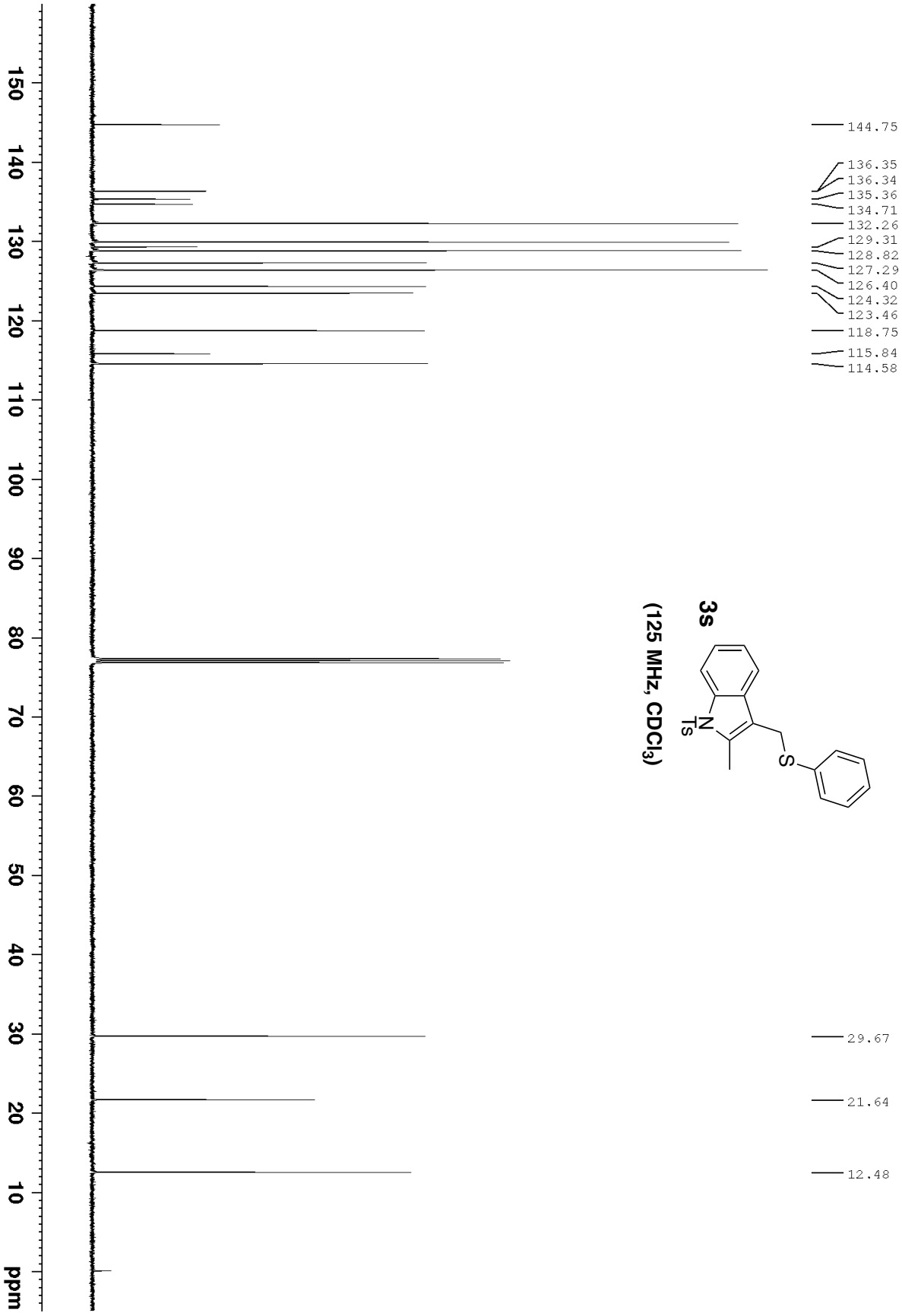

8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
ppm
1.00
1.02
1.01
1.02
1.02
1.02
2.08
3.01
3.00
7.95
7.93
7.80
7.79
7.69
7.67
7.53
7.53
7.51
7.50
7.50
7.44
7.43
7.41
7.29
7.28
4.64
2.52
2.37
3o
(500 MHz, CDCl3)
O
S

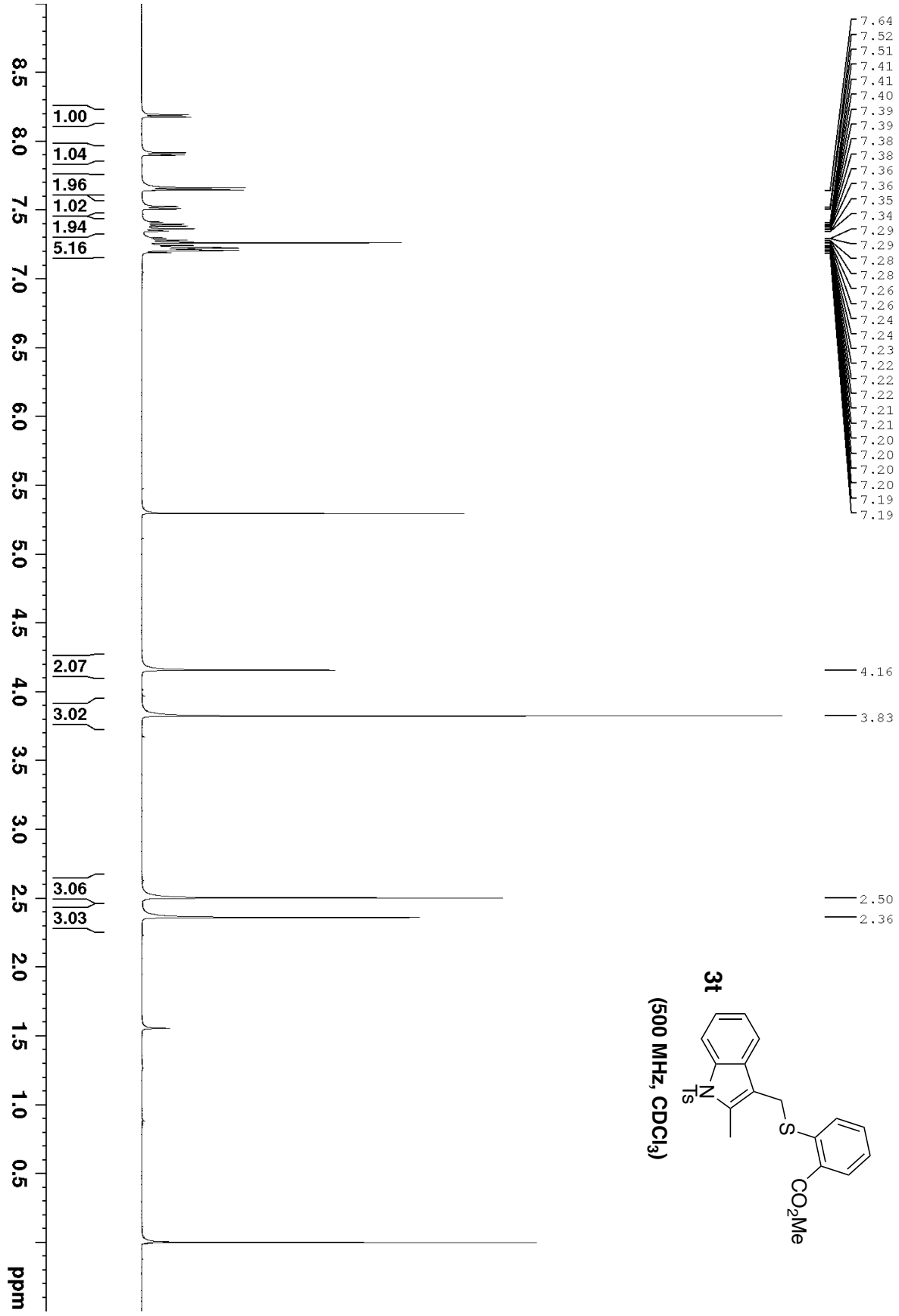

196.05
135.00
132.56
132.08
129.12
128.98
128.73
128.03
126.68
125.07
123.30
30.41
27.45
20.32
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm
3o
(125 MHz, CDCl3)
S
O

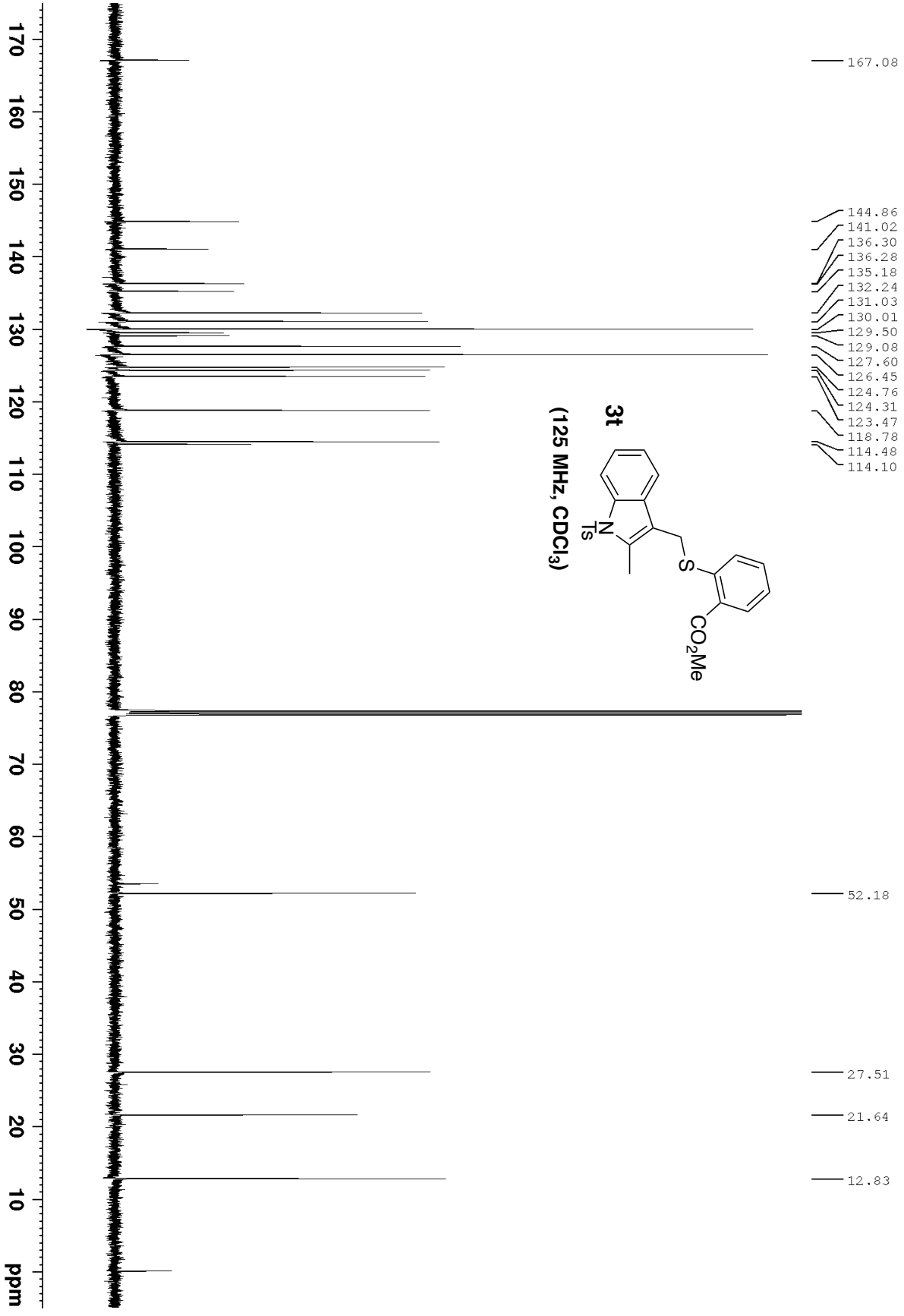

8.08
8.06
7.80
7.78
7.69
7.67
7.54
7.54
7.53
7.52
7.50
7.50
7.44
7.44
7.42
7.42
7.40
7.40
7.30
7.28
4.67
3.05
2.94
2.56
1.00
0.99
1.00
1.01
1.01
1.01
2.04
6.06
3.04
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
ppm
3p
(500 MHz, CDCl3)
N
S
O

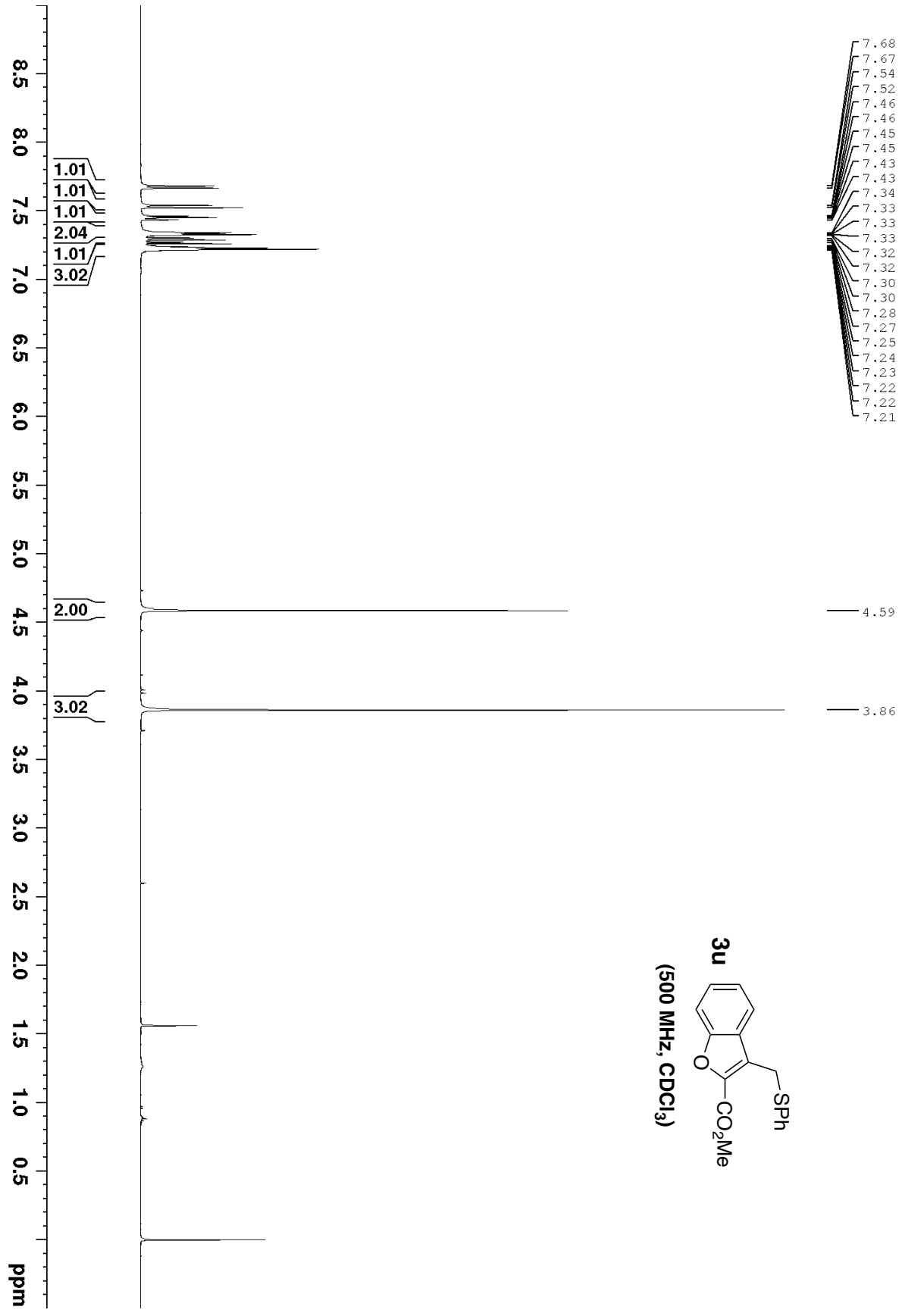

3p
(125 MHz, CD3CN, 50 °C
168.43
136.29
133.84
133.34
131.37
130.31
129.69
128.88
127.63
126.20
124.81
37.17
29.60
20.48
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm

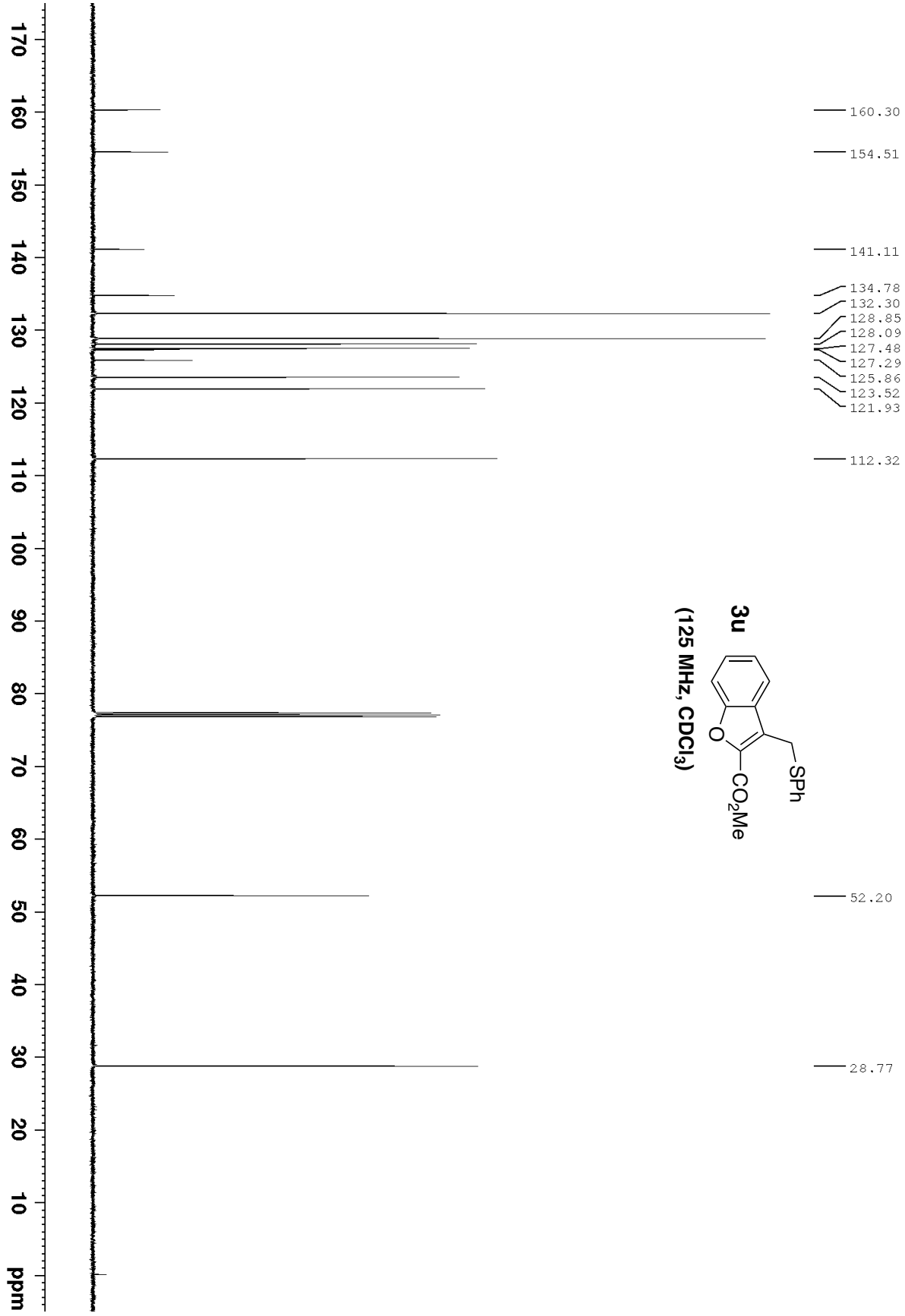

8.18
8.17
7.60
7.58
7.49
7.48
7.30
7.30
7.28
7.27
7.26
7.25
7.25
7.24
7.22
7.21
7.20
7.20
7.19
7.18
7.16
7.14
7.14
7.13
7.13
7.13
4.06
2.35
2.24
1.01
2.01
0.99
9.41
2.00
3.01
3.01
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
ppm
3s
(500 MHz, CDCl3)
N
Ts
S

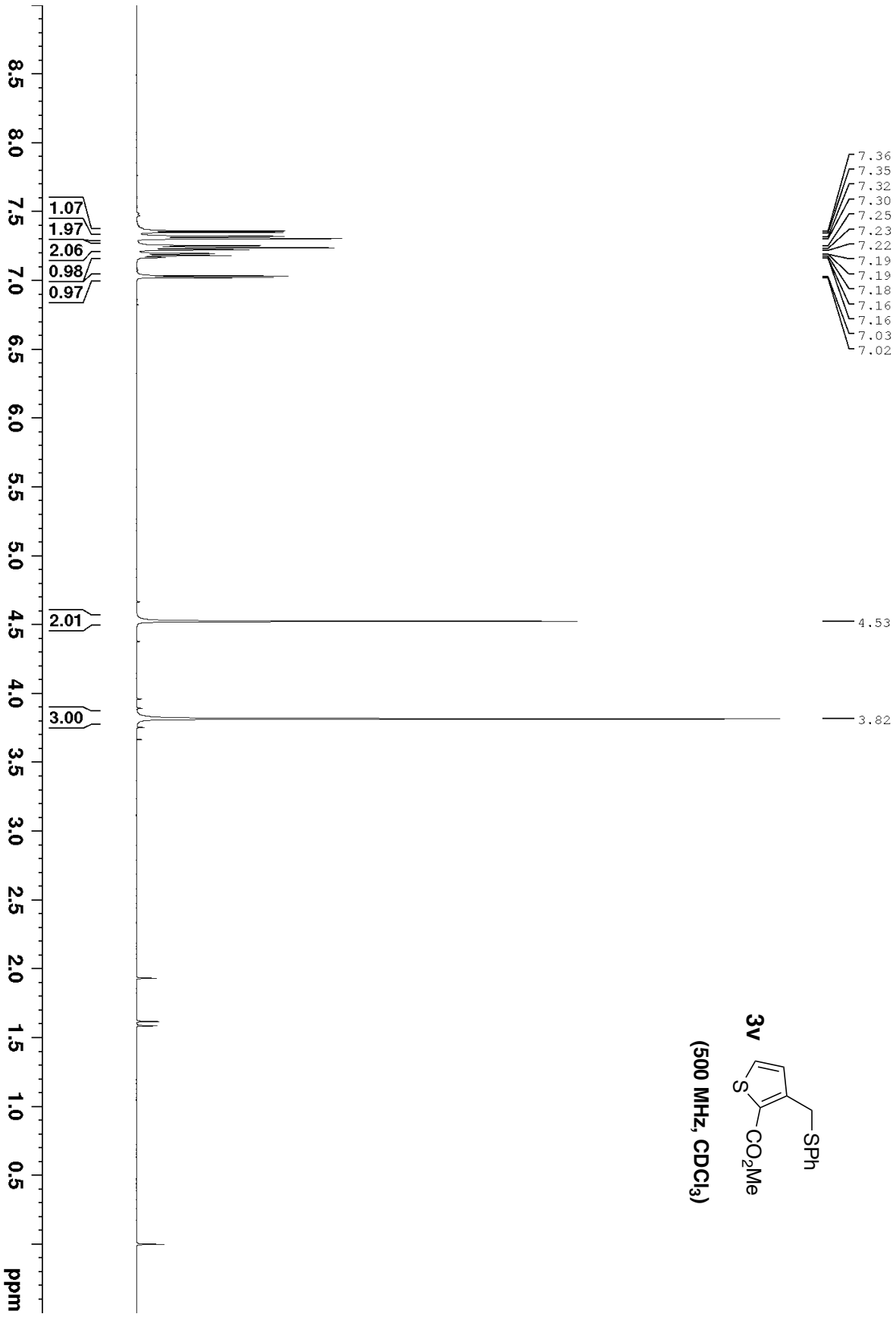

144.75
136.35
136.34
135.36
134.71
132.26
129.31
128.82
127.29
126.40
124.32
123.46
118.75
115.84
114.58
29.67
21.64
12.48
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm
3s
(125 MHz, CDCl3)
N
Ts
S

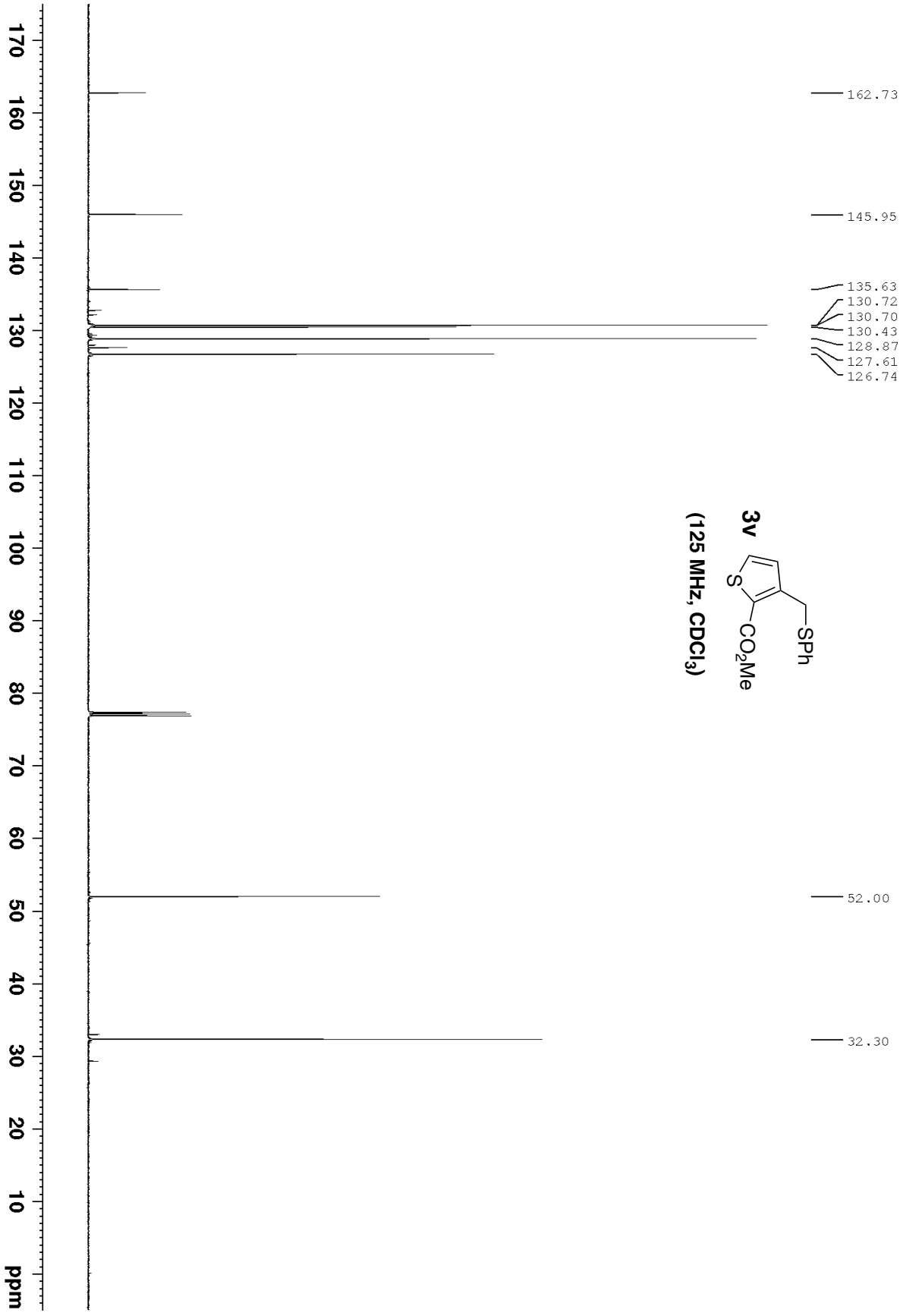

7.64
7.52
7.51
7.41
7.41
7.40
7.39
7.39
7.38
7.38
7.36
7.36
7.35
7.34
7.29
7.29
7.28
7.28
7.26
7.26
7.24
7.24
7.23
7.22
7.22
7.22
7.21
7.21
7.20
7.20
7.20
7.20
7.19
7.19
1.00
1.04
1.96
1.02
1.94
5.16
2.07
3.02
3.06
3.03
4.16
3.83
2.50
2.36
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
ppm
3t
(500 MHz, CDCl3)
N
Ts
S
CO2Me

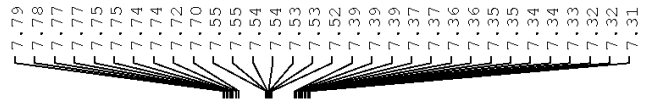

3t
(125 MHz, CDCl3)
N
Ts
S
CO2Me
167.08
144.86
141.02
136.30
136.28
135.18
132.24
131.03
130.01
129.50
129.08
127.60
126.45
124.76
124.31
123.47
118.78
114.48
114.10
52.18
27.51
21.64
12.83
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm

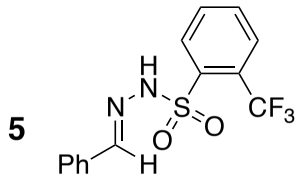

7.68
7.67
7.54
7.52
7.46
7.46
7.45
7.45
7.43
7.43
7.34
7.33
7.33
7.33
7.32
7.32
7.30
7.30
7.28
7.27
7.25
7.24
7.23
7.22
7.22
7.21
4.59
3.86
1.01
1.01
1.01
2.04
1.01
3.02
2.00
3.02
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
ppm
3u
(500 MHz, CDCl3)
O
CO2Me
SPh


160.30
154.51
141.11
134.78
132.30
128.85
128.09
127.48
127.29
125.86
123.52
121.93
112.32
52.20
28.77
3u
(125 MHz, CDCl3)
O
CO2Me
SPh
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm


7.36
7.35
7.32
7.30
7.25
7.23
7.22
7.19
7.19
7.18
7.16
7.16
7.03
7.02
4.53
3.82
1.07
1.97
2.06
0.98
0.97
2.01
3.00
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
ppm
3v
(500 MHz, CDCl3)
S
CO2Me
SPh

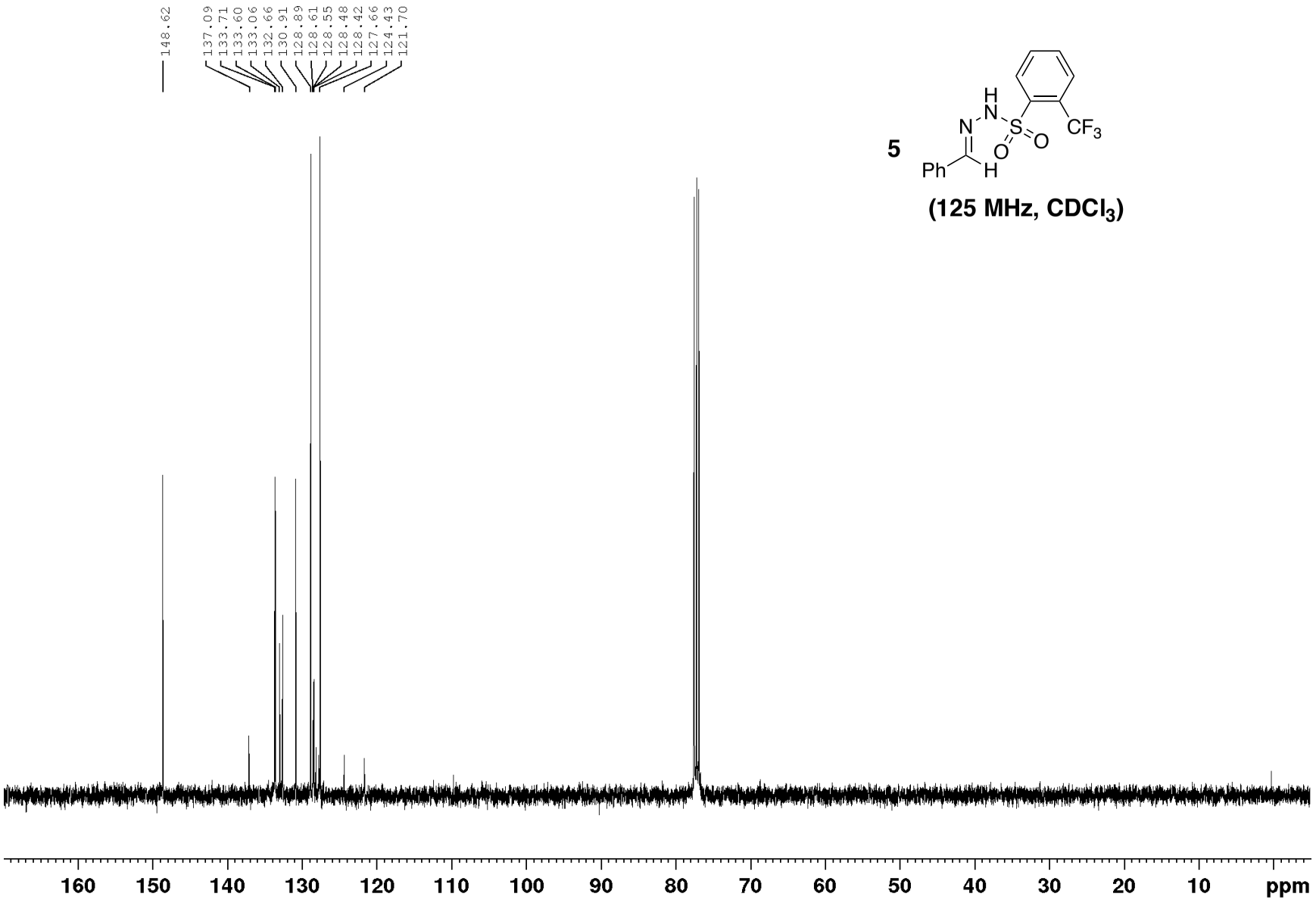

162.73
145.95
135.63
130.72
130.70
130.43
128.87
127.61
126.74
52.00
32.30
3v
(125 MHz, CDCl3)
S
CO2Me
SPh
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm

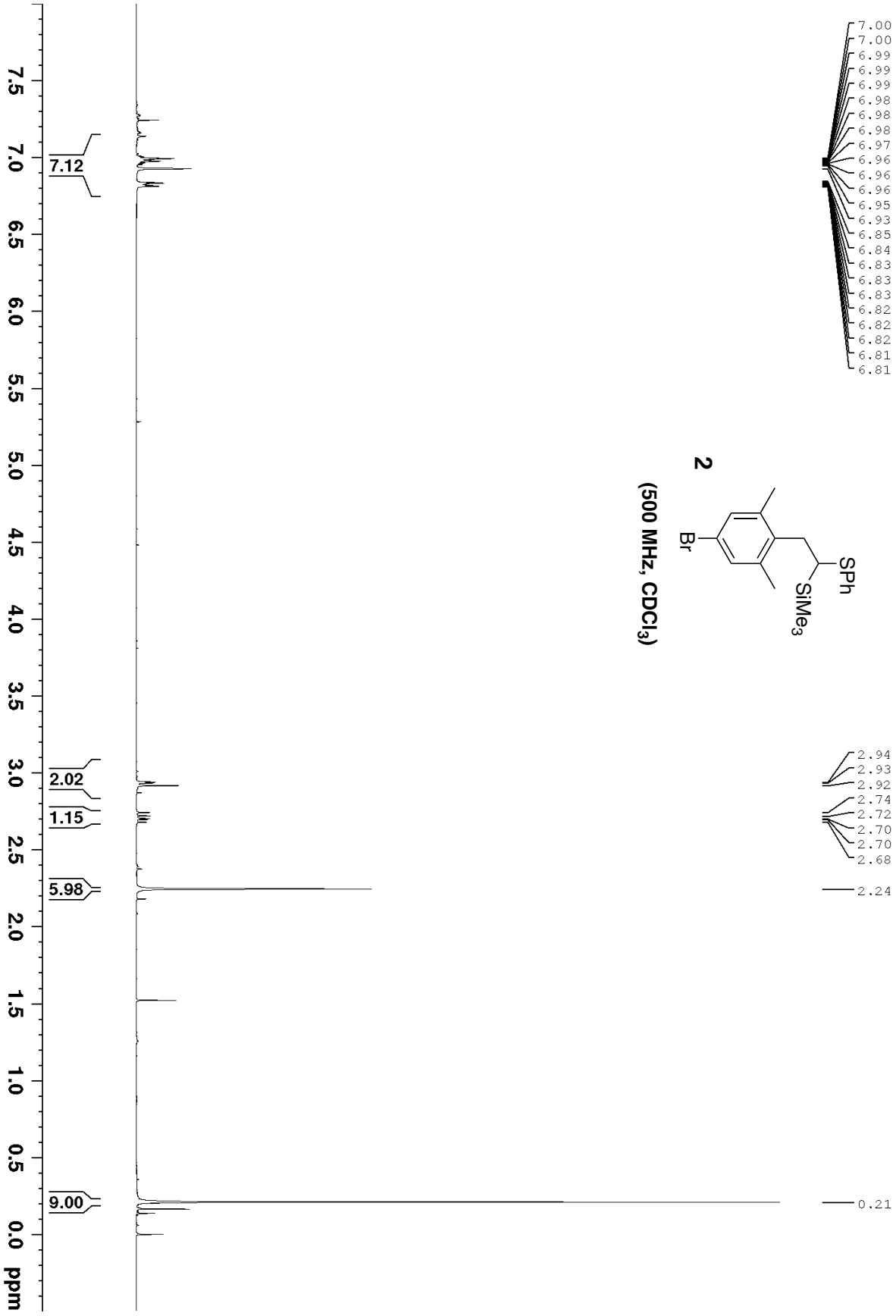


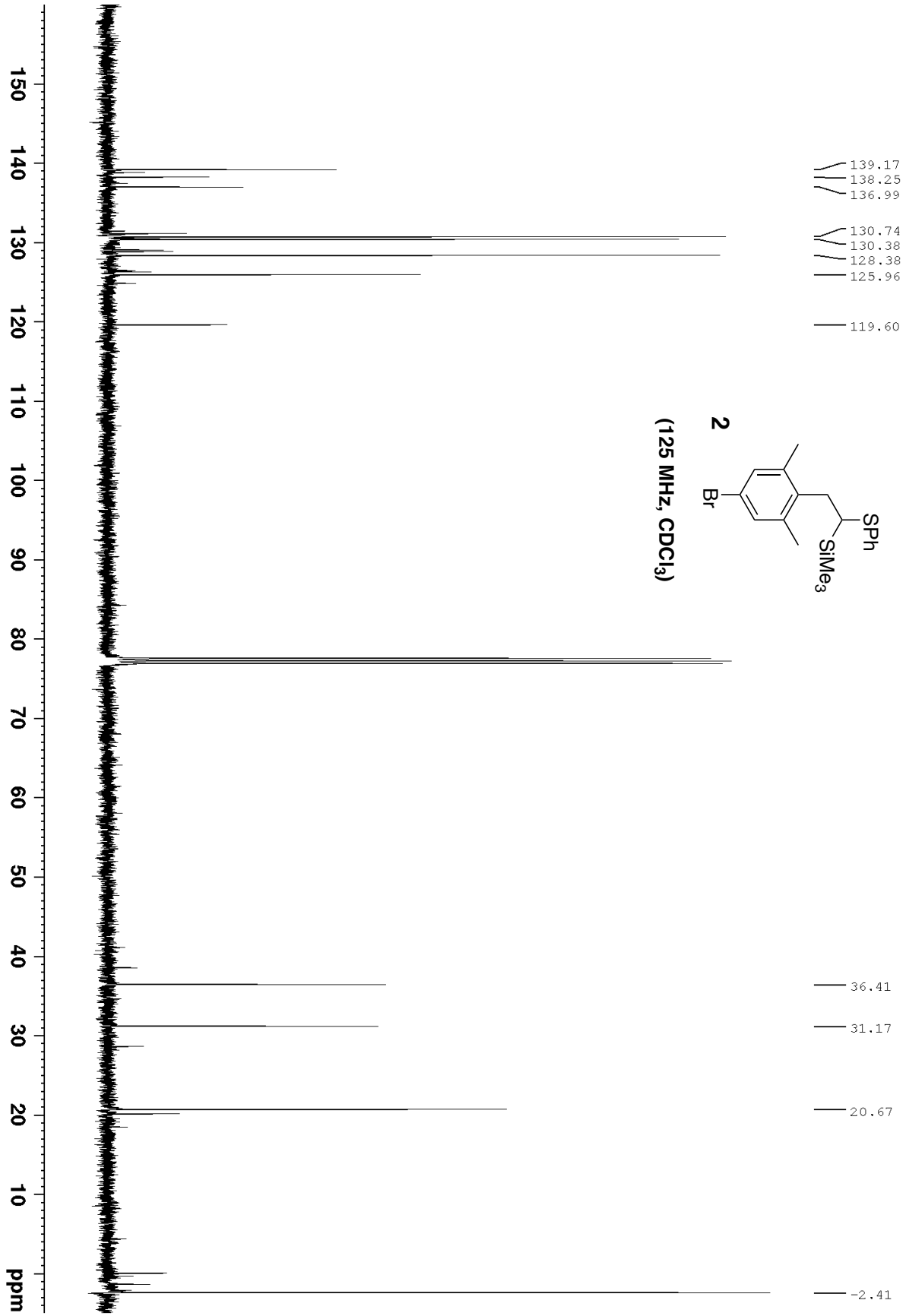


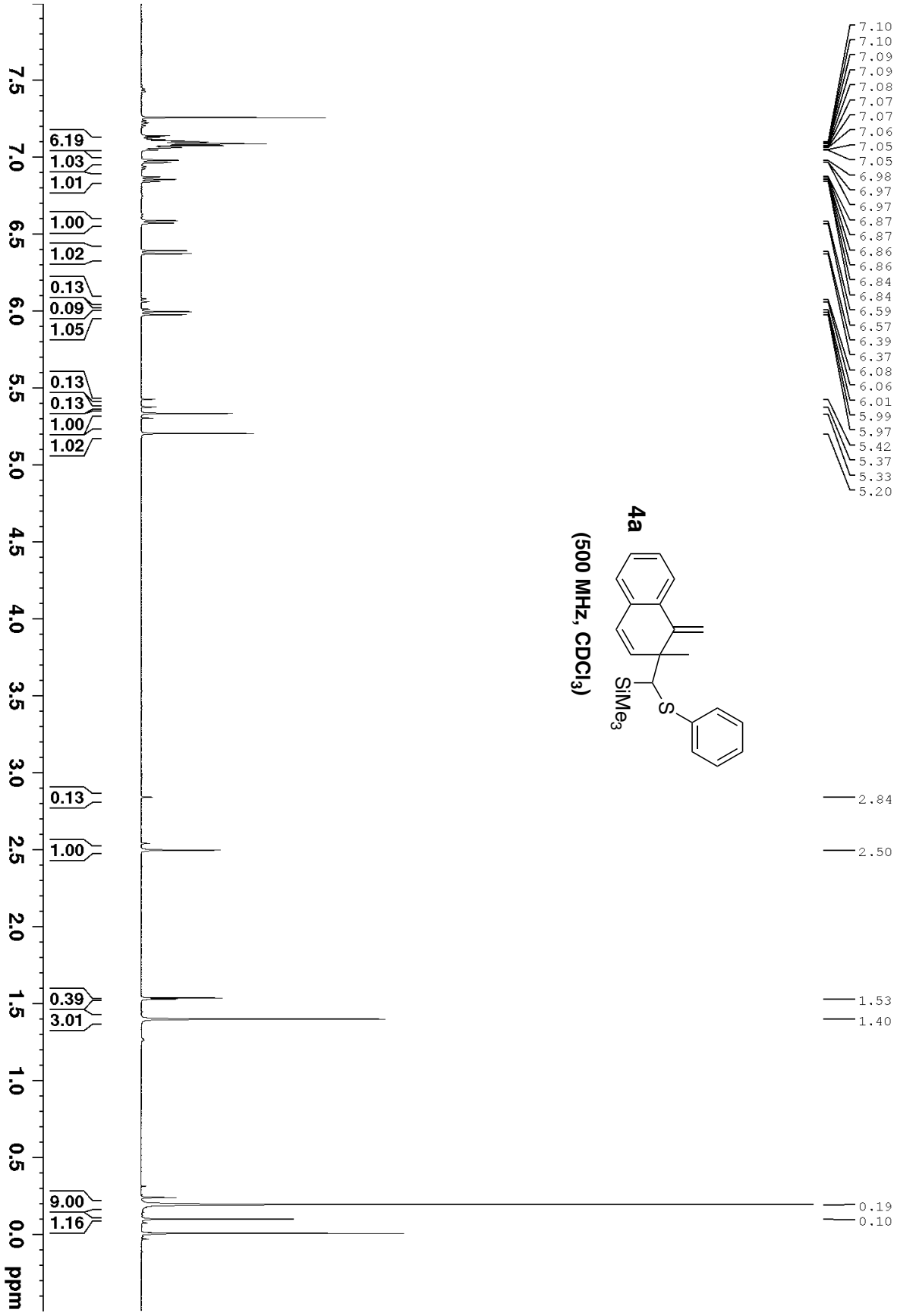
5

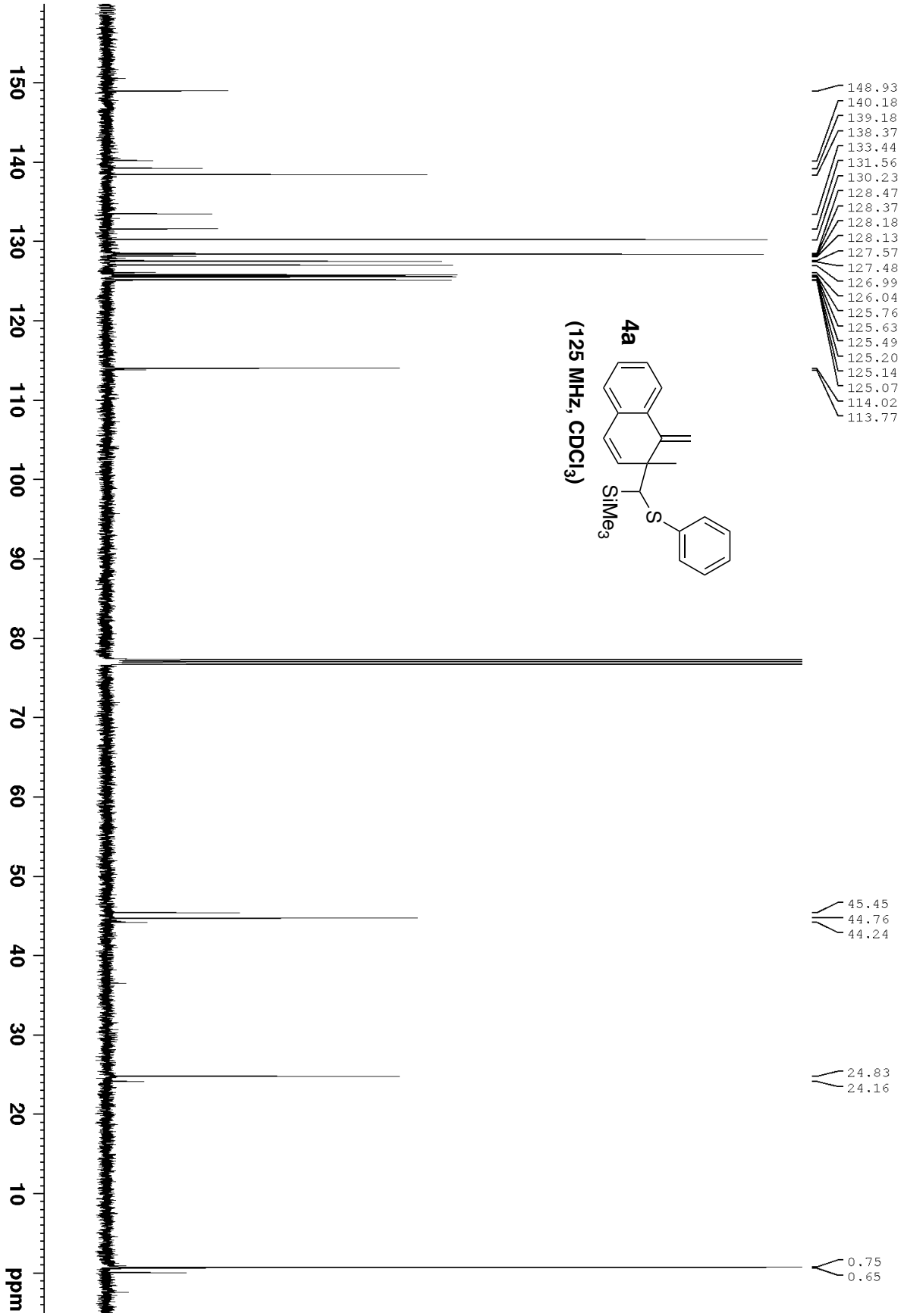
(500 MHz, $CDCl_3$)

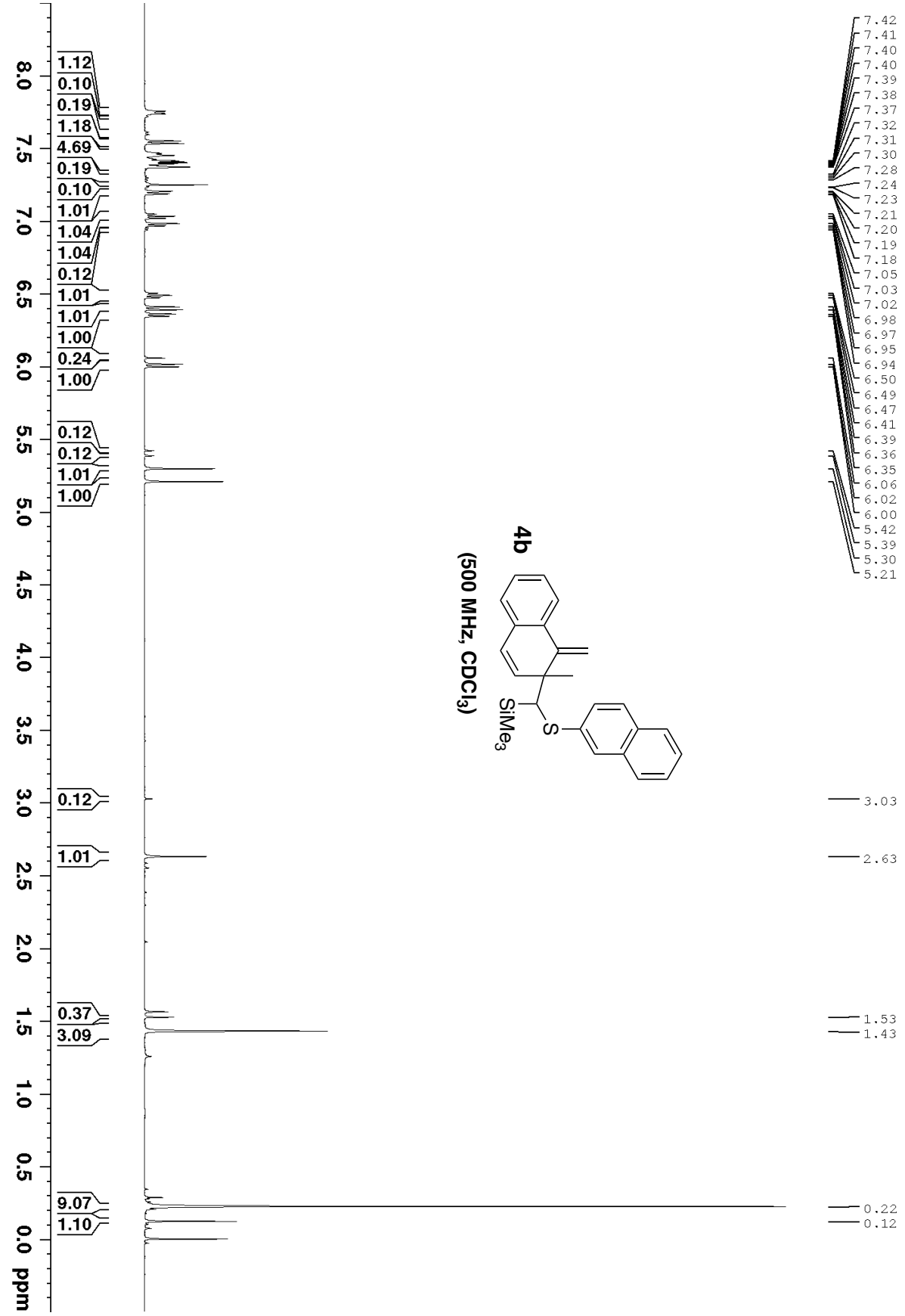

148.62
137.09
133.71
133.60
133.06
132.66
130.91
128.89
128.61
128.55
128.48
128.42
127.66
124.43
121.70
5
(125 MHz, CDCl3)
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm

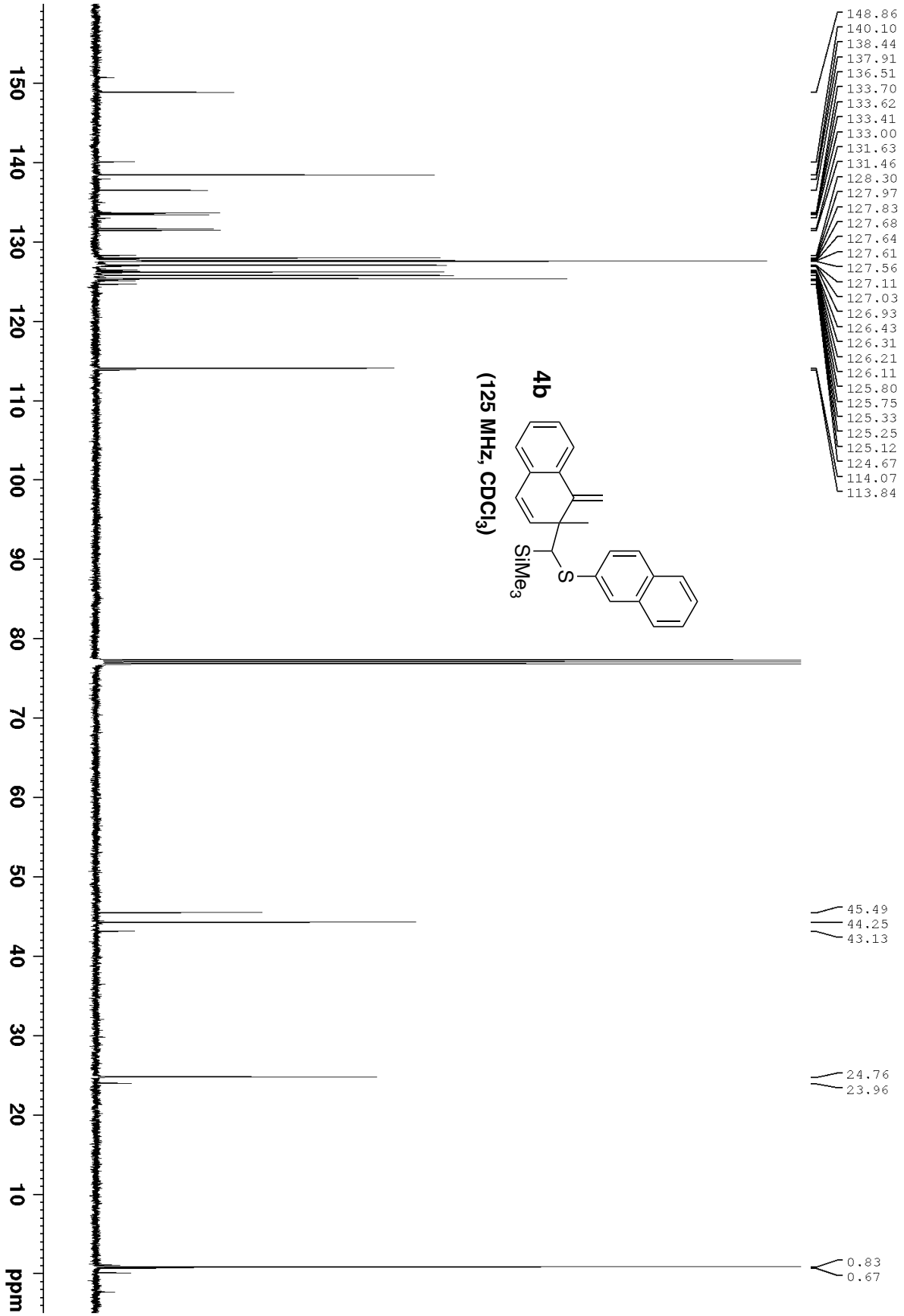

2
(500 MHz, CDCl3)
Br
SiMe3
SPh
7.00
7.00
6.99
6.99
6.99
6.98
6.98
6.98
6.97
6.96
6.96
6.96
6.96
6.95
6.93
6.85
6.84
6.83
6.83
6.83
6.82
6.82
6.82
6.81
6.81
2.94
2.93
2.92
2.74
2.72
2.70
2.70
2.68
2.24
0.21
7.12
2.02
1.15
5.98
9.00
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ppm

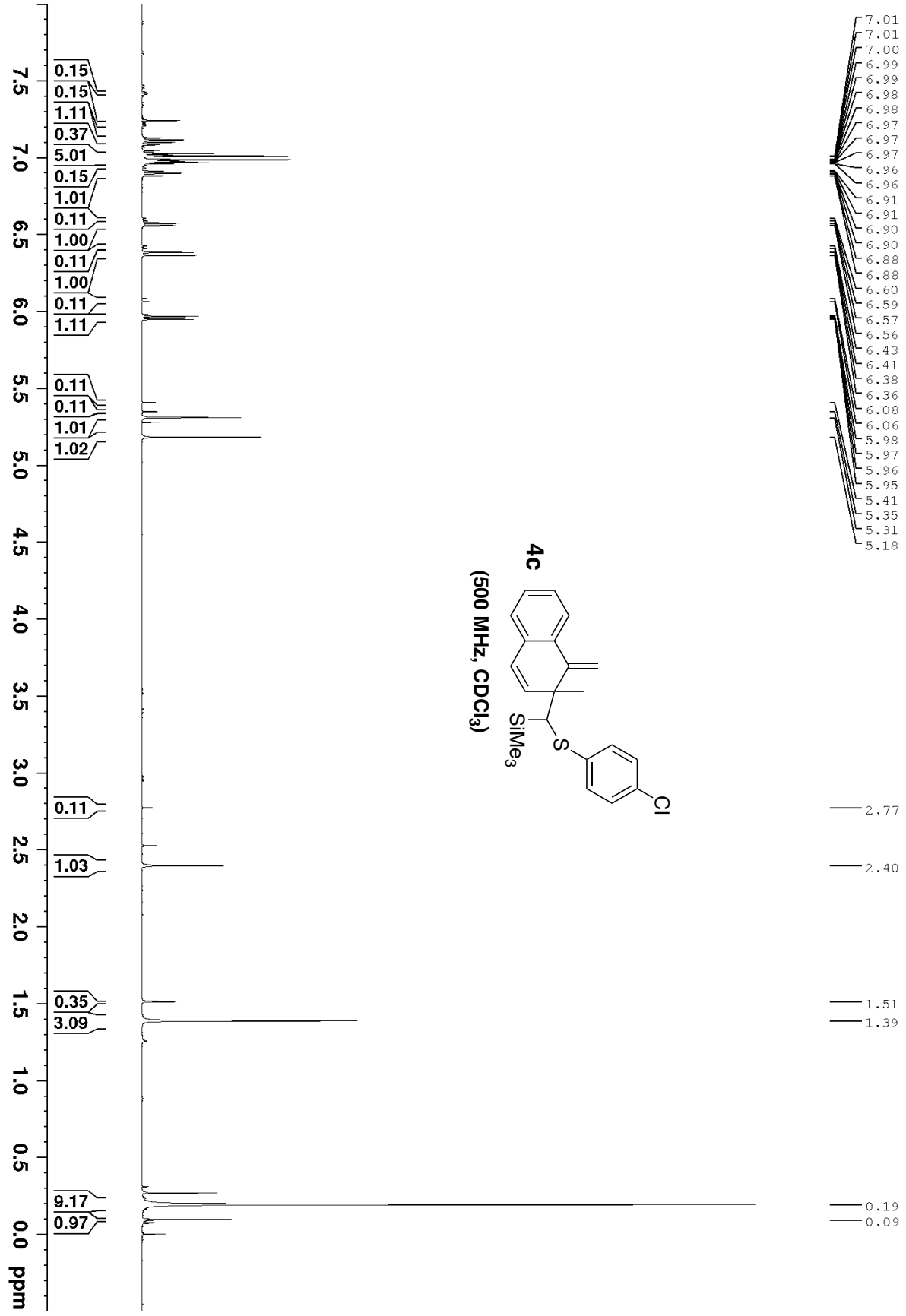

2
(125 MHz, CDCl3)
Br
SiMe3
SPh
139.17
138.25
136.99
130.74
130.38
128.38
125.96
119.60
36.41
31.17
20.67
-2.41
ppm

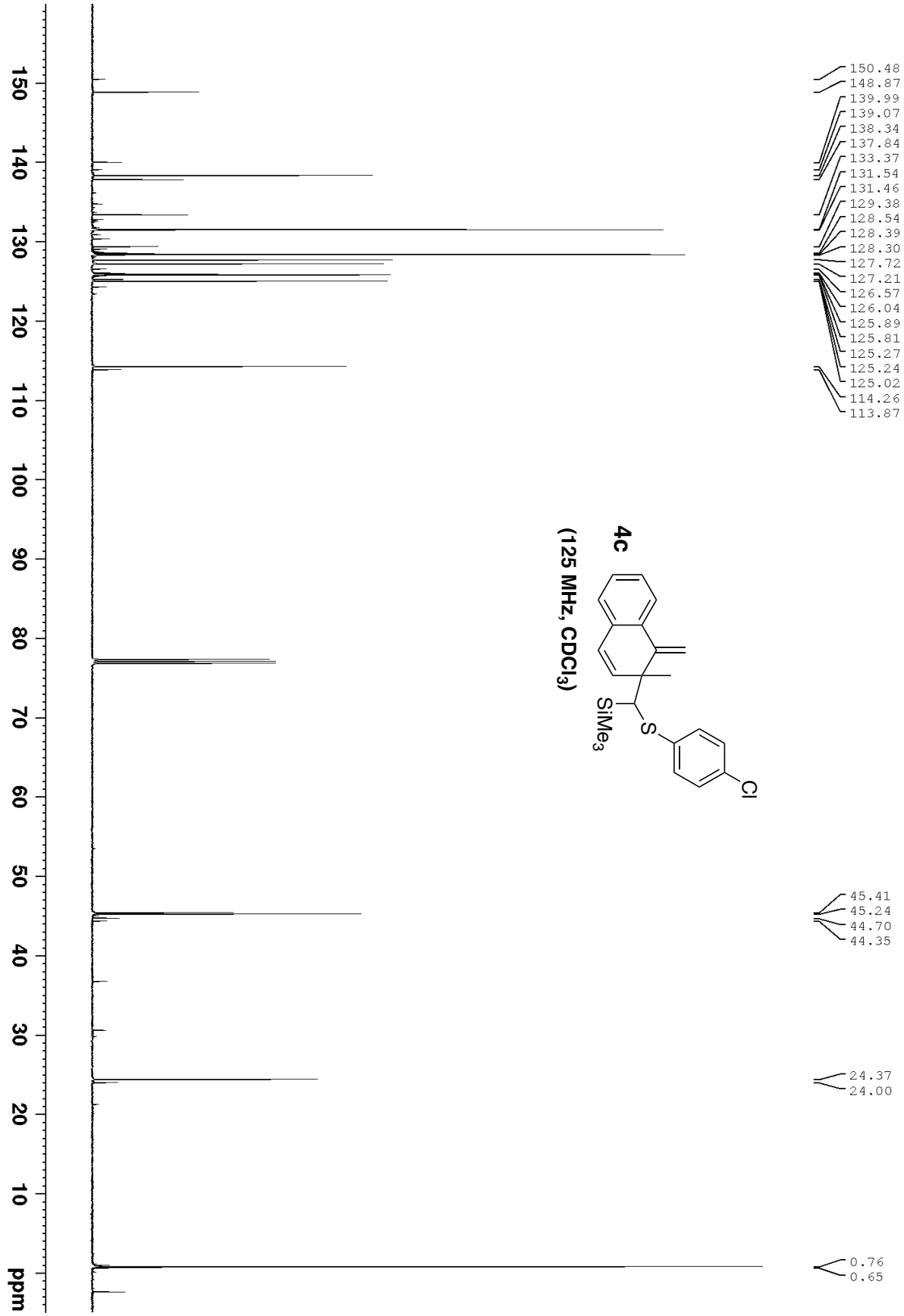

4a
(500 MHz, CDCl3)
SiMe3
S
7.10
7.10
7.09
7.09
7.08
7.07
7.07
7.06
7.05
7.05
6.98
6.97
6.97
6.87
6.87
6.86
6.86
6.84
6.84
6.59
6.57
6.39
6.37
6.08
6.06
6.01
5.99
5.97
5.42
5.37
5.33
5.20
2.84
2.50
1.53
1.40
0.19
0.10
6.19
1.03
1.01
1.00
1.02
0.13
0.09
1.05
0.13
0.13
1.00
1.02
0.13
1.00
0.39
3.01
9.00
1.16
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ppm

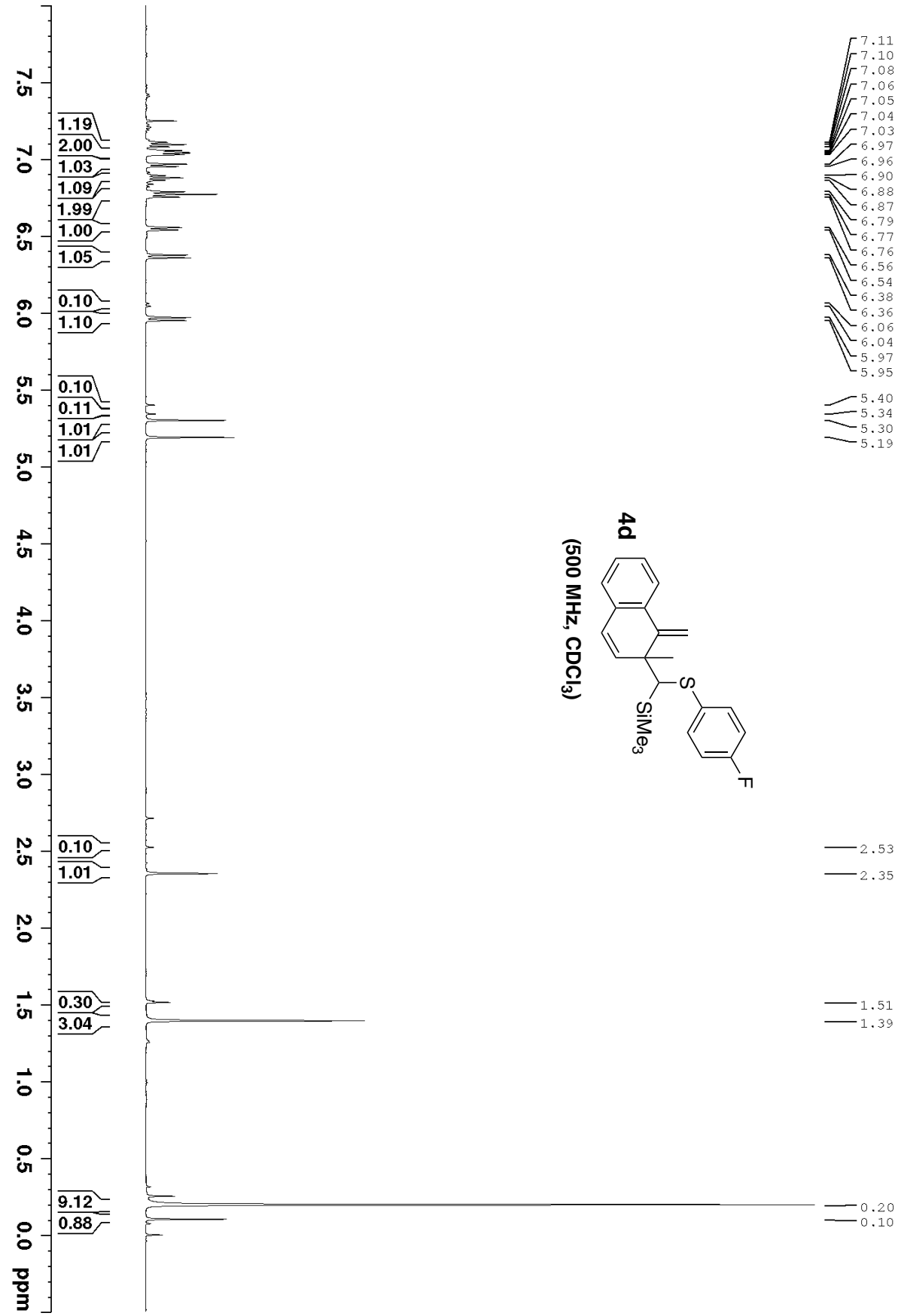

4a
(125 MHz, CDCl3)
SiMe3
S
148.93
140.18
139.18
138.37
133.44
131.56
130.23
128.47
128.37
128.18
128.13
127.57
127.48
126.99
126.04
125.76
125.63
125.49
125.20
125.14
125.07
114.02
113.77
45.45
44.76
44.24
24.83
24.16
0.75
0.65
ppm

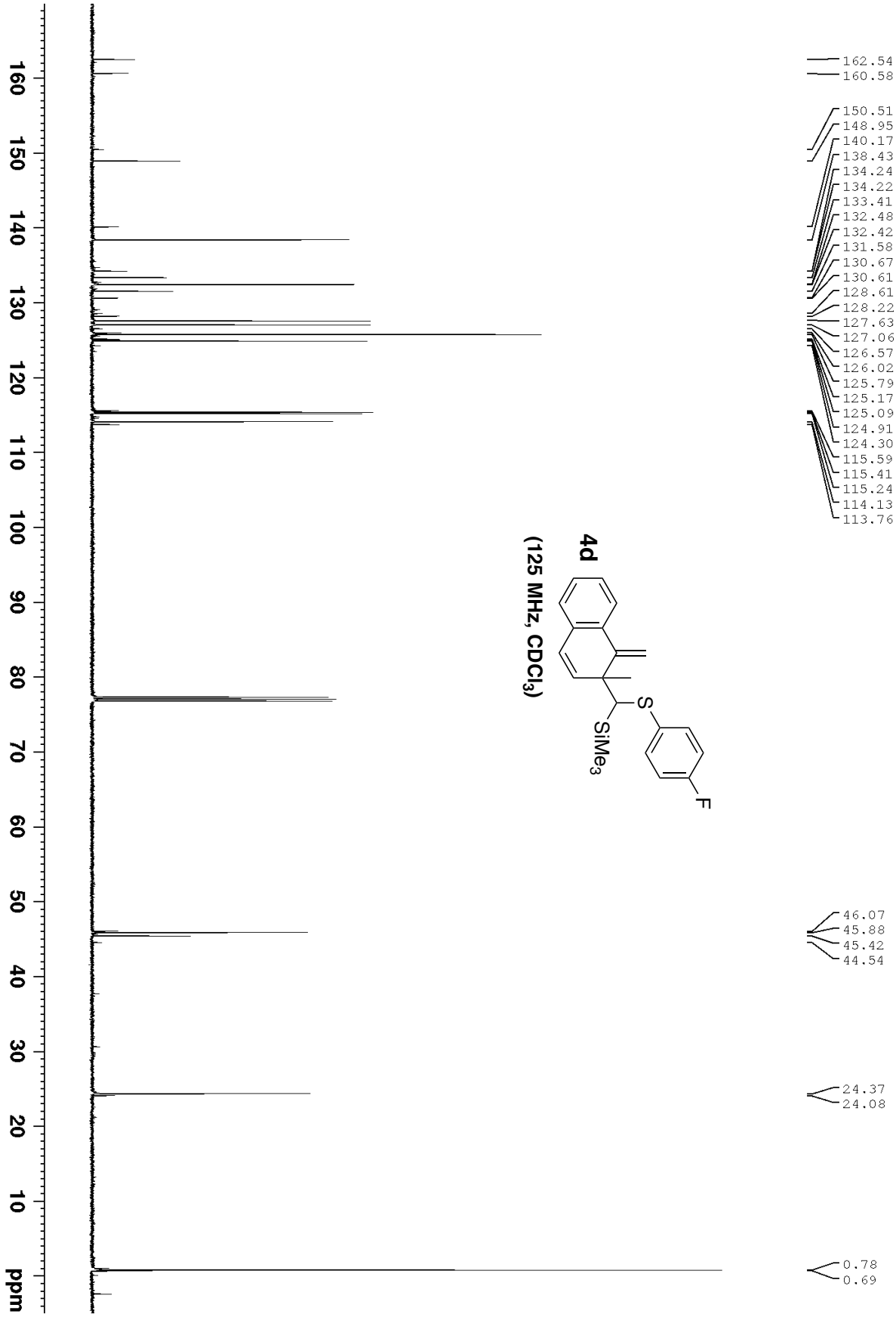

4b
(500 MHz, CDCl3)
SiMe3
S
7.42
7.41
7.40
7.40
7.39
7.38
7.37
7.32
7.31
7.30
7.28
7.24
7.23
7.21
7.20
7.19
7.18
7.05
7.03
7.02
6.98
6.97
6.95
6.94
6.50
6.49
6.47
6.41
6.39
6.36
6.35
6.06
6.02
6.00
5.42
5.39
5.30
5.21
3.03
2.63
1.53
1.43
0.22
0.12
1.12
0.10
0.19
1.18
4.69
0.19
0.10
1.01
1.04
1.04
0.12
1.01
1.01
1.00
0.24
1.00
0.12
0.12
1.01
1.00
0.12
1.01
0.37
3.09
9.07
1.10
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ppm

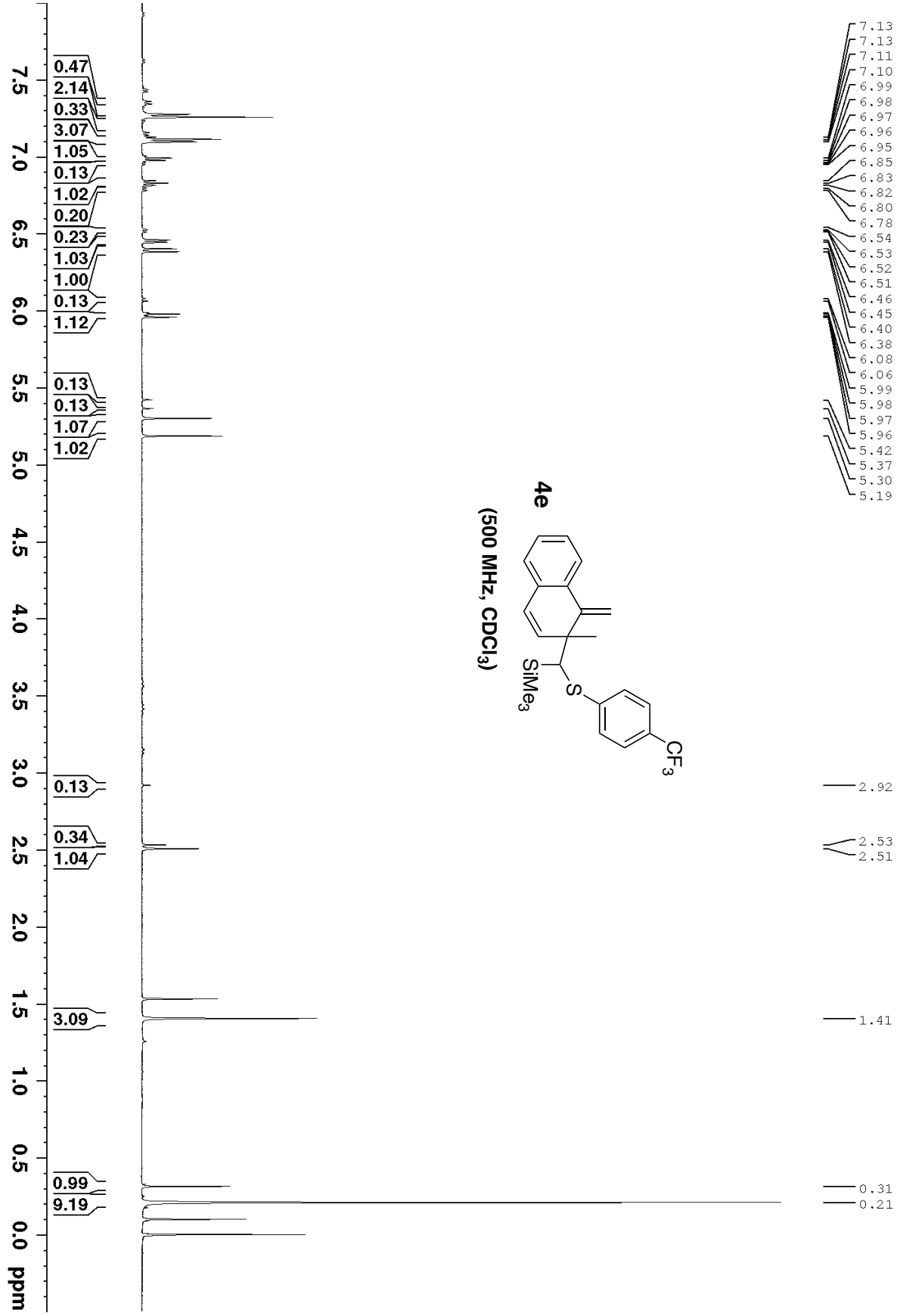

4b
(125 MHz, CDCl3)
SiMe3
S
148.86
140.10
138.44
137.91
136.51
133.70
133.62
133.41
133.00
131.63
131.46
128.30
127.97
127.83
127.68
127.64
127.61
127.56
127.11
127.03
126.93
126.43
126.31
126.21
126.11
125.80
125.75
125.33
125.25
125.12
124.67
114.07
113.84
45.49
44.25
43.13
24.76
23.96
0.83
0.67
ppm

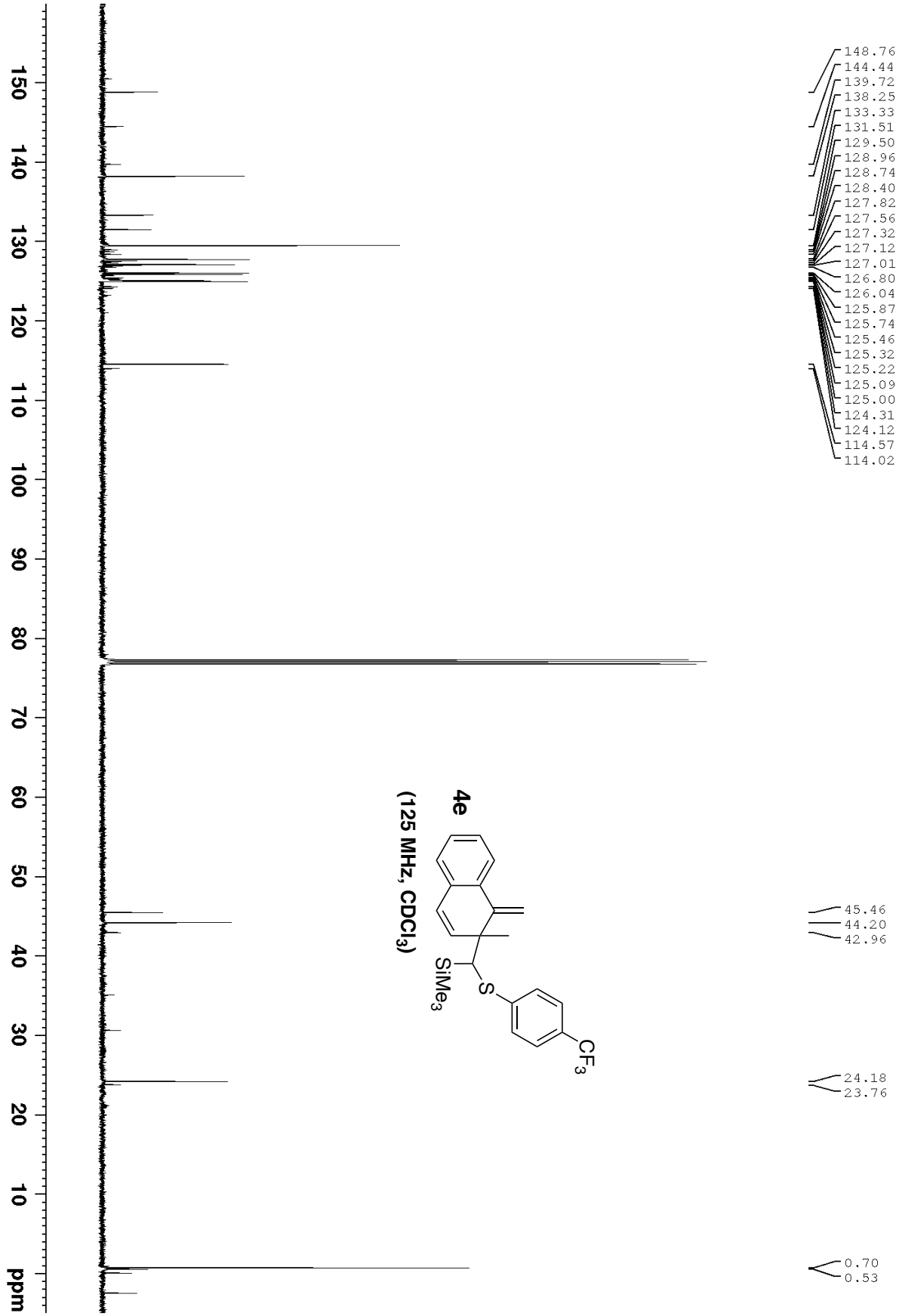

4c
(500 MHz, CDCl3)
SiMe3
S
Cl
7.01
7.01
7.00
6.99
6.99
6.98
6.98
6.97
6.97
6.97
6.96
6.96
6.91
6.91
6.90
6.90
6.88
6.88
6.60
6.59
6.57
6.56
6.43
6.41
6.38
6.36
6.08
6.06
5.98
5.97
5.96
5.95
5.41
5.35
5.31
5.18
2.77
2.40
1.51
1.39
0.19
0.09
0.15
0.15
1.11
0.37
5.01
0.15
1.01
0.11
1.00
0.11
1.00
0.11
1.11
0.11
0.11
1.01
1.02
0.11
1.03
0.35
3.09
9.17
0.97
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ppm

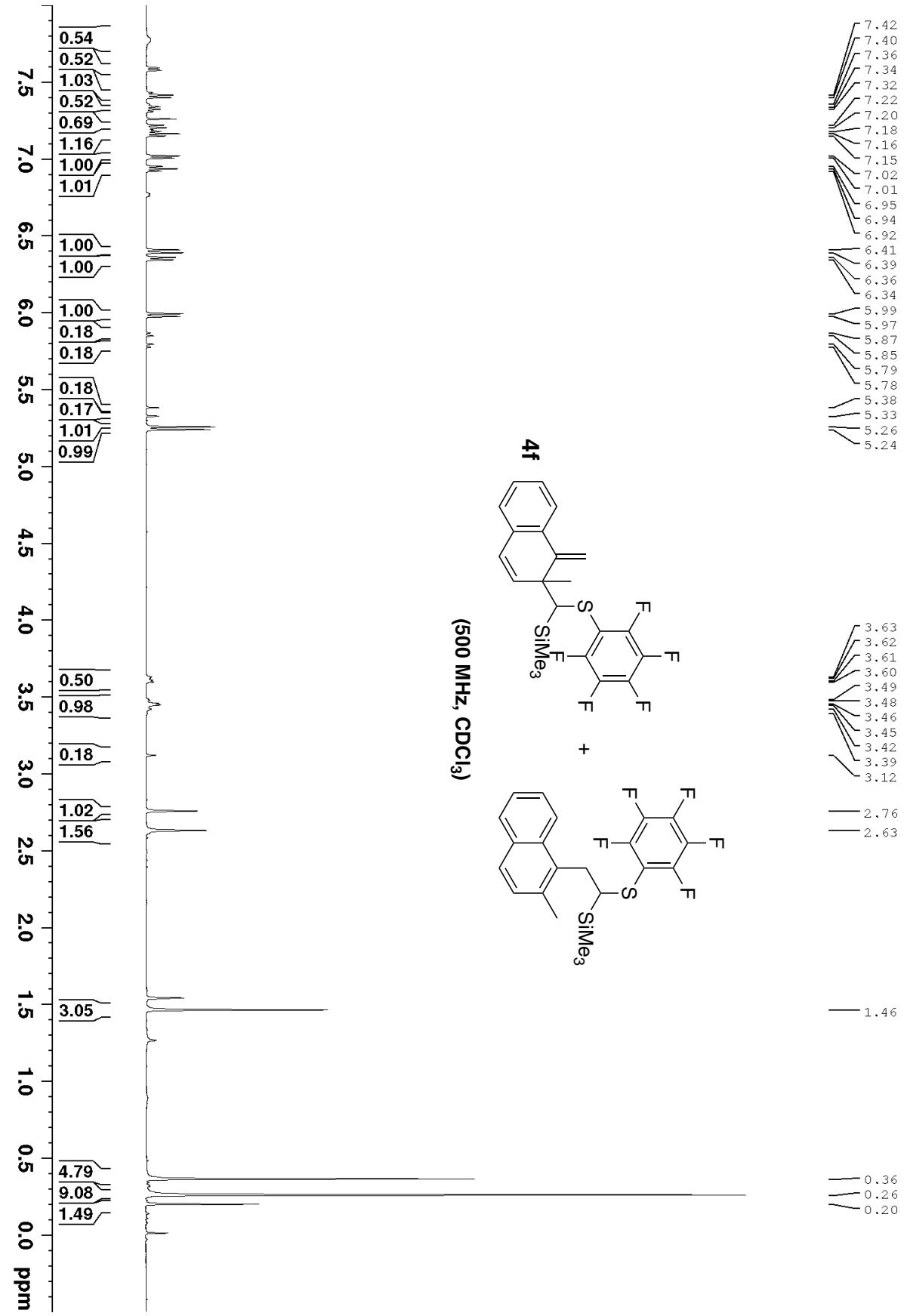

150.48
148.87
139.99
139.07
138.34
137.84
133.37
131.54
131.46
129.38
128.54
128.39
128.30
127.72
127.21
126.57
126.04
125.89
125.81
125.27
125.24
125.02
114.26
113.87
4c
(125 MHz, CDCl3)
SiMe3
S
Cl
45.41
45.24
44.70
44.35
24.37
24.00
0.76
0.65
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm

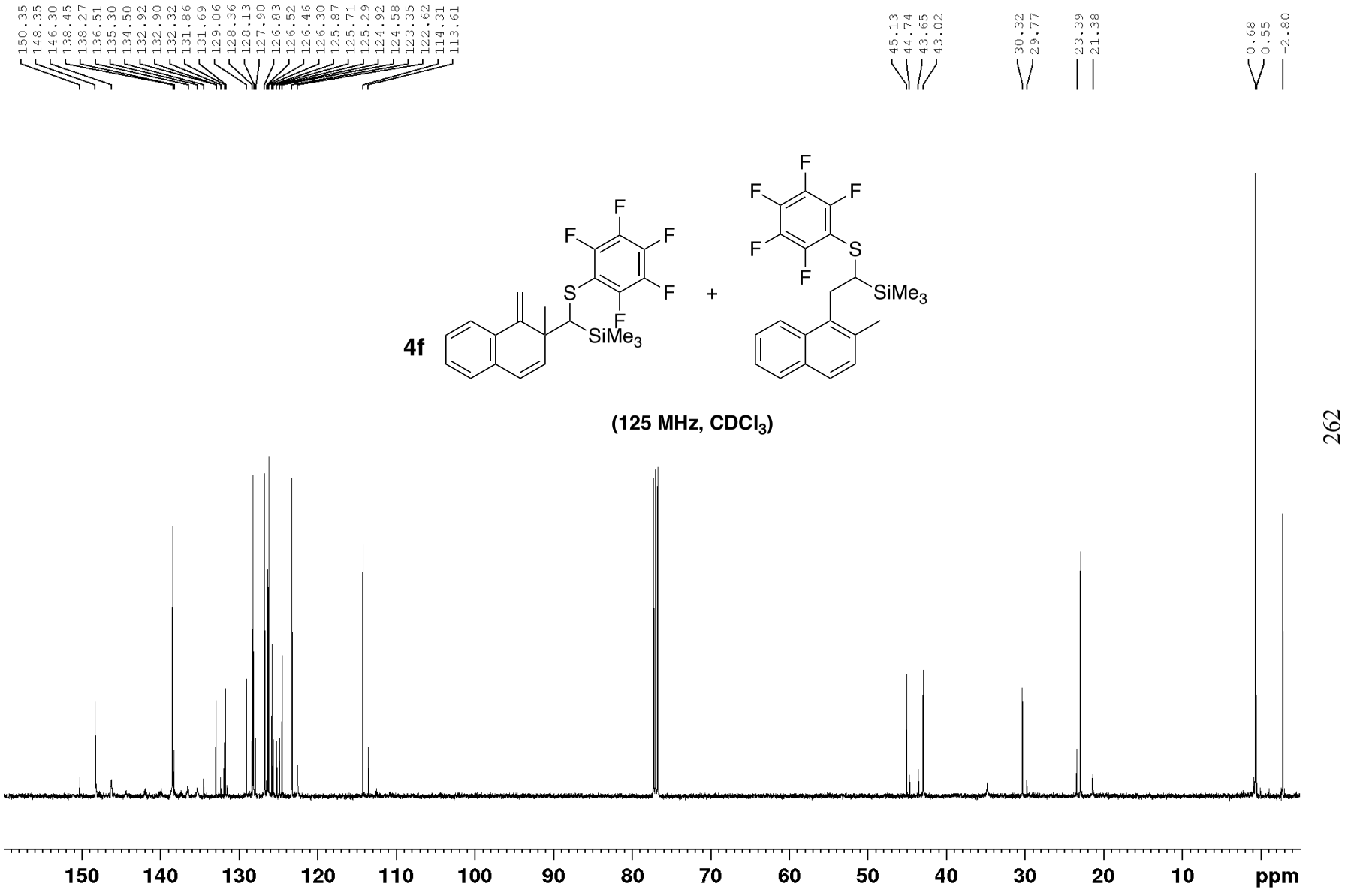

4d
(500 MHz, CDCl3)
SiMe3
S
F
7.11
7.10
7.08
7.06
7.05
7.04
7.03
6.97
6.96
6.90
6.88
6.87
6.79
6.77
6.76
6.56
6.54
6.38
6.36
6.06
6.04
5.97
5.95
5.40
5.34
5.30
5.19
2.53
2.35
1.51
1.39
0.20
0.10
1.19
2.00
1.03
1.09
1.99
1.00
1.05
0.10
1.10
0.10
0.11
1.01
1.01
0.10
1.01
0.30
3.04
9.12
0.88
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ppm

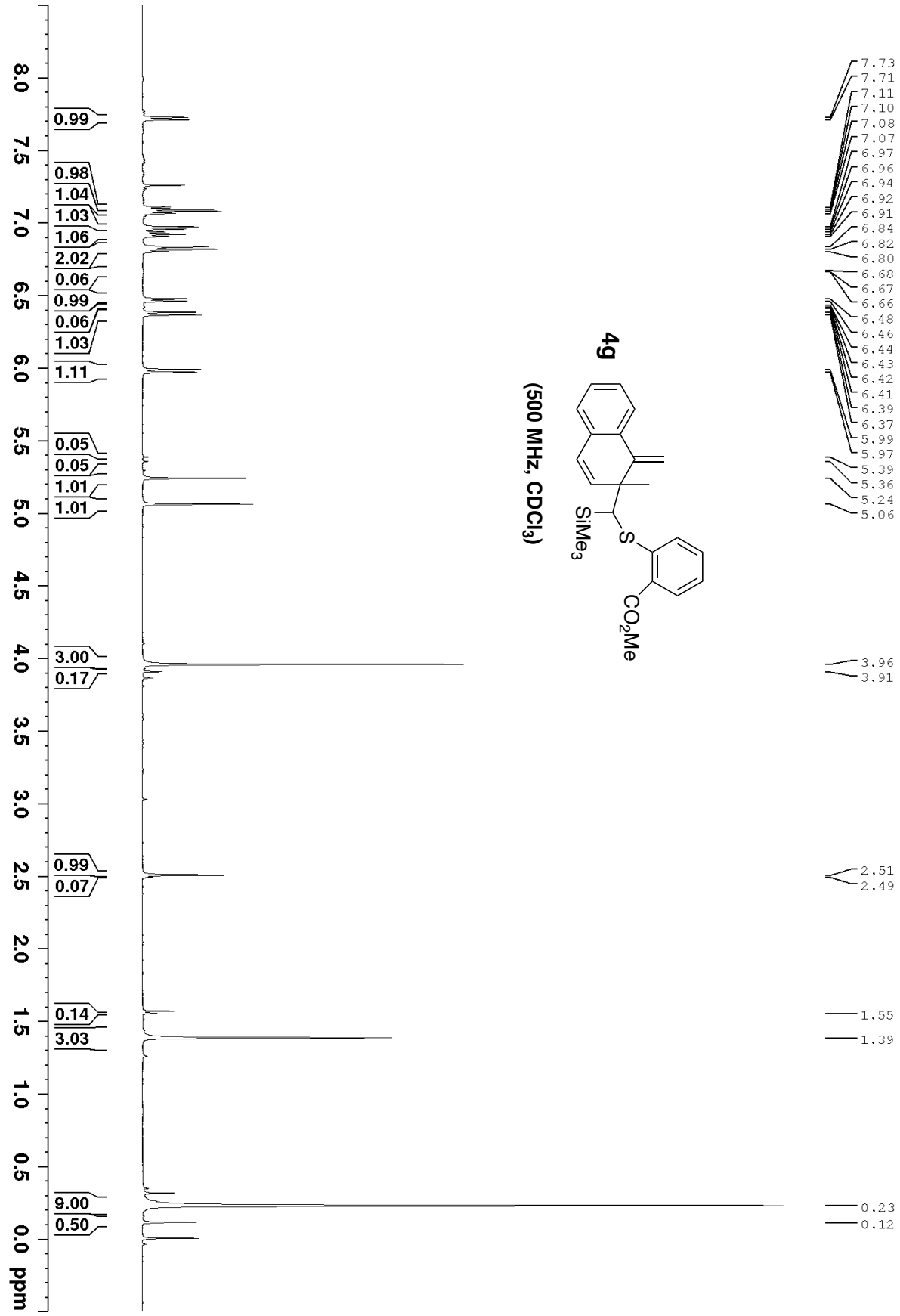

4d
(125 MHz, CDCl3)
SiMe3
S
F
162.54
160.58
150.51
148.95
140.17
138.43
134.24
134.22
133.41
132.48
132.42
131.58
130.67
130.61
128.61
128.22
127.63
127.06
126.57
126.02
125.79
125.17
125.09
124.91
124.30
115.59
115.41
115.24
114.13
113.76
46.07
45.88
45.42
44.54
24.37
24.08
0.78
0.69
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm

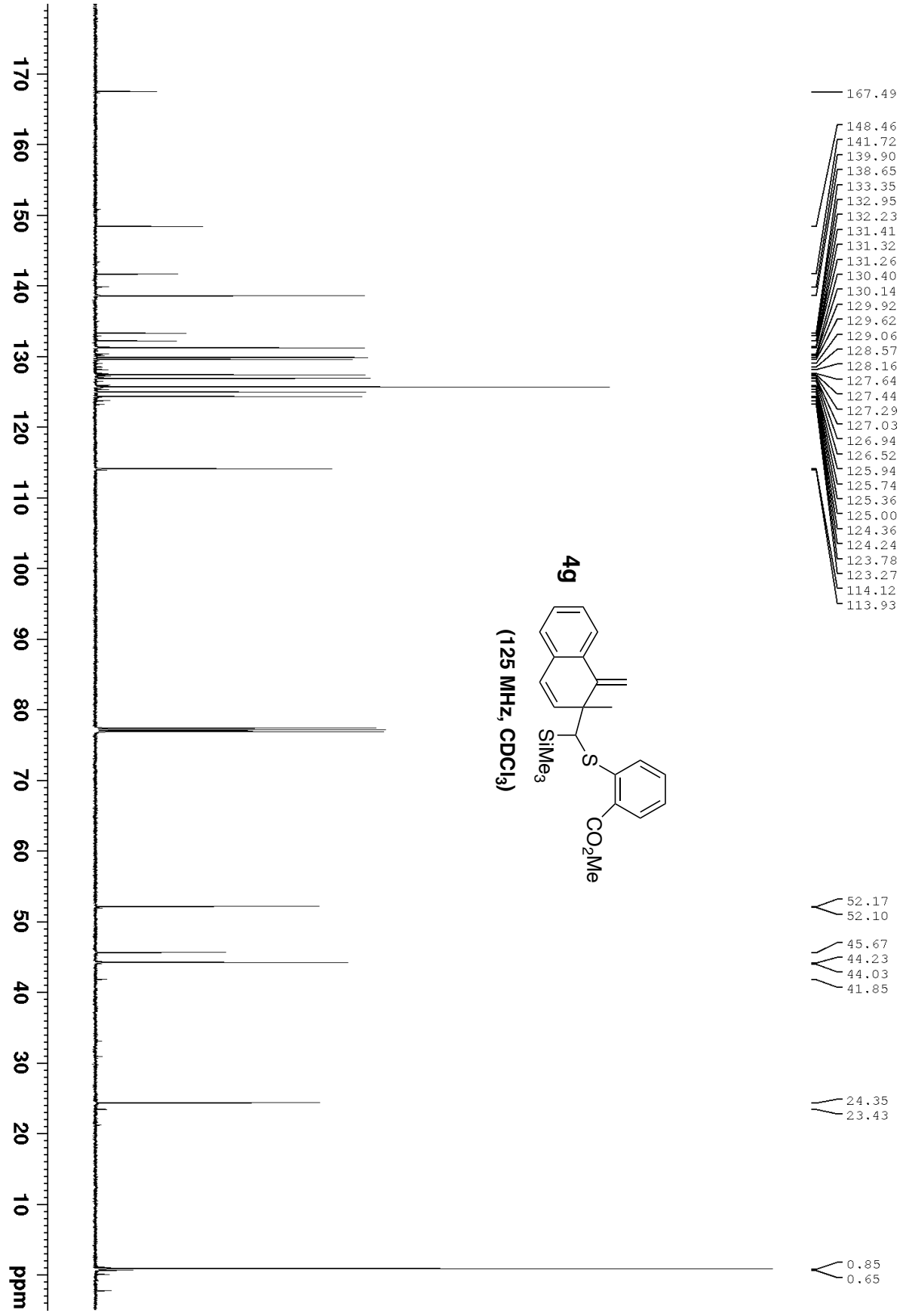

4e
(500 MHz, CDCl3)
SiMe3
S
CF3
7.13
7.13
7.11
7.10
6.99
6.98
6.97
6.96
6.95
6.85
6.83
6.82
6.80
6.78
6.54
6.53
6.52
6.51
6.46
6.45
6.40
6.38
6.08
6.06
5.99
5.98
5.97
5.96
5.42
5.37
5.30
5.19
2.92
2.53
2.51
1.41
0.31
0.21
0.47
2.14
0.33
3.07
1.05
0.13
1.02
0.20
0.23
1.03
1.00
0.13
1.12
0.13
0.13
1.07
1.02
0.13
0.34
1.04
3.09
0.99
9.19
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ppm

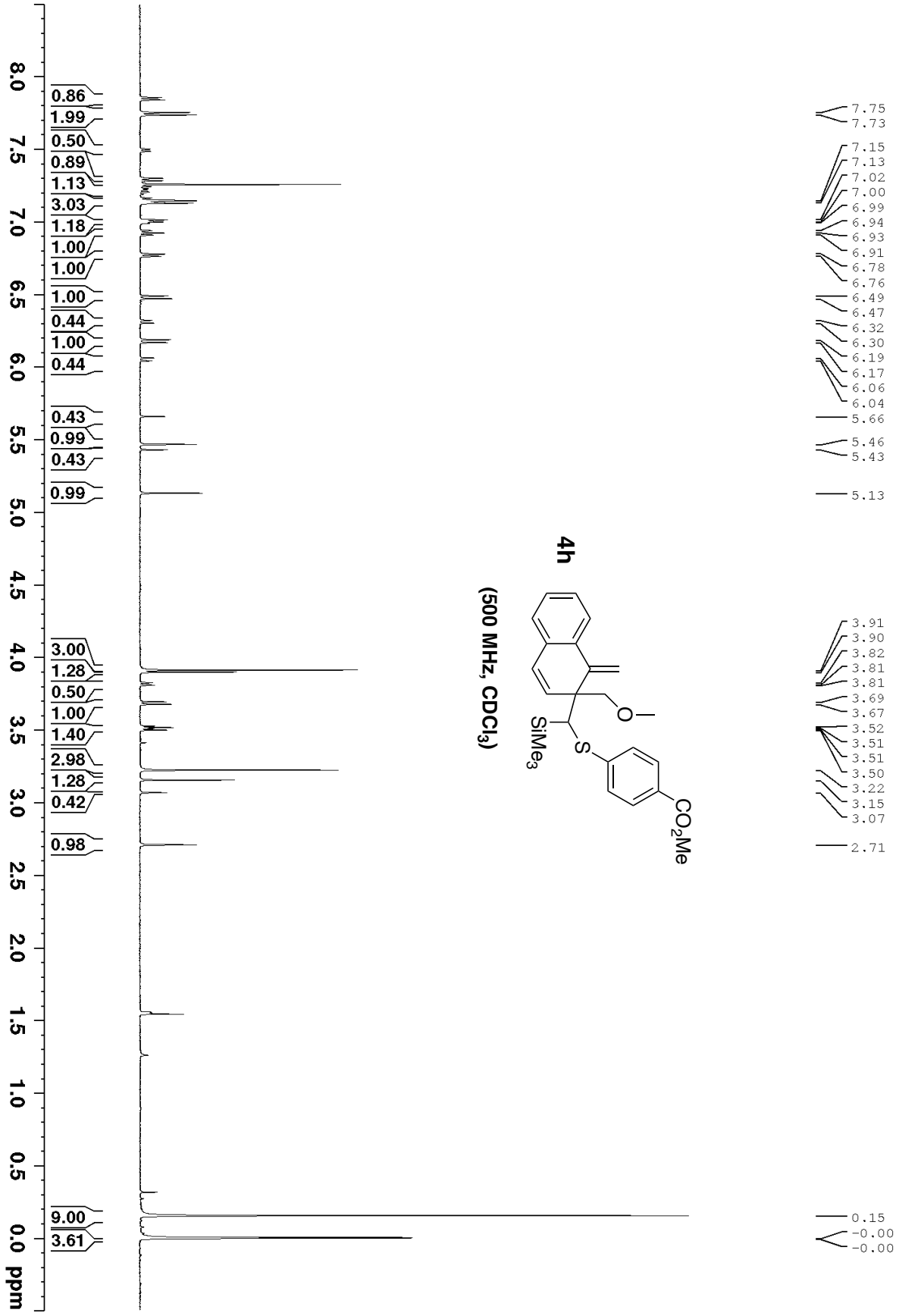

148.76
144.44
139.72
138.25
133.33
131.51
129.50
128.96
128.74
128.40
127.82
127.56
127.32
127.12
127.01
126.80
126.04
125.87
125.74
125.46
125.32
125.22
125.09
125.00
124.31
124.12
114.57
114.02
45.46
44.20
42.96
24.18
23.76
0.70
0.53
4e
(125 MHz, CDCl3)
SiMe3
S
CF3
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm

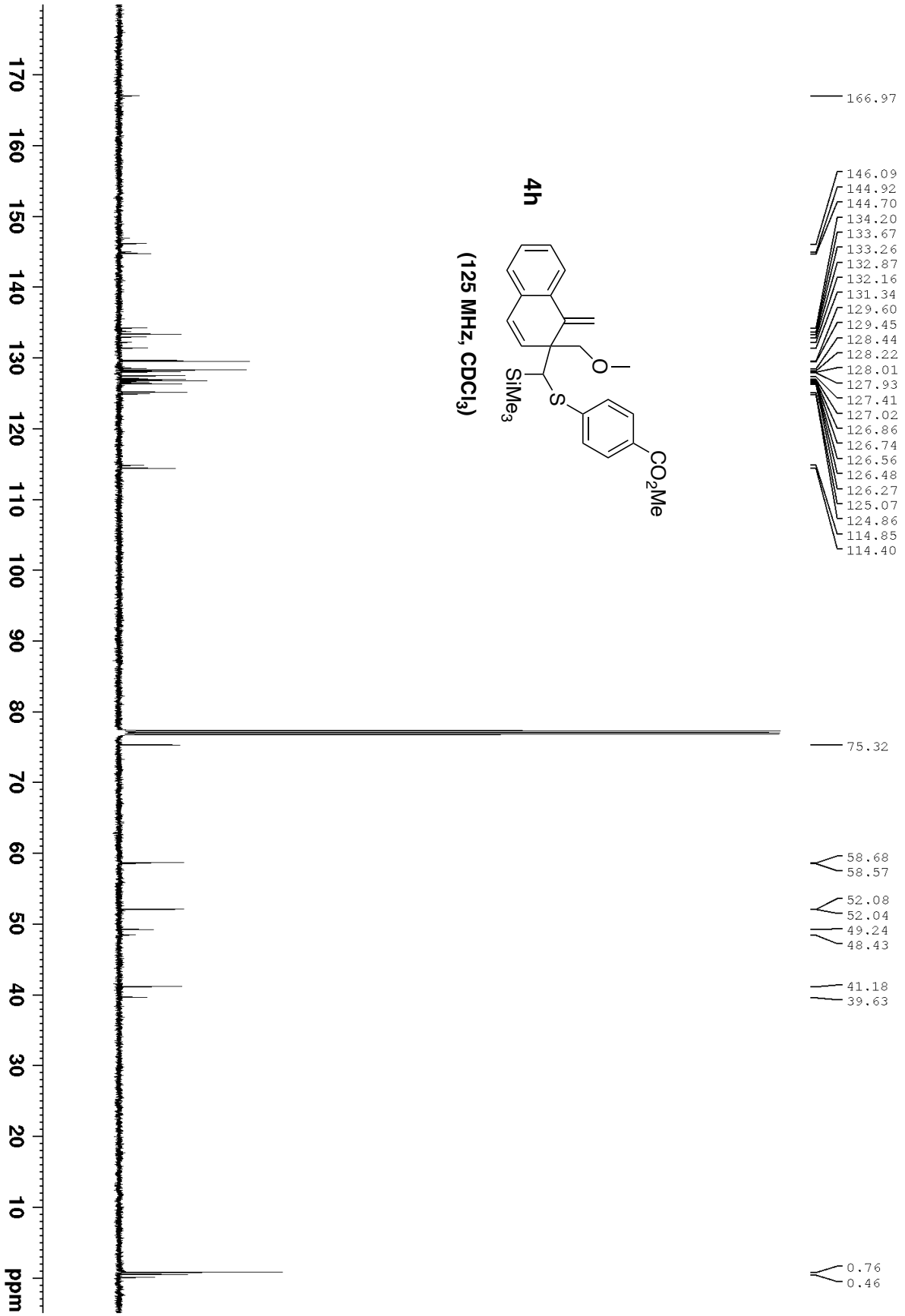

4f
(500 MHz, CDCl3)
SiMe3
SiMe3
7.42
7.40
7.36
7.34
7.32
7.22
7.20
7.18
7.16
7.15
7.02
7.01
6.95
6.94
6.92
6.41
6.39
6.36
6.34
5.99
5.97
5.87
5.85
5.79
5.78
5.38
5.33
5.26
5.24
3.63
3.62
3.61
3.60
3.49
3.48
3.46
3.45
3.42
3.39
3.12
2.76
2.63
1.46
0.36
0.26
0.20
0.54
0.52
1.03
0.52
0.69
1.16
1.00
1.01
1.00
1.00
1.00
0.18
0.18
0.18
0.17
1.01
0.99
0.50
0.98
0.18
1.02
1.56
3.05
4.79
9.08
1.49
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ppm

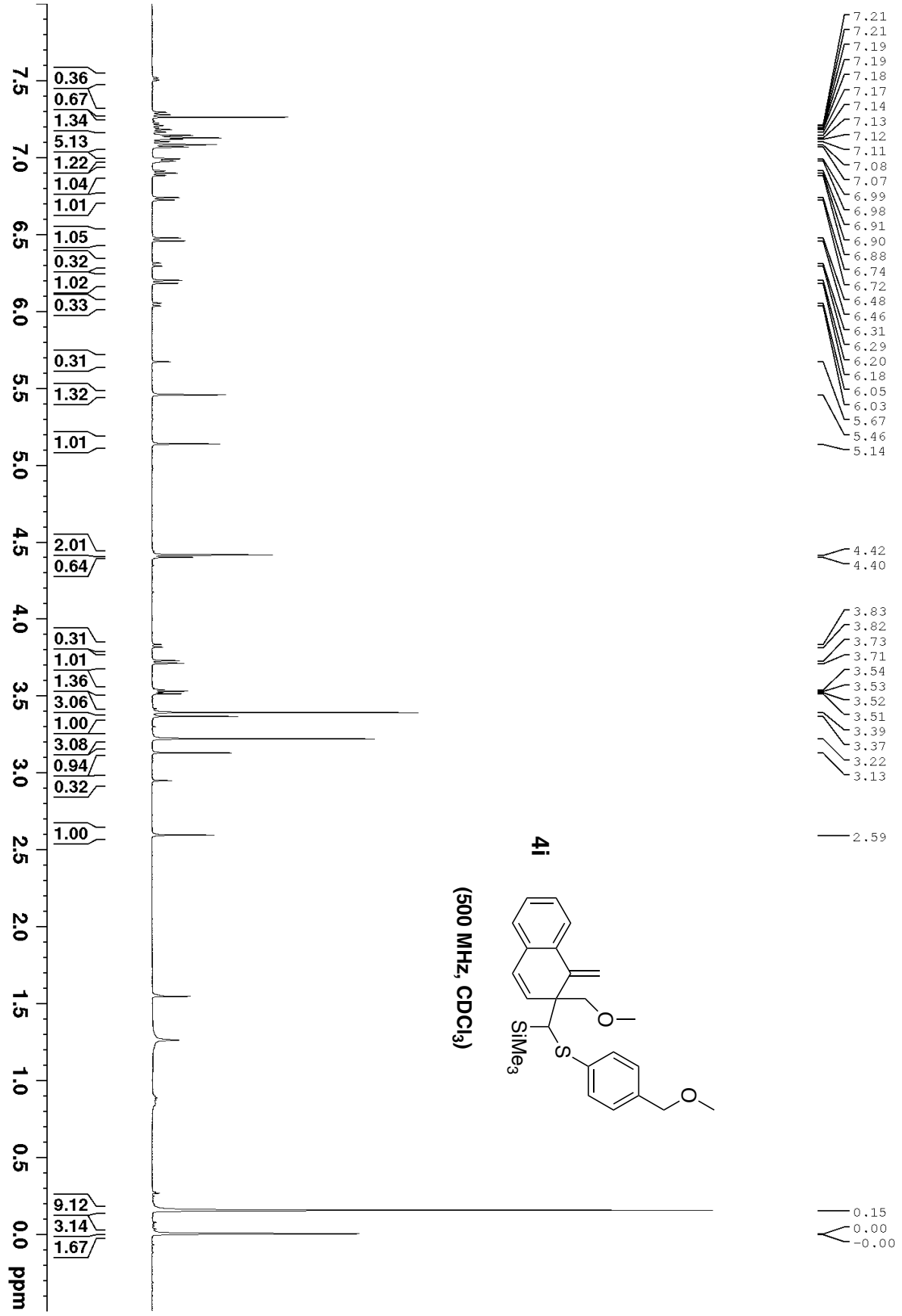

150.35
148.35
146.30
138.45
138.27
136.51
135.30
134.50
132.92
132.90
132.32
131.86
131.69
129.06
128.36
128.13
127.90
126.83
126.52
126.46
126.30
125.87
125.71
125.29
124.92
124.58
123.35
122.62
114.31
113.61
45.13
44.74
43.65
43.02
30.32
29.77
23.39
21.38
0.68
0.55
-2.80
4f
F
F
F
F
F
S
SiMe3
+
F
F
F
F
F
S
SiMe3
(125 MHz, CDCl3)
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm

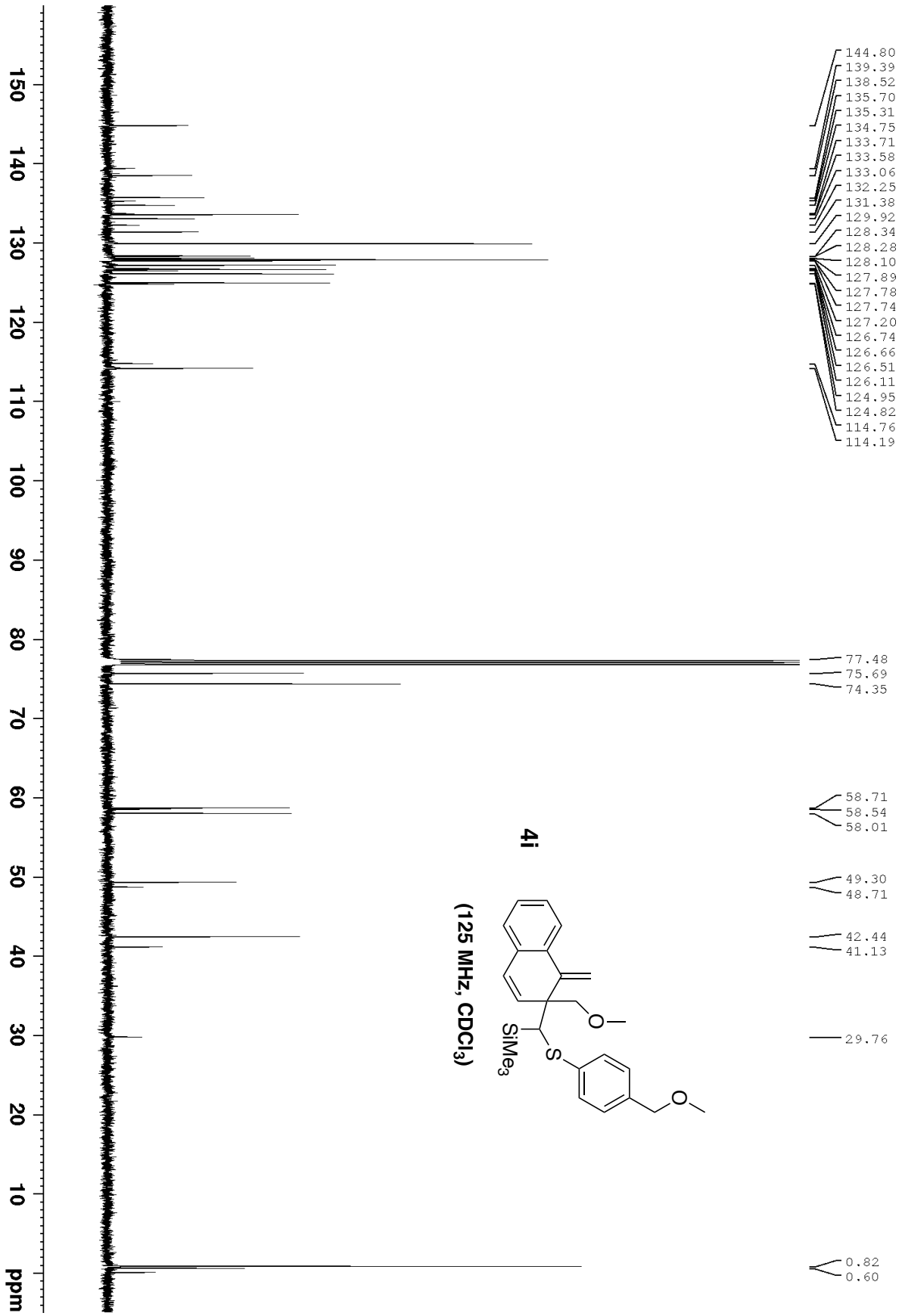

4g
(500 MHz, CDCl3)
SiMe3
S
CO2Me
7.73
7.71
7.11
7.10
7.08
7.07
6.97
6.96
6.94
6.92
6.91
6.84
6.82
6.80
6.68
6.67
6.66
6.48
6.46
6.44
6.43
6.42
6.41
6.39
6.37
5.99
5.97
5.39
5.36
5.24
5.06
3.96
3.91
2.51
2.49
1.55
1.39
0.23
0.12
0.99
0.98
1.04
1.03
1.06
2.02
0.06
0.99
0.06
1.03
1.11
0.05
0.05
1.01
1.01
3.00
0.17
0.99
0.07
0.14
3.03
9.00
0.50
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ppm

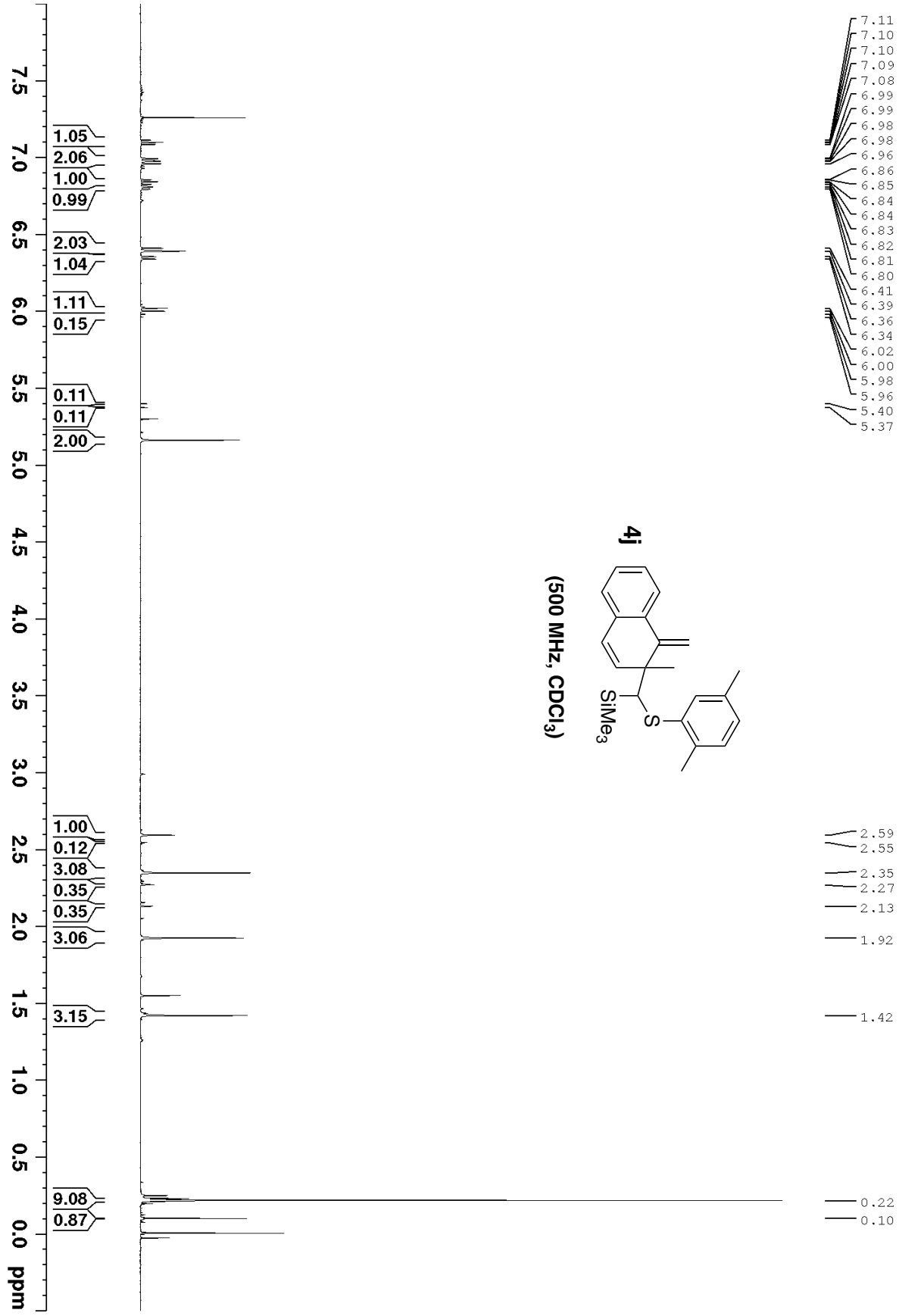

4g
(125 MHz, CDCl3)
SiMe3
S
CO2Me
167.49
148.46
141.72
139.90
138.65
133.35
132.95
132.23
131.41
131.32
131.26
130.40
130.14
129.92
129.62
129.06
128.57
128.16
127.64
127.44
127.29
127.03
126.94
126.52
125.94
125.74
125.36
125.00
124.36
124.24
123.78
123.27
114.12
113.93
52.17
52.10
45.67
44.23
44.03
41.85
24.35
23.43
0.85
0.65
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm

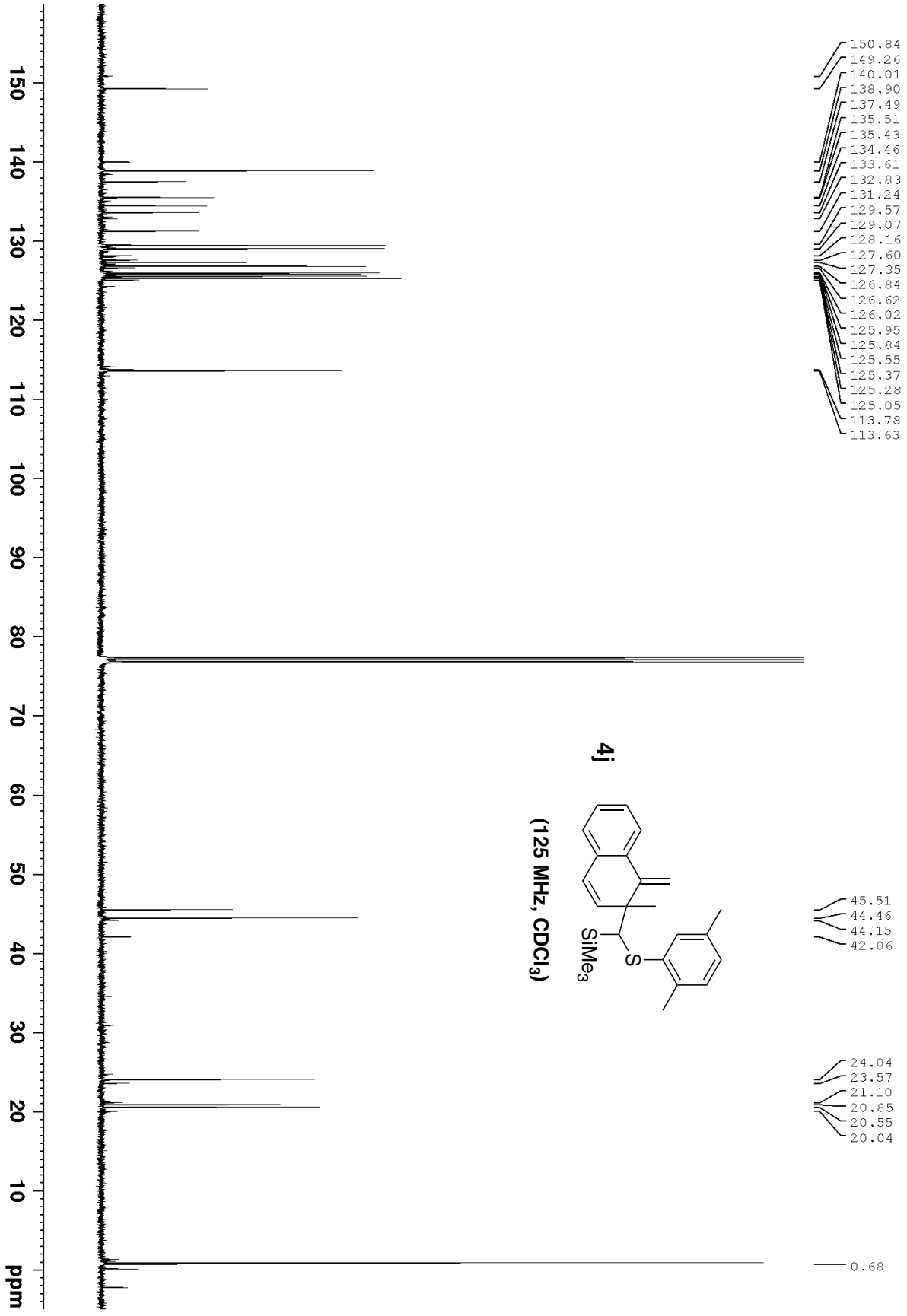

4h
(500 MHz, CDCl3)
SiMe3
O
S
CO2Me
0.86
1.99
0.50
0.89
1.13
3.03
1.18
1.00
1.00
1.00
0.44
1.00
0.44
0.43
0.99
0.43
0.99
3.00
1.28
0.50
1.00
1.40
2.98
1.28
0.42
0.98
9.00
3.61
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ppm
7.75
7.73
7.15
7.13
7.02
7.00
6.99
6.94
6.93
6.91
6.78
6.76
6.49
6.47
6.32
6.30
6.19
6.17
6.06
6.04
5.66
5.46
5.43
5.13
3.91
3.90
3.82
3.81
3.81
3.69
3.67
3.52
3.51
3.51
3.50
3.22
3.15
3.07
2.71
0.15
-0.00
-0.00

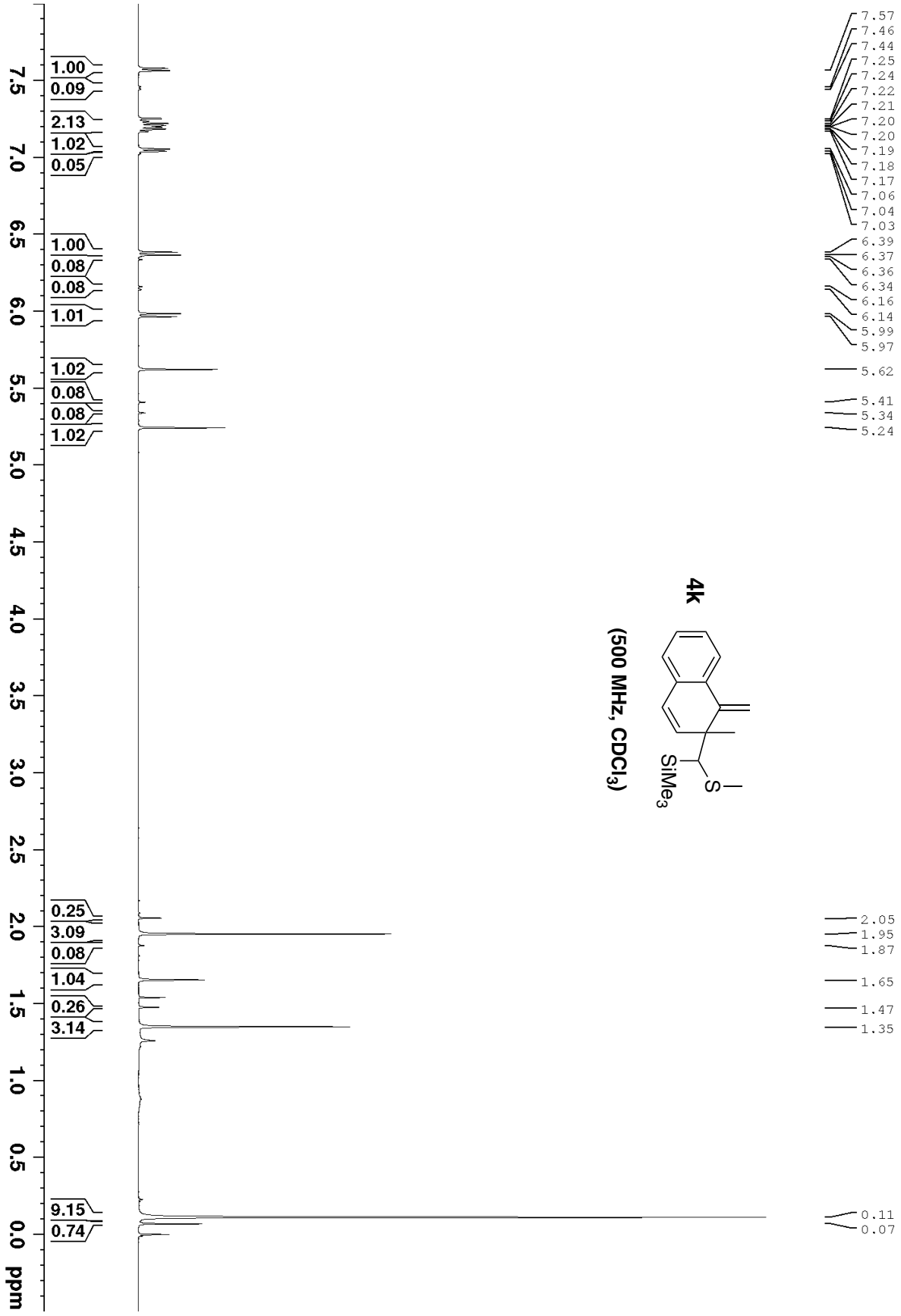

4h
(125 MHz, CDCl3)
SiMe3
S
O
CO2Me
166.97
146.09
144.92
144.70
134.20
133.67
133.26
132.87
132.16
131.34
129.60
129.45
128.44
128.22
128.01
127.93
127.41
127.02
126.86
126.74
126.56
126.48
126.27
125.07
124.86
114.85
114.40
75.32
58.68
58.57
52.08
52.04
49.24
48.43
41.18
39.63
0.76
0.46
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm

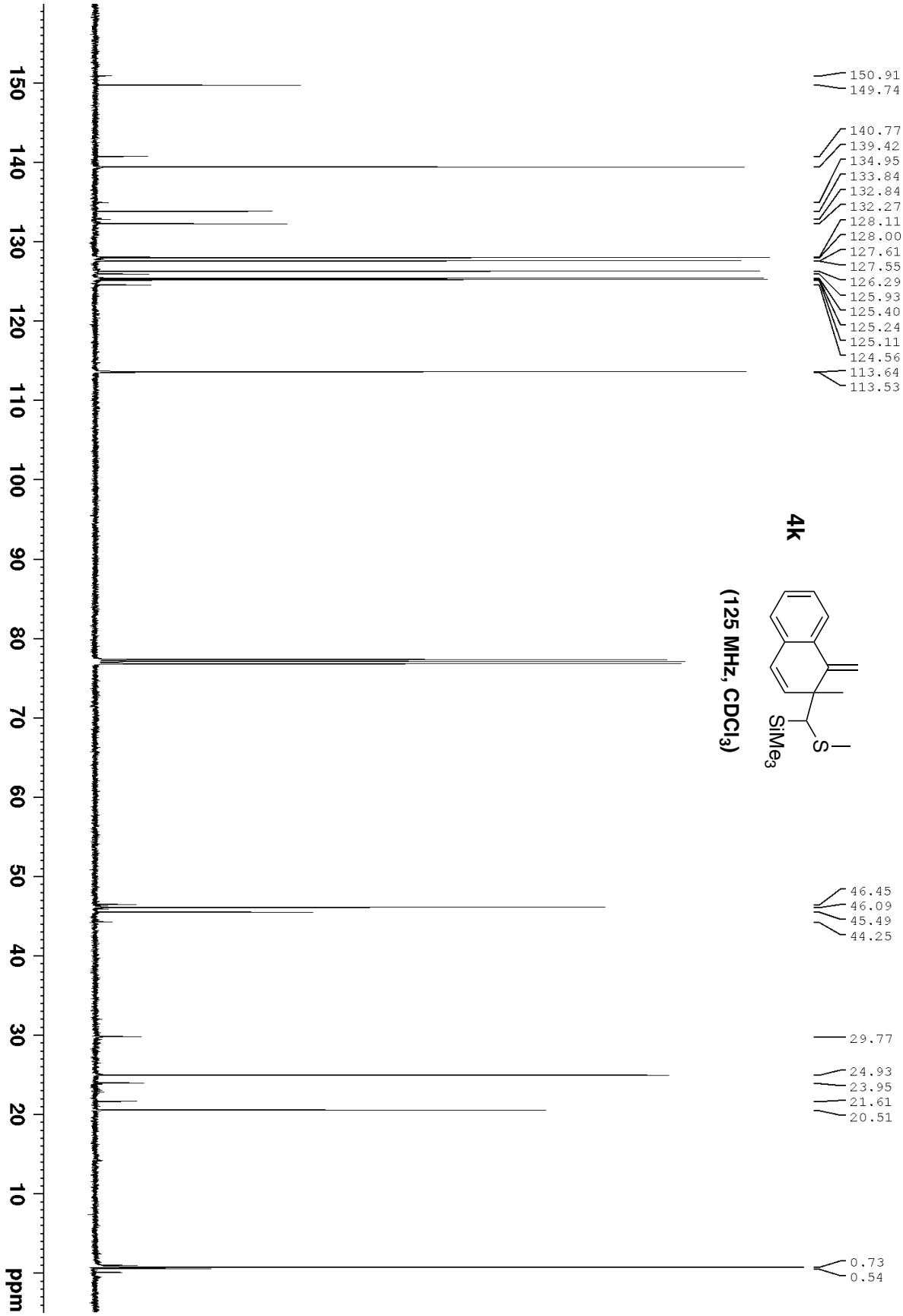

4i
(500 MHz, CDCl3)
SiMe3
O
S
O
7.21
7.21
7.19
7.19
7.18
7.17
7.14
7.13
7.12
7.11
7.08
7.07
6.99
6.98
6.91
6.90
6.88
6.74
6.72
6.48
6.46
6.31
6.29
6.20
6.18
6.05
6.03
5.67
5.46
5.14
4.42
4.40
3.83
3.82
3.73
3.71
3.54
3.53
3.52
3.51
3.39
3.37
3.22
3.13
2.59
0.15
0.00
-0.00
0.36
0.67
1.34
5.13
1.22
1.04
1.01
1.05
0.32
1.02
0.33
0.31
1.32
1.01
2.01
0.64
0.31
1.01
1.36
3.06
1.00
3.08
0.94
0.32
1.00
9.12
3.14
1.67
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ppm

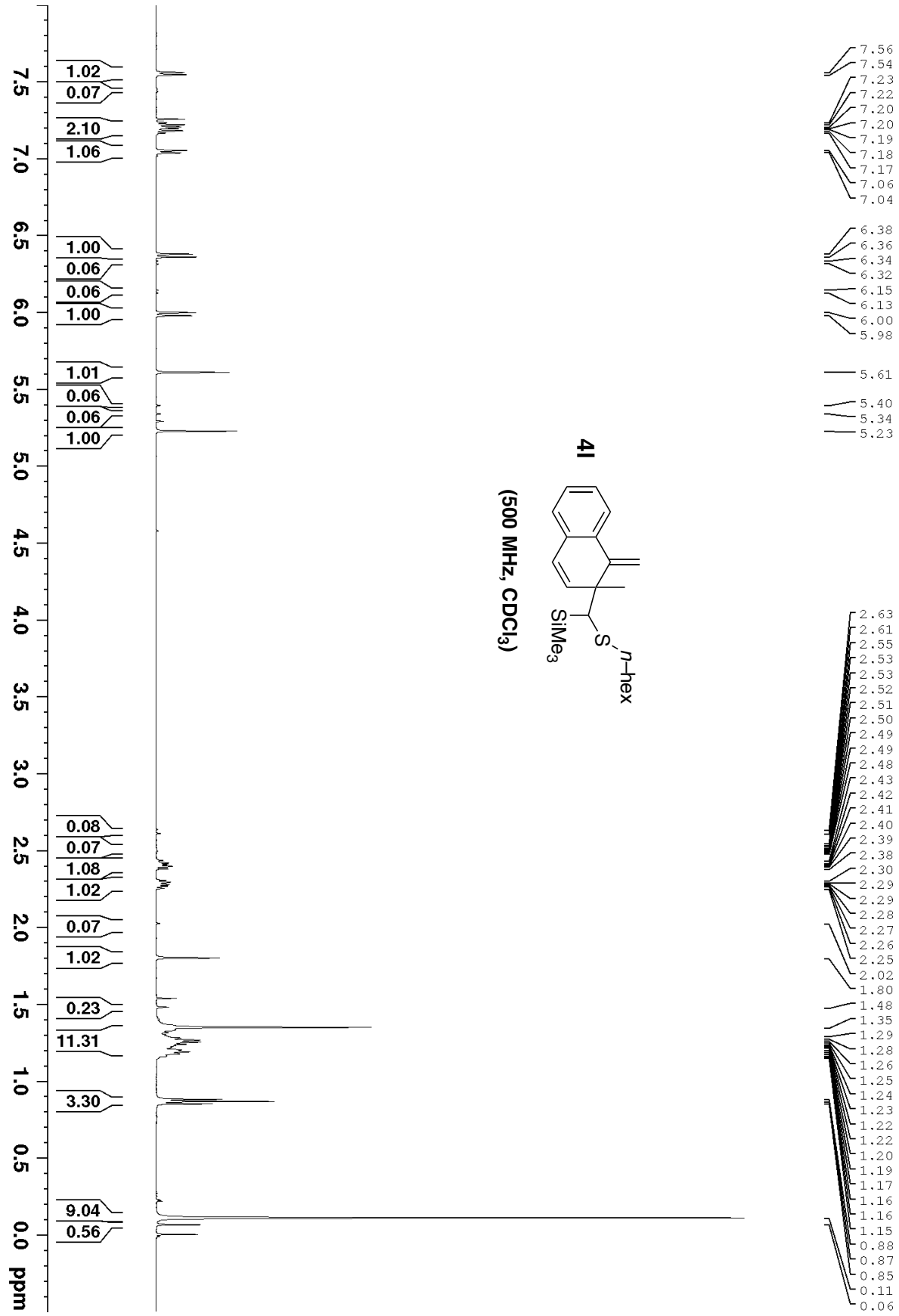

144.80
139.39
138.52
135.70
135.31
134.75
133.71
133.58
133.06
132.25
131.38
129.92
128.34
128.28
128.10
127.89
127.78
127.74
127.20
126.74
126.66
126.51
126.11
124.95
124.82
114.76
114.19
77.48
75.69
74.35
58.71
58.54
58.01
49.30
48.71
42.44
41.13
29.76
0.82
0.60
ppm
4i
(125 MHz, CDCl3)
SiMe3
S
O
O

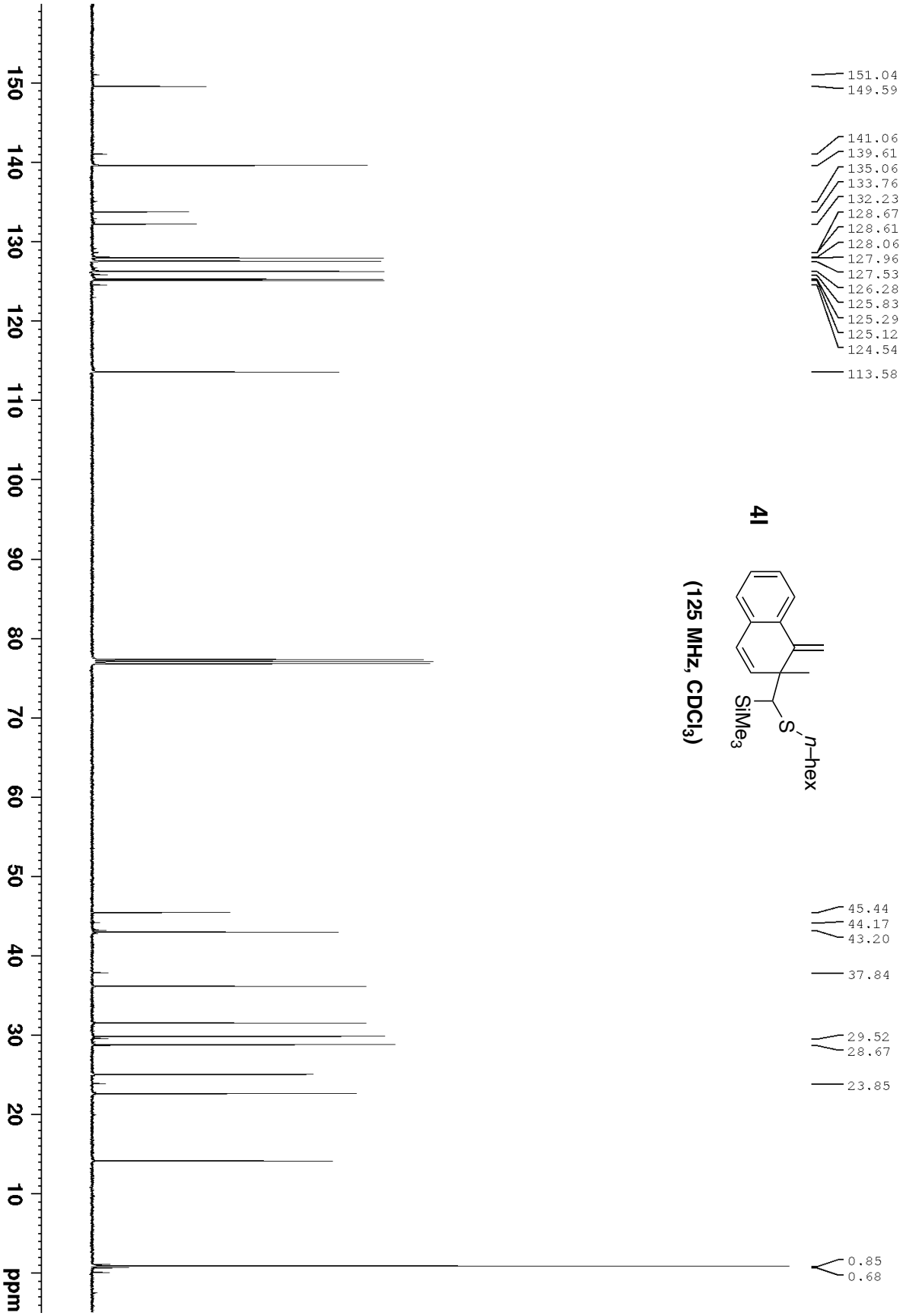

4j
(500 MHz, CDCl3)
SiMe3
S
7.11
7.10
7.10
7.09
7.08
6.99
6.99
6.98
6.98
6.96
6.86
6.85
6.84
6.84
6.83
6.82
6.81
6.80
6.41
6.39
6.36
6.34
6.02
6.00
5.98
5.96
5.40
5.37
2.59
2.55
2.35
2.27
2.13
1.92
1.42
0.22
0.10
1.05
2.06
1.00
0.99
2.03
1.04
1.11
0.15
0.11
0.11
2.00
1.00
0.12
3.08
0.35
0.35
3.06
3.15
9.08
0.87
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ppm

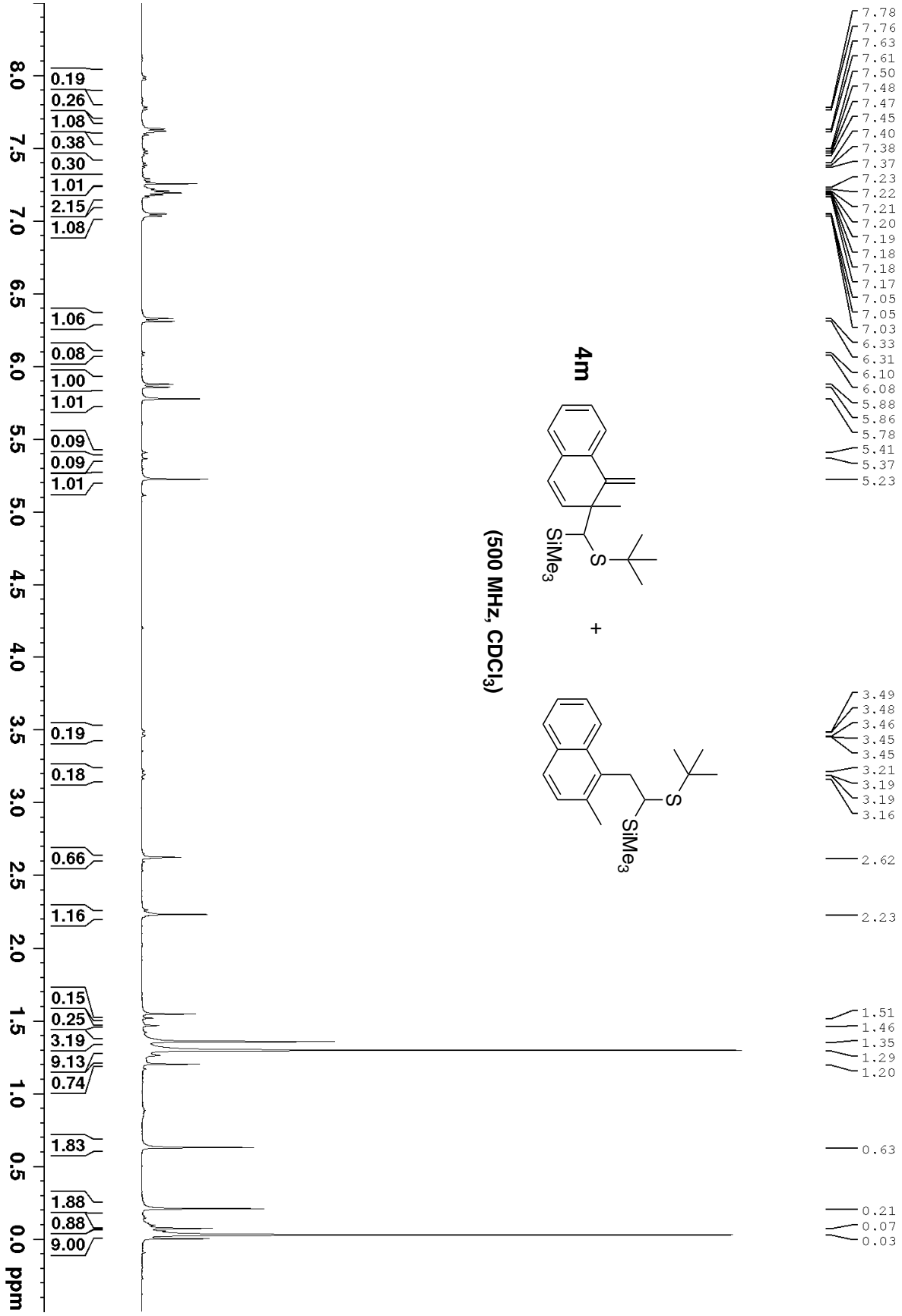

150.84
149.26
140.01
138.90
137.49
135.51
135.43
134.46
133.61
132.83
131.24
129.57
129.07
128.16
127.60
127.35
126.84
126.62
126.02
125.95
125.84
125.55
125.37
125.28
125.05
113.78
113.63
45.51
44.46
44.15
42.06
24.04
23.57
21.10
20.85
20.55
20.04
0.68
4j
(125 MHz, CDCl3)
SiMe3
S
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm

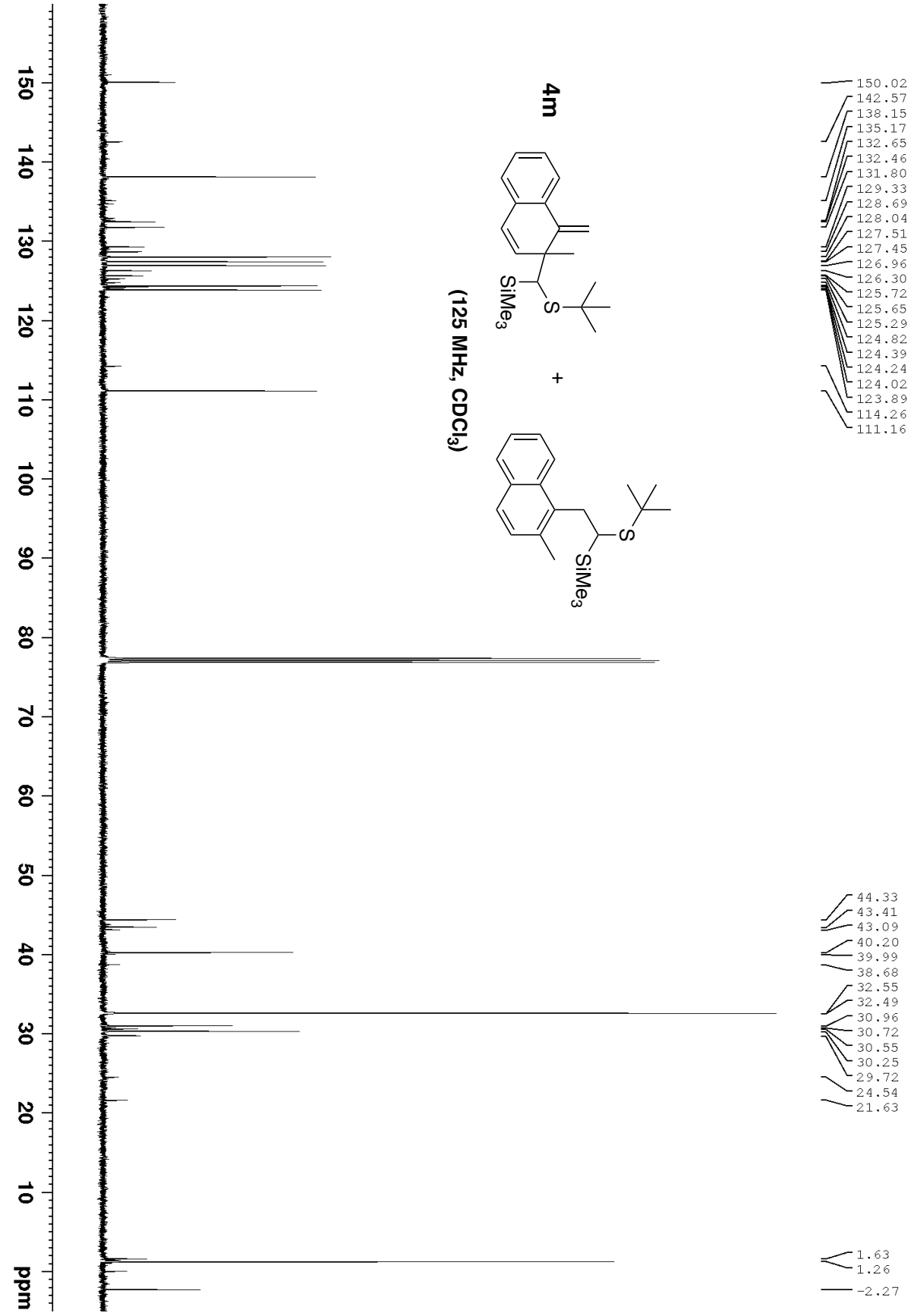

4k
(500 MHz, CDCl3)
SiMe3
S
7.57
7.46
7.44
7.25
7.24
7.22
7.21
7.20
7.20
7.19
7.18
7.17
7.06
7.04
7.03
6.39
6.37
6.36
6.34
6.16
6.14
5.99
5.97
5.62
5.41
5.34
5.24
2.05
1.95
1.87
1.65
1.47
1.35
0.11
0.07
1.00
0.09
2.13
1.02
0.05
1.00
0.08
0.08
1.01
1.02
0.08
0.08
1.02
0.25
3.09
0.08
1.04
0.26
3.14
9.15
0.74
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ppm

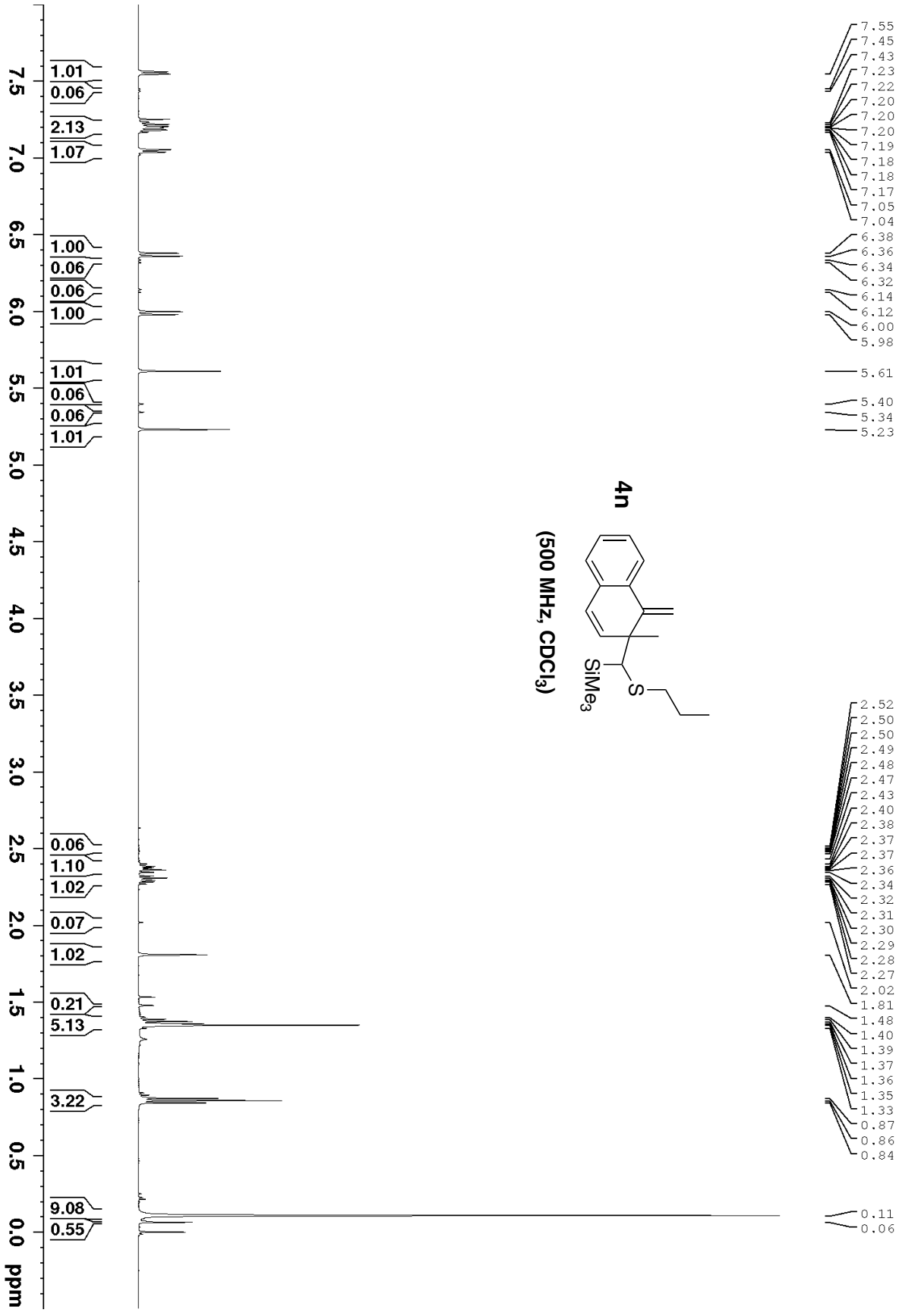

150.91
149.74
140.77
139.42
134.95
133.84
132.84
132.27
128.11
128.00
127.61
127.55
126.29
125.93
125.40
125.24
125.11
124.56
113.64
113.53
4k
(125 MHz, CDCl3)
SiMe3
S
46.45
46.09
45.49
44.25
29.77
24.93
23.95
21.61
20.51
0.73
0.54
ppm

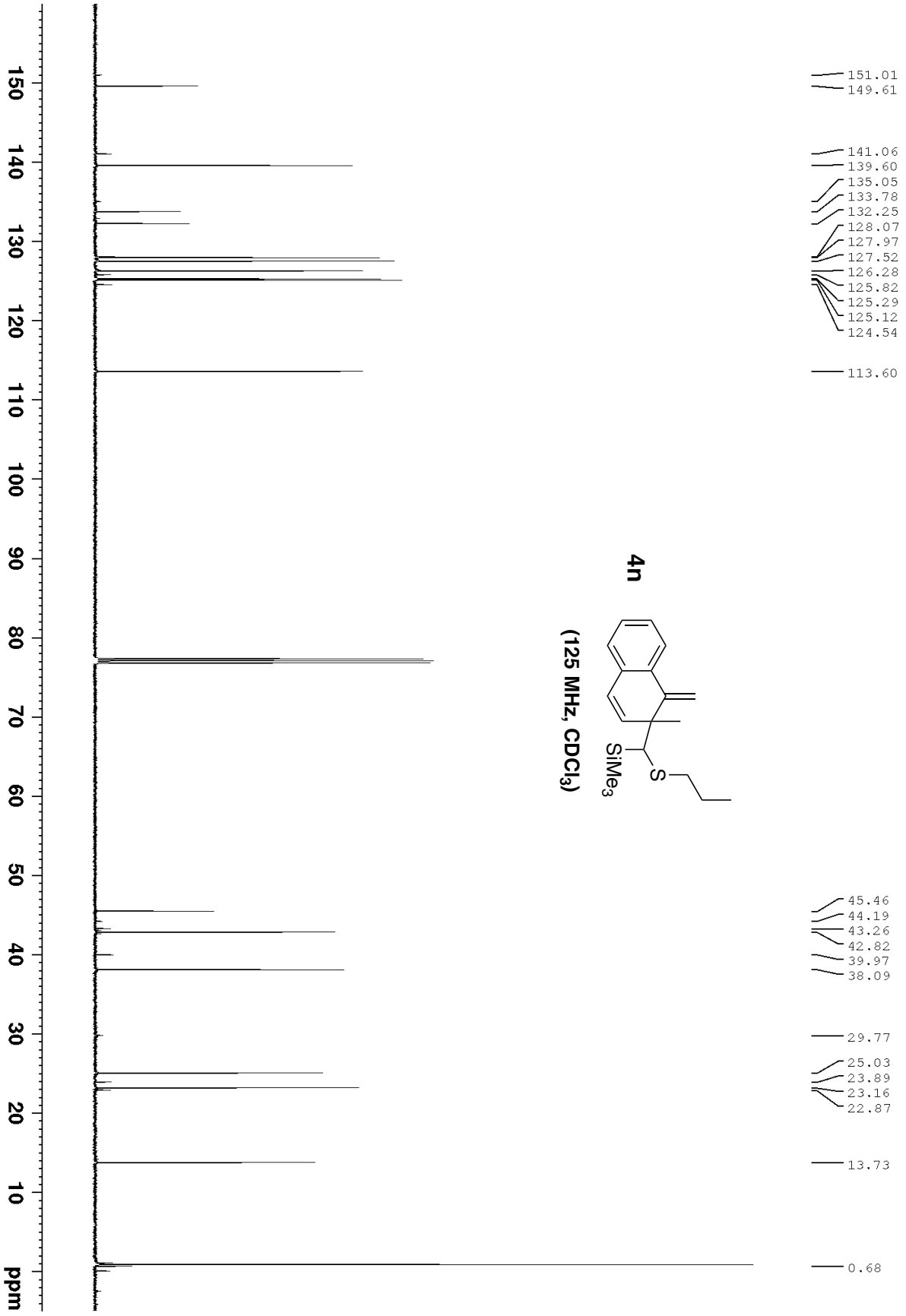

4l
(500 MHz, CDCl3)
SiMe3
S
n–hex
7.56
7.54
7.23
7.22
7.20
7.20
7.19
7.18
7.17
7.06
7.04
6.38
6.36
6.34
6.32
6.15
6.13
6.00
5.98
5.61
5.40
5.34
5.23
2.63
2.61
2.55
2.53
2.53
2.52
2.51
2.50
2.49
2.49
2.48
2.43
2.42
2.41
2.40
2.39
2.38
2.30
2.29
2.29
2.28
2.27
2.26
2.25
2.02
1.80
1.48
1.35
1.29
1.28
1.26
1.25
1.24
1.23
1.22
1.22
1.20
1.19
1.17
1.16
1.16
1.15
0.88
0.87
0.85
0.11
0.06
1.02
0.07
2.10
1.06
1.00
0.06
0.06
1.00
1.01
0.06
0.06
1.00
0.08
0.07
1.08
1.02
0.07
1.02
0.23
11.31
3.30
9.04
0.56
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ppm

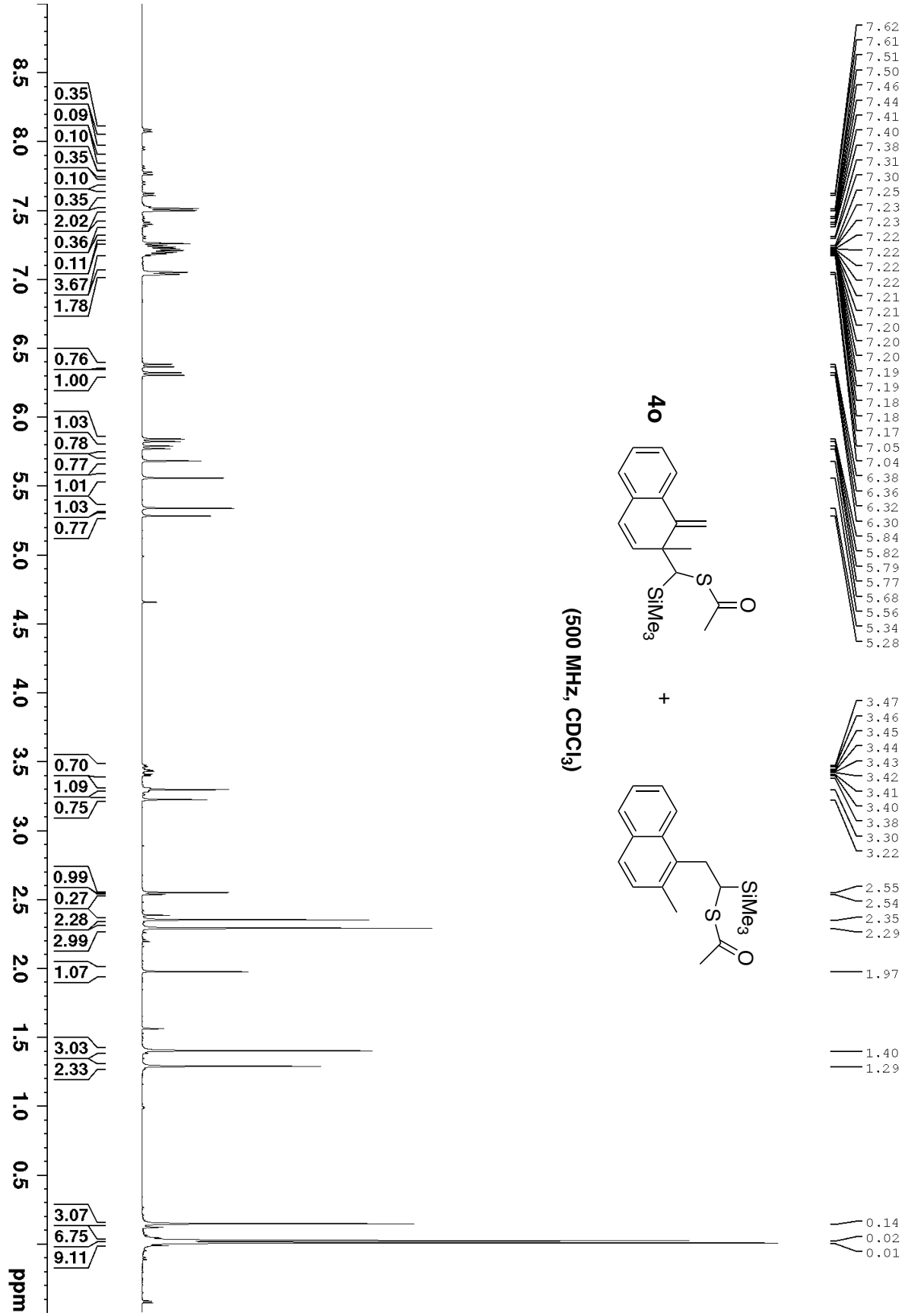

151.04
149.59
141.06
139.61
135.06
133.76
132.23
128.67
128.61
128.06
127.96
127.53
126.28
125.83
125.29
125.12
124.54
113.58
4l
(125 MHz, CDCl3)
SiMe3
S
n–hex
45.44
44.17
43.20
37.84
29.52
28.67
23.85
0.85
0.68
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm

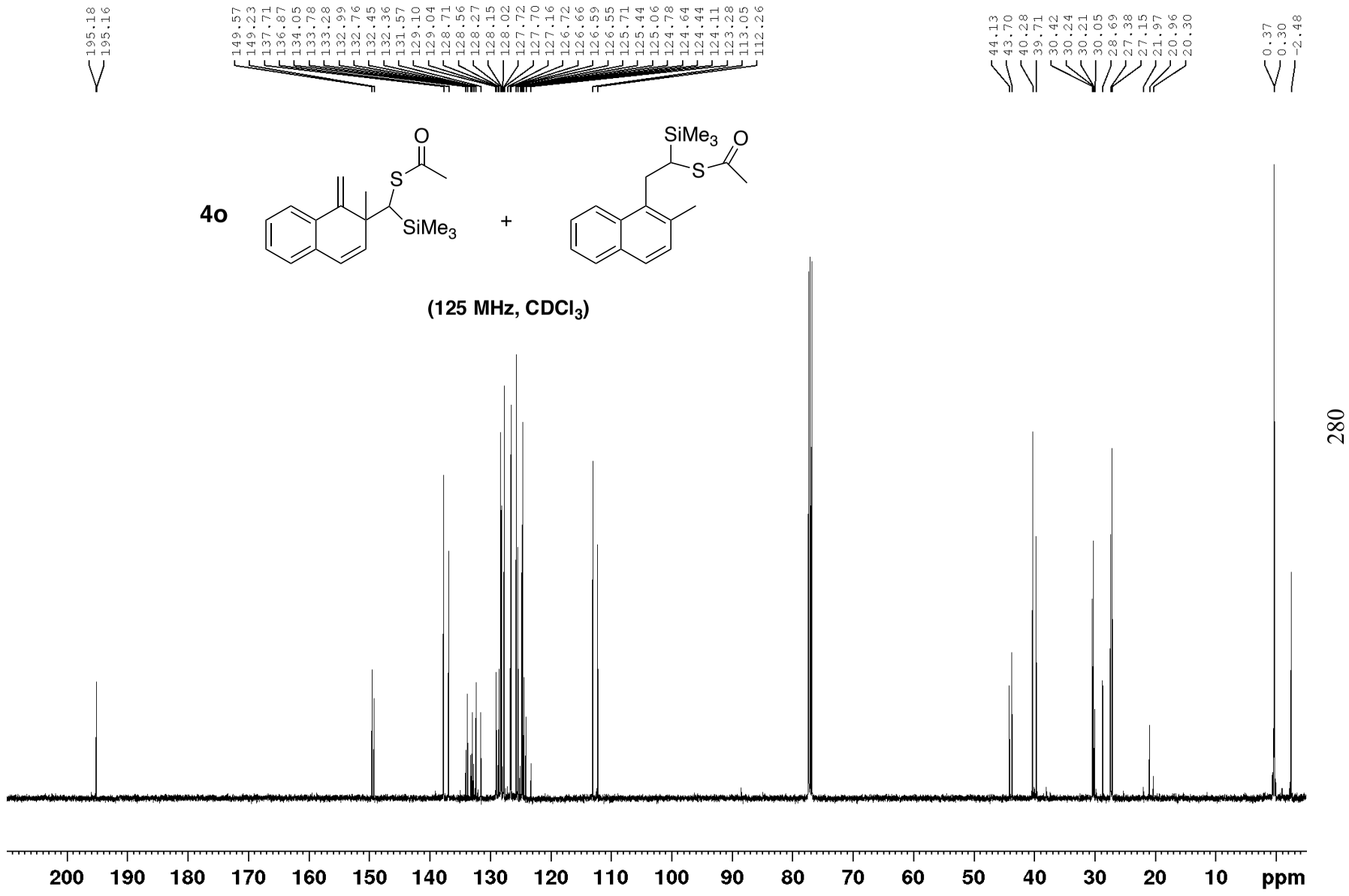

4m
(500 MHz, CDCl3)
SiMe3
S
+
SiMe3
S
7.78
7.76
7.63
7.61
7.50
7.48
7.47
7.45
7.40
7.38
7.37
7.23
7.22
7.21
7.20
7.19
7.18
7.18
7.17
7.05
7.05
7.03
6.33
6.31
6.10
6.08
5.88
5.86
5.78
5.41
5.37
5.23
3.49
3.48
3.46
3.45
3.45
3.21
3.19
3.19
3.16
2.62
2.23
1.51
1.46
1.35
1.29
1.20
0.63
0.21
0.07
0.03
0.19
0.26
1.08
0.38
0.30
1.01
2.15
1.08
1.06
0.08
1.00
1.01
0.09
0.09
1.01
0.19
0.18
0.66
1.16
0.15
0.25
3.19
9.13
0.74
1.83
1.88
0.88
9.00
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ppm


4m
(125 MHz, CDCl3)
SiMe3
S
+
SiMe3
S
150.02
142.57
138.15
135.17
132.65
132.46
131.80
129.33
128.69
128.04
127.51
127.45
126.96
126.30
125.72
125.65
125.29
124.82
124.39
124.24
124.02
123.89
114.26
111.16
44.33
43.41
43.09
40.20
39.99
38.68
32.55
32.49
30.96
30.72
30.55
30.25
29.72
24.54
21.63
1.63
1.26
-2.27
ppm

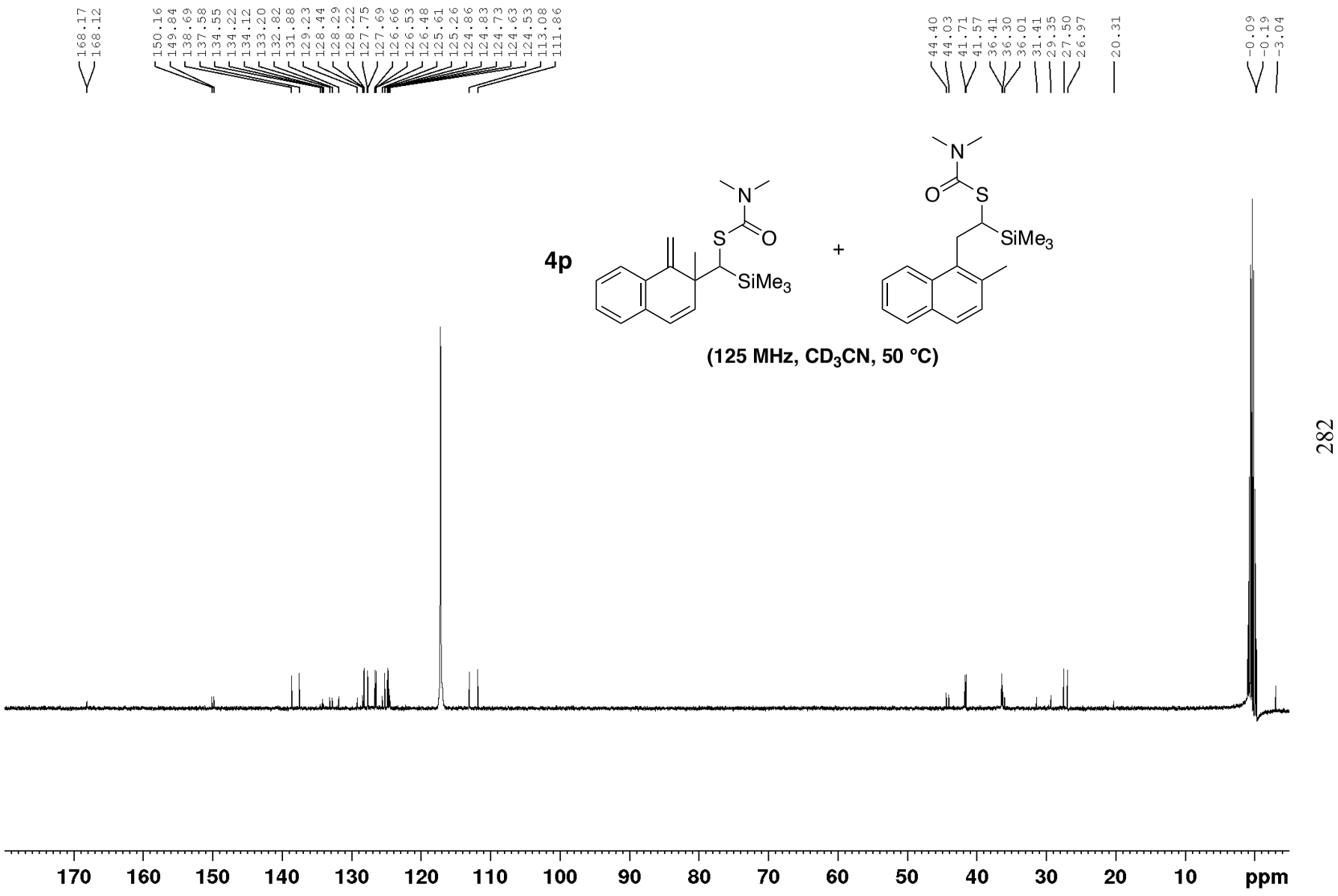

4n
(500 MHz, CDCl3)
SiMe3
S
7.55
7.45
7.43
7.23
7.22
7.20
7.20
7.20
7.19
7.18
7.18
7.17
7.05
7.04
6.38
6.36
6.34
6.32
6.14
6.12
6.00
5.98
5.61
5.40
5.34
5.23
2.52
2.50
2.50
2.49
2.48
2.47
2.43
2.40
2.38
2.37
2.37
2.36
2.34
2.32
2.31
2.30
2.29
2.28
2.27
2.02
1.81
1.48
1.40
1.39
1.37
1.36
1.35
1.33
0.87
0.86
0.84
0.11
0.06
1.01
0.06
2.13
1.07
1.00
0.06
0.06
1.00
1.01
0.06
0.06
1.01
0.06
1.10
1.02
0.07
1.02
0.21
5.13
3.22
9.08
0.55
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ppm

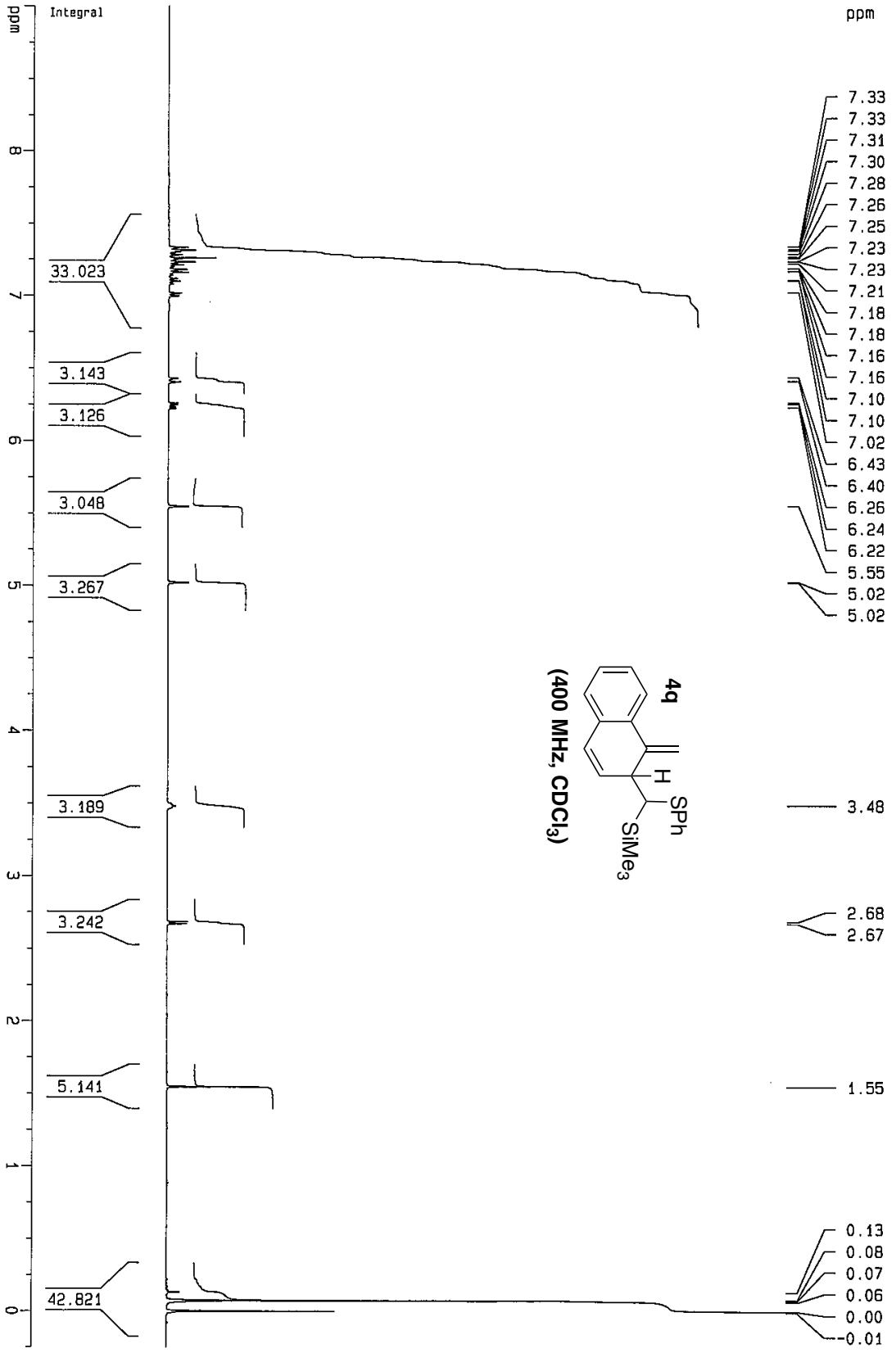

4n
(125 MHz, CDCl3)
SiMe3
S
151.01
149.61
141.06
139.60
135.05
133.78
132.25
128.07
127.97
127.52
126.28
125.82
125.29
125.12
124.54
113.60
45.46
44.19
43.26
42.82
39.97
38.09
29.77
25.03
23.89
23.16
22.87
13.73
0.68
ppm

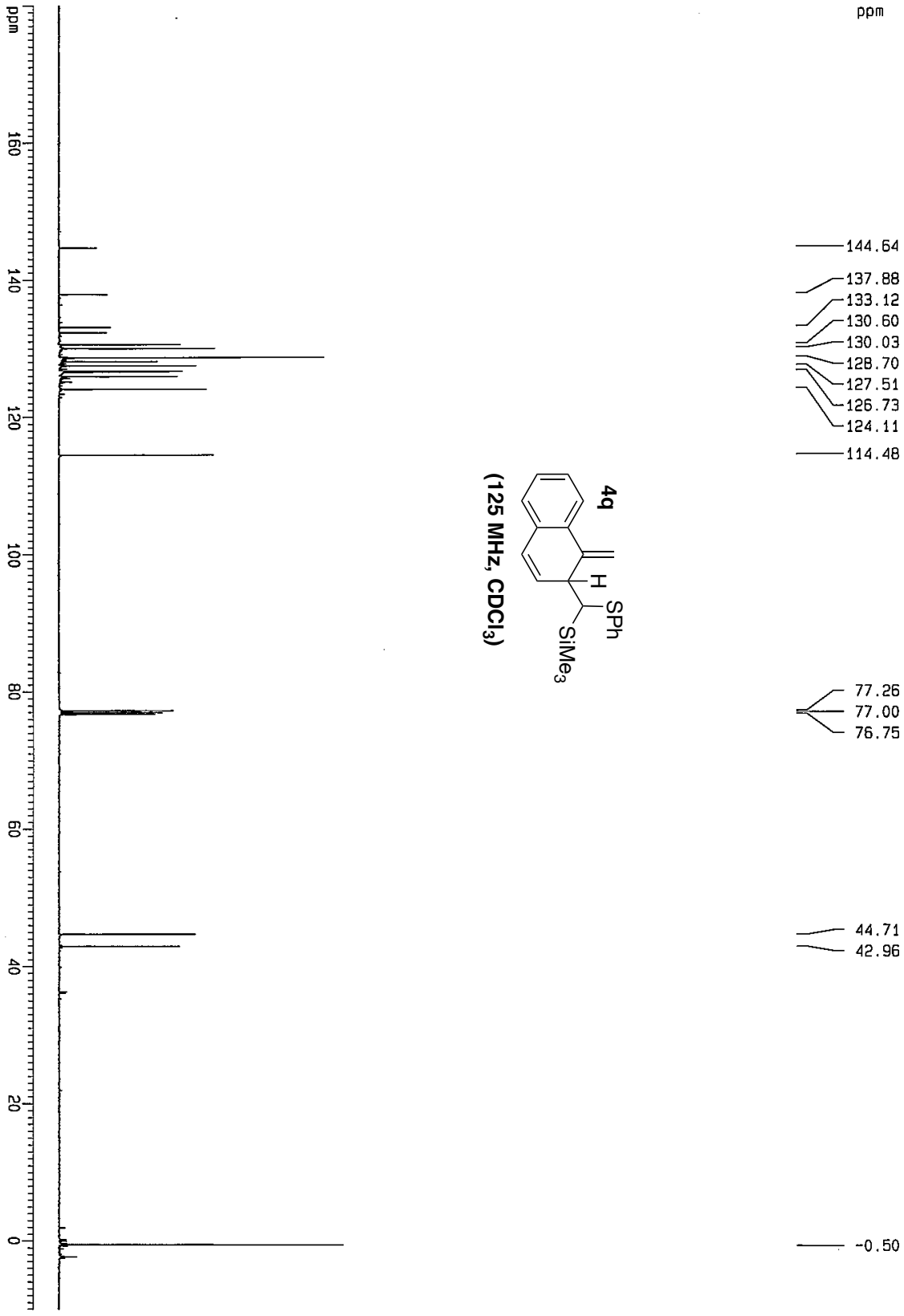

4o
(500 MHz, CDCl3)
SiMe3
S
O
+
SiMe3
S
O
ppm

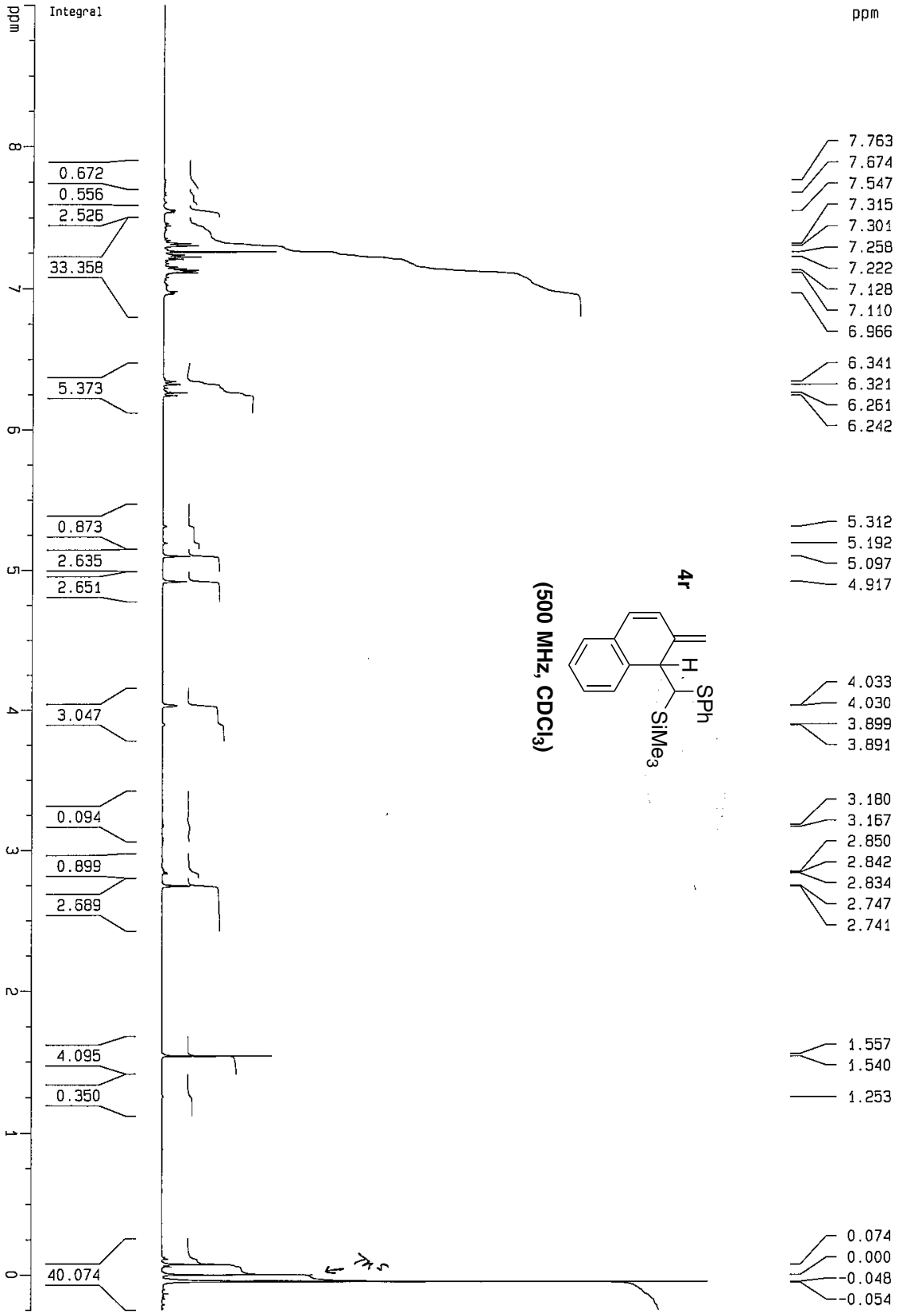

195.18
195.16
149.57
149.23
137.71
136.87
134.05
133.78
133.28
132.99
132.76
132.45
132.36
131.57
129.10
129.04
128.71
128.56
128.27
128.15
128.02
127.72
127.70
127.16
126.72
126.66
126.59
126.55
125.71
125.44
125.06
124.78
124.64
124.44
124.11
123.28
113.05
112.26
44.13
43.70
40.28
39.71
30.42
30.24
30.21
30.05
28.69
27.38
27.15
21.97
20.96
20.30
0.37
0.30
-2.48
4o
O
S
SiMe3
+
SiMe3
O
S
(125 MHz, CDCl3)
280
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm


4p
(125 MHz, CDCl3)
SiMe3
S
O
N
+
7.59
7.52
7.50
7.50
7.49
7.47
7.21
7.21
7.20
7.19
7.18
7.17
7.17
7.16
7.16
7.15
7.14
7.03
7.03
7.01
6.35
6.34
6.33
6.32
5.85
5.83
5.81
5.79
5.59
5.40
5.38
3.37
3.27
3.05
2.97
1.42
1.29
0.01
-0.00
0.30
0.33
0.60
1.98
0.33
0.38
4.06
2.03
1.00
0.95
1.05
1.94
0.95
2.02
0.65
0.99
0.99
6.04
6.06
0.28
1.81
0.86
3.00
3.07
2.67
18.02
ppm

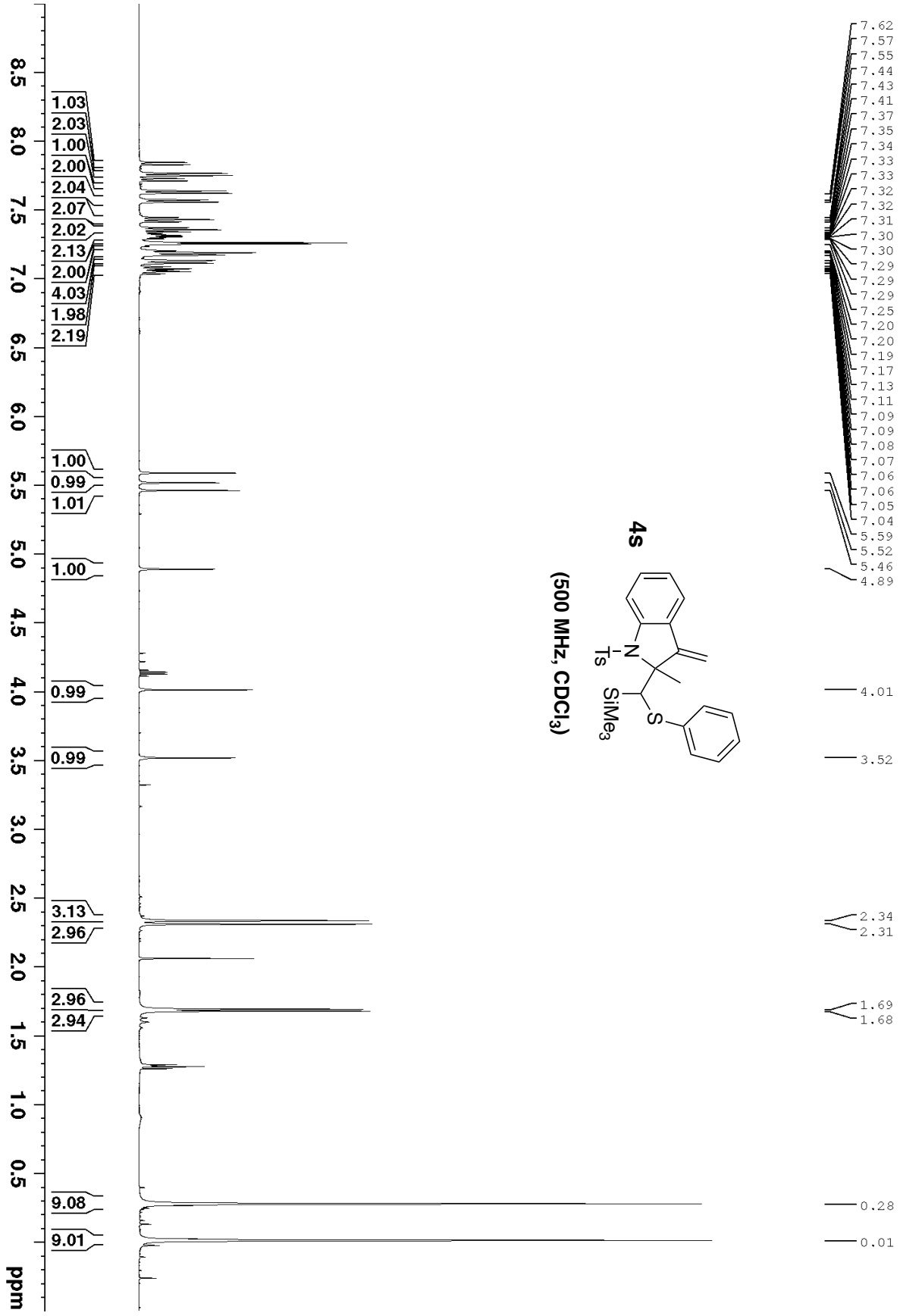

168.17
168.12
150.16
149.84
138.69
137.58
134.55
134.22
134.12
133.20
132.82
131.88
129.23
128.44
128.29
128.22
127.75
127.69
126.66
126.53
126.48
125.61
125.26
124.86
124.83
124.73
124.63
124.53
113.08
111.86
44.40
44.03
41.71
41.57
36.41
36.30
36.01
31.41
29.35
27.50
26.97
20.31
-0.09
-0.19
-3.04
4p
N
S
O
SiMe3
+
N
O
S
SiMe3
(125 MHz, CD3CN, 50 °C)
282
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm

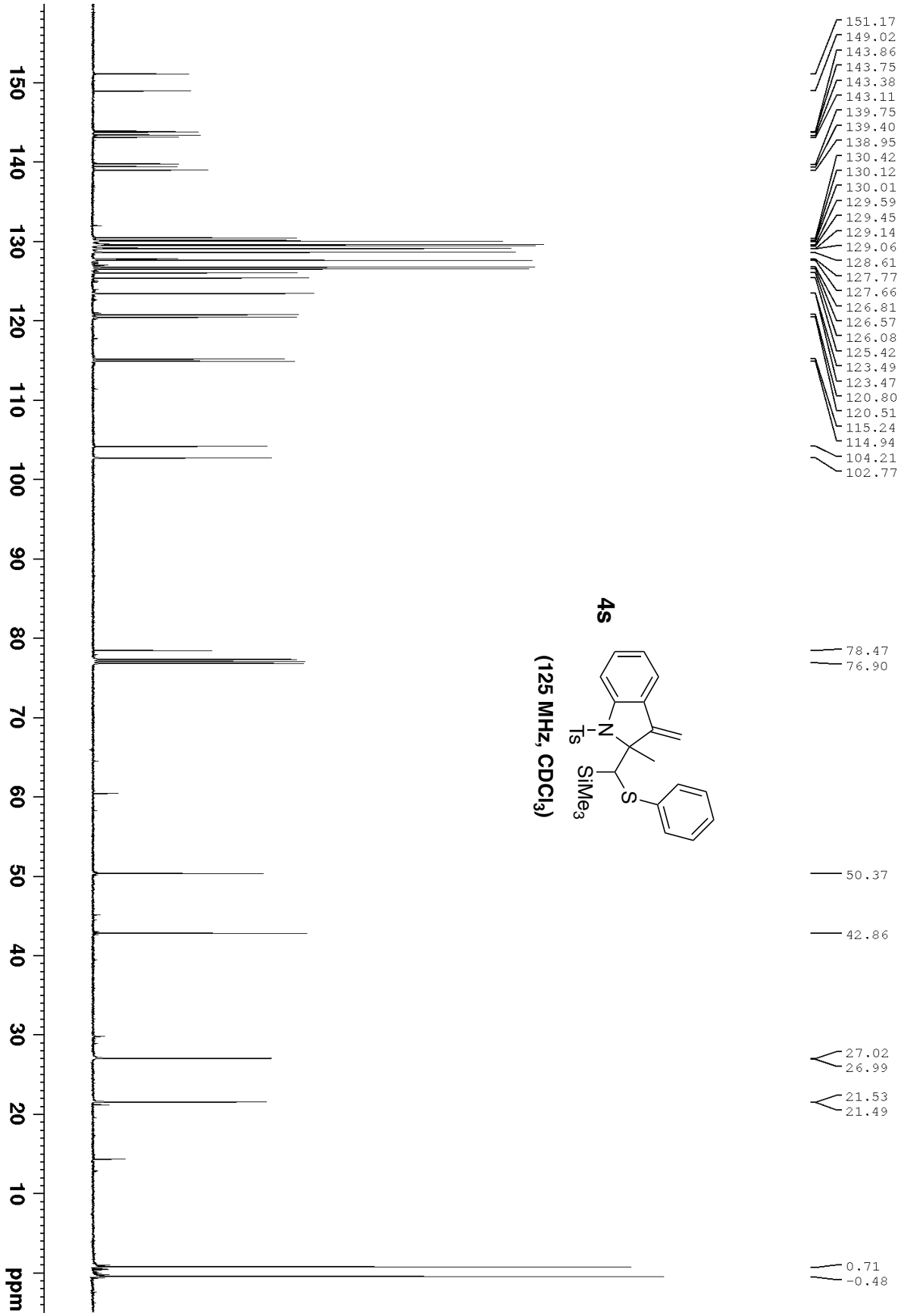

Integral
ppm
33.023
3.143
3.126
3.048
3.267
3.189
3.242
5.141
42.821
7.33
7.33
7.31
7.30
7.28
7.26
7.25
7.23
7.23
7.21
7.18
7.18
7.16
7.16
7.10
7.10
7.02
6.43
6.40
6.26
6.24
6.22
5.55
5.02
5.02
3.48
2.68
2.67
1.55
0.13
0.08
0.07
0.06
0.00
-0.01
4q
(400 MHz, CDCl3)
H
SPh
SiMe3

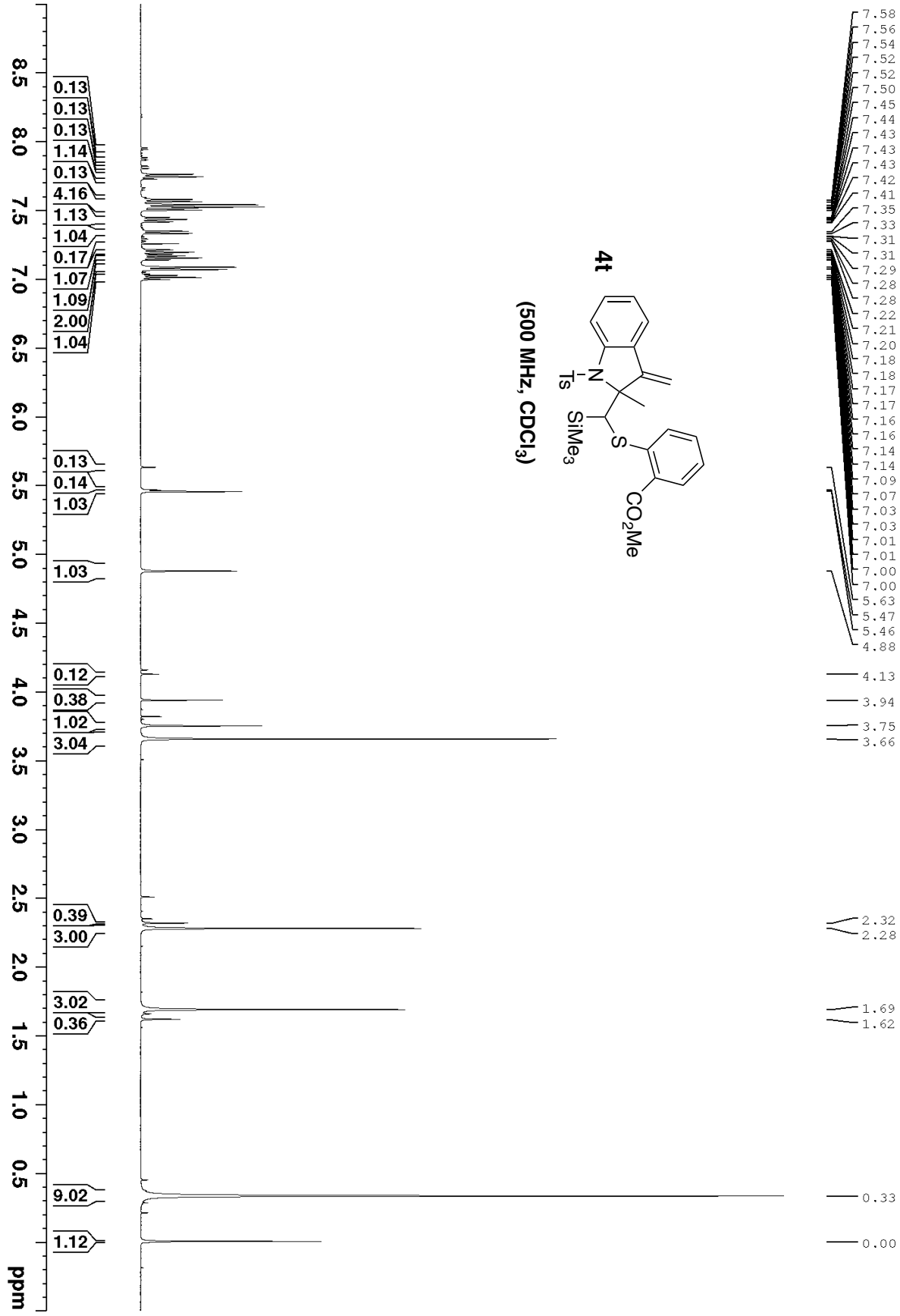

ppm
160
140
120
100
80
60
40
20
0
4q
(125 MHz, CDCl3)
H
SPh
SiMe3
ppm
144.64
137.88
133.12
130.60
130.03
128.70
127.51
126.73
124.11
114.48
77.26
77.00
76.75
44.71
42.96
-0.50

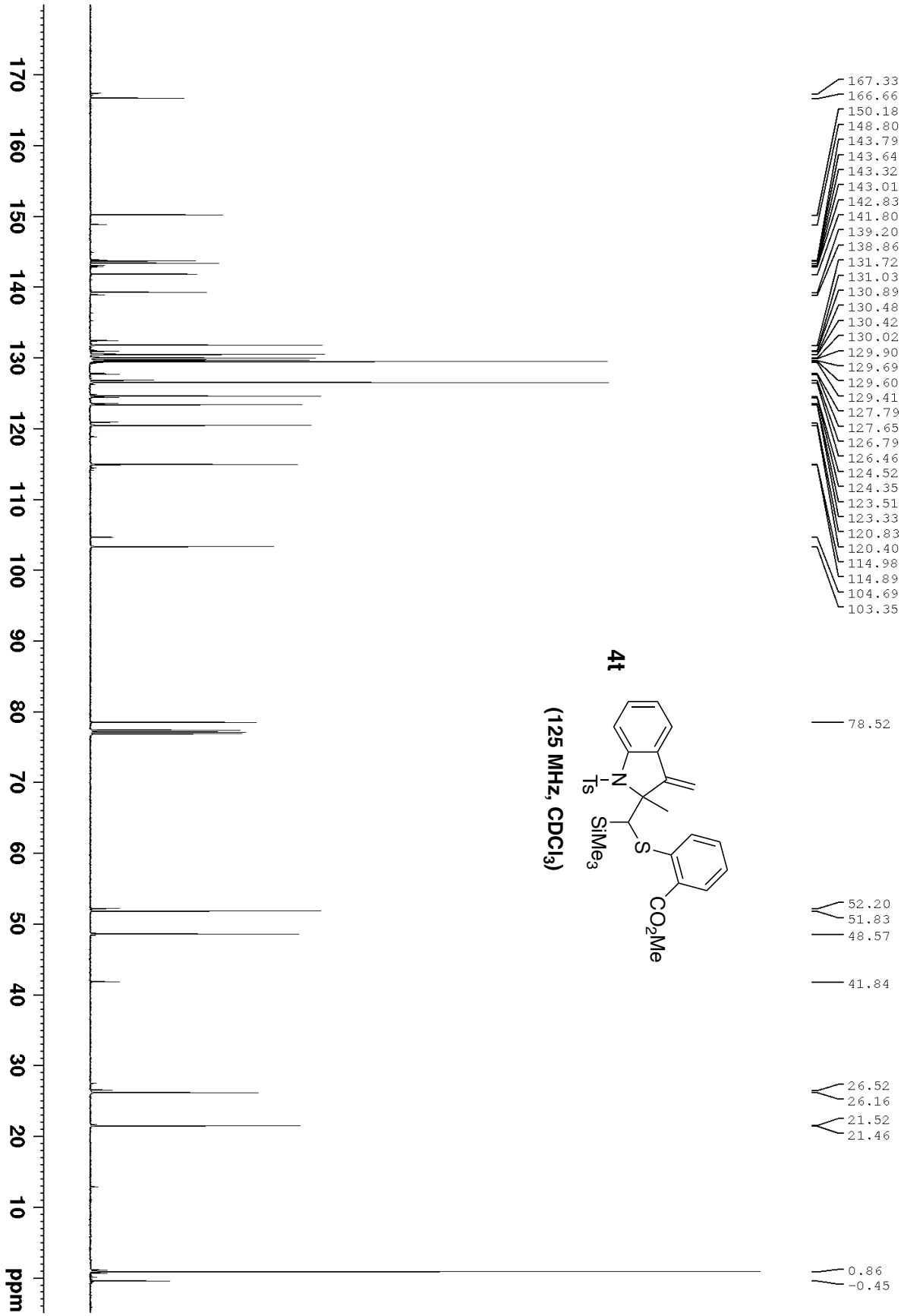

Integral
ppm
0.672
0.556
2.526
33.358
5.373
0.873
2.635
2.651
3.047
0.094
0.899
2.689
4.095
0.350
40.074
7.763
7.674
7.547
7.315
7.301
7.258
7.222
7.128
7.110
6.966
6.341
6.321
6.261
6.242
5.312
5.192
5.097
4.917
4.033
4.030
3.899
3.891
3.180
3.167
2.850
2.842
2.834
2.747
2.741
1.557
1.540
1.253
0.074
0.000
-0.048
-0.054
4r
(500 MHz, CDCl3)
H
SPh
SiMe3

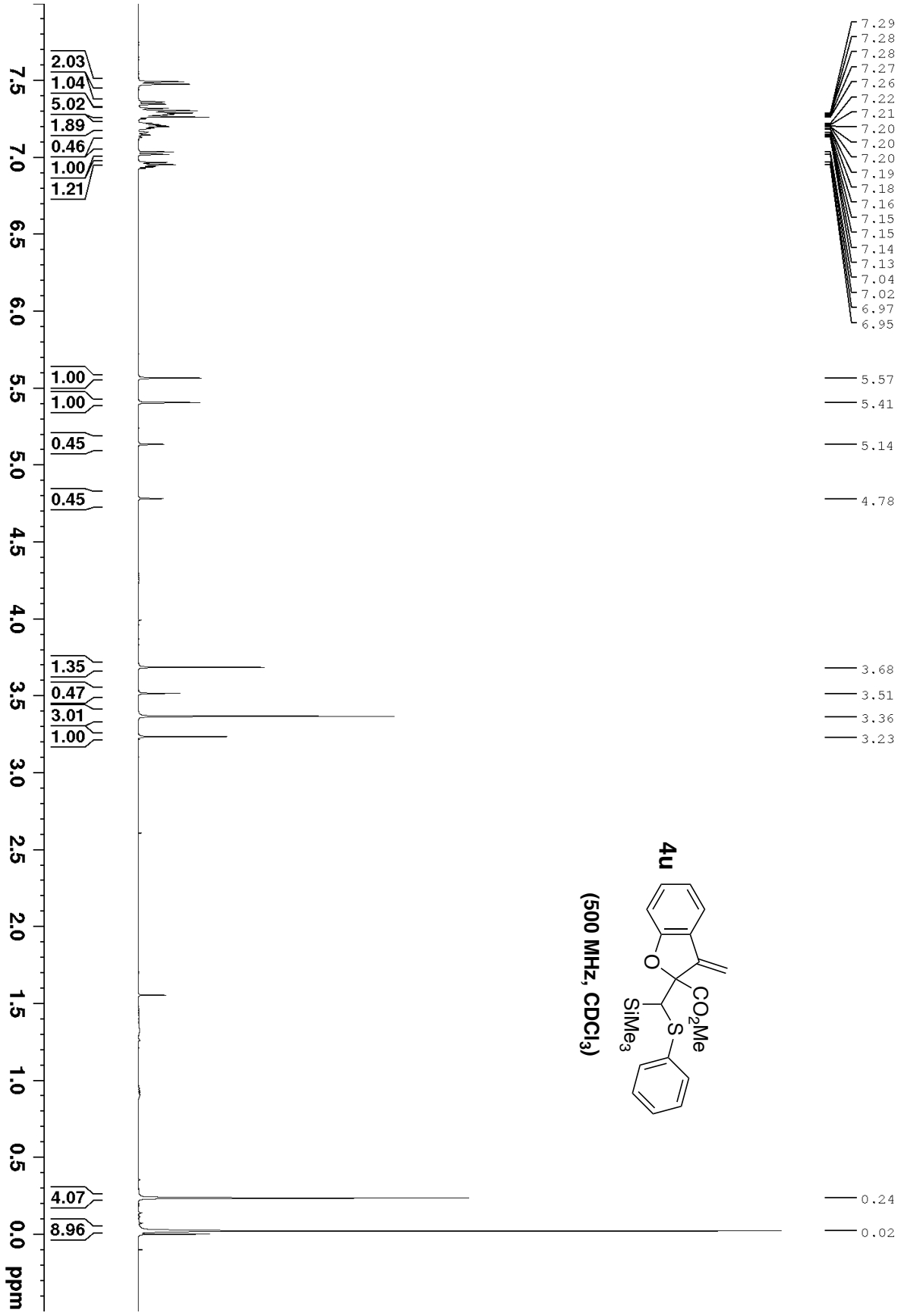
ppm
160
140
120
100
80
60
40
20
0
4r
(125 MHz, CDCl3)
H
SPh
SiMe3
ppm
146.18
142.29
137.86
137.76
130.34
129.13
128.67
126.96
126.78
126.07
118.54
116.62
77.26
77.00
76.75
49.92
46.56
45.32
45.20
38.34
36.67
-0.54
-0.65
-0.75
-0.96
-2.17

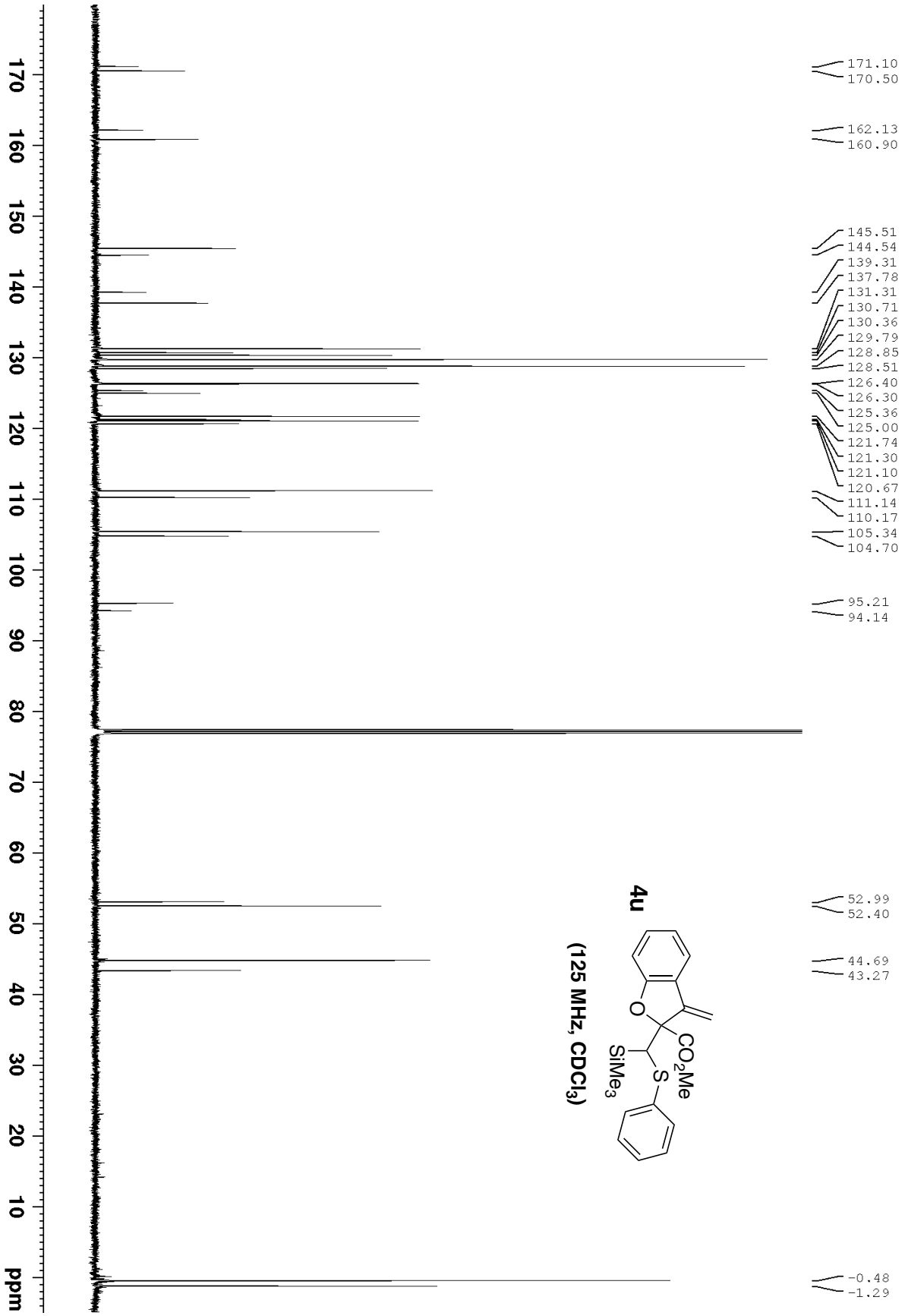

4s
(500 MHz, CDCl3)
Ts
N
SiMe3
S
7.62
7.57
7.55
7.44
7.43
7.41
7.37
7.35
7.34
7.33
7.33
7.32
7.32
7.31
7.30
7.30
7.29
7.29
7.29
7.25
7.20
7.20
7.19
7.17
7.13
7.11
7.09
7.09
7.08
7.07
7.06
7.06
7.05
7.04
5.59
5.52
5.46
4.89
4.01
3.52
2.34
2.31
1.69
1.68
0.28
0.01
1.03
2.03
1.00
2.00
2.04
2.07
2.02
2.13
2.00
4.03
1.98
2.19
1.00
0.99
1.01
1.00
0.99
0.99
3.13
2.96
2.96
2.94
9.08
9.01
ppm

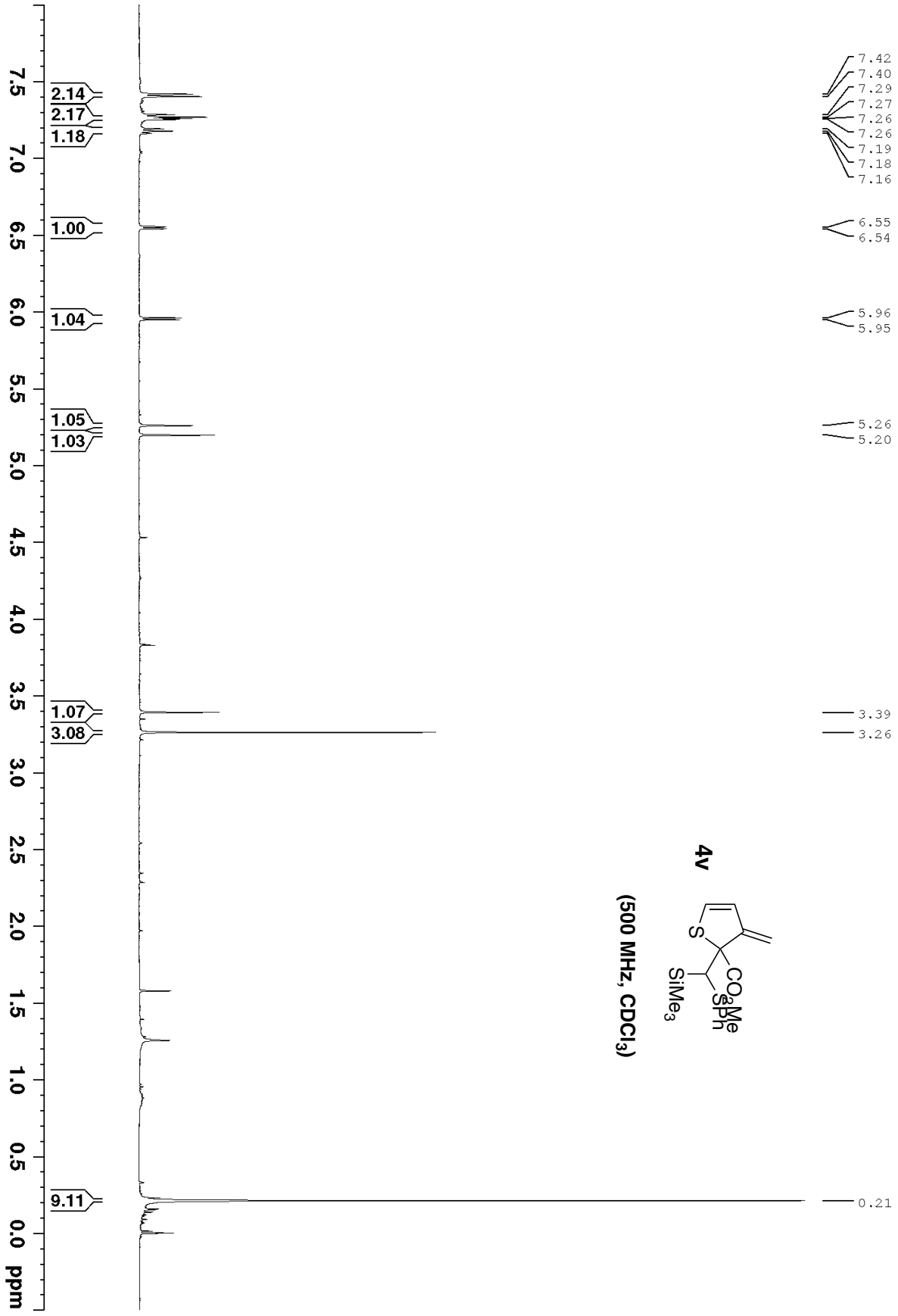

151.17
149.02
143.86
143.75
143.38
143.11
139.75
139.40
138.95
130.42
130.12
130.01
129.59
129.45
129.14
129.06
128.61
127.77
127.66
126.81
126.57
126.08
125.42
123.49
123.47
120.80
120.51
115.24
114.94
104.21
102.77
78.47
76.90
50.37
42.86
27.02
26.99
21.53
21.49
0.71
-0.48
4s
(125 MHz, CDCl3)
N
Ts
SiMe3
S
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm

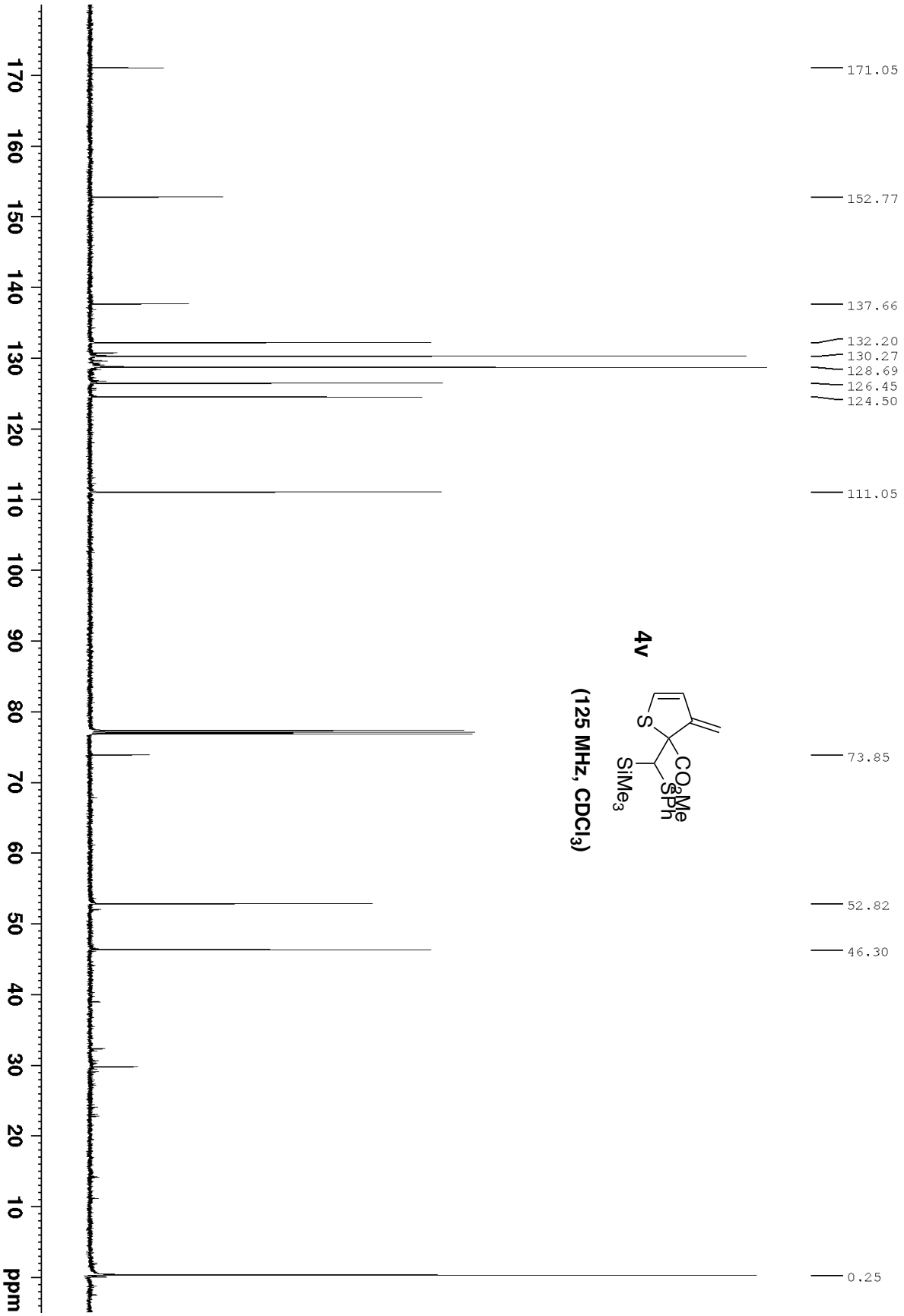

4t
(500 MHz, CDCl3)
Ts
N
SiMe3
S
CO2Me
7.58
7.56
7.54
7.52
7.52
7.50
7.45
7.44
7.43
7.43
7.43
7.42
7.41
7.35
7.33
7.31
7.31
7.29
7.28
7.28
7.22
7.21
7.20
7.18
7.18
7.17
7.17
7.16
7.16
7.14
7.14
7.09
7.07
7.03
7.03
7.01
7.01
7.00
7.00
5.63
5.47
5.46
4.88
4.13
3.94
3.75
3.66
2.32
2.28
1.69
1.62
0.33
0.00
0.13
0.13
0.13
1.14
0.13
4.16
1.13
1.04
0.17
1.07
1.09
2.00
1.04
0.13
0.14
1.03
1.03
0.12
0.38
1.02
3.04
0.39
3.00
3.02
0.36
9.02
1.12
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
ppm

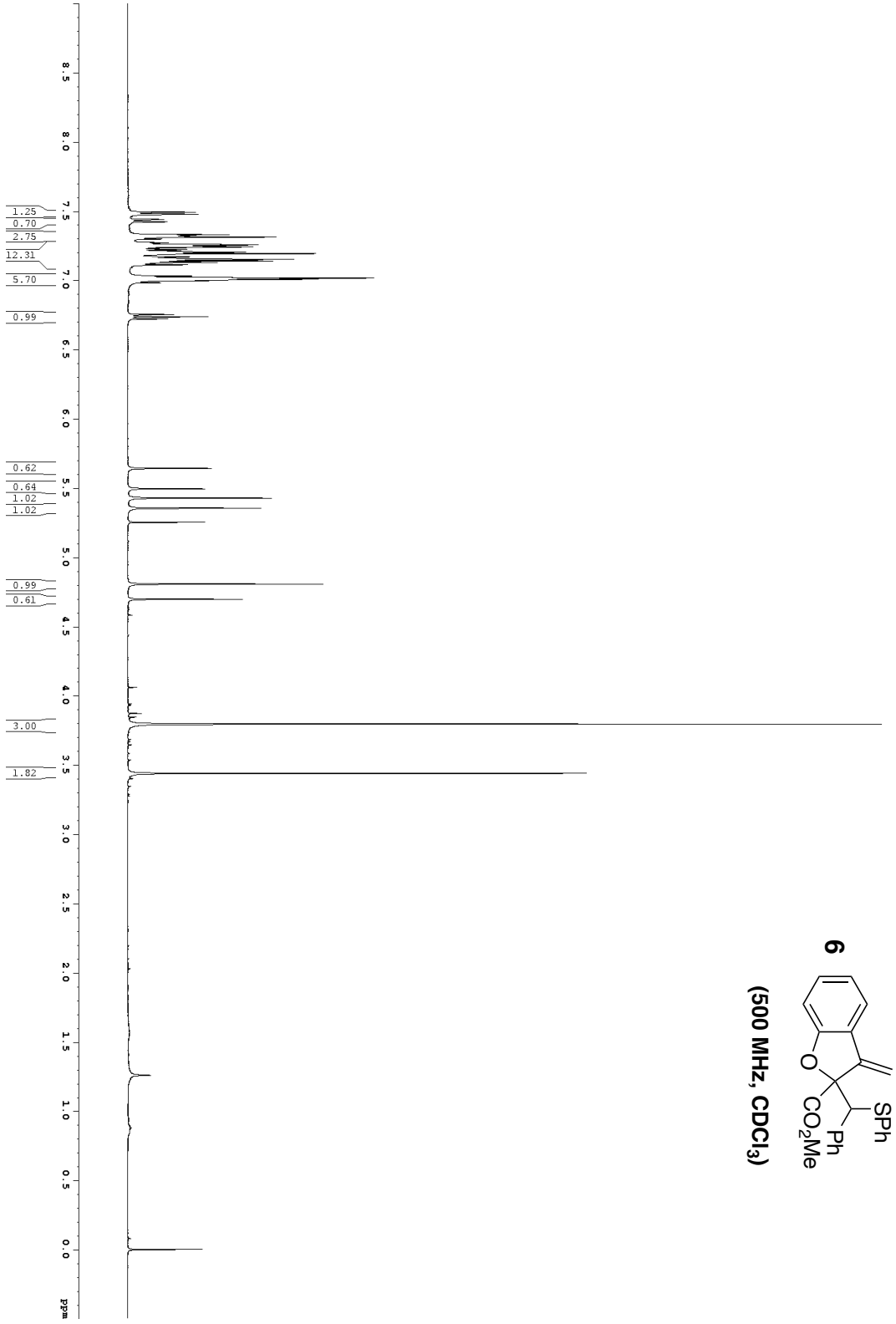

4t
(125 MHz, CDCl3)
Ts
N
SiMe3
S
CO2Me
167.33
166.66
150.18
148.80
143.79
143.64
143.32
143.01
142.83
141.80
139.20
138.86
131.72
131.03
130.89
130.48
130.42
130.02
129.90
129.69
129.60
129.41
127.79
127.65
126.79
126.46
124.52
124.35
123.51
123.33
120.83
120.40
114.98
114.89
104.69
103.35
78.52
52.20
51.83
48.57
41.84
26.52
26.16
21.52
21.46
0.86
-0.45
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm


4u
(500 MHz, CDCl3)
CO2Me
SiMe3
S
O
2.03
1.04
5.02
1.89
0.46
1.00
1.21
1.00
1.00
0.45
0.45
1.35
0.47
3.01
1.00
4.07
8.96
7.29
7.28
7.28
7.27
7.26
7.22
7.21
7.20
7.20
7.20
7.19
7.18
7.16
7.15
7.15
7.14
7.13
7.04
7.02
6.97
6.95
5.57
5.41
5.14
4.78
3.68
3.51
3.36
3.23
0.24
0.02
ppm


171.10
170.50
162.13
160.90
145.51
144.54
139.31
137.78
131.31
130.71
130.36
129.79
128.85
128.51
126.40
126.30
125.36
125.00
121.74
121.30
121.10
120.67
111.14
110.17
105.34
104.70
95.21
94.14
52.99
52.40
44.69
43.27
-0.48
-1.29
4u
(125 MHz, CDCl3)
O
CO2Me
SiMe3
S
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm

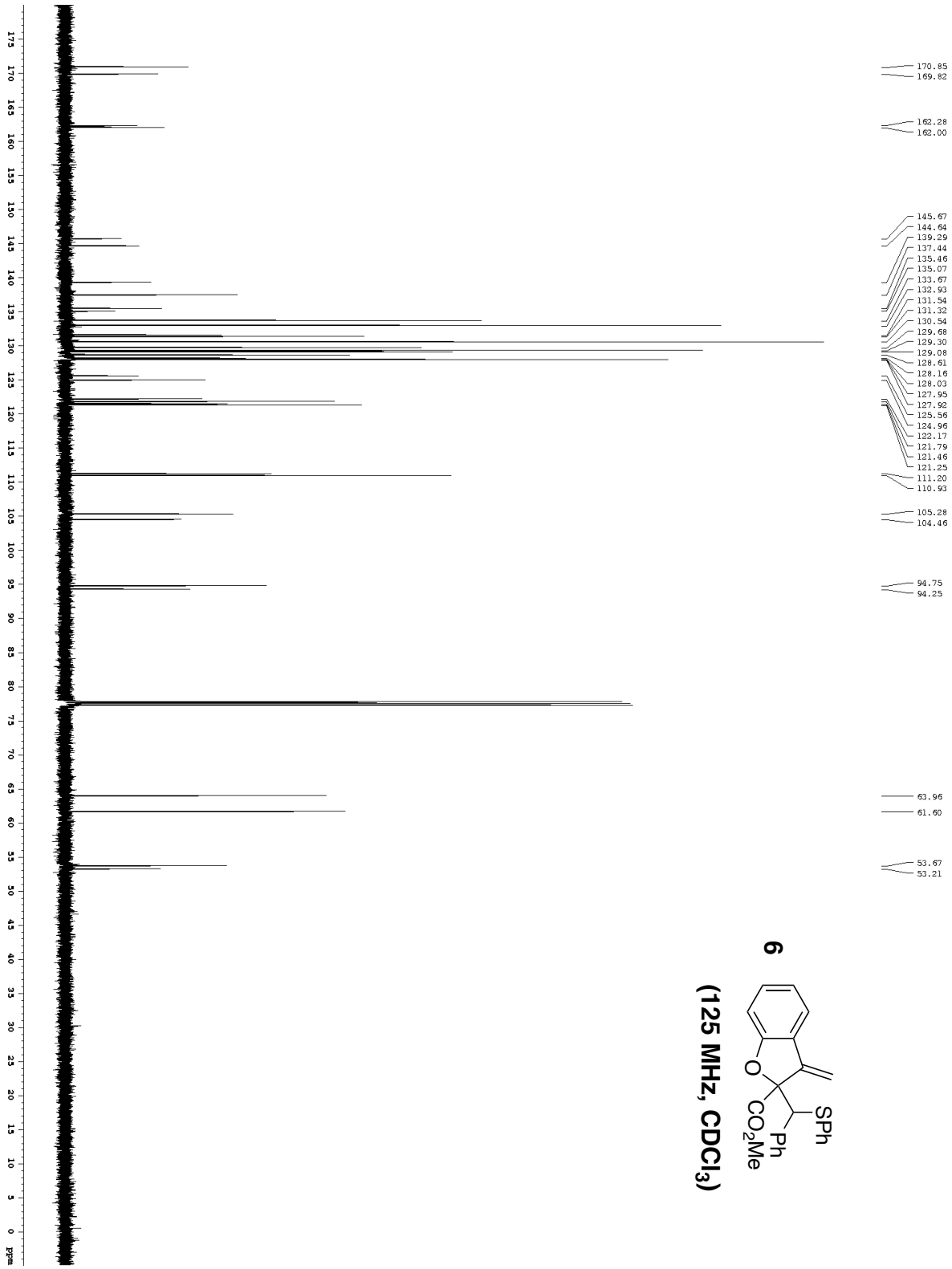

4v
(500 MHz, CDCl3)
7.42
7.40
7.29
7.27
7.26
7.26
7.19
7.18
7.16
6.55
6.54
5.96
5.95
5.26
5.20
3.39
3.26
0.21
2.14
2.17
1.18
1.00
1.04
1.05
1.03
1.07
3.08
9.11
ppm

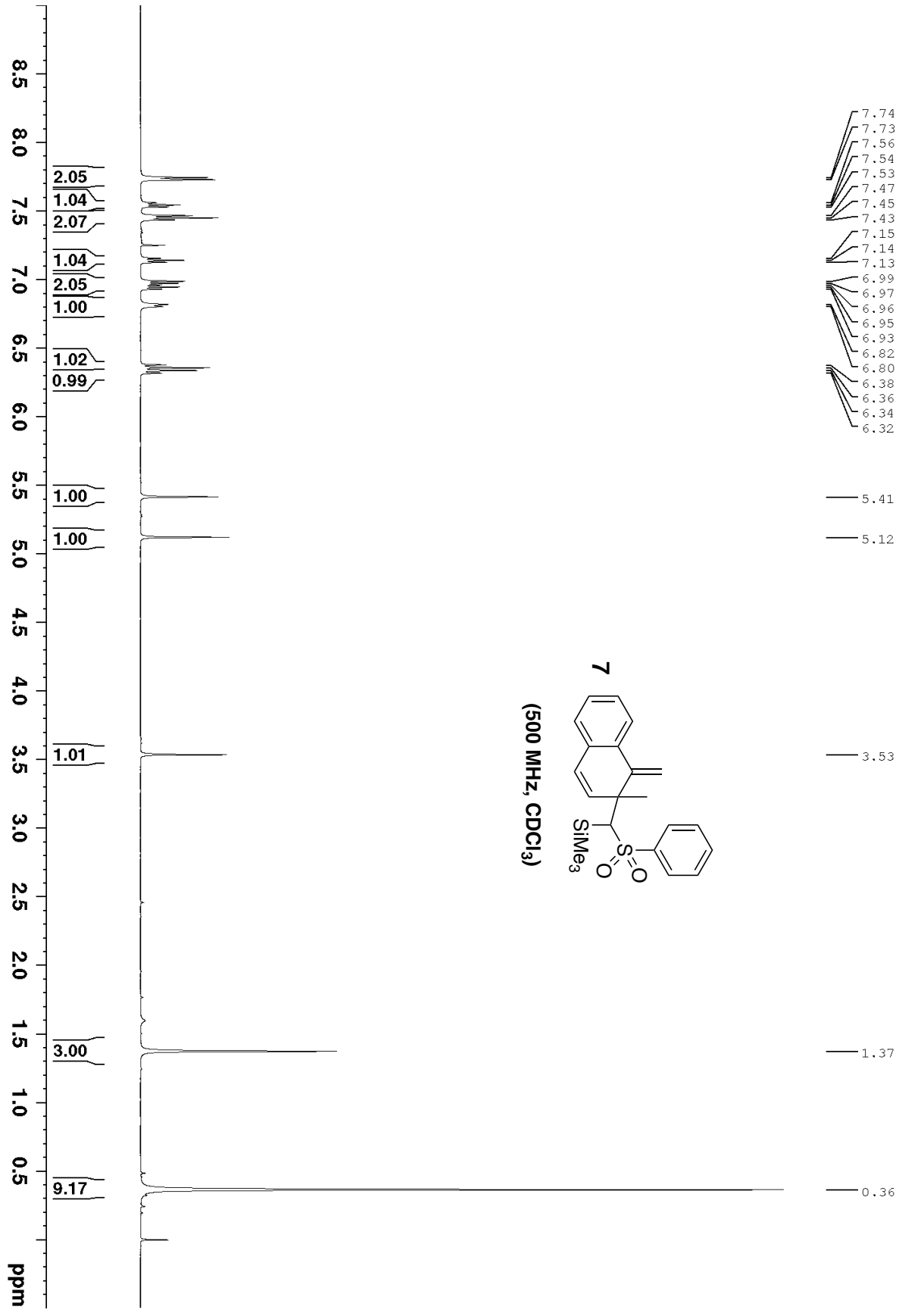

171.05
152.77
137.66
132.20
130.27
128.69
126.45
124.50
111.05
73.85
52.82
46.30
0.25
4v
(125 MHz, CDCl3)
S
CO2Me
SiMe3
Ph
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm

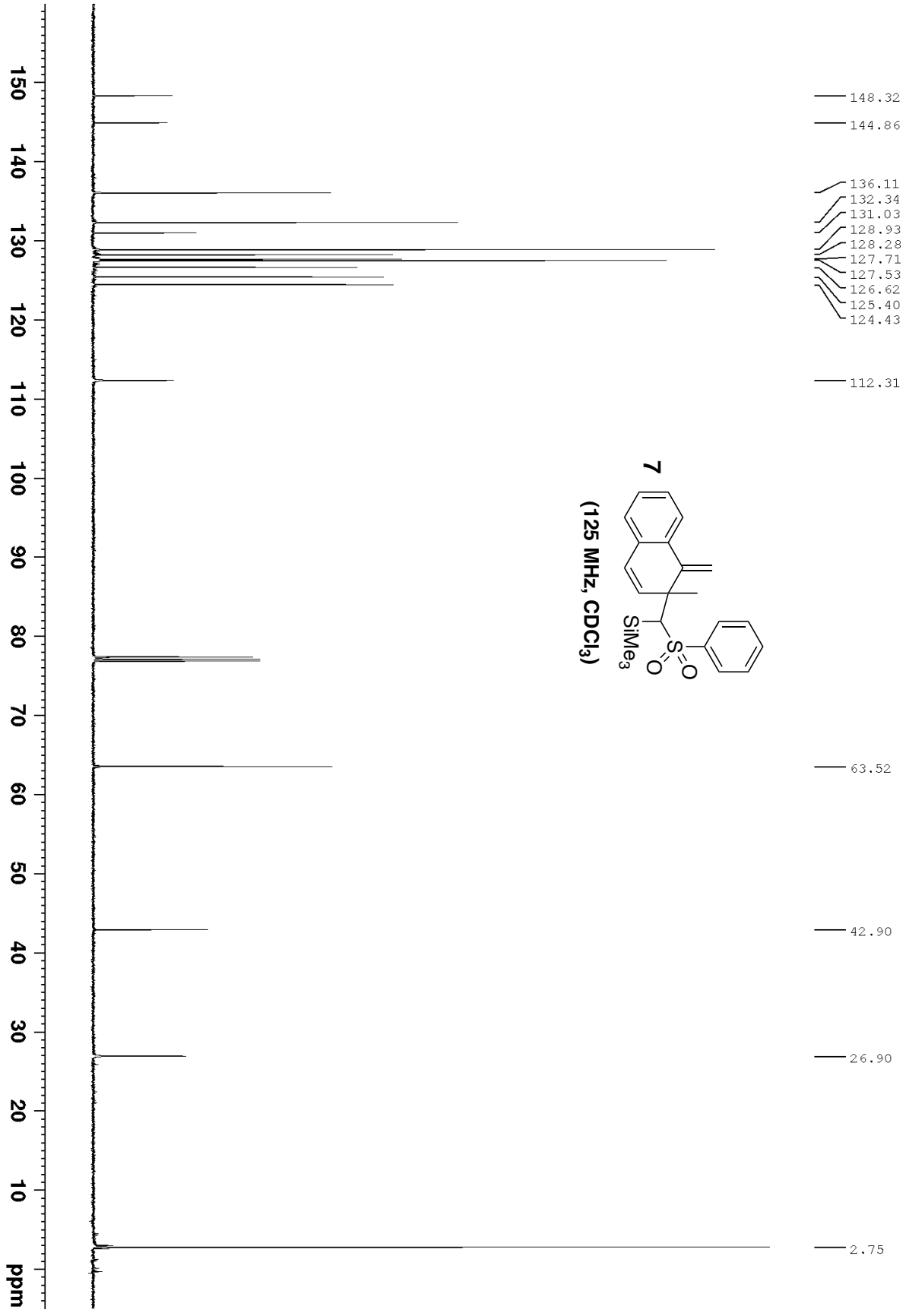


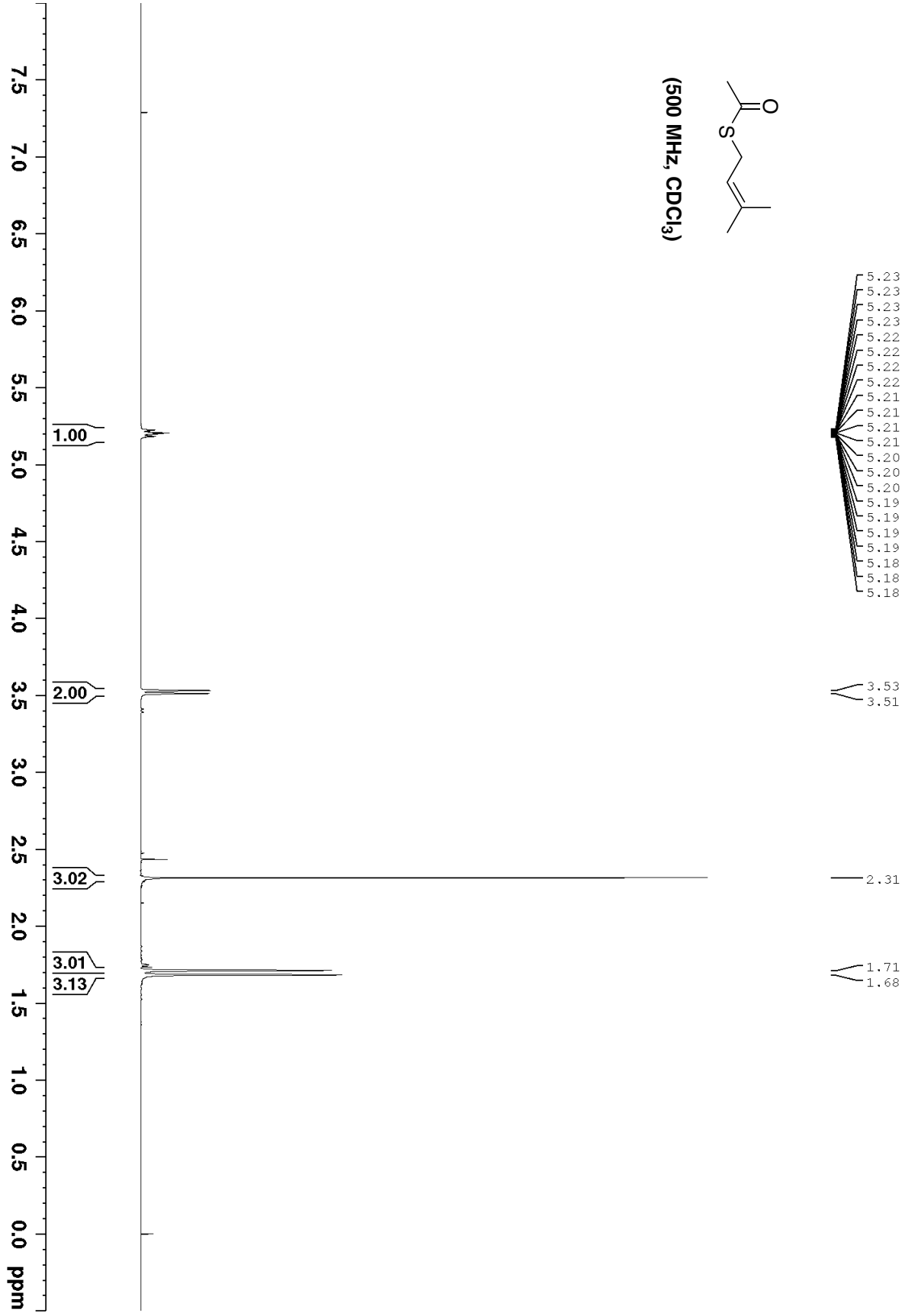
6

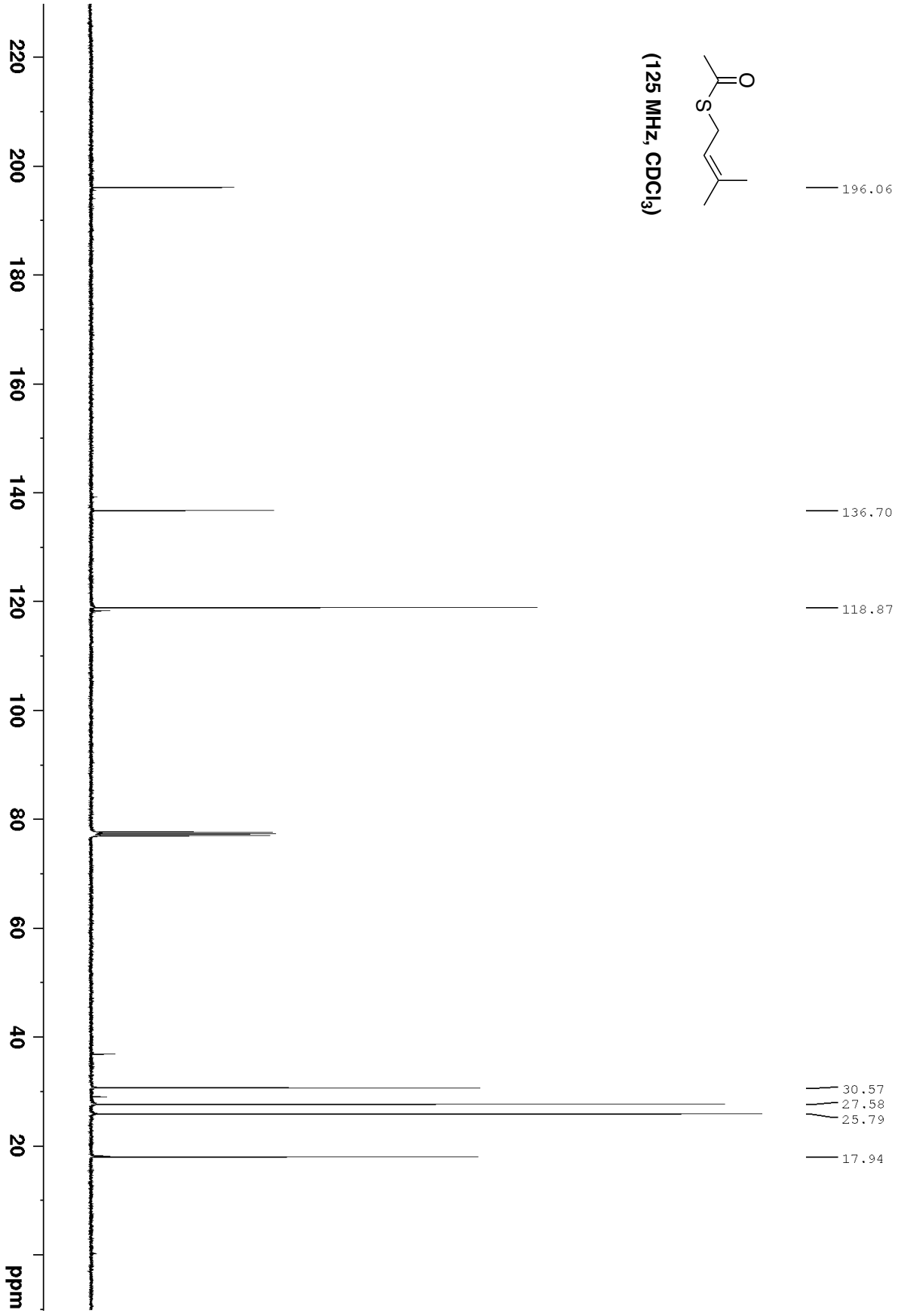
(500 MHz, $CDCl_3$)

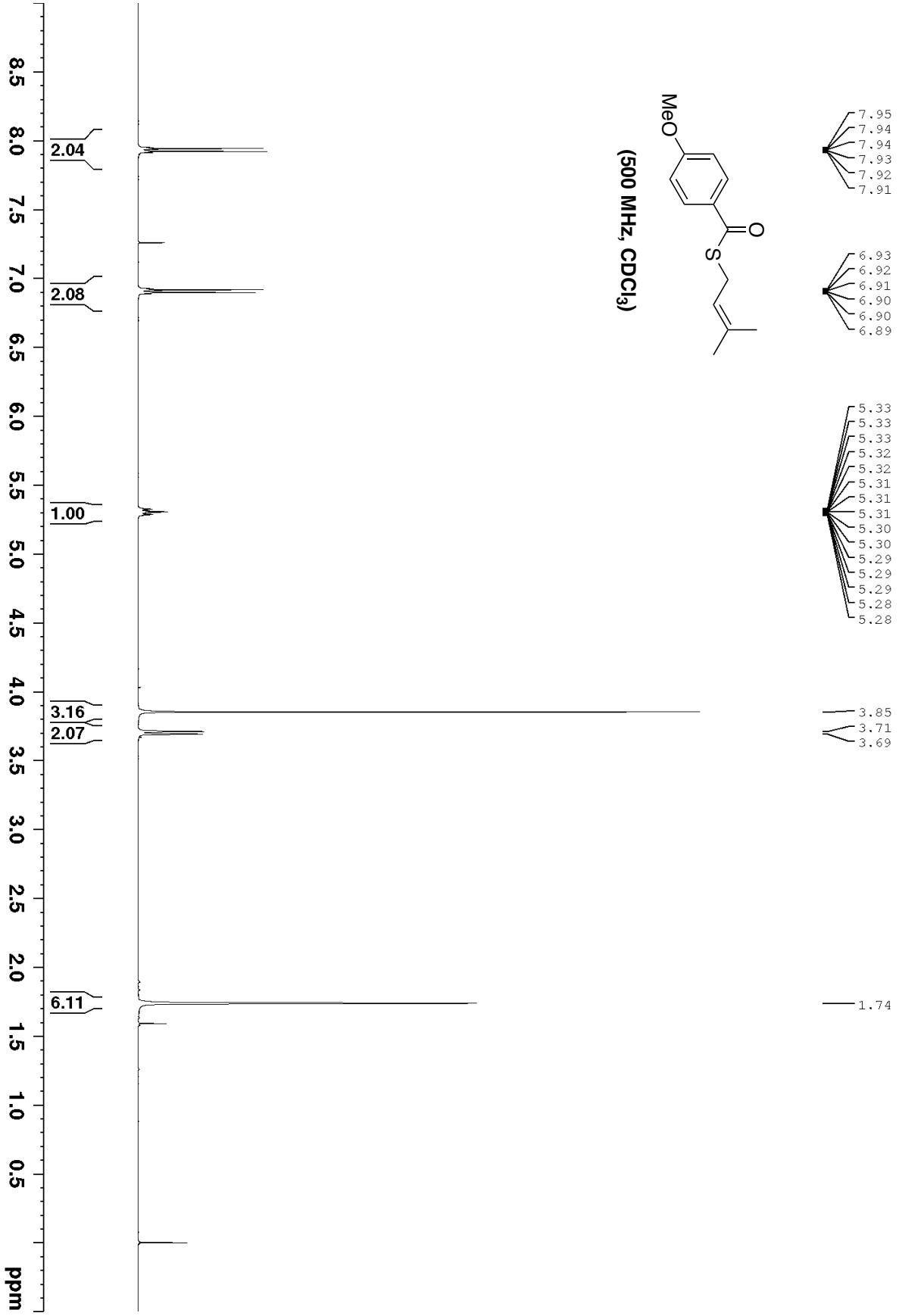

170.85
169.82
162.28
162.00
145.67
144.64
139.29
137.44
135.46
135.07
133.67
132.93
131.54
131.32
130.54
129.68
129.30
129.08
128.61
128.16
128.03
127.95
127.92
125.56
124.96
122.17
121.79
121.46
121.25
111.20
110.93
105.28
104.46
94.75
94.25
63.96
61.60
53.67
53.21
6
SPh
Ph
CO2Me
O
(125 MHz, CDCl3)

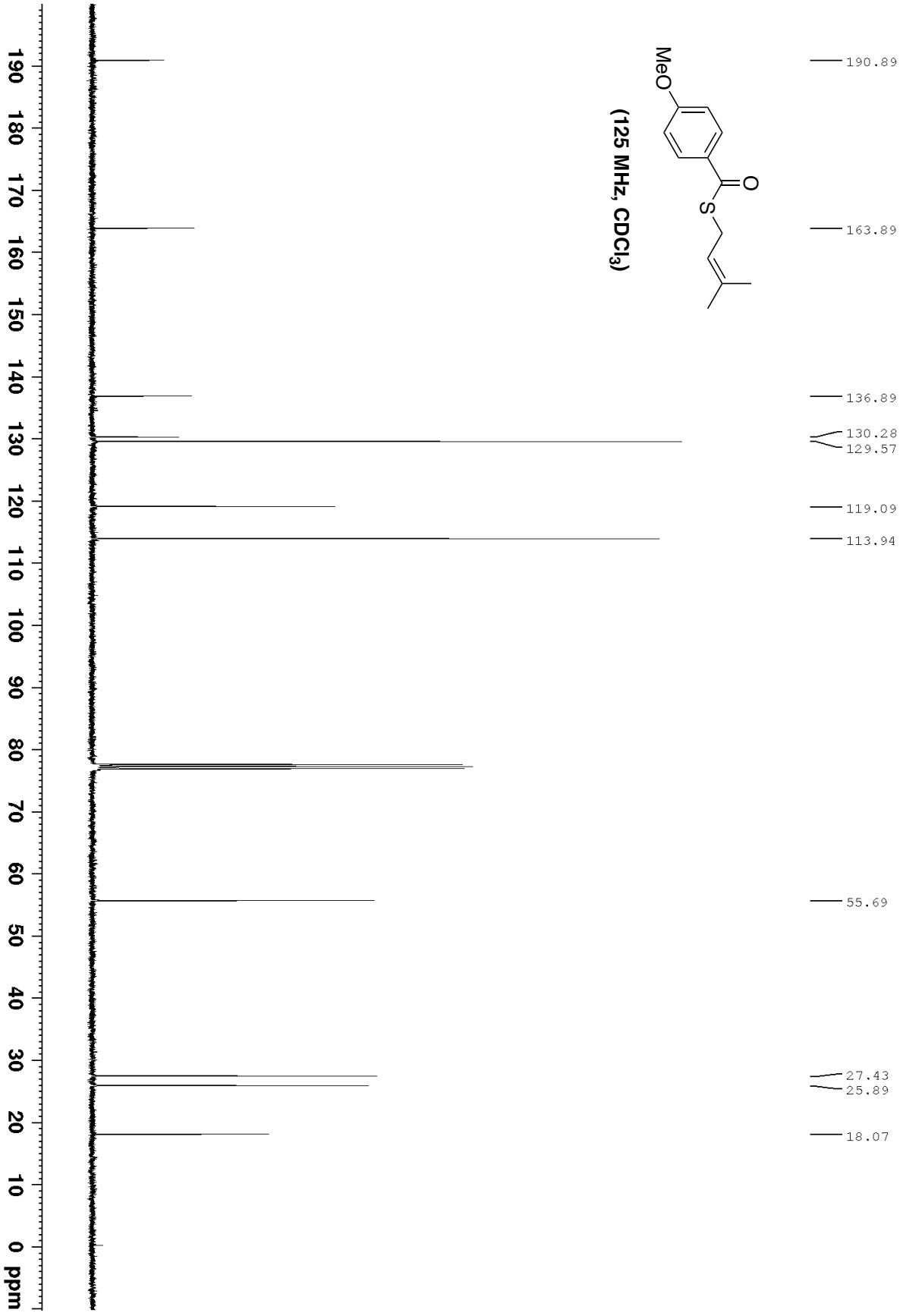

7
(500 MHz, CDCl3)
SiMe3
S
O
O
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
ppm
2.05
1.04
2.07
1.04
2.05
1.00
1.02
0.99
1.00
1.00
1.01
3.00
9.17
7.74
7.73
7.56
7.54
7.53
7.47
7.45
7.43
7.15
7.14
7.13
6.99
6.97
6.96
6.95
6.93
6.82
6.80
6.38
6.36
6.34
6.32
5.41
5.12
3.53
1.37
0.36

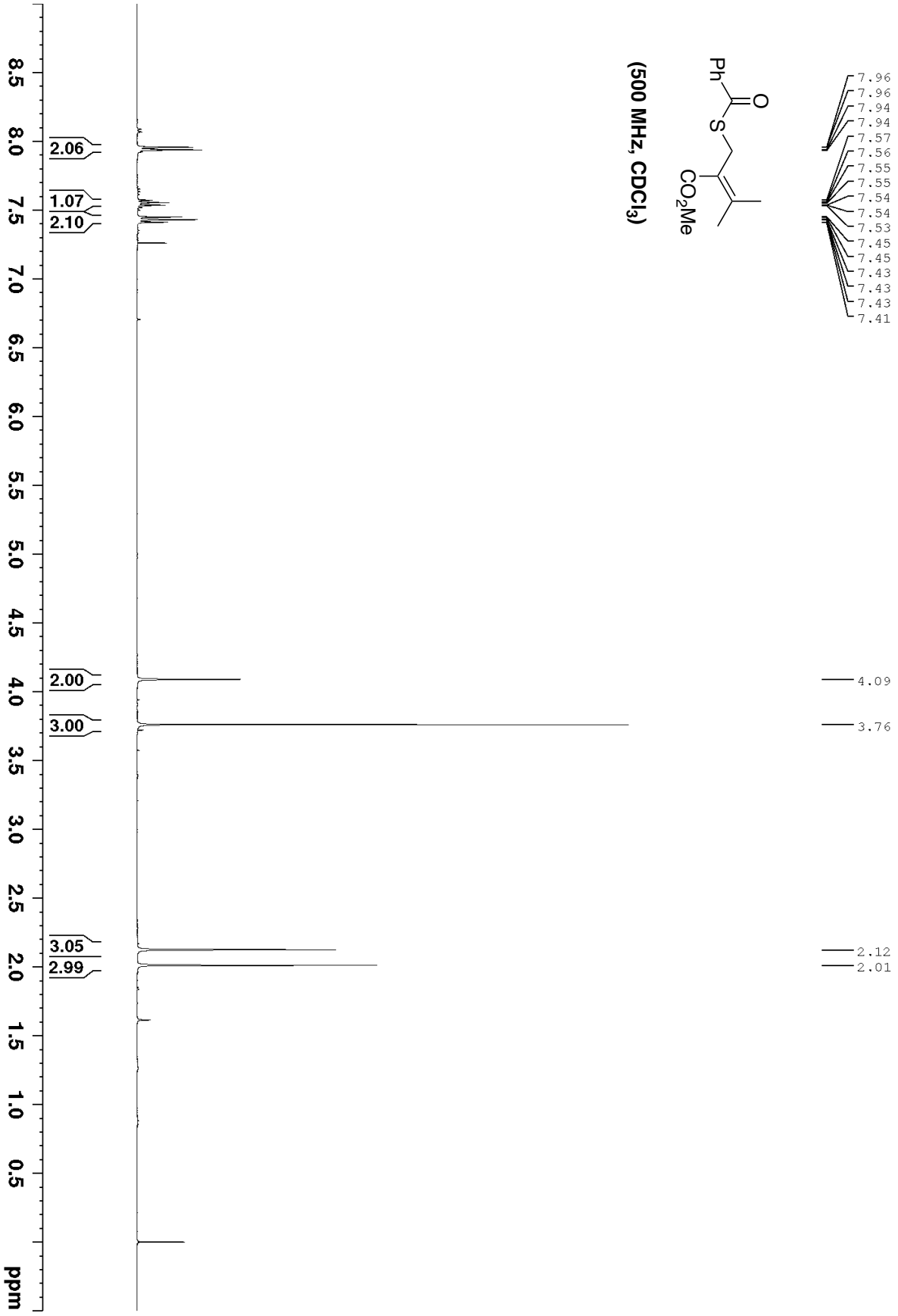

148.32
144.86
136.11
132.34
131.03
128.93
128.28
127.71
127.53
126.62
125.40
124.43
112.31
63.52
42.90
26.90
2.75
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm
7
(125 MHz, CDCl3)
SiMe3
S
O
O

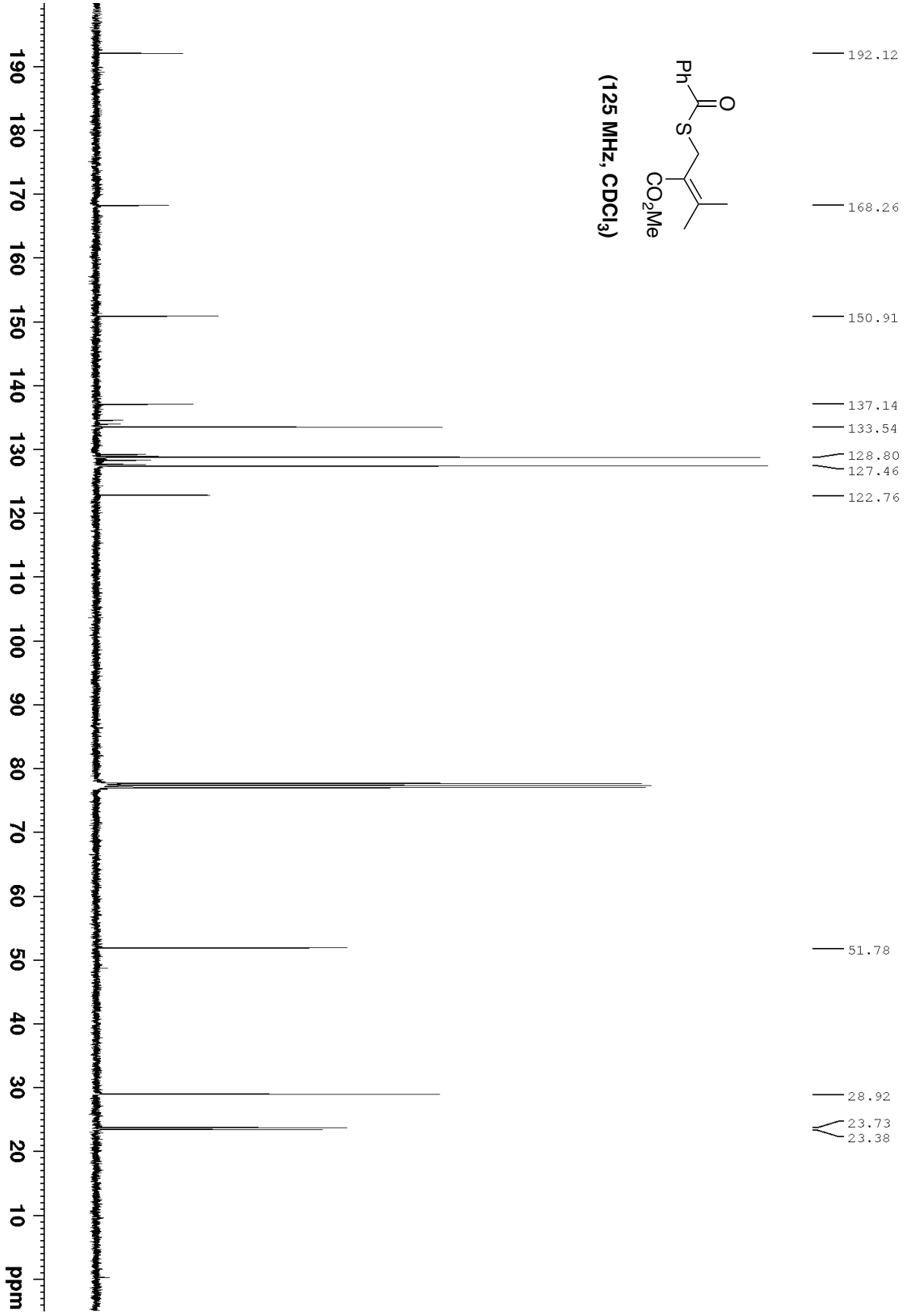

(500 MHz, CDCl3)
O
S
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ppm
1.00
2.00
3.02
3.01
3.13
5.23
5.23
5.23
5.23
5.22
5.22
5.22
5.22
5.21
5.21
5.21
5.21
5.20
5.20
5.20
5.19
5.19
5.19
5.19
5.18
5.18
5.18
3.53
3.51
2.31
1.71
1.68

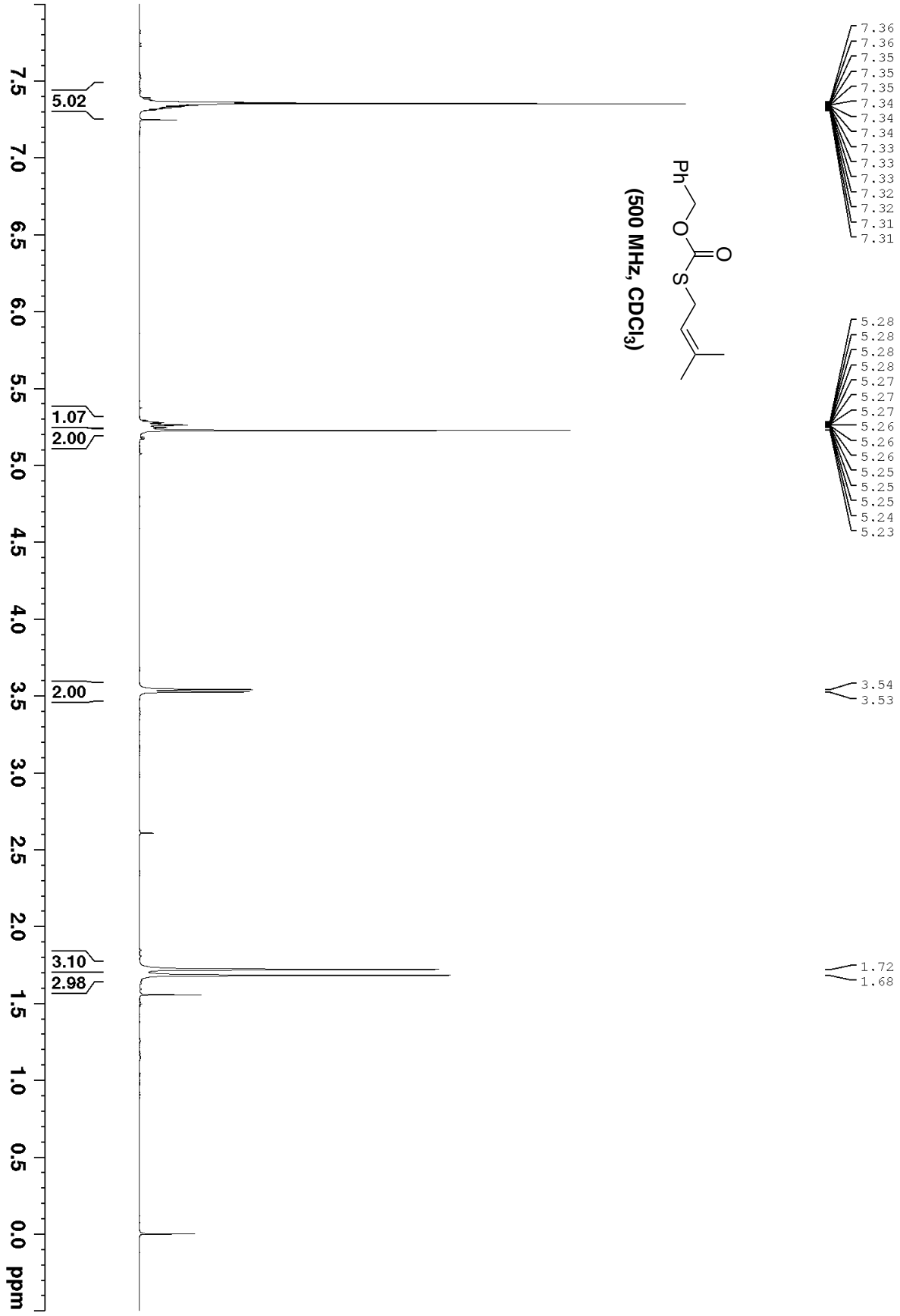

(125 MHz, CDCl3)
O
S
196.06
136.70
118.87
30.57
27.58
25.79
17.94
220
200
180
160
140
120
100
80
60
40
20
ppm

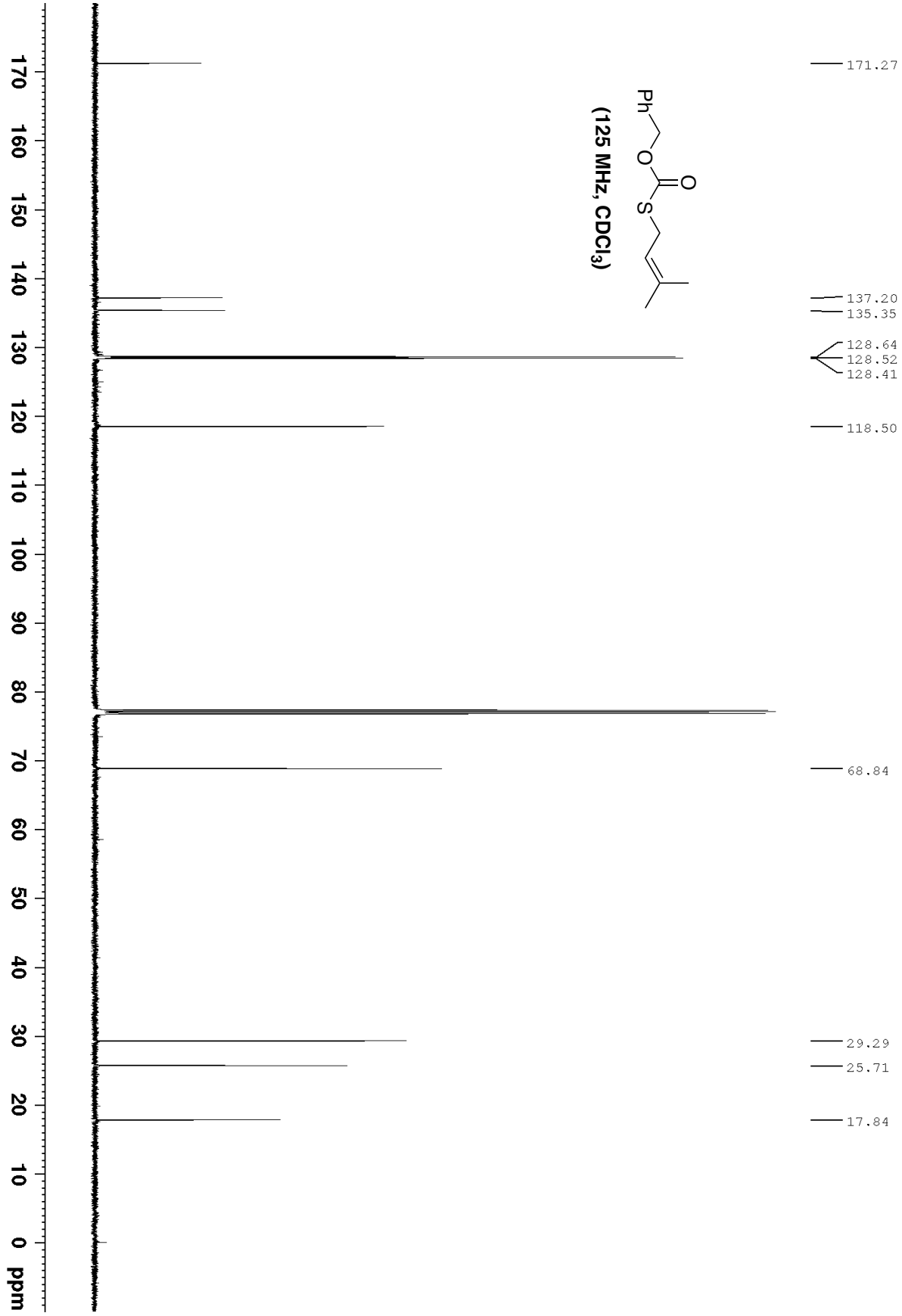

(500 MHz, CDCl3)
MeO
O
S
7.95
7.94
7.94
7.93
7.92
7.91
6.93
6.92
6.91
6.90
6.90
6.89
5.33
5.33
5.33
5.32
5.32
5.31
5.31
5.31
5.30
5.30
5.29
5.29
5.29
5.28
5.28
3.85
3.71
3.69
1.74
2.04
2.08
1.00
3.16
2.07
6.11
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
ppm

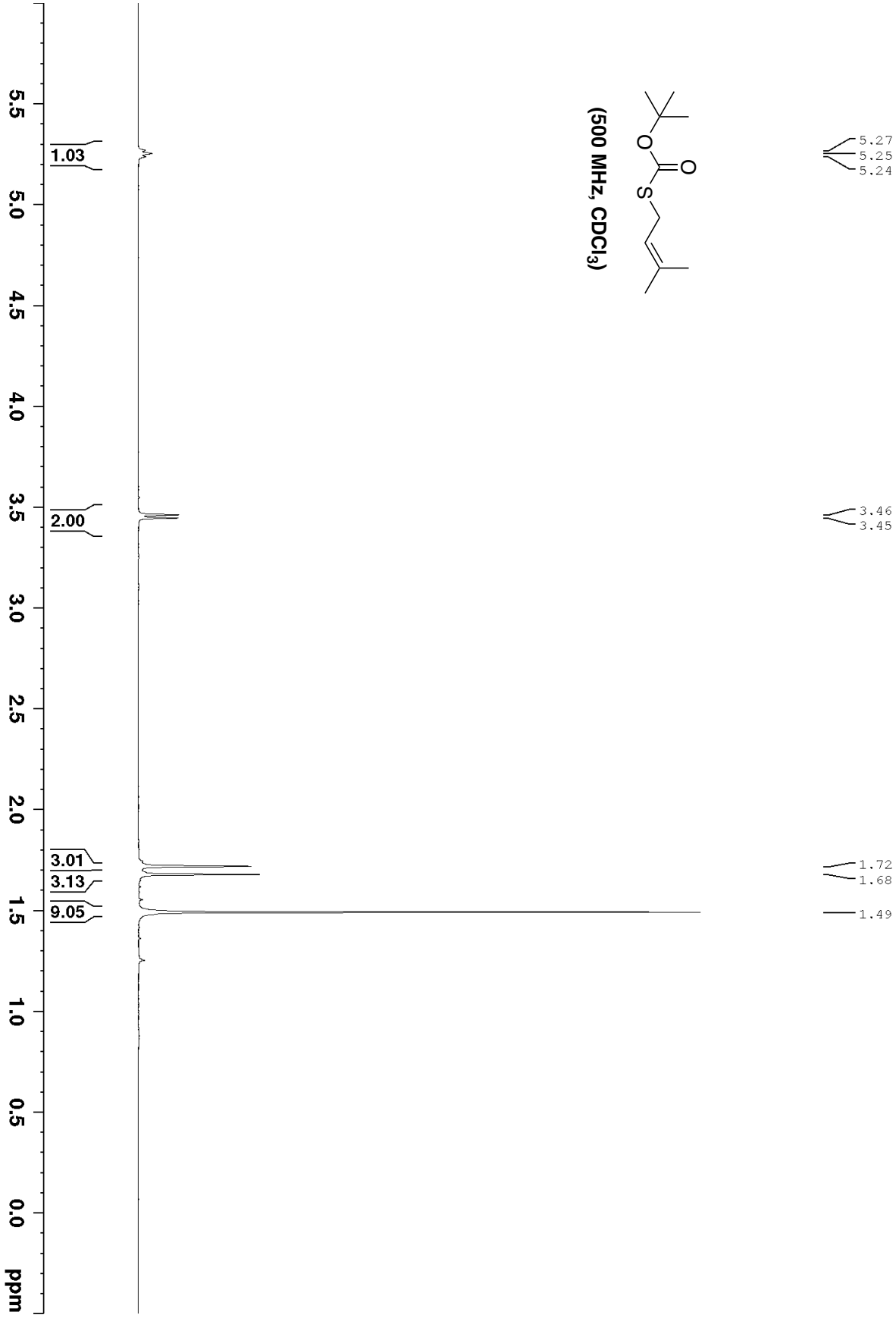

(125 MHz, CDCl3)
MeO
O
S
190.89
163.89
136.89
130.28
129.57
119.09
113.94
55.69
27.43
25.89
18.07
190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 ppm

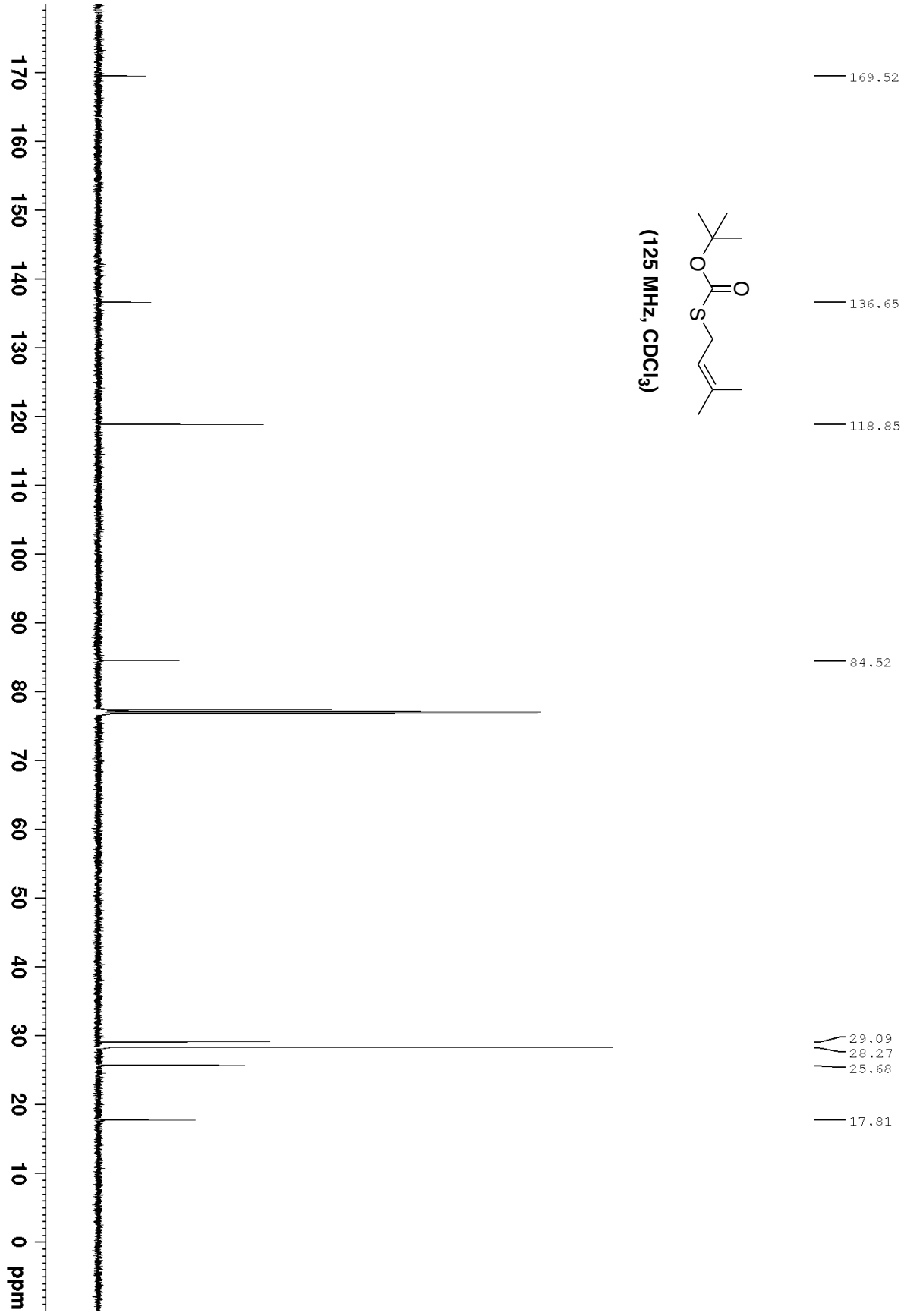

(500 MHz, CDCl3)
Ph
O
S
CO2Me
7.96
7.96
7.94
7.94
7.57
7.56
7.55
7.55
7.54
7.54
7.53
7.45
7.45
7.43
7.43
7.43
7.41
4.09
3.76
2.12
2.01
2.06
1.07
2.10
2.00
3.00
3.05
2.99
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
ppm

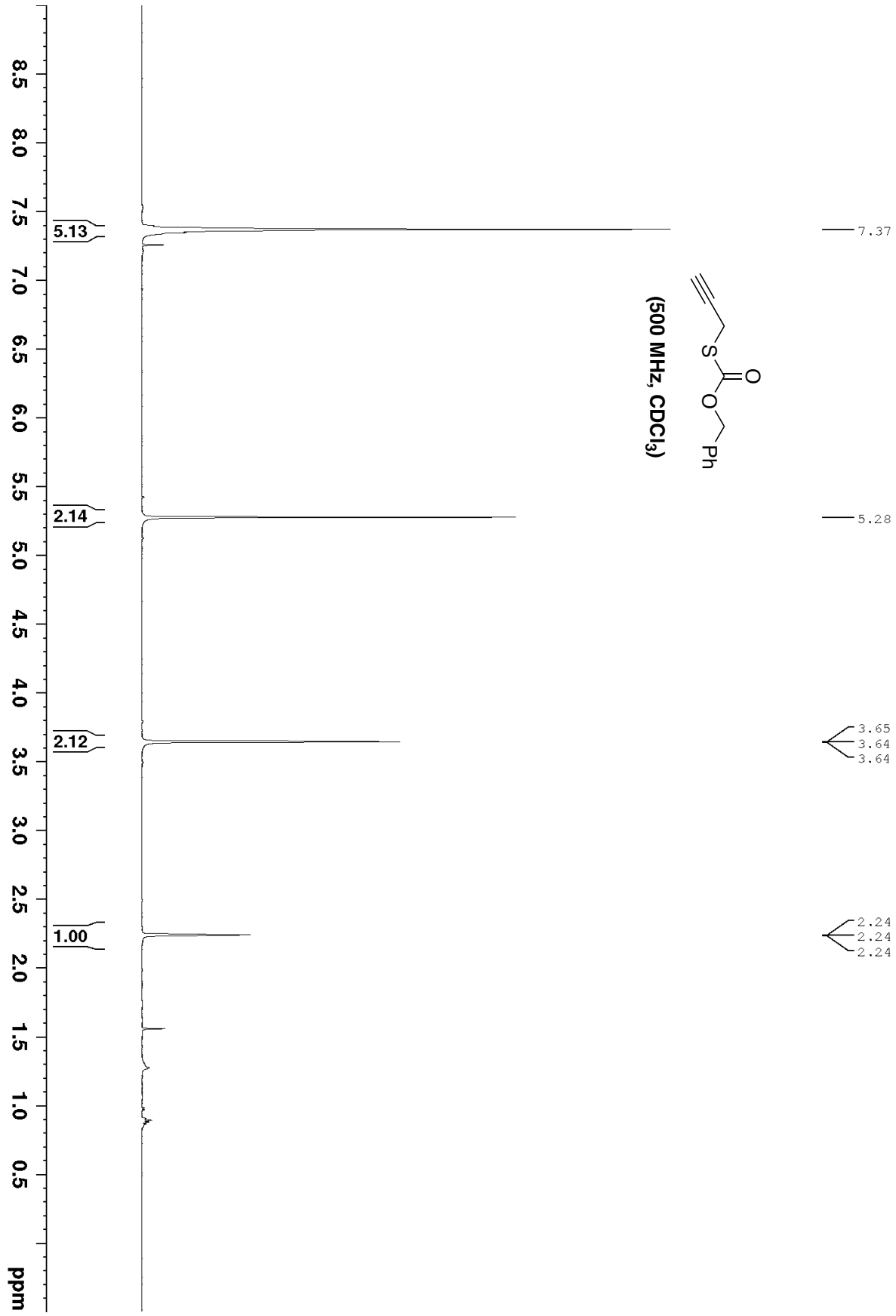

(125 MHz, CDCl3)
Ph
O
S
CO2Me
192.12
168.26
150.91
137.14
133.54
128.80
127.46
122.76
51.78
28.92
23.73
23.38
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm

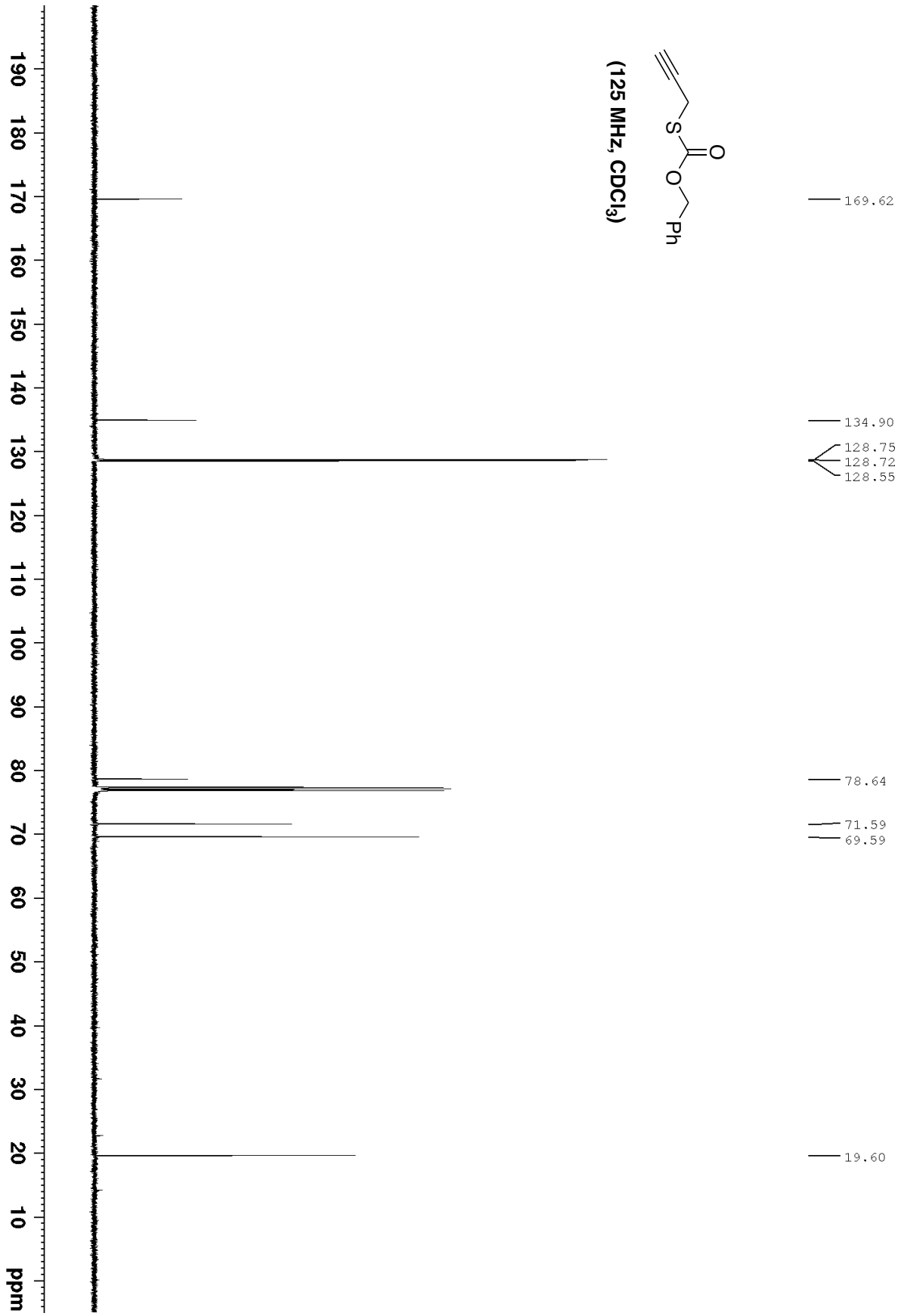

(500 MHz, CDCl3)
Ph
O
O
S
7.36
7.36
7.35
7.35
7.35
7.34
7.34
7.34
7.33
7.33
7.33
7.32
7.32
7.31
7.31
5.28
5.28
5.28
5.28
5.27
5.27
5.27
5.26
5.26
5.26
5.25
5.25
5.25
5.24
5.23
3.54
3.53
1.72
1.68
5.02
1.07
2.00
2.00
3.10
2.98
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ppm

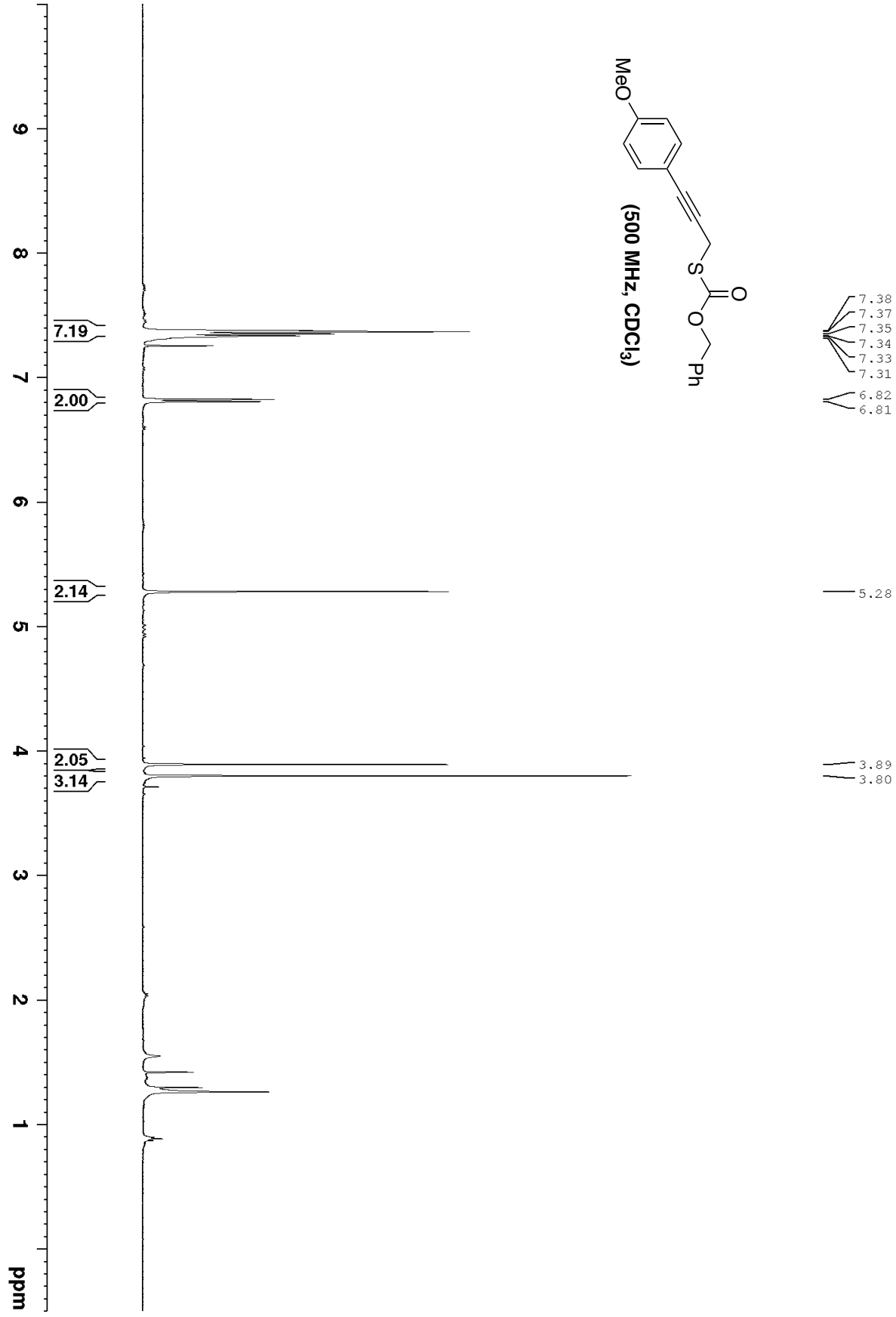

(125 MHz, CDCl3)
Ph
O
O
S
171.27
137.20
135.35
128.64
128.52
128.41
118.50
68.84
29.29
25.71
17.84
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
ppm

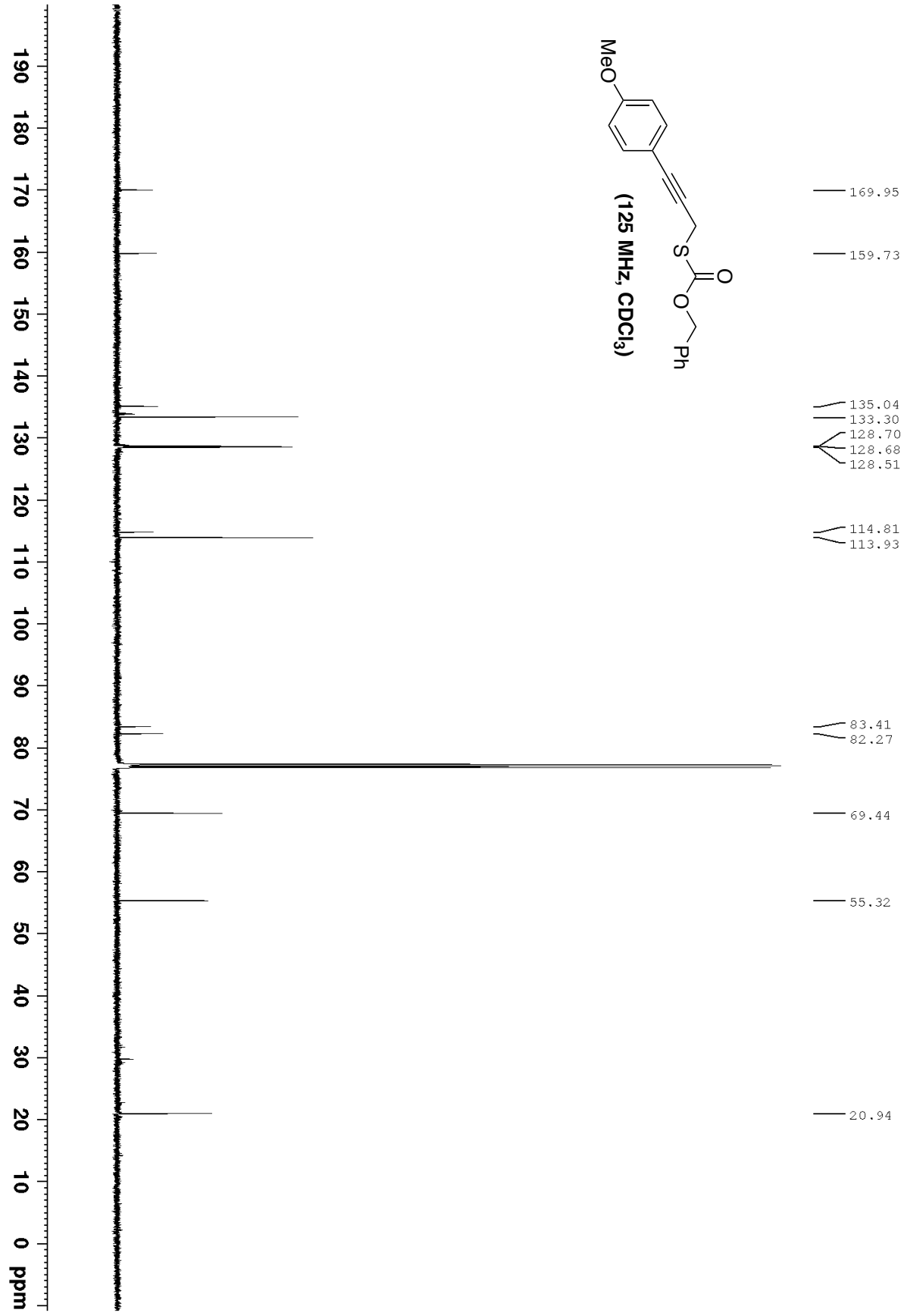

(500 MHz, CDCl3)
5.27
5.25
5.24
3.46
3.45
1.72
1.68
1.49
1.03
2.00
3.01
3.13
9.05
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ppm

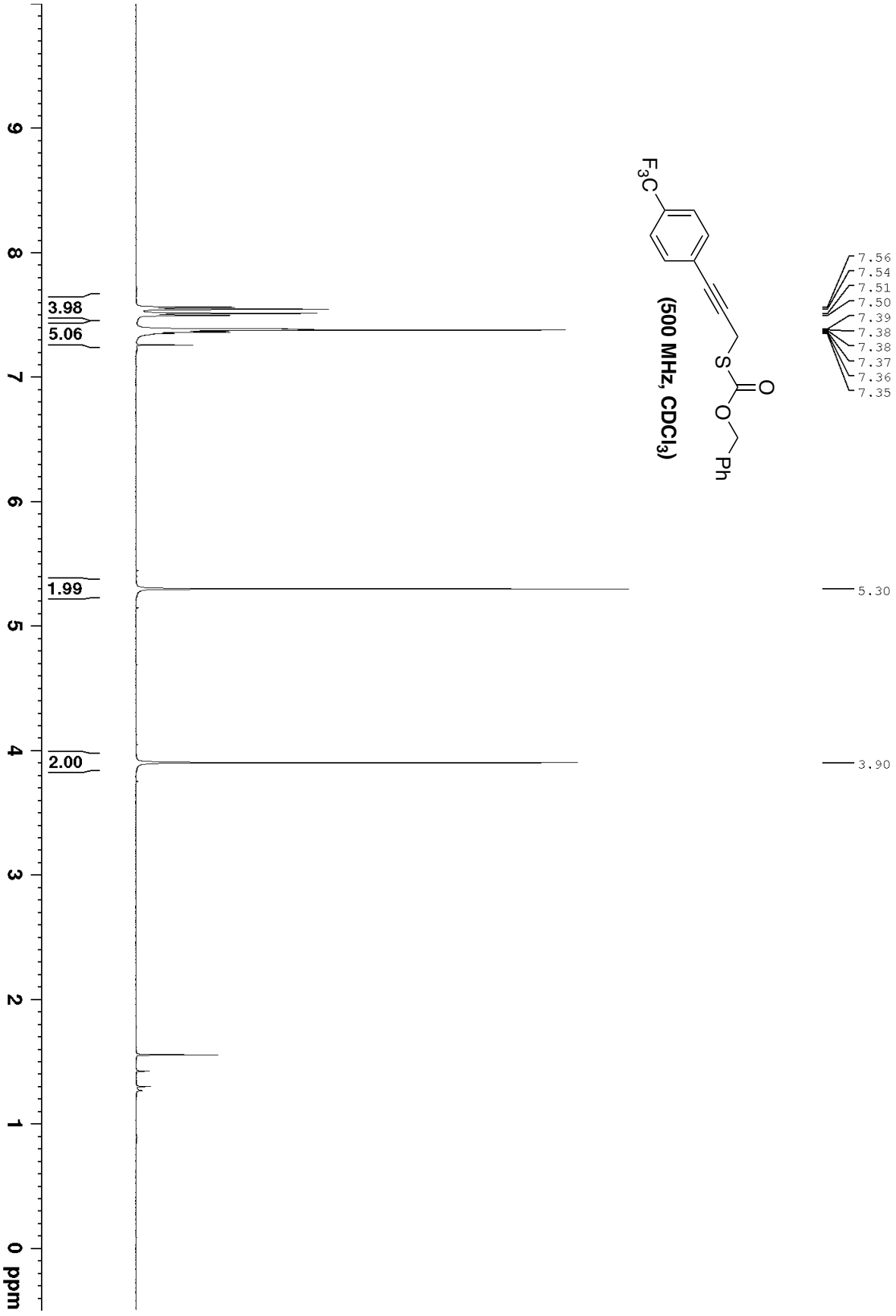

(125 MHz, CDCl3)
O
O
S
169.52
136.65
118.85
84.52
29.09
28.27
25.68
17.81
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
ppm

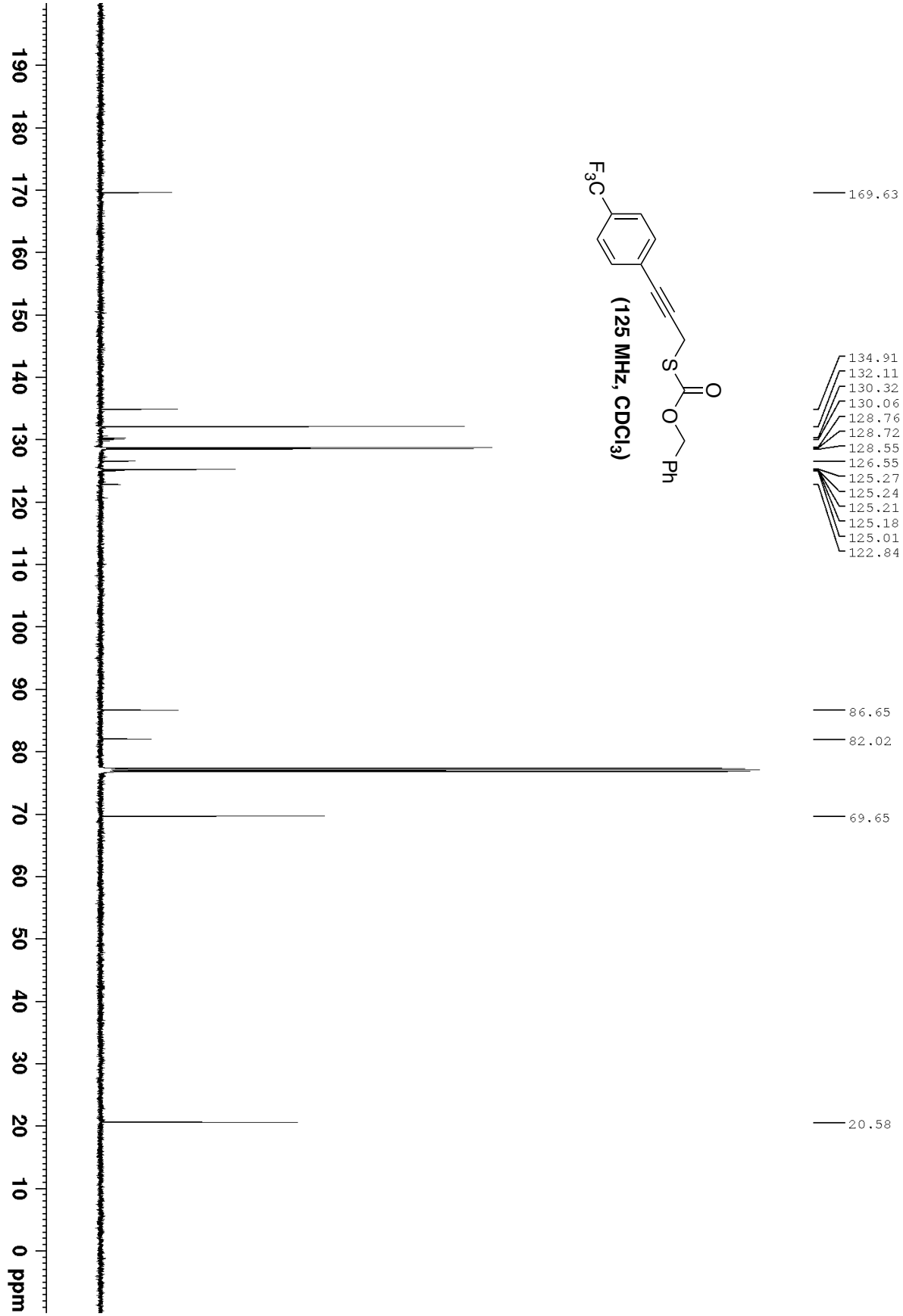

(500 MHz, CDCl3)
S
O
O
Ph
7.37
5.28
3.65
3.64
3.64
2.24
2.24
2.24
5.13
2.14
2.12
1.00
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
ppm

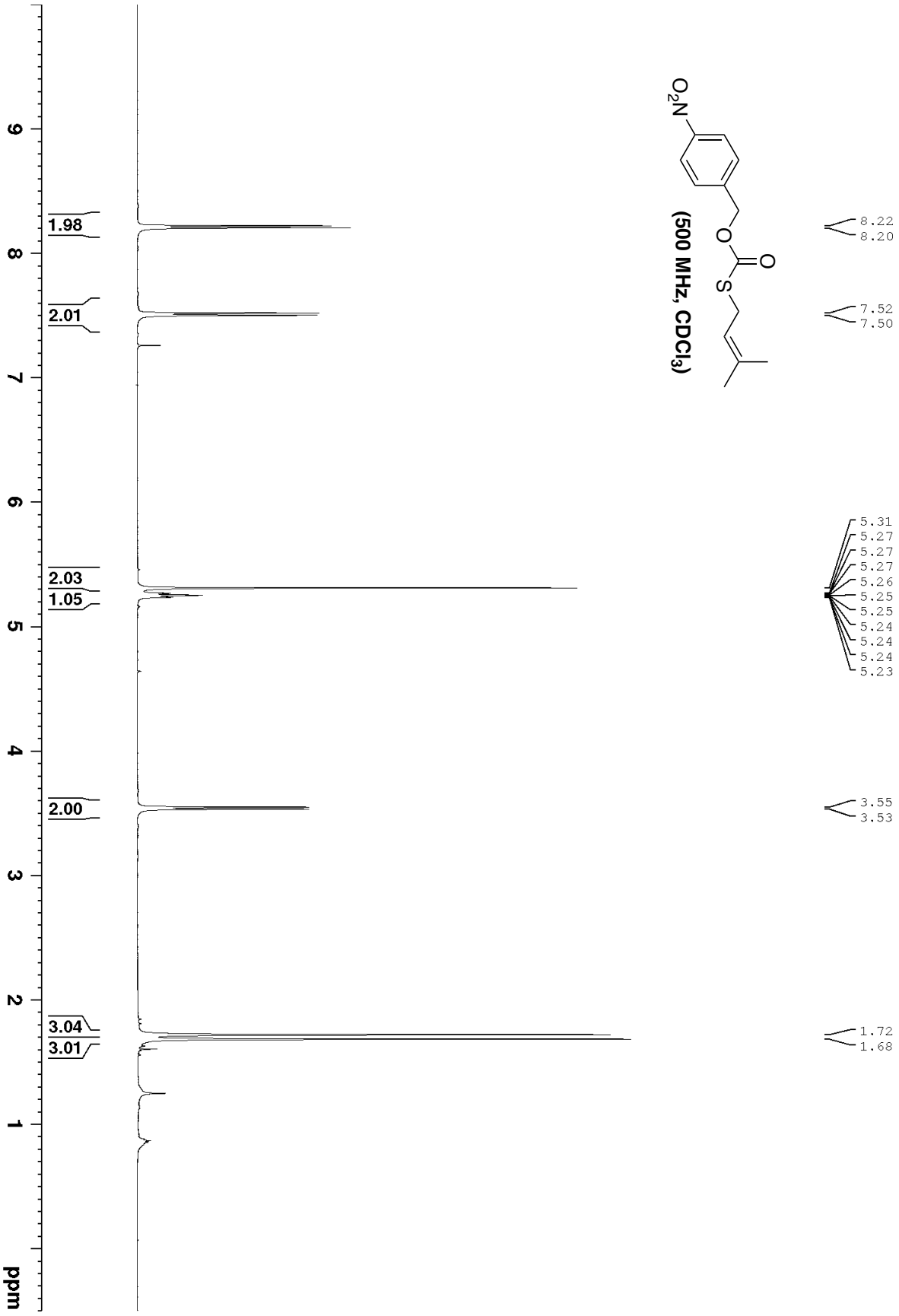

(125 MHz, CDCl3)
S
O
O
Ph
169.62
134.90
128.75
128.72
128.55
78.64
71.59
69.59
19.60
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm

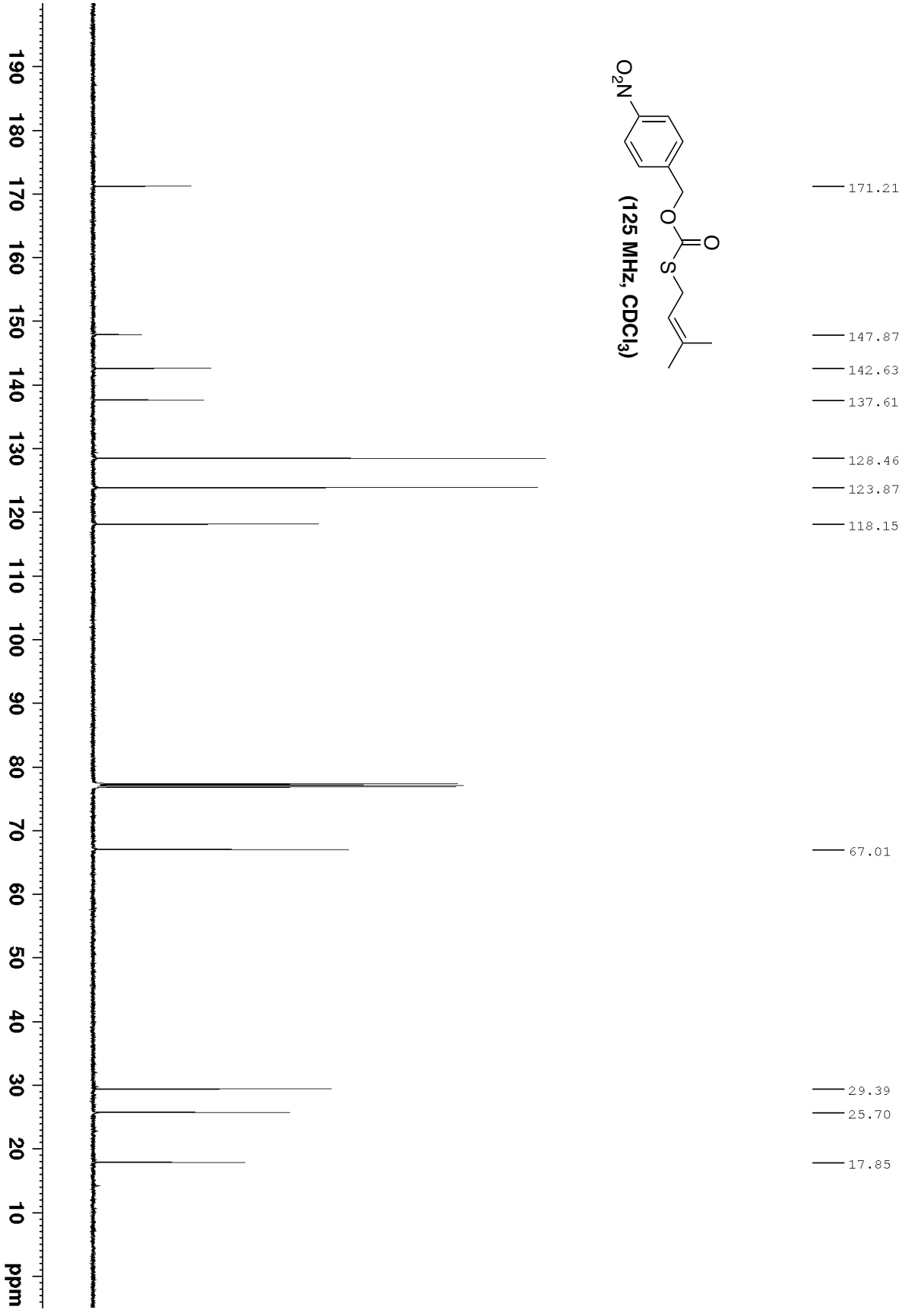

(500 MHz, CDCl3)
MeO
S
O
O
Ph
7.38
7.37
7.35
7.34
7.33
7.31
6.82
6.81
5.28
3.89
3.80
7.19
2.00
2.14
2.05
3.14
ppm

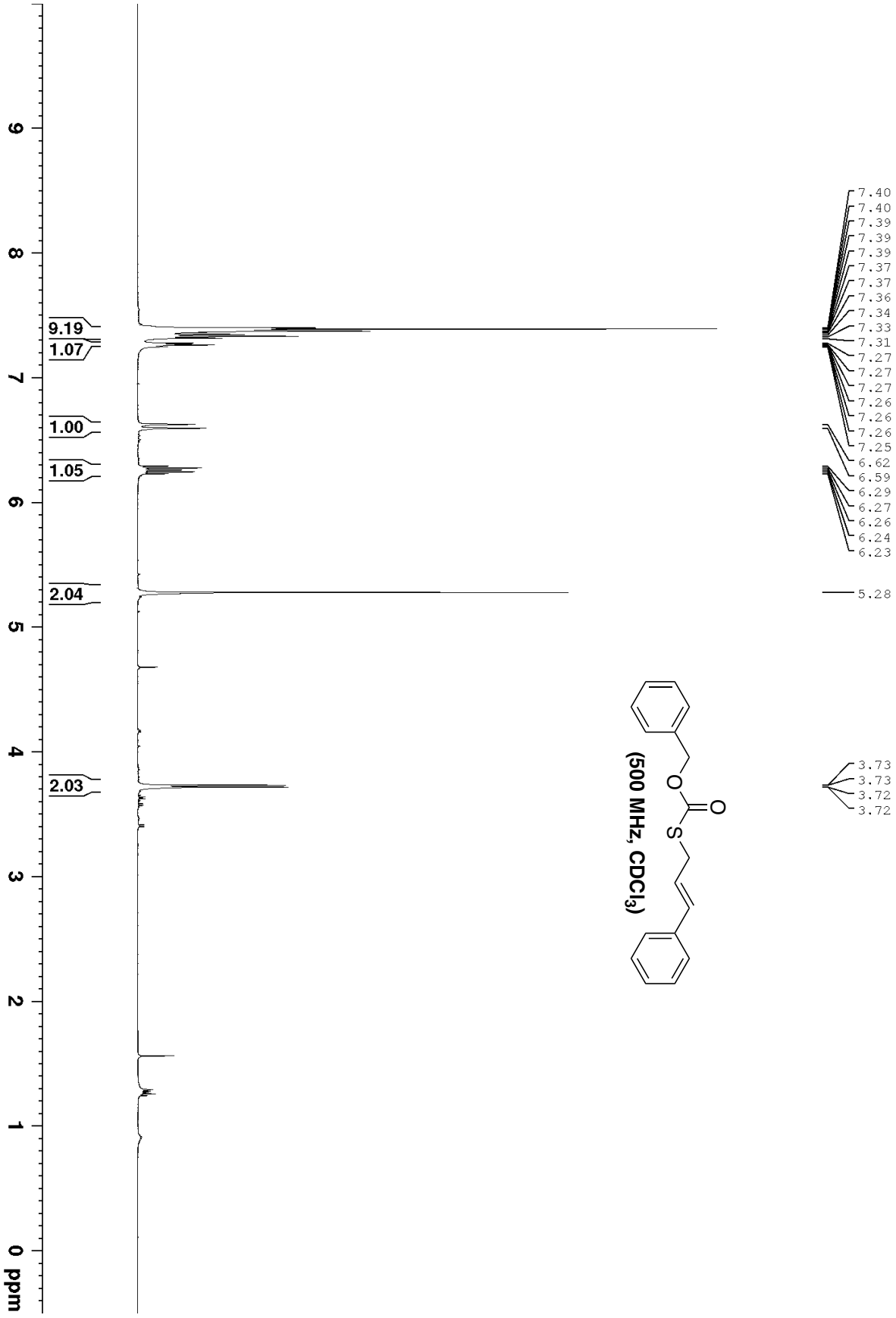

MeO
S
O
O
Ph
(125 MHz, CDCl3)
169.95
159.73
135.04
133.30
128.70
128.68
128.51
114.81
113.93
83.41
82.27
69.44
55.32
20.94
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
ppm

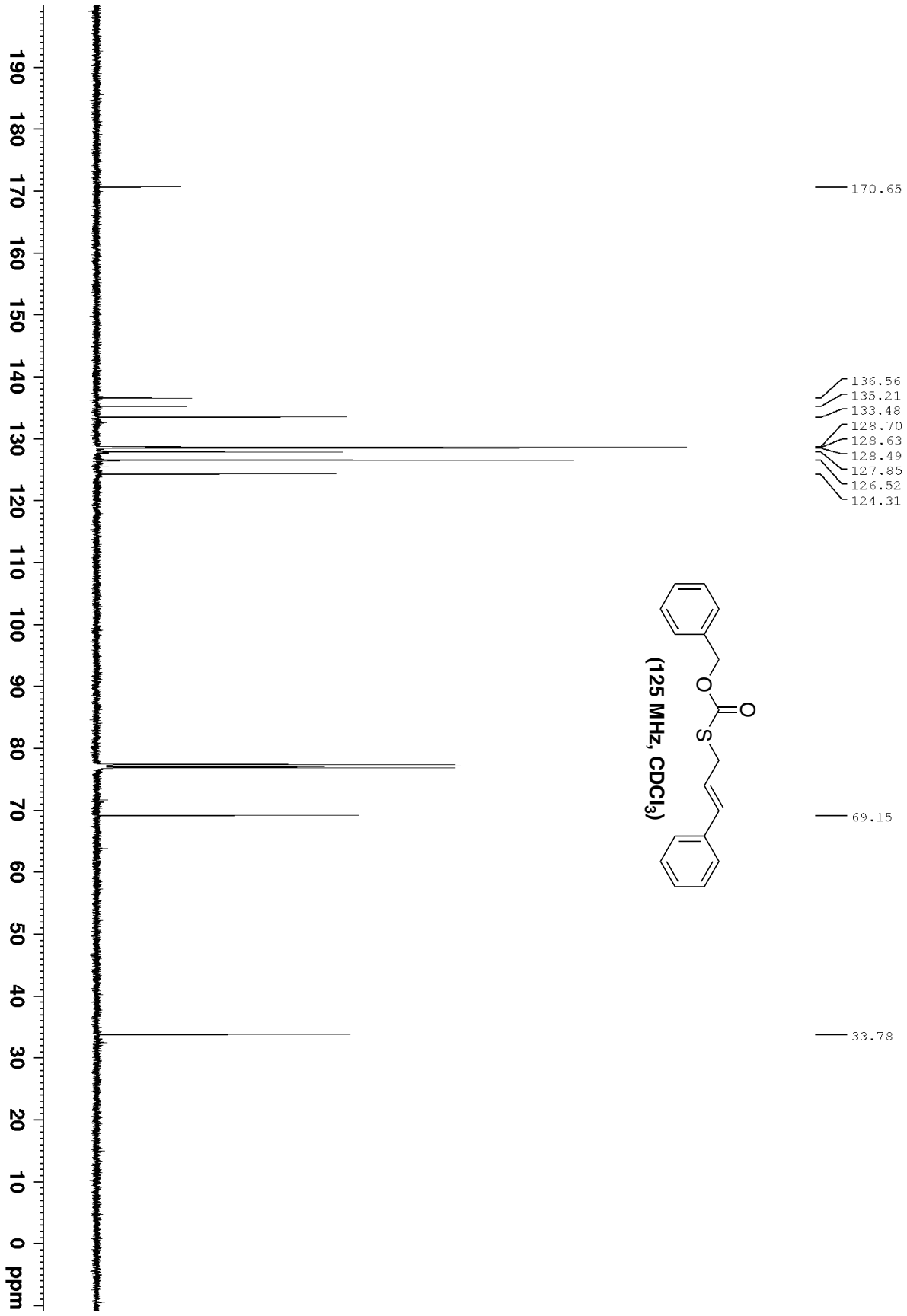

F3C
S
O
O
Ph
(500 MHz, CDCl3)
7.56
7.54
7.51
7.50
7.39
7.38
7.38
7.37
7.36
7.35
5.30
3.90
3.98
5.06
1.99
2.00
9
8
7
6
5
4
3
2
1
0 ppm

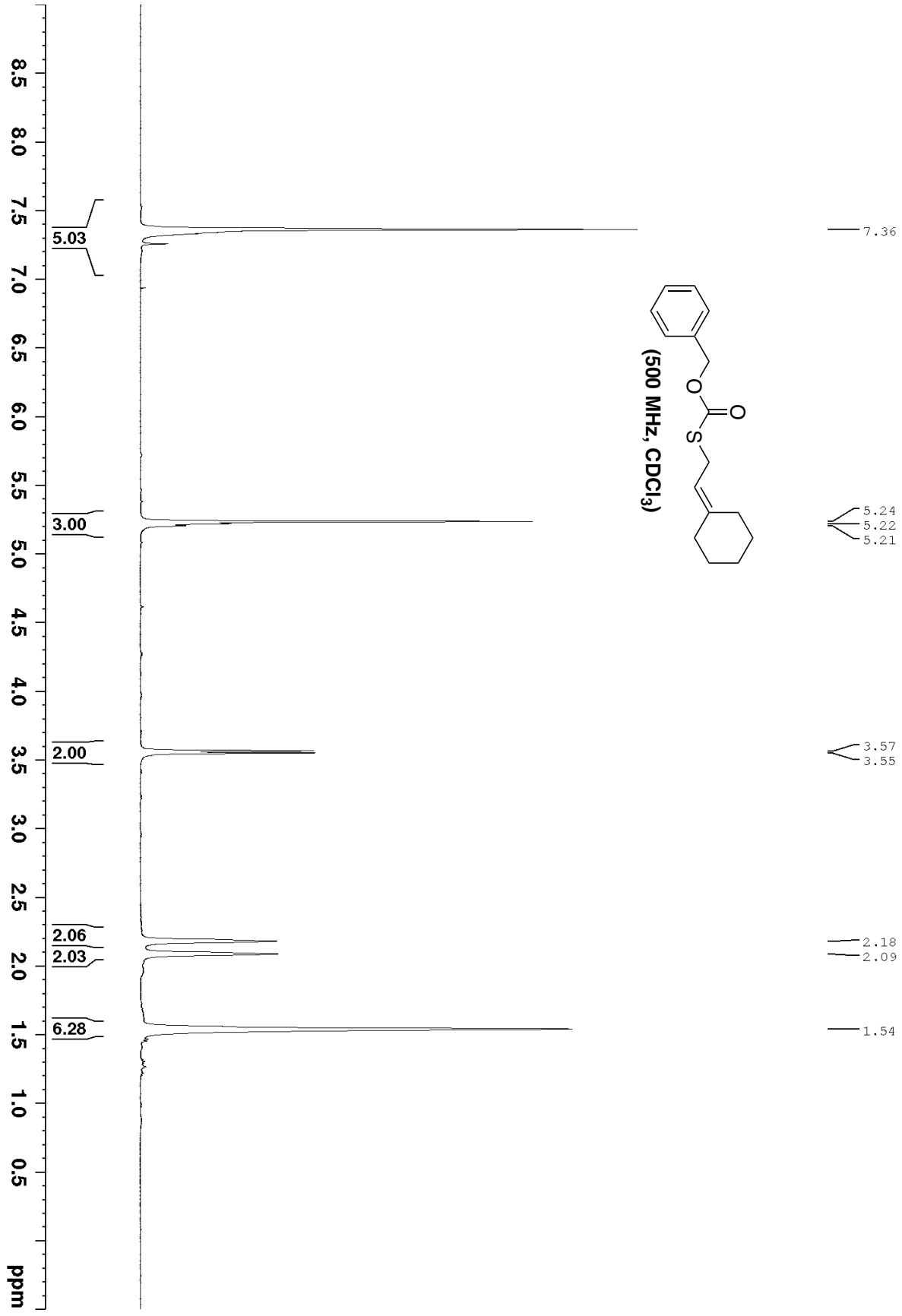

F3C
S
O
O
Ph
(125 MHz, CDCl3)
169.63
134.91
132.11
130.32
130.06
128.76
128.72
128.55
126.55
125.27
125.24
125.21
125.18
125.01
122.84
86.65
82.02
69.65
20.58
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0 ppm

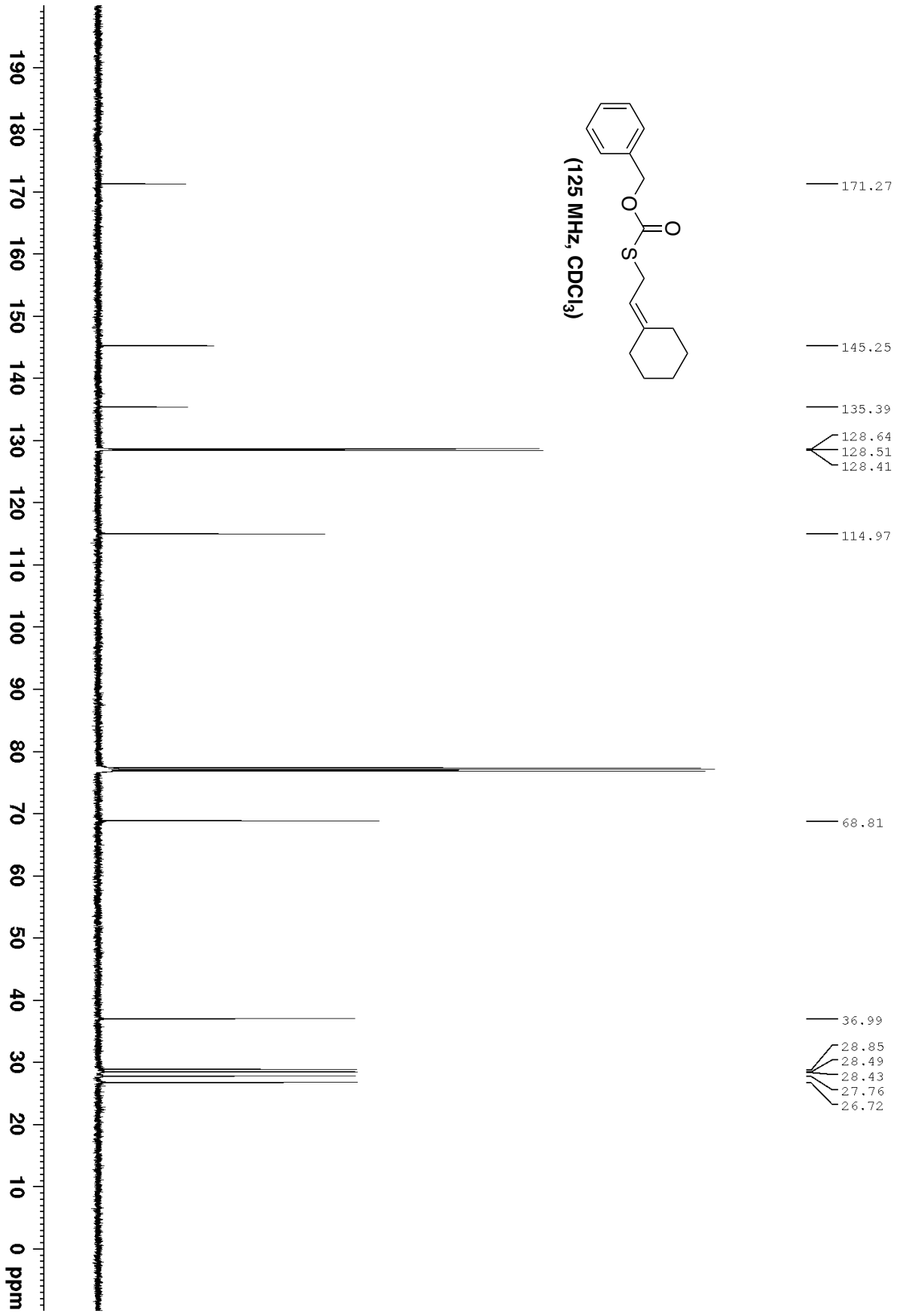

(500 MHz, CDCl3)
8.22
8.20
7.52
7.50
5.31
5.27
5.27
5.27
5.26
5.25
5.25
5.24
5.24
5.24
5.23
3.55
3.53
1.72
1.68
1.98
2.01
2.03
1.05
2.00
3.04
3.01
ppm

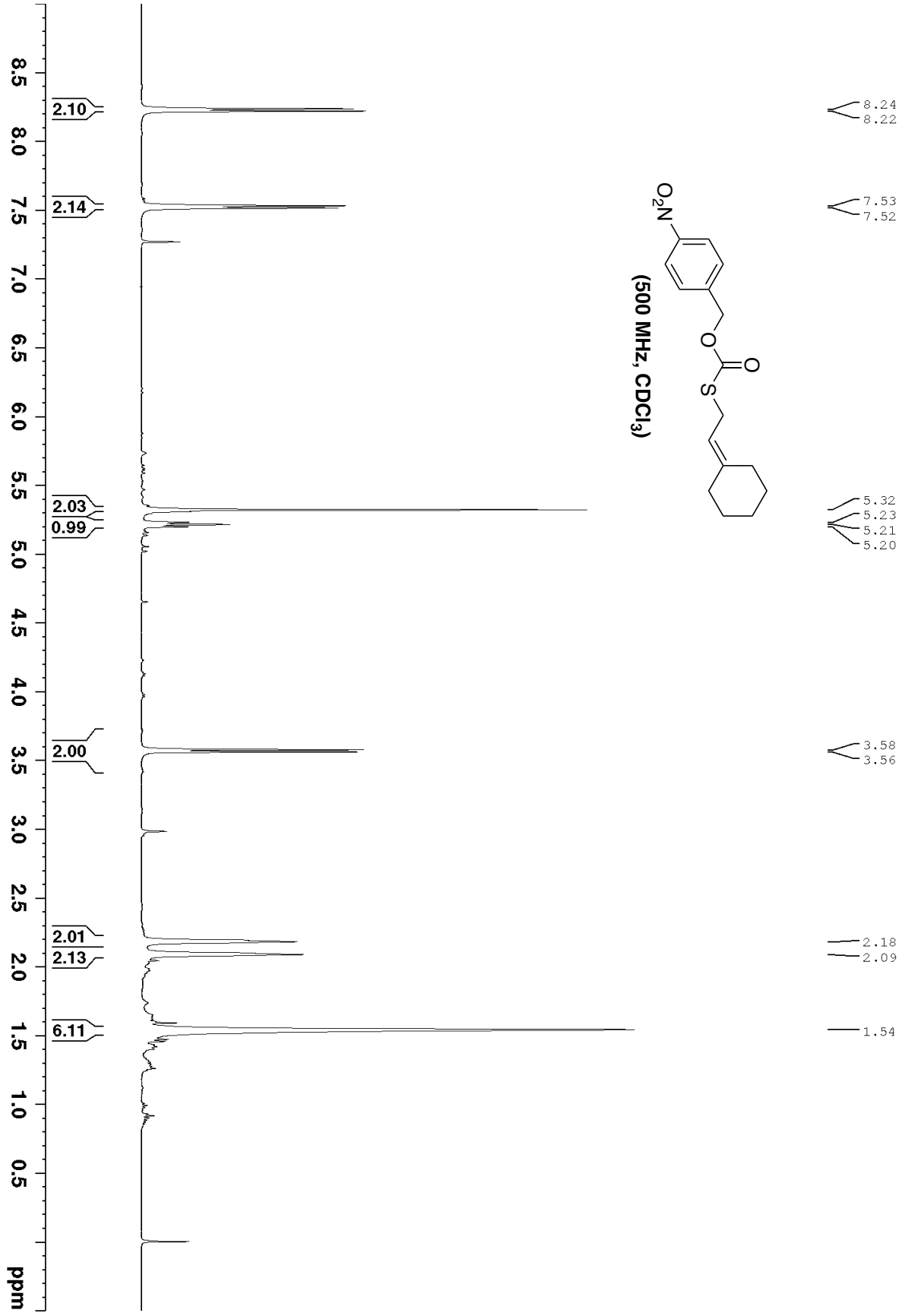

O2N
O
O
S
(125 MHz, CDCl3)
171.21
147.87
142.63
137.61
128.46
123.87
118.15
67.01
29.39
25.70
17.85
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm

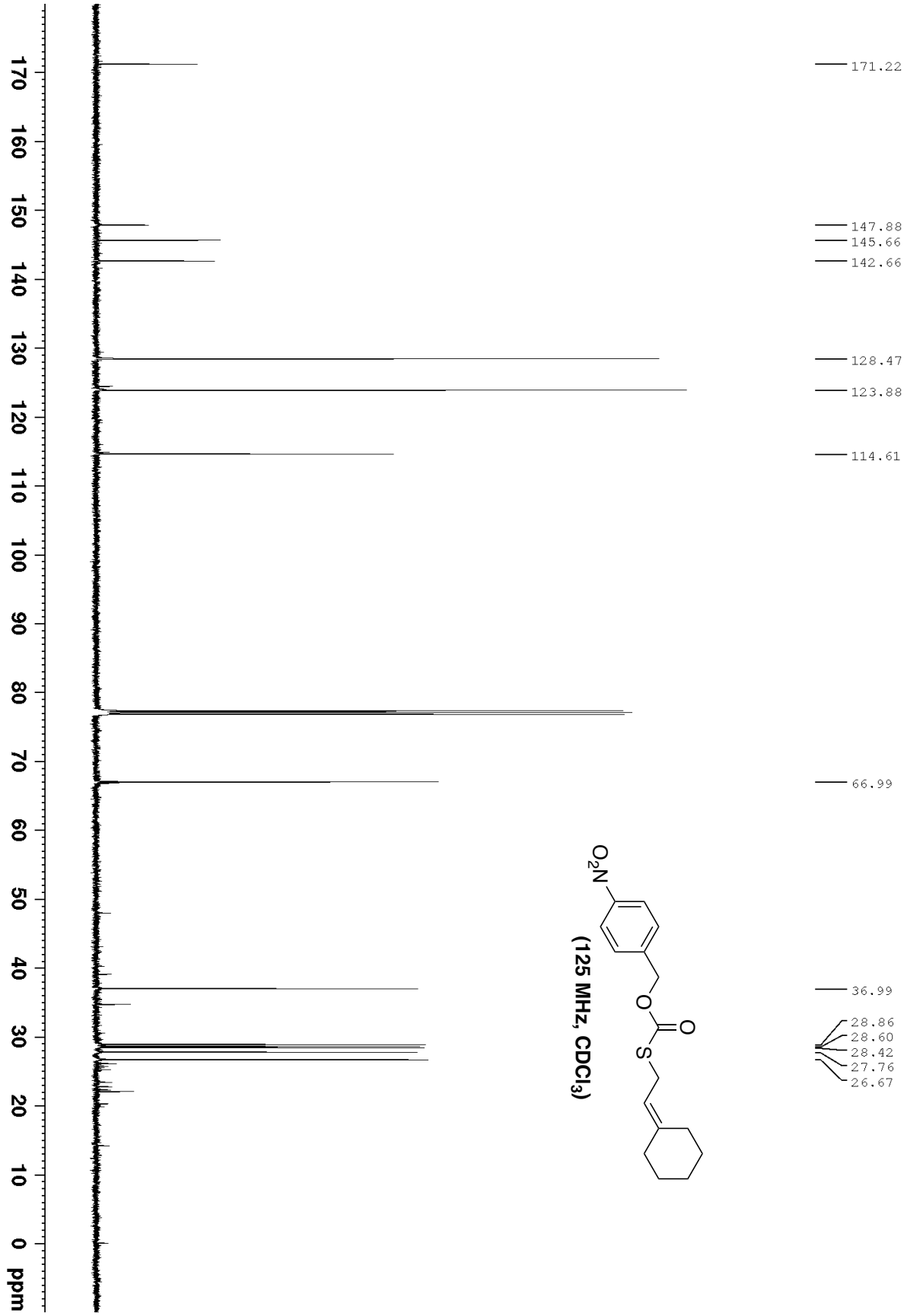

9.19
1.07
1.00
1.05
2.04
2.03
0 ppm
7.40
7.40
7.39
7.39
7.39
7.37
7.37
7.36
7.34
7.33
7.31
7.27
7.27
7.27
7.26
7.26
7.26
7.25
6.62
6.59
6.29
6.27
6.26
6.24
6.23
5.28
3.73
3.73
3.72
3.72
(500 MHz, CDCl3)

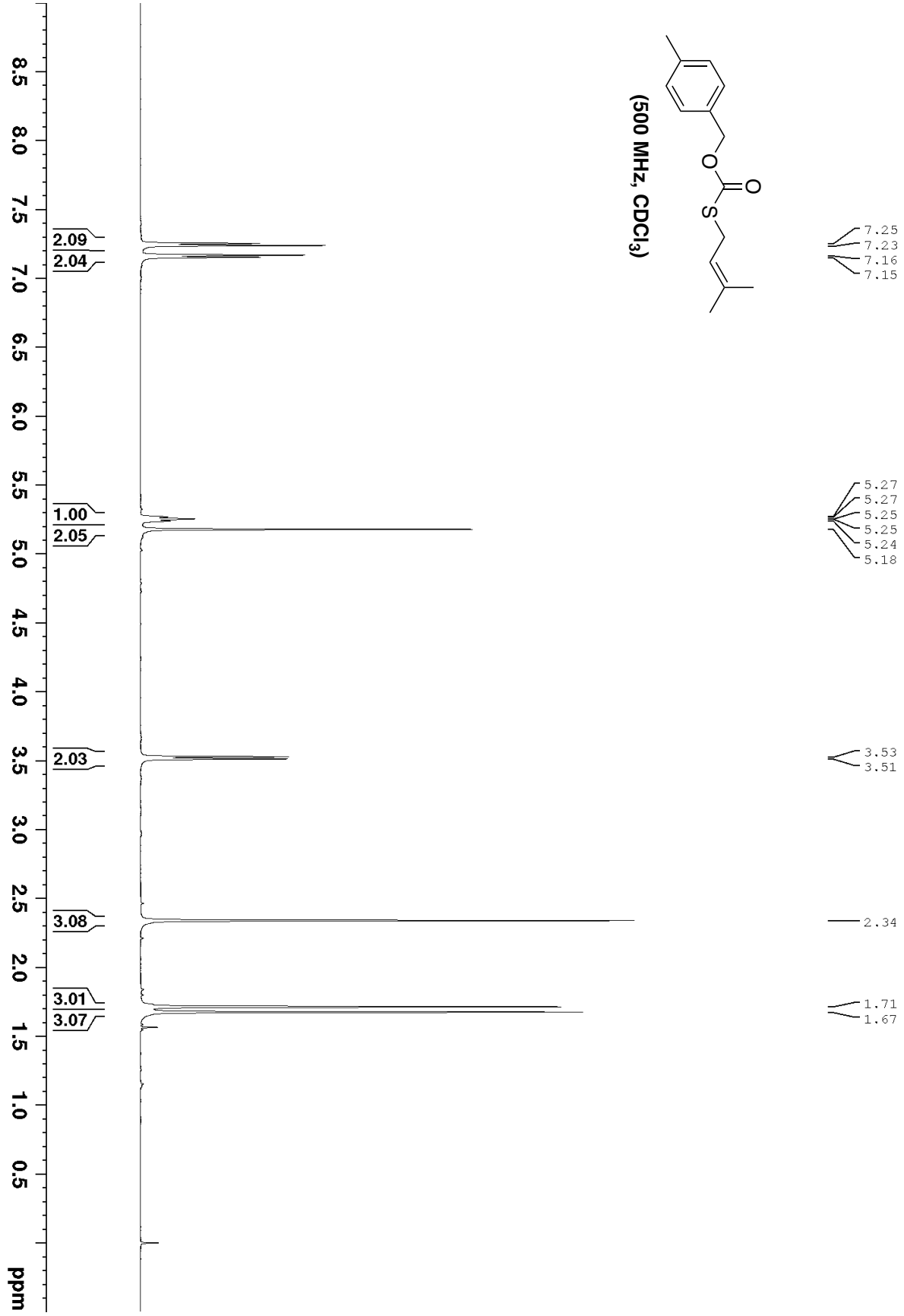

170.65
136.56
135.21
133.48
128.70
128.63
128.49
127.85
126.52
124.31
69.15
33.78
190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 ppm
(125 MHz, CDCl3)

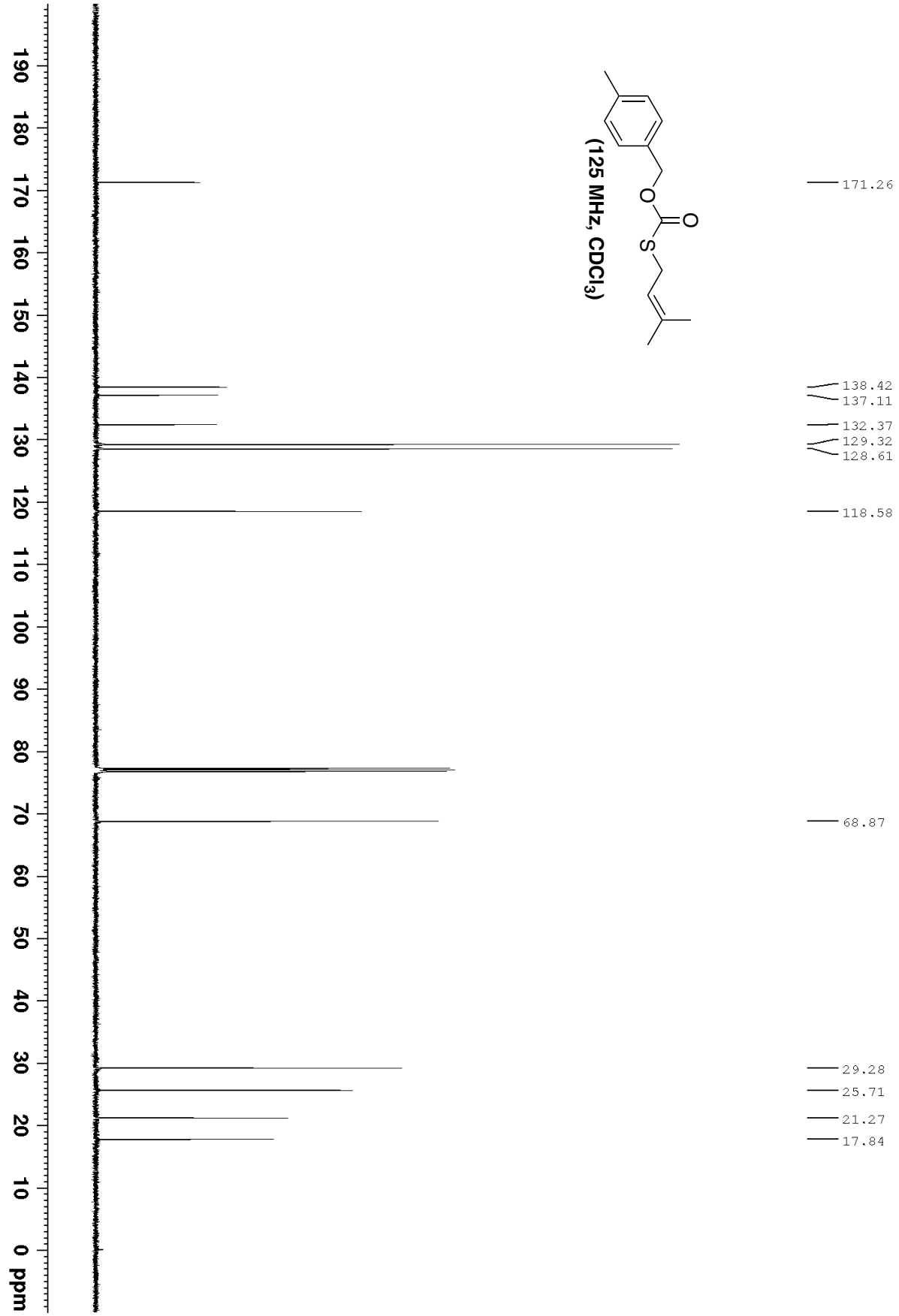

(500 MHz, CDCl3)
7.36
5.24
5.22
5.21
3.57
3.55
2.18
2.09
1.54
5.03
3.00
2.00
2.06
2.03
6.28
ppm

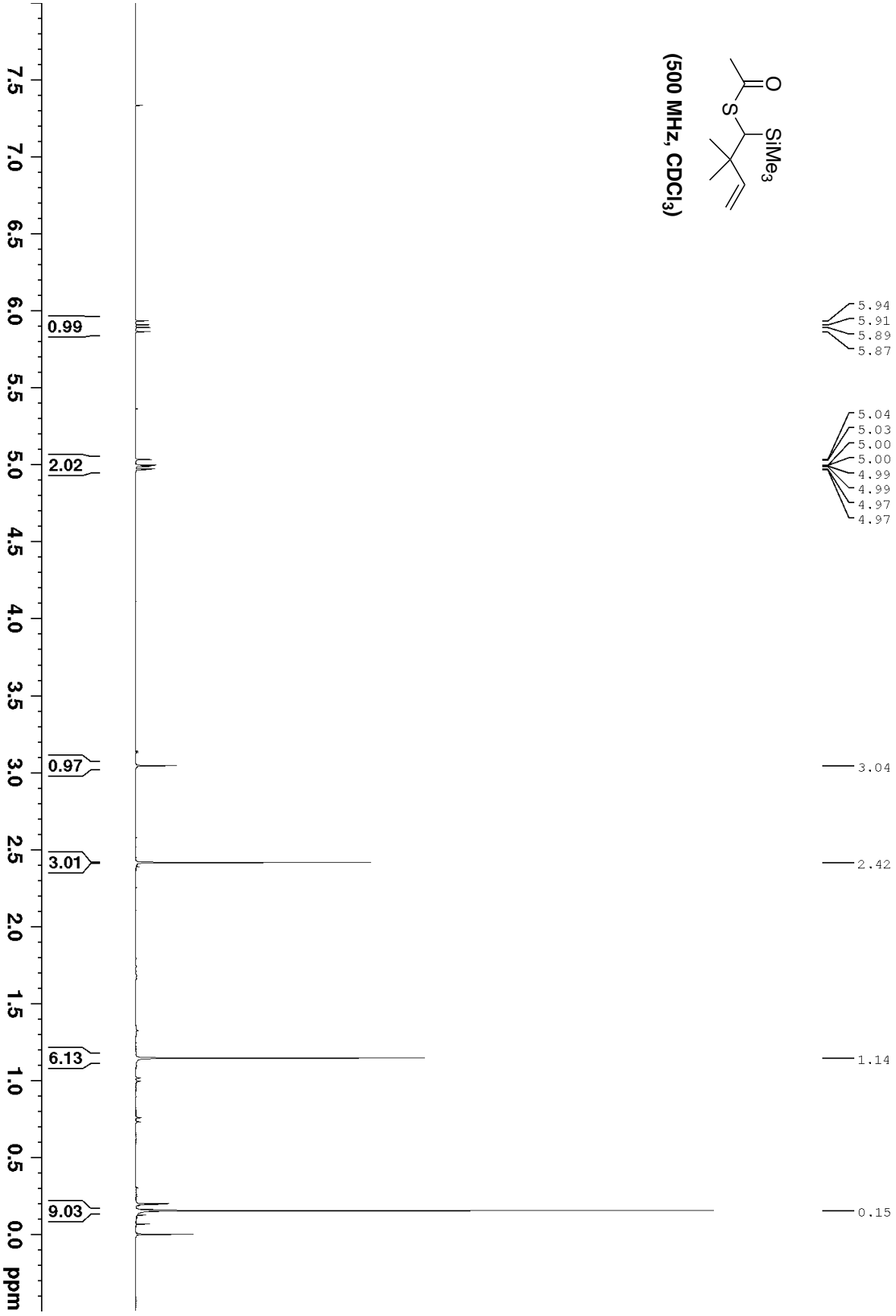

(125 MHz, CDCl3)
O
O
S
O
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0 ppm
171.27
145.25
135.39
128.64
128.51
128.41
114.97
68.81
36.99
28.85
28.49
28.43
27.76
26.72

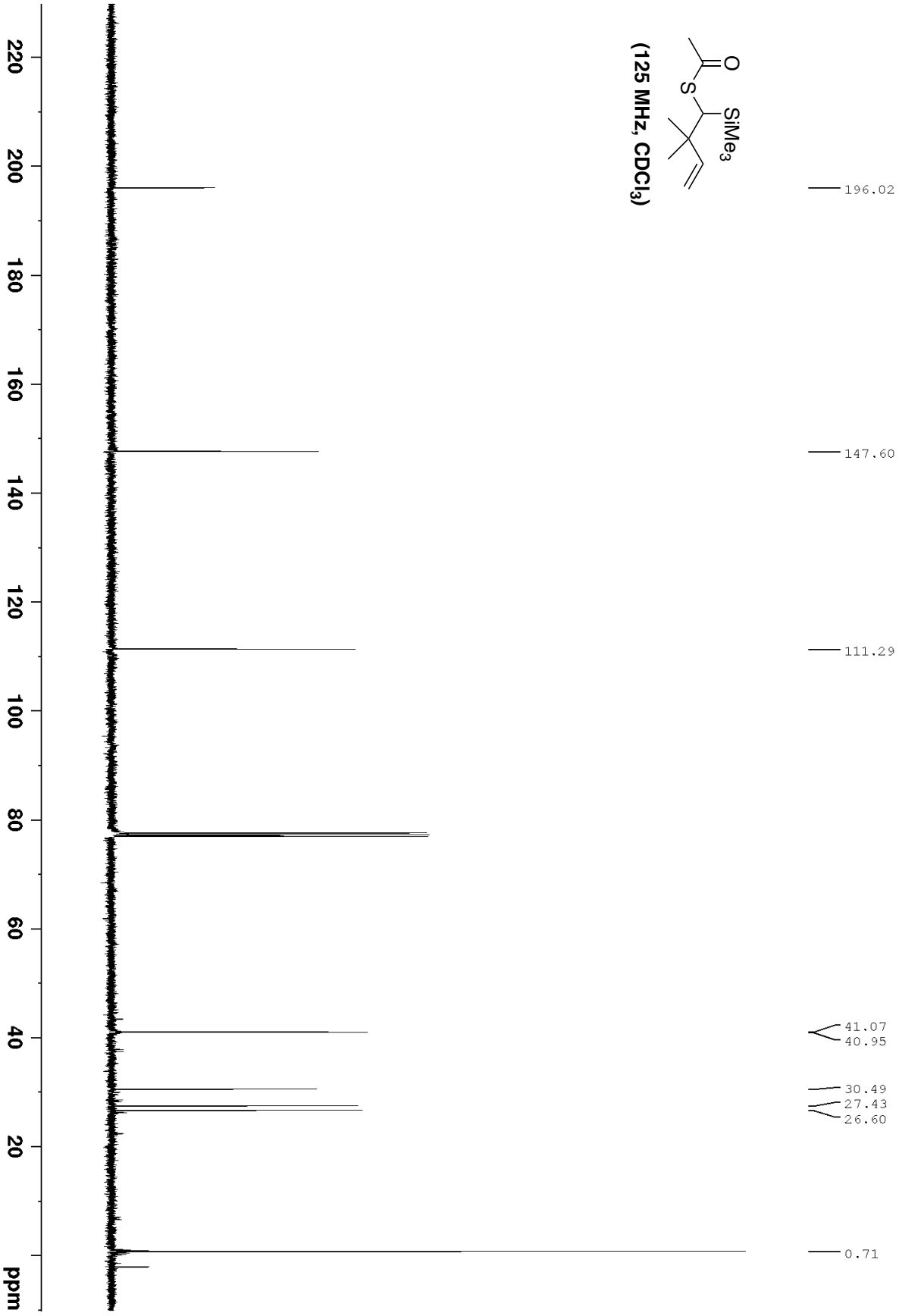

(500 MHz, CDCl3)
O2N
O
O
S
8.24
8.22
7.53
7.52
5.32
5.23
5.21
5.20
3.58
3.56
2.18
2.09
1.54
2.10
2.14
2.03
0.99
2.00
2.01
2.13
6.11
ppm

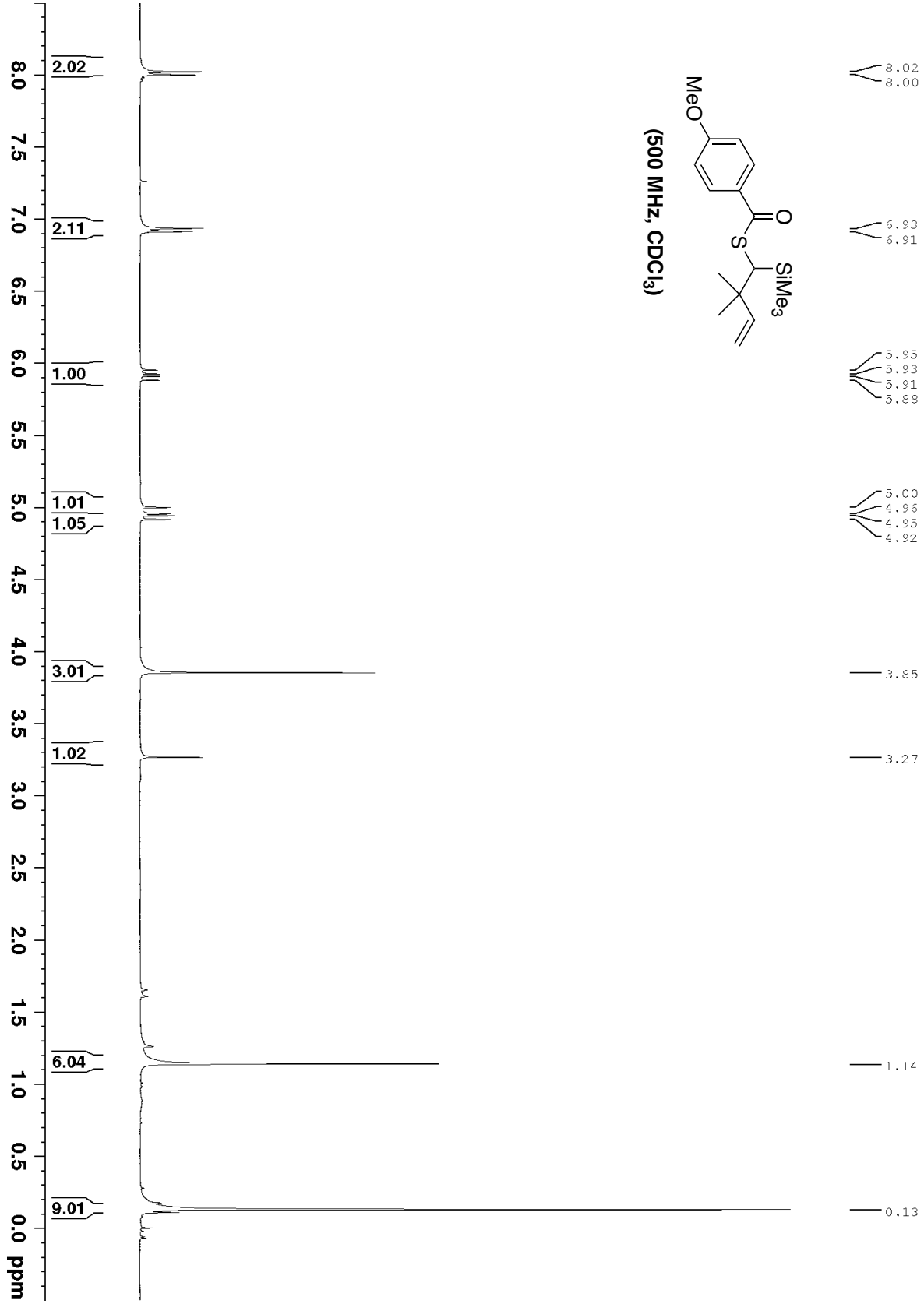

171.22
147.88
145.66
142.66
128.47
123.88
114.61
66.99
36.99
28.86
28.60
28.42
27.76
26.67
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
ppm
O2N
O
O
S
(125 MHz, CDCl3)

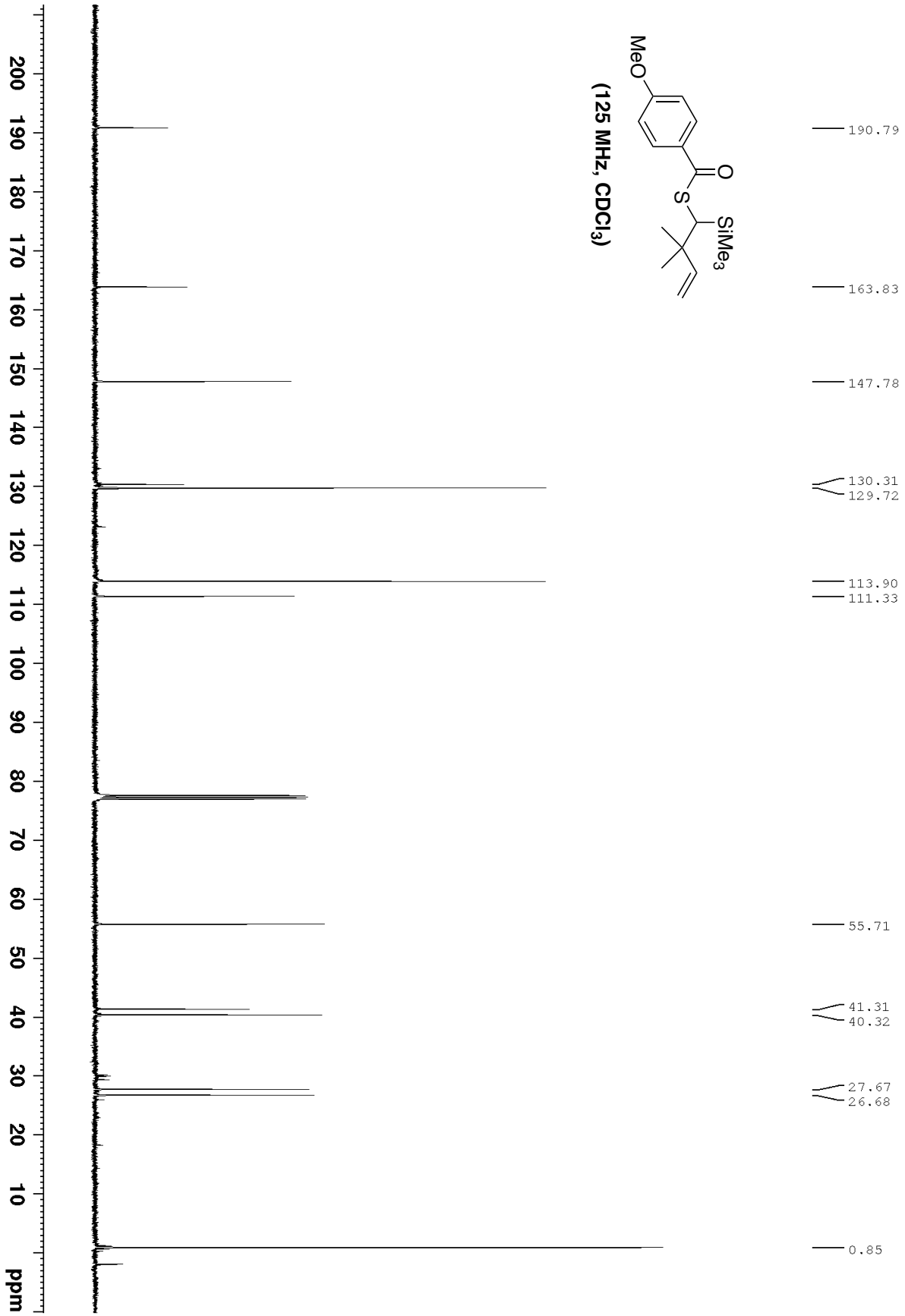

(500 MHz, CDCl3)
7.25
7.23
7.16
7.15
5.27
5.27
5.25
5.25
5.24
5.18
3.53
3.51
2.34
1.71
1.67
2.09
2.04
1.00
2.05
2.03
3.08
3.01
3.07
ppm

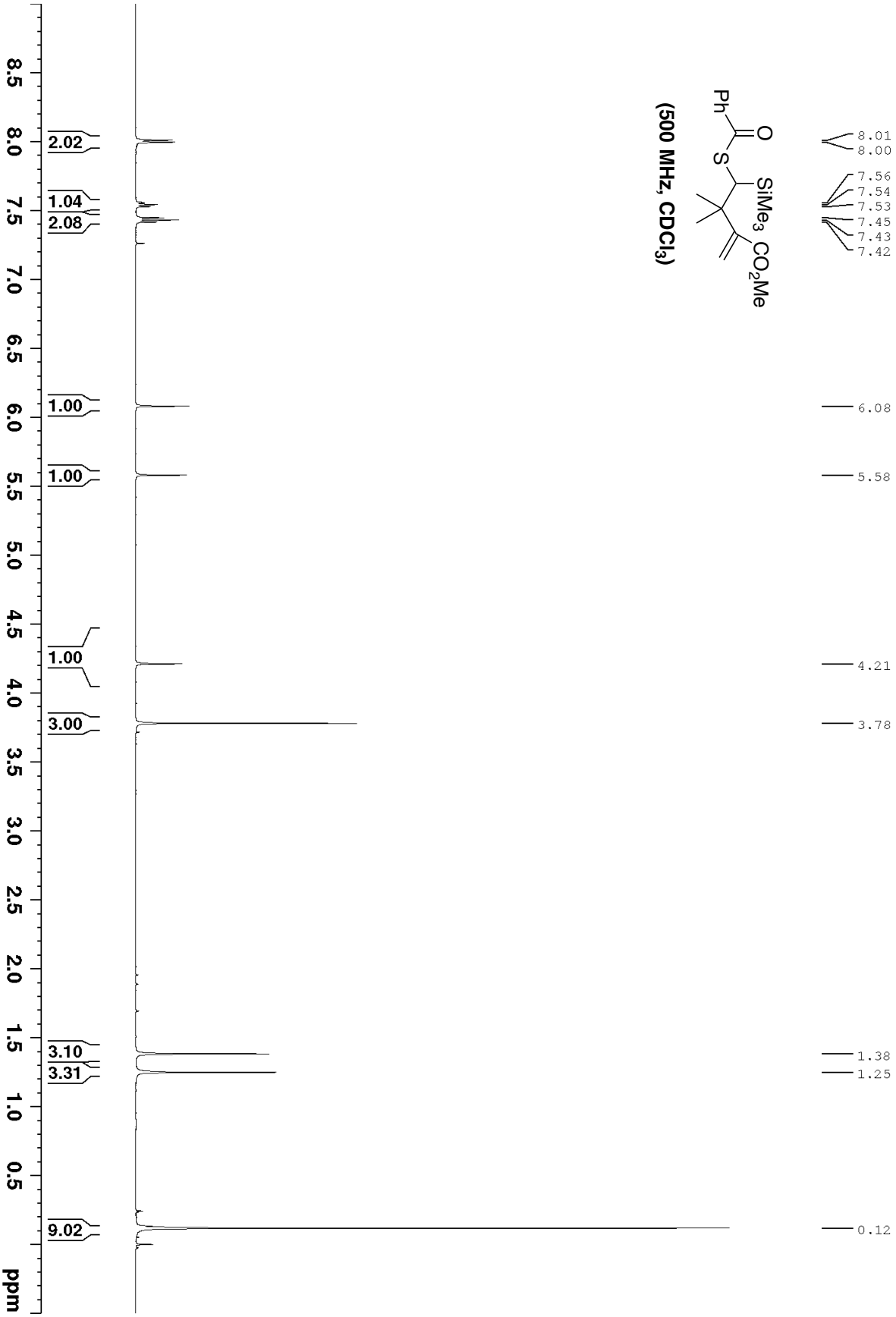

(125 MHz, CDCl3)
O
O
S
171.26
138.42
137.11
132.37
129.32
128.61
118.58
68.87
29.28
25.71
21.27
17.84
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0 ppm

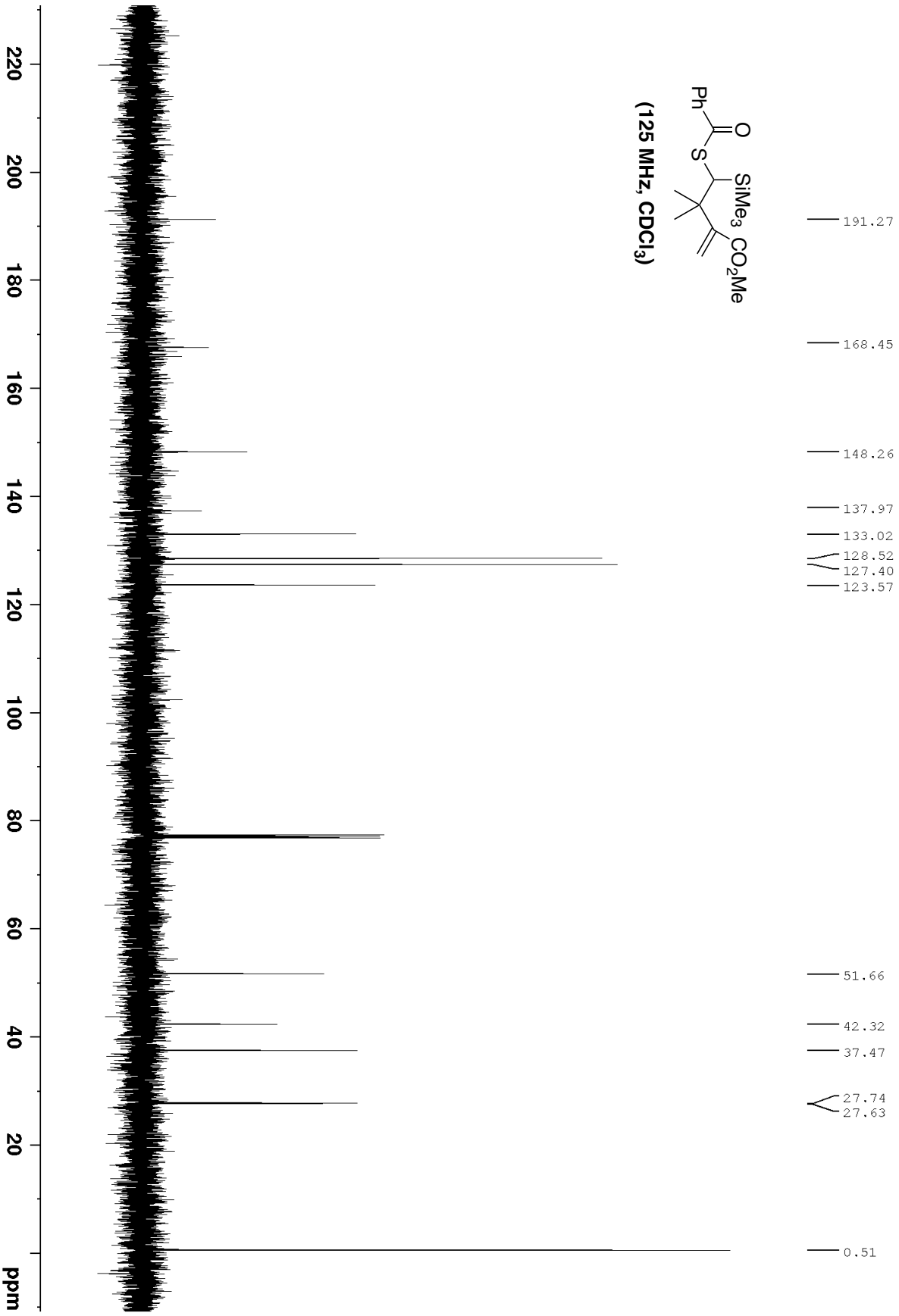

(500 MHz, CDCl3)
O
S
SiMe3
5.94
5.91
5.89
5.87
5.04
5.03
5.00
5.00
4.99
4.99
4.97
4.97
3.04
2.42
1.14
0.15
0.99
2.02
0.97
3.01
6.13
9.03
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ppm

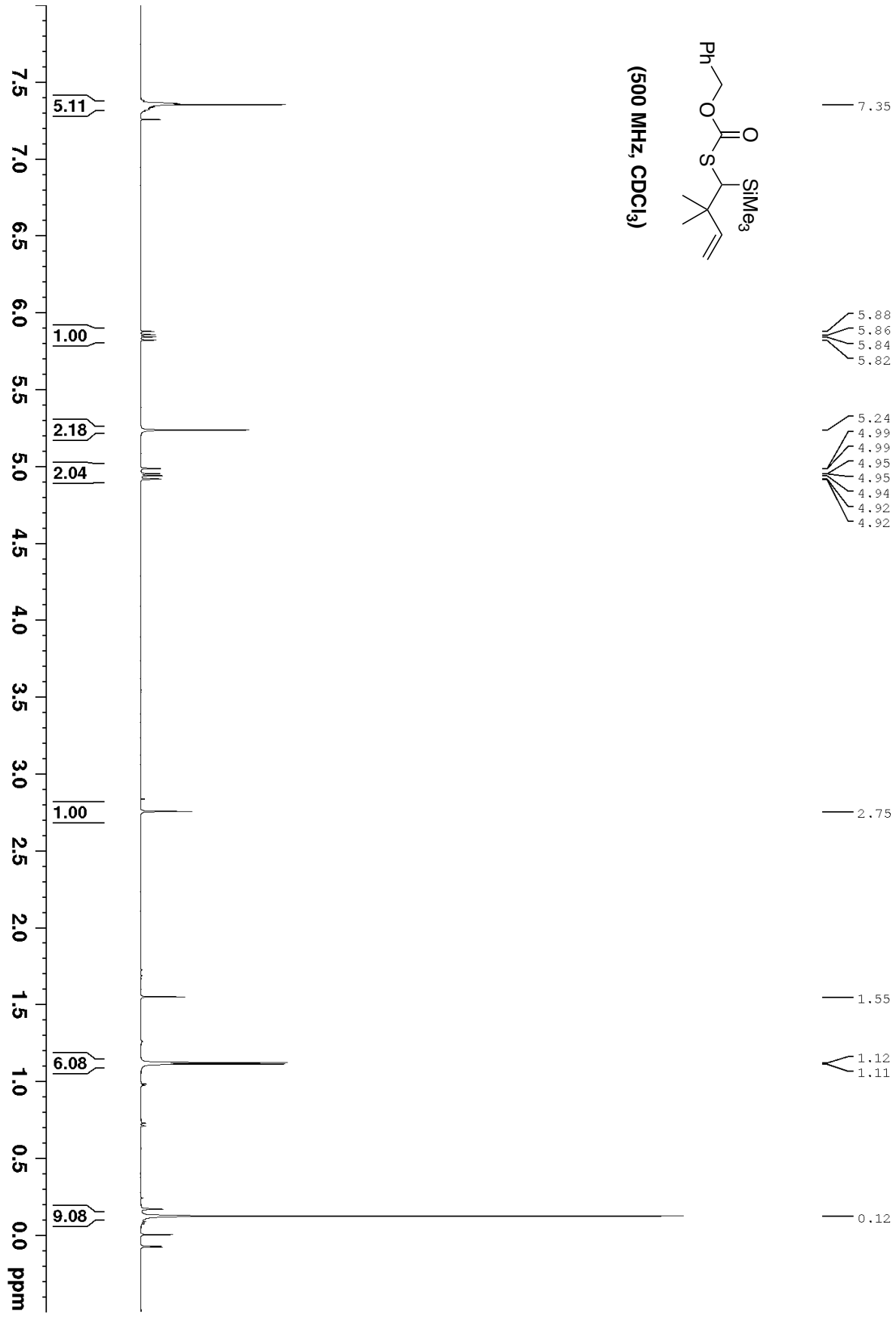

(125 MHz, CDCl3)
O
S
SiMe3
196.02
147.60
111.29
41.07
40.95
30.49
27.43
26.60
0.71
220
200
180
160
140
120
100
80
60
40
20
ppm

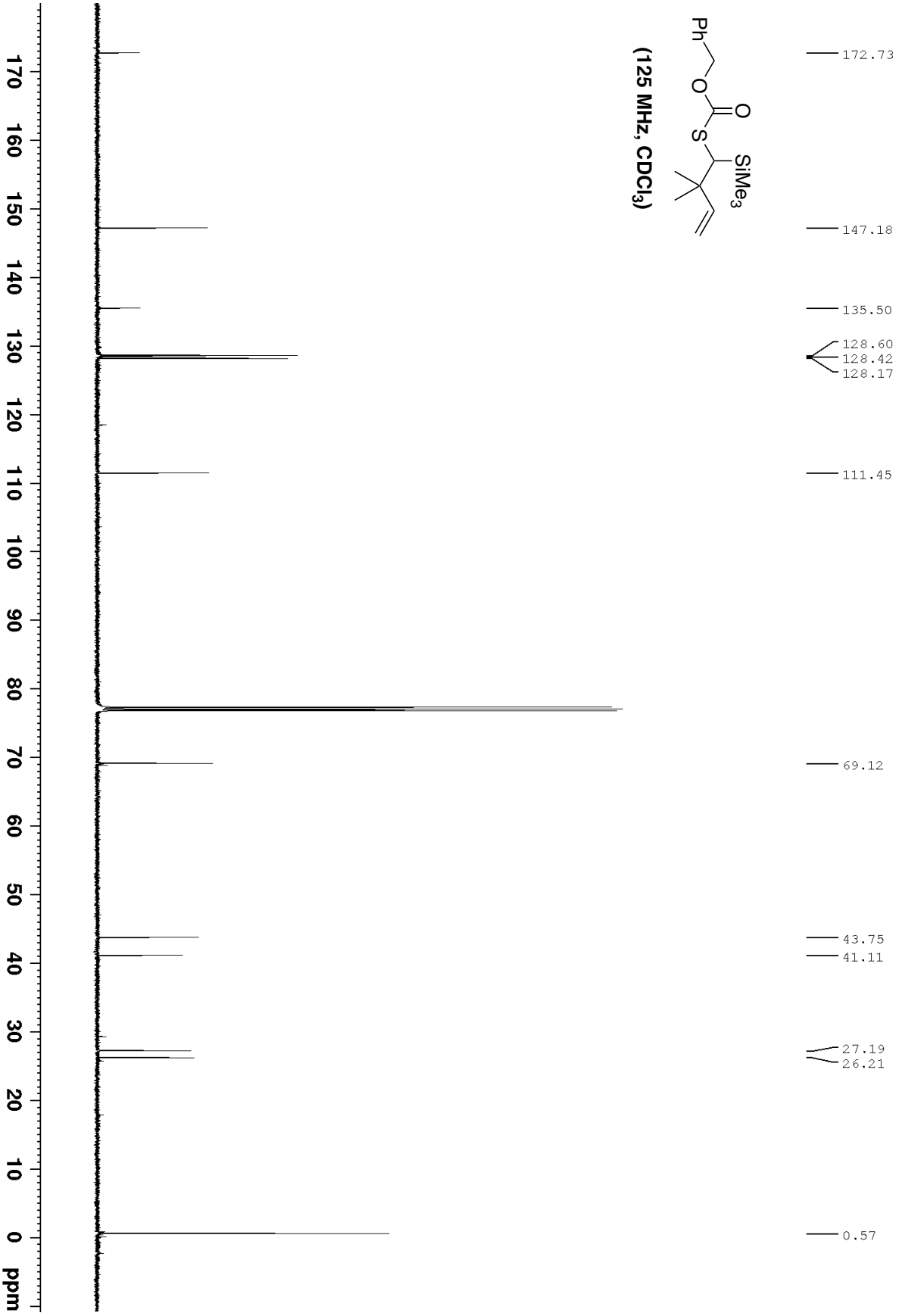

(500 MHz, CDCl3)
MeO
O
S
SiMe3
8.02
8.00
6.93
6.91
5.95
5.93
5.91
5.88
5.00
4.96
4.95
4.92
3.85
3.27
1.14
0.13
2.02
2.11
1.00
1.01
1.05
3.01
1.02
6.04
9.01
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ppm

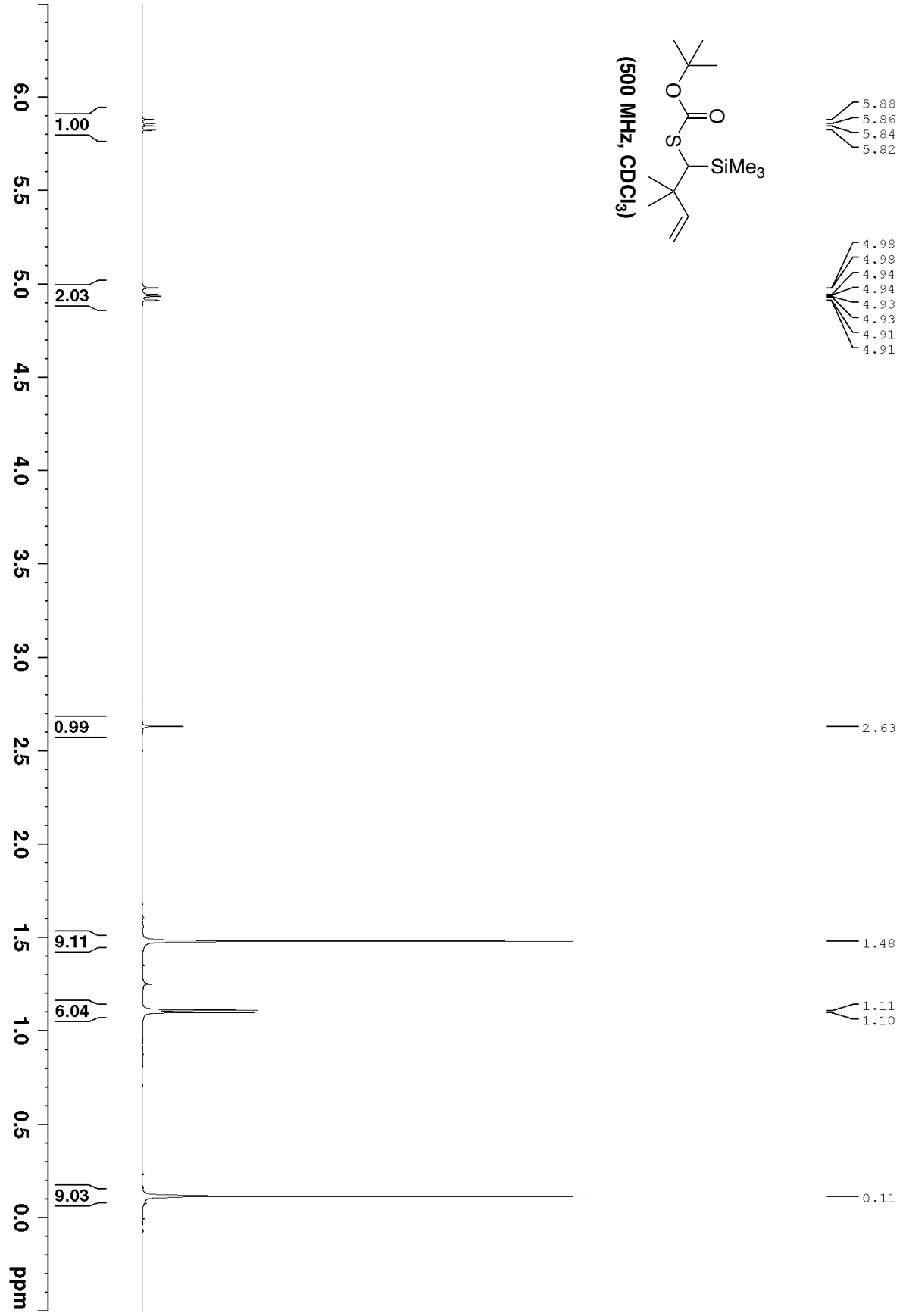

MeO
O
S
SiMe3
(125 MHz, CDCl3)
190.79
163.83
147.78
130.31
129.72
113.90
111.33
55.71
41.31
40.32
27.67
26.68
0.85
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm

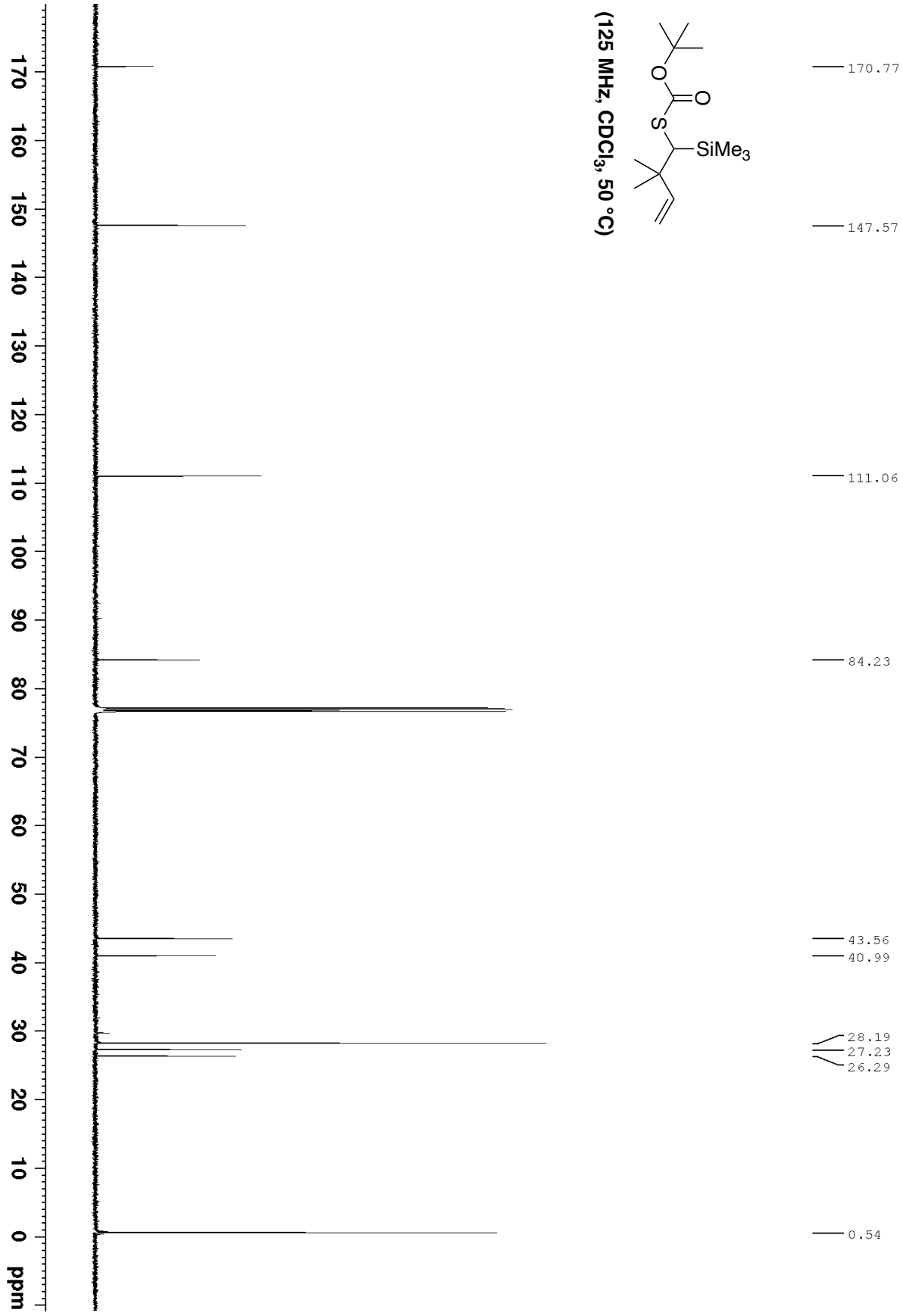

(500 MHz, CDCl3)
Ph
O
S
SiMe3
CO2Me
8.01
8.00
7.56
7.54
7.53
7.45
7.43
7.42
6.08
5.58
4.21
3.78
1.38
1.25
0.12
2.02
1.04
2.08
1.00
1.00
1.00
3.00
3.10
3.31
9.02
ppm

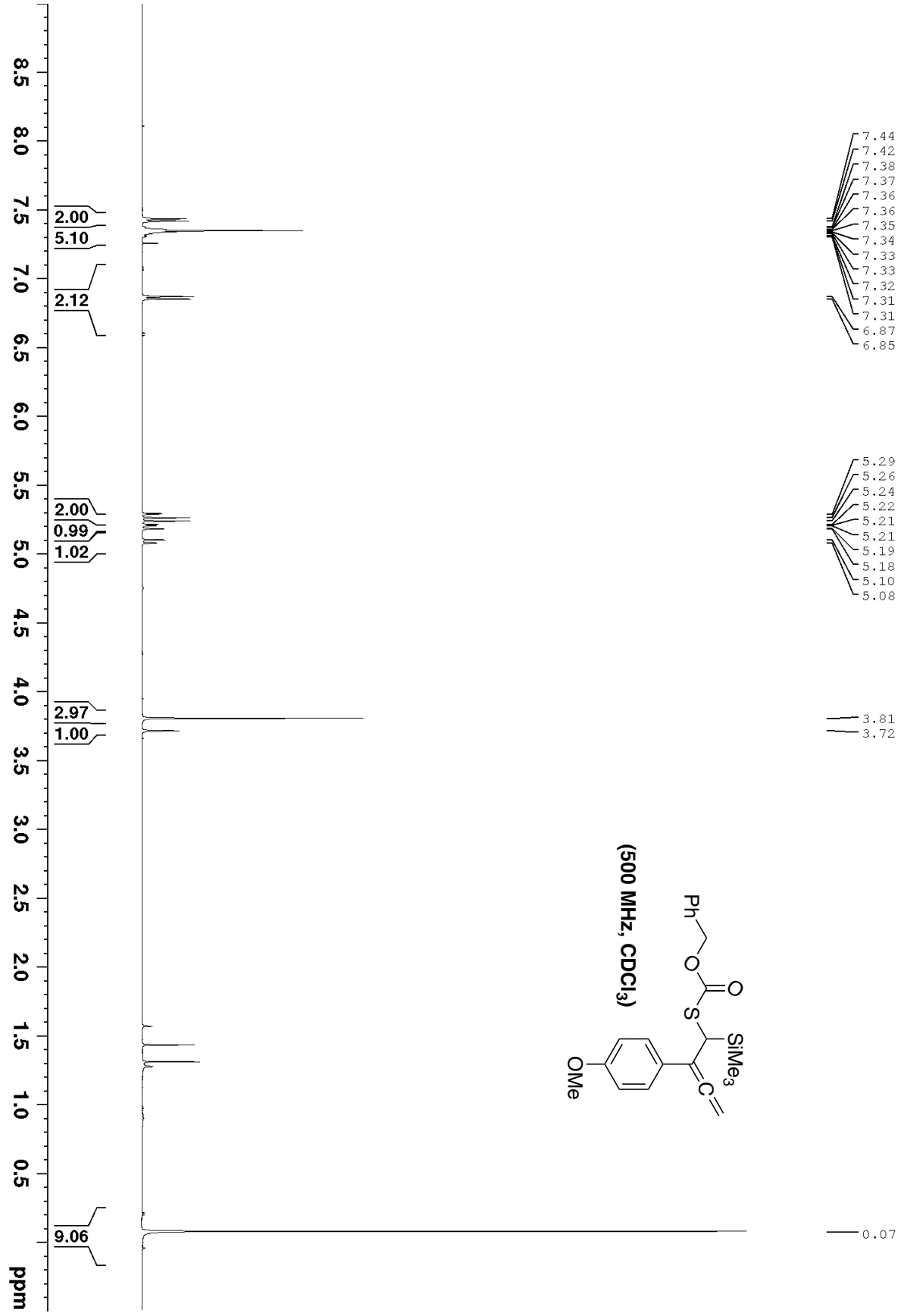

(125 MHz, CDCl3)
Ph
O
S
SiMe3
CO2Me
191.27
168.45
148.26
137.97
133.02
128.52
127.40
123.57
51.66
42.32
37.47
27.74
27.63
0.51
220
200
180
160
140
120
100
80
60
40
20
ppm

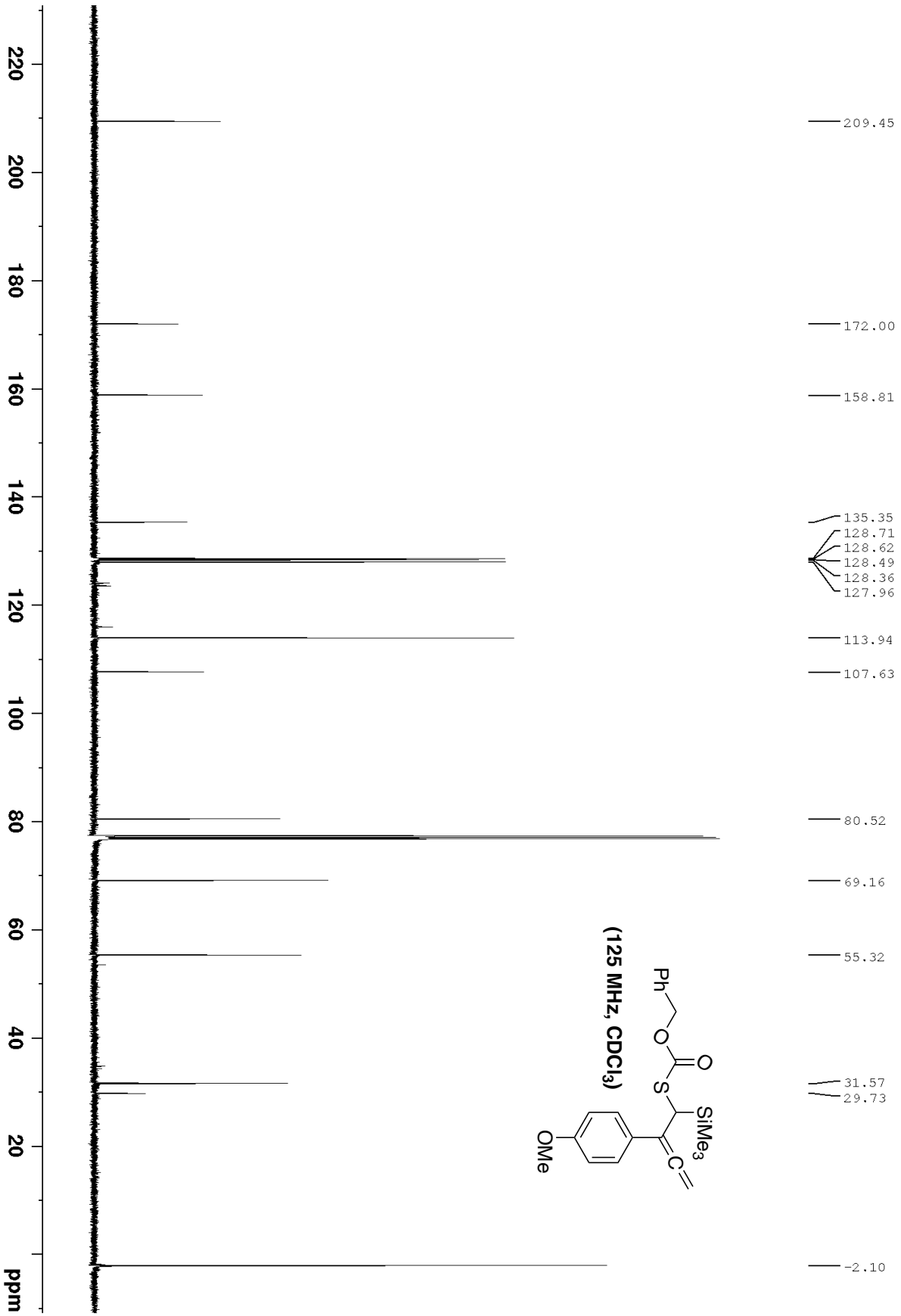

(500 MHz, CDCl3)
Ph
O
O
S
SiMe3
7.35
5.88
5.86
5.84
5.82
5.24
4.99
4.99
4.95
4.95
4.94
4.92
4.92
2.75
1.55
1.12
1.11
0.12
5.11
1.00
2.18
2.04
1.00
6.08
9.08
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ppm

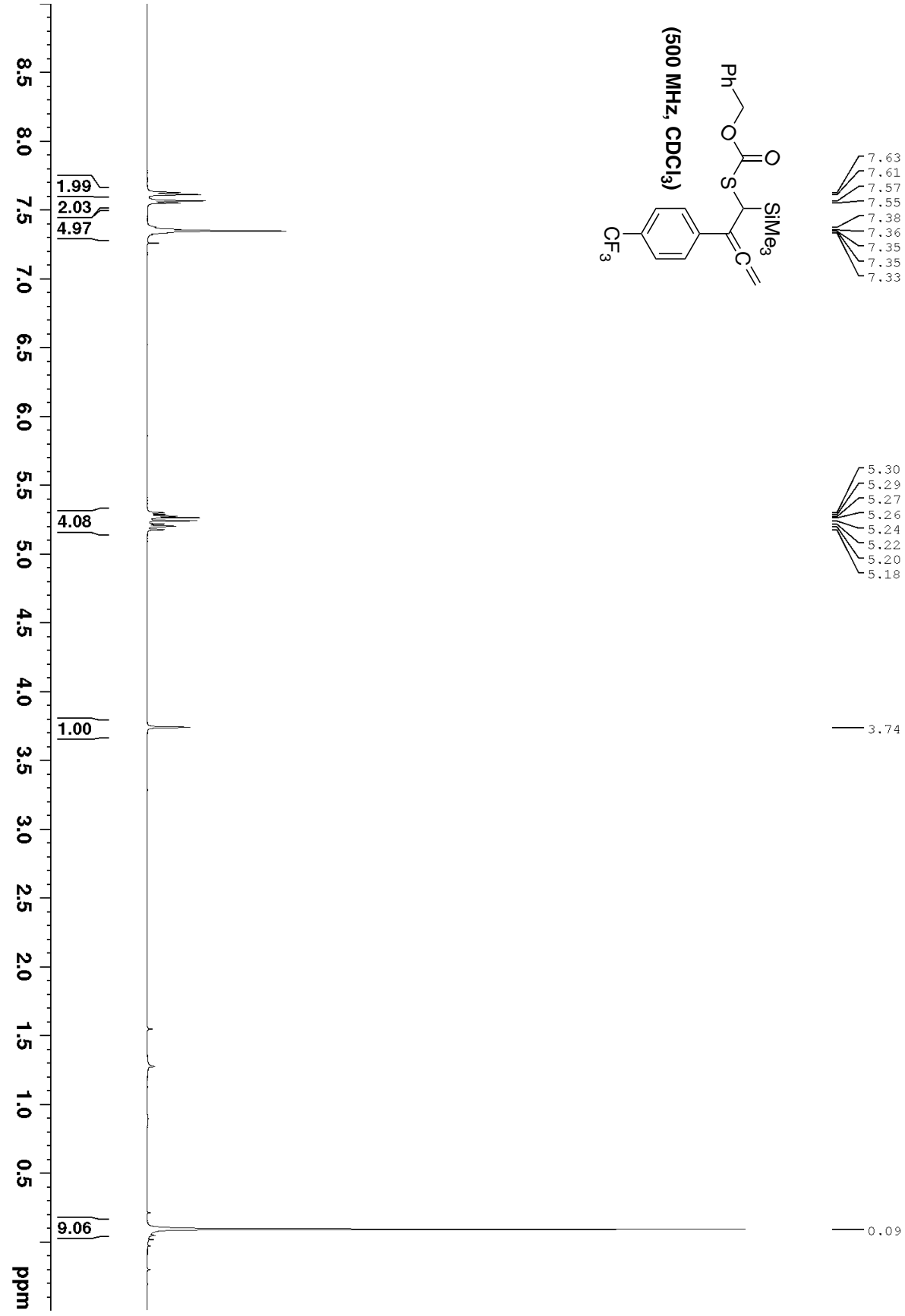

(125 MHz, CDCl3)
Ph
O
O
S
SiMe3
172.73
147.18
135.50
128.60
128.42
128.17
111.45
69.12
43.75
41.11
27.19
26.21
0.57
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
ppm

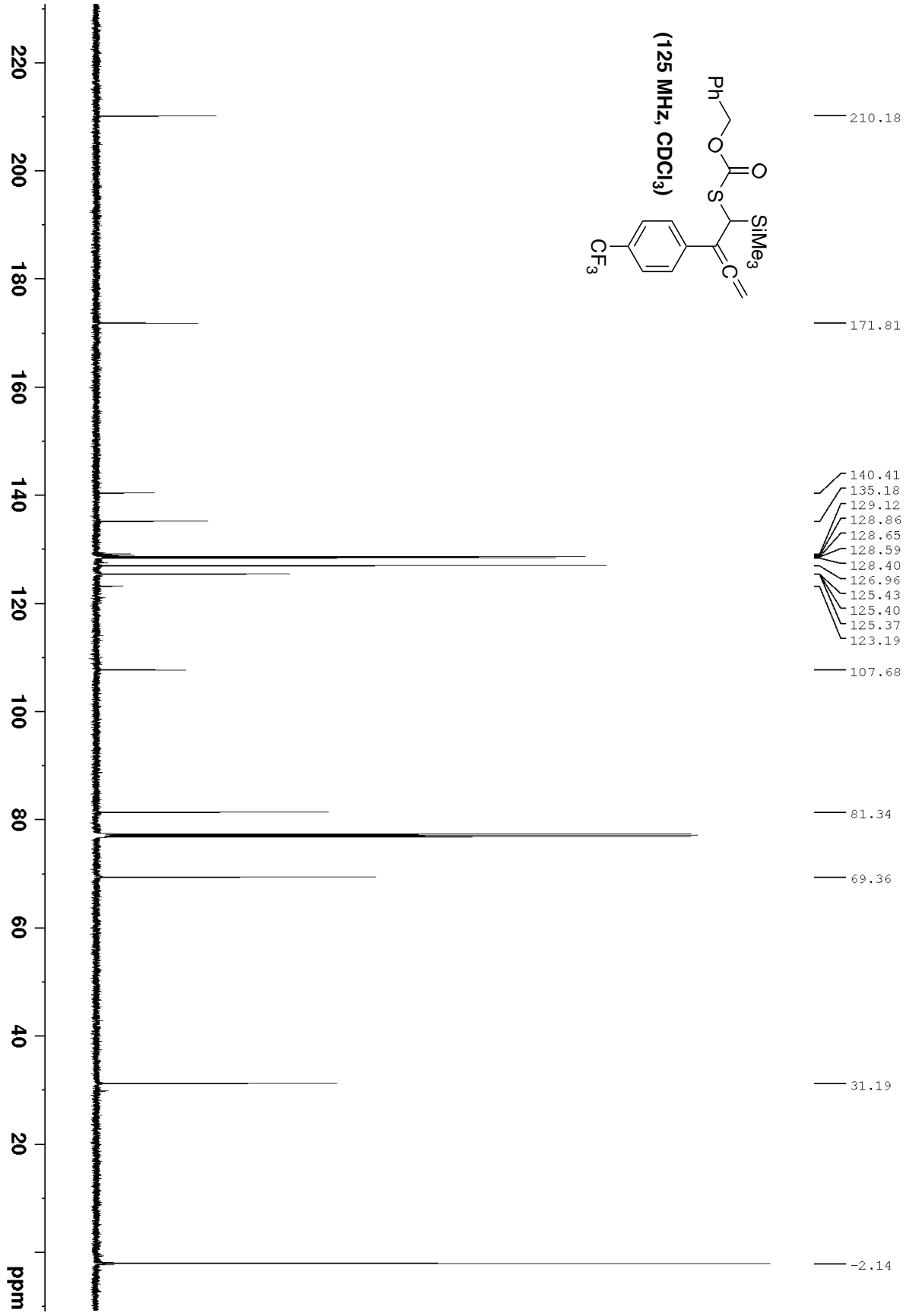

(500 MHz, CDCl3)
SiMe3
O
O
S
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ppm
1.00
2.03
0.99
9.11
6.04
9.03
5.88
5.86
5.84
5.82
4.98
4.98
4.94
4.94
4.93
4.93
4.91
4.91
2.63
1.48
1.11
1.10
0.11

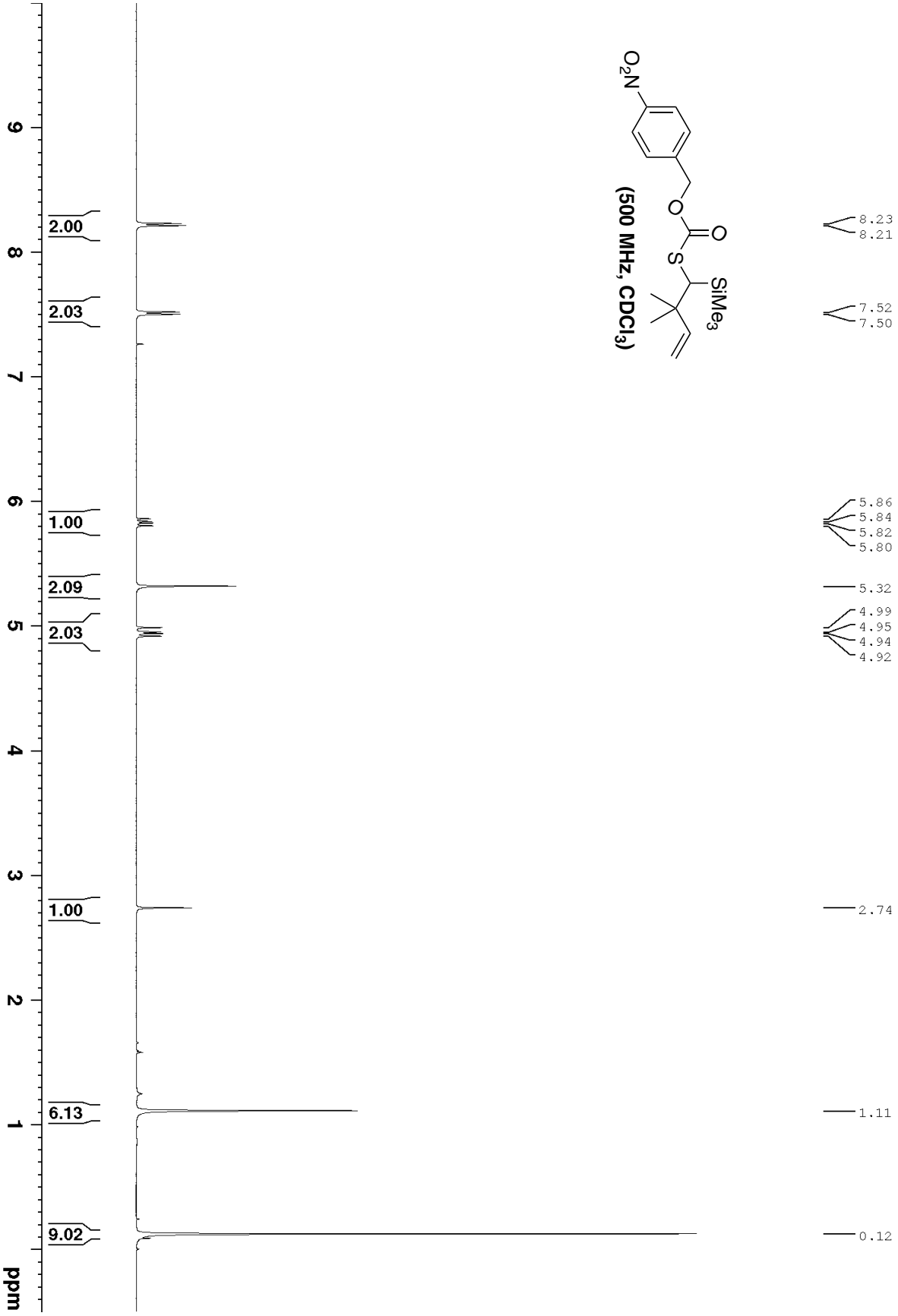

(125 MHz, CDCl3, 50 °C)
SiMe3
170.77
147.57
111.06
84.23
43.56
40.99
28.19
27.23
26.29
0.54
ppm

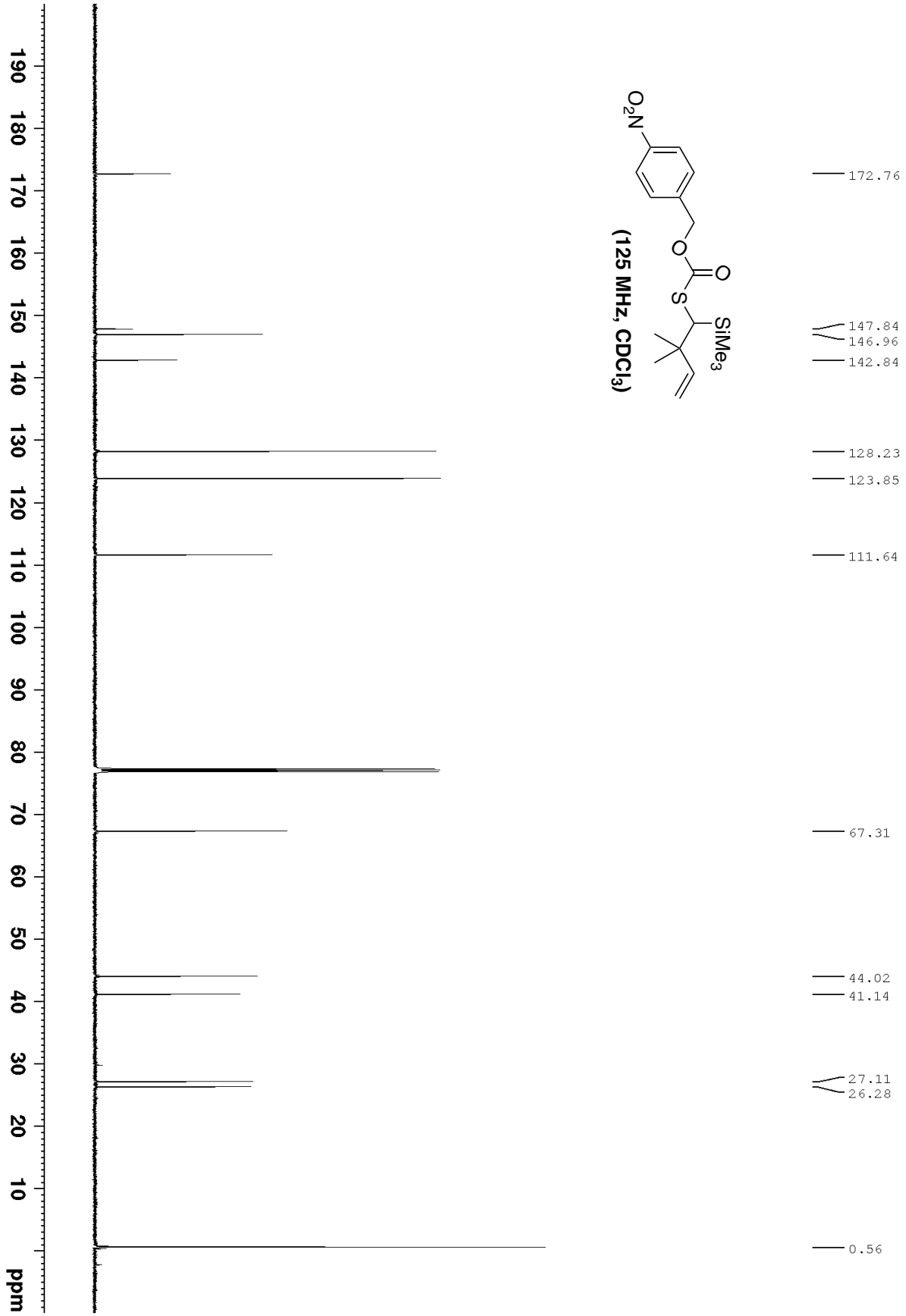

8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
ppm
2.00
5.10
2.12
2.00
0.99
1.02
2.97
1.00
9.06
7.44
7.42
7.38
7.37
7.36
7.36
7.35
7.34
7.33
7.33
7.32
7.31
7.31
6.87
6.85
5.29
5.26
5.24
5.22
5.21
5.21
5.19
5.18
5.10
5.08
3.81
3.72
0.07
(500 MHz, CDCl3)
Ph
O
O
S
SiMe3
C
OMe

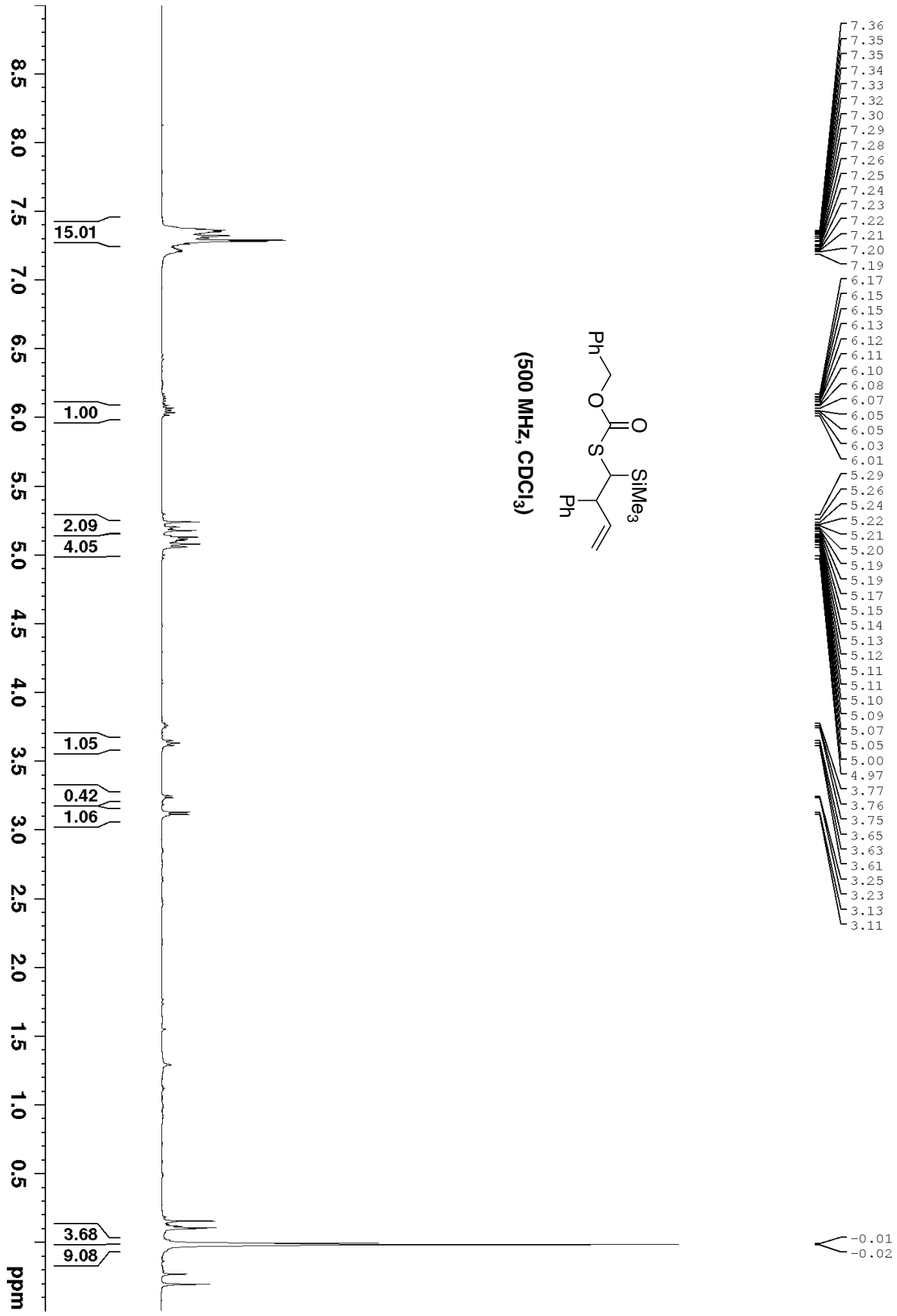

220
200
180
160
140
120
100
80
60
40
20
ppm
209.45
172.00
158.81
135.35
128.71
128.62
128.49
128.36
127.96
113.94
107.63
80.52
69.16
55.32
31.57
29.73
-2.10
(125 MHz, CDCl3)
Ph
O
O
S
SiMe3
C
OMe

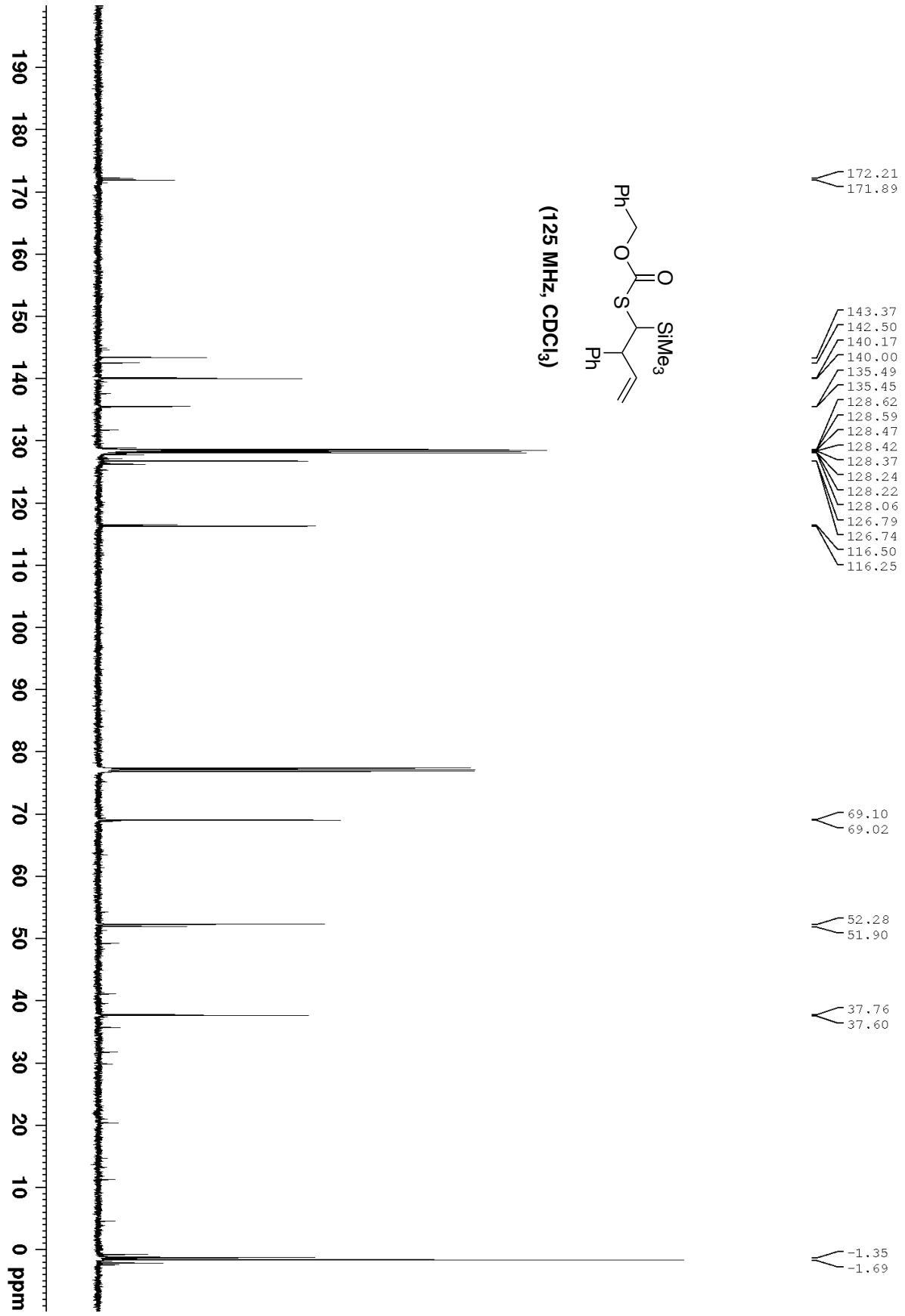

(500 MHz, CDCl3)
Ph
O
O
S
SiMe3
CF3
C
1.99
2.03
4.97
4.08
1.00
9.06
7.63
7.61
7.57
7.55
7.38
7.36
7.35
7.35
7.33
5.30
5.29
5.27
5.26
5.24
5.22
5.20
5.18
3.74
0.09
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
ppm

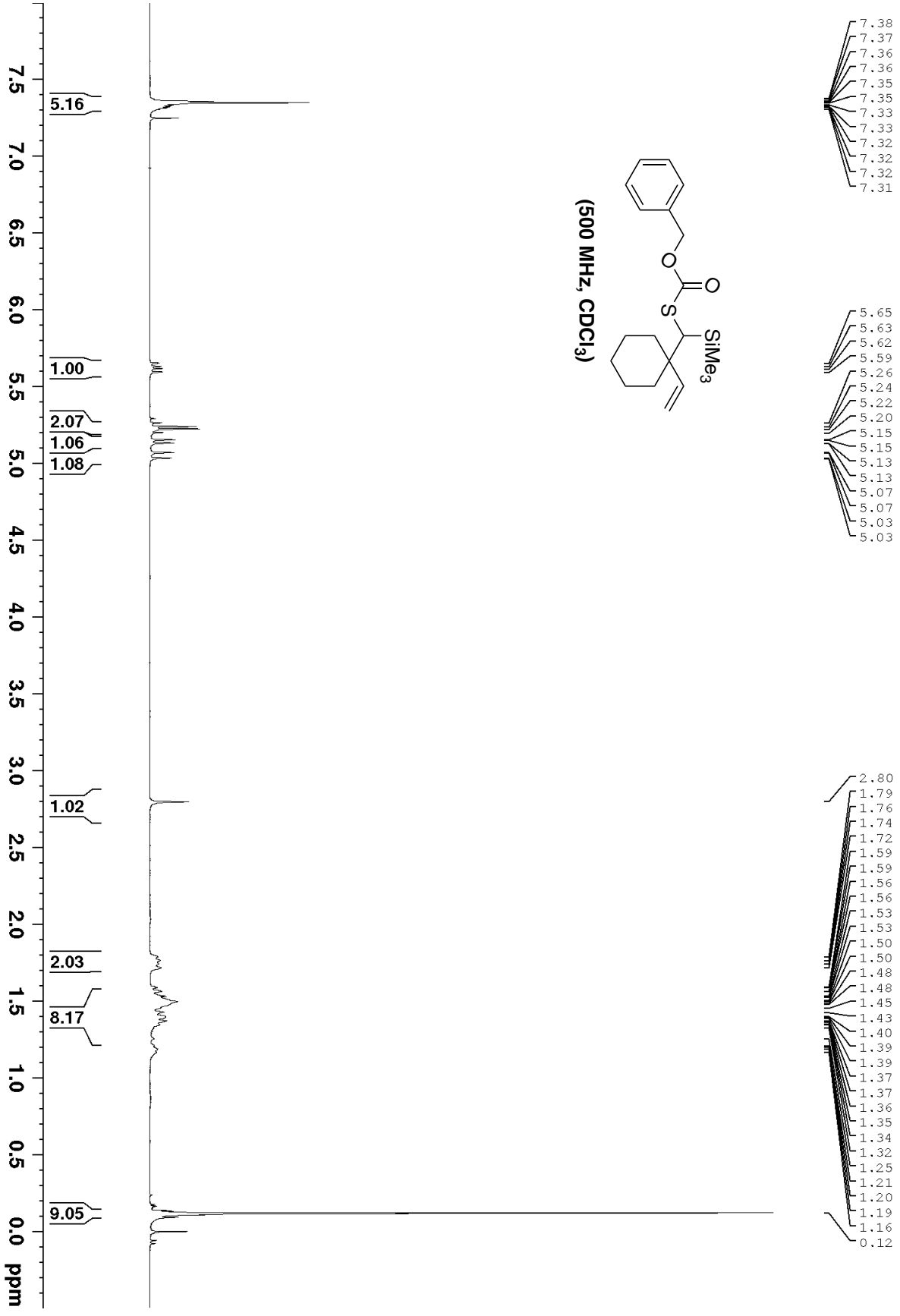

(125 MHz, CDCl3)
Ph
O
O
S
SiMe3
C
CF3
210.18
171.81
140.41
135.18
129.12
128.86
128.65
128.59
128.40
126.96
125.43
125.40
125.37
123.19
107.68
81.34
69.36
31.19
-2.14
220
200
180
160
140
120
100
80
60
40
20
ppm

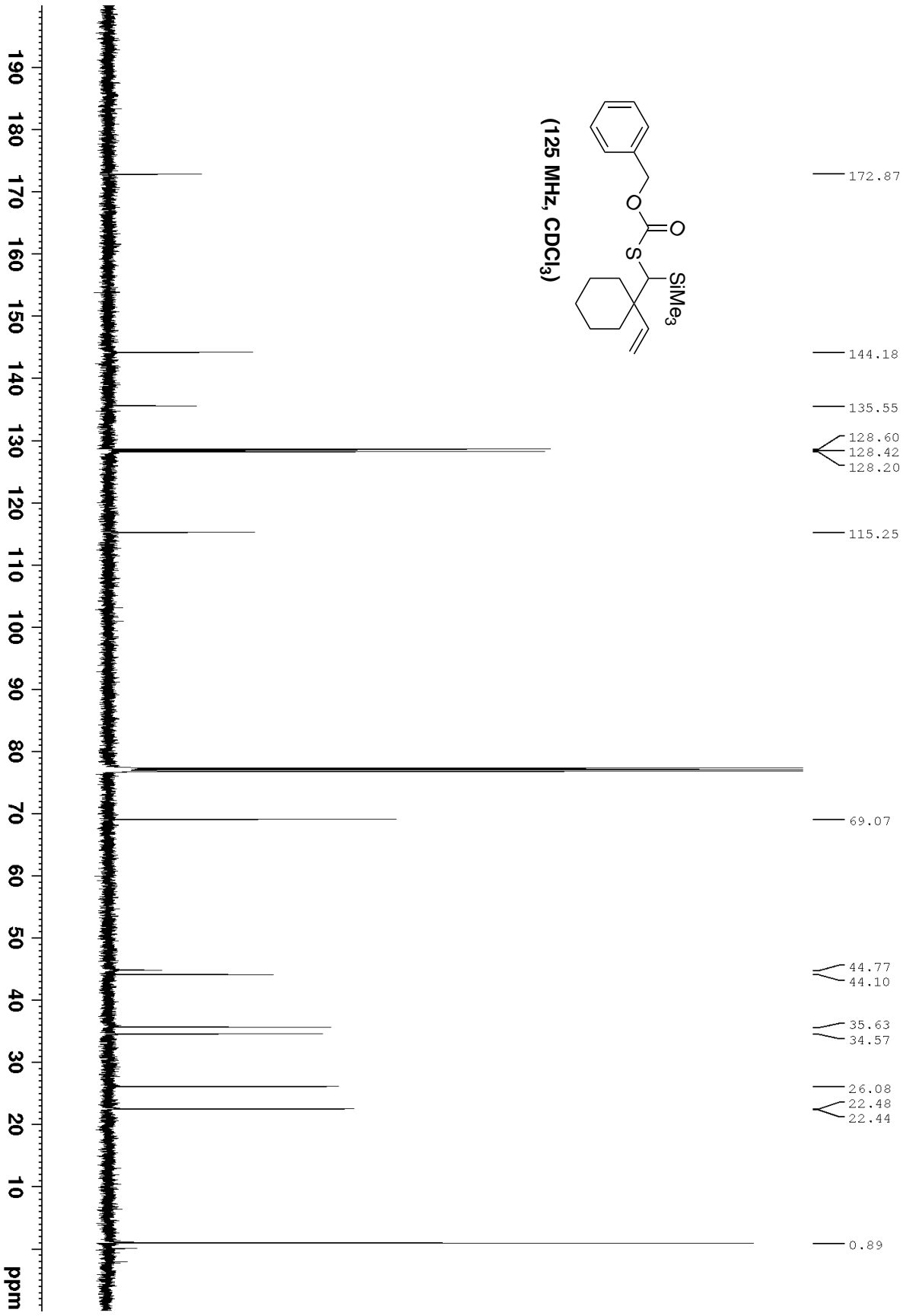

O2N
O
O
S
SiMe3
(500 MHz, CDCl3)
8.23
8.21
7.52
7.50
5.86
5.84
5.82
5.80
5.32
4.99
4.95
4.94
4.92
2.74
1.11
0.12
2.00
2.03
1.00
2.09
2.03
1.00
6.13
9.02
ppm

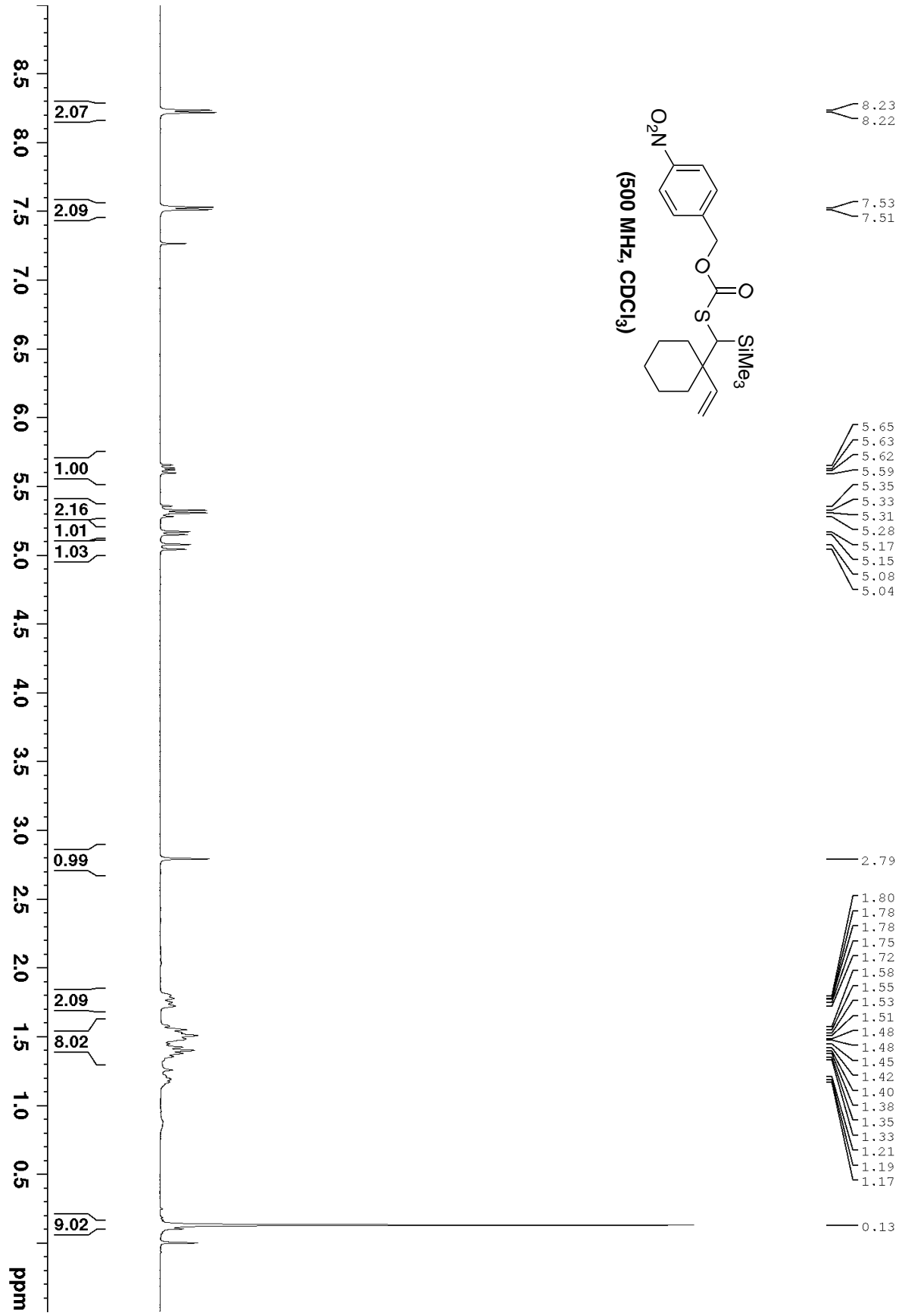

O2N
O
O
S
SiMe3
(125 MHz, CDCl3)
172.76
147.84
146.96
142.84
128.23
123.85
111.64
67.31
44.02
41.14
27.11
26.28
0.56
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm

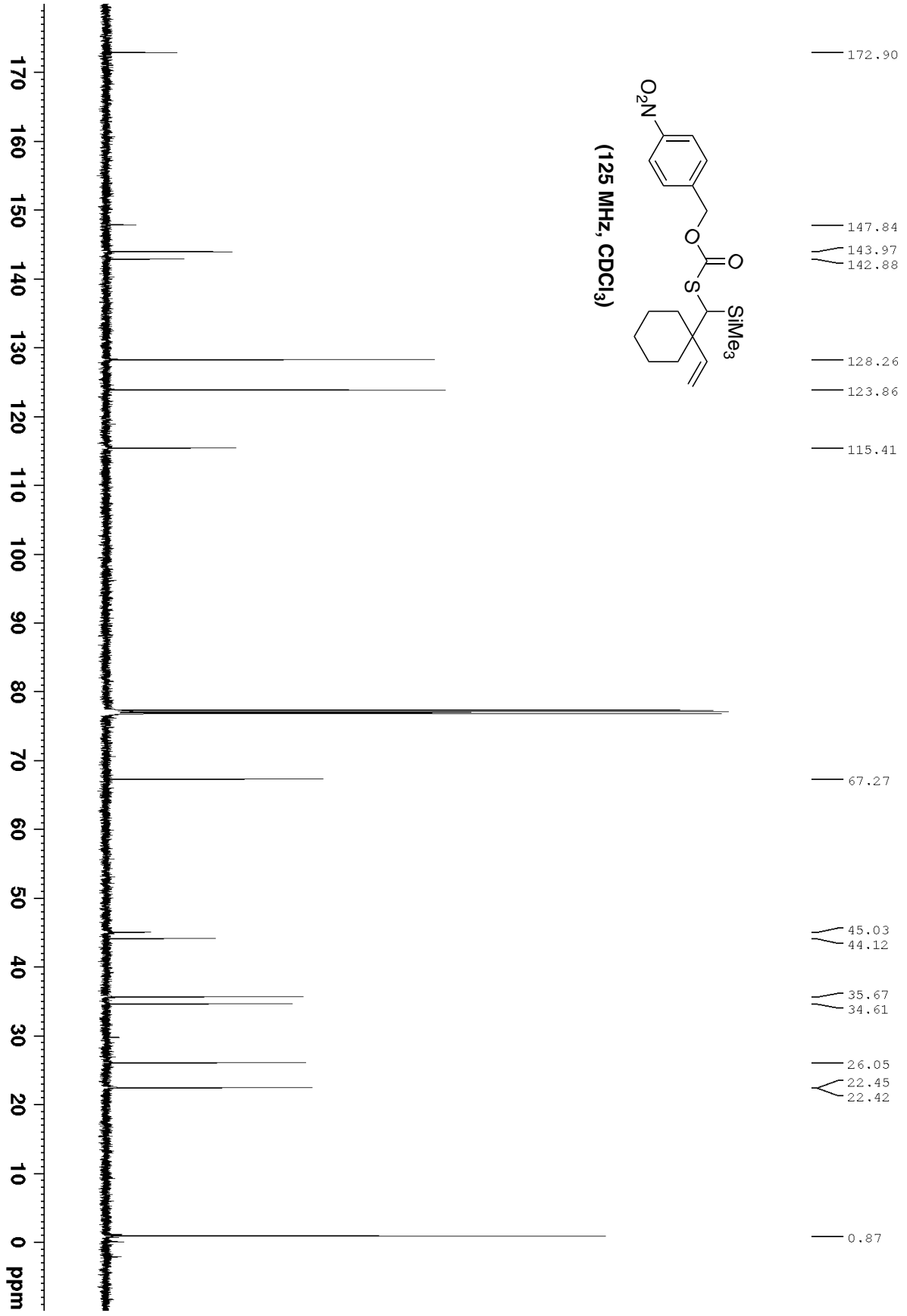

(500 MHz, CDCl3)
Ph
O
O
S
SiMe3
Ph
7.36
7.35
7.35
7.34
7.33
7.32
7.30
7.29
7.28
7.26
7.25
7.24
7.23
7.22
7.21
7.20
7.19
6.17
6.15
6.15
6.13
6.12
6.11
6.10
6.08
6.07
6.05
6.05
6.03
6.01
5.29
5.26
5.24
5.22
5.21
5.20
5.19
5.19
5.17
5.15
5.14
5.13
5.12
5.11
5.11
5.10
5.09
5.07
5.05
5.00
4.97
3.77
3.76
3.75
3.65
3.63
3.61
3.25
3.23
3.13
3.11
-0.01
-0.02
15.01
1.00
2.09
4.05
1.05
0.42
1.06
3.68
9.08
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
ppm

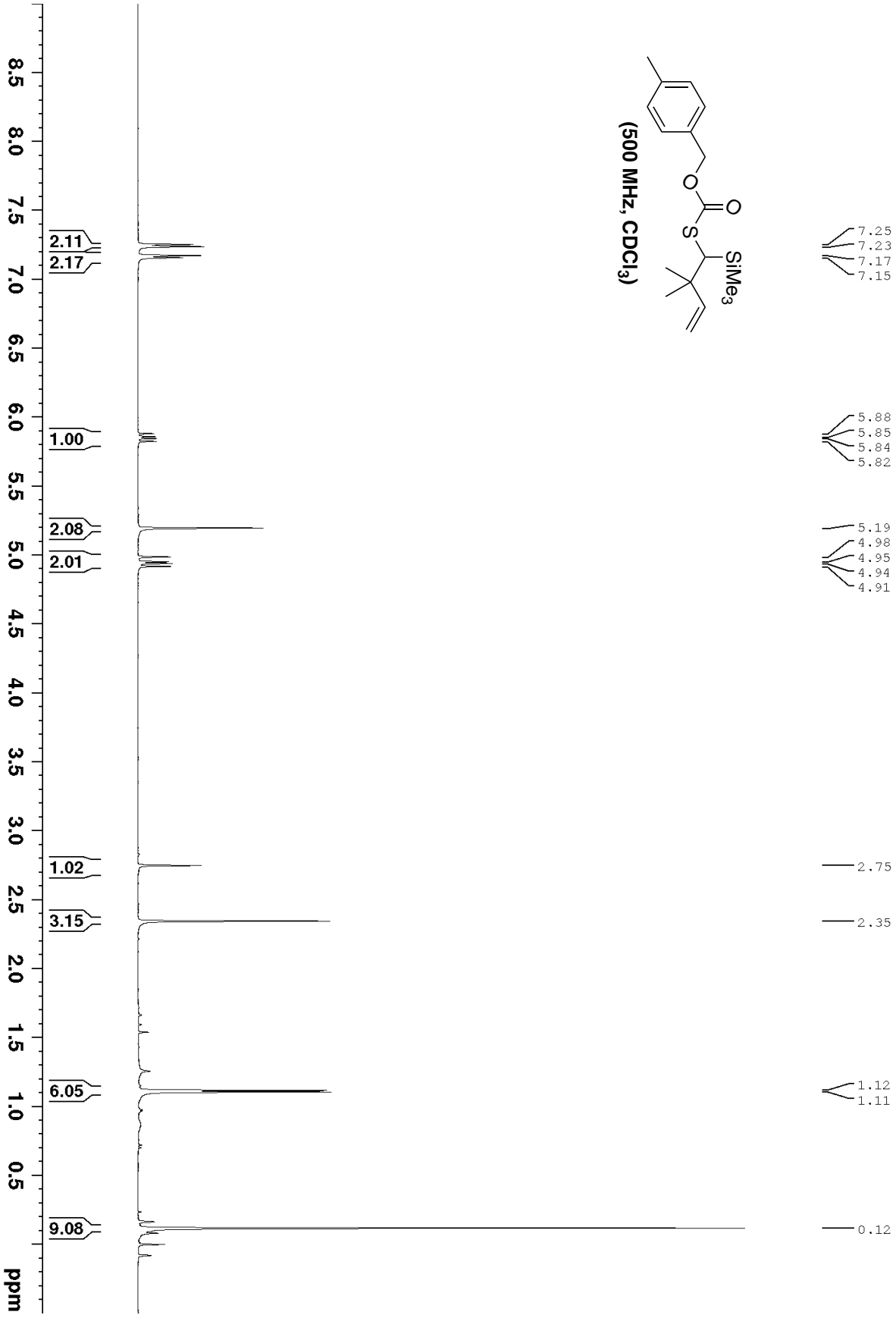

(125 MHz, CDCl3)
Ph
O
O
S
SiMe3
Ph
172.21
171.89
143.37
142.50
140.17
140.00
135.49
135.45
128.62
128.59
128.47
128.42
128.37
128.24
128.22
128.06
126.79
126.74
116.50
116.25
69.10
69.02
52.28
51.90
37.76
37.60
-1.35
-1.69
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0 ppm

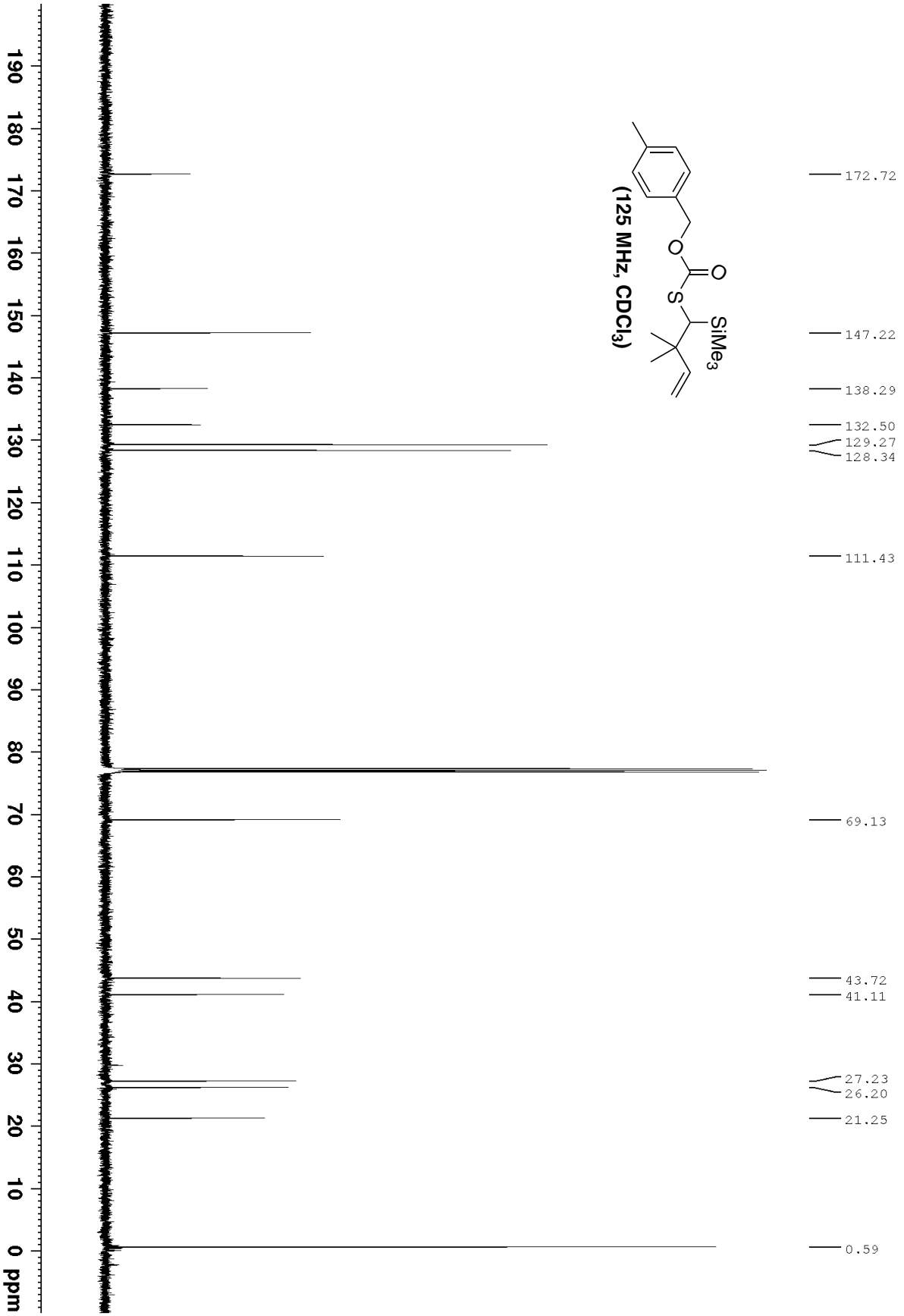

(500 MHz, CDCl3)
SiMe3
7.38
7.37
7.36
7.36
7.35
7.35
7.33
7.33
7.32
7.32
7.32
7.31
5.65
5.63
5.62
5.59
5.26
5.24
5.22
5.20
5.15
5.15
5.13
5.13
5.07
5.07
5.03
5.03
2.80
1.79
1.76
1.74
1.72
1.59
1.59
1.56
1.56
1.53
1.53
1.50
1.50
1.48
1.48
1.45
1.43
1.40
1.39
1.39
1.37
1.37
1.36
1.35
1.34
1.32
1.25
1.21
1.20
1.19
1.16
0.12
5.16
1.00
2.07
1.06
1.08
1.02
2.03
8.17
9.05
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
ppm


(125 MHz, CDCl3)
O
O
S
SiMe3
172.87
144.18
135.55
128.60
128.42
128.20
115.25
69.07
44.77
44.10
35.63
34.57
26.08
22.48
22.44
0.89
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
ppm


(500 MHz, CDCl3)
O2N
O
S
SiMe3
8.23
8.22
7.53
7.51
5.65
5.63
5.62
5.59
5.35
5.33
5.31
5.28
5.17
5.15
5.08
5.04
2.79
1.80
1.78
1.78
1.75
1.72
1.58
1.55
1.53
1.51
1.48
1.48
1.45
1.42
1.40
1.38
1.35
1.33
1.21
1.19
1.17
0.13
2.07
2.09
1.00
2.16
1.01
1.03
0.99
2.09
8.02
9.02
ppm


(125 MHz, CDCl3)
O2N
O
O
S
SiMe3
172.90
147.84
143.97
142.88
128.26
123.86
115.41
67.27
45.03
44.12
35.67
34.61
26.05
22.45
22.42
0.87
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
ppm


(500 MHz, CDCl3)
SiMe3
O
O
S
2.11
2.17
1.00
2.08
2.01
1.02
3.15
6.05
9.08
7.25
7.23
7.17
7.15
5.88
5.85
5.84
5.82
5.19
4.98
4.95
4.94
4.91
2.75
2.35
1.12
1.11
0.12
8.5
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
ppm


(125 MHz, CDCl3)
SiMe3
172.72
147.22
138.29
132.50
129.27
128.34
111.43
69.13
43.72
41.11
27.23
26.20
21.25
0.59
190 180 170 160 150 140 130 120 110 100 90 80 70 60 50 40 30 20 10 0 ppm