Supporting Information
Competition H(D) Kinetic Isotope Effects in the Autoxidation of Hydrocarbons

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Contents

1 Materials, methods, and instrumentation

All reagents and solvents were commercial grade and purified prior to use when necessary. Acetonitrile (MeCN) and tetrahydrofuran (THF) were dried by passage through a column of activated alumina as described by Grubbs.[1] For microscale reactions, tetrahydrofuran was distilled from sodium–benzophenone ketyl. Flame-dried (under vacuum) glassware was used for all reactions. Stainless steel syringes or cannulae were used to transfer air- and moisture-sensitive liquids. All organic extracts were dried over $MgSO_4$ or Na_2SO_4 unless otherwise indicated.

Thin layer chromatography (TLC) was performed using glass-backed silica gel (250 µm) plates and flash chromatography utilized 230–400 mesh silica gel from EMD. Products were visualized by UV light, and/or the use of potassium iodoplatinate, potassium permanganate, or phosphomolybdic acid solutions.

Normal phase HPLC was conducted at 5 mL/min on a Waters 1525 system coupled with Waters 2996 Photoiode Array Detector and Waters 717plus Autosampler using Beckman Coulter™ Ultrasphere™ Silica 250 mm × 10 mm column.

Nuclear magnetic resonance spectra (NMR) were acquired on either a Bruker instrument: AV-400 (400 MHz), DRX-500 (500 MHz), or AVII-600 (600 MHz). Chemical shifts are measured relative to residual solvent peaks as an internal standard set to δ 7.26 and δ 77.0 (CDCl3) or δ 7.16 and 128.06 (C_6D_6) for ^{1}H and ^{13}C, respectively. Multiplicities are reported as singlet (s), doublet (d), triplet (t), quartet (q) or combinations thereof while higher coupling patterns are not abbreviated.

1,2,3,4-tetrahydronaphthalene-1,1-d_2,[2] 1-(3-ethylphenyl)ethan-1-one,[3] (3-bromophenyl)-(phenyl)methanol,[4] 1-benzyl-3-bromobenzene,[4] 1,3-dibenzylbenzene,[5] γ-butyrolac-tone-d_2,[6] 3,4-dihydronaphthalen-1(2*H*)-one-4,4-d_2[7] were prepared according to the literature procedures.

2 Experimental procedures

2.1 Deuterium Kinetic Isotope Effect Experiments

General Autoxidation Procedure. A stream of oxygen gas was passed through a solution of the hydrocarbon (3 M in C_6D_6) for 3 min. To a screw-cap vial (in triplicate) was added 300 µL of the solution and AIBN (2.9 mg, 0.06 M final concentration). The vial was capped and heated at 65 °C for 6 h. For hydroperoxide analysis, the reaction mixture was purified directly by semipreparative normal phase HPLC to give the hydroperoxide products. For alcohol analysis, the vials were cooled to rt and and excess of triphenylphosphine was added. The alcohol products were isolated from the resulting solution by semipreparative normal phase HPLC. Purified hydroperoxides and alcohols were analyzed by ^{1}H NMR with delay time set to 20 s–30 s. Automatic baseline correction (abs, Bruker Topspin 2.1) was applied to all NMR spectra. Figure S1. shows the level of tetralin-d_2 conversion after 6 h of reaction.

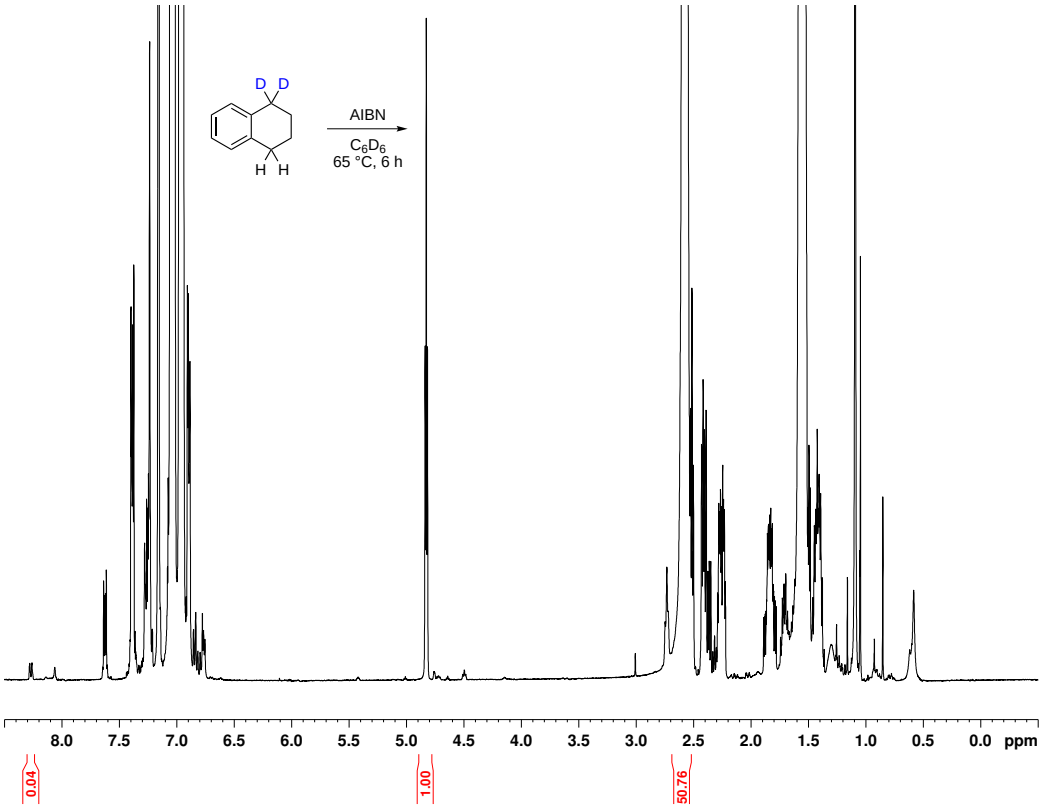


Figure S1. ^{1}H NMR (C_6D_6) showing the level of conversion during autoxidation of tetralin-d_2 after 6 h.

2.1.1 Chain length calculation

The rate constant for AIBN decomposition at 65 °C was calculated from the Arhenius equation (eq 1).[8] The rate of initiation (R_i) was calculated using escape factor of 0.65[9] and concentration of 0.06 M. The rate of oxidation (eq 4) was calculated using the Arrhenius equations published by Howard and Ingold.[10]

$$k_d = 1.99 \times 10^{15} \exp(\frac{-30,900}{RT}) = 2.08 \times 10^{-5} s^{-1} \tag{1}$$

$$R_i = 2 \times 0.65 \times k_d \times c_{AIBN} = 1.62 \times 10^{-6} M \cdot s^{-1} \tag{2}$$

$$\frac{k_p}{(2k_t)^{1/2}} = 44 \times \exp(\frac{-6,000}{RT}) = 5.8 \times 10^{-3} M^{-1/2} \cdot s^{-1/2} \tag{3}$$

$$rate = 5.8 \times 10^{-3} \times 3 \times \sqrt{R_i} = 2.2 \times 10^{-5} M \cdot s^{-1} \tag{4}$$

The chain length can be then calculated using the following equation:

$$CL = \frac{rate}{R_i} = \frac{2.2 \times 10^{-5}}{1.62 \times 10^{-6}} = 14 \tag{5}$$

2.1.2 Autoxidation of deuterotetralin

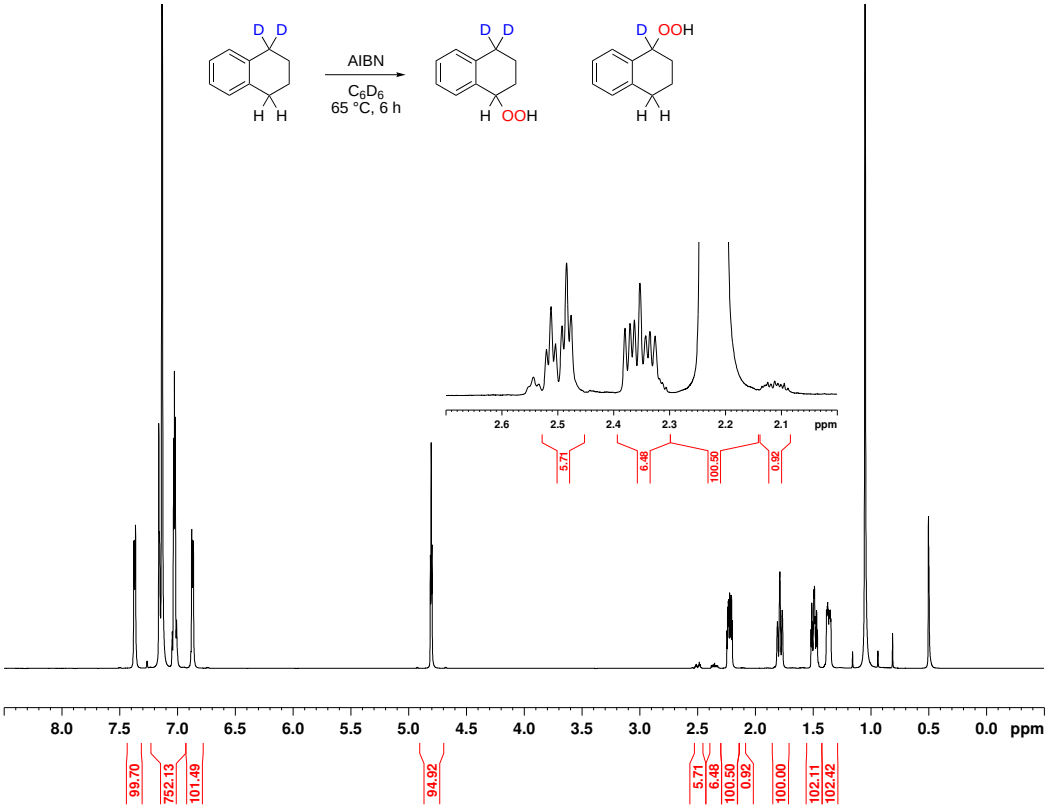


Figure S2. Example ^{1}H NMR (C_6D_6) spectrum of hydroperoxide products from autoxidation of tetralin-d_2.

Table S1. Deuterium kinetic isotope effect in autoxidation of tetralin-d_2. Analysis of hydroperoxides.

entry	NMR integrations methylene	methine	KIE ($k_{H,h}/k_{D,d}$)
1	5.71	94.92	16.62
2	6.10	92.52	15.17
3	5.91	93.80	15.87
		AVERAGE	**15.89**
		STDEV	**0.73**

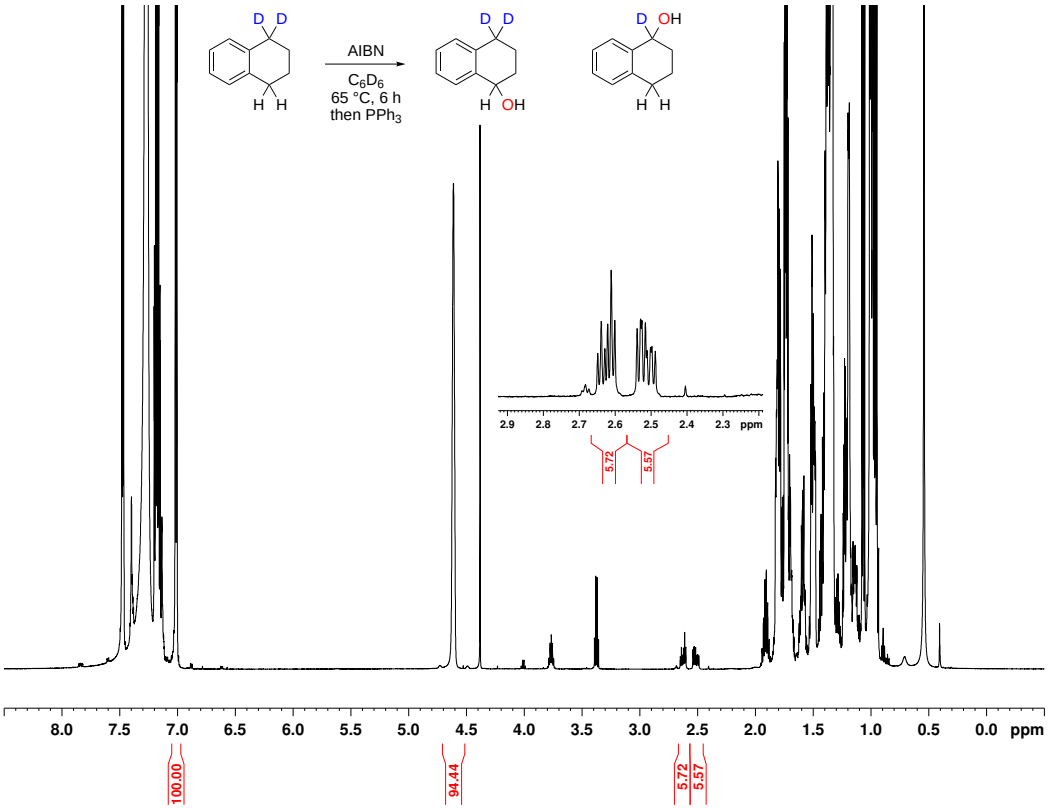


Figure S3. Example ^{1}H NMR (C_6D_6) spectrum of alcohol products from autoxidation of tetralin-d_2.

Table S2. Deuterium kinetic isotope effect in autoxidation of tetralin-d_2. Analysis of alcohols.

entry	NMR integrations methylene	methine	KIE ($k_{H,h}/k_{D,d}$)
1	6.03	93.97	15.58
2	5.90	94.10	15.95
3	5.57	94.43	16.95
		AVERAGE	**16.16**
		STDEV	**0.71**

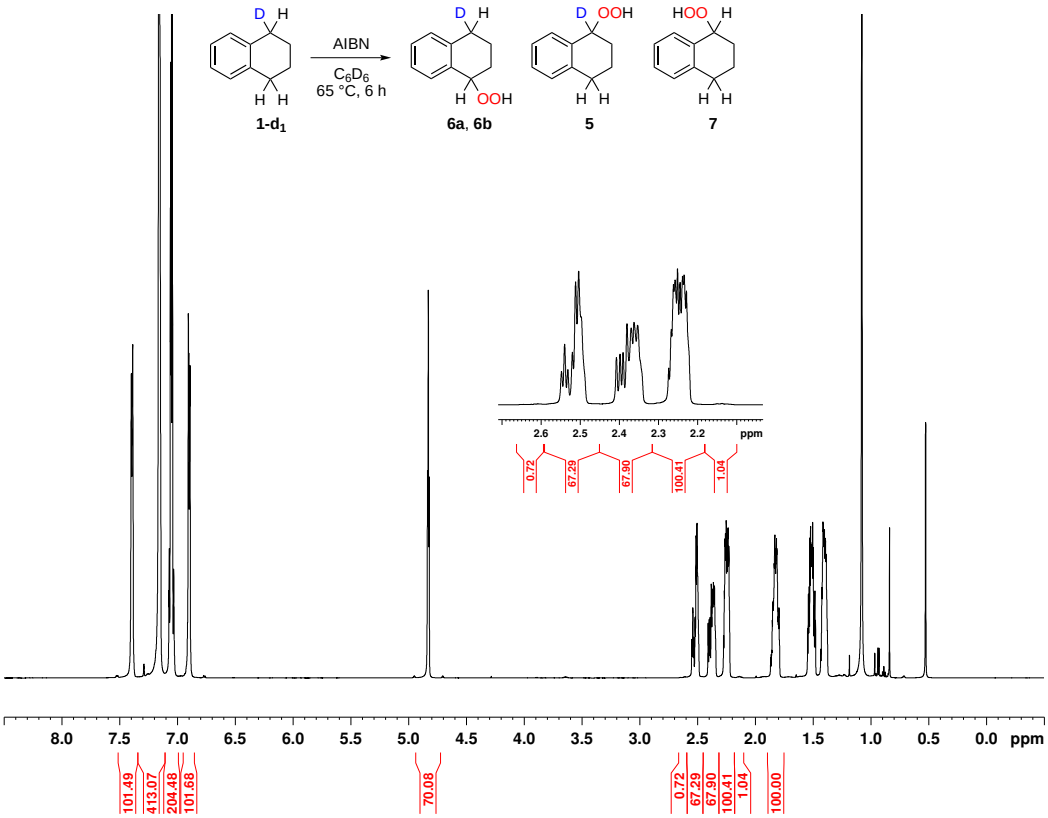


Figure S4. Example ^{1}H NMR (C_6D_6) spectrum of hydroperoxide products from autoxidation of tetralin-d_2.

Integrations of resonances used for analysis were corrected for the contribution from satellite peaks of surrounding resonances. For example, in the above spectrum (Figure S4, Table S3, entry 1) the integration of the resonance at 2.38 ppm (67.90) is reduced by 0.72 and 1.04, estimated integrations of satellite resonances of peaks at 2.52 ppm and 2.25 ppm, respectively, to give 66.14. Integrations for presented in Table S4, Table S5, and Table S6 are corrected the same way.

Table S3. Deuterium kinetic isotope effect in autoxidation of tetralin-d_1. Analysis of hydroperoxides.

	NMR integrations		Isomer composition		KIE
entry	**6a** + **6b** + **7**	**6a** + **5** + **7**	**6a**	**5**	($k_{H,h}/k_{H,d}$)
1	70.08	66.14	33.86	29.92	**1.13**
2	69.59	64.81	35.19	30.41	**1.16**
3	70.71	65.46	34.54	29.29	**1.18**
				AVERAGE	**1.16**
				STDEV	**0.02**

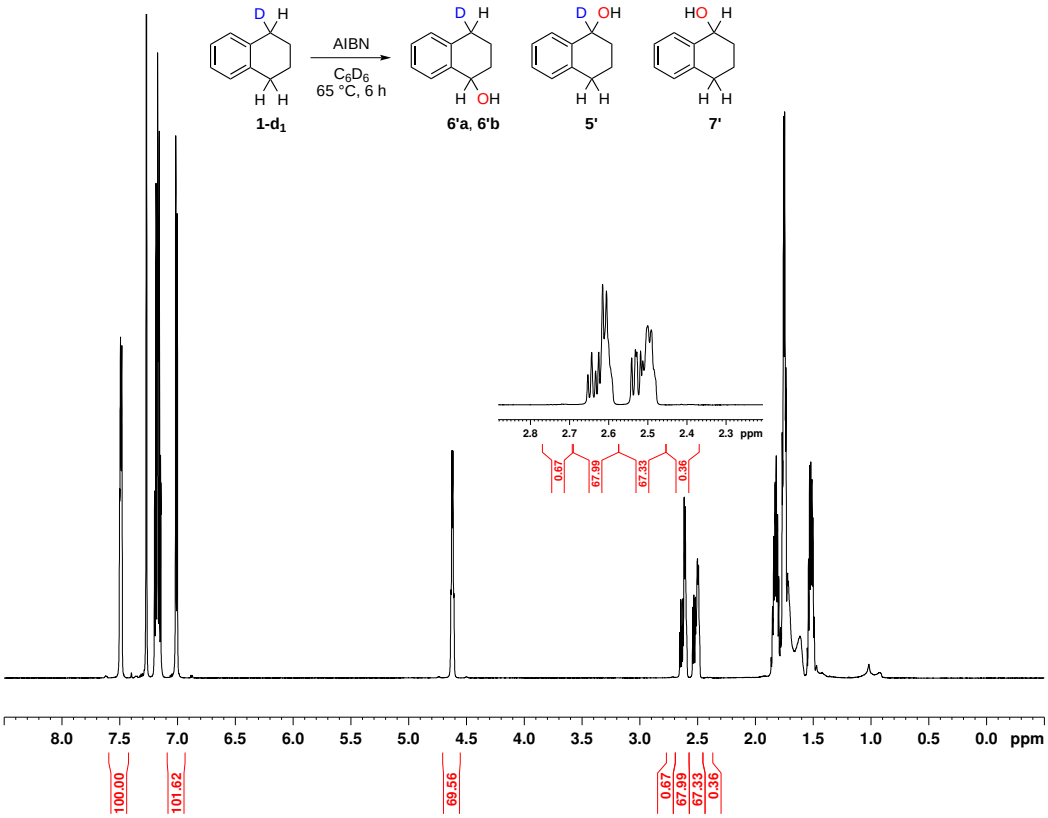


Figure S5. Example ^{1}H NMR (C_6D_6) spectrum of alcohol products from autoxidation of tetralin-d_1.

Table S4. Deuterium kinetic isotope effect in autoxidation of tetralin-d_1. Analysis of alcohols.

	NMR integrations		Isomer composition		KIE
entry	**6′a** + **6′b** + **7′**	**6′a** + **5′** + **7**	**6a**	**5**	($k_{H,h}/k_{H,d}$)
1	69.56	66.66	33.34	30.44	**1.10**
2	69.72	65.58	34.42	30.28	**1.14**
3	70.71	66.10	33.90	31.84	**1.06**
				AVERAGE	**1.10**
				STDEV	**0.04**

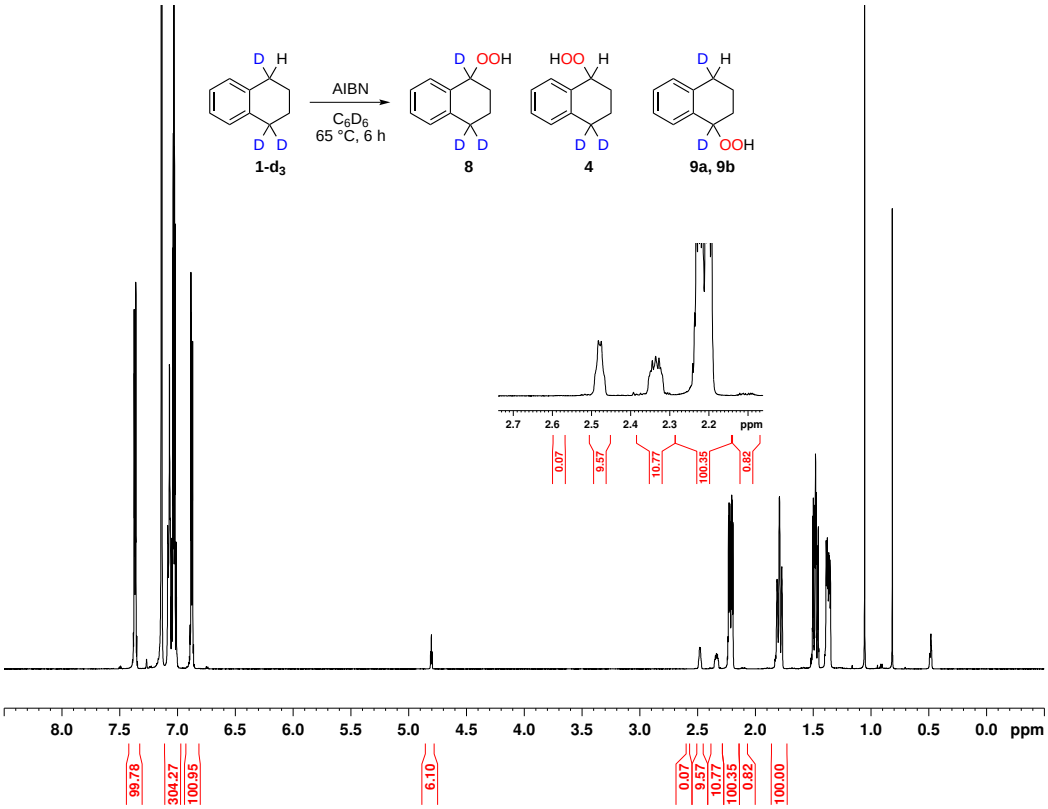


Figure S6. Example ^{1}H NMR (C_6D_6) spectrum of hydroperoxide products from autoxidation of tetralin-d_3.

Table S5. Deuterium kinetic isotope effect in autoxidation of tetralin-d_3. Analysis of hydroperoxides.

	NMR integrations		Isomer composition		KIE
entry	**9a** + **9b**	**4**	**9a**	**4**	($k_{D,h}/k_{D,d}$)
1	9.50	6.10	4.75	6.10	**1.28**
2	9.61	6.12	4.81	6.12	**1.27**
3	9.73	6.01	4.87	6.01	**1.24**
				AVERAGE	**1.26**
				STDEV	**0.03**

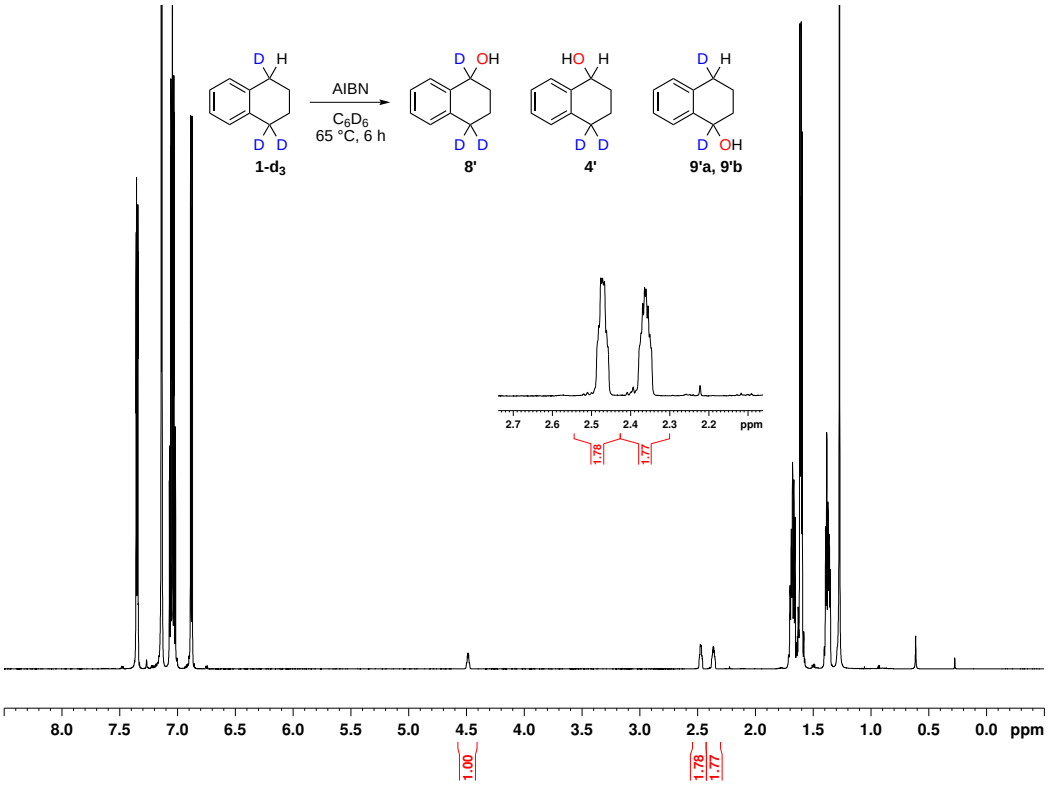


Figure S7. Example ^{1}H NMR (C_6D_6) spectrum of alcohol products from autoxidation of tetralin-d_3.

Table S6. Deuterium kinetic isotope effect in autoxidation of tetralin-d_3. Analysis of alcohols.

	NMR integrations		Isomer composition		KIE
entry	**9a** + **9b**	**4**	**9a**	**4**	($k_{D,h}/k_{D,d}$)
1	1.79	1.00	0.90	1.00	**1.14**
2	1.75	1.00	0.88	1.00	**1.12**
3	1.78	1.00	0.89	1.00	**1.12**
				AVERAGE	**1.13**
				STDEV	**0.01**

2.1.3 Autoxidation of 1,3-diethylbenzene

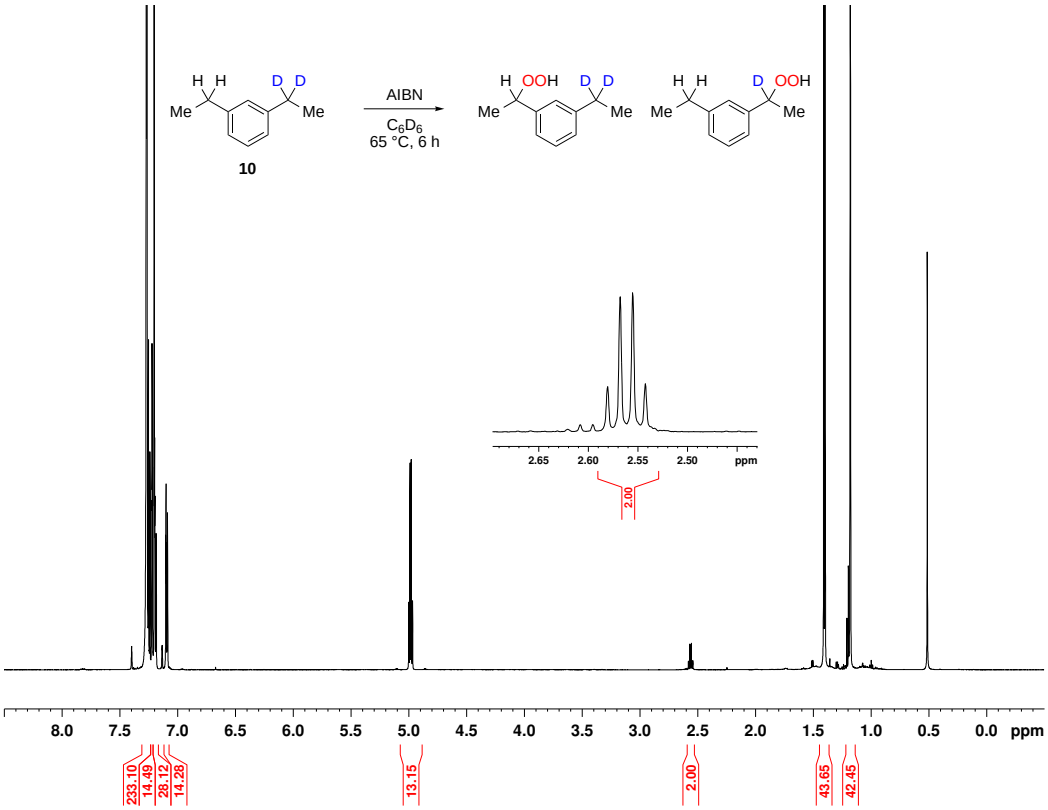


Figure S8. Example ^{1}H NMR (C_6D_6) spectrum of hydroperoxide products from autoxidation of dibenzylbenzene-d_2.

Table S7. Deuterium kinetic isotope effect in autoxidation of 1,3-diethylbenzene-d_2. Analysis of hydroperoxides.

	NMR integrations		KIE
entry	methylene	methine	($k_{H,h}/k_{D,d}$)
1	2.00	13.15	13.15
2	2.00	12.76	12.76
3	2.00	12.09	12.09
		AVERAGE	**12.67**
		STDEV	**0.51**

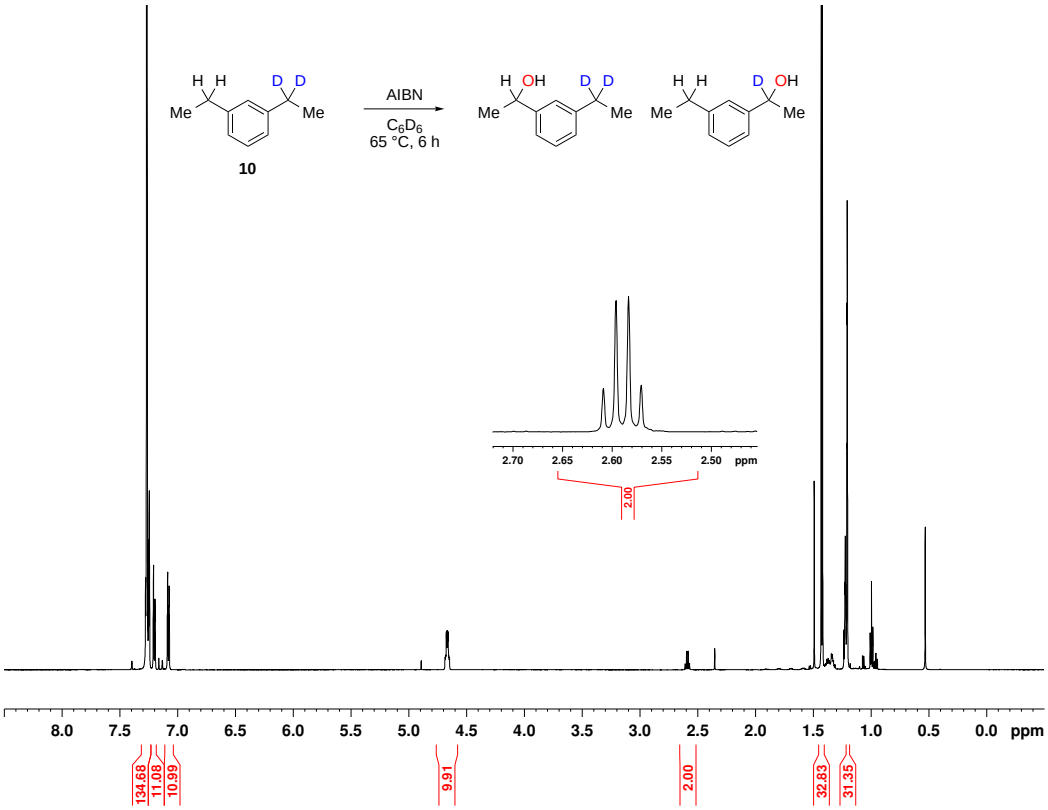


Figure S9. Example ^{1}H NMR (C_6D_6) spectrum of alcohol products from autoxidation of 1,3-diethylbenzene-d_2.

Table S8. Deuterium kinetic isotope effect in autoxidation of 1,3-diethylbenzene-d_2. Analysis of alcohols.

entry	NMR integrations methylene	methine	KIE ($k_{H,h}/k_{D,d}$)
1	2.00	9.91	9.91
2	2.00	11.58	11.58
3	2.00	11.04	11.04
		AVERAGE	**10.84**
		STDEV	**0.85**

2.1.4 Autoxidation of 1,3-dibenzylbenzene

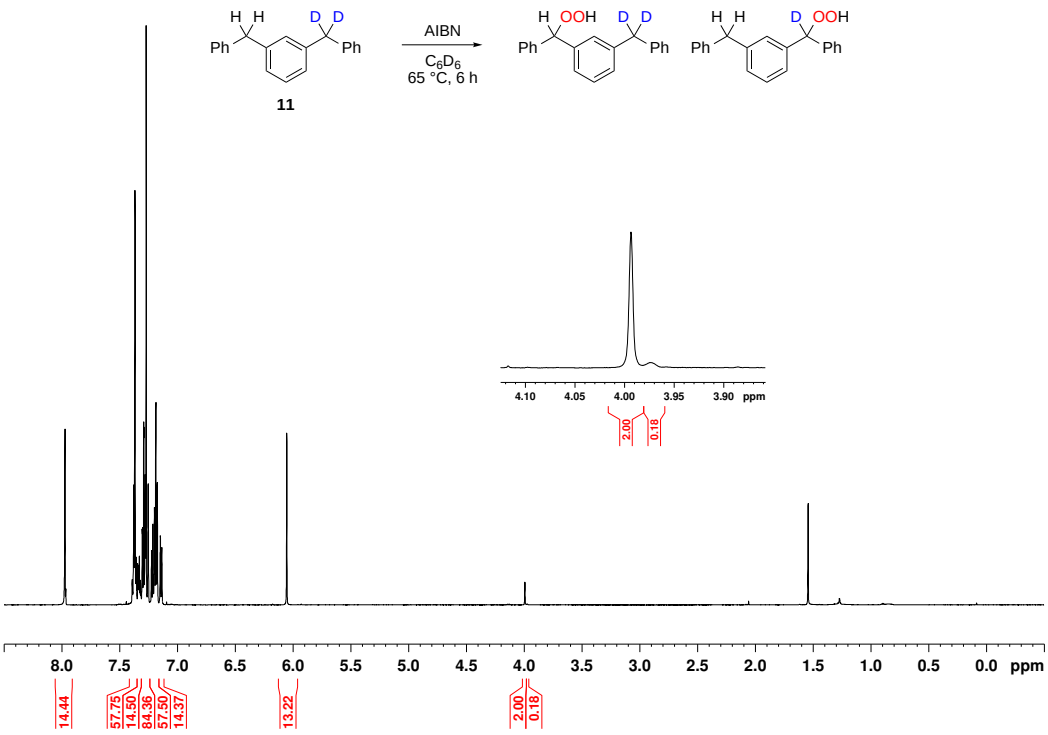


Figure S10. Example ^{1}H NMR (C_6D_6) spectrum of hydroperoxide products from oxidation of 1,3-dibenzylbenzene-d_2.

Table S9. Deuterium kinetic isotope effect in autoxidation of 1,3-dibenzylbenzene-d_2. Analysis of hydroperoxides.

	NMR integrations		KIE
entry	methylene	methine	($k_{H,h}/k_{D,d}$)
1	2.00	13.22	13.22
2	2.00	13.06	13.60
3	2.00	14.80	14.80
		AVERAGE	**13.69**
		STDEV	**0.96**

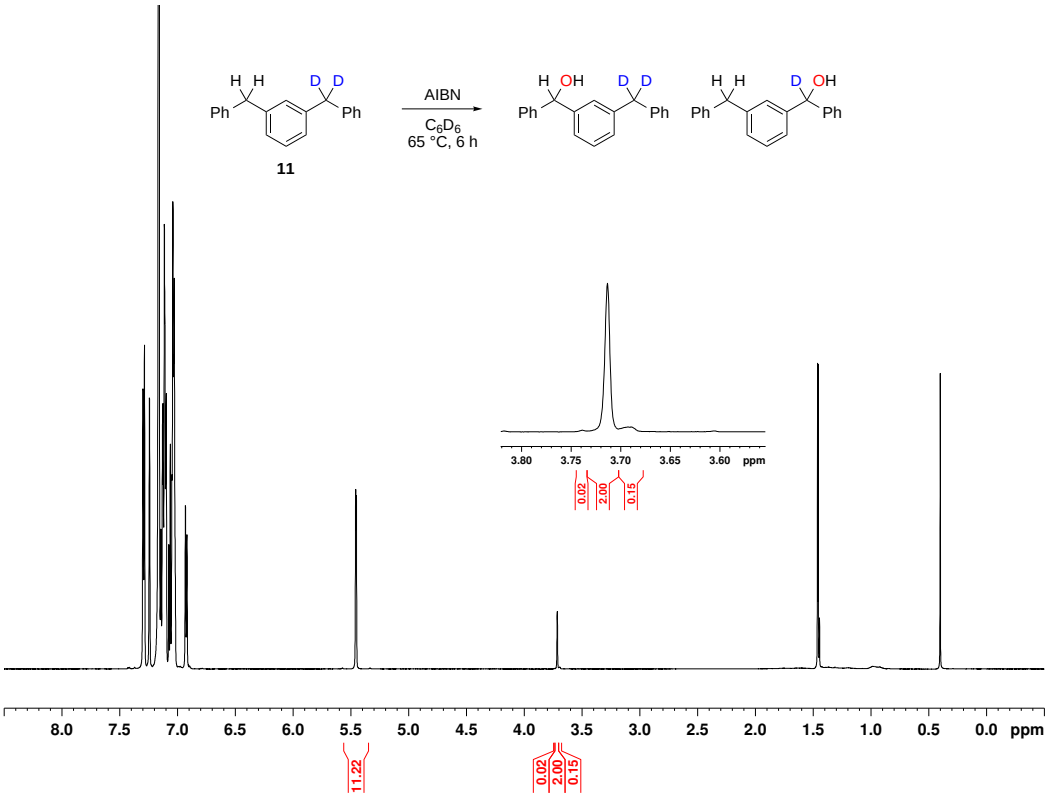
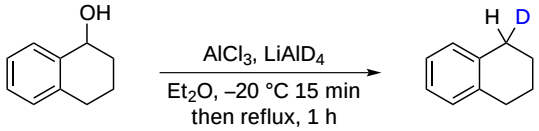


Figure S11. Example ^{1}H NMR (C_6D_6) spectrum of alcohol products from oxidation of 1,3-dibenzylbenzene-d_2.

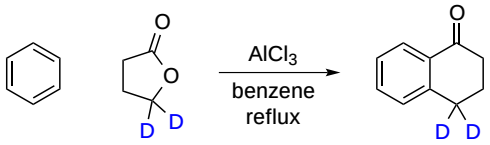
Table S10. Deuterium kinetic isotope effect in autoxidation of 1,3-dibenzylbenzene-d_2. Analysis of alcohols.

entry	NMR integrations methylene	methine	KIE ($k_{H,h}/k_{D,d}$)
1	2.00	9.60	9.60
2	2.00	11.10	11.10
3	2.00	12.50	12.50
		AVERAGE	**11.07**
		STDEV	**1.45**

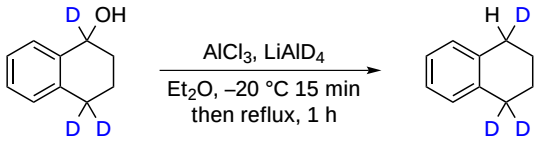
2.2 Synthetic procedures



1,2,3,4-tetrahydronaphthalene-1-d. In a 200 mL two-neck round bottom flask with reflux condenser and argon inlet, $LiAlD_4$ (0.80 g, 19 mmol) was suspended in anhydrous ether 40 mL and the suspension was cooled to −20 °C. Aluminum chloride (2.66 g, 20.0 mmol) was added in small portions and the suspension was stirred for 15 min. At −20 °C a solution of 1-hydroxytetralin (1.5 g, 20 mmol) in ether (10 mL) was added slowly and the solution was warmed and stirred under reflux for 1 h. The reaction was quenched with EtOAc, cooled to 0 °C and a solution of H_2SO_4 (20 %, 60 mL) was added very slowly. Layers were separated, the gray aqueous suspension was extracted with ether and the combined organic layers were washed with brine, dried and concentrated. The resulting yellow oil was redisolved in CH_2Cl_2 and excess of *m*-CPBA was added, the suspension was stirred for 1 h and then filtered. The resulting solution was concentrated and purified using flash chromatography (SiO_2, pentane) to afford the product as a pale yellow oil. Additional purification using flash chromatography (SiO_2, dichloromethane) afforded tetralin-d1 as a clear oil (750 mg, 57 %). R_f = 0.7 (hexanes); IR (film): 3075, 3061, 3040, 3010, 2931, 1496 1/cm; ^{1}H NMR (400 MHz, $CDCl_3$, δ): 7.15 (m, 4H), 2.84 (m, 3H), 1.87 (m, 4H); ^{13}C NMR (100 MHz, $CDCl_3$, δ): 137.1, 137.0, 129.1, 125.4, 29.4, 29.0 (t, J = 19.6 Hz), 23.2, 23.1.

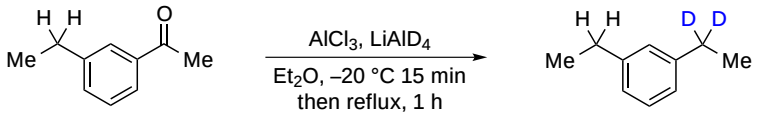


3,4-dihydronaphthalen-1(2*H*)-one-4,4-d$_2$. This compound was prepared according to a published procedure[7] using γ-butyrolactone-d_2.[6] Yield: (2.5 g, 81 %) R_f = 0.3 (10 % EtOAc/hexanes); IR (film): 3068, 3025, 2945, 2880, 2867, 2835, 1683, 1602 1/cm; ^{1}H NMR (400 MHz, $CDCl_3$, δ): 8.02 (dd, J = 7.9, 1.1 Hz, 1H), 7.46 (ddd, J = 7.5, 7.5, 1.5 Hz, 1H), 7.30 (ddd, J = 7.7, 7.7, 1.4 Hz, 1H), 7.24 (dd, J = 7.6, 0.9 Hz, 1H), 2.65 (dd, J = 6.5, 2.0 Hz, 1H), 2.64 (dd, J = 6.7, 1.8 Hz, 1H), 2.12 (d, J = 6.7 Hz, 1H), 2.11 (d, J = 6.4 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$, δ): 198.4, 144.4, 133.4, 132.7, 128.8, 127.2, 126.6, 39.1, 29.0 (quintet, J = 20.0 Hz), 23.1.

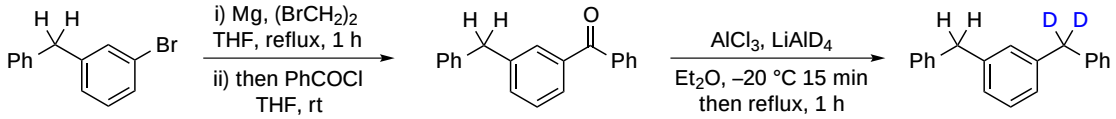


1,2,3,4-tetrahydronaphthalene-1,1,4-d$_3$. In a 200 mL two-neck round bottom flask with reflux condenser and argon inlet, $LiAlD_4$ (1.3 g, 30 mmol) was suspended in anhydrous ether 90 mL and the suspension was cooled to −20 °C. Aluminum chloride (4.4 g, 33 mmol) was added in small portions and the suspension was stirred for 15 min. At −20 °C a solution of 1,2,3,4-tetrahydronaphthalen-1,4,4-d_3-1-ol (2.50 g, 16.5 mmol) in ether (10 mL) was added slowly and the solution was warmed and stirred under reflux for 1 h. The reaction was quenched with EtOAc, cooled to 0 °C and a solution of H_2SO_4 (20 %, 120 mL) was added very slowly.

Layers were separated, the gray aqueous suspension was extracted with ether and the combined organic layers were washed with brine, dried and concentrated. The resulting yellow oil was redisolved in CH_2Cl_2 and excess of *m*-CPBA was added, the suspension was stirred for 1 h and then filtered. The resulting solution was concentrated and purified using flash chromatography (SiO_2, pentane) to afford the product as a pale yellow oil. Additional purification using flash chromatography (SiO_2, dichloromethane) afforded tetralin-d_3 as a clear oil (1.2 g, 54 %). R_f = 0.7 (hexanes); ^{1}H NMR (400 MHz, $CDCl_3$, δ): 7.10 (m, 4H), 2.77 (m, 1H), 1.81 (m, 4H). ^{13}C NMR (100 MHz, $CDCl_3$, δ): 136.7, 136.6, 129.1, 125.5, 28.9 (t, J = 19.9 Hz), 28.5 (quintet, J = 19.3 Hz), 23.1, 23.0.



1,3-diethylbenzene-d_2. In a 200 mL two-neck round bottom flask with reflux condenser and argon inlet, $LiAlD_4$ (0.75 g, 18 mmol) was suspended in anhydrous ether 40 mL and the suspension was cooled to −20 °C. Aluminum chloride (2.7 g, 20 mmol) was added in small portions and the suspension was stirred for 15 min. At −20 °C a solution of 3-ethylacetophenone (2.7 g, 18 mmol) in ether (10 mL) was added slowly and the solution was warmed and stirred under reflux for 1 h. The reaction was quenched with EtOAc, cooled to 0 °C and a solution of H_2SO_4 (20 %, 70 mL) was added very slowly. Layers were separated, the gray aqueous suspension was extracted with ether and the combined organic layers were washed with brine, dried and concentrated. The resulting yellow oil was redisolved in CH_2Cl_2 and excess of *m*-CPBA was added, the suspension was stirred for 1 h and then filtered. The resulting solution was concentrated and purified using flash chromatography (SiO_2, pentane) to afford the product as a pale yellow oil. Additional purification using flash chromatography (SiO_2, dichloromethane) afforded 1,3-diethylbenzene-d_2 as a clear oil (1.9 g, 77 %). ^{1}H NMR (400 MHz, $CDCl_3$, δ): 7.23 (dd, J = 7.8, 7.1 Hz, 1H), 7.05 (m, 3H), 2.66 (q, J = 7.7 Hz, 2H), 1.26 (t, J = 7.6 Hz, 3H), 1.24 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$, δ): 144.23, 144.17, 128.3, 127.5, 125.1, 28.8, 28.1 (quintet, J = 19.2 Hz), 15.6, 15.5.



(1-benzyl-3-(phenylmethyl-d_2)benzene. A 100 mL flask was charged with magnesium turnings (0.18 g, 7.4 mmol) and the contents were vigorously stirred under argon overnight. Added a solution of the bromide (1.5 g, 6.0 mmol) in THF (10 mL) followed by 1,2-dibromoethane (103 µL, 1.2 µmol). The reaction was heated under reflux for 1 h and then cooled to rt. To the resulting solution was added benzoyl chloride (1.0 mL, 9.0 mmol), the reaction was stirred overnight, quenched with satd aq NH_4Cl and concentrated. The residue was extracted with diethyl ether and the combined extracts were washed with satd aq $NaHCO_3$, dried, and concentrated. The resulting oil was filtered through a plug of silica gel (SiO_2, 10 % ethyl acetate in hexanes) to afford the ketone as a colorless oil. The oil was dissolved in benzene and concentrated (total of 3 times). The resulting oil was added to a cooled (−20 °C) suspension of mixed aluminum hydride

prepared from $LiAlD_4$ (140 mg, 3.3 mmol) and $AlCl_3$ (500 mg, 3.7 mmol) in anhydrous ether (7.5 mL). The reaction was heated to reflux and stirred for 1 h. The reaction was quenched with EtOAc, cooled to 0 °C and a solution of H_2SO_4 (20 %, 40 mL) was added very slowly. Layers were separated, the gray aqueous suspension was extracted with ether and the combined organic layers were washed with brine, dried and concentrated. The resulting oil was purified using flash chromatography (SiO_2, pentane) to afford the product as a pale yellow oil. Additional purification using flash chromatography (SiO_2, dichloromethane) afforded 1,3-dibenzylbenzene-d_2 as a clear oil (267 mg, 56 %). R_f = 0.5 (10 % EtOAc/hexanes); IR (film): 3085, 3065, 3030, 2910, 2845, 1599, 1496, 1464 1/cm; ^{1}H NMR (400 MHz, $CDCl_3$, δ): 7.23 (dd, $J = 7.8, 7.1$ Hz, 1H), 7.05 (m, 3H), 2.66 (q, $J = 7.7$ Hz, 2H), 1.26 (t, $J = 7.6$ Hz, 3H), 1.24 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$, δ): 144.23, 144.17, 128.3, 127.5, 125.1, 28.8, 28.1 (quintet, $J = 19.2$ Hz), 15.6, 15.5;

3 Spectra

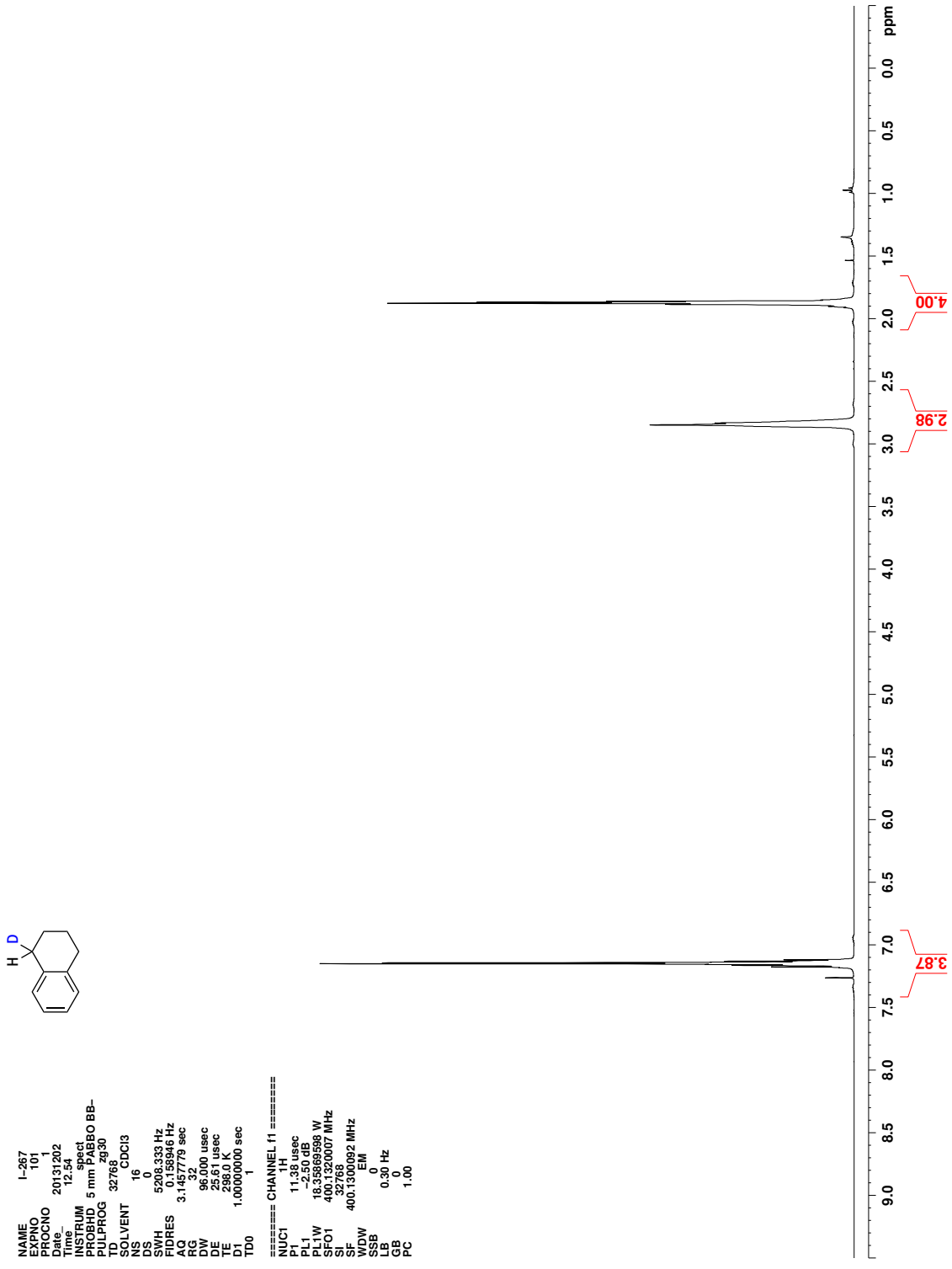


Figure S12. ^{1}H NMR ($CDCl_3$) of **1-d$_1$**.

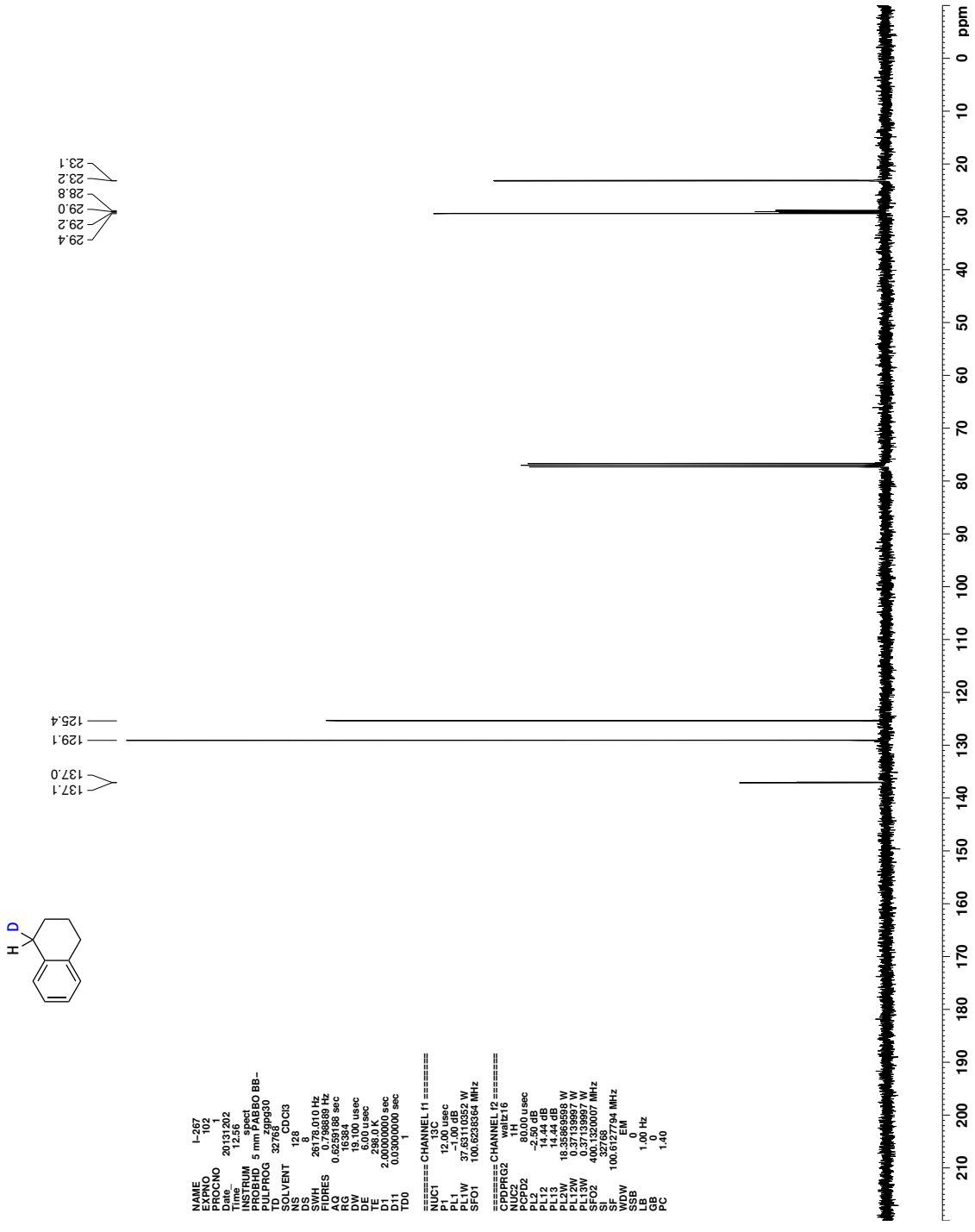


Figure S13. ^{13}C NMR ($CDCl_3$) of **1-d$_1$**.

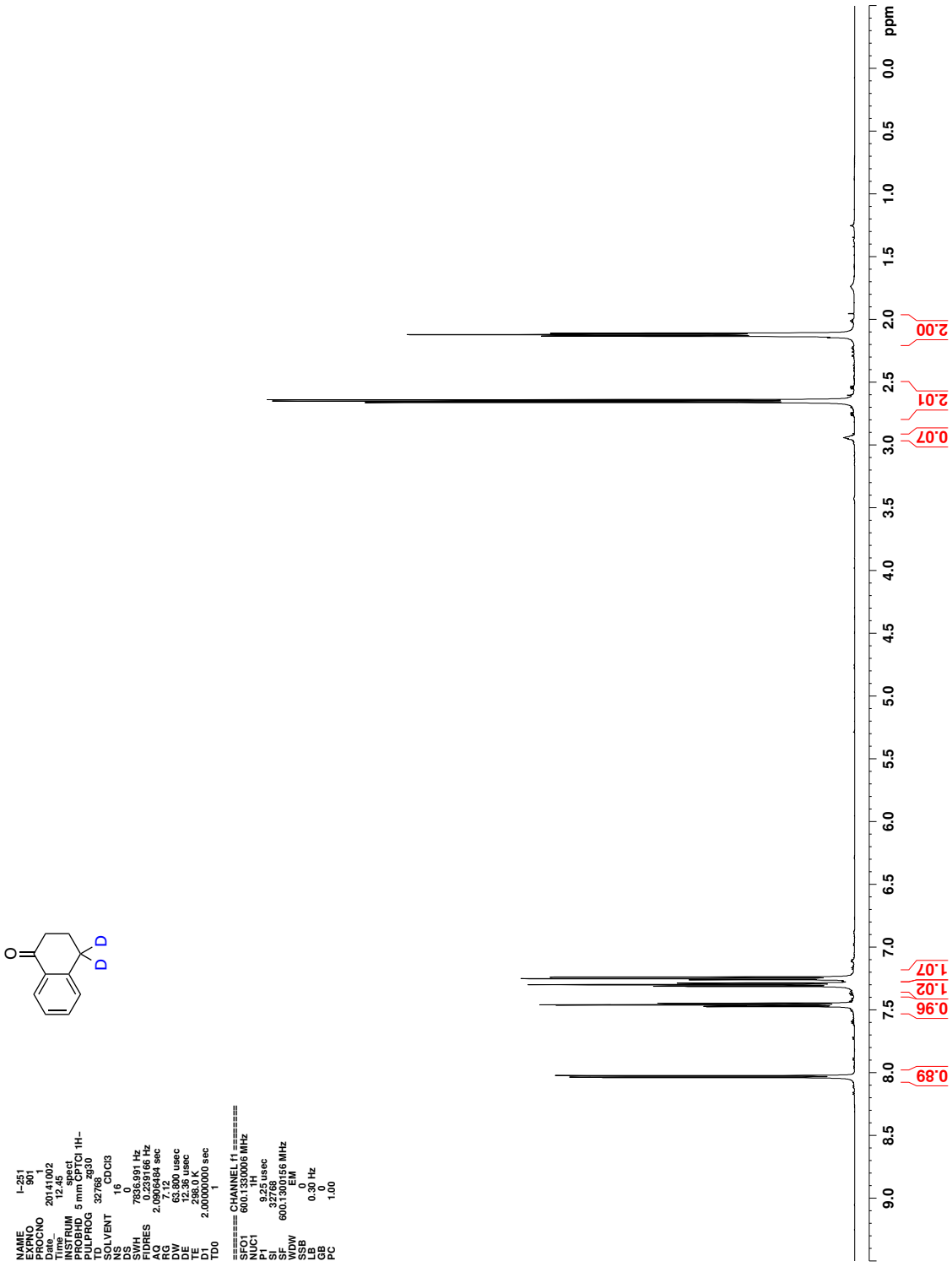


Figure S14. ^{1}H NMR ($CDCl_3$) of tetralone-d_2.

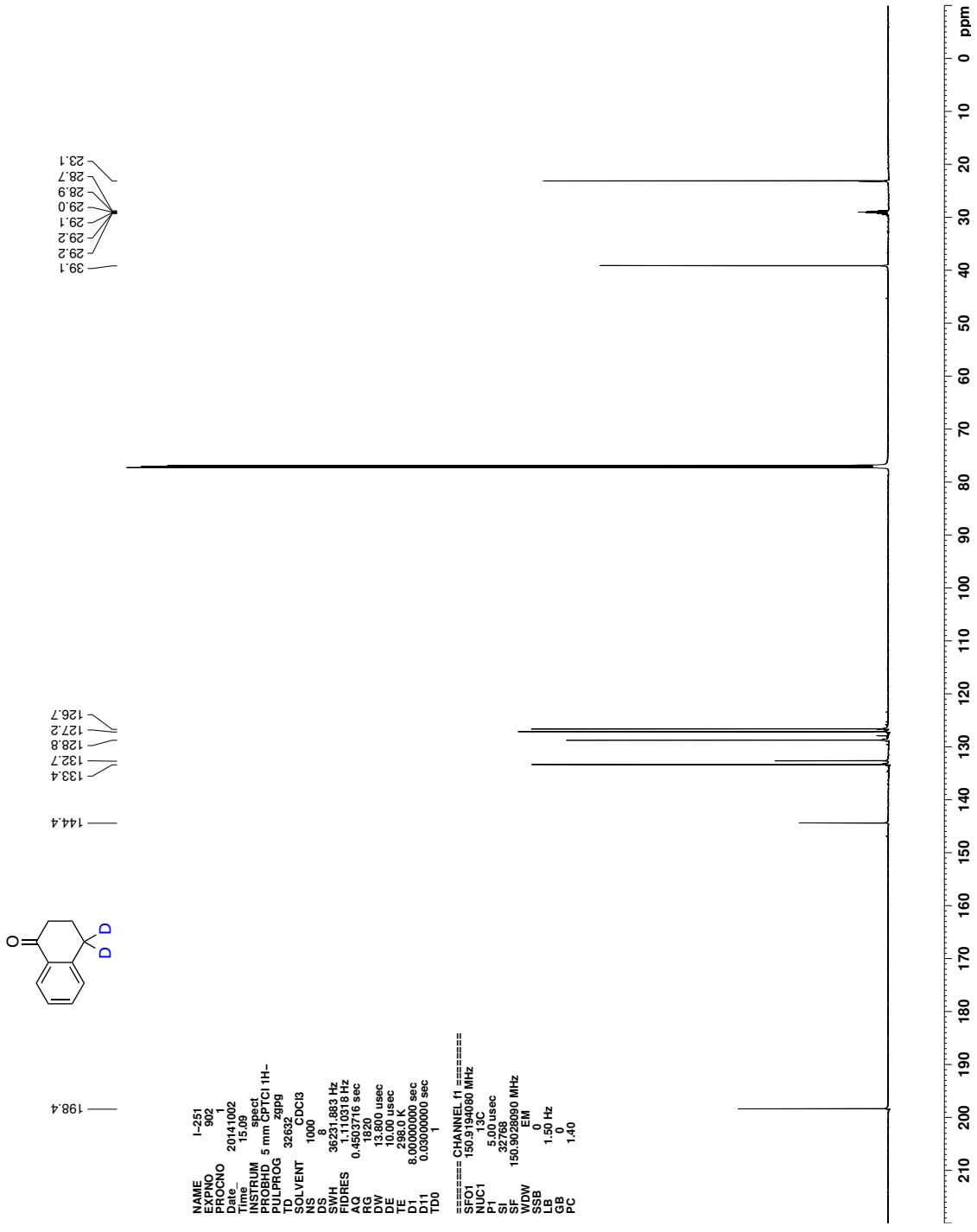


Figure S15. ^{13}C NMR ($CDCl_3$) of tetralone-d_2.

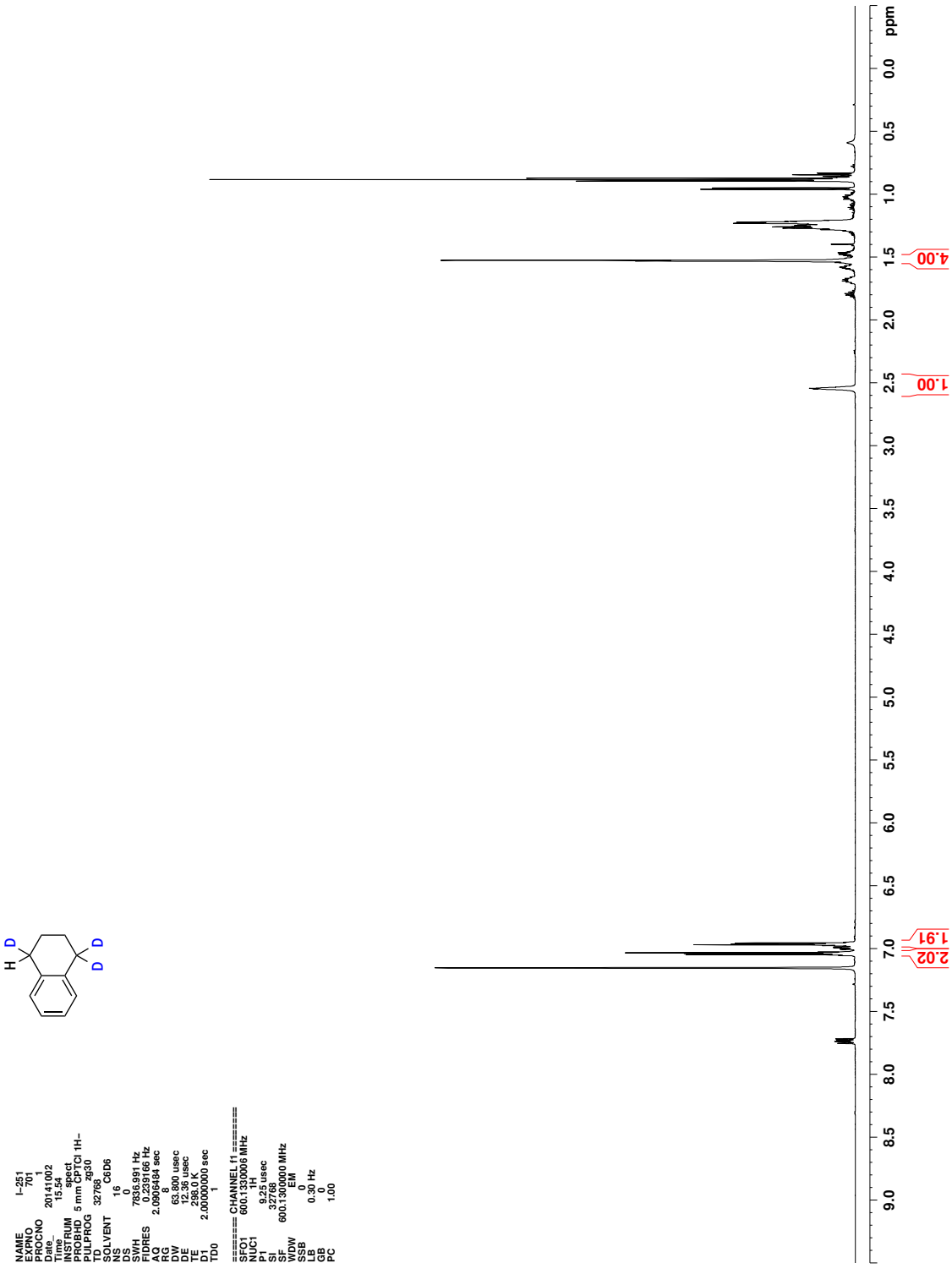


Figure S16. ^{1}H NMR ($CDCl_3$) of **1-d$_3$**.

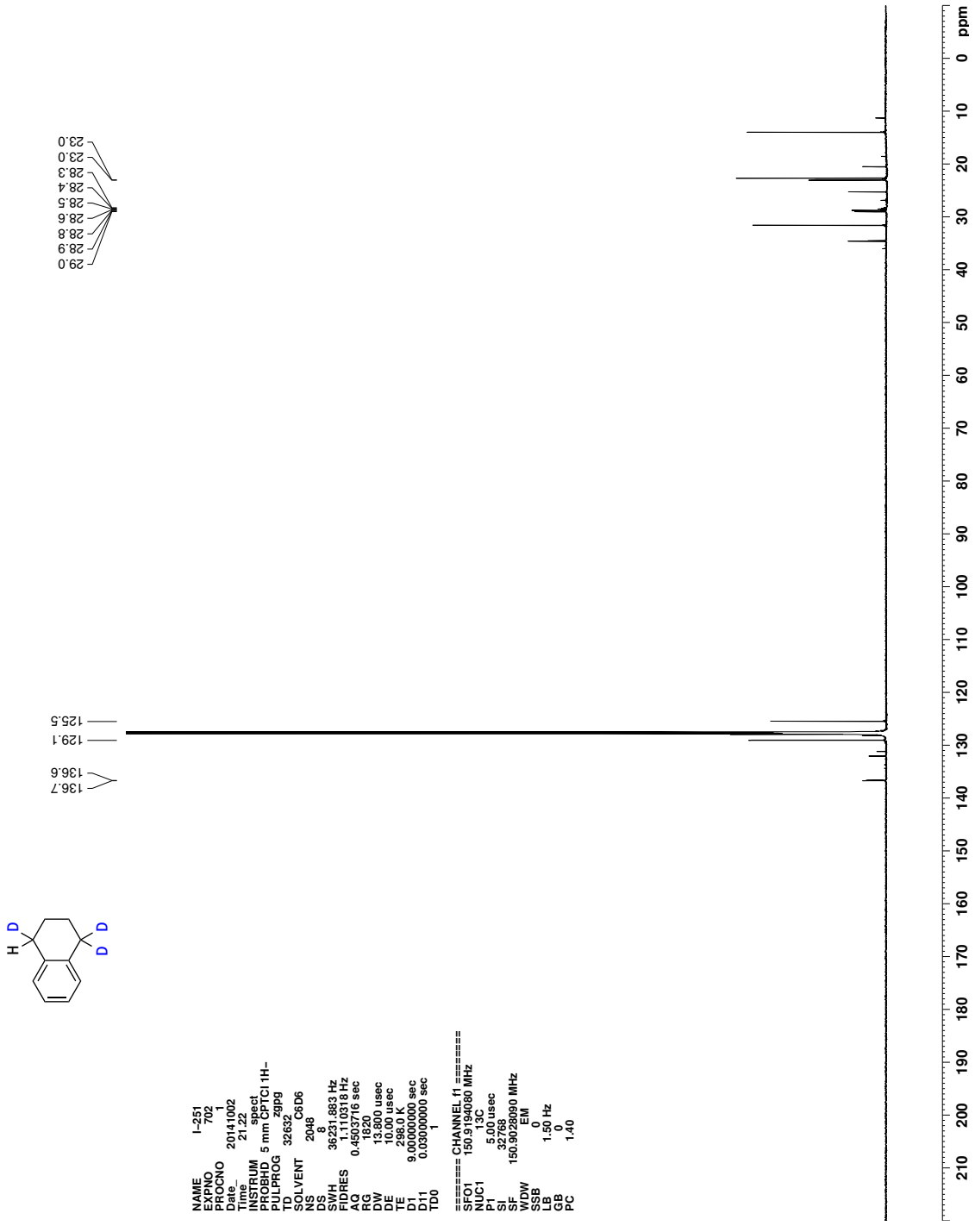


Figure S17. ^{13}C NMR ($CDCl_3$) of **1-d$_3$**.

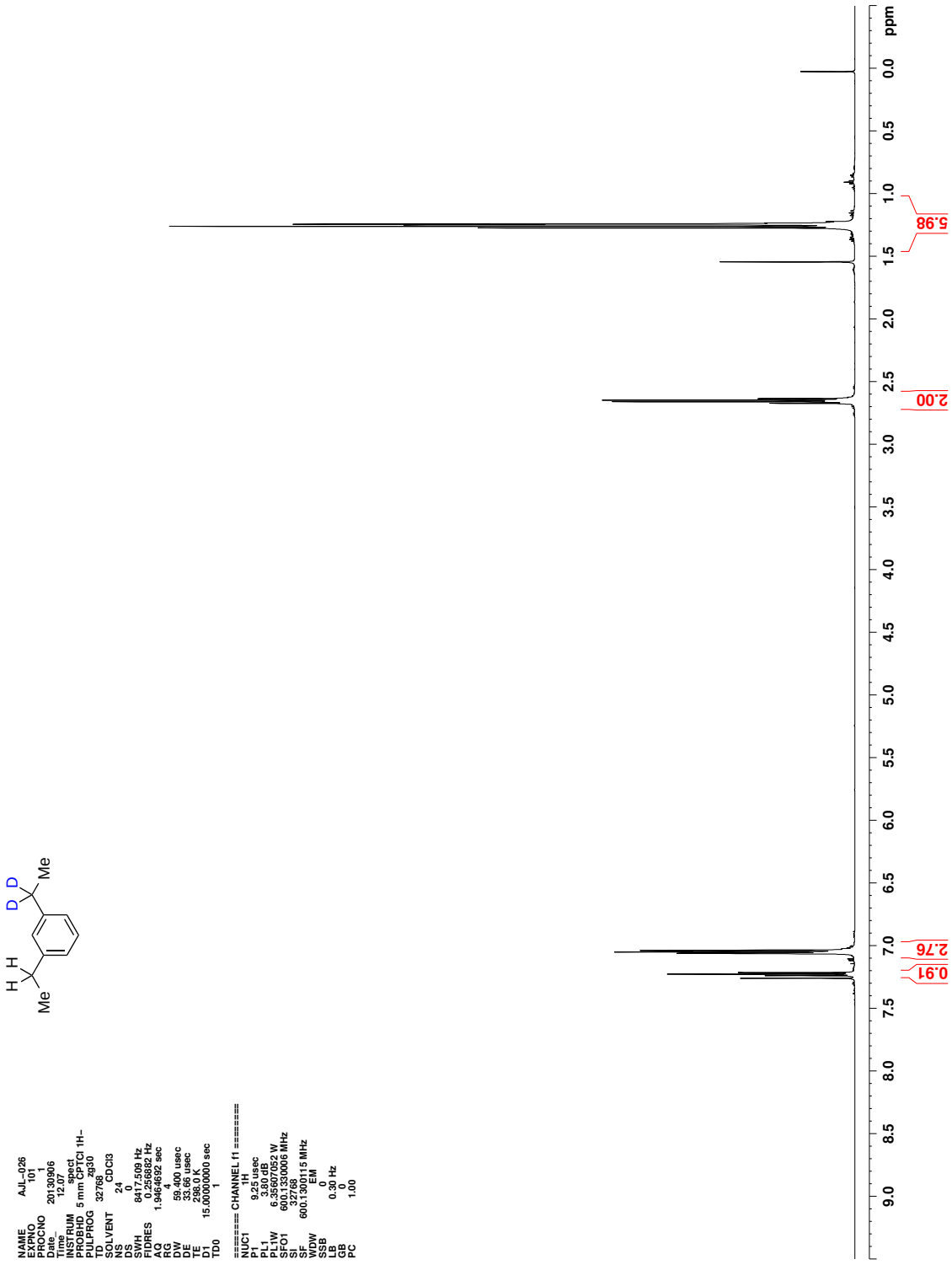


Figure S18. ^{1}H NMR ($CDCl_3$) of **10**.

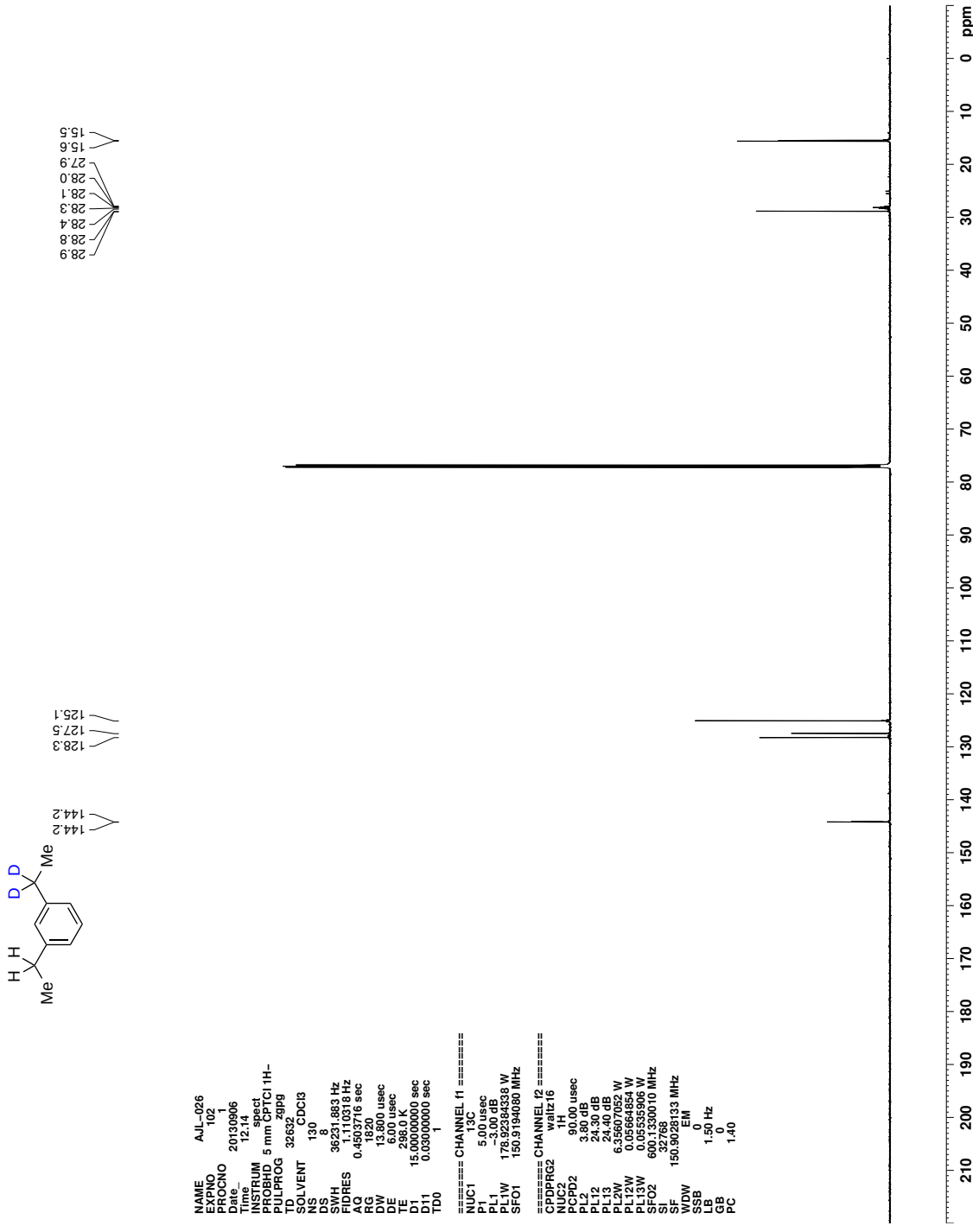


Figure S19. ^{13}C NMR ($CDCl_3$) of **10**.

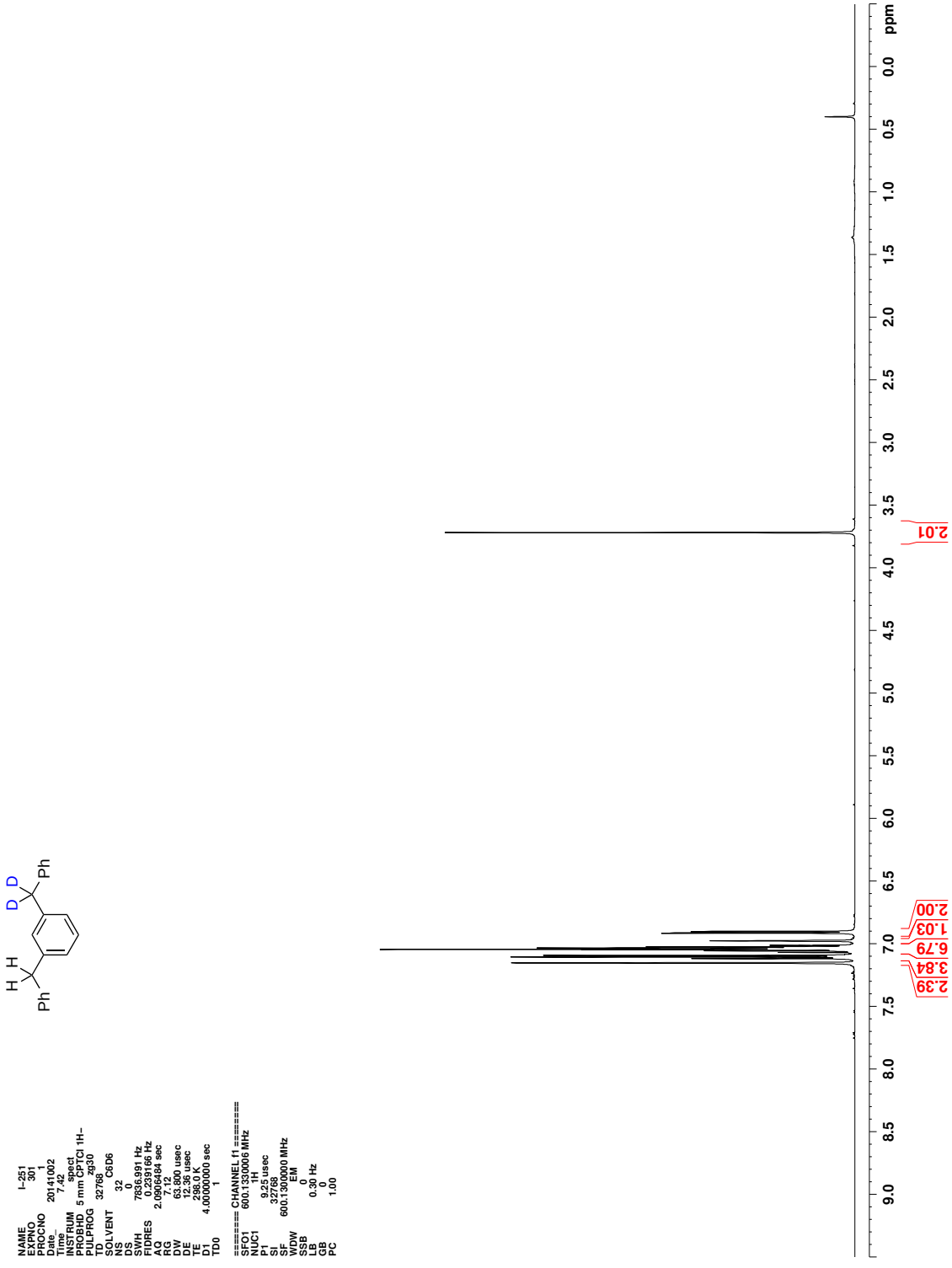


Figure S20. ^{1}H NMR ($CDCl_3$) of **11**.

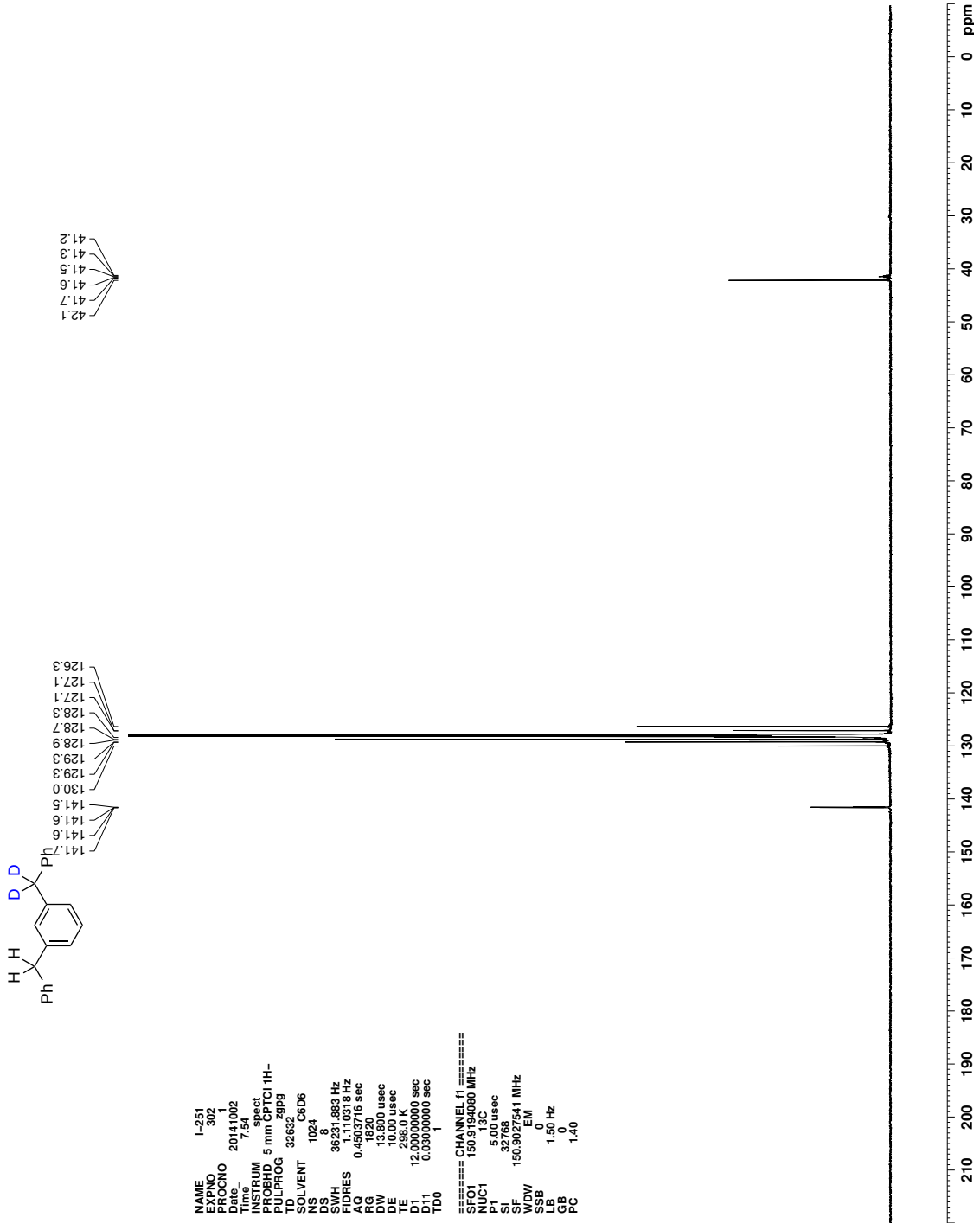


Figure S21. ^{13}C NMR ($CDCl_3$) of **11**.

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