

Electronic supplementary information

STEP-BY-STEP SYNTHESIS OF UNSYMMETRICALLY SUBSTITUTED PYRANOISOCOUMARINS FROM TEREPHTHALIC ACID

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General information

All catalytic reactions were carried out in an argon atmosphere, distilled solvents were used. Catalysts $[\text{Cp}^*\text{RhCl}_2]_2$ and $[\text{Cp}^*\text{RhI}_2]_n$ were prepared as described in the literature [S1, S2]. Monoalkyl terephthalate **1** was prepared according to the published method [S3]. Alkynes **2c**, **2e–2i** were prepared by the literature procedures [S4–S6]. All other reagents were purchased from Acros or Aldrich and used as received. Column chromatography was carried out using Macherey-Nagel silica gel 60 (particle size 0.04–0.063 mm). The ^1H , and $^{13}\text{C}\{^1\text{H}\}$ spectra were recorded on a Varian Inova 400 and Bruker Avance 300 spectrometers operating at 400 (or 300) and 101 MHz, respectively. The chemical shifts are given in ppm using residual solvent signals as internal standards in the case of ^1H and ^{13}C NMR spectra. The HRMS (ESI) spectra were recorded using a TripleTOF 5600+ mass spectrometer (SCIEX), which was equipped with electrospray ionization.

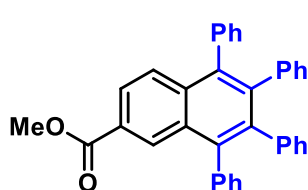
General procedure for the Cp^*RhCl_2 -catalyzed C–H Activation/Annulation of Monoalkyl Terephthalate with Alkynes

Monoalkyl terephthalate **1** (1.0 equiv., 0.5 mmol), alkyne **2** (1.0 equiv., 0.6 mmol), catalyst $[\text{Cp}^*\text{RhCl}_2]_2$ (2 mol % on Rh, 0.005 mmol, 3.1 mg), and oxidant Ag_2CO_3 (1.2 equiv., 0.6 mmol., 166 mg) were dissolved in DMF (3 mL) in a dried 10 mL Schlenk tube equipped with a magnetic stirring bar. The reaction mixture was stirred at 120 °C under an argon atmosphere for 8 h and then cooled to room temperature. Afterwards, CH_2Cl_2 was added to the reaction mixture. Insoluble metal Ag^0 , reduced during the reaction, was separated by centrifugation. The reaction mixture was washed several times with saturated aq. NaCl using a separatory funnel to remove DMF. The organic layer was dried over anhydrous Na_2SO_4 . The solvent was removed under vacuum, and the residue was purified by chromatography on a silica gel column (~ 15 cm). Petroleum ether was used as the first eluent to remove the excess unreacted alkyne. Then a small amount of naphthalene derivatives **4** were eluted as a first band, desired isocoumarins **3** were eluted as a second color band with mixtures of non-polar PE with polar dichloromethane (*see below for the specific ratios for each product*). The solvent was removed under vacuum to give desired isocoumarin derivatives **3**.

Characterization of isocoumarins **3**

Methyl 5,6,7,8-tetraphenyl-2-naphthoate (**4a**)

Starting from **1** and **2a**, side product **4a** was isolated as a colorless powder (37 mg, 15% yield); eluent: $\text{CH}_2\text{Cl}_2/\text{PE}$ (1:10).



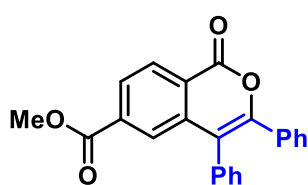
^1H NMR (400 MHz, CDCl_3): δ 8.51 (d, $J = 1.9$ Hz, 1H), 8.04 (dd, $J = 8.9, 1.9$ Hz, 1H), 7.78 (d, $J = 8.9$ Hz, 1H), 7.38–7.26 (m, 10H), 7.00–6.87 (m, 10H), 3.94 (s, 3H) ppm.

^{13}C NMR (101 MHz, CDCl_3): δ 167.31, 141.20, 140.11, 140.08, 139.88, 139.80, 139.05, 138.69, 138.42, 134.17, 131.32, 131.22 (2C), 131.18 (4C, overlapped), 131.03 (2C), 129.98, 127.66 (4C, overlapped), 127.35, 127.28, 126.79, 126.65 (5C, overlapped), 125.56, 125.51, 125.16, 52.16 ppm.

HRMS (ESI, m/z) calcd. for $\text{C}_{36}\text{H}_{26}\text{O}_2[\text{M}+\text{H}]^+$: 491.2011, found: 491.2015.

Methyl 1-oxo-3,4-diphenyl-1H-isochromene-6-carboxylate (**3a**)

Starting from **1** and **2a**, desired product **3a** was isolated as a yellow powder (140 mg, 79% yield); eluent: $\text{CH}_2\text{Cl}_2/\text{PE}$ (1:1).



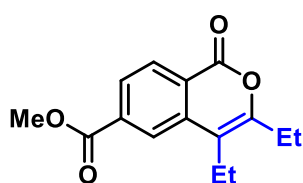
^1H NMR (400 MHz, CDCl_3): δ 8.49 (d, $J = 8.2$ Hz, 1H), 8.15 (dd, $J = 8.2, 1.6$ Hz, 1H), 7.91 (d, $J = 1.6$ Hz, 1H), 7.50–7.43 (m, 3H), 7.39–7.11 (m, 7H), 3.91 (s, 3H) ppm.

^{13}C NMR (101 MHz, CDCl_3): δ 154.46, 138.88, 135.53, 133.60, 131.13 (2C), 131.02, 129.89, 129.50, 129.26 (2C), 129.23 (2C), 129.19, 128.70, 128.43, 128.28, 127.90 (3C, overlapped), 127.28, 126.77, 52.66 ppm.

HRMS (ESI, m/z) calcd. for $\text{C}_{23}\text{H}_{16}\text{O}_4[\text{M}+\text{H}]^+$: 357.1127, found: 357.1126.

Methyl 1-oxo-3,4-diethyl-1*H*-isochromene-6-carboxylate (**3b**)

Starting from **1** and **2b**, desired product **3b** was isolated as a colorless powder (100 mg, 77% yield); eluent: $\text{CH}_2\text{Cl}_2/\text{PE}$ (1:2).



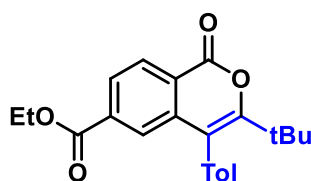
^1H NMR (400 MHz, CDCl_3): δ 8.24 (d, J = 8.2 Hz, 1H), 8.09 (s, 1H), 7.95 (d, J = 8.0 Hz, 1H), 3.92 (s, 3H), 2.64–2.53 (m, 4H), 1.22 (t, J = 7.2 Hz, 3H), 1.14 (t, J = 7.3 Hz, 3H) ppm.

^{13}C NMR (101 MHz, CDCl_3): δ 165.91, 161.92, 155.70, 137.60, 135.23, 129.95, 127.12, 123.95, 123.68, 112.91, 52.55, 24.00, 19.18, 14.25, 12.32 ppm.

HRMS (ESI, m/z) calcd. for $\text{C}_{15}\text{H}_{16}\text{O}_4[\text{M}+\text{H}]^+$: 261.1121, found: 261.1125.

Ethyl 3-(*tert*-butyl)-1-oxo-4-(*p*-tolyl)-1*H*-isochromene-6-carboxylate (**3c**)

Starting from **1** and **2c**, desired product **3c** was isolated as a colorless powder (135 mg, 74% yield); eluent: $\text{CH}_2\text{Cl}_2/\text{PE}$ (1:2).



^1H NMR (300 MHz, CDCl_3): δ 8.37 (d, J = 8.2 Hz, 1H), 8.03 (dd, J = 8.2, 1.6 Hz, 1H), 7.47 (d, J = 1.6 Hz, 1H), 7.28 (d, J = 7.8 Hz, 2H), 7.13 (d, J = 8.0 Hz, 2H), 4.32 (q, J = 7.1 Hz, 2H), 2.46 (s, 3H), 1.33 (t, J = 7.1 Hz, 3H) ppm.

^{13}C NMR (101 MHz, CDCl_3): δ 165.46, 161.79, 160.61, 140.56, 138.01, 135.45, 131.35, 131.11 (2C), 129.25 (2C), 129.01, 127.40, 126.98, 122.60, 115.01, 61.48,

38.25, 30.14 (3C), 21.31, 14.06 ppm.

HRMS (ESI, m/z) calcd. for $\text{C}_{23}\text{H}_{24}\text{O}_4[\text{M}+\text{H}]^+$: 365.1753, found: 365.1751.

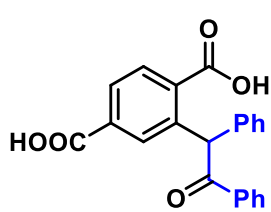
Ring-opening hydrolysis of isocoumarins **3**

Corresponding isocoumarin **3** (1.0 equiv., 0.5 mmol) and KOH (3.0 equiv., 1.5 mmol, 84 mg) were dissolved in ethanol (5 mL) in a 10 mL round-bottom flask equipped with a magnetic stirring bar. The reaction mixture was stirred at 80 °C in air for 2–5 h. The solution gradually discolored from intense yellow to pale yellow. Afterwards, the reaction mixture was poured into aq. HCl (1M) to afford a white suspension. EtOAc was added, and the organic layer was separated using a separatory funnel. The solvent was removed under vacuum. The residue was reprecipitated from a small amount of CH_2Cl_2 with petroleum ether and dried in air to give compound **5** as a colorless powder.

Characterization of compounds **5**

2-(2-Oxo-1,2-diphenylethyl)terephthalic acid (**5a**)

Starting from **3a**, desired product **5a** was isolated as a colorless powder (162 mg, 90% yield).



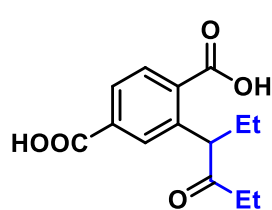
^1H NMR (400 MHz, acetone- d_6): δ 8.18 (d, J = 8.0 Hz, 1H), 8.06 (d, J = 7.4 Hz, 2H), 8.02 (dd, J = 8.0, 1.7 Hz, 1H), 7.70 (d, J = 1.7 Hz, 1H), 7.51 (t, J = 7.4 Hz, 1H), 7.45–7.35 (m, 6H), 7.32–7.28 (m, 1H), 7.22 (s, 1H) ppm.

^{13}C NMR (101 MHz, acetone- d_6): δ 167.47, 165.92, 132.56, 131.92, 131.28, 130.88, 130.00 (2C), 129.53, 129.23, 129.11 (2C), 128.82 (2C), 128.53, 128.40 (2C), 128.32, 127.91, 127.73, 127.50, 56.07 ppm.

HRMS (ESI, m/z) calcd. for $C_{22}H_{16}O_5[M+H]^+$: 361.1071, found: 361.1071.

2-(4-Oxohexan-3-yl)terephthalic acid (**5b**)

Starting from **3b**, desired product **5b** was isolated as a colorless powder (118 mg, 89% yield).



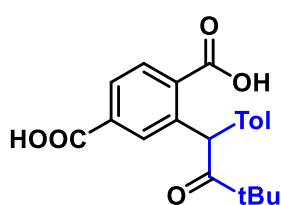
1H NMR (400 MHz, $dmso-d_6$): δ 13.42 (bs, 2H), 7.89 (s, 2H), 7.78 (s, 1H), 4.67–4.39 (m, 1H), 2.45–2.30 (m, 2H), 2.10–1.91 (m, 1H), 1.73–1.50 (m, 1H), 0.86 (t, J = 7.2 Hz, 3H), 0.72 (t, J = 7.3 Hz, 3H) ppm.

^{13}C NMR (101 MHz, $dmso-d_6$): δ 210.42, 169.06, 166.96, 139.72, 136.25, 133.65, 130.60, 129.50, 128.00, 54.78, 35.08, 25.43, 12.37, 8.20 ppm.

HRMS (ESI, m/z) calcd. for $C_{14}H_{16}O_5[M+H]^+$: 265.1071, found: 265.1072.

2-[3,3-Dimethyl-2-oxo-1-(*p*-tolyl)butyl]terephthalic acid (**5c**)

Starting from **3c**, desired product **5c** was isolated as a colorless powder (157 mg, 89% yield).



The resulting product was used for the next stage without additional characterization.

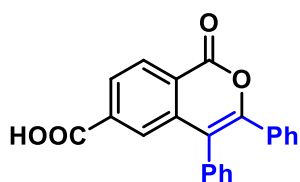
Ring-closing synthesis of isocoumarin-6-carboxylic acids **6a-c**

Corresponding terephthalic acid derivative **5** (1.0 equiv., 0.25 mmol) and *p*-TsOH (1.0 equiv., 0.25 mmol, 48 mg) were dissolved in toluene (3 mL) in a 10 mL round-bottom flask equipped with a magnetic stirring bar. The reaction mixture was stirred at 110 °C in air for 6 h. The suspension dissolved when heated. Afterwards, the reaction mixture was poured into the brine water solution. EtOAc was added and organic layer was separated using a separatory funnel. The solvent was removed under vacuum. The residue was reprecipitated from a small amount of CH_2Cl_2 with petroleum ether and dried in air to give compound **6** as a colorless powder.

Characterization of isocoumarin-6-carboxylic acids **6a-c**

3,4-Diethyl-1-oxo-1*H*-isochromene-6-carboxylic acid (**6a**)

Starting from **5a**, desired product **6a** was isolated as a yellow powder (81 mg, 94% yield).



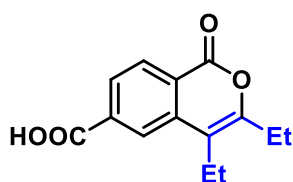
1H NMR (400 MHz, $acetone-d_6$): δ 8.50 (d, J = 8.1 Hz, 1H), 8.25 (dd, J = 8.1, 1.7 Hz, 1H), 7.94 (d, J = 1.7 Hz, 1H), 7.57–7.50 (m, 3H), 7.47–7.43 (m, 4H), 7.38–7.31 (m, 3H) ppm.

The ^{13}C NMR spectrum wasn't recorded due to the low solubility of **6a** in $acetone-d_6$.

HRMS (ESI, m/z) calcd. for $C_{22}H_{14}O_4[M+H]^+$: 343.0965, found: 343.0967.

3,4-Diethyl-1-oxo-1*H*-isochromene-6-carboxylic acid (**6b**)

Starting from **5b**, desired product **6b** was isolated as a colorless powder (57 mg, 92% yield).



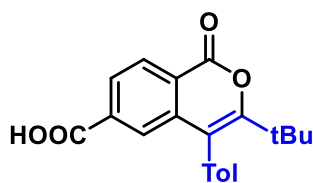
^1H NMR (400 MHz, CDCl_3): δ 11.79 (bs, 1H), 8.43 (d, $J = 8.2$ Hz, 1H), 8.31 (d, $J = 1.5$ Hz, 1H), 8.16 (dd, $J = 8.2, 1.5$ Hz, 1H), 2.78–2.63 (m, 4H), 1.32 (t, $J = 7.5$ Hz, 3H), 1.26 (t, $J = 7.4$ Hz, 3H) ppm.

^{13}C NMR (101 MHz, CDCl_3): δ 170.97, 162.16, 156.06, 137.88, 134.49, 130.35, 127.71, 124.80, 124.47, 113.03, 24.13, 19.33, 14.31, 12.42 ppm.

HRMS (ESI, m/z) calcd. for $\text{C}_{14}\text{H}_{14}\text{O}_4[\text{M}+\text{H}]^+$: 247.0965, found: 247.0965.

3-(*tert*-Butyl)-1-oxo-4-(*p*-tolyl)-1*H*-isochromene-6-carboxylic acid (6c)

Starting from **5c**, desired product **6c** was isolated as a yellow powder (75 mg, 89% yield).



^1H NMR (400 MHz, acetone- d_6): δ 8.30 (d, $J = 8.2$ Hz, 1H), 8.07 (dd, $J = 8.2, 1.5$ Hz, 1H), 7.47 (d, $J = 1.5$ Hz, 1H), 7.34 (d, $J = 7.8$ Hz, 2H), 7.25 (d, $J = 7.8$ Hz, 2H), 2.42 (s, 3H), 1.13 (s, 9H) ppm.

^{13}C NMR wasn't recorded due to low solubility of **6c** in acetone- d_6 .

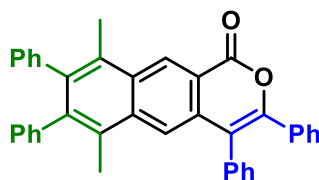
General procedure for the Rh^{III} -catalyzed C–H Activation/Annulation of **6a–c** with Alkynes

Isocoumarin-6-carboxylic acid **6** (1.0 equiv., 0.1 mmol), alkyne **2** (1.1 equiv., 0.11 mmol), catalyst $[\text{Cp}^*\text{RhCl}_2]_2$ or $[\text{CpRhI}_2]_n$ (5 mol% on Rh, 0.0025 mmol), oxidant Ag_2CO_3 (1.2 equiv., 0.12 mmol., 33 mg) were dissolved in DMF (3 mL) or *t*AmOH (3 mL) in a dried 10 mL Schlenk tube equipped with a magnetic stir bar. The reaction mixture was stirred at 120°C under argon atmosphere for 8h and then cooled to room temperature. Afterwards, CH_2Cl_2 was added to the reaction mixture. Insoluble metal Ag^0 reduced during the reaction was separated by centrifugation. The reaction mixture was washed several times with saturated aq. NaCl using a separatory funnel to remove DMF (*t*AmOH was just removed under vacuum). The organic layer was dried over anhydrous Na_2SO_4 . The solvent was removed under vacuum and the residue was purified by chromatography on a silica gel column (~15 cm). Petroleum ether was used as the first eluent to remove the excess unreacted alkyne. Then the desired products were eluted with mixtures of non-polar PE and polar dichloromethane or EtOAc (*see below for the specific ratios for each product*). The solvent was removed under vacuum to give desired products **7** or **8**.

Characterization of compounds **7** and **8**

6,9-Dimethyl-3,4,7,8-tetraphenyl-1*H*-benzo[*g*]isochromen-1-one (**8ad**)

Starting from **6a** and **2d** (CpRhI_2 as a catalyst), desired product **8ad** was isolated as a yellowish powder (37 mg, 70% yield).



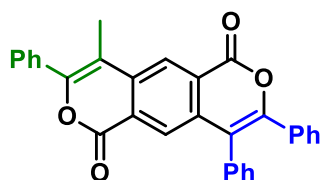
^1H NMR (400 MHz, CDCl_3): δ 9.31 (s, 1H), 7.89 (s, 1H), 7.46–7.34 (m, 7H), 7.25–7.18 (m, 3H), 7.17–7.03 (m, 6H), 6.97–6.92 (m, 2H), 6.92–6.87 (m, 2H), 2.56 (s, 3H), 2.17 (s, 3H) ppm.

^{13}C NMR (101 MHz, CDCl_3): δ 162.86, 142.91, 140.96, 140.85, 140.56, 135.60, 134.77, 133.68, 131.43, 131.26 (2C), 130.83, 130.16 (2C), 129.92 (2C), 129.72, 129.25 (2C), 129.03 (2C), 128.82, 128.74, 128.57, 128.13, 127.81 (2C), 127.41 (2C), 127.36 (2C), 126.20 (2C), 124.17, 121.83, 118.25, 117.21, 17.10, 16.68 ppm.

HRMS (ESI, m/z) calcd. for $\text{C}_{39}\text{H}_{28}\text{O}_2[\text{M}+\text{H}]^+$: 529.2162, found: 529.2168.

4-Methyl-3,8,9-triphenylpyrano[3,4-*g*]isochromene-1,6-dione (**7ad**)

Starting from **6a** and **2d**, desired product **7ad** was isolated as a yellow powder (24 mg, 53% yield).



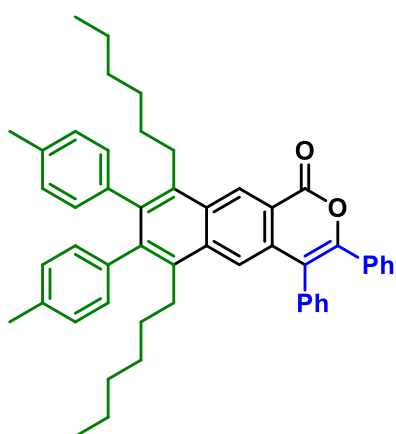
^1H NMR (400 MHz, CDCl_3): δ 8.69 (s, 1H), 8.25 (s, 1H), 7.65–7.61 (m, 2H), 7.54–7.46 (m, 6H), 7.40–7.20 (m, 7H), 2.46 (s, 3H) ppm.

^{13}C NMR (101 MHz, CDCl_3): δ 161.48, 161.24, 151.73, 137.35, 137.25, 133.29, 132.64, 132.38, 131.01 (2C), 129.87, 129.71, 129.47 (2C), 129.45 (2C), 129.31, 129.22 (2C), 128.68, 128.35 (2C), 127.95 (2C), 127.39, 125.44, 125.32, 124.92, 116.64, 108.92, 13.79 ppm.

HRMS (ESI, m/z) calcd. for $\text{C}_{31}\text{H}_{20}\text{O}_4[\text{M}+\text{H}]^+$: 457.1435, found: 457.1436.

6,9-Dihexyl-3,4-diphenyl-7,8-di-*p*-tolyl-1H-benzo[*g*]isochromen-1-one (8ae)

Starting from **6a** and **2e**, side product **8ae** was isolated as a yellowish powder (17 mg, 25% yield).



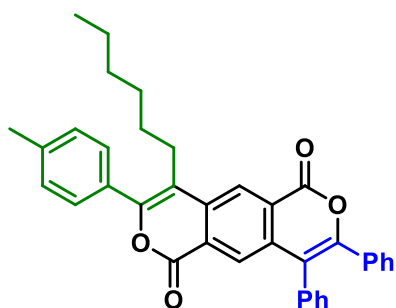
^1H NMR (300 MHz, CDCl_3): δ 9.31 (s, 1H), 7.85 (s, 1H), 7.47–7.43 (m, 4H), 7.40–7.37 (m, 2H), 7.27–7.21 (m, 4H), 6.98–6.92 (m, 4H), 6.86 (d, J = 7.8 Hz, 2H), 6.82 (d, J = 7.8 Hz, 2H), 3.00–2.85 (m, 2H), 2.55–2.43 (m, 2H), 2.28 (s, 3H), 2.26 (s, 3H), 1.70–1.56 (m, 2H), 1.37–1.11 (m, 10H), 0.87–0.81 (m, 6H) ppm.

^{13}C NMR (101 MHz, CDCl_3): δ 142.91, 137.86, 137.72, 136.90, 135.37, 135.08, 134.98, 134.89, 133.24, 131.17 (2C), 130.77, 129.99, 129.77 (2C), 129.41 (2C), 129.18 (2C), 128.99 (2C), 128.65, 128.56, 128.49, 128.39, 127.98, 127.93 (2C), 127.88 (2C), 127.81 (2C), 122.32, 118.00, 31.69, 31.28 (2C), 31.13, 30.50, 30.12, 29.57 (2C), 22.46 (2C), 21.12 (2C), 14.01 (2C) ppm. The signals of two carbon nuclei in the ^{13}C NMR spectrum overlapped. The signal of carboxylic C_4 carbon nucleus was not observed due to the low concentration.

HRMS (ESI, m/z) calcd. for $\text{C}_{51}\text{H}_{52}\text{O}_2[\text{M}+\text{H}]^+$: 697.4046, found: 697.4036.

4-Hexyl-8,9-diphenyl-3-(*p*-tolyl)pyrano[3,4-*g*]isochromene-1,6-dione (7ae)

Starting from **6a** and **2e**, desired product **7ae** was isolated as a yellow powder (28 mg, 51% yield).



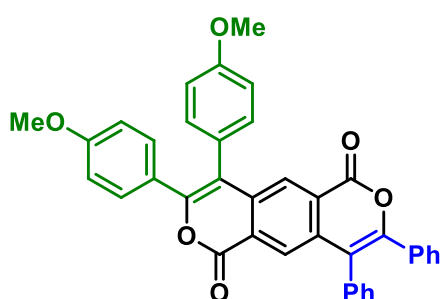
^1H NMR (400 MHz, CDCl_3): δ 8.69 (s, 1H), 8.25 (s, 1H), 7.50–7.44 (m, 5H), 7.39–7.22 (m, 9H), 2.84–2.79 (m, 2H), 2.45 (s, 3H), 1.76–1.65 (m, 2H), 1.45–1.39 (m, 2H), 1.36–1.28 (m, 4H), 0.90 (t, J = 6.5 Hz, 3H) ppm.

^{13}C NMR (101 MHz, CDCl_3): δ 161.46, 161.33, 152.22, 139.84, 136.96, 136.59, 133.34, 132.44, 131.00 (2C), 129.87, 129.44 (2C), 129.26, 129.21 (2C), 129.09 (2C), 128.90 (2C), 128.64, 127.94 (2C), 127.57, 125.85, 125.36, 124.93, 122.97, 116.64, 113.68, 31.33, 29.89, 29.12, 26.84, 22.55, 21.40, 13.99 ppm.

HRMS (ESI, m/z) calcd. for $\text{C}_{37}\text{H}_{32}\text{O}_4[\text{M}+\text{H}]^+$: 541.2379, found: 541.2369.

3,4-Bis(4-methoxyphenyl)-8,9-diphenylpyrano[3,4-*g*]isochromene-1,6-dione (7af)

Starting from **6a** and **2f**, desired product **7af** was isolated as a yellow powder (42 mg, 73% yield).



^1H NMR (400 MHz, CDCl_3): δ 8.28 (s, 1H), 8.25 (s, 1H), 7.50–7.47 (m, 3H), 7.37–7.28 (m, 6H), 7.25–7.19 (m, 5H), 7.07–7.01 (m, 2H), 6.79–6.72 (m, 2H), 3.93 (s, 3H), 3.79 (s, 3H) ppm.

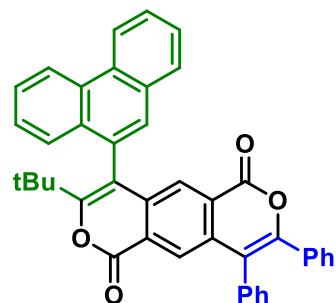
^{13}C NMR (101 MHz, CDCl_3): δ 161.22, 160.16, 159.64, 154.08, 138.07, 136.91, 133.42, 132.44, 132.14 (2C), 131.03 (2C), 130.69 (2C), 129.45 (2C), 129.23, 129.20 (2C), 128.63, 127.91 (2C), 127.17, 127.04,

125.60, 124.84, 124.71, 121.05, 116.60, 115.09 (2C), 114.96, 113.42 (2C), 110.27, 55.31, 55.21 ppm. The signal of one C₄ carbon nucleus in the ¹³C NMR spectrum overlapped.

HRMS (ESI, *m/z*) calcd. for C₃₈H₂₆O₆[M+H]⁺: 579.1808, found: 579.1798.

3-(*tert*-Butyl)-4-(phenanthren-9-yl)-8,9-diphenylpyrano[3,4-*g*]isochromene-1,6-dione (**7ag**)

Starting from **6a** and **2g**, desired product **7ag** was isolated as a yellow powder (41 mg, 69% yield).



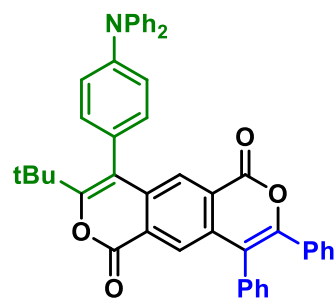
¹H NMR (400 MHz, CDCl₃): δ 8.83 (t, *J* = 8.5 Hz, 2H), 8.25 (s, 1H), 7.93 (d, *J* = 7.9 Hz, 1H), 7.79 (t, *J* = 7.4 Hz, 1H), 7.74 (d, *J* = 8.9 Hz, 2H), 7.72–7.67 (m, 2H), 7.63 (d, *J* = 8.2 Hz, 1H), 7.53 (d, *J* = 7.4 Hz, 1H), 7.51–7.44 (m, 3H), 7.31–7.24 (m, 4H), 7.22 (d, *J* = 6.7 Hz, 1H), 7.18 (d, *J* = 7.6 Hz, 2H), 1.11 (s, 9H) ppm.

¹³C NMR (101 MHz, CDCl₃): δ 161.67, 161.36, 151.15, 138.63, 137.08, 133.45, 132.40, 132.16, 131.11, 131.03 (2C, overlapped), 130.79, 130.69, 130.56, 130.26, 129.44 (2C), 129.19, 129.13 (2C), 128.90, 128.64, 127.88 (2C), 127.53, 127.47, 127.21, 127.11 (2C), 126.73, 126.26, 124.96, 124.60, 123.53, 122.87, 116.44, 112.61, 38.64, 29.51 (3C) ppm. The signal of one C₄ carbon nucleus in the ¹³C NMR spectrum overlapped.

HRMS (ESI, *m/z*) calcd. for C₄₂H₃₀O₄[M+H]⁺: 599.2217, found: 599.2215.

3-(*tert*-Butyl)-4-[4-(diphenylamino)phenyl]-8,9-diphenylpyrano[3,4-*g*]isochromene-1,6-dione (**7ah**)

Starting from **6a** and **2h**, desired product **7ah** was isolated as a yellow powder (50 mg, 75% yield).



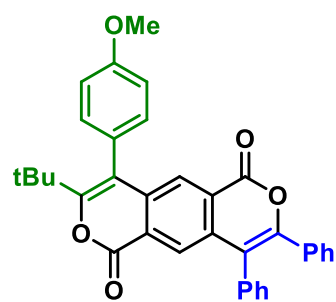
¹H NMR (400 MHz, CDCl₃): δ 8.14 (s, 1H), 7.97 (s, 1H), 7.43 (s, 3H), 7.35–7.27 (m, 6H), 7.26–7.13 (m, 11H), 7.10–7.04 (m, 4H), 1.19 (s, 9H) ppm.

¹³C NMR (101 MHz, CDCl₃): δ 161.28, 161.22, 160.86, 151.04, 148.14, 147.45, 139.17, 136.79, 133.47, 132.02 (2C), 131.01 (2C), 129.44 (6C, overlapped), 129.19 (3C, overlapped), 128.61, 127.90 (2C), 127.41, 127.16, 126.57, 125.01 (4C), 124.68, 124.50, 123.42 (2C), 122.61 (2C), 116.52, 114.61, 38.38, 30.14 (3C) ppm. The signals of two carbon nuclei in the ¹³C NMR spectrum overlapped.

HRMS (ESI, *m/z*) calcd. for C₄₆H₃₅NO₄[M+H]⁺: 666.2644, found: 666.2633.

3-(*tert*-Butyl)-4-(4-methoxyphenyl)-8,9-diphenylpyrano[3,4-*g*]isochromene-1,6-dione (**7ai**)

Starting from **6a** and **2i**, desired product **7ai** was isolated as a yellow powder (41 mg, 79% yield).



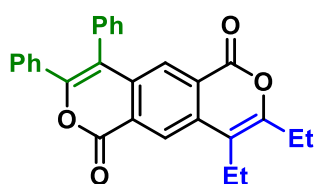
¹H NMR (400 MHz, CDCl₃): δ 8.13 (s, 1H), 7.84 (s, 1H), 7.44–7.41 (m, 3H), 7.27 (d, *J* = 8.2 Hz, 2H), 7.25–7.14 (m, 7H), 7.00 (d, *J* = 8.6 Hz, 2H), 3.90 (s, 3H), 1.13 (s, 9H) ppm.

¹³C NMR (101 MHz, CDCl₃): δ 161.28, 161.11, 160.91, 159.66, 151.04, 139.29, 136.73, 133.45, 132.45, 132.29 (2C), 131.00 (2C), 129.41 (2C), 129.18 (3C, overlapped), 128.59, 127.89 (2C), 127.32, 126.53, 126.02, 124.65, 124.42, 116.48, 114.52, 114.26 (2C), 55.27, 38.33, 30.13 (3C) ppm.

HRMS (ESI, *m/z*) calcd. for C₃₅H₂₈O₅[M+H]⁺: 529.2010, found: 529.2023.

3,4-Diethyl-8,9-diphenylpyrano[3,4-*g*]isochromene-1,6-dione (**7ba**)

Starting from **6b** and **2a**, desired product **7ba** was isolated as a yellow powder (35 mg, 83% yield).



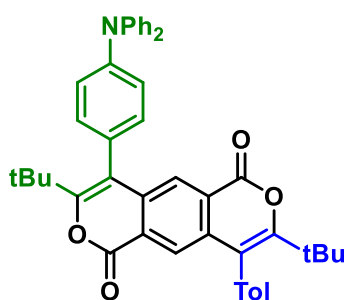
^1H NMR (400 MHz, CDCl_3): δ 8.59 (s, 1H), 8.20 (s, 1H), 7.51–7.43 (m, 3H), 7.38–7.18 (m, 7H), 2.79 (q, $J = 7.5$ Hz, 2H), 2.67 (q, $J = 7.5$ Hz, 2H), 1.34–1.26 (m, 6H) ppm.

^{13}C NMR (101 MHz, CDCl_3): δ 161.65, 161.54, 155.81, 150.97, 136.50, 136.28, 133.35, 132.44, 130.99 (2C), 129.42 (2C), 129.21, 129.18 (2C), 128.62, 127.92 (2C), 127.58, 125.60, 124.91, 124.26, 116.60, 112.97, 24.13, 19.45, 14.37, 12.41 ppm.

HRMS (ESI, m/z) calcd. for $\text{C}_{28}\text{H}_{22}\text{O}_4[\text{M}+\text{H}]^+$: 423.1591, found: 423.1596.

3,8-Di-*tert*-butyl-4-[4-(diphenylamino)phenyl]-9-(*p*-tolyl)pyrano[3,4-*g*]isochromene-1,6-dione (7ch)

Starting from **6c** and **2h**, desired product **7ch** was isolated as a yellow powder (39 mg, 59% yield).



^1H NMR (300 MHz, CDCl_3): δ 7.93 (s, 1H), 7.79 (s, 1H), 7.41–7.31 (m, 7H), 7.28–7.11 (m, 11H), 2.53 (s, 3H), 1.24 (s, 9H), 1.19 (s, 9H) ppm.

^{13}C NMR (101 MHz, CDCl_3): δ 161.54, 161.34, 160.32, 160.14, 148.03, 147.48, 138.56, 138.27, 132.00 (2C), 131.11, 131.03 (2C), 129.48 (2C), 129.41 (4C), 129.18, 127.47, 126.63 (2C), 124.90 (4C), 124.21, 124.14, 123.33 (2C), 122.75 (2C), 114.78, 114.47, 38.28 (2C, overlapped), 30.13 (3C), 30.10 (3C), 21.40 ppm. The signal of one C_4 carbon nucleus in the ^{13}C NMR spectrum overlapped.

HRMS (ESI, m/z) calcd. for $\text{C}_{45}\text{H}_{41}\text{NO}_4[\text{M}+\text{H}]^+$: 660.3114, found: 660.3101.

NMR spectra

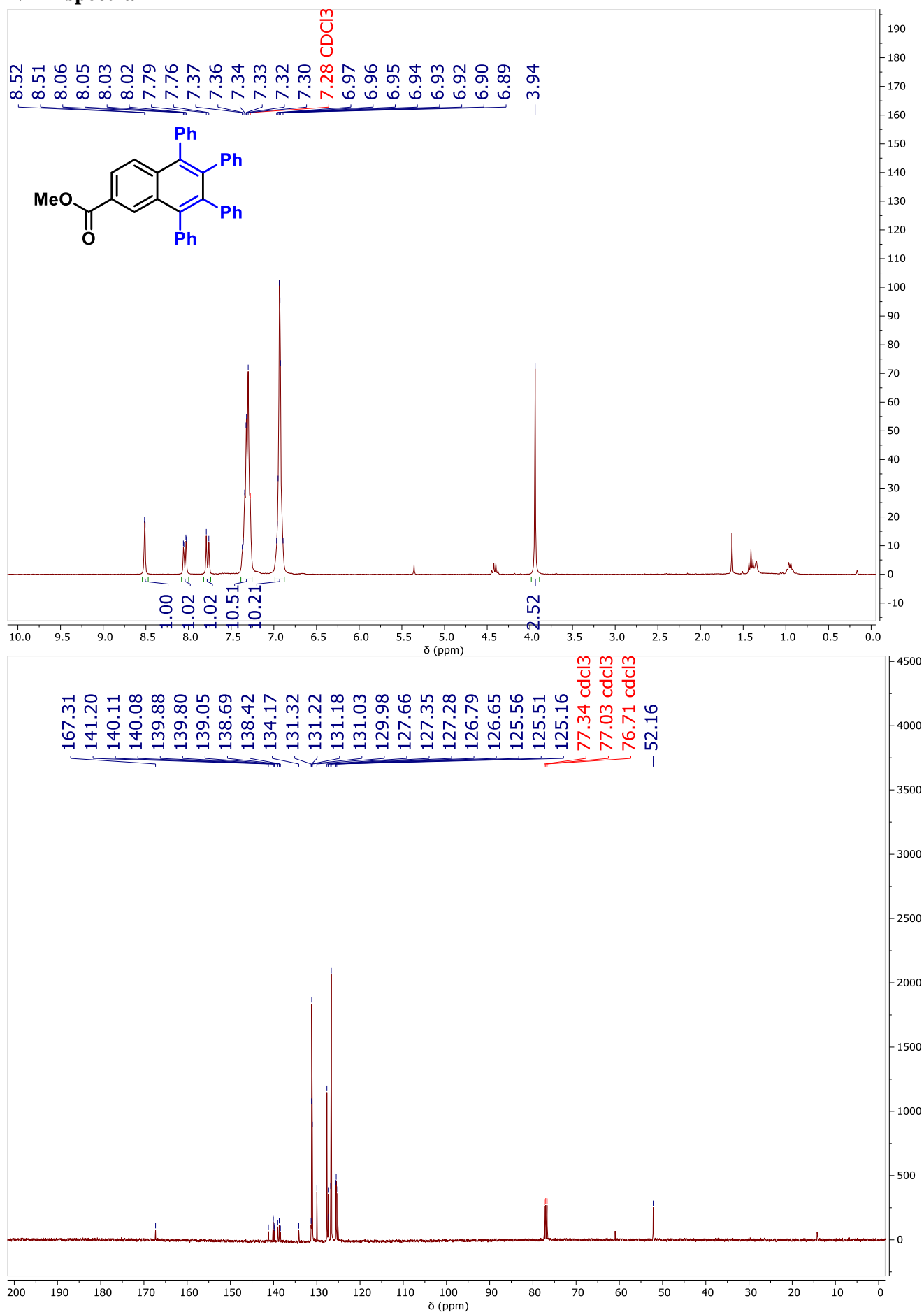


Figure S1. ¹H (400 MHz) and ¹³C (101 MHz) NMR spectra of **4a** (in CDCl₃)

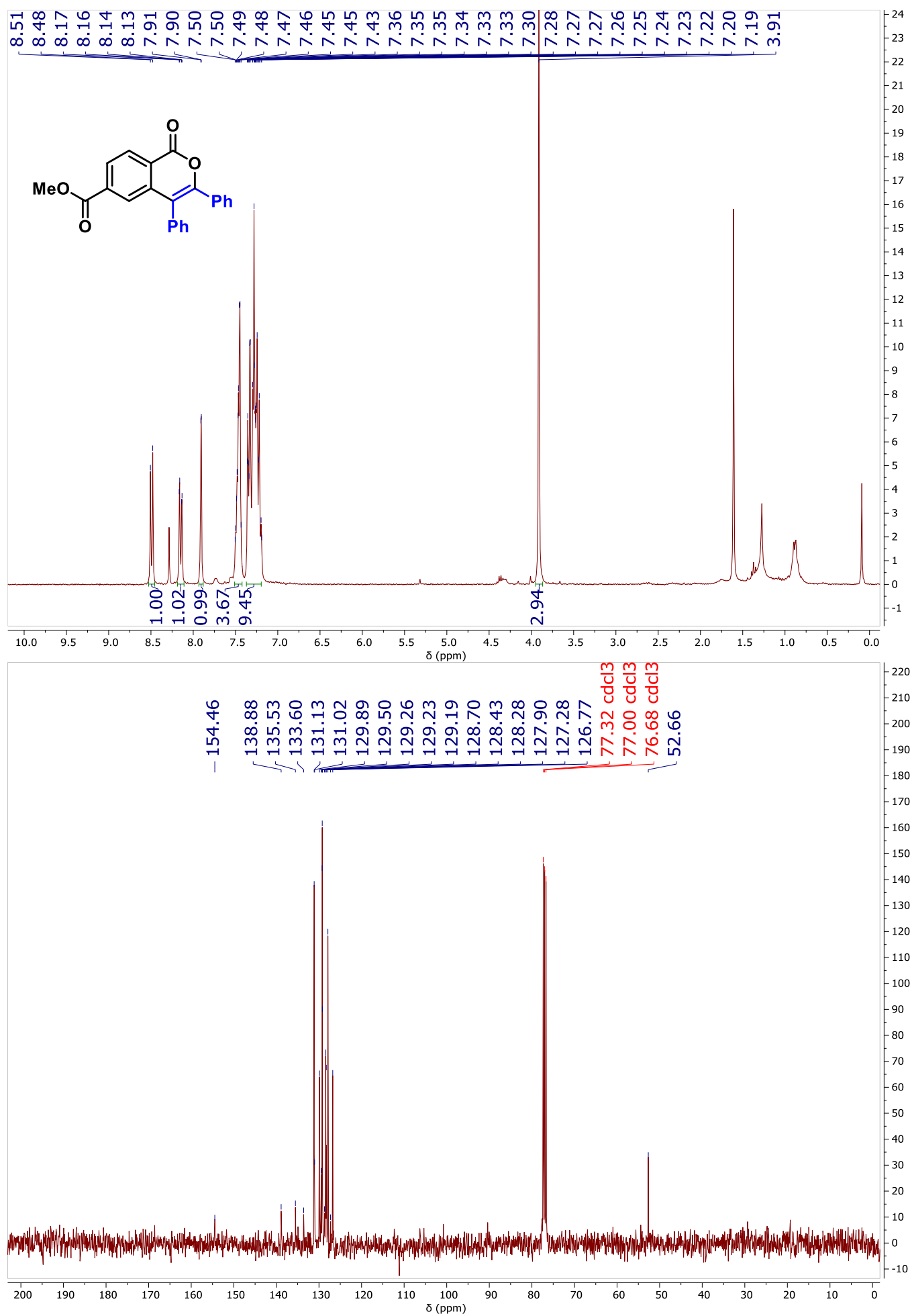


Figure S2. ¹H (400 MHz) and ¹³C (101 MHz) NMR spectra of **3a** (in CDCl₃)

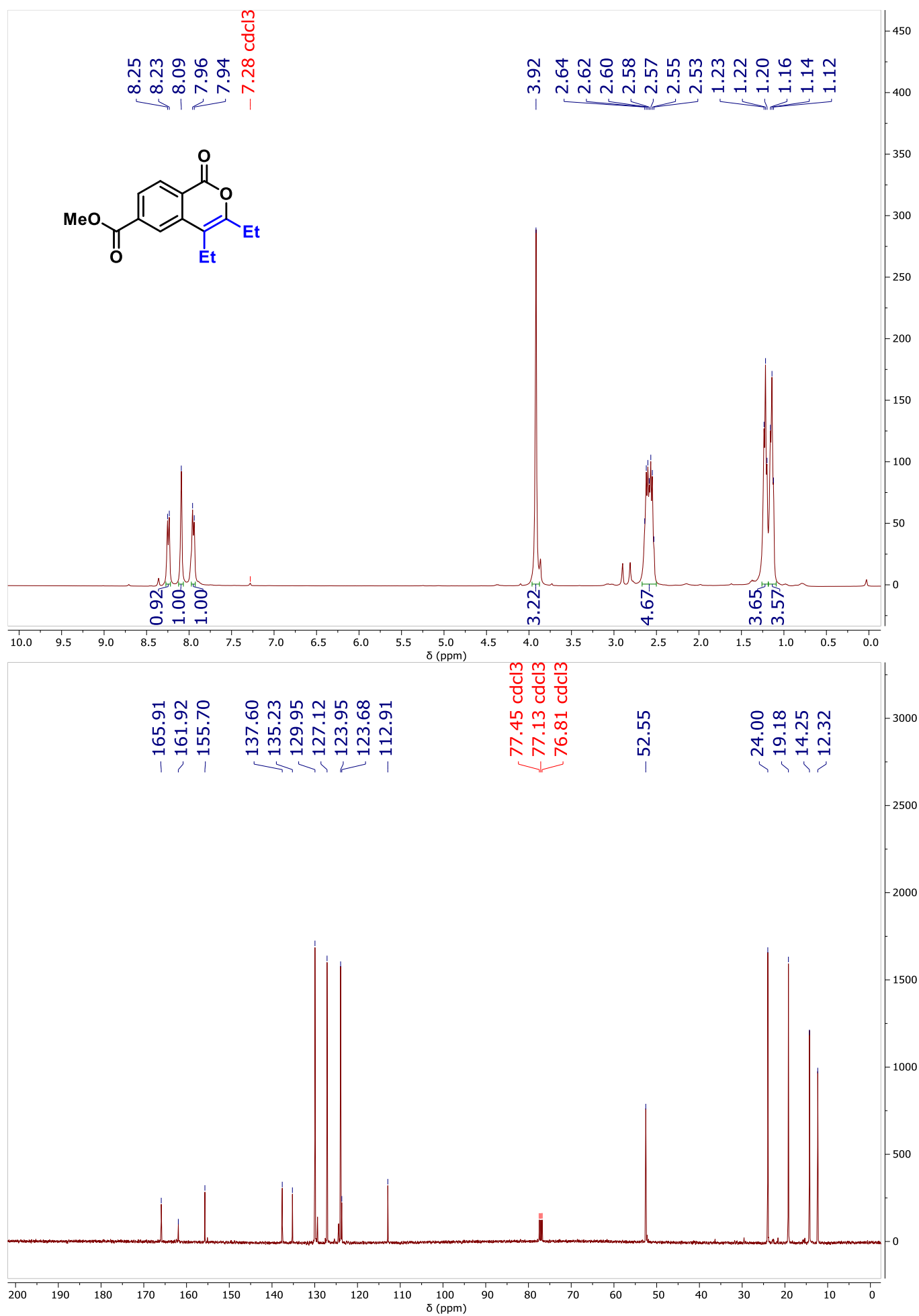


Figure S3. ¹H (400 MHz) and ¹³C (101 MHz) NMR spectra of **3b** (in CDCl₃)

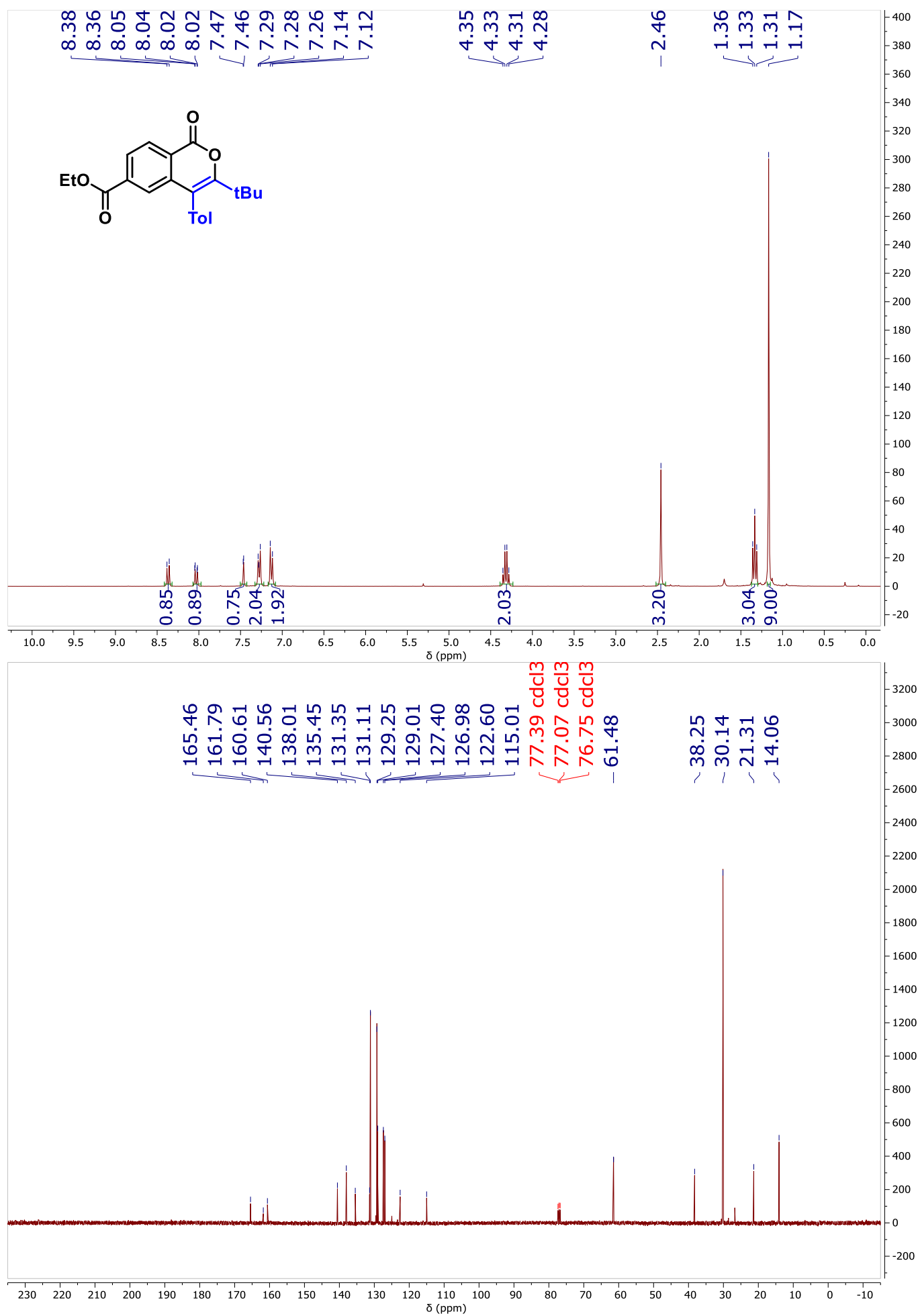


Figure S4. ¹H (300 MHz) and ¹³C (101 MHz) NMR spectra of **3c** (in CDCl₃)

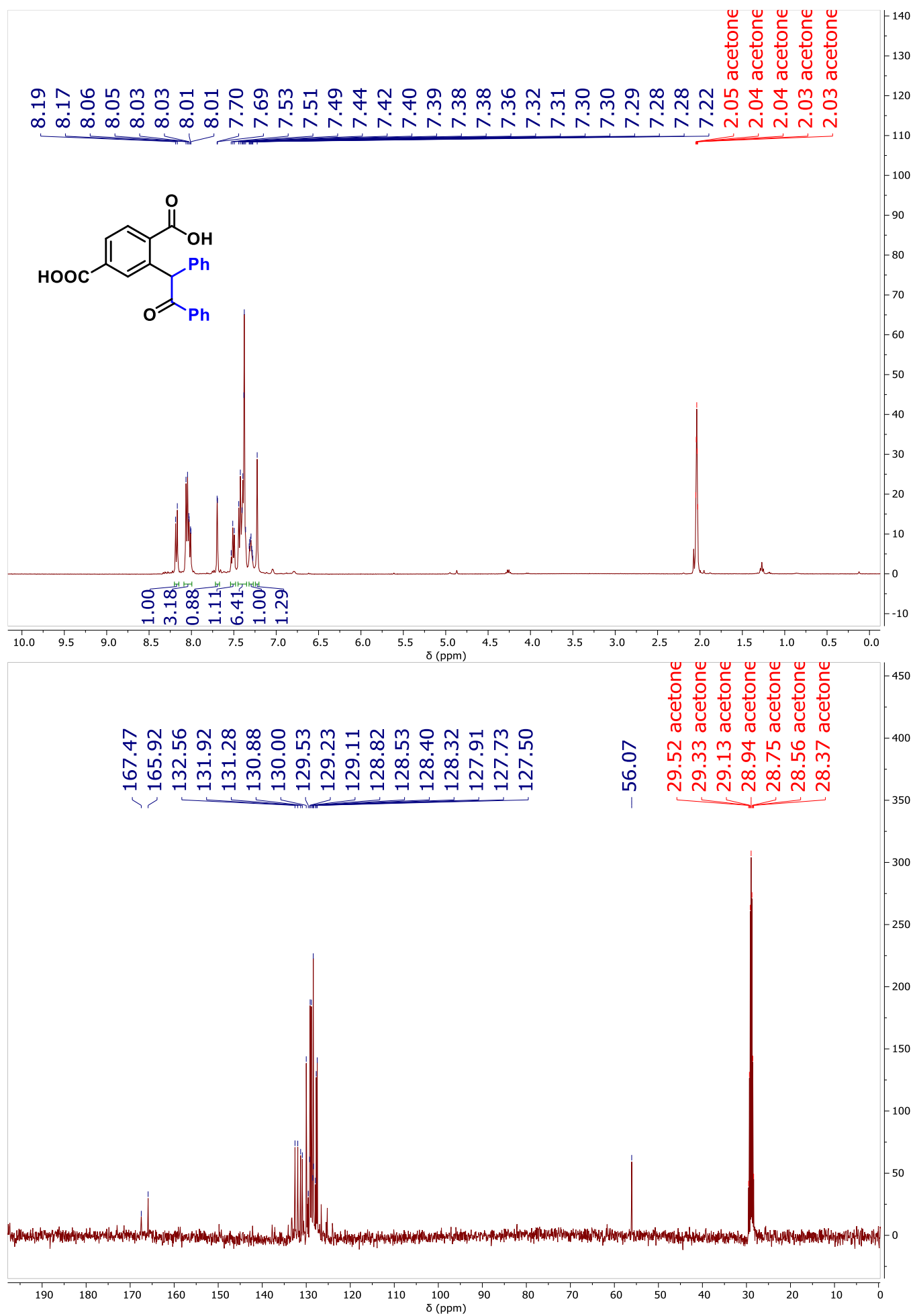


Figure S5. ¹H (400 MHz) and ¹³C (101 MHz) NMR spectra of **5a** (in acetone-d₆)

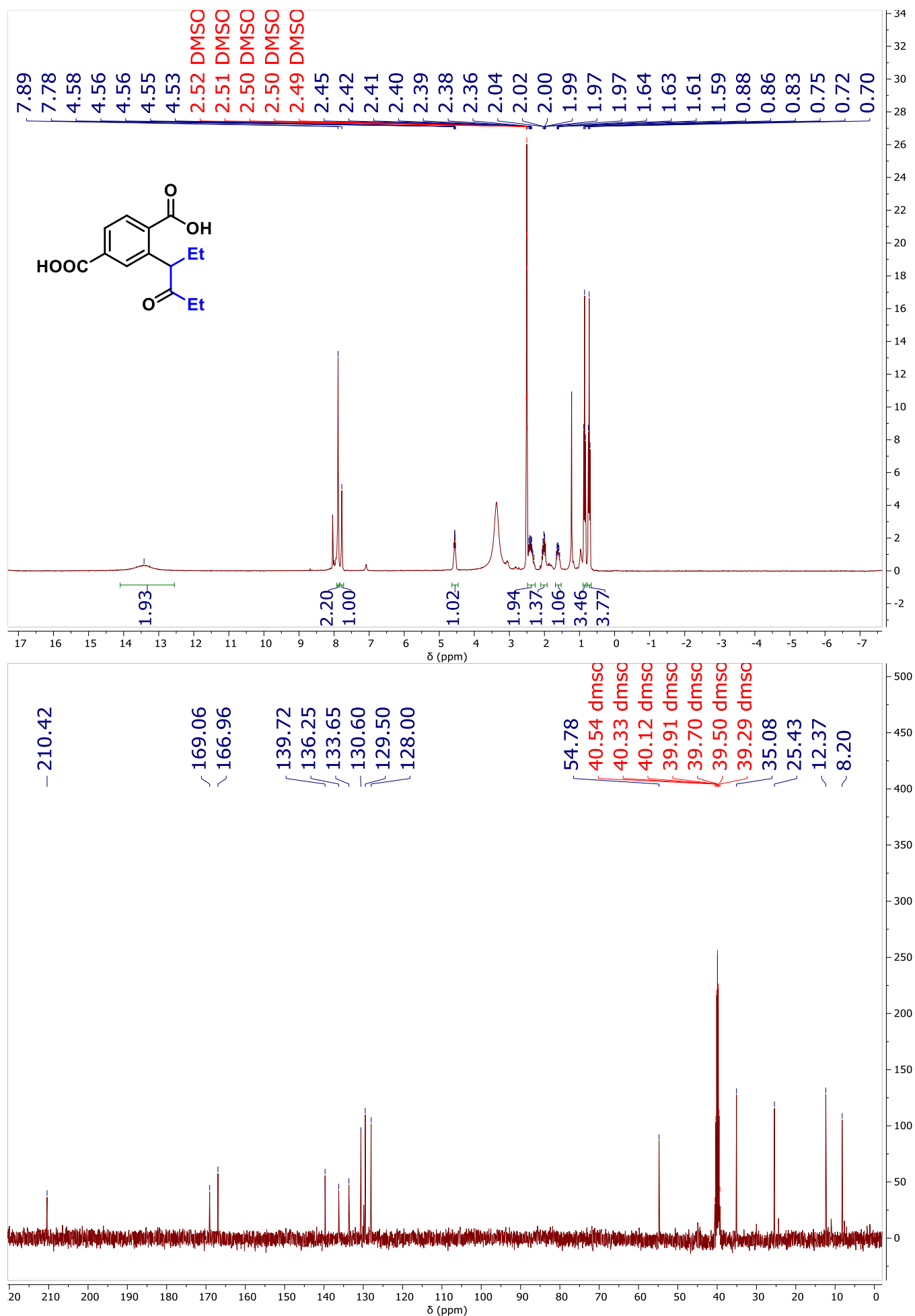


Figure S6. ¹H (400 MHz) and ¹³C (101 MHz) NMR spectra of **5b** (in dmsO-d₆)

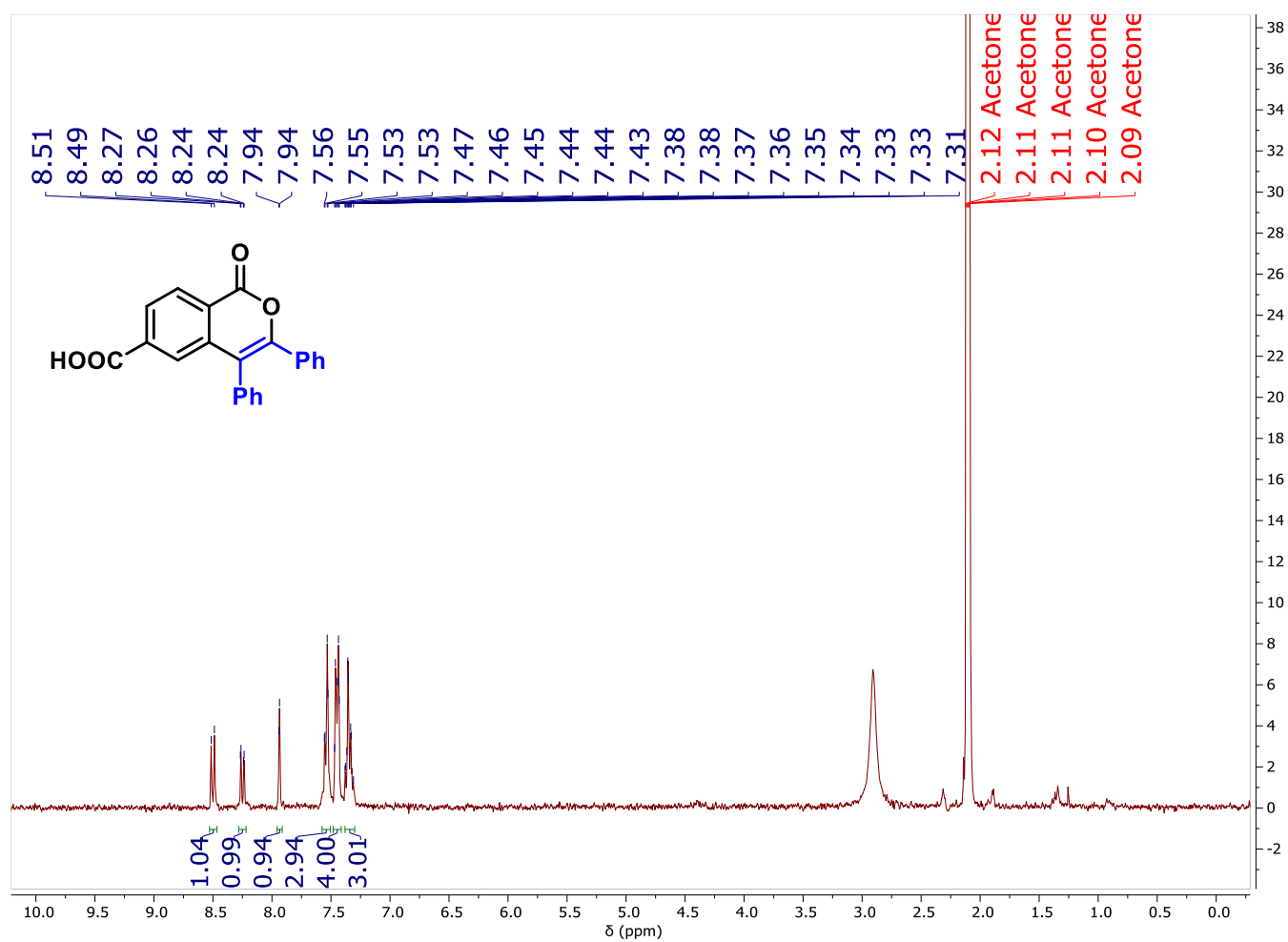


Figure S7. ¹H (400 MHz) NMR spectrum of **6a** (in acetone-d₆)

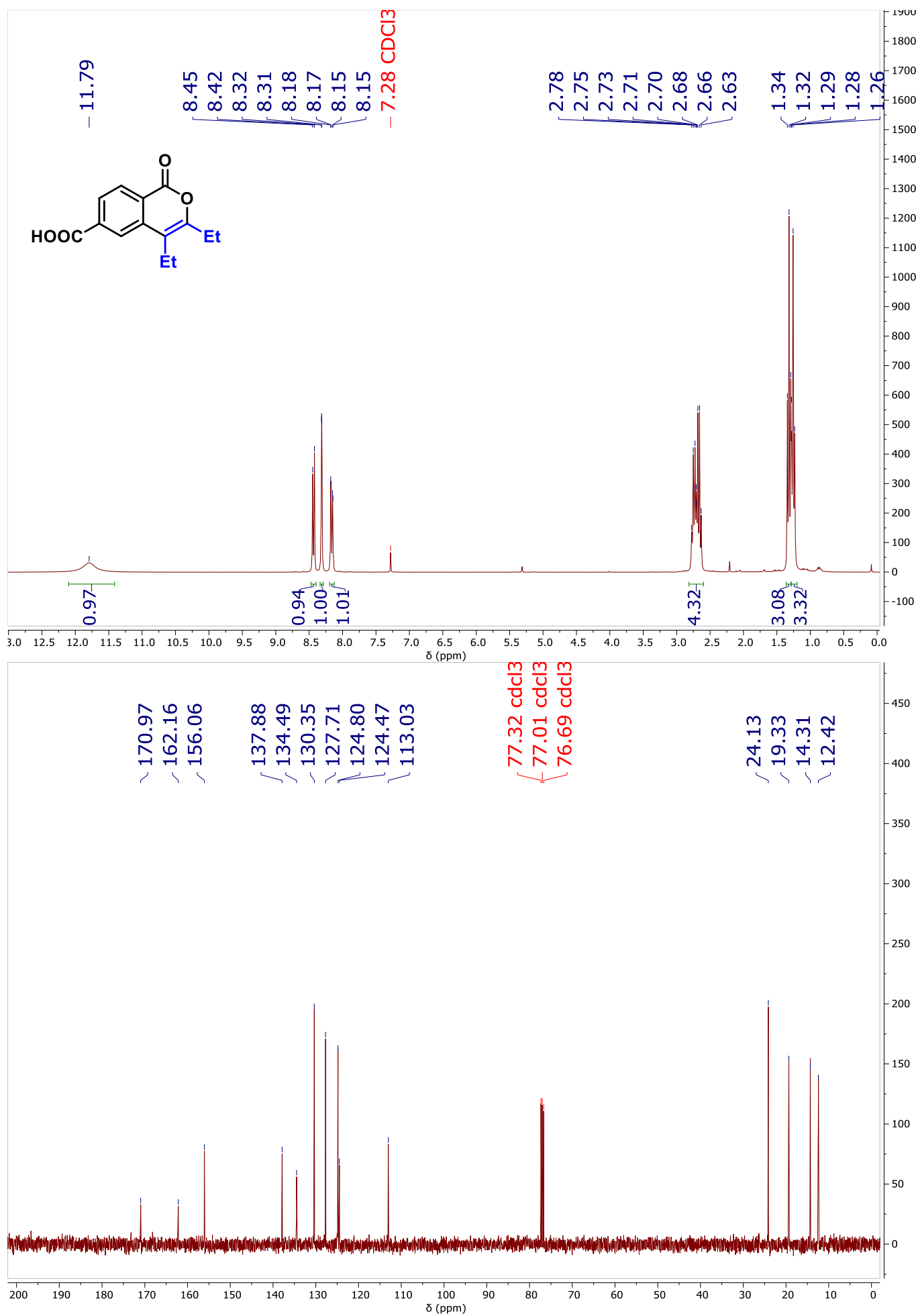


Figure S8. ¹H (400 MHz) and ¹³C (101 MHz) NMR spectra of **6b** (in CDCl₃)

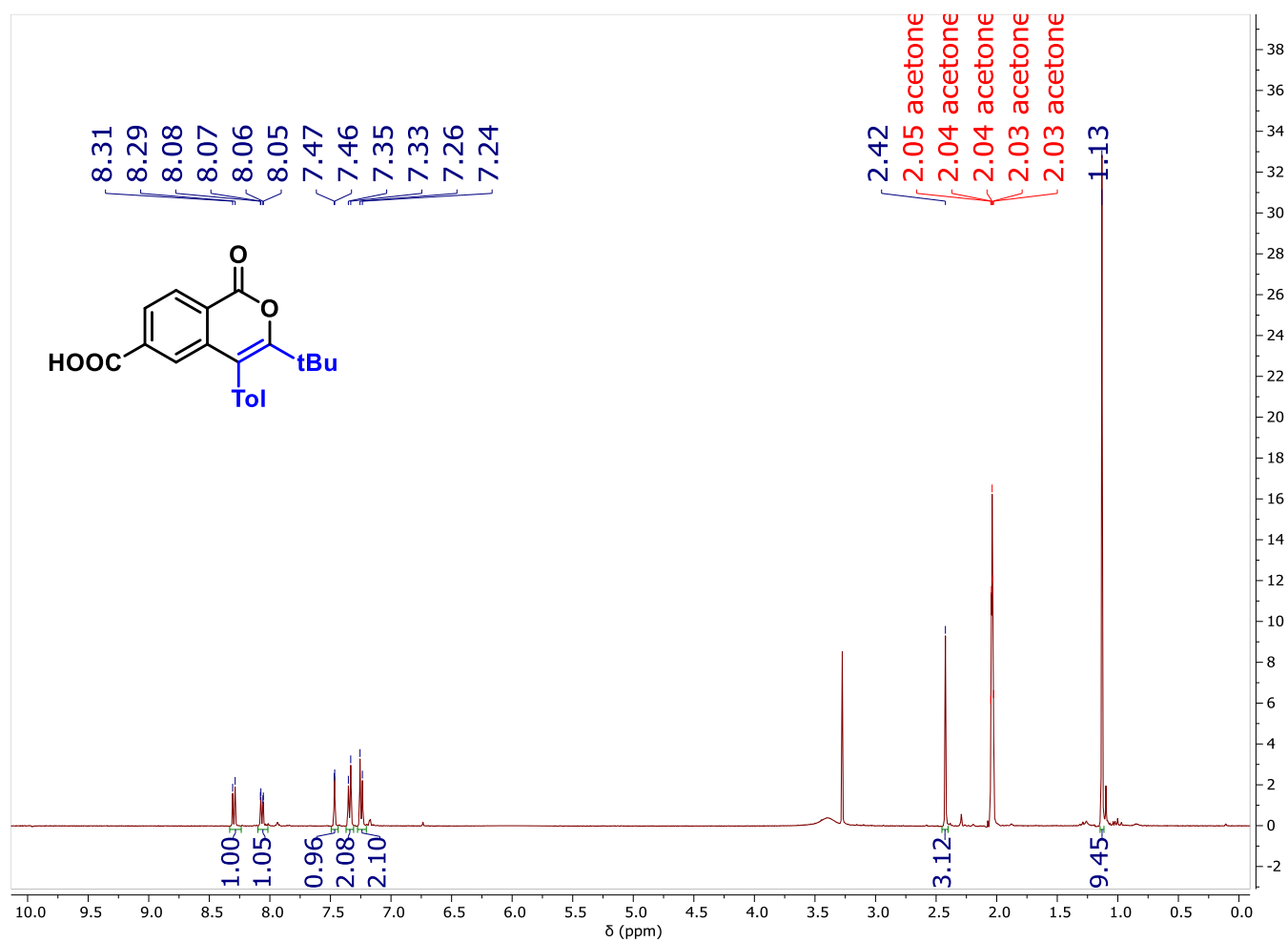


Figure S9. ¹H (400 MHz) NMR spectrum of **6c** (in acetone-d₆)

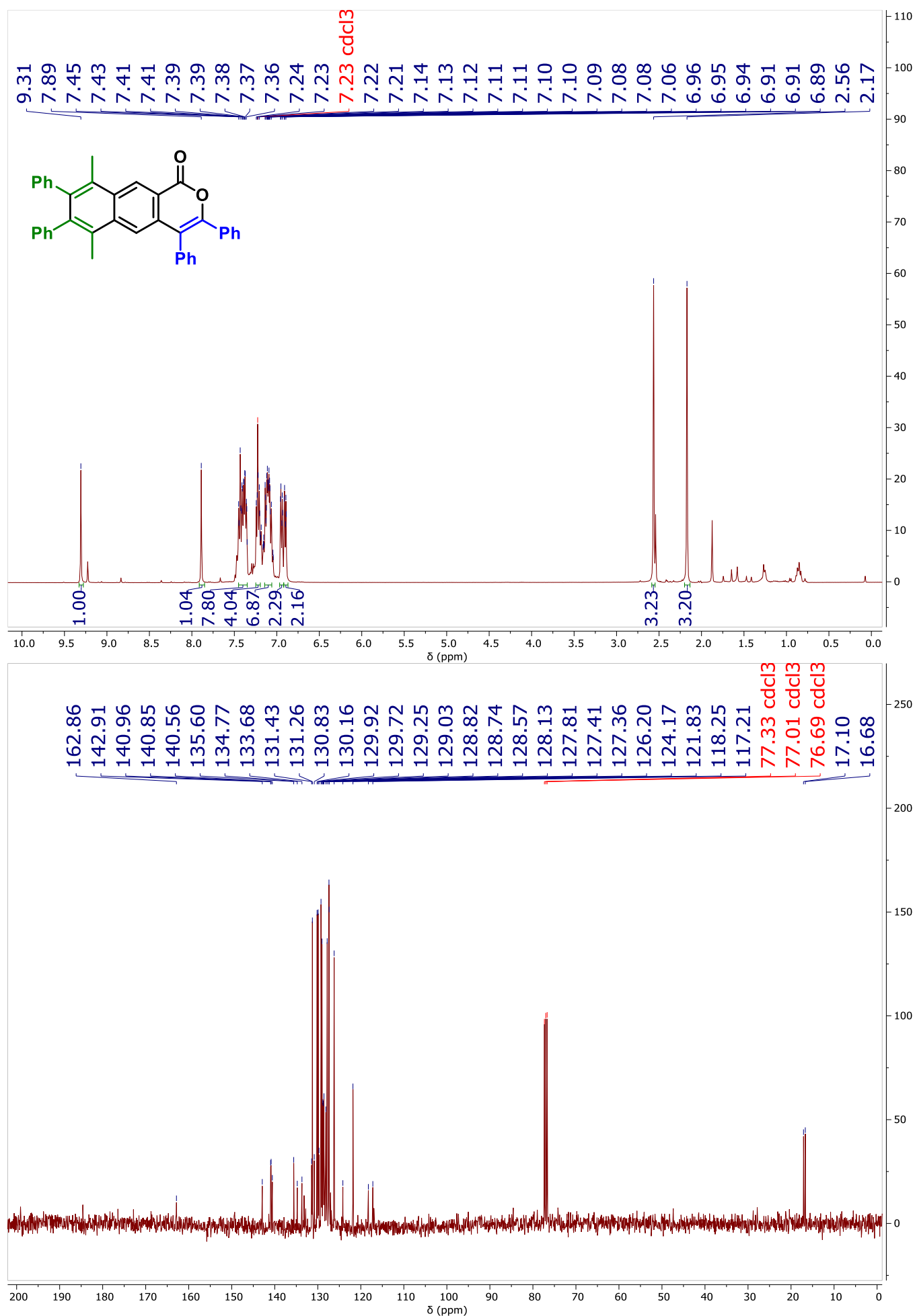


Figure S10. ¹H (400 MHz) and ¹³C (101 MHz) NMR spectra of **8ad** (in CDCl₃)

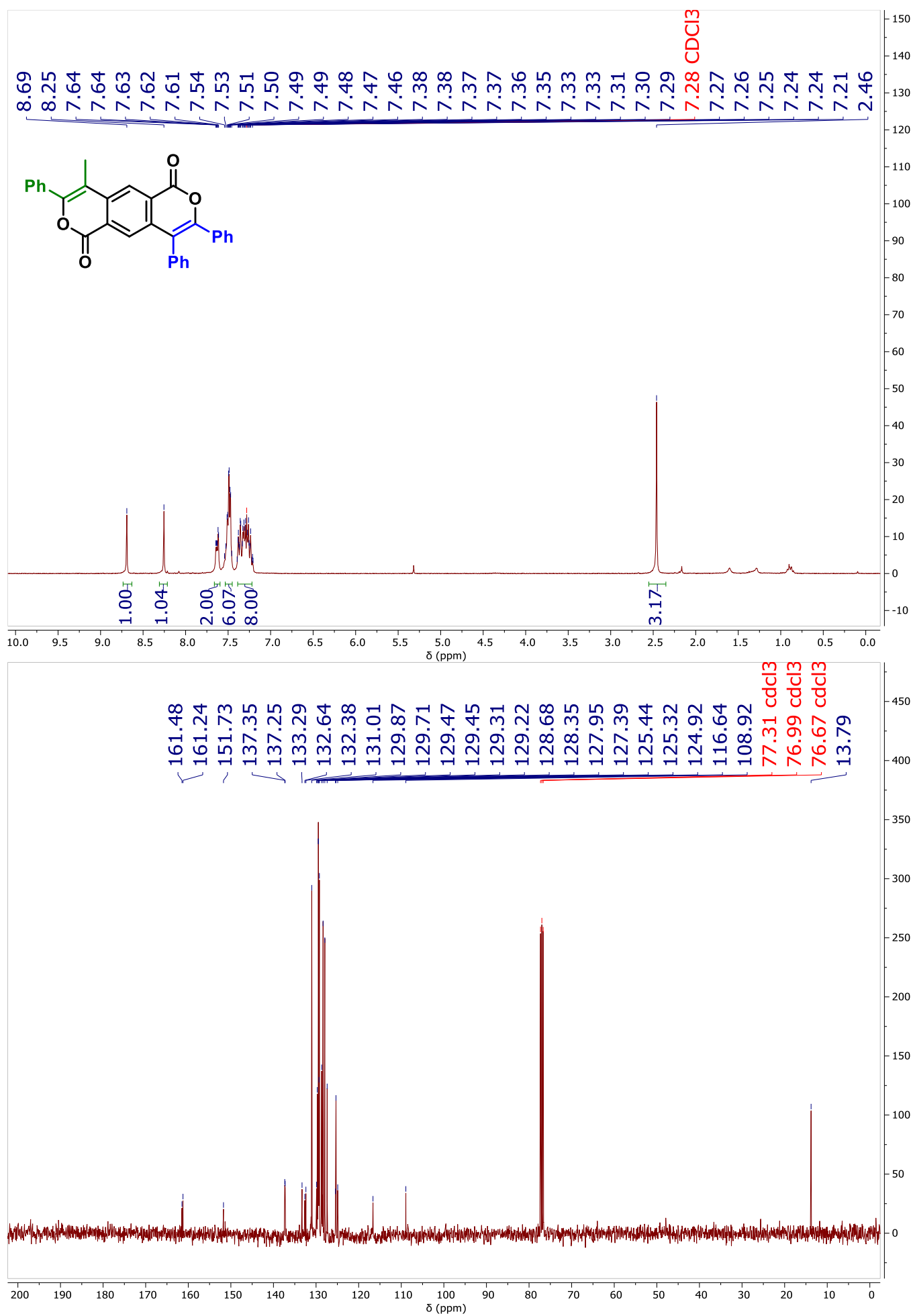


Figure S11. ^1H (400 MHz) and ^{13}C (101 MHz) NMR spectra of **7ad** (in CDCl_3)

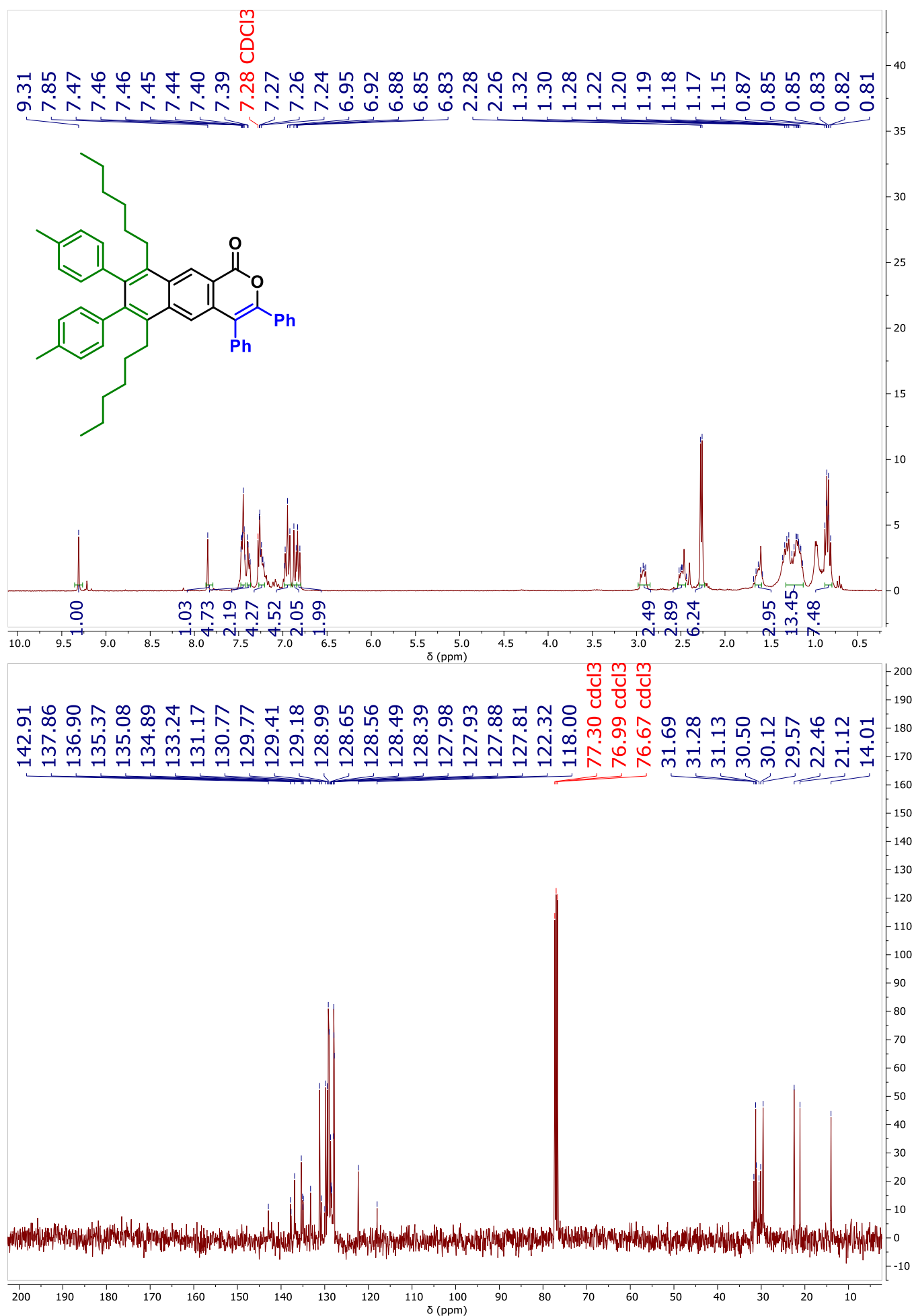


Figure S12. ^1H (300 MHz) and ^{13}C (101 MHz) NMR spectra of **8ae** (in CDCl_3)

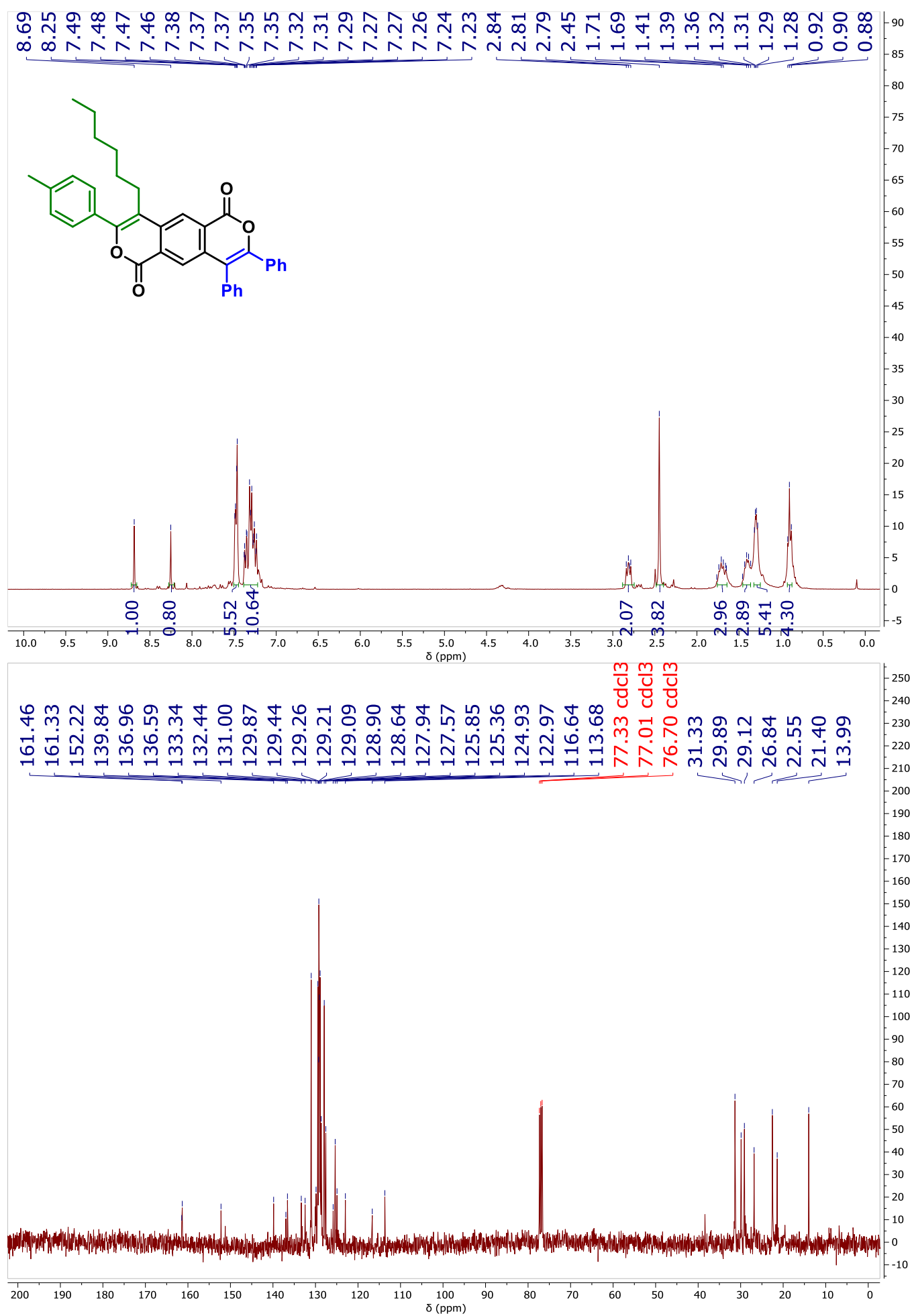


Figure S13. ^1H (400 MHz) and ^{13}C (101 MHz) NMR spectra of **7ae** (in CDCl_3)

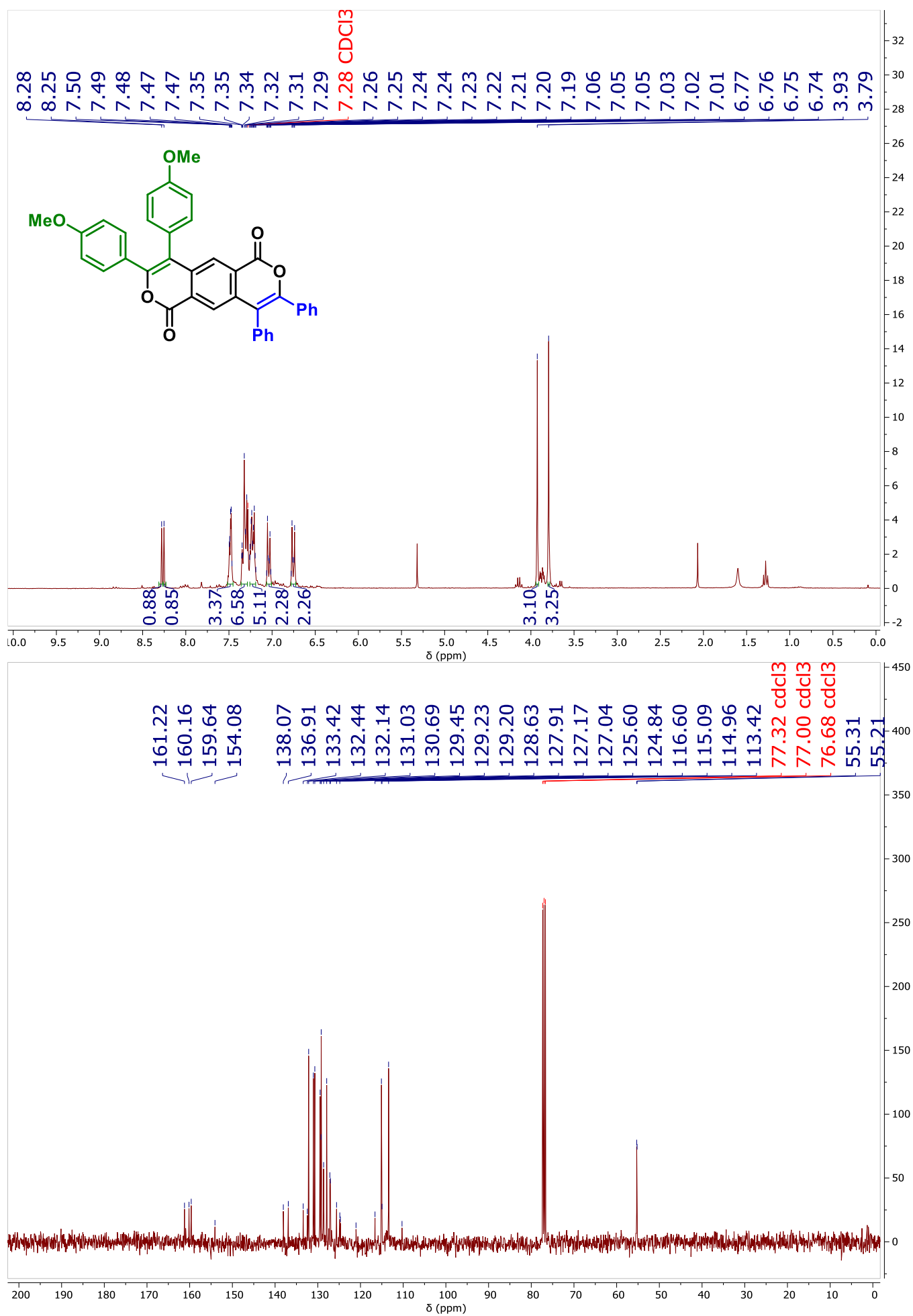


Figure S14. ^1H (400 MHz) and ^{13}C (101 MHz) NMR spectra of **7af** (in CDCl_3)

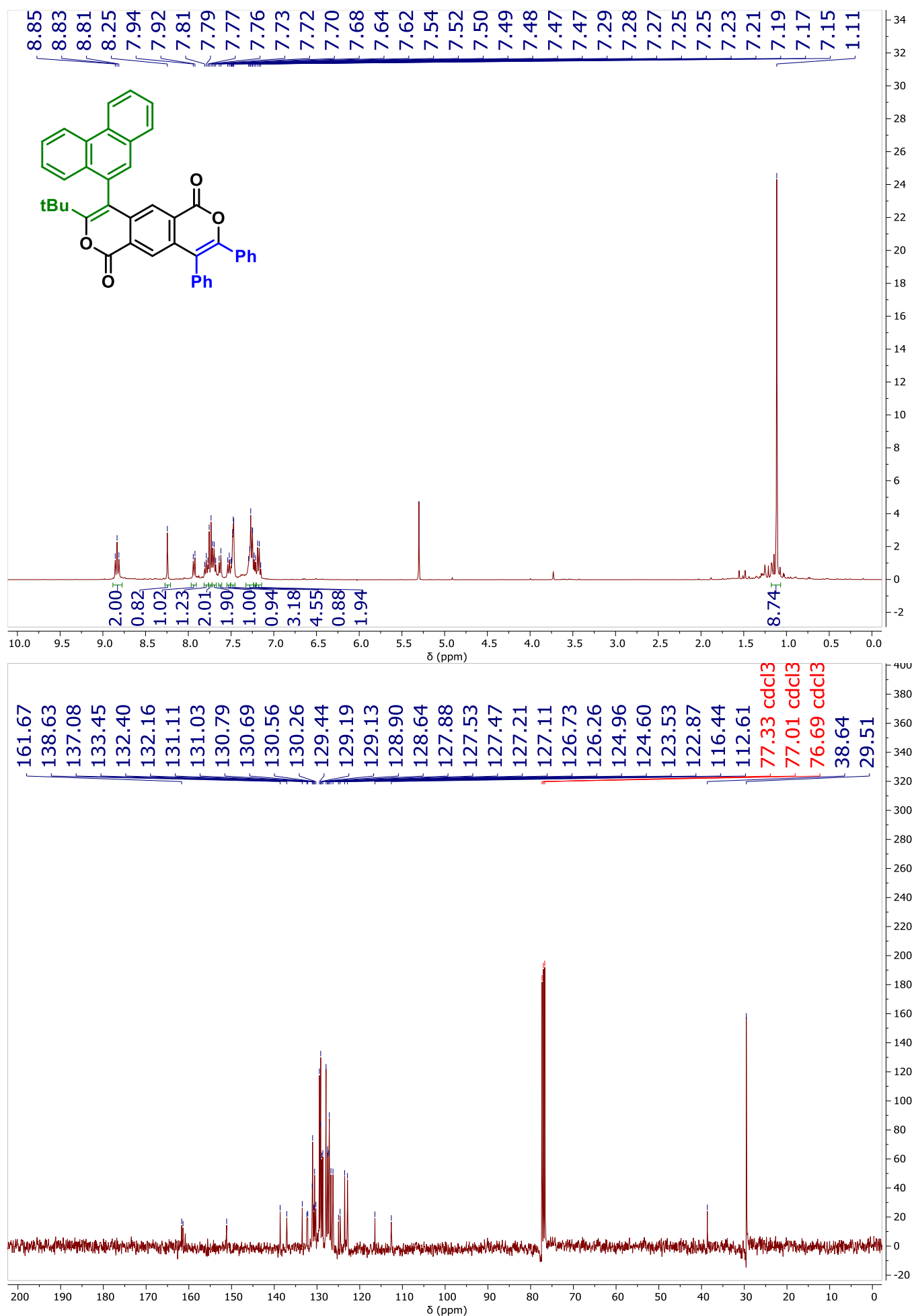


Figure S15. ¹H (400 MHz) and ¹³C (101 MHz) NMR spectra of **7ag** (in CDCl₃)

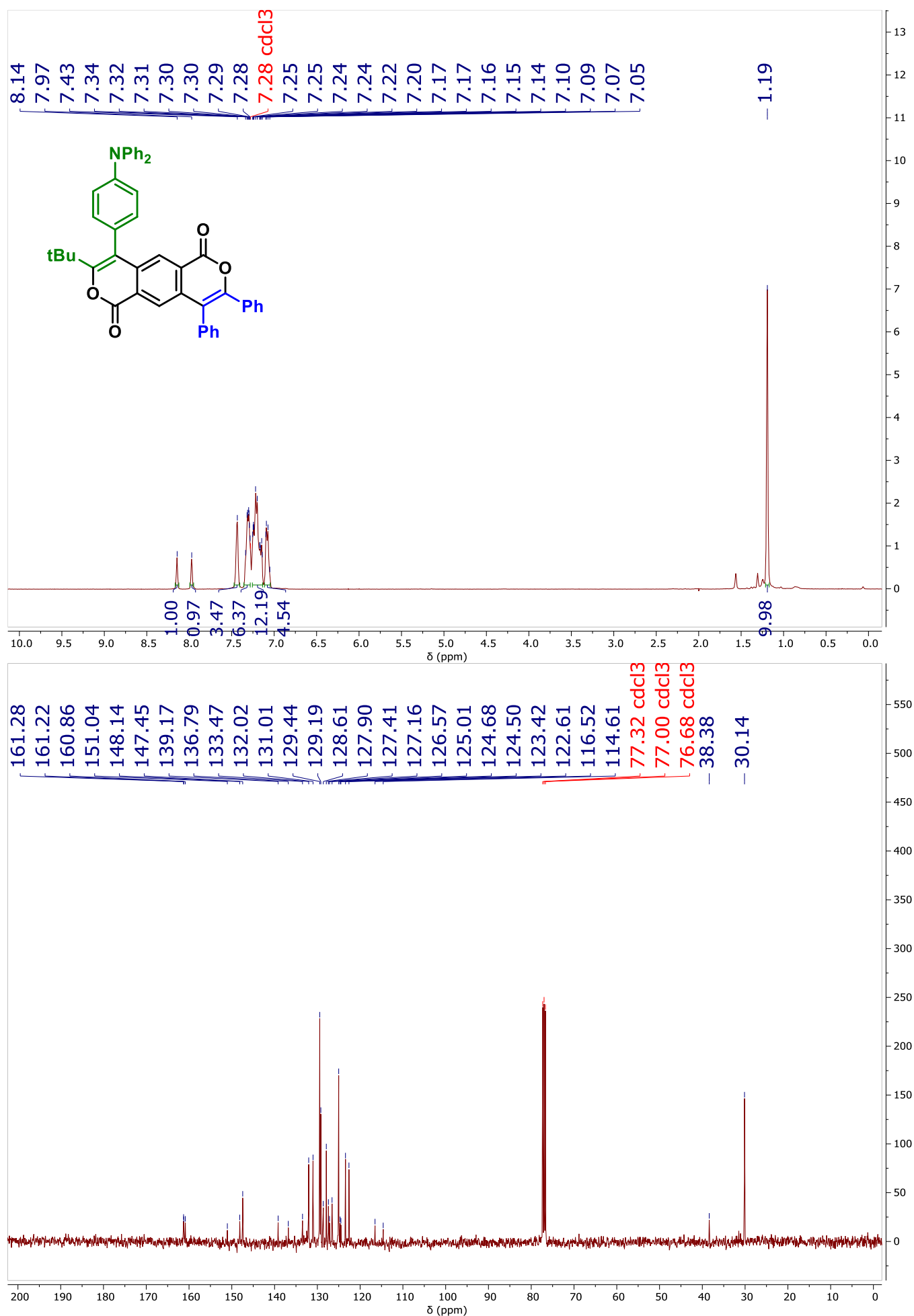


Figure S16. ^1H (400 MHz) and ^{13}C (101 MHz) NMR spectra of **7ah** (in CDCl_3)

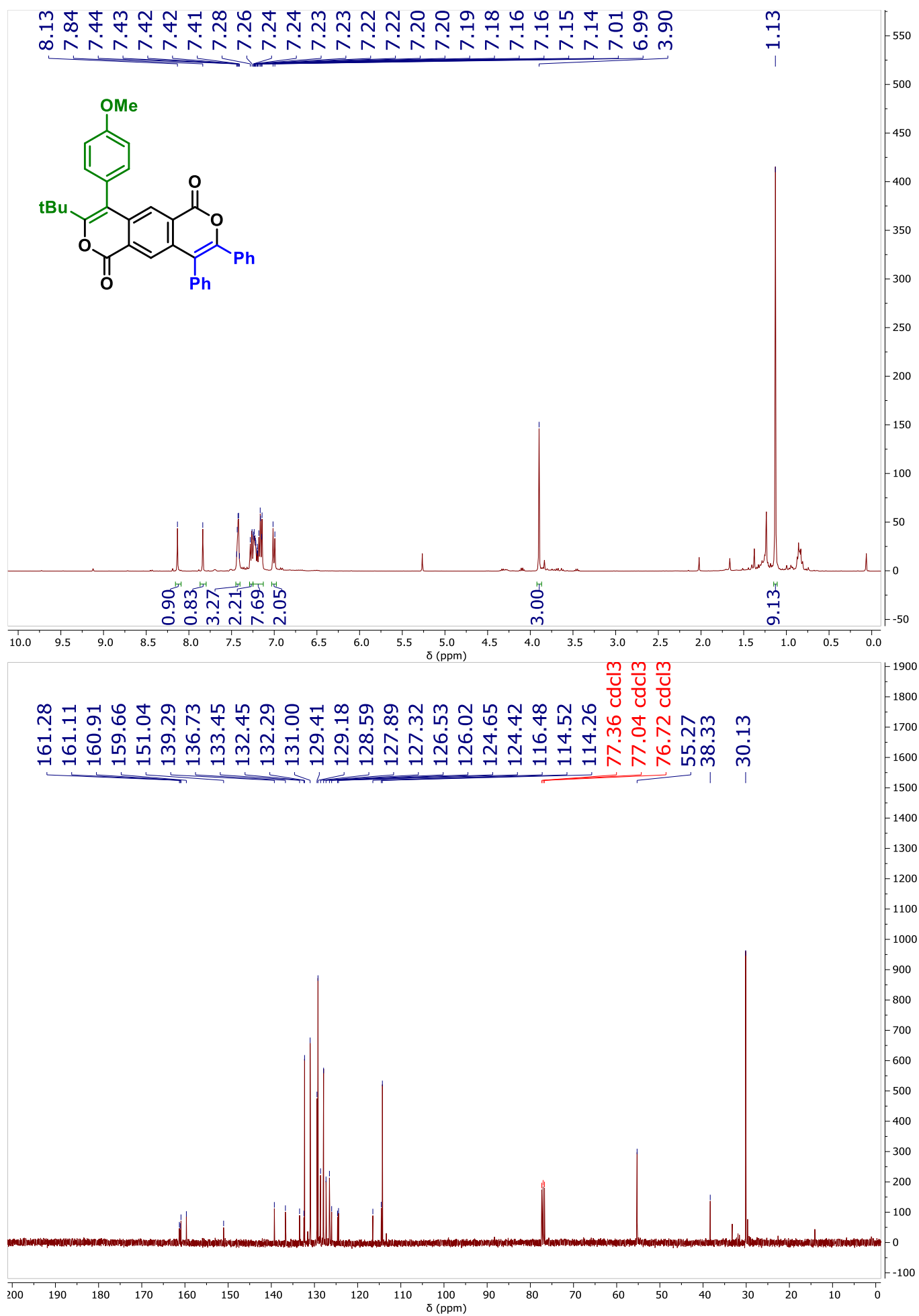


Figure S17. ^1H (400 MHz) and ^{13}C (101 MHz) NMR spectra of **7ai** (in CDCl_3)

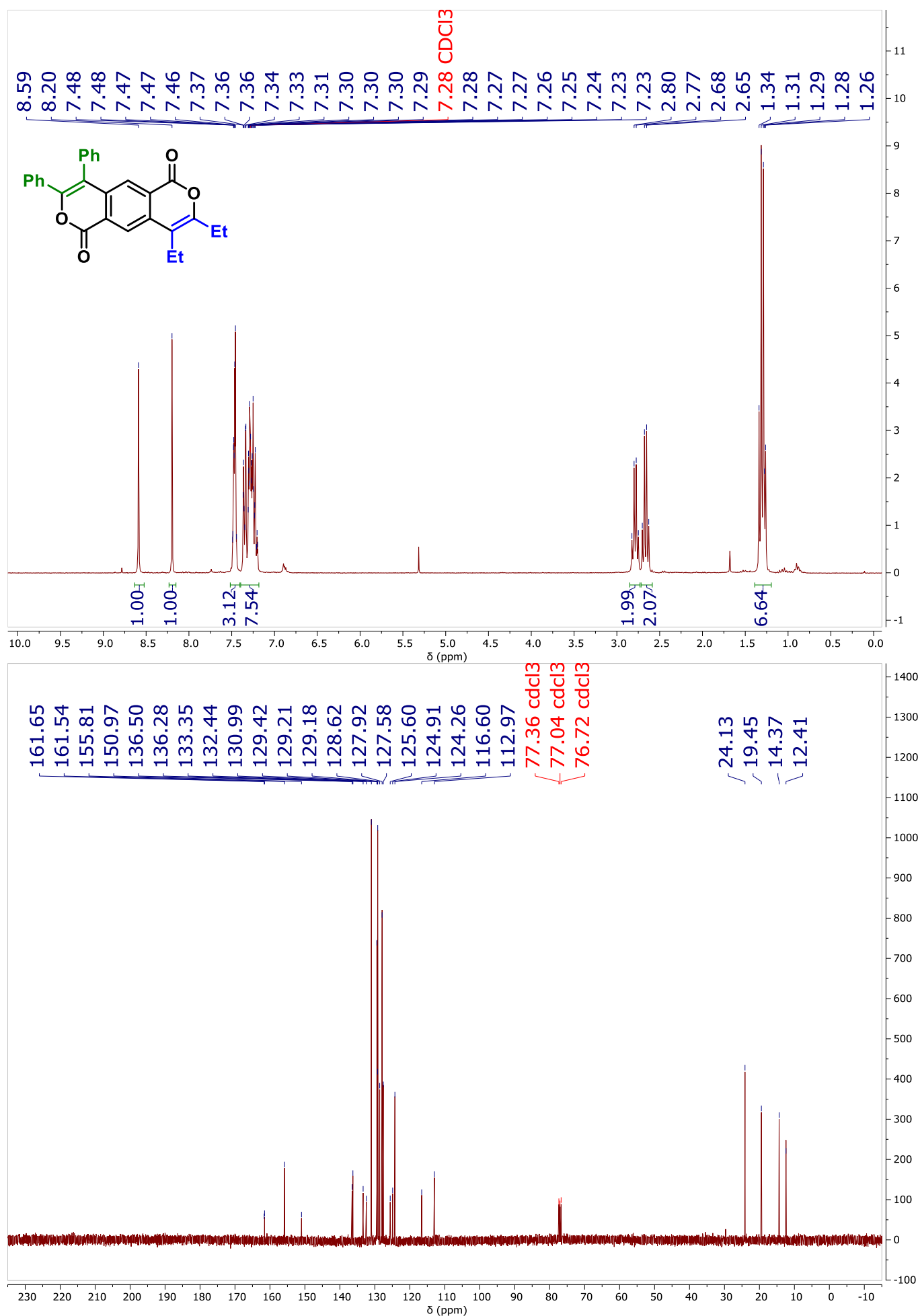


Figure S18. ^1H (400 MHz) and ^{13}C (101 MHz) NMR spectra of **7ba** (in CDCl_3)

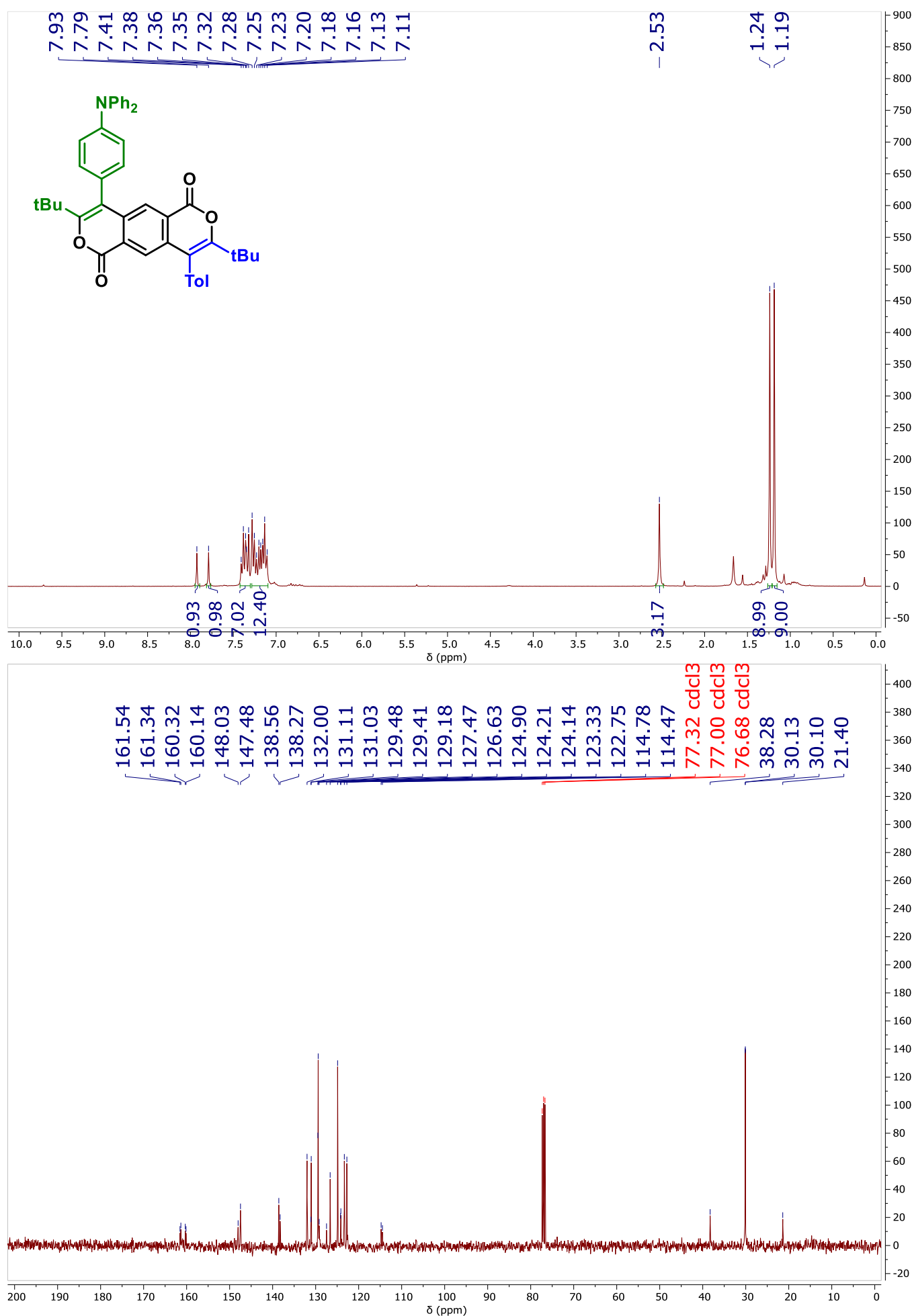


Figure S19. ¹H (300 MHz) and ¹³C (101 MHz) NMR spectra of **7ch** (in CDCl₃)

DFT Calculations

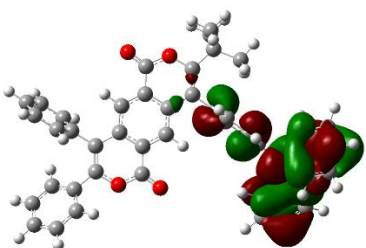
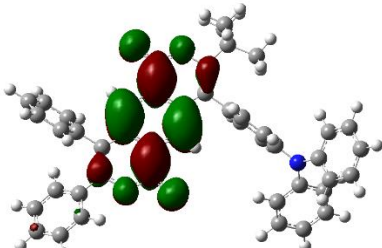
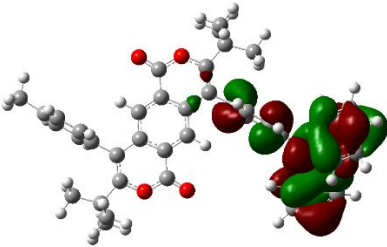
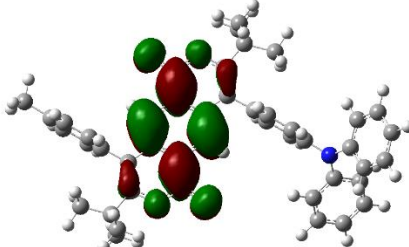
Geometry optimizations at the S_0 minimum were performed without constraints at the B3LYP/6-31G(d) level using the Gaussian 09 software (revision D.01) [S7] with corrections for solvation in dichloromethane (PCM model). The optimized geometry was verified to have no negative frequencies. Then, at the same level, TD-DFT was adopted to estimate the energies of the vertical excitations based on the optimized S_0 geometries (Table S1). The first 10 singlet and triplet excited states were considered.

Table S1. General analysis of the absorption bands of compounds **7ah** and **7ch** by TD-DFT calculations at the B3LYP/6-31G(d) level with corrections for solvation in dichloromethane (PCM model)

Compound	Calculated absorption maxima ($S_0 \rightarrow S_1$) / oscillator strength / Main MOs responsible for excitation ^a	Calculated absorption maxima ($S_0 \rightarrow S_2$) / oscillator strength / Main MOs responsible for excitation ^a	Calculated absorption maxima ($S_0 \rightarrow S_3$) / oscillator strength / Main MOs responsible for excitation ^a
7ah	495 nm / 0.0002 / HOMO \rightarrow LUMO (99%)	419 nm / 0.0001 / HOMO \rightarrow LUMO+1 (99%)	405 nm / 0.2292 / HOMO-1 \rightarrow LUMO (98%)
7ch	485 nm / 0.0001 / HOMO \rightarrow LUMO (99%)	387 nm / 0.0003 / HOMO \rightarrow LUMO+1 (99%)	386 nm / 0.2171 / HOMO-1 \rightarrow LUMO (97%)

^a Values in parentheses give the percentage contribution of the corresponding orbitals to the total transition.

Table S2. Frontier molecular orbitals of **7ah** and **7ch** at the B3LYP/6-31G(d) level (isovalue = 0.02 a.u.). Energies of the orbitals are given in eV

Compound	HOMO	LUMO
7ah	 -5.14	 -2.22
7ch	 -5.13	 -2.17

Cartesian coordinates and energies optimized at B3LYP/6-31G(d)

7ah

$S_0E = -2129.674832$ Hartree

ZPVE = 0.687581 Hartree

Thermal correction to Gibbs Free Energy = 0.729673 Hartree

6 -0.700840000 0.170755000 -0.001184000

6	-1.943665000	-0.456320000	0.067882000
6	-3.159626000	0.274623000	0.012863000
6	-3.058400000	1.668952000	-0.093462000
6	-1.814246000	2.293512000	-0.163465000
6	-0.599393000	1.564471000	-0.123641000
6	-1.769459000	3.753408000	-0.281825000
8	-0.518734000	4.305809000	-0.348473000
6	0.686432000	2.261569000	-0.201239000
6	0.684855000	3.618005000	-0.312397000
6	-1.976795000	-1.915261000	0.223511000
8	-3.224607000	-2.487294000	0.278291000
8	-1.014765000	-2.651145000	0.304699000
8	-2.725673000	4.501500000	-0.326323000
6	-4.432990000	-0.431666000	0.092458000
6	-4.415865000	-1.789896000	0.206808000
6	-5.705937000	0.351592000	0.111491000
6	-6.143077000	1.041980000	-1.030620000
6	-7.323184000	1.787022000	-1.001874000
6	-8.080152000	1.856529000	0.170010000
6	-7.649573000	1.179783000	1.313331000
6	-6.469470000	0.435372000	1.285459000
6	-5.554000000	-2.731059000	0.285104000
6	-5.448576000	-3.869957000	1.104923000
6	-6.496156000	-4.785020000	1.185709000
6	-7.660450000	-4.588513000	0.439285000
6	-7.767137000	-3.470880000	-0.391756000
6	-6.725058000	-2.548669000	-0.470657000
1	0.187495000	-0.446002000	0.046959000
1	-3.945502000	2.288949000	-0.124859000
1	-5.560259000	0.986683000	-1.946308000
1	-7.650564000	2.311190000	-1.895447000
1	-8.998365000	2.436820000	0.192530000
1	-8.230287000	1.233458000	2.230091000
1	-6.135380000	-0.087644000	2.177020000
1	-4.543789000	-4.031510000	1.681034000
1	-6.401170000	-5.653338000	1.831597000
1	-8.475566000	-5.304217000	0.499443000
1	-8.661727000	-3.318466000	-0.988966000

1	-6.815069000	-1.694812000	-1.131627000
6	1.801916000	4.661063000	-0.421932000
6	1.650092000	5.656950000	0.757457000
1	1.781875000	5.147670000	1.719035000
1	2.418644000	6.433610000	0.677429000
1	0.670987000	6.142271000	0.755127000
6	1.617981000	5.421527000	-1.761288000
1	2.376891000	6.207828000	-1.840434000
1	1.740642000	4.744956000	-2.614889000
1	0.632306000	5.888563000	-1.829418000
6	3.232944000	4.097084000	-0.387237000
1	3.929151000	4.938941000	-0.475209000
1	3.452918000	3.577728000	0.548511000
1	3.431238000	3.411831000	-1.214728000
6	1.915039000	1.408008000	-0.153689000
6	2.506945000	1.061446000	1.069369000
6	2.449920000	0.849892000	-1.323701000
6	3.605632000	0.207969000	1.124676000
6	3.558531000	0.008764000	-1.281628000
6	4.154075000	-0.328176000	-0.053551000
1	2.096281000	1.457865000	1.994264000
1	2.005644000	1.093901000	-2.285103000
1	4.039812000	-0.050423000	2.084808000
1	3.966582000	-0.391153000	-2.203891000
7	5.274573000	-1.192475000	-0.004421000
6	6.321667000	-0.960900000	0.932202000
6	6.812426000	0.336752000	1.149878000
6	6.884328000	-2.031350000	1.645829000
6	7.836274000	0.555691000	2.070728000
6	7.920681000	-1.805642000	2.550952000
6	8.400196000	-0.512280000	2.773433000
1	6.389906000	1.168473000	0.594924000
1	6.506042000	-3.036336000	1.487344000
1	8.204385000	1.566275000	2.226736000
1	8.344706000	-2.645756000	3.094513000
1	9.202866000	-0.338876000	3.484371000
6	5.367405000	-2.296183000	-0.900669000
6	6.574548000	-2.574002000	-1.561417000

6	4.256421000	-3.123428000	-1.131392000
6	6.666184000	-3.660815000	-2.430255000
6	4.351775000	-4.197068000	-2.015934000
6	5.556120000	-4.475393000	-2.667592000
1	7.435981000	-1.935828000	-1.391265000
1	3.322358000	-2.921879000	-0.616266000
1	7.607985000	-3.861709000	-2.933978000
1	3.482319000	-4.827127000	-2.183321000
1	5.628847000	-5.317027000	-3.350366000

7ch $S_0E = -2095.188429$ Hartree

ZPVE = 0.747015 Hartree

Thermal correction to Gibbs Free Energy = 0.791842 Hartree

6	-0.715179000	-0.146278000	0.026248000
6	-1.879290000	-0.906667000	0.128193000
6	-3.170187000	-0.322764000	0.083318000
6	-3.228677000	1.069600000	-0.072131000
6	-2.064396000	1.829876000	-0.174458000
6	-0.773565000	1.246068000	-0.127991000
6	-2.187838000	3.281195000	-0.334056000
8	-1.009006000	3.971435000	-0.427622000
6	0.423540000	2.083514000	-0.239311000
6	0.265674000	3.427024000	-0.386170000
6	-1.755106000	-2.358098000	0.285653000
8	-2.933344000	-3.048370000	0.383170000
8	-0.719119000	-2.991143000	0.335732000
8	-3.223414000	3.914294000	-0.389229000
6	-4.366374000	-1.160654000	0.198653000
6	-4.208271000	-2.503853000	0.347120000
6	-5.686034000	-0.454558000	0.144854000
6	-6.324241000	-0.217278000	-1.080592000
6	-7.525193000	0.490189000	-1.133839000
6	-8.120546000	0.997693000	0.029478000
6	-7.470496000	0.771920000	1.250338000
6	-6.269093000	0.064827000	1.308631000
1	0.236723000	-0.660074000	0.069394000
1	-4.180519000	1.583586000	-0.115183000
1	-5.882124000	-0.599048000	-1.997250000

1	-8.007421000	0.650375000	-2.095488000
1	-7.909453000	1.153929000	2.169126000
1	-5.783863000	-0.095298000	2.268022000
6	1.255045000	4.588291000	-0.532516000
6	1.005142000	5.583785000	0.630480000
1	1.213651000	5.114249000	1.598733000
1	1.673336000	6.445093000	0.520838000
1	-0.025176000	5.947979000	0.637942000
6	0.968855000	5.296182000	-1.882656000
1	1.636520000	6.158273000	-1.989454000
1	1.151368000	4.619605000	-2.725459000
1	-0.062654000	5.652146000	-1.942492000
6	2.741227000	4.191632000	-0.508116000
1	3.336347000	5.104789000	-0.623350000
1	3.030869000	3.720643000	0.434314000
1	3.005300000	3.515358000	-1.324490000
6	1.742486000	1.378505000	-0.182460000
6	2.376431000	1.131256000	1.043695000
6	2.333156000	0.858979000	-1.343312000
6	3.567431000	0.413256000	1.109723000
6	3.533082000	0.154557000	-1.291054000
6	4.169715000	-0.081781000	-0.060146000
1	1.927131000	1.498530000	1.962635000
1	1.858348000	1.026300000	-2.306540000
1	4.033140000	0.229174000	2.072164000
1	3.980718000	-0.215845000	-2.207263000
7	5.385407000	-0.805110000	0.001134000
6	6.395935000	-0.432651000	0.933243000
6	6.740334000	0.916895000	1.112192000
6	7.067403000	-1.413130000	1.681008000
6	7.727384000	1.274777000	2.029758000
6	8.066112000	-1.047794000	2.582917000
6	8.399193000	0.296535000	2.767392000
1	6.232937000	1.679889000	0.530163000
1	6.802722000	-2.457853000	1.551751000
1	7.981666000	2.323817000	2.155980000
1	8.575816000	-1.819320000	3.153878000
1	9.172707000	0.578104000	3.476044000
6	5.609692000	-1.909730000	-0.869786000

6	6.848036000	-2.065153000	-1.513059000
6	4.600660000	-2.860790000	-1.092280000
6	7.071207000	-3.153932000	-2.355106000
6	4.826370000	-3.936328000	-1.950426000
6	6.062138000	-4.092905000	-2.583603000
1	7.630782000	-1.331104000	-1.349618000
1	3.643601000	-2.753484000	-0.591458000
1	8.035589000	-3.259079000	-2.845002000
1	4.034692000	-4.663126000	-2.111676000
1	6.236598000	-4.936228000	-3.245566000
6	-9.406252000	1.788459000	-0.034806000
1	-10.054248000	1.434434000	-0.843558000
1	-9.963912000	1.721841000	0.904934000
1	-9.206937000	2.852109000	-0.221179000
6	-5.196775000	-3.665233000	0.499378000
6	-4.957252000	-4.657749000	-0.668306000
1	-5.623855000	-5.519767000	-0.554580000
1	-5.175006000	-4.186012000	-1.633432000
1	-3.926784000	-5.021302000	-0.686189000
6	-6.682948000	-3.268083000	0.489858000
1	-6.981979000	-2.795223000	-0.448545000
1	-7.277330000	-4.181118000	0.609377000
1	-6.938686000	-2.593037000	1.309912000
6	-4.898915000	-4.376750000	1.845115000
1	-5.567038000	-5.237954000	1.955982000
1	-3.867524000	-4.734538000	1.894665000
1	-5.072562000	-3.701909000	2.691184000

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