Rh-Catalyzed Reactions of 1,4-Benzoquinones with Electrophiles: C-H Iodination, Bromination and Phenylselenation

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General Experimental Details

Starting materials sourced from commercial suppliers were used as received unless otherwise stated. All reagents requiring purification were purified using standard laboratory techniques according to methods published by Perrin, Armarego, and Perrin (Pergamon Press, 1966). Catalytic reactions were run under an atmosphere of dry nitrogen or argon; glassware, syringes and needles were either flame dried immediately prior to use or placed in an oven (200 °C) for at least 2 h and allowed to cool either in a desiccator or under an atmosphere of nitrogen or argon; liquid reagents, solutions or solvents were added via syringe through rubber septa; solid reagents were added inside a glovebox. All optimization reactions were filtered through a sinter funnel charged with a pad of celite and silica for copper removal. Coupling partners for Stille reactions were distilled before use. Anhydrous solvents were obtained by distillation using standard procedures or by passage through drying columns supplied by Anhydrous Engineering Ltd. Anhydrous dichloromethane (CH_2Cl_2) was purged with argon for 10 minutes prior use. Flash column chromatography (FCC) was performed using silica gel (Aldrich 40-63 μm, 230-400 mesh). Thin layer chromatography (TLC) was performed using aluminium backed 60 F254 silica plates. Visualization was achieved by UV fluorescence or a basic $KMnO_4$ solution and heat. Proton nuclear magnetic resonance spectra (NMR) were recorded using either a Varian 400 MHz, Varian 500 MHz or Bruker AVANCE DRX400 MHz. ^{13}C NMR spectra were recorded at 100 MHz or 125 MHz as stated. Chemical shifts (δ) are given in parts per million (ppm). Peaks are described as singlets (s), doublets (d), double doublets (dd), triplets (t), double triplets (dt), and multiplets (m). ^{1}H and ^{13}C NMR spectra were referenced to the appropriate residual solvent peak. Coupling constants (J) are quoted to the nearest 0.5 Hz. All assignments of NMR spectra were based on 2D NMR data (DEPT-135, COSY, HSQC and HMBC). In situ yields were determined by employing 1,4-dinitrobenzene as an internal standard. Mass spectra were recorded using a Brüker Daltonics FT-ICRMS Apex 4e 7.0T FT-MS (ESI^+ mode) and Shimadzu GCMS QP2010+ (EI^+ mode). Infrared spectra were recorded on a Perkin Elmer Spectrum One FTIR spectrometer as thin films or solids compressed on a diamond plate. Melting points were determined using Stuart SMP30 melting point apparatus and are uncorrected.

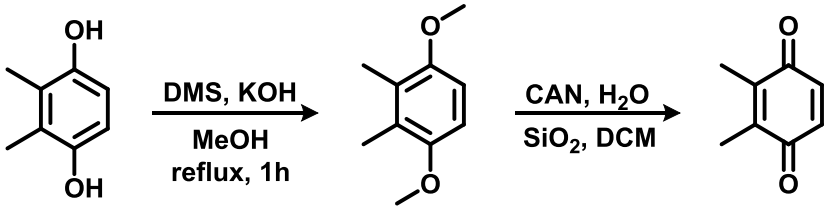
Synthesis of Substrates and Known Compounds:

All commercially available benzoquinones and further commercial chemicals were purchased from Sigma Aldrich, Alfa Aesar, Strem Chemicals and Santa Cruz Biotechnology. $[RhCp^{*}Cl_2]_2$ and $[RhCp^{t}Cl_2]_2$ were purchased from Sigma Aldrich. $[RhCp^{t}Cl_2]_2$, $[RhCp^{CF3}Cl_2]_2$ and $[RhCp^{i\text{-}Pr}Cl_2]_2$ were synthesised via literature procedures already described by our research group.[1]

2-Methoxy-1,4-benzoquinone (1b)

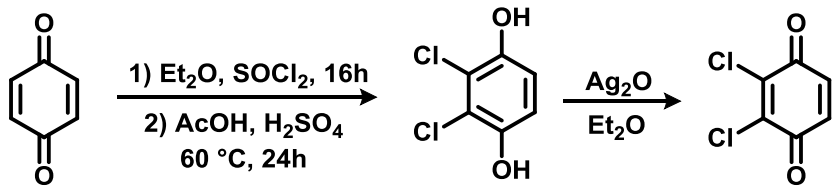
Compound **1b** was synthesized (267.9 mg, 97% yield) as a yellow powder using a previously reported procedure.[3] **m.p. (°C) =** 133.8-134.1 (Petrol/CH_2Cl_2); **HRMS (EI^+):** 138.0311 $[M]^+$. Cald. for $[C_7H_6O_3]$: 138.0317; **^{1}H NMR (400 MHz, $CDCl_3$) δ:** 6.69 (s, 2H), 5.92 (s, 1H), 3.81 (s, 3H); **^{13}C NMR (100 MHz, $CDCl_3$) δ:** 187.4, 181.7, 158.6, 137.2, 134.4, 107.7, 56.2. Data are consistent with those reported in the literature.[3]

2,3-Dimethyl-1,4-benzoquinone (1c)



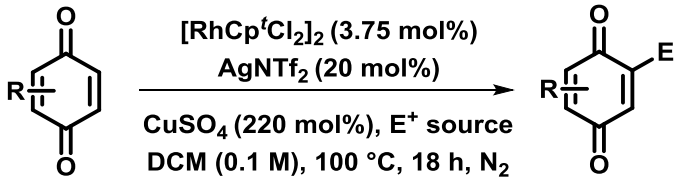
Compound **1c** was synthesised (1.68 g, 90% yield) as yellow crystals using previously reported procedures.[2,3] **m.p. (°C) =** 54.9-56.4 (Petrol/CH_2Cl_2); **HRMS (EI^+):** 136.0569 $[M]^+$. Cald. for $[C_8H_8O_2]$: 136.0524; **^{1}H NMR (400 MHz, $CDCl_3$) δ:** 6.70 (s, 2H), 2.01 (s, 6H); **^{13}C NMR (100 MHz, $CDCl_3$) δ:** 187.4, 141.0, 136.2, 12.2. Data are consistent with those reported in the literature.[3]

2,3-Dichloro-1,4-benzoquinone (1f)



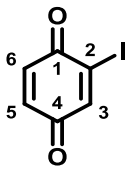
Compound **1f** was synthesised (1.79 g, 60% yield) as yellow crystals using previously reported procedure.[4] **m.p. (°C) =** 102.9-103.7 (Petrol/CH_2Cl_2); **HRMS (EI$^+$):** 175.9421 $[M]^+$. Cald. for $[C_6H_2Cl_2O_2]$: 175.9432; **^{1}H NMR (400 MHz, $CDCl_3$) δ:** 6.97 (s, 2H); **^{13}C NMR (100 MHz, $CDCl_3$) δ:** 177.4, 141.2, 136.1. Data are consistent with those reported in the literature.[4]

<u>General procedure for halogenation/selenylation at the 2-position</u>:



In a glovebox, an oven dried re-sealable tube was charged with the corresponding benzoquinone (0.10 mmol), $[RhCp^tCl_2]_2$ (3.75 mol%, 2.6 mg), silver bis(trifluoromethanesulfonyl)imide (20 mol%, 7.8 mg), the electrophile source (see below) and anhydrous copper sulfate (220 mol%, 0.22 mmol, 34.9 mg). The tube was removed from the glovebox and an inert atmosphere was maintained. Anhydrous CH_2Cl_2 (1 mL) was added via syringe and tube was sealed. The mixture was heated at 100 °C for 18h. After cooling, the mixture was filtered through a pad of celite and purified by FCC, under the conditions noted.

2-Iodo-1,4-benzoquinone (2a)



The product was obtained by the general procedure described above using 1,3-diiodo-5,5-dimethylhydantoin (DIH) (150 mol %, 0.12 mmol, 56.9 mg) and a reaction time of 18 h. Purification by FCC (toluene) afforded product **2a** (22 mg, 95% yield) as orange crystals; **m.p. (°C) =** 58.3-58.9 (Petrol/CH_2Cl_2); **IR (solid, cm^{-1}) *ν*:** 3042 (w), 1644 (s), 1269 (s), 914 (s); **HRMS (EI$^+$):** 233.9174 $[M]^+$. Cald. for $[C_6H_3IO_2]$: 233.9178; **Elemental analysis – Calculated (%) C:** 30.80 **H:** 1.29. **Found (%) C:** 31.01 **H:** 1.30; **^{1}H NMR (400 MHz, $CDCl_3$) *δ*:** 7.67 (d, *J* = 2.4 Hz, C**3**-H), 7.00 (d, *J* = 10.0 Hz, C**6**-H), 6.84 (dd, *J* = 10.1, 2.4 Hz, C**5**-H); **^{13}C NMR (100 MHz, $CDCl_3$) *δ*:** 184.0 (C**4**), 180.2 (C**1**), 146.1 (C**3**), 136.6 (C**5**), 134.56 (C**6**), 119.6 (C**2**). Data are consistent with those reported in the literature.[5]

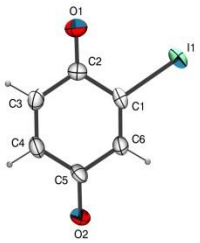
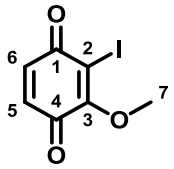


Figure 1: Crystal structure of compound **2a**.

2-Iodo-3-methoxy-1,4-benzoquinone (2b)



The product was obtained by the general procedure described above using 1,3-diiodo-5,5-dimethylhydantoin (DIH) (120 mol%, 0.12 mmol, 45.5 mg) and a reaction time of 18 h. Purification by FCC (toluene) afforded product **2b** (24.0 mg, 91% yield) as orange crystals; **m.p. (°C) =** 98.1-99.9 (Petrol/CH_2Cl_2); **IR (solid, cm^{-1}) *ν*:** 3027 (w), 1698 (s),

1354 (s), 991 (s); **HRMS (EI$^+$):** 261.9493 $[M]^+$. Cald. for $[C_7H_5IO_3]$: 263.9283; **Elemental analysis – Calculated (%) C:** 31.85 **H:** 1.91. **Found (%) C:** 32.10 **H:** 1.93; **^{1}H NMR (400 MHz, $CDCl_3$) δ:** 6.91 (d, *J* = 10.0 Hz, C**6**-H), 6.67 (d, *J* = 10.0 Hz, C**5**-H), 4.21 (s, C**7**-H_3); **^{13}C NMR (100 MHz, $CDCl_3$) δ:** 181.73 (C**1**), 179.36 (C**4**), 161.43 (C**3**), 135.10 (C**6**), 134.66 (C**5**), 100.93 (C**2**), 61.67 (C**7**).

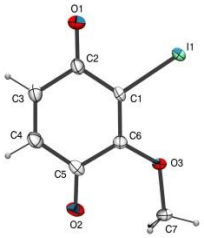
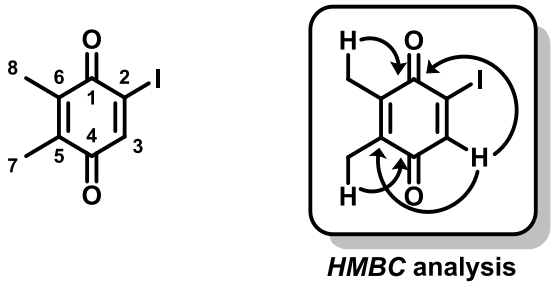


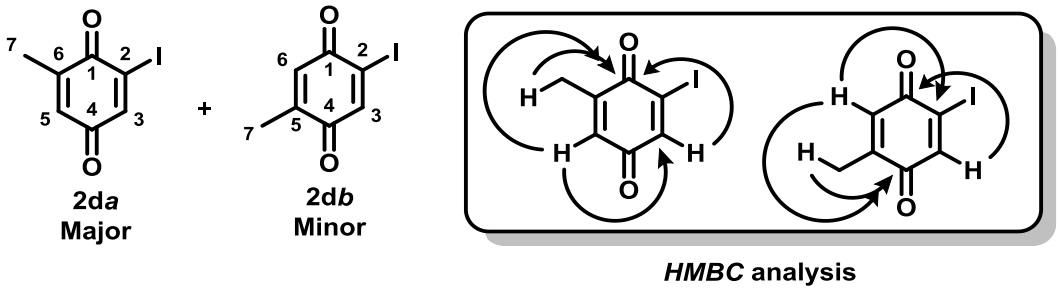
Figure 2: Crystal structure of compound **2b**.

2-Iodo-5,6-dimethyl-1,4-benzoquinone (2c)



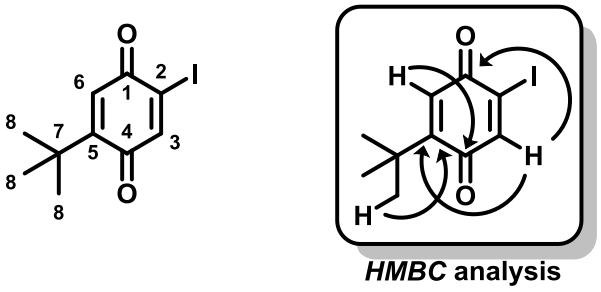
The product was obtained by the general procedure described above using 1,3-diiodo-5,5-dimethylhydantoin (DIH) (150 mol%, 0.15 mmol, 56.9 mg) and a reaction time of 18 h. Purification by FCC (toluene) afforded product **2c** (21.2 mg, 81% yield) as a red oil; **IR (solid, cm^{-1}) ν:** 2921 (w), 1638 (s), 1236 (s), 838 (s); **HRMS (EI$^+$):** 261.9493 $[M]^+$. Cald. for $[C_8H_7IO_2]$: 261.9491; **^{1}H NMR (400 MHz, $CDCl_3$) δ:** 7.60 (s, C**3**-H), 2.11 (d, *J* = 1.2 Hz, C**8**-H_3), 2.03 (d, *J* = 1.2 Hz, C**7**-H_3); **^{13}C NMR (100 MHz, $CDCl_3$) δ:** 184.4 (C**4**), 180.4 (C**1**) 146.0 (C**3**), 141.4 (C**5**), 140.0 (C**6**), 119.0 (C**2**), 13.7 (C**8**), 12.4 (C**7**). *The structural assignment of the product was supported by **HMBC** analysis, as indicated above.*

2-Iodo-6-methyl-1,4-benzoquinone (2d*a*) and 2-Iodo-5-methyl-1,4-benzoquinone (2d*b*)



The product was obtained by the general procedure described above using 1,3-diiodo-5,5-dimethylhydantoin (DIH) (150 mol%, 0.15 mmol, 56.9 mg) and a reaction time of 18 h. Purification by FCC (toluene) afforded products **2d*a*** and **2d*b*** (mixture of isomers, 5:4/***a*:*b***) (20 mg, 81% yield) as an orange powder; **HRMS (EI$^+$):** 247.9326 $[M]^+$. Cald. for $[C_7H_5IO_2]$: 247.9334; **^{1}H NMR (500 MHz, $CDCl_3$) *δ*:** 7.64 (d, *J* = 1.4 Hz, C**3*b***-H), 7.59 (dd, *J* = 2.4, 1.5 Hz, C**3*a***-H), 6.84 (t, *J* = 1.6 Hz, C**6*b***-H), 6.66 (dt, *J* = 2.4, 1.5 Hz, C**5*a***-H), 2.14 (t, *J* = 1.5 Hz, C**7*a***-H_3), 2.07 (t, *J* = 1.5 Hz, C**7*b***-H_3); **^{13}C NMR (125 MHz, $CDCl_3$) *δ*:** 184.6 (C**4*b***), 184.5 (C**4*a***), 180.8 (C**1*a***), 180.4 (C**1*b***), 146.4 (C**5*b***), 146.2 (C**3*a***), 146.1 (C**3*b***), 144.6 (C**6*a***), 133.5 (C**5*a***), 131.4 (C**6*b***), 119.7 (C**2-I*b***), 119.3 (C**2-I*a***), 17.3 (C**7*a***), 15.8 (C**7*b***). *The structural assignments of the products were supported by **HMBC** analysis, as indicated above.*

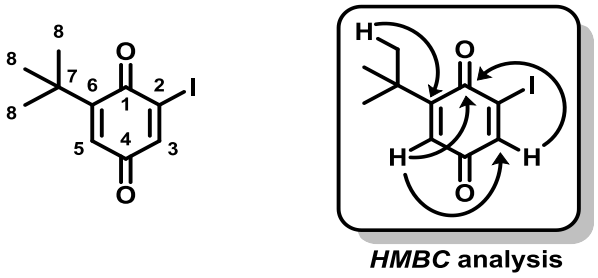
2-Iodo-5-(*tert*-butyl)-1,4-benzoquinone (2e)



The product was obtained by the general procedure described above using 1,3-diiodo-5,5-dimethylhydantoin (DIH) (120 mol%, 0.12 mmol, 45.5 mg) and a reaction time of 18 h. Purification by FCC (toluene) afforded product **2e** (19.2 mg, 66% yield) as a deep

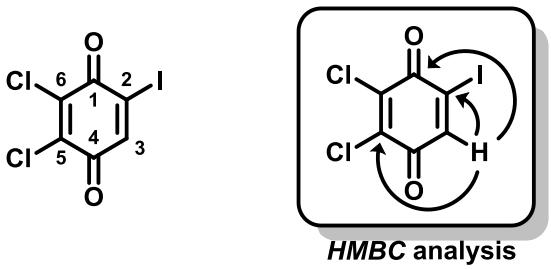
yellow solid; **m.p. (°C) =** 70.5-71.0 (Petrol/CH_2Cl_2); **IR (solid, cm^{-1}) *ν*:** 2960 (s), 1651 (s), 1180 (s), 1009 (s); **HRMS (EI$^+$):** 289.9798 $[M]^+$. Cald. for $[C_{10}H_{11}IO_2]$: 289.9804; **Elemental analysis – Calculated (%) C:** 41.40 **H:** 3.82. **Found (%) C:** 41.69 **H:** 3.85; **^{1}H NMR (400 MHz, $CDCl_3$) *δ*:** 7.54 (s, C**3**-H), 6.81 (s, C**6**-H), 1.27 (s, C**8**-H_9); **^{13}C NMR (100 MHz, $CDCl_3$) *δ*:** 184.2 (C**4**), 181.3 (C**1**), 156.6 (C**5**), 147.9 (C**3**), 129.8 (C**6**), 117.5 (C**2**), 35.5 (C**7**), 29.0 (C**8**). *The structural assignment of the product was supported by **HMBC** analysis, as indicated above.*

2-Iodo-6-(*tert*-butyl)-1,4-benzoquinone (2e')



Continued elution afforded product **2e'** (5.2 mg, 18% yield) as a deep yellow solid; **m.p. (°C) =** 71.8-72.9 (Petrol/CH_2Cl_2); **IR (solid, cm^{-1}) *ν*:** 2965 (s), 1689 (s), 1218 (s), 1124 (s); **HRMS (EI$^+$):** 289.9807 $[M]^+$. Cald. for $[C_{10}H_{11}IO_2]$: 289.9804; **^{1}H NMR (400 MHz, $CDCl_3$) *δ*:** 7.59 (d, *J* = 2.4 Hz, C**3**-H), 6.65 (d, *J* = 2.4 Hz, C**5**-H), 1.28 (s, C**8**-H_9); **^{13}C NMR (100 MHz, $CDCl_3$) *δ*:** 185.3 (C**4**), 179.9 (C**1**), 155.1 (C**6**), 145.1 (C**3**), 131.9 (C**5**), 122.7 (C**2**), 36.2 (C**7**), 29.1 (C**8**). *The structural assignment of the product was supported by **HMBC** analysis, as indicated above.*

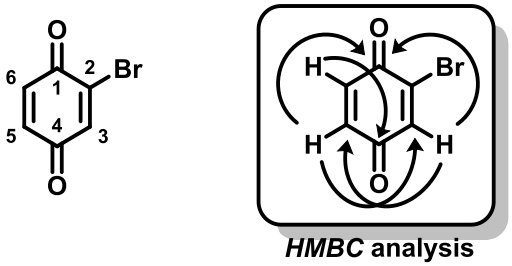
2-Iodo-5,6-dichloro-1,4-benzoquinone (2f)



The product was obtained by the general procedure described above using 1,3-diiodo-5,5-dimethylhydantoin (DIH) (150 mol%, 0.15 mmol, 56.9 mg) and a reaction time of

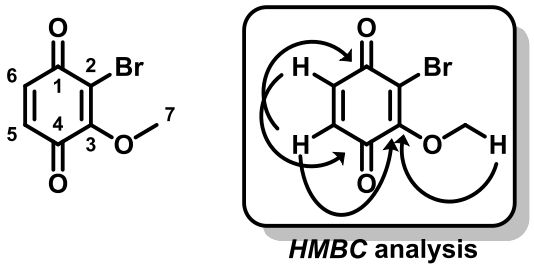
18 h. Purification by FCC (toluene) afforded product **2f** (16.9 mg, 56% yield) as yellow crystals; **m.p. (°C) =** 162.8-163.5 (Petrol/CH_2Cl_2); **IR (solid, cm^{-1}) *ν*:** 2973 (w), 1667 (s), 1046 (m), 881 (s); **HRMS (EI^+):** 301.8402 $[M]^+$. Cald. for $[C_6HICl_2O_2]$: 301.8398; **Elemental analysis – Calculated (%) C:** 23.79 **H:** 0.33. **Found (%) C:** 23.98 **H:** 0.33; **^{1}H NMR (400 MHz, $CDCl_3$) *δ*:** 7.83 (s, C**3**-H); **^{13}C NMR (100 MHz, $CDCl_3$) *δ*:** 175.3 (C**4**), 171.9 (C**1**), 145.2 (C**3**), 141.6 (C**5**), 138.2 (C**6**), 117.4 (C**2**). *The structural assignment of the product was supported by **HMBC** analysis, as indicated above.*

2-Bromo-1,4-benzoquinone (3a)



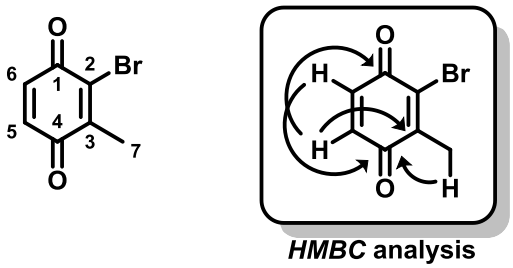
The product was obtained by the general procedure described above using 1,3-dibromo-5,5-dimethylhydantoin (DBH) (120 mol%, 0.12 mmol, 34.3 mg) and a reaction time of 18 h. Purification by FCC (toluene) afforded product **3a** (15.3 mg, 82% yield) as yellow crystals; **m.p. (°C) =** 54.5-55.1 (Petrol/CH_2Cl_2); **IR (solid, cm^{-1}) *ν*:** 3042 (w), 1661 (s), 1276 (s), 967 (s); **HRMS (EI^+):** 185.9312 $[M]^+$. Cald. for $[C_6H_3BrO_2]$: 185.9316; **Elemental analysis – Calculated (%) C:** 38.54 **H:** 1.62. **Found (%) C:** 38.77 **H:** 1.63; **^{1}H NMR (400 MHz, $CDCl_3$) *δ*:** 7.29 (d, *J* = 2.4 Hz, C**3**-H), 6.96 (d, *J* = 10.1 Hz, C**6**-H), 6.82 (dd, *J* = 10.1, 2.4 Hz, C**5**-H); **^{13}C NMR (100 MHz, $CDCl_3$) *δ*:** 184.55 (C**4**), 179.17 (C**1**), 138.12 (C**3**), 137.50 (C**2**), 136.63 (C**5**), 135.79 (C**6**). Data are consistent with those reported in the literature.[6] *The structural assignment of the product was supported by **HMBC** analysis, as indicated above.*

2-Bromo-3-methoxy-1,4-benzoquinone (3b)



The product was obtained by the general procedure described above using 1,3-dibromo-5,5-dimethylhydantoin (DBH) (120 mol%, 0.12 mmol, 34.3 mg) and a reaction time of 18 h. Purification by FCC (toluene) afforded product **3b** (16.1 mg, 74% yield) as an orange powder; **m.p. (°C) =** 85.7-86.3 (Petrol/CH_2Cl_2); **IR (solid, cm^{-1}) *ν*:** 2960 (w), 1651 (s), 1555 (s), 1092 (s); **HRMS (EI^+):** 215.9410 $[M]^+$. Cald. for $[C_7H_5BrO_3]$: 215.9422; **Elemental analysis – Calculated (%) C:** 38.74 **H:** 2.32. **Found (%) C:** 39.09 **H:** 2.34; **^{1}H NMR (400 MHz, $CDCl_3$) *δ*:** 6.87 (d, *J* = 10.0 Hz, C**6**-H), 6.68 (d, *J* = 10.1 Hz, C**5**-H), 4.21 (s, C**7**-H_3); **^{13}C NMR (100 MHz, $CDCl_3$) *δ*:** 180.8 (C**4**), 180.3 (C**1**), 157.0 (C**3**), 135.8 (C**6**), 134.6 (C**5**), 118.5 (C**2**), 61.6 (C**7**). *The structural assignment of the product was supported by **HMBC** analysis, as indicated above.*

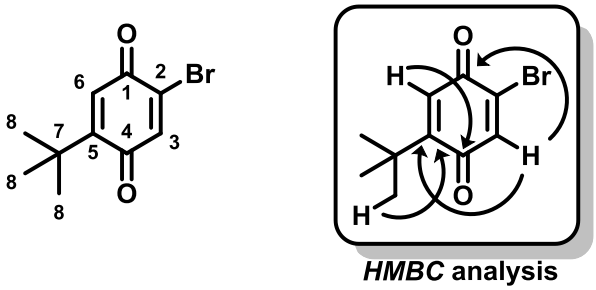
2-Bromo-3-methyl-1,4-benzoquinone (3d)



The product was obtained by the general procedure described above using 1,3-dibromo-5,5-dimethylhydantoin (DBH) (120 mol%, 0.12 mmol, 34.3 mg) and a reaction time of 18 h. Purification by FCC (toluene) afforded product **3d** (13.7 mg, 68% yield) as a yellow powder; **m.p. (°C) =** 55.1-56.7 (Petrol/CH_2Cl_2); **IR (solid, cm^{-1}) *ν*:** 2987 (w), 1596 (s), 1233 (s), 870 (s); **HRMS (EI^+):** 199.9461 $[M]^+$. Cald. for $[C_7H_5BrO_2]$: 199.9473; **Elemental analysis – Calculated (%) C:** 41.83 **H:** 2.51. **Found (%) C:**

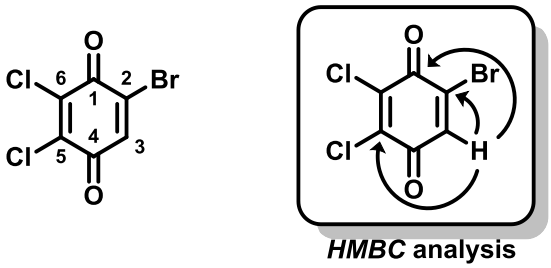
41.74 **H:** 2.66; **^{1}H NMR (400 MHz, $CDCl_3$) δ:** 6.92 (d, *J* = 10.0 Hz, C**6**-H), 6.81 (d, *J* = 10.0 Hz, C**5**-H), 2.23 (s, C**7**-H_3); **^{13}C NMR (100 MHz, $CDCl_3$) δ:** 183.9 (C**4**), 179.1 (C**1**), 146.2 (C**3**), 136.3 (C**5**), 136.1 (C**2**), 135.8 (C**6**), 16.9 (C**7**). *The structural assignment of the product was supported by **HMBC** analysis, as indicated above.*

2-Bromo-5-(*tert*-butyl)-1,4-benzoquinone (3e)



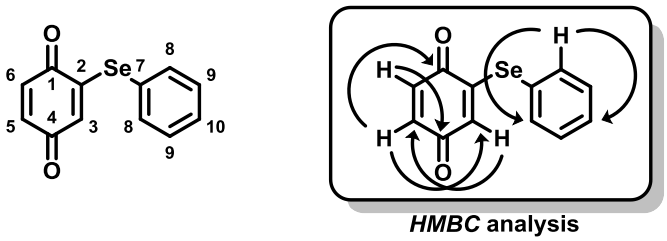
The product was obtained by the general procedure described above using 1,3-dibromo-5,5-dimethylhydantoin (DBH) (120 mol%, 0.12 mmol, 34.3 mg) and a reaction time of 18 h. Purification by FCC (toluene) afforded product **3e** (13.9 mg, 57% yield) as a yellow powder; **m.p. (°C) =** 100.2-101.1 (Petrol/CH_2Cl_2); **IR (solid, cm^{-1}) *v*:** 2963 (s), 1654 (s), 1013 (s), 733 (s); **HRMS (EI^{+}):** 241.9932 $[M]^{+}$. Cald. for $[C_{10}H_{11}BrO_2]$: 241.9942; **Elemental analysis – Calculated (%) C:** 49.39 **H:** 4.56. **Found (%) C:** 49.39 **H:** 4.44; **^{1}H NMR (400 MHz, $CDCl_3$) δ:** 7.19 (s, C**3**-H), 6.78 (s, C**6**-H), 1.28 (s, C**8** -H_9); **^{13}C NMR (100 MHz, $CDCl_3$) δ:** 184.7 (C**4**), 180.4 (C**1**), 156.7 (C**5**), 139.9 (C**3**), 135.7 (C**2**), 130.9 (C**6**), 35.5 (C**7**), 29.1 (C**8**). *The structural assignment of the product was supported by **HMBC** analysis, as indicated above.* Minor traces of regioisomer **3e'** (10:1 **3e:3e'**), where bromination had occurred at C3, were detected, but, due to the low quantities of material formed, good quality NMR data could not be obtained. Assignment was made by comparison to **2e'**: **^{1}H NMR (500 MHz, $CDCl_3$) δ:** 7.43 (d, *J* = 2.2 Hz, 1H), 6.54 (d, *J* = 2.2 Hz, 1H), 1.26 (s, 9H).

2-Bromo-5,6-dichloro-1,4-benzoquinone (3f)



The product was obtained by the general procedure described above using 1,3-dibromo-5,5-dimethylhydantoin (DBH) (120 mol%, 0.12 mmol, 34.3 mg) and a reaction time of 18 h. Purification by FCC (toluene) afforded product **3f** (11.5 mg, 45% yield) as yellow crystals; **m.p. (°C) =** 153.9-155.1 (Petrol/CH_2Cl_2); **IR (solid, cm^{-1}) *ν*:** 2970 (w), 1671 (s), 1187 (m), 1052 (s); **HRMS (EI^+):** 253.8542 $[M]^+$. Cald. for $[C_6HBrCl_2O_2]$: 253.8537; **Elemental analysis – Calculated (%) C:** 28.16 **H:** 0.39. **Found (%) C:** 28.30 **H:** 0.39; **^{1}H NMR (400 MHz, $CDCl_3$) *δ*:** 7.46 (s, C**3**-H); **^{13}C NMR (100 MHz, $CDCl_3$) *δ*:** 175.3 (C**4**), 171.0 (C**1**), 141.4 (C**5**), 140.1 (C**6**), 137.4 (C**3**), 136.6 (C**2**). *The structural assignment of the product was supported by **HMBC** analysis, as indicated above.*

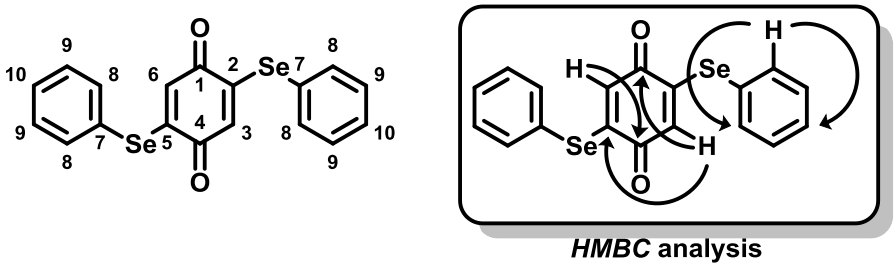
2-(Phenylselanyl)-1,4-benzoquinone (4a)



The product was obtained by the general procedure described above using *N*-phenyl selenium phthalimide (100 mol%, 0.1 mmol, 30.2 mg) and a reaction time of 18 h. Purification by FCC (toluene) afforded product **4b** (16.0 mg, 61% yield) as a red powder; **m.p. (°C) =** 100.4-101.1 (Petrol/CH_2Cl_2); **IR (solid, cm^{-1}) *ν*:** 2921 (w), 1631 (s), 1279 (m), 967 (s); **HRMS (EI^+):** 263.9682 $[M]^+$. Cald. for $[C_{12}H_8SeO_2]$: 263.9690; **Elemental analysis – Calculated (%) C:** 54.77 **H:** 3.06. **Found (%) C:** 54.99 **H:** 3.07; **^{1}H NMR (400 MHz, $CDCl_3$) *δ*:** 7.64-7.53 (m, C**8**-H, C**12**-H), 7.53-7.39 (m, C**9**-H, C**10**-H, C**11**-H), 6.85 (d, *J* = 10.0 Hz, C**6**-H), 6.68 (dd, *J* = 10.0, 2.4 Hz, C**5**-H), 6.15

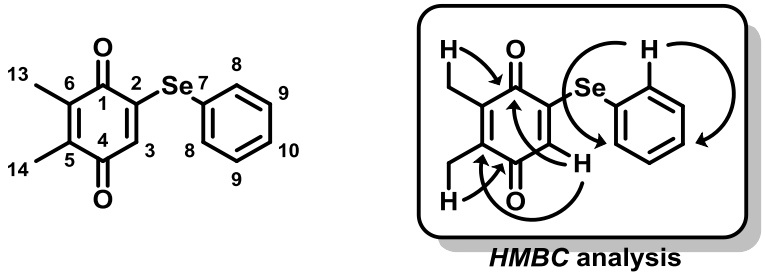
(d, *J* = 2.4 Hz, C**3**-H); **^{13}C NMR (100 MHz, $CDCl_3$) δ:** 184.8 (C**1**), 184.1 (C**4**), 154.5 (C**2**), 137.5 (C**5**), 137.0 (C**8**), 135.9 (C**6**), 130.5 (C**3**), 130.4 (C**9**), 130.2 (C**10**), 123.9 (C**7**). *The structural assignment of the product was supported by **HMBC** analysis, as indicated above.* Compound **4a'** was eluted first and obtained (5.4 mg, 13% yield) as an orange powder. The data for this compound are given at the end of the next procedure.

2,5-Bis(phenylselanyl)-1,4-benzoquinone (4a')



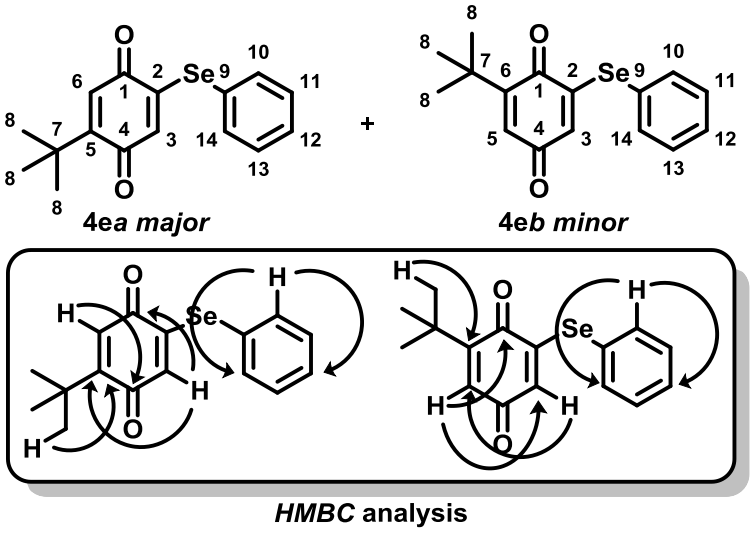
The product was obtained by the general procedure described above using *N*-phenyl selenium phthalimide (250 mol%, 0.25 mmol, 75.5 mg) and a reaction time of 18 h. Purification by FCC (toluene) afforded product **4a** (30.9 mg, 74% yield) as an orange powder; **m.p. (°C) =** 230.3-231.0 (Petrol/CH_2Cl_2); **IR (solid, cm^{-1}) *v*:** 3055 (w), 1634 (s), 1546 (m), 990 (s); **HRMS (ESI$^+$):** 420.9263 $[M+H]^+$. Cald. for $[C_{18}H_{13}Se_2O_2]$: 420.9244; **Elemental analysis – Calculated (%) C:** 51.70 **H:** 2.89. **Found (%) C:** 52.11 **H:** 2.91; **^{1}H NMR (400 MHz, $CDCl_3$) δ:** 7.63-7.53 (m, C**8**-H), 7.54-7.39 (m, C**9**-H, C**10**-H), 6.21 (s, C**3**-H, C**6**-H); **^{13}C NMR (100 MHz, $CDCl_3$) δ:** 181.38 (C**1**, **C4**), 157.1 (C**2**, C**5**), 136.9 (C**8**), 130.4 (C**9**), 130.2 (C**10**), 129.4 (C**3**, C**6**), 124.1 (C**7**). *The structural assignment of the product was supported by **HMBC** analysis, as indicated above.*

2,3-Dimethyl-5-(phenylselanyl)-1,4-benzoquinone (4c)



The product was obtained by the general procedure described above using *N*-phenyl selenium phthalimide (120 mol%, 0.12 mmol, 36.2 mg) and a reaction time of 18 h. Purification by FCC (toluene) afforded product **4c** (21.3 mg, 73% yield) as red crystals; **m.p. (°C) =** 98.1-99.0 (Petrol/CH_2Cl_2); **IR (solid, cm^{-1}) *ν*:** 2930 (w), 1634 (s), 1236 (m), 746 (s); **HRMS (EI$^+$):** 292.0006 $[M]^+$. Cald. for $[C_{14}H_{12}SeO_2]$: 292.0003; **Elemental analysis – Calculated (%) C:** 57.74 **H:** 4.15. **Found (%) C:** 58.17 **H:** 4.18; **^{1}H NMR (500 MHz, $CDCl_3$) *δ*:** 7.62-7.54 (m, C**8**-H), 7.51-7.37 (m, C**9**-H, C**10**-H), 6.11 (s, C**3**-H), 2.06 (s, C**13**-H_3), 1.99 (s, C**14**-H_3); **^{13}C NMR (125 MHz, $CDCl_3$) *δ*:** 184.9 (C**1**), 184.2 (C**4**), 153.6 (C**2**), 141.9 (C**6**), 140.5 (C**5**), 137.0 (C**8**), 130.5 (C**3**), 130.2 (C**9**), 129.9 (C**10**), 124.5 (C**7**), 12.4 (C**13,** C**14**). *The structural assignment of the product was supported by **HMBC** analysis, as indicated above.*

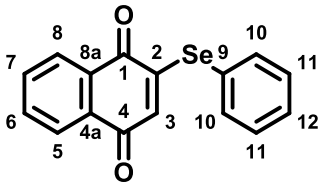
5-(*tert*-Butyl)-2-(phenylselanyl)-1,4-benzoquinone (4e*a*) and 6-(*tert*-butyl)-2-(phenylselanyl)-1,4-benzoquinone (4e*b*)



The product was obtained by the general procedure described above using *N*-phenyl selenium phthalimide (120 mol %, 0.12 mmol, 36.2 mg) and a reaction time of 18h. Purification by FCC (toluene) afforded products **4e*a*** and **4e*b*** (mixture of isomers, 5:2/***a*:*b***) (19.5 mg, 61% yield) as a red oil; **HRMS (EI$^+$):** 321.0405 $[M+H]^+$. Cald. for $[C_{16}H_{17}O_2Se]$: 321.0393; **^{1}H NMR (400 MHz, $CDCl_3$) *δ*:** 7.65 - 7.58 (m, 5H), 7.52 – 7.41 (m, 5H), 6.69 (s, C**3*a***-H), 6.52 (d, *J* = 2.4 Hz C**3*b***-H), 6.11 (d, *J* = 2.4 Hz, C**6*b***-H), 6.07 (s, C**6*a***-H), 1.32 (s, C**8*b***-H_9), 1.27 (s, C**8*a***-H_9); **^{13}C NMR (125 MHz, $CDCl_3$) *δ*:** 185.7 (C**1*a***), 185.0 (C**4*b***), 184.8 (C**1*b***), 184.3 (C**4*a***), 157.2 (C**5*a***), 155.8 (C**6*a***) 152.0

(C**6*b***), 137.0 (C**11*a***, C**12*a***, C**13*a***), 132.6 (C**3*a***), 132.5 (C**3*b***), 130.9 (C**10*b***, C**14*b***), 130.3 (C**11*b***, C**12*b***, C**13*b***, C**9*a***), 130.1 (C**9*b***) 130.0 (C**10*a***, C**14*a***), 129.7 (C**5*b***), 124.7 (C**2*b***), 124.1 (C**2*a***), 35.4 (C**7*a***,C**7*b***), 29.3 (C**8*a***), 29.2 (C**8*b***). *The structural assignment of the product was supported by **HMBC** analysis, as indicated above.*

2-(Phenylselanyl)-1,4-naphthoquinone (6)



The product was obtained by the general procedure described above using *N*-phenyl selenium phthalimide (120 mol%, 0.12 mmol, 36.2 mg) and a reaction time of 18 h. Purification by FCC (toluene) afforded product **6** (26.9 mg, 86% yield) as orange crystals; **m.p. (°C) =** 152.8-153.7 (Petrol/CH_2Cl_2); **IR (solid, cm^{-1}) *ν*:** 2930 (w), 1664 (s), 1296 (m), 690 (s); **HRMS (EI$^+$):** 313.9848 $[M]^+$. Cald. for $[C_{16}H_{10}SeO_2]$: 313.9846; **Elemental analysis – Calculated (%) C:** 61.36 **H:** 3.22. **Found (%) C:** 61.43 **H:** 3.56; **^{1}H NMR (400 MHz, $CDCl_3$) *δ*:** 8.14 (dd, *J* = 7.2, 1.9 Hz, C**8**-H), 8.03 (dd, *J* = 6.1, 1.9 Hz, C**5**-H), 7.82-7.67 (m, C**6**-H, C**7**-H), 7.68-7.61 (m, C**10**-H), 7.57-7.42 (m, C**11**-H, C**12**-H), 6.40 (s, C**3**-H); **^{13}C NMR (100 MHz, $CDCl_3$) *δ*:** 183.0 (C**1**), 181.7 (C**4**), 157.0 (C**2**), 137.1 (C**10**), 134.3 (C**6**), 133.3 (C**7**), 132.8 (C**3**), 132.3 (C**4a**), 131.6 (C**8a**), 130.4 (C**11**), 130.2 (C**12**), 126.9 (C**8**), 126.7 (C**5**), 124.4 (C**9**). Data are consistent with those reported in the literature.[7]

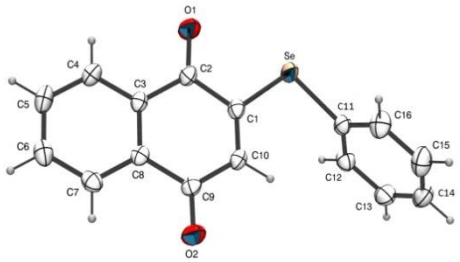
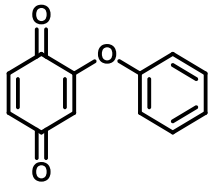


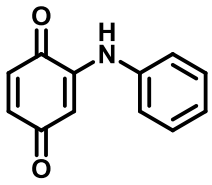
Figure 3: Crystal structure of compound **6**.

2-Phenoxy-1,4-benzoquinone (7a)



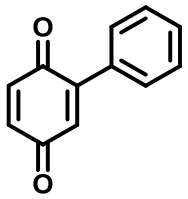
Product **7a** was synthesised using a previously reported procedure.[8] A 5 mL reaction tube was charged with **2a** (0.10 mmol, 23.4 mg) or **3a** (0.1 mmol, 18.7 mg), phenol (0.11 mmol, 10.3 mg), KF (0.3 mmol, 17.4 mg) and DMF (1 mL). The mixture was stirred and heated at 90 °C for 1h. After cooling and solvent removal, the mixture was purified by FCC (toluene) to afford **7a (**16.2 mg, 81% yield from **2a**, 15.8 mg, 79% yield from **3a**) as a yellow solid; **m.p. (°C) =** 133.8-134.1 (Petrol/CH_2Cl_2); **HRMS (EI$^+$):** 200.0468 $[M]^+$. Cald. for [$C_{12}H_8O_3$]: 200.0473; **^{1}H NMR (400 MHz, $CDCl_3$) δ:** 7.49-7.39 (m, 2H), 7.35-7.28 (m, 1H), 7.14-7.05 (m, 2H), 6.81 (d, *J* = 10.1 Hz, 1H), 6.72 (dd, *J* = 10.1, 2.3 Hz, 1H), 5.73 (d, *J* = 2.3 Hz, 1H); **^{13}C NMR (100 MHz, $CDCl_3$) δ:** 187.5, 181.5, 158.6, 152.3, 137.0, 137.0, 134.5, 130.4, 126.7, 120.9, 111.0. Data are consistent with those reported in the literature.[9]

2-Phenylamino-1,4-benzoquinone (7b)



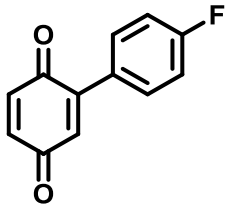
Compound **7b** was synthesised using a previously reported procedure.[10] A 5 mL reaction tube was charged with **2a** (0.10 mmol, 23.4 mg), aniline (0.12 mmol, 11.2 µL) and H_2O (0.5 mL). The mixture was stirred for 1h. The precipitate was collected by filtration and purified by FCC (toluene) to afford **7b** (19.1 mg, 96% yield) as a dark yellow powder; **m.p. (°C) =** 131.5-133.4 (Petrol/CH_2Cl_2); **MS (EI$^+$):** 199.1 $[M]^+$. Cald. for [$C_{12}H_9NO_2$]: 199.1; **^{1}H NMR (400 MHz, $CDCl_3$) δ:** 8.14 (s, 1H), 7.10-6.95 (m, 4H), 6.63-6.51 (m, 4H); **^{13}C NMR (100 MHz, $CDCl_3$) δ:** 184.9, 181.6, 159.0, 158.5, 146.5, 138.4, 129.8, 128.6, 127.0, 123.0. Data are consistent with those reported in the literature.[11]

2-Phenyl-1,4-benzoquinone (7c)



Compound **7c** was synthesised using a previously reported procedure.[1] A oven dried re-sealable tube was charged with **2a** (0.10 mmol, 23.4 mg), Pd(d^{t}bpf)Cl_2 (5 mol %, 3.7 mg), CuI (20 mol %, 4.0 mg) and CsF (0.20 mmol, 30.0 mg). The tube was purged with N_2 and $PhSnBu_3$ (0.12 mmol, 40.0 µL) and *N*,*N*-dimethylacetamide (1 mL) were added via syringe. The tube was sealed and the mixture was heated at 45 °C for 18h. After cooling, the solvent was removed under reduced pressure. The residue was dissolved in CH_2Cl_2 (5 mL) and filtered through a pad of celite. The filtrate was concentrated under reduced pressure and the residue was purified by FCC (hexane/EtOAc 5:1) to afford **7c** (13.1 mg, 71% yield) as an golden powder; **m.p. (°C) =** 108.8-110.0 (Petrol/CH_2Cl_2); **HRMS (EI$^+$):** 184.0511 $[M]^+$. Cald. for $[C_{12}H_8O_2]$: 184.0524; **^{1}H NMR (400 MHz, $CDCl_3$) *δ*:** 7.52-7.39 (m, 5H), 6.92-6.79 (m, 3H); **^{13}C NMR (100 MHz, $CDCl_3$) *δ*:** 187.6, 186.6, 145.9, 137.0, 136.2, 132.7, 130.1, 129.2, 128.5. Data are consistent with those reported in the literature.[12]

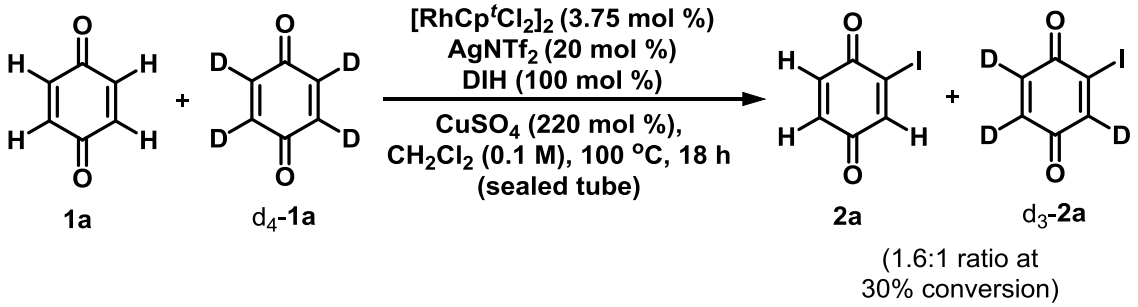
2-(4-fluorophenyl)-1,4-benzoquinone (7d)



Compound **7d** was synthesised using a previously reported procedure[13] with small modifications. A oven dried re-sealable tube was charged with **2a** (0.10 mmol, 23.4 mg), Pd(d^{t}bpf)Cl_2 (5 mol %, 3.7 mg), Na_2CO_3 (200 mol %, 21.2 mg) and (4-fluorophenyl)boronic acid (0.11 mmol, 15.4 mg). The tube was purged with N_2 and *N*,*N*-dimethylacetamide (1 mL) were added via syringe. The tube was sealed and the mixture was heated at 50 °C for 14h. After cooling, the solvent was removed under reduced pressure. The residue was dissolved in CH_2Cl_2 (5 mL) and filtered through a

pad of celite. The filtrate was concentrated under reduced pressure and the residue was purified by FCC (toluene) to afford **7d** (11.1 mg, 55% yield) as an golden powder; **m.p. (°C) =** 149.8-152.2 (Petrol/CH_2Cl_2); **MS (EI$^+$):** 202.0 $[M]^+$. Cald. for $[C_{12}H_7FO_2]$: 202.0; **^{1}H NMR (400 MHz, $CDCl_3$) δ:** 7.48-7.51 (m, 2H), 7.12-7.14 (m, 2H)**,** 6.80-6.89 (m, 3H); **^{13}C NMR (100 MHz, $CDCl_3$) δ:** 187.6, 186.8, 165.2, 144.7, 136.9, 136.7, 132.7, 131.2 (d, J = 8.2 Hz), 129.5, 115.6 (d, J = 21.6 Hz). Data are consistent with those reported in the literature.[14]

Intermolecular competition experiment between 1a and d_4-1a



A competition experiment involving the iodination of equimolar quantities of **1a** and *deuterio*-**1a** was conducted. At 30% conversion, a 1.6;1 ratio of **2a** to d_3-**2a** was obtained as determined by $^1H/^2H$ NMR analysis against a 1:1 mixture of **1a** and d_4-**1a**. This result confirms that C-H cleavage is kinetically significant, but does not elucidate whether or not this is the rate determining step.

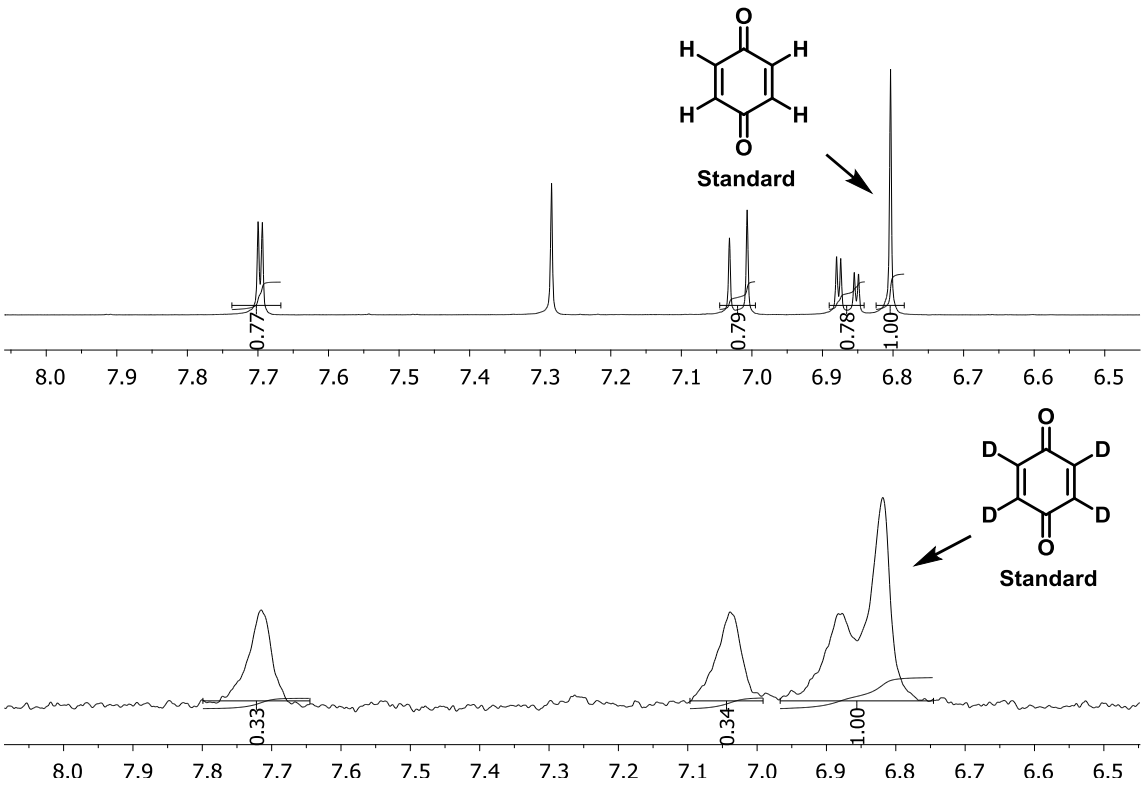


Figure 4: ^{1}H NMR spectra (400 MHz, $CDCl_3$) and ^{2}H NMR spectra (400 MHz, $CHCl_3$) for determination of the **2a**/d_3-**2a** ratio. A 1:1 ratio of benzoquinone:d_4-benzoquinone was used as a standard.

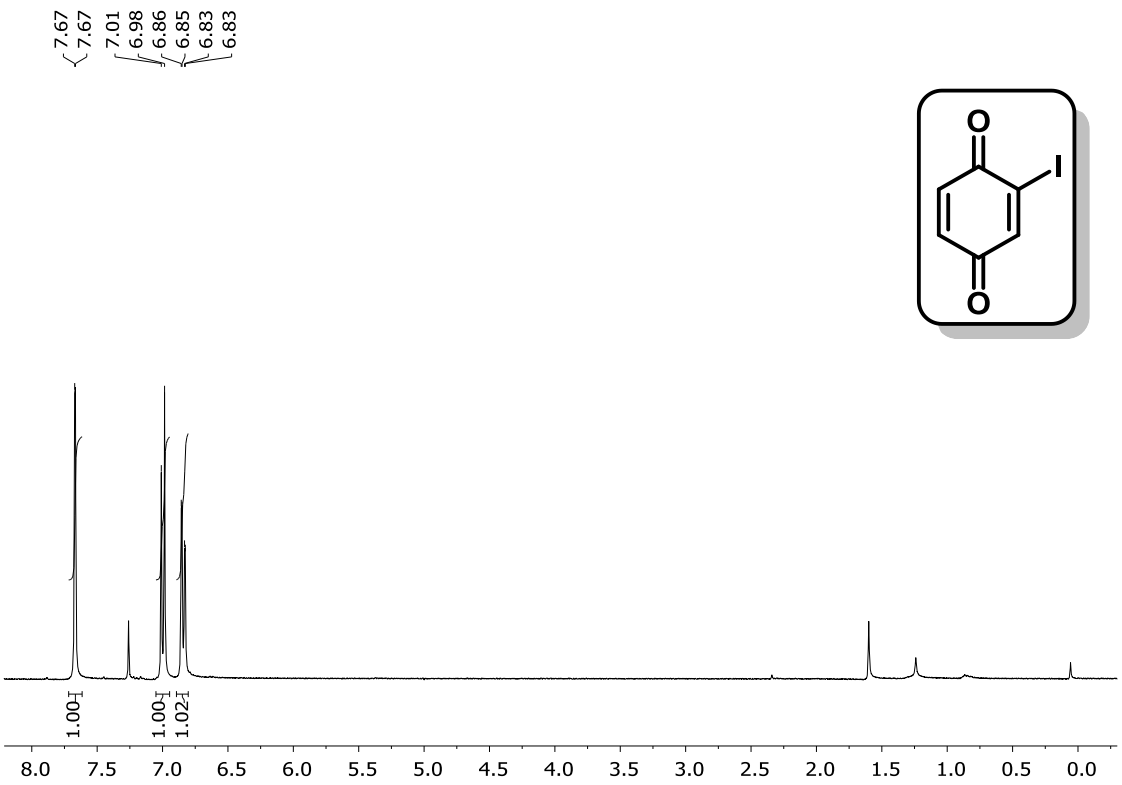


Figure 4: ^{1}H NMR spectrum (400 MHz, $CDCl_3$) of compound **2a**.

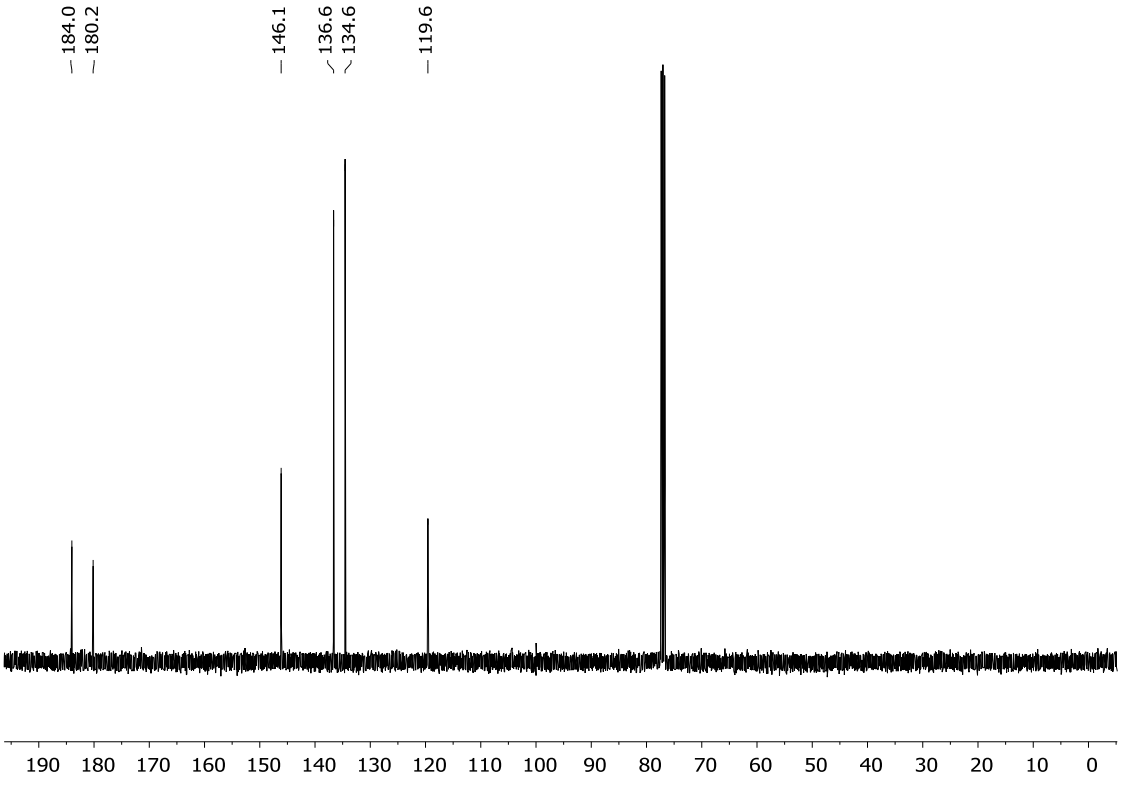


Figure 5: ^{13}C NMR spectrum (100 MHz, $CDCl_3$) of compound **2a**.

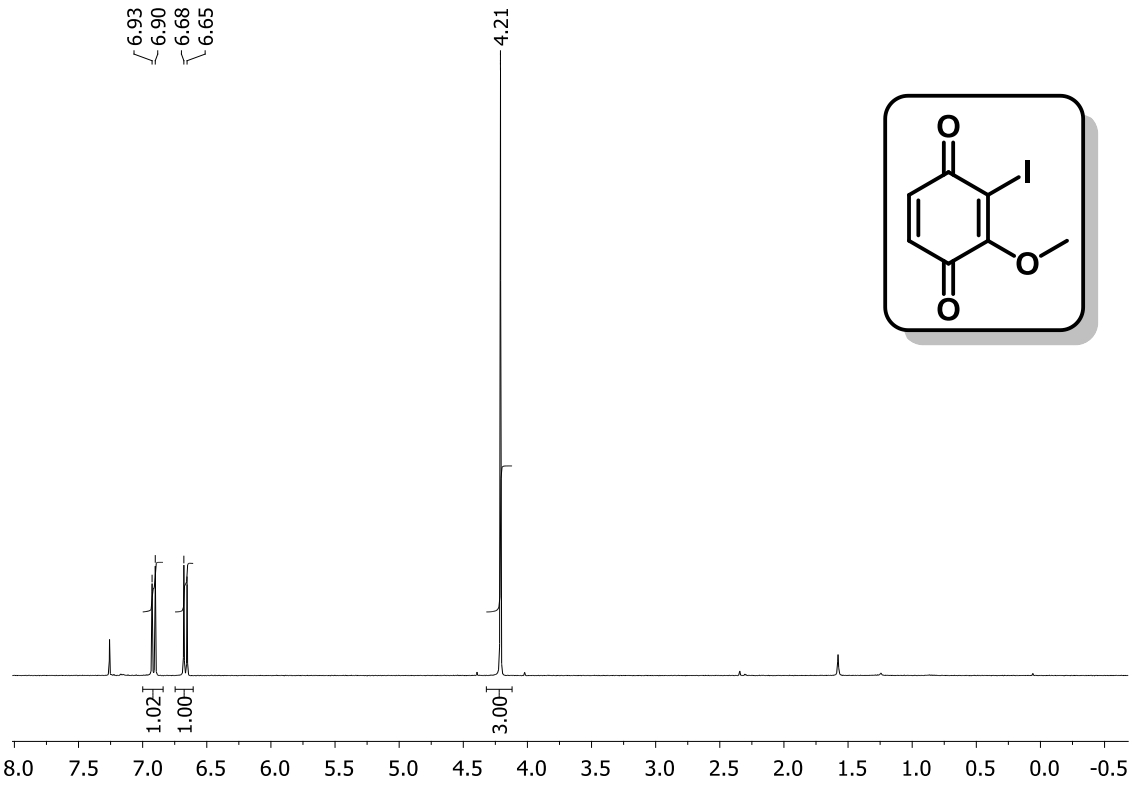


Figure 6: ^{1}H NMR spectrum (400 MHz, $CDCl_3$) of compound **2b**.

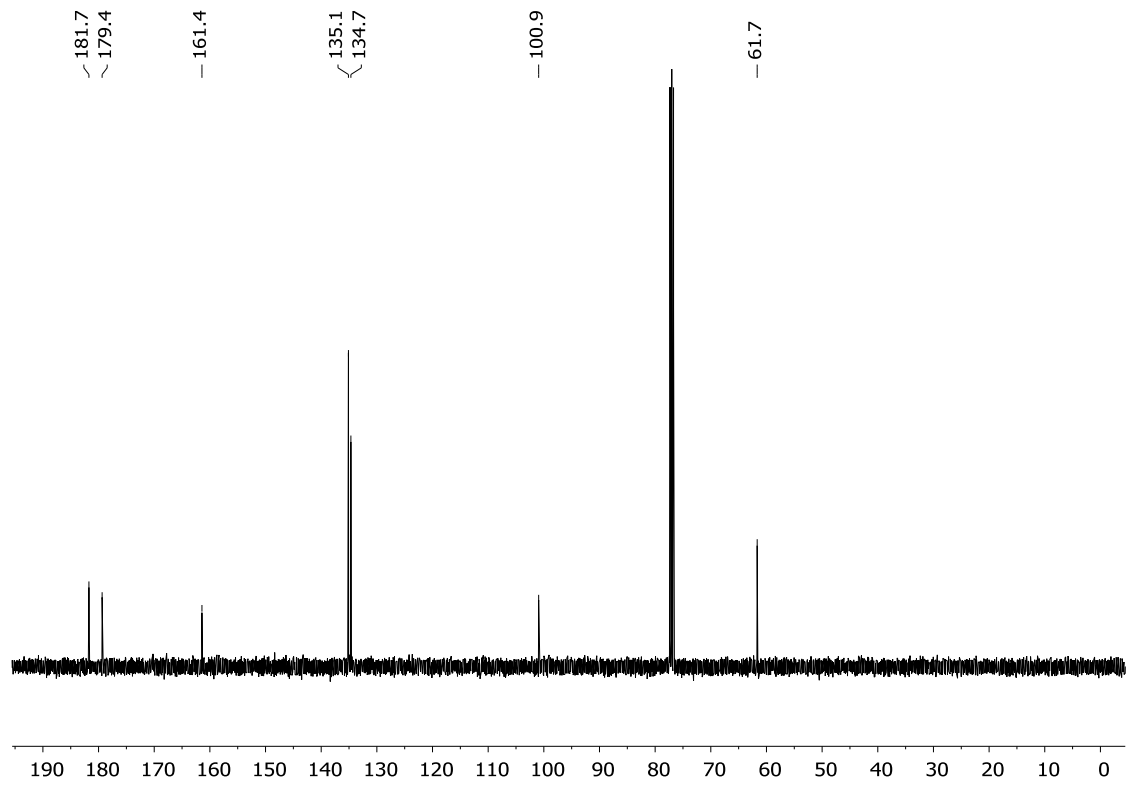


Figure 7: ^{13}C NMR spectrum (100 MHz, $CDCl_3$) of compound **2b**.

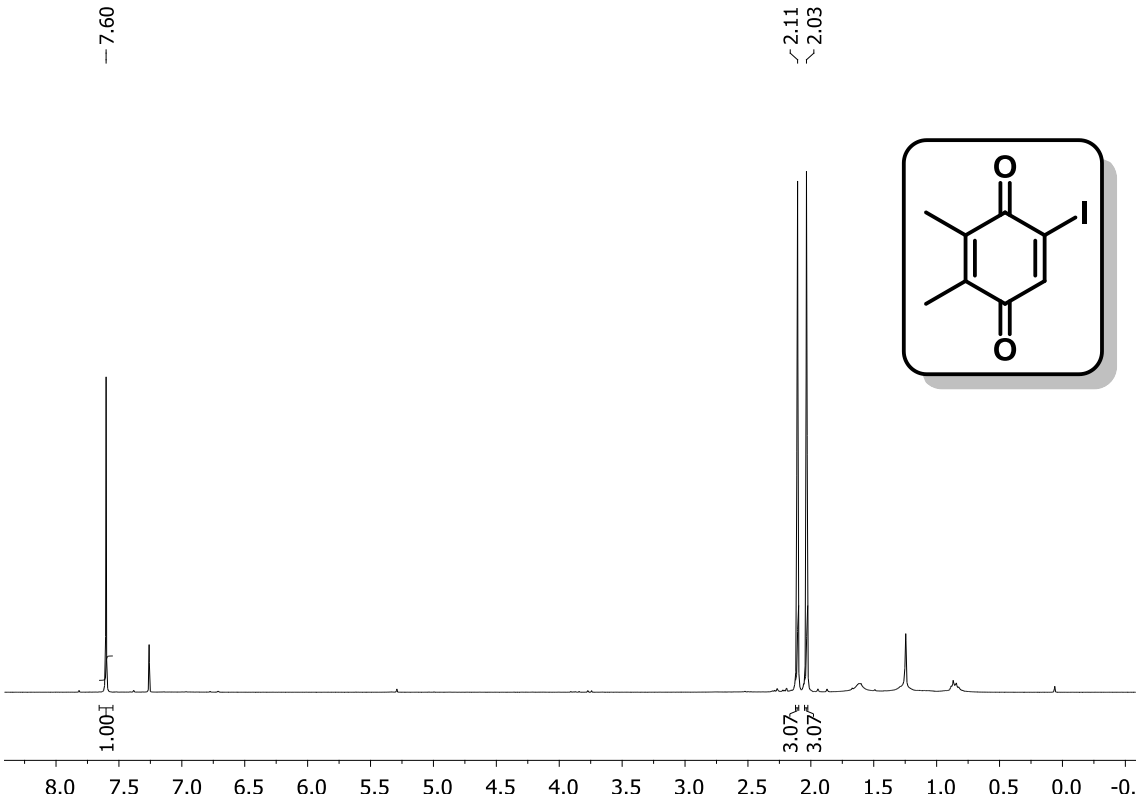


Figure 8: ^{1}H NMR spectrum (400 MHz, $CDCl_3$) of compound **2c**.

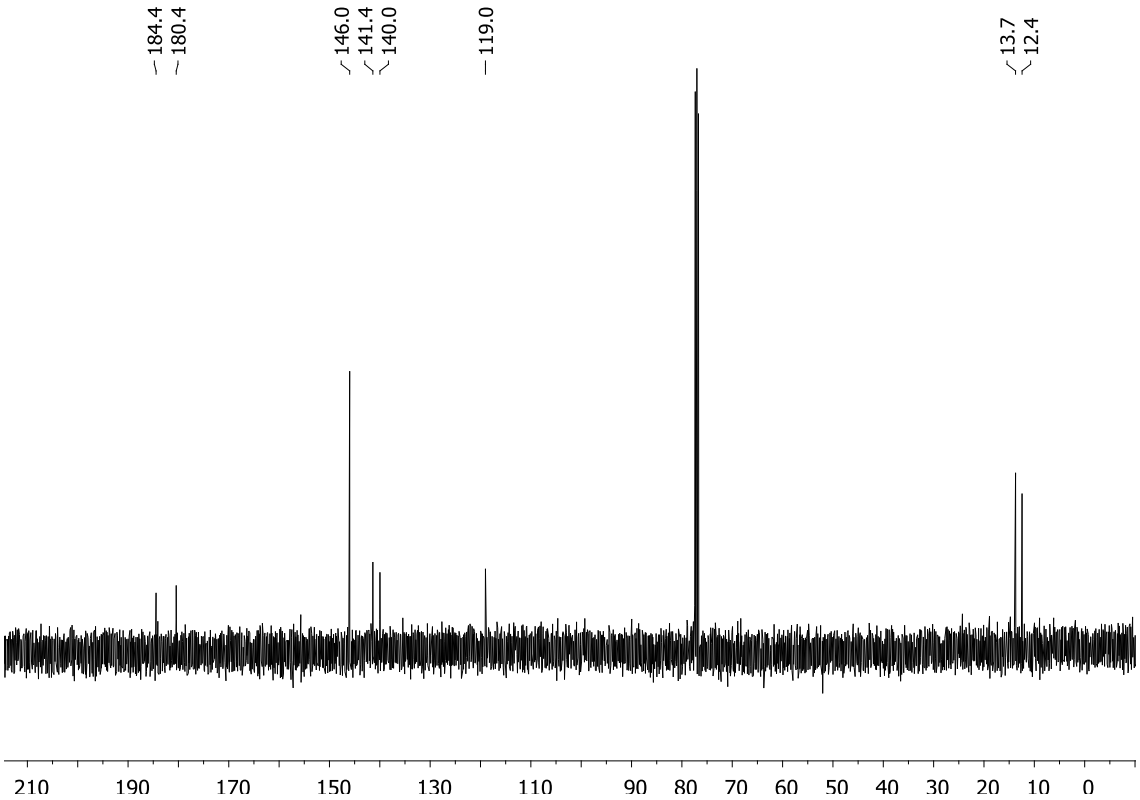


Figure 9: ^{13}C NMR spectrum (100 MHz, $CDCl_3$) of compound **2c**.

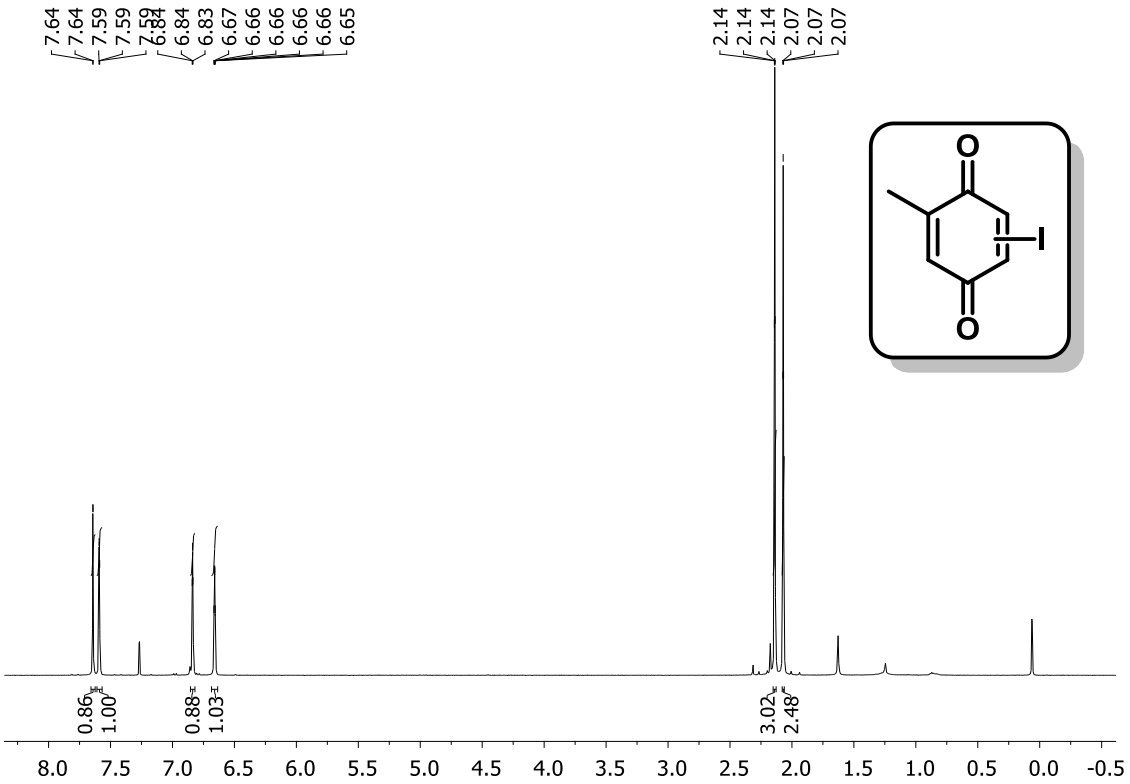


Figure 10: ^{1}H NMR spectrum (500 MHz, $CDCl_3$) of compound **2d**.

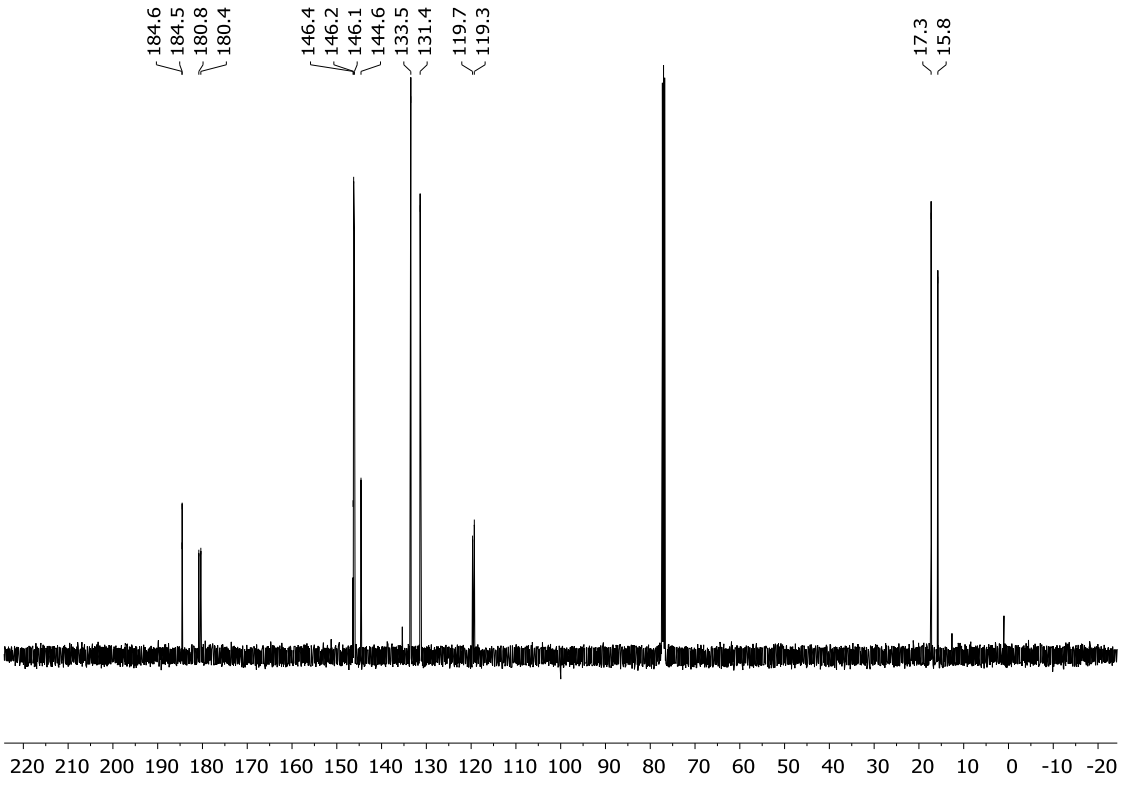


Figure 11: ^{13}C NMR spectrum (125 MHz, $CDCl_3$) of compound **2d**.

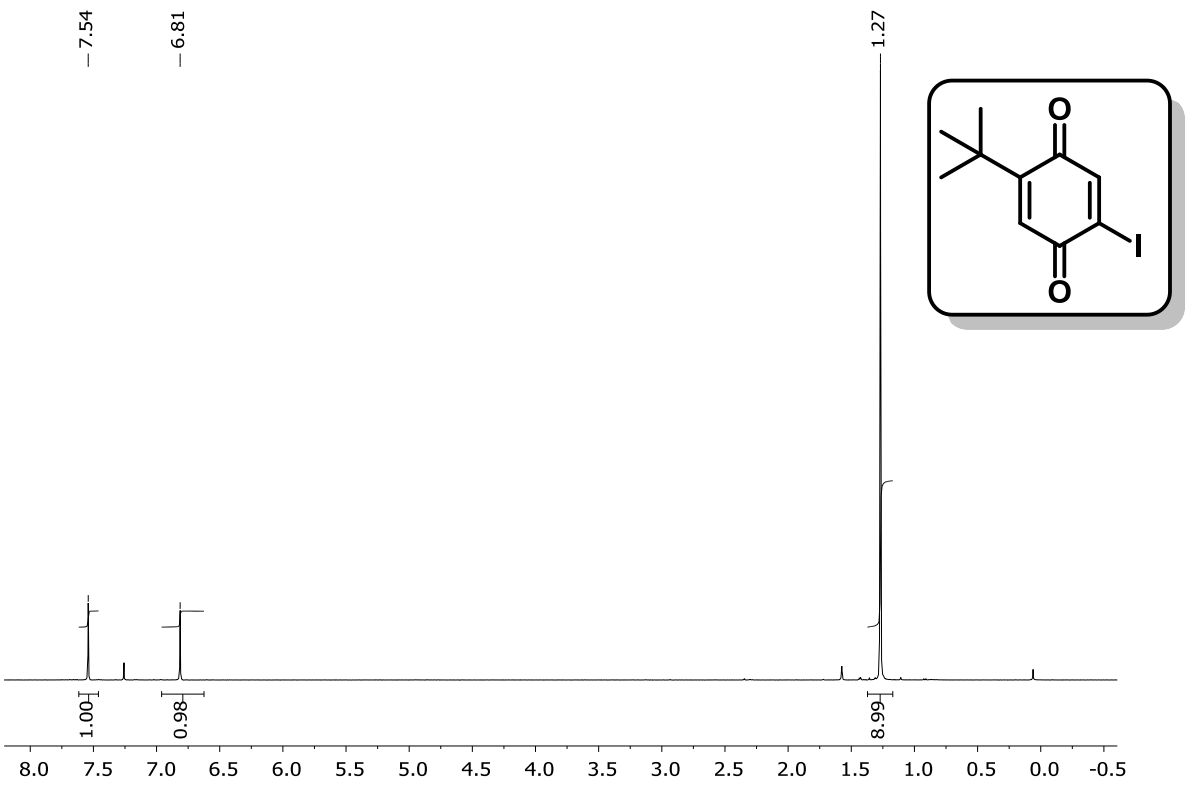


Figure 12: ^{1}H NMR spectrum (400 MHz, $CDCl_3$) of compound **2e**.

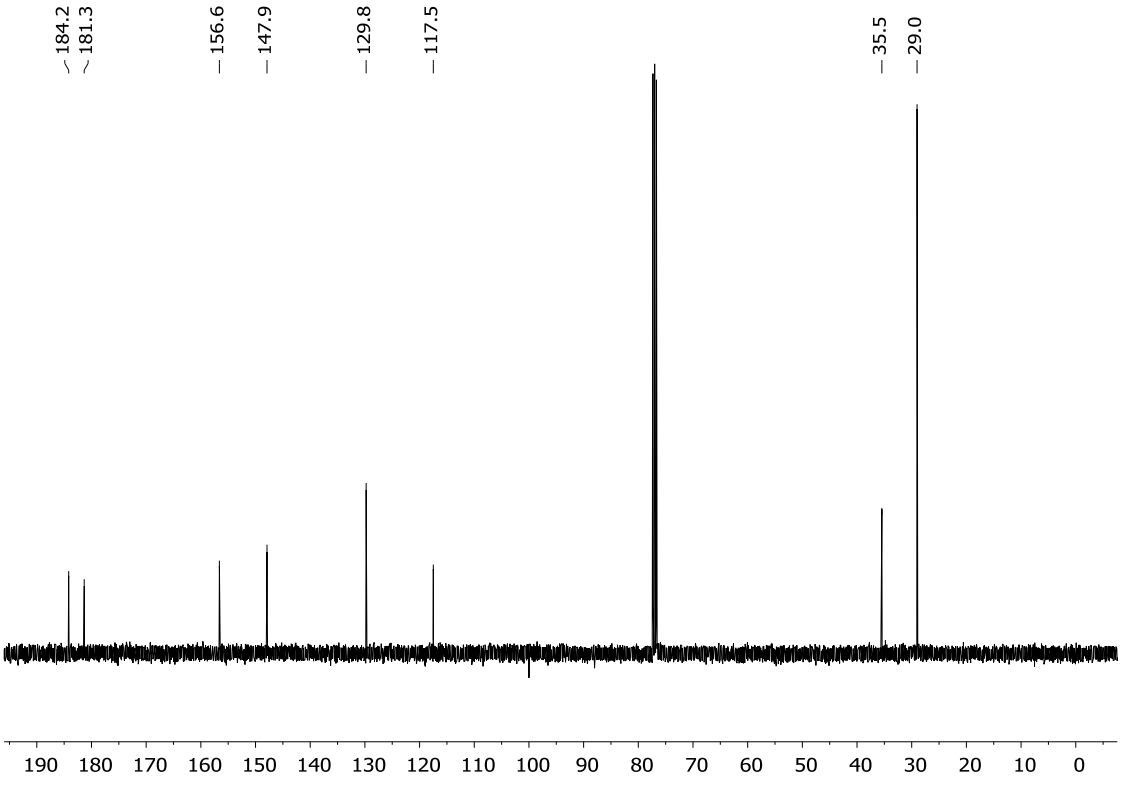


Figure 13: ^{13}C NMR spectrum (100 MHz, $CDCl_3$) of compound **2e**.

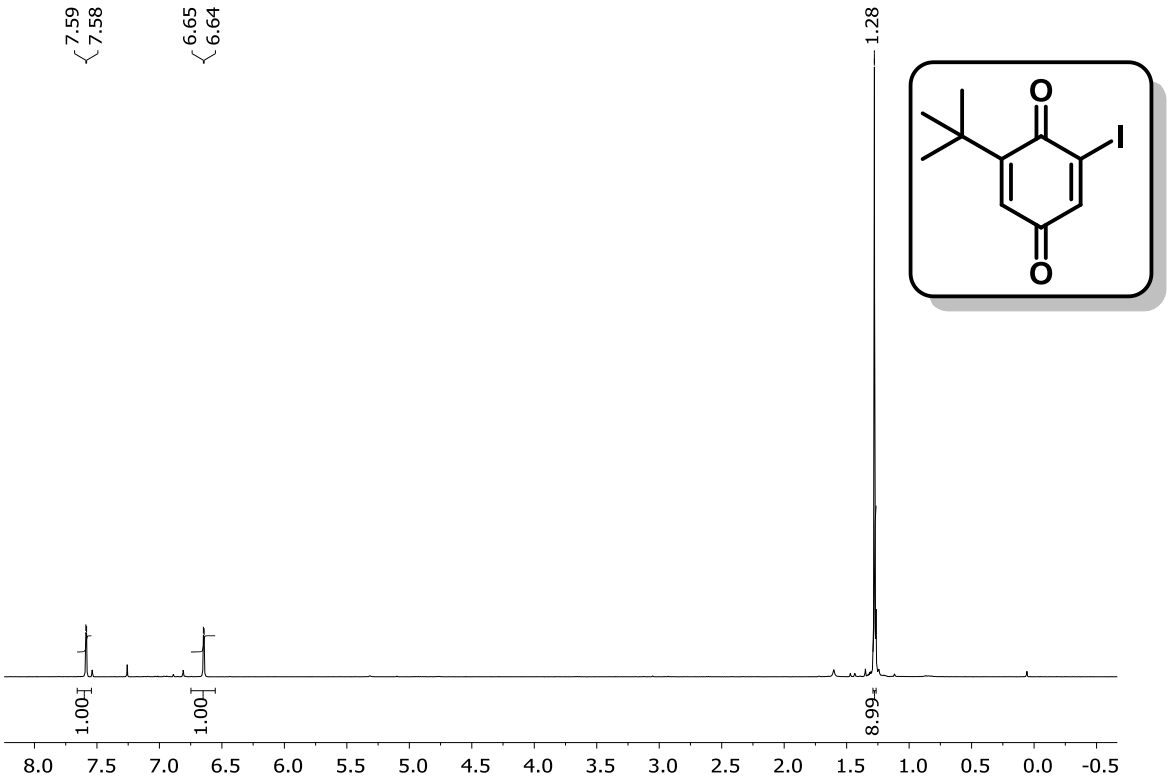


Figure 14: ^{1}H NMR spectrum (400 MHz, $CDCl_3$) of compound **2e'**.

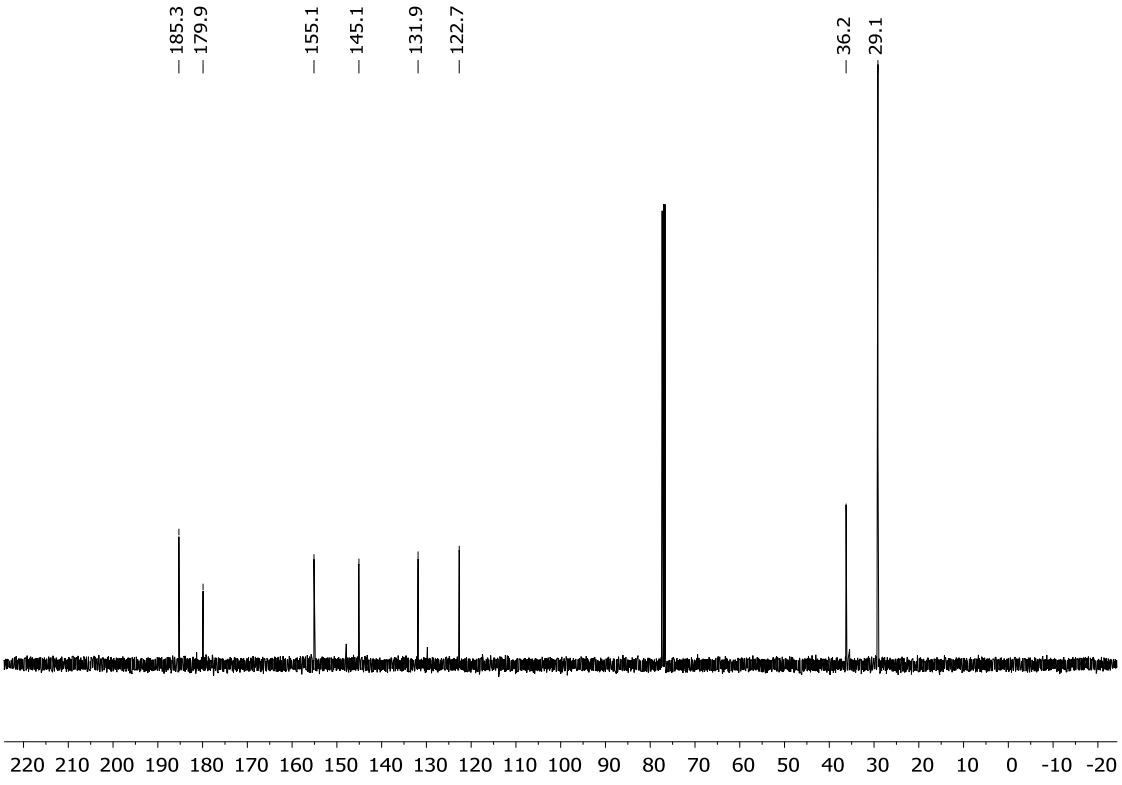


Figure 15: ^{13}C NMR spectrum (100 MHz, $CDCl_3$) of compound **2e'**.

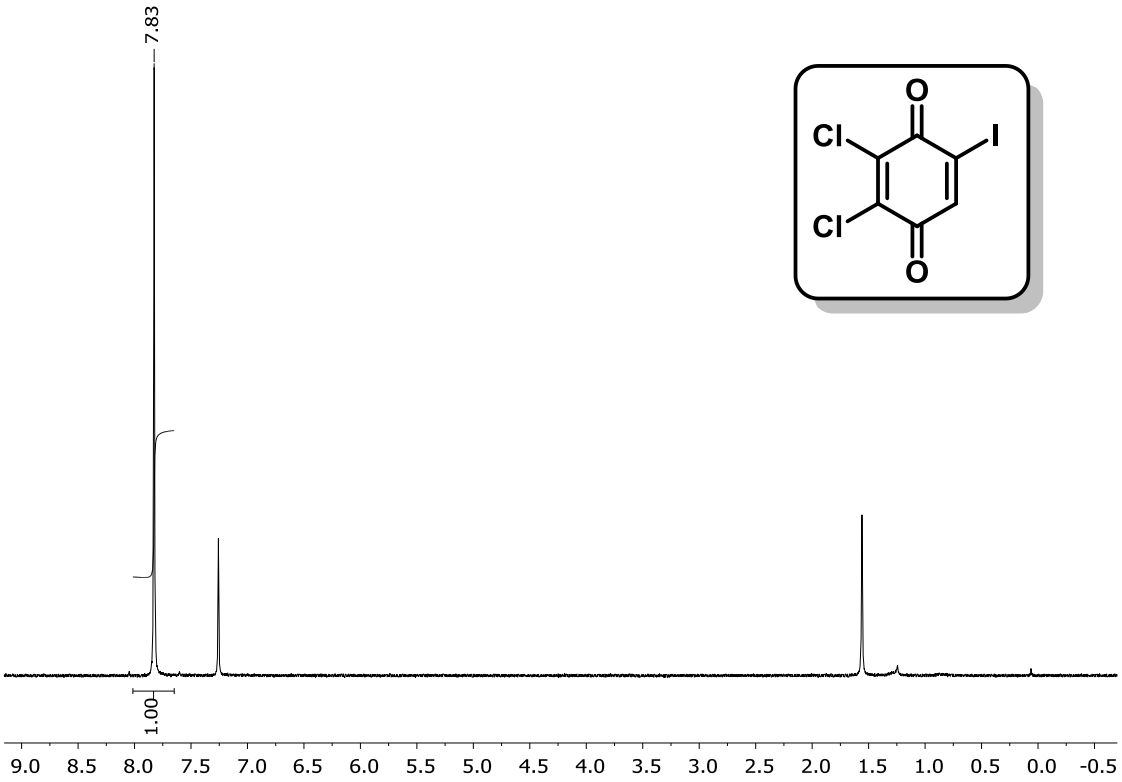


Figure 16: ^{1}H NMR spectrum (400 MHz, $CDCl_3$) of compound **2f**.

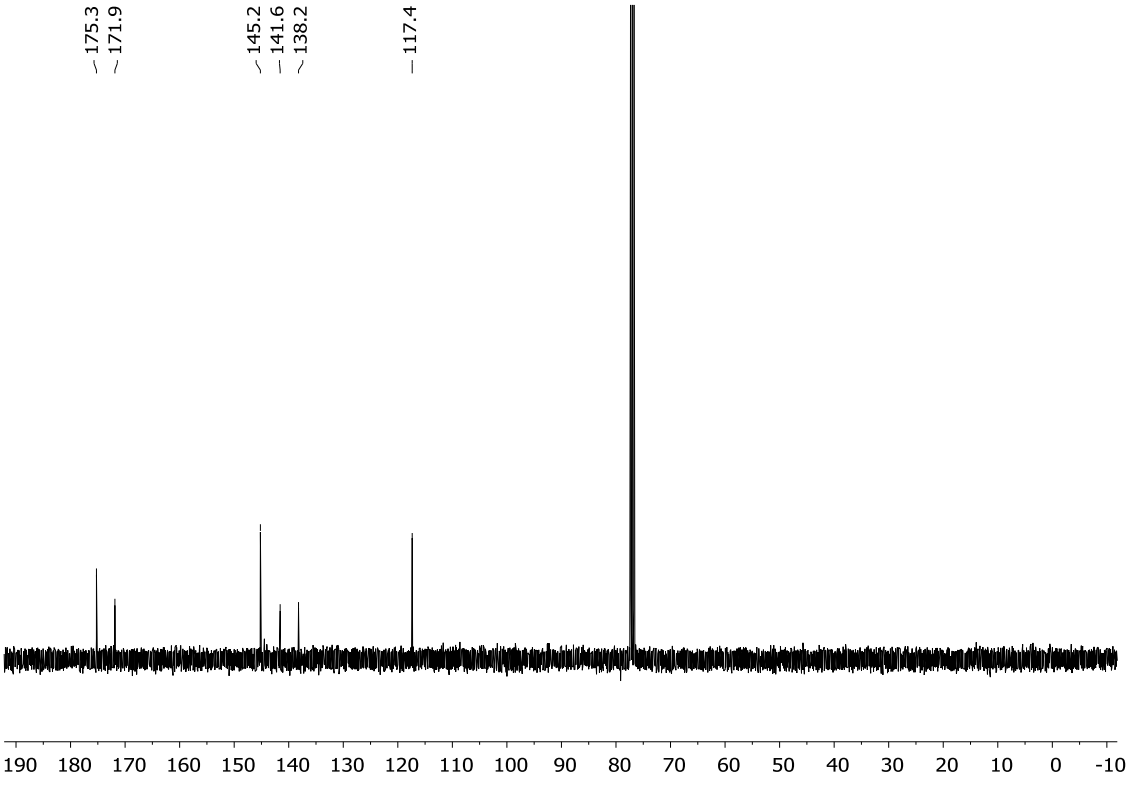


Figure 17: ^{13}C NMR spectrum (100 MHz, $CDCl_3$) of compound **2f**.

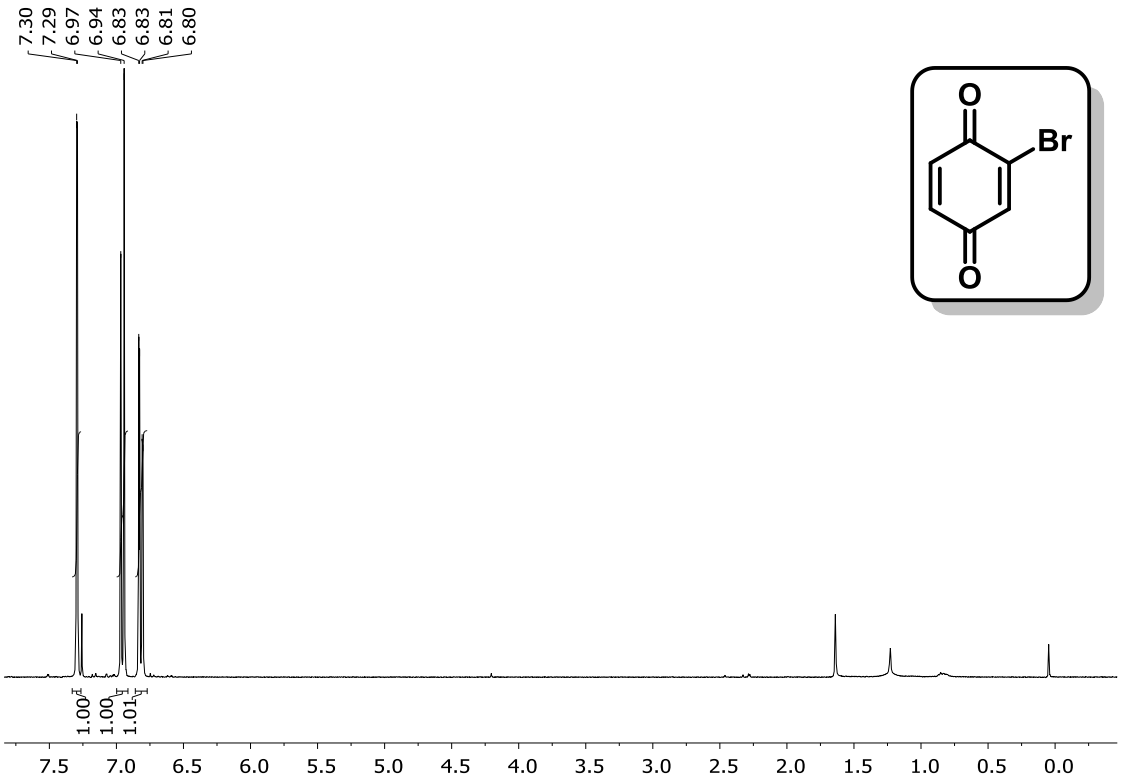


Figure 18: ^{1}H NMR spectrum (400 MHz, $CDCl_3$) of compound **3a**.

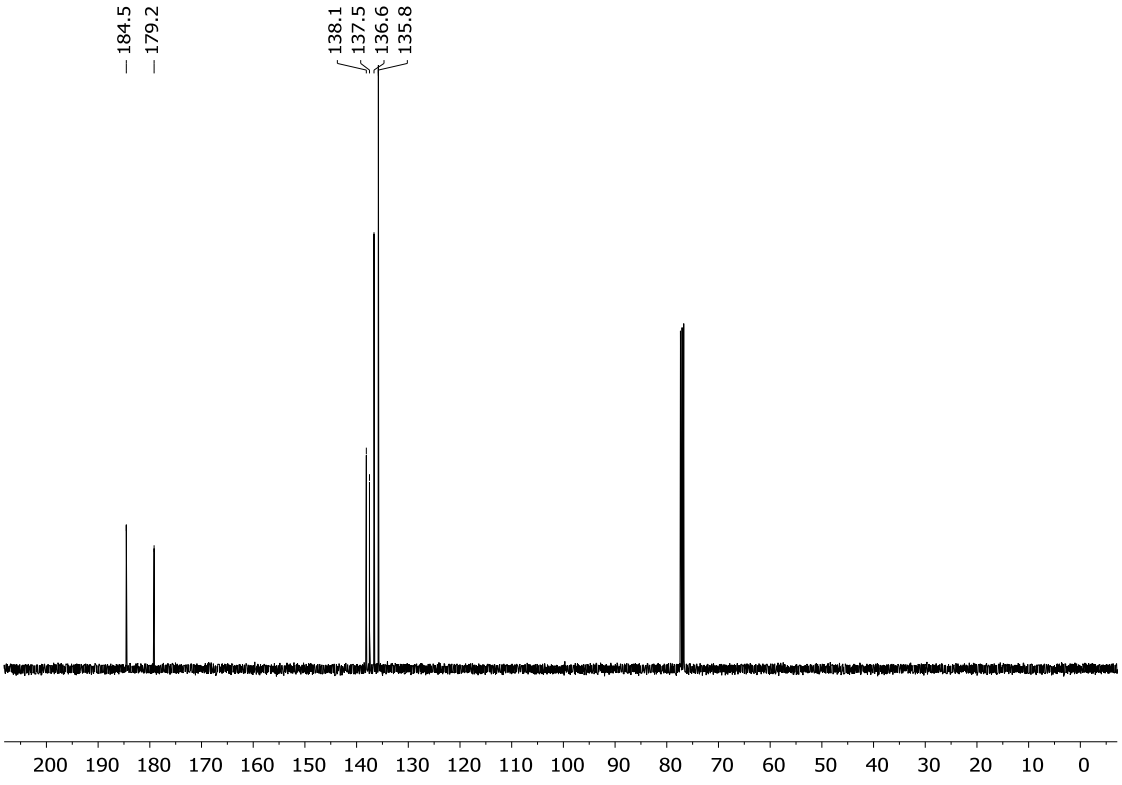


Figure 19: ^{13}C NMR spectrum (100 MHz, $CDCl_3$) of compound **3a**.

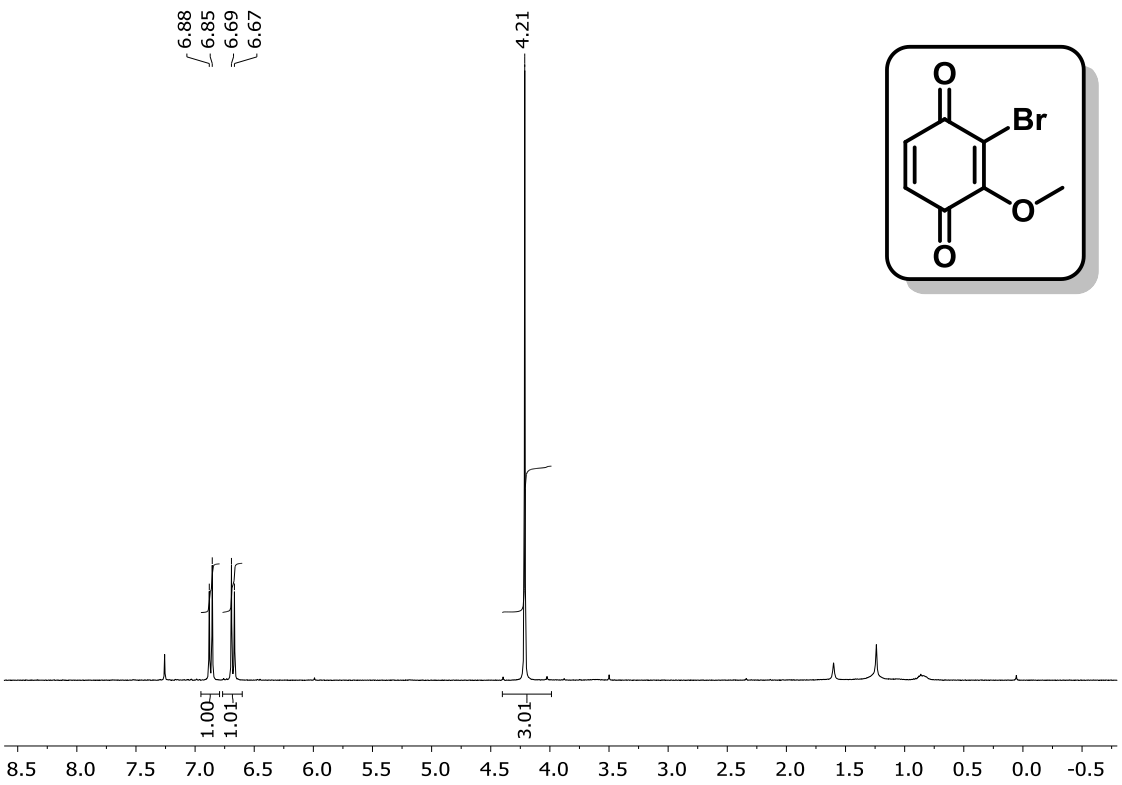


Figure 20: ^{1}H NMR spectrum (400 MHz, $CDCl_3$) of compound **3b**.

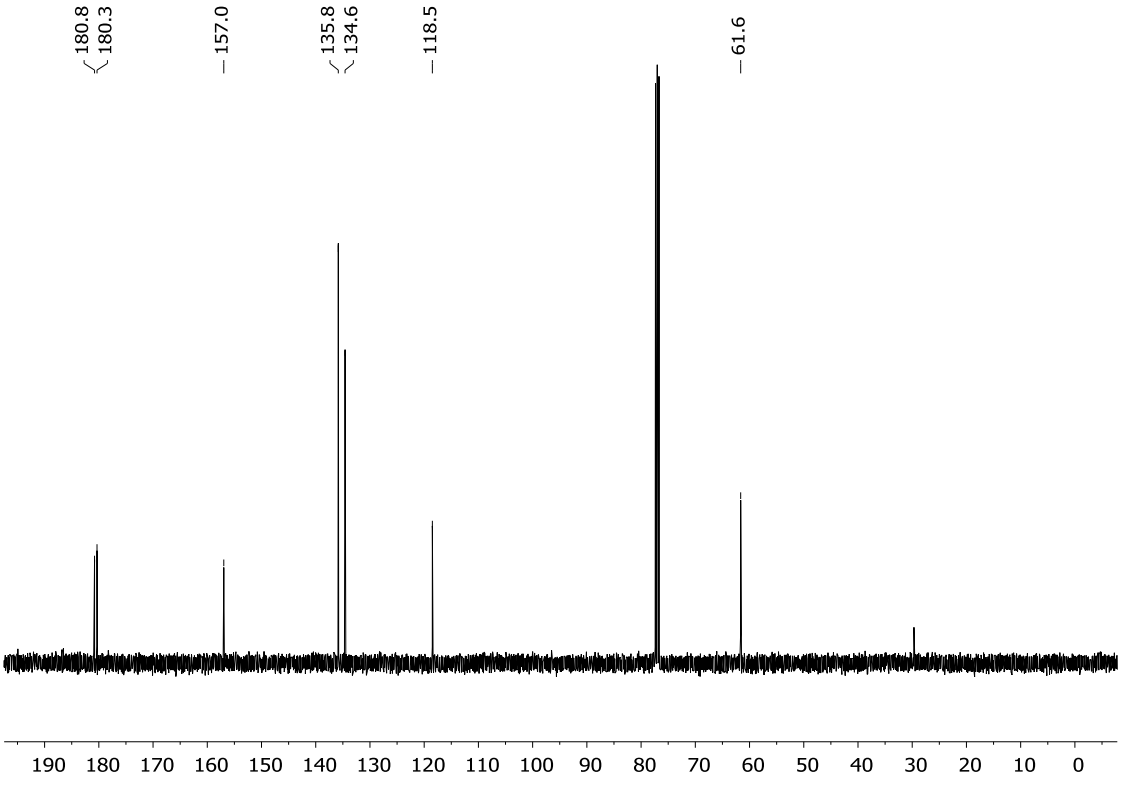


Figure 21: ^{13}C NMR spectrum (100 MHz, $CDCl_3$) of compound **3b**.

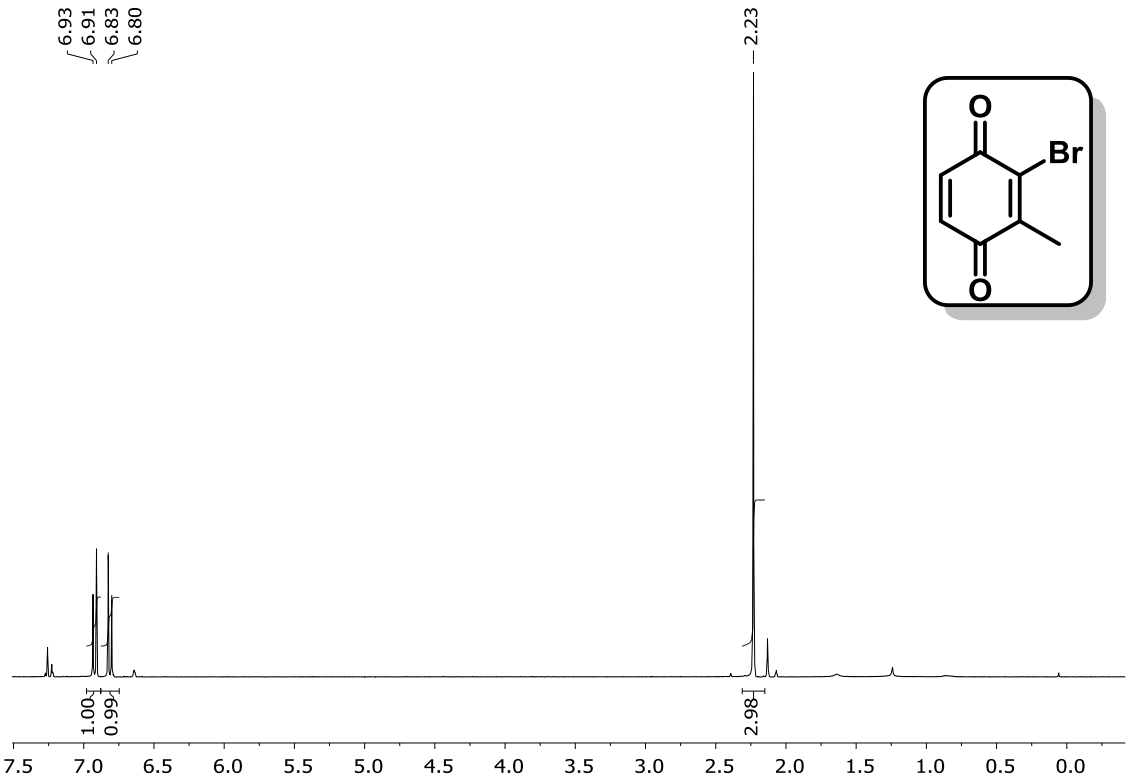


Figure 22: ^{1}H NMR spectrum (400 MHz, $CDCl_3$) of compound **3d**.

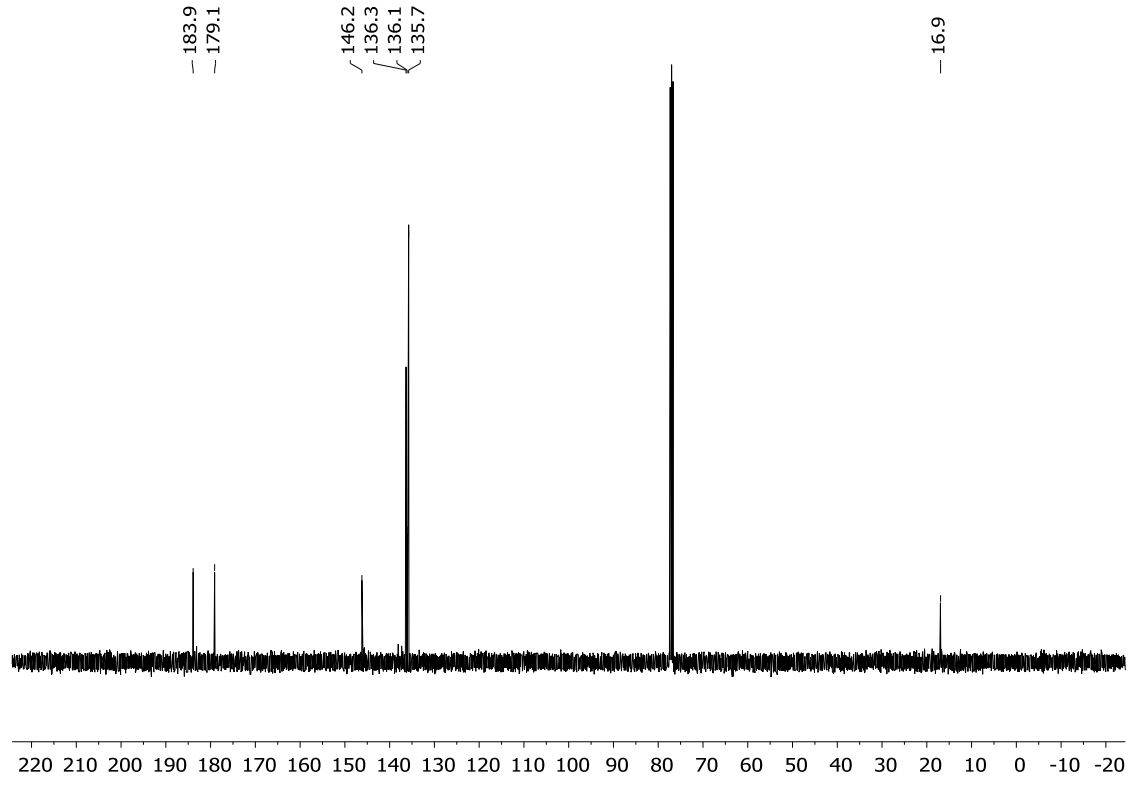


Figure 23: ^{13}C NMR spectrum (100 MHz, $CDCl_3$) of compound **3d**.

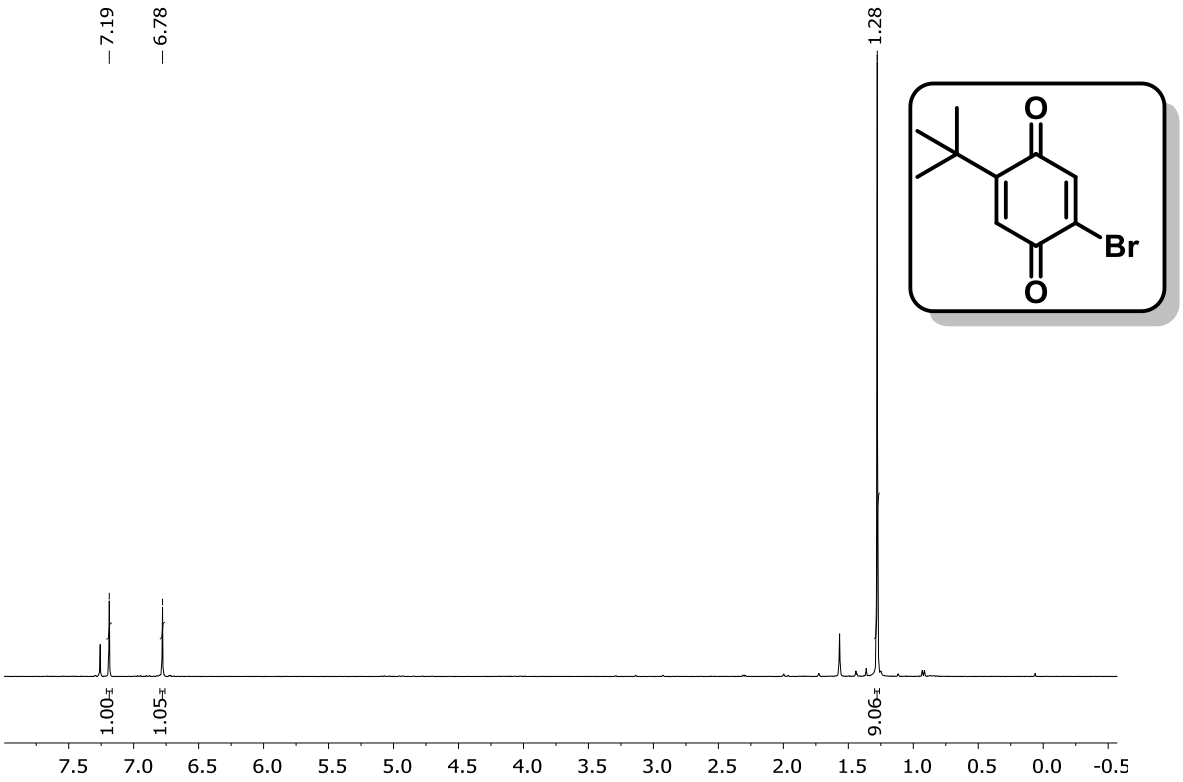


Figure 24: ^{1}H NMR spectrum (400 MHz, $CDCl_3$) of compound **3e**.

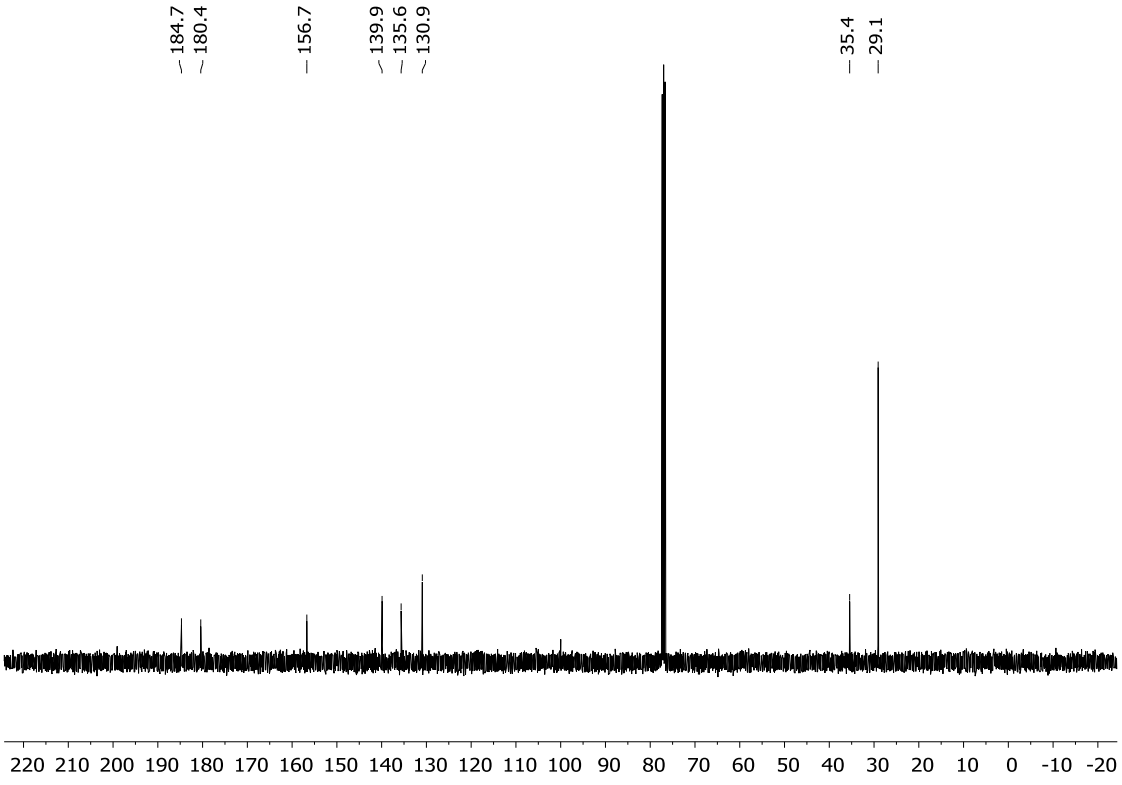


Figure 25: ^{13}C NMR spectrum (100 MHz, $CDCl_3$) of compound **3e**.

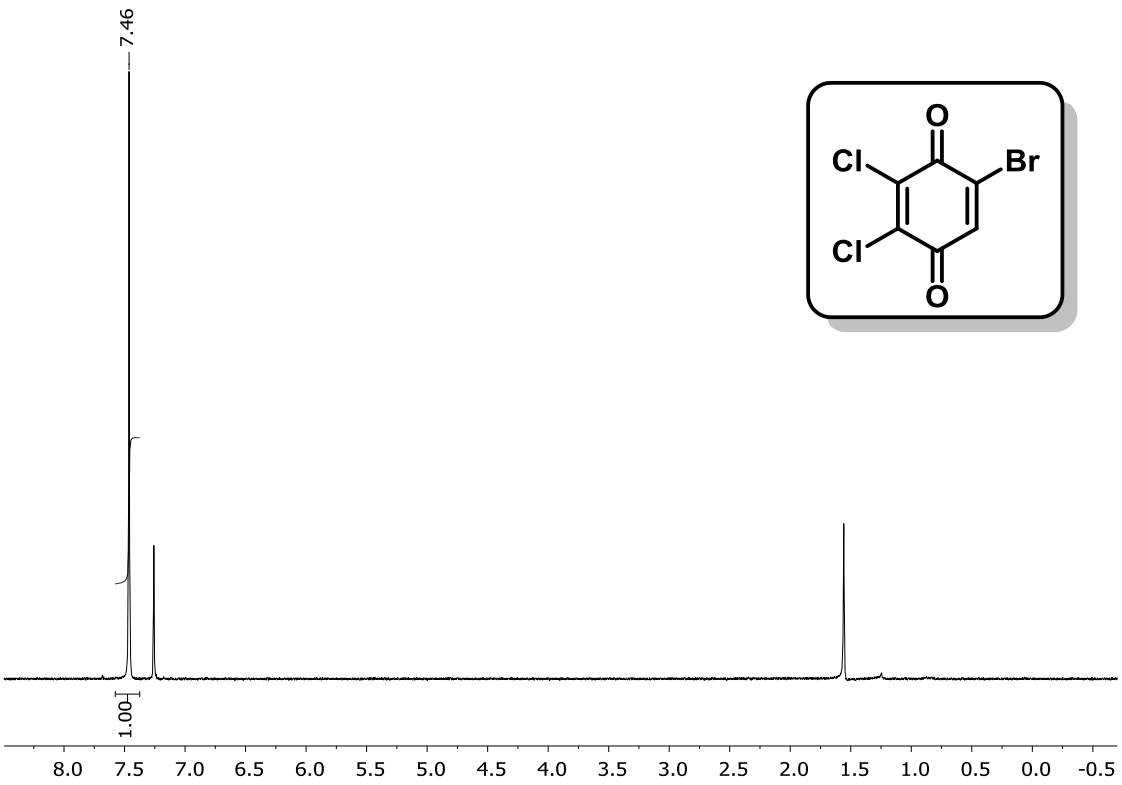


Figure 26: ^{1}H NMR spectrum (400 MHz, $CDCl_3$) of compound **3f**.

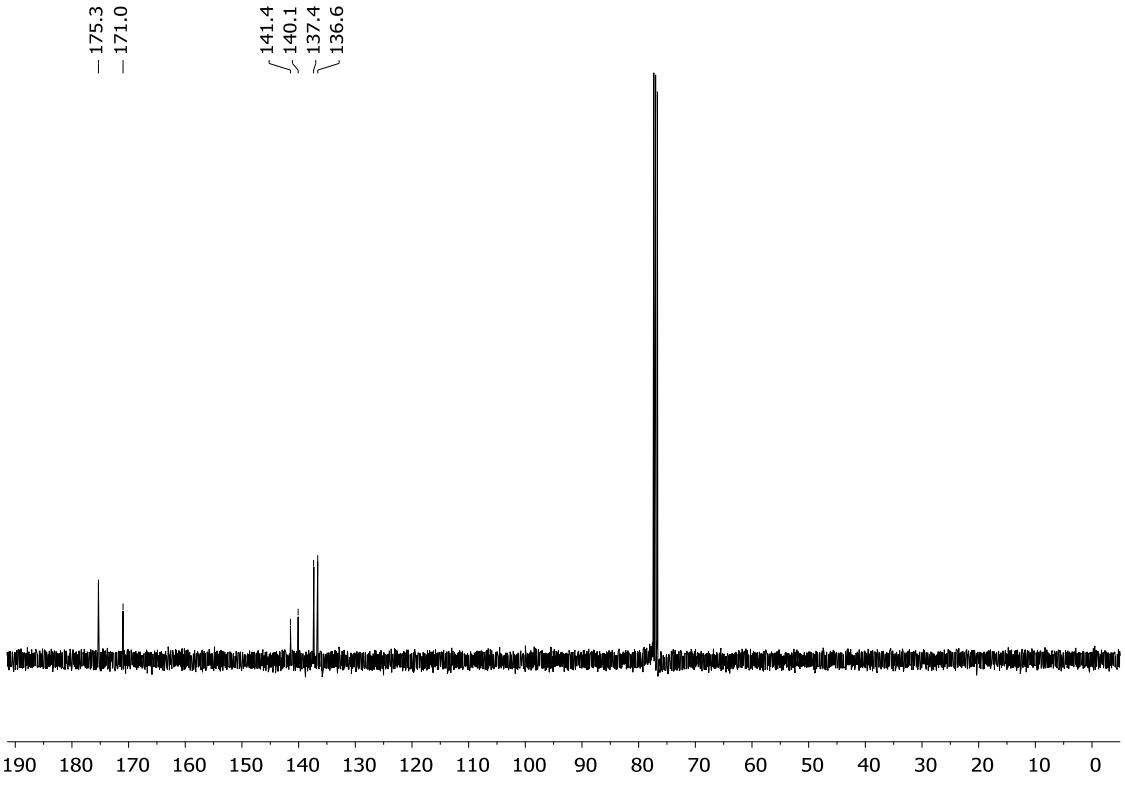


Figure 27: ^{13}C NMR spectrum (100 MHz, $CDCl_3$) of compound **3f**.

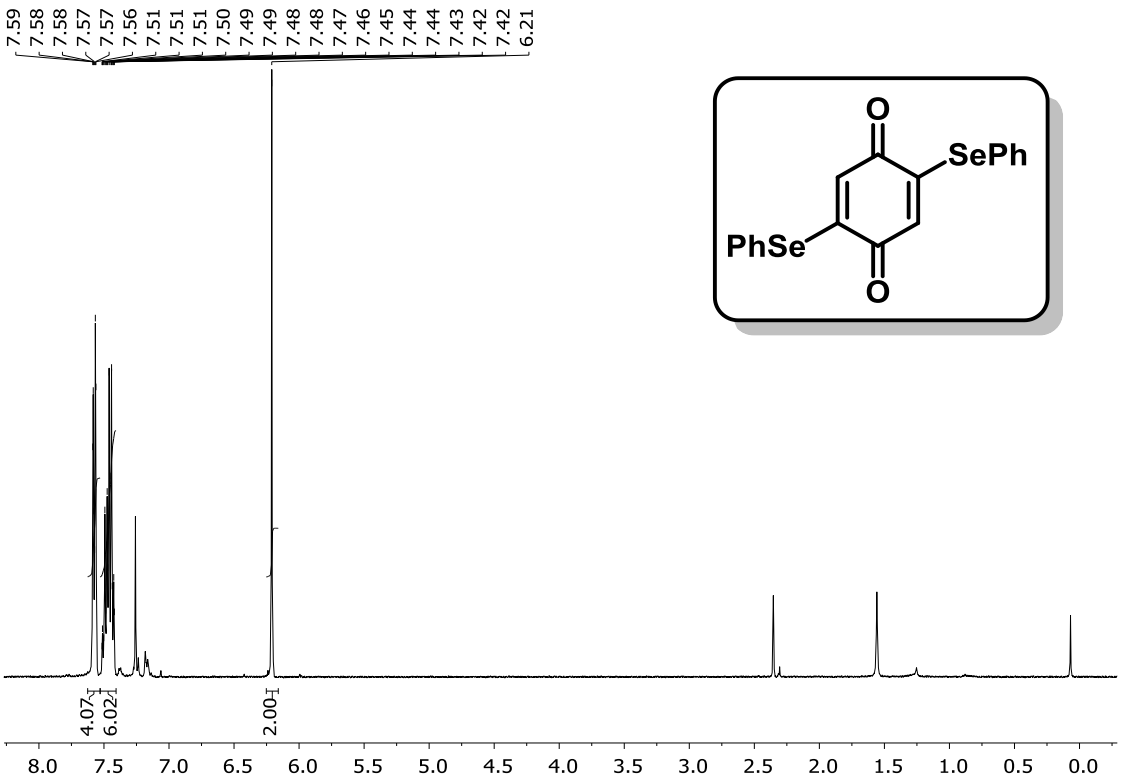


Figure 28: ^{1}H NMR spectrum (400 MHz, $CDCl_3$) of compound **4a'**.

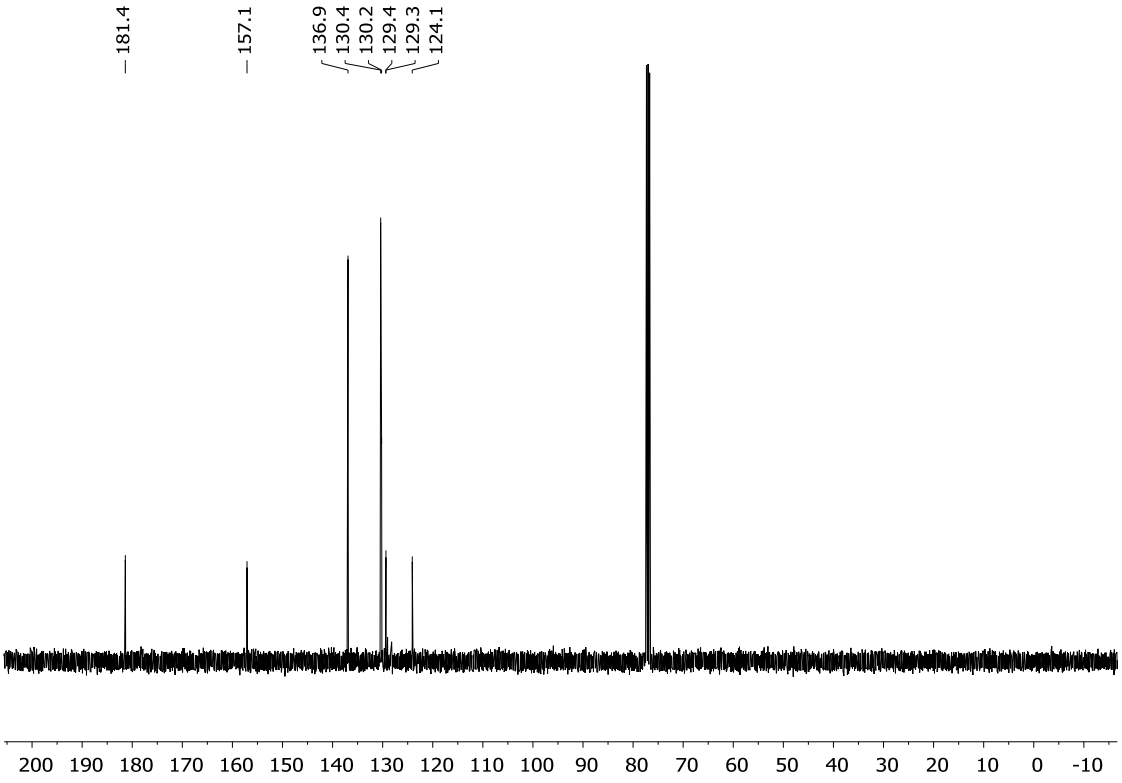


Figure 29: ^{13}C NMR spectrum (100 MHz, $CDCl_3$) of compound **4a'**.

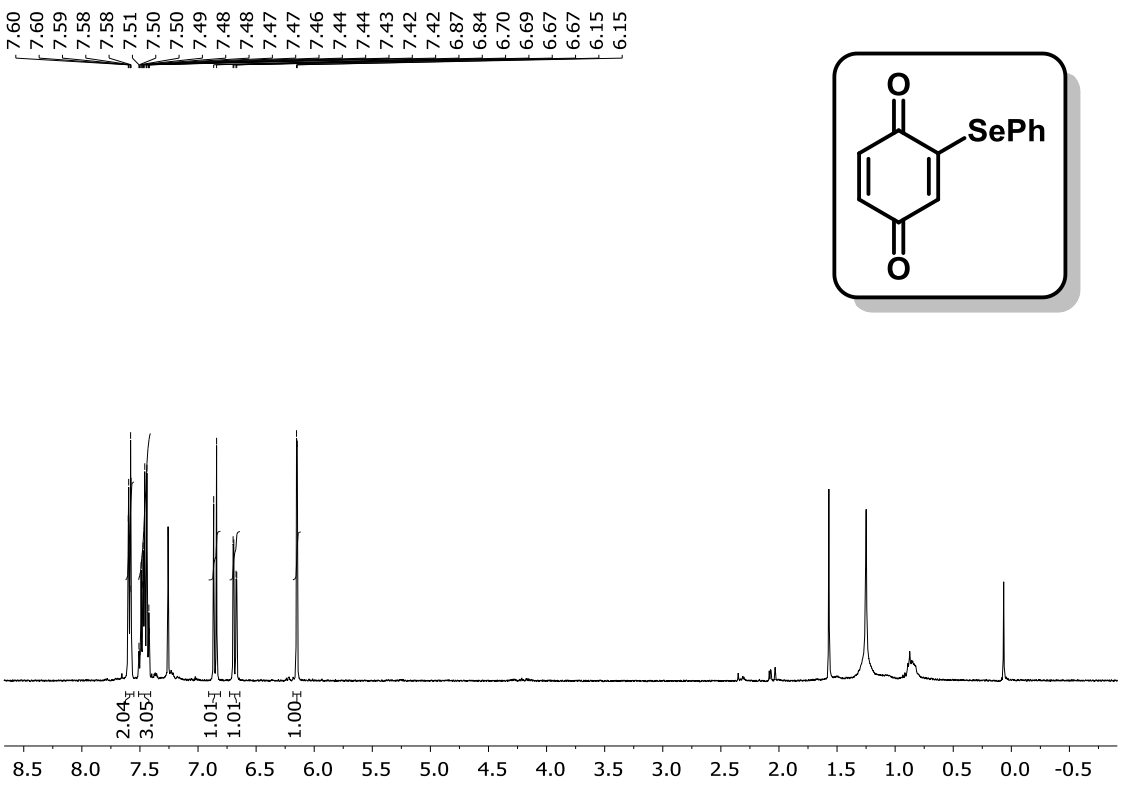


Figure 30: ^{1}H NMR spectrum (400 MHz, $CDCl_3$) of compound **4a**.

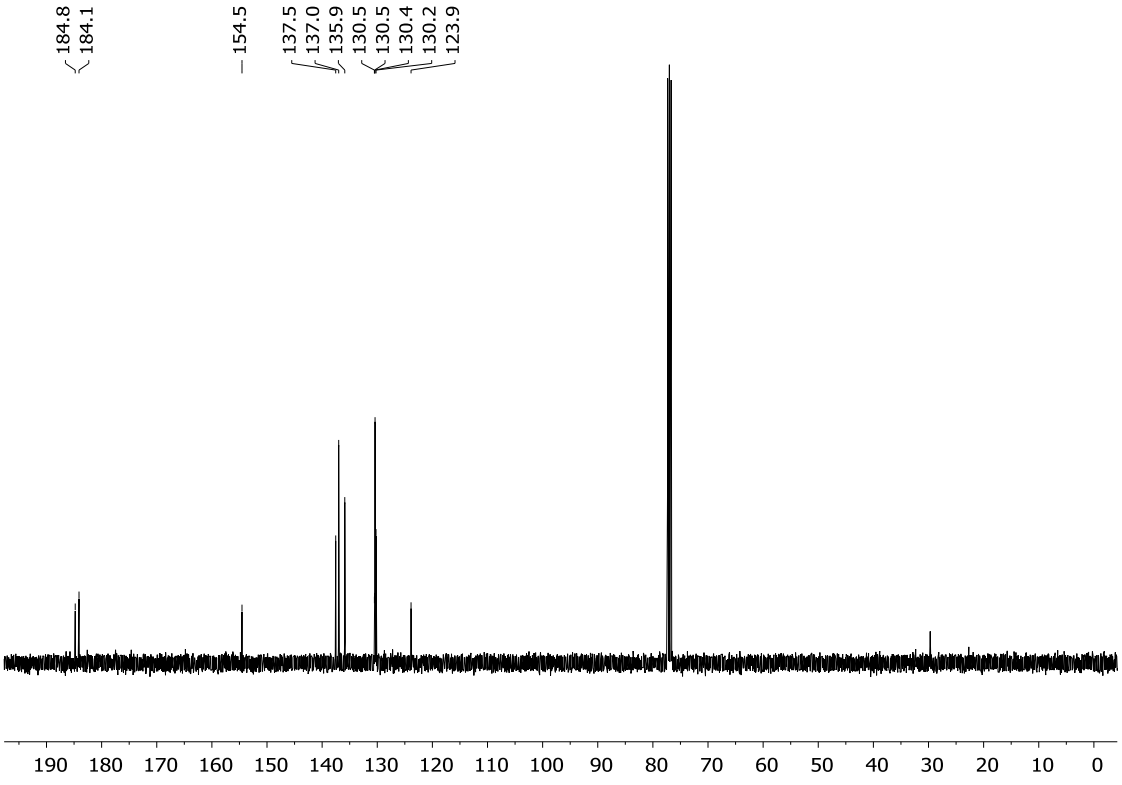


Figure 31: ^{13}C NMR spectrum (100 MHz, $CDCl_3$) of compound **4a**.

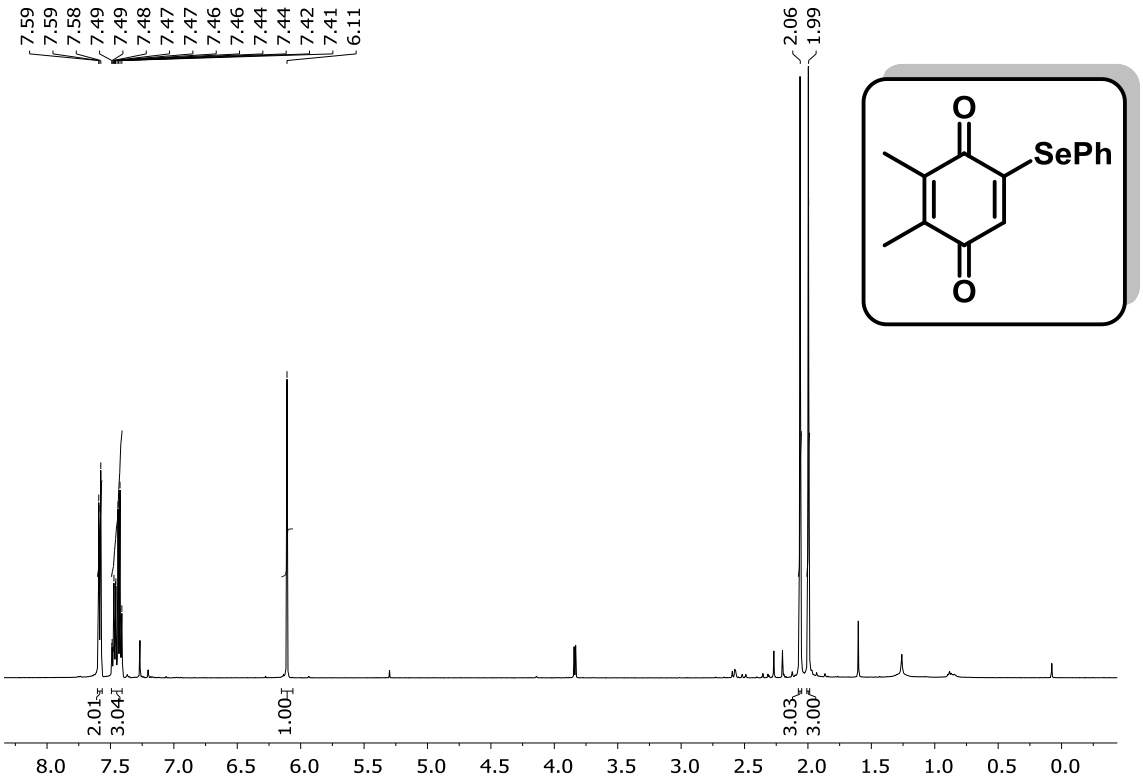


Figure 32: ^{1}H NMR spectrum (500 MHz, $CDCl_3$) of compound **4c**.

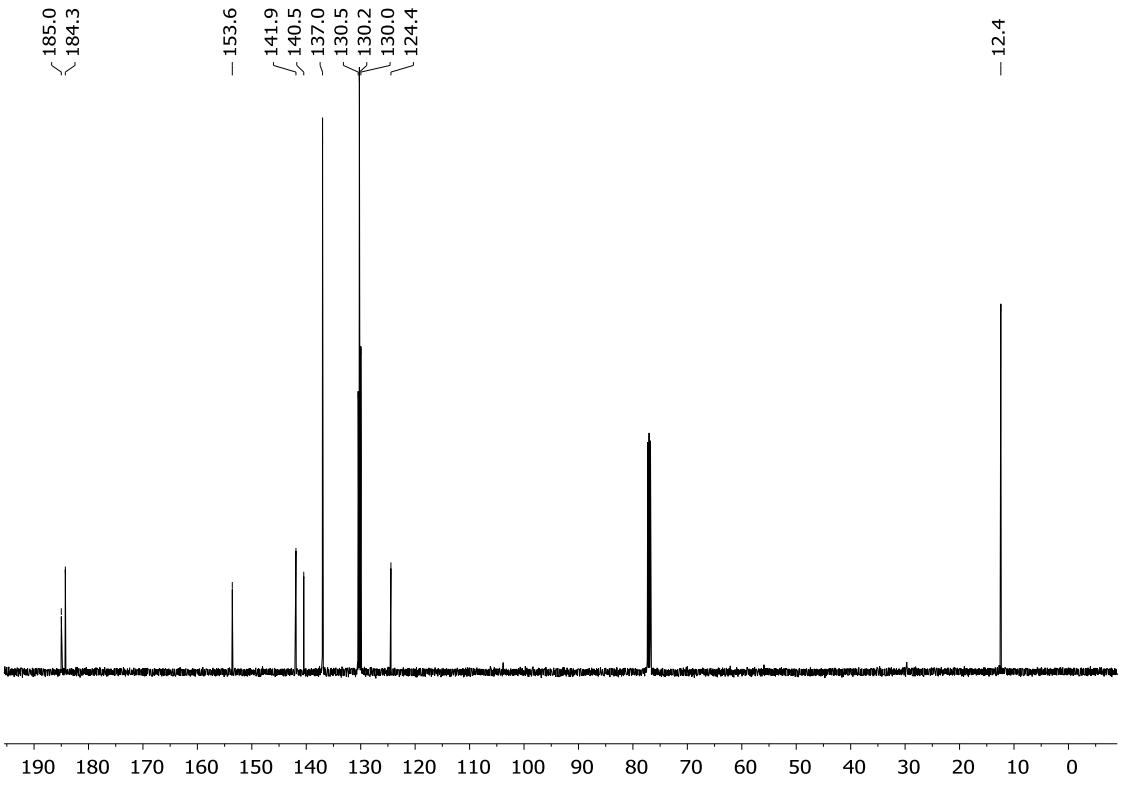


Figure 33: ^{13}C NMR spectrum (125 MHz, $CDCl_3$) of compound **4c**.

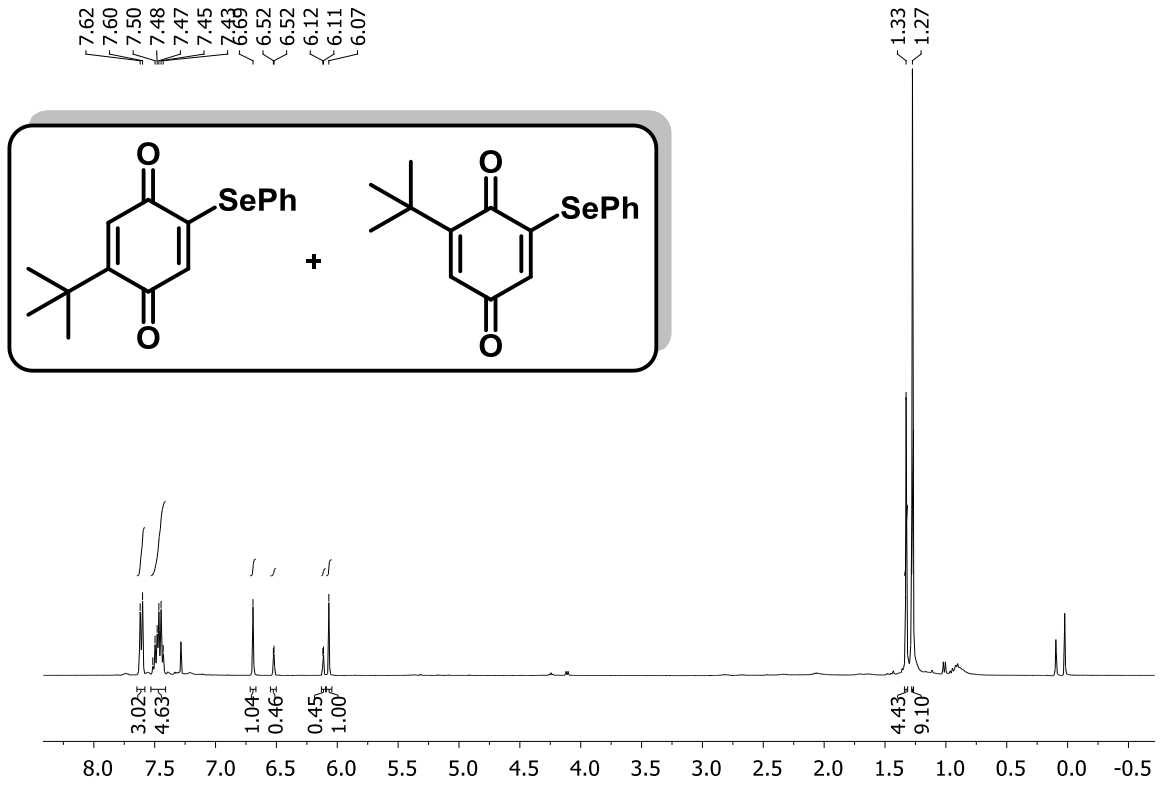


Figure 34: ^{1}H NMR spectrum (400 MHz, $CDCl_3$) of compound **4e**.

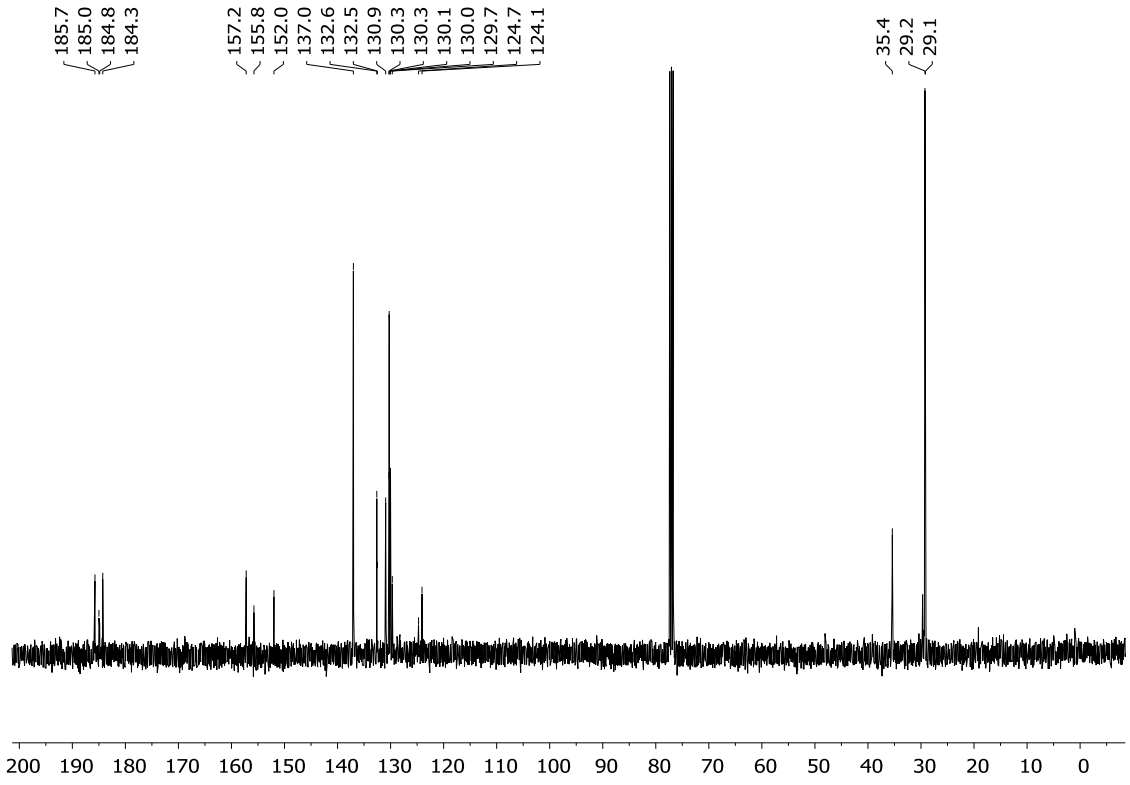


Figure 35: ^{13}C NMR spectrum (100 MHz, $CDCl_3$) of compound **4e**.

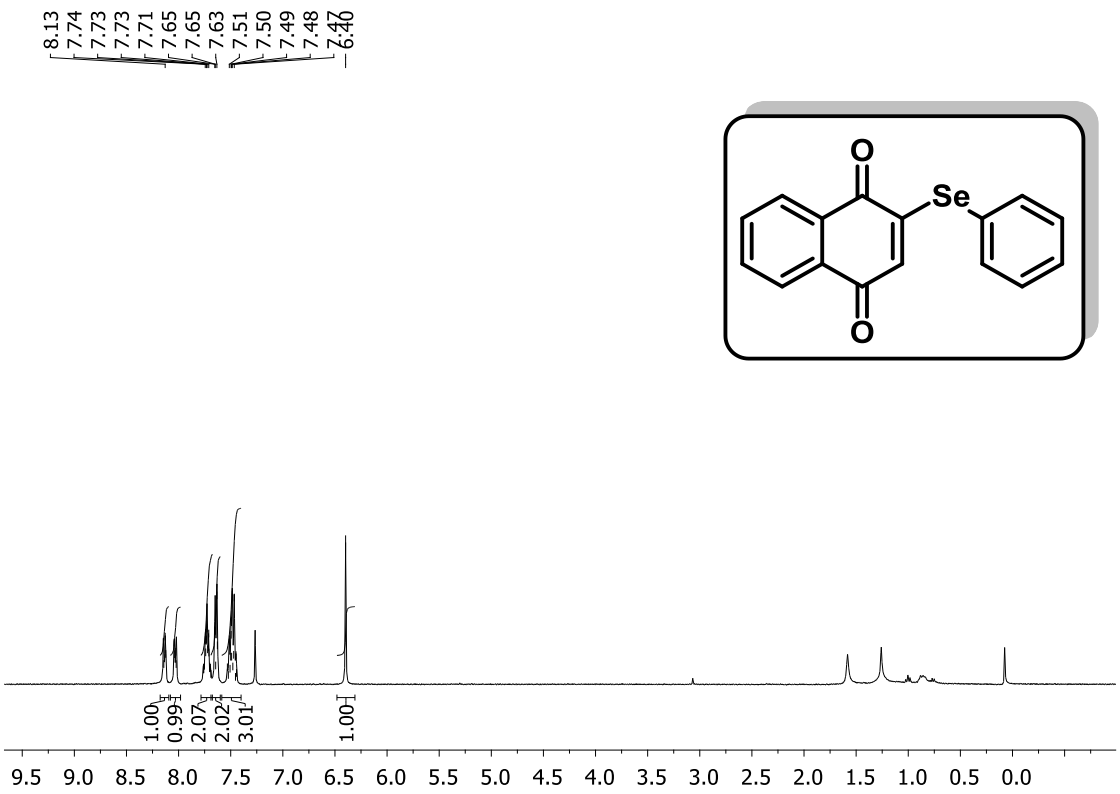


Figure 36: ^{1}H NMR spectrum (400 MHz, $CDCl_3$) of compound **6**.

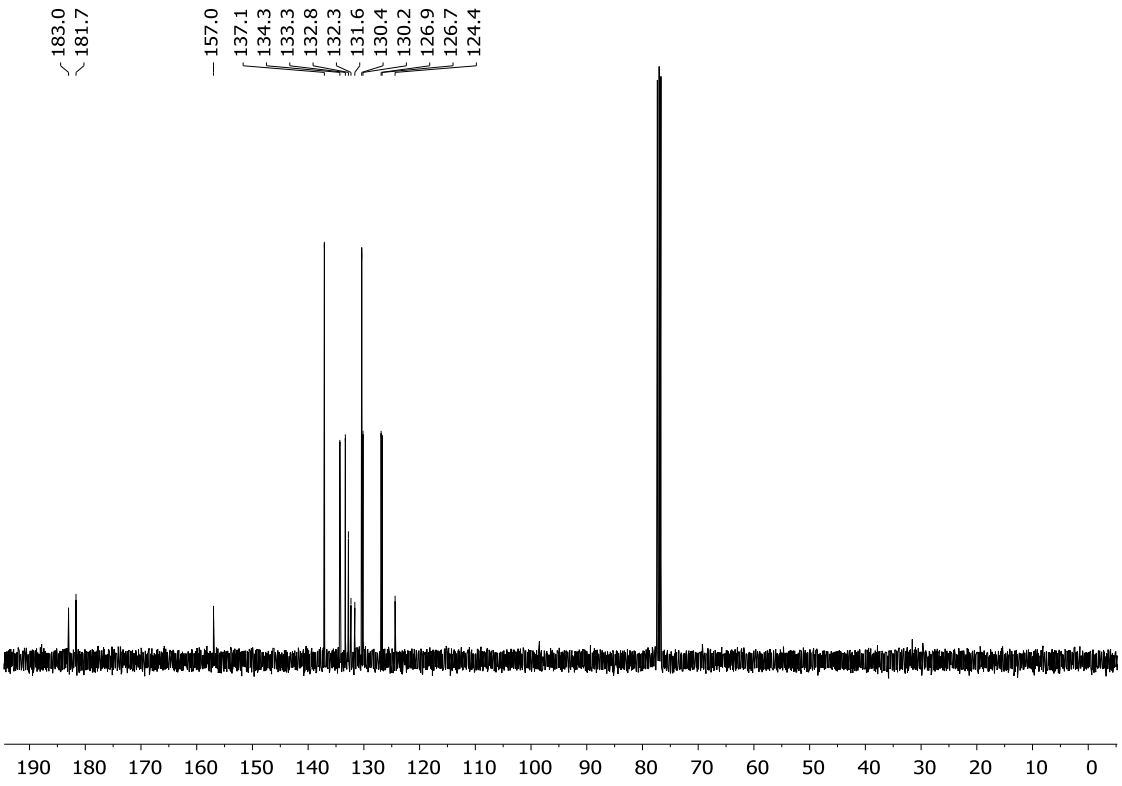


Figure 37: ^{13}C NMR spectrum (100 MHz, $CDCl_3$) of compound **6**.

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