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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). ^1H 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. $[\text{RhCp}^*\text{Cl}_2]_2$ and $[\text{RhCp}'\text{Cl}_2]_2$ were purchased from Sigma Aldrich. $[\text{RhCp}'\text{Cl}_2]_2$, $[\text{RhCp}^{\text{CF}_3}\text{Cl}_2]_2$ and $[\text{RhCp}^{i\text{-Pr}}\text{Cl}_2]_2$ 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 $[\text{M}]^+$. Cald. for $[\text{C}_7\text{H}_6\text{O}_3]$: 138.0317; ^1H 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 $[\text{M}]^+$. Cald. for $[\text{C}_8\text{H}_8\text{O}_2]$: 136.0524; ^1H 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/CH₂Cl₂); **HRMS (EI⁺)**: 175.9421 [M]⁺. Cald. for [C₆H₂Cl₂O₂]: 175.9432; **¹H NMR (400 MHz, CDCl₃)** δ : 6.97 (s, 2H); **¹³C NMR (100 MHz, CDCl₃)** δ : 177.4, 141.2, 136.1. Data are consistent with those reported in the literature.⁴

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

In a glovebox, an oven dried re-sealable tube was charged with the corresponding benzoquinone (0.10 mmol), [RhCp^{*}Cl₂]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 CH₂Cl₂ (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/CH₂Cl₂); **IR (solid, cm⁻¹)** ν : 3042 (w), 1644 (s), 1269 (s), 914 (s); **HRMS (EI⁺)**: 233.9174 [M]⁺. Cald. for [C₆H₃IO₂]: 233.9178; **Elemental analysis – Calculated (%)** C: 30.80 H: 1.29. **Found (%)** C: 31.01 H: 1.30; **¹H NMR (400 MHz, CDCl₃)** δ : 7.67 (d, J = 2.4 Hz, C3-H), 7.00 (d, J = 10.0 Hz, C6-H), 6.84 (dd, J = 10.1, 2.4 Hz, C5-H); **¹³C NMR (100 MHz, CDCl₃)** δ : 184.0 (C4), 180.2 (C1), 146.1 (C3), 136.6 (C5), 134.56 (C6), 119.6 (C2). 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/CH₂Cl₂); **IR (solid, cm⁻¹)** ν : 3027 (w), 1698 (s),

1354 (s), 991 (s); **HRMS (EI⁺)**: 261.9493 [M]⁺. Cald. for [C₇H₅IO₃]: 263.9283; **Elemental analysis – Calculated (%)** C: 31.85 **H**: 1.91. **Found (%)** C: 32.10 **H**: 1.93; **¹H NMR (400 MHz, CDCl₃)** δ : 6.91 (d, *J* = 10.0 Hz, C6-H), 6.67 (d, *J* = 10.0 Hz, C5-H), 4.21 (s, C7-H₃); **¹³C NMR (100 MHz, CDCl₃)** δ : 181.73 (C1), 179.36 (C4), 161.43 (C3), 135.10 (C6), 134.66 (C5), 100.93 (C2), 61.67 (C7).

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 [C₈H₇IO₂]: 261.9491; **¹H NMR (400 MHz, CDCl₃)** δ : 7.60 (s, C3-H), 2.11 (d, *J* = 1.2 Hz, C8-H₃), 2.03 (d, *J* = 1.2 Hz, C7-H₃); **¹³C NMR (100 MHz, CDCl₃)** δ : 184.4 (C4), 180.4 (C1), 146.0 (C3), 141.4 (C5), 140.0 (C6), 119.0 (C2), 13.7 (C8), 12.4 (C7). The structural assignment of the product was supported by **HMBC** analysis, as indicated above.

2-Iodo-6-methyl-1,4-benzoquinone (2da) and 2-Iodo-5-methyl-1,4-benzoquinone (2db)

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 **2da** and **2db** (mixture of isomers, 5:4/**a:b**) (20 mg, 81% yield) as an orange powder; **HRMS (EI⁺)**: 247.9326 [M]⁺. Calcd. for [C₇H₅IO₂]: 247.9334; **¹H NMR (500 MHz, CDCl₃)** δ : 7.64 (d, J = 1.4 Hz, C3**b**-H), 7.59 (dd, J = 2.4, 1.5 Hz, C3**a**-H), 6.84 (t, J = 1.6 Hz, C6**b**-H), 6.66 (dt, J = 2.4, 1.5 Hz, C5**a**-H), 2.14 (t, J = 1.5 Hz, C7**a**-H₃), 2.07 (t, J = 1.5 Hz, C7**b**-H₃); **¹³C NMR (125 MHz, CDCl₃)** δ : 184.6 (C4**b**), 184.5 (C4**a**), 180.8 (C1**a**), 180.4 (C1**b**), 146.4 (C5**b**), 146.2 (C3**a**), 146.1 (C3**b**), 144.6 (C6**a**), 133.5 (C5**a**), 131.4 (C6**b**), 119.7 (C2-**Ib**), 119.3 (C2-**Ia**), 17.3 (C7**a**), 15.8 (C7**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/CH₂Cl₂); **IR (solid, cm⁻¹)** ν : 2960 (s), 1651 (s), 1180 (s), 1009 (s); **HRMS (EI⁺)**: 289.9798 [M]⁺. Cald. for [C₁₀H₁₁IO₂]: 289.9804; **Elemental analysis – Calculated (%)** C: 41.40 **H**: 3.82. **Found (%)** C: 41.69 **H**: 3.85; **¹H NMR (400 MHz, CDCl₃)** δ : 7.54 (s, C3-H), 6.81 (s, C6-H), 1.27 (s, C8-H); **¹³C NMR (100 MHz, CDCl₃)** δ : 184.2 (C4), 181.3 (C1), 156.6 (C5), 147.9 (C3), 129.8 (C6), 117.5 (C2), 35.5 (C7), 29.0 (C8). 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/CH₂Cl₂); **IR (solid, cm⁻¹)** ν : 2965 (s), 1689 (s), 1218 (s), 1124 (s); **HRMS (EI⁺)**: 289.9807 [M]⁺. Cald. for [C₁₀H₁₁IO₂]: 289.9804; **¹H NMR (400 MHz, CDCl₃)** δ : 7.59 (d, *J* = 2.4 Hz, C3-H), 6.65 (d, *J* = 2.4 Hz, C5-H), 1.28 (s, C8-H); **¹³C NMR (100 MHz, CDCl₃)** δ : 185.3 (C4), 179.9 (C1), 155.1 (C6), 145.1 (C3), 131.9 (C5), 122.7 (C2), 36.2 (C7), 29.1 (C8). 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/CH₂Cl₂); **IR** (solid, cm⁻¹) ν : 2973 (w), 1667 (s), 1046 (m), 881 (s); **HRMS** (EI⁺): 301.8402 [M]⁺. Cald. for [C₆HICl₂O₂]: 301.8398; **Elemental analysis** – Calculated (%) C: 23.79 H: 0.33. Found (%) C: 23.98 H: 0.33; **¹H NMR** (400 MHz, CDCl₃) δ : 7.83 (s, C3-H); **¹³C NMR** (100 MHz, CDCl₃) δ : 175.3 (C4), 171.9 (C1), 145.2 (C3), 141.6 (C5), 138.2 (C6), 117.4 (C2). 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/CH₂Cl₂); **IR** (solid, cm⁻¹) ν : 3042 (w), 1661 (s), 1276 (s), 967 (s); **HRMS** (EI⁺): 185.9312 [M]⁺. Cald. for [C₆H₃BrO₂]: 185.9316; **Elemental analysis** – Calculated (%) C: 38.54 H: 1.62. Found (%) C: 38.77 H: 1.63; **¹H NMR** (400 MHz, CDCl₃) δ : 7.29 (d, *J* = 2.4 Hz, C3-H), 6.96 (d, *J* = 10.1 Hz, C6-H), 6.82 (dd, *J* = 10.1, 2.4 Hz, C5-H); **¹³C NMR** (100 MHz, CDCl₃) δ : 184.55 (C4), 179.17 (C1), 138.12 (C3), 137.50 (C2), 136.63 (C5), 135.79 (C6). 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/CH₂Cl₂); **IR** (solid, cm⁻¹) ν : 2960 (w), 1651 (s), 1555 (s), 1092 (s); **HRMS** (EI⁺): 215.9410 [M]⁺. Cald. for [C₇H₅BrO₃]: 215.9422; **Elemental analysis** – **Calculated** (%) C: 38.74 H: 2.32. **Found** (%) C: 39.09 H: 2.34; ¹H NMR (400 MHz, CDCl₃) δ : 6.87 (d, *J* = 10.0 Hz, C6-H), 6.68 (d, *J* = 10.1 Hz, C5-H), 4.21 (s, C7-H₃); ¹³C NMR (100 MHz, CDCl₃) δ : 180.8 (C4), 180.3 (C1), 157.0 (C3), 135.8 (C6), 134.6 (C5), 118.5 (C2), 61.6 (C7). 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/CH₂Cl₂); **IR** (solid, cm⁻¹) ν : 2987 (w), 1596 (s), 1233 (s), 870 (s); **HRMS** (EI⁺): 199.9461 [M]⁺. Cald. for [C₇H₅BrO₂]: 199.9473; **Elemental analysis** – **Calculated** (%) C: 41.83 H: 2.51. **Found** (%) C:

41.74 **H**: 2.66; ^1H NMR (400 MHz, CDCl_3) δ : 6.92 (d, $J = 10.0$ Hz, C6-H), 6.81 (d, $J = 10.0$ Hz, C5-H), 2.23 (s, C7-H₃); ^{13}C NMR (100 MHz, CDCl_3) δ : 183.9 (C4), 179.1 (C1), 146.2 (C3), 136.3 (C5), 136.1 (C2), 135.8 (C6), 16.9 (C7). 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.** ($^{\circ}\text{C}$) = 100.2-101.1 (Petrol/ CH_2Cl_2); **IR** (solid, cm^{-1}) ν : 2963 (s), 1654 (s), 1013 (s), 733 (s); **HRMS** (EI^+): 241.9932 $[\text{M}]^+$. Cald. for $[\text{C}_{10}\text{H}_{11}\text{BrO}_2]$: 241.9942; **Elemental analysis** – Calculated (%) **C**: 49.39 **H**: 4.56. **Found** (%) **C**: 49.39 **H**: 4.44; ^1H NMR (400 MHz, CDCl_3) δ : 7.19 (s, C3-H), 6.78 (s, C6-H), 1.28 (s, C8 -H₉); ^{13}C NMR (100 MHz, CDCl_3) δ : 184.7 (C4), 180.4 (C1), 156.7 (C5), 139.9 (C3), 135.7 (C2), 130.9 (C6), 35.5 (C7), 29.1 (C8). 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'**: ^1H 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/CH₂Cl₂); **IR** (solid, cm⁻¹) ν : 2970 (w), 1671 (s), 1187 (m), 1052 (s); **HRMS** (EI⁺): 253.8542 [M]⁺. Cald. for [C₆HBrCl₂O₂]: 253.8537; **Elemental analysis – Calculated (%)** C: 28.16 H: 0.39. **Found (%)** C: 28.30 H: 0.39; **¹H NMR** (400 MHz, CDCl₃) δ : 7.46 (s, C3-H); **¹³C NMR** (100 MHz, CDCl₃) δ : 175.3 (C4), 171.0 (C1), 141.4 (C5), 140.1 (C6), 137.4 (C3), 136.6 (C2). 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/CH₂Cl₂); **IR** (solid, cm⁻¹) ν : 2921 (w), 1631 (s), 1279 (m), 967 (s); **HRMS** (EI⁺): 263.9682 [M]⁺. Cald. for [C₁₂H₈SeO₂]: 263.9690; **Elemental analysis – Calculated (%)** C: 54.77 H: 3.06. **Found (%)** C: 54.99 H: 3.07; **¹H NMR** (400 MHz, CDCl₃) δ : 7.64-7.53 (m, C8-H, C12-H), 7.53-7.39 (m, C9-H, C10-H, C11-H), 6.85 (d, *J* = 10.0 Hz, C6-H), 6.68 (dd, *J* = 10.0, 2.4 Hz, C5-H), 6.15

(d, $J = 2.4$ Hz, C3-H); ^{13}C NMR (100 MHz, CDCl_3) δ : 184.8 (C1), 184.1 (C4), 154.5 (C2), 137.5 (C5), 137.0 (C8), 135.9 (C6), 130.5 (C3), 130.4 (C9), 130.2 (C10), 123.9 (C7). 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.** ($^{\circ}\text{C}$) = 230.3-231.0 (Petrol/ CH_2Cl_2); **IR** (solid, cm^{-1}) ν : 3055 (w), 1634 (s), 1546 (m), 990 (s); **HRMS** (ESI^+): 420.9263 $[\text{M}+\text{H}]^+$. Cald. for $[\text{C}_{18}\text{H}_{13}\text{Se}_2\text{O}_2]$: 420.9244; **Elemental analysis** – Calculated (%) C: 51.70 H: 2.89. Found (%) C: 52.11 H: 2.91; ^1H NMR (400 MHz, CDCl_3) δ : 7.63-7.53 (m, C8-H), 7.54-7.39 (m, C9-H, C10-H), 6.21 (s, C3-H, C6-H); ^{13}C NMR (100 MHz, CDCl_3) δ : 181.38 (C1, C4), 157.1 (C2, C5), 136.9 (C8), 130.4 (C9), 130.2 (C10), 129.4 (C3, C6), 124.1 (C7). 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/CH₂Cl₂); **IR** (solid, cm⁻¹) ν : 2930 (w), 1634 (s), 1236 (m), 746 (s); **HRMS** (EI⁺): 292.0006 [M]⁺. Cald. for [C₁₄H₁₂SeO₂]: 292.0003; **Elemental analysis** – Calculated (%) C: 57.74 H: 4.15. Found (%) C: 58.17 H: 4.18; **¹H NMR** (500 MHz, CDCl₃) δ : 7.62-7.54 (m, C8-H), 7.51-7.37 (m, C9-H, C10-H), 6.11 (s, C3-H), 2.06 (s, C13-H₃), 1.99 (s, C14-H₃); **¹³C NMR** (125 MHz, CDCl₃) δ : 184.9 (C1), 184.2 (C4), 153.6 (C2), 141.9 (C6), 140.5 (C5), 137.0 (C8), 130.5 (C3), 130.2 (C9), 129.9 (C10), 124.5 (C7), 12.4 (C13, C14). The structural assignment of the product was supported by **HMBC** analysis, as indicated above.

5-(*tert*-Butyl)-2-(phenylselanyl)-1,4-benzoquinone (4ea) and 6-(*tert*-butyl)-2-(phenylselanyl)-1,4-benzoquinone (4eb)

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 **4ea** and **4eb** (mixture of isomers, 5:2/*a:b*) (19.5 mg, 61% yield) as a red oil; **HRMS** (EI⁺): 321.0405 [M+H]⁺. Cald. for [C₁₆H₁₇O₂Se]: 321.0393; **¹H NMR** (400 MHz, CDCl₃) δ : 7.65 - 7.58 (m, 5H), 7.52 - 7.41 (m, 5H), 6.69 (s, C3a-H), 6.52 (d, *J* = 2.4 Hz C3b-H), 6.11 (d, *J* = 2.4 Hz, C6b-H), 6.07 (s, C6a-H), 1.32 (s, C8b-H₉), 1.27 (s, C8a-H₉); **¹³C NMR** (125 MHz, CDCl₃) δ : 185.7 (C1a), 185.0 (C4b), 184.8 (C1b), 184.3 (C4a), 157.2 (C5a), 155.8 (C6a) 152.0

(C6b), 137.0 (C11a, C12a, C13a), 132.6 (C3a), 132.5 (C3b), 130.9 (C10b, C14b), 130.3 (C11b, C12b, C13b, C9a), 130.1 (C9b), 130.0 (C10a, C14a), 129.7 (C5b), 124.7 (C2b), 124.1 (C2a), 35.4 (C7a, C7b), 29.3 (C8a), 29.2 (C8b). 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/CH₂Cl₂); **IR** (solid, cm⁻¹) ν : 2930 (w), 1664 (s), 1296 (m), 690 (s); **HRMS** (EI⁺): 313.9848 [M]⁺. Calcd. for [C₁₆H₁₀SeO₂]: 313.9846; **Elemental analysis – Calculated (%)** C: 61.36 **H:** 3.22. **Found (%)** C: 61.43 **H:** 3.56; **¹H NMR** (400 MHz, CDCl₃) δ : 8.14 (dd, *J* = 7.2, 1.9 Hz, C8-H), 8.03 (dd, *J* = 6.1, 1.9 Hz, C5-H), 7.82-7.67 (m, C6-H, C7-H), 7.68-7.61 (m, C10-H), 7.57-7.42 (m, C11-H, C12-H), 6.40 (s, C3-H); **¹³C NMR** (100 MHz, CDCl₃) δ : 183.0 (C1), 181.7 (C4), 157.0 (C2), 137.1 (C10), 134.3 (C6), 133.3 (C7), 132.8 (C3), 132.3 (C4a), 131.6 (C8a), 130.4 (C11), 130.2 (C12), 126.9 (C8), 126.7 (C5), 124.4 (C9). 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/CH₂Cl₂); **HRMS (EI⁺):** 200.0468 [M]⁺. Cald. for [C₁₂H₈O₃]: 200.0473; **¹H NMR (400 MHz, CDCl₃) 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); **¹³C NMR (100 MHz, CDCl₃) 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 H₂O (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/CH₂Cl₂); **MS (EI⁺):** 199.1 [M]⁺. Cald. for [C₁₂H₉NO₂]: 199.1; **¹H NMR (400 MHz, CDCl₃) δ:** 8.14 (s, 1H), 7.10-6.95 (m, 4H), 6.63-6.51 (m, 4H); **¹³C NMR (100 MHz, CDCl₃) 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^tbpf)Cl₂ (5 mol %, 3.7 mg), CuI (20 mol %, 4.0 mg) and CsF (0.20 mmol, 30.0 mg). The tube was purged with N₂ and PhSnBu₃ (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 CH₂Cl₂ (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/CH₂Cl₂); **HRMS (EI⁺)**: 184.0511 [M]⁺. Cald. for [C₁₂H₈O₂]: 184.0524; **¹H NMR (400 MHz, CDCl₃)** δ: 7.52-7.39 (m, 5H), 6.92-6.79 (m, 3H); **¹³C NMR (100 MHz, CDCl₃)** 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 procedure¹³ with small modifications. A oven dried re-sealable tube was charged with **2a** (0.10 mmol, 23.4 mg), Pd(d^tbpf)Cl₂ (5 mol %, 3.7 mg), Na₂CO₃ (200 mol %, 21.2 mg) and (4-fluorophenyl)boronic acid (0.11 mmol, 15.4 mg). The tube was purged with N₂ 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 CH₂Cl₂ (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/CH₂Cl₂); **MS (EI⁺)**: 202.0 [M]⁺. Cald. for [C₁₂H₇FO₂]: 202.0; **¹H NMR (400 MHz, CDCl₃)** δ : 7.48-7.51 (m, 2H), 7.12-7.14 (m, 2H), 6.80-6.89 (m, 3H); **¹³C NMR (100 MHz, CDCl₃)** 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 **d₄-1a**

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 d₃-**2a** was obtained as determined by ¹H/²H NMR analysis against a 1:1 mixture of **1a** and d₄-**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: ¹H NMR spectra (400 MHz, CDCl₃) and ²H NMR spectra (400 MHz, CHCl₃) for determination of the **2a**/d₃-**2a** ratio. A 1:1 ratio of benzoquinone:d₄-benzoquinone was used as a standard.

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

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

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

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

Figure 8: ¹H NMR spectrum (400 MHz, CDCl₃) of compound 2c.

Figure 9: ¹³C NMR spectrum (100 MHz, CDCl₃) of compound 2c.

Figure 10: ¹H NMR spectrum (500 MHz, CDCl₃) of compound **2d**.

Figure 11: ¹³C NMR spectrum (125 MHz, CDCl₃) of compound **2d**.

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

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

Figure 14: ¹H NMR spectrum (400 MHz, CDCl₃) of compound **2e'**.

Figure 15: ¹³C NMR spectrum (100 MHz, CDCl₃) of compound **2e'**.

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

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

Figure 18: ¹H NMR spectrum (400 MHz, CDCl₃) of compound **3a**.

Figure 19: ¹³C NMR spectrum (100 MHz, CDCl₃) of compound **3a**.

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

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

Figure 22: ¹H NMR spectrum (400 MHz, CDCl₃) of compound **3d**.

Figure 23: ¹³C NMR spectrum (100 MHz, CDCl₃) of compound **3d**.

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

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

Figure 26: ¹H NMR spectrum (400 MHz, CDCl₃) of compound **3f**.

Figure 27: ¹³C NMR spectrum (100 MHz, CDCl₃) of compound **3f**.

Figure 28: ¹H NMR spectrum (400 MHz, CDCl₃) of compound **4a'**.

Figure 29: ¹³C NMR spectrum (100 MHz, CDCl₃) of compound **4a'**.

Figure 30: ¹H NMR spectrum (400 MHz, CDCl₃) of compound **4a**.

Figure 31: ¹³C NMR spectrum (100 MHz, CDCl₃) of compound **4a**.

Figure 32: ¹H NMR spectrum (500 MHz, CDCl₃) of compound **4c**.

Figure 33: ¹³C NMR spectrum (125 MHz, CDCl₃) of compound **4c**.

Figure 34: ¹H NMR spectrum (400 MHz, CDCl₃) of compound 4e.

Figure 35: ¹³C NMR spectrum (100 MHz, CDCl₃) of compound 4e.

Figure 36: ¹H NMR spectrum (400 MHz, CDCl₃) of compound 6.

Figure 37: ¹³C NMR spectrum (100 MHz, CDCl₃) of compound 6.

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