Acids Direct 2-Styrylcyclobutanone into Two Distinctly Different Reaction Pathways

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Supporting Information

General. All reactions were carried out under a nitrogen atmosphere. Column chromatography was performed with silica gel 60 N (Kanto). Preparative thin-layer chromatography was performed with silica gel 60 PF₂₅₄ (Merck). ¹H and ¹³C NMR spectra were recorded on a Varian Gemini 2000 (¹H at 300.07 Hz and ¹³C at 75.46 Hz) spectrometer or a Varian Mercury 400 (¹H at 400.44 MHz). All NMR data were obtained in CDCl₃. Proton chemical shifts were referenced to the residual proton signal of the solvent at 7.26 ppm. Carbon chemical shifts were referenced to the carbon signal of the solvent at 77.00 ppm. High resolution mass spectra (EI) were recorded on a JEOL JMS-SX102A spectrometer. IR spectra were recorded on a Shimadzu FTIR-8100 spectrometer.

Materials. Unless otherwise noted, all chemicals and anhydrous solvents were obtained from commercial suppliers and used as received. Chlorobenzene and 1,4-dioxane were distilled from P₄O₁₀ and sodium–benzophenone ketyl, respectively, under nitrogen atmosphere. Ytterbium(III) chloride was prepared by heating YbCl₃·6H₂O under reduced pressure (140–150 °C/5 mmHg) for 2 h. Triphenylboroxin–pyridine complex,¹ cyclopropyldiphenylsulfonium tetrafluoroborate,² and 2-vinylbenzophenone³ were prepared according to the literature procedures.

(1) Kerins, F.; O'Shea, D. F. *J. Org. Chem.* **2002**, 67, 4968.

(2) Bogdanowicz, M. J.; Trost, B. M. *Org. Synth. Coll. Vol.* VI, p 34.

(3) Jason, M. E. *Tetrahedron Lett.* **1982**, 23, 1635.

Typical Procedures for the Preparation of 2-(*o*-Styryl)cyclobutanones **1**.

Procedure A: 2-Methyl-2-(2-vinylphenyl)cyclobutanone (1a**).** A solution of *o*-bromoacetophenone (8.07 g, 40.6 mmol) and tetrakis(triphenylphosphine)palladium(0) (463 mg, 0.40 mmol) in 1,2-dimethoxyethane (320 mL) was stirred for 20 min. To the mixture were added K_2CO_3 (5.61 g, 41.0 mmol), water (100 mL), and trivinylboroxin–pyridine complex (7.23 g, 30.0 mmol), and the mixture was stirred under reflux 14 h. The reaction mixture was extracted with Et_2O , dried over Na_2SO_4 , diluted with hexane, filtered, and concentrated. The residue was purified by column chromatography on silica gel (hexane:AcOEt = 10:1) to give *o*-vinylacetophenone (5.66 g, 95%). To a mixture of cyclopropyldiphenylsulfonium tetrafluoroborate (13.6 g, 43.3 mmol), *o*-vinylacetophenone (5.14 g, 35.2 mmol), and DMSO (90 mL) was added powdered KOH (3.95 g, 70.4 mmol), and the mixture was stirred at ambient temperature for 2 h. The reaction mixture was extracted with hexane, washed with saturated $NaHCO_3$ aqueous solution, dried over Na_2SO_4 , filtered, and concentrated. To the crude oxaspiropentane were added $LiClO_4$ (372 mg, 3.5 mmol) and benzene (250 mL), and the mixture was stirred under reflux overnight. The reaction mixture was cooled to ambient temperature, filtered, and concentrated. The residue was purified by column chromatography on silica gel (hexane:AcOEt = 15:1) to give **1a** (5.26 g, 80%): 1H NMR (300 MHz) δ 2.29 (ddd, J = 11.3, 9.9, 6.5 Hz, 1H), 2.54 (dt, J = 10.9, 7.1 Hz, 1H), 3.06 (ddd, J = 18.1, 10.7, 6.5 Hz, 1H), 3.15 (ddd, J = 18.1, 9.7, 7.1 Hz, 1H), 5.33 (d, J = 10.8 Hz, 1H), 5.67 (d, J = 17.2 Hz, 1H), 6.99 (dd, J = 17.2, 10.8 Hz, 1H), 7.19–7.27 (m, 2H), 7.56–7.60 (m, 2H); ^{13}C NMR δ 25.4, 27.5, 42.7, 67.6, 115.3, 125.6, 127.03, 127.08, 127.6, 135.0, 135.3, 139.5, 212.2; HRMS (EI) calcd for $C_{13}H_{14}O$ (M^+) 186.1045, found 186.1044.

Procedure B: 2-(4,5-dimethoxy-2-vinylphenyl)cyclobutanone (1d). To a mixture of tetrakis(triphenylphosphine)palladium(0) (231 mg, 0.20 mmol), 2,6-di-*t*-butyl-*p*-cresol (331 mg, 1.50 mmol), and 2-bromo-4,5-dimethoxybenzaldehyde (2.61 g, 10.7 mmol) in toluene (16.0 mL) was added a toluene solution (9.0 mL) of tributylvinylstannane (3.81 g, 12.0 mmol), and the mixture was stirred under reflux for 7 h. The reaction mixture was poured into saturated KF aqueous solution, extracted with Et₂O, dried over MgSO₄, and concentrated. The residue was purified by column chromatography on silica gel (hexane:AcOEt = 3:1) to give 2-vinyl-4,5-dimethoxybenzaldehyde (1.18 g, 58%). A suspension of dry NaH (192 mg, 8.00 mmol), 3-bromopropyltriphenylphosphonium bromide (1.86 g, 4.01 mmol), and a few drops of EtOH in 1,2-dimethoxyethane (6.0 mL) was stirred at 65 °C for 4 h. To the mixture was added a DME solution (3.0 mL) of 2-vinyl-4,5-dimethoxybenzaldehyde (769 mg, 4.00 mmol), and the mixture was stirred at 65 °C for 3 h. The solvent was removed under reduced pressure, and the residue was purified by column chromatography on silica gel (hexane:AcOEt = 3:1) to give 1-cyclopropylidenemethyl-4,5-dimethoxy-2-vinylbenzene (533 mg, 62%). To a CH₂Cl₂ solution (14 mL) of 1-cyclopropylidenemethyl-4,5-dimethoxy-2-vinylbenzene (533 mg, 2.46 mmol) was added *m*-chloroperbenzoic acid (551 mg, 2.46 mmol) at 0 °C, and the mixture was stirred at 0 °C for 8 h. The reaction mixture was washed with saturated NaHCO₃ aqueous solution and brine, dried over MgSO₄, and concentrated. The residue was dissolved in CH₂Cl₂ (21 mL), and 15% HBF₄ aqueous solution was added to the solution at ambient temperature. After being stirred for 9 h, the mixture was extracted with CH₂Cl₂, washed with saturated NaHCO₃ aqueous solution and brine, dried over MgSO₄, and concentrated. The residue was purified by preparative thin-layer chromatography

(hexane:AcOEt = 3/1) to give **1d** (243 mg, 42%): ^1H NMR (300 MHz) δ 2.11 (ddt, J = 10.6, 9.7, 8.2 Hz, 1H), 2.57 (dq, J = 4.7, 10.8 Hz, 1H), 3.03 (dddd, J = 18.0, 9.7, 4.7, 2.3 Hz, 1H), 3.22 (dddd, J = 18.0, 10.6, 8.2, 2.3 Hz, 1H), 3.88 (s, 3H), 3.90 (s, 3H), 4.73 (ddt, J = 10.6, 8.2, 2.3 Hz, 1H), 5.25 (dd, J = 10.8, 1.2 Hz, 1H), 5.55 (dd, J = 17.1, 1.2 Hz, 1H), 6.83 (dd, J = 17.1, 10.8 Hz, 1H), 6.85 (s, 1H), 7.02 (s, 1H); ^{13}C NMR δ 19.4, 44.6, 55.9, 56.0, 61.7, 108.9, 109.6, 114.4, 127.0, 128.8, 133.9, 148.0, 148.7, 208.4; HRMS calcd for $\text{C}_{14}\text{H}_{16}\text{O}_3$ (M^+) 232.1099, found 232.1095.

Procedure for the Synthesis of Naphthalenes 2.

2-(2-Chloroethyl)-1-methylnaphthalene (2a-Cl). To a suspension of YbCl_3 (224 mg, 0.80 mmol) in 1,4-dioxane (2.0 mL) was added a 1,4-dioxane solution (6.0 mL) of 2-(*o*-styryl)cyclobutanone **1a** (74.5 mg, 0.40 mmol). After heating under reflux for 24 h, the mixture was passed through a plug of Florisil[®] eluting with AcOEt. The solvent was removed under reduced pressure, and the residue was purified by preparative thin-layer chromatography of silica gel (hexane:AcOEt = 10:1) to give **2a** (67.7 mg, 83%): ^1H NMR (400 MHz) δ 2.68 (s, 3H), 3.32 (d, J = 7.8 Hz, 2H), 3.73 (d, J = 7.8 Hz, 2H), 7.31 (d, J = 8.4 Hz, 1H), 7.45-7.56 (m, 2H), 7.69 (d, J = 8.4 Hz, 1H), 7.82 (dd, J = 8.2, 1.0 Hz, 1H), 8.06 (dd, J = 8.4, 0.8 Hz, 1H); ^{13}C NMR δ 14.3, 37.7, 44.0, 124.1, 125.3, 126.1, 126.4, 128.2, 128.5, 131.8, 132.7, 133.0, 133.1; HRMS calcd for $\text{C}_{13}\text{H}_{13}\text{Cl}$ (M^+) 204.0706, found 204.0704.

2-(2-Bromoethyl)-1-methylnaphthalene (2a-Br).⁴ A mixture of **1a** (55.9 mg, 0.30 mmol) and YbBr₃ (248 mg, 0.60 mmol) in 1,4-dioxane (6.0 mL) was heated under reflux for 5 h. The reaction mixture was passed through a plug of Florisil[®] (AcOEt). Purification by preparative thin-layer chromatography of silica gel (hexane:AcOEt = 10:1) afforded **2a-Br** (64.3 mg, 86%): ¹H NMR (300 MHz) δ 2.68 (s, 3H), 3.40 (t, J = 8.0 Hz, 2H), 3.58 (t, J = 8.0 Hz, 2H), 7.31 (d, J = 8.4 Hz, 2H), 7.46-7.58 (m, 2H), 7.70 (d, J = 8.4 Hz, 2H), 7.83 (d, J = 8.1 Hz, 2H), 8.07 (d, J = 8.4 Hz, 2H); ¹³C NMR δ 14.4, 31.8, 38.0, 124.0, 125.2, 126.0, 126.4, 128.0, 128.4, 131.6, 132.6, 132.9, 133.9; HRMS calcd for C₁₃H₁₃Br (M⁺) 248.0201, found 248.0198.

2-(2-Chloroethyl)-1-phenylnaphthalene (2b-Cl). A mixture of **1b** (99.3 mg, 0.40 mmol) and YbCl₃ (224 mg, 0.80 mmol) in 1,4-dioxane (8.0 mL) was heated under reflux for 24 h. The reaction mixture was passed through a plug of Florisil[®] (AcOEt). Purification by preparative thin-layer chromatography of silica gel (hexane:AcOEt = 5:1) afforded **2b-Cl** (84.5 mg, 79%): mp 59-60 °C; ¹H NMR (300 MHz) δ 3.05 (t, J = 7.7 Hz, 2H), 3.61 (t, J = 7.7 Hz, 2H), 7.26-7.42 (m, 4H), 7.42-7.58 (m, 5H), 7.88 (d, J = 8.4 Hz, 2H); ¹³C NMR δ 37.1, 44.4, 125.4, 126.0, 126.5, 127.40, 127.43, 127.69, 127.72, 128.4, 130.1, 132.3, 132.96, 133.01, 138.6, 139.0; HRMS calcd for C₁₈H₁₅Cl (M⁺) 266.0862, found 266.0866.

2-(2-Bromoethyl)-1-phenylnaphthalene (2b-Br). A mixture of **1b** (74.5 mg, 0.30 mmol) and YbBr₃ (248 mg, 0.60 mmol) in 1,4-dioxane (6.0 mL) was heated under reflux for 5 h. The reaction mixture was passed through a plug of Florisil[®] (AcOEt). Purification by preparative thin-layer chromatography of silica gel (hexane:AcOEt = 10:1) afforded **2b-Br** (87.5 mg, 94%): mp 71-72 °C; ¹H NMR δ 3.13 (t, J = 7.8 Hz, 2H), 3.45 (t, J = 7.8 Hz, 2H),

(4) [107517-26-0].

7.28-7.41 (m, 4H), 7.41-7.56 (m, 5H), 7.87 (d, $J = 8.1$ Hz, 2H); ^{13}C NMR δ 32.2, 37.3, 125.4, 126.0, 126.5, 127.3, 127.4, 127.7, 127.8, 128.4, 130.1, 132.3, 133.0, 133.8, 138.6, 138.9.0; HRMS calcd for $\text{C}_{18}\text{H}_{15}\text{Br}$ (M^+) 310.0357, found 310.0360.

2-(2-Chloroethyl)naphthalene (2c-Cl).⁵ A mixture of **1c** (87.4 mg, 0.51 mmol) and YbCl_3 (280 mg, 1.00 mmol) in 1,4-dioxane (10 mL) was heated under reflux for 32 h. The reaction mixture was passed through a plug of Florisil[®] (CHCl_3). Purification by preparative thin-layer chromatography of silica gel (hexane:AcOEt = 10:1) afforded **2c-Cl** (66.2 mg, 68%). ^1H NMR (400 MHz) δ 3.26 (d, $J = 7.3$ Hz, 2H), 3.83 (d, $J = 7.3$ Hz, 2H), 7.37 (dd, $J = 8.4, 1.6$ Hz, 1H), 7.46-7.54 (m, 2H), 7.70 (s, 1H), 7.81-7.88 (m, 4H); ^{13}C NMR δ 39.2, 44.8, 125.7, 126.2, 127.0, 127.4, 127.6, 127.7, 128.3, 132.4, 133.5, 135.5; HRMS calcd for $\text{C}_{12}\text{H}_{11}\text{Cl}$ (M^+) 190.0549, found 190.0551.

6-(2-Chloroethyl)-2,3-dimethoxynaphthalene (2d-Cl).⁶ A mixture of **1d** (69.7 mg, 0.30 mmol) and YbCl_3 (168 mg, 0.60 mmol) in 1,4-dioxane (6.0 mL) was heated under reflux for 2 h. The reaction mixture was passed through a plug of Florisil[®] (AcOEt). Purification by preparative thin-layer chromatography of silica gel (hexane:AcOEt = 5:2) afforded **2d-Cl** (48.7 mg, 65%). ^1H NMR (300 MHz) δ 3.19 (t, $J = 7.5$ Hz, 2H), 3.79 (t, $J = 7.5$ Hz, 2H), 3.99 (s, 3H), 4.00 (s, 3H), 7.10 (d, $J = 4.8$ Hz, 2H), 7.20 (dd, $J = 8.3, 1.7$ Hz, 1H), 7.53 (s, 1H), 7.65 (d, $J = 8.3$ Hz, 1H); ^{13}C NMR δ 39.3, 45.1, 55.8, 106.0, 106.1, 125.2, 125.9, 126.6, 128.0, 129.2, 133.8, 149.3, 149.6; HRMS calcd for $\text{C}_{14}\text{H}_{15}\text{ClO}_2$ (M^+) 250.0761, found 250.0760.

(5) [20849-71-2].

(6) [72337-08-7].

2-(2-Chloroethyl)-1,4-dimethylnaphthalene (2e-Cl). A mixture of **1e** (108.9 mg, 0.54 mmol) and YbCl₃ (304 mg, 1.09 mmol) in 1,4-dioxane (2.7 mL) was heated under reflux for 2 h. The reaction mixture was passed through a plug of Florisil[®] (AcOEt). Purification by preparative thin-layer chromatography of silica gel (hexane:AcOEt = 10:1) afforded **2e-Cl** (60.5 mg, 51%). ¹H NMR (300 MHz) δ 2.64 (s, 3H), 2.66 (s, 3H), 3.22-3.29 (m, 2H), 3.66-3.73 (m, 2H), 7.14 (s, 1H), 7.46-7.56 (m, 2H), 7.94-8.00 (m, 1H), 8.02-8.09 (m, 1H); ¹³C NMR δ 14.4, 19.3, 37.8, 44.1, 124.5, 124.6, 125.1, 125.7, 129.0, 129.7, 131.8, 132.3, 132.5, 133.0; HRMS calcd for C₁₄H₁₅Cl 218.0862, found 218.0865.

9-(2-Chloroethyl)-10-methylphenanthrene (2f-Cl). A mixture of **1f** (94.5 mg, 0.40 mmol) and YbCl₃ (224 mg, 0.80 mmol) in Bu₂O (8.0 mL) was heated under reflux for 2 h. The reaction mixture was passed through a plug of Florisil[®] (AcOEt). Purification by preparative thin-layer chromatography of silica gel (hexane:AcOEt = 10:1) afforded **2f-Cl** (49.7 mg, 49%): ¹H NMR (300 MHz) δ 2.77 (s, 3H), 3.68-3.81 (m, 4H), 7.61-7.69 (m, 4H), 8.08-8.16 (m, 2H), 8.70-8.75 (m, 2H); ¹³C NMR δ 15.9, 33.1, 42.8, 122.7, 123.1, 123.8, 124.8, 125.7, 126.2, 126.8, 127.0, 129.1, 129.75, 129.78, 130.7, 131.0, 131.7; HRMS calcd for C₁₇H₁₅Cl (M⁺) 254.0862, found 254.0862.

Procedure for the Synthesis of Eight-Membered Ring Ketones **5**.

10-Methyl-9,10-dihydrobenzocycloocten-7(8H)-one (5a). To a suspension of Yb(OTf)₃ (49.6 mg, 0.080 mmol) in chlorobenzene (2.0 mL) was added a chlorobenzene solution (6.0 mL) of 2-(*o*-styryl)cyclobutanone **1a** (74.5 mg, 0.40 mmol). After heating under reflux for 3 h, the mixture was passed through a pad of Florisil® (AcOEt). The solvent was removed under reduced pressure, and the residue was purified by preparative thin-layer chromatography of silica gel (toluene:AcOEt = 15:1) to give **5a** (61.4 mg, 82%): IR (nujol) 1653.2 cm⁻¹; ¹H NMR (400 MHz) δ 1.34 (d, *J* = 6.8 Hz, 3H), 1.56-1.66 (m, 1H), 2.14-2.24 (m, 2H), 2.34-2.44 (m, 1H), 3.11-3.22 (m, 1H), 6.19 (dd, *J* = 12.7, 1.8 Hz, 1H), 7.12 (d, *J* = 12.7 Hz, 1H), 7.25-7.32 (m, 2H), 7.37-7.42 (m, 2H); ¹³C NMR δ 19.6, 33.5, 39.0, 40.8, 125.1, 126.1, 129.7, 130.2, 132.3, 135.7, 141.2, 144.6, 203.9; HRMS calcd for C₁₃H₁₄O (M⁺) 186.1045, found 186.1046.

10-Phenyl-9,10-dihydrobenzocycloocten-7(8H)-one (5b). A mixture of **1b** (99.3 mg, 0.40 mmol) and Yb(OTf)₃ (49.6 mg, 0.080 mmol) in PhCl (8.0 mL) was heated under reflux for 10 h. The reaction mixture was passed through a plug of Florisil® (AcOEt). Purification by preparative thin-layer chromatography of silica gel (hexane:AcOEt = 5:1) afforded **5b** (89.6 mg, 90%): mp 94-95 °C; ¹H NMR (300 MHz) δ 2.30-2.61 (m, 4H), 4.47 (dd, *J* = 13.4, 3.6 Hz, 1H), 6.30 (dt, *J* = 12.8, 1.6 Hz, 1H), 6.89 (d, *J* = 7.6 Hz, 1H), 7.20-7.34 (m, 9H); ¹³C NMR δ 36.1, 38.5, 44.1, 126.1, 126.6, 128.27, 128.34, 129.6, 129.8, 132.7, 135.6, 141.1, 142.9, 144.2, 203.2; HRMS calcd for C₁₈H₁₆O (M⁺) 248.1201, found 248.1195.

9,10-dihydrobenzocycloocten-7(8H)-one (5c).⁷ A mixture of **1c** (86.3 mg, 0.50 mmol) and Yb(OTf)₃ (62.0 mg, 0.10 mmol) in PhCl (10 mL) was heated under reflux for 8 h. The

(7) [144744-96-7]. Matsuda, T.; Fujimoto, A.; Ishibashi, M.; Murakami, M. *Chem. Lett.* **2004**, 33, 876.

reaction mixture was passed through a plug of Florisil® (CHCl₃). Purification by preparative thin-layer chromatography of silica gel (hexane:AcOEt = 10:1) afforded **5c** (54.9 mg, 64%): ¹H NMR (400 MHz) δ 2.04-2.12 (m, 2H), 2.33-2.37 (m, 2H), 2.75-2.80 (m, 2H), 6.16 (d, *J* = 12.8 Hz, 1H), 7.11 (d, *J* = 12.8 Hz, 1H), 7.25-7.37 (m, 4H); ¹³C NMR δ 32.0, 32.5, 37.9, 126.5, 129.7, 129.9, 130.8, 132.0, 135.7, 140.8, 141.2, 204.3. Anal. Calcd. For C₁₂H₁₂O: C, 83.69; H, 7.02. Found: C, 83.49; H, 7.05.

2,3-Dimethoxy-9,10-dihydrobenzocycloocten-7(8H)-one (5d). A mixture of **1d** (69.7 mg, 0.30 mmol) and Yb(OTf)₃ (37.2 mg, 0.060 mmol) in PhCl (6.0 mL) was heated under reflux for 2 h. The reaction mixture was passed through a plug of Florisil® (AcOEt). Purification by preparative thin-layer chromatography of silica gel (hexane:AcOEt = 5:2) afforded **5d** (58.9 mg, 85%): ¹H NMR (300 MHz) δ 2.09 (quint, *J* = 6.7 Hz, 2H), 2.37 (t, *J* = 6.7 Hz, 2H), 2.71 (t, *J* = 6.7 Hz, 2H), 3.89 (s, 3H), 3.92 (s, 3H), 6.08 (d, *J* = 12.8 Hz, 1H), 6.75 (d, *J* = 10.5 Hz, 2H), 7.02 (d, *J* = 12.8 Hz, 2H); ¹³C NMR δ 32.0, 33.2, 38.0, 55.9, 56.0, 112.2, 113.2, 128.0, 130.5, 134.4, 141.0, 147.2, 150.0, 204.3; HRMS calcd for C₁₄H₁₆O₃ (M⁺) 232.1099, found 232.1096.

2-(1,4-Dimethylnaphthalen-2-yl)ethanol (2e-OH).⁸ A mixture of **1e** (96.0 mg, 0.48 mmol) and Yb(OTf)₃ (59.5 mg, 0.096 mmol) in PhCl (2.4 mL) was heated under reflux for 3 h. The reaction mixture was passed through a plug of Florisil® (AcOEt). After washing with K₂CO₃ aqueous solution, purification by preparative thin-layer chromatography of silica gel (hexane:AcOEt = 5:1) afforded **2e-OH** (50.3 mg, 52%): ¹³C NMR δ 14.3, 19.3, 34.8, 71.4, 124.42, 124.45, 124.6, 125.4, 129.4, 129.5, 131.6, 131.8, 133.0, 133.1.

(8) [147595-50-4]. Sharma, P. K. *Synth. Commun.* **1993**, 23, 389.9

¹³C spectrum of **1a**

¹H spectrum of 2a-Cl

¹³C spectrum of **2a-Cl**

¹³C spectrum of **2a-Br**

¹H spectrum of 2c-Cl

¹H spectrum of **2c-Cl**

^1H spectrum of **2e-Cl**

¹³C spectrum of 2e-Cl

¹H spectrum of 2f-Cl

¹³C spectrum of 2f-Cl