

Supporting Information for

Catalytic, Asymmetric α -Chlorination of Acid Halides

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General. Unless otherwise stated, all reactions were carried out under strictly anhydrous, air-free conditions. All reagents used were commercially available from Aldrich, Fluka and Acros Chemicals. The jacketed addition funnels were purchased from ChemGlass. All solvents were dried and distilled by standard methods. Halogenating agents **5a**,¹ **5b**,² **5c**,³ **5e**⁴ and **5f**⁴ were prepared according to literature procedures. BEMP was purchased from Aldrich and specified as 100-200 mesh, 1% cross-linked with a typical loading of 2.0-2.5 mmol/g. All acid fluorides were prepared by standard methods.⁵ All acid halides were purified by standard procedures, usually distillation. Merck Silica Gel 60 (0.040-0.063) was used for standard chromatography. ¹H and ¹³C NMR spectra were acquired on a Varian Unity Plus 400 MHz instrument in CDCl₃. The ¹H (400 MHz) and ¹³C (101 MHz) chemical shifts are given in parts per million (δ) with respect to internal TMS standard or residual solvent peaks. FTIR spectra were recorded on a Bruker Vector 22 spectrometer and optical rotations were recorded on a Perkin Elmer 120 polarimeter at room temperature. HPLC analysis was performed with a Waters Millipore Model 510 head unit, a Chiralcel AD analytical column, a Waters Millipore Lambda-Max Model 481LC spectrophotometer and a Hewlett Packard integrator. Racemates for **6a**, **6b**, and **6h** were prepared by derivatizing commercially available α -halogenated acids. For all other substrates, equimolar mixtures of the “pseudoenantiomers” **3a** and **3b** were used as catalyst to prepare the racemic mixture (both have essentially the same catalytic activity). For photochemical reactions, a Southern New England Ultra-Violet Company Rayonet Photo Mini-Reactor (8x4W bulbs) was employed. For ReactIR experiments, an ASI Applied Systems ReactIRTM 1000 was used.

General Procedure for the Synthesis of α -Chloroesters **6** using Proton Sponge **4a**.

To a stirred solution of BQ **3a** (0.015 mmol) and proton sponge **4a** (0.165 mmol) in 10 mL toluene at -78 °C, a solution of phenylacetyl chloride (0.150 mmol) in 1 mL toluene was added dropwise. A solution of **5a** (0.150 mmol) in 1 mL toluene was added dropwise over 5 min. The solution was allowed to stir for 5 h while warming to room temperature. The reaction mixture was then quenched with water and extracted three times with Et₂O. The organic layers were combined, dried and purified by column chromatography (100% hexanes) affording **6a** in 40% yield and 95% ee.

¹ Hedayatullah, M.; Lion, C.; Tourki, A. *Bull. Soc. Chim. Belg.* **1993**, *102*, 281-291.

² Denivelle, L. *Bull. Soc. Chim. Fr.* **1956**, 1834-1836.

³ Reed, R. *J. Am. Chem. Soc.* **1958**, *80*, 219-223.

⁴ Denivelle, L. *Bull. Soc. Chim. Fr.* **1957**, 724-728.

⁵ Olah, G. A. *J. Org. Chem.* **1979**, *44*, 3872-3881.

General Procedure for the Synthesis of α -Chloroesters **6 using BEMP.** A jacketed addition funnel was plugged with glass wool above the stopcock and loaded with the BEMP resin (75 mg, 0.150 mmol) and a magnetic stir bar. It was then connected to a 10 mL three-neck round bottom flask containing BQ **3a** (0.0065 mmol) to which 1 mL THF was added. Into the addition funnel was added 2 mL THF and an overhead stirrer was positioned close to the funnel to ensure vigorous agitation of the heterogeneous BEMP/acid chloride solution. The funnel and the flask were both cooled to $-78\text{ }^{\circ}\text{C}$ and a solution of phenylacetyl chloride **1a** (0.130 mmol) in THF (1 mL) was added dropwise to the funnel and stirred vigorously for 4 min. The stopcock was opened, allowing the ketene solution to drip into the bottom flask. The chlorinating agent **5a** (0.065 mmol in 1 mL THF) was then added via syringe and the reaction was kept at $-78\text{ }^{\circ}\text{C}$ for 3 h before being allowed to slowly warm to room temperature. The reaction mixture was then adsorbed onto a plug of silica gel and underwent flash column chromatography (100% hexanes) affording **6a** in 80% yield and 99% ee.

General Procedure for the Synthesis of α -Chloroesters **6 Using Sodium Hydride.** To a suspension of NaH (0.068 g, 2.7 mmol), **3a** (0.055 g, 0.13 mmol), and 15-crown-5 (0.028 g, 0.13 mmol) in 20 mL of THF at $-78\text{ }^{\circ}\text{C}$ was added phenylacetyl chloride **1a** (0.417 g, 2.7 mmol) in THF (1 mL). A solution of the chlorinating agent **5a** (0.407 g, 1.35 mmol) in 20 mL of THF was added via syringe pump over 3 h and the reaction was subsequently allowed to warm to room temperature. It was then quenched with 150 mL of water and the aqueous layer was extracted twice with 25 mL of diethyl ether and once with 20 mL of CH_2Cl_2 . The organic layers were combined and dried with MgSO_4 , filtered and concentrated. The residue was taken up in chloroform and absorbed on silica gel before undergoing flash column chromatography (100% hexanes) affording 0.356 g (63%) of **6a** in 95% ee. A large-scale reaction was performed using 2.085 g (13.5 mmol) of phenylacetyl chloride. Accordingly, all reagents were scaled up by a factor of five under the same procedure and the reaction yielded 1.84 g (65%) of **6a** in 91% ee.

General Procedure for the Synthesis of α -Chloroesters **6 Using Sodium Bicarbonate.** To a vigorously stirred suspension of NaHCO_3 (1.3 mmol), **3a** (0.055 g, 0.13 mmol) and 15-crown-5 (0.028 g, 0.13 mmol) in 20 mL chlorobenzene at $-35\text{ }^{\circ}\text{C}$, a solution of phenylacetyl chloride (0.417 g, 2.7 mmol) in 1 mL chlorobenzene was added dropwise. A solution of **5a** (0.407 g, 1.35 mmol) in 10 mL chlorobenzene was added dropwise over 5 min. The solution was allowed to stir for 5 h while warming to room temperature. The reaction mixture was quenched with water and extracted twice with methylene chloride. The organic layers were combined, dried and purified by column chromatography (100% hexanes) affording 0.385 g (68%) of **6a** in 90% ee. A large-scale reaction was performed using 13.5 mmol) of phenylacetyl chloride. Accordingly, all reagents were scaled up by a factor of five under the same procedure and the reaction yielded 1.70 g (60%) of **6a** in 90% ee.

General Procedure for the Synthesis of Catalysts **3a and **3b**.** Quinine (5.0 g, 15.4 mmol) was dissolved in 50 mL of THF and triethylamine (7.8 g, 77.0 mmol) and cooled to $0\text{ }^{\circ}\text{C}$. Benzoyl chloride (3.25 g, 23.1 mmol) was added by syringe over 5 min and the

reaction was allowed to warm to room temperature overnight. The THF was removed under reduced pressure and the crude residue was dissolved in 70 mL CH₂Cl₂ and then washed three times with 20 mL 25% (w/w) NaOH solution. The combined aqueous fractions were back extracted with 30 mL CH₂Cl₂, the organic layers were combined, dried over MgSO₄, filtered and concentrated. The crude residue was purified on a short plug of silica with 99.5% EtOAc/0.5% triethylamine to yield a white solid (foam). The solid was recrystallized from boiling Et₂O/hexanes to yield benzoylquinine **3a** (6.21 g, 94%). All data was consistent with literature precedent.⁶

General Preparation of Chlorinating Agent 5d. To a solution of 8-hydroxyquinoline (3.0 g, 12.1 mmol) in 30 mL CH₂Cl₂, tert-butyl hypochlorite⁷ (5.4 mL, 48.3 mmol) was added dropwise. The reaction was allowed to stir at room temperature for 2 h. The solvent was removed under reduced pressure and 20 mL Et₂O was added to the crude residue. The solid was collected by vacuum filtration to afford **5d** in 84% yield as a pale solid. All data consistent with literature values.⁸

Proof of Absolute Stereochemical Configuration: (S)-2-Chloro-2-phenylacetic acid pentachlorophenyl ester (6a). White crystalline solid; analytical sample was recrystallized from hexanes; mp= 98 °C; [α]₂₅= +36 (c=0.01, CHCl₃) HPLC (99.5% Hexanes/0.5% i-PrOH, 1.0 mL/min) (S)= 8.1, (R)= 16.0 min. ¹H NMR (CDCl₃) δ 7.6 (d, 2H), 7.41 (m, 3H), 5.68 (s, 1H) ppm; ¹³C NMR (CDCl₃) δ 164.2, 143.2, 133.9, 131.9, 129.8, 128.9, 128.2, 127.4, 123.6, 58.1; IR (CHCl₃): 1791, 1420, 1263 cm⁻¹. Anal Calcd for C₁₄H₆O₂Cl₆, C, 40.4; H, 1.45; Cl, 50.45. Found C, 40.93; H, 1.61; Cl, 49.82. Proof of absolute configuration was obtained for the ethyl ester of (S)-2-Chloro-2-phenyl acetic acid ethyl ester.⁹

(R)-2-Chloro-2-phenylacetic acid pentachlorophenyl ester (6a). [α]₂₅= -35.5 (c=0.01, CHCl₃). All other data are consistent with (S)-**6a**.

(S)-2-Chloro-3-phenoxypropionic acid pentachlorophenyl ester (6b). White crystalline solid; analytical sample was recrystallized from hexanes; mp= 84-85 °C; [α]₂₅= +19.5 (c=0.01, CHCl₃) HPLC (99.7% hexanes/0.3% i-PrOH, 1.0 mL/min) (S)= 20.2, (R)= 22.4 min. ¹H NMR (CDCl₃) δ 7.27-7.31 (m, 2H), 6.89-6.99 (m, 3H), 4.79-4.82 (m, 1H), 4.45-4.47 (m, 1H) ppm; ¹³C NMR (CDCl₃) δ 163.9, 143.4, 132.5, 132.4, 129.9, 127.7, 122.3, 129.9, 127.7, 122.3, 114.9, 68.7, 53.2; IR (CHCl₃): 1793, 1466 cm⁻¹. Anal Calcd for C₁₅H₈O₃Cl₆, C, 40.13; H, 1.8; Cl, 47.06. Found C, 40.17; H, 1.96; Cl, 46.84.

(R)-2-Chloro-2-phenoxypropionic acid pentachlorophenyl ester (6b). [α]₂₅= -20 (c=0.01, CHCl₃). All other data are consistent with (S)-**6b**.

Proof of Absolute Stereochemical Configuration: (S)-2-Chloro-3-(1-naphthyl)acetic acid pentachlorophenyl ester (6c). White crystalline solid; analytical sample was

⁶ Pracejus, H.; Maetje, H. *J. Prakt. Chem.* **1964**, *24*, 195-205.

⁷ Mintz, M.J.; Walling, C.; *Organic Syntheses*, CV 5, 184.

⁸ Kobrina, L. S.; Bogachev, A. A. *J. Fluorine Chem.* **1993**, *62*, 243-258.

⁹ Puy, C. H.; Breitbeil, F. W.; DeBruin, K. R. *J. Am. Chem. Soc.* **1966**, *88*, 3347-3354.

recrystallized from hexanes; mp= 116-117 °C; $[\alpha]_{25} = +24$ (c=0.007, CHCl₃) HPLC (99.5% hexanes/0.5% i-PrOH, 1.0 mL/min) (S)= 13.7, (R)= 29.3 min. ¹H NMR (CDCl₃) δ 8.2 (d, 1H), 7.84-7.93 (m, 3H), 7.49-7.63 (m, 3H), 6.4 (s, 1H) ppm; ¹³C NMR (CDCl₃) δ 164.6, 143.4, 133.9, 132.1, 130.9, 130.8, 130.3, 129.8, 129.2, 128.8, 127.7, 127.2, 126.4, 125.3, 123.1, 56.4 ppm; IR (CHCl₃): 1792, 1642 cm⁻¹. Anal Calcd for C₁₈H₈O₂Cl₆, C, 46.37; H, 1.73; Cl, 45.04. Found C, 46.28; H, 1.69; Cl, 45.24. Proof of absolute configuration was obtained for the ethyl ester of **(S)-6d** by correlation to the literature.¹⁰

(S)-2-Chloro-2-(2-naphthyl)acetic acid pentachlorophenyl ester (6d). White crystalline solid; analytical sample was recrystallized from hexanes; mp= 124-125 °C; $[\alpha]_{25} = +42$ (c=0.007, CHCl₃) HPLC (99% hexanes/1% i-PrOH, 1.0 mL/min) (S)= 16.5, (R)= 30.9 min. ¹H NMR (CDCl₃) δ 8.07 (s, 1H), 7.88-7.94 (m, 3H), 7.71-7.74 (dd, 1H), 7.55-7.57 (m, 2H), 5.87 (s, 1H) ppm; ¹³C NMR (CDCl₃) δ 164.3, 143.3, 133.7, 132.9, 132.1, 131.3, 129.1, 128.3, 128.2, 128.1, 127.8, 127.5, 127.3, 126.9, 124.9, 58.6 ppm; IR (CHCl₃): 1790, 1672 cm⁻¹. Anal Calcd for C₁₈H₈O₂Cl₆, C, 46.37; H, 1.73; Cl, 45.04. Found C, 46.41; H, 1.72; Cl, 45.15.

2-Chlorocrotonic acid pentachlorophenyl ester (6e). White paste; analytical sample was recrystallized from hexanes. Stereochemistry was not assigned. ¹H NMR (CDCl₃) δ 7.53 (q, 1H), 2.1 (d, 3H), 7.84-7.93 (m, 3H), 7.49-7.63 (m, 3H), 6.4 (s, 1H) ppm; ¹³C NMR (CDCl₃) δ 158.6, 142.6, 132.4, 132.2, 127.9, 123.8, 119.9, 15.9 ppm; IR (CHCl₃): 1766, 1630 cm⁻¹. Anal Calcd for C₁₀H₄O₂Cl₆, C, 32.56; H, 1.09; Cl, 57.67. Found C, 32.78; H, 1.13; Cl, 57.26.

(S)-2-Bromo-2-chloroacetic acid pentachlorophenyl ester (6f). White crystalline solid; analytical sample was recrystallized from hexanes; mp= 71-73 °C; $[\alpha]_{25} = +21$ (c=0.01, CHCl₃) HPLC (100% hexanes i-PrOH, 1.0 mL/min) (S)= 18.0, (R)= 20.2 min. ¹H NMR (CDCl₃) δ 6.24 (s, 1H) ppm; ¹³C NMR (CDCl₃) δ 160.5, 142.6, 132.5, 132.3, 127.4, 46.8 ppm; IR (CHCl₃): 1782, 1419 cm⁻¹. Anal Calcd for C₈HO₂BrCl₆, C, 22.78; H, 0.24; Cl, 58.84. Found C, 22.798; H, 0.24; Cl, 59.04.

(S)-2-Chloro-2-thienylacetic acid pentachlorophenyl ester (6g). White crystalline solid; analytical sample was recrystallized from hexanes; mp= 85 °C; $[\alpha]_{25} = -5$ (c=0.003, CHCl₃) HPLC (99.75% hexanes/0.25% i-PrOH, 1.0 mL/min) (S)= 12.4, (R)= 18.7 min. ¹H NMR (CDCl₃) δ 7.45 (dd, 1H), 7.36 (dd, 1H), 7.04 (q, 1H), 5.97 (s, 1H) ppm; ¹³C NMR (CDCl₃) δ 163.4, 143.2, 135.9, 132.3, 132.2, 129.1, 128.6, 127.5, 127.0, 53.3 ppm; IR (CHCl₃): 1789, 1579, 1463 cm⁻¹. Anal Calcd for C₁₂H₄O₂SCl₆, C, 34.14; H, 0.963; Cl, 49.79. Found C, 34.23; H, 1.02; Cl, 49.86.

(S)-2-Chloro-2-(p-nitrophenyl)acetic acid pentachlorophenyl ester (6h). Crystalline solid; analytical sample was recrystallized from hexanes; mp= 101-103 °C; $[\alpha]_{25} = +23$ (c=0.01, CHCl₃) HPLC (99.75% hexanes/0.25% i-PrOH, 1.0 mL/min) (S)= 14.6, (R)= 16.3 min. ¹H NMR (CDCl₃) δ 8.26 (d, 2H), 7.58 (d, 2H), 6.14 (s, 1H) ppm; ¹³C NMR (CDCl₃) δ 170.2, 156.1, 147.3, 141.1, 134.5, 134.3, 131.1, 127.8, 123.6, 64.2 ; IR

¹⁰ McKenzie, A.; Gow, E. R. L. *J. Chem. Soc.* **1933**, 705-714.

(CHCl₃) 1760, 1565; Anal Calcd for C₁₄H₅NO₄Cl₆, C, 36.25; H, 1.09; Cl, 45.85; N, 3.02. Found C, 36.40; H, 1.11; Cl, 45.36.

(R)-2-Chloro-(2-chlorophenyl)acetic acid pentachlorophenyl ester (6i). Crystalline solid; analytical sample was recrystallized from hexanes; mp= 98-99 °C; [α]₂₅= -3.2 (c=0.01, CHCl₃) HPLC (99.9% hexanes/0.1% i-PrOH, 1.0 mL/min) (S)= 15.0, (R)= 16.2 min. ¹H NMR (CDCl₃) δ ; ¹³C NMR (CDCl₃) δ 164.6, 154.8, 135.6, 135.3, 134.6, 133.8, 131.2, 129.2, 128.7, 128.5, 127.2, 54.5; IR (CHCl₃) 1770, 1540; Anal Calcd for C₁₄H₅O₂Cl₇, C, 37.09; H, 1.11; Cl, 54.74. Found C, 37.40; H, 1.11; Cl, 53.83.

(S)-2-Chloro-2-butyric acid pentachlorophenyl ester (6j). Crystalline solid; analytical sample was recrystallized from hexanes; mp= 88 °C; [α]₂₅= +17 (c=0.01, CHCl₃) HPLC (99.9% hexanes/0.1% i-PrOH, 1.0 mL/min) (S)= 16.3, (R)= 18.1 min. ¹H NMR (CDCl₃) δ 4.3 (t, 1H), 1.96 (m, 2H), 0.98 (t, 1H), 3.62 (s, 3H); ¹³C NMR (CDCl₃) δ 163.4, 154.6, 134.6, 134.1, 128.2, 63.0, 25.7, 8.2; IR (CHCl₃): 1760, 1580; Anal Calcd for C₁₀H₆Cl₆O₂, C, 32.39; H, 1.63; Cl, 57.36. Found C, 31.76; H, 1.70; Cl, 58.10.

(S)-2-Chloro-2-(p-methoxyphenyl)acetic acid pentachlorophenyl ester (6k). Crystalline solid; analytical sample was recrystallized from hexanes; mp= 78 °C; [α]₂₅= +15 (c=0.01, CHCl₃) HPLC (99.75% hexanes/0.25% i-PrOH, 1.0 mL/min) (S)= 11.3, (R)= 14.1 min. ¹H NMR (CDCl₃) δ 7.17 (d, 2H), 6.78 (d, 2H), 5.7 (s, 1H), 3.62 (s, 3H); ¹³C NMR (CDCl₃) δ 164.8, 160.3, 154.8, 134.8, 134.3, 130.8, 126.8, 127.7, 114.7, 63.4, 55.8; IR (CHCl₃): 1778, 1560; Anal Calcd for C₁₅H₈Cl₆O₃, C, 40.13; H, 1.40; Cl, 47.38. Found C, 40.35; H, 1.41; Cl, 48.50.

2-Chloro-phenylacetic acid (9,11-dichloro-8-hydroxyquinolyl) ester (23). To a stirred solution of indium triflate (0.04 mmol), BQ (0.04 mmol), NaH (1.21 mmol), 15-crown-5 (0.04 mmol) in 6 mL THF at -78 °C, a solution of phenylacetyl chloride (0.806 mmol) in 1 mL THF was added dropwise. Compound **5c** (0.403 mmol) in 3 mL THF was added to the reaction via syringe pump over 3 h. The reaction was quenched with 10 mL water, extracted three times with 10 mL Et₂O, and dried over MgSO₄. Column chromatography (2% Et₂O/hexanes) afforded **23** in 22% yield. Crystalline solid; analytical sample was recrystallized from hexanes; mp= 113-115 °C; HPLC¹¹ (99.9% hexanes/0.1% i-PrOH, 1.0 mL/min) (S)= 31.3, (R)= 33.4 min. ¹H NMR (CDCl₃) δ 8.98 (d, 1H), 8.57 (d, 1H), 7.70 (s, 1H), 7.35 (dd, 1H), 7.25-7.31 (m, 5H), 5.65 (s, 1H); ¹³C NMR δ 165.5, 155.3, 144.6, 143.1, 135.8, 131.9, 130.6, 129.8, 128.7, 127.5, 126.3, 126.2, 124.1, 121.9, 63.7.; Anal Calcd for C₁₇H₁₀C₁₃NO₂ C, 55.69; H, 2.75; Cl, 29.01. Found C, 55.65; H, 2.68; Cl, 30.01.

General Procedure for the ReactIR experiments.¹² Phenylacetyl chloride was dissolved in 1 mL THF and added into the side arm of the ReactIR cell containing a THF or chlorobenzene solution of NaH, 15-crown-5, and benzoylquinine **3a**. The cell was cooled to -40 °C. The desired bands (2328 cm⁻¹, 1799 cm⁻¹) were monitored over 2 h. The latter solution was used for the background spectrum to avoid interference. Similar reactions were performed with and without the presence of BQ and crown ether.

¹¹ This assay was obtained using the (R,R)-Whelk-01 chiral column.

¹² Taggi, A. E.; Hafez, A. M.; Wack, H.; Young, B.; Ferraris, D.; Lectka, T. *J. Am. Chem. Soc.* **2002**, *124*, 6626-6635.

Photolysis of 8. Phenyldiazoketone **8** (0.13 mmol), quinone **5a** (0.13 mmol) and BQ (0.013 mmol) were weighed into a long, narrow quartz vessel equipped with a stir bar and dissolved in 15 mL THF. This was placed into the Rayonet reactor, cooled to 0 °C and photolyzed for 90 min. The solvent was removed under reduced pressure and the crude mixture was subjected to column chromatography (100% hexanes) to yield **6a** (45% yield, 85% ee).

Solvent Screening Study. To stirred solution of NaH (0.323 mmol), 15-crown-5 (0.013 mmol), and BQ (0.013 mmol) in 3 mL of desired solvent at the indicated temperature, phenylacetyl chloride in 1 mL of solvent was added dropwise. Compound **5a** in 2 mL solvent was added dropwise over 2 h. Following normal aqueous workup and chromatography, yields of **6a** and **7a** were recorded.

Relation of Concentration of Chlorinating Agent to Rate of Product Formation. To a stirred solution of BQ (0.026 mmol), NaHCO₃ (5.32 mmol), and 15-crown-5 (0.026 mmol) in 3 mL THF, phenylacetyl chloride (0.266 mmol) in 1 mL THF was added dropwise. After 15 min, varied amounts of **5a** (0.133 mmol vs. 0.266 mmol vs. 0.532 mmol) in 3 mL THF were added dropwise over 3 h. After 30 min, the reaction mixture was quenched with water and extracted twice with Et₂O. The organic layers were combined, dried and purified by column chromatography (100% hexanes). Product **6a** was isolated in 3.4% yield for 0.133 mmol of **5a**, 7% yield for 0.266 mmol of **5a**, and 15% yield for 0.532 mmol of **5a**. Runs terminated at 15 min were also performed and were found in general to have produced slightly more than half the product of the 30 min runs (1.8%; 3.6%; 7.8% at 0.133 mmol, 0.266 mmol, and 0.532 mmol, respectively). A similar dependence on rates was obtained with the use of NaH as stoichiometric base.

Relation of Catalyst Concentration to Rate of Product Formation for NaHCO₃ as Base. To a stirred solution of NaHCO₃ (2.6 mmol), 15-crown-5 (0.013), and varied amounts of BQ (10 mol %, 40 mol %, 100 mol %) in 3 mL THF, phenylacetyl chloride (0.32 mmol) in 1 mL THF was added dropwise. After 15 min, **5a** (0.13 mmol) in 3 mL THF was added dropwise over 3 h. After 30 min, the reaction mixture was quenched with water and extracted twice with methylene chloride. The organic layers were combined, dried and purified by column chromatography (100% hexanes). Product **6a** was isolated in 15-20% yield for all concentrations of BQ.

Proof of Reversibility of the NaHCO₃ Reaction. To a stirred solution of BQ (0.013 mmol), NaHCO₃ (2.6 mmol), and 15-crown-5 (0.013 mmol) in 3 mL THF, α,α -deuteriophenylacetyl chloride **1a-d₂** (0.323 mmol) in 1 mL THF was added dropwise. After 15 min, **5a** (0.133 mmol) in 3 mL THF was added dropwise over 3 h. After 4 h, the reaction mixture was quenched with water and extracted twice with methylene chloride. The organic layers were combined, dried and purified by column chromatography (100% hexanes) affording **6a** in 67% yield. Alternatively, **1a** can be reisolated quantitatively (except that H's have replaced D's) if the addition of **5a** is forgone.

N-Chloroquinine (3c). 1.0 g of polymer-supported quinine (2.00 mmol/g, 1.00 mmol),¹³ through which a solution of **5a** and phenylketene **2a** had been passed on a column, was suspended in 25 mL EtOH. The suspension was cooled to 0 °C and NaBH₄ (151 mg, 4.00 mmol) was added portionwise over 15 min. The reaction was then allowed to warm to room temperature and subsequently heated to reflux overnight. At the end of this period the reaction was cooled and filtered through Celite. The solvent was removed in vacuo and the residual crude solid purified by column chromatography to give a white crystalline solid. ¹H NMR (CDCl₃) δ 8.51 (d, 1H), 7.84 (d, 1H), 7.43 (d, 1H), 7.25 (dd, 1H), 7.19 (d, 1H), 5.54 (m, 1H), 5.49 (d, 1H), 4.7 (bs, 1H), 4.58 (m, 2H), 3.65 (2, 3H), 3.40 (m, 1H), 3.05 (m, 2H), 2.52 (m, 2H), 2.43 (m, 1H), 1.53-1.56 (m, 3H), 1.40-1.51 (m, 2H ppm; m/z 359.2 (35.15).

N-Chlorination of 2-(N,N-dibenzylaminomethyl)naphthalene (11). To a stirred solution of **11** (0.013 mmol), NaH (0.323 mmol) and 15-crown-5 (0.013 mmol) in 3 mL THF at -78 °C, phenylacetyl chloride (0.323 mmol) in 1 mL THF was added dropwise. After 15 min, **5a** (0.133 mmol) in 2 mL THF was added dropwise over 5 min. After 4 h, the reaction mixture was quenched with water and extracted twice with methylene chloride. The organic layers were combined, dried and purified by column chromatography (100% hexanes) affording **6a** in 30% yield. 2-Naphthaldehyde **14** was also isolated in 30% yield.

Phenolysis of Benzoyl Chloride. To a stirred solution of BQ (7 mg, 0.016 mmol), NaH (10 mg, 0.4 mmol), and 15-crown-5 (4 mg, 0.017 mmol) in 3 mL THF, benzoyl chloride (56 mg, 0.4 mmol) in 1 mL THF was added dropwise. After 15 min, **5a** (50 mg, 0.166 mmol) in 2 mL THF was added dropwise over 5 min. After 4 h, the reaction mixture was quenched with water and extracted twice with methylene chloride. The organic layers were combined, dried and purified by column chromatography (100% hexanes) affording **16** in 45% yield.

Thermal Degradation of 5a in THF. A solution of **5a** (0.333 mmol) in 2 mL THF was stirred at temperatures ranging from -78 °C to reflux. At room temperature and higher, pentachlorophenol formation was monitored by HPLC. In a parallel experiment, 10 mol % BQ was added and the reaction was monitored for phenol formation. Only a slight enhancement of phenol formation was observed with BQ.

Putative Chlorination of 2,5-dimethyl-THF. To a stirred solution of BQ (0.016 mmol), NaH (0.4 mmol), and 15-crown-5 (0.016 mmol) in 3 mL 2,5-dimethyl-THF, phenylacetyl chloride (0.4 mmol) in 1 mL 2,5-dimethyl-THF was added dropwise. After 15 min, **5a** (0.166 mmol) in 2 mL 2,5-dimethyl-THF was added dropwise over 5 min. After 4 h, the reaction mixture was quenched with water and extracted twice with methylene chloride. The organic layers were combined, dried and purified by column chromatography (100% hexanes) affording **6a** in 37% yield. Byproduct **7a** was isolated in 52% yield.

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Effect of NaH on Byproduct 7 Formation. To a stirred solution of NaH (0.666 mmol), BQ (0.033 mmol), and 15-crown-5 (0.033 mmol) in 3 mL CCl₄ at 0 °C, **5a** (0.333 mmol) in 1 mL CCl₄ was added. Only trace amounts of phenol formation were observed by TLC and HPLC. An experiment without BQ also showed little observable formation of phenol.

Effect of Light on Byproduct 7 Formation. (a) To a stirred solution of BQ (0.016 mmol), NaH (0.4 mmol), and 15-crown-5 (0.016 mmol) in 3 mL THF at -78 °C under a 60 watt lamp, phenylacetyl chloride (**1a**, 0.4 mmol) in 1 mL THF was added dropwise. After 15 min, **5a** (0.166 mmol) in 2 mL THF was added dropwise over 5 min. After 4 h, the reaction mixture was quenched with water and extracted twice with Et₂O. The organic layers were combined, dried and purified by column chromatography (100% hexanes) affording **6a** in 58% yield. (b) A parallel experiment was conducted where cumene (0.166 mmol) was present in the initial reaction setup. This reaction was performed in the dark. **6a** was formed in 58% yield. (c) An experiment was also conducted where AIBN (0.166 mmol) was added in the initial reaction setup in the presence of the 60 watt lamp. **6a** was formed in 58% yield. The yields of **7a** were also compared for each photo experiment.

Chlorination/esterification of Acid Bromides and Acid Fluorides. To a stirred solution of BQ (0.016 mmol), NaH (0.4 mmol), and 15-crown-5 (0.016 mmol) in 3 mL THF, phenylacetyl halide (0.4 mmol) in 1 mL THF was added dropwise. After 15 min, **5a** (0.166 mmol) in 2 mL THF was added dropwise over 5 min. After 4 h, the reaction mixture was quenched with water and extracted twice with methylene chloride. The organic layers were combined, dried and purified by column chromatography (100% hexanes) affording **6a** in 57% yield for the acid bromide and <10% for the acid fluoride.

Mystery Byproduct (19). To a solution of BQ (**3a**) (331 mg, 0.770 mmol) in 6 mL of toluene at -78 °C was added phenylacetyl chloride (100 mg, 0.640 mmol), then iminoester (**17**) (164 mg, .640 mmol), and lastly **5a** (194 mg, 0.640 mmol), all of which were dissolved in 1.5 mL of toluene. The reaction was left to stir for 18 h and return to room temperature. The reaction was then washed with water and extracted twice with methylene chloride. The organics were dried over MgSO₄, filtered through Celite, and concentrated down. The resulting residue was purified by column chromatography (100 % hexanes) to yield pentachlorophenol (12%), α-chloroester (**6a**) (40%), nonhalogenated ester (**7a**) (17%), mystery byproduct **19** (18%), and β-lactam (**18**) (13%). ¹H NMR (CDCl₃) for **19**: δ 7.90 (d, 1H), 7.73 (dd, 2H), 7.61 (dd, 2H), 6.10 (s, 1H); ¹³C NMR δ 130.1, 129.6, 129.5, 129.1, 128.9, 128.7, 128.6, 128.3, 59.4; m/z 375.2.

(S)-N-benzyl-2-chloro-2-phenylacetamide (21). (S)-2-Chloro-2-phenylacetic acid pentachlorophenyl ester (**6a**) (0.100 mmol) was dissolved in 1 mL THF and benzylamine (0.100) was then added to the solution. After 2h at room temperature the reaction was quenched with a saturated NaHCO₃. The aqueous solution was extracted three times with 5 mL Et₂O and the combined organic extracts were dried with Na₂SO₄. Absorption onto silica gel followed by column chromatography (5% Et₂O/hexanes) afforded **21** in 99% yield and 99% ee. [α]₂₅ = +19 (c=0.01, CHCl₃) HPLC (99% hexanes/1% i-PrOH, 1.0

mL/min) (S)= 13.0, (R)= 19.5 min. All other data are consistent with literature precedent.¹⁴

(S)-2-Chloro-phenylacetic acid methyl ester (22). **6a** (0.1 mmol) was dissolved in 5 mL methanol and vigorously stirred for 72 h. The solution was washed w/ saturated NaHCO₃, extracted 3 times with ether and dried over MgSO₄. Column chromatography with 5% Et₂O/hexanes yielded the product as a clear oil (89% yield). All data is consistent with literature values.¹⁵

(S)-2-Chloro-2-phenylethanol (24). To a vigorously stirred solution of **6a** (0.2 mmol) in 2-propanol (6 mL) at 0 °C, CaCl₂ (0.6 mmol) was added over 15 min. NaBH₄ (0.4 mmol) was added in portions over 1 h. The reaction mixture was stirred at 0 °C for 30 min, then allowed to stir at room temperature for 20 h. Water was slowly added in portions until gas evolution ceased. The mixture was extracted three times with ether; the organics were combined, dried over MgSO₄, and concentrated. Purification by column chromatography (10% Et₂O/hexanes) afforded **24** in 99 % yield. All data are consistent with literature values for the optically-pure material.¹⁶

Proof of Absolute Stereochemical Configuration: (R)-2-Phenyl-2-phenylsulfanyl ethanol (25). To a vigorously stirred solution of sodium thiophenolate (0.10 mmol) and 15-crown-5 (0.01 mmol) in 10 mL toluene, a solution of **24** (0.10 mmol) in 2 mL was added dropwise. The reaction was allowed to reflux over 10 h. The reaction was cooled, quenched with 10 mL water, extracted three times with Et₂O and dried over MgSO₄. Column chromatography yielded **25** in 99% yield. [α]₂₅ = +196 (c=0.01, CHCl₃), which is consistent with the established literature configuration.¹⁷ All other data are consistent with literature values.

(R)-N-Benzyl-2-piperidino-2-Phenylacetamide (26). To a stirred solution of silver triflate (0.783 mmol) in 5 mL toluene at 0 °C, a solution of **21** (0.783 mmol) in 1 mL toluene was added. Piperidine (1.57 mmol) in 1 mL toluene was added dropwise. The reaction was stirred at room temperature for 18 h. The reaction was filtered and washed (toluene) through a Celite pad. Column chromatography (20% Et₂O/hexanes) yielded **26** in 99% yield and 79% ee. [α]₂₅ = +19 (c=0.01, CHCl₃) HPLC (97% hexanes/3% i-PrOH, 1.0 mL/min) (S)= 33.0, (R)= 36.5 min. All other data are consistent with published literature values.¹⁸

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¹⁸ Najer, H.; Giudicelli, R. *Bull. Soc. Chim. Fr.* **1960**, 956-959.