Rhodium Catalyzed Disulfide Exchange Reaction

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Supplementary Materials

^{1}H-NMR and ^{13}C-NMR spectra were obtained on a Varian Mercury (400 MHz). Chemical shift values are given in ppm relative to internal Me_4Si. IR spectra were recorded on a JASCO FT/IR-410. MS spectra were taken with a JEOL JMS-DX303 or a JEOL JMS-AX500.

2-Benzoyloxyethyl butyl disulfide 3. In a two-necked flask equipped with a reflux condenser were placed tetrakis(triphenylphosphine)hydriderhodium[10] (3 mol%, 8.7 mg), tris(*p*-tolyl)phosphine (12 mol%, 9.1 mg), trifluoromethanesulfonic acid (6 mol%, 0.0014 mL), **1** (0.25 mmol, 90.5 mg), and **2** (1.0 mmol, 0.190 mL) in acetone (2.0 mL) under an argon atmosphere, and the solution was heated at reflux for 15 min. Then, the solvent was removed under reduced pressure, and the residue was purified by flash column chromatography on silica gel giving **3** (116.6 mg, 86%), the recovered **1** (10.6 mg, 12%), and **2** (134.6 mg, 76%). Colorless oil. ^{1}H-NMR (400 MHz, $CDCl_3$) δ 0.91 (3H, t, J = 7.2 Hz), 1.40 (2H, sixtet, J = 7.2 Hz), 1.67 (2H, quintet, J = 7.2 Hz), 2.73 (2H, t, J = 7.2 Hz), 3.04 (2H, t, J = 6.8 Hz), 4.58 (2H, t, J = 7.2 Hz), 7.44 (2H, t, J = 7.6 Hz), 7.57 (1H, t, J = 7.6 Hz), 8.06 (2H, d, J = 7.2 Hz). ^{13}C-NMR (100 MHz, $CDCl_3$) δ 13.8, 21.7, 31.3, 37.3, 39.0, 63.0, 128.2, 129.5, 129.8, 132.9, 166.1. IR (neat) 2957, 1721, 1451, 1271, 1111 cm^{-1}. MS (EI) m/z 270 (**M**$^{+}$, 6%), 149 (**M**$^{+}$-121, 100%). HRMS Calcd for $C_{13}H_{18}S_2O_2$: 270.0748. Found: 270.0746.

Butyl octyl disulfide (Table 1, Run 13).[11] Colorless oil. ^{1}H-NMR (400 MHz, $CDCl_3$) δ 0.88 (3H, t, J = 6.8 Hz), 0.93 (3H, t, J = 7.2 Hz), 1.24-1.30 (8H, m), 1.35-1.42 (2H, m), 1.42 (2H, sixtet, J = 7.2 Hz), 1.64-1.68 (2H, m), 2.68 (2H, t, J = 7.2 Hz), 2.69 (2H, t, J = 7.2 Hz). ^{13}C-NMR (100 MHz, $CDCl_3$) δ 13.8, 14.2, 21.8, 22.8, 28.6, 29.28, 29.30, 29.33, 31.4, 31.9, 39.0, 39.3. IR (neat) 2956, 2925, 2855, 1463 cm^{-1}. MS (EI) m/z 234 (**M**$^{+}$, 35%), 122 (**M**$^{+}$-112, 44%), 57 (**M**$^{+}$-177, 100%). HRMS Calcd for $C_{12}H_{26}S_2$: 234.1476. Found: 234.1492.

Benzyl butyl disulfide (Table 1, Run 14).[12] Colorless oil. ^{1}H-NMR (400 MHz, $CDCl_3$) δ 0.86 (3H, t, J = 7.6 Hz), 1.31 (2H, sixtet, J = 7.2 Hz), 1.54 (2H, quintet, J = 7.6 Hz), 2.40 (2H, t, J = 7.2 Hz), 3.88 (2H, s), 7.25-7.32 (5H, m). ^{13}C-NMR (100 MHz, $CDCl_3$) δ 13.8, 21.7, 31.2, 38.5, 43.8, 127.2, 128.3, 129.1, 137.5. IR (neat) 2957, 2927, 2870, 1494, 1454 cm^{-1}. MS (EI)

m/z 212 (**M**$^+$, 14%), 91 (**M**$^+$-121, 100%). HRMS Calcd for $C_{11}H_{16}S_2$: 212.0693. Found: 212.0721.

Butyl 6-(*t*-butyldimethylsilyloxy)ethyl disulfide (Table 1, Run 15). Colorless oil. ^{1}H-NMR (400 MHz, $CDCl_3$) δ 0.05 (6H, s), 0.89 (9H, s), 0.93 (3H, t, J = 7.2 Hz), 1.34-1.44 (6H, m), 1.52 (2H, quintet, J = 6.4 Hz), 1.62-1.71 (4H, m), 2.68 (4H, t, J = 7.2 Hz), 3.60 (2H, t, J = 6.8 Hz). ^{13}C-NMR (100 MHz, $CDCl_3$) δ 5.1, 13.8, 18.5, 21.8, 25.6, 26.1, 28.4, 29.3, 31.4, 32.8, 39.0, 39.2, 63.1. IR (neat) 2929, 2857, 1462, 1254, 1103 cm^{-1}. MS (EI) m/z 336 (**M**$^+$, 1%), 279 (**M**$^+$-57, 100%). HRMS Calcd for $C_{16}H_{36}S_2SiO$: 336.1977. Found: 336.1984.

Butyl phenyl disulfide (Table 1, Run 16).[13] Colorless oil. ^{1}H-NMR (400 MHz, $CDCl_3$) δ 0.88 (3H, t, J = 7.6 Hz), 1.39 (2H, sixtet, J = 7.2 Hz), 1.65 (2H, quintet, J = 7.2 Hz), 2.74 (2H, t, J = 7.6 Hz), 7.21 (1H, t, J = 7.2 Hz), 7.32 (2H, t, J = 8.0 Hz), 7.53 (2H, d, J = 8.0 Hz). ^{13}C-NMR (100 MHz, $CDCl_3$) δ 13.8, 21.7, 30.9, 38.7, 126.5, 127.2, 128.8, 137.5. IR (neat) 2927, 1578, 1475, 1437, 1024 cm^{-1}. MS (EI) m/z 198 (**M**$^+$, 100%), 142 (**M**$^+$-56, 59%). HRMS Calcd for $C_{10}H_{14}S_2$: 198.0537. Found: 198.0540.

Phenyl *p*-tolyl disulfide 7.[12, 14] Colorless oil. ^{1}H-NMR (400 MHz, $CDCl_3$) δ 2.31 (3H, s), 7.08 (2H, d, J = 7.2 Hz), 7.20 (1H, t, J = 8.0 Hz), 7.28 (2H, t, J = 8.0 Hz), 7.37 (2H, d, J = 8.0 Hz), 7.48 (2H, d, J = 7.2 Hz). ^{13}C-NMR (100 MHz, $CDCl_3$) δ 21.2, 126.9, 127.5, 128.2, 128.9, 129.7, 133.4, 137.1, 137.3. IR (neat) 3056, 2918, 1578, 1489, 1439, 1015, 803 cm^{-1}. MS (EI) m/z 232 (**M**$^+$, 75%), 123 (**M**$^+$-109, 100%). HRMS Calcd for $C_{13}H_{12}S_2$: 232.0380. Found: 232.0387.

***sec*-Butyl phenyl disulfide 8.**[13] Colorless oil. ^{1}H-NMR (400 MHz, $CDCl_3$) δ 0.95 (3H, t, J = 7.2 Hz), 1.28 (3H, d, J = 6.4 Hz), 1.53 (2H, sixtet, J = 6.8 Hz), 1.72 (2H, septet, J = 7.2 Hz), 2.83 (2H, sixtet, J = 6.4 Hz), 7.19 (1H, t, J = 7.2 Hz), 7.30 (2H, t, J = 8.0 Hz), 7.54 (2H, d, J = 8.0 Hz). ^{13}C-NMR (100 MHz, $CDCl_3$) δ 11.6, 20.0, 28.9, 48.4, 126.3, 126.9, 128.7, 138.1. IR (neat) 2963, 1580, 1476, 1439, 1023 cm^{-1}. MS (EI) m/z 198 (**M**$^+$, 59%), 142 (**M**$^+$-56, 100%). HRMS Calcd for $C_{10}H_{14}S_2$: 198.0537. Found: 198.0557.

***sec*-Butyl *p*-tolyl disulfide 9.** Colorless oil. ^{1}H-NMR (400 MHz, $CDCl_3$) δ 0.94 (3H, t, J = 7.6 Hz), 1.27 (3H, d, J = 7.6 Hz), 1.51 (1H, septet, J = 7.6 Hz), 1.71 (1H, septet, J = 7.2 Hz), 2.32 (3H, s), 2.81 (1H, sixtet, J = 7.2 Hz), 7.10 (2H, d, J = 8.0 Hz), 7.41 (2H, d, J = 8.0 Hz). ^{13}C-NMR (100 MHz, $CDCl_3$) δ 11.6, 20.0, 21.1, 28.9, 48.4, 127.8, 129.5, 129.7, 136.5. IR (neat) 2964, 2921, 1489, 1452, 804 cm^{-1}. MS (EI) m/z 212 (**M**$^+$, 60%), 92 (**M**$^+$-120, 100%). HRMS Calcd for $C_{11}H_{16}S_2$: 212.0693. Found: 212.0701.

Butyl (*R*)-{2-methoxycarbonyl-2-(*t*-butoxycarbonyl)amino}ethyl disulfide 11. The

optical purity of the (*R*)-product was determined by HPLC using Daicel Chiralcel OD-H (0.15 min/mL, hexane/2-PrOH = 3) (*R*)-product: t_1 = 26.8 min, (*S*)-product: t_2 = 25.6 min. Colorless oil. ^{1}H-NMR (400 MHz, $CDCl_3$) δ 0.93 (3H, t, J = 7.6 Hz), 1.41 (2H, sixtet, J = 7.6 Hz), 1.45 (9H, s), 1.65 (2H, quintet, J = 7.2 Hz), 2.70 (2H, t, J = 7.6 Hz), 3.10 (1H, dd, J = 14.0, 6.8 Hz), 3.15 (1H, dd, J = 14.4, 7.2 Hz), 3.76 (3H, s), 4.61 (1H, q, J = 6.4 Hz), 5.35 (1H, bd, J = 8.0 Hz). ^{13}C-NMR (100 MHz, $CDCl_3$) δ 13.8, 21.7, 28.4, 31.2, 38.7, 41.1, 52.6, 52.9, 80.1, 154.8, 171.1. IR (neat) 3370, 2958, 2873, 1716, 1504, 1167, 1051 cm^{-1}. MS (EI) m/z 323 (**M**$^+$, 29%), 146 (**M**$^+$-177, 100%). HRMS Calcd for $C_{13}H_{25}S_2O_4N$: 323.1225. Found: 323.1240. $[\alpha]_D^{23}$ +49.80 (c 1.0, $CHCl_3$).

***N*-[*N*-[*N*-[(1,1-Dimethylethoxy)carbonyl]-*L*-γ-glutamyl]-3-(butyldithio)-*L*-alanine] dimethyl ester 13.** Colorless solid. M.p. 104.0-105.0 °C (ether : hexane = 1 : 2). ^{1}H-NMR (400 MHz, $CDCl_3$) δ 0.92 (3H, t, J = 7.2 Hz), 1.40 (2H, sixtet, J = 7.2 Hz), 1.44 (9H, s), 1.65 (2H, quintet, J = 7.6 Hz), 1.90-1.98 (1H, m), 2.17-2.25 (1H, m), 2.37 (2H, t, J = 7.2 Hz), 2.72 (2H, t, J = 7.2 Hz), 3.11 (2H, bd, J = 7.6 Hz), 3.75 (6H, s), 4.01 (1H, dd, J = 17.6, 5.2 Hz), 4.08 (1H, dd, J = 17.6, 5.6 Hz), 4.76 (1H, q, J = 7.2 Hz), 5.33 (1H, bd, J = 8.8 Hz), 6.85 (1H, bs), 7.07 (1H, bs). ^{13}C-NMR (100 MHz, $CDCl_3$) δ 13.7, 21.7, 28.3, 28.7, 31.1, 32.2, 38.4, 39.5, 41.3, 52.4, 52.5, 52.7, 77.2, 80.1, 155.5, 169.7, 170.2, 172.2, 172.6. IR (neat) 3307, 2956, 1747, 1651, 1529, 1367, 1213, 1168 cm^{-1}. MS (EI) m/z 523 (**M**$^+$, 30%), 57 (**M**$^+$-466, 100%). HRMS Calcd for $C_{21}H_{37}S_2O_8N_3$: 523.2022. Found: 523.2046. $[\alpha]_D^{23}$ –49.40 (c 1.0, $CHCl_3$).

1-(2-Benzoyloxy)ethylthio butyl selenide. In a two-necked flask equipped with a reflux condenser were placed tetrakis(triphenylphosphine)hydriderhodium (5 mol%, 14.4 mg), tris(*p*-tolyl)phosphine (20 mol%, 15.2 mg), trifluoromethanesulfonic acid (5 mol%, 0.0012 mL), **1** (1.5 mmol, 543 mg), and dibutyl diselenide (0.25 mmol, 68 mg) in acetone (2.0 mL) under an argon atmosphere, and the solution was heated at reflux for 15 min. Then, the solvent was removed under reduced pressure, and the residue was purified by flash column chromatography on silica gel giving the title compound (114.1 mg, 72%), the recovered **1** (434.4 mg, 80%), and dibutyl diselenide (8.2 mg, 12%). Pale yellow oil. ^{1}H-NMR (400 MHz, $CDCl_3$) δ 0.92 (3H, t, J = 7.6 Hz), 1.41 (2H, sixtet, J = 7.6 Hz), 1.75 (2H, quintet, J = 7.6 Hz), 2.91 (2H, t, J = 7.2 Hz), 3.14 (2H, t, J = 6.8 Hz), 4.55 (2H, t, J = 7.6 Hz), 7.44 (2H, t, J = 7.2 Hz), 7.57 (1H, td, J = 7.6, 1.6 Hz), 8.06 (2H, d, J = 7.6, 1.6 Hz). ^{13}C-NMR (100 MHz, $CDCl_3$) δ 13.7, 22.8, 32.0, 32.1, 36.4, 64.1, 128.2, 129.5, 129.9, 132.9, 166.1. IR (neat) 2957, 2928, 1721, 1451, 1270, 1108 cm^{-1}. MS (EI) m/z 318 (**M**$^+$, 7%), 149 (**M**$^+$-169, 100%). HRMS Calcd for $C_{13}H_{18}O_2SSe$: 318.0193. Found: 318.0169.

1-(2-Benzoyloxy)ethylthio neopentyl selenide. Pale yellow oil. ^{1}H-NMR (400 MHz,

$CDCl_3$) δ 1.02 (9H, s), 3.02 (2H, s), 3.14 (2H, t, J = 6.8 Hz), 4.56 (2H, t, J = 6.8 Hz), 7.44 (2H, t, J = 7.2 Hz), 7.56 (1H, t, J = 7.2 Hz) 8.06 (2H, d, J = 7.2 Hz). ^{13}C-NMR (100 MHz, $CDCl_3$) δ 29.3, 32.6, 36.2, 50.9, 64.0, 128.2, 129.5, 129.9, 132.7, 166.1. IR (neat) 2957, 1719, 1451, 1269, 1110 cm^{-1}. MS (EI) m/z 332 (**M**$^+$, 12%), 105 (**M**$^+$-227, 100%). HRMS Calcd for $C_{14}H_{20}O_2SSe$: 332.0349. Found: 334.0327.

1-(2-Benzoyloxy)ethylthio phenyl selenide. Pale yellow oil. ^{1}H-NMR (400 MHz, $CDCl_3$) δ 3.20 (2H, t, J = 6.8 Hz), 4.51 (2H, t, J = 6.8 Hz), 7.23-7.29 (3H, m), 7.43 (2H, t, J = 7.2 Hz), 7.55 (1H, td, J = 7.2, 1.6 Hz), 7.63 (2H, dd, J = 8.0, 1.6 Hz), 8.01 (2H, dd, J = 7.6, 1.2 Hz). ^{13}C-NMR (100 MHz, $CDCl_3$) δ 36.3, 63.6, 127.5, 128.2, 129.1, 129.5, 129.8, 130.0, 131.6, 132.9, 166.0. IR (neat) 3059, 2955, 1716, 1269, 1110, 710 cm^{-1}. MS (EI) m/z 338 (**M**$^+$, 29%), 149 (**M**$^+$-189, 100%). HRMS Calcd for $C_{13}H_{14}O_2SSe$: 337.9880. Found: 337.9877.

1-Octylthio phenyl telluride.[15] In a two-necked flask equipped with a reflux condenser were placed tetrakis(triphenylphosphine)hydriderhodium (5 mol%, 14.4 mg), dioctyl disulfide (2.0 mmol, 580 mg), and diphenyl ditelluride (0.25 mmol, 102 mg) in acetone (2.0 mL) under an argon atmosphere, and the solution was heated at reflux for 15 min. Then, the solvent was removed under reduced pressure, and the residue was purified by flash column chromatography on silica gel giving 1-octylthio phenyl telluride (82 mg, 47%), the recovered dioctyl disulfide (464 mg, 80%), and diphenyl ditelluride (49 mg, 48%). Pale yellow oil. ^{1}H-NMR (400 MHz, $CDCl_3$) δ 0.87 (3H, t, J = 6.4 Hz), 1.19-1.24 (6H, m), 1.27-1.35 (4H, m), 1.59 (2H, quintet, J = 7.2 Hz), 3.00 (2H, t, J = 7.2 Hz), 7.26-7.28 (3H, m), 7.76 (2H, dd, J = 7.2, 2.4 Hz). ^{13}C-NMR (100 MHz, $CDCl_3$) δ 14.2, 22.8, 28.4, 29.2, 29.3, 31.9, 32.6, 38.4, 115.7, 127.9, 129.2, 135.2. IR (neat) 2924, 2853, 1573, 1472, 1434, 1017, 729 cm^{-1}. MS (EI) m/z 352 (**M**$^+$, 9%), 290 (**M**$^+$-62, 61%), 57 (**M**$^+$-295, 100%). HRMS Calcd for $C_{14}H_{22}STe$: 352.0504. Found: 352.0487.

1-(2-Benzoyloxy)ethylthio phenyl telluride. Pale yellow oil. ^{1}H-NMR (400 MHz, $CDCl_3$) δ 0.87 (3H, t, J = 6.4 Hz), 1.19-1.24 (6H, m), 1.27-1.35 (4H, m), 1.59 (2H, quintet, J = 7.2 Hz), 3.00 (2H, t, J = 7.2 Hz), 7.26-7.28 (3H, m), 7.76 (2H, dd, J = 7.2, 2.4 Hz). ^{13}C-NMR (100 MHz, $CDCl_3$) δ 14.2, 22.8, 28.4, 29.2, 29.3, 31.9, 32.6, 38.4, 115.7, 127.9, 129.2, 135.2. IR (neat) 2924, 2853, 1573, 1472, 1434, 1017, 729 cm^{-1}. MS (EI) m/z 352 (**M**$^+$, 9%), 290 (**M**$^+$-62, 61%), 57 (**M**$^+$-295, 100%). HRMS Calcd for $C_{14}H_{22}STe$: 352.0504. Found: 352.0487.

Exchange reaction of 4, 5, and 6 at room temperature. In a two-necked flask equipped with a reflux condenser were placed tetrakis(triphenylphosphine)hydriderhodium (1 mol%, 5.8 mg), 1,2-bis(diphenylphosphino)ethane (2 mol%, 4.0 mg), **4** (0.5 mmol, 89 mg), **5** (0.5 mmol, 109 mg), and **6** (0.5 mmol, 123 mg) in acetone (2.0 mL) under an argon atmosphere, and the solution was stirred for 1 min at room temperature. Then, the solvent was removed under reduced pressure, and

the residue was purified by flash column chromatography on silica gel giving **4** (0.48 mmol, 86 mg), and a mixture of **5**, **6**, and **7** (228 mg, 0.25 mmol : 0.25 mmol : 0.49 mmol). The ratio **5** : **6** : **7** = 1 : 1 : 2 was determined by HPLC using Cadenza CD-C18 (MeOH : H_2O = 9 : 1). **8** and **9** were not detected by ^{1}H-NMR. **Exchange reaction of 4, 5, and 6 at refluxing temperature.** In the presence of the same catalyst system, a mixture of **4** (0.5 mmol, 89 mg), **5** (0.5 mmol, 109 mg), and **6** (0.5 mmol, 123 mg) in acetone (2.0 mL) under an argon atmosphere was heated at reflux for 5 min. Then, the solvent was removed under reduced pressure, and the residue was purified by flash column chromatography on silica gel giving **4** (0.14 mmol, 25 mg), a mixture of **5**, **6**, and **7** (148 mg, 0.16 mmol : 0.16 mmol : 0.32 mmol), and a mixture of **8** and **9** (139 mg, 0.34 mmol : 0.34 mmol). The ratio **5** : **6** : **7** = 1 : 1 : 2 was determined by HPLC using Cadenza CD-C18 (MeOH : H_2O = 9 : 1), and the ratio **8** : **9** = 1 : 1 by ^{1}H-NMR.

Equilibrium experiment. A mixture of tetrakis(triphenylphosphine)hydriderhodium (3 mol%, 17.3 mg), tris(*p*-tolyl)phosphine (12 mol%, 18.2 mg), trifluoromethanesulfonic acid (3 mol%, 0.0014 mL), **1** (0.5 mmol, 181 mg), **2** (0.5 mmol, 0.095 mL), and 1,1,2-trichloroethane (0.5 mmol, 0.046 mL, internal standard) in acetone (2.0 mL) was heated at reflux for 10 min under an argon atmosphere. ^{1}H-NMR analysis indicated the presence of **3** (47%, 0.47 mmol) with the recovery of **1** (50%, 0.25 mmol) and **2** (48%, 0.24 mmol). Then, another portion of **2** (0.5 mmol, 0.095 mL) was added, and the mixture was heated at reflux for 10 min giving **3** (71%, 0.71 mmol). Next addition of **2** (1.0 mmol, 0.19 mL) gave **3** (86%, 0.86 mmol) after refluxing for 10 min, and further addition of **2** (1.0 mmol, 0.19 mL) gave **3** (92%, 0.92 mmol), which were determined by ^{1}H-NMR.

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