Microwave-Assisted Cross-Coupling for the Construction of Diaryl Sulfides

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The construction of diaryl sulfides through the cross-coupling of aryl iodides and thiols in microwave heating is described. By using this method, a variety of diaryl sulfides can be prepared in a mild condition and in high yields. Deactivated 4-nitrothiophenol was effective to afford the product in 94% yield. Sterically hindered *ortho*-substituted aryl iodides or thiophenols provided diaryl sulfides effectively by this microwave-assisted coupling reaction.

Keywords: Aryl iodide; Diaryl sulfide; Ligand; Copper iodide; Cross-coupling; Microwave heating.

INTRODUCTION

Aryl sulfides and their oxidized forms, sulfones and sulfoxides, are common functional groups in pharmaceutical agents such as nonsteroidal anti-inflammatory agents,[1] HIV protease inhibitors and antiviral agents,[2] selective M_2 muscarinic receptor antagonists,[3] leukocyte function-associated antigen-1/intracellular molecule-1 interaction antagonists,[4] leukotriene B_4 antagonists,[5] histone deacetylase inhibitors,[6] fatty acid amide hydrolase inhibitors,[7] α_2-adrenoceptor antagonists,[8] and gonadotropin-releasing hormone antagonists.[9] Most importantly, diaryl sulfides serve as useful starting materials for the construction of heterocycles containing sulfur atom and precursors leading to sulfones and sulfoxides.[10-13] As a result, the preparation of diaryl sulfides has caught a great attention.[14-17] Various traditional methods such as Chan-Lam coupling, Leuckart thiophenol reaction, Sandmeyer-type reaction through diazonium salts, and Ullmann reaction can form aryl-sulfur bonds. Although moderate to high yields can be obtained, often harsh reaction conditions or long reaction times are needed in these methods.[18-20]

Migita and co-workers reported the first cross-coupling reaction of aryl halides and thiols for the construction of aryl-sulfur bond by using catalyst $Pd(PPh_3)_4$ and base NaO*t*-Bu in ethanol at reflux or in DMSO at 90 °C.[21] Recently, catalysts containing transition metals such as palladium,[22,23] cobalt,[24] nickel,[25] and copper[19,26] have been capitalized in the condensation reactions of thiolates and aryl halides. To probe the utility of metal-containing ligands or auxiliary compounds in organic synthesis, a great number of applications for various coupling reactions have been realized with improvement in yields.[27,28] Nevertheless, it is often unlikely favored to adapt a Pd-catalyzed reaction due to the cost and physicochemical properties of environment-sensitizing of palladium unless there is no other choice. Copper-based catalysts, compared to palladium-based ones, are favorable in the application of coupling reactions from an economic standpoint and are more easily to handle with proper ligands.[29]

In 2002, Venkataraman and co-workers[19] reported a palladium-free condition for the cross-coupling reaction of aryl iodides and thiols by the catalyst of 10 mol % copper iodide and the ligand of 10 mol % neocuproine, and the base of NaO*t*-Bu in toluene. However, the reaction was carried out in 24-hr heating. Microwave heating has been considerably applied in synthesis. Compared to traditional heating, microwave heating remarkably results in shorter reaction time, less solvent consumption, and higher yields matching with green chemistry protocols.[30] Wu and his coworker[31] reported the first microwave-assisted cross-

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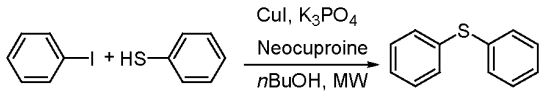
coupling of aryl halides and thiophenols by using copper iodide as the catalyst and cesium carbonate as the base. With microwave heating, higher yields were obtained as compared to conventional heating. However, the obtained yield was only 67-89% at high reaction temperature of 195 °C for 2 hours.[31] Recently, Bagley et al.[32] described another microwave-irradiated C-S cross coupling reaction with copper iodide as the catalyst, ethylene glycol as the ligand, and potassium carbonate as the base at a lower temperature of 120 °C.

RESULTS AND DISCUSSION

To our surprise, microwave heating failed to speed up the cross-coupling reaction compared to the traditional heating by using Venkataraman's reaction condition.[19] It was suspected that the low polarity of toluene might not be feasible under microwave dielectric heating. Polar solvents of water, *n*-butanol (bp = 118 °C) and (bp = 82 °C) were chosen as the reaction solvents. Normally, the insolubility of organic reactants results in the limited use of water in organic synthesis. Nevertheless, water-mediated C-S cross coupling was reported recently in the presence of tetrabutylammonium bromide (TBAB).[33] In our study, only trace amount of diaryl sulfide was observed with the use of water as a solvent. *t*-Butanol gave unsatisfied results due to the overpressure at the reaction temperature of 120 °C. *n*-Butanol gave comparable results as those in the Venkataraman's protocol and thus was chosen as the reaction solvent. As regard to the base, Venkataraman[19] reported that K_3PO_4 was as effective as KO*t*-Bu, and therefore it was chosen as the base in our study. In addition, the microwave-mediated cross-coupling reaction in the presences of CuI and Cs_2CO_3, reported by Wu,[31] was carried out at high temperature of 195 °C. In preliminary studies, the coupling reaction between thiophenol and iodobenzene was monitored for the reaction time from 1 minute to 3 hours (Table 1), and then was followed by the assessment of the reaction temperature ranged from 80 to 120 °C. The duration of microwave heating over 1 hr led to high yields, and 2-hr-microwave-heating resulted in nearly complete conversion. The optimal reaction temperature was found to be at 120 °C. A reaction temperature below 100 °C did not offer an efficient coupling. Thus, the reaction condition was adapted by CuI/neocuproine as the catalyst, K_3PO_4 as the base, and *n*-butanol as the solvent at 120 °C for 2 hr.

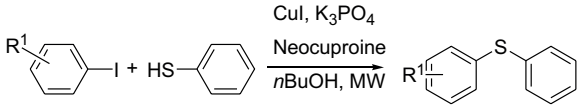
In general, electron-poor aryl iodides were more reactive than electron-rich ones in C-S cross-coupling. However, the electron-poor aryl iodides (2- and 4-methoxycarbonylbenzene iodides) gave lower yields (81% and 84%, respectively) in comparison to the electron-rich aryl iodides (>95%) in Venkataraman's protocol.[19] The reaction of substituted aryl iodides with thiophenol was examined under microwave heating. The 4-methyl-, 4-acetyl-, and 2-sulfonamidobenzene iodide underwent reaction in excellent yields (98% and above, Table 2). Besides, the sterically hindered aryl iodide (2-sulfonamidobenzene iodide) was unlikely a hurdle for the cross-coupling (Table 2, entry 3). As a result, both the electron-rich and electron-poor aryl iodides would provide quantitative yields in this microwave-assisted system.

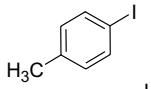
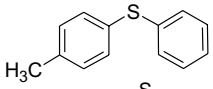
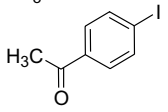
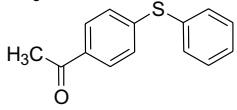
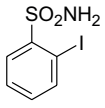
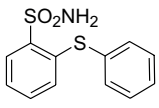
Table 1. Reaction time and temperature for the coupling reaction of thiophenol with iodobenzene



Entry	Time	Temperature	Yield
1	1 min	120 °C	18%
2	5 min	120 °C	30%
3	10 min	120 °C	45%
4	30 min	120 °C	72%
5	1 h	120 °C	90%
6	1.5 h	120 °C	94%
7	2 h	120 °C	> 99%
8	3 h	120 °C	> 99%
9	2 h	80 °C	51%
10	2 h	90 °C	70%
11	2 h	100 °C	78%
12	2 h	110 °C	96%

Table 2. Reactions of aryl iodides with thiophenol.



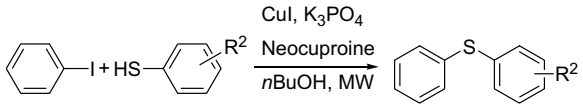
Entry	Aryl iodide	Product	Yield
1			98%
2			> 99%
3			98%

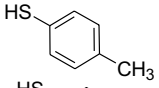
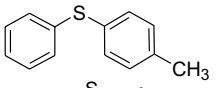
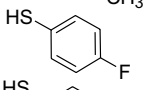
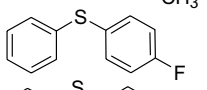
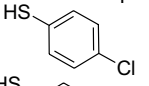
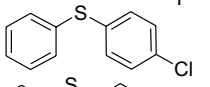
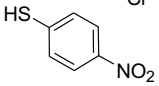
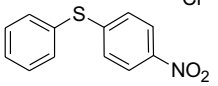
Next, we studied the cross-coupling of substituted thiophenols with iodobenzene. 4-Methyl-, 4-fluoro-, 4-chloro-, and 4-nitrothiophenol afforded the diaryl sulfides in 94-98% yield (Table 3). Electron-deficient thiophenols usually gave ineffective result for C-S cross-coupling.[34] Only few reports described yields over 90% for the cross-coupling of 4-nitrothiophenol and iodobenbenzene.[33,35] In our study, deactivated 4-nitrothiophenol was effective to couple with iodobenzene in 94% yield (Table 3, entry 4).

Furthermore, we investigated the cross-coupling reaction of substituted aryl iodides and substituted thiophenols. 4-Methyl-, 4-methoxy-, and 3,4-dimethoxythiophenol underwent cross-coupling reaction in 97-99% yield (Table 4).

Halogenated thiophenol such as 4-bromo-, 4-chloro-, and 2,4-dichlorothiophenol also afforded the coupling products in 94-99% yield. Similar results were observed with various aryl iodides. 2-NO_2, 4-NO_2, and even 4-NO_2-2-SO_2NH_2 substituted iodobezenes also underwent coupling reaction with various thiophenols in quantitative yield. This method afforded improved yields with this category of aryl iodides. In Bagley's condition, 1-bromo-2-iodobenzene underwent two C-S cross coupling with thiophenol.[32] Beneficially, our method also possessed selectivity on the aryl halides. The coupling reaction of 1-bromo-4-iodobenzene and 4-methylthiophenol provided sole product of 4-bromophenyl 4-tolyl disulfide (Entry 1, Table 4). The introduction of *ortho*-substituent either on aryl iodides or on thiophenol would not influence the efficiency of microwave-assisted coupling reactions.

Table 3. Reactions of iodobenzene with thiophenols



Entry	Thiophenol	Product	Yield
1			99%
2			98%
3			95%
4			94%

CONCLUSION

In summary, microwave-assisted cross coupling with the CuI/neocuproine, K_3PO_4 in n-butanol serves a generally clean and simple method for the construction of aryl-sulfur bonds. With the achievement of high yields, the cross-coupling reaction can be carried out not only at moderate temperature but also in a shorter time. In addition, the use of air-sensitive or costly catalysts and ligands can be avoided by utilizing this method.

EXPERIMENTAL

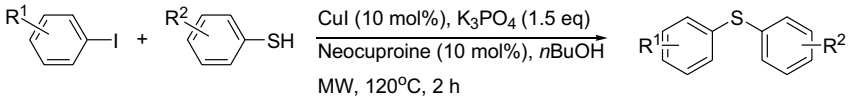
Materials and Methods

Analytical samples were homogeneous to be monitored by thin-layer chromatography (TLC) and afforded spectroscopic data that are consistent with those assigned structures. Melting points were obtained on the thermometer of MEL-TEMP®, Laboratory Devices Inc, USA. ^{1}H and ^{13}C NMR spectra were obtained using Brucker AV-400 spectrometer, in which chemical shifts were reported in parts per million (δ, ppm) using acetone-d_6 or $CDCl_3$ as the solvent. EI mass spectra were recorded on FINNIGAN MAT95S, Jeol SX 102A or FINNIGAN TSQ 7000 at the National Taiwan University, Taipei. Elemental analyses for C, H, and N were carried out within ± 0.4% of the theoretical values on HERAEUS VarioEL-III Elemental Analyzer at the National Taiwan University, Taipei. Except as otherwise indicated, all reactions were magnetically stirred and monitored by TLC of precoated plates (silica gel, Kieselgel $60F_{254}$, Merck). Column chromatography was preformed with Kieselgel 60 (230-400 or 70-230 mesh) silica gel (Merck) and spots on TLC were visualized with UV light. All starting materials were obtained from commercial suppliers (Aldrich, Acros, Fluka, Lancaster, TCI) and were used without purification. *n*-Butanol was purchased from KANTO chemical Co., Inc. Solvents for column chromatography were purchased from Baker Analyzed and Labscan having an HPLC quality. Drying of organic solutions during workup was done over anhydrous $MgSO_4$ or Na_2SO_4.

General Procedure

To a solution of aryl iodide (0.6 mmol, 1 eq) and thiophenol (0.6 mmol, 1 eq) in *n*-butanol (3 mL) in a 10-mL microwave vial were added copper(I) iodide (0.06 mmol, 0.1 eq), neocuproine (0.06 mmol, 0.1 eq), and potassium phosphate (0.9 mmol, 1.5 eq). The vial was sealed and heated in microwave reactor (Emrys Optimizer®, Personal Chemis-

Table 4. Reactions of aryl iodides with thiophenols



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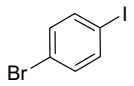
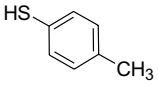
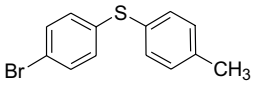
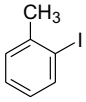
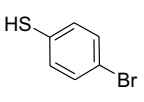
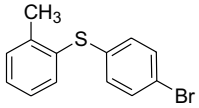
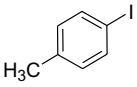
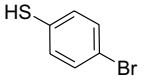
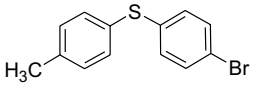
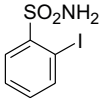
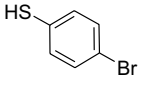
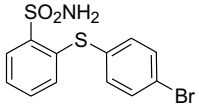
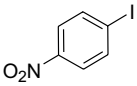
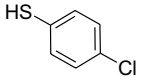
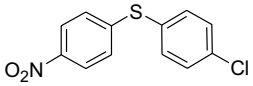
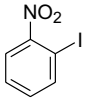
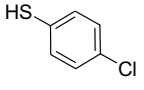
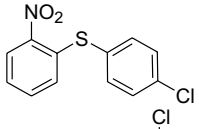
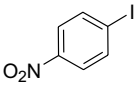
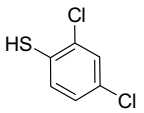
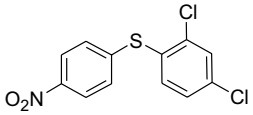
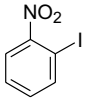
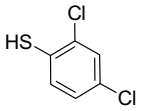
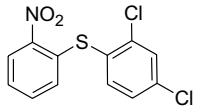
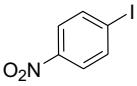
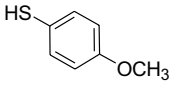
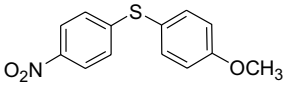
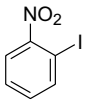
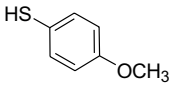
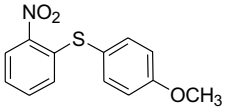
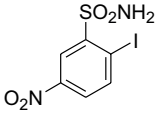
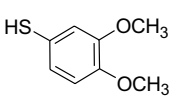
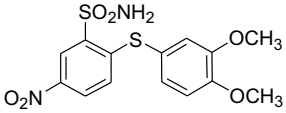
1				98%
2				94%
3				95%
4				99%
5				98%
6				99%
7				99%
8				> 99%
9				97%
10				99%
11				99%

try). The reaction temperature and the microwave power were monitored using a calibrated infrared temperature control mounted under the reaction vessel. The reaction temperature was constant during each reaction with the electric power of reactor ranged from 9-18 W. The air-cooled reaction mixture was purified by column chromatography to afford the corresponding diary sulfide.

Diphenyl sulfide

A colorless liquid. The product was purified by column chromatography (hexane/ethyl acetate (Hex/EA) 20:1). R_f = 0.5 (Hex/EA 1:1). ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.44-7.48 (m, 4H, ArH), 7.32-7.39 (m, 6H, ArH). ^{13}C NMR (100 MHz, $CDCl_3$) δ 135.7, 130.9, 129.1, 126.9. ^{1}H and ^{13}C NMR spectra are consistent with the literature.[28]

Phenyl 4-tolyl sulfide

A pale yellow liquid. The product was purified by column chromatography (Hex/EA 10:1). R_f = 0.45 (Hex/EA 1:1). ^{1}H NMR (400 MHz, acetone-d_6) δ 7.25-7.30 (m,

6H, ArH), 7.17-7.23 (m, 3H, ArH), 2.31 (s, 3H, CH_3). ^{13}C NMR (100 MHz, acetone-d_6) δ 138.6, 137.8, 133.0, 132.0, 130.9, 130.5, 130.0, 127.4, 21.1. ^1H and ^{13}C NMR spectra are consistent with the literature.[28]

4-Acetylphenyl phenyl sulfide

A white solid. The product was purified by column chromatography (Hex/EA 8:1). R_f = 0.55 (Hex/EA 1:1). Mp = 67 °C (lit.[19] Mp = 66-67 °C). ^1H NMR (400 MHz, acetone-d_6) δ 7.89 (dd, J = 6.7, 1.9 Hz, 2H, ArH), 7.45-7.53 (m, 5H, ArH), 7.26 (dd, J = 6.7, 1.9 Hz, 2H, ArH), 2.53 (s, 3H, CH_3). ^{13}C NMR (100 MHz, acetone-d_6) δ 196.8, 144.8, 135.8, 134.4, 133.0, 130.7, 129.7, 129.6, 128.4, 26.5.

2-Phenylsulfanylbenzenesulfonamide

A white solid. The product was purified by column chromatography (Hex/EA 2:1). R_f = 0.3 (Hex/EA 1:1). Mp = 111 °C (lit.[38] Mp = 111-113 °C). ^1H NMR (400 MHz, acetone-d_6) δ 8.0 (dd, J = 7.6, 1.2 Hz, 1H, ArH), 7.50-7.53 (m, 2H, ArH), 7.40-7.47 (m, 4H, ArH), 7.30-7.37 (m, 1H, ArH), 7.13 (dd, J = 7.6, 1.2 Hz, 1H, ArH), 6.68 (s, 2H, SO_2NH_2). ^{13}C NMR (100 MHz, acetone-d_6) δ 142.4, 137.4, 134.4, 134.1, 132.9, 131.9, 130.4, 129.4, 128.7, 126.8.

4-Nitrophenyl phenyl sulfide

A slightly yellow solid. The product was purified by column chromatography (Hex/EA 5:1). R_f = 0.42 (Hex/EA 1:1). Mp = 53-54 °C (lit.[39] Mp = 52.5-53 °C). ^1H NMR (400 MHz, $CDCl_3$) δ 8.04 (dd, J = 7.3, 1.8 Hz, 2H, ArH), 7.54-7.50 (m, 2H, ArH), 7.45-7.42 (m, 3H, ArH), 7.16 (d, J = 8.0 Hz, 2H, ArH). ^{13}C NMR (100 MHz, $CDCl_3$) δ 148.4, 145.4, 134.7, 130.5, 130.0, 129.6, 126.7, 124.0.

4-Fluorophenyl phenyl sulfide

A slight yellow liquid. The product was purified by column chromatography (Hex/EA 10:1). R_f = 0.58 (Hex/EA 1:1). Bp = 136 °C (lit.[40] Bp = 133-135 °C). ^1H NMR (400 MHz, $CDCl_3$) δ 7.40-7.44 (m, 4H, ArH), 6.97-7.01 (m, 5H, ArH). ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.8, 161.3, 132.1, 131.3, 131.2, 128.2, 116.4, 116.2.

4-Chlorophenyl phenyl sulfide

A white solid. The product was purified by column chromatography (Hex/EA 10:1). R_f = 0.6 (Hex/EA 1:1). Mp = 62-64 °C. ^1H NMR (400 MHz, $CDCl_3$) δ 7.38-7.41 (m, 4H, ArH), 7.25-7.28 (m, 5H, ArH). ^{13}C NMR (100 MHz, $CDCl_3$) δ 135.07, 133.58, 129.27, 129.26, 128.19, 128.15, 127.53, 127.48. MS (ESI) *m/z*: 222, 220 (lit.[41] *m/z* for M^+ 222, 220).

4-Bromophenyl 2-tolyl sulfide

A lightly yellow liquid.[42] The product was purified by column chromatography (Hex/EA 10:1). R_f = 0.52 (Hex/EA 1:1). ^1H NMR (400 MHz, acetone-d_6) δ 7.44 (dd, J = 6.6, 2.0 Hz, 2H, ArH), 7.29-7.35 (m, 4H, ArH), 7.06 (dd, J = 6.6, 2.0 Hz, 2H, ArH), 2.33 (s, 3H, CH_3). ^{13}C NMR (100 MHz, acetone-d_6) δ 141.3, 137.0, 134.7, 133.1, 133.0, 131.8, 131.3, 129.7, 127.9, 120.4, 20.7. MS (ESI) *m/z*: 278. Anal. Calcd. For $C_{13}H_{11}BrS$: C, 55.92; H, 3.97. Found: C, 55.78; H, 3.76.

4-Bromophenyl 4-tolyl sulfide

A pale orange solid. The product was purified by column chromatography (Hex/EA 20:1). R_f = 0.55 (Hex/EA 1:1). Mp = 83 °C (lit.[43] Mp = 83-84 °C). ^1H NMR (400 MHz, acetone-d_6) δ 7.74 (dd, J = 6.6, 2.0 Hz, 2H, ArH), 7.33 (d, J = 8.0 Hz, 2H, ArH), 7.23 (d, J = 8.0 Hz, 2H, ArH), 7.15 (dd, J = 6.6, 2.0 Hz, 2H, ArH), 2.34 (s, 3H, CH_3). ^{13}C NMR (100 MHz, acetone-d_6) δ 139.3, 137.9, 133.6, 132.9, 131.6, 131.2, 130.8, 120.5, 21.0.

2-(4-Bromophenylsulfanyl)benzenesulfona-mide

A light yellow solid. The product was purified by column chromatography (Hex/EA 3:1). R_f = 0.34 (Hex/EA 1:1). Mp = 117-119 °C. ^1H NMR (400 MHz, acetone-d_6) δ 8.01-8.04 (m, 1H, ArH), 7.58-7.60 (m, 2H, ArH), 7.38-7.46 (m, 4H, ArH), 7.21-7.22 (m, 1H, ArH), 6.67 (bs, 2H, SO_2NH_2). ^{13}C NMR (100 MHz, acetone-d_6) δ 142.6, 135.9, 135.3, 133.9, 133.0, 132.9, 132.4, 128.5, 127.1, 122.7. MS (ESI) *m/z*: 345, 343. Anal. Calcd. For $C_{12}H_{10}BrNO_2S_2$: C, 41.87; H, 2.93; N, 4.07. Found: C, 41.57; H, 2.86; N, 3.95.

(2-Aminosulfonyl-4-nitro)phenyl 3,4-dimethoxyphenyl sulfide

A yellow solid. The product was purified by column chromatography (Hex/EA 1:1). R_f = 0.2 (Hex/EA 1:1). Mp: 216 °C; ^1H NMR (400 MHz, acetone-d_6) δ 8.70 (d, J = 2.6 Hz, 2H, ArH), 8.18 (dd, J = 8.8, 2.6 Hz, 1H, ArH), 7.23 (dd, J = 8.2, 2.1 Hz, 1H, ArH), 7.13-7.18 (m, 3H, ArH), 6.97 (bs, 2H, SO_2NH_2), 3.90 (s, 3H, CH_3), 3.83 (s, 3H, CH_3). ^{13}C NMR (100 MHz, acetone-d_6) δ 152.5, 151.4, 149.4, 145.2, 140.5, 129.9, 129.5, 126.8, 123.9, 120.4, 119.2, 113.7, 56.2, 56.1. MS (ESI) *m/z*: 370. Anal. Calcd. For $C_{14}H_{14}N_2O_6S_2$: C, 45.40; H, 3.81; N, 7.56. Found: C, 45.37; H, 3.53; N, 7.48.

4-Chlorophenyl 4-nitrophenyl sulfide

A light yellow solid. The product was purified by column chromatography (Hex/EA 20:1). R_f = 0.55 (Hex/EA 1:1). Mp: 87-88 °C (lit.[44] Mp = 87 °C). ^1H NMR (400 MHz, acetone-d_6) δ 8.14 (d, J = 8.8 Hz, 2H, ArH), 7.59 (d, J = 8.8 Hz, 2H, ArH), 7.54 (d, J = 8.4 Hz, 2H, ArH), 7.35 (d, J = 8.8 Hz, 2H, ArH). ^{13}C NMR (100 MHz, acetone-d_6) δ 147.8, 136.7, 136.1, 131.0, 130.4, 130.1, 128.1, 124.9.

4-Chlorophenyl 2-nitrophenyl sulfide

A yellow solid. The product was purified by column chromatography (Hex/EA 20:1). R_f = 0.54 (Hex/EA 1:1). Mp = 97 °C (lit.[45] Mp = 95-97 °C). ^{1}H NMR (400 MHz, acetone-d_6) δ 8.22 (d, J = 8.0 Hz, 1H, ArH), 7.62-7.65 (m, 2H, ArH), 7.53-7.59 (m, 3H, ArH), 7.41 (m, 1H, ArH), 6.99 (d, J = 8.4 Hz, 1H, ArH). ^{13}C NMR (100 MHz, acetone-d_6) δ 146.4, 138.1, 137.8, 136.6, 134.8, 131.1, 130.9, 129.5, 126.7, 126.3.

2,4-Dichlorophenyl 4-nitrophenyl sulfide

A brownish-yellow solid. The product was purified by column chromatography (Hex/EA 20:1). R_f = 0.57 (Hex/EA 1:1). Mp = 91-92 °C (lit.[46] Mp = 89-91 °C). ^{1}H NMR (400 MHz, acetone-d_6) δ 8.19-8.16 (m, 2H, ArH), 7.72 (d, J = 2.4 Hz, 1H, ArH), 7.64 (d, J = 8.4 Hz, 1H, ArH), 7.49 (dd, J = 8.4, 2.0 Hz, 1H, ArH), 7.38-7.42 (m, 2H, ArH). ^{13}C NMR (100 MHz, acetone-d_6) δ 147.1, 145.2, 139.2, 137.8, 136.7, 131.1, 130.1, 129.5, 129.0, 125.1.

2,4-Dichlorophenyl 2-nitrophenyl sulfide

A bright yellow solid. The product was purified by column chromatography (Hex/EA 20:1). R_f = 0.57 (Hex/EA 1:1). Mp = 108-110 °C. ^{1}H NMR (400 MHz, acetone-d_6) δ 8.27 (d, J = 8.0 Hz, 1H, ArH), 7.74-7.81 (m, 2H, ArH), 7.47-7.61 (m, *2*H, ArH), 7.43-7.48 (m, 1H, ArH), 6.94 (d, J = 8.4 Hz, 1H, ArH). ^{13}C NMR (100 MHz, acetone-d_6) δ 146.6, 140.7, 139.6, 137.6, 135.9, 135.0, 131.3, 130.0, 129.7, 129.2, 127.2, 126.6. MS (ESI) *m/z* 298.96 (M^+), 299. Anal. Calcd. For $C_{12}H_7Cl_2NO_2S$: C, 48.02; H, 2.35; N, 4.67. Found: C, 48.15; H, 2.44; N, 4.53.

4-Methoxyphenyl 4-nitrophenyl sulfide

A light yellow solid. The product was purified by column chromatography (Hex/EA 20:1). R_f = 0.54 (Hex/EA 1:1). Mp = 67 °C (lit.[47] Mp = 66-67 °C). ^{1}H NMR (400 MHz, acetone-d_6) δ 8.00 (d, J = 8.8 Hz, 2H, ArH), 7.46 (d, J = 8.8 Hz, 2H, ArH), 7.10 (d, J = 8.8 Hz, 2H, ArH), 7.01 (d, J = 8.8 Hz, 2H, ArH), 3.81 (s, 3H, CH_3). ^{13}C NMR (100 MHz, acetone-d_6) δ 162.0, 150.4, 137.7, 132.9, 126.2, 124.5, 116.4, 115.4, 55.7.

2-Nitrophenyl 4-methoxyphenyl sulfide

A yellow solid. The product was purified by column chromatography (Hex/EA 20:1). R_f = 0.55 (Hex/EA 1:1). Mp = 96-97 °C (lit.[48] mp = 95 °C). ^{1}H NMR (400 MHz, acetone-d_6) δ 8.16 (dd, J = 8.0, 1.2 Hz, 1H, ArH), 7.41-7.49 (m, 3H, ArH), 7.27-7.29 (m, 1H, ArH), 7.04 (dd, J = 8.0, 1.8 Hz, 2H, ArH), 6.82-6.85 (m, 1H, ArH), 3.83 (s, 3H, CH_3). ^{13}C NMR (100 MHz, acetone-d_6) δ 162.1, 140.4, 138.3, 134.4, 128.6, 126.2, 125.9, 121.6, 116.5, 115.4, 55.7.

ACKNOWLEDGEMENTS

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