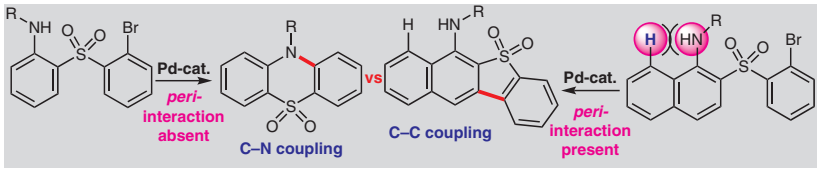
SynOpen S. Debnath, S. Mondal THIEME OPEN ACCESS Paper

Palladium-Catalysed Intramolecular C–N versus C–C Coupling: The Effect of 1,8-*peri*-Interaction in the Naphthalene System

Sudarshan Debnath
Shovan Mondal*

Department of Chemistry, Syamsundar College, Shyamsundar 713424, India
shovanku@gmail.com



Received: 22.12.2018
Accepted after revision: 02.01.2019
Published online: 31.01.2019
DOI: 10.1055/s-0037-1611667; Art ID: so-2019-d0046-op

Abstract Palladium-catalysed competitive intramolecular C–N and C–C coupling of 2-amino-2′-bromodiarylsulfones has been carried out based on 1,8-*peri*-interactions for the synthesis of phenothiazinedioxide and benzonaphthathiophenedioxide derivatives. A DFT study has been performed that provides support for the influence of the 1,8-*peri*-interaction.

Key words naphthalene, 1,8-*peri*-interaction, cyclization, fused-ring, heterocycles

Due to the rigidity of the naphthalene skeleton, the substituents on 1- and 8-positions are forced to be relatively close, at 2.5 Å, which is within the van der Waals radius for many atoms. In contrast, *ortho*-substituents on a benzene ring are separated by 3.3 Å.[1] This 1,8-interaction of naphthalenes, also known as a *peri*-interaction, results in some unique reactivity compared with substituted benzene derivatives.

During our continuing studies on developing novel synthetic routes to heterocycles,[2] we have prepared phenothiazine dioxides and benzonaphthathiophene dioxides via Pd-catalysed intramolecular C–N and C–C coupling and we have studied the effect of the 1,8-*peri*-interaction on the reactivity of the naphthalene moiety. Arylthiazine dioxides and arylthiophene dioxides are important classes of heterocycles because of their applications in medicinal and materials chemistry (Figure 1).[3] Moreover thiazine and thiophene cores are also found in various biologically active natural products and synthetic drugs.[4]

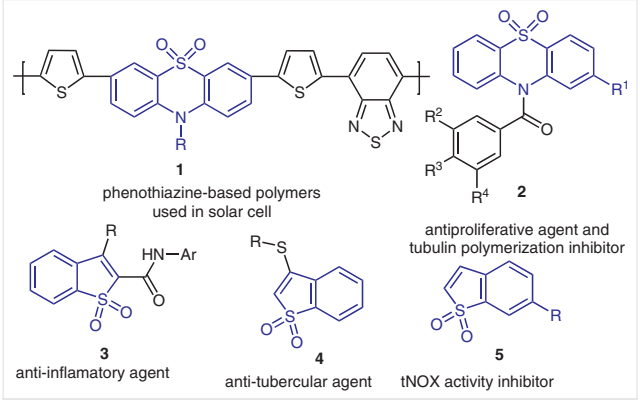
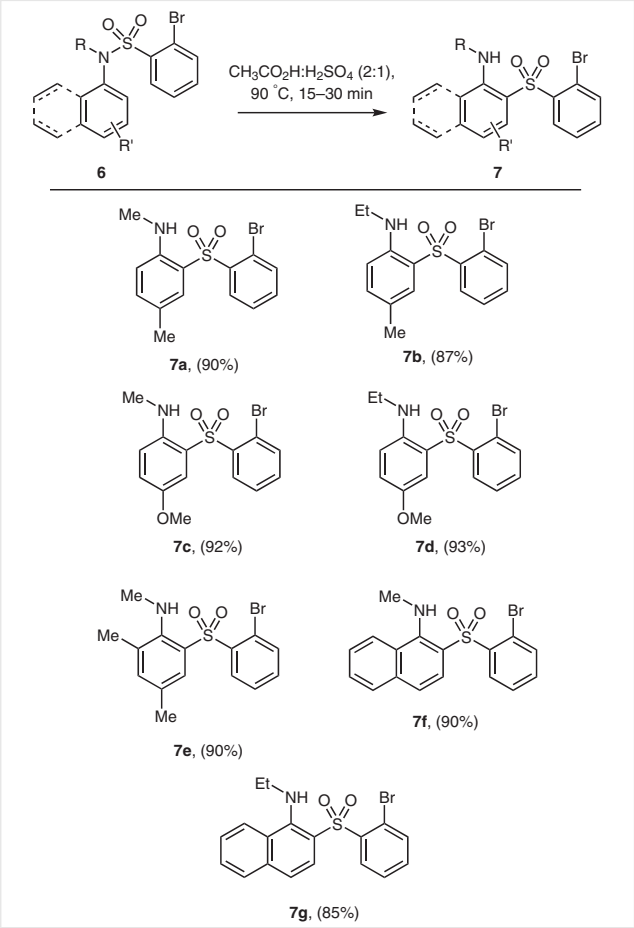


Figure 1 Examples of some useful arylthiazinedioxides and arylthiophenedioxides

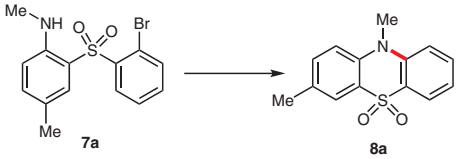
We began this work with 2-amino-2′-bromodiarylsulfones **7**, which were prepared from the corresponding 2-bromo-*N*-alkyl-*N*-arylbenzenesulfonamide derivatives **6** according to our reported procedure (Scheme 1).[5]



Scheme 1 Regioselective Fries type rearrangement for 2-amino-2′-bromodiarylsulfones synthesis

2-Amino-2′-bromodiarylsulfone **7a** was treated with $Pd(OAc)_2$ catalyst in DMF using Cs_2CO_3 as base at 100 °C for 1 h to effect intramolecular C–N coupling, leading to phenothiazine dioxide **8a** in 78% yield. We then optimised the reaction conditions by varying the Pd catalyst, base, solvent, additive, temperature and time. The summarised results are presented in Table 1. Among the three Pd catalysts examined, $Pd(OAc)_2$ provided the best result. Changing base from Cs_2CO_3 to K_2CO_3 led to a notable decrease in yield; whereas KOAc proved more effective. Among different solvents, DMF showed the best results compared with toluene and DMA. The addition of TBAB did not show any improvement in yield. Increasing time or temperature led to little a slight lowering of reaction yields. At low temperatures (50–70 °C), the reaction did not proceed even with extended reaction periods (entries 15 and 16). Increasing the temperature to 85 °C led to a 30% yield of product. The effect of catalyst loading was also studied and we observed the best result using 5 mol% $Pd(OAc)_2$ as catalyst, 2.5 equivalents KOAc as base, DMF as solvent at 100 °C for 1 h, obtaining phenothiazine dioxide in 96% yield (entry 10).

Table 1 Optimisation of Reaction Conditions for Pd-Catalysed Intramolecular C–N coupling[a]

Entry	Cat. System (mol%)	Base[b]	Solvent	Additive	Time (h)	Temp. (°C)	Yield (%)[c]
							
	7a				8a		
1	$Pd(OAc)_2$ (10)	Cs_2CO_3	DMF	–	1	100	78
2	$Pd(PPh_3)_2Cl_2$ (10)	Cs_2CO_3	DMF	–	1	100	67
3	Pd_2dba_3 (10)	Cs_2CO_3	DMF	–	1	100	65
4	$Pd(OAc)_2$ (10)	Cs_2CO_3	DMF	TBAB	1	100	75
5	$Pd(OAc)_2$ (10)	Cs_2CO_3	toluene	–	1	100	52
6	$Pd(OAc)_2$ (10)	K_2CO_3	DMF	–	1	100	55
7	$Pd(OAc)_2$ (10)	KOAc	DMF	–	1	100	92
8	$Pd(OAc)_2$ (10)	KOAc	DMF	–	2	100	81
9	$Pd(OAc)_2$ (10)	KOAc	DMF	–	1	120	79
10	**$Pd(OAc)_2$ (5)**	**KOAc**	**DMF**	**–**	**1**	**100**	**96**
11	$Pd(OAc)_2$ (5)	KOAc	DMF	TBAB	1	100	92
12	$Pd(OAc)_2$ (5)	KOAc	DMA	–	2	100	78
13	$Pd(OAc)_2$ (3)	KOAc	DMF	–	1	120	64
14	$Pd(OAc)_2$ (5)	KOAc	DMF	–	0.5	100	70
15	$Pd(OAc)_2$ (5)	KOAc	DMF	–	4	50	np
16	$Pd(OAc)_2$ (5)	KOAc	DMF	–	4	70	np
17	$Pd(OAc)_2$ (5)	KOAc	DMF	–	4	85	30

[a] All reactions were carried out in a sealed tube under nitrogen.
[b] In every case 2.5 equivalents of base were used.
[c] np = no product

After optimising the reaction conditions, 2-amino-2′-bromodiarylsulfone derivatives **7b–g** were used for the preparation of the corresponding phenothiazine dioxide derivatives **8b–g**. For compounds **7b–e** the corresponding phenothiazine dioxides **8b–e** were formed in excellent yields under the optimised reaction conditions (Scheme 2); however, for substrates **7f** and **7g** a different reaction course took place. The ^1H NMR spectra of the products obtained from precursors **7f** and **7g** showed the N-H proton to be present and one aromatic proton was absent; whilst the ^{13}C NMR spectra revealed the presence of two additional fully substituted aromatic carbon atoms. These data indicate that, for precursors **7f** and **7g**, intramolecular C–C coupling had occurred instead of intramolecular C–N cou-

pling, leading to the corresponding benzonaphthathiophene dioxide derivatives **8f** and **8g**. Finally we confirmed the structures of compound **8a**[6] and **8f**[7] by single-crystal X-ray analysis (Figure 2).

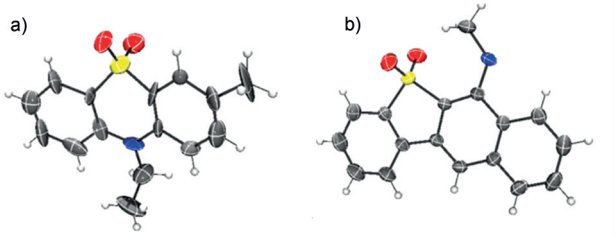
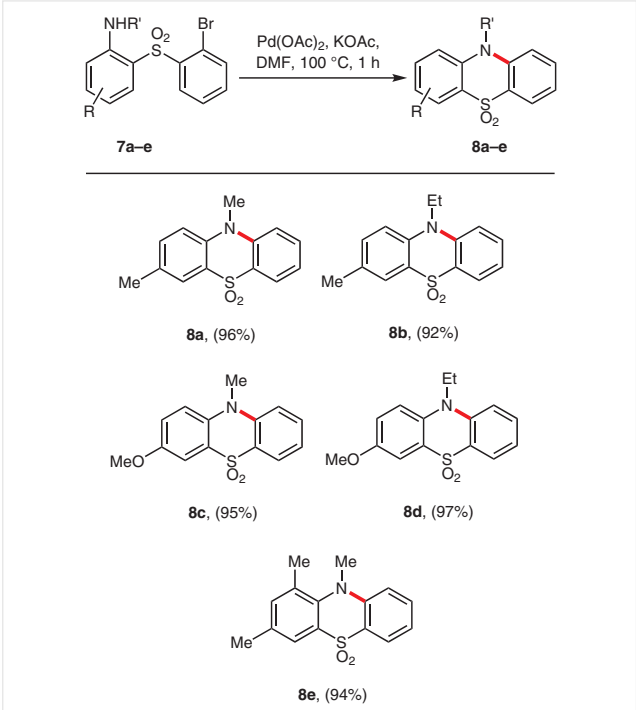


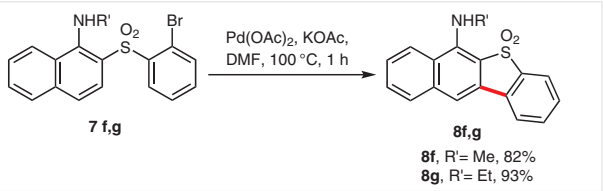
Figure 2 ORTEP diagrams of (a) phenothiazine dioxide **8a** and (b) benzonaphthathiophene dioxide **8f** (the thermal ellipsoids are drawn at the 50% probability level).



Scheme 2 Synthesis of phenothiazine dioxide derivatives

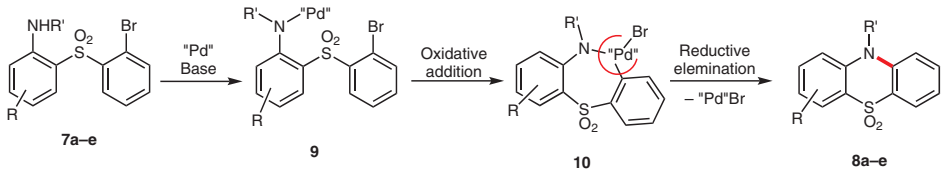
During cyclisation of compounds **7a–f**, two different modes of cyclisation, C–N and C–C, are possible. However, between these two possibilities, C–N coupling is preferred for compounds **7a–e**. A plausible mechanism for the formation of compounds **8a–e** is shown in Scheme 3. Initially, $Pd(OAc)_2$ is reduced to give the active Pd(0) species,[8] which complexes with **7a–e** via coordination with nitrogen to form aryl palladium intermediates **9a–e**. The intermediate then leads to the phenothiazine dioxide derivatives **8a–e** via oxidative addition followed by reductive elimination.

When compounds **7f** and **7g** were treated under the same reaction conditions, C–C coupling was observed instead of C–N coupling, leading to benzonaphthathiophene dioxide derivatives **8f** and **8g** (Scheme 4). A plausible mechanism for the formation of **8f** and **8g** is shown in Scheme 5. Here N-Pd complex **11** is not formed, which may be due to the *peri*-interaction between H-8 and the 1-alkyl-NPd group. Instead, Pd(0) first undergoes oxidative addition to form intermediates **12f** and **12g**, which then lead to the benzonaphthathiophene dioxide derivatives **8f** and **8g** via carbopalladation followed by elimination of PdBr.

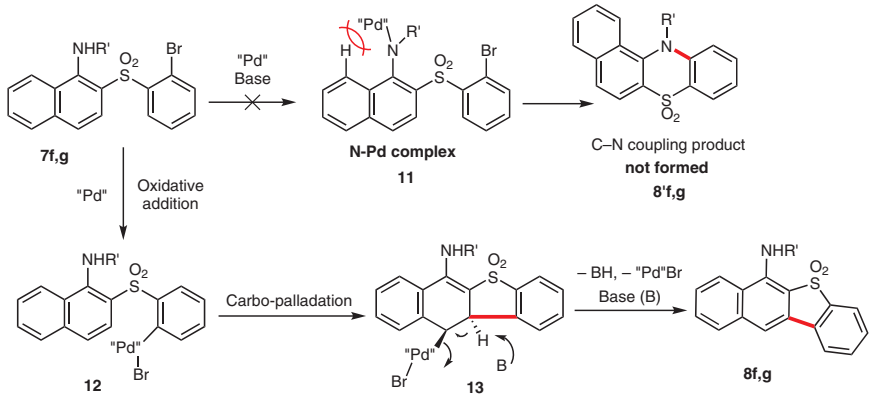


Scheme 4 Synthesis of benzonaphthathiophene dioxide derivatives

We performed DFT calculations to investigate the 1,8-*peri*-interaction in naphthalene systems and the results support the mechanism depicted in Scheme 5 for C–C coupling. All calculations were performed with the Gaussian09 program package[9] using hybrid density functional (B3LYP) theory and the 6-31G(d) basis set. For Pd, the LanL2DZ basis set was used with LanL2 effective core potential. This DFT study shows that the formation energy of complex **11** from the anion of **7f** is –420.48 kcal mol^{-1}; whereas the formation energy of intermediate **12** is –490.33 kcal mol^{-1}. This indicates that the formation of intermediate **12** is more energetically favourable than that of complex **11** by 69.85 kcal mol^{-1}. This could explain why the reaction passes through the successive oxidative addition of Pd(0) to the C–Br bond,



Scheme 3 Plausible mechanism for Pd-catalysed C–N coupling



Scheme 5 Plausible mechanism for Pd-catalysed C–C coupling.

carbopalladation and elimination of PdBr to give the corresponding benzonaphthathiophene dioxides **8f** and **8g** instead of phenothiazine dioxides **8'f** and **8'g**.

In conclusion we have synthesised phenothiazine dioxides **8a–e** and benzonaphthathiophene dioxides **8f** and **8g** by Pd-catalysed intramolecular C–N and C–C coupling reactions, respectively. The effect of the 1,8-*peri*-interaction in the naphthalene system was investigated by DFT calculations and the results support the observed outcomes.

Synthesis of 7e

Compound **7e** was prepared according to the previously reported procedure.[5]

IR (KBr): 3420, 2915, 1617, 1531, 1302, 1135, 708, 580 cm^{-1}.

^1H NMR ($CDCl_3$, 400 MHz): δ = 8.13 (d, *J* = 7.8 Hz, 1 H), 7.64 (d, *J* = 7.7 Hz, 1 H), 7.49–7.43 (m, 2 H), 7.38–7.34 (m, 1 H), 6.45 (s, 1 H), 5.99 (br s, 1 H), 2.80 (s, 3 H), 2.23 (s, 3 H), 2.13 (s, 3 H).

^{13}C NMR ($CDCl_3$, 100 MHz): δ = 146.9, 145.5, 140.6, 135.6, 133.8, 132.1, 127.3, 123.8, 120.7, 115.7, 112.8, 30.1, 20.6, 18.5.

LCMS (ES+): *m*/*z* $[M + H]^+$ calcd for $C_{15}H_{17}BrNO_2S^+$: 354.02; found: 354.

Synthesis of Phenothiazine Dioxides 8a–e and Benzonaphthathiophene Dioxides 8f and 8g; General Procedure

3,10-Dimethyl-10*H*-phenothiazine 5,5-dioxide (8a)

A solution of **7a** (200 mg, 0.59 mmol) in anhydrous DMF (2 mL) and KOAc (115 mg, 1.17 mmol) was purged with nitrogen for 10 min. $Pd(OAc)_2$ (7 mg, 5 mol%) was then added and the mixture was heated to 100 °C for 1 h in a sealed tube. The reaction mixture was cooled, H_2O (10 mL) was added, and the mixture was extracted with EtOAc (3 × 10 mL). The combined EtOAc extracts were washed with H_2O (10 mL), brine (10 mL), and dried (Na_2SO_4). The solvent was distilled off to furnish a viscous residue that was purified by column chromatography (EtOAc/petroleum ether, 1:4) on silica gel to yield compound **8a** (146 mg, 96%) as a white solid; mp 149–151 °C.

IR (KBr): 2975, 1597, 1477, 1273, 1154, 748, 577 cm^{-1}.

^1H NMR ($CDCl_3$, 400 MHz): δ = 8.12 (d, *J* = 7.8 Hz, 1 H), 7.94 (s, 1 H), 7.66–7.60 (m, 1 H), 7.44 (d, *J* = 8.6 Hz, 1 H), 7.33–7.20 (m, 3 H), 3.67 (s, 3 H), 2.46 (s, 3 H).

^{13}C NMR ($CDCl_3$, 100 MHz): δ = 142.1, 139.9, 134.2, 133.1, 131.9, 124.2, 123.4, 123.0, 121.5, 115.6, 115.5, 35.7, 20.5.

HRMS (ESI): *m*/*z* $[M + H]^+$ calcd for $C_{14}H_{14}NO_2S^+$: 260.0740; found: 260.0743.

10-Ethyl-3-methyl-10*H*-phenothiazine 5,5-dioxide (8b)

Yield: 92%; white solid; mp 136–138 °C.

IR (KBr): 2979, 1584, 1471, 1273, 1155, 746, 560 cm^{-1}.

^1H NMR ($CDCl_3$, 400 MHz): δ = 8.09 (dd, *J* = 7.8, 1.5 Hz, 1 H), 7.92–7.89 (m, 1 H), 7.59–7.54 (m, 1 H), 7.39 (dd, *J* = 8.7, 1.9 Hz, 1 H), 7.32 (d, *J* = 8.6 Hz, 1 H), 7.27–7.17 (m, 2 H), 4.19 (q, *J* = 7.1 Hz, 2 H), 2.39 (s, 3 H), 1.49 (t, *J* = 7.1 Hz, 3 H).

^{13}C NMR ($CDCl_3$, 100 MHz): δ = 140.6, 138.3, 134.4, 133.3, 131.8, 123.8, 123.7, 123.2, 121.4, 115.8, 115.6, 43.1, 20.5, 12.6.

HRMS (ESI): *m*/*z* $[M + H]^+$ calcd for $C_{15}H_{16}NO_2S^+$: 274.0896; found: 274.0898.

3-Methoxy-10-methyl-10*H*-phenothiazine 5,5-dioxide (8c)

Yield: 95%; white solid; mp 168–170 °C.

IR (KBr): 2929, 1584, 1479, 1275, 1150, 835, 746, 579 cm^{-1}.

^1H NMR ($CDCl_3$, 400 MHz): δ = 8.11 (dd, *J* = 7.8, 1.4 Hz, 1 H), 7.65–7.58 (m, 2 H), 7.30–7.24 (m, 3 H), 7.24–7.20 (m, 1 H), 3.91 (s, 3 H), 3.70 (s, 3 H).

^{13}C NMR ($CDCl_3$, 100 MHz): δ = 154.8, 142.3, 136.4, 133.2, 124.8, 123.6, 123.5, 121.8, 121.5, 117.4, 115.3, 105.4, 56.1, 35.8.

HRMS (ESI): *m*/*z* $[M + H]^+$ calcd for $C_{14}H_{14}NO_3S^+$: 276.0689; found: 276.0690.

10-Ethyl-3-methoxy-10*H*-phenothiazine 5,5-dioxide (8d)

Yield: 97%; white solid; mp 158–160 °C.

IR (KBr): 2934, 1578, 1478, 1269, 1145, 832, 752, 568 cm^{-1}.

^1H NMR ($CDCl_3$, 400 MHz): δ = 8.09 (dd, *J* = 7.9, 1.4 Hz, 1 H), 7.61–7.54 (m, 2 H), 7.34–7.29 (m, 2 H), 7.24–7.17 (m, 2 H), 4.21 (q, *J* = 7.0 Hz, 2 H), 3.86 (s, 3 H), 1.50 (t, *J* = 7.0 Hz, 3 H).

^{13}C NMR ($CDCl_3$, 100 MHz): δ = 154.6, 140.7, 134.7, 133.2, 124.3, 123.7, 122.9, 122.1, 121.3, 117.6, 115.4, 105.2, 56.1, 43.1, 12.7.

HRMS (ESI): *m*/*z* $[M + H]^+$ calcd for $C_{15}H_{16}NO_3S^+$: 290.0845; found: 290.0849.

2,4,10-Trimethyl-10*H*-phenothiazine 5,5-dioxide (8e)

Yield: 94%; white solid; mp 152–154 °C.

IR (KBr): 2973, 1594, 1465, 1273, 1148, 745, 570 cm^{-1}.

^1H NMR ($CDCl_3$, 400 MHz): δ = 8.08 (d, *J* = 7.7 Hz, 1 H), 7.83 (s, 1 H), 7.60–7.56 (m, 1 H), 7.25–7.21 (m, 2 H), 7.05 (s, 1 H), 3.66 (s, 3 H), 2.37 (s, 3 H), 2.31 (s, 3 H).

^{13}C NMR ($CDCl_3$, 100 MHz): δ = 142.9, 142.1, 140.1, 132.9, 130.9, 124.3, 123.4, 123.3, 121.8, 121.4, 116.4, 115.3, 35.6, 20.7, 18.9.

LCMS (ES+): *m*/*z* $[M + H]^+$ calcd for $C_{15}H_{16}NO_2S^+$: 274.09; found: 274.1.

***N*-Methylbenzo[*d*]naphtho[2,3-*b*]thiophen-6-amine-5,5-dioxide (8f)**

Yield: 82%; white solid; mp 183–185 °C.

IR (KBr): 3404, 2967, 1554, 1280, 1135, 758, 542 cm^{-1}.

^{1}H NMR ($CDCl_3$, 400 MHz): δ = 7.92 (d, *J* = 8.4 Hz, 1 H), 7.87–7.80 (m, 2 H), 7.77 (d, *J* = 7.9 Hz, 1 H), 7.60 (td, *J* = 7.5, 0.9 Hz, 1 H), 7.56–7.41 (m, 4 H), 5.25 (m, 1 H), 3.58 (d, *J* = 5.2 Hz, 3 H).

^{13}C NMR ($CDCl_3$, 100 MHz): δ = 144.6, 138.4, 136.5, 133.4, 132.3, 130.0, 129.6, 129.2, 129.0, 126.7, 126.1, 122.6, 121.6, 121.6, 114.7, 110.9, 34.9.

DEPT-135 ($CDCl_3$, 100 MHz): δ = 133.4, 130.0, 129.6, 129.0, 126.7, 122.6, 121.6, 121.6, 110.9, 34.9.

HRMS (ESI): *m*/*z* $[M + H]^+$ calcd for $C_{17}H_{14}NO_2S^+$: 296.0740; found: 296.0742.

***N*-Ethylbenzo[*d*]naphtho[2,3-*b*]thiophen-6-amine-5,5-dioxide (8g)**

Yield: 93%; white solid; mp 177–179 °C.

IR (KBr): 3407, 2968, 1549, 1272, 1136, 750, 537 cm^{-1}.

^{1}H NMR ($CDCl_3$, 400 MHz): δ = 7.93 (d, *J* = 8.4 Hz, 1 H), 7.81 (t, *J* = 7.7 Hz, 2 H), 7.74 (d, *J* = 8.0 Hz, 1 H), 7.58 (td, *J* = 7.6, 0.8 Hz, 1 H), 7.54–7.38 (m, 4 H), 4.81 (br s, 1 H), 3.89 (q, *J* = 7.1 Hz, 2 H), 1.45 (t, *J* = 7.1 Hz, 3 H).

^{13}C NMR ($CDCl_3$, 100 MHz): δ = 143.9, 138.5, 136.7, 133.5, 132.3, 130.0, 129.6, 129.0, 126.7, 123.2, 121.6, 116.4, 111.6, 43.2, 16.2.

DEPT-135 ($CDCl_3$, 100 MHz): δ = 133.5, 130.0, 129.6, 129.0, 126.7, 123.2, 121.7, 121.6, 111.6, 43.2, 16.2.

HRMS (ESI): *m*/*z* $[M + H]^+$ calcd for $C_{18}H_{16}NO_2S^+$: 310.0896; found: 310.0899.

Funding Information

The Science and Engineering Research Board of the Department of Science and Technology under the Government of India is gratefully acknowledged for an Early Career Research Award to S. M. (Sanction no. ECR/2017/000537).

Acknowledgment

We are very grateful to Professor S. K. Chandra, Department of Chemistry, Visva-Bharati for assistance with the X-ray analyses.

Supporting Information

Supporting information for this article is available online at https://doi.org/10.1055/s-0037-1611667.

References

(1) (a) Balasubramaniyan, V. *Chem. Rev.* **1966**, *66*, 567. (b) Robert, J.-B.; Sherfinski, J. S.; Marsh, R. E.; Roberts, J. D. *J. Org. Chem.* **1974**, *39*, 1152. (c) Banoglu, E.; Duffel, M. W. *Chem. Res. Toxicol.* **1999**, *12*, 278. (d) Hoefelmeyer, J. D.; Gabbaï, F. P. *Organometallics* **2002**, *21*, 982. (e) Mallinson, P. R.; Smith, G. T.; Wilson, C. C.; Grech, E.; Wozniak, K. *J. Am. Chem. Soc.* **2003**, *125*, 4259. (f) Kilian, P.; Knight, F. R.; Woollins, J. D. *Coord. Chem. Rev.* **2011**, *255*, 1387.

(2) (a) Mondal, S.; Debnath, S. *Synthesis* **2014**, *46*, 368. (b) Mondal, S.; Debnath, S. *Tetrahedron Lett.* **2014**, *55*, 1577. (c) Mondal, S.; Debnath, S.; Das, B. *Tetrahedron* **2015**, *71*, 476. (d) Mondal, S.; Debnath, S.; Pal, S.; Das, A. *Synthesis* **2015**, *47*, 3423. (e) Debnath, S.; Mondal, S. *J. Org. Chem.* **2015**, *80*, 3940. (f) Debnath, S.; Mondal, S. *Synthesis* **2016**, *48*, 710. (g) Debnath, S.; Malakar, S.; Mondal, S. *ChemistrySelect* **2017**, *2*, 3147. (h) Debnath, S.; Mondal, S. *Tetrahedron Lett.* **2018**, *59*, 2260.

(3) (a) Carbone, A.; Lucas, C. L.; Moody, C. J. *J. Org. Chem.* **2012**, *77*, 9179. (b) Hunt, C. A.; Mallorga, P. J.; Michelson, S. R.; Schwam, H.; Sondey, J. M.; Smith, R. L.; Sugrue, M. F.; Shepard, K. L. *J. Med. Chem.* **1994**, *37*, 240. (c) Kim, G.; Yeom, H. R.; Cho, S.; Seo, J. H.; Kim, J. Y.; Yang, C. *Macromolecules* **2012**, *45*, 1847. (d) Prinz, H.; Chamasmani, B.; Vogel, K.; Böhm, K. J.; Aicher, B.; Gerlach, M.; Günther, E. G.; Amon, P.; Ivanov, I.; Müller, K. *J. Med. Chem.* **2011**, *54*, 4247. (e) Encío, I.; Morré, D. J.; Villar, R.; Gil, M. J.; Martínez-Merino, V. *Br. J. Cancer* **2005**, *92*, 690. (f) Chandrasekera, N. S.; Bailey, M. A.; Files, M.; Alling, T.; Florio, S. K.; Ollinger, J.; Odingo, J. O.; Parish, T. *PeerJ 2*, e612 DOI: 10.7717/peerj.612. (g) Svoboda, J.; Štádler, M.; Jandera, A.; Panajotová, V.; Kuchař, M. *Collect. Czech. Chem. Commun.* **2000**, *65*, 1082.

(4) (a) Das, B.; Madhusudhan, P.; Venkataiah, B. *J. Chem. Res. Synop.* **2000**, 200. (b) Kato, J.; Kakehata, H.; Maekawa, Y.; Yamashita, T. *Chem. Commun.* **2006**, 4498. (c) Cecchetti, V.; Calderone, V.; Tabarrini, O.; Sabatini, S.; Filipponi, E.; Testai, L.; Spogli, R.; Martinotti, E.; Fravolini, A. *J. Med. Chem.* **2003**, *46*, 3670. (d) Sabatini, S.; Kaatz, G. W.; Rossolini, G. M.; Brandini, D.; Fravolini, A. *J. Med. Chem.* **2008**, *51*, 4321. (e) Calderone, V.; Spogli, R.; Martelli, A.; Manfroni, G.; Testai, L.; Sabatini, S.; Tabarrini, O.; Cecchetti, V. *J. Med. Chem.* **2008**, *51*, 5085. (f) Martelli, A.; Manfroni, G.; Sabbatini, P.; Barreca, M. L.; Testai, L.; Novelli, M.; Sabatini, S.; Massari, S.; Tabarrini, O.; Masiello, P.; Calderone, V.; Cecchetti, V. *J. Med. Chem.* **2013**, *56*, 4718. (g) Li, C. S.; Ding, Y.; Yang, B.-J.; Miklossy, G.; Yin, H.-Q.; Walker, L. A.; Turkson, J.; Cao, S. *Org. Lett.* **2015**, *17*, 3556.

(5) Debnath, S.; Mondal, S. *ChemistrySelect* **2018**, *3*, 4129.

(6) The CCDC reference number for the CIF file of compound **8a** is CCDC 1481104. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif

(7) The CCDC reference number for the CIF file of compound **8f** is CCDC 1481105. These data can be obtained free of charge from The Cambridge Crystallographic Data Centre via www.ccdc.cam.ac.uk/data_request/cif

(8) Beletskaya, I. P.; Cheprakov, A. V. *Chem. Rev.* **2000**, *100*, 3009.

(9) Frisch, M. J.; Trucks, G. W.; Schlegel, H. B.; Scuseria, G. E.; Robb, M. A.; Cheeseman, J. R.; Scalmani, G.; Barone, V.; Mennucci, B.; Petersson, G. A.; Nakatsuji, H.; Caricato, M.; Li, X.; Hratchian, H. P.; Izmaylov, A. F.; Bloino, J.; Zheng, G.; Sonnenberg, J. L.; Hada, M.; Ehara, M.; Toyota, K.; Fukuda, R.; Hasegawa, J.; Ishida, M.; Nakajima, T.; Honda, Y.; Kitao, O.; Nakai, H.; Vreven, T.; Montgomery, J. A.. Jr; Peralta, J. E.; Ogliaro, F.; Bearpark, M.; Heyd, J. J.; Brothers, E.; Kudin, K. N.; Staroverov, V. N.; Kobayashi, R.; Normand, J.; Raghavachari, K.; Rendell, A.; Burant, J. C.; Iyengar, S. S.; Tomasi, J.; Cossi, M.; Rega, N.; Millam, J. M.; Klene, M.; Knox, J. E.; Cross, J. B.; Bakken, V.; Adamo, C.; Jaramillo, J.; Gomperts, R.; Stratmann, R. E.; Yazyev, O.; Austin, A. J.; Cammi, R.; Pomelli, C.; Ochterski, J. W.; Martin, R. L.; Morokuma, K.; Zakrzewski, V. G.; Voth, G. A.; Salvador, P.; Dannenberg, J. J.; Dapprich, S.; Daniels, A. D.; Farkas, O.; Foresman, J. B.; Ortiz, J. V.; Cioslowski, J.; Fox, D. J. *Gaussian 09*; Gaussian Inc.: Wallingford, CT, **2009**.