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Synthesis of a redox-active molecular switch based on dibenzo[1,2]dithiine

Irantzu Llarena,[a] Andrew C. Benniston,[a,*] Guillaume Izzet,[a] Dorota B. Rewinska,[a]
Ross W. Harrington[b] and William Clegg[b]

[a]*Molecular Photonics Laboratory, School of Natural Sciences (Chemistry), Newcastle University, Newcastle upon Tyne NE1 7RU, UK*
[b]*Crystallography Laboratory, School of Natural Sciences (Chemistry), Newcastle University, Newcastle upon Tyne NE1 7RU, UK*

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Abstract—By taking advantage of the Newman–Kwart thermo-rearrangement reaction, the electrochemically switchable bridge unit dibenzo[1,2]dithiine has been prepared and subsequently functionalised with terminal groups.

Considerable effort, expended over many decades, has been focused on the design and construction of molecular systems capable of supporting efficient charge transport.[1] Most of the basic ideas have been inspired by the workings of the intricate machinery used by Nature in the form of photosynthesis. That in natural systems short-range,[2] long-range[3] and directional[4] charge-transport processes have evolved simultaneously clearly demonstrates the need in artificial assemblies to accommodate appropriate components, to control their spatial and orientational arrangements, and to manipulate the pathways for electron flux. This latter goal is one that we[5] and others[6] have sought to attain by engineering tailor-made multi-dimensional relays of redox-active cofactors. Identification of a single, universal modulator that can be externally controlled is essential, especially one where fast switching following the passage of initial charge can retard the return recombination process.[7] This could be realised in a strapped biphenyl-based subunit where a bond break would lead to a major alteration in the central dihedral angle (Fig. 1). In fact from previous work, we have been able to show that a modest angle change can discriminate electron flux by a factor of at least 50-fold.[8] This was achieved by using a variety of compounds, each of which maintains a discrete dihedral angle for the central bridging unit. We now seek to expand on this work by designing a prototype where the angle can be switched by application of an electrical pulse.

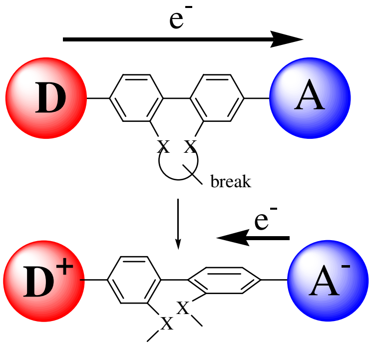

Figure 1. Conceptual illustration of a method to control charge recombination by bond-break and twisting in a biphenyl unit.

Disulfide bonds are readily cleaved by electrochemical reduction (i.e., 2e, $2H^+$) and such entities are often used in natural enzymes as a means by which to control local structure.[9] Hence, the dibenzo[1,2]dithiine subunit meets both criteria of containing an S–S bond and a biphenyl group where the dihedral angle can be switched between almost planar and orthogonal orientations (Fig. 2).[10] Here, we describe the synthesis of an asymmetric supermolecule built around a central dibenzo[1,2]dithiine group. Despite the wealth of known 4,4′-disubstituted dibenzo[1,2]dithiine compounds,[11,12] there is a scarcity

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[*] Corresponding author. Tel.: +44 191 222 5706; fax: +44 191 222 6929; e-mail: a.c.benniston@ncl.ac.uk

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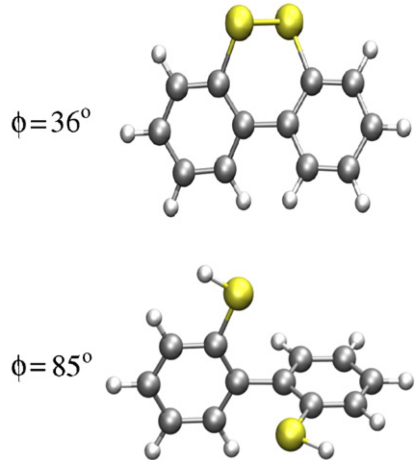
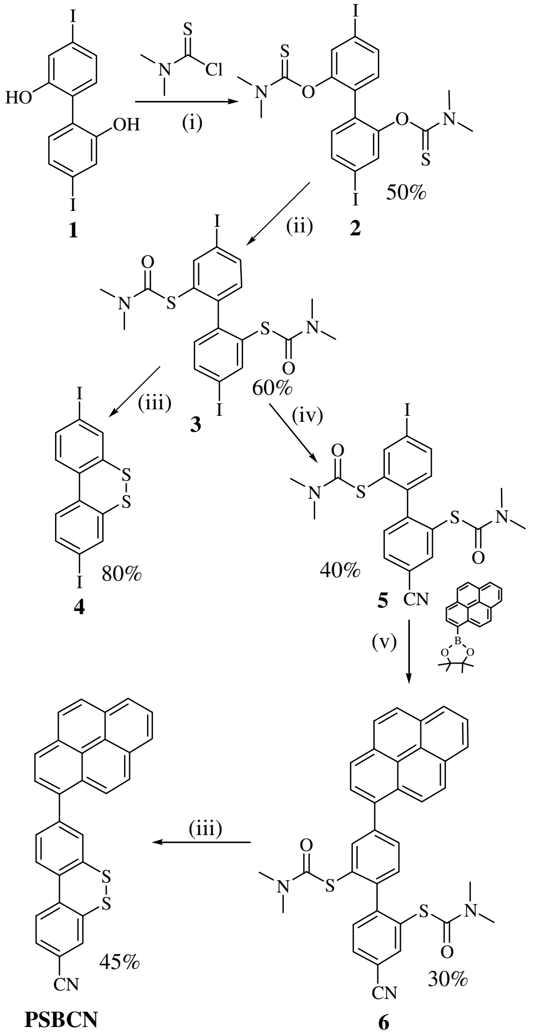


Figure 2. Molecular models for dibenzo[1,2]dithiine in the closed (top) and open (bottom) forms and the calculated dihedral angles.

of such systems that contain a well-defined chromophore that is also electroactive under mild conditions.

The synthetic procedures developed to create a dibenzo[1,2]dithiine-based multi-component array are outlined in Scheme 1. Deprotonation of the readily prepared 4,4′-diiodo-2,2-biphenol with NaH, followed by reaction with *N*,*N*-dimethylthiocarbamoyl chloride, produced derivative **2**[13] in 50% yield. Optimisation of conditions for the key Newman–Kwart thermal rearrangement step required, in particular, careful control of the reaction temperature. It was found that high temperatures (>290 °C) led to many side products, including 3,7-diiododibenzothiophene.[14] The related thiophene derivatives, fully deprotected, have been observed in other cases.[15] However, heating **2** for 1.5 h at a constant temperature of 265 °C, followed by careful column chromatography (silica gel, petrol/diethyl ether (1:3)), afforded **3**[16] as a white solid in 60% yield. At this stage of the synthetic procedure, the idea was to deprotect both sulfur atoms in order to provide easy access to 3,8-diiododibenzo[1,2]dithiine, **4**, and use this in later cross-coupling reactions. The deprotection strategy proceeded smoothly under basic conditions to afford **4**[17] in an isolated yield of 80%. Confirmation of the product was undertaken using single-crystal X-ray crystallography (Fig. 3).[18]

The dithiine ring in compound **4** has an almost ideal screw-boat conformation, with a non-crystallographic twofold rotational axis running through the mid-points of the S–S and opposite C–C bonds. The torsion angle about the S–S bond is 60.22(14)°, and the biphenyl torsion angle C(1)–C(6)–C(7)–C(12) is 30.4(4)°, similar to that calculated above for dibenzo[1,2]dithiine (36°). There are six previously reported crystal structures of dibenzo and dinaphtho[1,2]dithiines.[19] In these, the torsion angle about the S–S bond falls within the rather narrow range 55.8–60.8° and the S–S bond length is 2.051–2.056 Å [2.0595(12) Å in **4**]. The biphenyl (or binaphthyl) torsion angle is more variable, 24.2–46.3°, with larger values (37.5 and 46.3°) for the naphthyl compounds and smaller values (24.2–28.8°) for substituted dibenzo compounds; the C–C bond length ranges from 1.461 to 1.507 Å [1.489(4) Å in **4**]. Interestingly, the unsubstituted parent compound dibenzo[1,2]dithiine has a larger torsion angle than its substituted derivatives, at 33.0° (together with one of the shortest inter-ring C–C bonds at 1.465 Å), which is in very good agreement with the value of 36° obtained from our modeling studies.



Scheme 1. Reagents and conditions: (i) DMF, NaH, 24 h; (ii) 265 °C, 1.5 h; (iii) NaOH/MeOH, THF 1 h; (iv) 1.1 KCN, Pd(PPh$_3$)$_4$, CuI, THF, 16 h; (v) toluene, 1 M Na$_2$CO$_3$, Pd(PPh$_3$)$_4$, 18 h.

Attempts to couple functional groups (e.g., pyrene) to **4** under standard Suzuki coupling conditions [(Pd(PPh$_3$)$_4$)] gave mixtures that proved difficult to resolve. In the case where phenylboronic acid was used, the only product properly characterised and identified was triphenyl phosphine sulfide.[20] This material presumably arises from coordination of the 'soft' palladium catalyst to the 'soft' S–S group and subsequent decomposition. Because of such inherent difficulties, this synthetic approach was abandoned. Hence, coupling reactions were performed on **3** since both sulfur atoms are protected from coordination. Reaction of **3** in dry THF containing KCN (1.1 equiv) and [(Pd(PPh$_3$)$_4$)], in

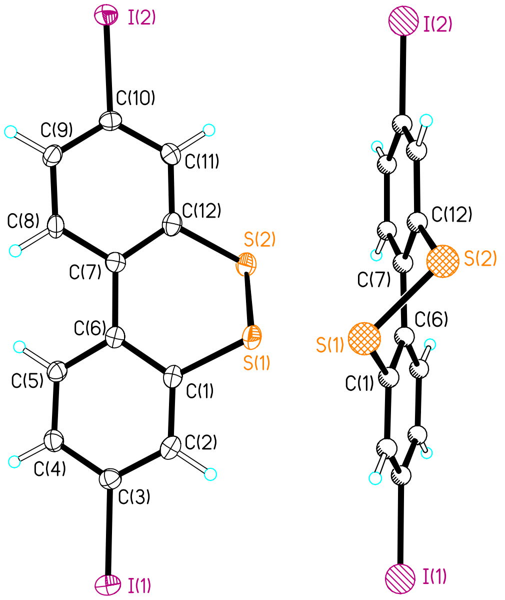


Figure 3. Molecular structure of compound **4**, showing the twisted biphenyl unit and S–S linker: left, a general view with 50% probability displacement ellipsoids; right, a view along the approximate molecular C_2 axis.

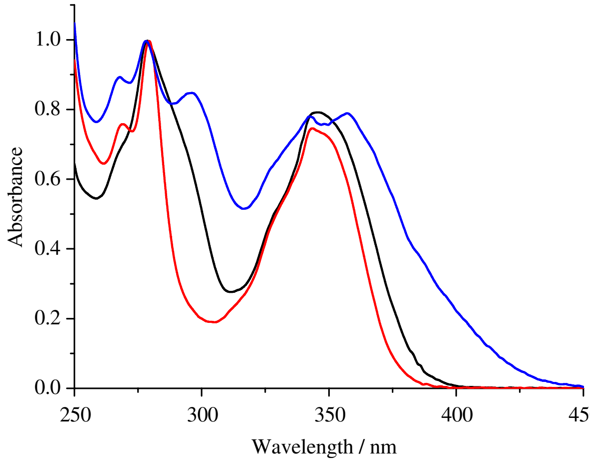


Figure 4. Absorption profiles recorded for **PSBCN** (blue), **6** (red) and **PBCN** (black) in acetonitrile.

the presence of CuI, gave after work-up and purification (silica gel, petrol/ethyl acetate 1:1) the mono-cyano derivative **5**[21] in 40% yield. Coupling **5** with 4,4,5,5-tetramethyl-2-pyren-yl-1,3,2-dioxaborolane[22] using typical Suzuki coupling conditions[23] gave, after purification, compound **6**.[24] Straightforward deprotection of the sulfur atoms under basic conditions afforded, after work up in air, the desired triad **PSBCN**.[25]

The basic electrochemistry of breaking and reforming the disulfide bridge was carried out on precursor **4** using cyclic voltammetry. Upon reductive scanning at a modest scan rate ($50\ \mathrm{mV\,s^{-1}}$) at a Pt electrode in dried CH_2Cl_2 containing 0.2 M tetra-*n*-butylammonium tetrafluoroborate, an irreversible wave was observed at -1.31 V versus SCE. This value is in good agreement with previously reported electrochemical data on related systems.[26] At a faster scan rate ($500\ \mathrm{mV\,s^{-1}}$), an additional irreversible oxidative wave became visible at -0.05 V versus SCE. This was also accompanied by a shift in the main reduction wave to the more negative potential of -1.47 V versus SCE. These results are analogous to those observed for PhSSPh[27] in which the initially generated thiophenolate is oxidised to form a radical species that rapidly dimerises to reform the disulfide bond. The interesting feature found for **4**, however, is a clear indication for potential inversion. This is important for the design of rapid electrochemical switches.

Shown in Figure 4 are the absorption spectra recorded for **PSBCN** in acetonitrile and, for comparison, compounds **6**, and the analogue of **PSBCN** where the sulfur bridge is absent (**PBCN**).[28] It is noted that for compound **3** the biphenyl dihedral angle is close to 66° (with an inter-ring C–C bond length almost identical to that of **4**),[29] so a similar result is expected for **6**. The broad feature at around 350 nm for all the compounds is characteristic of the π–π^* transitions associated with pyrene. Long wavelength (350–445 nm) absorption bands are well known for dibenzo-*o*-dithiine compounds, and assigned to transitions associated with the S–S group.[11b] Indeed, it is noticeable that for **PSBCN** the absorption profile at longer wavelength is much broader than that for both **6** and **PBCN**, and is presumably due to the additional electronic transitions. Whereas broad structureless pyrene-based emission profiles, centred at ca. 440 nm, are evident for **PBCN** and **6**, no discernable fluorescence is observed for **PSBCN**. This result would support efficient quenching of the pyrene first-excited singlet state by the disulfide bond. To test whether quenching was due to irreversible S–S bond breakage, a sample of **PSBCN** in N_2-purged butyronitrile was continuously irradiated with intense white light for up to 1 h. That the absorption profile did not show any appreciable alteration, nor was there any build up of a new absorption band shows that bond breaking, if it occurs under these conditions, is highly reversible. Time-resolved transient absorption experiments are underway to shed light into electron-transfer processes taking place within **PSBCN**. The detailed quenching mechanism will be published elsewhere where the 'angle effect' and involvement of the cyano-based acceptor group will be properly evaluated.

Crystallographic data (excluding structure factors) for compound **4** have been deposited with the Cambridge Crystallographic Data Centre as supplementary publication number CCDC 615838. Copies of the data can be obtained, free of charge, on application to CCDC, 12 Union Road, Cambridge CB2 1EZ, UK (fax: +44 (0)-1223-336033 or email: deposit@ccdc.cam.ac.uk).

Acknowledgements

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13. *Analytical data* **2**: ^{1}H NMR (300 MHz, $CDCl_3$) $\delta = 7.59$ (dd, 2H, $J = 8.0$ Hz, $J = 1.7$ Hz), 7.53 (d, 2H, $J = 1.7$ Hz), 7.12 (d, 2H, $J = 8.0$ Hz), 3.30 (s, 6H), 3.09 (s, 6H). ^{13}C NMR (75 MHz, $CDCl_3$) $\delta = 39.1$, 43.7, 93.1, 130.2, 132.8, 133.5, 135.1, 151.6, 186.8. (EI-MS) *m*/*z* calcd for $C_{18}H_{18}I_2N_2O_2S_2$: 612.3. Found: 612. Mp 200–202 °C. CHN analysis calcd (found) for $C_{18}H_{18}I_2N_2O_2S_2$: C, 35.31 (35.23); H, 2.96 (2.96); N, 4.58 (4.41).
14. *Analytical data*: ^{1}H NMR (300 MHz, $CDCl_3$) $\delta = 8.18$ (d, 2H, $J = 1.3$ Hz), 7.84 (d, 2H, $J = 8.3$ Hz), 7.75 (dd, 2H, $J = 8.4$ Hz $J' = 1.5$ Hz). ^{13}C NMR (75 MHz, $CDCl_3$) $\delta = 92.05$, 123.08, 131.7, 134.0, 134.7, 141.4. (EI-MS) *m*/*z* calcd for $C_{12}H_6S_1I_2$: 435.8. Found: 436. Mp 199–201 °C. CHN analysis calcd (found) for $C_{12}H_6S_1I_2$: C, 33.05 (33.06); H, 1.39 (1.33).
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16. *Analytical data* **3**: ^{1}H NMR (300 MHz, $CDCl_3$) $\delta = 7.93$ (d, 2H, $J = 1.8$ Hz), 7.71 (dd, 2H, $J = 8.1$ Hz, $J' = 1.8$ Hz), 7.00 (d, 2H, $J = 8.1$ Hz), 2.89 (s, 12H). ^{13}C NMR (75 MHz, $CDCl_3$) $\delta = 40.6$, 92.0, 92.5, 123.6, 127.3, 130.6, 133.2, 137.6, 135.5. Mp 190–192 °C. (EI-MS) *m*/*z* calcd for $C_{18}H_{18}I_2N_2O_2S_2$: 612.3. Found: 612. CHN analysis calcd (found) for $C_{18}H_{18}I_2N_2O_2S_2$: C, 35.51 (35.4); H, 2.96 (2.98); N, 4.58 (4.62).
17. *Analytical data* **4**: ^{1}H NMR (300 MHz, $CDCl_3$) $\delta = 7.85$ (d, 2H, $J = 1.8$ Hz), 7.69 (dd, 2H, $J = 8.3$ Hz, $J' = 1.8$ Hz), 7.35 (d, 2H, $J = 8.3$ Hz). ^{13}C NMR $\delta = 94.0$, 129.0, 137.2, 137.7, 138.1, 138.4. EI-MS *m*/*z* calcd for $C_{12}H_6I_2S_2$: 468.1. Found: 468.0. Mp 150–152 °C. CH analysis calcd (found) for $C_{12}H_6I_2S_2{\cdot}H_2O$: C, 29.65 (29.42); H, 1.66 (1.08).
18. *Yellow crystals of* **4** *were grown from a solution in chloroform. Selected crystallographic data*: $C_{12}H_6I_2S_2$, $M = 468.09$, monoclinic, $P2_1/c$, $a = 8.136$ (2), $b = 18.084$ (2), $c = 9.585$ (5) Å, $\beta = 113.698$ (15)°, $V = 1291.3$ (5) Å^3, $Z = 4$, $T = 150$ K; R ($F, F^2 > 2\sigma$) = 0.0218, R_w (F^2, all data) = 0.0554, goodness of fit on $F^2 = 1.187$, 145 parameters and 2963 unique reflections, final difference map extremes +0.52 and −0.83 e Å^{-3}.
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20. This product was confirmed by single-crystal X-ray crystallography and is a known literature compound.
21. *Analytical data* **5**: ^{1}H NMR (300 MHz, $CDCl_3$) $\delta = 7.93$ (dd, 2H, $J = 7.1$ Hz, $J' = 1.6$ Hz), 7.82 (m, 2H), 7.39 (d, 1H, $J = 7.8$ Hz), 6.99 (d, 1H, $J = 8.1$ Hz), 2.91 (s, 6H), 2.87 (s, 6H). ^{13}C NMR (75 MHz, $CDCl_3$) $\delta = 35.10$, 58.42, 91.77, 110.75, 116.09, 128.55, 129.19, 129.59, 129.84, 130.03, 136.33, 138.50, 142.08, 143.46, 147.45, 163.02, 163.26. Mp 140–142 °C. (EI-MS) *m*/*z* calcd for $C_{19}H_{18}I_1N_3O_2S_2$: 510.9. Found: 511. CHN analysis calcd (found) for $C_{19}H_{18}I_1N_3O_2S_2{\cdot}C_4H_8O$: C, 46.00 (45.44); H, 4.05 (4.01); N, 7.68 (7.35).
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24. *Analytical data* **6**: ^{1}H NMR (300 MHz, $CDCl_3$) $\delta = 8.29$ (d, 1H, $J = 9.3$ Hz), 8.22 (d, 1H, $J = 7.9$ Hz), 8.17 (d, 1H, $J = 7.9$ Hz), 8.05 (m, 4H), 7.96 (d, 1H, $J = 1.5$ Hz), 7.89 (d, 1H, $J = 1.7$ Hz), 7.72 (dd, 2H, $J = 1.8$ Hz, $J' = 1.3$ Hz), 7.69 (dd, 2H, $J = 3.0$ Hz, $J' = 1.8$ Hz), 7.56 (d, 1H, $J = 7.9$ Hz), 7.43 (d, 1H, $J = 7.8$ Hz), 2.98 (s, 6H), 2.92 (s, 6H). ^{13}C NMR (75 MHz, $CDCl_3$) $\delta = 38.32$, 41.24, 99.65, 111.40, 111.49, 118.76, 124.73, 125.03, 125.22, 125.34, 126.15, 127.39, 127.44, 127.48, 127.70, 127.76, 127.77, 128.14, 128.28, 128.70, 131.05, 131.13, 131.69, 132.71, 135.30, 136.84, 138.16, 141.99, 145.41. (EI-MS) *m*/*z* calcd for $C_{35}H_{27}O_2N_3S_2$: 585.75. Found: 585.
25. *Analytical data* **PSBCN**: ^{1}H NMR (300 MHz, $CDCl_3$) $\delta = 8.23$ (m, 4H), 8.13 (d, 2H, $J = 1.3$ Hz), 8.05 (m, 3H), 7.91 (d, 1H, $J = 8.0$ Hz), 7.88 (d, 2H, $J = 1.4$ Hz), 7.83 (d, 1H, $J = 1.7$ Hz), 7.72 (dd, 1H, $J = 1.7$ Hz $J' = 1.0$ Hz), 7.70 (dd, 1H, $J = 1.7$ Hz, $J' = 0.8$ Hz). EI-MS *m*/*z* accurate mass calcd for $C_{29}H_{15}NS_2$: 441.0640. Found: 441.0639.
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29. Calculated using the structure of **3** as determined by X-ray crystallography.