Synthesis of a new extended π-donor with 1,4-oxathiane annulation

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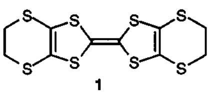
4,5;4′,5′-Bis(1,4-oxathiane-2,3-diyldithio)tetrathiafulvalene **7** (TOET) is synthesised in four steps from 1,4-oxathiane. Compound **7** shows two reversible redox couples at 0.56 and 0.90 V *vs.* SCE. Analysis of NMR spectra combined with energy minimisation calculations indicated that at least three isomers of TOET should be present in solution. TOET forms a charge-transfer complex with TCNQ which shows a conductivity of 3×10^{-3} S cm^{-1}.

Tetrathiafulvalene π-donors for molecular metals and superconductors have attracted considerable research interest. Most successful cation radical systems are based on ET **1** as donor, with various counter ions.[1] Taking a simplified view, the π-core is responsible for hosting the conduction process, whereas the peripheral substituents act as guides for the docking of the donor moieties between the anions. Changing these side groups will therefore lead to new unforeseen packing modes in the solid state. Although the initial high hopes for oxygen substitution[2] has not been fulfilled, a strong tendency to form metallic compounds has been noted.[3]



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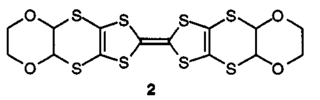

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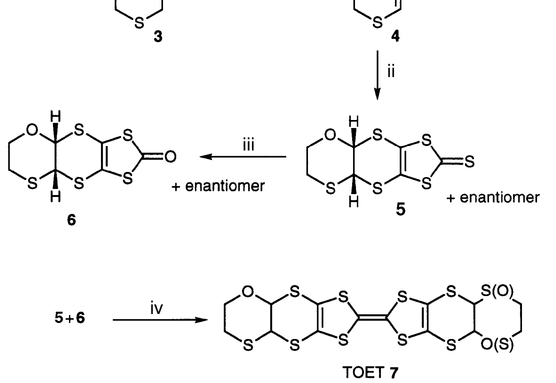
Newly aroused interest in the 1,4-dioxane fused-ET (BDDT-TTF) **2**,[4] together with the availability of 2,3-dihydro-1,4-oxathiine **4** in our group, prompted us to synthesise the analogous 4,5;4′,5′-bis(1,4-oxathiane-2,3-diyldithio)tetrathiafulvalene (ThiOxane-ET or TOET), which we report here.

The synthesis sequence is depicted in Scheme 1. Commercially available 1,4-oxathiane **3** was treated with sulfuryl chloride in carbon tetrachloride and refluxed for 3 days to yield 2,3-dihydro-1,4-oxathiine **4** in reasonable yield after distillation. Compound **4** is less stable than the corresponding dioxa derivative, but can be stored in a freezer for several months if pure; impurities seem to initiate polymerisation. Reaction of **4** with 1,3-dithiole-2,4,5-trithione oligomer was achieved in refluxing dioxane to yield the *cis*-fused 4,5-(1,4-oxathiane-2,3-diyldithio)-1,3-dithiole-2-thione **5** in 38% yield. Thione **5** was converted to the corresponding carbonyl derivative **6** *via* treatment with mercuric acetate in acetonitrile. Dimerization to TOET **7** could be achieved by treating either the thione, or the carbonyl, or a 1 : 1 mixture of the two, with trimethyl phosphite in benzene at reflux temperatures. Best yields (*ca.* 40%) were achieved with either the carbonyl or the mixture, while the thione alone gave slightly less product. The isolated TOET showed a good elemental analysis, whereas the EI-MS conditions produced clean retro Diels–Alder reactions and therefore showed only the mass spectrum of **4**. Proton NMR spectra in $CDCl_3$ or $[^2H_6]$DMSO could only give an indication of the purity because of the insolubility of TOET. However, in $[^2H_5]$pyridine at 353 K, a reasonable spectrum could be recorded which showed a heavily coupled system with the individual protons well separated (Fig. 1). At this temperature the retro Diels–Alder reaction was too fast to allow a ^{13}C NMR spectrum to be recorded, *i.e.* after 6 h *ca.* 50% had reverted to starting material. Also apparent from the spectrum was the presence of at least two stereoisomers, since one of the bridgehead methine protons was doubled.



Scheme 1 *Reagents and conditions*: i, SO_2Cl_2, CCl_4, reflux, 1 week; ii, dioxane, 1,3-dithiole-2,4,5-trithione oligomer, reflux, 18 h, 38%; iii, $Hg(OAC)_2$, MeCN; iv, $(MeO)_3P$, benzene, reflux, 3.5 h

At this point we found it necessary to try to estimate the isomeric purity of the TOET. If the cycloaddition step is assumed to give a product with the vicinal hydrogens between the oxathiane and dithiine *ring* arranged in a *cis*-fashion, the number of theoretically possible stereoisomers is reduced from sixteen to eight. Among these eight there are two pairs of identical molecules, which means that the final number of stereoisomers are six, namely the two non-chiral diastereomers *anti-trans* **A** and *syn-cis* **B**, and the two pairs of enantiomers, *syn-trans* **C**/**D** and *anti-cis* **E**/**F**, respectively. Rotation around the central double bond has been shown to occur even in

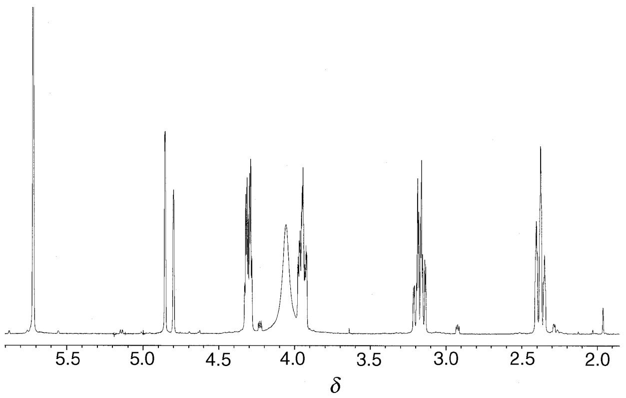


Fig. 1 500 MHz ^1H NMR spectrum of TOET **7** in $[^2H_5]$pyridine at 353 K

weakly protic solutions in related systems, which should make **A** equilibrate with **B**, as well as **C** with **E** and **D** with **F**, respectively. Our nomenclature for the stereoisomers, and representations of these, are given in Fig. 2 and 3.

A simulation of the coupling pattern present in the ^{1}H NMR spectrum of the carbonyl compound **6**, using coupling constants calculated from the global minimum conformation derived with the MACROMODEL program, was in good agreement with that obtained from the experimental spectrum (Fig. 4). The conformation of the global minimum is shown in Fig. 5. The second lowest conformation turned out to be 16 kJ mol^{-1} higher in energy (12 kJ mol^{-1} using AM1 calculations), indicating a highly populated global minimum.

Starting with this conformation we energy-minimized the four different diastereomers of **7** (**A**, **B**, **C**/**D**, **E**/**F**) assumed to be present. The four conformations so achieved were thus all in firm energy-minima with no other conformations energetically available. The energy differences between the four stereoisomers were negligible, the largest being 0.4 kJ mol^{-1}. This energy difference is probably within the calculation error-limit, and would lead to only a few percent difference in concentration between two isomers in equilibrium. AM1 optimization of the four isomers gave energy differences very close to zero. The four energy-minimized diastereomers are shown in Fig. 6. Noteworthy is the strong tendency for the sulfur atom in the oxathiane ring to point outwards from the convex part of the molecule, whereas the oxygen atom in the same ring is on the concave side towards the planar π-system.

The experimental ^{1}H NMR spectrum for TOET **7** could be simulated, anticipating two stereoisomers with identical coupling systems but slightly different shifts. Good agreement was found for all protons using the coupling constants found for **6**, with the two isomers present in approximately 2:3 ratio (see Fig. 7 for the proton around δ 3.95).

Since there do not seem to be any large differences in energy between the stereoisomers, the isomeric outcome is probably governed by solubility factors rather than thermodynamic stabilities. Our work-up procedure relies on the crystallisation of TOET from the cooled reaction mixture, so there is probably enrichment of the less soluble stereoisomers at this stage. As it has been shown that proton-assisted rotation–isomerization around the central double bond is prevented by the addition of pyridine, we can anticipate that this isomerization reaction is not present in our spectrum of TOET in pyridine.

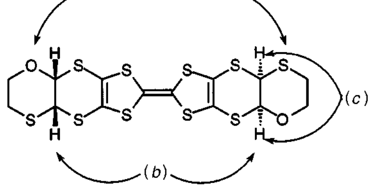


Fig. 2 Definitions of different stereoisomers of TOET **7**. (*a*) 'S–S' *cis-trans* iomers formed through proton-assisted rotation around central double bond. (*b*) 'H–H' *syn-anti* isomers formed during phosphite-assisted dimerization of **5**+**6**. (*c*) Only *cis* 'H–H' isomers are formed in the cycloaddition reaction to form **5**.

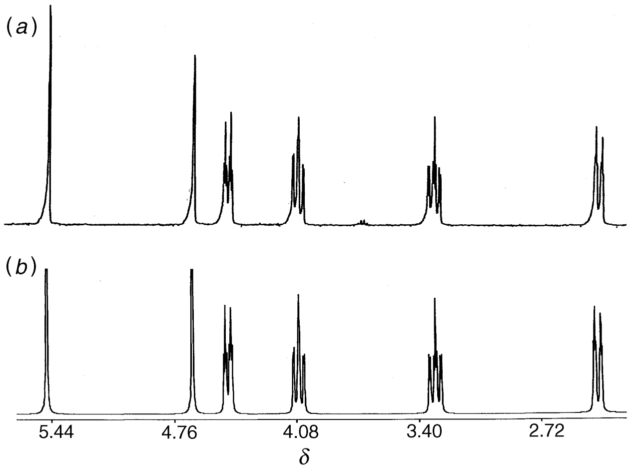


Fig. 4 (*a*) Experimental and (*b*) calculated ^{1}H NMR spectra for **6**

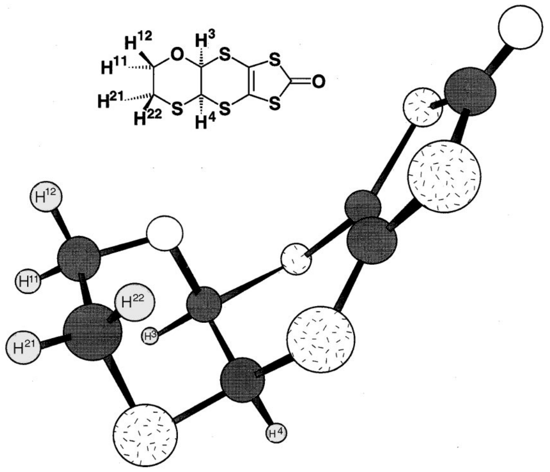


Fig. 5 Energy-minimized structure of carbonyl derivative **6** (MACROMODEL, MM3*). Experimental coupling constants: H^{11}–H^{12} = 12.1 Hz, H^{11}–H^{21} = 2.3 Hz, H^{11}–H^{22} = 11.9 Hz, H^{12}–H^{21} = 1.9 Hz, H^{12}–H^{22} = 4.3 Hz, H^{21}–H^{22} = 14 Hz, H^3–H^4 = 1.5 Hz.

So, without any definitive proof, is it then possible to say something about the stereoisomeric distribution in this system?

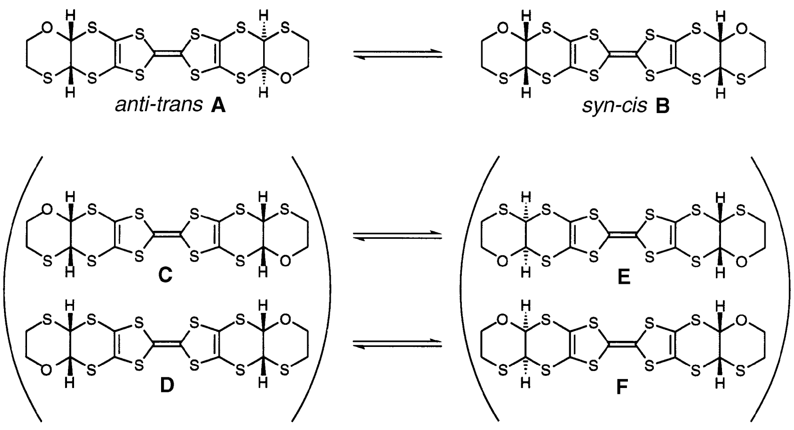


Fig. 3 Different possible stereoisomers of TOET **7**

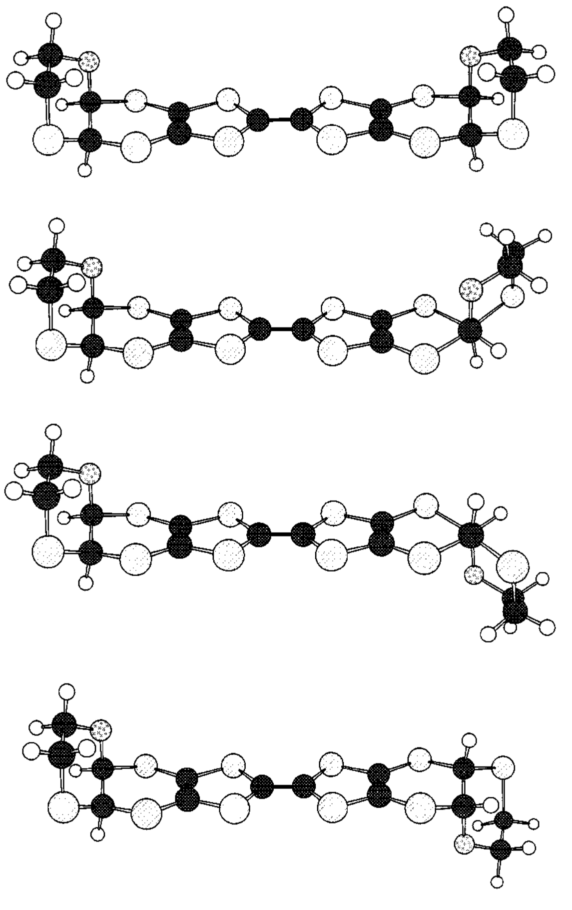


Fig. 6 The four different energy-minimized diastereomers of TOET **7** (AM1 calculated)

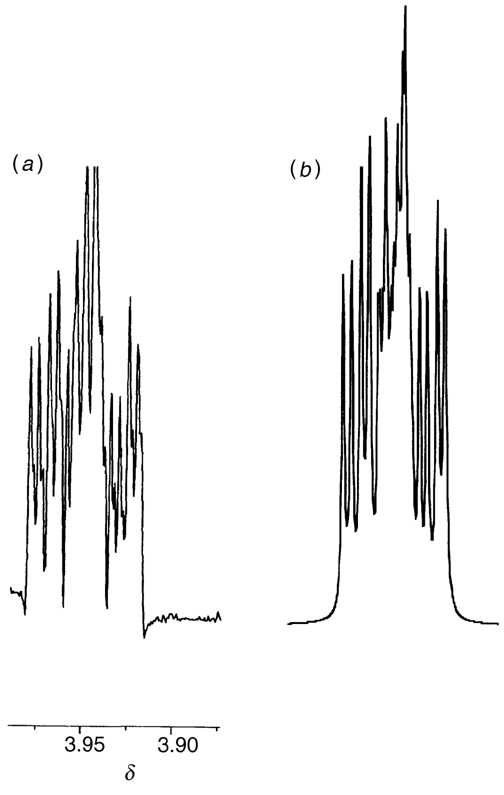


Fig. 7 (*a*) Experimental and (*b*) calculated ^{1}H NMR spectra for the proton at δ 3.95 in TOET **7**

Well, if one believes that it is the less soluble isomer that is crystallising, we get some guidance from the fact that Kini *et al.*[4b] were able to isolate a cation radical salt of an *anti* isomer of the analogous dioxaderivative BDDT-TTF. If the same situation is valid in our case, we can assume that the recorded spectrum is showing a mixture of isomers **A** and **E**/**F**.

Cyclic voltammetry of TOET in benzonitrile showed two reversible redox couples at $E_{1/2}=0.56$ and 0.90 V. These values are *ca.* 50 mV higher than ET **1** measured under the same conditions. Electrocrystallization of the new donor in benzonitrile in the presence of the anions NO_3 or PF_6 gave microcrystalline red–brown powders of poor quality. We could also isolate a 1 : 1 charge transfer complex with TCNQ as a microcrystalline powder, with a rather low conductivity (3×10^{-3} S cm^{-1} measured on a compressed pellet).

In conclusion, we have synthesised the new extended donor TOET in a short synthesis, and showed that there are at least two stereoisomers present in the crude reaction product. We are currently investigating alternative conditions for the electrocrystallization experiments in order to facilitate monoisomeric salts, but the difficulty of isolating pure isomers coupled with the inherent ease of isomerisation in these systems will probably prevent any extensive use of TOET as a donor for organic metals.

Experimental

NMR spectra were recorded on a Bruker AM 400 (400 MHz) or Bruker DMX 500 (500 MHz) spectrometer; *J* values are given in Hz. Mass spectra were recorded on a Finnigan SSQ 7000. THF was distilled from sodium–benzophenone, all other solvents were either distilled or HPLC grade. Cyclic voltammetry was carried out at 25 °C in benzonitrile at 100 mV s^{-1} with Bu_4NPF_6 (0.15 M) as electrolyte and measured *vs.* a SCE reference electrode. Electrocrystallizations were performed at ambient temperature, with a platinum wire anode of about 1 cm^2. Currents were typically 1.0 μA cm^{-2} and the experiment was run for 1–2 weeks.

Molecular mechanics modelling was carried out using the MACROMODEL program (ver. 4.5) using a Silicon Graphics Indigo 2 workstation. The following parameters were used in the conformational search on **7**: force field, MM3*; minimization algorithm, truncated Newton-Raphson; derivative convergent criteria, 0.05 kJ Å^{-1} mol^{-1}; permissible window above lowest energy conformation, 50 kJ mol^{-1}; number of Monte Carlo steps, 1000. Vicinal proton coupling constants (^3J) were calculated within the MACROMODEL program (using the method of Haasnoot *et al.*[5]). No Boltzmann averaging was performed since the energy difference of 16.2 kJ mol^{-1} between the global minimum and the second lowest conformer will result in an almost exclusive population of the former. Semiempirical calculations were performed using the AM1 parametrization as implemented in SPARTAN SGI ver. 4.0.3 GL, using global minima derived from MACROMODEL.

2,3-Dihydro-1,4-oxathiine 4

1,4-Oxathiane **3** (143,9 g, 1.38 mol) dissolved in carbon tetrachloride (1 l) was brought to reflux. Sulfuryl chloride (1.05 equiv. 196 g) dissolved in carbon tetrachloride (500 ml) was added dropwise to the refluxing solution over *ca.* 90 min. The solution was then refluxed for 3 days. The carbon tetrachloride was then evaporated under reduced pressure and the dark residue distilled under water aspirator vacuum. Pure compound **4** was collected at 70 °C (lit.,[6] 54 °C, 20 mmHg) in yields up to 73%. Yields varied considerably since polymerisation frequently occurred, especially at temperatures above 100 °C. Attempts to inhibit this side reaction previous to distillation by various drying and/or neutralizing procedures seemed to have little or no effect on the yield. ^{1}H NMR (400 MHz,

$CDCl_3$) δ 6.57 (d, *J* 6.5, 1H), 5.04 (d, *J* 6.5, 1H), 4.30 (2H, m), 3.00 (2H, m); ^{13}C NMR (126 MHz, $CDCl_3$) δ 140.2, 93.3, 65.3, 25.4; *m/z* 102 (100%, M^+), 74, (84, $M^+ - C_2H_4$), 45 (67, $M^+ - C_3H_5O$).

4,5-(1,4-Oxathiane-2,3-diyldithio)-1,3-dithiole-2-thione 5

A suspension of 2,3-dihydro-1,4-oxathiine **4** (4.2 g, 40.7 mmol) and 1,3-dithiole-2,4,5-trithione oligomer[7] in 1,4-dioxane (75 ml) was refluxed for 18 h. The hot mixture was filtered and the residue was washed with hot toluene. The solvent was evaporated under reduced pressure and the resulting dark brown sticky residue was dissolved in toluene and filtered through a short column of silica gel to remove unreacted oligomer. Evaporation of the toluene gave pure **5** (by NMR) (4.6 g 38%) as yellow–brown crystals. An analytically pure sample could be obtained by chromatography with a 2:1 hexane–CH_2Cl_2 gradient; mp 142–143 °C; ^1H NMR (400 MHz, $CDCl_3$) δ 5.47 (d, *J* 1.50, 1H), 4.66 (d, *J* 1.5, 1H), 4.46 (m, J_1 12.10, J_2 3.20, J_3 3.20, 1H), 4.07 (m, J_1 12.10, J_2 10.50, J_3 2.30, 1H), 3.31 (m, J_1 14.00, J_2 10.50, J_3 3.20, 1H), 2.41 (m, J_1 14.00, J_2 3.20, J_3 2.30, 1H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 208.8, 124.6, 117.9, 78.0, 71.6, 44.3, 23.8; *m/z* 298 (17%, M^+), 102 (100, $M^+ - C_3S_5$) (Calc. for $C_7H_6OS_6$: C, 28.16; H, 2.03. Found: C, 28.28; H, 2.09%).

4,5-(1,4-Oxathiane-2,3-diyldithio)-1,3-dithiol-2-one 6

Thione **5** (1.28 g, 4.3 mmol) was suspended in acetonitrile (130 ml) and mercuric acetate (1.60 g, 5.0 mmol) was added. The resulting mixture was refluxed for 3 h and then additional mercuric acetate (0.8 g, 2.5 mmol) was added and the mixture was stirred for an additional 10 min. The dark precipitate was filtered off and washed with CH_2Cl_2, and the combined filtrates were evaporated to give crude **6**. Chromatography on silica gel with a 1:4 hexane–CH_2Cl_2 gradient gave pure **6** as yellow crystals (0.8 g, 66%). An analytically pure specimen could be achieved *via* recrystallization from EtOH; mp 155–157 °C; ^1H NMR (400 MHz, $CDCl_3$) δ 5.47 (d, *J* 1.70, 1H), 4.63 (d, *J* 1.7, 1H), 4.47 (m, J_1 12.10, J_2 3.20, J_3 3.20, 1H), 4.09 (m, J_1 12.10, J_2 10.50, J_3 2.30, 1H), 3.32 (m, J_1 14.00, J_2 10.50, J_3 3.20, 1H), 2.41 (m, J_1 14.00, J_2 3.20, J_3, 2.30, 1H); ^{13}C NMR (126 MHz, $CDCl_3$) δ 198.4, 114.6, 108.5, 79.2, 71.3, 45.1, 23.9; *m/z* 282 (10%, M^+), 102 (100, $M^+ - C_3S_5$).

4,5;4′,5′-Bis(1,4-oxathiane-2,3-diyldithio)tetrathiafulvalene 7

Freshly distilled trimethyl phosphite (6 ml, 51 mmol) was added to a stirred suspension of thione **5** (0.62 g, 2.08 mmol) and carbonyl **6** (0.57 g, 2.02 mmol) in benzene (35 ml), and the mixture was refluxed under nitrogen during 3.5 h. After cooling to room temperature, fine crystals were filtered off and washed with EtOH, acetone and diethyl ether. Attempts to recrystallize the product led only to reversal of the Diels–Alder reaction. Comparable yields could be achieved when the same procedure was used with only one of the reactants **5** or **6**; ^1H NMR (500 MHz, [$^2H_5$]Pyridine) Isomer 1: δ 5.72 (d, *J* 1.80, 1H), 4.86 (d, *J* 1.8, 1H), 4.32 (m, J_1 12.10, J_2 3.20, J_3 3.20, 1H), 3.96 (m, J_1 12.10, J_2 10.50, J_3 2.30, 1H), 3.20 (m, J_1 14.00, J_2 10.50, J_3 3.20, 1H), 2.38 (m, J_1 14.00, J_2 3.20, J_3 2.30, 1H). Isomer 2: δ 5.71, 4.80, 4.31, 3.97, 3.23, 2.34; *m/z* 102 (100%), 74, (84) (Calc. for $C_{14}H_{12}O_2S_{10}$: C, 31.55; H, 2.27. Found: C, 31.67; H, 2.33%).

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