Monopyrrolo-Annelated Tetrathiafulvalenes

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Introduction

The chemistry of tetrathiafulvalene (TTF) and its derivatives has been intensely studied for more than two decades because of the ability of these compounds to form stable radical cation salts which have great potential as cationic components of molecular conductors or even superconductors.[1]

In a recent paper,[2] we reported practical syntheses of symmetrical bis[3,4-*d*]pyrrolo-annelated TTF derivatives and their favorable properties as a new class of donor molecules. These pyrrolo-annelated TTFs have appreciably lower oxidation potentials as compared to other annelated TTF derivatives and enjoy the great symmetry advantage of not existing as *cis* and *trans* isomers. As a further extension of this work, we now report the synthesis of a number of monopyrrolo[3,4-*d*]-annelated TTF derivatives by various procedures, as well as their characterization and electrochemical properties.

Results and Discussion

Phosphite-Promoted Cross-Couplings. Phosphite cross-couplings were first investigated because this method is generally simple when yields are good and when products are separable.[3] Several half-unit precursors of unsymmetrical TTF derivatives were prepared by known procedures.[1,4,5] The mixture of a trithiocarbonate and a pyrrolo-annelated dithiocarbonate[2] in neat triethyl phosphite was refluxed for 10 h, and the mixed TTF along with the two symmetrical ones were separated by chromatography. Unlike in some other cases, the polarity of the two precursors differed appreciably, and the resulting mixture of coupled products was easily resolved. Compounds **6**, **7**, **9**, and **11** were synthesized in this way in fair to good yields, but compounds **8** and **10** could be detected only in trace amounts (Scheme 1, Table 1). In all cases, the use of freshly distilled triethyl phosphite is essential. Interestingly, the reverse combination of half-unit precursors, that is, a dithiocarbonate for one and the pyrrolo-annelated trithiocarbonate[2] for the other, failed to give mixed products, and only symmetrical TTF derivatives were obtained. Also, neither thione−thione nor carbonyl−carbonyl combinations provided mixed TTF derivatives in significant yields. It was concluded from the observations that the pyrrolo-annelated dithiole unit is less reactive toward coupling than the other half unit. However, other factors may well be involved which are not evident at this time.

Scheme 1

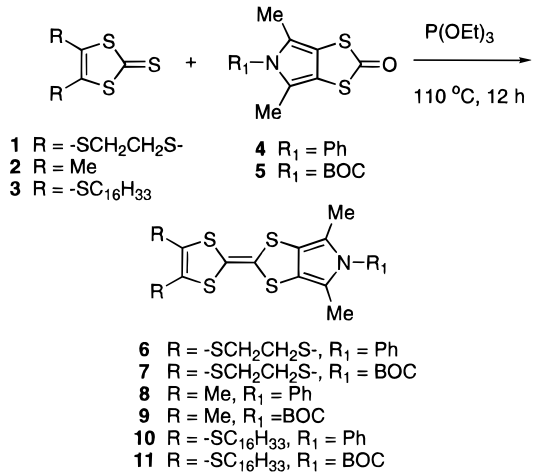

Table 1. Preparation of Mixed Pyrrolo[3,4-*d*]-Annelated TTF Derivatives by Cross-Coupling Reactions[a]

entry	combination of two reagents	product (yield %)
1	**1** + **4**	**6** (27)
2	**1** + **5**	**7** (48)
3	**2** + **4**	**8** (trace)
4	**2** + **5**	**9** (38)
5	**3** + **4**	**10** (trace)
6	**3** + **5**	**11** (12)

[a] Conditions: $P(OEt)_3$, 111 °C, 12 h.

Other Unsymmetrical Coupling Procedures. Several unsymmetrical monopyrrolo-TTFs were also obtained, making use of non-phosphite coupling methods. Thus, the little used reaction of a phosphorus ylide with an alkylselenodithiolium salt[7] afforded a good alternative synthesis of compound **6**. S-Methylation of thione **4a**[2] with methyl triflate gave salt **15**, which was reacted with sodium hydroselenide to give selone **16**. Direct methylation of crude **16** gave the Se-methylated triflate salt **17**, which reacted with the known phosphonium salt **14**[8] in the presence of triethylamine to give the mixed TTF **6** in quite satisfactory yield (43%) (Scheme 2).

A number of unsymmetrical TTFs have been prepared, making use of trithioorthoformate anions as intermediates.[9,10] We employed this methodology in an alternate synthesis of TTF **7**. Thus, the readily prepared trithioformate **13** was reacted sequentially with *n*-BuLi, thione **18**, and MeI to give the hexathiooxalate **19** as an orange oil. Thermolysis of **19** in refluxing trichloroethane afforded **7** in 48% yield (Scheme 3).

Monopyrrolo[3,4-*d*]-annelated TTF derivatives **9** and **11** were conveniently deprotected by treatment with 30% sodium methoxide. Alkylation of **20** and **21** by reaction with sodium hydride followed by methyl iodide afforded the N-methylated derivatives **22** and **23** in excellent yields. However, deprotection of **7** failed to give more

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(2) Zong, K. K.; Chen, W.; Cava, M. P.; Rogers, R. D. *J. Org. Chem.* **1996**, *61*, 8117.

(3) Kini, A. M.; Tytko, S. F.; Hunt, J. E.; Williams, J. M. *Tetrahedron Lett.* **1987**, *28*, 4153.

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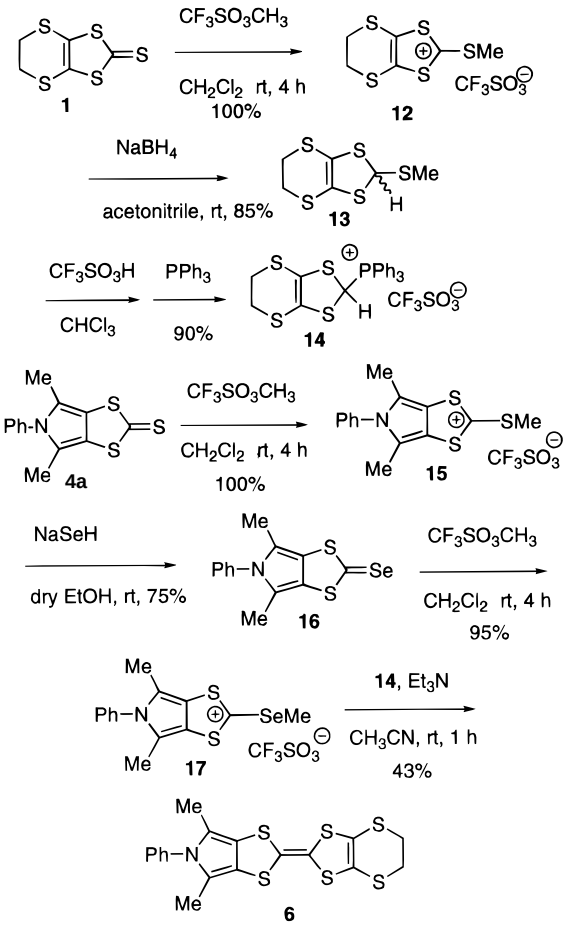
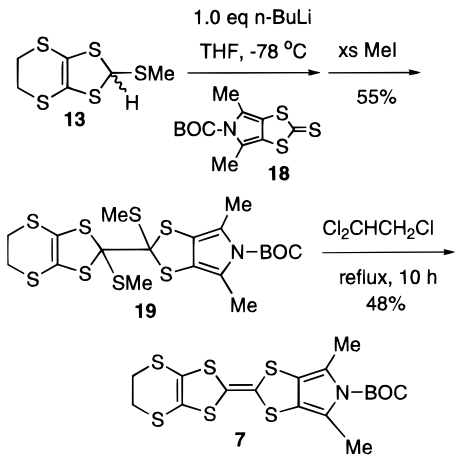
Scheme 2



Scheme 3



than trace amounts of **24** using either sodium methoxide or thermolysis (Scheme 4).[11] The nature of the decomposition products formed in these attempts was not further investigated, but we suspect that rupture of the ethano bridge of **7** under the reaction conditions is involved.

Cyclic Voltammetry. Electrochemical studies indicated that all of the new monopyrrolo[3,4-*d*]-annelated TTFs have excellent reversible redox properties and quite low oxidation potentials (Table 2). As expected, the highest oxidation potentials of the series are shown by the BOC-protected compounds **7**, **9**, and **11**, but even these values are low enough to be close to that of the

(11) Rawal, V. H.; Cava, M. P. *Tetrahedron Lett.* **1985**, *26*, 6141.

Scheme 4

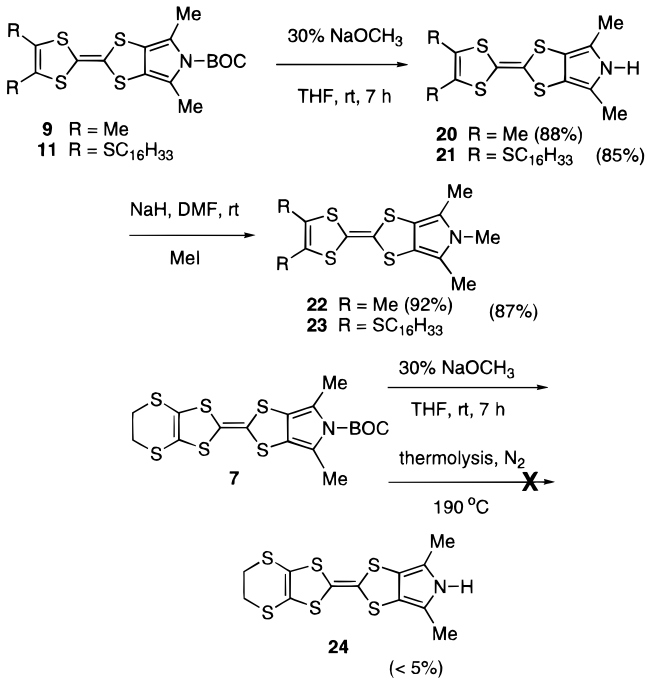


Table 2. Cyclic Voltammetry of Compounds vs SCE (Scan Speed 100 mV/s)[a]

compd	$E_{1/2}^1$	$E_{1/2}^2$
6	0.391	0.855
7	0.535	0.980
9	0.423	0.929
11	0.532	0.929
20	0.263	0.766
21	0.385	0.822
22	0.255	0.769
23	0.382	0.877
TTF	0.390	0.765
ET	0.510	0.921

[a] Cyclic voltammetry was carried out in a 0.1 M solution of Bu_4NPF_6 in dichloromethane at rt.

useful donor ET. Compounds **6**, **21**, and **23** are comparable to TTF as donors, while **20** and **22** are even better donors than TTF because of the methyl substituents.

The new unsymmetrical TTF derivatives show good solubility in most common organic solvents. This property, coupled with their attractive redox values, make them attractive donors for the synthesis of new conducting charge-transfer salts. Work in this direction is being initiated.

Experimental Section

General Method for Cross-Coupling Reactions. A mixture of 1.0 equiv of the appropriate thione and 1.0 equiv of the oxo analog in freshly distilled $P(OEt)_3$ (6.0 equiv) was immersed under N_2 in a preheated oil bath (110−120 °C). The mixture was stirred vigorously for 10 h, cooled to rt, and diluted with twice the volume of methanol for precipitation of the products. The reaction mixture was placed in a refrigerator overnight and filtered. The collected solid was usually a mixture of three TTF derivatives (two symmetric and one mixed), TLC of which ($CHCl_3$/hexane = 1:1) usually showed three different spots, the middle one of which usually represented the mixed TTF derivative. Purification by chromatography on silica using as eluent chloroform/hexane = 1:1 afforded the desired product as a yellow to orange solid.

Compound 6: orange solid (27%); mp 195−198 °C dec; ^{1}H NMR (360 MHz, $CDCl_3$) δ 7.50−7.40 (m, 3H), 7.25−7.1 (m, 2H), 3.29 (s, 4H), 1.96 (s, 6H); ^{13}C NMR (90 MHz, $CDCl_3$) δ 138.1,

129.3, 128.2, 122.8, 119.8, 117.9, 115.9, 113.5, 109.2, 30.2, 12.5. Anal. Calcd for $C_{18}H_{15}NS_6$: C, 49.39; H, 3.45; N, 3.20; S, 43.95. Found: C, 49.61; H, 3.50; N, 2.93; S, 43.65.

Compound 7: orange solid (48%); mp 195−197 °C dec; ^{1}H NMR (360 MHz, $CDCl_3$) δ 3.29 (s, 4H), 2.32 (s, 6H), 1.58 (s, 9H); ^{13}C NMR (90 MHz, $CDCl_3$) δ 149.4, 121.3, 120.8, 113.4, 110.9, 84.0, 30.1, 28.1, 16.3; MS *m/e* 125 (55), 149 (57), 169 (100), 181 (14), 201 (12), 213 (50), 245 (10), 257 (12), 271 (14), 333 (50), 361 (73). Anal. Calcd for $C_{17}H_{19}NO_2S_6$: C, 44.22; H, 4.14; N, 3.03; S, 41.67. Found: C, 44.77; H, 4.31; N, 3.22; S, 41.97.

Compound 9: yellow cotton-like crystals (38%); mp 195−198 °C dec; ^{1}H NMR (360 MHz, $CDCl_3$) δ 2.31 (s, 6H), 1.94 (s, 6H), 1.57 (s, 9H); ^{13}C NMR (90 MHz, $CDCl_3$) δ 149.9, 130.0, 122.3, 122.2, 120.6, 115.7, 83.8, 28.1, 16.3, 13.7. Anal. Calcd for $C_{17}H_{21}NO_2S_4$: C, 51.09; H, 5.30; N, 3.50; S, 32.10. Found: C, 50.94; H, 5.34; N, 3.47; S, 32.19.

Compound 11: orange crystals (12%); mp 64−65 °C; ^{1}H NMR (360 MHz, $CDCl_3$) δ 2.82 (t, J = 7.3 Hz, 4H), 2.32 (s, 6H), 1.61 (m, 4H), 1.59 (s, 9H), 1.49−1.20 (m, 52H), 0.89 (t, J = 7.0 Hz, 6H); ^{13}C NMR (90 MHz, $CDCl_3$) δ 149.4, 127.4, 121.6, 120.8, 116.6, 113.3, 84.0, 36.3, 31.9, 29.7, 29.6, 29.5, 29.4, 29.1, 28.5, 28.1, 22.7, 16.3, 14.1; MS *m/e* 111 (100), 126 (92), 159 (28), 196 (17), 224 (49), 250 (17), 283 (10), 314 (24), 629 (10), 784 (5), 885 (4). Anal. Calcd for $C_{47}H_{81}NO_2S_6$: C, 63.82; H, 9.23; N, 1.58; S, 21.75. Found: C, 63.53; H, 9.22; N, 1.56; S, 22.00.

Triphenylphosphonium salt 14: white crystals (90% from **13**); mp 195 °C dec (ref 8, 198 °C); all spectroscopic data corresponded to those from ref 8.

Triflate Salt 15. To a solution of thione **4a** (6.0 g, 21.63 mmol) in dichloromethane (25 mL) was added methyl triflate (3.55 g, 21.63 mmol) [*CAUTION*: methyl triflate is a powerful alkylating agent; it should be handled with rubber gloves and in the hood] via a syringe at rt. The reaction mixture was stirred for 4 h, and about triple the volume of dry ether was added for precipitation. The resulting red solid was collected by filtration, dried, and used for the next reaction without further purification: yield quantitative; ^{1}H NMR (360 MHz, $CDCl_3$) δ 7.60−7.20 (m, 5H), 3.25 (s, 3H), 2.22 (s, 6H).

2,5-Dimethyl-*N*-phenylpyrrolo[3,4-*d*]dithioselone (16). To a suspension of **15** (8.0 g, 18.12 mmol) in dry EtOH (80 mL) was added a sodium hydroselenide solution prepared from selenium (2.86 g, 36.23 mmol) and sodium borohydride (1.37 g, 36.23 mmol) in dry EtOH (20 mL) at rt. Upon addition of the hydroselenide, the deep red color faded immediately to pale yellow. After 1 h of stirring, the reaction mixture was diluted with water (150 mL) and extracted with $CHCl_3$ (2 × 200 mL). The combined organic layers were washed with water and brine and dried over sodium sulfate. Purification by chromatography on silica ($CHCl_3$/hexane = 1:1) afforded selone **16** (75%) as an orange solid: mp 135−145 °C; ^{1}H NMR (360 MHz, $CDCl_3$) δ 7.60−7.40 (m, 3H), 7.30−7.20 (m, 2H), 2.03 (s, 6H). The NMR spectrum showed that the product contained some starting thione which could not be readily separated. The crude product was used directly in the next step.

Triflate Salt 17. To a solution of the crude selone **16** (5.0 g, 15.42 mmol) in dichloromethane (25 mL) was added methyl triflate (2.53 g, 15.42 mmol) via a syringe at rt. The reaction mixture was stirred for 4 h, and about a triple volume of dry ether was added for precipitation. The resulting red solid was collected by filtration and used directly for the next reaction after being vacuum-dried: yield quantitative; ^{1}H NMR (360 MHz, $CDCl_3$) δ 7.60−7.20 (m, 5H), 3.30 (s, 3H), 2.20 (s, 6H).

Cross-Coupling of Triphenylphosphonium Salt 14 and Methylselenotriflate Salt 17. To a solution of triphenylphosphonium salt **14** (517 mg, 1.06 mmol) and triflate salt **17** (640 mg, 1.06 mmol) in acetonitrile (5 mL) was added triethylamine (1.5 mL) at rt. The deep-red color of the solution faded immediately. After 1 h of stirring, the reaction mixture was placed in a refrigerator for 2 h. The solid was filtered and dissolved in dichloromethane (30 mL). The organic phase was washed with water, dried over sodium sulfate, and concentrated. Purification by chromatography on silica, using $CHCl_3$/hexane (1:1) as eluent, afforded the mixed TTF derivative **6** (200 mg, 43%) as an orange solid. This compound was identical to the one obtained by phosphite cross-coupling by all spectroscopic criteria.

Hexathioorthooxalate 19. To a solution of **13** (650 mg, 2.7 mmol) in dry THF (100 mL) was added *n*-BuLi (1.5 M, 1.8 mL, 2.7 mmol). After 30 min, a solution of 2,5-dimethyl-*N*-BOC-pyrrolo[3,4-*d*]trithiocarbonate (815 mg, 2.7 mmol) in THF (100 mL) was added. After 1 h of stirring, excess MeI (1.0 mL) was added. The reaction mixture was concentrated, and the crude product was dissolved in dichloromethane (50 mL), washed with water, and dried over sodium sulfate. Purification by chromatography on silica using dichloromethane/hexane (1:1) as eluent gave the product (820 mg, 55%) as a thick orange oil: ^{1}H NMR (360 MHz, $CDCl_3$) δ 3.25 (s, 4H), 2.52 (s, 3H), 2.48 (s, 3H), 2.28 (s, 6H), 1.56 (s, 9H); ^{13}C NMR (90 MHz, $CDCl_3$) δ 149.4, 123.5, 120.7, 111.3, 83.8, 77.2, 30.0, 28.1, 18.7, 17.6, 16.3.

Synthesis of 7 via Cleavage of Hexathioorthooxalate 19. A solution of hexathioorthooxalate **19** (200 mg) in 1,1,2-trichloroethane was refluxed for 10 h. After the solvent was removed, the residue was purified by chromatography on silica using dichloromethane/hexane (1:1) to provide the product (**7**, 80 mg, 48%) as an orange solid, identical to that obtained by phosphite coupling.

General Procedure for Deprotection of the BOC Group. A solution of the BOC-TTF derivative (1.0 equiv) in dry THF was degassed by a nitrogen stream for 20 min. To this solution was added 30% $NaOCH_3$ in methanol (2.5 equiv) at rt, and the mixture was stirred for 7 h under nitrogen. Water was added, and the resulting precipitate was collected by filtration, washed with water and methanol, and purified by chromatography on silica using chloroform/hexane (2:1) to afford the deprotected TTF.

Compound 20: 88%, a light yellow solid; mp 228−230 °C dec; ^{1}H NMR (360 MHz, $CDCl_3$) δ 7.75 (s, 1H), 2.12 (s, 6H), 1.99 (s, 6H); ^{13}C NMR (90 MHz, $CDCl_3$) δ 122.3, 118.8, 114.1, 113.1, 105.2, 20.3, 12.6, 11.4. Anal. Calcd for $C_{12}H_{13}NS_4$: C, 48.12; H, 4.37; N, 4.67; S, 42.82. Found: C, 48.24; H, 4.36; N, 4.63; S, 42.72.

Compound 21: 85%, a dark orange solid; mp 83−85 °C; ^{1}H NMR (360 MHz, $CDCl_3$) δ 7.55 (s, 1H), 2.82 (t, J = 7.3 Hz, 4H), 2.16 (s, 6H), 1.70−1.10 (m, 56H), 0.88 (t, J = 7.3 Hz, 6H); ^{13}C NMR (90 MHz, $CDCl_3$) δ 127.4, 120.1, 117.2, 116.0, 111.4, 36.2, 31.9, 30.0−28.6 (11C), 28.5, 22.7, 14.1, 12.5. Anal. Calcd for $C_{42}H_{73}NS_6$: C, 64.31; H, 9.38; N, 1.78; S, 24.52. Found: C, 64.38; H, 9.40; N, 1.70; S, 24.43.

General Procedure for *N*-Alkylation of Deprotected TTF Derivative. To a solution of deprotected TTF **20** or **21** (1.0 equiv) in dry DMF was added sodium hydride (2.0 equiv, hexane-washed and dried) under nitrogen at rt. The reaction mixture was stirred for 30 min, excess iodomethane (4.0 equiv) was added, and the mixture was stirred for a further 2 h. Water was introduced carefully, and the precipitate was purified by chromatography on silica using chloroform/hexane (1:1).

Compound 22: 92%, a yellow solid; mp 213−215 °C; ^{1}H NMR (360 MHz, $CDCl_3$) δ 3.34 (s, 3H), 2.11 (s, 6H), 1.99 (s, 6H); ^{13}C NMR (90 MHz, $CDCl_3$) δ 128.0, 124.4, 122.3, 114.9, 109.4, 20.3, 12.0, 10.6. Anal. Calcd for $C_{13}H_{15}NS_4$: C, 49.80; H, 4.86; N, 4.47; S, 40.91. Found: C, 49.84; H, 4.86; N, 4.42; S, 40.80.

Compound 23: 87%, dark orange solid; mp 65−67 °C; ^{1}H NMR (360 MHz, $CDCl_3$) δ 3.47 (2, 3H), 2.80 (t, J = 7.3 Hz, 4H), 2.13 (s, 6H), 1.70−1.10 (m, 56H), 0.88 (t, J = 7.3 Hz, 6H); ^{13}C NMR (90 MHz, $CDCl_3$) δ 127.4, 119.7, 118.9, 114.4, 110.8, 36.2, 31.9, 31.0, 29.7−29.0 (11C), 28.5, 22.7, 14.1, 12.0. Anal. Calcd for $C_{43}H_{75}NS_6$: C, 64.68; H, 9.46; N, 1.75; S, 24.09. Found: C, 64.63; H, 9.39; N, 1.80; S, 24.16.

Compound 24: <5%, red crystals, mp 210 °C dec; ^{1}H NMR (360 MHz, $CDCl_3$) δ 7.40 (s, 1H), 3.28 (s, 4H), 2.15 (s, 6H); MS *m/e* 105 (96), 112 (53), 126 (34), 149 (100), 169 (35), 361 (29); HRMS calcd 360.9215, found 360.9214.

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