

## Synthesis, Isolation, and Full Characterization of the Parent Thiophene 1,1-Dioxide

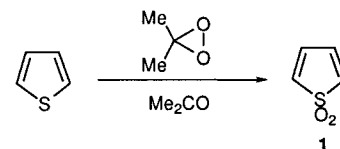
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Received June 12, 1997

Thiophene 1,1-dioxides are synthetically and theoretically important compounds which act as  $2\pi$ - or  $4\pi$ -components in a range of cycloadditions. A recent exhaustive literature survey has revealed that more than 300 papers had appeared on the chemistry of thiophene 1,1-dioxides.<sup>1,2</sup> Among them, at least 33 papers have been concerned with the chemistry of the parent thiophene 1,1-dioxide (**1**) theoretically or experimentally.<sup>3–5</sup> However, despite such enormous efforts, **1** has eluded isolation most likely as a result of a rapid cyclodimerization process. Thus, most of the evidence for its existence comes from chemical trapping experiments.<sup>3</sup> We report here the synthesis, isolation, and full characterization of **1**.

Previously **1** was mainly generated by dehydrobromination of 3-bromo-2,3-dihydrothiophene 1,1-dioxide.<sup>3a,b,p–r</sup> We have examined the preparation of **1** by oxidation of thiophene with dimethyldioxirane (DMD).<sup>6,7</sup> Thus, a dilute solution of thiophene in Me<sub>2</sub>CO was treated with DMD (3 equiv) at  $-20\text{ }^\circ\text{C}$  for 36 h. The solvent and the unreacted DMD and thiophene were removed thoroughly below  $-40\text{ }^\circ\text{C}$  under reduced pressure,



which left pure **1** as colorless crystals. Thus, the presumed intermediary thiophene 1-oxide is oxidized faster than thiophene with DMD and the yield of **1** is quantitative based on the thiophene consumed. Removal of the volatile materials below  $-40\text{ }^\circ\text{C}$  is crucial to isolate **1** in pure form to prevent decomposition in concentrated solution. For example, the oxidation at  $-20\text{ }^\circ\text{C}$  and removal of the solvent at  $-25\text{ }^\circ\text{C}$  afforded a 9:1 mixture of **1** and the dimerization product **2**.<sup>3a,c</sup> The dioxide **1** melted at about  $6\text{ }^\circ\text{C}$  with decomposition and then solidified slowly on standing because of the formation of dimerization and trimerization products (vide infra).<sup>8</sup>

The GCMS (EI, 70 eV) of **1** showed the molecular ion peak at  $m/z$  116 and the strongest peak at  $m/z$  68 due to the furan radical cation, and HRMS gave the satisfactorily results: calcd for C<sub>4</sub>H<sub>4</sub>O<sub>2</sub>S 115.9932, found 115.9931. In the <sup>1</sup>H NMR spectrum (400 MHz) at  $-40\text{ }^\circ\text{C}$  in CDCl<sub>3</sub>, the  $\alpha$ - and  $\beta$ -hydrogen signals appeared at  $\delta$  6.53–6.61 and 6.75–6.83 as multiplets, respectively, whereas, for thiophene, these signals appear as multiplets centered at  $\delta$  7.18 and 6.99, respectively.<sup>9</sup> The above assignment was confirmed by comparison of the spectra of **1** and 2-deuteriothiophene 1,1-dioxide prepared separately.<sup>10</sup> The <sup>13</sup>C NMR spectrum (100.6 MHz) at  $-40\text{ }^\circ\text{C}$  showed two signals at  $\delta$  131.1 and 129.3, which were assigned to the  $\alpha$ - and  $\beta$ -carbons, respectively, by a C–H COSY experiment.<sup>10,11</sup> In the FTIR spectrum in CDCl<sub>3</sub> solution, very strong SO<sub>2</sub> symmetric and asymmetric stretching absorptions appeared at 1152 and 1306 cm<sup>-1</sup>, respectively; the latter signal was accompanied by a weaker absorption at 1327 cm<sup>-1</sup>. In the Raman spectrum, the strong sharp absorption due to the C=C bond appeared at 1530 cm<sup>-1</sup> and the strong absorptions due to the SO<sub>2</sub> moiety at 1151 cm<sup>-1</sup> (sym) and 1305 cm<sup>-1</sup> (asym). The UV spectrum in CHCl<sub>3</sub> showed two absorption maxima at 245 ( $\epsilon$  870) and 288 (1070) nm.<sup>12</sup>

The half-life of **1** in solution depends on concentration. Thus, the half-lives of **1** at 298 K were 137, 371, and 747 min for 0.12, 0.047, and 0.025 M CDCl<sub>3</sub> solutions, respectively, indicating that decomposition of **1** is not a unimolecular path. In addition, the decomposition products depend on concentration. The decomposition in high dilute solution produces only **3**, which comes from cyclodimerization followed by loss of SO<sub>2</sub>. With increasing concentration of **1**, trimerization product **4** begins to form. Thus, although decomposition product in 0.024 M CDCl<sub>3</sub> solution is only **3**, products of 0.20 M solution and neat **1** were **3** and **4** in the ratios 1.0:0.36 and 1.0:1.5, respectively. The <sup>13</sup>C NMR of the trimer **4** showed six peaks

(8) A DSC analysis showed an exothermic peak at about  $8\text{ }^\circ\text{C}$  when the temperature was raised at a rate of  $1\text{ }^\circ\text{C}/\text{min}$ .

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(10) The previously reported <sup>1</sup>H and <sup>13</sup>C NMR data of **1**,<sup>3m</sup> which was generated by treatment of 3-bromo-2,3-dihydrothiophene 1,1-dioxide with Et<sub>3</sub>N, are not in harmony with the present data. It was reported that  $\alpha$ - and  $\beta$ -hydrogen signals appeared at  $\delta$  6.64 and 6.38, respectively, as multiplets in CDCl<sub>3</sub>. These chemical shift values differ from ours and at least the assignment should be reversed. In addition, reportedly, the <sup>13</sup>C NMR spectrum showed only one signal in C<sub>6</sub>D<sub>6</sub> at  $\delta$  131.0 because of accidental overlapping of C <sub>$\alpha$</sub>  and C <sub>$\beta$</sub>  signals, which appeared as a broad signal at  $\delta$  129.1 in CDCl<sub>3</sub>.

(11) For thiophene,  $\alpha$ - and  $\beta$ -carbon signals appear at  $\delta$  125.6 and 127.3, respectively.<sup>9</sup>

(12) It was reported that **1** showed absorptions at 220 ( $\epsilon$  2010), 254 (450), and 289 nm (1230) in CHCl<sub>3</sub><sup>3b</sup> and at 220 ( $\epsilon$  2000) and 289 nm (880) in MeOH.<sup>3c</sup>

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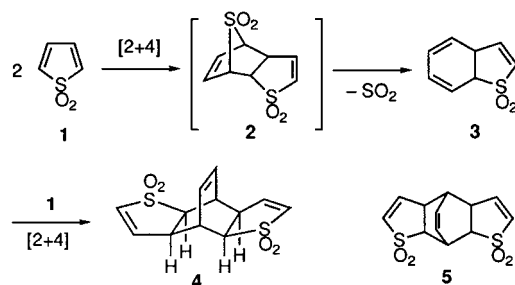
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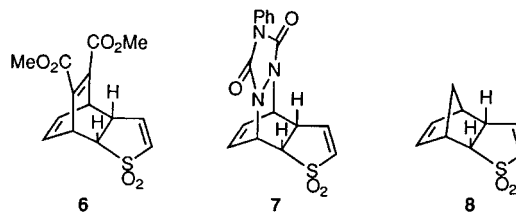
in accordance with the given structure and ruling out the isomeric structure **5**.<sup>13–15</sup>



The rate of decomposition of **1** was examined by <sup>1</sup>H NMR in a dilute solution (0.024 M CDCl<sub>3</sub> solution) where no trimerization product formed. The decomposition was second-order in **1**, and the rate constants at 303, 308, 313, and 318 K were  $1.65 \times 10^{-3}$ ,  $2.49 \times 10^{-3}$ ,  $3.78 \times 10^{-3}$ , and  $5.21 \times 10^{-3}$  mol<sup>-1</sup>·dm<sup>3</sup>·s<sup>-1</sup> with half-lives of 419, 279, 184, and 133 min, respectively. From these experiments, the activation parameters of  $E_a = 64.4 (\pm 0.3)$  kJ·mol<sup>-1</sup>,  $\Delta H^\ddagger = 62.0 (\pm 0.3)$  kJ·mol<sup>-1</sup>, and  $\Delta S^\ddagger = -59.8 (\pm 1.0)$  J·K<sup>-1</sup>·mol<sup>-1</sup> were obtained. The high negative  $\Delta S^\ddagger$  value reveals that the rate-determining step of the formation of **3** is the cyclodimerization of **1** in a Diels–Alder mode, but not the extrusion of SO<sub>2</sub> from **2**.<sup>16</sup> The  $E_a$  value is smaller than that of the dimerization of cyclopentadiene ( $E_a = 68.5$  kJ·mol<sup>-1</sup> in EtOH and C<sub>6</sub>H<sub>6</sub>).<sup>17</sup>

Attempted reactions of **1** with alkenic and alkynic dienophiles, such as dimethyl acetylenedicarboxylate (DMAD), 4-phenyl-

1,2,4-triazoline-3,5-dione (PTAD), *p*-benzoquinone, acenaphthylene, norbornene, and bis(diethylamino)acetylene, all failed to give cycloadducts, regardless of their electrophilic or nucleophilic properties, because self-dimerization leading to **3** took place more rapidly. In cases of DMAD and PTAD, compounds **6**<sup>15,18</sup> and **7**,<sup>15</sup> which came from cycloaddition of **3** with DMAD and PTAD, were formed in 22 and 15% yields, respectively.<sup>15</sup> As for cycloaddition with dienes, although reaction with cyclopentadiene did give the expected adduct **8**<sup>3h,15</sup> in 25% yield, reaction with 2,3-dimethyl-1,3-butadiene resulted only in self-dimerization of **1**.



In conclusion the parent thiophene 1,1-dioxide (**1**) was isolated for the first time in pure form and fully characterized spectroscopically and chemically.<sup>19</sup>

**Acknowledgment.** The present work was financially supported by a Grant-in-Aid for Scientific Research from the Ministry of Education, Science, Sports and Culture, Japan (No. 09440213).

**Supporting Information Available:** MS, <sup>1</sup>H NMR, <sup>13</sup>C NMR, FTIR, Raman, and UV spectra of **1**, kinetics data for the decomposition of **1**, and characterization data for **6–8** (11 pages). See any masthead page for ordering and Internet access instructions.

JA971934Z

(13) Only one report recognized the formation of the trimeric product, although the structure proof was not given in a reliable way.<sup>3a</sup>

(14) **4**: mp 245 °C (dec); <sup>1</sup>H NMR (400 MHz, CDCl<sub>3</sub>)  $\delta$  3.41–3.57 (m, 6H), 6.10 (d/d,  $J = 4.4/3.2$  Hz, 2H), 6.50 (d/d,  $J = 6.7/2.4$  Hz, 2H), 6.66 (d/d,  $J = 6.7/2.4$  Hz, 2H); <sup>13</sup>C NMR (100.6 MHz, CDCl<sub>3</sub>)  $\delta$  34.7, 45.5, 60.2, 129.0, 134.4, 138.9; MS (EI, 70 eV) 284 (M<sup>+</sup>); IR (KBr) 1126, 1290 cm<sup>-1</sup> (SO<sub>2</sub>).

(15) Although the stereochemistry of compounds **4**, **6**, and **8** could be unambiguously determined by NOESY experiments, that given for **7** is tentative.

(16) Extrusion of SO<sub>2</sub> is so fast that **2** could not be detected by <sup>1</sup>H NMR.

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(18) The structure, previously presented for the product of the reaction of **1** with dimethyl acetylenedicarboxylate, is seemingly erroneous.<sup>3d</sup> The correct structure should correspond to the present adduct **6**. Heating **6** in refluxing 1,2-dichloroethane gave dimethyl phthalate (85%) and **3** (78%) by a retro-Diels–Alder reaction, although no reaction took place in refluxing CHCl<sub>3</sub> appreciably.

(19) Thermally labile 2-methyl- and 3-methylthiophene 1,1-dioxides, which had eluded isolation, were also satisfactorily obtained as colorless crystals at -40 °C by application of the present method.