Synthesis and Reactivity of New 1,4-Bis(alkylthio)-3,6-diarylthieno[3,4-*c*]thiophene Derivatives

Noboru Matsumura,*,† Hirokazu Tanaka,† Yoshio Yagyu,† Kazuhiko Mizuno,† Hiroo Inoue,† Kiwamu Takada,‡ Masanori Yasui,‡ and Fujiko Iwasaki‡

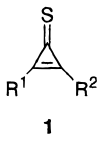
Department of Applied Chemistry, College of Engineering, Osaka Prefecture University, Sakai, Osaka 599, Japan and Department of Applied Physics and Chemistry, The University of Electro-Communications, Tokyo 182, Japan

Received September 11, 1997[⊗]

1,4-Bis(*tert*-butylthio)-3,6-diphenyl- and 3,6-di(2-thienyl)thieno[3,4-*c*]thiophenes (**2a,b**)were synthesized from 2-(*tert*-butylthio)-3-phenyl- and 3-(2-thienyl)cyclopropenethiones (**1a,b**) and triphenylphosphine in dry benzene at 50 °C, although similar treatment of 2,4,6-triisopropylphenyl, *N,N*-diethylamino, pyrrolidino, and diphenyl-substituted cyclopropenethiones (**1c**−**h**) did not result in the production of the corresponding thieno[3,4-*c*]thiophene derivatives. The possible reaction pathway for the formation of **2a,b** is described. The protonation of **2a** with trifluoroacetic acid (TFA) gave 4-(*tert*-butylthio)-3,6-diphenylthieno[3,4-*c*]thiophene-1(3*H*)-thione (**13a**), the treatment of which with sodium hydride and then isopropyl iodide led to 4-(*tert*-butylthio)-3,6-diphenyl-1-(isopropylthio)thieno[3,4-*c*]thiophene (**16**) by the regeneration of the thieno[3,4-*c*]thiophene ring system, this making possible the synthesis of other alkylthio-substituted thieno[3,4-*c*]thiophene derivatives. The reactions of **2a,b** with *N*-phenylmaleimide (NPM) gave predominantly the endo-cycloadducts (**17a,b**) at the 1- and 3-positions, and that of **2a** with dimethyl acetylenedicarboxylate (DMAD) led to the benzo[*c*]thiophene derivative (**19**) by desulfurization.

Introduction

Thieno[3,4-*c*]thiophenes have attracted much attention from both theoretical and spectroscopic viewpoints[1] as 10 π-electron heterocycles with nonclassical structures. However, the synthesis of thieno[3,4-*c*]thiophenes is not easy, and only a limited number of thieno[3,4-*c*]thiophenes, including tetraphenyl,[2] tetrakis(alkylthio),[3] tetra(2-thienyl),[4] tetrabromo,[5] 1,3-dibromo-4,6-dicyano[5] and 1,3-dibromo-4,6-bis(methoxycarbonyl)-substituted derivatives,[5] are known. Of these compounds, 1,3,4,6-tetrakis(alkylthio)thieno[3,4-*c*]thiophenes can be synthesized conveniently in one step from bis(alkylthio)cyclopropenethiones and triphenylphosphine or tributylphosphine,[3] although the yields were not high. To extend this synthetic method to the preparation of other substituted thieno[3,4-*c*]thiophenes and also to obtain mechanistic information on this reaction, we have initiated an exploration of the reactions of the substituted cyclopropenethiones **1a**−**h** with triphenylphosphine. This paper describes that 1,4-bis(*tert*-butylthio)-3,6-diphenyl- and 3,6-di(2-thienyl)thieno[3,4-*c*]thiophenes (**2a,b**) can be synthesized from 2-(*tert*-butylthio)-3-phenyl- and 3-(2-thienyl)cyclopropenethiones (**1a,b**),[6] respectively, by our method, whereas the reaction with diphenylcyclopropenethione (**1h**)[8] leads to 2,3,5,6-tetraphenylthieno[3,2-*b*]thiophene (**3**)[8] and those with 2,4,6-triisopropylphenyl, *N,N*-diethylamino, and pyrrolidino-substituted cyclopropenethiones (**1c**−**g**)[6] give no thienothiophene ring system; the presence of at least one alkylthio group in cyclopropenethiones is necessary for the formation of the thieno-[3,4-*c*]thiophene ring system,[7] and the bulky aryl and N,N-disubstituted amino-substituents are unsuitable for this reaction. Furthermore, we describe the reactions of **2a,b** with trifluoroacetic acid (TFA) protonating the 3-position with the aryl group and the cycloaddition reactions of **2a,b** with *N*-phenylmaleimide (NPM) and dimethyl acetylenedicarboxylate (DMAD). A part of this study has been reported in our preliminary paper.[7]



1

a: R^1 = Ph, R^2 = SBu^t
b: R^1 = 2-Thienyl, R^2 = SBu^t
c: R^1 = 2,4,6-Tri-*i*-PrPh, R^2 = SBu^t
d: R^1 = Pyrrolidino, R^2 = SBu^t
e: R^1 = NEt_2, R^2 = SBu^t
f: R^1 = Pyrrolidino, R^2 = Ph
g: R^1 = NEt_2, R^2 = Ph
h: R^1 = R^2 = Ph

† Osaka Prefecture University.
‡ University of Electro-Communications.
⊗ Abstract published in *Advance ACS Abstracts*, December 15, 1997.

(1) (a) Clark, D. H. *Tetrahedron* **1968**, *24*, 2567. (b) Dewar, M. J. S.; Trinajstic, N. *J. Am. Chem. Soc.* **1970**, *92*, 1453. (c) Glick, M. D.; Cook, R. E. *Acta Crystallogr. Sect. B* **1972**, *28*, 1336. (d) Cava, M. P.; Sprecker, M. A.; Hall, W. R. *J. Am. Chem. Soc.* **1974**, *96*, 1817. (e) Muller, C.; Schweig, A.; Cava, M. P.; Lakshmikantham, M. V. *J. Am. Chem. Soc.* **1976**, *98*, 7187. (f) Gleiter, R.; Bartetzko, R.; Brahler, G.; Bock, H. *J. Org. Chem.* **1978**, *43*, 3893. (g) Miller, K. J.; Moshner, K. F.; Potts, K. T. *J. Am. Chem. Soc.* **1983**, *105*, 1705. (h) Gimarc, B. M. *J. Am. Chem. Soc.* **1983**, *105*, 1979. (i) Ott, J. J.; Gimarc, B. M. *J. Am. Chem. Soc.* **1986**, *108*, 4303.

(2) (a) Cava, M. P.; Pollack, N. M. *J. Am. Chem. Soc.* **1967**, *89*, 3639. (b) Cava, M. P.; Pollack, N. M.; Dieterle, G. A. *J. Am. Chem. Soc.* **1973**, *95*, 2558. (c) Cava, M. P.; Behforouz, M.; Husbands, G. E. M.; Srinivasan, M. *J. Am. Chem. Soc.* **1973**, *95*, 2561.

(3) Yoneda, S.; Ozaki, K.; Inoue, T.; Sugimoto, A.; Yanagi, K.; Minobe, M. *J. Am. Chem. Soc.* **1985**, *107*, 5801.

(4) Ishii, A.; Nakayama, J.; Kazami, J.; Ida, Y.; Nakamura, T.; Hoshino, M. *J. Org. Chem.* **1991**, *56*, 78.

(5) Beye, N.; Cava, M. P. *J. Org. Chem.* **1994**, *59*, 2223.

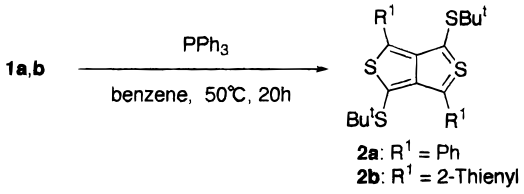
(6) (a)Yagyu, Y.; Matsumura, N.; Tanaka, H.; Maeda, Z.; Inoue, H. *J. Chem. Res. (S)* **1995**, 420. (b) Yoshida, Z. *Jpn. Kokai* **1977**, *42*, 852.

(7) Matsumura, N.; Yagyu, Y.; Tanaka, H.; Inoue, H.; Takada, K.; Yasui, M.; Iwasaki, F. *Chem. Lett.* **1996**, 421.

(8) Singh, S.; Ramamurthy,V. *J. Org. Chem.* **1982**, *47*, 3550.

S0022-3263(97)01698-8 CCC: $15.00
Published on Web 01/09/1998

Scheme 1



Results and Discussion

Reactions of Substituted Cyclopropenethiones with Triphenylphosphine. The reactions were carried out according to our synthetic method for the preparation of 1,3,4,6-tetrakis(alkylthio)thieno[3,4-*c*]thiophenes; a solution of triphenylphosphine (0.5 equiv) in dry benzene was added under argon to a solution of substituted cyclopropenethiones **1a**−**h** in dry benzene, and the mixture was stirred at 50 °C for 20 h. The reactions of **1a,b** with triphenylphosphine gave **2a,b** in 46 and 21% yields, respectively (Scheme 1). The use of triphenylamine, triethylamine, and pyridine instead of triphenylphosphine did not result in the formation of **2a,b**, but the starting materials were recovered unchanged. The structures of **2a,b** were determined by means of their IR, ^{1}H, and ^{13}C NMR spectra and elemental analyses. The ^{1}H NMR spectrum of **2a** in $CDCl_3$ showed one singlet, at δ 0.94, due to the *tert*-butylthio group and two multiplets, at δ 7.34−7.45 and 7.67−7.71, due to the phenyl protons. Compound **2b** also exhibited the spectrum analogous to that of **2a**. The ^{13}C NMR spectrum of **2a** in $CDCl_3$ showed two signals, at δ 30.17 and 49.34, for the *tert*-butyl carbons and seven signals, at δ 110.30, 127.51, 127.61, 130.76, 131.45, 132.50 and 147.78, for the thieno[3,4-*c*]thiophene ring and phenyl carbons. The signals due to the thieno[3,4-*c*]thiophene ring and 2-thienyl carbons of **2b** appeared at δ 111.12, 123.52, 126.35, 127.25, 129.90, 133.27, and 147.57. Furthermore, the structure of **2a** was confirmed by a single crystal X-ray diffraction.[9] The ORTEP drawing of **2a** is shown in Figure 1. Thus, it was established that the *tert*-butylthio and phenyl groups are attached to the 1,4- and 3,6-positions, respectively, the thieno[3,4-*c*]thiophene framework is planar, the plane of the phenyl groups is inclined at 34.17° to the thieno[3,4-*c*]thiophene ring, and the *tert*-butyl groups are perpendicular to the thieno[3,4-*c*]-thiophene ring. The UV-vis spectra of **2a,b** in hexane exhibited intense absorption peaks at 516 and 538 nm, respectively, which were shifted to longer wavelength side by 10 and 32 nm, respectively, as compared with that of 1,3,4,6-tetrakis(*tert*-butylthio)thieno[3,4-*c*]thiophene described previously.[10] These bathochromic shifts seem to be attributable to the phenyl and 2-thienyl groups.

In contrast to the reactions with **1a,b**, those with **1c**−**g** gave no product under similar conditions, but the starting materials were recovered unchanged. This may be caused by the steric hindrance due to the 2,4,6-triisopropylphenyl group, and by the electron-donating property of the N,N-disubstituted amino group.[8] Furthermore, a similar treatment of **1h** resulted in 9% yield of **3** without the thieno[3,4-*c*]thiophene derivative, as shown in Scheme 2, this being compatible with the fact that 2,3,5,6-tetrakis(3,5-di-*tert*-butyl-4-hydroxyphenyl)thieno[3,2-*b*]-thiophene is prepared from bis(3,5-di-*tert*-butyl-4-hydroxyphenyl)cyclopropenethione.[11] Thus, the presence of at least one alkylthio group in cyclopropenethiones was necessary for the formation of the thieno[3,4-*c*]thiophene ring system. In addition, the presence of N,N-disubstituted amino-substituents in cyclopropenethiones was found not to lead to the formation of the thienothiophene derivatives.

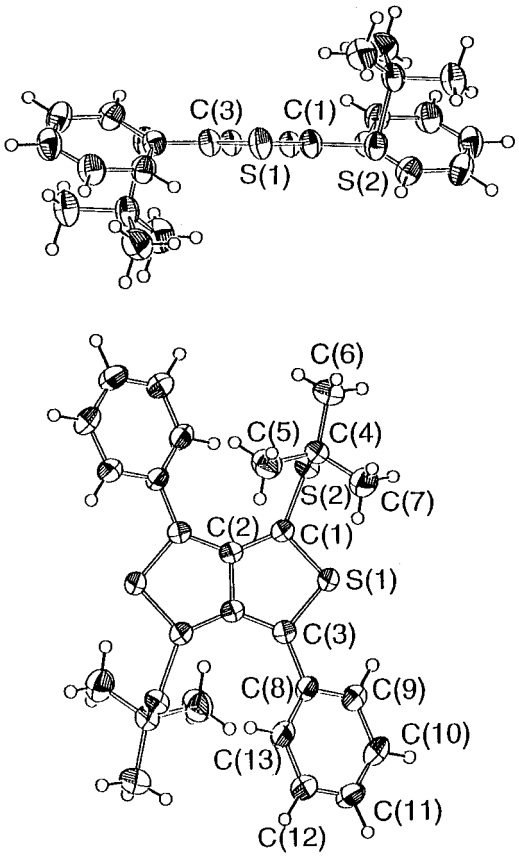
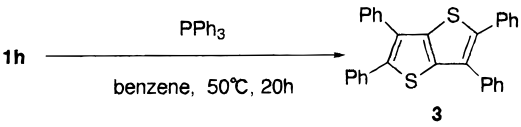


Figure 1. ORTEP drawing of **2a**, viewed perpendicular and parallel to the thieno[3,4-*c*]thiophene ring. Selected structural parameters, S(1)−C(1) 1.708(3), C(1)−C(2) 1.411(4), C(2)−C(2^i) 1.489(6), C(2^i)−C(3) 1.418(4), S(2)−C(1) 1.763(3), S(2)−C(4) 1.875(3), C(3)−C(8) 1.492(4), C(8)−C(9) 1.395(4) Å. C(1)−S(1)−C(3) 97.4(1), S(1)−C(1)−C(2) 109.3(2), C(1)−C(2)−C(2^i) 112.2-(2), S(1)−C(1)−S(2) 117.3(2), C(1)−S(2)−C(4) 103.4(1), C(8)−C(3)−C(2^i) 133.7(3), C(8)−C(13)−C(12) 121.4(3), C(11)−C(12)−C(13) 119.5(3)°. Symmetry code *i*: $-x, -y, -z$.

Scheme 2



Possible Reaction Pathway for the Formation of 2a,b and 3. Recently we have reported that the reaction of **1a** with phenyllithium proceeds by the nucleophilic attack of the phenyl anion on the 3-position with the phenyl group to form a cyclopropene intermediate **4** (Scheme 3).[12] Therefore, it is reasonable to consider that triphenylphosphine also attacks the 3-position of **1a,b,h**

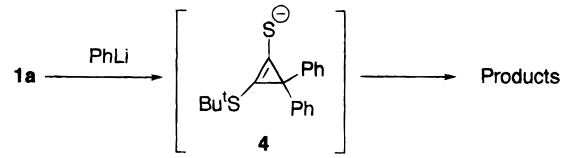
(9) The details of X-ray structure will be published elsewhere together with related compounds.

(10) Yoneda, S.; Tsubouchi, A.; Ozaki, K. *Nippon Kagaku Kaishi* **1987**, *7*, 1328.

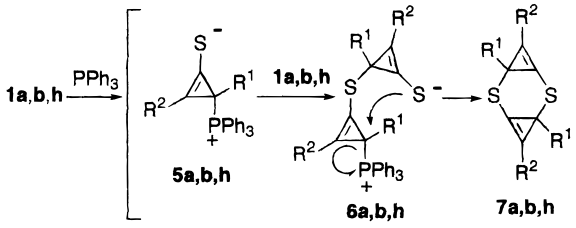
(11) Sugimoto, T.; Nagatomi, T.; Ando, H.; Yoshida, Z. *Angew. Chem., Int. Ed. Engl.* **1988**, *27*, 560.

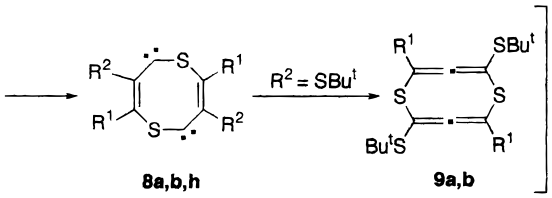
(12) Yagyu, Y.; Matsumura, N.; Tanaka, H.; Inoue, H.; Yasui, M.; Iwasaki, F. *J. Chem. Res. (S)* **1996**, 272.

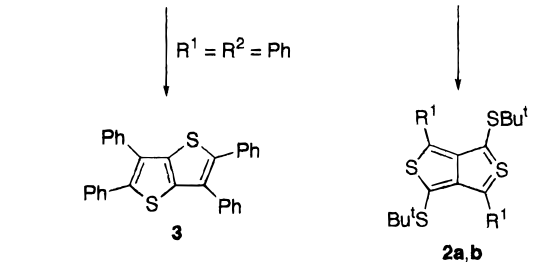
Scheme 3



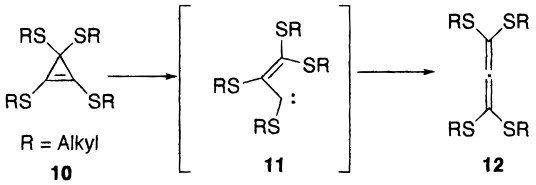
Scheme 4





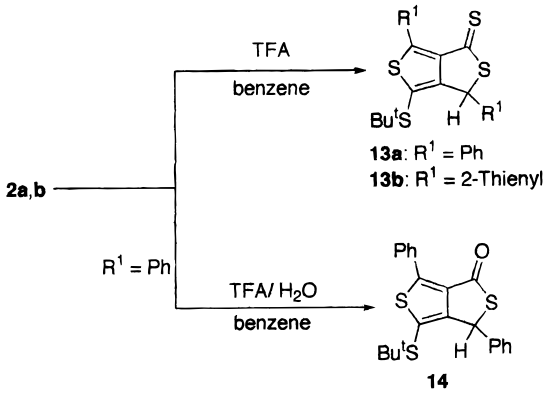


Scheme 5

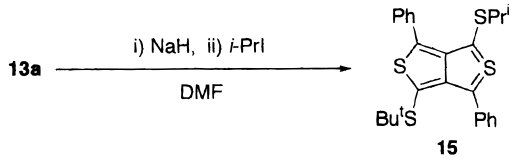


to form the adducts **5a,b,h** shown in Scheme 4. Furthermore, on account of the requirement of the dimerization of cyclopropenethiones for the formation of the thienothiophene skeleton, we consider the intermediary formation of cyclopropenes **7a,b,h** which are produced by addition of **5a,b,h** to **1a,b,h** followed by intramolecular cyclization, since the addition of the thiolate anion to the cyclopropenethione ring occurs easily. Recent studies have revealed that the alkylthio-substituted cyclopropenes **10** undergo easily ring-opening to form the vinylcarbene intermediates **11**, followed by the migration of the alkylthio group to the carbenic carbon to give the allene derivatives **12** (Scheme 5).[13] On the basis of these facts, the resulting cyclopropenes **7a,b** are thought to be converted into bis-allenes **9a,b** *via* the formation of vinylcarbenes **8a,b**.[14] In the absence of the *tert*-butylthio group, the coupling of the carbenic carbons of **8h** leads

Scheme 6



Scheme 7



to the thieno[3,2-*b*]thiophene ring system, as observed in the reaction of **1h** with triphenylphosphine. The intramolecular cyclization of bis-allenes **9a,b** gives **2a,b**, as shown in the intermediary formation of *o*-quinodimethane in the isomerization of *cis*-4-octene-1,7-diyne with potassium *tert*-butoxide.[15]

Reactions of 2a,b with TFA. The reaction of 1,3,4,6-tetrakis(*tert*-butylthio)thieno[3,4-*c*]thiophene with TFA proceeds by the protonation at the thienothiophene ring, followed by the cleavage of the *t*-Bu−S bond to give 3,4,6-tris(*tert*-butylthio)thieno[3,4-*c*]thiophene-1(3*H*)-thione.[16] This fact led us to explore the positional reactivity of **2a,b** toward a proton from TFA. The reaction was carried out according to the previous method; TFA (3 equiv) was added under argon to a dry benzene solution of **2a,b**, and the mixture was stirred at room temperature for 20 h. Compounds **2a,b** were converted into 4-*tert*-butylthio-3,6-diphenyl- or 3,6-di(2-thienyl)thieno[3,4-*c*]thiophene-1(3*H*)-thione (**13a,b**) in 97 and 98% yields, respectively (Scheme 6). The treatment of **13a** with sodium hydride and then isopropyl iodide resulted in the regeneration of the thieno[3,4-*c*]thiophene system to give 1-(*tert*-butylthio)-3,6-diphenyl-4-isopropylthiothieno[3,4-*c*]thiophene **15** in a 70% yield (Scheme 7). The structures of **13a,b** were determined by means of their IR, ^{1}H, and ^{13}C NMR spectra and elemental analyses. In addition, that of **13a** was established by a single crystal X-ray diffraction.[9] The ORTEP drawing of **13a** is shown in Figure 2. Furthermore, the reaction was followed by the ^{1}H NMR spectroscopy using benzene-d_6 as solvent. One singlet (δ 0.94) due to equivalent *tert*-butylthio groups of **2a** changed to two singlets (δ 0.99 and 1.06) meaning the presence of the unequivalent *tert*-butylthio groups, this supporting the formation of 1,4-bis(*tert*-butylthio)-3,6-diphenyl-3*H*-thieno[3,4-*c*]thiophenium trifluoroacetate (**16a**) shown in Scheme 8. This spectrum changed gradually to that of **13a**. When the reaction of **2a** with TFA was carried out in the presence

(13) Yoshida, Z.; Yoneda, S.; Miyamoto, T.; Miki, S. *Tetrahedron Lett.* **1974**, 813.

(14) Compounds **9a,b** would not be produced from two molecules of Bu^{t}S(S$^-$)C=C=C(P$^+$Ph$_3$)Ar formed by the ring-opening of **5a,b**, since the Ph$_3$P$^+$ group of (Bu^{t}S)$_2$C=C=C(P$^+$Ph$_3$)SBu^t [20] is not replaced by *t*-BuS$^-$.

(15) (a) Ben-Efraim, D. A.; Sandheimer, F. *Tetrahedron Lett.* **1963**, 313. (b) Errege, L. A. *J. Am. Chem. Soc.* **1961**, *83*, 949.

(16) Tsubouti, A.; Matsumura, N.; Inoue, H.; Yanagi, K. *J. Chem. Soc., Perkin Trans. 1* **1991**, 909.

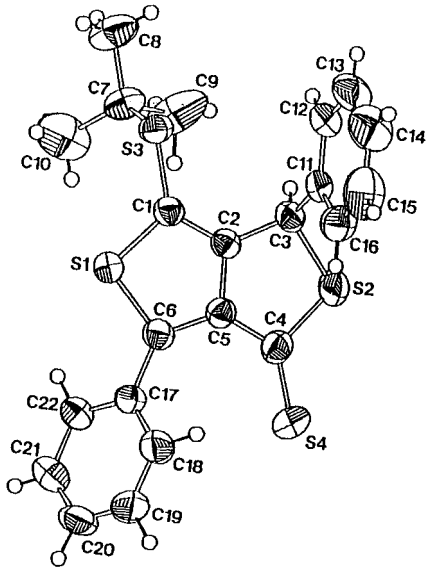


Figure 2. ORTEP drawing of **13a**.

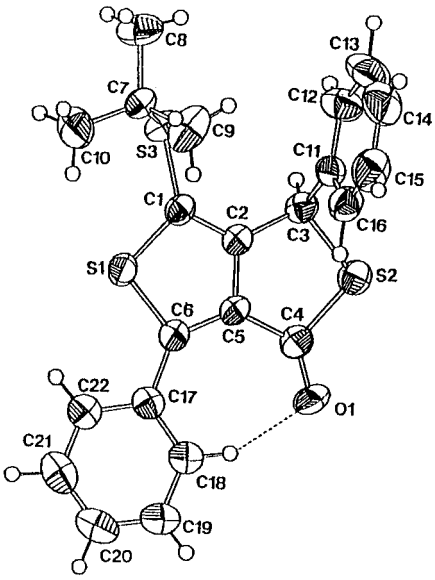
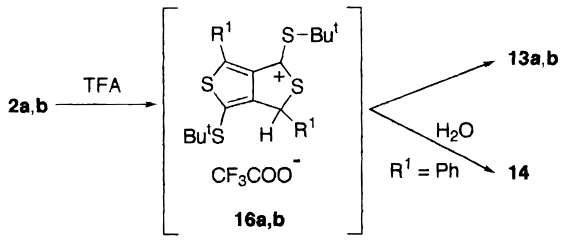


Figure 3. ORTEP drawing of **14**.

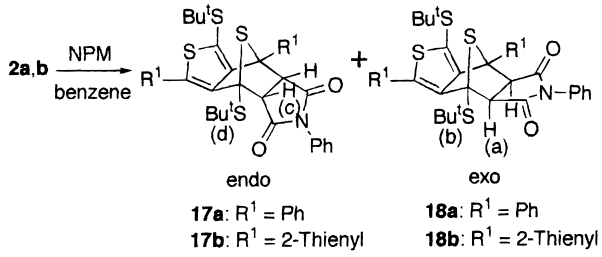
Scheme 8



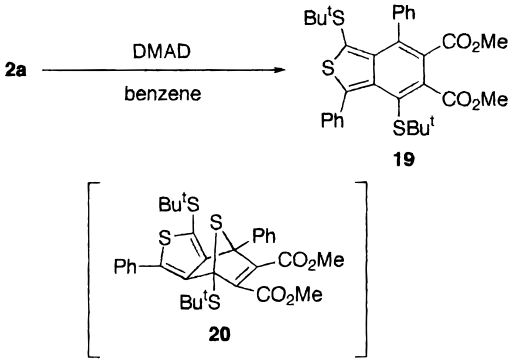
of water (10 equiv), 4-(*tert*-butylthio)-3,6-diphenylthieno-[3,4-*c*]thiophene-1(3*H*)-one (**14**) was produced in an 88% yield (Scheme 6). The structure of **14** was established by a single crystal X-ray diffraction.[9] The ORTEP drawing of **14** is shown in Figure 3. Thus, it was established that the 3-position having the aryl group is protonated by TFA in preference to the 1-position having the *tert*-butyl group.

Cycloaddition Reactions of 2a,b with NPM and DMAD. The reactions were carried out by refluxing a solution of **2a,b** and NPM or DMAD in benzene. The reaction of **2a** with NPM for 3 days gave the endo- and exo-cycloadducts (**17a** and **18a**) in 46 and 35% yields, respectively, while that with **2b** gave the endo- and exo-cycloadducts (**17b** and **18b**) in 69 and 13% yields, respectively (Scheme 9). The structures of **17a,b** and **18a,b** were assigned on the basis of their ^{1}H NMR, IR, and mass spectra and elemental analyses. The stereochemistry for the endo and exo adducts was determined by the measurement of the NOESY in the ^{1}H NMR spectra. The NOESY spectrum of **18a** showed a cross peak between H_a and H_b, but that of **17a** did not show it between H_c and H_d, this indicating that the endo-H of the exo-cycloadduct **18a** is situated close to the *tert*-butylthio group. Furthermore, the assignment of the stereochemistry for **17** and **18** was consistent with the description by Cava et al. that the exo-protons of an endo-cycloadduct in the ^{1}H NMR spectrum appear at the lower field than the endo-protons of an exo-cycloadduct in the ^{1}H NMR spectrum because of the deshielding effect of the sulfur bridge.[2c] Thus, the reactions of **2a,b** with NPM gave predominantly the endo-cycloadducts and the endo-selectivity became higher in the reaction with **2b**, being different from that in the reaction with 1,3,4,6-tetrakis-(alkylthio)thieno[3,4-*c*]thiophenes which gave selectively the exo-cycloadducts.[17] These results indicate that the endo/exo selectivity is governed by the steric effect of the substituents in the 4- and 6-positions on the cycloaddition in the 1- and 3-positions.

Scheme 9



Scheme 10



Next, the reaction of **2a** with DMAD for 4 days gave 1,4-bis(*tert*-butylthio)-5,6-bis(methoxycarbonyl)-3,7-diphenylbenzo[*c*]thiophene **19** in 29% yield by loss of a sulfur atom from the cycloadduct **20**, as shown in Scheme 10. This reaction can be used for the preparation of benzo-[*c*]thiophene derivatives.

Experimental Section

General. Melting points are uncorrected. ^{1}H and ^{13}C NMR spectra were recorded at 270 MHz for solutions in $CDCl_3$ with

(17) Yoneda, S.; Ozaki, K.; Tsubouchi, A.; Kojima, H.; Yanagi, K. *J. Heterocycl. Chem.* **1988**, *25*, 559.

tetramethylsilane (TMS) as an internal standard. Column chromatography was performed on silica gel (Wakogel C-300).

Preparation of Cyclopropenethiones 1a−h. Compounds **1a,b** and **1d−h** were prepared according to the methods described previously.[6−8] Compound **1c** was prepared from 2,3-bis(*tert*-butylthio)cyclopropenethione and (2,4,6-triisopropylphenyl)lithium by the procedure similar to that in the preparation of **1a**.

2-(*tert*-Butylthio)-3-(2,4,6-triisopropylphenyl)cyclopropenethione (1c): pale yellow crystals; yield 22%; mp 106−108 °C (methanol); ^{1}H NMR δ 1.26 (d, 12 H, J = 6.7 Hz), 1.28 (d, 6 H, J = 7.3 Hz), 1.80 (s, 9 H), 2.94 (sep, 1 H, J = 7.3 Hz), 3.82 (sep, 2 H, J = 6.7 Hz), 7.13 (s, 2 H); IR (KBr) 2958, 1716, 1597, 1455 cm^{-1}; UV (hexane) λ_{max} (nm) (log ϵ) 326 (4.18), 271 (4.21). Anal. Calcd for $C_{22}H_{32}S_2$: C, 73.28; H, 8.94. Found: C, 73.30; H, 9.13.

General Procedure for the Reactions of Cyclopropenethiones 1a−h with Triphenylphosphine. To a solution of **1a−h** (1 mmol) in dry benzene (20 mL) was added triphenylphosphine (0.5 mmol) under argon, and the mixture was stirred at 50 °C for 20 h. After removal of the solvent under reduced pressure, the residue was subjected to column chromatography with toluene−hexane (1:1) as eluent. Compounds **2a,b** and **3** were isolated, but **1c−g** were recovered unchanged (96−98% recoveries).

1,4-Bis(*tert*-butylthio)-3,6-diphenylthieno[3,4-*c*]thiophene (2a): red crystals; yield 46%; mp 177−178.5 °C dec (methanol); ^{1}H NMR δ 0.94 (s, 18 H), 7.34−7.45 (m, 6 H), 7.67−7.71 (m, 4 H); ^{13}C NMR δ 30.17, 49.34, 110.30, 127.51, 127.61, 130.76, 131.45, 132.5, 147.78; IR (KBr) 1455, 1362 cm^{-1}; UV (hexane) λ_{max} (nm) (log ϵ) 515.5 (4.34), 294.5 (4.36), 280.0 (4.31), 247.5 (4.34). Anal. Calcd for $C_{26}H_{28}S_4$: C, 66.62; H, 6.02. Found: C, 66.55; H, 6.04.

1,4-Bis(*tert*-butylthio)-3,6-di(2-thienyl)thieno[3,4-*c*]thiophene (2b): purple crystals; yield 21%; mp 199−201 °C dec (methanol); ^{1}H NMR δ 1.06 (s, 18 H), 7.10−7.14 (m, 2 H), 7.33−7.36 (m, 2 H), 7.48−7.49 (m, 2 H); ^{13}C NMR δ 30.12, 49.54, 111.12, 123.52, 126.35, 127.25, 129.90, 133.27, 147.57; IR (KBr) 1458, 1362 cm^{-1}; UV (hexane) λ_{max} (nm) (log ϵ) 538 (4.30), 297 (4.40), 245 (4.38). Anal. Calcd for $C_{22}H_{24}S_6$: C, 54.96; H, 5.03. Found: C, 54.80; H, 5.16.

2,3,5,6-Tetraphenylthieno[3,2-*b*]thiophene (3):[8] white crystals; yield 9%; mp 285−286 °C dec ($CHCl_3$−hexane); ^{1}H NMR δ 7.24−7.28 (m, 8 H), 7.31−7.40 (m, 8 H), 7.46−7.49 (m, 4 H); ^{13}C NMR δ 127.69, 128.56, 128.84, 129.10, 129.39, 134.64, 139.05, 139.10; IR (KBr) 1444 cm^{-1}; UV (CH λ_{max} (nm) (log ϵ) 259 (4.26), 337 (4.41). Anal. Calcd for $C_{30}H_{20}S_2$: C, 81.04; H, 4.53. Found: C, 80.78; H, 4.29.

Reactions of 2a,b with TFA. To a solution of **2a,b** (0.2 mmol) in dry benzene (10 mL) was added TFA (0.6 mmol) under argon, and the mixture was stirred at room temperature for 20 h. After removal of the solvent under reduced pressure, the residue was purified by column chromatography with toluene as eluent to give **13a,b**.

4-(*tert*-Butylthio)-3,6-diphenylthieno[3,4-*c*]thiophene-1(3*H*)-thione (13a): red crystals; yield 97%; mp 132−133.5 °C (methanol); ^{1}H NMR δ 1.20 (s, 9 H), 5.74 (s, 1 H), 7.28−7.47 (m, 8 H), 7.68−7.71 (m, 2 H); IR (KBr) 1517, 1451 cm^{-1}; UV (hexane) λ_{max} (nm) (log ϵ) 360 (4.11), 279 (4.27). Anal. Calcd for $C_{22}H_{20}S_4$: C, 64.04; H, 4.89. Found: C, 63.86; H, 4.78.

4-(*tert*-Butylthio)-3,6-di(2-thienyl)thieno[3,4-*c*]thiophene-1(3*H*)-thione (13b): red crystals; yield 98%; mp 65−68 °C (methanol); ^{1}H NMR δ 1.30 (s, 9 H), 6.06 (s, 1 H), 6.92−6.96 (m, 1 H), 7.08−7.11 (m, 2 H), 7.24−7.27 (m, 1 H), 7.44−7.46 (m, 1 H), 7.79−7.81 (m, 1 H); IR (KBr) 1519, 1448 cm^{-1}; UV (CH_2Cl_2) λ_{max} (nm) (log ϵ) 371 (4.02), 293 (4.17); Anal. Calcd for $C_{18}H_{16}S_6$: C, 50.91; H, 3.80. Found: C, 50.65; H, 3.61.

Detection of 1,4-Bis(*tert*-butylthio)-3,6-diphenyl-3*H*-thieno[3,4-*c*]thiophenium Trifluoroacetate (16a). TFA (0.06 mmol) was added to a solution of **2a** (0.02 mmol) in benzene-d_6 (0.90 mL) containing TMS as an internal standard in a sample tube at room temperature, and then the ^{1}H NMR spectrum of the solution was recorded immediately. The ^{1}H NMR spectrum showed peaks for the salt **16a** at δ 0.99 (s, 9 H, 4-SBu^t), 1.06 (s, 9 H, 1-SBu^t), 5.93 (s, 1 H, 3-H) and 7.01−7.35 (m, 10 H, 3,6-Ph). This spectrum changed to that of **13a** on keeping the sample tube at room temperature for 20 h.

Reaction of 2a with TFA in the Presence of Water. To a solution of **2a** (0.2 mmol) in dry benzene (10 mL) were added TFA (0.6 mmol) and water (2 mmol) under argon, and the mixture was stirred at room temperature for 20 h. After removal of the solvent under reduced pressure, the residue was purified by column chromatography with toluene−hexane (1:1) as eluent to give **14**.

4-(*tert*-Butylthio)-3,6-diphenylthieno[3,4-*c*]thiophene-1(3*H*)-one (14): white crystals; yield 88%; mp 154−155.5 °C (methanol); ^{1}H NMR δ 1.20 (s, 9 H), 5.72 (s, 1 H), 7.28−7.46 (m, 8 H), 7.80−7.83 (m, 2 H); IR (KBr) 1680, 1518, 1455 cm^{-1}; UV (hexane) λ_{max} (nm) (log ϵ) 340 (4.08), 280 (3.99). Anal. Calcd for $C_{22}H_{20}OS_3$: C, 66.63; H, 5.08. Found: C, 66.38; H, 4.96.

Alkylation of 13a with Isopropyl Iodide. A solution of **13a** (0.2 mmol) in dry DMF (10 mL) was added under argon to a suspension of sodium hydride (60% mineral oil dispersion) (0.4 mmol) in DMF (5 mL) at room temperature. The mixture was stirred for 30 min, and then isopropyl iodide (0.4 mmol) was added. After being stirred for 30 min, the mixture was poured into water and extracted with dichloromethane, and the extract was dried over anhydrous sodium sulfate. After the solvent was evaporated off under reduced pressure, the residue was purified by column chromatography with toluene as eluent to give **15**.

4-(*tert*-Butylthio)-3,6-diphenyl-1-(isopropylthio)thieno-[3,4-*c*]thiophene (15): red crystals; yield 70%; mp 156−158 °C (acetonitrile); ^{1}H NMR δ 0.92 (d, 6 H, J = 6.7 Hz), 0.94 (s, 9 H), 2.54 (sep, 1 H, J = 6.7 Hz), 7.33−7.46 (m, 6 H), 7.66−7.74 (m, 4 H); IR (KBr) 1592, 1494, 1443 cm^{-1}; UV (CH λ_{max} (nm) (log ϵ) 516 (4.29), 294 (4.33), 249 (4.31). Anal. Calcd for $C_{25}H_{26}S_4$: C, 66.03; H, 5.76. Found: C, 66.30; H, 5.86.

Reactions of 2a,b with NPM. To a solution of **2a,b** (0.2 mmol) in dry benzene (10 mL) was added NPM (0.2 mmol), and the mixture was refluxed for 3 days under argon. After the solvent was evaporated off under reduced pressure, the residue was separated by column chromatography with toluene as eluent to give the endo-cycloadducts **17a,b** and the exo-cycloadducts **18a,b**.

Endo-cycloadduct 17a: red crystals; yield 46%; mp 244−246 °C dec (methanol); ^{1}H NMR δ 1.08 (s, 9 H), 1.16 (s, 9 H), 4.53 (d, 1 H, J = 8.5 Hz), 4.76 (d, 1 H, J = 8.5 Hz), 6.88−6.92 (m, 2 H), 7.29−7.41 (m, 9 H), 7.66−7.67 (m, 2 H), 7.97−8.01 (m, 2 H); IR (KBr) 1709, 1492, 1385 cm^{-1}; UV (CH_2Cl_2) λ_{max} (nm) (log ϵ) 304 (4.00), 260 (4.21). Anal. Calcd for $C_{36}H_{35}NO_2S_4$: C, 67.36; H, 5.50; N, 2.18. Found: C, 67.33; H, 5.43; N, 1.94.

Exo-cycloadduct 18a: red crystals; yield 35%; mp 240−242.5 °C dec (methanol); ^{1}H NMR δ 1.07 (s, 9 H), 1.12 (s, 9 H), 3.91 (d, 1 H, J = 6.1 Hz), 4.25 (d, 1 H, J = 6.7 Hz), 7.24−7.42 (m, 11 H), 7.53−7.57 (m, 2 H), 7.67−7.71 (m, 2 H); IR (KBr) 1711, 1495, 1371 cm^{-1}; UV (CH_2Cl_2) λ_{max} (nm) (log ϵ) 303 (3.94), 259 (4.28). Anal. Calcd for $C_{36}H_{35}NO_2S_4$: C, 67.36; H, 5.50; N, 2.18. Found: C, 67.10; H, 5.44; N, 1.96.

Endo-cycloadduct 17b: pale yellow crystals; yield 69%; mp 242.5−243 °C dec (methanol); ^{1}H NMR δ 1.13 (s, 9 H), 1.24 (s, 9H), 4.50 (d, 1H, J = 8.5 Hz), 4.65 (d, 1 H, J = 9.1 Hz), 6.88−6.91 (m, 2H), 7.03−7.08 (m, 2 H), 7.27−7.36 (m, 5 H), 7.59−7.61 (m, 1 H), 7.84−7.85 (m, 1 H); IR (KBr) 1709, 1491, 1378 cm^{-1}; UV (CH_2Cl_2) λ_{max} (nm) (log ϵ) 319 (4.06); MS m/z 654 (M^+). Anal. Calcd for $C_{32}H_{31}NO_2S_6$: C, 58.77; H, 4.78; N, 2.14. Found: C, 58.79; H, 4.92; N, 1.90.

Exo-cycloadduct 18b: pale yellow crystals; yield 13%; mp 239−241 °C dec (methanol); ^{1}H NMR δ 1.20 (s, 9 H), 1.22 (s, 9 H), 3.82 (d, 1 H, J = 6.7 Hz), 4.07 (d, 1 H, J = 6.7 Hz), 7.04−7.11 (m, 2 H), 7.27−7.43 (m, 8 H), 7.62−7.64 (m, 1 H); IR (KBr) 1712, 1495, 1374 cm^{-1}; UV (CH_2Cl_2) λ_{max} (nm) (log ϵ) 313 (4.08). Anal. Calcd for $C_{32}H_{31}NO_2S_6$: C, 58.77; H, 4.74; N, 2.14. Found: C, 59.05; H, 4.74; N, 1.91.

Reaction of 2a with DMAD. To a solution of **2a** (0.2 mmol) in dry benzene (10 mL) was added DMAD (0.2 mmol), and the mixture was refluxed for 4 days under argon. After the solvent was evaporated off under reduced pressure, the residue was separated by column chromatography with toluene as eluent to give **19** in 29% yield with 43% recoveries of the starting material **2a**.

1,4-Bis(*tert*-butylthio)-5,6-bis(methoxycarbonyl)-3,7-diphenylbenzo[*c*]thiophene (19): yellow crystals; mp 149.5−150.5 °C (methanol); ^{1}H NMR δ 0.87 (s, 9 H), 0.99 (s, 9 H), 3.44 (s, 3 H), 3.87 (s, 3 H), 7.31−7.51 (m, 10 H); IR (KBr) 1736, 1439, 1377 cm^{-1}; UV (CH_2Cl_2) λ_{max} (nm) (log ϵ) 408 (2.93), 269 (4.24). Anal. Calcd for $C_{32}H_{34}O_4S_3$: C, 66.41; H, 5.92. Found: C, 66.29; H, 6.20.

X-ray Crystallography. Data were collected on a Rigaku AFC4 diffractometer with graphite monochromatized Cu Kα radiation (λ = 1.54184 Å). The structure was solved by a direct method using MULTAN78[18] and successive Fourier synthesis and refined by the block diagonal least-square method using UNICSIII.[19]

Crystal Data for 2a: $C_{26}H_{28}S_4$, fw = 468.77, triclinic, space group $P\bar{1}$, a = 11.640(2), b = 9.733(2), c = 5.6821(6) Å, α = 96.81(1), β = 101.99(1), γ = 105.86(1)°, V = 595.1(2) Å^3, Z = 1, Dx = 1.308 g cm^{-3}, μ(Cu Kα) = 3.683 mm^{-1}. A red crystal with dimensions of 0.075 × 0.1 × 0.2 mm was used for data collection. 2021 unique reflections were obtained up to 2θ of 130°, and 1685 observed reflections ($|F_o| > 3\sigma(F)$) were used for refinement. R = 0.040 and wR = 0.039.

Crystal Data for 13a: $C_{22}H_{20}S_4$, fw = 412.64, monoclinic, space group $P2_1/a$, a = 11.962(5), β = 15.611(4), c = 12.371(4) Å, α = 90.0, β = 114.63(2), γ = 90.0°, V = 2100(1) Å^3, Z = 4, Dx = 1.305 g cm^{-3}. A red crystal with dimensions of 0.30 × 0.20 × 0.40 mm was used for data collection. 5234 unique reflections were obtained up to 2θ of 130°, and 3628 observed reflections ($|F_o| > 3\sigma(F)$) were used for refinement. R = 0.045 and wR = 0.053.

Crystal Data for 14: $C_{22}H_{20}OS_3$, fw = 396.58, monoclinic, space group $C2/c$, a = 26.978(4), b = 8.958(7), c = 19.190(4) Å, α = 90.0, β = 122.023(9), γ = 90.0°, V = 3931(3) Å^3, Z = 8, Dx = 1.340 g cm^{-3}. A red crystal with dimensions of 0.10 × 0.08 × 0.40 mm was used for data collection. 4914 unique reflections were obtained up to 2θ of 130°, and 2589 observed reflections ($|F_o| > 3\sigma(F)$) were used for refinement. R = 0.043 and wR = 0.042.

Acknowledgment. This work was partially supported by a Grant-in-Aid for Scientific Research from the Ministry of Science, Culture, Sports and Education of Japan, which is gratefully acknowledged.

JO971698A

(18) Main, P.; Hull, S. E.; Lessinger, L.; Germain, G.; Declercq, J. P.; Woolfson, M. M. *MULTAN78*. A System of Computer Programs for the Automatic Solution of Crystal Structures from X-Ray Diffraction Data. Univs. of York, Endland and Louvain-la-Nerve, Belgium, **1978**.

(19) Sakurai, T.; Kobayashi, K. *Rikagaku Kenkyusho Hokoku* **1979**, *55*, 69.

(20) Kojima, H.; Ozaki, K.; Matsumura, N.; Inoue, H. *J. Chem. Res. (S)* **1991**, 324.