3-(2-(Hydroxymethyl)phenyl)-4-methylcyclobut-3-ene-1,2-dione (14d): yellow solid, 0.099 g (90%) from 0.133 g of **13d**; mp 93–94 °C (CH_2Cl_2/hexane); IR (CH_2Cl_2, cm^{-1}) 3600, 3500, 3050, 2950, 2890, 1790, 1770, 1595, 1375; ^1H NMR (300 MHz $CDCl_3$) δ 7.65–7.38 (m, 4 H), 4.70 (s, 2 H), 3.59 (br s, 1 H), 2.58 (s, 3 H). Anal. Calcd for $C_{12}H_{10}O_3$: C, 71.28; H, 4.98. Found: C, 71.08; H, 5.01.

4-Methyl-3-(2-thienyl)cyclobut-3-ene-1,2-dione (14e): orange solid: 0.079 g (99%) from 0.101 g of **13e**; mp 128–130 °C (CH_2Cl_2/hexane); IR (CH_2Cl_2, cm^{-1}) 3110, 3060, 2930, 1785, 1770, 1600, 1415; ^1H NMR (300 MHz, $CDCl_3$) δ 8.09 (dd, J = 3.8 Hz, J = 1.0 Hz, 1 H), 7.94 (dd, J = 5.0 Hz, J = 1.0 Hz, 1 H), 7.35 (dd, J = 5.0 Hz, J = 3.8 Hz, 1 H), 2.58 (s, 3 H). Anal. Calcd for $C_9H_6O_2S$: C, 60.66; H, 3.39. Found: C, 60.63; H, 3.43.

3-((*E*)-1-Hexenyl)-4-methylcyclobut-3-ene-1,2-dione (14f): yellow oil, 0.033 g (73%) from 0.056 g of **13f**; IR (CH_2Cl_2, cm^{-1}) 3040, 2960, 2930, 2860, 1775, 1765, 1625, 1570, 1380; ^1H NMR (360 MHz, $CDCl_3$) δ 7.35 (dt, J = 15.7 Hz, J = 7.0 Hz, 1 H), 6.50 (dt, J = 15.7 Hz, J = 1.2 Hz, 1 H), 2.36 (s, 3 H), 2.40–2.32 (m, 2 H), 1.52 (m, 2 H), 1.39 (m, 2 H), 0.94 (t, J = 7.3 Hz, 3 H). Anal. Calcd for $C_{11}H_{14}O_2$: C, 74.13; H, 7.92. Found: C, 74.04; H, 7.97.

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Generation and Electrophilic Reactions of the 2,2,2-Trifluoro-1-(phenylthio)ethyl Carbocation

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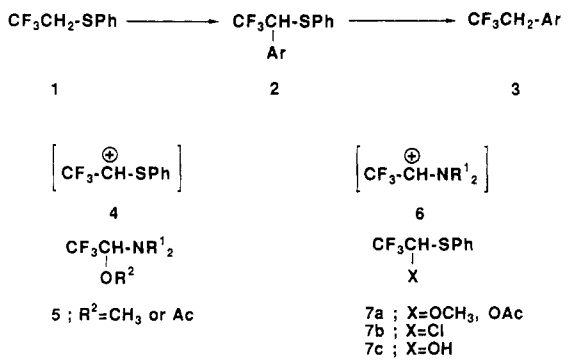
2,2,2-Trifluoro-1-(phenylthio)ethyl carbocation (**4**) has been generated by the reaction of 1-chloro-2,2,2-trifluoroethyl phenyl sulfide (**7b**) with $ZnCl_2$ in nitromethane or $SnCl_4$ in 1,2-dichloroethane. The carbocation **4** can be trapped with various aromatics bearing electron-donating groups, affording 1-aryl-2,2,2-trifluoroethyl phenyl sulfide **2** in 37–83% yields. Similarly, allyltrimethylsilane and various nitriles provided the corresponding allylated sulfide and amide sulfides, respectively. The reaction rate is affected by the electron-donor ability of the reactant aromatics. The optically active chloride **7b'** was prepared and subjected to a $ZnCl_2$-catalyzed reaction. Both product **2** and the recovered **7b'** were racemic, suggesting the formation of carbocation intermediate.

Because of increasing attention to organofluorine compounds in the medical and material sciences,[1] transformations to organofluorine compounds have been extensively studied in recent years. Trifluoroethylation, however, has been relatively unexplored. Trifluoroethyl aromatics have been of interest in agrochemistry, for example, as insecticides[2] and fungicides.[3] The Wurtz–Fittig reaction of 2,2,2-trifluoroethyl iodide with copper metal,[4] reduction of trifluoroacetyl aromatics prepared by an addition of aryl Grignard to trifluoroacetic acid,[5] and replacement of chlorine by fluorine of 2,2,2-trichloroethyl aromatics[6] have been proposed. However, these methods are limited because of vigorous conditions, low yields, or the use of expensive and hazardous reagents.

Carbon–carbon bond formation on the methylene carbon of 2,2,2-trifluoroethyl phenyl sulfide (**1**) and subsequent desulfurization would be a promising pathway. However, metalation of **1** followed by alkylation failed to yield alkylated compounds but led instead to defluorination.[7] This suggests that the 1-(phenylthio)-2,2,2-trifluoroethyl carbanion is very unstable, although a few successful alkylations on the carbon bearing the trifluoromethyl group have been reported.[8-10] On the other hand, the chemistry of the carbocation **4** has not been investigated, presumably due to the difficulty of its generation. Therefore, an electron-donating group must be introduced to the carbon attached to the trifluoromethyl group to compensate the deactivation by the trifluoromethyl group. Aryl group participation in the stabilization has been well demon-

Scheme I



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[‡] Department of Chemistry, Faculty of Education.

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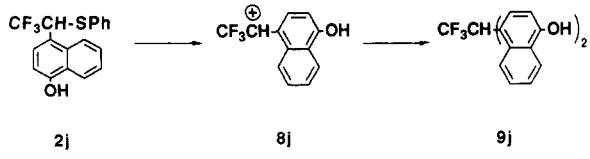
Scheme II



strated by Bonnet-Delpon,[11] and Aubert.[12] A successful example for the combination of an electron-donating heteroatom and a trifluoromethyl group has been reported by Guy,[13] Fuchigami, and Nonaka.[14] Thus, the methoxyl and acetoxyl amines **5** were good sources of the carbocation **6** on exposure to Lewis acid catalyst. However, the same reaction failed for the methoxyl and acetoxyl sulfides **7a**, probably because the carbon–oxygen bond is stronger than the carbon–sulfur bond and the desired carbocation **4** could not be formed. Any weaker C–X bonds must be substituted for a C–O bond. Tamura demonstrated the feasibility of the carbon–chlorine bond cleavage method for the generation of the (methylthio)acyl carbocation.[15] On this basis, 1-chloro-2,2,2-trifluoroethyl phenyl sulfide (**7b**) would be a promising precursor for **4**. This paper describes the generation, the electrophilic reaction, and some mechanistic aspects of the carbocation **4**.

Results and Discussion

Chlorination of **1** with sulfuryl chloride in hexane at room temperature provided the chloride **7b**[16] in 84% yield along with the dichlorinated sulfide (10%), which can be separated by column chromatography. The compound **7b** is stable to silica gel chromatography, in contrast to the facile hydrolysis of 1-chloroethyl phenyl sulfide. Benzyl 2,2,2-trifluoroethyl sulfide was regioselectively chlorinated at the CF_3-bearing methylene group to afford **10**, presumably because deprotonation from the chlorosulfonium intermediate took place exclusively at the trifluoroethyl side, due to the higher acidity of the CF_3-bearing methylene hydrogen than that of the benzyl group.[17]

The effects of Lewis acids and solvents for the dechlorinative generation of the carbocation **4** and its reaction with aromatics were examined. A combination of tin tetrachloride ($SnCl_4$) and 1,2-dichloroethane was found to be useful for less reactive aromatics, but not for more reactive aromatics such as furan, thiophene, and 1-naphthol. In contrast, a weaker Lewis acid such as $ZnCl_2$ in nitromethane provided good results. The chloride **7b** was recovered when other solvents such as CH_3CN, CS_2, CH_2Cl_2, and $ClCH_2CH_2Cl$ were employed in combination with $ZnCl_2$ for phenylation with benzene. The marked rate enhancement by α-phenylthio group is noteworthy. Similar electronic effects to the benzylic carbocation bearing a trifluoromethyl group by sulfur[18] and nitrogen[19] on aromatic ring have been known.

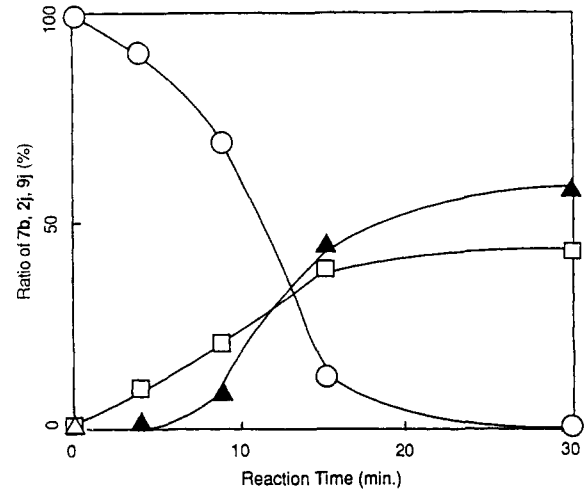


Figure 1. The relation between reaction time and the reacted chloride **7b**, products **2j**, and **9j**. Conditions: **7b** (1 mmol), naphthol (2 mmol), $ZnCl_2$ (2 mmol), CH_3NO_2 (2 mL), 60 °C; (○) **7b**; (□) **2j**; (▲) **9j**.

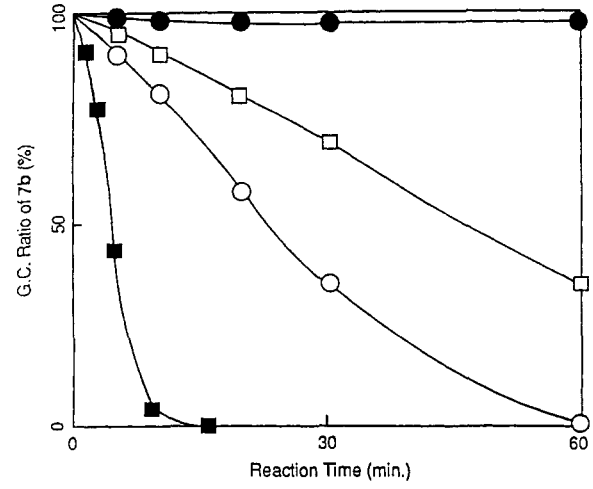


Figure 2. The relation between reaction time and the reacted chloride **7b** in the presence of aromatics. Conditions: **7b** (1 mmol), ArH (4 mmol), $ZnCl_2$ (4 mmol), CH_3NO_2 (3 mL), 55 °C; (□) benzene; (○) toluene, (■) anthracene; (●) chlorobenzene.

Various arenes were subjected to the reaction, and the results are summarized in the Table I. Most arenes with electron-donating groups reacted smoothly. Naphthalene reacted regioselectively at the α-position. Toluene and 1,2-diphenylethane provided a mixture of ortho and para isomers in a ratio of 1:12 and 1:10, respectively. Likewise, anisole gave a mixture (ortho:para = 3:7) in 70% yield. *N,N*-Dimethylaniline reacted very fast, affording the ortho isomer in 41% yield. The *N,N*-dimethylamino group at the para position may play a role in accelerating the desulfurization. In fact, the facile cleavage of the phenylthio group was observed in **2j** (Ar = 4-hydroxynaphthyl) and **2k**. The hydroxyl group at the 4-position of **2j** enhances the leaving of the phenylthio group, generating 1-(4-hydroxynaphthyl)-2,2,2-trifluoroethyl carbocation **8j**, which in turn reacts with another 1-naphthol to give **9j** (Scheme II). In fact, **2j** was transformed to **9j** in the acid-catalyzed dechlorination conditions. The time course of product distributions of **2j** and **9j** are shown in Figure 1. Methyl salicylate reacted at the 5-position (para to hydroxyl

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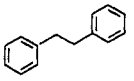
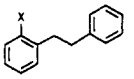
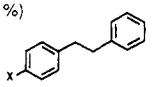
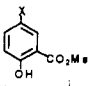
Table I. Reaction of 1 with Various Aromatic Compounds[a]

entry	ArH	conditions[b]	product (yield, %)
1		A[c]	 **2a** (66 %)
2[f]		A[d]	 **2b** (6 %)  **2c** (77 %)
3		B[d]	 **2d** (80 %)
4[f]		B[d]	 **2e** (7 %)  **2f** (70 %)
5		B[d]	 **2g** (21 %)  **2h** (49%)
6		A[e]	 **2i** (41 %)
7		A[e]	 **2j** (37 %)[h]
8		A[e]	 **2k** (41 %)[i]
9		A[e]	 **2l** (51 %)
10[g]		A[e]	 **2m** (58 %)  **2n** (15 %)

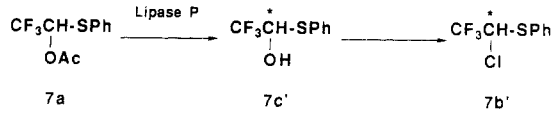
[a] X = CF_3CHSPh. [b] Reaction conditions: (A) $ZnCl_2/CH_3NO_2$/reflux; (B) $SnCl_4/ClCH_2CH_2Cl$/reflux. [c] Reaction time; 30 min. [d] Reaction time; 3 min. [e] These isomers were not separable. Isomer ratio was calculated by ^1H NMR of the mixture. [g] Isomer ratio was determined by ^1H NMR and VPC analyses. [h] 1,1,1-Trifluoro-2,2-bis(4-hydroxynaphthyl)ethane was obtained (27%). [i] 1,1,1-Trifluoro-2,2-bis(4-hydroxy-3-(methoxycarbonyl)phenyl)ethane was obtained (25%).

group), affording the desired product **2k** in 41% yield along with the bisarylated compound **9k** (25%). However, methyl benzoate was recovered intact.

Furan and thiophene gave the desired adducts in 51% (2-position) and 73% (2-substitution:3-substitution = 8:2), respectively in a $ZnCl_2$–CH_3NO_2 system. However, pyrrole was polymerized and quinoline was recovered intact in the same reaction conditions.

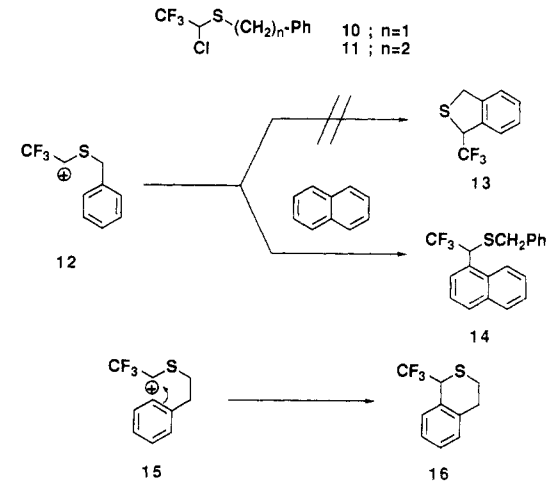
It is noteworthy that the rate of the consumption of the chloride **7b** was affected by the electronic nature of arenes. The chloride **7b** was consumed very fast in the presence of 1-naphthol, *N*,*N*-dimethylaniline, and anthracene. Figure 2 shows the time course of the consumption of **7b** in the presence of benzene, toluene, chlorobenzene, and anthracene. These results suggest that an arene may participate intermolecularly in the rate-determining step of the reaction, although it is not clear in the present stage whether the rate-determining step is the formation of **4** or its reaction with arenes. The intramolecular aryl group participation to the carbocation bearing the trifluoromethyl group has been proposed by Bonnet-Delpon[12] and Aubert.[13]

Scheme III



7a 7c' 7b'

Scheme IV



The formation of the carbocation intermediate **4** was clarified by the fact that both the recovered **7b'** and the product **2** (Ar = naphthyl) were racemic. Thus, the optically active **7b'** was prepared (Scheme III) and subjected to the acid-catalyzed reaction. Acetate **7a** (X = OAc) was prepared by the method of Fuchigami and Nonaka.[14] Alkaline hydrolysis of **7a** provided the hemithioacetal **7c** in a very low yield, presumably due to the facile dephenylthiolation under the reaction conditions. Then, enzymatic lipase-catalyzed hydrolysis was successfully employed, providing in 34% yield **7c'** whose MTPA ester revealed optical purity of 77% enantiomeric excess by ^{19}F NMR analysis, although the absolute stereochemistry was not clear at the present stage. The alcohol **7c'** was transformed to the chloride **7b'** with $[\alpha]_D = -12.2°$ by the action of trifluoromethanesulfonyl chloride in the presence of 4-(dimethylamino)pyridine.[20] The chloride **7b'** was allowed to react with naphthalene in an $SnCl_4$–$ClCH_2CH_2Cl$ system, and **2d** and **7b'** were recovered at about 50% consumption of **7b'**. Both **2d** and **7b'** were found to be racemic.

Intramolecular trapping of the carbocation was examined using the chlorides **10** and **11**. The chloride **10** was subjected to the Lewis acid catalyzed reaction. However, the cyclized benzodihydrothiophene **13** was not obtained. Then, the reaction of **10** was conducted in the presence of naphthalene, providing **14** in 77% yield. These results suggest that the carbocation **12** is conformationally unfavorable for the five-membered ring formation.[19,21] In contrast, the chloride **11** was transformed to the six-membered product **16** in 77% yield.

The trapping of the carbocation **4** with other nucleophiles can be performed by the use of allyltrimethylsilane and various nitriles, affording the allylated sulfide **17** (80% yield) and amides **18** (6–71% yield), respectively. De-

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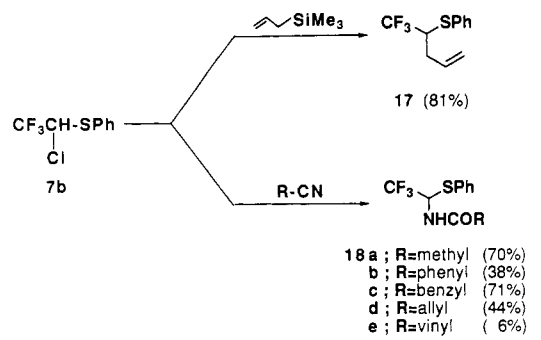
(22) The authors are grateful to the Ministry of Education, Culture, and Science of Japan (a Grant-in-Aid, No 63303009) and CIBA-GEIGY Foundation for the financial support and the SC-NMR Laboratory of Okayama University for 500-MHz NMR analyses.

Scheme V



sulfurization of **2b** by tributyltin hydride reduction provided 1-(2,2,2-trifluoroethyl)naphthalene in 90% yield.

Experimental Section

The boiling points are indicated by the temperature of a glass tube oven. Infrared spectra were taken on a Hitachi 270-30 spectrometer. The ^1H NMR spectra were measured on a Varian VXR-200 or -500 using TMS as an internal standard. Elemental analyses were obtained with Yanaco MT-3 CHN recorder. Optical rotation was measured by JASCO DIP-181 digital polarimeter.

Preparation of 2,2,2-Trifluoro-1-phenylethyl Phenyl Sulfide (2a). A suspension of **7b** (113 mg, 0.5 mmol), benzene (0.15 mL), and $ZnCl_2$ (150 mg, 1.1 mmol) in CH_3NO_2 (1 mL) was heated at reflux for 30 min. After cooling, the mixture was treated with aqueous sodium hydrogen carbonate and extracted with benzene–hexane (1:1). The extracts were washed with water and then dried over anhydrous sodium sulfate. After evaporation of the solvent, the residue was chromatographed through silica gel to yield **2a**, 89 mg (66%) as a viscous oil: bp 120 °C (3 mmHg); IR (neat) 3068, 1958, 1584, 858, 624 cm^{-1}; ^1H NMR ($CDCl_3$) δ 4.52 (q, J = 8.4 Hz, 1 H), 7.25–7.46 (m, 10 H). Anal. Calcd for $C_{14}H_{11}F_3S$: C, 62.67; H, 4.13. Found: C, 62.63; H, 4.12.

2,2,2-Trifluoro-1-(2- and 4-methylphenyl)ethyl Phenyl Sulfide. A mixture of **2b** and **2c** (1:12): bp 135 °C (3.5 mmHg); IR (neat) 3060, 3032, 1616, 1584, 1256, 866, 808, 742, 692 cm^{-1}; ^1H NMR ($CDCl_3$) δ 2.33 (s), 4.48 (q, J = 8.5 Hz, CF_3CH of **2c**), 4.81 (q, J = 10.0 Hz, CF_3CH of **2b**), 7.10–45 (m). Anal. Calcd for $C_{15}H_{13}F_3S$: C, 63.82; H, 4.64. Found: C, 63.93; H, 4.64.

2,2,2-Trifluoro-1-[2-(*N*,*N*-dimethylamino)phenyl]ethyl phenyl sulfide (2i): viscous oil; bp 120 °C (3.5 mmHg); IR (neat) 3068, 2944, 2868, 2832, 2792, 1584, 1264, 946, 850, 772, 686, 620 cm^{-1}; ^1H NMR ($CDCl_3$) δ 2.58 (s, 6 H), 5.76 (q, J = 9.3 Hz, 1 H), 7.25–7.46 (m, 9 H). Anal. Calcd for $C_{16}H_{16}F_3NS$: C, 61.72; H, 5.18; N, 4.49. Found: C, 61.46; H, 5.22; N, 4.28.

Preparation of 2,2,2-Trifluoro-1-(1-naphthyl)ethyl Phenyl Sulfide (2d). To a solution of **7b** (113 mg, 0.5 mmol) and naphthalene (128 mg, 1 mmol) in $ClCH_2CH_2Cl$ (1 mL) was added $SnCl_4$ (0.07 mL, 0.6 mmol), and the mixture was heated at reflux for 2 h. After cooling, the mixture was neutralized with aqueous sodium hydrogen carbonate and extracted with benzene–hexane (1:1). The extracts were washed with water and dried over anhydrous sodium sulfate. After evaporation of the solvent, the residue was chromatographed through silica gel to give **2d**, 127 mg (80%), as a viscous oil: bp 150 °C (3 mmHg); IR (neat) 3064, 1602, 1584, 778, 744, 690, 626 cm^{-1}; ^1H NMR ($CDCl_3$) δ 5.46 (q, J = 7.8 Hz, 1 H), 7.20–8.10 (m, 12 H). Anal. Calcd for $C_{18}H_{13}F_3S$: C, 67.91; H, 4.12. Found: C, 67.90; H, 4.19.

2,2,2-Trifluoro-1-(2- and 4-phenethylphenyl)ethyl Phenyl Sulfide. A mixture of **2e** and **2f** (1:10) as white crystals: mp 32 °C; IR (Nujol) 3032, 2920, 2856, 1668, 1606, 1472, 812, 790, 692 cm^{-1}; ^1H NMR ($CDCl_3$) δ 2.91 (s), 4.49 (q, J = 8.6 Hz, CF_3CH of **2e**), 4.50 (q, J = 8.6 Hz, CF_3CH of **2f**), 7.10–7.50 (m). Anal. Calcd for $C_{22}H_{19}F_3S$: C, 70.95; H, 5.14. Found: C, 70.90; H, 5.40.

2,2,2-Trifluoro-1-(2- and 4-methoxyphenyl)ethyl Phenyl Sulfide. 2g: a viscous oil; bp 140 °C (3.5 mmHg); IR (neat) 3068, 3012, 2972, 2844, 1606, 1588, 870, 752, 692, 620, 574 cm^{-1}; ^1H NMR ($CDCl_3$) δ 4.04 (s, 3 H), 5.49 (q, J = 9.0 Hz, 1 H), 7.09–7.70 (m, 9 H). Anal. Calcd for $C_{15}H_{13}F_3OS$: C, 60.39; H, 4.39. Found: C, 60.35; H, 4.46. **2h**: colorless crystals; mp 58–60 °C; IR (Nujol) 2924, 1612, 1516, 1464, 1378, 822, 748 cm^{-1}; ^1H NMR ($CDCl_3$) δ 3.91 (s, 3 H), 4.60 (q, J = 8.5 Hz, 1 H), 6.90–7.65 (m, 9 H). Anal. Calcd for $C_{15}H_{13}F_3OS$: C, 60.39; H, 4.39. Found: C, 60.36; H, 4.43.

Preparation of 2,2,2-Trifluoro-1-(2-furyl)ethyl Phenyl Sulfide (2l). To a suspension of **7b** (113 mg, 0.5 mmol) and $ZnCl_2$ (273 mg, 2 mmol) in CH_3NO_2 (1 mL) was added furan (0.15 mL, 2 mmol) dropwise at refluxing temperature. After being stirred for 3 min, the reaction mixture was cooled, neutralized with aqueous sodium hydrogen carbonate, and treated as usual to yield **2l**, 67 mg (51%): bp 60 °C (3 mmHg); IR (neat) 3136, 3068, 2952, 1586, 1502, 1482, 1442, 800, 746, 692, 598 cm^{-1}; ^1H NMR ($CDCl_3$) δ 4.81 (q, J = 8.5 Hz, 1 H), 6.27–7.45 (m, 8 H). Anal. Calcd for $C_{11}H_9F_3OS$: C, 55.81; H, 3.51. Found: C, 55.63; H, 3.66.

2,2,2-Trifluoro-1-(2- and 3-thienyl)ethyl Phenyl Sulfide. A mixture of **2m** and **2n** (8:2): bp 87–90 °C (3.5 mmHg); IR (neat) 3080, 2950, 1680, 1584, 1520, 832, 790, 582 cm^{-1}; ^1H NMR ($CDCl_3$) δ 4.69 (q, J = 9.0 Hz, CF_3CH of **2n**), 4.83 (q, J = 8.5 Hz, CF_3CH of **2m**), 6.95–7.50 (m). Anal. Calcd for $C_{12}H_9F_3S_2$: C, 52.54; H, 3.31. Found: C, 52.44; H, 3.33.

Reaction with 1-Naphthol. To a solution of **7b** (113 mg, 0.5 mmol) and 1-naphthol (288 mg, 2 mmol) in CH_3NO_2 (1 mL) was added $ZnCl_2$ (273 mg, 2 mmol), and the mixture was heated at reflux for 10 min. The usual working up provided **2j**, 62 mg (37%), and **9j**, 50 mg (27%). **2j**: mp 155 °C; IR ($CHCl_3$) 3608, 3068, 1630, 1604, 1518, 894, 762, 668 cm^{-1}; ^1H NMR ($CDCl_3$) δ 5.55 (s, 1 H), 6.09 (q, J = 10 Hz, 1 H), 6.84–8.24 (m, 11 H). Anal. Calcd for $C_{17}H_{13}F_3OS$: C, 67.07; H, 4.00. Found: C, 67.29; H, 4.10. **9j**: mp 60 °C; IR ($CHCl_3$) 3616, 3416 (broad peak), 3080, 1632, 1604, 1518, 870, 700, 590 cm^{-1}; ^1H NMR ($CDCl_3$) δ 5.50 (s, 2 H), 6.16 (q, J = 9.0 Hz, 1 H), 6.75–8.28 (m, 12 H). Anal. Calcd for $C_{22}H_{15}F_3O_2$: C, 71.74; H, 4.10. Found: C, 71.90; H, 4.22.

2,2,2-Trifluoro-1-[4-hydroxy-3-(methoxycarbonyl)-phenyl]ethyl Phenyl Sulfide (2k) and 1,1,1-Trifluoro-2,2-bis[4-hydroxy-3-(methoxycarbonyl)phenyl]ethane (9k). 2k: bp 130 °C (3.0 mmHg); IR (neat) 3172 (broad peak), 2960, 1690, 1618, 1594, 796, 794, 692 cm^{-1}; ^1H NMR ($CDCl_3$) δ 3.88 (s, 3 H), 4.42 (q, J = 12.2 Hz, 1 H), 6.90–7.75 (m, 8 H), 10.74 (s, 1 H). Anal. Calcd for $C_{16}H_{13}F_3O_3S$: C, 56.14; H, 3.83. Found: C, 56.13; H, 4.13. **9k**: white crystals; mp 130 °C; IR (Nujol) 3248 (broad peak), 3016, 2924, 2856, 1690, 1588, 820, 798 cm^{-1}; ^1H NMR ($CDCl_3$) δ 3.95 (s, 6 H), 4.57 (q, J = 9.8 Hz), 6.94–7.82 (m, 6 H), 10.74 (s, 2 H). Anal. Calcd for $C_{18}H_{15}F_3O_6$: C, 56.27; H, 3.94. Found: C, 56.27; H, 3.94.

Preparation of Optically Active Chloride (7b′). To a suspension of the acetate **7a** (600 mg, 2.52 mmol) in phosphate buffer (pH 7.2, 13 mL, 5.0 mL/mmol of the substrate) was added lipase P (*Pseudomonas* sp., 300 mg) in one portion, and the mixture was stirred for 10 h at 40 °C. After about 2 g of Celite was added, the reaction mixture was filtrated through a glass filter. The filtrate was extracted with ethyl ether. The organic layer was dried ($MgSO_4$) and evaporated in vacuo to give 380 mg of an oily residue which contained 34% of alcohol **7c′** of which ^1H NMR data agreed with that of the racemic one: ^1H NMR ($CDCl_3$) δ 5.17 (q, J = 6.2 Hz), 7.25–7.63 (m). To a solution of 10 mg of the crude residue contained 0.019 mmol of **7c′** and pyridine (0.1 mL) in CH_2Cl_2 (1 mL) was added 0.5 mL of a CH_2Cl_2 solution of (+)-MTPA chloride (9.7 mg, 0.0385 mmol) at room temperature. After being stirred for 5 h, the mixture was quenched by an addition of a small piece of ice, and the usual workup gave the (+)-MTPA ester of **7c′** (8.0 mg, 95%) whose enantiomeric excess was 77%; ^{19}F NMR ($CDCl_3$, C_6F_6) 86.85, 88.01 ppm.

The residue was subjected to chlorination without further purification of **7c′** as follows. To a solution of the crude product in CH_2Cl_2 (5 mL) was added 4-(dimethylamino)pyridine (92 mg, 0.75 mmol) at −30 °C. After stirring for 10 min, trifluoromethanesulfonyl chloride (0.08 mL, 0.75 mmol) was dropped to the mixture, which was stirred for 1 h while rising the temperature up to room temperature. After the usual workup, the crude product was chromatographed through silica gel to give optically active **7b′**, 40 mg (30%) whose ^1H NMR was in accord with that of the racemic chloride **7b**: ^1H NMR ($CDCl_3$) δ 5.26 (q, J = 6.5 Hz, 1 H), 7.40–7.70 (m, 5 H); $[\alpha]^{22}_D$ −12.2° (c = 0.605, $CHCl_3$).

1-(2,2,2-Trifluoroethyl)naphthalene. To a solution of **2d** (159 mg, 0.5 mmol) and 2,2′-azobis(isobutyronitrile) (16 mg, 0.1 mmol) in benzene (1 mL) was added tri-*n*-butyltin hydride (0.2 mL, 0.75 mmol), and the mixture was heated at reflux. After 10

min, the mixture was cooled and extracted with benzene–hexane (1:1). The extracts were washed with dilute hydrochloric acid, aqueous sodium hydrogen carbonate, and water and dried over anhydrous sodium sulfate. After evaporation of the solvent, the residue was distilled to give **3d**, 95 mg (90%), as white crystals: mp 55–57 °C; IR (Nujol) 2932, 2850, 1602, 1516, 1462, 1378, 1352, 1270, 1252, 1168, 778 cm^{-1}; ^1H NMR ($CDCl_3$) δ 3.85 (q, J = 10.6 Hz, 2 H), 7.44–8.03 (m, 7 H). Anal. Calcd for $C_{12}H_9F_3$: C, 68.57; H, 4.32. Found: C, 68.38; H, 4.45.

***N*-[2,2,2-Trifluoro-1-(phenylthio)ethyl]acetamide (18a).** To a solution of **7b** (113 mg, 0.5 mmol) in acetonitrile (1 mL) was added $SnCl_4$ (0.09 mL, 0.75 mmol), and the mixture was stirred at room temperature for 3 days. The reaction mixture was neutralized with aqueous sodium hydrogen carbonate and extracted with AcOEt several times. The extracts were washed with water and brine, dried over anhydrous sodium sulfate, and concentrated in vacuo. The residue was chromatographed on silica gel to provide **18a**, 85 mg (70%), as colorless crystals: mp 128 °C; IR (Nujol) 3284, 2952, 2924, 1670, 1532, 1254, 1168, 1112, 812, 748, 696 cm^{-1}; ^1H NMR ($CDCl_3$) δ 1.99 (s, 3 H), 5.82 (dq, J_{H-F} = 7.5 Hz, J_{H-H} = 3.0 Hz, 1 H), 5.89 (br d, 1 H), 7.35–7.56 (br, 5 H). Anal. Calcd for $C_{10}H_{10}F_3NOS$: C, 48.19; H, 4.04; N, 5.62. Found: C, 48.32; H, 3.95; N, 5.87.

***N*-[2,2,2-Trifluoro-1-(phenylthio)ethyl]benzamide (18b).** To a solution of **7b** (113 mg, 0.5 mmol) and benzonitrile (0.5 mL, 5.0 mmol) in dichloroethane (1.5 mL) was added boron trifluoride etherate (0.12 mL, 1.0 mmol), and the mixture was heated at reflux for 3 days. After cooling, the reaction mixture was neutralized with aqueous sodium hydrogen carbonate and extracted with AcOEt several times. The usual workup provided **18b**, 116 mg (71%), as colorless crystals: mp 135 °C; IR (Nujol) 3264, 3064, 2924, 2856, 1650, 1516, 1258, 1110, 862, 692 cm^{-1}; ^1H NMR ($CDCl_3$) δ 5.99 (dq, J_{H-F} = 7.3 Hz, J_{H-H} = 2.8 Hz, 1 H), 6.35–6.45 (br d, 1 H), 7.25–7.70 (m, 10 H). Anal. Calcd for $C_{15}H_{12}F_3NOS$: C, 57.87; H, 3.89; N, 4.50. Found: C, 57.70; H, 3.97; N, 4.72.

***N*-[2,2,2-Trifluoro-1-(phenylthio)ethyl]-3-butenamide (18d):** colorless crystals; mp 116 °C; IR (Nujol) 3264, 2924, 2856, 1964, 1660, 1106, 924, 750 cm^{-1}; ^1H NMR ($CDCl_3$) δ 2.98 (d, J = 7.7 Hz, 2 H), 5.19 (dd, J = 17.0 Hz, J = 1.5 Hz, 1 H), 5.24 (dd, J = 10.0 Hz, J = 1.5 Hz, 1 H), 5.78 (ddq, J = 10.0 Hz, J = 17.0 Hz, J = 7.0 Hz, 1 H), 5.81 (dq, J = 7.0 Hz, J = 10.0 Hz, 1 H), 5.85–5.95 (br d, 1 H), 7.25–7.60 (br, 5 H). Anal. Calcd for $C_{12}H_{12}F_3NOS$: C, 52.36; H, 4.39, N, 5.09. Found: C, 52.45; H, 4.34; N, 5.42.

***N*-[2,2,2-Trifluoro-1-(phenylthio)ethyl]-2-propenamide (18e):** colorless crystals; mp 118 °C; IR (Nujol) 3288, 2924, 1664, 1532, 1412, 1308, 1202, 1070, 972, 808, 694 cm^{-1}; ^1H NMR ($CDCl_3$) δ 5.76 (dd, J = 10.3 Hz, J = 1.0 Hz, 1 H), 5.85 (dq, J = 6.6 Hz, J = 2.2 Hz, 1 H), 5.80–6.00 (br, 1 H), 6.06 (dd, J = 10.3 Hz, J = 16.9 Hz, 1 H), 6.32 (dd, J = 16.9 Hz, J = 1.0 Hz, 1 H), 7.30–7.60 (br, 5 H). Anal. Calcd for $C_{11}H_{10}F_3NOS$: C, 50.57; H, 3.86; N, 5.36. Found: C, 50.33; H, 4.10; N, 5.20.

***N*-[2,2,2-Trifluoro-1-(phenylthio)ethyl]-2-phenylethanamide (18c):** colorless crystals; mp 143 °C; IR (Nujol) 3268, 2924, 1668, 1522, 1454, 1268, 1236, 1114, 976, 862, 816, 696 cm^{-1}; ^1H NMR ($CDCl_3$) δ 3.56 (s, 2 H), 5.67 (br, 1 H), 5.80 (dq, J_{H-F} = 7.2 Hz, J_{H-H} = 10.1 Hz, 1 H), 7.10–7.40 (m, 10 H). Anal. Calcd for $C_{16}H_{14}F_3NOS$: C, 59.07; H, 4.34; N, 4.31. Found: C, 59.02; H, 4.60; N, 4.19.

1-(Trifluoromethyl)isothiochroman (16): viscous oil; bp 105–110 °C (5 mmHg); IR (neat) 3032, 2932, 1498, 1312, 1248, 1160, 1104, 610, 880, 768, 680 cm^{-1}; ^1H NMR ($CDCl_3$) δ 2.71 (dt, J = 12.0 Hz, J = 6.0 Hz, 1 H), 3.10 (dd, J = 6.0 Hz, J = 6.0 Hz, 2 H), 3.17 (dd, J = 12.0 Hz, J = 6.0 Hz, 1 H), 4.34 (q, J = 9.3 Hz, 1 H), 7.15–7.35 (m, 4 H). Anal. Calcd for $C_{10}H_9F_3S$: C, 55.04; H, 4.16. Found: C, 54.80; H, 3.98.

1-(Trifluoromethyl)-3-butenyl phenyl sulfide (17): viscous oil; bp 85–90 °C (5 mmHg); IR (neat) 3084, 2988, 2920, 1740, 1646, 1252, 1168, 1102, 924, 704, 692 cm^{-1}; ^1H NMR ($CDCl_3$) δ 2.41 (m, 1 H), 2.65 (m, 1 H), 3.38 (ddq, J_{H-F} = 8.3 Hz, J = 4.3 Hz, J = 10.0 Hz, 1 H), 5.22 (dd, J = 6.9 Hz, J = 1.4 Hz, 1 H), 5.23 (dd, J = 16.7 Hz, J = 1.4 Hz, 1 H), 5.95 (dddd, J_1 = 16.7 Hz, J_2 = 10.4 Hz, J_3 = 7.0 Hz, J_4 = 7.0 Hz, 1 H), 7.25–7.55 (m, 6 H). Anal. Calcd for $C_{11}H_{11}F_3S$: C, 56.88; H, 4.77. Found: C, 56.87; H, 4.63.

Reactions of 2-Vinylindoles with Carbodienophiles: Synthetic and Mechanistic Aspects

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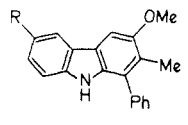
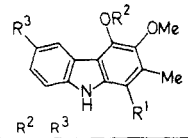
Reactions of selectively functionalized 2-vinylindoles with acyclic and cyclic carbodienophiles proceed with high regio- and/or stereoselectivities to furnish Diels–Alder adducts, Diels–Alder ene products, and Michael adducts. This methodology provides a convenient route to functionalized indoles, carbazoles, and [c]pyrrolo-annelated carbazoles with substitution patterns that are not easily obtained by the usual routes. Some mechanistic aspects of the chemistry of 2-vinylindoles are discussed.

Introduction

Carbazoles with carbon substituents at the 1- and 2-positions constitute the frameworks of both the hyellazoles **1**, isolated from the blue-green alga *Hyella caespitosa*,[1] and the carbazomycins **2**, produced by the actinomycete *Streptoverticillium ehimence*.[2] The same structural features are also to be found in the pyrido[4,3-*b*]carbazole alkaloids ellipticine (**3a**), 9-methoxyellipticine (**3b**), and olivacine (**4**). The significant antibiotic activity of carbazomycin B (**2b**)[2] as well as the antitumor action of **3**[3,4] and analogues of the series of annelated carbazoles[3,4] have



1a R = H hyellazole
b R = Cl chlorohyellazole



	R^1	R^2	R^3	
2a	Me	H	H	carbazomycin A
b	Me	Me	H	B
c	Me	H	OMe	C
d	Me	Me	OMe	D
e	CHO	H	H	E (=carbazomycinal)
f	CHO	H	OMe	F (=6-methoxycarbazomycinal)

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