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Reactions of 9,9′-Bibenzonorbornenylidene Sulfoxides with TMSOTf: Anomalous Pinacol-Type Rearrangement of Thiirane 1-Oxides

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ABSTRACT: *syn-9,9′-Bibenzonorbornenylidene sulfoxide* **8b** *underwent pinacol-type rearrangement to form* **9**, *together with a mixture of thiiranes* **4a** *and* **4b** *by reaction with TMSOTf in* CH_2Cl_2 *at room temperature. The rearrangement of anti-sulfoxide* **8a** *proceeded more slowly giving a mixture of* **9, 4a**, *and* **4b**. © 2009 Wiley Periodicals, Inc. Heteroatom Chem 20:29–34, 2009; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/hc.20507

INTRODUCTION

Quite recently, we succeeded in isolating thiirane 1-imides **1a** and **1b** for the first time and found that both undergo stereospecific ring enlargement, giving the corresponding 1,2-thiazetidines **2a** and **2b**, respectively, when keeping their solutions even at room temperature (Scheme 1) [1]. Ring enlargement of *S*-aminothiiranium salt **3b** proceeded to stereoselectively form 1,2-thiazetidin-2-ium salt **6b**, whereas reaction of **3a** under similar conditions gave the corresponding thiirane **4a** and alkene **5a** [2]. On the other hand, the related *S*-methylthiiranium salts, **7a** and **7b**, isomerized each other in solution [3]. The products of their thermal decomposition in solution seemed to vary with the kind of atom connecting with the sulfur atom in their thiirane ring. In general, heating a solution of thiirane 1-oxide results in the formation of the corresponding alkene with the extrusion of sulfur monoxide [4], which can be trapped with diene [5–7]. The C—S bond dissociation of the thiirane 1-oxides seemed to proceed homolytically in the initial stage of thermal decomposition. If the C—S bond is cleaved heterolytically with the assistance of acid, other reaction pathways would occur. We found that 9,9′-bibenzonorbornenylidene sulfoxides **8a** and **8b** undergo pinacol-type rearrangement to form ketone **9** by action with TMSOTf. Acid-catalyzed rearrangement of thiiranes and their derivatives to form thioketones or ketones has not been reported [8], whereas that of oxiranes is well-known [9], and we reported only one example of aza-pinacol rearrangement of aziridines [10,11].

RESULTS AND DISCUSSION

Reaction of thiirane 1-oxide **8**, which was synthesized by reaction of the corresponding thiirane **4** with *m*-CPBA in a good yield, with an equimolar amount of TMSOTf, was examined (Scheme 2), and the results are summarized in Table 1. Thus, **8a** reacted with TMSOTf in CH_2Cl_2 at room temperature for 8 days to give **4a** (4%), **4b** (1%), and **9** (5%),

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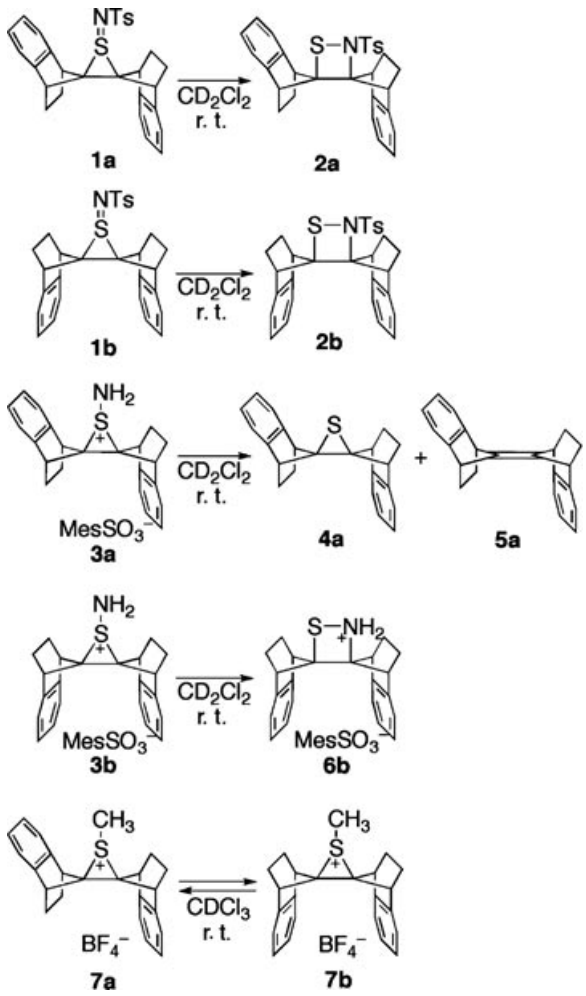
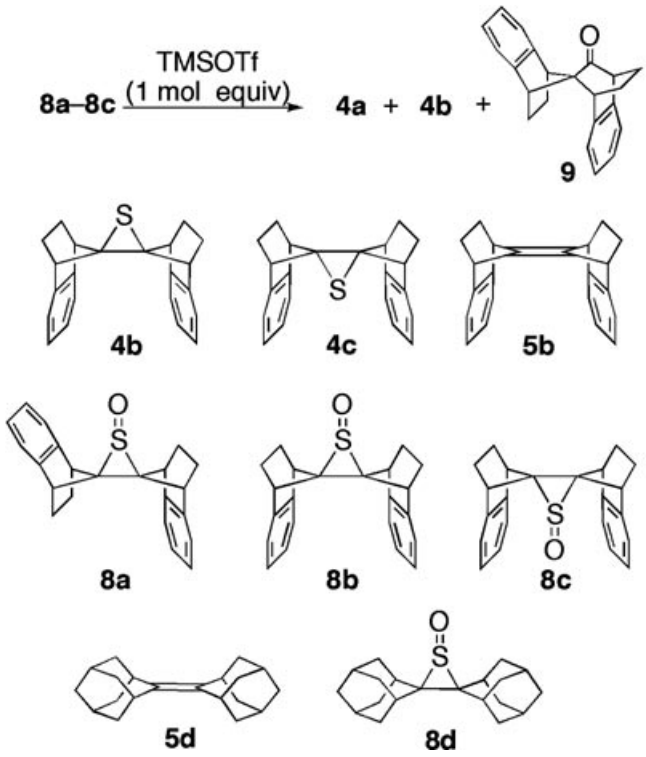


SCHEME 1



SCHEME 2

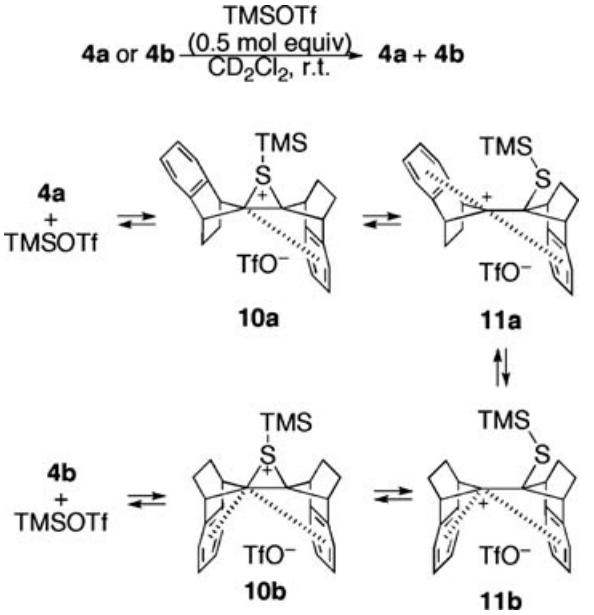
and the recovery of **8a** (90%) (entry 1). The stereochemistry of **9** was determined by COSY and NOESY experiments and ^1H and ^{13}C NMR experiments using $Eu(fod)_3$ [12]. The reaction in refluxing CH_2Cl_2 for 2 days resulted in the consumption of **8a** and the formation of a mixture of **4a** (24%), **4b** (10%), and **9** (65%) (entry 2). When the reaction of **8b** was performed at room temperature, the same ketone **9** was obtained in 58% yield, together with a 3:1 mixture of **4a** and **4b** (entry 3). The pinacol-type rearrangement of **8a** and **8b** to **9** proceeded in a stereoselective but nonstereospecific manner. Surprisingly, the reaction of **8c** in toluene, even at reflux, resulted in a quantitative recovery of **8c** (entry 5). The stereochemistry of **8a–8c** seemed to exert a great influence on the progression of the rearrangement. On the other hand, 2,2′-biadamantylidene sulfoxide **8d** reacted with TMSOTf in refluxing toluene for 36 h to form 2,2′-biadamantylidene **5d** and the recovery of **8d** (entry 6). This reaction proceeded more slowly than that without TMSOTf, giving **5d** as a sole product, reported by Harpp (entry 7) [6], indicating that TMSOTf seemed to prevent the extrusion of sulfur monoxide from **8**. Using other reagents, such as $BF_3{\cdot}OEt_2$, $Cu(OTf)_2$, and $PdCl_2$, in place of TMSOTf in the reactions of **8a** and **8b** did not produce a satisfactory rearrangement.

The formation of a 3:1 mixture of **4a–4b** in the reaction of each **8a** and **8b** suggests that isomerization between **4a** and **4b** probably proceeds under the reaction conditions. Therefore, reactions of **4a** and **4b** with TMSOTf (0.5 molar equivalent) in CD_2Cl_2 at room temperature were monitored by ^1H NMR (Scheme 3), and the results are summarized in Table 2. For the reaction of **4b**, signals of **4a** began to develop after mixing of **4b** and TMSOTf. The ratio of **4a–4b** decreased as time went by. For the reaction of **4a**, progression of the transformation of **4a–4b** slowed. The ratio was almost unchanged after 5 h. These observations indicate that **4a** and **4b** attained equilibrium under the applied conditions and the final equilibrium ratio of **4a–4b** was about 3:1. The isomerization must proceed through thiiranium salt **10** and carbenium salt **11**. Interestingly, **4a** and **4b** seemed to be more reactive against TMSOTf than **8a** and **8b**, but their pinacol-type rearrangement did not occur. These results are in harmony with

TABLE 1 Reactions of **8** with TMSOTf (1 Molar Equivalent)

Entry	*Thiirane 1-Oxide*	*Conditions*	*Products (Yield/%)*
1	**8a**	CH_2Cl_2, r. t., 8 d	**4a** (4), **4b** (1), **9** (5), **8a** (90)
2	**8a**	CH_2Cl_2, reflux, 2 d	**4a** (24), **4b** (10), **9** (65)
3	**8b**	CH_2Cl_2, r. t., 8 d	**4a** (31), **4b** (10), **9** (58)
4	**8c**	CH_2Cl_2, r. t., 8 d	**8c** (quant.)
5	**8c**	Toluene, reflux, 14 h	**8c** (quant.)
6	**8d**	Toluene, reflux, 36 h	**5d** (24), **8d** (74)
7[a]	**8d**	Toluene, reflux, 2.5 h	**5d** (97)

[a]Ref. 6. In the absence of TMSOTf.



SCHEME 3

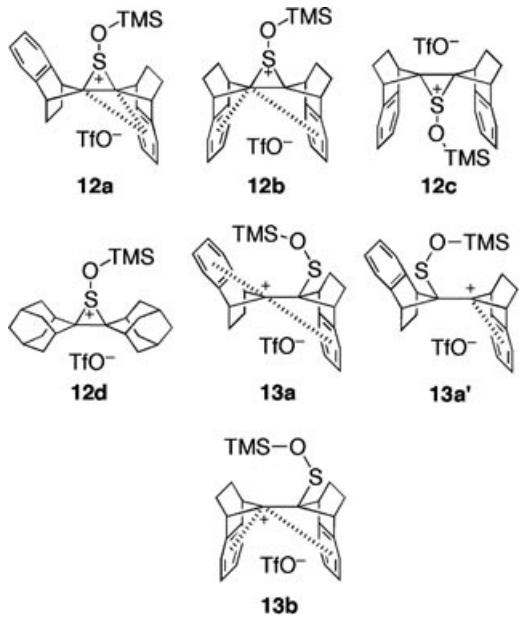


FIGURE 1

isomerization of methylthiiranium salt **7**, where the final equilibrium ratio of **7a–7b** was about 4:1 [3].

On the basis of these findings, the following are proposed as the mechanisms of the reactions. Initially, **8a–8d** and TMSOTf react, giving thiiranium salt **12a–12d** (Fig. 1). The C—S bond of the thiirane ring in **12b** is cleaved, forming ring-opened carbenium salt **13b** with the assistance of neighboring group participation of the two benzene rings, which also stabilize **13b** by homoconjugation [13–15]. This participation must also affect the reactivity of **8**. Thus, in the case of **12a**, only one benzene ring, which exists on the back of the cleaved C—S bond, participates electronically in the thiirane-ring opening. As a result, the ring opening of **12a** proceeds more slowly than that of **12b** to form carbenium salt **13a** or **13a′**. Similar to **13b, 13a** and **13a′** are stabilized by the participation of the two benzene rings and by the one benzene ring near its cation center, respectively. The process from **12a** to **13a′** is similar to that in the ring enlargement from **1a** to **2a** [1]. The reason **8c** and **8d** do not undergo the rearrangement is probably that no such participation acts on the C—S bond cleavage in **12c** and **12d**.

TABLE 2 Time-Course Study of Ratio of **4a–4b** in the Isomerization Between **4a** and **4b**[a]

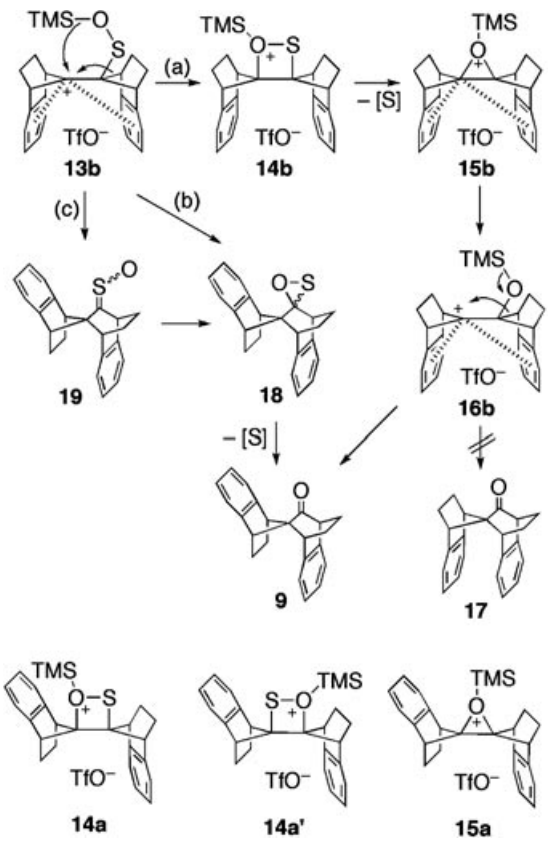
	4a : *4b*	
Time	*From 4a*	*From 4b*
25 min	41:1	1:13
2 h	11:1	1.4:1
3 h	5.0:1	1.2:1
5 h	3.0:1	2.7:1
7.5 h	2.9:1	3.0:1

[a]In CD_2Cl_2 at r. t. Monitored by ^1H NMR.

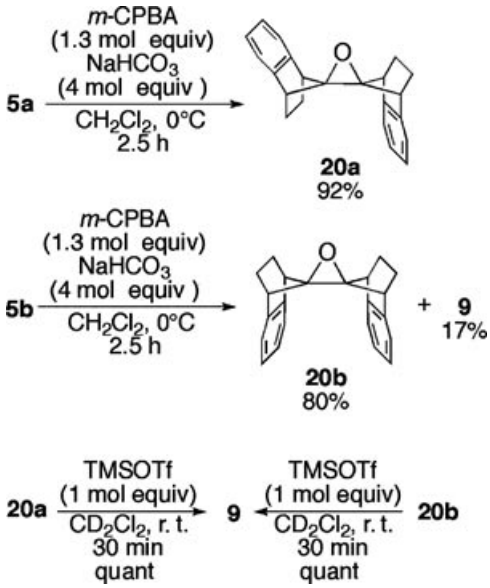
Three pathways from **13b** to **9** [paths (a)–(c)] would be possible (Scheme 4). Path (a) includes ring closure of **13b**, giving oxathietanium salt **14b**, which

then extrudes sulfur to form oxiranium salt **15b**. This is similar to the ring enlargement of **3b–6b**, followed by the decomposition of **6b** to aziridinium salt, where both proceeded with retention of the configuration of the original stereochemistry [2]. The salt **15b** undergoes pinacol-type rearrangement to form **9**. In the reaction of **8a**, oxiranium salt **15a**, which is formed either from **13a** through **14a** or from **13a′** through **14a′**, rearranges to form **9**. The stereoselectivity of the rearrangement can be interpreted by the neighboring group participation. Thus, this participation also acts as a leaving group in the rearrangement; hence, migration of the substituent occurs from the back of this participation [14]. In consequence, ketone **17**, which is a possible product, was not produced. The paths (b) and (c) contain direct pinacol-type rearrangement of **13**, giving oxathiirane **18** and sulfine **19**, which then transforms to **18** [16]. The oxathiirane **18** would be an unstable compound [17] and hence it extrudes sulfur to form **9**.

Oxiranes **20a** and **20b**, which are precursors of **15a** and **15b** [9], were synthesized by oxiranation of **5a** and **5b** with *m*-CPBA in the presence of $NaHCO_3$ at 0°C (Scheme 5). Interestingly, **9** was obtained as a



SCHEME 4



SCHEME 5

by-product in the oxiranation of **5b** even under the basic conditions, whereas no formation of **9** was observed in the oxiranation of **5a**. As expected, **20a** and **20b** underwent pinacol-type rearrangement to form the same **9** quantitatively, by action with TMSOTf. If **15** is an intermediate of the rearrangement of **8**, the transformation of **15** to **9** would proceed more rapidly than the ring opening of **12** forming **13**.

Formation of **4a** and **4b** from **8a** and **8b** under the reaction conditions seemed to proceed through a similar process to that of **4a** from **3a** [2]. Reactive species, such as sulfur, which is extruded from **14** or **18** as a by-product, may attack the oxygen atom next to the positively charged sulfur atom in **12a** and **12b** to form **4a** and **4b**, both of which isomerize each other under the reaction conditions, as mentioned above.

EXPERIMENTAL

Solvents were dried and purified in the usual manner. All the reactions were carried out under argon. Silica gel column chromatography was performed on silica gel 60N (Kanto, 63–210 μm, spherical, neutral). Melting points were determined on a Mel-Temp capillary tube apparatus and were uncorrected. ^1H and ^{13}C NMR spectra were recorded on a Bruker DRX400, a Bruker ARX400, a Bruker AM 400 (400 MHz for ^1H and 101 MHz for ^{13}C), a Bruker AC300P (300 MHz for for ^1H), or a Bruker AC200 (200 MHz for for ^1H and 50 MHz for ^{13}C) spectrometer using $CDCl_3$ or CD_2Cl_2 as the solvent with TMS

for ^{1}H and with $CDCl_3$ or CD_2Cl_2 for ^{13}C as the internal standard. IR spectra were recorded on a Hitachi FT-IR 660+ spectrophotometer. Elemental analyses were performed by the Molecular Analysis and Life Science Center of Saitama University.

Synthesis of Thiirane 1-Oxide **8c**

To a solution of **4c** (100 mg, 0.32 mmol) in CH_2Cl_2 (10 mL) was added *m*-CPBA (65 mg, 0.38 mmol) at 0°C. After being stirred at the same temperature for 30 min, 5% aqueous $NaHSO_3$ solution was added to the reaction mixture. The organic layer was separated, washed with saturated aqueous $NaHCO_3$ solution and then with H_2O twice, dried over $MgSO_4$, and evaporated. The residue was crystallized from CH_2Cl_2 and hexane to give 101 mg of **8c** (0.31 mmol, 96%). Thiirane 1-oxides **8a** and **8b** were synthesized by the same procedure [1]. **8c**: colorless crystals, mp < 202°C (dec) (CH_2Cl_2/hexane). ^{1}H NMR (200 MHz): δ 1.59–1.72 (m, 4H), 2.17–2.35 (m, 4H), 3.07–3.11 (m, 2H), 3.88–3.93 (m, 1H), 7.12–7.20 (m, 6H), 7.28–7.32 (m, 2H). ^{13}C NMR (50 MHz): δ 26.8, 29.0, 44.7, 46.5, 84.9, 120.5, 121.1, 126.4, 126.8, 144.7, 146.0. IR: 3073, 3023, 2944, 2864, 1459, 1449, 1039, 760, 730 cm^{-1}. Anal. Calcd for $C_{22}H_{20}OS$: C, 79.48; H, 6.06. Found: C, 79.26; H, 6.02.

Reaction of **8b** *with TMSOTf at Room Temperature*

To a solution of **8b** (50.1 mg, 0.15 mmol) in CH_2Cl_2 (5.0 mL) was added TMSOTf (27.5 μL, 0.15 mmol) at 0°C. After being stirred at room temperature for 8 days, saturated aqueous $NaHCO_3$ solution and CH_2Cl_2 were added to the reaction mixture. The organic layer was separated, washed with H_2O twice, dried over $MgSO_4$, and evaporated. The residue was placed on a column of silica gel and the column was eluted with $CHCl_3$/hexane (1:4) to give 14.8 mg of **4a** (46 μmol, 31%) and 4.9 mg of **4b** (15 μmol, 10%) and with $CHCl_3$ to give 26.1 mg of **9** (87 μmol, 58%). **9**: colorless powder, mp 227–229°C (Et_2O). ^{1}H NMR (400 MHz): δ 1.12–1.20 (m, 1H), 1.26–1.37 (m, 1H), 1.54–1.72 (m, 2H), 1.98–2.13 (m, 2H), 2.14–2.27 (m, 2H), 2.45–2.47 (m, 1H), 3.29–3.32 (m, 1H), 3.41–3.46 (m, 2H), 6.82–6.86 (m, 1H), 6.98–7.07 (m, 1H), 7.08–7.18 (m, 3H), 7.22–7.32 (m, 3H). ^{13}C NMR (101 MHz): δ 21.2, 24.9, 26.0, 26.3, 40.8, 49.0, 51.0, 53.9, 70.7, 120.0, 120.2, 124.3, 125.0, 125.6, 125.8, 126.9, 127.0, 137.0, 141.2, 145.3, 146.5, 211.8. IR: 3070, 3038, 3017, 2969, 2882, 1709, 1495, 1460, 761, 735 cm^{-1}. Anal. Calcd for $C_{22}H_{20}O$: C, 87.96; H, 6.71. Found: C, 87.59; H, 6.74.

Reaction of **8d** *with TMSOTf in Refluxing Toluene*

To a solution of **8d** (50.4 mg, 0.16 mmol) in toluene (5.0 mL) was added TMSOTf (29.0 μL, 0.16 mmol). After being heated at reflux for 36 h, the reaction mixture was evaporated and diluted with CH_2Cl_2. The organic layer was washed with saturated aqueous $NaHCO_3$ solution and then with H_2O twice, dried over $MgSO_4$, and evaporated. The residue was placed on a column of silica gel and the column was eluted with hexane to give 10.2 mg of **5d** (38 μmol, 24%) and with $CHCl_3/Et_2O$ (10:1) to give 37.3 mg of **8d** (118 μmol, 74%).

Reaction of **4** *with TMSOTf*

To a solution of **4a** or **4b** (10 mg, 32 μmol) and triptycene (3.0 mg, 12 μmol) as an internal standard in CD_2Cl_2 (0.45 mL) was added TMSOTf (3.0 μL, 17 μmol) at room temperature. The progression of the reactions was monitored by ^{1}H NMR. After 1.5 h, trace amounts of **5a** and **5b** were also detected by ^{1}H NMR.

Synthesis of Oxirane **20a**

To a suspension of **5a** (150 mg, 0.52 mmol) and $NaHCO_3$ (175 mg, 2.1 mmol) in CH_2Cl_2 (15 mL) was added *m*-CPBA (119 mg, 0.68 mmol) at 0°C. After being stirred at the same temperature for 2.5 h, 5% aqueous $NaHSO_3$ solution was added to the reaction mixture. The organic layer was separated, washed with saturated aqueous $NaHCO_3$ solution and then with H_2O twice, dried over $MgSO_4$, and evaporated. The residue was crystallized from CH_2Cl_2 and hexane to give 142 mg of **20a** (0.47 mmol, 92%). **20a**: colorless crystals, mp 161–162°C (CH_2Cl_2/hexane). ^{1}H NMR (300 MHz): δ 0.95–1.05 (m, 2H), 1.26–1.40 (m, 4H), 2.18–2.28 (m, 2H), 2.98–3.06 (m, 4H), 7.08–7.28 (m, 8H). ^{13}C NMR (50 MHz): δ 24.9, 25.1, 44.1, 45.1, 83.8, 87.4, 120.8, 121.5, 126.2, 126.3, 144.3, 144.6. IR: 3051, 3027, 2983, 2950, 2879, 1464, 1374, 1210, 937, 760, 751, 547 cm^{-1}. Anal. Calcd for $C_{22}H_{20}O$: C, 87.96; H, 6.71. Found: C, 87.96; H, 6.73.

Synthesis of Oxirane **20b**

The residue containing **9** and **20b**, which were obtained using the same procedure for **5b** (150 mg, 0.52 mmol) as **5a**, was placed on a column of silica gel and the column was eluted with $CHCl_3$/hexane (1:2) to give 123 mg of **20b** (0.41 mmol, 80%) and 26.6 mg of **9** (88 μmol, 17%). **20b**: colorless crystals, mp 172–173°C (CH_2Cl_2/hexane). ^{1}H NMR (300 MHz):

δ 0.86–0.94 (m, 4H), 1.95–2.10 (m, 4H), 2.36–2.46 (m, 4H), 6.88–6.96 (m, 4H), 7.09–7.17 (m, 4H). ^{13}C NMR (50 MHz): δ 25.9, 50.0, 94.6, 122.0, 125.8, 145.3. IR: 3045, 3024, 3962, 3945, 2867, 1463, 1258, 1028, 836, 741, 540 cm^{-1}. Anal. Calcd for $C_{22}H_{20}O$: C, 87.96; H, 6.71. Found: C, 87.82; H, 6.71.

Reaction of **20** *with TMSOTf*

To a solution of **20a** or **20b** (10 mg, 33 μmol) in CD_2Cl_2 (0.50 mL) was added TMSOTf (6.0 μL, 33 μmol) at room temperature. After keeping the solution at room temperature for 30 min, the quantitative formation of **9** was observed by ^{1}H NMR in each reaction.

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