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Cycloheptyne Intermediate in the Reaction of Chiral Cyclohexylidenemethyliodonium Salt with Sulfonates

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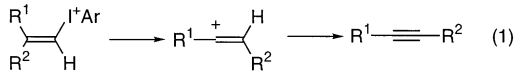
Reactions of (*R*)-4-methylcyclohexylidenemethyl(phenyl)iodonium salt and its 3-trifluoromethylphenyl and 4-methoxyphenyl derivatives (**1**) with tetrabutylammonium mesylate and triflate were carried out in chloroform at 60 °C. The products include (*S*)-4-methylcyclohexylidenemethyl sulfonate (**2**) and (*R*)-5-methylcyclohept-1-enyl sulfonate (**3**) as well as iodoarene. Reactions of (*S*)-**1** were confirmed to provide the counterpart results. The rearranged triflate (*R*)-**3Tf** formed in the reaction with triflate maintains mostly the ee (enantiomeric excess) of (*R*)-**1**, while the ee of the mesylate product **3Ms** is largely lost. The ^{13}C-labeling at the exocyclic position of **1** results in the isotopic scrambling of C-1 and C-2 of **3Ms** in the mesylate reaction. The degree of the scrambling agrees well with that of the loss of ee of (*R*)-**3Ms** obtained from (*R*)-**1**, implying that the racemization is not due to the intermediate formation of achiral, primary 4-methylcyclohexylidenemethyl cation. Reaction of **1** with mesylate in the presence of CH_3OD provided the **3Ms** deuterated at the 2-position. When tetraphenylcyclopentadienone was added to the mesylate reaction system, the adduct of the 4-methylcycloheptyne intermediate was obtained in 24% yield, but the normal products **2Ms** and **3Ms** were still formed. The **3Ms** obtained here in a low yield maintains the high ee of **1**. These results indicate that the cycloheptyne is an intermediate responsible for the formation of racemic product **3Ms** in the mesylate reaction. It is also concluded that the unrearranged products **2** are formed via the competitive pathways of in-plane and out-of-plane S_N2 reactions.

Introduction

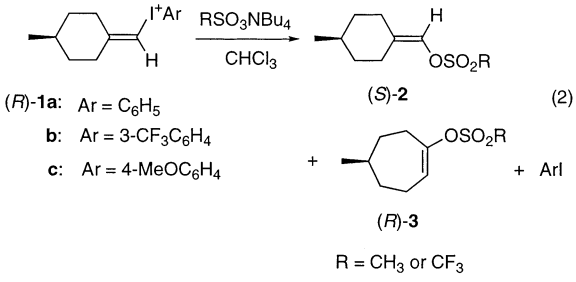
As presented in the accompanying paper,[1] a chirality probe approach showed that solvolysis of 4-methylcyclohexylidenemethyliodonium salt does not involve the primary vinyl cation as an intermediate. The high-energy primary cation is avoided by intramolecular nucleophilic assistance (σ-bond participation) under poorly nucleophilic conditions of solvolysis or by the participation of stronger external nucleophiles. The former reaction provides stereospecifically rearranged products maintaining the chirality of the substrate, while the latter gives unrearranged substitution products of both inversion and retention of configuration via σ^* and π^* attacks of the nucleophile.

Similar reactions have been observed with acyclic analogues, 2,2-dialkylvinyliodonium salts.[2,3] Extensive rearrangements through 1,2-alkyl shifts led to both substitution and elimination products. One of the main products was alkyne in the acyclic systems (eq 1), in contrast to



(1)

the results with the cyclic analogue. Cycloalkyne would not be impossible as an intermediate of the reactions involving cycloalkenyl systems, despite their ring strain.[4] Cycloheptyne, cyclohexyne, and even cyclopentyne have been generated in solution as transient species by various methods.[4] We have now found evidence for formation of cycloheptyne during the reaction of cyclohexylidenemethyliodonium salts with sulfonate ions (eq 2).



Sulfonate ions are in general regarded as good nucleofuges, and sulfonate esters are typical substrates for

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solvolysis.[5,6] However, they can react as nucleophile with vinyliodonium electrophiles. Hinkle and co-workers[2] found that thermolysis of 2,2-dialkylvinyl(aryl)iodonium triflates in chloroform provides products of triflate substitution as well as elimination of both unrearranged and rearranged structures. We are interested in these reactions and applied the chirality probe approach to the reaction of the vinyliodonium salt with triflate (trifluoromethanesulfonate) and mesylate (methanesulfonate) in chloroform. When optically active 4-methylcyclohexylidenemethyl(aryl)iodonium (**1**) tetrafluoroborate was treated with mesylate, largely racemized, rearranged product **3Ms** was obtained together with unrearranged one **2Ms**. This racemization is ascribed to an achiral 5-methylcycloheptyne intermediate,[7] which is detailed in this paper.

Results

Reaction of Sulfonates. Reactions of **1a-c**·BF_4^- with tetrabutylammonium triflate and mesylate were carried out in chloroform at 60 °C. The products include those of both unrearranged and rearranged substitution, **2** and **3**, as well as iodoarene (eq 2). The reaction of racemic **1a**·BF_4^- with tetrabutylammonium triflate gave 4-methylcyclohexylidenemethyl triflate (**2Tf**) (20% yield), 5-methylcyclohept-1-enyl triflate (**3Tf**) (60% yield), and iodobenzene (72% yield) as isolated products. In the case of the mesylate reaction, 4-methylcyclohexylidenemethyl mesylate (**2Ms**), 5-methylcyclohept-1-enyl mesylate (**3Ms**), and iodobenzene were isolated in 51%, 30%, and 70% yields, respectively. These sulfonate products were fully characterized by ^{1}H and ^{13}C NMR and mass spectroscopy. The product yields for other runs were usually determined by gas chromatographic analyses, and they are summarized in Tables 1 and 2. No other products were detected by gas chromatography unless any additives were involved in the reaction system. In the presence of added tetrabutylammonium tetrafluoroborate (0.09 M), 1-fluoro-5-methylcycloheptene (**3F**) was obtained in 53% yield during the triflate reaction in addition to **2Tf** and **3Tf** (Table 1, entry 5). Formation of the fluoro products was observed in the thermolysis of the tetrafluoroborate salts of various vinyliodonium ions.[8]

More rearranged product **3** is formed in the triflate reaction than in the mesylate reaction, as the ratios of **2**/**3** show. The rearrangement is more facile also when an electron-withdrawing group (CF_3) is introduced in the aryliodonio group of **1**. The concentrations of salts (ionic strength) affect the product ratio **2**/**3**, especially in the triflate reactions. The ratio **2Tf**/**3Tf** decreases with increasing concentration of tetrabutylammonium triflate. Reactions at still lower concentrations of the triflate nucleophile were examined by thermolysis of the triflate salt of **1a** in chloroform. At lower concentrations of the substrate salt **1a**·OTf^-, the products are **2Tf** and **3Tf** and the ratio **2Tf**/**3Tf** becomes larger (Table 1, entries 6−8). The ratio **2Tf**/**3Tf** seems to be affected not only by the concentration of the nucleophilic salt [TfO^-] but also by neutral salts such as tetrafluoroborate (entry 5). The salt effects are not obvious in the mesylate reactions (Table 2).

The enantiomeric purities (ee) of the products **2** and **3** were determined by the chiral gas chromatography with DEX-CB, β-DEX-325, and β-DEX-120 columns. The ee values were confirmed by comparing the results obtained with different chiral columns, and the values are included in Tables 1 and 2. The ee of the product **2** or **3** was found not to change within experimental errors during the course of reaction as examined for the reactions of (*R*)-**1c**·BF_4^- both with triflate and mesylate, indicating that no racemization of substrate **1** or the products occurs under the reaction conditions and the observed loss of

TABLE 1. Reaction of Iodonium Salt 1 with Triflate in Chloroform at 60 °C

entry	[TfO^-] (M)	time (h)	yield (%) 2Tf	3Tf	2/3	ArI	ee (%) (*S*)-2Tf	(*R*)-3Tf
	(a) (*R*)-**1a**·BF_4^- (69% ee, 2.5 mM) + $TfONBu_4$							
1	0.01	6.0	24	43	36/64	96	56	55
2	0.05	6.0	21	54	28/72	96	52	69
3	0.1	6.0	18	55	25/75	92	47	62
4	0.2	6.0	14	50	22/78	85	45	62
5	0.01[a]	5.5	3	8	27/73	89	32	64
	(b) **1a**·TfO^- without added $TfONBu_4$[b]							
6	0.002	10.5	31	46	40/60	94	b	b
7	0.006	10.5	29	53	35/65	99	b	b
8	0.013	10.5	23	45	34/66	83	b	b
	(c) (*R*)-**1b**·BF_4^- (63% ee, 2.1 mM) + $TfONBu_4$							
9	0.01	4.5	18	50	26/74	94	43	61
10	0.05	4.5	15	61	20/80	94	30	63
11	0.1	4.5	14	63	18/82	91	21	54
12	0.2	4.5	13	66	16/84	97	22	63
	(d) (*R*)-**1c**·BF_4^- (70% ee, 2.3 mM) + $TfONBu_4$							
13	0.01	22.5	29	36	45/55	84	59	57
14	0.05	22.5	25	48	34/66	86	53	61
15	0.1	22.5	24	56	30/70	83	54	60
16	0.2	22.5	20	57	26/74	82	55	65

[a] In the presence of 0.09 M Bu_4NBF_4, 1-fluoro-5-methylcycloheptene (**3F**) was also obtained (53% yield). [b] [TfO^-] = [**1a**·TfO^-]. Product ee values were not determined because of a racemic sample of the starting iodonium salt.

TABLE 2. Reaction of Iodonium Salt (*R*)-1·BF_4^- with Tetrabutylammonium Mesylate in Chloroform at 60 °C

entry	[MsO^-] (M)	time (h)	yield (%) 2Ms	3Ms	2/3	ArI	ee (%) (*S*)-2Ms	(*R*)-3Ms
	(a) (*R*)-**1a**·BF_4^- (69% ee, 2.5 mM) + $MsONBu_4$							
17	0.01	6.0	47	21	69/31	95	67	7
18	0.05	6.0	55	21	72/28	98	65	17
19	0.1	6.0	62	21	75/25	98	63	21
20	0.2	6.0	60	23	72/28	100	59	30
	(b) (*R*)-**1b**·BF_4^- (63% ee, 2.1 mM) + $MsONBu_4$							
21	0.01	4.5	38	20	66/34	76	63	10
22	0.05	4.5	45	18	71/29	87	57	12
23	0.1	1.5	47	14	77/23	100	49	26
24	0.2	2.0	28	8	78/22	91	43	37
	(c) (*R*)-**1c**·BF_4^- (70% ee, 2.3 mM) + $MsONBu_4$							
25	0.01	6.0	63	8	89/11	84	67	12
26	0.05	6.0	78	13	86/14	100	67	22
27	0.1	6.0	56	10	85/15	98	62	28
28	0.2	6.0	41	7	85/15	100	57	44

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(8) Okuyama, T.; Fujita, M.; Gronheid, R.; Lodder, G. *Tetrahedron Lett.* **2000**, *41*, 5125−5129.

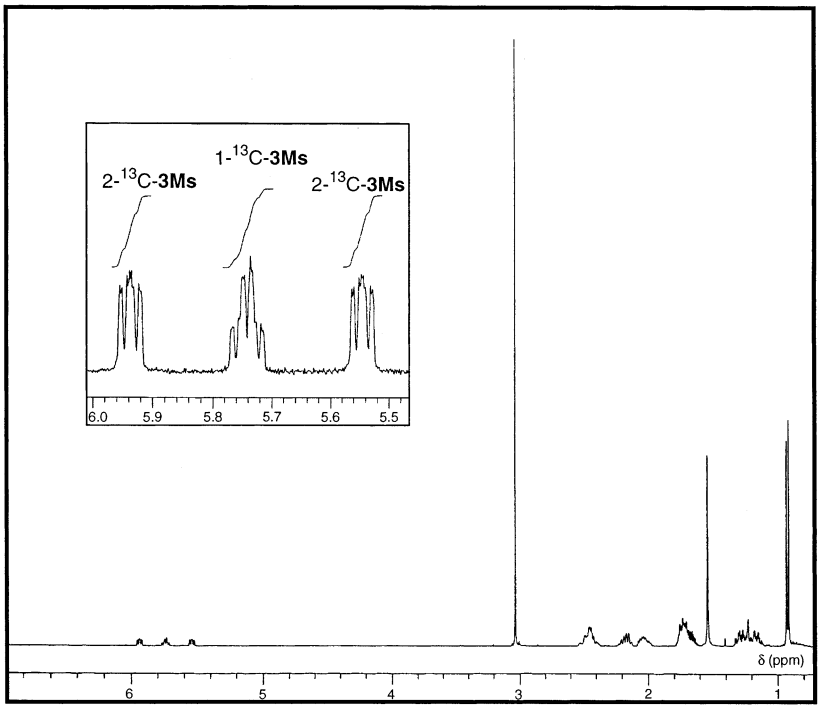


FIGURE 1. ^{1}H NMR spectrum of **3Ms** isolated from reaction of ^{13}C-**1a**·BF_4^- with tetrabutylammonim mesylate (0.10 M) in chloroform at 60 °C.

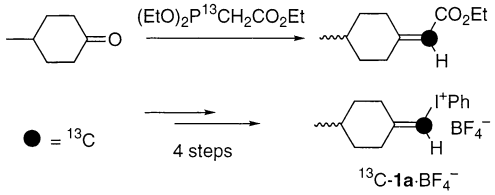
TABLE 3. Reaction of Labeled Iodonium Salt ^{13}C-1a·BF_4^- with Sulfonates in Chloroform at 60 °C[a]

[sulfonate] (M)	**2**:**3**	[1-^{13}C-**3**]/[2-^{13}C-**3**]	ee of **3** (%) calcd[b]	ee of **3** (%) obsd[c]
		$MsONBu_4$		
0.01	76:24	44/56	8	7
0.05	74:26	38/62	17	17
0.10	78:22	35/65	21	21
0.20	80:20	31/69	26	30
		$TfONBu_4$		
0.10	27:73	5/95	62	62

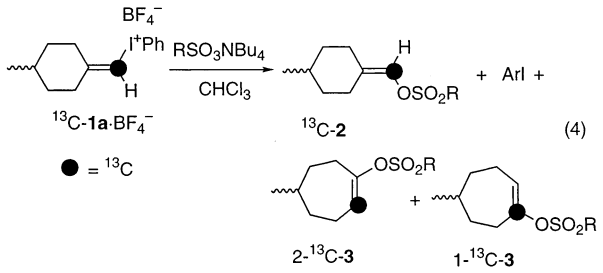
[a] [^{13}C-**1a**·BF_4^-] = 2.5 mM, reaction time = 4 h. [b] Calculated by eq 7 for the ee of **1a** = 69%. [c] Observed values in the reaction of (*R*)-**1a**·BF_4^- (69% ee), taken from Tables 1 and 2.

ee should not arise from any secondary or side reactions (See supplementary Tables S1 and S2). The unrearranged products **2Tf** and **2Ms** obtained from (*R*)-**1**·BF_4^- are all in excess of *S* configuration, which was determined by comparison with the authentic samples. The major enantiomers of the rearranged products **3Tf** and **3Ms** obtained from (*R*)-**1**·BF_4^- have *R* configuration, which was confirmed by the conversion to 4-methylcycloheptanone (**3C**).[1] It should be noted here that the ee of **3Ms** is largely lost from the starting iodonium salts **1**·BF_4^-, while that of **3Tf** is only slightly decreased from that of **1**·BF_4^-. The ee values of **2** and **3** depend also on the concentration of the sulfonate salts and on the substitution at the aryliodonio group.

^{13}C-Labeling Experiments. A ^{13}C-labeled iodonium salt ^{13}C-**1a**·BF_4^- was prepared by the Horner−Wadsworth−Emmons reaction of 4-methylcyclohexanone with ^{13}C-labeled triethyl phosphonoacetate, followed by the ordinary transformation to iodonium salt via the vinylsilane (eq 3). The ^{13}C content at the exocyclic position of



^{13}C-**1a**·BF_4^- was determined to be >98% ^{13}C by ^{1}H and ^{13}C NMR. The ^{13}C-**1a**·BF_4^- was subjected to the reaction with tetrabutylammonium mesylate (0.1 M) in chloroform at 60 °C (eq 4). Products **2Ms** and **3Ms** containing the



^{13}C label were obtained in 58% and 23% isolated yields, respectively. The ^{1}H and ^{13}C NMR spectra show that the ^{13}C label remains at the exocyclic position of **2Ms**, while the ^{13}C is located not only at the 2-position (2-^{13}C-**3Ms**) but also at the 1-position (1-^{13}C-**3Ms**) of the rearranged product **3Ms**. The ^{1}H NMR signal due to 2-H of 2-^{13}C-**3Ms** has a large coupling with 2-^{13}C (J = 157 Hz), while 2-H of 1-^{13}C-**3Ms** has a smaller coupling with 1-^{13}C (J = 6.8 Hz), as illustrated in Figure 1. The ratios 1-^{13}C-**3Ms**/2-^{13}C-**3Ms** can be calculated from the intensities of the relevant peaks and were determined at various concentrations of mesylate (Table 3). The triflate reaction of ^{13}C-

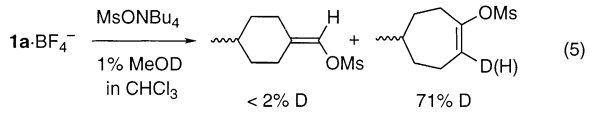
TABLE 4. Reaction of (*S*)-1a·BF_4^- with $MsONBu_4$ in the Presence of an Additive in Chloroform[a]

additive (concn, M)	yield (%)			ee (%)	
	2Ms	**3Ms**	PhI	(*R*)-**2Ms**	(*S*)-**3Ms**
none	72	35	78	77	11
MeOH (0.25)[b]	53	21	100	76	15
MeOD (0.25)[c,d]	62	28[e]	81		
4 (0.005)[d,f]	62[g]	2[g]	h	77	78
cyclohexene (0.25)[i]	66	22	68	76	12

[a] The (*S*)-**1a**·BF_4^- used was of 79% ee and the concentration was 2.5 mM. Reactions were carried out at 60 °C and [$MsONBu_4$] = 10 mM for 5 h. Product yields were determined by GC unless noted otherwise. [b] Methanol-trapping products such as **3C** were not detected by GC. [c] Racemic **1a** was used. [d] Isolated product yields are given. [e] Deuterium was incorporated at the 2-position to the extent of 71 atom %. [f] Benzoadduct **5** was also isolated in 24% yield. [g] Isolated as a mixture of **2Ms** and **3Ms**. The separate yields were calculated using the ratio of **2Ms**:**3Ms** (98:2) determined by GC. [h] Not determined. [i] Product **6** was not detected.

1a·BF_4^- was also examined, and the product was mostly 2-^{13}C-**3Tf**, as is given in Table 3.

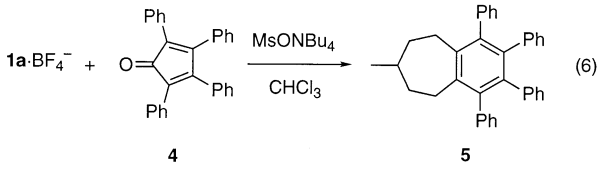
Reactions in the Presence of Various Additives. The mesylate reaction of (*S*)-**1a** was carried out in the presence of various additives (Table 4). When 1 vol % of CH_3OD (0.25 M) was added, deuterium was incorporated in **3Ms** at the 2-position to the extent of 71 atom % (eq 5), but deuterium incorporation in **2Ms** was not observed.



(5)

Independent experiments show that the H/D exchange of **3Ms** does not occur under the same conditions and added methanol does not much affect the product distribution or the ee (but in somewhat lower yields). In the triflate reaction, no deuterium incorporation into **3Tf** or **2Tf** was observed in the presence of CH_3OD.

The mesylate reaction of **1a** was also carried out in the presence of a trapping agent, tetraphenylcyclopentadienone (**4**), and benzoadduct **5** was obtained in 24% isolated yield (eq 6). The mesylate products were also

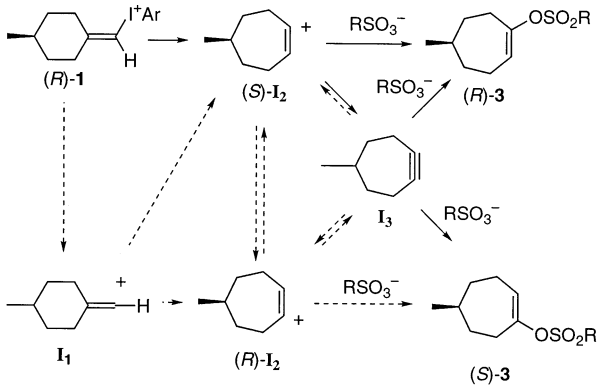


(6)

isolated as a mixture of **2Ms** and **3Ms**; the yield of **3Ms** was very low, but its ee was very high, maintaining essentially that of the substrate **1a**. Formation of **2Ms** was not much affected by added **4**. Addition of cyclohexene (0.25 M) did not influence the mesylate reaction of **1a**.

Competitive Reactions of Two Nucleophiles. The sulfonate reactions of **1a** were carried out in the presence of both mesylate and triflate. A sample of (*S*)-**1a** (79% ee) was employed for the competitive reactions. The results are summarized in Table 5. Individual mesylate and triflate reactions were also performed using the same (*S*)-**1a**·BF_4^- (entries 1 and 5 of Table 5). The ee values are well consistent with those observed for the reactions

SCHEME 1



of (*R*)-**1a** (69% ee) (entry 3 of Table 1 and entry 19 of Table 2). This indicates the reliability of the chiral GC analysis in a quantitative sense. In the competitive reactions, more mesylate products were obtained than triflate products due to the higher reactivity of mesylate than triflate. It is noteworthy that the ee values of **3Ms** and **3Tf** are quite different from each other.

Discussion

Mechanism Involving Cycloheptyne Intermediate. Remarkable results of the sulfonate reactions are the stereoselectivities of formation of the rearranged products **3**. The mesylate product **3Ms** loses most of the ee, while the triflate product **3Tf** maintains mostly the ee of the starting iodonium salt. No racemization of the starting iodonium salt **1a** or the product **3** was observed under the reaction conditions, as confirmed from the invariable product distribution and ee monitored throughout the course of reaction (Tables S1 and S2). That is, the products obtained must be primary products of the sulfonate reactions and the loss of ee cannot be due to any secondary reactions.

We first concentrated our attention on the loss of the optical purity observed during the formation of **3Ms** in the mesylate reaction. Possible mechanisms are illustrated in Scheme 1. The racemization cannot easily be rationalized within the framework of reaction mechanisms similar to those proposed for the solvolysis involving the rearranged vinyl cation **I2**. When tetraphenylcyclopentadienone (**4**) is added to the mesylate reaction system, benzoadduct **5** is obtained at the cost of mesylate product **3Ms** (eq 6). The adduct must be formed via [4 + 2]-cycloaddition of **4** to 5-methylcycloheptyne (**I_3**) followed by decarbonylation. This achiral cycloalkyne must be responsible for the formation of racemic **3Ms**. Cycloheptyne **I_3** may be formed by deprotonation of cycloheptenyl cation **I_2**.[9] In the trapping experiment, a small amount of **3Ms** still survives to be detected. It should also be noted that the remaining **3Ms** has a high ee (78%), maintaining the optical purity of the substrate (79%) (Table 4). This shows that there is an alternative route to give **3Ms** without loss of optical purity. Cation

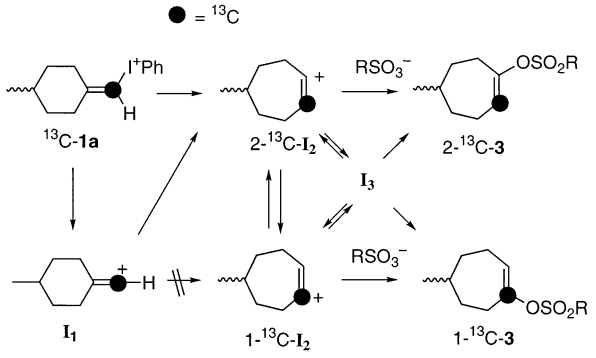
(9) Cycloheptyne is known as a transient species: (a) Wittig, G.; Meske-Schüller, J. *Liebigs Ann. Chem.* **1968**, *711*, 65−75. (b) Montgomery, L. K.; Applegate, L. E. *J. Am. Chem. Soc.* **1967**, *89*, 5305−5307. (c) Krebs, A.; Chicha, W.; Müller, M.; Eicher, T.; Pielartzik, H.; Schnöckel, H. *Tetrahedron Lett.* **1984**, *25*, 5027−5030.

TABLE 5. Competitive Reactions of (*S*)-1a·BF_4^- with Mesylate and Triflate in Chloroform[a]

			yield (%)					ee (%)				relative reactivity		
entry	[MsO^-] (M)	[TfO^-] (M)	**2Ms**	**3Ms**	**2Tf**	**3Tf**	PhI	(*R*)-**2Ms**	(*S*)-**3Ms**	(*R*)-**2Tf**	(*S*)-**3Tf**	M/T(**1a**)[b]	M/T($\mathbf{I_2}$)[c]	M/T($\mathbf{I_3}$)[d]
1	0.00	0.10	0	0	16	48	82			61 (53)[e]	71 (62)[e]			
2	0.01	0.09	40	27	5	13	70	79	11	52	75	70	3	300
3	0.02	0.08	51	32	3	8	67	77	10	47	77	70	2	500
4	0.03	0.07	57	32	2	5	62	78	13	43	76	70	3	300
5	0.10	0.00	64	18	0	0	91	71 (62)[e]	34 (30)[e]					

[a] The (*S*)-**1a**·BF_4^- used was of 79% ee and the initial concentration was 2.5 mM. Reactions were carried out at 60 °C for 6 h. [b] Reactivity toward **1a**. [c] Reactivity toward $\mathbf{I_2}$. [d] Reactivity toward $\mathbf{I_3}$. [e] The values in parentheses are the calculated ee for the starting **1a** of 69% ee for comparison with data in Tables 1 and 2.

SCHEME 2



$\mathbf{I_2}$ is chiral and (*R*)-**1** should give stereospecifically (*S*)-$\mathbf{I_2}$ via the σ-bond participation, as discussed in the accompanying paper.[1] This cation may be trapped by a nucleophilic reaction of mesylate to afford the optically active **3Ms**, which can survive the diene trapping.

There remains some doubt if the decrease in ee of **3Ms** is exclusively due to $\mathbf{I_3}$. Can any alternative route without $\mathbf{I_3}$ be involved for the loss of chirality or racemization in the reaction? There are possibilities of (1) racemization (or interconversion of isomeric forms) of $\mathbf{I_2}$ via 1,2-hydride shift across the double bond and (2) nonstereospecific rearrangement of the achiral primary vinyl cation intermediate $\mathbf{I_1}$ to racemic $\mathbf{I_2}$. The racemic **I2** leads to racemic **3Ms**. This can quantitatively be examined by the isotope labeling experiments. When the exocyclic position of **1a** is labeled with ^{13}C, the label should remain at the 2-position of the rearranged cation $\mathbf{I_2}$, irrespective of intervention of the primary cation $\mathbf{I_1}$, unless the interconversion of $\mathbf{I_2}$ or cycloheptyne $\mathbf{I_3}$ is involved (Scheme 2). The β-C−C bond migration either directly from **1a** (participation) or via the primary cation $\mathbf{I_1}$ should only give 2-^{13}C-$\mathbf{I_2}$, and the label should remain at the 2 position of **3** (2-^{13}C-**3**). However, the mesylate reaction of ^{13}C-**1a** actually resulted in the isotopic scrambling of C-2 and C-1 of **3Ms** (Table 3). This scrambling of carbon should lead to racemization if the optically active substrate **1a** is employed. The degree of the isotopic scrambling can be converted to the ee of **3** by using the ratio of 1-^{13}C-**3**/2-^{13}C-**3** and the ee of the starting iodonium salt **1a** according to eq 7.

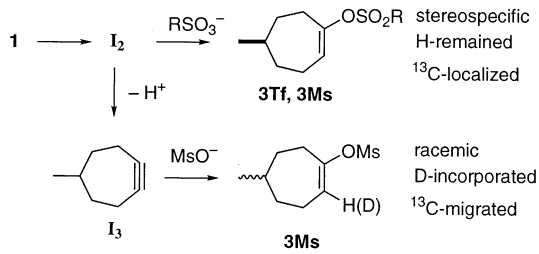
$$\text{ee of } \mathbf{3} = (\text{ee of } \mathbf{1a})([2\text{-}^{13}\text{C-}\mathbf{3}] - [1\text{-}^{13}\text{C-}\mathbf{3}])/([2\text{-}^{13}\text{C-}\mathbf{3}] + [1\text{-}^{13}\text{C-}\mathbf{3}]) \quad (7)$$

The calculated ee values of **3** are compared with those observed in the reaction of (*R*)-**1a**·BF_4^- of 69% ee under the same conditions in the last two columns of Table 3. The calculated values agree well with those observed, indicating that the primary vinyl cation $\mathbf{I_1}$ does not contribute at all to the decrease in ee of **3Ms** or **3Tf**. Thus, it can safely be concluded that the primary vinyl cation $\mathbf{I_1}$ is not involved in the formation of the rearranged product **3**. The 1,2-hydride shift within the cyclic vinyl cation $\mathbf{I_2}$ was found to have a very high energy barrier.[1] Since the mesylate ion is more nucleophilic than triflate ion and probably than alcohols, the effective progress of the 1,2-hydride shift of $\mathbf{I_2}$ is unlikely to occur during the mesylate reaction in competition with the nucleophilic trapping.

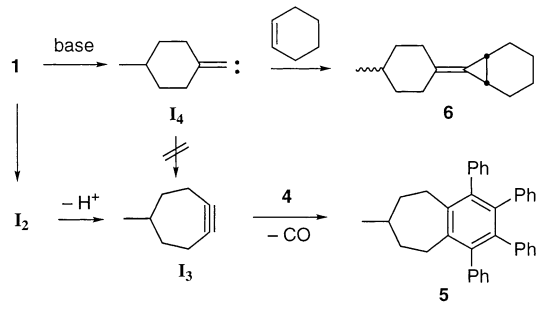
When the reaction of **1a** with mesylate was carried out in the presence of CH_3OD, deuterium incorporation (71% D) at the 2-position of **3Ms** was observed. This is incompatible with the 1,2-hydride shift mechanism of racemization of $\mathbf{I_2}$ but in agreement with a mechanism involving a cycloheptyne intermediate $\mathbf{I_3}$. Now, it is clear that the deuterium incorporation is due to $\mathbf{I_3}$ but not due to the additional stereospecific route to give **3Ms**, and the 71% D incorporation observed can be translated into the degree of racemization with the optically active substrate, which corresponds to 23% ee [$=79 \times (1 - 0.71)$] of the product starting with 79% ee of the iodonium salt. This calculated value is compatible with the ee (15%) of **3Ms** obtained from (*S*)-**1a** of 79% ee in the presence of methanol (Table 4).

Now, intermediary formation of 5-methylcycloheptyne ($\mathbf{I_3}$) is established during the mesylate reaction of **1a**. However, how is mesylate **3Ms** formed from cycloheptyne $\mathbf{I_3}$? Direct nucleophilic trapping of $\mathbf{I_3}$ by mesylate was suggested above, but reprotonation of $\mathbf{I_3}$ can reproduce racemic cation $\mathbf{I_2}$, which affords racemic **3Ms**. Competitive reactions of **1a** with mesylate and triflate provide further information regarding this problem. Reaction of **1a** in the presence of both mesylate and triflate gives the two rearranged products, **3Ms** and **3Tf**, but their ee values are quite different from one another (Table 5). The former has much lower ee than the latter, and the respective ee values are similar to those obtained in the independent reactions (Tables 1 and 2). This difference in the ee of **3Ms** and **3Tf** indicates that these products are derived from different intermediates involved. The triflate product **3Tf** with high ee must mainly be formed by nucleophilic trapping of $\mathbf{I_2}$, which keeps the enantiomeric purity of the starting iodonium salt, while the decrease in ee of the mesylate product **3Ms** comes from nucleophilic trapping of achiral $\mathbf{I_3}$. Intermediates $\mathbf{I_2}$ and $\mathbf{I_3}$ are not interchangeable; i.e., $\mathbf{I_3}$ cannot revert to $\mathbf{I_2}$ during the reaction as rationalized from different reactivities of the two sulfonates (vide infra). The strained cycloalkyne $\mathbf{I_3}$ reacts selectively with mesylate ion but

SCHEME 3



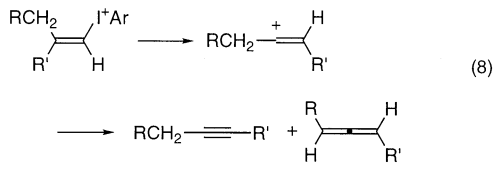
SCHEME 4



not much with poorly nucleophilic triflate ion, or it cannot be reprotonated to give $\mathbf{I_2}$ under the reaction conditions. The alkyne pathway should give a racemic, ^{13}C-scrambled, or deuterated product depending on the reaction conditions, while the vinyl cation product should maintain the enantiomeric purity of the starting iodonium salt as summarized in Scheme 3. No racemization of the cyclic cation $\mathbf{I_2}$ ever occurs in any way during the reaction.

The cycloalkyne intermediate $\mathbf{I_3}$ could have been generated via a rearrangement of 4-methylcyclohexylidenecarbene ($\mathbf{I_4}$) formed by α-elimination of **1**. However, the carbene could not be trapped with cyclohexene from the mesylate reaction of **1a**: the product distribution or the ee of the product was not affected by the added cyclohexene. For a control experiment, the carbene $\mathbf{I_4}$ was generated by the reaction of **1a** with triethylamine in the presence of cyclohexene, and trapping to give the cyclopropylidene adduct **6** was confirmed.[1a] These results rule out the possibility of the carbene route for formation of cycloalkyne or racemization (Scheme 4).

Cycloheptyne $\mathbf{I_3}$ is concluded to be generated by deprotonation of the intermediate cation $\mathbf{I_2}$ formed via trans-σ-bond participation. A similar reaction was previously observed with acyclic systems.[2,3] A secondary alkenyl cation formed via β-alkyl participation provides alkyne. In this case, 1,2-alkadiene is also formed by deprotonation from the adjacent saturated carbon (eq 8). Similar

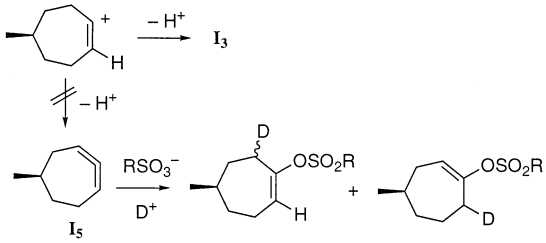


(8)

results could be expected, since the 1,2-diene is more stable than the cycloheptyne.[10] The 1,2-elimination of 1-halocycloheptene with strong base gives preferentially

(10) The ab initio calculation (B3LYP/6-31G*) shows that cycloheptyne is 7.6 kcal mol^{-1} less stable than the 1,2-diene.

SCHEME 5



1,2-diene.[11,12] However, no sign of 1,2-cycloheptadiene $\mathbf{I_5}$ was found in the present case. A possible product, 4-methylcyclohept-1-enyl sulfonate, has never been detected, nor has deuteration at a saturated carbon been observed in the presence of methanol-*d* (Scheme 5). Why is it? The present reaction proceeds via an E1-like mechanism (with the rearranged carbocation intermediate), and the energy of the transition state for the deprotonation of cation $\mathbf{I_2}$ determines the regioselectivity. An important factor controlling this energy is the dihedral angle between the unoccupied orbital of the positive carbon and the C−H bond undergoing elimination in cycloheptenyl cation $\mathbf{I_2}$. The angle involving the sp^2-H is smaller than that involving the sp^3-H, which is fixed by the cyclic structure. This structural constraint may raise the barrier for the deprotonation of the latter to lead to cyclic allene, as compared with the case of more flexible open-chain alkenyl cation. On the contrary, reaction conditions including a strong base and a poor leaving group of 1-halocycloalkene may favor an E1cB-like mechanism, which preferentially affords the more stable 1,2-diene over the cycloalkyne.

In summary, the loss of the optical purity observed during the reaction of optically active vinyl iodonium salt **1** with sulfonates is rationalized (Scheme 1) by intermediate formation of cycloheptyne $\mathbf{I_3}$, but the primary vinyl cation $\mathbf{I_1}$ is not involved in this reaction. The transient cycloheptyne $\mathbf{I_3}$ is generated by deprotonation of the cation $\mathbf{I_2}$ formed via concerted σ-bond participation in heterolysis of **1**. That is, mesylate works as a base for deprotonation of $\mathbf{I_2}$ and as a nucleophile for trapping of $\mathbf{I_3}$. Direct nucleophilic reaction of mesylate leads also to stereospecific trapping of $\mathbf{I_2}$, and competition between nucleophilic and basic reactivities of mesylate toward cation $\mathbf{I_2}$ determines the ee of **3Ms**.

Mechanism for Formation of the Unrearranged Product 2. The ratio of the unrearranged to the rearranged product, **2**/**3**, is larger in the mesylate reaction than in the reaction with less nucleophilic triflate. This is expected, since the rearrangement occurs via participation in competition with the external nucleophile. The stereochemistry of **2Ms** is inverted during the reaction of **1**, and the ee maintains most of the starting iodonium substrate **1**. These results strongly suggest that **2Ms** is formed via the in-plane S_N2 reaction of **1** with mesylate. In the triflate reaction, the ee of **2Tf** decreases considerably from that of the starting iodonium salt, the inversion rate ranging from 91% to 66%. The incomplete inversion cannot necessarily be ascribed to primary vinyl cation

(11) Johnson, R. P. *Chem. Rev.* **1989**, *89*, 1111−1124. Caubére, P. *Chem. Rev.* **1993**, *93*, 2317−2334.
(12) Brunet, J. J.; Fixari, B.; Caubere, P. *Tetrahedron* **1974**, *30*, 1237−1243, 1245−1251, 2931−2937.

$\mathbf{I_1}$, though we were tempted to do so.[2,3] Without the intermediary formation of $\mathbf{I_1}$, the stereochemically retained product can be derived via the out-of-plane S_N2 or ligand coupling mechanism, as discussed in the preceding paper.[1]

In the triflate reaction, the rearrangement occurs more readily as the concentration of triflate increases (Table 1). The tendency seems to be inconsistent with the discussion described above, because high concentrations of a nucleophile, if it is weak, are favorable for the S_N2 reaction. The concentration of the nucleophilic salt also changes the ionic strength of the medium. With increasing ionic strength, the medium becomes more polar, and this in turn favors a more polar transition state. The heterolysis (to give the rearranged cation $\mathbf{I_2}$ via participation) is preferred to the S_N2 reaction in such media. In the case of a weak nucleophile, triflate, this polarity effect may exceed the nucleophilicity effect. To confirm this assumption, the triflate reaction of **1a** was carried out in the presence of tetrabutylammonium tetrafluoroborate at the total salt concentration = 0.1 M (entry 5 of Table 1). Although the yield of the triflate product drastically decreases due to formation of a fluorinated product,[8] the fraction of rearrangement (**3Tf**/**2Tf**) increases up to that observed at 0.1 M of the ammonium triflate (entry 3). Thermolysis of the triflate salt of iodonium ion (**1a**·OTf^-) was also examined at low ionic strengths (entries 6−8); the product distribution depends on the concentration of the substrate salt, and the **3Tf**/**2Tf** values are an extrapolation of the results with **1a**·BF_4^- + $TfONBu_4$, the value at the concentration of 13 mM (entry 8) being in agreement with that of entry 1, where the total ionic strength is about 13 mM but with a low [**1a**]. In the mesylate reaction, the dependence of **3Ms**/**2Ms** on the concentration of mesylate is not so clear as that of the triflate reaction. This may be attributed to compensation of the two effects of the nucleophilicity and the ionic strength of the nucleophilic salt.

A decreasing leaving ability of the phenyliodonio group with a 4-methoxy substituent decreases the fraction of the rearranged product (**3**/**2**) as well as the reactivity of **1**. The 3-trifluoromethyl group has the opposite effect. This is compatible with the lack of contribution from the S_N1 process to the unrearranged product **2**. It is reasonable that the better nucleofuge is more favorable for spontaneous heterolysis of the C−I bond with participation that leads to the rearrangement.

Relative Reactivities of Sulfonates toward Some Electrophiles. Overall mechanisms for the sulfonate reaction of **1** can be expressed by the combination of Scheme 1 for the rearranged product **3** and the in-plane and out-of-plan S_N2 reactions for the unrearranged product **2**. Relative reactivities of mesylate vs triflate are calculated from the results of the competitive reaction under varying concentration ratios of mesylate and triflate. The ratio of **2Ms**/**2Tf** reflects the reactivities of the sulfonates toward **1a**, and the selectivity of **1a** for mesylate vs triflate M/T(**1a**) is represented by **2Ms**·[TfO^-]/**2Tf**·[MsO^-], where **2Ms** and **2Tf** stand for their yields in the competitive reactions. The calculated values are reasonably constant, M/T(**1a**) = 70, as given in Table 5. Higher reactivity of mesylate than triflate is consistent with the nucleophilic substitution mechanism for the formation of the unrearranged products **2**.

The mechanisms for the formation of the rearranged products include racemization via $\mathbf{I_3}$ and enantiospecific nucleophilic trapping of $\mathbf{I_2}$, and the selectivities of $\mathbf{I_2}$ and $\mathbf{I_3}$ for mesylate vs triflate can be calculated separately from the product ratio **3Ms**/**3Tf** and their ee values. They can be written by M/T($\mathbf{I_2}$) = (**3Ms**·ee(**3Ms**)[TfO^-])/(**3Tf**·ee(**3Tf**)[MsO^-]) and M/T($\mathbf{I_3}$) = (**3Ms**{79 − ee(**3Ms**)}-[TfO^-])/(**3Tf**{79 − ee(**3Tf**)}[MsO^-]), respectively, where ee(**3Ms**) and ee(**3Tf**) stand for their ee values when the substrate of 79% ee is used. The calculated value for $\mathbf{I_2}$ is very small [M/T($\mathbf{I_2}$) ≈ 3] compared with those for **1a** (70) and $\mathbf{I_3}$ (300−500). The low selectivity may be ascribed to the high reactivity of $\mathbf{I_2}$. The M/T(**I3**) value obtained is compatible with the nucleophilic addition of sulfonate ion to $\mathbf{I_3}$. The ring strain of cyloalkynes lowers the LUMO level and increases the reactivity with nucleophiles.[4,13] Although a very weak nucleophile, it is difficult for triflate to nucleophilically trap $\mathbf{I_3}$; mesylate reacts much more readily with $\mathbf{I_3}$ via nucleophilic addition to give racemic **3Ms**.

In conclusion, the sulfonate reaction of **1** involves cycloheptyne $\mathbf{I_3}$ as well as cycloheptenyl cation $\mathbf{I_2}$ as the intermediates.[9] Formation of cycloalkyne from the corresponding cyclic vinyl cation suggests general possibilities of generation of cycloalkynes from cycloalkenyliodonium salts. No evidence for the primary vinyl cation $\mathbf{I_1}$ intermediate was obtained, but the unrearranged substitution products are formed via the S_N2 reactions.

Experimental Section

4-Methylcyclohexylidenemethyl(phenyl)iodonium Triflate (1a·OTf^-). The same procedure as that for the tetrafluoroborate salt of **1a**[1] was employed, except for using sodium triflate in place of sodium tetrafluoroborate. From the vinylsilane, **1a**·OTf^- was obtained in 49% yield as a white solid: mp = 82.9−84.0 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.88 (d, J = 7.8 Hz, 2H), 7.56 (t, J = 7.8 Hz, 1H), 7.44 (t, J = 7.8 Hz, 2H), 6.67 (s, 1H), 2.73−2.63 (m, 2H), 2.44−2.30 (m, 2H), 1.87−1.80 (m, 2H), 1.62−1.59 (m, 1H), 1.13−0.97 (m, 2H), 0.89 (d, J = 6.8 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 163.5, 134.4, 132.1, 132.0, 120.3 (q, J = 320 Hz), 111.6, 93.3, 36.4, 36.2, 35.7, 35.1, 31.5, 21.0; MS (FAB+) *m*/*z* (relative intensity, %) 313 (100); HRMS (FAB+) calcd for $C_{14}H_{18}I$ (**1a**) 313.0453, found 313.0445.

^{13}C-Labeled Iodonium Salt, ^{13}C-1a·BF_4^-. 4-Methylcyclohexylideneacetic acid-*2*-^{13}C was prepared from 4-methylcyclohexanone and triethyl phosphonoacetate-*2*-^{13}C (Aldrich) in the same way as the normal sample in 95% yield. The ^{13}C-labeled iodonium salt ^{13}C-**1a**·BF_4^- was prepared in three steps (13% yield) from the labeled carboxylic acid according to the procedure of the preceding paper.[1] A doublet signal at 6.65 ppm with a coupling constant of 209.1 Hz due to the exocyclic proton of ^{13}C-**1a**·BF_4^- was observed in ^{1}H NMR, while a singlet signal (6.65 ppm) of the unlabeled byproduct was not detected within the limits of the spectroscopy. In ^{13}C NMR using decoupling without NOE, a strong signal at 91.8 ppm was observed and its peak area was more than 20 times of those of the other carbon signals. These results confirm the selective ^{13}C-labeling at the exocyclic position of the iodonium salt. Selected data for ^{13}C-**1a**·BF_4^-: mp = 87.5−89.5 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.65 (d, J = 209.1 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 91.8.

Standard Procedure for Reaction of 1 with Sulfonates. The tetrafluoroborate salt of **1** (1 mg) was dissolved

(13) (a) Gassmann, P. G.; Valcho, J. J. *J. Am. Chem. Soc.* **1975**, *97*, 4768−4770. (b) Strozier, R. W.; Caramella, P.; Houk, K. N. *J. Am. Chem. Soc.* **1979**, *101*, 1340−1343, and references therein.

in 1 mL of chloroform containing tetrabutylammonium sulfonates (0.2−0.01 M) and kept in a sealed tube at 60 °C for a specified reaction time. To the mixture was added water and 5 μmol of tetradecane as an ether solution. The products were extracted with ether and washed with water. The yields of the products from the racemic **1** were determined by gas chromatography with tetradecane as an internal standard, while the ee of the products from (*R*)-**1** was determined using a chiral GC column (DEX-CB, i.d. 0.25 mm × 25 m). The retention times of (*R*)-**2Tf**, (*S*)-**2Tf**, (*R*)-**3Tf**, and (*S*)-**3Tf** were 17.2, 18.1, 22.9, and 23.3 min at the column temperature of 90 °C at a linear velocity of 32 cm s^{-1} of the He carrier gas, while those of (*R*)-**2Ms**, (*S*)-**2Ms**, (*R*)-**3Ms**, and (*S*)-**3Ms** were 89.3, 90.7, 99.5 and 101.3 min at 110 °C. A normal column (DB-1, i.d. 0.25 mm × 30 m) was used for the determination of product yields: the retention times of **2Tf**, **3Tf**, **2Ms**, and **3Ms** were 6.4, 7.4, 16.6, and 16.7 min, respectively, when the column temperature was maintained at 100 °C during the initial 10 min and then raised to 250 °C at the rate of 10 °C min^{-1}.

4-Methylcyclohexylidenemethyl Triflate (2Tf) and 5-Methylcyclohept-1-enyl Triflate (3Tf). A solution containing racemic **1a**·BF_4^- (0.11 g, 0.27 mmol) and tetrabutylammonium triflate (425 mg, 1.1 mmol) in chloroform (110 mL) was stirred at 60 °C for 6 h. Then the mixture was quenched by water and extracted with ether three times. The combined extracts were concentrated in vacuo and the mixture was separated by chromatography (SiO_2; eluent, 15% EtOAc in hexane) into four fractions, iodobenzene (406 mg, 72% yield), **2Tf** (5 mg, 7% yield), a 1:3 mixture of **2Tf** and **3Tf** (37 mg, 53% yield), and **3Tf** (14 mg, 20% yield). **2Tf:** ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.34 (s, 1H), 2.77−2.70 (m, 1H), 2.20−2.12 (m, 1H), 2.00−1.93 (m, 1H), 1.83−1.78 (m, 3H), 1.59−1.50 (m, 1H), 1.05−0.93 (m, 2H), 0.90 (d, J = 6.4 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 133.3, 127.6, 118.6 (q, J = 318.5 Hz), 35.6, 34.6, 32.2, 29.3, 25.5, 21.8; MS (EI) *m*/*z* (relative intensity, %) 258 (6, M^+), 107 (78), 79 (76), 69 (83), 55 (100); HRMS (EI) calcd for $C_9H_{13}SO_3F_3$ (M) 258.0538, found 258.0557. **3Tf:** ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.78 (ddd, J = 7.1, 4.9, 1.5 Hz, 1H), 2.56−2.49 (m, 1H), 2.45−2.39 (m, 1H), 2.25−2.17 (m, 1H), 2.09−2.02 (m, 1H), 1.80−1.65 (m, 3H), 1.36−1.30 (m, 1H), 1.28−1.15 (m, 1H), 0.89 (d, J = 6.8 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 152.6, 122.8, 118.5 (q, J = 317.6 Hz), 35.3, 34.0, 32.4, 31.2, 23.2, 23.1; MS (EI) *m*/*z* (relative intensity, %) 258 (1, M^+), 230 (3), 125 (17), 108 (92), 93 (96), 69 (98), 55 (100); HRMS (EI) calcd for $C_9H_{13}SO_3F_3$ (M) 258.0538, found 258.0521.

4-Methylcyclohexylidenemethyl Mesylate (2Ms) and 5-Methylcyclohept-1-enyl Mesylate (3Ms). Reaction of racemic **1a**·BF_4^- with tetrabutylammonium mesylate in the same way as above for triflate gave iodobenzene (70% yield), **2Ms** (51% yield), and **3Ms** (30% yield). **2Ms:** ^{1}H NMR (400 MHz, $CDCl_3$) δ 6.29 (s, 1H), 3.03 (s, 3H), 2.75−2.69 (m, 1H), 2.18−2.10 (m, 1H), 1.98−1.90 (m, 1H), 1.80−1.70 (m, 3H), 1.57−1.46 (m, 1H), 1.03−0.90 (m, 2H), 0.87 (d, J = 6.3 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 131.8, 126.6, 36.7, 35.7, 34.8, 32.3, 29.6, 25.4, 21.8; MS (EI) *m*/*z* (relative intensity, %) 204 (41, M^+), 125 (28), 107 (65), 93 (79), 79 (65), 55 (100); HRMS (EI) calcd for $C_9H_{16}SO_3$ (M) 204.0820, found 204.0824. **3Ms:** ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.74 (ddd, J = 7.8, 4.9, 1.0 Hz, 1H), 3.04 (s, 3H), 2.48−2.39 (m, 2H), 2.20−2.14 (m, 1H), 2.07−2.00 (m, 1H), 1.76−1.64 (m, 3H), 1.33−1.24 (m, 1H), 1.21−1.12 (m, 1H), 0.93 (d, J = 7.2 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 152.1, 121.3, 37.5, 35.8, 34.3, 32.7, 31.5, 23.6, 23.3; MS (EI) *m*/*z* (relative intensity, %) 204 (3, M^+), 176 (21), 125 (12), 108 (20), 93 (82), 56 (100); HRMS (EI) calcd for $C_9H_{16}SO_3$ (M) 204.0820, found 204.0832.

Mesylate Reaction of ^{13}C-1a. A solution containing ^{13}C-**1a**·BF_4^- (60 mg, 0.015 mmol) and tetrabutylammonium mesylate (2.04 g, 6.0 mmol) in chloroform (60 mL) was stirred at 60 °C for 5 h. The product mixture was separated by chromatography (SiO_2, eluent: 15% EtOAc in hexane) to give iodobenzene (26 mg, 86% yield), **2Ms** (18 mg, 58% yield), and **3Ms** (7 mg, 23% yield). Proton NMR of **2Ms** showed only a doublet signal at 6.29 ppm with a large coupling constant (J = 197.4 Hz). The ratio of 1-^{13}C-**3Ms** and 2-^{13}C-**3Ms** was determined by ^{1}H and ^{13}C NMR. The ^{1}H NMR spectrum of the product **3Ms** has two kinds of signals for 2-H at 5.74 ppm, one with a large coupling constant (J = 157 Hz) of 2-^{13}C-**3Ms** coupled to 2-^{13}C and the other with a small coupling constant to 1-^{13}C of 1-^{13}C-**3Ms**. The ratio of 1-^{13}C-**3Ms** and 2-^{13}C-**3Ms** was determined to be 35:65 by comparing the peak areas of the separate signals of 2-H. The isolated **3Ms** was also employed for ^{13}C NMR using decoupling without NOE. The ratio of 1-^{13}C-**3Ms** and 2-^{13}C-**3Ms** was determined to be 33:67 from the peak areas due to 1-C (152 ppm) and 2-C (121 ppm). Selected data for ^{13}C-**2Ms**: ^{1}H NMR (400 MHz, $CDCl_3$) 6.29 (d, J_{H-C} = 197.4 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 126.6; MS (EI) *m*/*z* (relative intensity, %) 205 (33, M^+), 126 (28), 108 (85), 79 (79), 55 (100); HRMS (EI) calcd for $^{12}C_8{}^{13}CH_{16}SO_3$ (M) 205.0854, found 205.0867. Selected data for 2-^{13}C-**3Ms**: ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.74 (dddd, J = 156.8, 7.8, 4.9, 1.0 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 121.3. Selected data for 1-^{13}C-**3Ms**: ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.74 (qd J = 6.8, 1.0 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 152.1. A mixture of 2-^{13}C-**3Ms** and 1-^{13}C-**3Ms**: MS (EI) *m*/*z* (relative intensity, %) 205 (16, M^+), 177 (20), 126 (24), 109 (49), 94 (65), 55 (100); HRMS (EI) calcd for $^{12}C_8{}^{13}CH_{16}SO_3$ (M) 205.0854, found 205.0882.

The mesylate reaction of ^{13}C-**1a** at various concentrations of mesylate was carried out using a smaller amount of ^{13}C-**1a**·BF_4^- (10 mg) in chloroform (10 mL). The reaction mixture extracted with ether was analyzed by ^{1}H NMR to determine the product distribution (**2Ms**/**3Ms** and 2-^{13}C-**3Ms**/1-^{13}C-**3Ms**).

Triflate Reaction of ^{13}C-1a. A solution containing ^{13}C-**1a**·BF_4^- (17.3 mg, 0.043 mmol) and tetrabutylammonium triflate (677 mg, 1.73 mmol) in chloroform (17.3 mL) was stirred at 60 °C for 6 h. The products extracted were separated by chromatography (SiO_2, eluent: hexane) to give iodobenzene (6 mg, 68% yield), **2Tf** (2 mg, 18% yield), and **3Tf** (5 mg, 45% yield). The ratio of **2Tf**/**3Tf** was determined to be 27/73 by GC of the crude product, while the ratio of 2-^{13}C-**3Tf**/1-^{13}C-**3Tf** was found to be 95/5 from both ^{1}H and ^{13}C NMR spectra. Selected data for ^{13}C-**2Tf:** ^{1}H NMR (400 MHz, $CDCl_3$) 6.34 (d, J_{H-C} = 205.1 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 127.6. Selected data for 2-^{13}C-**3Tf**: ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.78 (dddd, J = 158.2, 7.1, 4.9, 1.5 Hz, 1H), ^{13}C NMR (100 MHz, $CDCl_3$) δ 122.8. Selected data for 1-^{13}C-**3Tf**: ^{1}H NMR (400 MHz, $CDCl_3$) δ 5.84−5.72 (m, 1H),^{13}C NMR (100 MHz, $CDCl_3$) δ 152.6. A mixture of 1-^{13}C-**3Tf** and 1-^{13}C-**3Tf**: MS (EI) *m*/*z* (relative intensity, %) 259 (8, M^+), 109 (48), 94 (37), 56 (100); HRMS (EI) calcd for $^{12}C_8{}^{13}CH_{13}SO_3F_3$ (M) 259.0571, found 259.0590.

Mesylate Reaction in the Presence of Cyclopentadienone. A solution containing racemic **1a**·BF_4^- (50 mg, 0.125 mmol), tetrabutylammonium mesylate (168.5 mg, 0.50 mmol), and **4** (94 mg, 0.24 mmol) in chloroform (50 mL) was stirred at 60 °C for 5 h. Then the mixture was quenched by water and extracted with ether three times. The combined extracts were dried ($MgSO_4$) and concentrated in vacuo. The mixture was separated by chromatography (SiO_2, eluent: 60% $CHCl_3$ in hexane) to give the adduct **5** (14.1 mg, 24% yield) and a mixture of **2Ms** and **3Ms** (16.3 mg, 64% yield). The ratio of **2Ms**/**3Ms** was determined to be 98/2 by ^{1}H NMR and GC. **5**: mp = 249−253 °C; ^{1}H NMR (400 MHz, $CDCl_3$) δ 7.15−6.93 (m, 10H), 6.78−6.69 (m, 10H), 2.79−2.74 (m, 2H), 2.64−2.58 (m, 2H), 1.78−1.74 (m, 3H), 1.24−1.12 (m, 2H), 0.90 (d, J = 6.0 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 141.4, 141.0, 140.6, 139.7, 138.5, 131.4, 131.0, 130.6, 130.3, 127.2, 127.1, 126.3, 126.2, 125.7, 124.8, 37.8, 35.9, 30.0, 23.5; MS (EI) *m*/*z* (relative intensity, %) 464 (75, M^+), 149 (100); HRMS (EI) calcd for $C_{36}H_{32}$ (M) 464.2504, found 464.2520.

The salt (*S*)-**1a**·BF_4^- (79% ee, 1 mg), tetrabutylammonium mesylate (3.4 mg), and **4** (1.9 mg) were dissolved in chloroform, and the mixture stirred at 60 °C for 5 h. A mixture of **2Ms**

and **3Ms** was separated from the product mixture by ether extraction and chromatography (SiO_2; eluent, 15% EtOAc in hexane). The ratio of **2Ms**/**3Ms** was determined to be 97/3 by GC. Chiral GC analyses indicated that **2Ms** and **3Ms** were 77% ee of *R* and 78% ee of *S* isomer, respectively.

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Supporting Information Available: Time profiles of products during the sulfonate reactions of **1** (Tables S1 and S2) and the experimental procedures in the presence of an additive such as deuterium source (PDF). This material is available free of charge via the Internet at http://pubs.acs.org.

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