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Different Reactivity Modes of Cis and Trans Di-*tert*-butylthiiranium Tetrafluoroborates[1] with Water. A New Insight in the Electrophilic Additions to *Z* and *E* Di-*tert*-butylethylenes[†]

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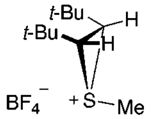
Our continuing interest in the chemistry of thiiranium and thiirenium ions[2−6] and in the electrophilic additions to carbon−carbon double and triple bonds[2] prompted us to investigate the reactivity of stable thiiranium ions with nucleophiles. Thiiranium and thiirenium ions (and the selenium analogues[7]) are the most stable cyclic intermediates in the electrophilic addition to alkenes and alkynes, and considering that the attack of a nucleophile to the sulfonium sulfur of the thiiranium ion is the inverse reaction of the electrophilic addition to the olefin, we may acquire mechanistic information on this still unclear process.[2,8] Furthermore, in the last decade a growing interest on the use of thiiranium ions as key intermediates in many processes with a high degree of stereochemical control have been developed.[9] Therefore studies on the relative reactivities of nucleophiles at sulfur and carbon atoms of thiiranium ions may be helpful in organic synthesis.[6,10]

In this paper we report the different reactivity modes of cis and trans thiiranium tetrafluoroborates **1** and **2** toward the nucleophile water.[11]

Salts **1** and **2** are obtained from the reaction of the appropriate olefins, **3** and **4**, with methylbis(methylthio)sulfonium tetrafluoroborate[12] in liquid SO_2 at −78 °C. After evaporation of the solvent the salts have been dissolved in CH_2Cl_2 and crystallized by addition of pentane at −20 °C.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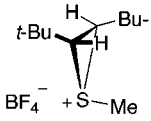
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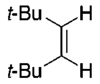
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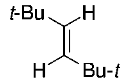
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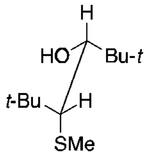
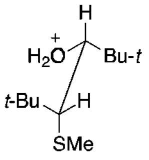
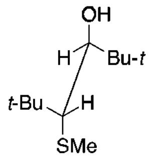

threo-**5**


threo-**5⁺**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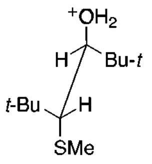
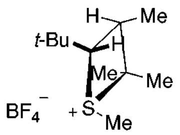

erythro-**6⁺**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The cis isomer **1**, treated with an excess (11 equiv) of water in CD_2Cl_2 at 25 °C, undergoes a quantitative formation of *threo*-2,2,5,5-tetramethyl-4-(methylthio)-3-hexanol (**5**),[13] as monitored by ^1H NMR. No trace of the *Z* di-*tert*-butylethylene **3**, which would result from nucleophilic attack of water on sulfur, could be detected. The reaction is described by the first two equations of Scheme 1.

Scheme 1

$$\mathbf{1} + H_2O \xrightarrow{k_C} \textit{threo-}\mathbf{5}^+$$

$$\textit{threo-}\mathbf{5}^+ + H_2O \rightleftharpoons \textit{threo-}\mathbf{5} + H_3O^+$$

$$\textit{threo-}\mathbf{5}^+ + H_2O \rightleftharpoons \textit{erythro-}\mathbf{6}^+ + H_2O$$

$$\textit{erythro-}\mathbf{6}^+ + H_2O \rightleftharpoons \textit{erythro-}\mathbf{6} + H_3O^+$$

$$\textit{erythro-}\mathbf{6}^+ \rightleftharpoons \mathbf{2} + H_2O$$

$$\mathbf{2} \xrightarrow{k_R} \mathbf{7}$$

Under the same conditions, but using 0.7 equiv of water, the reaction is more complex, as revealed by accurate analysis of the ^1H NMR spectra taken at regular time intervals. The decrease of the cis thiiranium ion **1** was monitored, accompanied by the formation of the threo alcohol **5**, the trans thiiranium ion **2**, and the thietanium ion **7**.[14] Also in this case no traces of the olefin **3** could be detected. Considering the higher proton activity with respect to the previous case, and in light of

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[†] This paper is dedicated to Prof. George A. Olah in the occasion of his 70th birthday.

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[1] For easier reading we use the trivial names cis and trans di-*tert*-butylthiiranium ions for the *t*-2,*t*-3- and *c*-2,*t*-3-di-*tert*-butyl-*r*-1-methylthiiranium ions **1** and **2**, respectively .

[2] Capozzi, G.; Modena, G.; Pasquato, L. *The Chemistry of Sulfenic Acids and Their Derivatives*; Patai, S., Ed.; Wiley: Chichester, U.K., 1990; Chapter 10.

[3] (a) Lucchini, V.; Modena, G.; Pasquato, L. *J. Am. Chem. Soc.* **1988**, *110*, 6900. (b) Lucchini, V.; Modena, G.; Pasquato, L. *J. Am. Chem. Soc.* **1991**, *113*, 6600.

[4] Modena, G.; Pasquato, L.; Lucchini, V. *Phosphorous, Sulfur, Silicon* **1994**, *95−96*, 265.

[5] Lucchini, V.; Modena, G.; Pasquato, L. *J. Am. Chem. Soc.* **1993**, *115*, 4527. Lucchini, V.; Modena, G.; Pasquato, L. *J. Am. Chem. Soc.* **1995**, *117*, 2297.

[6] Lucchini, V.; Modena, G.; Pasquato, L. *J. Chem. Soc., Chem. Commun.* **1994**, 1565.

[7] Back, T. G. *The Chemistry of Organic Selenium and Tellurium Compounds*; Patai, S., Ed.; Wiley: Chichester, U.K., 1987; Vol 2, Chapter 3.

[8] For bromination, see: Cossi, M.; Persico, M.; Tomasi, J. *J. Am. Chem. Soc.* **1994**, *116*, 5373. Ruasse, M.-F. *Adv. Phys. Org. Chem.* **1993**, *28*, 207.

[9] Harring, S. R.; Edstrom, E. D.; Livinghouse, T. *Adv. Heterocycl. Nat. Prod. Synth.* **1992**, *2*, 319. Rayner, C. M. *Organosulfur Chemistry. Synthetic Aspects*; Page, P., Ed.; Academic Press: London, 1995; Chapter 3.

[10] For selenium, see, for example: Toshimtsu, A.; Nakano, K.; Mukai, T.; Tamao, K. *J. Am. Chem. Soc.* **1996**, *118*, 2756.

[11] We used the tetrafluoroborate anion because preliminary experiments with the hexachloroantimonate ion showed a possible attack of water on the anion.

[12] Capozzi, G.; DaCol, L.; Lucchini, V.; Modena, G. *J. Chem. Soc., Perkin Trans. 2* **1980**, 68.

[13] Raynolds, P.; Zonnebelt, S.; Bakker, S.; Kellogg, R. M. *J. Am. Chem. Soc.* **1974**, *96*, 3146.

[14] No traces of the *E* olefin **4**, eventually formed from the trans ion **2**, generated in turn from the cis isomer **1**, could be detected.

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the known rearrangement of thiiranium ion **2** to thietanium ion **7**,[3] the reaction shown in Scheme 1 can be suggested. The attack of water on a ring carbon atom of the cis thiiranium ion **1** gives the threo alcohol **5**$^+$, in equilibrium with its conjugate base **5**; both species will readily assume the most stable conformation (with antiperiplanar *tert*-butyl groups) which prevents the anchimeric assistance by the nucleophilic methylthio group to the detachment of the hydroxyl group. The threo alcohol **5** undergoes the acid-catalyzed nucleophilic substitution by a water molecule, yielding the epimeric erythro alcohol **6**. This latter gives, in an acid-catalyzed process, trans thiiranium ion **2**, which then rearranges to the stable thietanium ion **7**.[15]

The proposed mechanism is supported by an independent experiment. The addition of CF_3SO_3H to a solution of the threo alcohol **5** in CD_2Cl_2, obtained using an excess of water, shows indeed that alcohol **5** is converted to trans thiiranium ion **2** and, subsequently, to thietanium ion **7**.

As the key point in the reaction Scheme 1 is the acid-catalyzed interconversion of alcohols **5** and **6**, the behavior of cis thiiranium ion **1** with a large excess of water may be understood: under these conditions the generated threo alcohol **5** is not effectively protonated.

The differential equations related to the consecutive and competitive reactions shown in Scheme 1 have been numerically integrated[16] and fitted (with a Simplex procedure[17]) to the concentrations of **1**, **2**, and **7** and the sum of the concentration of **5** and **5**$^+$. The most relevant rate constants k_C, describing the consumption of cis thiiranium ion **1** by reaction with water, and k_R, for the rearrangement of the trans thiiranium ion **2** to thietanium ion **7**, are reported in Table 1.

Table 1. Initial Concentrations and Rate Constants[a] for the Reaction of Cis Thiiranium Ion 1 with Water, in CD_2Cl_2 at 25 °C (cf Scheme 1)

	[**1**], M	[H_2O], M	k_C, $M^{-1\,s^{-1}}$	k_R, s^{-1}
1	7.5×10^{-3}	8.4×10^{-2}	$9.6(\pm 0.4) \times 10^{-4}$	
2	6.6×10^{-3}	4.7×10^{-3}	$11.9(\pm 1.5) \times 10^{-4}$	$8.9(\pm 0.5) \times 10^{-6}$

[a] Average and standard deviation from three determinations.

Scheme 2

$$\mathbf{2} + H_2O \xrightarrow{k_S} \mathbf{4} + MeSOH_2^+$$

$$\mathbf{2} \xrightarrow{k_R} \mathbf{7}$$

Under the same reaction conditions we monitored the behavior of trans thiiranium ion **2** in the presence of water. We could follow the formation of thietanium ion **7** and of different amounts of the *E* di-*tert*-butylethylene **4**, depending on water concentration. No trace of erythro alcohol **6** could be observed. The reaction is therefore described by Scheme 2. The related differential equations, integrated and fitted to the concentrations of **2**, **4**, and **7**, give the selected rate constants k_S and k_R reported in Table 2. The rate constants k_R are in good agreement with those measured in the case of the reactions of the cis thiiranium ion **1** (Table 1).

Table 2. Initial Concentrations and Rate Constants[a] for the Reaction of Trans Thiiranium Ion 2 with Water, in CD_2Cl_2 at 25 °C (cf. Scheme 2)

	[**2**], M	[H_2O], M	k_S, M^{-1} s^{-1}	k_R, s^{-1}
1	1.4×10^{-2}	5.7×10^{-2}	$3.6(\pm 1.1) \times 10^{-5}$	$10.4(\pm 0.5) \times 10^{-6}$
2	1.2×10^{-2}	1.9×10^{-2}	$5.9(\pm 1.0) \times 10^{-5}$	$11.2(\pm 0.8) \times 10^{-6}$

[a] Average and statndard deviation from three determinations.

A further point deserves a comment. No traces of *E* olefin **4** could be detected in the reaction of thiiranium ion **1**, which also generates thiiranium ion **2**, although the reaction of authentic **2** gives rise to a small amount of the same olefin. We propose the following rationale. The attack of water to the ring carbons of **1** is about 2 orders of magnitude faster that the attack to sulfonium sulfur of **2**. Thus, during the greatest part of the reaction, water is effectively sequestered by **1** in the form of threo alcohol **5** or is deactivated as nucleophile by protonation so that the attack to the newly formed thiiranium ion **2** is minimized. The *E* olefin **4** might be generated, but at such a low concentration to escape detection.

The results herein reported outline the different reactivity modes of cis and trans thiiranium ions **1** and **2**, even though the study is limited to only one nucleophile and to a small range of concentrations. The reactivity modes seem to be highly specific, and within the detection limits of ^{1}H NMR spectroscopy, the competitive attacks at sulfur in cis thiiranium ion **1** and at the ring carbon in trans thiiranium ion **2** may be considered at least 2 orders of magnitude slower than the observed ones.

If the different behavior of thiiranium ions **1** and **2** toward the nucleophile water holds for other nucleophiles, and particularly for halide ions, then these results call for a reconsideration in interpreting the reactivities of *Z* and *E* di-*tert*-butylethylene **3** and **4** toward sulfenyl chlorides and other electrophiles. The relevant rate ratio of 1.6×10^5 measured for the addition of 4-chlorobenzenesulfenyl chloride to isomers **3** and **4**[18] is to be compared with the much reduced rate ratios of 13.6 for the addition of bromine[19] and of 0.37 for the addition of chlorine.[20]

The huge reactivity ratio for the addition of the sulfenyl chloride was explained by invoking the spatial characteristic of the olefins, i.e., by the greater steric hindrance opposed to the approaching electrophile by two trans *tert*-butyl groups than by two cis group.[18] This rationalization cannot account for the smaller reactivity ratios for the addition of the halogens. Rather, the different spatial characteristics of the electrophiles sulfenyl chloride and bromine have been invoked.[19] In thiiranium ions **10** (Scheme 3) the S−R′ bond is nearly perpendicular to the three-membered ring;[21] if this orientation is already present in the transition state, then a nonbonding interaction between R′ of the sulfenyl chloride **9** and the cis-oriented *tert*-butyl group may lower the addition rate to olefin **4**.

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[15] This hypothesis is in agreement with the formation of thiiranium ion **2** from *erythro*-2,2,5,5-tetramethyl-4-(methylthio)-3-chlorohexane in liquid SO_2, as reported in ref 3.

[16] Press, W. H.; Flannery, B. P.; Teukolsky, S. A.; Vetterling, W. T. *Numerical Recipes. The Art of Scientific Computing*; Cambridge University Press: Cambridge, U.K., 1986; p 547.

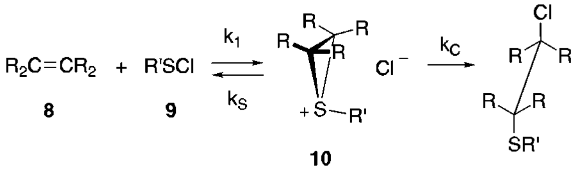
[17] Nash, J. C. *Compact Numerical Methods for Computers*; Adam Hilger Ltd.: Bristol, U.K., 1979; p 141.

[18] Dean, C. L.; Garratt, D. G.; Tidwell, T. T.; Schmid, G. H. *J. Am. Chem. Soc.* **1974**, *96*, 4958.

[19] Ruasse, M. F., Argile, A., Bienvenue-Goëtz, E., Dubois, J. E. *J. Org. Chem.* **1979**, *44*, 2758.

[20] Fahey, R. C. *J. Am. Chem. Soc.* **1966**, *88*, 4681.

Scheme 3



The different steric hindrances presented by alkenes **3** and **4** to the approaching electrophile may contribute to the reactivity ratios, but only as a minor factor. Indeed our results suggest an alternative rationalization. Considering the general reaction scheme for the addition of sulfenyl chlorides to alkenes (Scheme 3) and assuming that the steady state approximation can be applied to the intermediates thiiranium ion **10** and chloride ion, which have never been observed in reactions carried out in chlorinated solvents,[2] eq 1 expresses the rate of product formation. In the case of the cis thiiranium ion **1**, $k_C > k_S$ and eq 1 simplifies to eq 2, while in the case of the trans isomer **2**, $k_C < k_S$ and eq 1 becomes eq 3.

$$\frac{d[\mathrm{Product}]}{dt} = \frac{k_1 k_C}{k_S + k_C}[\mathbf{8}][\mathbf{9}] \qquad (1)$$

$$k_C > k_S \qquad \frac{d[\mathrm{Product}]}{dt} = k_1 [\mathbf{8}][\mathbf{9}] \qquad (2)$$

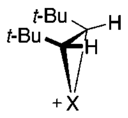
$$k_S > k_C \qquad \frac{d[\mathrm{Product}]}{dt} = \frac{k_1 k_C}{k_S}[\mathbf{8}][\mathbf{9}] \qquad (3)$$

In this second instance the observed reaction rate is reduced by the presence of a high value of k_S at the denominator. It may then be proposed that the low rate for the addition of sulfenyl chlorides to the *E* alkene **4** is mainly due to the reversibility of the first step of the reaction, while the equivalent step for the addition to the *Z* isomer **3** is substantially irreversible. The rational for this different behavior is straightforward: the presence of the substituent at sulfur in thiiranium ions constrains the approach of the nucleophile Cl^- to sulfur from a direction which is strongly hindered in cis thiiranium ion **1**.

The difference in hindrance cannot explain the very reduced rate ratios measured for the additions of bromine or chlorine to **3** and **4**. Rather, the addition rates are similar because the first steps for the additions are equally reversible: the approach of the nucleophile Br^- or Cl^- to the halogen center in cis and trans haloiranium ions **11** and **12**, the proposed intermediates, is hindered to the same extent in both isomers, or even more hindered in the trans isomer.

Experimental Section

General. Melting points are uncorrected. NMR spectra were recorded at 200 or 250 MHz. Commercial reagents and known compounds used in this research were either purchased from standard chemical suppliers or prepared according to literature procedures and purified to match the reported physical and spectral data. Solvents were purified according to standard procedures.



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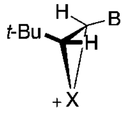

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X = Cl, Br

Kinetic Measurements. The decrease in the concentrations of cis and of trans thiiranium ions **1** and **2** and the formation of cumulated *threo*-**5** and *threo*-$\mathbf{5}^+$ alcohols were followed by measuring the ^{1}H NMR integrated area of the *S*-methyl resonances; the formation of the thietanium ion **7** was followed by measuring the integrated area of the two singlets of the geminal methyl groups in the reactions of *cis*-**1** and the doublet of the methylene proton geminal to the *tert*-butyl in the reaction of *trans*-**2**; the formation of *E* alkene was followed by monitoring the integrated area of the *tert*-butyl resonance. The initial concentrations of thiiranium ions **1** and **2** have been determined by weighing. These concentrations and the concentration of water in CD_2Cl_2 have been verified by comparison of the integrated areas of selected resonances with that of the proton impurity of the solvent. The concentration of the impurity has been previously measured by comparison with the signal of 1,4-dinitrobenzene, at a concentration determined by weighing. The reactions have been monitored, at appropriate intervals of time, using NMR tubes equipped with air-tight screw caps. In order to compensate for the varying spectrometer conditions, the monitored intensities were normalized against their sum. The differential equations relative to Schemes 1 and 2 have been numerically integrated[16] and fitted to the normalized concentrations with the Simplex procedure.[17]

***t*-2,*t*-3-Di-*tert*-butyl-*r*-1-methylthiiranium Tetrafluoroborate (1).** In a 25 mL three necked flask containing methylbis(methylthio)sulfonium tetrafluoroborate[12] (0.155 g, 0.68 mmol), SO_2 was condensed to 10 mL at −78 °C under nitrogen atmosphere and the *Z* alkene **3**[3b] (0.095 g, 0.68 mmol), dissolved in 1 mL of dry methylene chloride, was added in one portion. The reaction mixture was left 40 min at −78 °C, and then, after addition of 5 mL of dry methylene chloride, the SO_2 was allowed to evaporate. The salt was precipated with pentane and recrystallized from methylene chloride/pentane at −20 °C in 63% yield. ^{1}H NMR (200 MHz, CD_2Cl_2): δ 1.32 (9 H, s), 2.77 (3 H, s), 4.44 (2 H, s). ^{13}C (62.9 MHz, CD_2Cl_2): δ 24.22, 29.97, 33.71, 78.12. Anal. Calcd for $C_{11}H_{23}BF_4S$: C, 48.19; H, 8.45. Found: C, 48.04; H, 8.38.

***c*-2,*t*-3-Di-*tert*-butyl-*r*-1-methylthiiranium Tetrafluoroborate (2).** This salt was prepared as described for isomer **1** using the *E* alkene **4**[3b] and crystallized from methylene chloride/pentane at −20 °C, 68% yield. ^{1}H NMR (200 MHz, CD_2Cl_2): δ 1.14 (9 H, s), 1.32 (9 H, s), 2.80 (3 H, s), 3.65 (1 H, d, J = 13.4 Hz), 4.38 (1 H, d, J = 13.4 Hz). ^{13}C (62.9 MHz, CD_2Cl_2): δ 17.86, 26.76, 28.77, 33.09, 34.72, 68.44, 73.34. Anal. Calcd for $C_{11}H_{23}BF_4S$: C, 48.19; H, 8.45. Found: C, 48.08; H, 8.40.

***t*-4-*tert*-Butyl-*r*-1,2,2,*c*-3-tetramethylthietanium tetrafluoroborate (7)**[3b] was obtained from the rearrangement of **2** in methylene chloride at 25 °C and recrystallized from methylene chloride/pentane at −20 °C. ^{1}H NMR (250 MHz, CD_2Cl_2): δ 1.08 (9 H, s), 1.23 (3 H, d, J = 6.8 Hz), 1.72 (3 H, s), 1.74 (3 H, s), 3.00 (3 H, s), 3.03 (1 H, dq, J = 11.3, 6.8 Hz), 3.91 (1 H, d, J = 11.3 Hz). ^{13}C (62.9 MHz, CD_2Cl_2): δ 15.87, 18.04, 22.76, 26.56, 28.92, 33.64, 44.29, 65.32, 72.49. Anal. Calcd for $C_{11}H_{23}BF_4S$: C, 48.19; H, 8.45. Found: C, 48.12; H, 8.35.

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