Transacetalization with Gaseous Carboxonium and Carbosulfonium Ions

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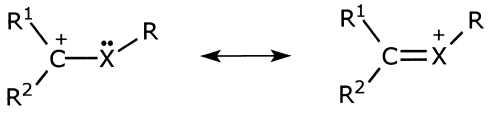
Primary carboxonium ($H_2C{=}O^+{-}R$) and carbosulfonium ($H_2C{=}S^+{-}R$) ions (R = CH_3, C_2H_5, Ph) and the prototype five-membered cyclic carboxonium ion are found to react in the gas phase with cyclic acetals and ketals by transacetalization to form the respective O-alkyl-1,3-dioxolanium and S-alkyl-1,3-oxathiolanium ions. The reaction, which competes mainly with proton transfer and hydride abstraction, initiates by O-alkylation and proceeds by ring opening and recyclization via intramolecular displacement of the carbonyl compound previously protected in its ketal form. As indicated by product ion mass spectra, and confirmed by competitive reactions, carbosulfonium ions are, by transacetalization, much more reactive than carboxonium ions. For acyclic secondary and tertiary carboxonium ions bearing acidic α-hydrogens, little or no transacetalization occurs and proton transfer dominates. This structurally related reactivity distinguishes primary from both secondary and tertiary ions, as exemplified for the two structural isomers $H_2C{=}O^+{-}C_2H_5$ and $CH_3C(H){=}O^+{-}CH_3$. The prototype five- and six-membered cyclic carboxonium ions react mainly by proton transfer and adduct formation, but the five-membered ring ion also reacts by transacetalization to a medium extent. Upon CID, the transacetalization products of the primary ions often dissociate by loss of formaldehyde, and a +44 u neutral gain/−30 u neutral loss MS^3 scan is shown to efficiently detect reactive carboxonium and carbosulfonium ions. Transacetalization with either carboxonium or carbosulfonium ions provides a route to 1,3-oxathiolanes and analogs alkylated selectively either at the sulfur or oxygen atom. (J Am Soc Mass Spectrom 2001, 12, 14–22) © 2001 American Society for Mass Spectrometry

Carboxonium ions, **1**, a major class of unsaturated oxonium ions, and their sulfur analogs, the carbosulfonium ions, **2**, are formally carbenium ions substituted by alkoxy or thioalkoxy groups. These ions gain stability by delocalizing their positive charge into the neighboring X atom through a resonance interaction [1].



1 , X = O
2 , X = S

The reactivity of carboxonium and carbosulfonium ions is rich and with many synthetic uses, and has been exploited vastly both in the condensed [1] and gas phase [2]. Their reactivity reflects their hybrid carbenium–oxonium or carbenium–sulfonium ion nature and, accordingly, these ambident ions can react either as oxo(sulfo)nium ions by acting as alkylating agents (Scheme **1a**) or as carbenium ions by suffering nucleophilic attack at the carbenium center to form tetrahedral addition products (Scheme **1b**).

Acylium ions, $R{-}C^+{=}O$ [3], and their sulfur analogs, the thioacylium ions $R{-}C^+{=}S$, constitute other major classes of unsaturated oxonium ions; for them, nucleophilic attack occurs via a single pathway, and at the chemically unsaturated carbonyl carbon. In both the condensed [3] and gas phase [4], acylium and thioacylium ions also display rich reactivity with important synthetic uses. When isolated in the diluted gas-phase environment, acylium ions are stable and long-lived; hence, their intrinsic bimolecular reactivity has been vastly investigated and novel reactions observed [4–7]. For instance, gaseous acylium and thioacylium ions undergo rapid ketalization with diols and analogs [5] and transacetalization with five- and six-membered cyclic acetals and ketals [6]. By transacetalization, a reaction also observed in solution [3c,d], acylium and thioacylium ions replace the neutral carbonyl compound deactivated in its acetal or ketal form. As evidenced by ^{18}O-labeling and MS^3 experiments and as predicted by molecular orbital (MO) calculations [6], transacetalization with acylium ions forms cyclic ionic ketals by a mechanism (Scheme **2**) that initiates by

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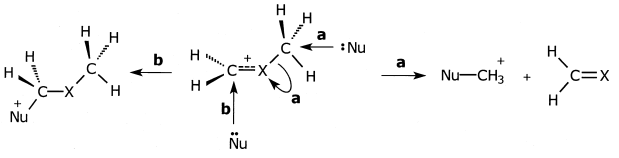
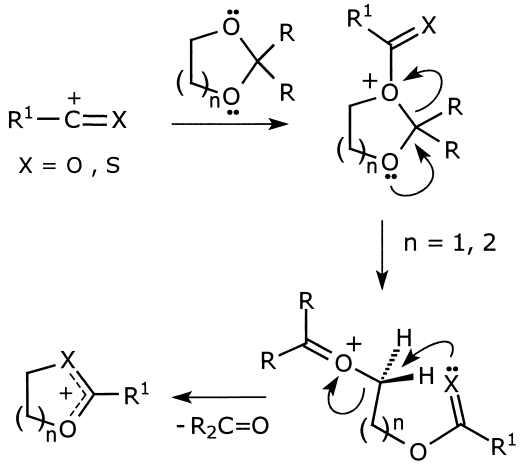


Scheme 1

O-acylation, and proceeds by ring opening and recyclization via intramolecular displacement of the carbonyl compound. Seven-membered cyclic acetals and ketals are, however, unique; they react with acylium ions predominantly or exclusively by ring contraction [7].

Transacetalization with gaseous acylium and thioacylium ions has been studied extensively, and this reaction has found analytical and synthetic applications [6]. For both the ions and neutral reactants, transacetalization characterizes them as a class [6], reveals specific structural details [6b, c], converts thioacylium into acylium ions [6c], and distinguishes the ions and the neutral reactants from their isomers and isobars [6]. The gas phase synthesis of several heterocycles has been performed via related transacetalizations with other amphoteric cations such as sulfinyl [8], silylium [9], phosphonium [10], and borinium ions [11].

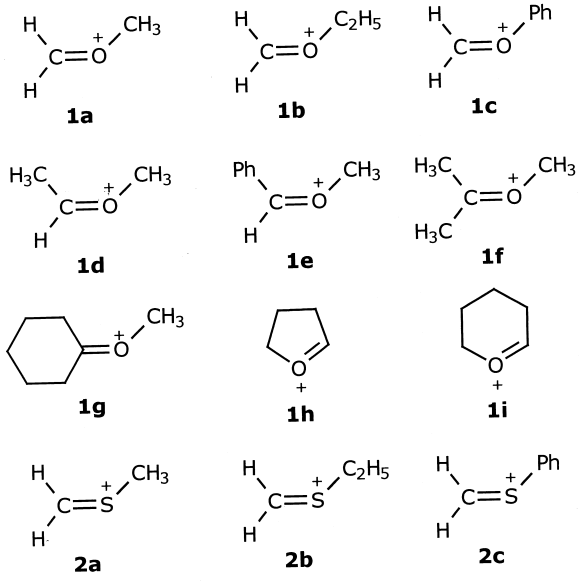
Carboxonium and carbosulfonium ions, owing to their related unsaturated oxo(sulfo)nium ion and carbenium-oxo(sulfo)nium amphoteric nature [1], are also potential candidates for transacetalization with cyclic acetals and ketals. Herein we report that gaseous primary carboxonium and carbosulfonium ions react with cyclic acetals and ketals by transacetalization to form cyclic O(S)-alkylated onium ions. The transacetalization reactivity of a carboxonium versus a carbosulfonium ion in competitive reactions is compared and related to structural effects, and MS^2 and MS^3 experiments are shown to, and proposed as, a method to characterize the ions and to distinguish primary from secondary and tertiary isomers and analogs. Transacetalization with either carboxonium or carbosulfonium ions is also found to provide a unique route to 1,3-oxathiolanes and analogs selectively alkylated *either* at the sulfur or oxygen atom.



Scheme 2

Methods

Double- (MS^2) and triple-stage (MS^3) mass spectrometric experiments performed with an Extrel (Pittsburgh, PA) pentaquadrupole ($Q_1q_2Q_3q_4Q_5$) mass spectrometer [12] were used to form the gaseous ions, to mass select the reactant ions, to react them with selected neutrals, and to characterize the product ions. Appropriate precursors were used to form the reactant ions; by CH_3I CI of acetaldehyde: **1d**, of benzaldehyde: **1e**, of acetone: **1f**, and of cyclohexanone: **1g**. By 70 eV EI of ethyl methyl ether followed by the loss of a methyl radical: **1a**, of diethyl ether: **1b**; of ethyl phenyl ether: **1c**, of 2-methoxy-tetrahydro-furan: **1h**, of 2-methoxy-tetrahydropyran: **1i**, of ethyl methyl sulfide: **2a**, of diethyl sulfide: **2b**, and of ethyl phenyl sulfide: **2c**.



The ion/molecule reactions were performed by MS^2 experiments. The ion of interest was mass selected by Q1 for further reaction in q2 with the neutral reagent. Ion translational energy was set to near 1 eV as calibrated by the *m/z* 39:41 ratio in neutral ethylene/ionized ethylene reactions [13]. To record the product ion mass spectra, Q5 was scanned while operating Q3 in the broadband rf-only mode. Multiple collision conditions that caused typical beam attenuations of 50%–70% were used in q2 so as to increase reaction yields and promote collisional quenching of both the reactant and product ions [14].

For structural characterization via MS^3 experiments [15], a q2 product ion of interest was mass selected by Q3 and further dissociated by 15 eV collision dissocia-

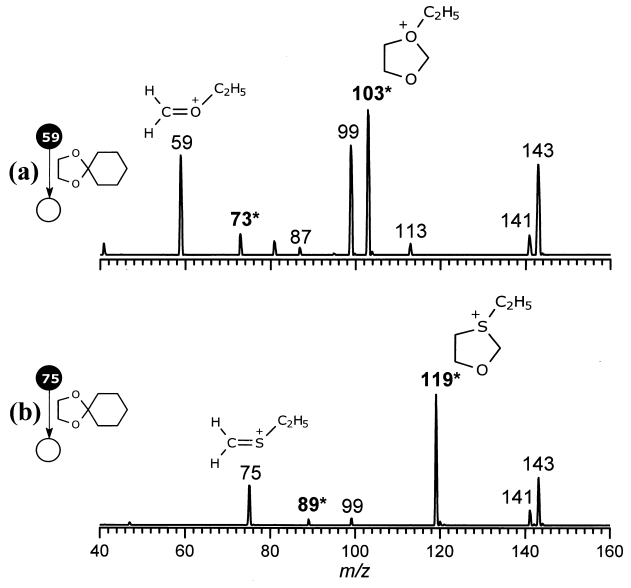


Figure 1. Double-stage (MS^2) product ion mass spectra for reactions with 1,4-dioxa-spiro[4.5]decane of (**a**) the carboxonium ion **1b** of *m/z* 59 and (**b**) the carbosulfonium ion **2b** of *m/z* 75. The marked ions are the primary transacetalization product and its fragment formed by formaldehyde loss.

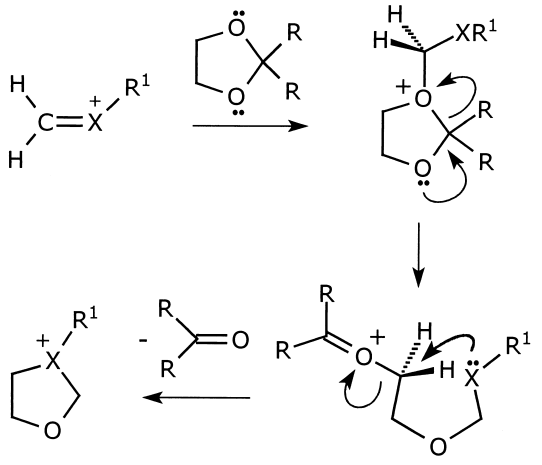
tion with argon in q4, while scanning Q5 to acquire the spectra. The 15 eV collision energies were taken as the voltage difference between the ion source and the collision quadrupoles. The indicated pressures in each differentially pumped region were typically 2×10^{-6} (ion source), 8×10^{-6} (q2) and 8×10^{-5} (q4) torr, respectively.

The total and zero-point vibrational energies of optimized geometries for idealized conformations with no symmetry constraints were provided by molecular orbital calculations at the HF/6-31G(*d*,*p*) level of theory [16] run on Gaussian98 [17]. Improved energies were obtained by single point calculations at the MP2/6-31G(*d*,*p*) level [18], which were corrected for ZPE scaled by 0.89.

Results and Discussion

General Reactivity: Carboxonium and Carbosulfonium Ions

Figure 1 illustrates for **1b** and **2b** the product ion mass spectra for reactions with the cyclic ketal 1,4-dioxa-spiro[4.5]decane (selected as a reference ketal). The primary carboxonium ion **1b** (Figure 1a) reacts diversely: it forms MH^+, the protonated ketal of *m/z* 143 (note that proton transfer, owing to the multiple collision conditions used, may involve either the reactant ion or its primary product ions, or both); $[M - H]^+$, the hydride abstraction product of *m/z* 141; $[M - C_2H_5]^+$ of *m/z* 113, an ion most likely formed by primary electron transfer ($M^{+\cdot}$) followed by rapid dissociation with ethyl radical loss of the nascent ionized ketal; $[M - C_3H_7]^+$ of *m/z* 99, which (as shown by MS^3 data) is a major



Scheme 3

dissociation product of MH^+, $M^{+\cdot}$, and $[M - H]^+$; and two products most likely formed by transacetalization: those of *m/z* 103 and 73. As shown by MS^3 data (see the corresponding section), the *m/z* 73 ion is a secondary transacetalization product formed by dissociation of *m/z* 103 by formaldehyde loss.

Transacetalization of **1b** with 1,4-dioxa-spiro[4.5]decane is expected to release cyclohexanone that was protected in its cyclic ethylene glycol ketal form to yield the cyclic O-ethyl-1,3-dioxolanium ion of *m/z* 103 (Scheme **3**; X = O; R,R = $(CH_2)_5$; $R^1 = C_2H_5$).

The carbosulfonium ion **2b**, the sulfur analog of **1b**, forms with 1,4-dioxa-spiro[4.5]decane a similar set of products except that of electron transfer. Transacetalization (Scheme **3**; X = S; R,R = $(CH_2)_5$; $R^1 = C_2H_5$) that yields the S-ethyl-1,3-oxathiolanium ion of *m/z* 119 (and the minor *m/z* 89 via dissociation of *m/z* 119 by formaldehyde loss) occurs for **2b**, however, to a much greater extent (Figure 1b).

Table 1 summarizes the product ion mass spectra for reactions with 1,4-dioxa-spiro[4.5]decane of all carboxonium and carbosulfonium ions tested. These spectra show that all the primary ions **1a–c** and **2a–c** are reactive by transacetalization. The acyclic secondary **1d,e** and tertiary **1f,g** ions and the prototype six-membered cyclic ion **1i** fail, however, to react by transacetalization, and proton transfer dominates. This drastic change in reactivity and the dominance of proton transfer can, however, be easily rationalized for **1d** and **1f–i**; these ions, which can be viewed as protonated vinyl ethers, bear acidic hydrogens positioned α to the carbenium charge site, hence they tend to react readily by proton transfer (Scheme **4**).

Ion **1e** displays very low reactivity toward 1,4-dioxa-spiro[4.5]decane (Table 1). The behavior of this secondary carboxonium ion is unique because it bears no acidic α-hydrogen and its charge is highly delocalized through the α-benzene ring, an effect that accounts for its extra stabilization and overall low reactivity. The main product observed in its product ion mass spectrum is MH^+ of *m/z* 143.

Table 1. Major ionic products from reactions of several carboxonium and carbosulfonium ions with the cyclic ketal 1,4-dioxa-spiro[4.5]decane

Reactant ion		Product ions *m/z* (relative abundance)							
Ion	*m/z*	Transacetalization	MH^+	$[M - H]^+$	$M^{+\cdot}$	$[M - C_2H_5]^+$ [a]	$[M - C_3H_7]^+$ [b]	Adduct	Others
1a	45	89 (11)	143 (32)	141 (7)	142 (26)	113 (22)	99 (100)	none	87 (83)
1b	59	103 (100), 73[c] (12)	143 (61)	141 (12)	none	113 (7)	none	none	87 (4)
1c	107	151 (24), 79[d] (21), 77[d] (3)	143 (100)	141 (6)	none	none	none	none	none
1d	59	none	143 (100)	141 (1)	142 (2)	113 (8)	99 (2)	none	none
1e[e]	121	none	143 (100)	141 (12)	none	none	none	none	91 (5)
1f	73	none	143 (100)	141 (5)	none	none	none	none	none
1g	113	none	143 (100)	141 (3)	none	113 (?)[f]	none	none	81 (8)
1h	71	115 (18)	143 (100)	141 (8)	none	none	99 (3)	213 (25)	none
1i	85	none	143 (100)	141 (1)	none	none	none	227 (22)	none
2a	61	105 (100), 75[c] (29)	143 (14)	141 (2)	none	113 (1)	99 (9)	none	none
2b	119	119 (100), 89[c] (10)	143 (8)	141 (1)	none	none	99 (9)	none	none
2c	123	167 (100), 137[c] (8)	143 (38)	141 (9)	none	none	99 (12)	none	none

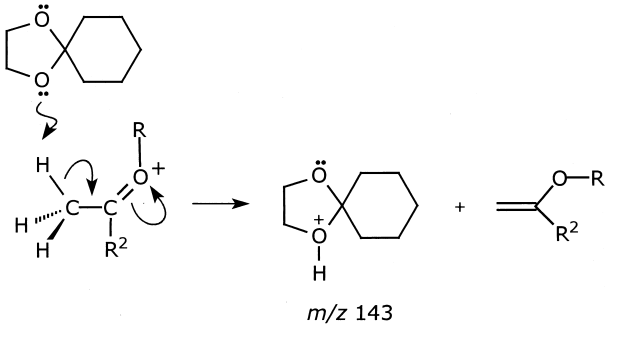
[a]Fragment ion formed from $M^{+\cdot}$ by the loss of an ethyl radical.
[b]MS^3 spectra show that *m/z* 99 is formed from dissociation of $M^{+\cdot}$, MH^+, and $[M - H]^+$.
[c]Product ions formed from the primary transacetalization product by formaldehyde loss (30 u), see Scheme **6a**.
[d]Fragments of the *m/z* 151 transacetalization product as shown by its MS^3 spectrum, see the text.
[e]Ion **1e** displays low reactivity toward 1,4-dioxa-spiro[4.5]decane, and a low conversion to products is observed.
[f]The $[M - C_2H_5]^+$ product of *m/z* 113 is isobaric with **1g**.

The prototype cyclic ions **1h** and **1i** are secondary carboxonium ions that bear acidic α-hydrogens and, as expected by now, they react predominantly with 1,4-dioxa-spiro[4.5]decane by proton transfer (Table 1). These two cyclic ions behave uniquely, however, as they form adducts with 1,4-dioxa-spiro[4.5]decane to medium extents, whereas adducts were not observed for the other carboxonium or carbosulfonium ions tested. To a minor extent, **1h** also reacts by transacetalization forming *m/z* 115, which is likely the bicyclic saturated dioxonium ion shown in Scheme **5**.

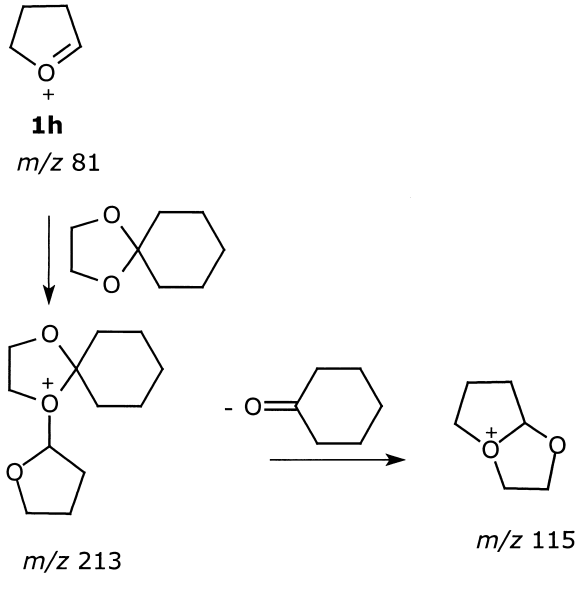
Competitive Reactions: Carboxonium Versus Carbosulfonium Ions

The product ion mass spectra for the analogous carboxonium and carbosulfonium primary ions summarized in Table 1 indicate greater transacetalization reactivity for carbosulfonium ions. Reactions of the ethyl-substituted analog ions **1b** and **2b** performed under comparable experimental conditions (it is difficult to reproduce with great accuracy the pressure of the neutral reactant in q2) indicate greater *overall* reactivity for **1b** but greater *transacetalization* reactivity for **2b**.

To further compare reactivity under the same experimental conditions, an equal mixture of **1b** and **2a** were reacted competitively with the neutral ketal. Although their O(S)-alkyl substituents differ (methyl versus ethyl) which may affect reactivity to some extent, their *m/z* ratios are close enough as to allow their simultaneous mass selection by Q1 when this quadrupole is set to operate at low resolution. Hence, both **1b** and **2a** in approximately equal amounts were simultaneously mass selected by Q1 (Figure 2a), and reacted in q2 with 1,4-dioxa-spiro[4.5]decane, therefore under the same



Scheme 4



Scheme 5

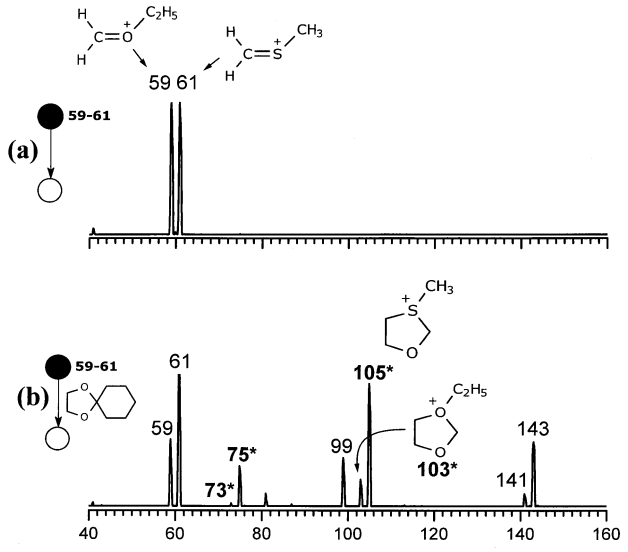


Figure 2. (**a**) Double stage (MS^2) product ion mass spectrum for an ionic beam constituted of an equal mixture of ions **1b** of *m/z* 59 and **2a** of *m/z* 61, and mass selected by Q1 operating at low resolution. (**b**) Double-stage (MS^2) product ion mass spectrum for reactions of the **1b**/**2a** ion beam with 1,4-dioxa-spiro[4.5]decane.

reaction conditions. As the resulting product ion mass spectrum shows (Figure 2b), the carboxonium ion **1b** is, overall, more reactive than the carbosulfonium ion **2a**; that is, **1b** of *m/z* 59 is consumed more rapidly than **2a** of *m/z* 61. But when transacetalization reactivity is compared, **2a** is far more reactive than **1b**: *m/z* 105 (and its fragment of *m/z* 75) are formed nearly five times as much as *m/z* 103 (and its fragment of *m/z* 73). Therefore, both the reactivity trends observed for **1b** and **2b** under similar reaction conditions and for **1b** and **2a** under the same reaction conditions indicate greater overall reactivity of carboxonium ions but much greater transacetalization reactivity of carbosulfonium ions.

The 2-substituent effect in cyclic acetals and ketals. Table 2 summarizes the product ion mass spectra for reactions of **2b** with 1,3-dioxolane and several of its 2-substituted analogs. With 1,3-dioxolane (R^1,R^2 = H), **2b** reacts little by transacetalization (*m/z* 119 and 89). The transacetalization mechanism (Scheme **3**) indicates that charge stabilizing 2-substituents should facilitate ring opening, and accordingly **2b** reacts more favorably by transacetalization with 2-methyl-1,3-dioxolane, but the effect of the 2-methyl substituent is minor. The 2-phenyl, 2,2-dimethyl, and 2,2-pentamethylene substituents are, however, much more effective as charge stabilizing substituents; hence they greatly favor transacetalization with **2b**: for them, *m/z* 119 is by far the most abundant product (Table 2).

Isomer Distinction

The contrasting reactivity of the isomeric carboxonium ions **1b** and **1d** toward 1,4-dioxa-spiro[4.5]decane exemplifies the use of transacetalization to distinguish structural isomers. Ion **1b** is a *primary* O-ethyl substituted carboxonium ion with no acidic α-hydrogens, whereas **1d** is a *secondary* C-methyl substituted carboxonium ion with acidic α-hydrogens. Accordingly, **1b** reacts readily with 1,4-dioxa-spiro[4.5]decane by transacetalization (Figure 1a, Table 1), whereas **1d** reacts predominantly by proton transfer (Table 1).

Triple-Stage (MS^3) Scans

For structural assignments, triple-stage (MS^3) sequential product ion mass spectra were recorded for the transacetalization products. Figure 3 displays some representative examples of the resulting spectra, whereas the others are summarized in the text that follows. In general, the transacetalization products of the acyclic primary ions show a major and characteristic dissociation by 30 u loss, likely by formaldehyde loss (Scheme **6a**). Accordingly, the transacetalization product of **1a** of *m/z* 89 dissociates to *m/z* 59 (Figure 3a), that of **1b** of *m/z* 103 to 73 (Figure 3b); that of **2a** of *m/z* 105 to 75 [*m/z* 75 (100%), *m/z* 47 (8%), *m/z* 41 (7%)], that of **2b** of *m/z* 119 to 89 (Figure 3c), and that of **2c** of *m/z* 167 to

Table 2. Major ionic products from reactions of the carbosulfonium ion $H_2C{=}S^+{-}C_2H_5$ (**2b**) of *m/z* 75 with several cyclic acetals and ketals[a]

Neutral reactant[a]		Product ions *m/z* (relative abundance)				
R^1	R^2	Transacetalization[b]	MH^+	$[M - H]^+$	$[M - R]^+$	Others
H	H	119 (4), 89 (8)	75 (?)[c]	73 (100)	···	147 (13)[d]
H	CH_3	119 (10), 89 (?)[e]	89 (42)[e]	87 (100)	73 (3)	none
H	Ph	119 (100), 89 (92)	151 (42)	149 (8)	none	91 (12)
CH_3	CH_3	119 (100), 89 (18)	103 (52)	101 (3)	87 (4)	none

[a]For the product ions from reactions of **2b** with 1,4-dioxa-spiro[4.5]decane [R^1, R^2 = $(CH_2)_5$], see Table 1.
[b]The product of *m/z* 89 is formed by formaldehyde loss from the primary transacetalization product of *m/z* 119, see Scheme **6a**.
[c]The MH^+ product ion of *m/z* 75 is isobaric with the reactant ion **2b**.
[d]The proton bound dimer of the neutral reactant, a secondary product of proton transfer.
[e]The *m/z* 89 secondary product of transacetalization[b] is isobaric with MH^+, but it is likely that most of *m/z* 89 is composed of MH^+.

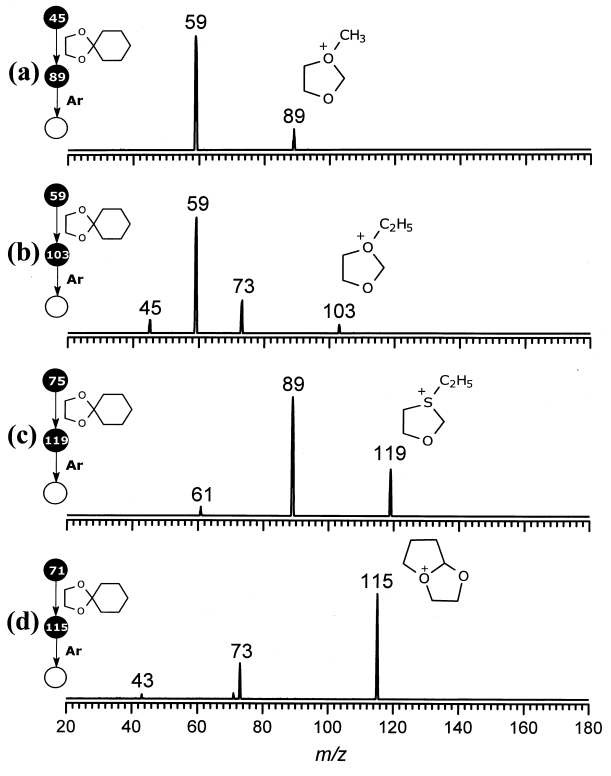
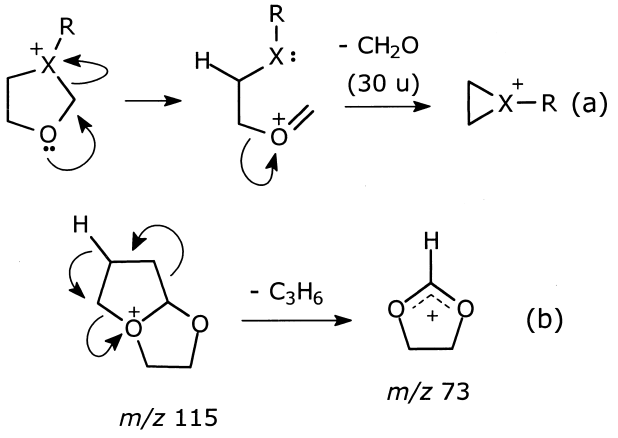


Figure 3. Triple-stage (MS^3) sequential product ion mass spectra of the transacetalization products formed in reactions with 1,4-dioxa-spiro[4.5]decane of (**a**) **1a**, (**b**) **1b**, (**c**) **2b**, and (**d**) **1h**.

137 [*m/z* 137 (100%), *m/z* 109 (3%)]. The only exception to this dissociation trend is observed for the transacetalization product of **1c** of *m/z* 151; likely it dissociates to *m/z* 107 (21%) by reforming the reactant ion; to protonated benzene of *m/z* 79 (72%), to the phenyl cation of *m/z* 77 (100%), and to the 1,3-dioxolanylium ion of *m/z* 73 (22%) by benzene loss. As expected from its bicyclic structure, the 1,3-dioxonium ion of *m/z* 115 formed by transacetalization with **1h** also dissociates distinctively (Figure 3d); it is more resistant toward dissociation, and forms mainly *m/z* 73 by C_3H_6 loss (Scheme **6b**).



Scheme 6

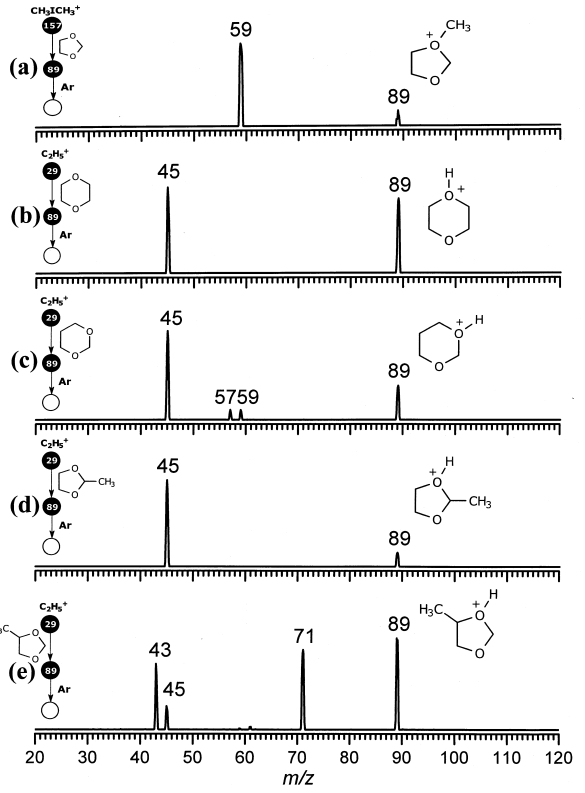


Figure 4. Triple-stage (MS^3) sequential product ion mass spectra of (**a**) the authentic O-methyl-1,3-dioxolanium ion of *m/z* 89 formed by reactions of $CH_3ICH_3^+$ with 1,3-dioxolane; and of isomeric ions formed by proton transfer from $C_2H_7^+$ to (**b**) 1,4-dioxane, (**c**) 1,3-dioxane, (**d**) 2-methyl-1,3-dioxolane, and (**e**) 4-methyl-1,3-dioxolane.

Authentic and isomeric ions. MS^3 CID scans were also performed for two authentic ions (ions with predictable structures formed by independent routes) and for four isomeric ions. The O-methyl and O-ethyl-1,3-dioxolanium ions were generated by reacting either the Q1-mass selected $CH_3ICH_3^+$ or $C_2H_5IC_2H_5^+$ ions (major ions in the CI plasma of methyl and ethyl iodide, respectively) [19] with neutral 1,3-dioxolane in q2, and by dissociating the resulting O-alkylated ions in q4 via 15 eV collisions with argon. The resulting sequential product ion mass spectra acquired by scanning Q5 are displayed in Figures 4a and 5, and they closely resemble

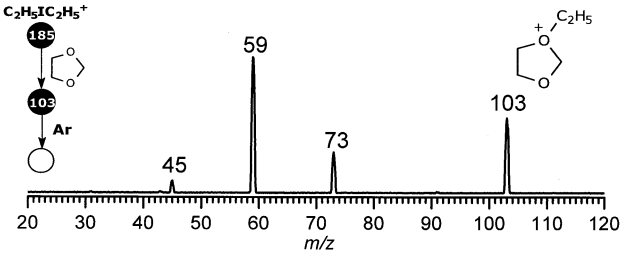


Figure 5. Triple-stage (MS^3) sequential product ion mass spectrum of the authentic O-ethyl-1,3-dioxolanium ion of *m/z* 103 formed by reactions of $C_2H_5IC_2H_5^+$ with 1,3-dioxolane.

those of the corresponding transacetalization products displayed in Figure 3a,b.

Four isomeric ions of *m/z* 89 were also formed by proton transfer from $C_2H_5^+$ and their triple-stage CID mass spectra collected. Compared with the spectra of the *m/z* 89 transacetalization product (Figure 3a), the spectra of Figure 4b–e greatly differ. These findings for both authentic and isomeric ions provide therefore solid evidence for the proposed structures of the transacetalization products of carboxonium and carbosulfonium ions and, consequently, for the transacetalization mechanism depicted in Scheme **3** (Figure 4b–e).

Selective O- and S-alkylation of oxathiolanes. Two attempts were made to generate the authentic S-ethyl-1,3-oxathiolanium ion of *m/z* 109: (i) by C_2H_5I CI of 1,3-oxathiolane and (ii) by reactions in q2 of $H_5C_2IC_2H_5^+$ with the neutral ketal. In both experiments, an ion of *m/z* 119 was formed and its CID spectrum recorded. The double-stage CID mass spectrum for the CI-generated *m/z* 119 ion (Figure 6a) shows the same fragments of *m/z* 89 and 61 as those seen in Figure 3c, but a third fragment of *m/z* 59 is also observed. This *m/z* 59 fragment indicates that the O-ethylated ion was also formed; hence that both S- and O-ethylation of 1,3-oxathiolane occurs at the less gentle CI conditions. The triple-stage CID mass spectrum of the ion generated by $H_5C_2IC_2H_5^+$ reactions (Figure 6b) closely resembles that of Figure 3c indicating that selective S-alkylation of 1,3-oxathiolane occurs via reactions with mass-selected $H_5C_2IC_2H_5^+$, and that the S-ethyl-1,3-oxothiolanium ion is formed exclusively by transacetalization of **2b** with 1,4-dioxa-spiro[4.5]decane.

Then, an attempt was made to form selectively the O-ethyl-1,3-oxathiolanium ion by transacetalization of **1b** with 1,3-oxathiolane via preferential S-alkylation [6b]. The desired product ion of *m/z* 119 was formed and, upon CID, it dissociates little to *m/z* 89 and mainly to *m/z* 59 (Figure 6c). When Figure 6c and 3c are compared with Figure 6a,b, it is concluded that transacetalization of 1,3-oxathiolane with the carboxonium ion **1b** indeed formed the desired O-ethylated ion; hence that transacetalization with either carboxonium or carbosulfonium ions forms selectively *either* O- or S-alkyl 1,3-oxathiolanium ions.

Consecutive +44 u neutral gain/−30 u neutral loss MS^3 scan. The triple-stage (MS^3) mass spectra just discussed show that most of the O-alkyl substituted primary carboxonium and carbosulfonium ions form transacetalization products that dissociate upon CID by formaldehyde loss. Acylium ions form, instead, transacetalization products that dissociate to reform the reactant ion [6]; and a consecutive +44 u neutral gain/−44 u neutral loss MS^3 scan [15] (Scheme **7**) has been proposed and used for their identification [14]. Thiacylium ions behave uniquely because they form +44 u transacetalization products but these products dissociate upon CID to form the O-analog acylium ion by

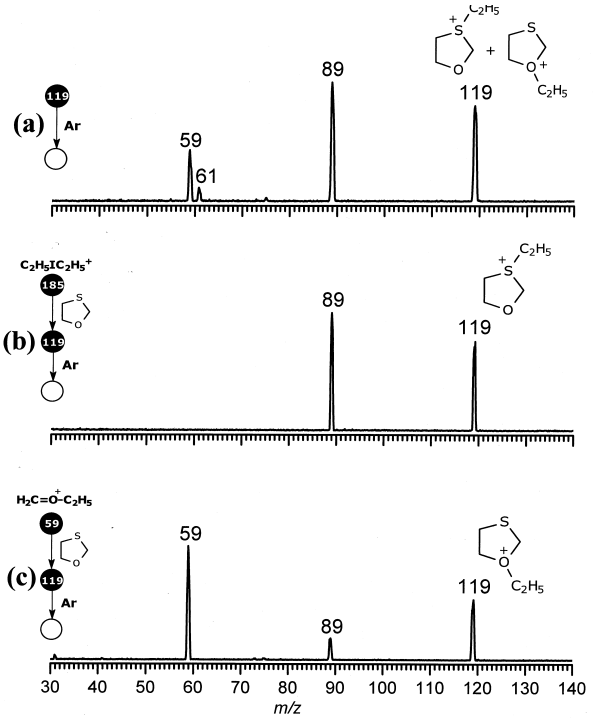
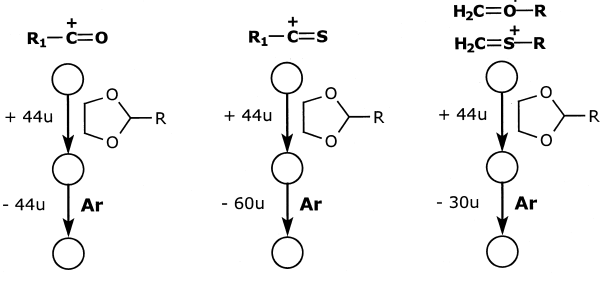


Figure 6. (**a**) Double-stage (MS^2) product ion mass spectrum of the *m/z* 119 ion formed by ethyl iodide CI of 1,3-oxathiolane. Triple-stage (MS^3) sequential product ion mass spectra of the *m/z* 119 ion formed: (**b**) by ethylation of 1,3-oxathiolane with $C_2H_5IC_2H_5^+$ and (**c**) by transacetalization of **2b** with 1,3-oxathiolane.

S-by-O replacement, thus thioacylium ions are identified by a +44 u neutral gain/−60 u neutral loss MS^3 scan (Scheme **7**) [8, 14]. Yet, as the present results show, several O-alkyl substituted primary and acyclic carboxonium and carbosulfonium ions can be identified by a +44 u neutral gain/−30 u neutral loss scan (Scheme **7**).

Figure 7b exemplifies a +44 u neutral gain/−30 u neutral loss scan used to screen carbosulfonium ions among the ions formed by 70 eV EI of diethylsulfide (Figure 7a), that is, those responding to the +44 u/−30 u test. Ion **2b** of *m/z* 75 and its ^{33}S (*m/z* 76) and ^{34}S (*m/z* 77) isotopomers respond readily to the test. Two other carbosulfonium ions are also identified: those of *m/z* 61 and 47. Straightforward dissociation mechanisms [20]



Scheme 7

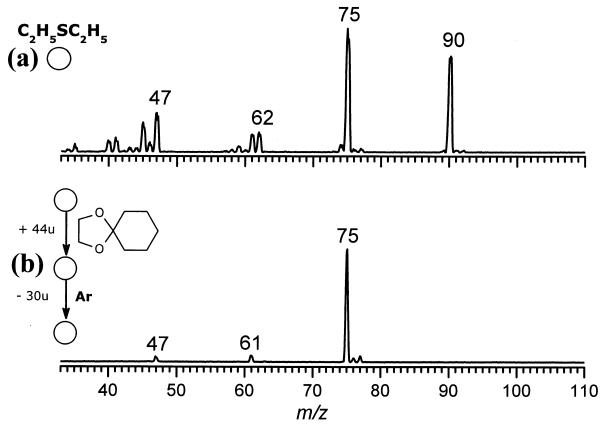


Figure 7. (**a**) 70 eV EI mass spectrum (70 eV EI) of ethyl disulfide and (**b**) triple-stage (MS^3) consecutive +44 u neutral gain/−30 u neutral loss spectrum for the 70 eV EI ions of ethyl disulfide acquired when performing reactions with 1,4-dioxaspiro[4.5]decane in q2 and 15 eV CID with argon in q4.

for ionized diethyl sulfide can account for formation of protonated thioacetaldehyde, CH_3–HC=SH^+ of *m/z* 61, and protonated thioformaldehyde, H_2C=SH^+ of *m/z* 47.

Ab Initio Calculations: Reaction Enthalpies

Figure 8 shows a potential energy surface diagram for a model reaction, that of the carbosulfonium ion **2b** with the parent cyclic acetal: 1,3-dioxolane. Because the related acylium ions are known to react with five- and six-membered acetals and ketals by transacetalization [6], and with seven-membered cyclic acetals by ring

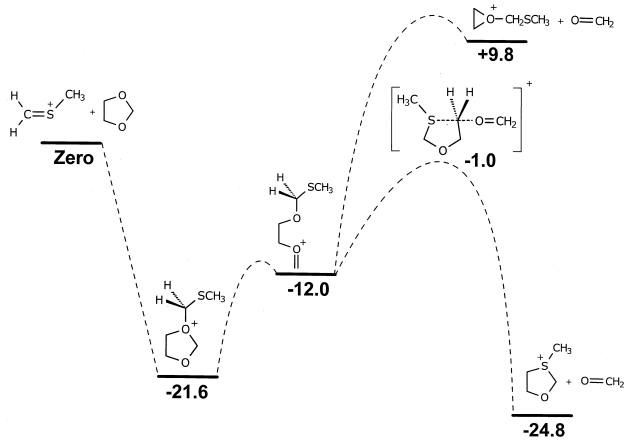


Figure 8. MP2/6-31G(*d*,*p*)//HF/6-31G(*d*,*p*) + 0.89ZPE ab initio potential energy surface diagram for reaction of **2b** with 1,3-dioxolane. Some energy barriers are indicated, but only that for the crucial ring-closure step via intramolecular formaldehyde displacement was calculated. The MP2/6-31G(*d*,*p*)//HF/6-31G(*d*,*p*) and ZPE energies for the species are: **2b** (−472.21222; 0.06868), 1,3-dioxolane (−267.48296; 0.10046), O-alkylated intact adduct (−743.72944; 0.17500), acyclic adduct (−743.73450; 0.13867), TS (−743.69401; 0.16883), S-methyl-1,3-oxathiolanium ion (−629.57901; 0.13867), ring-contraction product ion (−629.52415; 0.13658), formaldehyde (−114.15548; 0.02898).

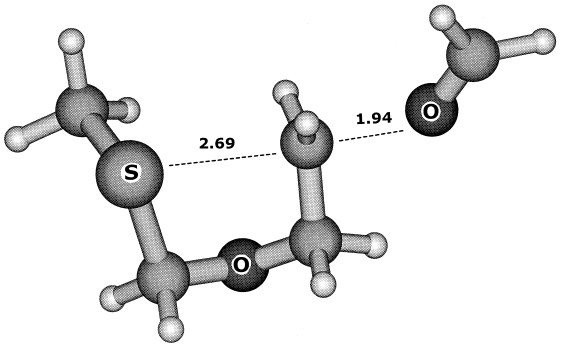


Figure 9. HF/6-31G(*d*,*p*) optimized structure for the transition state of the final ring-closure step of transacetalization of **2b** with 1,3-dioxolane.

contraction [7], the energetics of these two competitive reactions were calculated. Addition of **2b** to 1,3-dioxolane is predicted to be exothermic by −21.6 kcal/mol, and ring opening of the O-alkylated adduct is overall exothermic by −12.0 kcal/mol. Then, transacetalization that forms the cyclic S-methyl-1,3-oxathiolanium ion is kinetically favored since it proceeds via a five-membered TS (characterized by a negative vibrational frequency of −382 cm^{-1}, see its optimized structure in Figure 9) which is placed −1.0 kcal/mol below the reactants and is exothermic by −24.8 kcal/mol. Ring contraction via a three-membered TS and O-intramolecular formaldehyde displacement is, however, endothermic by +9.8 kcal/mol and therefore its is both kinetically and thermodynamically unfavorable. As observed, therefore, transacetalization should dominate.

Conclusion

Primary carboxonium and carbosulfonium ions and the prototype five-membered cyclic carboxonium ion react in the gas phase by transacetalization with cyclic acetals and ketals to form the respective O-alkyl-1,3-dioxolanium and S-alkyl-1,3-oxothiolanium ions. Carbosulfonium ions are, by transacetalization, much more reactive than carboxonium ions. Secondary and tertiary ions bearing acidic α-hydrogens react predominantly by proton transfer, and transacetalization is either suppressed or occurs to a minor extent. Transacetalization serves therefore as a tool to distinguish primary from secondary and tertiary ions, hence to distinguish structural isomers of both carboxonium and carbosulfonium ions. Because most of the transacetalization product ions dissociate by formaldehyde loss, a +44 u neutral gain/−30 u neutral loss MS^3 scan can be used to screen for primary carboxonium and sulfonium ions. Transacetalization of cyclic acetals and ketals with carbosulfonium ions provides a route to 1,3-oxathiolanes and analogs selectively alkylated either at the sulfur or oxygen atom. EI of methyl ethyl sulfide is known to form mostly 2a and a minor amount of an isomer [21]. A recent FT-MS study [22] has provided evidence for

the co-generation of triplet $CH_3CH_2S^+$, an ion with relatively high recombination energy. The minor $[M - C_2H_5]^+$ and $[M - C_3H_7]^+$ productions (Table 1) may be formed, therefore, by electron transfer to $CH_3CH_2S^+$ and dissociation of the nascent $M^{+\cdot}$ ions.

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