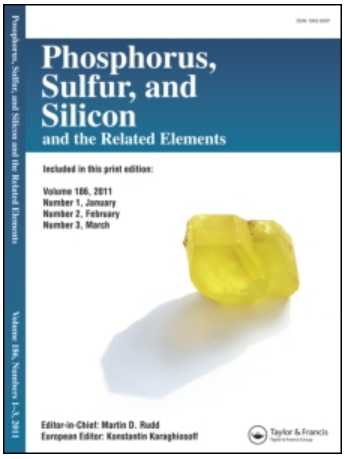

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GAS PHASE CHEMISTRY OF SULFONATE ANIONS: BASICITIES AND FRAGMENTATION REACTIONS[1]

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The gas phase relative acidities of 15 sulfonic acids, RSO_3H, have been determine via Cooks' kinetic method. The following acidity scale was established (starting with the weakest acid): methane sulfonic acid < ethane sulfonic acid < methoxy sulfonic acid < sulfuric acid < m-aminobenzene sulfonic acid ≈ p-aminobenzene sulfonic acids < p-toluene sulfonic acid < benzene sulfonic acid < o-aminobenzene sulfonic acid < 5-sulfosalicylic acid < o-nitrobenzene sulfonic acid < cysteic acid < m-aminobenzene sulfonic acid < p-nitrobenzene sulfonic acid < triflic acid. In addition the gas phase fragmentation reactions of the conjugate bases, the sulfonate anions RSO_3^-, have been studied using MS/MS techniques. A general loss of R, resulting in the formation of the radical anion $SO_3^{\cdot -}$ is observed in all cases. Other fragmentation pathways are discussed in detail.

Keywords: Gas Phase Acidities; Sulfonic Acids; Cooks' Kinetic Method; Sulfonate Anions; Tandem Mass Spectrometry; Collision Induced Dissociation

INTRODUCTION

Sulfonic acids and their derivatives play an important role in chemistry.[2] For example the conjugate bases, the sulfonates, are used as anionic surfactants while triflates, mesylates and tosylates all make use of the excellent leaving group RSO_3^-. Our interest in sulfonic acids is twofold: (i) which of the sulfonic

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acids are super acids (i.e. stronger acids than sulfuric acid) in the gas phase?[3,4] and (ii) what are the gas phase fragmentation reactions of sulfonate anions (RSO_3^-) under tandem mass spectrometric (MS/MS) conditions?[5–7]

The first question can be addressed via a number of experimental techniques which indirectly measure the gas phase aciditiy of a sulfonic acid (defined in eq. 1).

$$RSO_3H \xrightarrow{\Delta G^{\circ}_{acid}} RSO_3^- + H^+ \quad (1)$$

The types of techniques available include:

(a) Bracketing methods using a selected ion flow tube (SIFT), which involves examining the occurrence or non occurrence of proton transfer reactions (eq. 2 and eq. 3) using a series of reference compounds (AH) of known gas phase acidity;

$$A^- + RSO_3H \longrightarrow AH + RSO_3^- \quad (2)$$

$$RSO_3^- + AH \longrightarrow RSO_3H + A^- \quad (3)$$

(b) Equilibrium techniques using a Fourier transform ion cyclotron resonance (FT-ICR) mass spectrometer, in which an equilibrium constant is determined for proton transfer involving an acid (AH) of known gas phase acidity (eq. 4);

$$A^- + RSO_3H \overset{K_{eq}}{\rightleftharpoons} AH + RSO_3^- \quad (4)$$

(c) Cooks' kinetic method. This involves studying the competing fragmentation reactions of a series of mass selected dimer cluster ions $[RSO_3^-...H^+...^-O_3SR']^-$. The relative abundance (I) of each of the product sulfonate anions RSO_3^- (eq. 5) and $R'SO_3^-$ (eq. 6) observed correlates with the relative acidities of RSO_3H and $R'SO_3H$ via eq. 7.[8]

The second question can be addressed by examining the collision induced dissociation (CID) reactions of the sulfonate anions via standard tandem mass spectrometric (MS/MS) techniques.[5] Part of our interest in these MS/MS studies is to evaluate their analytical use in determining the structure of sulfonate anions. Thus we have chosen a range of sulfonic acids including aliphatic, alkoxy, aromatic as well as cysteic acid, as a model of fully oxidized cysteine residues in peptides and proteins. Previous studies have shown that a common fragmen-

$$[RSO_3^- \ldots\ldots H^+ \ldots\ldots {}^-O_3SR'] \rightarrow RSO_3^- + R'SO_3H \quad (5)$$

$$[RSO_3^- \ldots\ldots H^+ \ldots\ldots {}^-O_3SR'] \rightarrow R'SO_3^- + RSO_3H \quad (6)$$

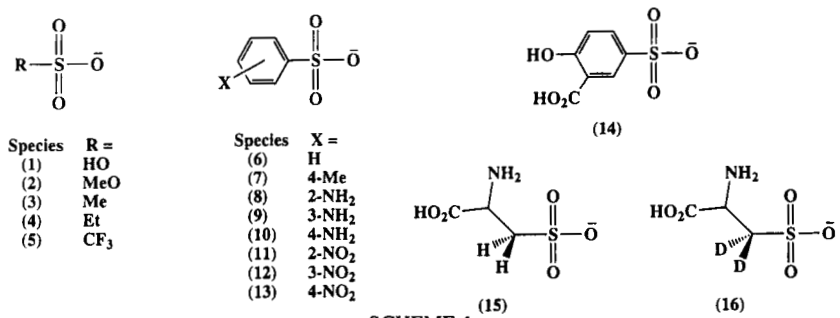
$$\ln\left(\frac{I_{RSO_3^-}}{I_{R'SO_3^-}}\right) = \frac{\Delta G^o_{acid}(RSO_3H) - \Delta G^o_{acid}(R'SO_3H)}{RT} \quad (7)$$

tation reaction of sulfonate anions (RSO_3^-) occurs via homolytic bond cleavage with the general loss of the substituent R and the formation of the radical anion of $SO_3^{\cdot -}$ (eq. 8).

$$RSO_3^- \rightarrow R\cdot + SO_3^{\cdot -} \quad (8)$$

RESULTS AND DISCUSSION

All experiments were performed on a VG Autospec-Q instrument (see experimental section for details). The sulfonate anions that were studied are shown in scheme 1.



Species	R =
(1)	HO
(2)	MeO
(3)	Me
(4)	Et
(5)	CF_3

Species	X =
(6)	H
(7)	4-Me
(8)	2-NH_2
(9)	3-NH_2
(10)	4-NH_2
(11)	2-NO_2
(12)	3-NO_2
(13)	4-NO_2

(14) (15) (16)

SCHEME 1

(a) Relative Gas Phase Acidities of Sulfonic Acids

The relative gas phase acidities of the 15 sulfonic acids (Scheme 1) were determined in a series of MS/MS experiments on the mixed dimer cluster ions $[RSO_3^- \ldots H^+ \ldots {}^-O_3SR']^-$, which were formed via FAB/MS. A typical MIKE spectrum is shown in figure 1 for the dimer cluster ion formed from methane

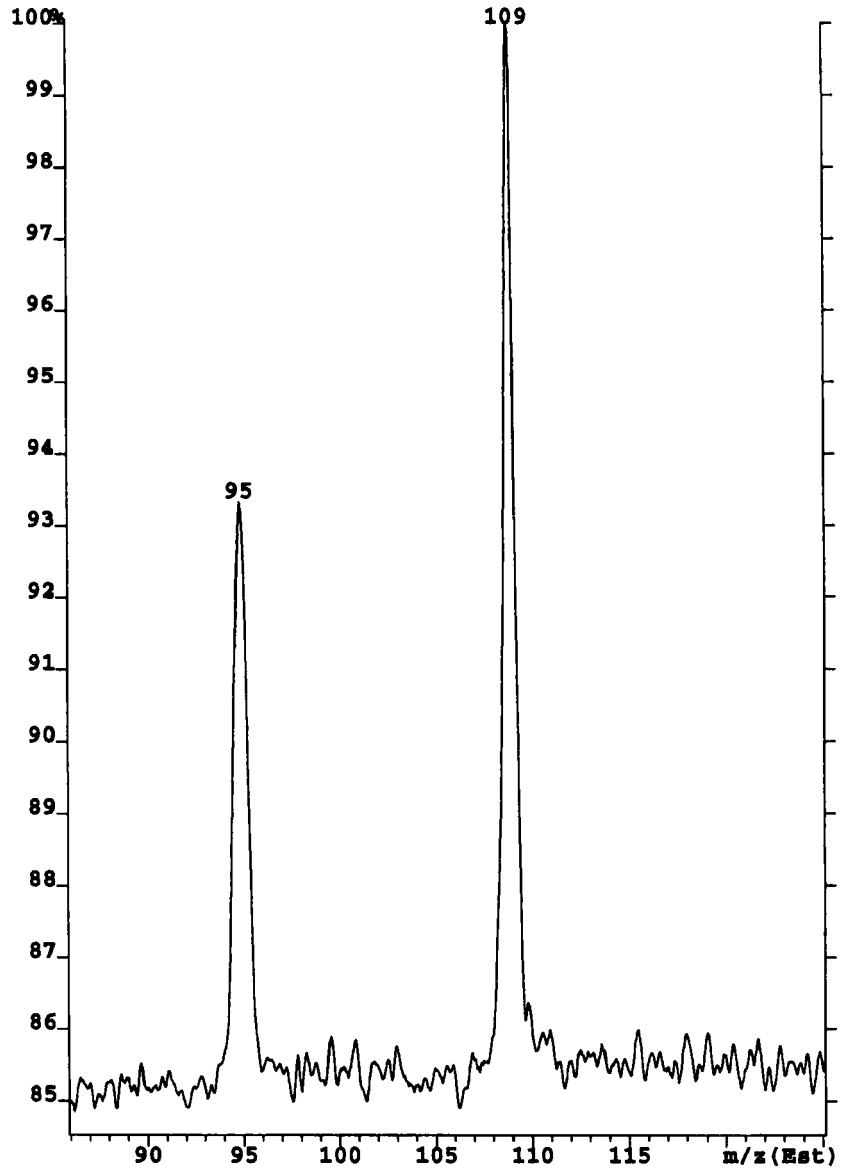


FIGURE 1 Unimolecular MIKE spectrum of the dimer ion $[CH_3SO_3^-...H^+...^-O_3SCH_2CH_3]^-$ formed via FAB.

sulfonic acid and ethane sulfonic acid. The ion $CH_3CH_2SO_3^-$ (*m/z* 109) is more abundant than $CH_3SO_3^-$ (*m/z* 95), indicating that $CH_3CH_2SO_3H$ is a stronger acid than CH_3SO_3H. The results of the related experiments are listed in Table I.

Based upon these experimental results, the following acidity scale is proposed (starting with the weakest acid): methane sulfonic acid < ethane sulfonic acid < methoxy sulfonic acid < sulfuric acid < m-aminobenzene sulfonic acid ≈ p-aminobenzene sulfonic acids < p-toluene sulfonic acid < benzene sulfonic acid < o-aminobenzene sulfonic acid < 5-sulfosalicyclic acid < o-nitrobenzene sulfonic acid < cysteic acid < m-aminobenzene sulfonic acid < p-nitrobenzene sulfonic acid < triflic acid. This acidity ranking is similar to those of the analogous carboxylic acids except for the p-toluene and benzene sulfonic acids which show a reverse order.[9]

It is interesting to note that an ortho substituent can either increase or decrease the acidity relative to the meta and para isomers. Thus while o-aminobenzene sulfonic acid is a stronger acid than m- and p-aminobenzene sulfonic acids, o-nitrobenzene sulfonic acid is a weaker acid than m- and p-nitrobenzene sulfonic acids. A possible explaination is shown in scheme 2. In the first case, a hydrogen donor in the ortho position can help stabilize the sulfonate anion (i.e. product) via intramolecular hydrogen bonding, thereby increasing the acidity

TABLE I MIKE spectra of the sulfonate anion dimer cluster ions, $[RSO_3^-...H^+...^-O_3SR']^-$

R =	*R'* =	$[RSO_3^-]^a$	$[R'SO_3^-]^b$
Et	Me	100	54.7
MeO	Et	100	<5
HO	MeO	100	15.9
m-NH_2Ph	HO	100	24.6
p-NH_2Ph	HO	100	22.0
p-CH_3Ph	HO	100	5.3
Ph	p-NH_2Ph	100	37.1
Ph	m-NH_2Ph	100	48.3
Ph	p-CH_3Ph	100	57.8
o-NH_2Ph	Ph	100	16.8
1-CO_2H-4-OH-5-$SO_3HC_6H_3$	o-NH_2Ph	100	<5
o-NO_2Ph	1-CO_2H-4-OH-5-$SO_3HC_6H_3$	100	52.2
$CO_2CH(NH_2)CH_2$	1-CO_2H-4-OH-5-$SO_3HC_6H_3$	100	21.8
$CO_2CH(NH_2)CH_2$	o-NO_2Ph	100	11.4
m-NO_2Ph	$CO_2CH(NH_2)CH_2$	100	69.8
p-NO_2Ph	$CO_2CH(NH_2)CH_2$	100	12.6
CF_3	m-NO_2Ph	100	6.1
CF_3	p-NO_2Ph	100	10.2

[a] $[RSO_3^-]$ represents the relative peak intensity of RSO_3^- in the MIKE spectrum; [b] $[R'SO_3^-]$ represents the relative peak intensity of $R'SO_3^-$ in the MIKE spectrum.

relative to the meta and para isomers. In the second case, a hydrogen acceptor in the ortho position can help stabilize the sulfonic acid (i.e. reactant) via intramolecular hydrogen bonding, thereby decreasing the acidity relative to the meta and para isomers. Similar observations have been made for the gas phase acidities of substitued benzoic acids and have been rationalized in terms of a number of effects including intramolecular hydrogen bonding and steric inhibition of resonance.[9]

(b) CID Fragmentation Reactions of Sulfonate Anions

The CID fragmentation reactions (Ar gas, 70% parent beam attenuation) of the sulfonate anions **1–16** were studied in a series of FAB MS/MS experiments. The resultant MIKE spectra of the anions **1–15** are listed in Table II, while that of **16** (2,2-[$^2H_2$] cysteic acid) is shown in figure 2.

All sulfonate anions examined in this study fragment via the loss of the substituent R with concomitant formation of $SO_3.^-$ (eq. 8). In addition, all of the non aromatic sulfonate anions also fragment via homolytic bond cleavage of the adjacent bond as shown in eq. 9. This latter cleavage varies from being a major pathway for deprotonated sulfuric acid to being a minor pathway for the ethane

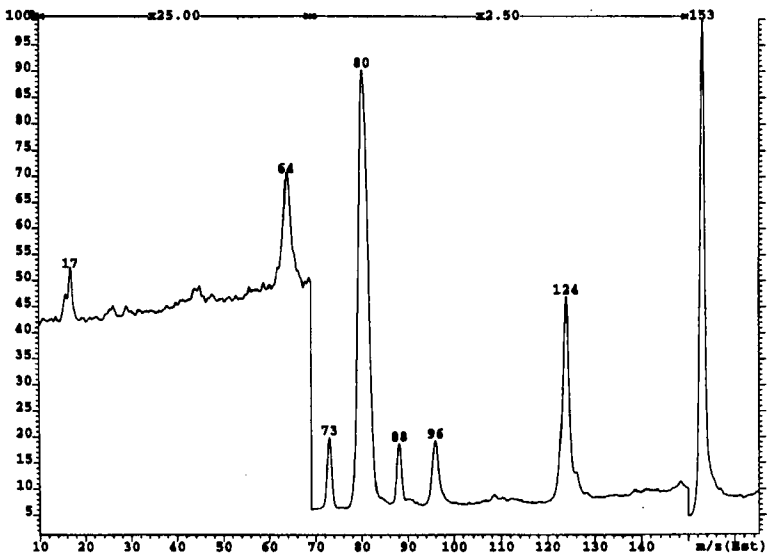


FIGURE 2 CID MIKE spectrum of deprotonated 2,2-[$^2H_2$] cysteic acid formed via FAB.

TABLE II CA/MS/MS spectra of the sulfonate anions, RSO_3^-

$[M - H]^-$ Ion, m/z	*CA/MIKE Spectra [m/z* (abundance)]
(1), 97	96 (100); 80 (46); 64 (*); 48 (*)
(2), 111	97 (18); 96 (99); 80 (100)
(3), 95	94 (52); 80 (100); 64 (1)
(4), 109	107 (22); 94 (2); 91 (1); 80 (100); 64 (*)
(5), 149	130 (6); 99 (35); 83 (12); 80 (100); 69 (6); 64 (1); 19 (4)
(6), 157	141 (3); 93 (100); 80 (92); 64 (2)
(7), 171	156 (38); 107 (100); 80 (74); 64 (2)
(8), 172	156 (10); 144 (16); 108 (100); 80 (94); 64 (2)
(9), 172	156 (36); 144 (32); 124 (10); 108 (100); 80 (92); 64 (3)
(10), 172	156 (45); 144 (13); 124 (10); 108 (91); 80 (100); 64 (3)
(11), 202	186 (16); 172 (11); 156 (100); 144 (3); 138 (4); 122 (1); 108 (3); 91 (3); 80 (14); 64 (1); 46 (2)
(12), 202	186 (21); 172 (33); 156 (100); 144 (6); 138 (9); 122 (1); 108 (2); 91 (*); 80 (13); 64 (*); 46 (*)
(13), 202	186 (18); 172 (18); 156 (100); 144 (3); 138 (26); 122 (3); 108 (11); 91 (1); 80 (13); 64 (1); 46 (1)
(14), 217	199 (100); 171 (8); 153 (*); 143 (2); 137 (11); 119 (*); 109 (1); 93 (*); 80 (2); 64 (*).
(15), 168	151 (100); 124 (2); 122 (12); 94 (3); 86 (5); 80 (24); 71 (5); 64 (*); 17 (*).

*abundance of ion is less than 1% of the base peak.

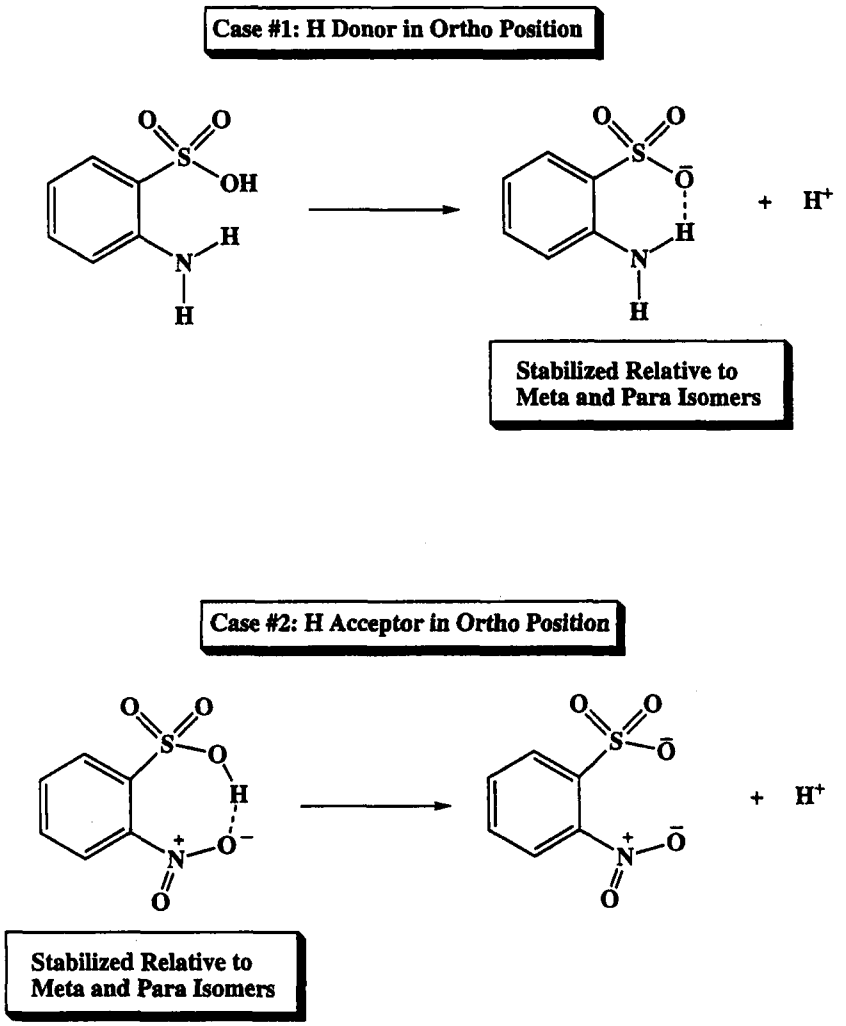
sulfonate anion and deprotonated cysteic acid. The methyl sulfate anion also fragments via loss of $:CH_2$ (eq. 10), which is directly related to one of the fragmentation channels for phosphonate anions.[10]

$$RXSO_3^- \rightarrow R\cdot + XSO_3^- \tag{9}$$

$$CH_3OSO_3^- \rightarrow CH_2: + HOSO_3^- \tag{10}$$

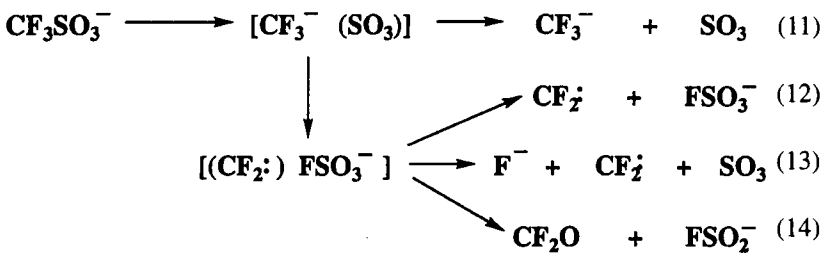
The triflate anion undergoes an additional series of reactions, which can be best rationalized by invoking a mechanism in which an ion-molecule complex $[CF_3^-(SO_3)]$ (**A**) initially forms.[11] Fragmentation of this complex results in the formation of the products shown in eq. 11, while fluoride ion transfer results in the formation of a new ion-molecule complex $[FSO_3^-(:CF_2)]$ (**B**). The products of eqs. 12–14 all result from the subsequent reactions of the second complex (**B**).

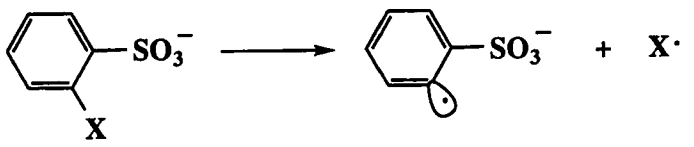
The deprotonated aromatic sulfonic acids undergo several different fragmentation pathways, including loss of SO_2 via a rearrangement reaction. Possible mechanisms for this type of rearrangement reaction have been previously discussed by Binkley et al.[7d] In addition, all of the nitro sulfonate anions undergo loss of NO. Indeed anions derived from many nitroaromatic compounds undergo similar losses of NO, which are also thought to proceed via rearrangement reactions.[12]



SCHEME 2

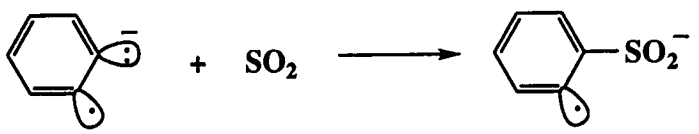
With the exception of deprotonated 5-sulfosalicyclic acid, all of the substituted aromatic sulfonate anions (where the substituent is either NH_2, CH_3, or NO_2) undergo a general loss of the substituent (NH_2, CH_3, or NO_2) to form a distonic radical anion $C_6H_4SO_3^{\cdot -}$ (e.g. eq. 15). The related distonic radical anion $C_6H_4SO_2^{\cdot -}$ has been formed via an ion-molecule reaction (eq. 16).[13] These ions belong to a general class of ions which have recently been called "charged phenyl radicals".[14]





(15)

(X = NH_2 and NO_2)

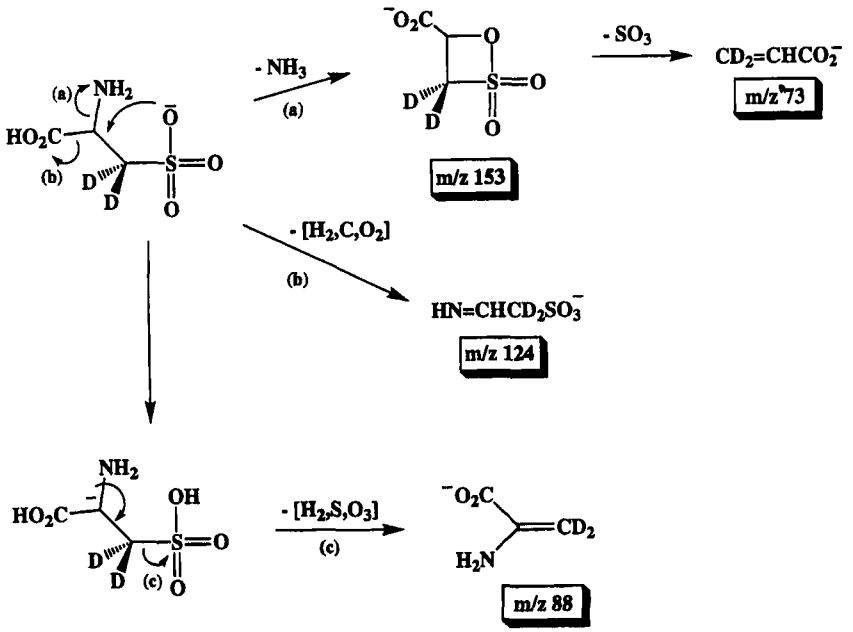


(16)

Deprotonated 2,2-[$^2H_2$] cysteic acid undergoes several fragmentation reactions, including those described for other sulfonate anions (eqs. 8 and 9). Possible mechanism for the fragmentation reactions which are unique to deprotonated 2,2-[$^2H_2$] cysteic acid are shown in scheme 3. Pathways (**a**) and (**b**) (Scheme 3) proceed via intramolecular displacement reactions involving the SO_3^- group. In contrast, pathway (**c**) involves initial intramolecular proton transfer to form the enolate anion which subsequently undergoes fragmentation. The loss of H_2S from deprotonated cysteine may proceed via a related mechanism.[15] Note that for pathways (**b**) and (**c**), the nature of the neutral(s) lost are unknown since our experiments do not analyze and detect the neutral fragments. Thus the neutral(s) lost via pathway (**b**) could either be formic acid or H_2O and CO.

EXPERIMENTAL SECTION

All experiments were performed on a VG Autospec-Q instrument of E1BE2qQ geometry (where E = electric sector, B = magnetic sector, q = RF only quadrupole and Q = quadrupole). Dimer clusters with the general formula of $[RSO_3^-...H^+...^-O_3SR']^-$ were formed from a 1:1 mixture of the sulfonic



SCHEME 3

acids via fast atom bombardment (FAB, cesium ion gun operating at 25 kV, glycerol matrix), mass selected using E1B and the metastable fragments were then analyzed using unimolecular MIKES by scanning E2. Using the same range of sulfonic acids, the fragmentation patterns of the monomer sulfonate anions (RSO_3^-) were investigated via FAB/MS/MS techniques. Sulfonate anions, RSO_3^-, were formed from the corresponding sulfonic acid via FAB (cesium ion gun operating at 25 kV, glycerol matrix). CA/MIKES was performed using CID (Ar gas) with attenuation of the parent RSO_3^- ion beam by 70%.

All reagents were commercially available and were used without further purification. All other compounds were synthesized via known literature procedures.[16] For example, 2,2-[$^2H_2$] cysteic acid was formed via oxidation of 2,2-[$^2H_2$] cysteine (Cambridge Isotope Laboratories, 98% D).[16a]

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References

[1] Presented at the 43rd ASMS conference: J. D. Smith, R. A. J. O'Hair, J. A. R. Schmidt and T. D. Williams, *Proceedings of the 43rd ASMS Conference on Mass Spectrometry and Allied Topics*, Atlanta, Georgia, May 21–26, p. 1035, (1995).

[2] S. Patai, Z. Rappoport, Eds *The Chemistry of Sulfonic Acids, Esters and their Derivatives*, Wiley, New York, (1991).

[3] A. A. Viggiano, M. J. Henchman, F. Dale, C. A. Deakyne and J. F. Paulson, *J. Am. Chem. Soc.*, **114**, 4299, (1992).

[4] I. A. Koppel, R. W. Taft, F. Anvia, S. Zhu, L. Hu, K. Sung, D. D. DesMarteau, L. M. Yagupolskii, Y. L. Yagupolskii, N. V. Ignat'ev, N. V. Kondratenko, A. Y. Volkonskii, V. M. Vlasov, R. Notario and P. Maria, *J. Am. Chem. Soc.*, **116**, 3047, (1994).

[5] K. L. Busch, G. L. Glish, and S. A. McLuckey, *Mass Spectrometry/Mass Spectrometry. Techniques & Applications of Tandem Mass Spectrometry* (VCH, NY), (1988).

[6] For some recent reviews of the fragmentation reactions of deprotonated organic compounds under MS/MS conditions, see: (a) J. H. Bowie, in *Experimental Mass Spectrometry* (D. H. Russell Ed.), Plenum Press, NY, (1994); (b) JU. H. Bowie, *Mass Spectrom. Rev.*, **9**, 349, (1990).

[7] For previous MS/MS studies of sulfonate anions see: (a) P. A. Lyon, W. L. Stebbings, F. W. Crow, K. B. Tomer, D. L. Lippstreu and M. L. Gross, *Anal. Chem.*, **56**, 8, (1984); (b) P. A. Lyon, K. B. Tomer, and M. L. Gross, *Anal. Chem.*, **57**, 2984, (1985); (c) J. J. Conboy, J. D. Henion, M. W. Martin, and J. A. Zweigenbaum, *Anal. Chem.*, **56**, 8, (1984); (d) R. W. Binkley, T. W. Flechtner, M. J. S. Tevesz, W. Winnik and B. Zhong, *Org. Mass Spec.*, **28**, 769, (1993).

[8] R. G. Cooks, J. S. Patrick, T. Kotiaho, S. A. McLuckey, *Mass Spectrom. Rev.*, **13**, 287, (1994).

[9] (a) G. Caldwell, R. Renneboog and P. Kebarle, *Can. J. Chem.*, **67**, 611, (1989); (b) T. B. McMahon and P. Kebarle, *J. Am. Chem. Soc.*, **99**, 2222, (1977); (c) R. Yamdagni, T. B. McMahon and P. Kebarle *J. Am. Chem. Soc.*, **96**, 4035, (1974).

[10] R. A. J. O'Hair, J. H. Bowie and R. N. Hayes, *J. Chem. Soc. Perkin Trans.* **2**, 473, (1990).

[11] For an excellent review of ion-molecule complexes (sometimes called ion-neutral complexes) in the gas phase (including their role in isomerization reactions) see: R. D. Bowen, *Acc. Chem. Res.*, **24**, 364, (1991).

[12] J. H. Bowie, *Mass Spectrom. Rev.*, **3**, 161, (1984).

[13] Y. Guo and J. J. Grabowski, *J. Am. Chem. Soc.*, **113**, 5923, (1991).

[14] R. L. Smith and H. I. Kenttämaa, *J. Am. Chem. Soc.*, **117**, 1393, (1995).

[15] M. Eckersley, J. H. Bowie and R. N. Hayes, *Int. J. Mass Spectrom. Ion Proc.*, **93**, 199, (1989).

[16] (a) J. P. Greenstein, and M. Winitz; *Chemistry of the Amino Acids*; Vol. 3; John Wiley & Sons; New York, 1908–1910; (b) E. Wertheim, *Organic Syntheses*, vol. 2, A. H. Blatt ed, John Wiley & Sons, New York, 1943, 471–473, (1961); (c) C. Shimanskas, K. Ng, J. Karliner, *Rapid. Commun. Mass Spectrom.*, **3**, 300, (1989).