Journal of Sulfur Chemistry
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713926081

Ionic Reactions of Sulfonic Acid Esters

Richard Francis Langler[a]
[a] Department of Chemistry, Mount Allison University, New Brunswick, Canada

To cite this Article Langler, Richard Francis(1996) 'Ionic Reactions of Sulfonic Acid Esters', Journal of Sulfur Chemistry, 19: 1, 1 — 59
To link to this Article: DOI: 10.1080/01961779608047904
URL: http://dx.doi.org/10.1080/01961779608047904

Sulfur Reports, Volume 19, pp. 1–59
Reprints available directly from the publisher
Photocopying permitted by license only

IONIC REACTIONS OF SULFONIC ACID ESTERS

RICHARD FRANCIS LANGLER

Department of Chemistry, Mount Allison University, Sackville, New Brunswick, Canada E0A 3CO

(Received 27 July 1995)

This review covers recent progress (since the late 1980's) in the solution phase reactions of sulfonic acid esters. Some discussion of reactions which have yet to be explored experimentally is also provided.

Keywords: Sulfonates, substitutions, eliminations, single electron transfer, molecular orbital computations

CONTENTS

1. INTRODUCTION

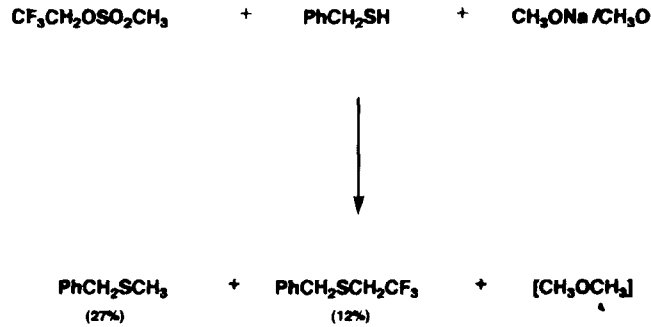
The present review outlines representative sulfonic acid ester reactions which produce and/or consume ions. Because they have each been included in extensive recent reviews, photochemical,[1] electrochemical[2] and rearrangement[3] reactions of sulfonates are not covered here.

After an examination of sulfonate structures, the principal foci of this essay are those reactions of sulfonic acid esters leading to (i) CS bond rupture (S_NAr reactions[4]), (ii) SO bond rupture (S_N2 and S_AN reactions) and (iii) formation of radical anions via single electron transfer ($S_{RN}1$ reactions[5]). Wherever necessary, PM3 semi-empirical molecular orbital calculations have been carried out to provide a self-consistent theoretical basis for discussions.

2. STRUCTURAL CONSIDERATIONS

2.1. *Sulfonates as Electrophiles*

Recently,[6] the following transformation was reported.

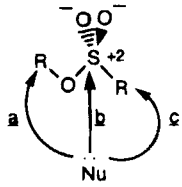


SCHEME 1

The unexpected formation of benzyl methyl sulfide as the major sulfur-containing product, opens up the possibility that nucleophilic attack occured at the methyl carbon of the starting mesylate. Thus, exploration of sulfonic acid ester electrophilicity should, as a minimum, include possible attack at the three sites indicated on **1**.

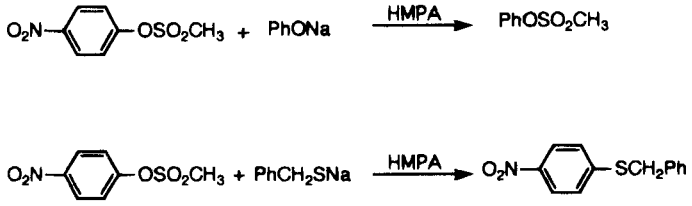
2.2. *Linkage-isomeric Exophiles: RSO_2O- vs -SO_2OR*

2.2.1. ***Exophilicity Predictions from pK_a's.*** Pathways **a** and **b** on structure **1** depict the best-known modes of attack on sulfonic acid esters. When S_NAr and S_N2-S processes are competitive, sulfur serves as the



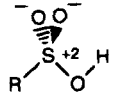
STRUCTURE 1

preferred hard acid site[7a] and the carbon attached to oxygen serves as an appreciably softer acid site. Results taken from ref. 6 illustrate this dichotomy (Scheme 2)

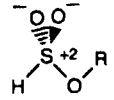


SCHEME 2

Expected exophilicities[7b] are commonly anticipated by listing potential exophiles[7b] in the order dictated by the pK_a's of their conjugate acids (ref. 4, p. 374). The application of this argument to an analysis of soft acid sites in sulfonates (pathway *a* vs pathway *c* on **1**) would lead to an answer dependent upon the relative pK_a's of **2** and **3**.



STRUCTURE 2



STRUCTURE 3

While sulfonic acid pK_a's are well known[8a] (see entry 1, Table 1), species with the sulfonate-analogue structure **3** do not appear to be known. Given that (i) sulfinic acids are protonated preferentially at oxygen[9] and (ii) protons on sulfur in thiols are considerably more acidic than protons on oxygen in alcohols (entries 2 and 3 in Table 1), it is not difficult to see that **2** and **3** might have comparable pK_a's. In support of this view, wet H-SO_2O-H has estimated pK_a's of ≈ -1.0 for the proton on sulfur and ≈ -2.6 for the proton on oxygen.[8b] Thus, in principle, pathways *a* and *c* (on **1**) might well be competitive.

In simple sulfonates, S_N2 substitution by pathway *a* is generally superior to bimolecular substitution by pathway *b*, because attack at carbon (CO bond rupture) displaces a sulfonate anion while attack at sulfur (SO bond rupture) displaces a much less exophilic[7b] alkoxide ion.

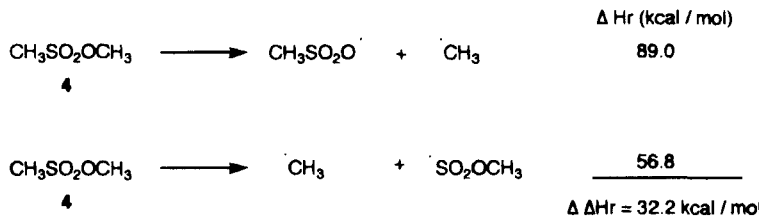
2.2.2. *Exophilicity[7b] Predictions from Computed Bond Strengths.* A brief computational study[10] has been carried out using the PM3[11] semi-empirical molecular orbital method to obtain RHF enthalpies of formation for the optimized structures shown in Scheme 3.

The differences in ΔH_r values for the equations in Scheme 3 correspond to the differences in Bond Dissociation Energies for the CS and the CO bonds in methyl methanesulfonate. PM3 results suggest that the CS bond is more readily broken by some 32.2 kcals/mol. Corresponding *ab initio* results obtained at the 6 –31G* (UMP2) level[12] show that the CS bond is

TABLE I Equilibrium Acidities[a] in Dimethyl Sulfoxide at 25 °C.

Acid	pK_a
CH_3SO_3H	1.6
$CH_3(CH_2)_3SH$	16.9
CH_3OH	29.0
CH_3SO_2OPh	25.2
CH_3COCH_3	26.5
$CH_3SO_2CH_3$	31.1
$PhSO_2H$	7.1
CH_4	56
$PhC{\equiv}CH$	28.7
C_6H_5OH	18.0
p-$O_2NC_6H_4OH$	10.8

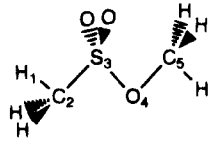
[a]pK_a's are taken from ref. 8a.



SCHEME 3

expected to be more fragile by 23.0 kcals/mol. On this basis, the carbon attached to sulfur is expected to be the superior soft acid site in methyl methanesulfonate.

2.2.3. ***Expected Electrophilicity[7b] from LUMO's.*** Electrophilicity may also be assessed by inspection of the lowest unoccupied molecular orbital (LUMO)[13] associated with a given sulfonate. Those centres with the largest coefficients in the LUMO will be the most electrophilic sites. Results of our PM3 computations[10] on methyl methanesulfonate **4** are presented in Table 2.



STRUCTURE 4

In accord with previous discussion, the molecular orbital results shown in Table 2 suggest that C_2 (soft acid) should be more electrophilic than C_5 (soft acid) in concerted reactions, although primary electrophilicity in **4** is associated with sulfur (hard acid).

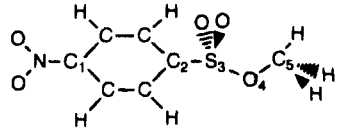
Computational results[10] on methyl *p*-nitrobenzenesulfonate **5** are also presented in Table 2.

The π-type LUMO of **5** indicates no significant electrophilicity at S_3 or C_5 but suggests that all such reactivity should be focussed on C_1 (soft acid) and C_2 (soft acid). Precisely this sort of result has been reported[14] for a nitrobenzenesulfonate (see Scheme 4).

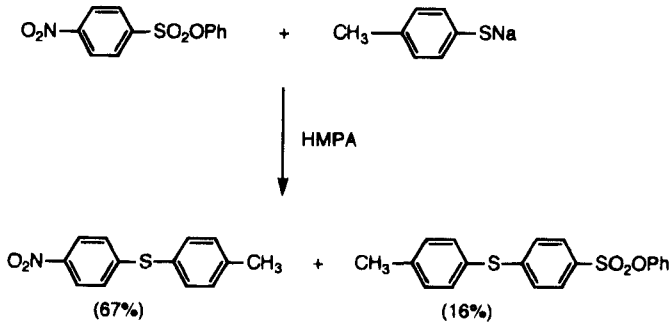
TABLE II PM3 LUMO Coefficients for Selected Sulfonyl Species.

Species	*Atom*	*LUMO type*	*LUMO Coefficient[a]/ Orbital*
$CH_3SO_2OCH_3$	C_2[b]	σ	−0.2852/2s
			−0.1472/$2p_x$
4			−0.3649/$2p_y$
			−0.0004/$2p_z$
	S_3		0.5301/3s
			0.1249/3_x
			−0.3197/$3p_y$
			−0.0025/$3p_z$
	O_4		−0.1510/2s
			0.2276/$2p_x$
			−0.2308/$2p_y$
			−0.0008/$2p_z$
	C_5		0.0756/2s
			−0.1405/$2p_x$
			−0.1185/$2p_y$
			0.0029/$2p_z$
p-$O_2NC_6H_4SO_2OCH_3$	C_1[b]	π	0.4939/$2p_z$
5	C_2		0.5087/$2p_z$
	S_3		0.0481/$3p_z$
	C_5		0.0007/$2p_z$
$CH_3SO_2^+$	S	π	−0.7639/$3p_z$
8a	O		0.4353/$2p_z$
	O		0.4341/$2p_z$
$ClCH_2SO_2OPh$	Cl_1[c]	σ	−0.0291/3s
			0.2466/$3p_x$
20			−0.0222/$3p_y$
			−0.1373/$3p_z$
20	C_2		0.3044/2s
			−0.1480/$2p_x$
			−0.0985/$2p_y$
			−0.2565/$2p_z$
	S_3		−0.4549/3s
			−0.0540/$3p_x$
			−0.1007/$3p_y$
			−0.3182/$3p_z$
	O_4		0.1530/2s
			0.0222/$2p_x$
			−0.0624/$2p_y$
			−0.2534/$2p_z$
CH_2SO_2	C	π	0.4778/$2p_z$
30	S		−0.7313/$3p_z$
	O		−0.3441/$2p_z$
	O		−0.3441/$2p_z$

[a]For each sulfonate, eigenvalues of the LUMO and the next highest-lying orbital were separated by approximately 1 eV.
[b]Skeletal numbering is given in Section 2.2.3.
[c]Skeletal numbering is given in Section 3.6.

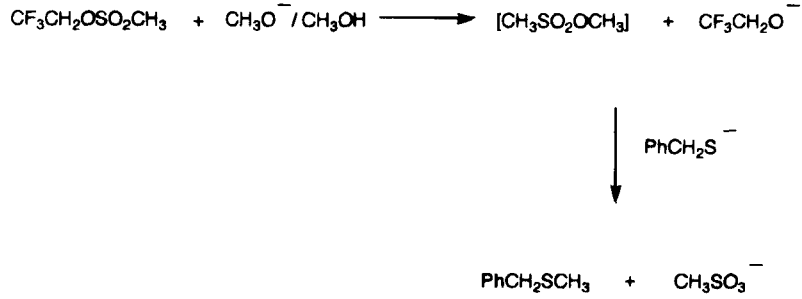


STRUCTURE 5



SCHEME 4

2.2.4. ***Expected Electrophilicity from Calculated Framework Polarization.*** Given the reactions shown in Schemes 1 and 4, and the foregoing arguments based on conjugate base acidity, bond strengths and LUMO coefficients, it would seem that CS bond rupture should be a commonplace in the chemistry of saturated sulfonic acid esters. However, evidence gathered in the study[6] of the Scheme 1 reaction indicates that it very likely proceeds as shown in Scheme 5 i.e. *without* CS bond rupture.



SCHEME 5

To the best of my knowledge, the displacement of sulfur by nucleophilic attack at sp^2 carbon (illustrated in Scheme 4) was unprecedented prior to the publication of ref. 14 and the corresponding displacement via nucleophilic attack at sp^3 carbon is still unprecedented. The same generalizations apply to sulfones for which sulfur displacement by attack at sp^2 carbon is amply precedented[15,16a] but the corresponding process at sp^3 carbon in acyclic sulfones is still unknown (see ref. 16b for a possible exception). However, nucleophilic attack on ethylene episulfone has been observed.[16c,d,e,f] Given that the PM3 skeletal atomic charges[10] for dimethyl sulfone (Fig. 1) and ethylene episulfone are essentially identical, ring-opening by nucleophilic attack at carbon can be attributed to ring-strain release.

The traditional view of bonding in the sulfonyl group[17,18] invokes d_π-p_π backbonding between sulfur and oxygen leading to a moderately polarized functionality. Coupled with the traditional view of inductive effects,[19] one expects moderate positive charge on the sulfonyl sulfur and modest positive charge on the carbon attached to it. This view of polarity in sulfonyl compounds does nothing to discourage the expectation of electrophilicity at the sp^3 carbon in question.

Modern molecular orbital computations[20,21] have begun to undermine the traditional view of d_π-p_π backbonding by showing[21] that computed results "do not depend on the inclusion or exclusion of d orbitals". Some propose instead[22] that electrostatics are dominant in the "π-bonding" within such functionalities. Indeed, it has been suggested that electrostatics have generally been underappreciated in chemical structures and behaviour.[23]

Fig. 1 presents PM3 results[10] (semi-empirical) and 6–31G* results[12] (*ab initio*) for the calculated atomic charges in dimethyl sulfone. Note that PM3 results do not rely on problematic Mulliken population analyses (e.g. see the warning: ref. 12, p. 20).

Clearly, the very substantial buildup of negative charge at carbon (Fig. 1) provides a powerful disincentive for nucleophilic attack there. The substan-

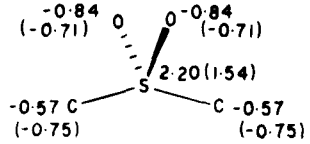


FIGURE 1 PM3 and (in brackets) 6-31G* calculated skeletal atomic charges for dimethyl sulfone.

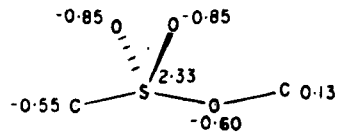
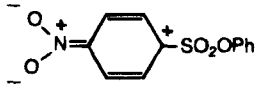


FIGURE 2 PM3 calculated skeletal atomic charges for methyl methanesulfonate **4**.

tial electrostatic stabilization enjoyed by the sulfone sulfonyl group in Fig. 1, is also a central feature of the sulfonate linkage as shown in Fig. 2 for methyl methanesulfonate **4**.

Major electrostatic stabilization requires alternating adjacent opposed charges which, given substantial positive charge on sulfur, leads to the expectation that the methyl carbon on sulfur should have a partial negative charge while the methyl carbon on oxygen should have a partial positive charge. Thus, a clear basis has emerged for a systematic preference for CO bond rupture in nucleophilic substitutions involving saturated sulfonic acid esters e.g. **4**.

In contrast, appropriately substituted benzenesulfonates may be expected to undergo CS bond rupture based on calculated LUMO coefficients (see section 2.2.3 and Scheme 4). In Valence Bond terms, such a prediction may be rationalized by invoking a resonance form like **6**.



STRUCTURE 6

2.3. *Sulfonates as One-electron Acceptors*

The literature features a growing number of reports[24–30] of sulfonic acid ester chemistry which proceeds through the intermediacy of sulfonate radical anions.

SCHEME 6

TABLE III Semi-empirical LUMO Eigenvalues (eV) for Selected sulfonates.

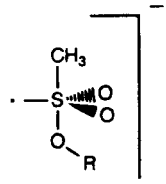
Compound	*ZINDO*[a]	*PM3*[b]
$CH_3SO_2OCH_3$	—	−0.0738
$CH_3SO_2OC_6H_4OCH_3$-*p*	—	−0.4017
$CH_3SO_2OC_6H_4CH_3$-*p*	—	−0.4215
CH_3SO_2OPh	0.3516	−0.4444
$CH_3SO_2OC_6H_4Cl$-*p*	−0.0201	−0.5821
$CH_3SO_2OC_6H_4Br$-*p*	—	−0.6225
$CH_3SO_2OC_6H_4CF_3$-*m*	—	−0.7887
$CH_3SO_2OC_6H_4CN$-*p*	−0.5714	−0.9412
$CH_3SO_2OC_6H_4SO_2CH_3$-*p*	−0.6193	−0.9263
$CH_3SO_2OC_6H_2Br_3$-*o,o, p*	−1.0038	−0.8231
$CH_3SO_2OC_6H_4CHO$-*p*	−1.0468	−0.8399
$CH_3SO_2OC_6H_4NO_2$-*p*	−1.9839	−1.3048
$O_2NC_6H_4SO_2OCH_3$-*p*	—	−1.8204

[a]ZINDO eigenvalues are taken from ref. 29 and 30.
[b]PM3 eigenvalues were obtained for this review.[10]

These reports propose that sulfonates can accept one electron from aromatic hydrocarbon radical anions,[24–26] lithium aluminum hydride,[27] sodium hydride[30] or thiolate anions.[28,30]

For a given single electron donor, the viability of single electron transfer (SET) chemistry hinges on the LUMO eigenvalue for the sulfonic acid ester. In general, one would expect that aromatic sulfonates would have lower-lying LUMO's than saturated sulfonates and that aromatic sulfonate LUMO's would be lower-lying when the ring bears electron-withdrawing substituents than when the ring bears electron-donating substituents. Table 3 presents calculated LUMO eigenvalues for a selection of simple sulfonate esters which support the foregoing generalizations.

A SET reaction on a sulfonic acid ester will produce a radical anion which is believed to have the additional electron primarily associated with the sulfonyl group. Closson *et al.*[26] have proposed the sulfuranyl radical anion structure **7**.



STRUCTURE 7

Based on a growing experience,[31–35] one can speculate with greater confidence about the structures of these sulfuranes. ESR evidence (ref. 36, pp. 201, 202) on the radical anions of methanesulfonic acid and sulfuryl chloride provides *no support* for the presence of an unpaired electron in a sulfur sp^2 orbital. Instead, the unpaired electron appears to be located in a σ antibonding orbital[37] (SOMO) associated with the bonds to the apical ligands as shown in **8**.

STRUCTURE 8

This picture leads to the expectation that SO bond rupture should be a commonplace feature of sulfonic acid ester radical anion behaviour.

2.4. *Sulfonates as Acids*

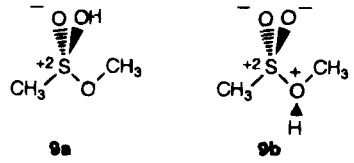
Sulfonic acid esters which have a proton on sp^3 carbon (α to sulfur) are weak acids. Like simple ketones, they are significantly stronger acids than simple sulfones (see entries 4–6 in Table 1).

2.5. *Sulfonates as Bases*

Although sulfonamides have been the subject of such studies,[39] sulfonic acid esters have not been examined as bases. Simple sulfonates offer terminal oxygen and non-terminal oxygen as potential base sites. The higher atomic charge on the terminal oxygen atoms (see Fig. 2) suggests that those oxygens might be the better base sites.

PM3 calculations on the cations **9a** and **9b** show that (in the gas phase) protonation at terminal oxygen (**9a**) is favored by some 22.2 kcal/mol.

Note that PM3 results ascribe an atomic charge of –0.459 to the oxygen atom which bears the formal positive charge in **9b**.

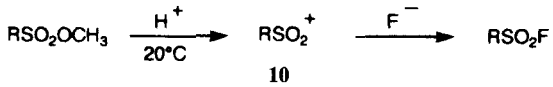


STRUCTURE 9

3. EVEN-ELECTRON IONIC REACTIONS: SULFONATES AS ELECTROPHILES

3.1. *Attack at S; SO Bond Rupture*

Sulfonic acid esters can undergo substitution at sulfur (path *b*, structure 1) via S_N1, S_AN or S_N2 mechanisms. Acid-catalyzed *unimolecular* substitution through sulfonylium ions **10** is known[39,40] for methyl sulfonates.



SCHEME 7

Both the changes in PM3 calculated SO bond lengths (1.437 Å in **4** and 1.360 Å in **10a** (**10a** = **10** with R = CH_3)) and calculated SO bond orders (1.209 in **4** and 1.485 in **10a**) requires that formation of the methyl sulfonylium ion **10a** from methyl methanesulfonate **4** be accompanied by the development of significant p-p π bonding. The methyl sulfonylium ion **10a** (Table 2) has a π-type LUMO which indicates that electrophilicity is centered on sulfur in accord with the behaviour depicted in Scheme 7. As argued earlier (Section 2.2.4) for sulfones and sulfonate esters, framework polarization in the methyl sulfonylium ion **10a** (Fig. 3) militates against nucleophilic attack at sp^3 carbon with displacement of SO_2.

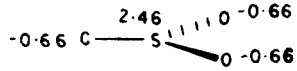


FIGURE 3 PM3 calculated skeletal atomic charges for the methyl sulfonylium ion **10a**.

Given the earlier discussion (Section 2.2.1 and Scheme 5) of sulfonyl sulfur as a hard acid site, it is not surprising that recent studies of *bimolecular* substitution at sulfonyl sulfur[41–44] all employ oxyanions as nucleophiles. *A priori*, such substitutions could proceed by (i) an S_N2 mechanism going through a single transition state **11a** or by (ii) an S_AN mechanism going through a trigonal bipyramidal intermediate **11b**.

11a **11b**

STRUCTURE 11

Although some authors[45, 46] invoke sulfuranes in such reactions, a recent study[41] has reached the conclusion that sulfonyl transfer to oxyanion acceptors, in the cases examined, proceeds by a classical S_N2 mechanism involving **11a**.

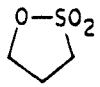
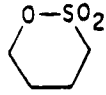
In contrast, Buncel and Pregel[44] interpret their results in terms of an S_AN mechanism (intermediacy of **11b**) for alkoxide ion-induced substitutions at S in *m*-nitrophenyl and *p*-trifluoromethylphenyl methane- and benzenesulfonates.

King *et al.*[43a] have reported a fascinating study of sultone hydrolyses. The generalized reaction is portrayed in Scheme 8 and the results presented in Table 4.

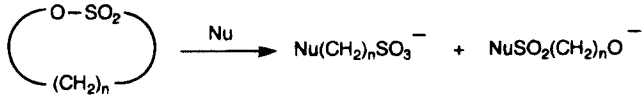
Since CO bond rupture displaces the better exophile (formation of **A** in Scheme 8), it comes as no surprise that all sultones ring-open by nucleophilic attack of water at carbon. Furthermore, the very substantial positive charge on sulfur (see Fig. 2) should offer a powerful disincentive to attack there by water because the nucleophile would be expected to develop positive charge in the transition state.

The unexpected predilection for the smaller sultones in Table 4 to undergo nucleophilic attack at sulfur (formation of **B** in Scheme 8) by hydroxide ions was rationalized[43a] in terms of the COSC dihedral angle, Θ (see **13**).

TABLE 4 Percent SO vs Percent CO Bond Rupture in the Hydrolysis of Small Ring Sultones.

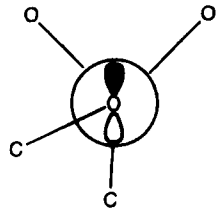
Sultone	*Nucleophile*	*Sultone C-O*	*Cleavage (%) S-O*
	H_2O	97	3
	$\bar{O}H$	~10[b]	~90[b]
	H_2O	96	4
	$\bar{O}H$	45	55
	$\bar{O}H$	96	4

[a]Formed *in situ* from $HO(CH_2)_2SO_2Cl$.
[b]Average of three runs.



12a n = 2
12b n = 3
12c n = 4

SCHEME 8



STRUCTURE 13

They proposed that "... the delocalization $C\text{-}SO_2\text{-}OC \leftrightarrow C\text{-}\bar{S}O_2\text{=}\overset{+}{O}C$ varies with the CSOC dihedral angle and that the delocalization is greatest with Θ around 75° and least with $\Theta = 0°$ ...". Thus reduced delocalization in the four- and five-membered sultones **12a, 12b** would lead to "... (a) lowering of the S-O bond order, (b) decrease in the magnitude of the partial

positive charge on carbon and (c) increase in the partial positive charge on sulfur, thereby facilitating nucleophilic attack at sulfur." The foregoing analysis presumes increased electron density at non-terminal oxygen.

Figures 4 and 5 present a PM3-based comparison of the β-sultone **12a** and methyl methanesulfonate **4**.[43b] The calculated differences in atomic charges (Fig. 4) are not in harmony with the analysis proposed in ref. 43a. The sultone **12a** has (i) the same atomic charge at C_1 (% change = 0), (ii) *decreased* negative charge at non-terminal oxygen (% change = 7.1), (iii) a small increase in positive charge at sulfur (% change = 1.4), (iv) decreased negative charge at terminal oxygen (% change = 3.5) and (v) major increase in negative charge at C_2 (% change = 11.1). Rather than a major change in the relative atomic charges at non-terminal oxygen and sulfur as suggested in ref. 43a, **12a** has substantially reduced electron density at all three oxygen atoms and a substantial increase in electron density at CS carbon. Consider the hypothetical conversion depicted in Scheme 9.

In terms of skeletal polarization, the introduction of a bond between C_1 and C_2 (Fig. 4) permits new electrostatic stabilization because C_1 has a partial positive charge and C_2 has a partial negative charge. Since all of the hydrogen atoms have a positive charge (from +0.030 to +0.120), an attempt

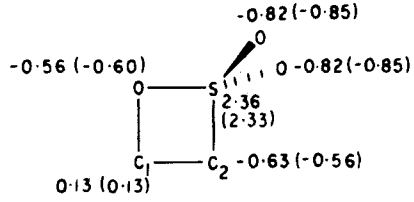


FIGURE 4 PM3 calculated skeletal atomic charges for the β-sultone **12a** and (in brackets) PM3 skeletal atomic charges for methyl methanesulfonate **4**.

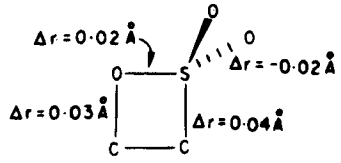
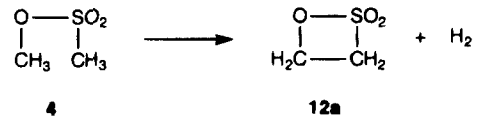


FIGURE 5 PM3 calculated bond length differences for the β-sultone **12a** and methyl methanesulfonate **4** (positive numbers imply longer bonds in the sultone).



4 **12a**

SCHEME 9

to enhance polarization stabilization in **12a** by increasing positive charge at C_1 would be offset by repulsions between C_1 and its protons. However, increased electron density at C_2 would increase the ionic bond orders for *all* bonds involving C_2.

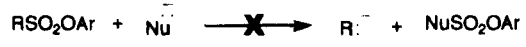
Calculated bond length changes associated with the Scheme 9 transformation (see Fig. 5) are at variance with the analysis suggested in ref. 43a. The sultone **12a** has (i) a small increase in S-O (non-terminal) bond length (% change = 1.1), (ii) a moderate decrease in S-O (terminal) bond length (% change = 1.4) and (iii) a larger increase in C-O (% change = 2.1) and C-S (% change = 2.1) bond lengths. Thus, PM3 results for the hypothetical conversion of **4** to **12a** (Scheme 9) suggest that (i) the least important change in atomic charge occurs at sulfur while the most important changes occur at oxygen and CS carbon and (ii) the smallest change (absolute and relative) in bond length is associated with the S-O (non-terminal) bond while the most important change is associated with lengthening of the C-O bond.

Bimolecular substitutions at carbon require linear departure of the leaving group. Attack at carbon in the sultone **12a** should require that the oxygen exophile depart along a path almost perpendicular to the ideal path. While the same is true for attack at sulfur, its much larger orbitals should lead to better transition state stabilization. That is the proposed basis for the breakdown of Baldwin's rules[47] in reactions involving larger atoms. From this point of view, attack at carbon in the series of sultones **12a–12c** would become progressively more competative as displacement of the superior leaving group (sulfonate) is permitted to better follow the ideal line of departure.

Shashidar and Bhatt[42] have reported that 2-formylbenzenesulfonates, derived from phenols, hydrolyze about 10^6 times faster than the corresponding 4-formyl sulfonates. This useful rate acceleration is attributed to a neighboring group effect exerted by the carbonyl. Selective protection/deprotection of phenolic OH groups was effected in the presence of alcohol and carboxylic ester functionalities.

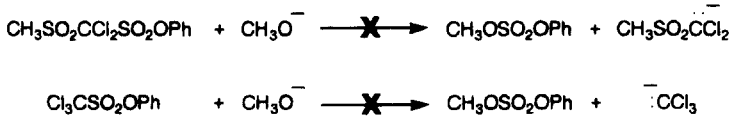
3.2. *Attack at S; CS Bond Rupture*

Nucleophilic attack at sulfonate sulfur (path *b*, structure **1**) with displacement of the carbon substituent does not seem to have been observed (Scheme 10). Note that the corresponding product has been observed in reactions of ethylene episulfone[16f] e.g. the ethanesulfonate anion upon reaction with $Ba(OH)_2$ or KOH.



SCHEME 10

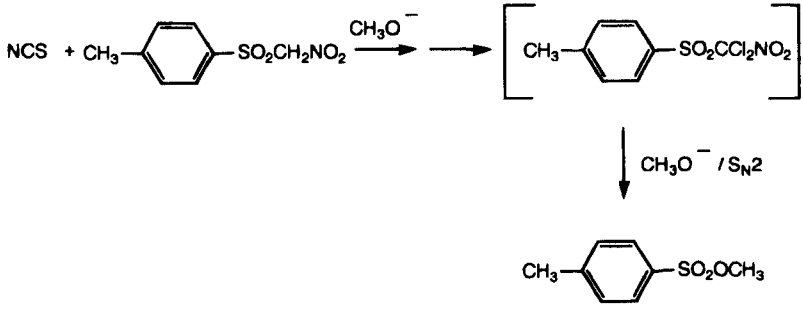
We have examined[29,48] two types of sulfonate structures which appear to be suitably functionalized for such behaviour. Despite the use of methoxide ions (hard bases), no attack at sulfonyl sulfur (hard acid) was observed for either of the sulfonates depicted in Scheme 11.



SCHEME 11

Presumably, the presence of bulky substituents on the α-carbon discourages attack at sulfonyl sulfur.

The report[49a] of the nitro sulfone reaction presented in Scheme 12 might lead to the conclusion that **14** would be a good candidate for study.



SCHEME 12

$O_2NCCl_2SO_2OPh$

STRUCTURE 14

3.3. *Attack at C; CO Bond Rupture*

Sulfonic acid esters can undergo substitution at CO carbon (path *a*, structure **1**) via S_N1, S_N2 or S_NAr mechanisms. Their use as alkylating/arylating agents in synthesis is so commonplace that a complete list of those reports would constitute a substantial portion of the existing literature. Modern practice tends to exploit sulfonates in which the substituent on sulfur is perfluorinated because that confers enhanced exophilicity on the sulfonate leaving groups.[50–52]

Recently,[6] the novel reaction shown in Scheme 1 was reported. Here the trifluoroethyl group suppresses attack at carbon leading to substitution at sulfur as indicated in Scheme 5. The explanation advanced by the authors focussed on the exophilicity of the trifluoroethoxyl group (pK_a CF_3CH_2OH: 12.4[53]). When the more hindered isopropoxide ions replaced methoxide ions, attack at sulfur was suppressed and attack occured exclusively at carbon as shown in Scheme 13.

$$CF_3CH_2OSO_2CH_3 + CH_3O^- / PhCH_2SH \longrightarrow [CH_3SO_2OCH_3] \longrightarrow PhCH_2SCH_3$$

$$CF_3CH_2OSO_2CH_3 + (CH_3)_2CHO^- / PhCH_2SH \longrightarrow PhCH_2SCH_2CF_3$$

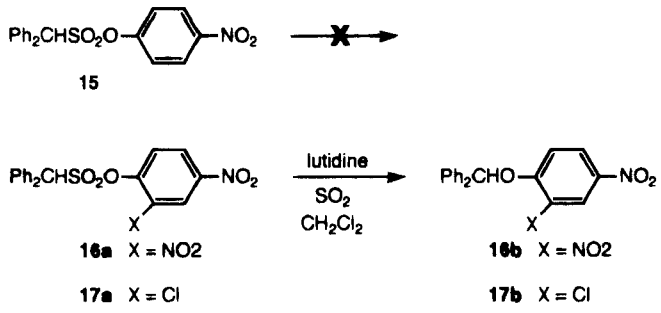
SCHEME 13

In view of the enormous number of reports of nucleophilic attack on sulfonates at CO carbon, it appears to be surprisingly simple (vide Schemes 2, 8, and 13) to shift the preferred site of attack for hard bases, especially oxyanions, to sulfonyl sulfur.

3.4. *Attack at C; CS Bond Rupture*

Nucleophilic attack at CS carbon (path *c*, structure **1**) may proceed by S_N1 or S_NAr mechanisms.[14,54] The structural bases for CS rupture via substitution mechanisms other than S_N2 have been presented in Sections 2.2.1–2.2.4.

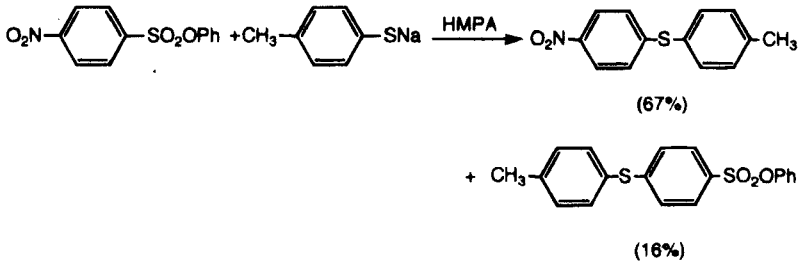
King and Aslam[54] have examined the reactions of some diphenylmethanesulfonates in the presence of SO_2 and 2,6-lutidine. The simple *p*-nitrophenyl ester **15** failed to react but both of the more heavily substituted sulfonates **16** and **17** underwent desulfonylation to furnish the corresponding ethers as shown in Scheme 14.



SCHEME 14

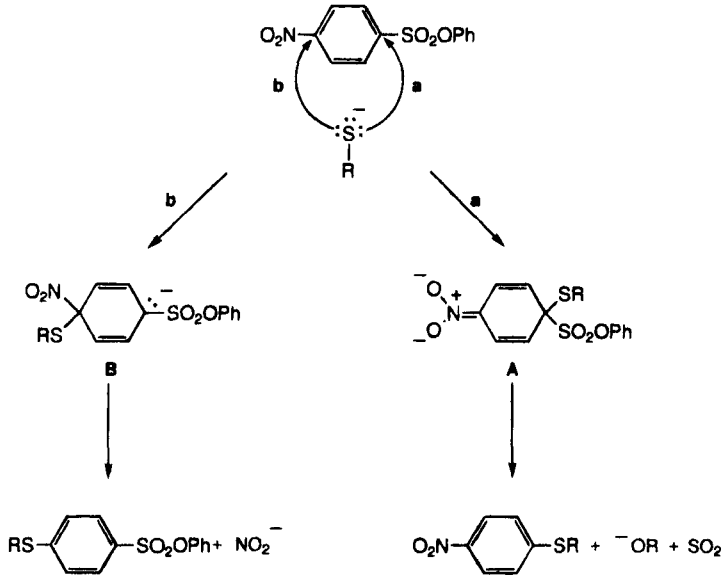
It seems unlikely that a radical mechanism would account for the difference in reactivity between **15** and **16**. Furthermore, benzhydryl chloride and the appropriate phenol furnished the same ether **17b**, presumably through the diphenylmethyl carbocation, under these reaction conditions.

Sulfonates serve as good leaving groups in S_NAr substitutions. The well-known process in which CO bond rupture occurs is exemplified in Scheme 2. Scheme 15 presents a novel example[14] of sulfonate departure with CS bond rupture.



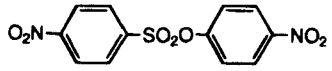
SCHEME 15

ZINDO computations led to the conclusion that this chemistry was unlikely to involve radical anions and that it most likely proceeds as shown in Scheme 16A.



SCHEME 16A

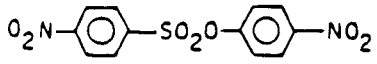
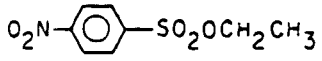
CO cleavage was not expected to be competative with CS rupture in Scheme 15 because the phenoxy phenyl is not activated for nucleophilic attack. It did seem likely that CO cleavage would dominate when both phenyl rings were nitro substituted. In the event, model systems served to establish that the dinitrosulfonate **19** would react with *p*-methylbenzenethiolate anions almost exclusively at CS carbon.



STRUCTURE 19

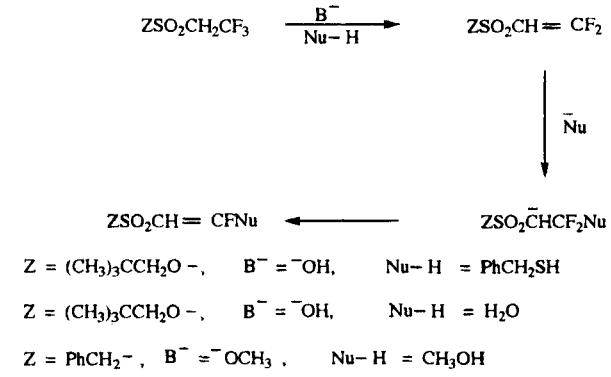
Even ethyl 4-nitrobenzenesulfonate reacted under these conditions to give some CS cleavage.[55a] These results are summarized in Table 5. In

TABLE 5 Ratio of CS to CO Rupture in Substitution Reactions of Nitrobenzenesulfonates with *p*-Methylbenzenethiolate Anions in HMPA.

Sulfonate	*CS*	*CO*
	19	1
	1	15

accord with experiment, ZINDO calculations[14] on dinitrosulfonates related to **19**, show the LUMO's to be of the π-type with all of the non-zero coefficients on the nitrophenyl group attached to sulfur. Note that similar displacements have been observed for pyridyl sulfones.[55b]

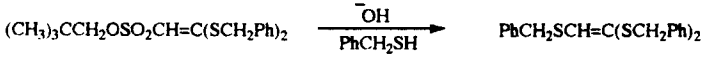
Recent work[49a,49b] on 2,2,2-trifluoroethyl sulfones and sulfonates (tresylates) has prompted the authors to propose elimination/addition sequences which would accomplish displacement of fluorine as shown in Scheme 16B.



SCHEME 16B

Treatment[49b] of the appropriate bissulfide-sulfonate ester with phenylmethanethiolate anions then led to displacement of the sulfonate group with CS bond rupture. This result, shown in Scheme 16C, is clearly another example of path a, Scheme 16A behaviour.

In accord with King and Gill's assumption,[49b] PM3 computations[10] provide a frontier-orbital based expectation that soft-base attack on the bissulfide-sulfonate ester (Scheme 16C) should occur at the α-carbon (sulfonyl-

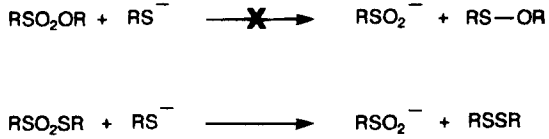


SCHEME 16C

bearing) at least as readily as at the β-carbon (Michael addition). To wit, PM3 computations on the model system $CH_3O_3SCH{=}C(SCH_3)_2$ assign a LUMO coefficient of $0.6235p_z$ to the sulfonyl-bearing vinyl carbon and a LUMO coefficient of $0.5991p_z$ to the sulfenyl sulfur-bearing vinyl carbon.

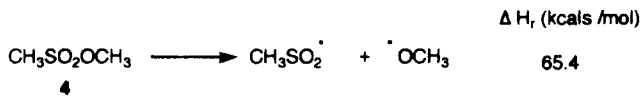
3.5. *Attack at O; SO Bond Rupture*

Nucleophilic attack at oxygen with displacement of a sulfinate anion does not seem to have been observed, although the corresponding behaviour is amply precedented[28,56] in the chemistry of thiolsulfonic acid esters (vide Scheme 17).



SCHEME 17

A discussion of nucleophilic attack at oxygen parallels the earlier discussion of CS rupture offered in Sections 2.2.1–2.2.4. The PM3 calculated Bond Dissociation Energy (BDE) for the SO bond (compare Schemes 3 and 18) indicates that the SO bond would be intermediate in strength.



SCHEME 18

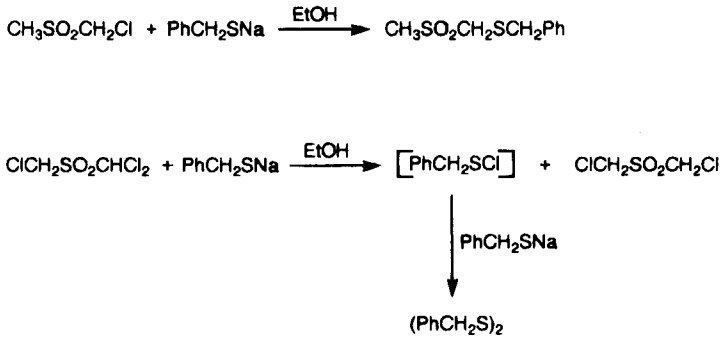
Furthermore, the LUMO coefficients (O_4 in entry 1, Table 2) indicate moderate electrophilicity at oxygen in **4** and a sulfinate anion (see pK_a for benzene-

sulfinic acid, Table 1) is a respectable leaving group. What protects the ester oxygen in **4** from nucleophilic attack is its high electron density (see Fig. 2).

In the foregoing discussion, sulfonate esters are viewed as formally analogous to simple peroxides which are well-known oxygen electrophiles. I note, in accord with experiment, that PM3 calculations on dimethyl peroxide show a much smaller BDE (O-O, 21.0 kcals/mol), a much larger LUMO coefficient at O (0.6361 p_x) and a much smaller atomic charge on oxygen (q = –0.17) than is the case for the sulfonate ester oxygen (O_4, structure **4**, Section 2.2.3).

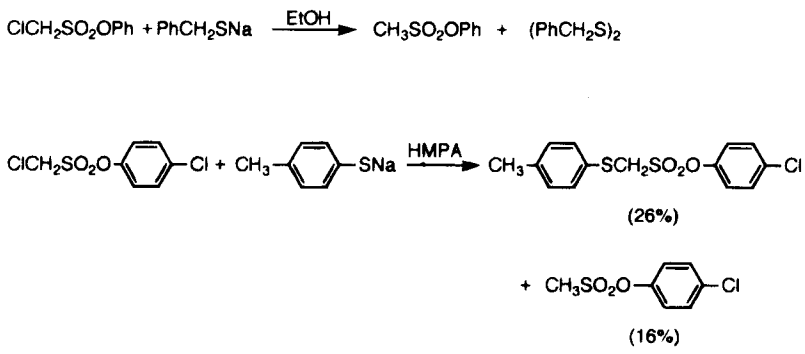
3.6. *Attack at C vs Attack At X; CX Bond Rupture*

Some time ago, we examined thiolate anion-induced dechlorinations of simple α-polychloro sulfones.[57] Nucleophilic attack at halogen is called X-philic attack[58a] or Z-philic attack[58b] and has been the subject of a review.[58a] We found[57] that nucleophilic attack occured at chlorine in dichloro- and trichloromethyl systems but occurred exclusively at carbon in chloromethyl sulfones (see Scheme 19).



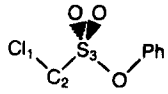
SCHEME 19

Reaction on phenyl chloromethanesulfonate[57] under these same conditions gave only nucleophilic attack at chlorine. This result is not surprising in view of the expected enhancement in carbon exophilicity when its substituent is changed from a simple sulfonyl to a sulfonyloxy group (see relevant pK_a's, Table 1). Interestingly, a similar reaction gave significant nucleophilic attack at carbon when the reaction was carried out in hexamethylphosphoramide[29,59] (see Scheme 20).



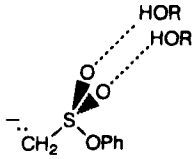
SCHEME 20

PM3 computations on phenyl chloromethanesulfonate **20** are presented in Table 2.



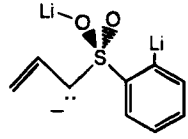
STRUCTURE 20

These calculations suggest, in accord with the Scheme 20 results in HMPA, that soft-acid electrophilicity in 20 should be more pronounced at C_2 than at chlorine. Perhaps the shift to exclusive attack at chlorine (in ethanol), might be rationalized by enhanced exophilicity for C_2 induced by H-bonding to sulfonyl oxygens as shown in **21**.



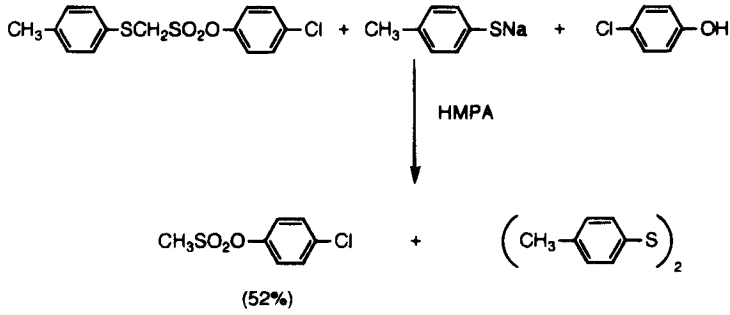
STRUCTURE 21

In related behaviour, sulfonyl oxygen in sulfones may be drawn into neighboring group participation.[60, 61] Note the fascinating dilithiated sulfone structure **22** reported by Gais and Vollhardt.[62]



STRUCTURE 22

Finally, closely related behaviour has been observed[30] for a sulfide-sulfonate ester (Scheme 21).



SCHEME 21

3.7. *Michael Additions; α,β-Unsaturated Sulfonates*

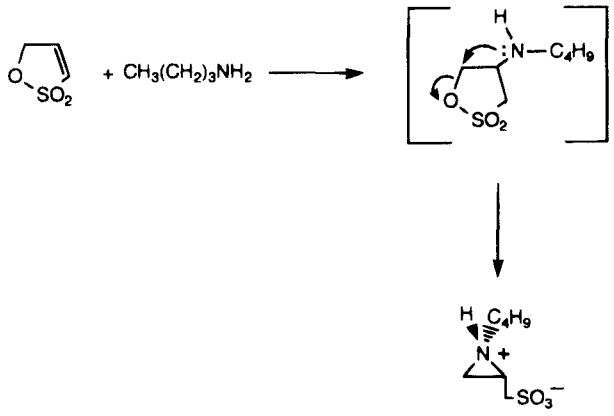
Conjugate or Michael additions may be successfully carried out on conjugated sulfonates. Schemes 22[63] and 23[64] present novel examples.

Note the preferential soft-soft interaction leading to CC bond formation and the hard-hard interaction leading to SO bond formation in Scheme 23.

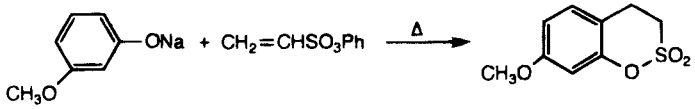
4. EVEN-ELECTRON IONIC REACTIONS: SULFONATE-DERIVED CARBANIONS IN SUBSTITUTIONS

4.1. *Effective Bases*

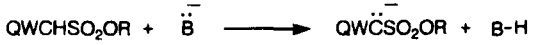
Typically, carbanions α to sulfonyloxy are accessed by simple sulfonate deprotonation (see Scheme 24), although X-philic attack (Section 3.6) is an alternative route to these species.



SCHEME 22



SCHEME 23



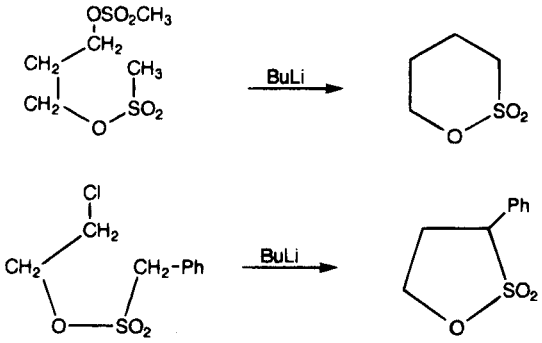
SCHEME 24

Sulfonate deprotonation (Q = W = H, Scheme 24) has been accomplished with an alkyllithium,[65] a lithium acetylide[66] and sodium hydride.[29] With sodium hydride, simple acid-base behaviour may be complicated by reduction reactions.[29,30]

Chloro- and dichloromethanesulfonates (Q = H, W = Cl or Q = W = Cl, Scheme 24) may be deprotonated in hexamethylphosphoramide (HMPA) by sodium methoxide,[48] sodium phenoxide[48] and sodium *p*-mesylphenoxide.[48] Sodium *p*-nitrophenoxide is not sufficiently basic to deprotonate aryl chloromethanesulfonates in HMPA.[48] Appropriate pK_a's are included in Table 1.

4.2. *Sulfonate Alkylations*

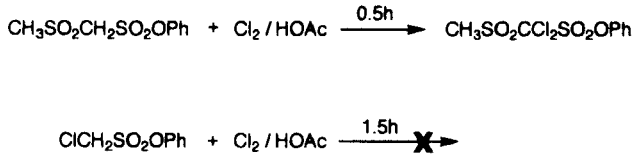
Alkylation of sulfonate-derived carbanions has been exploited for the preparation of acyclic sulfonates and sultones.[65, 66]



SCHEME 25

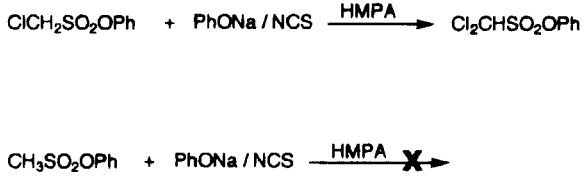
4.3. *Sulfonate Chlorinations and Sulfenylations*

We have subjected sulfonic acid ester chlorinations to some scrutiny. Aryl sulfone-sulfonates will react with molecular chlorine,[29] in the absence of added base, whereas aryl chloromethanesulfonates will not[10] (Scheme 26).



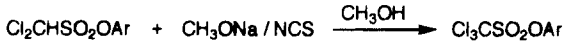
SCHEME 26

The more weakly acidic aryl chloromethanesulfonates can be chlorinated[48] smoothly by *N*-chlorosuccinimide (NCS) with phenoxide ion catalysis although methanesulfonates do not react under those same conditions[10] (see Scheme 27).



SCHEME 27

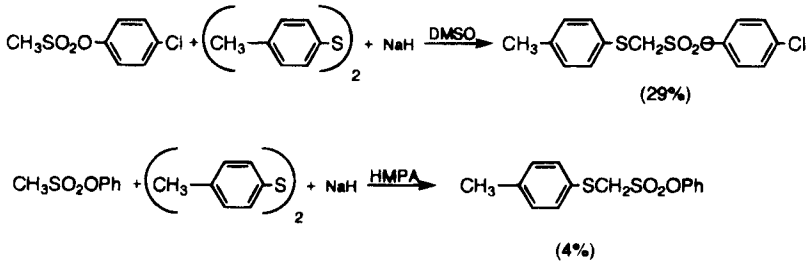
Aryl dichloromethanesulfonates chlorinate nicely with methoxide ion catalysis in methanol[48] (vide Scheme 28).



SCHEME 28

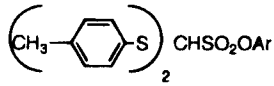
Scheme 28 yields are 58–71%, suggesting little complication by methoxide ion attack at sulfonyl sulfur.

Base-catalyzed sulfenylations have proved to be much less successful. Sulfide-sulfonate esters form in yields[29, 30] of less than 30% (Scheme 29).



SCHEME 29

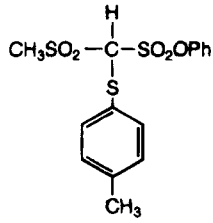
The chemistry which complicates these seemingly simple preparations is discussed in Section 7.2. Bissulfenylation appears to produce bissulfide-sulfonate esters **23** which are completely destroyed by column chromatography.



STRUCTURE 23

Presumably **23** hydrolyses during column chromatography with unimolecular expulsion of $-SO_2OAr$. The related sulfone-sulfide-sulfonate ester **24** survives column chromatography.[10]

Finally, we note that the failure to monochlorinate mesylates (Scheme 27) cannot be remedied by replacing sodium phenoxide with sodium hydride because sodium hydride smoothly reduces NCS in HMPA.



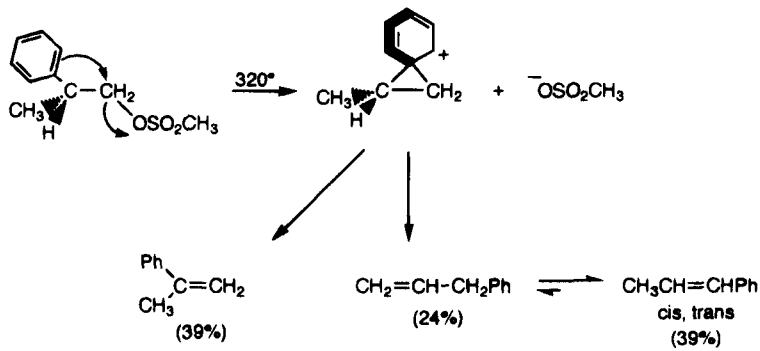
STRUCTURE 24

5. EVEN-ELECTRON IONIC REACTIONS: SULFONATES IN ELIMINATION REACTIONS

5.1. *Elimination of RSO_3H*

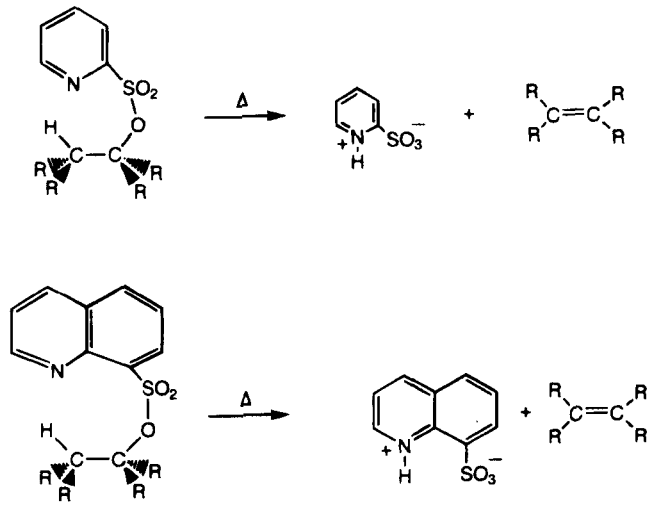
5.1.1. *Unimolecular Eliminations.* The formation of alkenes via carbonium ions produced by the loss of sulfonate anions has long been known.[67] Such reactions are favored by electron-releasing groups attached to the reaction center and solvents of high ionizing strengths.

Gas phase elimination of sulfonic acids, might be expected to proceed by paene-concerted syn eliminations in analogy to the gas-phase behaviour of carboxylic acid esters.[60] However, recent studies[69,70] have shown that gas-phase pyrolysis of small methanesulfonates proceeds with Wagner-Meerwein rearrangement implicating intimate ion pairs as shown in Scheme 30 for 65% reaction of 2-phenyl-1-propyl methanesulfonate.



SCHEME 30

In contrast to the behaviour of simple methanesulfonate pyrolyses, concerted syn eliminations might seem more likely for the vacuum pyrolyses of the pyridyl and quinolyl sulfonates of Scheme 31.

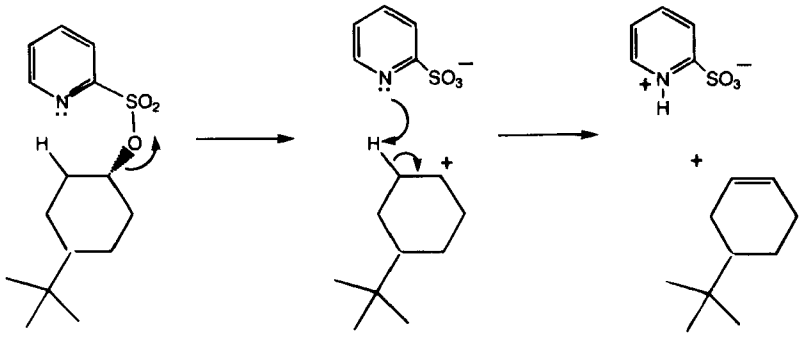


SCHEME 31

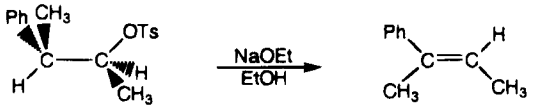
However, vacuum pyrolyses of such sulfonates[71] gave results (including rearrangements) consistent with ionic reactions. Primary pyridyl and quinolyl sulfonates required temperatures 100 °C higher for olefin formation than temperatures which sufficed for secondary sulfonates. Finally, *trans*-4-*t*-butylcyclohexyl-3-pyridine sulfonate produces 4-*t*-butylcyclohexene in the same yield under the same conditions which worked for the 2-pyridyl and 8-quinolyl sulfonates. Scheme 32 shows the proposed ionic mechanism for that transformation.

Perhaps the stepwise ionic pathway that appears to be followed by the Scheme 31 reactions is less surprising given that concerted eliminations would require seven- and eight-membered cyclic transition states.

5.1.2. *Bimolecular Eliminations.* Typically, bimolecular eliminations proceed through a transantiparallel transition state (ref. 5, p. 356 and Scheme 33).

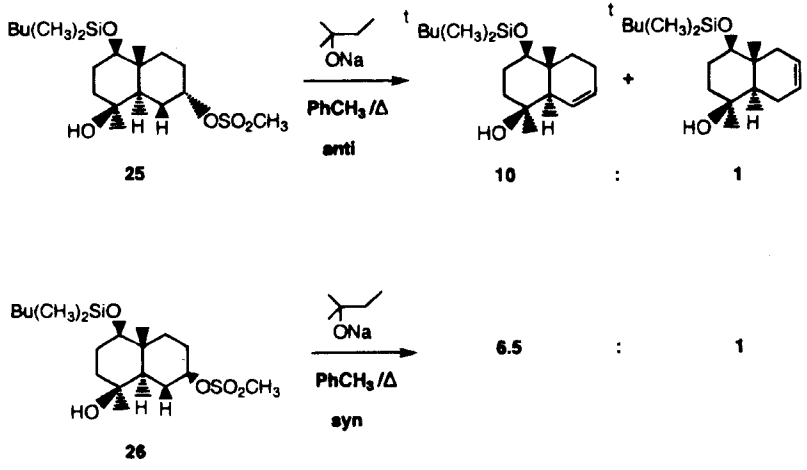


SCHEME 32



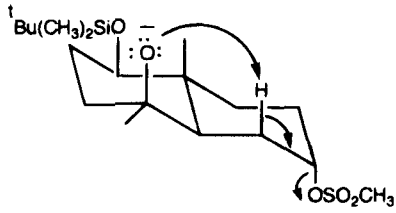
SCHEME 33

A fascinating report of strong-base induced sulfonate elimination has appeared recently.[72] A pair of epimeric mesylates were prepared and reacted with sodium *t*-amylate to give the results shown in Scheme 34.



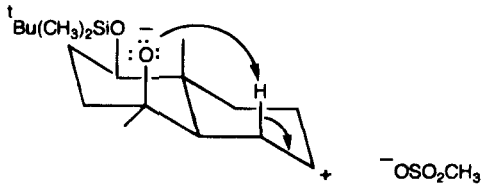
SCHEME 34

To account for the high regioselectivity, initial deprotonation of the tertiary hydroxyl group was assumed. Thus, **25** would be expected to undergo a simple anti elimination as in **27**.



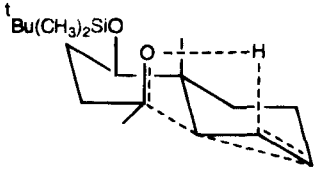
STRUCTURE 27

Unexpectedly, **26** gave a very similar result (Scheme 34) *in the same reaction time*. The authors suggest initial formation of an intimate ion pair followed by proton abstraction as in **28**.



STRUCTURE 28

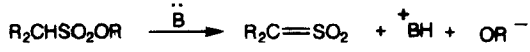
Note that proton abstraction in **28** could be viewed as a pseudo-[1,5] sigmatropic rearrangement which proceeds through the aromatic transition state **29**.



STRUCTURE 29

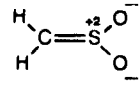
5.2. *Elimination of ROH*

The elimination of an alcohol or phenol from a sulfonate leads to the formation of a sulfene (see Scheme 35).



SCHEME 35

PM3 results (Table 2 and Fig. 6) suggest that sulfene **30** is a hard acid at sulfur and a soft acid at carbon.



STRUCTURE 30

The reactions of sulfenes have been thoroughly reviewed[73] and will not be treated in detail here.

Although sulfonic acid esters are frequently the products of reactions which proceed through sulfenes, they have only infrequently been deployed as starting materials. Earlier workers have demonstrated[74] that aryl arylmethanesulfonates form sulfenes via reversible and irreversible $E1_{cb}$ processes. Such eliminations are quite sensitive to small changes in leaving group structure.[75a]

Pregel and Buncel[44] have reported a detailed study of aryl methanesulfonates which react with ethoxide ions by (i) S_AN substitution at sulfur and (ii) $E1_{cb}$ elimination to furnish sulfene (see Scheme 36).

Elimination-addition becomes the dominant pathway as leaving group nucleofugality increases in the aryl mesylate series: *p*-trifluorophenyl, *m*-nitrophenyl and *p*-nitrophenyl.

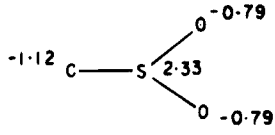
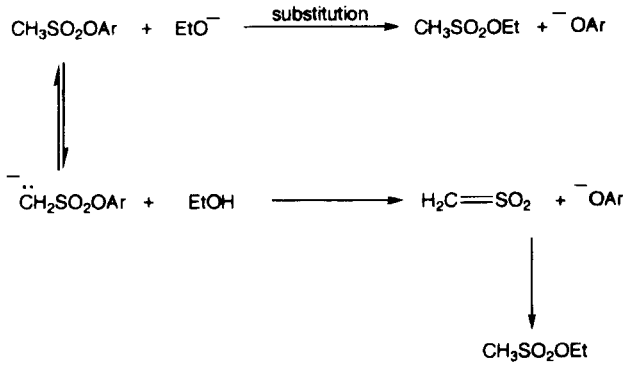
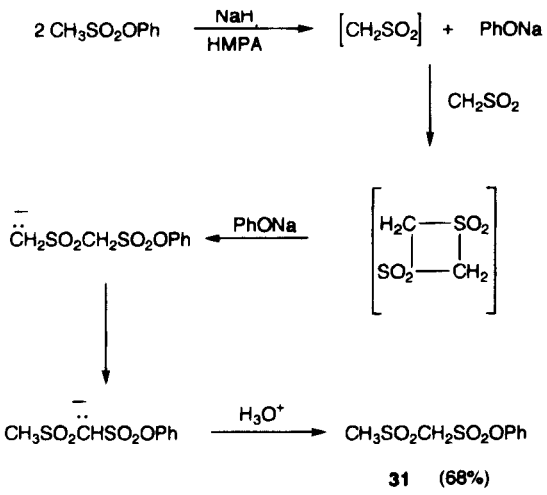


FIGURE 6 PM3 calculated skeletal atomic charges for sulfene **30**.

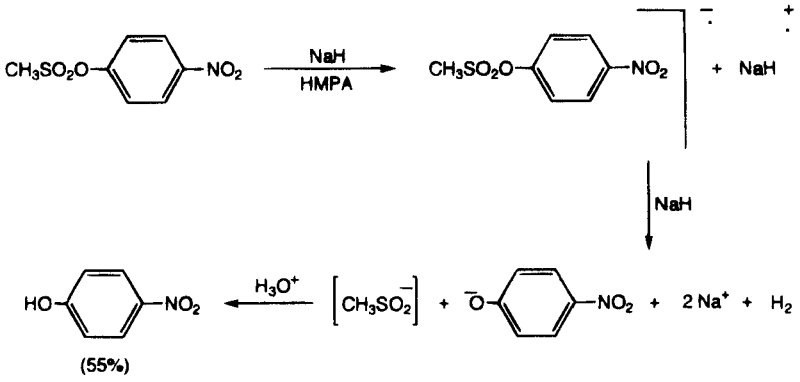


SCHEME 36

We have proposed[29] that aryl methanesulfonates react through a competition between sulfene-forming elimination leading to dimers (see Scheme 37) and Single Electron Transfer (SET) leading to simple sulfonate reduction in reactions of sulfonic acid esters with sodium hydride (see Scheme 38). SET chemistry (discussed in detail in Section 7.2) should dominate as the LUMO energies of the aryl mesylates decline (see Table 3) in a series including phenyl and *p*-nitrophenyl.



SCHEME 37



SCHEME 38

Alternative mechanisms, including nucleophilic attack by $\bar{C}H_2SO_2OAr$ on sulfene, were considered[29] in addition to the Scheme 37 proposal.

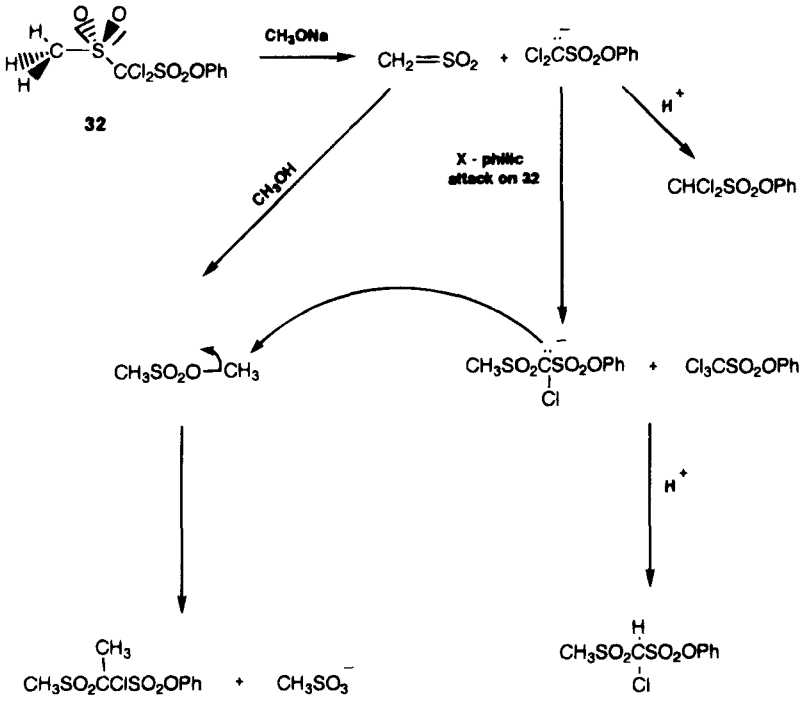
The referee has pointed out that those structures (Table 3) which have the lowest-lying LUMO's also have the best leaving groups attached to sulfonyl sulfur. He suspects that particularly facile expulsion of $Ar\bar{O}$ from $\bar{C}H_2SO_2OAr$ would be a more reasonable alternative to the SET chemistry depicted in Scheme 38 as a rationale for sulfonate reduction by sodium hydride.

A number of points militate against this view. Firstly, reaction mixtures of sodium hydride and *p*-nitrophenyl methanesulfonate in HMPA turn black when the chemicals are mixed. This observation is consistent with the formation of radical anions i.e. species with very loosely held electrons. Secondly, the corresponding reaction of 2,4,6-tribromophenyl methanesulfonate leads to debromination of the ring (see Section 7.2 for a detailed discussion) consistent with the intermediacy of radical anions. Thirdly, reaction of sodium hydride with a related functionality, phenyl benzenethiolsulfonate in HMPA produced methanesulfinate anions[29] in accord with SET reduction. Finally, the sulfene proposal leaves open the question of the fate of the sulfene that is supposed to form. *p*-Nitrophenoxide ions trap sulfene dimers in acetonitrile.[75b] Why wouldn't they be able to trap sulfene or its dimer in HMPA?

5.3. *Elimination of HCl_2CSO_2OPh*

In the course of our investigation of the chemistry of sulfone-sulfonates[29] e.g. **31** (Scheme 37), we have treated the corresponding dichlorinated sys-

tem **32** with methoxide ions. The resultant array of products was consistent with expulsion of a dichloromethanesulfonate-derived carbanion as depicted in Scheme 39.



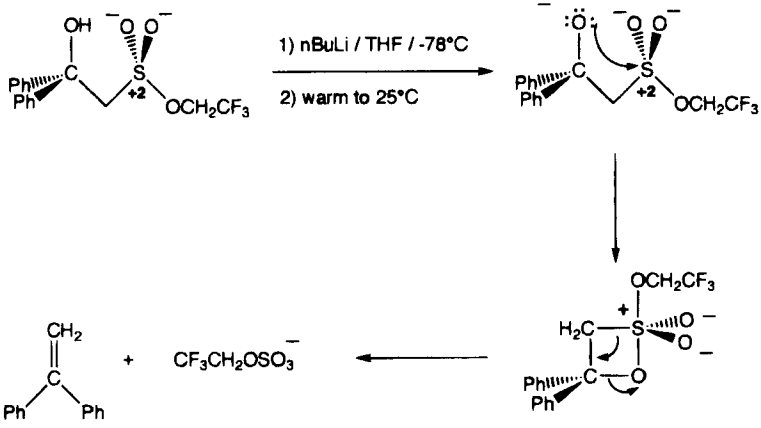
SCHEME 39

Presumably steric crowding precludes S_AN substitution by methoxide ions at sulfonyloxy sulfur in **32**.

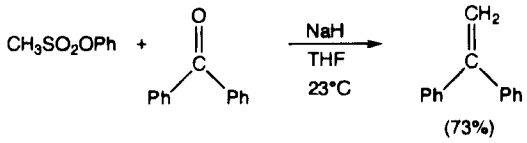
5.4. *Elimination of $HOSO_2OR$*

Hawkins *et al.*[76] have examined strong-base catalysed reactions of β-hydroxy sulfonates. These reactions are believed to produce alkenes in the manner presented in Scheme 40.

The process can be used as a one-pot methylenation procedure starting with methanesulfonates (vide Scheme 41).



SCHEME 40



SCHEME 41

5.5. *Elimination of HSO_2OR*

Nucleophilic aromatic substitutions may displace sulfinate anions in reactions of appropriately substituted aryl sulfones. This behaviour is key to understanding the well-known Smiles rearrangement.[77] S_NAr chemistry has recently been observed for aryl sulfonates (see ref. 14 and Section 3.4).

Sulfones have been used to build up carbon skeleta, prior to sulfinate expulsion in a step which links up previously isolated components of an extended π-system. Scheme 42 presents an example from ref. 78.

To the best of my knowledge, this strategy has not been applied to sulfonate esters.

PM3 results on ethyl ethanesulfonate (Fig. 7) suggest that β-eliminations, on appropriately designed sulfonates could also proceed by CS bond rupture. (Note that each proton shown in Fig. 7 has an atomic charge of +0.045). Although, based on acidity arguments (Section 2.2.1 and Table 1), one would expect that sulfonate eliminations would be more facile than sul-

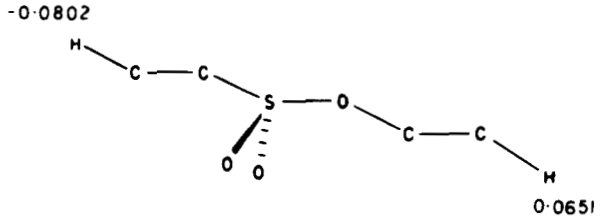
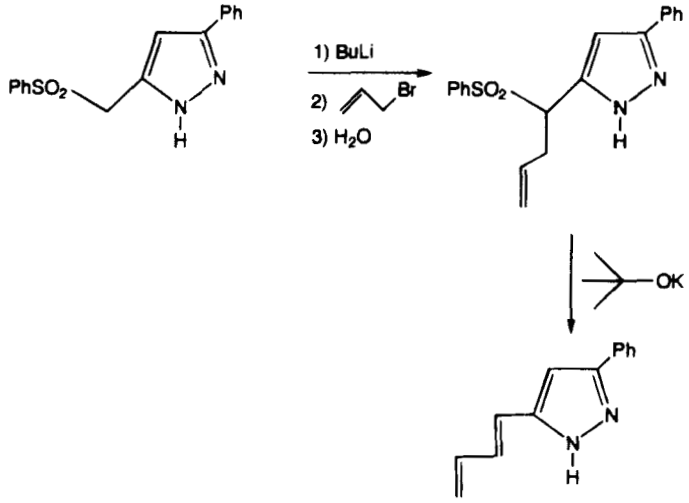


FIGURE 7 Selected LUMO coefficients for ethyl ethanesulfonate.



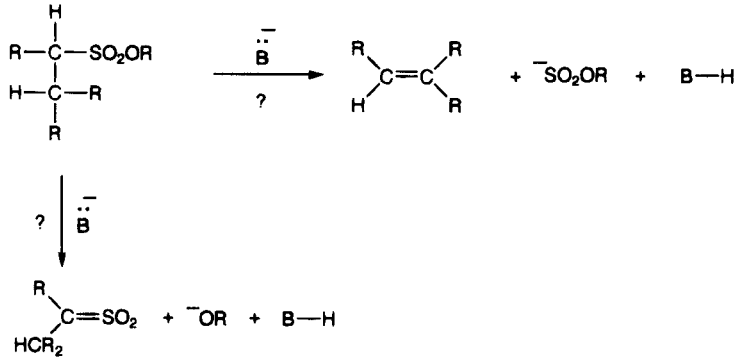
SCHEME 42

fone eliminations, some sulfonate behaviour should be complicated by sulfene formation as illustrated in Scheme 43.

6. EVEN-ELECTRON IONIC REACTIONS: SULFONATES AS π-DONORS

6.1. *Acid-catalyzed Hydration of Vinyl and Acetylenic Toluenesulfonates*

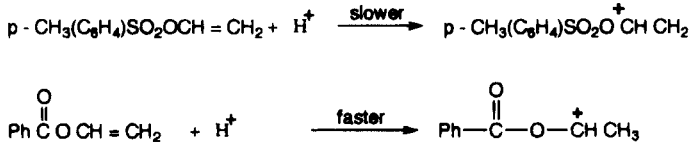
Sulfonyloxy groups have long been known to be effective carbanion stabilizers for carbon groups attached to sulfonyl sulfur (see Table 1). It is only



SCHEME 43

more recently[79, 80] that sulfonyloxy groups have been examined as electron donors to carbon π systems attached to sulfonyloxy oxygen.

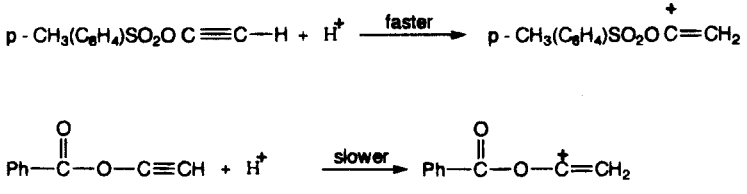
Tidwell *et al.*[79] have shown that, in acid-catalyzed hydrations, vinyl tosylates undergo rate-limiting protonation more slowly than do vinyl benzoates (Scheme 44).



SCHEME 44

The authors suggest that this observation is reasonable because the tosylate group has greater electron-withdrawing ability than the benzoate group.

In sharp contrast, the *opposite* order of reactivities is observed for the corresponding alkynyl esters as shown in Scheme 45.



SCHEME 45

The authors suggest that the alkynyl sulfonates might have a higher reactivity as a result of the attachment of a strongly electronegative tosylate group to an electronegative sp carbon.

PM3 computed enthalpies of reaction[10] for some simple model systems are shown in Table 6. In contrast to the solution-phase results, the calculated gas-phase results suggest that *both vinyl and acetylenic sulfonates should protonate more readily* than the carboxylic acid ester analogues. Inspection of the PM3 results for protonated vinyl acetate and methanesulfonate (**33a** and **33b**) shows that the key CO bonds have the same bond orders. Furthermore, electron density in the p_z of the carbocationic center is *higher* in **33a** (0.487 electrons) than in **33b** (0.478 electrons). Total charge at the carbocationic center is significantly higher in **33b** (+0.526) than in **33a** (+0.443). Thus these familiar rationales for the facility of carbocationic formation fail to make sense of the calculated enthalpies of reaction shown in Table 6.

From the discussion in Section 2.2.4 and the sulfonate polarization depicted in Fig. 2, it is obvious that the protonated vinyl mesylate **33b** should have much greater electrostatic (polarization) stabilization than the protonated vinyl acetate **33a**. The results shown in Fig. 8 demonstrate that this is indeed the case and account for the shorter calculated CO bond length in **33b**. A parallel discussion of the computational results for the alkynyl systems could be offered.

TABLE 6 PM3 Calculated Enthalpies of Reaction for Protonation of Simple Alkenyl and Alkynyl Sulfonates.

$XOCH{=}CH_2 + H^+$	⟶	$XO\overset{+}{C}H\text{-}CH_3$
X		$\Delta\Delta H_f$ (kcal/mol)
H-		−177.2
CH_3CO-		−179.3
CH_3SO_2		−191.5
$XOC{\equiv}CH + H^+$	⟶	$XO\overset{+}{C}{=}CH_2$
X		$\Delta\Delta H_f$ (kcal/mol)
H-		−153.1
CH_3CO-		−174*
CH_3SO_2-		−183.3

*The enthalpy of reaction was calculated from a non-optimized enthalpy of formation for $CH_3\,COO\overset{+}{C}{=}CH_2$ because optimized calculations on this system led to an acylium ion and ketene. The acyl group oxygen atom bond was set at the optimized value for the corresponding bond length in $CH_3\,COO\overset{+}{C}H - CH_3$ and all other parameters optimized.

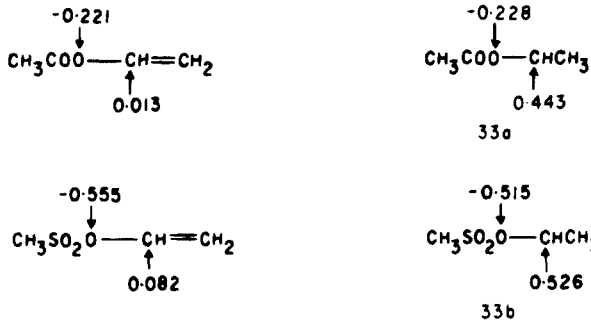
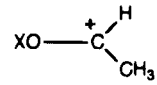


FIGURE 8 Selected PM3 calculated atomic charges for vinyl compounds and the corresponding carbocations.



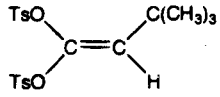
33a X = CH_3O

33b X = CH_3SO_2

STRUCTURE 33

Experimental results for sulfonate and carboxylate comparisons suggest that Scheme 44 results are expected and that Scheme 45 results are surprising. Computationally, alkenyl and alkynyl systems should give similar results and Scheme 45 presents the expected order of reactivities. It is the Scheme 44 results which should require arguments about differential solvation of intermediates and so on and the Scheme 45 results that appear to reflect inherent stabilities of the requisite intermediates.

Experimentally,[79] the 1,1-bistosylate **34** is *less* reactive than the simple tosylate shown in Scheme 44.

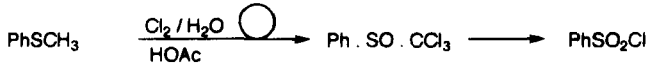


STRUCTURE 34

The authors suggest that **34** may be *O*-protonated first thus slowing *C*-protonation.

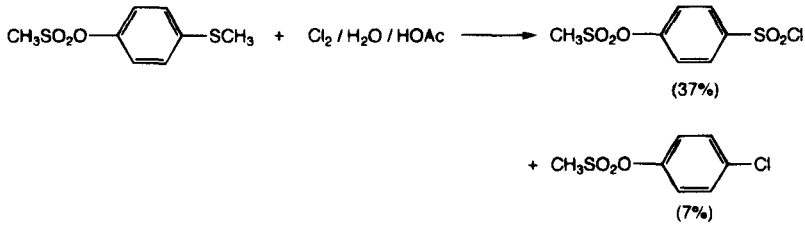
6.2. *Exhaustive Aqueous Chlorinolysis of an Aryl Sulfide-sulfonate*

Some time ago, we have shown[81] that phenyl methyl sulfide is smoothly transformed into benzenesulfonyl chloride by aqueous chlorinolysis (vide Scheme 46).



SCHEME 46

Recent work[10] has revealed the results depicted in Scheme 47.



SCHEME 47

The unexpected formation of *p*-chlorophenyl methanesulfonate seems to arise from some ring chlorination in competition with *S*-chlorination as shown in Scheme 48.

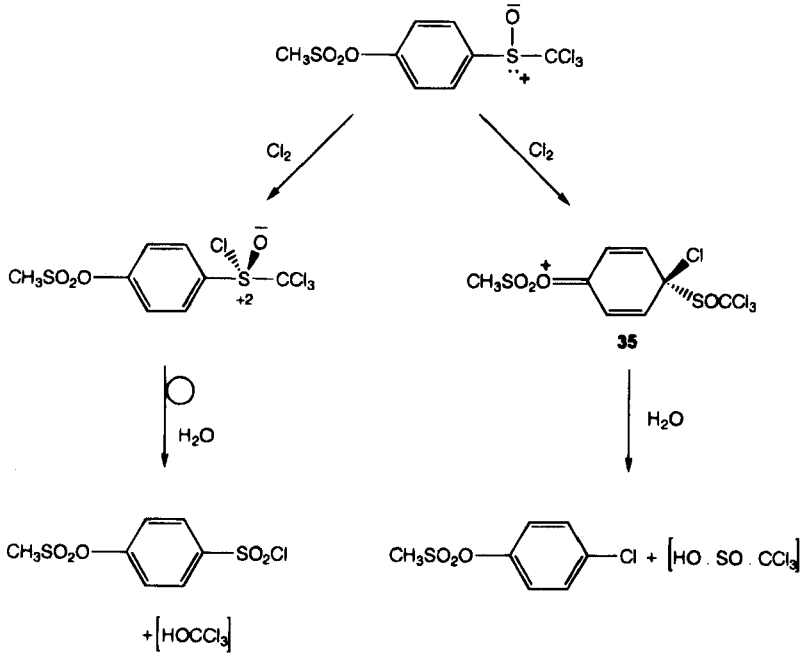
C-Chlorination would be attributable to π-donation from the mesylate oxygen as depicted for **35**.

7. ODD-ELECTRON IONIC REACTIONS: SULFONATE RADICAL ANIONS

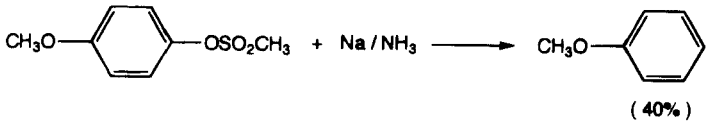
7.1. *Solution Phase Reactions with Odd-electron Reagents*

In 1955, Kenner and Williams[82] reported the conversion of *p*-methoxyphenyl methanesulfonate into anisole in moderate yield (Scheme 49).

Subsequently, Closson *et al.*[83] showed that toluenesulfonates, in contrast to Scheme 49 behaviour, undergo SO bond rupture with either sodium naphthalene or sodium phenanthrene.



SCHEME 48

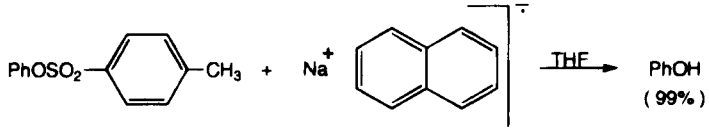


SCHEME 49

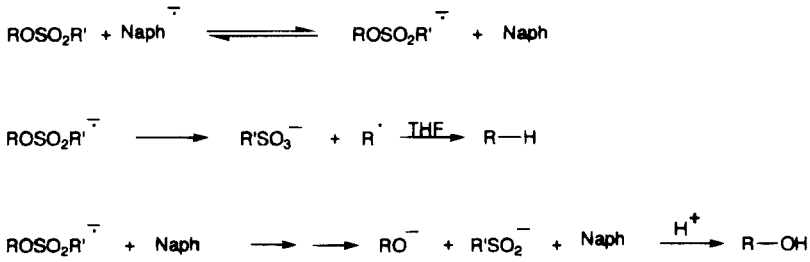
They also noted that methanesulfonates react with sodium naphthalene to give alkanes and alcohols (CO and SO rupture) in accord with Schemes 49 and 50.

Further examination[24] of reactions of sodium naphthalene with alkyl alkanesulfonates led to the mechanistic proposal depicted in Scheme 51.

In a later study,[26] Closson *et al.* advanced more detailed mechanisms for reactions of aryl alkanesulfonates and sodium naphthalene, sodium anthracene or sodium fluoranthrene. Scheme 52 presents a complete proposal for a representative reaction.



SCHEME 50



SCHEME 51

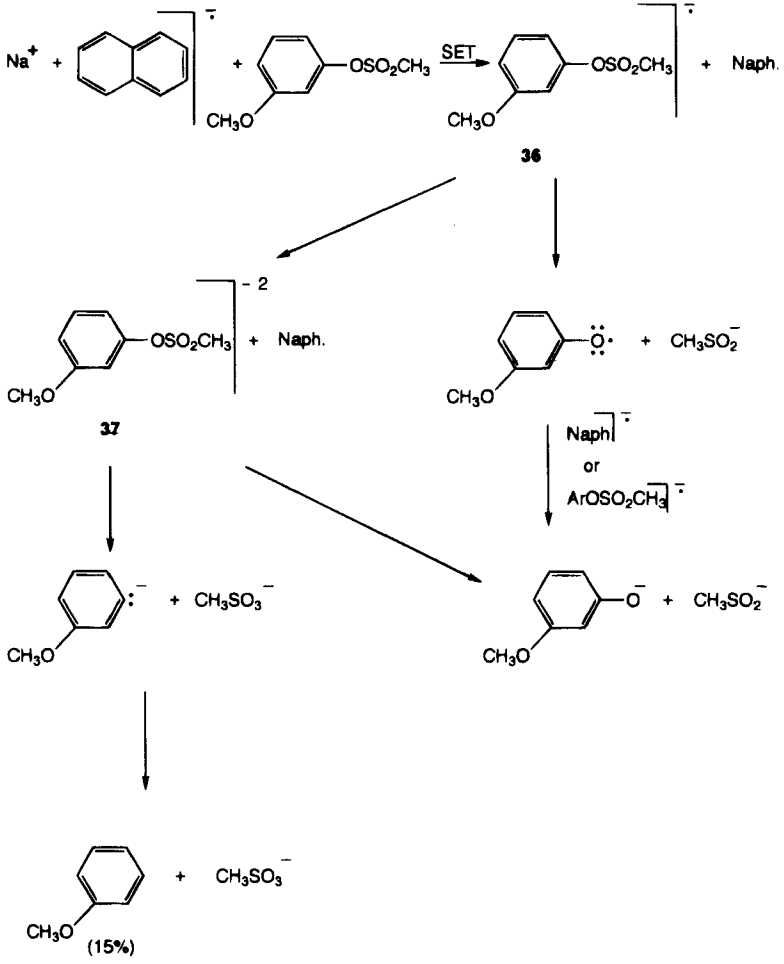
Typically, aryl methanesulfonates give rise to radical anions like **36** (Scheme 52) by single-electron transfer (SET). These radical anions are expected, based on the pK_a's of phenols and sulfinic acids (see Table 1), to form phenoxy radicals and sulfinate anions[26] en route to the observed phenol and sulfinic acid products as shown in Scheme 52.

In a few cases, significant amounts of arene products are formed (note the isolation of anisole in 15% yield in Scheme 52). In this case, Closson *et al.* propose the intermediacy of the dianion **37** to account for the formation of the arene.

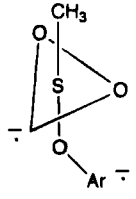
They propose that initial electron transfer is directly to sulfonyl sulfur as previously depicted in section 2.3 for structure **7**. The second electron transfer is presumed to build electron density in the phenyl ring as indicated in **38**.

Since structure **7** is inconsistent with available e.s.r. data (see **8** in Section 2.3), **38** likely needs revision. It seems reasonable to suppose that dianions like **37** would be ground state triplets, with the lowest-lying SOMO centered on the S-OAr bond and the higher-lying SOMO centered on the C-O bond.

None of the organic articles covered in this review raise the question of outer-sphere vs inner-sphere electron transfer. This issue is widely discussed by inorganic chemists[84] in connection with SET processes and will undoubtedly need consideration in future organic articles.



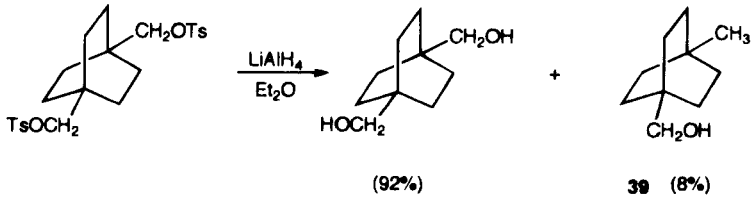
SCHEME 52



STRUCTURE 38

7.2. *Solution Phase Reactions with Even-electron Reagents*

Following the seminal work by Closson's group, a number of fascinating reports of radical anion intervention in the chemistry of sulfonates has appeared. Reduction of the ditoluenesulfonate shown in Scheme 53 proceeds in ether[27] to give precedented products.

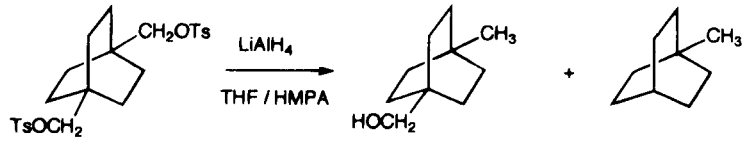


(92%) **39** (8%)

SCHEME 53

These products were presumed to arise by ionic substitution. However, a change in solvent to HMPA/THF mixtures produced the following results.

Wang and Sukenik[27] attribute the shift in outcomes for Schemes 53 and 54 to the ability of the solvent to solvate Li^+. They point out that ether is unable to solvate Li^+ well, resulting in tight ion pairs which undergo simple substitution at carbon or sulfur. Alternatively, Closson's proposals (Schemes 51 and 52) readily account for both SO and CO cleavage via radical anions. Lithium aluminum hydride is a well-known SET reagent.[85a,b,c]

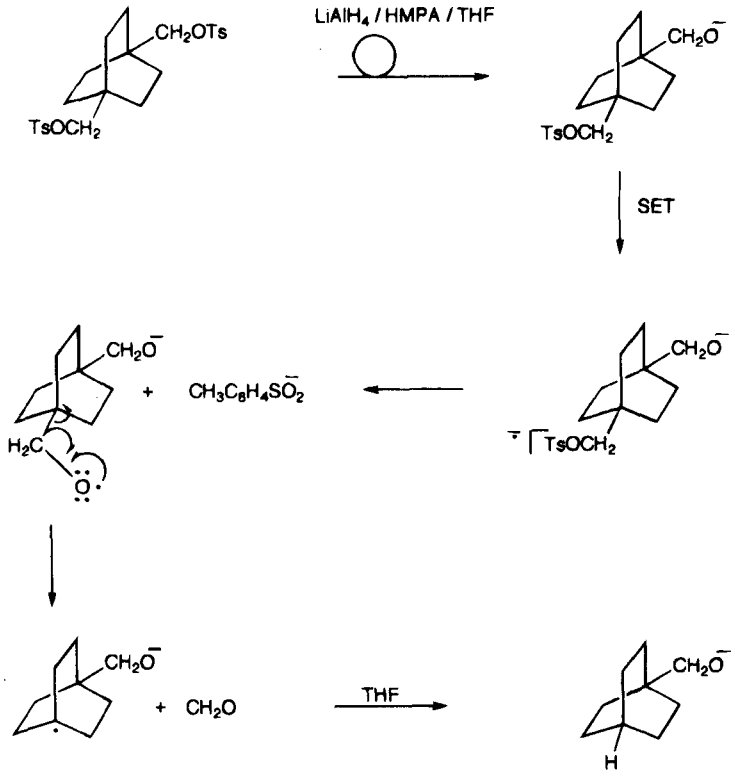


39 (85%) **40** (15%)

SCHEME 54

In contrast to any mechanistic ambiguity surrounding the formation of the Scheme 53 products, the loss of a hydroxymethyl group leading to **40** in

Scheme 54 requires the intervention of a carbon radical. The intermediacy of at least one sulfonate radical anion[27] as depicted in Scheme 55, seems very likely.

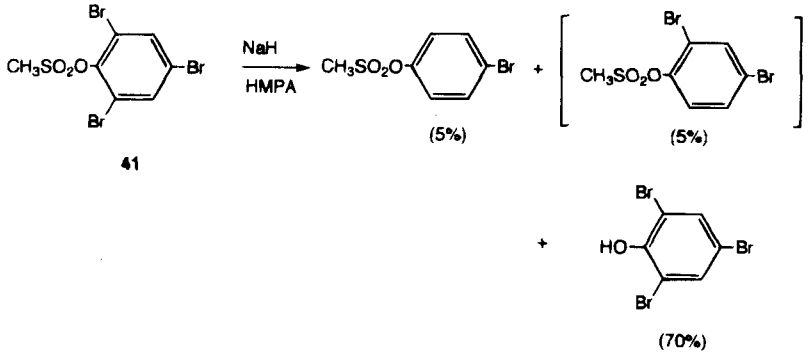


SCHEME 55

We have reported[29] that sodium hydride will reduce phenyl benzenethiosulfonate and aryl sulfonates with particularly low-lying LUMO's (see Scheme 38 and Table 3). Aryl methanesulfonates with high-lying LUMO's react with NaH/HMPA to form sulfene as outlined in Section 5.2.

Subsequently,[30] the tribromophenyl methanesulfonate **41** was treated with NaH/HMPA as shown in Scheme 56.

In accord with the SET mechanism we have proposed for these reactions (Scheme 38), sodium hydride induces some debromination of **41**.



SCHEME 56

Closson *et al.* have shown[26] that radical anions derived from halogenated aryl methanesulfonates do expel halide anions. Furthermore, the presence of *m*-dinitrobenzene in the Scheme 56 reaction completely suppresses dehalogenation pathways. The selective expulsion of ortho bromines in **41** would be readily understood if the SOMO's of the radical anion intermediates only have non-zero ring coefficients at the ortho and meta carbons.

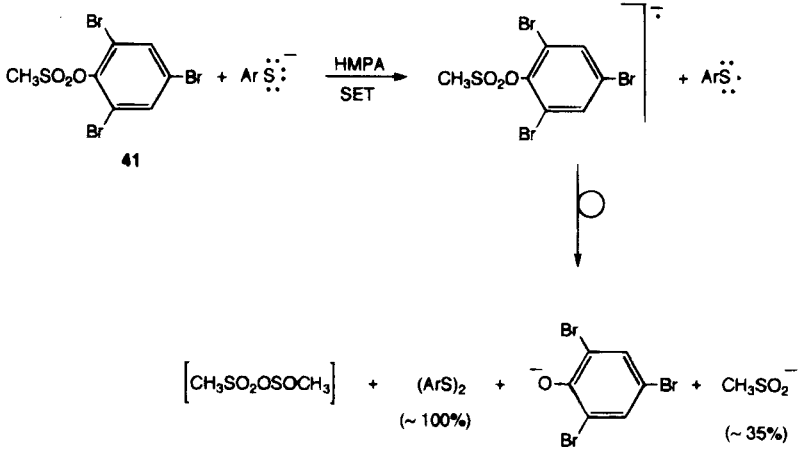
Tribromophenyl methane- and benzenesulfonates have been established[28] as mild and very efficient oxidizing agents for arenethiolate anions. Saturated thiolate anions are converted into disulfides in somewhat lower yields. Only moderate yields of sulfinate anions were obtained, leading to the proposal that SET furnishes a sulfinate-sulfonate mixed anhydride (see Scheme 57).

Further exploration[30] of reactions between aryl methanesulfonates and thiolate anions revealed the unexpected result presented in Scheme 58.

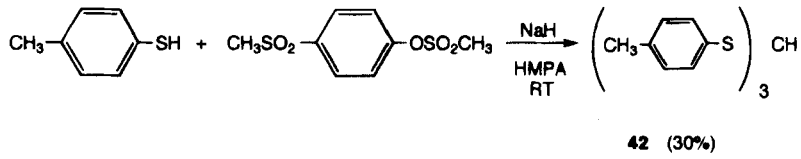
(Note that % yield is in terms of methanesulfonate). We have called this the Trithioorthoformate Reaction.

Yields of the trithioorthoformate **42** correlate with LUMO eigenvalues (see entries 4, 5 and 9, Table 3) until electron transfer becomes so facile that disulfide is the exclusive product (see Scheme 57 and entry 10, Table 3). An important intermediate was isolated when *p*-chlorophenyl methanesulfonate was employed in this reaction.

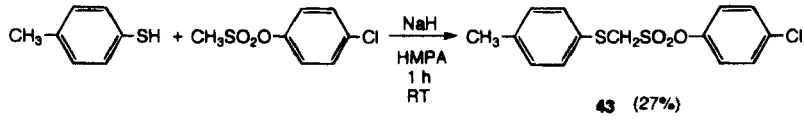
It is now possible to see how sulfenylation at carbon can occur.



SCHEME 57

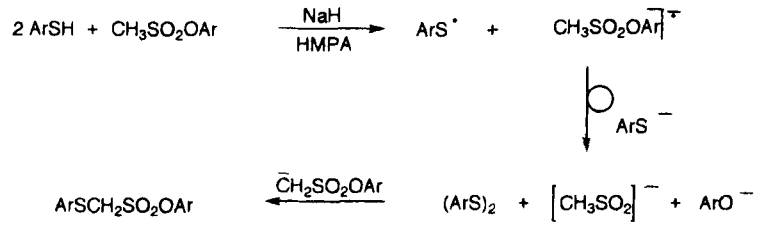


SCHEME 58



SCHEME 59

An alternative to the SET mechanism shown in Scheme 60, would have $Ar\bar{S}$ attack mesylate sulfur to provide CH_3SO_2SAr. Thiosulfonate could then sulfenylate the carbanion derived from the mesylate to furnish the intermediate sulfide sulfonate. This traditional mechanistic picture faces several difficulties.



SCHEME 60

p-methylbenzenethiol/ethanol/NaH react with phenyl methanesulfonate in HMPA *at ambient temperature* to furnish *p*-tolyl ethyl sulfide.[28] Presumably the reaction proceeds via tandem substitutions as pictured for the corresponding reaction of trifluoroethyl methanesulfonate in Scheme 5. However, *at 100 °C*, *p*-methylbenzenethiol/ethanol/NaH react with phenyl methanesulfonate to furnish the trithioorthoformate through the corresponding sulfide-sulfonic acid ester.[30] It is difficult to see why heating the reaction would simply reverse the ambient-temperature preference for ethoxide (hard base) attack at sulfonyl sulfur (hard acid[7]). Experimental support for the importance of HSAB theory to understanding closely related reactions is presented in Scheme 2. Moreover, SET chemistry (Scheme 60) is materially facilitated by HMPA.[85d,85e] In accord with this assertion, Wang and Sukenik[27] observed SET chemistry (Scheme 55) once HMPA was introduced into their solvent system. Furthermore, the observation of tribromophenyl methanesulfonate debromination by sodium hydride (see Scheme 56, discussion earlier in this section and in section 5.2) requires the intervention of sulfonate radical anions. If sodium hydride can generate radical anions from this aryl methanesulfonate, *p*-methylbenzenethiolate anions certainly can.[85f]

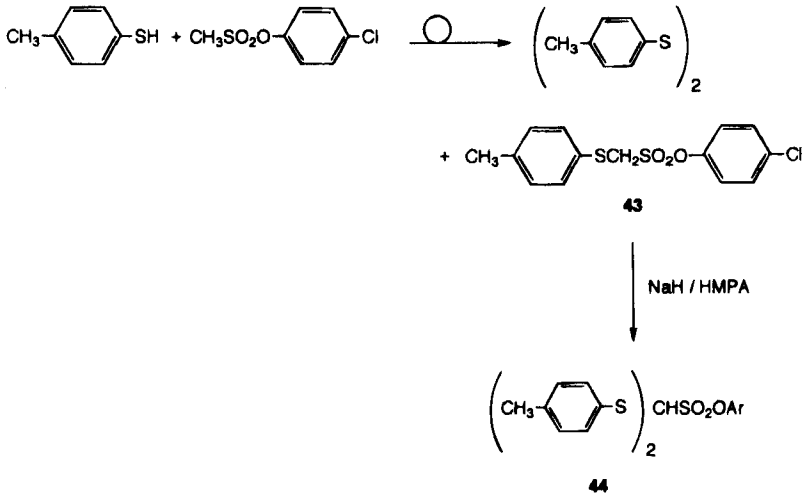
Repetition of the same processes on **43** would produce a bissulfide-sulfonate ester (Scheme 61).

Unpublished results[10] suggest that the final *p*-tolylthio group is introduced via a dithiosulfene as shown in Scheme 62.

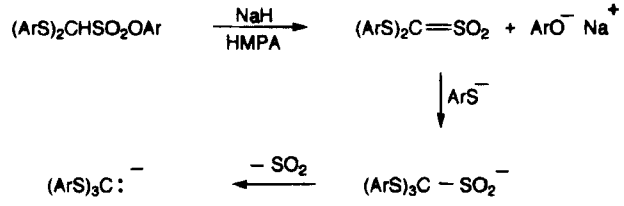
So called "carbophilic attack" (nucleophilic attack at sp^2 C in a sulfene) is now recognized as having ample precedent.[73d]

7.3. *Gas Phase Reactions*

Sulfonate radical anions have been generated in the mass spectrometer under chemical-ionization conditions.[86] In solution, sulfonate radical



SCHEME 61



SCHEME 62

anions undergo CO and/or SO bond rupture (see Scheme 52). In the gas phase,[86] toluenesulfonates undergo CS homolysis (Scheme 63).

SCHEME 63

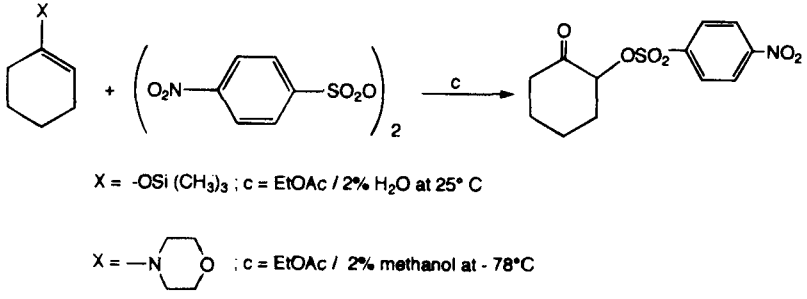
This drastic alteration of behaviour for gas-phase radical anions was attributed to the extreme base strength observed for the formation of a gas-phase alkoxide ion.

8. SULFONATES IN SYNTHESIS AND MEDICINE

8.1. *Synthesis*

Some novel preparations of familiar sulfonates have appeared recently. Fujita *et al.*[87] have reported site-specific hydroxyl sulfonation in α-cyclodextrin: C_2-hydroxyl sulfonation with *m*-nitrobenzenesulfonyl chloride and C_3-hydroxyl sulfonation with 2-naphthalenesulfonyl chloride. Schenk and Pfeffermann[88] have reported the conversion of some organometallic hydroxyethyl ethers into methyl sulfonates with SO_2.

There have also been some recent reports of the preparation of novel sulfonate esters. Hoffman *et al.*[89] have devised a useful preparation of α-arylsulfonyloxy ketones from silyl enol ethers or enamines (Scheme 64).

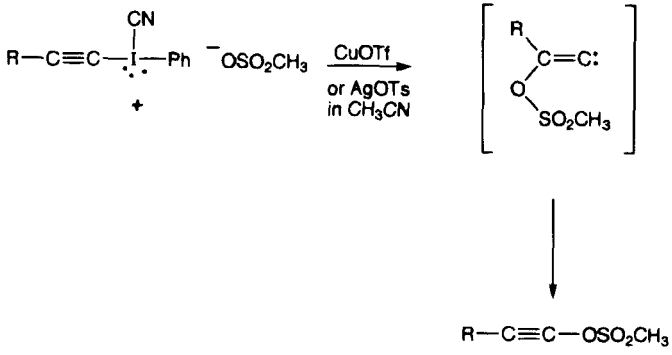


SCHEME 64

An overview of solvolysis reactions of α-sulfonyloxy ketones is available.[90]

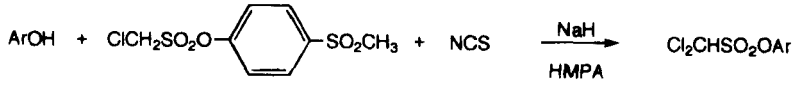
Stang *et al.* have devised effective synthetic methodology[80] for the preparation of alkynyl sulfonates via alkylidene carbenes as outlined in Scheme 65.

In contrast to a recent report,[91] "conventional routes", in our hands (phenol/triethylamine/pyridine/1 week at ambient temperature or sodium phe-



SCHEME 65

noxide in acetone for 1 week at ambient temperature) failed to convert either trichloromethane- or dichloromethanesulfonyl chloride into aryl polychloromethanesulfonates. Application of a counterattack strategy[92] permitted us to devise effective one-pot methodology[48] for either of the target systems (vide Scheme 66).



SCHEME 66

Finally, sulfonic acid ester chemistry continues to find application in the preparation of non-sulfur compounds e.g. alkenes[25] and ketones.[93]

8.2 *Medicine*

In the search for effective anticancer agents, early work led to the observation that *N*-methyl-*N'*-nitro-*N*-nitrosoguanidine was active against leukemia L1210 in mice. Subsequent work suggested that nitrosoureas were antileukemic by virtue of alkylating DNA. Unhappily, their severe toxicity to bone marrow limits their use in clinical settings.[94]

One chloroethylating agent that has significant merit as an anticancer agent is Clomesone **45**.

One hopes that structural modification of **45** will permit transport across membranes without impairing its chloroethylating ability.[94]

$CH_3SO_2CH_2SO_2OCH_2CH_2Cl$

STRUCTURE 45

Acknowledgements

Mr. M. Frederiksen has kindly provided English translations of some articles which appeared in German. Professor J. F. King has provided extensive thoughtful commentary of the original version of this review which has led to material improvement of it. This acknowledgement should not be construed to mean that Professor King shares my views of probable mechanism in every case.

References

[1] Horspool, W. H. (1991). *The Chemistry of Sulphonic Acids, Esters and Their Derivatives*, Eds. S. Patai and Z. Rappoport, Wiley, Chichester, pp. 501–552.
[2] Simonet, J. (1991). *The Chemistry of Sulphonic Acids, Esters and Their Derivatives*, Eds. S. Patai and Z. Rappoport, Wiley, Chichester, pp. 553–582.
[3] Iley, J. (1991). *The Chemistry of Sulphonic Acids, Esters and Their Derivatives*, Eds. S. Patai and Z. Rappoport, Wiley, Chichester, pp. 453–500.
[4] Lowry, T. H. and Richardson, K. S. (1987). *Mechanism and Theory in Organic Chemistry*, 3rd Ed., Harper and Row, New York, pp. 640–643.
[5] Carey, F. A. and Sundberg, R. J. (1984). *Advanced Organic Chemistry*, 2nd Ed., Part A, Plenum, New York, pp. 683–690.
[6] Langler, R. F. and Morrison, N. A. (1987). *Can. J. Chem.*, **65**, 2385.
[7] (a) Kice, J. L., Kasperek, G. J. and Patterson, D. (1969). *J. Am. Chem. Soc.* **91**, 5516.
(b) Exophilic and nucleofugal are synonyms. Nucleofugality and exophilicity are synonyms.
[8] (a) Bordwell, F. G. (1988). *Acc. Chem. Res.* **12**, 456.
(b) Guthrie, J. P. (1979). *Can. J. Chem.* **57**, 454.
[9] Oae, S. and Kunieda, N. (1977). *Organic Chemistry of Sulfur*, Ed. S. Oae, Plenum, New York, pp. 606–610.
[10] Langler, R. F. unpublished results.
[11] Stewart, J. J. P. (1989). *J. Comp. Chem.* **10**, 209.
[12] Basch, H. and Hoz, T. (1991). *The Chemistry of Sulphonic Acids, Esters and Their Derivatives*, Eds. S. Patai and Z. Rappoport, Wiley, Chichester, pp. 1–62.
[13] Fleming, I. (1976). *Frontier Orbitals and Organic Chemical Reactions*, Wiley, Chichester, pp. 23–32.
[14] Baum, J. C., Bolhassan, J., Langler, R. F., Pujol, P. J. and Raheja, R. K. (1990). *Can. J. Chem.* **68**, 1450.
[15] (a) Warren, L. A. and Smiles, S. (1932). *J. Chem. Soc.*, 1040.
(b) Bunnett, J. F. and Zahler, R. E. (1951). *Chem. Rev.* **49**, 273.
[16] (a) Kulkarni, S. and Grimmett, M. R. (1985). *Aust. J. Chem.* **40**, 1415.
(b) Bostick, T. M., Christie, S. D., Connolly, T. J., Copp, S., Langler, R. F., Reid, D. L. and Zaworotko, M. (1996) *Aust. J. Chem.*, **49**, 243.
(c) Vilsmaier, E., Tropitzsch, R. and Vostrowsky, O. (1974). *Tetrahedron Lett.*, 3275.
(d) Vilsmaier, E., Tropitzsch, R. and Vostrowsky, O. (1974). *Tetrahedron Lett.*, 3987.
(e) Vilsmaier, E. and Becker, G. (1975). *Synthesis*, 55.
(f) King, J. F., Hillhouse, J. H. and Khemani, K. C. (1985). *Can. J. Chem.* **63**, 1.

[17] Cotton, F. A. and Wilkinson, G. (1966). *Advanced Inorganic Chemistry*, 2nd Ed., New York, pp. 409–413.
[18] Aroney, M. J., LeFevre, R. J. W., Pierens, R. K., Stootman, H. J. and Yong, M. G. M. (1987). *Aust. J. Chem.* **40**, 619 and references therein.
[19] Aissani, A. M., Baum, J. C., Langler, R. F. and Ginsburg, J. L. (1986). *Can. J. Chem.* **64**, 532.
[20] (a) Schleyer, P. v. R., Clark, T., Kos, A. J., Spitznagel, G. W., Rohde, C., Arad, D., Houk, K. N. and Rondan, N. G. (1984). *J. Am. Chem. Soc.* **106**, 6467.
(b) Reed, A. E. and Schleyer, P. v. R. (1990). *J. Am. Chem. Soc.* **112**, 1434.
(c) For a case against major d-orbital participation in trigonal bipyramids and octahedra for compounds of Si, S, P, Cl see: Magnusson, E. (1990) *J. Am. Chem. Soc.* **112**, 7940.
[21] Marriott, S. and Topsom, R. D. (1985). *J. Chem. Soc., Perkin Trans. 2*, 1045.
[22] Roja, A. and Lee, K. H. (1989). *J. Am. Chem. Soc.* **111**, 4166.
[23] Klein, J. (1988). *Tetrahedron* **44**, 503.
[24] Ganson, J. R., Schulenberg, S. and Closson, W. D. (1970). *Tetrahedron Lett.* **26**, 4397.
[25] Carnahan, J. C. Jr. and Closson, W. D. (1972). *Tetrahedron Lett.* **28**, 3447.
[26] Carnahan, J. C. Jr., Closson, W. D., Ganson, J. R., Juckett, D. A. and Quaal, K. S. (1976). *J. Am. Chem. Soc.* **98**, 2526.
[27] Wang, S. S. and Sukenik, C. N. (1985). *J. Org. Chem.* **50**, 653.
[28] Durkin, K. A., Langler, R. F. and Morrison, N. A. (1988). *Can. J. Chem.* **66**, 3070.
[29] Baum, J. C., Durkin, K. A., Precedo, L., O'Blenes, S. B., Goehl, J. E., Langler, R. F., MacCormack, G. K. and Smith, L. L. (1991). *Can. J. Chem.* **69**, 2127.
[30] Baum, J. C., Black, B. E., Precedo, L., Goehl, J. E. and Langler, R. F. (1995). *Can. J. Chem.* **73**, 444.
[31] Martin, L. D., Perozzi, E. F. and Martin, J. C. (1979). *J. Am. Chem. Soc.* **101**, 3595.
[32] Nakashima, W., Kusuyama, Y., Ikeda, Y. and Iwamura, H. (1983). *Bull. Chem. Soc. Jpn.* **56**, 3123.
[33] Perkins, C. W., Clarkson, R. B. and Martin, J. C. (1986). *J. Am. Chem. Soc.* **108**, 3206.
[34] Perkins, C. W. and Martin, J. C. (1986). *J. Am. Chem. Soc.* **108**, 3211.
[35] Chatgilialoglu, C., Griller, D. and Rossini, S. (1989). *J. Org. Chem.* **54**, 2734.
[36] Bassindale, A. R. and Iley, J. N. (1991). *The Chemistry of Sulphonic Acids, Esters and Their Derivatives*, Eds. S. Patai and Z. Rappoport, Wiley, Chichester, pp. 197–247.
[37] Koutecky, V. B. and Musher, J. I. (1974). *Theoret. Chim. Acta* **33**, 227.
[38] King, J. F. (1991). *The Chemistry of Sulphonic Acids, Esters and Their Derivatives*, Eds. S. Patai and Z. Rappoport, Wiley, Chichester, pp. 249–259.
[39] Olah, G. A., Ku, A. T. and Olah, J. A. (1970). *J. Org. Chem.* **35**, 3908.
[40] Bentley, T. W., Roberts, K., Jurczyk, S. and Williams, D. J. (1987). *J. Chem. Soc., Perkin Trans. 2*, 293.
[41] D'Rozario, P., Smyth, R. L. and Williams, A. (1984). *J. Am. Chem. Soc.* **106**, 5027.
[42] (a) Shashidhar, M. S. and Bhatt, M. V. (1986). *Tetrahedron Lett.* **27**, 2165.
(b) Shashidhar, M. S. and Bhatt, M. V. (1987). *J. Chem. Soc., Chem. Commun.*, 654.
[43] (a) King, J. F., Khemani, K. C., Skonieczny, S. and Payne, N. C. (1988). *J. Chem. Soc., Chem. Commun.*, 415.
(b) Discussion here cites results for the PM3 energy-minimized anti conformation shown as Fig. 2. Calculated bond lengths and atomic charges show no significant sensitivity to conformational change.
[44] Pregel, M. J. and Buncel, E. (1991). *J. Chem. Soc., Perkin Trans. 2*, 307.
[45] Hardstaff, W. R. and Langler, R. F. (1982). *Sulfur in Organic and Inorganic Chemistry*, Ed. A. Senning, M. Dekker, New York, p. 242.
[46] Graafland, T., Wagenaar, A., Kirby, A. J. and Engberts, J. (1979). *J. Am. Chem. Soc.* **101**, 6981.
[47] Baldwin, J. E. (1976). *J. Chem. Soc., Chem. Commun.*, 734.
[48] Langler, R. F., LeBlanc, L. M. and Smith, L. L. (1993). *Aust. J. Chem.* **46**, 1085.

[49] (a) Langler, R. F. and Steeves, J. L. (1994). *Aust. J. Chem.* **47**, 1641.
(b) King, J. F. and Gill, M. S. (1995). *Angew. Chem., Int. Ed. Engl.* **34**, 1612.
[50] Kawazoe, Y., Ninomiya, S., Kohda, K. and Kimoto, H. (1986). *Tetrahedron Lett.* **27**, 2897.
[51] Simchen, G. (1991). *Adv. Silicon Chem.* **1**, 189.
[52] (a) Gassman, P. G. and Harrington, C. K. (1984). *J. Org. Chem.* **49**, 2258.
(b) Bhide, R. S., Levison, B. S., Sharma, R. B., Ghosh, S. and Salomon, R. G. (1986). *Tetrahedron Lett.* **27**, 671.
(c) Martinez, A. G., Vilar, E. T., Martin, M. G. and Franco, C. R. (1985). *Chem. Ber.* **118**, 1282.
(d) Martinez, A. G., Alvarez, R. M., Fraile, A. G., Subramanian, L. R. and Hanack, M. (1987). *Synthesis*, 49.
(e) Bentz, H., Subramanian, L. R., Hanack, M., Martinez, A. G., Martin, M. G. and Perez-Ossorio, R. (1977). *Tetrahedron Lett.*, 9.
(f) Allen, A. D., Ambidge, I. C., Michael, C. C. H., Muir, R. J. and Tidwell, T. T. (1983). *J. Am. Chem. Soc.* **105**, 2343.
(g) Hanack, M. and Auchter, G. (1985). *J. Am. Chem. Soc.* **107**, 5238.
(h) Subramanian, L. R. and Hanack, M. (1972). *Chem. Ber.* **105**, 1465.
(i) Adcock, W., Coope, J., Shiner, V. J. Jr. and Trout, N. A. (1990). *J. Org. Chem.* **55**, 1411.
(j) Shiner, V. J. Jr. and Ensinger, M. W. (1990). *J. Org. Chem.* **55**, 653.
(k) Adcock, W., Krstic, A. R., Duggan, P. J., Shiner, V. J. Jr., Coope, J. and Ensinger, M. E. (1990). *J. Am. Chem. Soc.* **112**, 3140.
(l) Wilgis, F. P., Neumann, T. E. and Shiner, V. J. Jr. (1990). *J. Am. Chem. Soc.* **112**, 4435.
(m) Stang, P. J. and Zhdankin, V. V. (1990). *J. Am. Chem. Soc.* **112**, 6437.
(n) Stang, P. J. and Zhdankin, V. V. (1991). *J. Am. Chem. Soc.* **113**, 4571.
(o) Stang, P. J., Williamson, B. L. and Zhdankin, V. V. (1991). *J. Am. Chem. Soc.* **113**, 5870.
(p) Zhong, Z., Hinkle, R. J., Arif, A. A. and Stang, P. J. (1991). *J. Am. Chem. Soc.* **113**, 6196.
(q) Zefirov, N. S., Gakh, A. A., Zhdankin, V. V. and Stang, P. J. (1991). *J. Org. Chem.* **56**, 1416.
(r) Bachi, M. D., Bar-Ner, N., Crittell, C. M., Stang, P. J. and Williamson, B. L. (1991). *J. Org. Chem.* **56**, 3912.
(s) Imhoff, M. A., Ragain, R. M., Moore, K. and Shiner, V. J. Jr. (1991). *J. Org. Chem.* **56**, 3542.
(t) Martinez, A. G., Fernandez, A. H., Jimenez, F. M., Fraile, A. G., Subramanian, L. R. and Hanack, M. (1992). *J. Org. Chem.* **57**, 1627.
(u) Stang, P. J., Tykwinski, R. and Zhdankin, V. V. (1992). *J. Org. Chem.* **57**, 1861.
(v) Stang, P. J. and Crittell, C. M. (1992). *J. Org. Chem.* **57**, 4305.
(w) Shiner, V. J. Jr. and Tai, J. J. (1981). *J. Am. Chem. Soc.* **103**, 436.
(x) Shiner, V. J. Jr. and Seib, R. C. (1979). *Tetrahedron Lett.*, 123.
(y) Stoetling, D. T. and Shiner, V. J. Jr. (1993). *J. Am. Chem. Soc.* **115**, 1695.
(z) Sunko, D. E., Vancik, H., Mihalic, Z., Shiner, V. J. Jr. and Wiglis, F. P. (1994). *J. Org. Chem.* **59**, 7051.
[53] Mukherjee, L. and Grunwald, E. (1958). *J. Phys. Chem.* **62**, 1311.
[54] King, J. F. and Aslam, M. (1979). *Can. J. Chem.* **55**, 3278.
[55] (a) Langler, R. F. and Morkin, T. L. unpublished results.
(b) Furukawa, N., Ogawa, S., Kawai, T. and Oae, S. (1984). *J. Chem. Soc., Perkin Trans. 1*, 1839.
[56] Field, L. (1977). *Organic Chemistry of Sulfur*, Ed. S. Oae Plenum, New York, p. 320.
[57] Langler, R. F. and Pincock, J. A. (1977). *Can. J. Chem.* **55**, 2316.
[58] (a) Zefirov, N. S. and Makhonkov, D. I. (1982). *Chem. Rev.* **82**, 615.
(b) Vernon, A. and Stirling, C. J. M. (1993). *J. Chem. Soc., Chem. Commun.*, 1609.

[59] Precedo, L. (1988). *M. S. Thesis*, Florida Institute of Technology, Melbourne, Florida, U.S.A.
[60] Cadogan, J. I. G., Cameron, D. K., Gosney, I., Highcock, R. M. and Newlands, S. F. (1985). *J. Chem. Soc., Chem. Commun.*, 1751.
[61] Cadogan, J. I. G., Cameron, D. K., Gosney, I., Highcock, R. M. and Newlands, S. F. (1986). *J. Chem. Soc., Chem. Commun.*, 766.
[62] Gais, H. J. and Vollhardt, J. (1988). *Tetrahedron Lett.* **29**, 1529.
[63] Goodwin, B. J. F., Roberts, D. W., Williams, D. J. and Parke, D. V. (1983). *Immunotoxicology*, Eds. Gibson, G. G., Hubbard, R. and Parke, D. V. Academic Press, London.
[64] Drozd, V. N. and Saks, T. K. (1975). *Zh. Org. Khim.*, **11**, 351.
[65] (a) Durst, T. and Tin, K. C. (1970). *Can. J. Chem.* **48**, 845.
(b) Truce, W. E. and Vrencur, D. J. (1969). *Can. J. Chem.* **47**, 860.
(c) Truce, W. E. and Vrencur, D. J. (1969). *J. Org. Chem.* **35**, 1226.
(d) Durst, T. and du Manoir, J. (1969). *Can. J. Chem.* **47**, 1230.
[66] (a) Fraser-Reid, B., Sun, K. M., Tsang, R. Y. K., Sinay, P. and Pietraszkiewicz, M. (1981). *Can. J. Chem.* **59**, 260.
(b) Truce, W. E. and Christensen, L. W. (1970). *J. Org. Chem.* **35**, 3969.
(c) Musicki, B. and Widlanski, T. S. (1990). *J. Org. Chem.* **55**, 4231.
[67] (a) Hückel, W. and Tappe, W. (1939). *Ann.* **537**, 113.
(b) Streitwieser, A. (1962). Solvolytic Displacement Reactions, McGraw-Hill, New York.
[68] Amin, H. B. and Taylor, R. (1978). *J. Chem. Soc., Perkin Trans. 2*, 1090.
[69] Chuchani, G., Alvarez, J. and Martin, I. (1991). *J. Phys. Org. Chem.* **4**, 399.
[70] Chuchani, G., Martin, I., Dominguez, R., Rotinov, A., Pekerar, S. and Gomez, M. (1993). *J. Phys. Org. Chem.* **6**, 85.
[71] Corey, E. J., Posner, G. H., Atkinson, R. F., Wingard, A. K., Halloran, D. J., Radzik, D. M. and Nash, J. J. (1989). *J. Org. Chem.* **54**, 389.
[72] Jenniskens, L. H. D., Wijnberg, J. B. P. A. and deGroot, A. (1991). *J. Org. Chem.* **56**, 6585.
[73] (a) Opitz, G. (1967). *Angew. Chem., Int. Ed Engl.* **6**, 107.
(b) Truce, W. E. and Liu, L. K. (1969). *Mech. React. Sulfur Compounds* **4**, 145.
(c) King, J. F. (1975). *Acc. Chem. Res.* **8**, 10.
(d) King, J. F. and Rathore, R. (1991). *The Chemistry of Sulphonic Acids, Esters and Their Derivatives*, Eds. S. Patai and Z. Rappoport, Wiley, Chichester, pp. 697–766.
[74] (a) King, J. F. and Beatson, R. P. (1975). *Tetrahedron Lett.*, 973.
(b) Davy, M. B., Douglas, K. T., Loran, J. S., Steltner, A. and Williams, A. (1977). *J. Am. Chem Soc.* **99**, 1196.
[75] (a) Stirling, C. J. M. (1979). *Acc. Chem. Res.* **12**, 198.
(b) Opitz, G., Kleeman, M., Bucher, D., Walz, G. and Rieth, K. (1966). *Angew. Chem., Int. Ed. Engl.* **5**, 594.
[76] Hawkins, J. M., Lewis, T. A. and Raw, A. S. (1990). *Tetrahedron Lett.* **31**, 981.
[77] Kent, B. A. and Smiles, S. (1934). *J. Chem. Soc.*, 422.
[78] Yokoyama, M., Tsuji, K. and Imamoto, I. (1984). *Bull. Chem. Soc. Jpn.* **57**, 2954.
[79] Cox, R. A., McAllister, M., Roberts, K. A., Stang, P. J. and Tidwell, T. T. (1989). *J. Org. Chem.* **54**, 4899.
[80] Stang, P. J. (1991). *Acc. Chem. Res.* **24**, 304.
[81] Grossert, J. S., Hardstaff, W. R. and Langler, R. F. (1973). *J. Chem. Soc., Chem. Commun.*, 50.
[82] Kenner, G. W. and Williams, N. R. (1955). *J. Chem. Soc.*, 522.
[83] Closson, W. D., Wriede, P. and Bank, S. (1966). *J. Am. Chem. Soc.* **88**, 1581.
[84] Jordan, R. (1991). *Reaction Mechanisms of Inorganic and Organometallic Systems*, Oxford University Press, New York.

[85] (a) Ashby, E. C., DePriest, R. N. and Goel, A. B. (1981). *Tetrahedron Lett.* **22**, 1763.
(b) Ashby, E. C., DePriest, R. Goel, A. B., Wenderoth, B. and Pham, T. N. (1984). *J. Org. Chem.* **49**, 3545.
(c) Ashby, E. C. (1988). *Acc. Chem. Res.* **21**, 414.
(d) Bunnett, J. F. (1978). *Acc. Chem. Res.* **11**, 413.
(e) Kornblum, N., Ackermann, P., Manthey, J. W., Masser, M. T., Pinnick, H. W., Singaram, S. and Wade, P. A. (1988). *J. Org. Chem.* **53**, 1475.
(f) For examples of $ArS^{\cdot}$ as a one electron donor see ref. 85d and Chanon, M. and Tobe, M. L. (1982). *Angew. Chem., Int. Ed. Engl.* **21**, 1.
[86] Hehemann, D. G., Binkley, R. W. and Masnovi, J. (1989). *J. Org. Chem.* **54**, 3256.
[87] Fujita, K., Nagamura, S., Imoto, T., Tahara, T. and Koga, T. (1985). *J. Am. Chem. Soc.* **107**, 3233.
[88] Schenk, W. A. and Pfeffermann, J. (1992). *J. Organometal. Chem.* **440**, 341.
[89] Hoffman, R. V., Carr, C. S. and Jankowski, B. C. (1985). *J. Org. Chem.* **50**, 5148.
[90] Creary, X. (1985). *Acc. Chem. Res.* **18**, 3.
[91] Culshaw, P. N. and Walton, J. C. (1990). *Tetrahedron Lett.* **31**, 2457.
[92] Hwu, J. R. and Gilbert, B. A. (1989). *Tetrahedron* **45**, 1233.
[93] Pestchanker, M. J. and Giordano, O. S. (1990). *Tetrahedron Lett.* **31**, 463.
[94] Montgomery, J. A. (1986). *Acc. Chem. Res.* **19**, 293.