Acknowledgment. Support for this work was provided by the Research Corp., the Catalysts of Bethany Nazarene College, the Research Associates of Point Loma College, and the donors of the Petroleum Research Fund, administered by the American Chemical Society.

Registry No. **1**, 95-13-6; **2**, 19598-15-3; **3**, 19598-04-0; **4**, 20245-19-6; **5**, 74947-77-6; **6**, 5837-70-7; **7**, 74984-78-4; **8**, 19598-12-0; **9**, 19598-02-8; **10**, 19598-14-2; **11**, 19598-03-9; **12**, 5927-94-6; **13**, 74947-78-7; **14**, 19598-11-9; **15**, 74947-79-8; **16**, 74947-80-1; **17**, 74947-81-2; **18**, 74947-82-3; **19**, 74947-83-4; **20**, 480-90-0; acetyl hypobromite, 4254-22-2; acetyl hypochlorite, 758-11-2; methyl hypochlorite, 593-78-2; methyl hypobromite, 28078-73-1; trichloramine, 10025-85-1; iodobenzene dichloride, 932-72-9; bromine chloride, 13863-41-7; chlorine, 7782-50-5; bromine, 7726-95-6; *trans*-2,3-dibromoindanone, 40774-43-4; *trans*-2-bromo-3-chloroindanone, 74947-84-5; *trans*-2,3-dichloroindanone, 74947-85-6; *cis*-2,3-dichloroindanone, 74947-86-7.

Desulfurization of Organic Trisulfides by Tris(dialkylamino)phosphines. Mechanistic Aspects[1]

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Tris(dialkylamino)phosphines effect a rapid desulfurization of trisulfides to disulfides under mild conditions. The reaction mechanism involves a bimolecular process, proceeding by the rate-determining formation of a phosphonium salt intermediate. The central sulfur atom of a diaryl trisulfide is removed in the process, while a dialkyl trisulfide loses a terminal sulfur atom to the aminophosphine.

A wide variety of organosulfur compounds have been desulfurized by trivalent phosphorus compounds[2] as represented by the general expression given in eq 1. There

$$RSX + R'_3P \rightarrow RX + R'_3P{=}S \qquad (1)$$

$$X = SR, SS_xR, SH, S(O)R, SO_2R, SSO_2R, S(C{=}O)OR, S(C{=}O)R, S(C{=}S)R, N[(C{=}O)R]_2, OR, CH_2(C{=}O)R, CN, Cl$$

$$R' = RO, R_2N, R$$

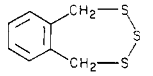
are several reports in the literature of the selective desulfurization of trisulfides (1) to disulfides by the action

$$R{-}S{-}\underset{1}{S}{-}S{-}R$$

of triphenylphosphine.[3e,i,4] The first studies to determine which sulfur atom (central or terminal) in a trisulfide is removed by a tertiary phosphine were performed by Safe and Taylor.[4e,f] Two epitrithiodioxopiperazines, thiodehydrogliotoxin and sporidesmin E, were shown to lose their central sulfur atoms (radiochemically labeled with

Table I. Desulfurization of Trisulfides by Tris(dialkylamino)phosphines

$$RSSSR' + R''_3P \longrightarrow RSSR' + R''_3P{=}S$$

trisulfide R and R'	R''	% yield RSSR'[a]
$4\text{-}CH_3C_6H_4$	Et_2N	88
$4\text{-}CH_3OC_6H_4$	Et_2N	62
C_6H_5	Et_2N	92
$C_6H_5CH_2$	Et_2N	94
	Me_2N	100[b,c]
	morpholino	100[b,d]
$C_6H_5CHCH_3$	Me_2N	100[c,e]
	morpholino	75[f]
	Me_2N	77
$R = C_6H_5CH_2$, $R' = (CH_3)_2CH$	Et_2N	96
$R = C_6H_5CH_2$, $R' = CH_3(CH_2)_2$	Et_2N	100[b]
$CH_3(CH_2)_2$	Et_2N	80
	Me_2N	100[b]
	morpholino	100[b,g]
$CH_3(CH_2)_4$	Et_2N	71
$CH_3OC(O)CH_2$	Et_2N	91
$CH_3(CH_2)_5CHCH_3$	Me_2N	60[h]
$(CH_3)_3C$	Me_2N	0[i]

[a] Yield as isolated by silica gel column chromatography unless otherwise noted. Reaction conditions were 2-3 h at room temperature in anhydrous diethyl ether or benzene with a 0-10% excess of R''_3P, unless otherwise noted. [b] Quantitative by GC analysis. [c] Quantitative by NMR analysis. [d] Reaction solvent was 2:1 Et_2O-CH_3CN or CH_3CN. [e] Reaction conditions were ca. 2 days at room temperature in acetonitrile-d_3 to 9 days at room temperature in cyclohexane-d_{12}. [f] Percentage conversion by NMR after 10 days at 65 °C in CD_3CN. [g] Reaction conditions were 3 h at reflux in acetonitrile. [h] Percentage conversion by GC and NMR after 7 days at room temperature in benzene. [i] No reaction detected by GC, even after 40 min of reflux in acetonitrile with a five-fold excess of $(Me_2N)_3P$.

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(1) Organic Sulfur Chemistry. Part 38. For Part 37, see D. N. Harpp and A. Granata, *J. Org. Chem.*, **45**, 271 (1980).

(2) The following is not an exhaustive review of desulfurization reactions but provides leading references for most types of ionic desulfurization reactions: X = SR,[3a-d] SS_xR,[3d-f] SH,[3c,g] S(O)R,[3d,h] SO_2R,[3d,i] SSO_2R,[3j] S(C=O)OR,[1] S(C=O)R,[3k] S(C=S)R,[3l] $N[(C{=}O)R]_2$,[3d,m] OR,[3n] CH_2(C=O)R,[3o] CN,[3o] Cl.[3p] See also: R. F. Hudson, "Structure and Mechanism in Organo-Phosphorus Chemistry", Academic Press, New York, 1965, p 172; A. J. Kirby and S. G. Warren, "The Organic Chemistry of Phosphorus", Elsevier, New York, 1967, p 95; J. I. G. Cadogan and R. K. Mackie, *Chem. Soc. Rev.*, **3**, 87 (1974).

(3) (a) D. N. Harpp and R. A. Smith, *Org. Synth.*, **58**, 138 (1978); (b) D. N. Harpp and J. G. Gleason, *J. Am. Chem. Soc.*, **93**, 2437 (1971); (c) T. Mukaiyama and H. Takei, *Top. Phosphorus Chem.*, **8**, 614 (1976); (d) D. N. Harpp, J. Adams, J. G. Gleason, D. Mullins, and K. Steliou, *Tetrahedron Lett.*, 3989 (1978); (e) D. N. Harpp and D. K. Ash, *Chem. Commun.*, 811 (1970); (f) D. N. Harpp and R. A. Smith, *J. Org. Chem.*, **44**, 4140 (1979); (g) T. Nakbayashi, J. Tsurugi, S. Kawamura, T. Kitao, M. Ui, and M. Nose, *ibid.*, **31**, 4174 (1966); (h) J. F. Carson and F. F. Wong *ibid.*, **26**, 1467 (1961); (i) S. Hayashi, M. Furukawa, J. Yamamoto, and K. Hamamura, *Chem. Pharm.* Bull., **15**, 1310 (1967); (j) D. N. Harpp, D. K. Ash, and R. A. Smith, *J. Org. Chem.*, **44**, 4135 (1979); (k) S. Kawamura, A. Sato, T. Nakabayashi, and M. Hamada, *Chem. Lett.*, 1231 (1975); (l) T. Katada, S. Tsuji, T. Sugiyama, S. Kato, and M. Mizuta, *ibid.*, 441 (1976); (m) D. N. Harpp and B. A. Orwig, *Tetrahedron Lett.*, **31**, 2691 (1970); (n) D. H. R. Barton, G. Page, and D. A. Widdowson, *Chem. Commun.*, 1466 (1970); (o) D. N. Harpp and S. M. Vines, *J. Org. Chem.*, **39**, 647 (1974); (p) E. E. Gilbert and C. J. McGough, U.S. Patent 2 690 451 (1951); *Chem. Abstr.*, **49**, 11683 (1955).

(4) (a) F. Fehér and D. Kurz, *Z. Naturforsch. B: Anorg. Chem., Org. Chem.*, **23**, 1030 (1968); (b) C. G. Moore and B. R. Trego, *Tetrahedron*, **19**, 1251 (1963); (c) D. Brewer, R. Rahman, S. Safe, and A. Taylor, *Chem. Commun.*, 1571 (1968); (d) R. Rahman, S. Safe, and A. Taylor, *J. Chem. Soc. C*, 1665 (1969); (e) S. Safe and A. Taylor, *ibid.*, 1189 (1971); (f) S. Safe and A. Taylor, *Chem. Commun.*, 1466 (1969).

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Table II. Summary of Kinetic Results

$RSSSR + (Et_2N)_3P \longrightarrow RSSR + (Et_2N)_3P{=}S$

R	solvent	temp, °C	k_2,[a] L mol^{-1} s^{-1}	$\Delta H^{\ddagger}$, kcal mol^{-1}	$\Delta S^{\ddagger}$,[b] eu
4-BrC_6H_4	C_6H_6	30.0	$3.2 \pm 0.01 \times 10^{-2}$	9.7 ± 0.9	−24
		40.0	$4.5 \pm 0.02 \times 10^{-2}$		
		50.0	$9.1 \pm 0.03 \times 10^{-2}$		
4-$(CH_3)_3CC_6H_4$	C_6H_6	30.0	$4.4 \pm 0.03 \times 10^{-3}$	4.5 ± 0.4	−45
		40.0	$6.0 \pm 0.03 \times 10^{-3}$		
		50.0	$7.4 \pm 0.04 \times 10^{-3}$		
4-$CH_3C_6H_4$	C_6H_6	30.0	$5.4 \pm 0.04 \times 10^{-3}$	5.0 ± 0.4	−43
		40.0	$6.6 \pm 0.04 \times 10^{-3}$		
		50.0	$9.6 \pm 0.04 \times 10^{-3}$		
	c-C_6H_{12}	50.0	$1.3 \pm 0.03 \times 10^{-3}$		
	EtOAc	50.0	$1.5 \pm 0.07 \times 10^{-2}$		
4-$CH_3OC_6H_4$	C_6H_6	30.0	$6.4 \pm 0.04 \times 10^{-3}$	4.4 ± 0.9	−44
		40.0	$6.9 \pm 0.04 \times 10^{-3}$		
		50.0	$1.1 \pm 0.01 \times 10^{-2}$		
$C_6H_5CH_2$	C_6H_6	21.0	$6.8 \pm 0.03 \times 10^{-1}$	2.9 ± 0.2	−40
		30.0	$7.9 \pm 0.04 \times 10^{-1}$		
		40.0	$9.8 \pm 0.05 \times 10^{-1}$		
$CH_3CH_2CH_2$	C_6H_6	30.0	$5.9 \pm 0.05 \times 10^{-3}$	8.3 ± 0.1	−32
		40.0	$9.3 \pm 0.03 \times 10^{-3}$		
		50.0	$1.5 \pm 0.02 \times 10^{-2}$		
	c-C_6H_{12}	50.0	$5.6 \pm 0.06 \times 10^{-4}$		
	EtOAc	50.0	$3.8 \pm 0.03 \times 10^{-2}$		

[a] Average of two runs; errors are standard deviations; reproducibility ±5%. [b] Error ±10%.

sulfur-35) in desulfurization reactions with triphenylphosphine. Recent studies on the desulfurization of disulfide analogues[5] provide a number of reaction pathways which indicate that the removal of a terminal sulfur atom of an epitrithiodioxopiperazine is not mechanistically "impossible"; however, it would seem that the use of these bicyclic trisulfides to generalize on the mechanism of desulfurization of trisulfides might be misleading. Accordingly, an investigation in our laboratory showed that the desulfurization of ^{35}S-labeled dibenzyl trisulfide by triphenylphosphine, tri-*n*-butylphosphine, and tris(diethylamino)phosphine involves ca. 88, 72, and 4% central sulfur removal, respectively.[3e] We have also recently demonstrated the use of tris(1,2,3,4-tetrahydroisoquinolino)phosphine and polymeric tris(dialkylamino)phosphines to desulfurize dibenzyl trisulfide and other organosulfur substrates.[3d] Thus, as part of our continued interest in the reactions of trisulfides and other organosulfur compounds with trivalent phosphorus compounds,[6] we have undertaken a study of the desulfurization of trisulfides by tris(dialkylamino)phosphines.

Results and Discussion

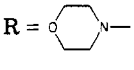
We have found that a wide spectrum of trisulfides **1** may be readily desulfurized at room temperature by aminophosphines **2**–**4** to the corresponding disulfides (Table I).

R_3P

2, R = $(CH_3CH_2)_2N$

3, R = $(CH_3)_2N$

4, R =



Despite the rapid rate of conversion of disulfides to monosulfides by tris(diethylamino)phosphine (**2**),[3a,b] no monosulfides were detected in the product mixtures from reaction of trisulfides with aminophosphines. Additionally, unsymmetrical trisulfides were desulfurized to the corresponding unsymmetrical disulfides without formation of significant amounts of symmetrical compounds. It should be noted that in most cases reactions are complete in 2–3 h at room temperature (Table I). It was found that the reactivity of tris(dimethylamino)phosphine (**3**) is comparable to that of tris(diethylamino)phosphine (**2**); tris(morpholino)phosphine (**4**) is somewhat less reactive, presumably due to decreased nucleophilicity of the phosphorus atom by the electron-withdrawing effect of the oxygen atoms. The relative reactivities of these aminophosphines are thus in agreement with those found in previous investigations.[3b,7]

Reactions of trivalent phosphorus compounds with organosulfur compounds (excluding those only observed in the presence of a radical initiator) are generally believed to occur via phosphonium salt intermediates.[2,3] To gain insight into the mechanism of desulfurization of trisulfides by aminophosphines, we undertook a kinetic study. The desulfurization of four diaryl and two dialkyl trisulfides was studied by ultraviolet spectroscopy under pseudo-first-order conditions with aminophosphine **2** as the excess (20–330-fold) reagent. A linear plot of ln $[(A_0 - A_\infty)/(A_t - A_\infty)]$ vs. time (where A_0, A_t, and A_∞ are the optical densities at times $t = 0$, $t = t$, and $t = \infty$, respectively) indicated the reaction was first order in trisulfide in each case. By variation of the concentration of aminophosphine **2**, the first-order dependence of rate on phosphine concentration was also demonstrated (Table II).

The effect of solvent polarity on the rate of desulfurization of trisulfides is graphically shown in Figure 1; the shapes of these curves are similar to those observed for the desulfurization of disulfides.[3b] Comparison of the solvent effects of a variety of desulfurization reactions is given in Table III. The solvent effect experienced by the desulfurization of di-[3b] and trisulfides by tris(diethylamino)-

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[5] (a) J. M. D. Herscheid, M. W. Tijhuis, J. H. Noordik, and H. C. J. Ottenheijm, *J. Am. Chem. Soc.*, **101**, 1159 (1979); (b) T. Sato and T. Hino, *Tetrahedron*, **32**, 507 (1976).

[6] See D. N. Harpp and R. A. Smith, ref 3f, and references cited therein.

[7] T. Thorstenson and J. Songstad, *Acta Chem. Scand., Ser. A*, **30**, 781 (1976).

[8] (a) E. M. Kosower, "An Introduction to Physical Organic Chemistry", Wiley, New York, 1968, pp 301, 305; (b) M. H. Abraham, *Prog. Phys. Org. Chem.*, **11**, 3 (1974); (c) C. Reichardt, *Angew. Chem., Int. Ed. Engl.*, **18**, 98 (1979).

[9] A. A. Maryott and E. R. Smith, *Natl. Bur. Stand. (U.S.), Circ.*, 514 (1951).

Table III. Solvent Effects of Desulfurization Reactions

			rel rate of reaction^c					
solvent	E_T^{a}	ϵ (25 °C)^b	A	B	C	D	E	F
c-C_6H_{12}	31.2	2.01	1.0	1.0	1.0	1.0	1.0	
m-$C_6H_4(CH_3)_2$	33.3	2.37						1.0
C_6H_6	34.5	2.27	7.4	27	31	40	79	
C_6H_5Cl	37.5	5.62					220	
EtOAc	38.1	6.02	12	68	80	130		
o-$C_6H_4Cl_2$	38.1	9.93			1400			
c-$C_6H_{10}O$	40.8	18.3						1.3
DMF	43.8	36.71						1.5

[a] Reference 8. [b] References 8b, 9 (the value of 18.3 for cyclohexaanone is for 20 °C). [c] A: $(4\text{-}CH_3C_6H_4S)_2S + (Et_2N)_3P \rightarrow (4\text{-}CH_3C_6H_4S)_2 + (Et_2N)_3PS$; 50 °C; this work. B: $(n\text{-}PrS)_2S + (Et_2N)_3P \rightarrow (n\text{-}PrS)_2 + (Et_2N)_3PS$; 50 °C; this work. C: $(PhCH_2S)_2 + (Et_2N)_3P \rightarrow (PhCH_2)_2S + (Et_2N)_3PS$; 30 °C; ref 3b. D: $PhSSCH_3 + (Et_2N)_3P \rightarrow PhSCH_3 + (Et_2N)_3PS$; 30 °C; ref 3b. E: $^1/_8S_8 + Ph_3P \rightarrow Ph_3PS$; 25 and 35 °C corrected to 25 °C; ref 10a. F: cis-$(CH_3CH)_2S + Ph_3P \rightarrow$ cis-$CH_3CH{=}CHCH_3 + Ph_3PS$, 40 °C; ref 10b.

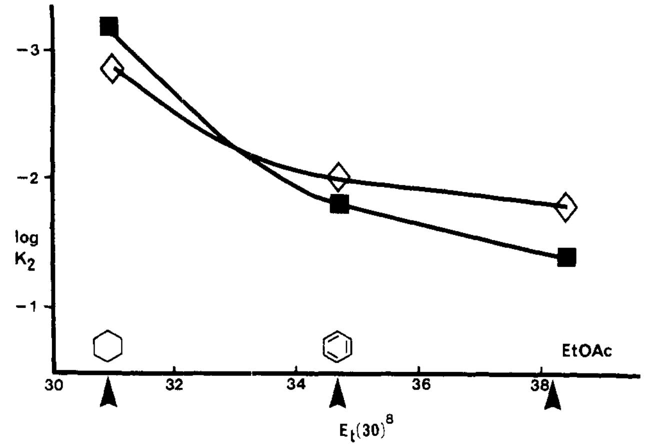
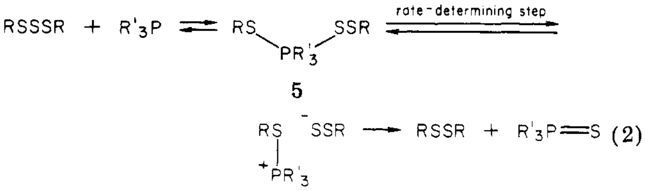


Figure 1. Solvent effect in the desulfurization of di-n-propyl trisulfide (boxes) and di-4-tolyl trisulfide (diamonds) by tris(diethylamino)phosphine.

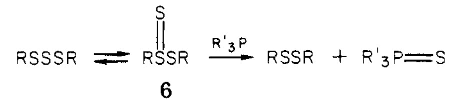
phosphine is somewhat less than that for the reaction of elemental sulfur with triphenylphosphine.[10a] However, the effect is much greater than that observed for the desulfurization of episulfides,[10b] which is considered to proceed in one step via a transition state having little charge separation. The desulfurization of trisulfides by aminophosphines is therefore concluded to be mechanistically similar to the corresponding reaction of disulfides, which was considered to involve the rate-determining formation of a phosphonium salt. That the solvent effect is less than that in the triphenylphosphine–sulfur reaction may indicate the formation of a (nonpolar) pentacovalent species 5 (eq 2) prior to the rate-limiting step.[11] By virtue of the Hammond postulate,[12] if the conversion from the intermediate 5 to the phosphonium salt is rate determining and exothermic, the activated complex would be less charge polarized than if the rate-determining step is a direct endothermic conversion of starting materials to phosphonium salt.[3b] An alternative explanation is provided by considering that at low solvent polarity, desulfurization via a thiosulfoxide intermediate 6[13] (eq 3) may become significant.



$$\mathrm{RSSSR} + \mathrm{R'_3P} \rightleftharpoons \underset{\mathrm{PR'_3}}{\mathrm{RS\diagdown\;\diagup SSR}} \xrightarrow{\text{rate-determining step}}$$

5

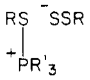
$$\underset{^+\mathrm{PR'_3}}{\mathrm{R\underset{|}{S}}}\ {}^-\mathrm{SSR} \longrightarrow \mathrm{RSSR} + \mathrm{R'_3P{=}S} \quad (2)$$



$$\mathrm{RSSSR} \rightleftharpoons \mathrm{R}\overset{\mathrm{S}}{\overset{\|}{\mathrm{S}}}\mathrm{SR} \xrightarrow{\mathrm{R'_3P}} \mathrm{RSSR} + \mathrm{R'_3P{=}S} \quad (3)$$

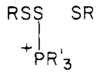
6

It has been considered that the thiomercaptide anion RSS$^-$ is a better leaving group than mercaptide ion RS$^-$, due to possible resonance stabilization and inductive electron withdrawal by the adjacent sulfur atom.[14] Block[15] has recently shown that the rate of S_N1 formation of $CH_3SCH_2^+$ is about 7000 times that of $CH_3SSCH_2^+$; it is therefore reasonable to consider the $RSP^+R'_3$ cation to be more stable than $RSSP^+R'_3$. We thus conclude that formation of phosphonium salt 7 is much preferred over



$$\underset{^+\mathrm{PR'_3}}{\mathrm{R\underset{|}{S}}}\ {}^-\mathrm{SSR}$$

7



$$\underset{^+\mathrm{PR'_3}}{\mathrm{RS\underset{|}{S}}}\ {}^-\mathrm{SR}$$

8

formation of 8. If formation of a phosphonium salt is the rate-determining step in the desulfurization of trisulfides by aminophosphines, products resulting from decomposition of salt 7 would therefore be expected. Indeed, we have previously shown[3e] by radiochemical labeling experiments that a terminal sulfur atom of dibenzyl trisulfide is removed preferentially by phosphine 2. The desulfurization of dialkyl trisulfides by aminophosphines is

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(10) (a) P. D. Bartlett and G. Meguerian, *J. Am. Chem. Soc.*, **78**, 3710 (1956); (b) D. B. Denney and M. J. Boskin, *ibid.*, **82**, 4736 (1960).

(11) While thiooxyphosphoranes are known (sulfenate + phosphite), see: L. L. Chang, D. B. Denney, D. Z. Denney, and R. J. Kazior, *J. Am. Chem. Soc.*, **99**, 2293 (1977); A. P. Stewart and S. Trippett., *Chem. Commun.*, 84 (1974). To our knowledge, the only dithiaphosphoranes reported are either derived from 3,4-bis(trifluoromethyl)-1,2-dithietene [N. J. De'Ath and D. B. Denney, *Chem. Commun.*, 395 (1972); S. A. Bone, S. Trippett, and P. Whittle, *J. Chem. Soc., Perkin Trans. 1* 80 (1977)] or obtained indirectly [J.-P. Majoral, R. Kraemer, T. N'Gando M'Pondo, and J. Navech, *Tetrahedron Lett.*, 1307 (1980)]. The first mention of a dithiaphosphorane appears to be due to A. Schönberg, *Chem. Ber.*, **68**, 163 (1935).

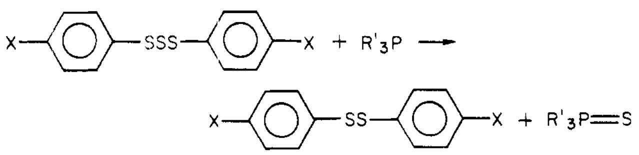
(12) J. March, "Advanced Organic Chemistry: Reactions, Mechanisms, and Structure", 2nd ed., McGraw-Hill, New York, pp 26–28.

(13) For information regarding the equilibrium RSSSR ⇌ RSS(=S)R, see: (a) S. Safe and A. Taylor, *J. Chem. Soc. C*, 432 (1970); (b) B. K. Tidd, *Int. J. Sulfur Chem. Part C*, **6**, 101 (1971). For related information, see: (c) D. Barnard, T. H. Houseman, M. Porter, and B. K. Tidd, *Chem. Commun.*, 371 (1969); (d) G. Höfle and J. E. Baldwin, *J. Am. Chem. Soc.*, **93**, 6307 (1971); (e) R. D. Baechler, J. P. Hummel, and K. Mislow, *ibid.*, **95**, 4442 (1973); (f) B. I. Stepanov, V. Y. Rodionov, and T. A. Chibisova, *Zh. Obshch. Khim.*, **10**, 78 (1974); (g) I. W. J. Still, S. K. Hasan, and K. Turnbull, *Can. J. Chem.*, **56**, 1423 (1978); (h) R. D. Baechler and S. K. Daley, *Tetrahedron Lett.*, 101 (1978). We are currently investigating the reality of **6**.

(14) M. B. Evans and B. Saville, *Proc. Chem. Soc., London*, 18 (1962).

(15) E. Block, *J. Org. Chem.*, **39**, 734 (1974).

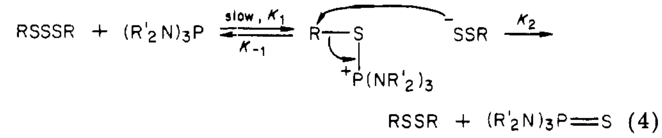
Table IV. Desulfurization of Diaryl Trisulfides



		rel rate of reaction	
X	σ_p[18]	R' = Et$_2$N[a]	R' = Ph[b]
Br	+0.232	1.0	1.0
CH_3	−0.170	0.15	0.18
$C(CH_3)_3$	−0.197	0.13	0.26
OCH_3	−0.268	0.15	0.09

[a] In benzene at 40 °C; $\rho = +1.04$; this work. [b] In toluene at 40 °C; $\rho = +0.98$ for ten different para substituents from NO_2 ($\sigma_p = 0.778$) to NH_2 ($\sigma_p = -0.660$).[4a] Desulfurization by $(Et_2N)_3P$ is 3.3–11 times the rate found for Ph_3P in the above cases.

therefore concluded to involve the rate-limiting formation of phosphonium salt **7**, as represented in eq 4 (R = alkyl).



The second step of the reaction presumably involves an inversion at one α-carbon, as noted for the desulfurization of disulfides.[3b] The high negative $\Delta S^{\ddagger}$ measured (Table II) suggests considerable ordering in the activated complex and is in accord with that observed in other bimolecular reactions.[3b,16] It is interesting to note that the relative rate of desulfurization by phosphine **2** at 30 °C for dibenzyl trisulfide/dibenzyl disulfide is 1.7×10^4, and for di-*n*-propyl trisulfide/di-*n*-pentyl disulfide the value is 3.7×10^6.[3b] This large difference in reaction velocity is believed to be a result of the better leaving group[14] RSS^- in dialkyl trisulfide desulfurization compared to the RS^- leaving group in disulfide desulfurization.

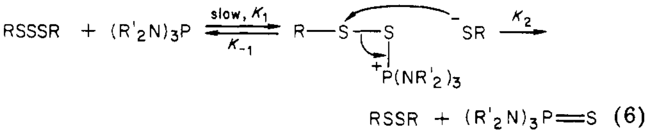
The assumption that the rate-determining step in this process involves displacement of thiomercaptide anion RSS^- permits an estimate of the pK_a of alkyl hydrodisulfides RSSH. It has been shown that the rate of desulfurization of disulfides may be correlated with the pK_a of the displaced mercaptide.[3b] From this linear plot and the second-order rate constants for the desulfurization of dibenzyl and di-*n*-propyl trisulfides at 30 °C the *estimated* pK_a of $PhCH_2SSH$ is 8.7, and that of *n*-PrSSH is 10.3. Thus hydrodisulfides appear to be more acidic than the corresponding mercaptans by ca. 2–3 pK_a units. To our knowledge no literature values for the pK_a of RSSH exist.

A kinetic study of the desulfurization of para-substituted diaryl trisulfides by aminophosphine **2** afforded a positive Hammett ρ value of 1.04 (correlation coefficient 0.98). This indicates that electron-withdrawing groups accelerate the rate of reaction,[17] as expected. It is interesting to compare the kinetic data for desulfurization of para-substituted diaryl trisulfides by aminophosphine **2** with data for parallel desulfurizations by triphenylphosphine as determined by Fehêr and Kurz[4a] (Table IV). The near-equal ρ values for these reactions suggest that the charge separation in the activated complex is similar for desulfurization by either of these phosphines. Fehêr and Kurz[4a] did not comment on a possible mechanism for desulfurization by triphenylphosphine.

For the same reasons as discussed earlier, formation of phosphonium salt **7** should be preferred over that of **8** in the case of diaryl trisulfides. However, decomposition of intermediate **7** for R = aryl to give disulfide and phosphine sulfide would require an S_N2 displacement at the sp^2-hybridized α-carbon on the phenyl ring. The reaction is therefore expected to proceed via intermediate **8**, followed by a displacement at sulfenyl sulfur to give products. The net effect would be removal of the central sulfur atom. This was confirmed by radiochemical means, as it was found that desulfurization of ^{35}S-labeled di-4-tolyl trisulfide (**9**) by tris(diethylamino)phosphine (**2**) removed exclusively (within experimental error) the central sulfur atom (eq 5).

$$\underset{\mathbf{9}}{(4\text{-}CH_3C_6H_5S)_2{}^{35}S} + \underset{\mathbf{2}}{(Et_2N)_3P} \rightarrow (4\text{-}CH_3C_6H_5S)_2 + (Et_2N)_3P{=}{}^{35}S \quad (5)$$

Desulfurization of **9** by triphenylphosphine gave similar results, with the triphenylphosphine sulfide product containing essentially all of the radiochemical label. The desulfurization of diaryl trisulfides by aminophosphines is thus concluded to proceed via the rate-limiting formation of phosphonium salt **8**, as represented in eq 6 (R = aryl).



The second step of the reaction would involve a rapid displacement at sulfenyl sulfur to provide the disulfide and phosphine sulfide products. A discussed earlier, the solvent effect indicates that nonpolar intermediates may also have a significant role in the desulfurization of diaryl trisulfides.

It remains to be rationalized what factors cause triphenylphosphine to preferentially remove the central sulfur atom and tris(diethylamino)phosphine the terminal sulfur atom of dibenzyl trisulfide.[3e] These aspects of the desulfurization process are currently under study.

Experimental Section[19]

Symmetrical Trisulfides. These were prepared by the procedure described by Schöberl and Wagner.[20] The thiol (40 mmol) was added dropwise to a stirred solution of freshly purified sulfur dichloride[3f] (20 mmol) in anhydrous diethyl ether (200 mL) at room temperature. In some cases cooling of the reaction solution in an ice–water bath was required, as the ether began to reflux. After complete addition, the nearly colorless solution was stirred 30 min and then evaporated under reduced pressure.

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(16) K. B. Wiberg, "Physical Organic Chemistry", Wiley, New York, 1964, pp 379–381.

(17) J. March, ref 12, pp 251–259.

(18) H. H. Jaffé, *Chem. Rev.*, **53**, 191 (1953).

(19) Unless stated otherwise, chemical reagents were obtained from commercial sources and were used directly. Acetonitrile (see footnotes of Table I) was distilled from phosphorus pentoxide. Melting points were obtained on a Gallenkamp block apparatus and are uncorrected. Boiling points are also uncorrected. Infrared spectra were recorded on a Perkin-Elmer Model 257 grating spectrophotometer, calibrated with the 1602-cm^{-1} band of a polystyrene film. Nuclear magnetic resonance spectra were measured with a Varian Associates T-60 spectrometer. Mass spectra were obtained on an AEI-MS-902 mass spectrometer with a direct-insertion probe, while gas chromatographic–mass spectral analyses were performed by using a Hewlett Packard 5984A system. Gas chromatographic analyses were obtained by using a Hewlett Parkard F&M Model 5751A research chromatograph, equipped with a 6 ft × 0.125 in. stainless-steel column of 5% OV-101 on Chromosorb 750 (100/200 mesh). Elemental analyses were performed by Scandinavian Microanalytical Laboratories or Galbraith Laboratories.

(20) A. Schöberl and A. Wagner, "Methoden der Organishen Chemie (Houben-Weyl)", 4th ed., Georg Thieme Verlag, Stuttgart, 1955, Vol. 9, p 87.

The residue was recrystallized or distilled as appropriate.

Thus were prepared di-4-tolyl trisulfide,[3f] bis(4-methoxyphenyl) trisulfide [85%, mp 73-76 °C (lit.[4a] mp 73–74 °C)], diphenyl trisulfide [84%, oil[21] (lit.[4a] mp ca. -5 °C)], bis(4-bromophenyl) trisulfide [78%, mp 68–71 °C (lit.[4a] mp 70–71 °C)], bis(4-*tert*-butylphenyl) trisulfide [79%, mp 52.5–54 °C (lit.[4a] mp 51–52 °C)], dibenzyl trisulfide,[3f] di-*n*-propyl trisulfide,[3f] di-*n*-pentyl trisulfide [61%, bp 121.5–124 °C (0.2 mm), lit.[22] bp 76–96 °C (1.0 mm)], di-2-octyl trisulfide,[3f] and di-*tert*-butyl trisulfide [66%, bp 48–52 °C (0.01 mm), $n^{25}{}_D$ 1.5195 [lit.[23] bp 86 °C (4 mm), $n^{20}{}_D$ 1.5225]].

Bis[(carbomethoxy)methyl] trisulfide was obtained in 78% yield: bp 123–126 °C (0.07 mm); NMR (CCl_4) δ 3.8 (s, 3 H), 3.7 (s, 2 H); IR (neat) 3000, 2960, 1760, 1450, 1420, 1290, 1200, 1160, 1130, 1010, 890 cm^{-1}; mass spectrum, *m/e* (relative intensity) 242 (30, M^+), 210 (34), 178 (33), 150 (32), 138 (43), 119 (30), 106 (60), 105 (54), 95 (58), 74 (57), 59 (100). Anal. Calcd for $C_6H_{10}O_4S_3$: C, 29.74; H, 4.16; S, 39.70. Found: C, 29.95; H, 4.28; S, 39.94.

In the case of bis(1-phenylethyl) trisulfide, prepared from (±)-1-phenylethanethiol,[24] the reaction solution was washed with water and twice with saturated Na_2CO_3 solution, dried ($MgSO_4$), and evaporated to quantitatively yield a ca. 1:1 mixture (by NMR analysis) of meso and *dl* diastereomers of this trisulfide as an oil: $n^{24}{}_D$ 1.6333 (lit.[24] $n^{20}{}_D$ 1.6330); NMR (CCl_4) δ 7.1 (s, 5 H), 4.1 (two overlapped quartets with $\Delta\delta$ = 3 Hz, 1 H, *J* = 7 Hz), 1.7 (d, *J* = 7 Hz); IR (neat) 3020, 2960, 2920, 1600, 1490, 1450, 1370, 1210, 1030, 770, 700 cm^{-1}; mass spectrum, *m/e* (relative intensity) 306 (4, M^+), 274 (3), 242 (2), 210 (1), 138 (2), 137 (2), 106 (12), 105 (100), 104 (37). Anal. Calcd for $C_{16}H_{18}S_3$: C, 62.70; H, 5.93; S. 31.39. Found: C, 62.70; H, 6.15; S, 31.23.

2,3,4-Benzotrithiepin. This cyclic trisulfide was prepared in 72% yield from disodium *o*-phenylene dithiosulfate as described by Milligan and Swan;[25] mp 101–104.5 °C (lit.[25] mp 101–102 °C).

Unsymmetrical Trisulfides. The preparation of these compounds has been previously reported.[26]

Tris(dialkylamino)phosphines. Commerically available phosphines **2** and **3** were distilled before use and stored under dry argon or nitrogen (avoiding rubber septums[3a]).

Tris(morpholino)phosphine (**4**) was prepared as follows. A solution of 34.4 g (0.25 mol) of distilled phosphorus trichloride in 190 mL of $CHCl_3$ was added dropwise over a 45-min period to a solution of 131 g (1.5 mol) of distilled morpholine in 190 mL of $CHCl_3$ stirred in an ice–water bath. A white precipitate was formed, and after complete addition the mixture was heated to reflux (bath temperature 80 °C) for 1.5 h. When the mixture cooled to room temperature, the morpholine hydrochloride was removed by filtration (washing three times with $CHCl_3$), and the filtrate was evaporated to yield a wet white solid. This was dissolved in hot toluene, insoluble fluffy white material was removed by filtration, and the filtrate was allowed to cool to afford 32.1 g (44%) of tris(morpholino)phosphine (**4**) as colorless needles, mp 159–161 °C (lit.[27] mp 154 °C, lit.[7] mp 157 °C).

Desulfurization of Trisulfides. Except as noted in Table I, the general procedure was as follows. To a solution of the trisulfide (2.0 mmol) in 10 mL of anhydrous diethyl ether or benzene was added the aminophosphine (2.0 to 2.2 mmol). After being stirred 2–3 h at room temperature, the reaction mixture was evaporated under reduced pressure. The residue was chromatographed over a column of 10–20 g of silica gel (E. Merck, catalog No. 7734) with 9:1 hexanes–chloroform as eluant. Collection of the first component to elute afforded the disulfide product, with yields (recrystallized) as noted in Table I: di-4-tolyl disulfide, mp 44–47 °C (lit.[4a] mp 47–48 °C); bis(4-methoxyphenyl) disulfide, mp 36.5–38 °C (lit.[4a] mp 44–45 °C); diphenyl disulfide, mp 61–62 °C (lit.[4a] mp 61–62 °C); dibenzyl disulfide, mp 68–71.5 °C (lit.[3i] mp 71 °C); 2,3-benzodithiin, mp 77.5–79 °C (lit.[28] mp 80 °C). Di-*n*-propyl, di-*n*-pentyl, and bis[(carbomethoxy)methyl] disulfide products isolated were homogeneous by GC and were identical with authentic samples. The benzyl isopropyl disulfide isolated was an oil, almost homogeneous by GC; this material was identical with an authentic sample.[3f] The disulfide products in Table I not isolated by chromatography were identified by GC and NMR by comparison with authentic samples and/or by GC/MS.

By further elution of the silica gel column with chloroform it was possible to isolate the tris(dialkylamino)phosphine sulfide product: $(Et_2N)_3PS$ and $(Me_2N)_3PS$ as crude oils identical with authentic samples[3a,29] and tris(morpholino)phosphine sulfide recrystallized from diethyl ether; mp 145–146 °C (lit.[30] mp 145.5–146 °C).

Kinetics of Desulfurization. All materials were recrystallized or redistilled before use in these kinetic experiments. Benzene and cyclohexane were distilled from sodium metal, and ethyl acetate was distilled from phosphorus pentoxide. A Hitachi-Coleman 124 spectrophotometer equipped with a Hitachi-Coleman 165 recorder and a Neslab constant-temperature regulator (±0.1 °C) were utilized at constant wavelength (320 nm) to monitor the disappearance of trisulfide with time. The solutions of trisulfide and phosphine were equilibrated for a minimum of 15 min before each experiment. Each experiment was performed in duplicate.

Pseudo-first-order conditions were used for the reactions with an excess (at least 20-fold) of tris(diethylamino)phosphine. The values of the pseudo-first-order rate constant (k') were calculated from plots of ln $[(A_0 - A_\infty)/(A_t - A_\infty)]$ vs. time by the method of least squares; all calculations were performed by an IBM 360/50 computer.

Radiochemical Experiments. Sulfur-35 dichloride (purchased from Amersham/Searle) was diluted in freshly purified[3f] unlabeled sulfur dichloride [1.0 mCi (ca. 21 mg) in 25 g of SCl_2] before use. The preparation of di-4-tolyl trisulfide-^{35}S (**9**) was as described above for the unlabeled compound, from sulfur-35 dichloride and 4-toluenethiol.

Desulfurization of di-4-tolyl trisulfide-^{35}S (**9**) with tris(diethylamino)phosphine (**2**) was performed in anhydrous diethyl ether as described above for the unlabeled trisulfide. The radioactivity of each sample, mounted on cardboard and covered with a Mylar film, was measured on a Baird-Atomic Model 135 scaler timer equipped with a Baird-Atomic Model 255 proportional counter amplifier under an atmosphere of 9:1 argon–methane. The radioactivities of desulfurization products [relative to $(4\text{-}CH_3C_6H_5S)_2{}^{35}S$ at 100%] were 3% for $(4\text{-}CH_3C_6H_5S)_2$ and 98% for $(Et_2N)_3PS$.

The desulfurization of di-4-tolyl trisulfide-^{35}S (**9**) was also performed with triphenylphosphine in anhydrous diethyl ether. After being stirred 1 h at room temperature, the reaction mixture was evaporated and chromatographed over silica gel as described above for desulfurization of trisulfides to afford a 42% yield of di-4-tolyl disulfide, mp 41–45 °C (lit.[4a] mp 47–48 °C), and a 61% yield of triphenylphosphine sulfide, mp 159–162 °C (lit.[4a] mp 161 °C). The radioactivities of these products [relative to $(4\text{-}CH_3C_6H_5S)_2$, ^{35}S at 100%] were ca. 1% for $(4\text{-}CH_3C_6H_5S)_2$ and 100% for Ph_3PS.

Acknowledgment. We thank the Natural Sciences and Engineering Research Council of Canada for financial support of this work. We are especially grateful to Professor J. J. Hogan for helpful discussions regarding the radiochemical experiments.

Registry No. 1 (R = $4\text{-}CH_3C_6H_4$), 4991-51-9; 1 (R = $4\text{-}CH_3OC_6H_4$), 20057-92-5; 1 (R = C_6H_5), 20057-88-9; 1 (R = $C_6H_5CH_2$), 6493-73-8; *meso*-1 (R = $C_6H_5CHCH_3$), 75030-36-3; (±)-1 (R = $C_6H_5CHCH_3$), 75030-37-4; 1 (R = $2\text{-}CH_2C_6H_4CH_2$), 3354-86-7; 1 (R

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[21] Diphenyl trisulfide (an oil) decomposed on attempted distillation. A yellow oil was collected [bp 156–171 °C (0.5 mm)] which crystallized; mp 59–61 °C. This decomposition to diphenyl disulfide has been reported: H. Lecher, *Chem. Ber.*, **58**, 417 (1925).

[22] E. I. Tinyakova, E. K. Khrennikova, and B. A. Dolgoplosk, *Izv. Akad. Nauk SSSR, Ser. Khim.* 1152; *Chem. Abstr.*, **51**, 4038*i* (1957).

[23] S. F. Birch, T. V. Cullum, and R. A. Dean, *J. Inst. Petrol.*, **39**, 206 (1953).

[24] F. Asinger and K. Halcour, *Monatsh. Chem.*, **94**, 1029 (1963); *Chem. Abstr.*, **60**, 9190*a* (1964).

[25] B. Milligan and J. M. Swan, *J. Chem. Soc.*, 2901 (1965).

[26] D. N. Harpp and D. K. Ash, *Int. J. Sulfur Chem., Part A*, **1**, 211 (1971).

[27] (a) W. Franke, German Patent 1024967; *Chem. Abstr.*, **54**, P7744*h* (1960); (b) R. Burgada, *Ann. Chim. (Rome)*, 8, 347 (1963); *Chem. Abstr.*, **59**, 15164*f* (1963).

[28] A. Lüttringhaus and K. Hägele, *Angew. Chem.*, **67**, 304 (1955).

[29] C. Stuebe and H. P. Lankelma, *J. Am. Chem. Soc.*, **78**, 976 (1956).

[30] L. F. Audrieth and A. D. F. Toy, *J. Am. Chem. Soc.*, **64**, 1553 (1942).

= $CH_3(CH_2)_2$), 6028-61-1; 1 (R = $CH_3(CH_2)_4$), 13730-36-4; 1 (R = $CH_3OC(O)CH_2$), 75030-38-5; 1 (R = $CH_3(CH_2)_5CHCH_3$), 71243-24-8; 1 (R = $(CH_3)_3C$), 4253-90-1; 1 (R = 4-BrC_6H_4), 20057-86-7; 1 (R = 4-$(CH_3)_3CC_6H_4$), 13846-49-6; **2**, 2283-11-6; **3**, 1608-26-0; **4**, 5815-61-2; **9**, 75030-41-0; (±)-1-phenylethanethiol, 75081-57-1; benzyl isopropyl trisulfide, 75030-39-6; benzyl propyl trisulfide, 75030-40-9; di-4-tolyl disulfide, 103-19-5; bis(4-methoxyphenyl) disulfide, 5335-87-5; diphenyl disulfide, 882-33-7; dibenzyl disulfide, 150-60-7; 2,3-benzodithiin, 253-59-8; di-*n*-propyl disulfide, 629-19-6; di-*n*-pentyl disulfide, 112-51-6; bis[(carbomethoxy)methyl] disulfide, 1665-64-1; benzyl isopropyl disulfide, 57413-29-3; tris(morpholino)phosphine sulfide, 14129-98-7; *meso*-bis(1-phenylethyl) disulfide, 50999-18-3; (±)-bis(1-phenylethyl) disulfide, 50999-19-4; benzyl propyl disulfide, 27657-11-0; bis(isopropyl) disulfide, 4253-89-8; bis(2-octyl) disulfide, 1574-31-8; di-*tert*-butyl disulfide, 110-06-5; bis(4-bromophenyl) disulfide, 5335-84-2; bis(4-*tert*-butylphenyl) disulfide, 7605-48-3.

Proton Nuclear Magnetic Resonance Study of the Addition of Methoxide Ion to 2,4,6-Triphenylpyrylium, 2,4,6-Triphenylthiopyrylium, 1,2,4,6-Tetraphenylpyridinium, and 1-(*p*-Nitrophenyl)-2,4,6-triphenylpyridinium Cations

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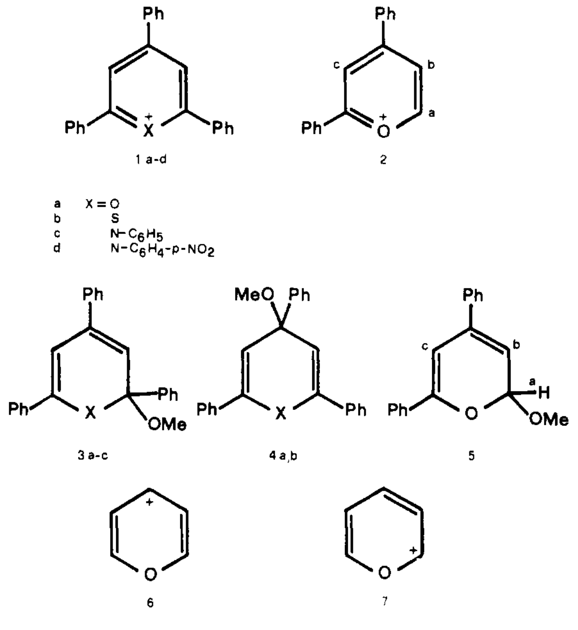
The reactions of 2,4,6-triphenylpyrylium (**1a**) and 2,4,6-triphenylthiopyrylium (**1b**) with methoxide ion are shifted toward the formation of adducts, as shown by ^{1}H NMR. The former yields practically only a 2*H*-pyran adduct in MeCN, Me_2SO, or MeOH. In MeOH, **1b** yields an adduct with a 2*H*-thiopyran structure, whereas in MeCN this adduct is obtained together with the isomeric 4*H*-thiopyran adduct. In Me_2SO or MeCN, the 1,2,4,6-tetraphenylpyridinium cation yields a 1,2-dihydropyridine. In contrast, in MeOH this equilibrium is shifted toward the reagents. The lower degree of delocalization of the positive charge in the pyridinium cation seems to be the main cause of its lower tendency to undergo nucleophilic addition.

Six-membered heteroaromatic cations can react with anionic nucleophilic reagents to give neutral adducts. In the absence of a sufficiently good leaving group at the reaction center, substitution cannot occur, and adducts can be isolated or, at least, detected. Addition occurs preferentially at the α and γ positions, where the electron density is lower. Furthermore, 2-adducts can undergo a thermally allowed, concerted ring-opening reaction, yielding dienic valence tautomers. The synthetic relevance of these reactions has been recently discussed.[1]

In a preceding work[2] we have examined the course of addition of methoxide ion to 2,6-diphenylpyrylium and 4-methoxy-2,6-diphenylpyrylium cations and have shown that the reaction pattern may be strongly affected by the nature of the substrates and the solvent.

Here we describe the results concerning the role of the heteroatom on the pattern of addition of methoxide ion. For this study we have examined the behavior of 2,4,6-triphenylpyrylium (**1a**), 2,4,6-triphenylthiopyrylium (**1b**), and 1,2,4,6-tetraphenylpyridinium (**1c**) cations in different solvents (see Chart I). These substrates share the presence of three phenyl groups at the ring positions conjugated with the heteroatom. A ^{13}C NMR investigation on the reaction of **1b** in Me_2SO-d_6 has been recently carried out.[3]

Chart I



Besides the phenylpyridinium cation **1c**, we have also considered the 1-(*p*-nitrophenyl)-2,4,6-triphenylpyridinium cation (**1d**), where the presence of an electron-withdrawing substituent was expected to increase the electrophilicity of the pyridinium cation and to shift the equilibrium toward a dihydropyridine adduct, as already observed[4] in the reaction of 1-arylpyridinium cations with MeO^-.

The choice of an aryl rather than an alkyl group in position 1 of pyridinium cations is due to the fact that the

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(1) (a) Balaban, A. T. In "New Trends in Heterocyclic Chemistry"; Mitra, R. B., Ayyangar, N. R., Gogte, V. N., Acheson, R. M., Cromwell, N., Eds.; Elsevier: Amsterdam, 1979. (b) Katritzky, A. R. *Tetrahedron* **1980**, *36*, 679.

(2) Bersani, S.; Doddi, G.; Fornarini, S.; Stegel, F. *J. Org. Chem.* **1978**, *43*, 4112.

(3) Katritzky, A. R.; Brownlee, R. T. C.; Musumarra, G. *Heterocycles* **1979**, *12*, 775. Cognate work on the interactions between pyrylium cations and nucleophiles has been carried out at the East Anglia University. We thank Professor A. R. Katritzky and his co-workers for comments and discussions. Precedent work on the reaction of **1a** with MeO^- (Balaban, A. T.; Silhan, W. *Tetrahedron* **1970**, *26*, 743) was not able to indicate whether a 2*H*-pyran or a dienone was formed.

(4) Beránek, V.; Lyčka, A.; Stěrba, V. *Collect. Czech. Chem. Commun.* **1975**, *40*, 1919.

0022-3263/80/1945-5160$01.00/0