

Organic and Biological Chemistry

The Mechanism of the Substitution Reaction on Sulfur Atoms by Radicals or Nucleophiles^{1,2}

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Abstract: The stereochemistry and mechanism of the substitution reaction on sulfur by free radicals is discussed. We had previously studied the reaction of phenyl radicals with alkyl disulfides as an approach to this problem, and we have now repeated that work and extended it to a similar study of the *p*-nitrophenyl radical. The importance of such radical displacement reactions on sulfur in biochemical systems is discussed briefly. We find that the relative rate constants for the reaction of both the phenyl and *p*-nitrophenyl radicals with disulfides correlate excellently in a log-log plot with the rate constants for the S_N2 reaction. In order to ascertain the significance of a log-log correlation between the rate constants for two reactions in such an aliphatic series, we have attempted the correlation of all the reactions for which we could find data in the literature with the S_N2 reaction on carbon. Surprisingly, *all of the reactions* correlate with the S_N2 reaction at the 1% level of significance. Consequently, a good correlation in a log-log graph between two such reactions is not diagnostic of mechanism. Furthermore, even the magnitude of the slope is not significant. Two reactions which are known to have similar mechanisms may not correlate with a slope any closer to unity than do two reactions with quite different mechanisms. The literature of substitution reactions by nucleophiles and radicals at sulfur atoms is reviewed. It is concluded that attack on sulfur usually does occur from the back side. However, it is likely that many of the substitutions on sulfur by nucleophiles or radicals do not involve a simple, one-step displacement reaction but rather involve an addition-elimination sequence involving a metastable intermediate.

The stereochemistry and mechanism of the substitution³ reaction by free radicals has fascinated chemists for over four decades. There are three possibilities: the mechanism could involve a back-side attack, three-atoms-in-a-line transition state of the type followed by nucleophiles in the well-known Walden inversion mechanism; it could involve a front-side attack such as is sometimes applicable to electrophiles in an S_E2 reaction; or it could be a third type not easily characterized as either front- or back-side attack.³⁻⁵ Theoretical calculations⁶ have indicated that

simple radical displacement reactions such as



involve a back-side attack.⁷

Clearly, the most direct way for determining the stereochemistry of the S_H2 reaction would be to study a displacement by a radical on a dissymmetrically substituted atom in a system in which optically active products are obtained. Unfortunately, to date, no such reaction is known.⁸

ibid., 48, 2700 (1968); (e) H. Conroy and B. L. Brumer, *ibid.*, 47, 921 (1967).

(7) We use the terms *Walden inversion* or *back-side attack* mechanism to describe that configuration for a displacement reaction in which approach to an atom by an attacking group occurs sufficiently from the opposite side of the leaving group so that an inversion of configuration would occur if the atom were properly substituted and were in a valence state such that inversion would be an operational possibility. The transition state need not necessarily have "three-atoms-in-a-line" but may be nonlinear. For example, Karplus, Porter, and Sharma^{6b} find that the reaction of hydrogen atoms with hydrogen molecules is a direct displacement (*i.e.*, does not involve an intermediate), but that the transition state is nonlinear and the three atoms form an angle from 150 to 170°. We would still term this a Walden inversion transition state. I. Dostrovsky, E. D. Hughes, and C. K. Ingold, [*J. Chem. Soc.*, 173 (1946)], and later P. B. D. de la Mare, L. Fowden, E. D. Hughes, C. K. Ingold, and J. D. H. Mackie [*ibid.*, 3200 (1955)] calculated the geometry of the transition state for the displacement reaction on compounds of the type RCH₂X, where R is methyl, ethyl, isopropyl, or *t*-butyl. In the case of *t*-butyl, the transition state is skewed and is not a "linear, three-atoms-in-a-line" configuration, yet this reaction still is a Walden inversion. Only reactants which have an axis of symmetry along the reaction coordinate would be expected to produce a transition state which is exactly linear.

(8) The reaction of optically active *sec*-butyl iodide with iodine has been studied elegantly and in detail by Benson and by Noyes, but it now appears that this system cannot be used to determine the stereochemistry of the S_H2 reaction by iodine atoms on an optically active carbon. See J. E. Bujake, Jr., M. W. T. Pratt, and R. M. Noyes, *J. Amer. Chem. Soc.*, 83, 1547 (1961); M. Nakashima and R. M. Noyes, *Intern. J. Kinetics*, 1, 391 (1969); and S. W. Benson, *J. Chem. Phys.*, 38, 1945 (1963). Also see D. M. Golden and S. W. Benson, *Chem. Rev.*, 69,

(1) (a) Reactions of Radicals. Part 24. Presented at the 158th Meeting of the American Chemical Society, New York, N. Y., 1969. Abstracts of Papers of the Organic Division, paper ORGN-119. (b) Abstracted in part from the Ph.D. Dissertation of William Kennedy Smith, Louisiana State University, Baton Rouge, La., Aug 1969.

(2) (a) This work was partially supported by Grant GM 11908 from the National Institutes of Health, U. S. Public Health Service. (b) W. K. Smith held a petroleum Research Fund terminal year predoctoral fellowship (No. 249) for the 1968-1969 academic year; acknowledgment is made to the donors of the Petroleum Research Fund, administered by the American Chemical Society, for partial support of this work. Dr. Smith was a postdoctoral fellow supported on NIH Grant GM 11908 during the summer of 1969.

(3) The following terms are defined for use in this paper. *Substitution reaction* is used to describe a replacement reaction without implying any mechanism. A *displacement reaction* is a one-step, direct substitution reaction. The displacement reaction by nucleophiles is symbolized S_N2 and that by radicals S_H2 (see ref 4 and 5). A substitution reaction which is *not* a direct displacement but involves the formation of a metastable intermediate involves a pathway which we term *addition-elimination*. For nucleophiles and radicals, in the cases discussed here, such a mechanism is applicable only when the atom being attacked is able to expand its electronic octet (see later discussion in the text).

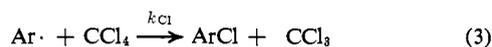
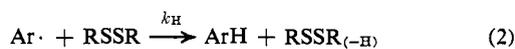
(4) W. A. Pryor, "Free Radicals," McGraw-Hill Book Co., Inc., New York, N. Y., 1966, pp 9, 151-153.

(5) W. A. Pryor, "Mechanisms of Sulfur Reactions," McGraw-Hill Book Co., Inc., New York, N. Y., 1962, pp 46-70.

(6) (a) See the references cited in ref 4, p 151. Also see (b) M. Karplus, R. N. Porter, and R. D. Sharma, *J. Chem. Phys.*, 40, 2033 (1964); 43, 3259 (1965); (c) A. A. Westenberg and N. de Haas, *ibid.*, 47, 1393 (1967); (d) L. Shavitt, R. M. Stevens, F. L. Minn, and M. Karplus,

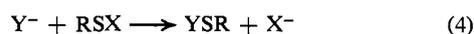
There are numerous examples of substitution or replacement reactions by recoil atoms, and the stereochemistry of some of these reactions has been studied.⁹ It is not clear, however, whether data on the reaction of these extremely excited ("hot") species can be used to deduce mechanisms for the reaction of normal, thermalized organic radicals in solution.

A few years ago we reported on the reaction of phenyl radicals with a series of alkyl disulfides.¹⁰ Aromatic radicals react with disulfides either by attack on sulfur to cleave the sulfur-sulfur bond (eq 1) or by attack on one of the hydrogen atoms of the alkyl groups (eq 2). By studying the reaction in the presence of the cosolvent carbon tetrachloride, the rate constants for both k_S and k_H can be obtained relative to k_{Cl} . The



equations and techniques have already been described.^{10,11}

In our previous paper,^{10a} we compared the rate profile for reaction 1 as the R group was varied with the profile obtained for the SN2 reaction on sulfur or carbon, reactions 4 and 5. Fava had previously compared the



rate profiles for reactions 4 and 5 for various R groups and found them to be nearly identical.¹² From this, he concluded that the SN2 reaction on sulfur proceeds by the Walden inversion mechanism. We utilized this same kinetic method to test whether homolytic substitution on sulfur might also involve a Walden inversion. We here wish to present further data on the reaction of aromatic radicals with disulfides and to extend and modify our previous conclusions.

The mechanism of the reaction of radicals or ions with divalent sulfur, and particularly with the sulfur atom of a disulfide bond, is of great importance in biochemistry. The sulfur-sulfur bond is involved in determining the tertiary structure of many proteins. Sulfur atoms are very susceptible to attack both by radicals and by nucleophiles, and radiation damage to enzymes and other protein materials can occur through attack on their disulfide bonds.^{13,14} The importance of

thiols, thiyl radicals, and disulfides in radiation protection is well established.^{14,15} Radiolytic damage to mammalian cells is often postulated to involve mutagenic damage to DNA,¹⁶ and their natural aging also probably occurs at least in part because of an increase in chromosome aberrations.¹⁷ Radiation accelerates aging,¹⁸ and, since sulfur compounds protect cells against radiation damage, there is the hope that some of these same compounds might retard aging. In fact, it has been reported that 2-mercaptoethylamine increases the mean life span of mice.¹⁹ We have initiated a program of research on the mechanisms of the reactions of sulfur compounds which might be important in some of these biochemical systems.

Results

Experiments with Phenylazotriphenylmethane (PAT).

We first wished to repeat the experiments of Pryor and Guard¹⁰ on the reaction of phenyl radicals from PAT with disulfides both because of the improvements made in gas chromatography instrumentation since that work was done and also to determine whether extrapolation of the yields to infinite dilution¹¹ in PAT affected the values of k_H/k_{Cl} or k_S/k_{Cl} . The data are given in Table I and the comparison with the older data is given in Table II. It can be seen that the agreement is

Table I. The Reaction of Phenyl Radicals with Disulfides in the Presence of Carbon Tetrachloride at 60°

R in RSSR	[CCl ₄ /[PAT]] ^a		% yield ^c			k_S/k_{Cl}	k_H/k_{Cl}
	[RSSR] ^b	PhSR	PhCl	PhH			
Methyl	0.1120	0.94	71.0	3.12	1.34	19.6	
	0.1712	4.24	36.0	9.1	1.58	16.8	0.73
	0.1220		41.8	10.2	1.60	17.3	0.66
	0.0523		48.9	11.8	1.53	17.5	0.55
	0 ^d		54.8	13.0	1.50	17.9	0.50
Isopropyl	0.0655	1.69	27.2	11.3	14.5	4.06	2.17
	0.0295		27.0	13.5	14.7	3.38	1.82
	0.0096		28.3	13.6	14.6	3.26	1.69
	0 ^d		28.8	13.8	14.7	3.52	1.81
	<i>t</i> -Buyl	0.0987	0.96	8.80	37.6	16.9	0.22
	0.0752		8.99	42.5	18.5	0.22	0.45
	0.0476		8.92	46.2	16.4	0.19	0.34
	0.0242		8.90	49.0	15.3	0.18	0.30
	0 ^d		8.80	52.5	15.0	0.16	0.28

^a Initial concentration in moles per liter. ^b Mole ratio. ^c Per cent yield based on original concentration of PAT. ^d The values listed for zero molarity PAT are values extrapolated from the graphs of per cent yield vs. PAT concentration.

excellent for all the values except k_S/k_{Cl} for methyl disulfide. Despite the difference in the result for this

W. Snipes, Ed., "Electron Spin Resonance and the Effects of Radiation on Biological Systems," National Academy of Sciences, National Research Council, Washington, D. C., 1966.

(15) Z. M. Baqç, "Chemical Protection Against Ionizing Radiation," Charles C. Thomas, Publisher, Springfield, Ill., 1965.

(16) See, for example, (a) H. J. Curtis in "Current Topics in Radiation Research," Vol. 3, M. Ebert and A. Howard, Ed., North-Holland Publishing Co., Amsterdam, 1967; (b) K. G. Zimmer in ref 16a, Vol. 5, 1969; (c) J. S. Mitchell in "Radiation Chemistry of Aqueous Systems," G. Stein, Ed., Interscience Publishers, New York, N. Y., 1968.

(17) (a) H. J. Curtis, "Biological Mechanisms of Ageing," Charles C. Thomas, Publisher, Springfield, Ill., 1966; (b) L. Szilard, *Proc. Natl. Acad. Sci., U. S.*, **45**, 30 (1959).

(18) See ref 16a and 17. Also see (a) P. J. Lindop and G. A. Sacher, "Radiation and Ageing," Taylor and Francis Ltd., London, 1966; (b) H. J. Curtis, *Symp. Soc. Exptl. Biol.*, **21**, 51 (1967); (c) H. J. Curtis, *Brookhaven Symp. Biol.*, **20**, 223 (1967).

(19) (a) D. Harman, *J. Gerontol.*, **16**, 247 (1961); (b) *ibid.*, **23**, 476 (1968); (c) *The Gerontologist*, **8** (III), 13 (1968).

125 (1969); H. R. Ward, R. G. Lawler, and R. A. Cooper, *Tetrahedron Lett.*, 527 (1969); W. G. Bentrude, J. H. Hargis, and P. E. Rusek, *Chem. Commun.*, 296 (1969).

(9) See, for example, H. Keller and F. S. Rowland, *J. Phys. Chem.*, **62**, 1373 (1958); M. Henchman and R. Wolfgang, *J. Amer. Chem. Soc.*, **83**, 2991 (1961); J. G. Kay, R. P. Malsan, and F. S. Rowland, *ibid.*, **81**, 5050 (1959); R. Wolfgang, *Accounts Chem. Res.*, **2**, 248 (1969).

(10) (a) W. A. Pryor and H. Guard, *J. Amer. Chem. Soc.*, **86**, 1150 (1964); (b) also see W. A. Pryor and P. K. Platt, *ibid.*, **85**, 1496 (1963).

(11) W. A. Pryor, J. T. Echols, Jr., and K. Smith, *ibid.*, **88**, 1189 (1966).

(12) For a review see E. Ciuffarin and A. Fava, *Progr. Phys. Org. Chem.*, **6**, 81 (1968); also see ref 5.

(13) (a) R. Shapira and G. Stein, *Science*, **162**, 1489 (1968); (b) G. Stein in "Energetics and Mechanisms in Radiation Biology," G. O. Phillips, Ed., Academic Press, New York, N. Y., 1968; (c) L. K. Mee, G. Navon, and G. Stein, *Biochim. Biophys. Acta*, **104**, 151 (1965); (d) G. Navon and G. Stein, *Israel J. Chem.*, **2**, 151 (1964).

(14) (a) G. O. Phillips, Ed., "Energetics and Mechanisms in Radiation Biology," Academic Press, New York, N. Y., 1968; (b) K. Dose in "Physical Processes in Radiation Biology," L. Augenstein, R. Mason, and B. Rosenberg, Ed., Academic Press, New York, N. Y., 1964; (c)

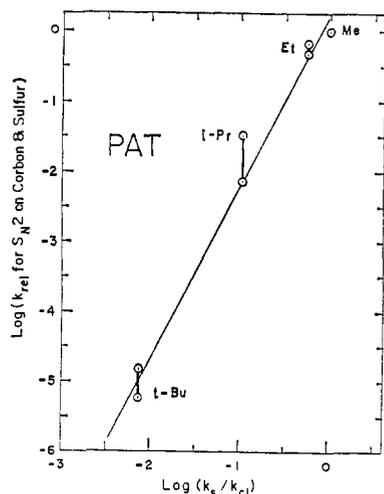


Figure 1. A log-log correlation of the reaction of phenyl radicals with disulfides with the S_N2 reaction on carbon (reaction A in the text) and the S_N2 reaction on sulfur (reaction J). The relative rate constants for attack on sulfur by the phenyl radicals is plotted on the horizontal axis; on the vertical axis the upper end of the bars is the point for the S_N2 reaction on carbon and the lower end is the point for the sulfur reaction. In the correlations given in Table V, reaction A is plotted vertically and the variable reaction is plotted horizontally.

compound, the older and the new data correlate essentially identically with the S_N2 reaction on sulfur. We will present these data and comment on the lack of sensitivity of this kinetic test later. Now it need only be pointed out that the agreement in the data is sufficient for our present purposes. It is also clear that extrapolation to infinite dilution does not affect the data.

Table II. Relative Rate Constants for Phenyl Radical Attack on Disulfides

R in RSSR	k_{II}/k_{CI}		k_S/k_{CI}	
	Pryor & Guard ^c	This work	Pryor & Guard ^c	This work
Methyl	0.57	0.50 ^a 0.65 ^b	31.0	17.9 ^a 17.2 ^b
Isopropyl	1.90	1.81 ^a 1.89 ^b	3.30	3.52 ^a 3.56 ^b
<i>t</i> -Butyl	0.25	0.28 ^a 0.38 ^b	0.23	0.16 ^a 0.20 ^b

^a Values calculated from data extrapolated to zero molarity in PAT. ^b Average value. ^c Reference 10a.

Experiments with *p*-Nitrophenylazotriphenylmethane (NAT). Since sulfur atoms can expand their electronic octet, the possibility exists that the reaction of aryl radicals with disulfides is not a one-step displacement reaction but rather proceeds by an addition-elimination sequence.^{3,20a} We attempted to test this possibility by



examining the rate profile for the reaction of the *p*-nitrophenyl radical with the same series of disulfides. The *para*-nitro group has an enormous effect on the stability of radicals of the triarylmethyl type,^{20b} and we expected a similar effect on the stability of the intermediate radical shown in eq 6. It seemed possible that the

(20) (a) W. A. Pryor, *Proc. Indiana Acad. Sci.*, **72**, 121 (1962); (b) ref 4, p 254.

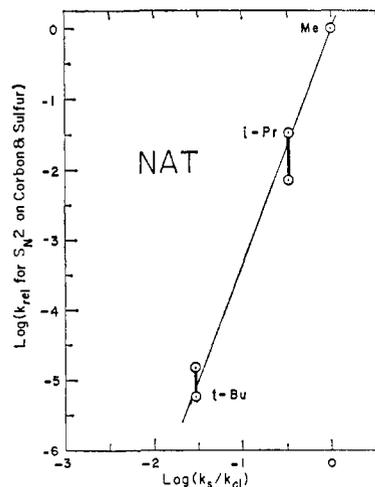


Figure 2. The same type of correlation as shown in Figure 1 except for the *p*-nitrophenyl radical.

rate profile for the reaction of phenyl radicals with disulfides might parallel the S_N2 reaction but that for the reaction of the *p*-nitrophenyl radical might not. Table III gives the data for the reaction of *p*-nitrophenyl radicals with three disulfides.²¹

Table III. The Reaction of *p*-Nitrophenyl Radicals with Disulfides in the Presence of Carbon Tetrachloride at 60°

R in RSSR	NAT ^a	[CCl ₄]/[RSSR] ^b	% yield ^c		
			ArSR	ArCl	ArH
Methyl	0.0444	18.95	83.3	7.70	1.40
Isopropyl	0.488	0.66	76.8	0.73	16.3
<i>t</i> -Butyl	0.0407	0.99	51.6	8.70	14.0

^a Initial concentration in moles per liter. ^b Initial mole ratio. ^c Per cent yield based on original concentration of NAT.

The Correlation of the Relative Rate Constants for the Reaction of Phenyl and *p*-Nitrophenyl Radicals with Rate Constants for the S_N2 Reaction. Figure 1 shows the log-log plot of the relative rate constant for the reaction of phenyl radicals with disulfides *vs.* the S_N2 reaction of nucleophiles on either sulfur or carbon,^{10a} and Figure 2 shows similar data for *p*-nitrophenyl radicals. It is clear that the reactions of the two radicals correlate similarly with the S_N2 reaction although the slope of the reaction for the *p*-nitrophenyl radical is larger. This is not a significant finding in the present context, but merely reflects the higher electrophilicity of the *p*-nitrophenyl radical.^{11,21}

The Reactivity of Different Types of Hydrogens toward the Phenyl and *p*-Nitrophenyl Radicals. Table IV compares relative rates of abstraction of different hydrogens by the phenyl and *p*-nitrophenyl radical and also compares disulfide hydrogens with benzylic hydrogens. The data show that the *p*-nitrophenyl radical is somewhat more selective than is the phenyl radical,¹¹ and that a hydrogen adjacent to a disulfide bond has about the same reactivity as does a benzylic hydrogen in both systems. It is interesting that despite this high reactivity of the hydrogens, most of the attack on disulfides occurs on the sulfur atom.

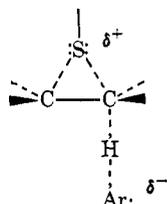
(21) For a more detailed discussion of polar effects and of the effect of extrapolation to infinite dilution in PAT on these data see W. K. Smith, Ph.D. Dissertation, L.S.U., Baton Rouge, La., August 1969.

Table IV. Relative Reactivities of Some Carbon-Hydrogen Bonds toward Phenyl and *p*-Nitrophenyl Radicals (per Reactive Hydrogen)

Type of hydrogen	Ph·	<i>p</i> -NO ₂ Ph·
Alkyl aromatic		
Primary benzylic	(1) ^a	(1) ^b
Tertiary benzylic	9.5 ^a	26 ^b
Primary β ^c	0.13 ^a	0.038 ^b
Disulfide ^d		
Primary α	1.2	1.02
Tertiary α	9.1	12
Primary β	0.23	0.16

^a Calculated from data of R. F. Bridger and G. A. Russell, *J. Amer. Chem. Soc.*, **85**, 3754 (1963). ^b Calculated from data of Pryor, Echols, and Smith, ref 11. ^c Hydrogens in *t*-butylbenzene. ^d Hydrogens in methyl disulfide, isopropyl disulfide, and *t*-butyl disulfide, respectively.

Participation by Sulfur in Bond Homolyses. The data of Table IV show that hydrogens β to a sulfur-sulfur bond have much higher reactivity than do those β to a phenyl group, although the hydrogens adjacent to sulfur and to a phenyl group have very similar reactivity. This noteworthy difference can be rationalized by postulating participation by sulfur in the homolysis of the carbon-hydrogen bond. It is interesting that the effect is largest for the *p*-nitrophenyl radical where a dipolar structure would increase the stability of the transition state for participation by sulfur. Participa-



tion by sulfur has been postulated to occur by Skell²² in thiyl radical additions to olefins and by Martin²³ in anchimeric assistance to perester O-O bond homolysis. In all of these cases, participation by sulfur requires that sulfur expand its electronic octet; we shall return to this topic later.²⁴

Discussion

The Theory of the Log-Log Correlation of Rate Constants for Different Reactions. It will be useful to develop the criteria for a correlation between the logarithms of two rate constants in a formal way before

(22) P. S. Skell, Special Publication, No. 19, The Chemical Society, London, 1965, pp 131 ff.

(23) T. H. Fisher and J. C. Martin, *J. Amer. Chem. Soc.*, **88**, 3382 (1966); J. C. Martin and T. W. Koenig, *ibid.*, **86**, 1771 (1964); D. L. Tuleen, W. G. Bentrude, and J. C. Martin, *ibid.*, **85**, 1988 (1963); W. G. Bentrude and J. C. Martin, *ibid.*, **84**, 1561 (1962).

(24) W. A. Pryor and T. L. Pickering [*J. Amer. Chem. Soc.*, **84**, 2705 (1962)] have discussed hydrogen abstraction from sulfides and disulfides and a number of factors other than participation must be considered. For example, consider the transfer constants ($C \times 10^4$) for the following five compounds toward the polystyryl radical at 60° (these transfer constants are proportional to the rate constants for reaction of the compounds with the polystyryl radical): butyl sulfide 22, *t*-butyl sulfide 250, butyl disulfide 24, *t*-butyl disulfide 1, (CH₃)₂CCH₂CH₃ 0.4. Clearly the transfer constant for *t*-butyl sulfide is enhanced relative to the others by some effect. This compound is the most strained, and we have suggested that the data can be rationalized by postulating that a synchronous carbon-sulfur bond scission accompanies hydrogen abstraction to relieve the steric strain of the substrate: M· + (*t*-butyl)₂S → MH + isobutylene + *t*-butyl-S·, where M· represents the polystyryl radical. J. A. Kampmeier, R. P. Geer, A. J. Meskin, and R. M. D'Silva [*ibid.*, **88**, 1257 (1966)] have discussed this type of reaction in detail.

we turn to an examination of data. The influence of changes in the structure of the substrate on the standard free energy of a reaction, at constant temperature, may be expressed as a function of a number of independent variables²⁵

$$d\Delta G^\ddagger = \left(\frac{\partial\Delta G^\ddagger}{\partial R}\right)_T dR + \left(\frac{\partial\Delta G^\ddagger}{\partial Y}\right)_T dY + \dots \quad (7)$$

where *R* and *Y* represent discrete properties of the substrate. For a finite change in *R* from some arbitrary standard, all other variables held constant, the change in free energy will be

$$\Delta G^\ddagger_i - \Delta G^\ddagger_0 = \left(\frac{\partial\Delta G^\ddagger}{\partial R}\right)_T (R_i - R_0) \quad (8)$$

The change in free energy from ΔG^\ddagger_i to ΔG^\ddagger_0 produces a corresponding change in the rate constant which is

$$\ln k_i/k_0 = \frac{\Delta G^\ddagger_i - \Delta G^\ddagger_0}{RT} \quad (9)$$

The influence of the change in the variable *R* upon the rate constant for a particular reaction series, a, is then

$$\ln (k_i/k_0)_a = -\left(\frac{\partial\Delta G^\ddagger}{\partial R}\right)_T \left(\frac{R_i - R_0}{RT_a}\right) \quad (10)$$

The influence of the same change in the variable *R* on two reaction series, a and b, at the temperatures *T_a* and *T_b*, can be expressed as

$$\ln (k_i/k_0)_a = \frac{T_b(\partial\Delta G^\ddagger/\partial R)_a(R_i - R_0)_a}{T_a(\partial\Delta G^\ddagger/\partial R)_b(R_i - R_0)_b} \ln (k_i/k_0)_b \quad (11)$$

or, in an abbreviated form, as

$$\ln (k_{rel})_a = \frac{T_b g_a \Delta R_a}{T_a g_b \Delta R_b} \ln (k_{rel})_b \quad (12)$$

Equations 11 and 12 predict that there will be a linear correlation between the logarithm of the relative rate constants for two reaction series provided that (1) all other variables but *R* remain constant; (2) the ratio *g_a/g_b* remains constant throughout the range of variation of *R*. However, note that *g_a* and *g_b* as well as ΔR_a and ΔR_b need not be individually constant, but only the product of their ratios.

There should *not* be a linear relationship between the log of the relative rate constants for two reactions when (a) the ratio of partial derivatives, *g_a/g_b*, does not remain constant, as might result if a change in mechanism occurred in one series; (b) other variables in the system are not constant and their changes are not linear functions of the changes in *R*; (c) the ratio $\Delta R_a/\Delta R_b$ does not remain constant. This could be caused by some unique action of the variable *R* in one of the reaction series; (d) the relationship between $\partial\Delta S^\ddagger/\partial R$ and $\partial\Delta H^\ddagger/\partial R$ is not constant. Since it is likely that $\partial\Delta H^\ddagger/\partial R$ and $\partial\Delta S^\ddagger/\partial R$ will be completely different functions of the variable *R*, in order for the partial derivative of ΔG^\ddagger with respect to *R* to remain constant throughout the reaction series it is necessary that either $(\partial\Delta S^\ddagger/\partial R)_T = 0$, *i.e.*, the series be isoentropic; or $(\partial\Delta H^\ddagger/\partial R)_T = 0$, *i.e.*, the series be isoenthalpic; or $(\partial\Delta H^\ddagger/\partial R)_T$ and $(\partial\Delta S^\ddagger/\partial R)_T$ be linearly related.

If we consider the restrictions a-d above, then a linear correlation between the log of the relative rate

(25) P. R. Wells, *Chem. Rev.*, **63**, 171 (1963).

constants for two reaction series, subject to the same variation in R , should indicate a similarity in the transition states for the two reaction series. There is, however, one caveat. Log-log plots are often quite insensitive to subtle changes in the variables, and it is possible that eq 11 will give a linear correlation between any two bimolecular reactions. This possibility is especially likely when the variable is the steric hindrance at the reaction site because this parameter can only be varied over a narrow range.

Correlation of Several Reaction Series vs. the S_N2 Reaction. We wished to test the possibility that log-log graphs of the rate constants for *all* reactions in which an R group was varied through the usual series methyl, ethyl, isopropyl, t -butyl correlated with each other. In Table V are collected ten reaction series of widely

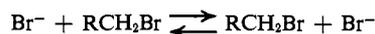
Table V. The Correlation of the Relative Rate Constants for a Series of Dissimilar Reactions with those for the S_N2 Reaction (Reaction A) Using Equation 11

Reaction code ^a	Reaction	Slope ^b	r^c
	Ph· + RSSR	2.30	0.9879
	NO ₂ Ph· + RSSR	2.52	0.9987
C	RSO-tolyl racemization	0.89	0.9966
D	RMe ₂ SiH + RO ⁻	1.70	0.9946
E	RNH ₂ + BMe ₃	1.09	0.9951
F	2-Alkylpyridine + MeI	1.50	0.9946
G-a	RCO ₂ Et + H ⁺	3.14	0.9999
G-b	RCO ₂ Et + HO ⁻	2.19	0.9926
H	RCO ₂ H + MeOH + H ⁺	3.40	0.9996
I	RSOPh oxidation	5.95	0.9964
J	RSSO ₃ ⁻ + SO ₃ ²⁻	0.92	0.9940

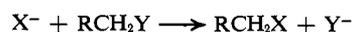
^a See text for details and references on each reaction. ^b Slope of graph plotting $\log k$ (S_N2 on carbon) on vertical axis and $\log k$ (for variable reaction) on horizontal axis. ^c The correlation coefficient.

varying mechanistic types for which we could find the necessary data. The reaction series are coded by letters from A to J and are described in the following paragraphs.

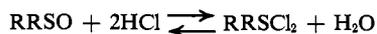
Reaction A is the exchange of radioactive bromide in a series of alkyl bromides as reported in a classical study of the S_N2 reaction by de la Mare.²⁶ At 25° in acetone, the relative rate constants are 1:0.65:0.033:1.5 × 10⁻⁵ for R equal methyl, ethyl, isopropyl, and t -butyl.



Reaction B is the typical pattern of reactivity for the S_N2 reaction which has been tabulated by Streitwieser.²⁷ For R equals methyl, ethyl, isopropyl, and t -butyl, the relative rate constants are 1:0.4:0.03:1.0 × 10⁻⁵.



Reaction C is the racemization of sulfoxides catalyzed by hydrogen chloride reported by Mislow.²⁸ The reaction involves the equilibrium

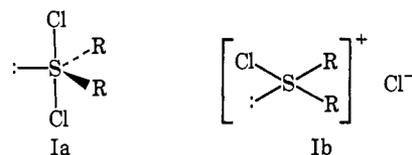


(26) P. D. B. de la Mare, *J. Chem. Soc.*, 3180 (1955).

(27) A. Streitwieser, Jr., *Chem. Rev.*, 56, 571 (1958); "Solvolytic Displacement Reactions," McGraw-Hill Book Co., New York, N. Y., 1962.

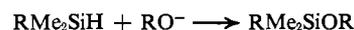
(28) K. Mislow, T. Simmons, J. T. Melillo, and A. L. Ternay, Jr., *J. Amer. Chem. Soc.*, 86, 1452 (1964).

The structure of the dichloride could be either a trigonal bipyramid with a plane of symmetry, Ia, or a rapidly exchanging set of ionic structures, Ib. The mechanism of this reaction involves substitution by chloride ion on the conjugate acid of the sulfoxide. The relative



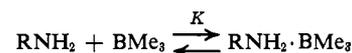
rate constants for racemization at 25° in a 2:1 v/v mixture of dioxane and 12 M aqueous HCl are 1:0.258:7.9 × 10⁻³:2.8 × 10⁻⁶ for R equals methyl, ethyl, isopropyl, and t -butyl.

Reaction D is the alkali-catalyzed hydrolysis of silanes reported by Steward and Pierce and by Sommer.²⁹ The mechanism of this reaction most probably is an addition-elimination sequence involving a pentacoordinate intermediate and an expansion of the electronic octet of the silicon atom.^{29c} The relative rate constants



at 0° in 93.7% wt % ethanol are 1:0.39:0.34:0.075:1.11 × 10⁻³ for R equals methyl, ethyl, propyl, isopropyl, and t -butyl.

Reaction E is the equilibrium between amines and trimethylborane measured by Brown.³⁰ The relative values of $1/K$ at 100° for the gas phase equilibrium



are 1:0.51:0.098:3.79 × 10⁻⁵ for R equals methyl, ethyl, isopropyl, and t -butyl.

Reaction F is the quaternization of 2-alkylpyridines with methyl iodide.³¹ The relative rate constants at 30° are 1:0.477:0.155:5.4 × 10⁻⁴ for R equal methyl, ethyl, isopropyl and t -butyl.

Reaction G-a is the acid-catalyzed hydrolysis of carboxylic ethyl esters at 25°. These are the data which were used by Taft to establish the σ^* scale.³² The relative rate constants are 1:0.851:0.435:0.339:2.89 × 10⁻² for R equals methyl, ethyl, propyl, isopropyl, t -butyl.

Reaction G-b is the basic hydrolysis of ethyl esters at 25°. These data also are part of Taft's original σ^* studies.³² The relative rate constants are 1:0.490:0.229:0.115:5.25 × 10⁻³ for R equals methyl, ethyl, propyl, isopropyl, and t -butyl. The mechanism of this hydrolysis is an addition-elimination sequence.

Reaction H is the acid-catalyzed esterification of carboxylic acids studied by Newman.³³ At 40° in methanol, the relative rate constants are 1:0.84:0.51:0.334:3.74 × 10⁻² for R equals methyl, ethyl, propyl, isopropyl, and t -butyl. This reaction also involves an addition-elimination mechanism.

(29) (a) Unpublished data very kindly furnished by Professor Leo Sommer; (b) O. W. Steward and O. R. Pierce, *J. Amer. Chem. Soc.*, 83, 1916 (1961); (c) L. Sommer, "Stereochemistry, Mechanisms, and Silicon," McGraw-Hill Book Co., Inc., New York, N. Y., 1965.

(30) H. C. Brown and G. K. Barbaras, *J. Amer. Chem. Soc.*, 75, 6 (1953).

(31) H. C. Brown and A. Cohn, *ibid.*, 77, 1715 (1955).

(32) R. W. Taft, Jr. in "Steric Effects in Organic Chemistry," M. S. Newman, Ed., John Wiley & Sons, Inc., New York, N. Y., 1956, pp 591-599.

(33) K. L. Loenig, A. B. Garrett, and M. S. Newman, *J. Amer. Chem. Soc.*, 74, 3929 (1952).

Reaction I is the oxidation of sulfoxides by peroxy acids in alkaline media reported by Curci and Modena.³⁴ The relative rate constants at 25° in 40/60 dioxane-water are 1:0.818:0.614:0.479:0.147 for R equal methyl, ethyl, propyl, isopropyl, and *t*-butyl. The mechanism of this reaction is not conclusively established, but the authors favor a metastable intermediate and an addition-elimination path. They suggest that the reaction occurs by attack by the anion of the peroxy acid on the sulfur atom from a direction that is perpendicular to the R-S-R plane.

Reaction J is the exchange of radioactive sulfur between the Bunté salt RSSO_3^- and inorganic sulfite as originally studied by Fava.³⁵ This is the work that led to the conclusion that sulfur is attacked by nucleophiles from the back-side direction in a Walden inversion mechanism.¹² The relative rate constants are 1:0.50:7 × 10⁻³:6.0 × 10⁻⁶ for R equal methyl, ethyl, isopropyl, and *t*-butyl.

Table V shows the results of correlation graphs of the type shown in Figures 1 and 2 for all of the reactions examined. In these correlations, the logarithm of the relative rate constant for the SN2 reaction on carbon, reaction A, is always plotted on the vertical axis and the variable reaction is plotted on the horizontal axis. The first feature to be noticed is that all of the reactions correlate excellently with the SN2 reaction on carbon. (The correlations are all significant at the 1% level or better.³⁶) Thus, it is clear that *no mechanistic significance at all* can be attached to a good correlation between the relative rate constants for two different reactions in a log-log plot when the variable is the R group as it is here. This is either because of the inherent insensitivity of log-log plots, or because of the narrow range over which the R group can be varied.³⁷

It is clear that the correlation of two reactions of these types with each other in eq 11 is not significant. We must next inquire whether a slope of near unity in such a correlation can be used to prove the mechanistic similarity of two reactions. Unfortunately, this possibility also must be rejected. Although it is true that the SN2 reaction on sulfur, reaction J, correlates with

(34) R. Curci and G. Modena, *Tetrahedron*, **22**, 1227 (1966).

(35) A. Fava and A. Iliceto, *J. Amer. Chem. Soc.*, **80**, 3487 (1958).

(36) In the graphs for which data is tabulated in Table V, only four points were available for the correlation; that is, the points for methyl, ethyl, isopropyl, and *t*-butyl. Five points are available for some of the correlations shown in Table VII. The correlation coefficients at the 5 and 1% level of significance are 0.950 and 0.990, respectively, for correlations involving four data points (*i.e.*, two degrees of freedom), and 0.878 and 0.959 for five data points and three degrees of freedom. See G. W. Snedecor, "Statistical Methods," The Iowa State College Press, Ames, Iowa, 4th ed, 1946, p 149.

The correlation of reaction A with the phenyl radical reaction is significant at better than the 1.5% level; that with the *p*-nitrophenyl radical is significant at better than the 5% level. In the *p*-nitrophenyl reaction, only three points were available for the correlation, and that perhaps is the reason for the slightly poorer correlation. In all of these correlations in which there are few points, the correlation coefficients are surprisingly insensitive to variations in the value of one of the points.

(37) It should be remarked that the reactions examined here are all related in the sense that they all involve an increase in the coordination number of the central atom at the transition state. Presumably, it is for this reason that they all correlate with each other with positive slopes. These reactions differ, however, in the extent to which the entering group (if there is one) is coordinated with the central atom as the leaving group departs. That is, they differ in following either a direct displacement or an addition-elimination mechanism. Nevertheless, if reactions as dissimilar as those grouped in Table V correlate with each other, we must be extremely cautious about drawing conclusions from the fact that two unknown reactions correlate with each other in such plots. See also ref 38, and the detailed discussion of the meaning of linear free energy relationships in the references cited in ref 39.

the SN2 reaction on carbon with a slope of 0.92, the racemization of sulfoxides, reaction C, correlates with the SN2 reaction with the very similar slope of 0.89. This certainly cannot be accepted as evidence for the mechanism of the sulfoxide reaction. Furthermore, the two amine reactions, reactions E and F, correlate with the SN2 reaction with slopes of 1.1 and 1.5; clearly these two reactions have mechanisms which are entirely unlike the Walden inversion mechanism.³⁷

Not only may unlike reactions correlate with each other with slopes near unity, but reactions which have the *same mechanism* may correlate with slopes which are *not* unity. For example, the reaction of triethylamine and quinuclidine with a series of alkyl iodides certainly has the same SN2 mechanism. Yet, as the data in Table VI show, the correlation graph of the same type

Table VI. The Log-Log Correlation of the Relative Rate Constants for the Reaction of Triethylamine and Quinuclidine with Alkyl Iodides^a

RI	—Relative rate constants—	
	Et ₃ N	Q ^b
Methyl	29,000	2,360
Ethyl	170	61
Isopropyl	(1)	(1)

^a H. C. Brown and N. R. Eldred, *J. Amer. Chem. Soc.*, **71**, 445 (1949); slope = 1.30; *r* = 0.9996. ^b Quinuclidine.

as described in Table V has a slope of 1.3. Although both reactions occur by the SN2 mechanism, in quinuclidine the substituents are "tied back" making it much less responsive to steric effects. This use of log-log plots to determine the relative selectivity of reagents in two reactions which are known to follow similar mechanisms has often been used in the study of radical reactions. For example, Trotman-Dickenson used this plot to compare the selectivity of different radicals in hydrogen abstraction reactions,^{38a} and in addition reactions.^{38b,c} The well-known Hammett $\sigma\rho$ equation also is sometimes used in this way.³⁹ However, in the Hammett equation the restrictions on the types of substituents that can be used and the types of reactions which can be compared are codified and standardized, and the correlations can often be used to identify mechanistic similarities. Clearly, our conclusions here are restricted to reactions at aliphatic side-chain-like positions where R groups are varied through the usual series from methyl to *t*-butyl.^{37,40}

Finally, it is perhaps worth stating explicitly that any two of the reactions in Table V which correlate with reaction A also correlate against each other. Table VII shows the results of a correlation of the entire series of reactions against the reaction of phenyl radicals with disulfides. All the correlations, predictably, are excellent.

(38) A. F. Trotman-Dickinson, "Free Radicals," Methuen and Co., London, 1959; (a) p 80; (b) p 109; other examples of these correlations are given in ref 4, p 226. Also see W. A. Pryor and T. F. Fiske, *Trans. Faraday Soc.*, **65**, 1865 (1969).

(39) L. P. Hammett, "Physical Organic Chemistry," McGraw-Hill Book Co., Inc., New York, N. Y., 1940; J. E. Leffler and E. Grunwald, "Rates and Equilibria of Organic Reactions," John Wiley & Sons, Inc., New York, N. Y., 1963. Also see the discussion in ref 32, pp 642 ff.

(40) Note, however, that the substituent in reaction F in Table V is located at a ring position. This reaction series, however, would not be correlated by the Hammett equation.

Table VII. The Correlation of the Relative Rate Constants for a Series of Dissimilar Reactions with those for the Reaction of Phenyl Radicals with Aliphatic Disulfides^a

Reaction code ^b	Slope	r^c	n^d
A	0.47	0.9979	4
B	0.41	0.9873	4
C	0.38	0.9964	4
D	0.74	0.9951	5
E	0.46	0.9718	4
F	0.63	0.9745	4
G-a	1.36	0.9730	5
G-b	0.96	0.9844	5
H	1.48	0.9835	5
I	2.60	0.9851	5
J	0.40	0.9980	4

^a The standard reaction, the reaction of phenyl radicals with disulfides, is plotted on the vertical axis. Data from ref 10a. ^b See Table V and the text for details on the reactions. ^c Correlation coefficient. ^d Number of points. In some cases the points for R equal propyl were available and were included with those for methyl, ethyl, isopropyl, and *t*-butyl.

The Mechanism of the Reaction of Nucleophiles or Radicals with Sulfur Atoms. The studies described in the preceding paragraphs make it necessary to reconsider the problem of the stereochemistry of both the SN2 and the SH2 reactions on sulfur. As the literature on substitution reactions on sulfur is examined, two facts stand out. One is that in all the ionic substitution reactions where stereochemistry has been investigated, the central sulfur undergoes a net inversion. The other is that although some substitution reactions on sulfur by nucleophiles appear to be direct SN2 reactions, in many substitutions by nucleophiles or radicals there is evidence for the existence of a metastable intermediate in which sulfur has expanded its coordination number and its electronic octet. Thus, it appears that inversion is the usual stereochemical result, but that kinetically the reactions may be either direct displacements or addition-elimination processes.⁴¹ It should be recognized that inversion can arise either by a direct SN2 mechanism *or* by an addition-elimination mechanism in which the attacking and leaving groups are both apically (or both equatorially) located and where pseudo-rotation is slow relative to ejection of the leaving group.^{42a} Mislow^{42b} has suggested that pseudo-rotation indeed may be slower in some sulfur compounds than in the analogous phosphorus derivatives. It is possible that sulfur compounds frequently react by an addition-elimination process involving a trigonal bipyramidal intermediate, with the entering and leaving groups located apically, and with slow pseudo-rotation so that net inversion is observed.^{42b,e-g}

(41) A working hypothesis at present is that addition-elimination mechanisms are favored when the attacking group is a good one, when the leaving group is poor, and, perhaps, when the electronegativity of the central sulfur is high. Some of these factors probably hold for most radical displacements on sulfur, and we suggest that most of these processes involve an addition-elimination mechanism.

(42) (a) F. H. Westheimer, *Accounts Chem. Res.*, **1**, 70 (1968); (b) R. Tang and K. Mislow, *J. Amer. Chem. Soc.*, **91**, 5644 (1969); (c) C. R. Johnson and D. McCants, Jr., *ibid.*, **87**, 5404 (1965); (d) M. A. Sabol and K. K. Andersen, *ibid.*, **91**, 3603 (1969); also see H. Phillips, *J. Chem. Soc.*, **127**, 2552 (1927); H. F. Herbradson and C. M. Cusano, *J. Amer. Chem. Soc.*, **83**, 2124 (1961); and K. K. Andersen, *Tetrahedron Lett.*, **93** (1963); (e) N. C. Baenziger, R. E. Buckles, R. J. Manor, and T. D. Simpson, *J. Amer. Chem. Soc.*, **91**, 5749 (1969); (f) also see R. Ramirez, *Accounts Chem. Res.*, **1**, 168 (1968); (g) K. L. Marsi, *J. Amer. Chem. Soc.*, **91**, 4724 (1969); (h) S. J. Benkovic and K. J. Schray, *ibid.*, **91**, 5653 (1969); (i) R. Belloli, *J. Chem. Educ.*, **46**, 640 (1969).

The stereochemistry of ionic substitution reactions on sulfur has been investigated by Johnson,^{42c} Mislow,^{42b} and Andersen.^{42d} In all cases, substitution is accompanied by inversion. The theoretical work summarized in the beginning of this article leads to the expectation that attack on sulfur by radicals or nucleophiles would occur from the back side. In this connection, it is relevant that the crystal structure of a chlorine complex of an aromatic sulfide has been determined from X-ray diffraction data.^{42e} This complex, which is formally pentacoordinated about sulfur if the unshared pair is regarded as a ligand, has a trigonal bipyramidal geometry with the electronegative chloride ligands in apical positions and the aryl groups and the lone pair equatorial. In pentacoordinate intermediates involving sulfur, phosphorus, or similar metalloid atoms, it is expected that both the attacking nucleophile and the leaving group would prefer to be apical, and that lone pairs prefer an equatorial position.⁴²

Reactions of Nucleophiles with Sulfur Compounds which Appear to Involve a Direct Displacement Reaction. Ciuffarin and Fava¹² have reviewed the literature on ionic substitution reactions on sulfur and have concluded that many of these reactions are direct SN2 displacements. In some cases the data are ambiguous and inconclusive, but a few examples can be cited where evidence has been presented favoring the SN2 mechanism. The alkaline hydrolysis of sulfones has been studied by Christman and Oae,^{43d} and the hydrolysis of organic sulfites by Bunton, *et al.*^{43a} Sulfur-oxygen bond fission was proven in both reactions by the use of O-18 labels, and it was shown that the unreacted sulfone recovered after partial hydrolysis had not exchanged with the solvent water at all, and the sulfites had exchanged to only a small extent. The absence of prior exchange, of course, would indicate that these reactions proceed by a SN2 mechanism. Davis, however, has suggested^{43b} that the small extent of exchange observed for the sulfite esters indicates an addition-elimination mechanism applies for these compounds, and if this is correct the sulfones also would be expected to hydrolyze by this mechanism.

Kice^{43c} has studied nucleophilic substitution on aryl Bunté salts from this viewpoint. He has argued from the values of ρ in Hammett equation correlations that these sulfur esters, unlike analogous reactions in the silicon series, proceed by a direct displacement reaction.

Reactions of Nucleophiles at Sulfur in which an Intermediate has been Postulated. The search for stable pentavalent intermediates resulting from attack on tetracoordinated sulfur has a long and classical history.^{44,45} Recently, a number of reports have been published where there is suggestive if not conclusive evidence for a metastable intermediate. For example, we have suggested that a pentavalent intermediate may be involved in the acid-catalyzed exchange of oxygen-18 between thiosulfate and water.⁴⁶ More

(43) (a) C. A. Bunton, P. B. D. de la Mare, P. M. Greaseley, D. R. Llewellyn, N. H. Pratt, and J. G. Tillett, *J. Chem. Soc.*, 4751 (1958); (b) R. E. Davis, *J. Amer. Chem. Soc.*, **84**, 599 (1962); (c) J. L. Kice and J. M. Anderson, *J. Org. Chem.*, **33**, 3331 (1968); (d) also see D. R. Christman and S. Oae, *Chem. Ind. (London)*, 1251 (1959).

(44) See, for example, G. Wittig and K. Clauss, *Ann.*, **577**, 26, 39 (1952).

(45) The literature is reviewed in ref 5 and by N. Kharasch, B. S. Thyagarajan, and A. I. Khodair, "Mechanisms of Reactions of Sulfur Compounds," Vol. 1, IntraScience Research Foundation, Santa Monica, Calif., 1966.

recently, Trost has suggested the existence of a pentavalent intermediate in the reaction of triarylsulfonium salts with alkylolithium reagents.⁴⁷ Harvey, Jacobson, and Jensen have published evidence for an intermediate with an expanded octet at sulfur in the reaction of disulfides with trivalent phosphorus esters.⁴⁸ Perhaps the most interesting report is one by Kice⁴⁹ suggesting that nucleophilic attack at sulfur is "at least 10^9 – 10^{10} faster than the displacement at sp^3 carbon" and that "an analogous statement (might be made) about nucleophilic substitutions at some other second-row elements as well." Ciuffarin and Fava¹² also have pointed out that bimolecular substitution is faster at second row elements and that the S_N1 mechanism is virtually unknown. If second row elements are attacked at rates some 10^9 faster than analogous first row elements in displacement reactions, then a possible mechanistic conclusion would be that their reactions involve addition of the attacking group to form an intermediate with an expanded electronic octet and that the ability of higher row elements to follow this path is responsible for their more rapid reaction.

Reactions of Radicals with Sulfur in which an Intermediate with an Expanded Octet has been Postulated. The ability of sulfur atoms to expand their electronic octet to accommodate more than eight electrons has been reviewed.⁵⁰ In 1950, Price explained radical additions to vinyl sulfides by postulating expansion of the octet of sulfur.⁵¹ Martin and his coworkers have found evidence for intermediates with expanded octets in the anchimeric effect of neighboring sulfur on the rates of homolysis of peroxy esters.^{23,52} Gritter has reported that the oxidation of sulfides to sulfoxides by *t*-butoxy radicals involves a metastable intermediate in which the alkoxy radical has added to the sulfur.⁵³ McEwen has found evidence for triarylsulfur radicals, $Ar_3\dot{S}$, produced from the reaction of triarylsulfonium salts with alkoxide ions.⁵⁴ Selbin has reported that uranium(V) complexes with Ph_2X_2 , where X is sulfur,

(46) W. A. Pryor and U. Tonellato, *J. Amer. Chem. Soc.*, **89**, 3379, 6391 (1967). Although in this report we suggest that the application of the principle of microscopic reversibility to the radio-exchange data establishes the existence of a pentavalent intermediate, a mechanism can be written which does not involve a stable intermediate and which satisfies microscopic reversibility. The mechanism requires that H_2O attack $-SSO_2OH$ at the same rate as OH^- attacks $-SSO_2OH_2^+$ and that these two paths occur in parallel. See R. L. Burwell and R. G. Pearson, *J. Phys. Chem.*, **70**, 30 (1966).

(47) B. M. Trost, R. LaRochelle, and R. C. Atkins, *J. Amer. Chem. Soc.*, **91**, 2175 (1969).

(48) R. G. Harvey, G. I. Jacobson, and E. V. Jensen, *ibid.*, **85**, 1618 (1963).

(49) J. L. Kice and N. A. Favstritsky, *ibid.*, **91**, 1751 (1969); note especially ref 16 therein.

(50) (a) C. Cilento, *Chem. Rev.*, **60**, 147 (1960); (b) see ref 5, pp 27–42; (c) C. C. Price and S. Oae, "Sulfur Bonding," Roland Press Co., New York, N. Y., 1962, pp 55–60.

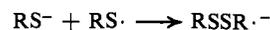
(51) C. C. Price and J. Zomlefer, *J. Amer. Chem. Soc.*, **72**, 14 (1950).

(52) The anchimeric effect by neighboring sulfur in solvolytic systems is known but does not involve an expansion of the octet of sulfur. See, for example, M. Hojo, T. Ichi, Y. Tamaru, and Z. Yoshida, *J. Amer. Chem. Soc.*, **91**, 5170 (1969).

(53) R. J. Gritter and D. J. Carey, *J. Org. Chem.*, **29**, 1160 (1964).

(54) J. W. Knapczyk and W. E. McEwen, *J. Amer. Chem. Soc.*, **91**, 145 (1969), and earlier references cited therein.

selenium, or tellurium. In the case of the heavier of the two elements, much of the odd electron density from the uranium is spread to the heteroatom as judged by esr.⁵⁵ Probably the most direct evidence for a sulfur intermediate with nine electrons is the observation of the radical anion $RSSR\cdot^-$ by pulse radiolysis techniques.⁵⁶ The species has an absorption at 410 nm and



is produced in the reaction shown with a rate constant of $5 \times 10^9 M^{-1} sec^{-1}$.

Table VIII gives preliminary data of ours comparing the reaction of phenyl radicals from PAT with *t*-butyl disulfide and *t*-butyl peroxide. Although the rate constants for attack on hydrogen are equal for the two compounds, attack on sulfur in the disulfide is far more rapid than is attack on oxygen in the peroxide. Experimental difficulties have so far prohibited us from reducing the upper limit yield of the ether any more than is shown, but we believe that it is probably much smaller than the maximum estimate given.

Table VIII. Yields of Products from the Reaction of Phenyl Radicals from PAT with *t*-Butyl Disulfide or Peroxide in the Presence of Carbon Tetrachloride^a

	% yield from			
	Thioether or ether	Benzene	PhCl	k_B/k_{Cl}
<i>t</i> -Butyl peroxide	<0.2	18	60	0.30
<i>t</i> -Butyl disulfide ^b	9.0	15	52	0.30

^a $[PAT]_0 = 24 \times 10^{-3} M$; mole ratio of CCl_4 to the peroxide or sulfide is about unity. ^b Unpublished data of Mr. T. Bickley.

Conclusions. Use of the kinetic test—that is, the log–log correlation of rate constants—in the aliphatic series is not useful for determining the mechanism of an unknown reaction. Such a log–log plot of the rate constants for two similar reactions can be used to rank the relative selectivity of two reagents, however.

It appears probable that most reactions in which either nucleophiles or radicals attack a sulfur atom occur by a back-side attack mechanism.⁴² However, many of these reactions probably do not involve a direct, one-step displacement reaction, but rather proceed through an addition–elimination pathway involving a metastable intermediate in which sulfur has expanded its electronic octet.⁵⁷

(55) J. Selbin, N. Ahmad, and M. J. Pribble, *Chem. Commun.*, 759 (1969).

(56) For a recent report, see G. E. Adams, R. C. Armstrong, A. Charlesby, B. D. Michael, and R. L. Wilson, *Trans. Faraday Soc.*, **65**, 732 (1969).

(57) See, for example, ref 5, 29c, 42, 45, 46, 49, and references cited therein. Also see, for attack on phosphorus: E. A. Dennis and F. H. Westheimer, *J. Amer. Chem. Soc.*, **88**, 3431, 3432 (1966); W. G. Ben-trude and R. A. Wielasek, *ibid.*, **91**, 2406 (1969); attack on silicon: L. E. Nelson, N. C. Angelotti, and D. R. Weyenberg, *ibid.*, **85**, 2662 (1963); on arsenic: H. Goldwhite, *Inorg. Nuclear Chem. Lett.*, **2**, 5 (1966). Further papers of interest in this connection are R. F. Jensen and H. E. Guard, *J. Amer. Chem. Soc.*, **90**, 3250 (1968); E. Ciuffarin and G. Guaraldi, *ibid.*, **91**, 1745 (1969); J. F. Harris, *J. Org. Chem.*, **31**, 931 (1966); L. H. Sommer, J. D. Citron, and G. A. Parker, *J. Amer. Chem. Soc.*, **91**, 4729 (1969).