tivation and the frequency factors are interpreted to mean that the isomerizations are not complicated by steric requirements or the necessity for oriented energetic collisions.

The Nucleophilic Reactivity of Sodium Thiophenoxide with Aromatic Substrates [1,2]

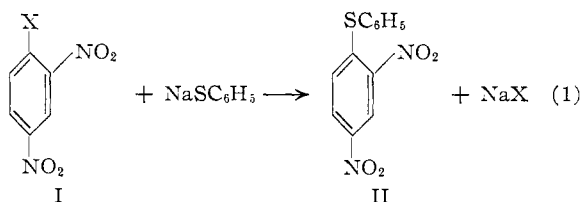By J. F. Bunnett and Will D. Merritt, Jr.[3]

Rates of reactions of sodium thiophenoxide with several 1-substituted-2,4-dinitrobenzenes have been measured. Four substituents, the nitro, phenylsulfonyl, phenylsulfinyl and pyridinio groups, were displaced too fast to measure by the technique used. Fluorine was displaced much faster than the other halogens, while chlorine, bromine, iodine and the p-nitrophenoxy group were all displaced at nearly the same rate. This sameness of rate shows the absence of an "element effect," and indicates that in the transition states of these displacements there is little or no breaking of the bond to the group being displaced. Thiophenoxide:methoxide rate ratios have been found to vary in a systematic fashion: the relative effectiveness of thiophenoxide increases with increasing polarizability of the halogen being displaced and with increasing activation by nitro groups.

In recent years the thiophenoxide ion has been recognized to be a very strong nucleophilic reagent in reactions with several aliphatic[4] and aromatic[5] substrates. For example, sodium thiophenoxide reacts (S_N2 + S_N2') with 3,3-dichloropropene-1 240 times faster than does sodium ethoxide.[4c] It was therefore something of a surprise when Bevan and Hirst[6] reported that thiophenoxide is no more reactive than methoxide ion toward the substrate p-fluoronitrobenzene. This discovery suggested that interesting relationships might be revealed by measuring the rates of reactions of sodium thiophenoxide with a group of appropriately chosen aromatic substrates. We now report a series of such measurements, and interesting relationships have indeed been found.

We have measured the rates of reactions (1) of sodium thiophenoxide with several 1-substituted-

2,4-dinitrobenzenes in methanol solution. These are fast reactions, and only at low concentrations were they slow enough for kinetic observation. Photometric analysis, depending on the color of the product, 2,4-dinitrodiphenyl sulfide (II), was used;

this technique is especially satisfactory for reactions run at low concentrations.

Some preliminary observations on the rates of reactions of thiophenoxide with 1-substituted-4-nitrobenzenes also were made.

Experimental

Materials.—p-Fluoronitrobenzene, p-chloronitrobenzene, p-bromonitrobenzene, p-iodonitrobenzene, 2,4-dinitrofluorobenzene, 2,4-dinitrochlorobenzene, 2,4-dinitrobromobenzene, 2,4-dinitrodiphenyl sulfone and thiophenol were prepared by standard methods or were commercial products repurified. 1,2,4-Trinitrobenzene, 2,4,4'-trinitrodiphenyl ether, 2,4-dinitroiodobenzene and 2,4-dinitrodiphenyl sulfoxide were available from another investigation.[7] Reagent grade methanol was dried by the method of Hartley and Raikes.[8] Standard sodium thiophenoxide solutions were prepared from a weighed amount of thiophenol and an equivalent amount of a standard solution of methanolic sodium methoxide diluted to volume with methanol in a volumetric flask. The solutions were not kept more than eight hours, a new solution being prepared for each set of kinetics runs.

Rate Measurements.—A weighed portion of the substrate (in one series an aliquot of a standard solution) was placed in a flask in the thermostat and 100 cc. of methanol at thermostat temperature was added. After the substrate had dissolved, an exactly equivalent amount of a standard sodium thiophenoxide solution in methanol, at thermostat temperature, was added with swirling by means of a fast-delivery 9.88-cc. pipet. An accurate zero time was not necessary. Samples (8 or 9 per run) were taken with a fast-delivery pipet, precooled to thermostat temperature, and were discharged into a standard volume of dilute methanolic sulfuric or hydrochloric acid, the time of release being recorded. Thermostats were constant to ±0.03° and their temperatures were determined with a thermometer certified by the National Bureau of Standards.

Upon completion of a run, the optical densities of the quenched samples were determined in a Beckman model B spectrophotometer at wave lengths in the vicinity of 410 mμ, the exact wave length for any run being chosen with regard to the absorption characteristics of the original substrates and the concentration of 2,4-dinitrodiphenyl sulfide in the quenched solutions. In the case of runs with 2,4-dinitroiodobenzene, it was necessary to add a few drops of aqueous sodium thiosulfate solution just prior to photometric measurements; otherwise, falsely high optical densities were read, no doubt owing to the presence of traces of iodine generated by air oxidation of iodide ion in acidic medium.

That the reactions had occurred quantitatively as repre-

(1) Work supported in part by the Office of Ordnance Research, U. S. Army.

(2) This paper is based on the Ph.D. thesis of Will D. Merritt, Jr., April, 1957.

(3) R. J. Reynolds Fellow, 1955–1956.

(4) (a) O. R. Quayle and E. E. Royals, This Journal, **64**, 226 (1942); (b) J. Hine and W. H. Brader, ibid., **75**, 3964 (1953); (c) P. B. D. de la Mare and C. A. Vernon, J. Chem. Soc., 3331 (1952); (d) B. S. Baldwin and H. J. Dauben, Jr. (Univ. of Washington), unpublished work.

(5) (a) J. F. Bunnett and R. E. Zahler, Chem. Revs., **49**, 340 (1951); (b) J. F. Bunnett and G. T. Davis, This Journal, **76**, 3011 (1954); (c) J. F. Bunnett and R. F. Snipes, ibid., **77**, 5422 (1955).

(6) C. W. L. Bevan and J. Hirst, Chemistry & Industry, 1422 (1954); J. Chem. Soc., 254 (1956).

(7) J. F. Bunnett, E. W. Garbisch, Jr., and K. M. Pruitt, This Journal, **79**, 385 (1957).

(8) H. Hartley and H. R. Raikes, J. Chem. Soc., 127, 524 (1925).

sented by equation 1 was verified by comparison of the optical density of an infinity sample with that of a sample of mock infinity solution[9] quenched in the standard way. In all cases, the two readings were essentially identical.

In calculation of rate coefficients, the reciprocal of (O.D. ∞ − O.D.) for each sample was plotted against the time recorded for that sample; the resulting plots were straight lines. The slope of each line, determined by the method of least squares, was multiplied by $O.D._{\infty}/a$, where a is the initial concentration of the substrate (and also of sodium thiophenoxide); the resulting value was the second-order rate coefficient. Data from a typical run are displayed in Table I.

TABLE I

REACTION OF 2,4-DINITROBROMOBENZENE WITH SODIUM THIOPHENOXIDE AT 0.0°

Initial concentrations: 2,4-dinitrobromobenzene, 9.00×10^{-3} M; sodium thiophenoxide, 8.95×10^{-3} M; volume of sampling pipet, 9.88 cc.; volume of quenching solution, 24.86 cc. The rate coefficient calculated for this run was 6.73 l. mole^{-1} sec.$^{-1}$

Time, sec.	O.D. (425 mμ)	O.D.∞ − O.D.	$1/(O.D._{\infty} - O.D.)$
15.8	0.277	0.225	4.44
30.8	.339	.163	6.13
46.6	.377	.125	8.00
62.8	.401	.101	9.90
79.2	.419	.083	12.05
96.5	.431	.071	14.08
114.0	.440	.062	16.13
132.8	.450	.052	19.23
"Infinity"	.500		
Mock infinity	.504		

The Arrhenius activation energy, ΔE, and the entropy of activation, ΔS^*, were calculated from standard expressions.[10]

TABLE II

REACTIONS OF 1-SUBSTITUTED-2,4-DINITROBENZENES WITH SODIUM THIOPHENOXIDE IN METHANOL

1-Substituent	Temp., °C.	[Substrate]₀	Rate coefficient,[a] l. mole^{-1} sec.$^{-1}$
F	0.0	9.05×10^{-4}	103.3; 99.5; 107.5
Cl	0.0	9.23×10^{-3}	3.89; 3.87; 3.91
	7.66	4.47×10^{-3}	6.39; 5.70; 6.30; 7.15
	15.12	4.47×10^{-3}	10.0; 10.6; 10.9
	14.93	4.43×10^{-3}	10.7
Br	0.0	8.94×10^{-3}	6.56; 6.74
		9.00×10^{-3}	6.73
		4.51×10^{-3}	6.85
	7.67	4.47×10^{-3}	9.60; 9.87; 10.5; 11.0; 12.0; 12.0; 13.0
	14.90	4.43×10^{-3}	16.6 17.2; 17.3
I	0.0	4.47×10^{-3}	5.01; 5.10; 5.39
	7.66	4.43×10^{-3}	8.96; 9.26; 9.58
	14.87	4.39×10^{-3}	13.5; 14.1; 15.4
$-OC_6H_4NO_2$-p	0.0	4.63×10^{-3}	1.53; 1.59
	14.92	4.50×10^{-3}	4.98; 5.30
	24.00	4.91×10^{-3}	8.38
	25.42	4.12×10^{-3}	11.1

[a] Each value given represents a separate run.

Results and Discussion

Results in the 2,4-dinitrohalobenzene series are summarized in Table III. This table includes not only rate coefficients and energies and entropies of activation for reactions with thiophenoxide ion, but also rate coefficients (from other laboratories) concerning reactions of the same substrates with methoxide ion.

(9) J. F. Bunnett and H. D. Crockford, *J. Chem. Educ.*, **33**, 552 (1956).

(10) S. Glasstone, K. J. Laidler and H. Eyring, "The Theory of Rate Processes," McGraw–Hill Book Co., Inc., New York, N. Y., 1941, p. 199.

Concerning the rates of reaction with thiophenoxide listed in Table III, it should be noted that fluorine is the most rapidly replaced of the halogens and that the other four groups are replaced at nearly the same rate, the maximum variation among the four being less than fivefold. These four groups have first atoms representing four elements, and the sameness of their rates of replacement shows the absence of an "element effect"[7] in this reaction series. This result and the high replaceability of fluorine both indicate that in this reaction series, as in reactions of the same substrates with the reagent piperidine, there is little or no breaking of the old bond in the transition state. The reasoning has been set forth at length elsewhere.[7]

Four substrates in the 1-substituted-2,4-dinitrobenzene series reacted with sodium thiophenoxide at 0° too fast for their rates to be measured by the technique we used. These were 1,2,4-trinitrobenzene, 2,4-dinitrophenylpyridinium chloride, 2,4-dinitrodiphenyl sulfoxide and 2,4-dinitrodiphenyl sulfone. From each of these reactions, the expected product (II) was isolated. It should be noted that, with the nucleophilic reagent piperidine, 1,2,4-trinitrobenzene reacts slower than 2,4-dinitro*fluoro*benzene, while 2,4-dinitrodiphenyl sulfoxide and sulfone react at about the same rate as 2,4-dinitro*chloro*benzene. Thus the nitro, phenylsulfonyl and phenylsulfinyl groups appear to have an unusually high replaceability when the reagent is the thiophenoxide ion. That the phenylsulfonyl group is especially susceptible to replacement by the thiophenoxide ion was suggested by work of Loudon and co-workers[11] nearly twenty years ago.

Concerning the relative nucleophilic reactivities of the thiophenoxide and methoxide ions, it is clear from the last column of Table III that thiophenoxide is a much more active reagent than methoxide with all of the substrates listed.[12] Thus the earlier assignments[5a,b] of very high nucleophilic reactivity to thiophenoxide ion are upheld. Bevan and Hirst's[6] observation, which we have verified, that the two reagents are nearly equal in their rates of reaction with p-fluoronitrobenzene therefore appears to be a special case.[13]

The variation of the thiophenoxide:methoxide reactivity ratio from one substrate to another is especially interesting. Aside from the fact that fluorine is the most replaceable of the halogens, there is little regularity in the relative replaceabilities of these substituents. Thus, with methoxide the order of mobility is F >> Cl > Br > I while with thiophenoxide it is F >> Br > I > Cl. With p-halonitrobenzenes, the order with methoxide is as given above,[14] while with thiophenoxide the order[15] is

(11) J. D. Loudon and N. Shulman, *J. Chem. Soc.*, 722 (1941), and earlier papers.

(12) Comparison with data of Y. Ogata and M. Okano, THIS JOURNAL, **71**, 3212 (1949), shows that thiophenoxide is about a hundred times as reactive as methoxide toward 2,4,4'-trinitrodiphenyl ether.

(13) Such a strong interdependence of substrate and reagent reactivity cautions against considering a single table of relative nucleophilic reactivities derived from data concerning more than one substrate[6] to have precise numerical significance.

(14) G. P. Briner, J. Miller, M. Liveris and P. G. Lutz, *J. Chem. Soc.*, 1265 (1954); see also C. W. L. Bevan, *ibid.*, 2340 (1951).

(15) Our preliminary rate coefficients for reactions of 1-substituted-4-nitrobenzenes with sodium thiophenoxide in methanol at 49.2° are as follows: F, 23; Cl, 3.2; Br, 7.3; I, 7.9; p-nitrophenoxy, 1.9 (all in l.

TABLE III

REACTIONS OF 1-SUBSTITUTED-2,4-DINITROBENZENES WITH THIOPHENOXIDE AND METHOXIDE IONS

1-Substituent	Reactions with thiophenoxide			Reactions with methoxide	$\dfrac{k_{\text{thiophenoxide}}}{k_{\text{methoxide}}}$
	k at 0.0°, 1. mole $^{-1}$ sec. $^{-1}$	ΔE, kcal.	ΔS^*, cal./deg.	k at 0.0°, 1. mole $^{-1}$ sec. $^{-1}$	
F	103.4			1.76^a	59
Cl	3.89	10.3	−20.0	2.00×10^{-3b}	1950
Br	6.68	9.8	−20.6	1.38×10^{-3b}	4850
I	5.17	10.7	−17.9	3.08×10^{-4b}	16800
$-OC_6H_4NO_2\text{-}p$	1.56	12.1	−15.2		

^{a} From C. W. L. Bevan and G. C. Bye, *J. Chem. Soc.*, 3091 (1954). ^{b} From A. L. Beckwith, J. Miller and G. D. Leahy, *ibid.*, 3552 (1952).

F > I ~ Br > Cl. However, the thiophenoxide: methoxide ratio varies in a regular manner as shown in the far right-hand column of Table III. Thiophenoxide is relatively most effective in the displacement of iodine and relatively least effective in displacing fluorine; chlorine and bromine fall between in regular order. Of the two reagents thiophenoxide has the higher polarizability, and in the series of four halogens polarizability increases steadily from fluorine (least) to iodine (greatest).[17] The reagent of greater polarizability is relatively more effective in displacing a halogen substituent of greater polarizability. This is a general tendency in bimolecular nucleophilic substitution reactions, and it will be discussed more fully in another article.

The thiophenoxide:methoxide ratio also varies with the degree of activation of the substituent being replaced. This is shown in Chart I in which

CHART I

THIOPHENOXIDE : METHOXIDE RATE RATIOS
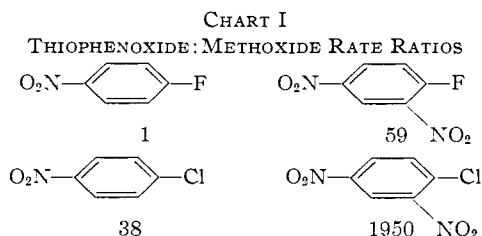
mole $^{-1}$ sec. $^{-1}$ × 10⁴). These runs were followed by titration of unconsumed thiophenol (in acid-quenched solutions) with iodine with use of a polarized end-point detector.[16]

(16) C. N. Reilley, W. D. Cooke and N. H. Furman, *Anal. Chem.*, **23**, 1223 (1951).

(17) C. K. Ingold, "Structure and Mechanism in Organic Chemistry," Cornell University Press, Ithaca, N. Y., 1953, p. 124.

this ratio is set directly beneath the structure of each substrate.[18] Notice that thiophenoxide is not only relatively more reactive in the displacement of chlorine rather than fluorine in both the mononitro and dinitro series, but also that thiophenoxide is relatively more reactive in the displacement of a given halogen when it is activated by two nitro groups rather than by one. The latter implies that the Hammett ρ constant[19] for displacements initiated by thiophenoxide should be significantly higher than for displacements initiated by methoxide ion, and suggests that the provisional ρ value for the reactions of thiophenoxide with 4-substituted-2-nitrochlorobenzenes[5c] may be too low. Further data bearing on this question would be of interest.

This investigation has thus shown that the thiophenoxide ion is in general a much stronger nucleophilic reagent than methoxide ion in reactions with aromatic substrates, but that its degree of dominance varies with the substituent being replaced and with the extent of activation by electron-withdrawing groups. With one substrate it is no stronger than methoxide, and it is likely that with yet other substrates, such as fluorobenzene itself, thiophenoxide ion may be much less reactive than methoxide ion.[20]

(18) The values given are derived from data in Table III, in footnote 15, and from ref. 14.

(19) L. P. Hammett, "Physical Organic Chemistry," McGraw–Hill Book Co., Inc., New York, N.Y., 1940. p. 186.

(20) Preliminary experiments in this Laboratory have indicated that unactivated aryl bromides are remarkably unreactive toward sodium thiophenoxide in alcoholic solvents at elevated temperatures.

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A New Factor Affecting Reactivity in Bimolecular Nucleophilic Displacement Reactions[1]

BY JOSEPH F. BUNNETT

In several bimolecular nucleophilic substitution reaction series, reagents such as iodide and thiophenoxide ions are found to be, in respect to reagents such as methoxide ion, especially reactive with substrates having halogen substituents of larger size and weight at or near the site of substitution. For example, the thiophenoxide:methoxide rate ratio is higher for reaction with α-iodo than with α-bromo substrates. The special characteristics in both reagents and substrates responsible for this behavior are tentatively identified as polarizabilities, and their special interaction is thought to be of the nature of London forces.

In this article, attention is called to a heretofore unrecognized factor having an important influence on reactivity in bimolecular nucleophilic displace-

ment reactions. This factor has escaped notice because, although significant, it is not a primary determinant of reactivity, and therefore its effect is not usually evident from examination of rate coefficients for a single reaction series. It becomes evi-