Electronic Effect, Steric Hindrance, and Anchimeric Assistance in Oxidation of Sulphides. Neighbouring-group Participation through Sulphur–Oxygen Non-bonded Interaction

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Using a set of sulphides *o*- and *p*-XC_6H_4SMe, the electronic effect, steric hindrance, and anchimeric assistance for electrophilic Cl^+ addition by TsNHCl and *O*-transfer by $NaIO_4$ were investigated by a kinetic method. The steric effect and anchimeric assistance of the *ortho*-substituents were evaluated by comparing the reactivity of *ortho*- and *para*-substituted compounds ($\kappa = k^o/k^p$). For neighbouring-group activity the following order was obtained: $CH_2OH \sim CH_2OMe \sim CH_2CO_2Me < CH_2CO_2H \sim CH_2NMe_2 \ll CH_2CO_2^- \sim CHO < CO_2Me \sim CO_2H < COMe \sim CONH_2 \ll CO_2^-$. Reaction rates show that the anchimeric assistance is governed by an $S \cdots O$ or $S \cdots N$ close contact developed in the transition state between oppositely polarized heteroatoms. Factors controlling neighbouring-group participation through attractive non-bonded interactions are discussed.

Neighbouring-group participation has been widely investigated for nucleophilic substitutions occurring at the sulphonium reaction site.[1] However, only few data are available for elecrophilic addition to bivalent sulphur, increasing the number of *S*-substituents from two to three. In previous papers we have shown that the oxidation of sulphides by chloramine T[2,3] and sodium periodate[4] are anchimerically assisted by *o*-CO_2H and *o*-CO_2Me groups, both having approximately the same effect on the reaction rate.

In reaction A TsNHCl, the conjugate acid of chloramine T, converts sulphides in the rate-determining step into a chlorosulphonium–sulphonamidate intermediate from which sulphimide and sulphoxide products are formed in competitive, fast, nucleophilic displacements [equations (1) and (2)].[2,3]

Reaction A

$$XC_6H_4SMe + TsNHCl \xrightarrow[\text{slow}]{k_A} [XC_6H_4(Me)S^+Cl, TsNH^-]$$

$$\xrightarrow[-HCl]{\text{fast}} XC_6H_4(Me)SNTs \qquad (1)$$

$$\xrightarrow{H_2O} XC_6H_4(Me)SO + TsNH_2 \qquad (2)$$

The oxidation of sulphides with $NaIO_4$ (reaction B) is a one-step electrophilic oxygen-transfer from the periodate anion to the bivalent sulphur atom.[4]

Reaction B

$$XC_6H_4SMe + IO_4^- \xrightarrow[\text{slow}]{k_B} XC_6H_4(Me)SO + IO_3^- \qquad (3)$$

In order to find further examples of this new type of neighbouring-group effect, we investigated the conversion of a set of sulphides *o*- and *p*-XC_6H_4SMe, using kinetic measurements. On the basis of reaction rate data, we attempted to distinguish between the electronic effect, steric hindrance, and anchimeric assistance caused by *ortho*-substituents, and to explain the neighbouring-group effect observed in addition reactions by non-bonded interactions.

Results and Discussion

Products.—In reaction A aryl methyl sulphides were converted by chloramine T into a mixture of *N*-tosylsulphimides and sulphoxides accompanied by $TsNH_2$. Product distributions were investigated by n.m.r. spectroscopy (Table 1, see Experimental section). Reaction B yielded only sulphoxides which were analysed by i.r. spectroscopy. The characteristic ν(S=O) frequencies are listed in Table 1.

Electronic and Steric Effects.—Using the methods described previously,[2–4] the rate constants k_A and k_B were determined for reactions A and B involving *o*- and *p*-XC_6H_4SMe (Table 2). The k^p values obtained for *para*-derivatives (see Table 2, Nos. 1, 2, 5, 7, 10, 12, 14, 15, 17, 18, 18a, and 20 for reaction A, and Nos. 1, 2, 5, 7, 9, 10, 12, 14, 15, 17, 18, and 20 for reaction B) correlated well with the Hammett equation (4). σ_p Values were taken from ref. 5, but data from refs. 6—10 were used for OMe, CH_2OH, $CONH_2$, CO_2^-, and CH_2CO_2H groups, respectively.

$$\log k^p = \rho\sigma_p + c \qquad (4)$$

$$\log k_A^p = -(4.60 \pm 0.09)\sigma_p + (1.36 \pm 0.02) \qquad (4A)$$
$$r = 0.9973, \quad F = 1\,749, \quad s = 0.09, \quad n = 12$$

$$\log k_B^p = -(1.45 \pm 0.07)\sigma_p - (1.39 \pm 0.03) \qquad (4B)$$
$$r = 0.9841, \quad F = 329, \quad s = 0.09, \quad n = 12$$

The reaction constants, ρ_A −4.60 and ρ_B −1.45, obtained from equations (4A and B) do not differ markedly from the ρ_A −4.25[2] and ρ_B −1.40[4] values determined previously from smaller sets of experimental data. When calculating the substituent effects in reaction B, the $k_B{}^p$ values obtained for sulphides with a charge (Table 2, Nos. 12a, 18a, and 20a) were omitted, as reaction rates were strongly influenced by the Coulomb interaction between the charged sulphide and IO_4^- reactants.

For *p*-X = $CH_2NH^+Me_2$, $CONMe_2$, CH_2CO_2Me, and $CH_2CO_2^-$, σ_p 0.27, 0.26, 0.06, and −0.11, respectively, were calculated from ρ_A and k_A^p values obtained for reaction A which is more sensitive to substituent effects than reaction B (Table 2, Nos. 12a, 16, 19 and 20a). For *p*-$CH_2NH^+Me_2$ an improbably high σ_p of 0.43 has been reported.[5] The lower σ_p of 0.27 computed by us seems to be more consistent with σ_p 0.29 determined for the analogous $CH_2NH_3{}^+$ group.

The reactivity of sulphides may be markedly decreased by the steric effect of *ortho*-substituents. For some cases this can be seen by comparing the rate constants of the *ortho*- and *para*-substituted sulphides ($k^o < k^p$, Table 2, Nos. 2—9). Since the electronic effect of *ortho*-substituents is similar to that of the *para*-substituents, the steric effect of the former groups can be

Table 1. Yield of $XC_6H_4(Me)SNTs$ and characteristic i.r. data for $XC_6H_4(Me)SO$ formed in reactions A and B, respectively, involving *p*- and *o*-XC_6H_4SMe

		Reaction A Yield of sulphimide (%)[a]		Reaction B ν(S=O)[b]/cm^{-1}		
Sulphide	Substituent X	*para*	*ortho*	*para*	*ortho*	Δν(S=O)[c]
1	H	55	55	1 047	1 047	
2	Me	56	41	1 044	1 065	−21
3	Pr^i		40		1 070	
4	CH_2CN		35		1 067	
5	OMe	69	52	1 043	1 036	+7
6	F		37		1 073	
7	Cl	46	23	1 050	1 062	−12
8	Br		26		1 055	
9	NO_2			1 068	1 054	+14
10	CH_2OH	49	5	1 040	1 028	+12
11	CH_2OMe		43		1 035	+5[d]
12	CH_2NMe_2	47	23	1 042	1 021	+21
13	CHO		0		1 070, 1 034[e]	
14	COMe	40	25	1 049	1 027	+22[f]
15	$CONH_2$	38	12	1 012[g]	1 012[g]	0
16	$CONMe_2$	39	15	1 050	1 033	+17
17	CO_2Me	39	23	1 048	1 031	+17[h]
18	CO_2H	32	0	1 002[g]	945[g]	+57
19	CH_2CO_2Me	50	44	1 054	1 064	−10
20	CH_2CO_2H	39	12	1 043	1 038	+5

[a] The yield of $XC_6H_4(Me)SO$ is (100 − sulphimide)%, as measured by n.m.r. [b] In CH_2Cl_2 solution. [c] $\Delta\nu(S{=}O) = \nu_p(S{=}O) - \nu_o(S{=}O)$. [d] Calculated by using the $\nu_p(S{=}O)$ value obtained for *p*-$HOCH_2C_6H_4(Me)SO$. [e] Two ν(S=O) and ν(C=O) (1 700, 1 681 cm^{-1}) bands appear for the two possible conformations of the S–C(ar)=C(ar)–CH=O moiety. [f] The $\nu_p(C{=}O) - \nu_o(C{=}O) = \Delta\nu(C{=}O)$ values are 1 687 − 1 678 = 9 and 1 682 − 1 678 = 4 cm^{-1} for $MeCOC_6H_4S(Me)O$ and $MeCOC_6H_4SMe$, respectively. [g] In KBr pellet. [h] The $\nu_p(C{=}O) - \nu_o(C{=}O) = \Delta\nu(C{=}O)$ values are 1 722 − 1 713 = 9 and 1 723 − 1 720 = 3 cm^{-1} for $MeO_2CC_6H_4S(Me)O$ and $MeO_2CC_6H_4SMe$, respectively.

roughly estimated by the $\kappa = k^o/k^p$ ratio. For entries 2—9 the average values $\bar{\kappa}_A$ 0.03 and $\bar{\kappa}_B$ 0.4 were obtained indicating that *S*-chlorination with TsNHCl (reaction A) was more sterically hindered than *S*-oxidation with $NaIO_4$ (reaction B).

Starting from the k_A^o and k_B^o data, obtained for *ortho*-substituted compounds in reactions A and B (Table 2, Nos. 1—8 and 1—9, respectively), we attempted to separate rate-controlling electronic and steric effects. Equations (5),[11] (6),[12] and (7)[13] were used with the substituent constants σ_o,[14] E_s^c,[15] σ_I,[16] σ_R,[16] υ[5,16b] and F_o[8] taken from the literature.

$$\log k^o = \rho\sigma_o + \delta E_s^c + c \qquad (5)$$

$$\log k^o = \alpha\sigma_I + \beta\sigma_R + \psi\upsilon + h \qquad (6)$$

$$\log k^o = \rho\sigma_o + \delta E_s^c + fF_o + c \qquad (7)$$

$$\log k^o = -3.33\sigma_o + 0.76E_s^c + 0.61 \qquad (5A)$$
$$(\pm 0.83)\ (\pm 0.28)\ (\pm 0.34)$$
$$r = 0.9152,\quad F = 25.8,\quad s = 0.52,\quad n = 8$$

$$\log k^o = -3.85\sigma_I - 2.64\sigma_R - 2.06\upsilon + 1.13 \qquad (6A)$$
$$(\pm 0.60)\ (\pm 0.64)\ (\pm 0.35)\ (\pm 0.20)$$
$$r = 0.9215,\quad F = 22.5,\quad s = 0.56,\quad n = 8$$

$$\log k^o = -2.51\sigma_o + 0.85E_s^c - 1.46F_o + 1.00 \qquad (7A)$$
$$(\pm 0.77)\ (\pm 0.14)\ (\pm 0.59)\ (\pm 0.17)$$
$$r = 0.9422,\quad F = 31.6,\quad s = 0.48,\quad n = 8$$

$$\log k^o = -1.35\sigma_o + 0.02E_s^c - 1.76 \qquad (5B)$$
$$(\pm 0.29)\ (\pm 0.12)\ (\pm 0.15)$$
$$r = 0.9107,\quad F = 29.2,\quad s = 0.25,\quad n = 9$$

$$\log k^o = -1.80\sigma_I - 0.67\sigma_R - 0.20\upsilon - 1.42 \qquad (6B)$$
$$(\pm 0.03)\ (\pm 0.03)\ (\pm 0.01)\ (\pm 0.01)$$
$$r = 0.9991,\quad F = 2\,697,\quad s = 0.03,\quad n = 9$$

$$\log k^o = -0.50\sigma_o + 0.09E_s^c - 1.35F_o - 1.42 \qquad (7B)$$
$$(\pm 0.04)\ (\pm 0.01)\ (\pm 0.04)\ (\pm 0.01)$$
$$r = 0.9982,\quad F = 1\,420,\quad s = 0.04,\quad n = 9$$

No satisfactory correlations were observed for reaction A which is highly sensitive to electronic effects. In this case steric inhibition of resonance [17] seems to be of great importance and this effect cannot be measured by the substituent constants available in the literature.

For reaction B, which is less sensitive to electronic effects, the experimental data can be well correlated by both equations (6) and (7). The low values of steric reaction constants in equations (6B and 7B) (ψ −0.20 and δ 0.09, respectively) show that *S*-oxidation is only moderately controlled by steric factors. The comparison of reaction constants related to inductive and resonance effects (α −1.80 *versus* β −0.67, and *f* −1.35 *versus* ρ −0.50) indicates that the inductive effect has the greater influence on reaction B (*cf.* ref. 13).

Anchimeric Assistance.—The k^o and k^p values in Table 2 also reveal that the reactivity of an appreciable number of *ortho*-substituted sulphides (Nos. 10—20a) is nearly the same or even greater than that of the corresponding *para*-derivatives ($\kappa = k^o/k^p \geqslant 1$). This phenomenon is obviously due to anchimeric assistance which may overcompensate for the steric hindrance of the reaction site caused usually (*cf.* Nos. 2—9) by bulky but non-interactive *ortho*-substituents. In order to evaluate the ordering of substituents, at least qualitatively, according to the magnitude of their anchimeric assistance, the ratios $\kappa/\bar{\kappa}$ were

Table 2. Substituent effect and anchimeric assistance in the reactions of *o*- and *p*-XC_6H_4SMe with TsNHCl (A) and $NaIO_4$ (B); solvent 1:1 (v/v) water–ethanol; 20 °C for reaction A and 25 °C for reaction B

		Rate constants				Anchimeric assistance		
		Reaction A k_A/dm^3 mol^{-1} s^{-1}		Reaction B 10^2k_B/dm^3 mol^{-1} s^{-1}		Reaction A	Reaction B	
Sulphide	Substituent X	*para*	*ortho*	*para*	*ortho*	$\kappa_A/\bar{\kappa}_A$ [a]	$\kappa_B/\bar{\kappa}_B$ [b]	ξ_B [c]
1	H	21.7 [d]	21.7 [d]	3.82 [e]	3.82 [e]			
2	Me	103 [d]	1.76	6.31	3.92	0.57	1.6	0.97
3	Pr^i	112 [f]	0.385	6.72 [f]	3.72	0.11	1.4	1.03
4	CH_2CN	3.4 [f]	0.097	2.23 [f]	1.15	0.95	1.3	0.97
5	OMe	416 [d]	24.7 [d]	8.97 [e]	2.30 [e]	2.0	0.64	0.99
6	F	4.70 [f]	0.137	2.50 [f]	0.716	0.97	0.72	0.94
7	Cl	2.54 [d]	0.0640 [d]	2.18 [e]	0.640 [e]	0.84	0.73	1.02
8	Br	1.47 [f]	0.0687	1.73 [f]	0.671	1.6	0.97	1.12
9	NO_2			0.300 [e]	0.105 [e]		0.88	0.97
10	CH_2OH	32.9	10.0	4.47	2.77	10	1.5	
11	CH_2OMe	18.6 [f]	5.98	3.85 [f]	2.24	11	1.5	
12	CH_2NMe_2	26.5	18.1	5.78	5.99	23	2.6	
12a	$CH_2N^+HMe_2$	1.27	0.0136	4.35	2.69	0.36	1.5	
13	CHO	0.158 [f]	0.647	0.848 [f]	0.438	140	1.3	1.04
14	COMe	0.168	3.67	1.01	0.994	730	2.5	2.35
15	$CONH_2$	0.469	10.4	1.22	2.02	740	4.1	3.66
16	$CONMe_2$	1.46	0.275	1.83	1.42	6.3	1.9	
17	CO_2Me	0.154 [d]	0.997 [d]	0.708 [e]	0.697 [e]	220	2.5	1.64
18	CO_2H	0.249 [d]	2.26 [d]	0.735 [e]	0.829 [e]	300	2.8	1.77
18a	CO_2^-	7.84 [d]	492 [d]	1.66 [e]	1.75 [e]	2 100	2.6	
19	CH_2CO_2Me	12.2 [d]	3.14 [d]	3.80	1.75	8.6	1.2	0.98
20	CH_2CO_2H	9.32 [d]	5.77 [d]	3.71	1.86	21	1.3	1.04
20a	$CH_2CO_2^-$	72.2 [d]	207 [d]	5.58 [g]	2.94 [g]	96	1.3	

[a] $\kappa_A = k_A^o/k_A^p$; $\bar{\kappa}_A$ 0.03. [b] $\kappa_B = k_B^o/k_B^p$; $\bar{\kappa}_B$ 0.4. [c] $\xi_B = k_B^o(\text{obs.})/k_B^o(\text{calc.})$. [d] Taken from refs. 2 and 3. [e] Taken from ref. 4. [f] Calculated from the Hammett equation (4A, B). [g] The solvent contained 0.05M Britton–Robinson buffer; pH 8.56.

calculated. As mentioned earlier, $\bar{\kappa}$ is the average of $\kappa = k^o/k^p$ values obtained only for sulphides (Nos. 2—9) incapable of neighbouring-group participation. For these compounds $\kappa/\bar{\kappa} \sim 1$, while a $\kappa/\bar{\kappa}$ value of 2 or more points to neighbouring-group activity.

Data show that *S*-chlorination with TsNHCl (reaction A) is more effectively assisted by *ortho*-neighbouring groups than *S*-oxidation with $NaIO_4$ (reaction B). From the observed $\kappa/\bar{\kappa}$ values the following order of anchimeric assistance was obtained: $CH_2OH \sim CH_2OMe \sim CH_2CO_2Me < CH_2CO_2H \sim CH_2NMe_2 \ll CH_2CO_2^- \sim CHO < CO_2Me \sim CO_2H <$ COMe $\sim CONH_2 \ll CO_2^-$.

Since the electronic and steric effects in reaction B can be described quantitatively, we also tried to evaluate the magnitude of anchimeric assistance by another method. Using equation (6B) and known σ_I, σ_R, and υ constants,[5,16] k^o values for *ortho*-substituted sulphides were calculated, k^o(calc.), taking the electronic and steric effects of *ortho*-substituents into account, and the observed rate constant values, k^o(obs.), were divided with the calculated ones: $\xi = k^o(\text{obs.})/k^o(\text{calc.})$. Although the ξ values cannot be regarded as an exact measure of anchimeric assistance, the same order of neighbouring-group activity was obtained as with the $\kappa/\bar{\kappa}$ data presented above.

Data in Table 2 unequivocally show that neighbouring-group participation associated with bivalent sulphur essentially differs from that occurring in nucleophilic displacements at three-co-ordinated sulphur. In the latter case, reactions are accelerated by neighbouring CO_2H, NH_2, and OH groups (k_{rel} *ca.* 10^4, 500, and 50, respectively),[1a,18] due to the formation of a cyclic sulphonium ion intermediate. Accordingly, CO_2Me and OMe, incapable of reacting with the sulphonium centre to form a covalent S–O bond, exhibit no appreciable anchimeric assistance. In contrast, the neighbouring-group activity of CO_2Me and CH_2OMe groups in reactions A and B involving a bivalent sulphur atom is commensurable with that of CO_2H and CH_2OH, respectively. As no similar examples are known in organic sulphur chemistry, it is surprising that COMe and $CONH_2$ prove to be more efficient neighbouring groups than CO_2H. These findings point to the fact that neighbouring-group participation in reactions A and B may be related to a non-bonded interaction between the sulphur reaction centre and the neighbouring *ortho*-group, rather than to the formation of a covalent S–O or S–N bond yielding a cyclic sulphonium ion intermediate (*cf.* refs. 3 and 4).

Neighbouring-group Participation via S $\cdots$ O *Interaction.*— From experimental data it can be concluded that anchimeric assistance in reactions A and B is increased by (*a*) an increase of the positive polarity of the sulphur reaction site in the transition state (reaction A is assisted by the neighbouring-group effect to a greater degree than B, as $\rho_A \ll \rho_B$); (*b*) by an increase of the negative polarity of the neighbouring oxygen atom which follows the order: oxy < carboxy ~ carbonyl < carboxylate; and (*c*) by an increase of the electron-releasing ability of the neighbouring heteroatom (NMe_2 > OMe). These findings can be well explained by supposing that the transition states of anchimerically assisted reactions A and B occurring between sulphides and electrophiles (E = Cl^+ or O) are stabilized by S $\cdots$ O or S $\cdots$ N non-bonded interaction, *i.e.* by Coulombic forces and a weak hypervalent bond (see ref. 19). Furthermore, stabilization is greater in the transition state involving both

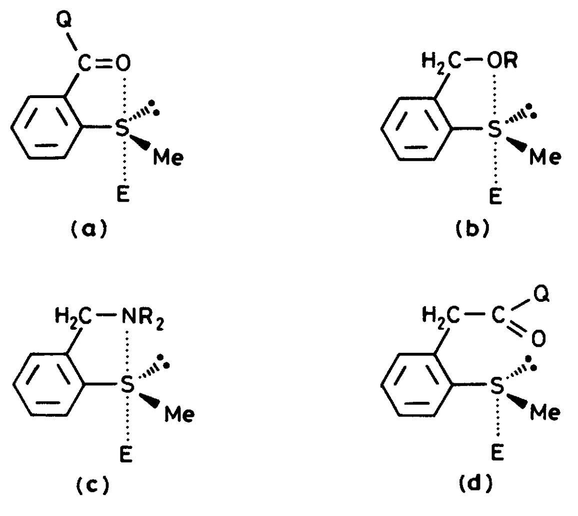

Figure. Neighbouring-group participation of (*a*) *o*-COQ, (*b*) *o*-CH_2OR, (*c*) *o*-CH_2NR_2 and (*d*) *o*-CH_2COQ groups (Q = OMe, OH, O^-, Me, and NH_2; R = H and Me; E = Cl and O)

substrate and reactant (Figure) than in the starting sulphide alone.

Non-bonded interactions between proximal sulphur and oxygen atoms in both S^{II} and S^{IV} valence states[19] have recently been extensively investigated, using different methods, *e.g.* i.r. spectroscopy,[20] *X*-ray and electron diffraction,[21] and SCF-MO calculations.[19b,22] An earlier *X*-ray analysis of 2-methoxycarbonyl-substituted methyl phenyl sulphide (No. 17)[21a] and that of the corresponding sulphoxide[21b] gave direct evidence for close contact in the solid state between the central sulphur atom and the carbonyl oxygen of the neighbouring *o*-methoxycarbonyl group [see Figure (*a*)]. In the present work, the i.r. spectra of sulphoxide products provided further support for O=S···O close contact causing a decrease in ν(S=O) frequency, due to bond polarization and an *n*–σ* type stereoelectronic effect (see refs. 19 and 20). As shown in Table 1, the ν(S=O) band of sulphoxides carrying an active neighbouring group in the *ortho*-position appears at markedly lower frequency than that of the *para*-derivatives (Δν positive). It should be noted, however, that in some cases the hydrogen bond may also be responsible for a Δν(S=O) frequency shift. The ν(C=O) band is also affected by sulphur–oxygen interaction; a marked decrease in ν(C=O) frequency may also be ascribed to S···O=C close contact in compounds with *o*-CHO, *o*-COMe, and *o*-CO_2Me groups (see refs. 19 and 20).

Unfortunately there is no independent evidence to show that S···O interaction in the transition states represented in the Figure is more effective than that in the corresponding initial states. There is no doubt, however, that the attractive electrostatic interaction between the oppositely polarized non-bonded atoms must be enhanced by the linking of an electrophile to the sulphur atom. Further, the linear E–S···O moiety with E = Cl and O, heteroatoms of high electronegativity, developing in the transition state, must be more favourable for electron delocalization (to form a weak hypervalent bond) than the C(sp^3)–S···O sequence in the starting compounds (see ref. 19).

In the case of the *o*-CHO group a striking decrease in neighbouring-group activity was observed, compared with the *o*-COMe group. The difference in anchimeric assistance may be ascribed to the different size of H and Me linked to the carbonyl group. The rotation about C(O, Q)–C(ar) bond, which counteracts the attractive S···O interaction, seems to be less hindered in the formyl group (Q = H) than in the acetyl group (Q = Me). As shown by n.m.r. measurements in CCl_4 solution,[23] formyl-H and formyl-O are placed with about equal probability in the vicinity of the sulphur atom in *o*-$MeSC_6H_4CHO$. On the other hand, approach to the sulphur atom by the acetyl-Me group in *o*-MeS–C_6H_4–COMe seems to be sterically hindered and therefore cannot markedly decrease S···O interaction.

The role of the neighbouring *ortho*-nitro group in reactions A and B is not quite clear. Activity should be expected for the neighbouring *o*-NO_2 group exhibiting strong S···O interactions, as shown by SCF-MO calculations[19b] and i.r. data [see *e.g.* Δν(S=O) values in Table 1]. Unfortunately, however, the anchimeric assistance cannot be tested as reaction A is completely suppressed by the very strong electron-withdrawing effect of the *ortho*- and *para*-nitro groups and the rate constants cannot be measured. In addition, reaction B is not sensitive enough to detect clearly a moderate neighbouring group effect.

The substantial decrease in neighbouring-group activity of the homologous *o*-CH_2CO_2Me, *o*-CH_2CO_2H, and *o*-$CH_2CO_2^-$ groups (compared with that of *o*-CO_2Me, *o*-CO_2H, and *o*-CO_2^-) also points to the importance of S···O interaction in the transition state. From *X*-ray investigations it is known[21] that compound No. 19 with the *o*-CH_2CO_2Me group and the corresponding *S*-oxide do not exhibit any S···O non-bonded contact which would require the formation of an unfavourable six-membered 'ring' without full conjugation [Figure (*d*); *cf.* ref. 19].

Experimental

Materials.—Sulphides were prepared by known methods and purified by distillation or crystallization. The purity of chloramine T and $NaIO_4$ was checked by iodometric titrations.

2-(2-*Methylthiophenyl*)*propan*-2-*ol*.—To an ethereal solution (200 ml) of a Grignard reagent prepared from Mg (6.1 g, 250 mmol) and MeI (16 ml, 250 mmol) was added dropwise methyl 2-(methylthio)benzoate (9.1 g, 50 mmol) in dry ether (100 ml) with stirring and mild boiling. The mixture was boiled (1 h), then cooled (0 °C), and a saturated aqueous solution of NH_4Cl (100 ml) was added in small portions. The mixture was diluted with water (50 ml), the aqueous layer was separated, and extracted with ether (3 x 150 ml). The combined ethereal solutions were washed with water (200 ml) and dried ($MgSO_4$). The solvent was removed under reduced pressure. The residue was distilled *in vacuo* to yield a yellow oil (6.5 g, 71%), b.p. 95 °C at 0.1 mmHg;[24] $\nu_{max.}$(film) 3 430 (OH), 3 093, and 3 059 (aromatic C–H), 2 981, 2 928, and 2 872 (CH_3), 1 585, 1 564, and 1 466 (aromatic C=C), 1 170 (C–O), and 753 cm^{-1} (aromatic C–H); δ_H($CDCl_3$) 1.68 (s, 6 H, CMe_2), 2.42 (s, 3 H, SMe), 4.17 (s, 1 H, OH), and 7.05—7.55 (m, 4 H, ArH).

Methyl 2-*Isopropenylphenyl Sulphide*.—To 2-(2-methylthiophenyl)propan-2-ol (3 g, 16.5 mmol) was dropped acetyl bromide (5 ml, 67 mmol). After boiling for 2 h acetic acid and acetyl bromide were removed under reduced pressure (40 mmHg; bath temperature 100—110 °C). To the residue was added acetyl bromide (2 ml) which was distilled off again. To remove the remaining HBr and acetyl bromide distillation under reduced pressure was repeated twice, after adding dry ether (5 ml) to the mixture. After distillation *in vacuo* a yellow oil was obtained (2.2 g, 81%), b.p. 107 °C at 15 mmHg;[24] $\nu_{max.}$(film) 3 086, 3 062, and 3 014 (olefinic and aromatic C–H), 2 977, 2 925, and 2 856 (CH_3), 1 639 (C=C), 1 589, 1 560, and 1 470 (aromatic C=C), 902 (C=CH_2), and 758 and 737 cm^{-1} (aromatic C–H); δ_H($CDCl_3$) 2.12 (m, 3 H, =CMe), 2.40 (s, 3 H, SMe), 4.97 (m, 1 H, =CH), 5.24 (m, 1 H, =CH), and 7.00—7.30 (m, 4 H, ArH).

Table 3. Rate constants for the reactions of XC_6H_4SMe with chloramine T; 20 °C; solvent 1:1 (v/v) water–ethanol; 0.05M-K_2HPO_4–KH_2PO_4 or Britton–Robinson buffer

			para			*ortho*	
Sulphide	Substituent X	pH	k^1_A/dm^3 mol^{-1} s^{-1}	k^d_A/dm^3 mol^{-1} s^{-1}	pH	k^1_A/dm^3 mol^{-1} s^{-1}	k^d_A/dm^3 mol^{-1} s^{-1}
2	Me				3.25	1.75	0.06
3	Pr^i				3.25	0.384	0.063
4	CH_2CN				3.25	0.097	0.063
6	F				3.25	0.137	0.063
8	Br				3.25	0.0685	0.064
10	CH_2OH	8.05	0.168	0.104	8.05	0.051	0.104
11	CH_2OMe				3.25	5.96	*a*
12	CH_2NMe_2	8.05	0.065	0.100	8.05	0.055	0.101
		3.25	1.27	0.06	3.25	0.014	0.062
13	CHO				3.25	0.645	0.060
14	COMe	3.25	0.167	0.063	3.25	3.66	*a*
15	$CONH_2$	3.25	0.468	0.060	3.25	10.4	*a*
16	$CONMe_2$	3.25	1.46	0.06	3.25	0.274	0.062

[a] Since $k^d_A \ll k^1_A$, k^d_A cannot be observed.

Methyl (2-Isopropylphenyl) Sulphide.—To a cooled (0 °C) and stirred solution of methyl 2-isopropenylphenyl sulphide (2.2 g, 13.4 mmol) in hexane (5 ml) was injected Me_2SBH_3 (0.5 ml, 5 mmol) under dry argon. Stirring was continued at 0 °C (30 min), then at 20 °C (2 h). To the mixture, propionic acid (30 ml) was added and the solution refluxed (2 h). After distilling off a liquid mixture (20 ml) the residue was dissolved in ether (50 ml), washed with dilute (4%) aqueous NaOH solution, and dried ($MgSO_4$). The solvent was removed under reduced pressure, and the residue (0.9 g) was distilled *in vacuo* to yield a pure product (10.5 g, 22%), b.p. 120 °C (bath temperature) at 13 mmHg; $\nu_{max.}$(film) 3 089, 3 063, and 3 018 (aromatic C–H), 2 969, 2 928, and 2 872 (CH_3), 1 589 and 1 472 (aromatic C=C), 1 385 and 1 362 ($CHMe_2$), and 749 cm^{-1} (aromatic C–H); δ_H($CDCl_3$) 1.24 (d, *J* 7 Hz, 6 H, $CHMe_2$), 2.42 (s, 3 H, SMe), 3.42 (sep, *J* 7 Hz, 1 H, $CHMe_2$), and 7.05—7.40 (m, 4 H, ArH).

Product Analysis.—*Reaction A.* Sulphides (0.2 mmol) were dissolved in ethanol (96%; 20 ml) and treated with chloramine T (0.2 mmol) at room temperature for 2 days. The solvent was evaporated off and the residue was kept in a desiccator for 1 day, then dissolved in $CDCl_3$, and analysed by n.m.r. spectroscopy (Varian A-60D). The methyl signals of the $MeC_6H_4SO_2$ group in sulphimides and $TsNH_2$, and those of the S^{IV}-Me group in sulphoxides and sulphimides were found at δ 2.35, 2.40, 2.70, and 2.85 (±0.1), respectively. Product distributions were determined from the intensity of the signals.

Reaction B. As described previously,[4] sulphoxides (0.2 mmol) were prepared from sulphides by treating with $NaIO_4$. The products were analysed by i.r. spectroscopy (IR 75, Zeiss, Jena). In several cases the assignment of the ν(S=O) band was confirmed by the solvent-shift procedure.[25]

Kinetics.—*Reaction A.* Experiments were carried out in 1:1 (v/v) water–ethanol at constant pH (0.05M-K_2HPO_4–KH_2PO_4 or Britton–Robinson buffer) and 20.00 ± 0.05 °C by measuring the absorption of the reaction mixture. The absorptions of the reactants in the range 260—330 nm were much higher than that of the products. The initial concentration of the reactants was varied between 5×10^{-3}—5×10^{-4}M. The reaction proceeded in two parallel rate-determining steps, the reaction of sulphides with TsNHCl (characterized by rate constant k^1_A) and the formation of $TsNCl_2$ by disproportionation (k^d_A, *cf.* refs. 2 and 3).* Since k^1_A and k^d_A depend differently on pH, the ratio k^1_A/k^d_A could be varied by pH. The measured k^1_A and k^d_A values are listed in Table 3. As described earlier,[2] the pH-independent rate constant k_A for the reaction of sulphides with TsNHCl was calculated from equation (8), where k^1_A is the rate constant

$$k^1_A = \frac{[H^+]k_A}{[H^+] + K_a} \qquad (8)$$

measured at a given $[H^+]$ and K_a is the dissociation constant of TsNHCl; pK_a 5.76 in 1:1 (v/v) EtOH–H_2O. With sulphides having a CO_2H or NMe_2 group, equation (9) was used, where

$$k^1_A = \frac{[H^+]K^s_a k^b_A}{([H^+] + K_a)(K^s_a + [H^+])} + \frac{[H^+]^2 k^a_A}{([H^+] + K_a)(K^s_a + [H^+])} \qquad (9)$$

K^s_a is the dissociation constant of sulphides, k^a_A and k^b_A are the pH-independent rate constants of the acidic (CO_2H, NH^+Me_2) and basic (COO^-, NMe_2) form of the sulphides, respectively.

Reaction B. Kinetic measurements were carried out in 1:1 (v/v) EtOH–H_2O at 25.00 ± 0.05 °C following the absorption of the reaction mixture as described previously.[4] The k^a_B and k^b_B rate constants of the acidic and basic forms of sulphides with NMe_2 groups were calculated by using equation (10).† For

$$k^2_B = \frac{K^s_a k^b_B}{(K^s_a + [H^+])} + \frac{[H^+]k^a_B}{(K^s_a + [H^+])} \qquad (10)$$

p-$Me_2NCH_2C_6H_4SMe$ k^2_B 5.67×10^{-2} and 4.34×10^{-2} dm^3 mol^{-1} s^{-1} were measured at pH 8.96 and 2.83; for *o*-$Me_2NCH_2C_6H_4SMe$ k^2_B values were 5.73×10^{-2} and 2.68×10^{-2} dm^3 mol^{-1} s^{-1} at pH 8.95 and 2.83, respectively. For the carboxy-substituted sulphides, the measured rate constants in acidic and basic regions agreed (within experimental error) with those calculated from equation (10).

pK_a *Measurement.*—Dissociation exponents of the carboxy-substituted sulphides investigated were published earlier.[3] pK^s_a

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* In refs. 2 and 3, k^1_A, k^d_A, and k_A are designated as k_1, k_d, and k'_1, respectively.

† In ref. 4, k^2_B is designated as k_2.

7.88 and 8.13 were measured by a potentiometric method for *o*- and *p*-$Me_2NCH_2C_6H_4SMe$, respectively, at 20 °C in 1:1 (v/v) $EtOH-H_2O$.

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