# Proton Transfer from Carbon. A Study of the Acid–Base-catalysed Relaxation and the Bromination of Aryl-substituted Methanedisulfones

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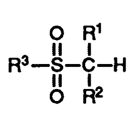
Seven aryl-substituted derivatives of bis(ethylsulfonyl)methane have been synthesized and studied thermodynamically and kinetically in aqueous solution with respect to proton abstraction from the central carbon atom. The acidities of the six carbon acids are in the range p$K_A$ 10–12. The relaxation times of the reactions were studied by a spectrophotometric temperature-jump technique (hydroxide ion and phenolates as proton acceptors) and are in the microsecond range. The rates of bromination of the various carbanions have also been studied (potentiometrically) and the reactions are shown to be almost diffusion-controlled, with no marked trend with aromatic substituent. A small chemical activation may be due to a steric effect by the two sulfonyl groups. The rates of deprotonation, however, show considerable chemical activation, *i.e.*, intrinsic rates are 3–4 orders of magnitude lower than for normal acids, indicating partial delocalization of the negative charge on the carbanion. This effect is somewhat larger than for cyano-activated carbon acids but considerably smaller than for carbon acids activated by carbonyl or nitro groups. It is concluded that sulfonyl groups interact with carbanions primarily by polar effects, but also, to some extent, mesomerically. The degree of mesomerism is, however, uncertain because part of the intrinsic barrier may derive from steric effects, as is also observed for bromination.

The two extremes of Brønsted acids with respect to intrinsic acid dissociation rates are (*a*) normal acids, where the proton is bound to strongly electronegative atoms and which exhibit fast proton dissociation, and (*b*) carbon acids, where the proton is bound to carbon and for which the intrinsic dissociation rate constants (those measured under thermoneutral conditions) are usually very low.[1]

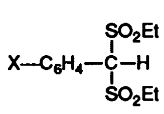
Intermediate in behaviour are a number of 'almost normal' carbon acids, including HCN,[2] malononitriles,[3] phenylacetylene,[4] chloroform,[4] and the thiazolium ion (C-2 proton exchange),[5] the acid–base reactions of which have been investigated recently. In all of these cases the negative charge of the carbanion is believed to reside primarily on the carbon atom, resulting in observed intrinsic proton-transfer rates of the same order of magnitude as those for proton transfer between electronegative atoms, such as oxygen or nitrogen.

For some time we have been particularly interested in the acid–base behaviour of carbon acids activated by sulfonyl groups (**1**). It was suggested by Bell[6] and Hibbert,[7] on the basis of experimental studies of the acid–base behaviour of these compounds, that they show strong evidence in favour of being 'normal' acids. This view is supported by an earlier observation that the isotopic proton exchange in optically active sulfones, such as 2-phenylsulfonyloctane, takes place more rapidly than racemisation.[8,9] This indicates the existence of an asymmetric, pyramidal (sp$^3$-hybridised) carbanion which is protonated faster than it undergoes inversion. Corey and co-workers,[9] however, advanced the suggestion that these experimental facts could equally well be explained by assuming an asymmetric sp$^2$-hybridised carbanion, with possible overlap between the p-orbitals of carbon, with its pair of electrons, and the sulfur 3d-orbitals. The essential ingredients of this debate have been thoroughly reviewed, first by Hibbert,[10a] later by Werstiuk and Banerjee,[10b] and recently by Shorter.[10c] Recent experimental and theoretical studies, however, have produced conflicting results. For example, X-ray structure analyses of Li-chelated α-sulfonyl carbanions indicate an almost planar structure for this ion, with the length of the C–S bond almost the same as that of a C=S bond.[11a,b] This is supported by an IR-spectroscopic observation of an increased C–S force constant in the carbanion of $CH_2(SO_2C_6H_5)Li$,[11c] and from *ab initio* calculations of a cation-free α-sulfonyl carbanion.[11d] However, the results of a study of the alkylation of metallated allyl sulfones are in accord with a pyramidal structure,[12] although the presence of the allyl group should promote further delocalisation of the negative charge.



$$R^3{-}\overset{\overset{\displaystyle O}{\|}}{\underset{\underset{\displaystyle O}{\|}}{S}}{-}\overset{\overset{\displaystyle R^1}{|}}{\underset{\underset{\displaystyle R^2}{|}}{C}}{-}H$$

**1**



$$X{-}C_6H_4{-}\overset{\overset{\displaystyle SO_2Et}{|}}{\underset{\underset{\displaystyle SO_2Et}{|}}{C}}{-}H$$

**2**

The kinetics of proton transfer reactions of sulfonyl activated carbon acids are of some interest in this context, as they will be quite sensitive to the structure of the carbanion. An sp$^2$-hybridised carbanion, with d–p π-bonding, would involve delocalisation of the negative charge away from carbon, considerable structural (geometric) rearrangement, and a significant decrease in intrinsic rate constants compared with normal acids, *i.e.*, behaviour typical of carbon acids activated by carbonyl or nitro groups. Intrinsic rate constants have not been reported for sulfonyl-activated carbon acids, presumably because they are very high and because it is difficult to lower the p$K_a$ values of the substrates sufficiently in water to achieve a suitable thermoneutral reaction. To date, ionisation rates have primarily been measured indirectly by either tritium exchange[7] or by bromination.[13]

We have found that aryl-substituted derivatives of *bis*-(ethylsulfonyl)methane (**2**) form a series of compounds with p$K_a$ in the range 10–12. The application of a temperature-jump relaxation technique has enabled us to determine the catalytic constants for the deprotonation of these substances by hydroxide ion and by a series of phenolates. The work has been complemented by the determination of the rates of bromination of the carbanions. The results are compared with those of corresponding studies of normal acids and typical carbon acids.

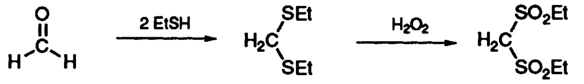
**Table 1** p$K_a$ values of aryl[bis(ethylsulfonyl)]methanes in water at 25 °C

| Substituent | p$K_a$(SH) | $\varepsilon_S$/mol ¹ dm$^3$ cm | $\lambda_{max}$ S$^-$/nm |
|---|---|---|---|
| H | 12.01 | 2300 | 280 |
| 4-Cl | 11.51 | 3450 | 285 |
| 3-Cl | 11.35 | 3010 | 290 |
| 3,4-Cl$_2$ | 10.75 | 3700 | 294 |
| 3-NO$_2$ | 10.39 | 9900 | 280 |
| 4-NO$_2$ | 10.08 | 7400 | 400 |
| 4-CN | 10.06 | 4200 | 330 |

The proton-transfer studies indicate intrinsic rate constants 3–4 orders of magnitude lower than for normal acids, suggesting a considerable degree of charge delocalisation. Possible explanations for this are discussed.

## Experimental and Results

*Materials.*—The disulfones were synthesised using a general procedure based on that of Cronyn[14] involving the oxidation of the corresponding disulfides, *e.g.*, (Scheme 1) for bis(ethylsulfonyl)methane [(EtSO$_2$)$_2$CH$_2$]. Details for individual sulfones are given below. $^1$H NMR spectra and $^{13}$C NMR spectra were run on a Bruker AD-250 instrument at 250 and 62.9 MHz, respectively. Signals are referenced to internal Me$_4$Si ($^1$H) and residual CHCl$_3$ in the deuteriochloroform solvent ($^{13}$C). Mass spectra were run on a VG TRIO-2 instrument under electron impact conditions.



**Scheme 1**

*Bis(ethylsulfonyl)methane* [(EtSO$_2$)$_2$CH$_2$]. Paraformaldehyde (BDH) (9 g, 0.7 mol) in water (30 cm$^3$) plus hydrochloric acid (1.1 cm$^3$, 30% v/v) was stirred at room temperature for 2 h before the addition of ethanethiol (44.5 cm$^3$, 0.3 mol). The mixture was stirred for 2 h under a carbon dioxide/acetone-cooled condenser. Acetic acid (150 cm$^3$) was added and the mixture was cooled in an ice-bath. Hydrogen peroxide (130 cm$^3$, 27%) was added with stirring at such a rate that the temperature remained between 15–20 °C (approx. 2 h). Stirring was continued for 48 h, using a water bath to prevent the temperature rising above 30 °C. A white precipitate formed during this period. Water (100 cm$^3$) was added and the product was collected by filtration. Additional product was obtained by evaporation of the filtrate on a steam bath. The product was recrystallised from ethanol, m.p. 102–103 °C (lit.,[13] 103–104 °C), yield 37%.

*Aryl disulfones* [(EtSO$_2$)$_2$CHPhY]. The above procedure was not successful for any of the aryl-substituted sulfones, but replacing water with benzene as the solvent in the first step (disulfide formation) with continuous removal of water using a Dean–Stark trap proved successful in all cases. The typical procedure, described for the parent *α,α-bis(ethylsulfonyl)toluene*, was as follows.

Ethanethiol (28.5 cm$^3$, 0.377 mol) and freshly distilled benzaldehyde (20 cm$^3$, 0.189 mol) were dissolved in benzene (200 cm$^3$). A few crystals of toluene-*p*-sulfonic acid were added as catalyst and the mixture was refluxed with a Dean–Stark trap and under a carbon dioxide/acetone-cooled condenser (to prevent loss of ethanethiol) until approx. 4 cm$^3$ of water had been collected (2–3 h). The oxidation was then carried out in a similar manner to that for bis(ethylsulfonyl)methane. Glacial acetic acid (80 cm$^3$) and hydrogen peroxide (70 cm$^3$, 37%) were added over 2–3 h with careful monitoring of the temperature. The solution was then left to stir for 2–3 days, during which time a white precipitate formed. The mixture was diluted with water (100 cm$^3$) and the product was recovered by filtration and evaporation of the filtrates. Purification was by recrystallisation from ethanol. M.p. 134 °C (lit.,[13] m.p. 133–134 °C), yield 50%.

The above procedure was repeated for the following aryl methanedisulfones (recrystallisation solvent and m.p. in brackets).

*4-Chlorophenyl[bis(ethylsulfonyl)]methane* (ethanol, 136 °C) $\delta_H$(CDCl$_3$) 1.41 (6 H, m, 2 × CH$_3$), 3.38 (4 H, m, 2 × CH$_2$), 5.24 [1 H, s, C*H*(SO$_2$Et)$_2$], 7.48 (2 H, br d, half of AB system, 2 × ArH) and 7.63 (2 H, br d, half of AB system 2 × ArH); $\delta_C$(CDCl$_3$) 5.6 (CH$_3$), 47.9 (CH$_2$), 81.6 (CH), 122.8, 129.5, 132.2 and 137.2 (ArCs); *m/z* 310 (M$^+$), 217, 141 and 77.

*3-Chlorophenyl[bis(ethylsulfonyl)]methane* (ethanol, 125–126 °C) $\delta_H$(CDCl$_3$) 1.41 (6 H, m, 2 × CH$_3$), 3.4 (4 H, m, 2 × CH$_2$), 5.22 [1 H, s, C*H*(SO$_2$Et)$_2$] and 7.4–7.7 (4 H, m, 3 × ArH); $\delta_C$(CDCl$_3$) 5.65 (CH$_3$), 47.95 (CH$_2$), 81.8 (CH), 126.2, 129.0 130.4, 130.9 (2 C) and 135.1 (ArCs); *m/z* 310 (M$^+$), 217, 141 and 77.

*3,4-Dichlorophenyl[bis(ethylsulfonyl)]methane* (ethanol 143–145 °C) $\delta_H$(CDCl$_3$) 1.43 (6 H, m, 2 × CH$_3$), 3.4 (4 H, m, 2 × CH$_2$), 5.20 [1 H, s, C*H*(SO$_2$Et)$_2$], 7.58 (2 H, m, 2 × ArH) and 7.78 (1 H, br s, ArH); $\delta_C$(CDCl$_3$) 5.6 (CH$_3$), 48.0 (CH$_2$), 80.95 (CH), 124.3, 129.9, 131.1, 132.7, 133.5 and 135.6 (ArCs); *m/z* 344 (M$^+$), 251, 175 and 77.

*4-Nitrophenyl[bis(ethylsulfonyl)]methane* (ethyl acetate 201–204 °C) $\delta_H$(CDCl$_3$) 1.45 (6 H, m, 2 × CH$_3$), 3.41 (4 H, m, 2 × CH$_2$), 5.35 [1 H, s, C*H*(SO$_2$Et)], 7.9 (2 H, br d, half of AB system, 2 × ArH) and 8.37 (2 H, br d, half of AB system, 2 × ArH); $\delta_C$(CDCl$_3$) 5.75 (CH$_3$), 48.0 (CH$_2$), 81.95 (CH), 124.2, 131.2, 132.1 and 149.1 (ArCs); *m/z* 321 (M$^+$), 229, 152, 136 and 77.

*3-Nitrophenyl[bis(ethylsulfonyl)]methane* (ethyl acetate, 173–176 °C) 1.48 (6 H, m, 2 × CH$_3$), 3.44 (4 H, m, 2 × CH$_2$), 5.34 [1 H, s, C*H*(SO$_2$Et)$_2$], 7.73 (1 H, m, ArH), 8.1 (1 H, m, ArH), 8.4 (1 H, m, ArH) and 8.5 (1 H, m, ArH); $\delta_C$(CDCl$_3$) 5.8 (CH$_3$), 48.0 (CH$_2$), 81.73 (CH), 125.6, 126.2, 126.5, 130.4 and 136.5 (ArCs); *m/z* 321, (M$^+$), 228, 184, 152 and 77.

*4-Cyanophenyl[bis(ethylsulfonyl)]methane* (ethyl acetate, 171–173 °C) $\delta_H$(CDCl$_3$) 1.43 (6 H, m, 2 × CH$_3$), 3.4 (4 H, m, 2 × CH$_2$), 5.30 [1 H, s, C*H*(SO$_2$Et)$_2$] and 7.8 (4 H, m, 4 × ArH); $\delta_C$(CDCl$_3$) 5.75 (CH$_3$), 48.0 (CH$_2$), 82.15 (CH), 114.8 (CN), 117.5, 129.4, 131.7 and 132.8 (ArCs); *m/z* 301 (M$^+$), 209, 164, 132, 116 and 77.

Phenols were commercially available and were purified by vacuum sublimation at or just above ambient temperature. Milli-Q pore water (temperature-jump experiments) or doubly distilled water was used throughout. Other chemicals were high grade commercial products, used without further purification.

p$K_a$ *Values.*—The acid dissociation constants of the aryl disulfones were determined spectrophotometrically, using a Perkin-Elmer Lambda 5 UV–VIS spectrophotometer. The anions of the disulfones exhibit strong UV absorption, and the equilibrium constant for the reaction SH + OH$^-$ $\rightleftharpoons$ S$^-$, where SH represents the disulfone, could be determined spectrophotometrically. This equilibrium constant is equal to $K_w/K_a$(SH), where $K_w$ is the ionisation constant of water and $K_a$(SH) is the acid dissociation constant of the substrate. For solutions of moderate ionic strength ($I \leqslant 0.1$ mol dm$^{-3}$) we can assume that $\gamma_{OH}/\gamma_S = 1$ and $\gamma_{SH} = 1$, and $K_w/K_a$(SH) is equal to the ratio of the thermodynamic constants. It is easily shown that $A = A_S - AK_w/K_a(\mathrm{SH})[\mathrm{OH}^-]$ where $A$ is the apparent (specific) absorption and $A_S$ is the (specific) absorption of the anion. A plot of $A$ against $A/[\mathrm{OH}^-]$ therefore gives a straight line of slope $-K_w/K_a$(SH) and intercept $A_S$. Solutions of known hydroxide concentration were prepared directly (NaOH) or using buffers prepared from mixtures of hydroxide

**Table 2** Rate constants for bromination of aryl[bis(ethylsulfonyl)]-methane anions in water at 25 °C

| Substituent | $k_{Br_2}$/dm$^3$ mol$^{-1}$ s$^{-1}$ | $k_{Br_3}$/dm$^3$ mol$^{-1}$ s$^{-1}$ |
|---|---|---|
| H | $1.64 \times 10^9$ | $2.21 \times 10^8$ |
| 4-Cl | $0.90 \times 10^9$ | $1.40 \times 10^8$ |
| 3-Cl | $1.10 \times 10^9$ | $1.06 \times 10^8$ |
| 3,4-$Cl_2$ | $0.66 \times 10^9$ | $< 10^8$ |
| 3-$NO_2$ | $1.16 \times 10^9$ | $1.14 \times 10^8$ |
| 4-$NO_2$ | $1.38 \times 10^9$ | $1.86 \times 10^8$ |
| 4-CN | $1.23 \times 10^9$ | $2.92 \times 10^8$ |

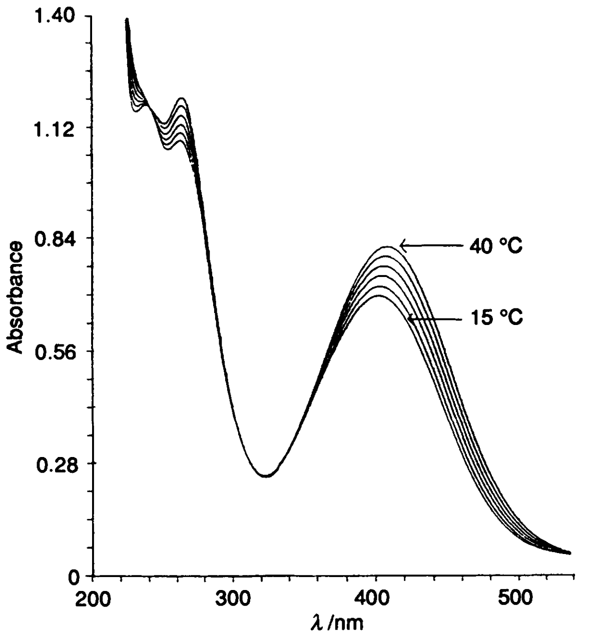


**Fig. 1** Temperature dependence of the ionisation of 4-nitrophenyl-[bis(ethylsulfonyl)]methane in bicarbonate buffers: [sulfone] = $1.25 \times 10^{-4}$ mol dm$^{-3}$; [$HCO_3^-$] = $7 \times 10^{-3}$ mol dm$^{-3}$; [$CO_3^{2-}$] = $1.78 \times 10^{-2}$ mol dm$^{-3}$; pH = 10.5 (25 °C)

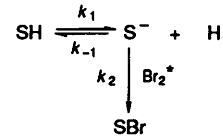
with borax (pH 8.2–10.8), $NaHCO_3$ (pH 9.8–11) or $Na_2HPO_4$ (pH 11–11.4).

For the *m*-nitro derivative the spectra of the neutral and ionised forms show considerable overlap and it was not possible to find a convenient wavelength at which only the anion had a significant absorption. Therefore, measurements of absorbance, $A$, were carried out at a fixed wavelength (280 nm) in several different solutions: 0.1 mol dm$^{-3}$ HCl (SH only present), $A_A$; 0.2 mol dm$^{-3}$ NaOH ($S^-$ only present), $A_B$; carbonate/bicarbonate buffers (both SH and $S^-$ present), $A_C$. It is easily shown that the fraction, α, of the anion form, $S^-$, present in a given buffer is given by $\alpha = (A_C - A_A)/(A_B - A_A)$, and hence $K_a$(SH) follows from $K_a(SH) = [\alpha/(1 - \alpha)][H^+]\gamma_\pm^2$. p$K_a$(SH) values for all of the disulfones, together with the absorption coefficients of the anions at the wavelengths used, are given in Table 1.

In all cases the required activity coefficients were calculated using the Davies equation[15] where $I$ is the ionic strength and $A$ (= 0.509) is the Debye–Hückel parameter.

$$\log \gamma_\pm = -\frac{AzI^{\frac{1}{2}}}{1 + I^{\frac{1}{2}}} + \frac{AI}{3}$$

*Kinetic Measurements*—(*a*) *Bromination rates.* Rates of bromination were measured potentiometrically[16] in a cell thermostatted at 25 ± 0.1 °C. Reactions were performed under first-order conditions (see below) with disulfone concentrations in the range $4 \times 10^{-4} \leqslant$ [SH]/mol dm$^{-3}$ $\leqslant 2 \times 10^{-3}$ and initial bromine concentrations $\leqslant 2 \times 10^{-5}$ mol dm$^{-3}$; bromide concentrations were varied between 0.02 and 0.2 mol dm$^{-3}$ (normally 0.1 mol dm$^{-3}$) at a constant ionic strength of 0.2 mol dm$^{-3}$ ($NaClO_4$). All rates were measured in acidic media with pH values being controlled by known concentrations of HCl or by benzoic acid buffers.



**Scheme 2**

The reaction may be represented by Scheme 2, in which [$Br_2$*] = [$Br_2$] + [$Br_3^-$] is the total amount of bromine present.

Application of the steady state principle to [$S^-$] leads to eqn. (1)

$$-d[Br_2^*]/dt = k_e[Br_2^*] \qquad (1)$$

where

$$k_e = k_1k_2[SH]/(k_{-1}[H^+] + k_2[Br_2^*])$$

for the loss of bromine. This reduces to eqn. (2) for the observed first-order rate constant, $k_e$, when reprotonation of $S^-$ is much faster than bromination (*i.e.* $k_{-1}[H^+] \gg k_2[Br_2^*]$).

$$k_e = k_2K_a(SH)[SH]/[H^+] \qquad (2)$$

In eqns. (1) and (2), $k_2$ is a composite term representing bromination of the carbanion by both $Br_2$ (rate constant $k_{Br_2}$) and $Br_3^-$ (rate constant $k_{Br_3}$). It is readily shown[13] that the rate constants are related through eqn. (3), in which $K = [Br_3^-]/[Br_2][Br^-]$ is the equilibrium constant for tribromide formation ($K$ = 16.7 dm$^3$ mol$^{-1}$).[17]

$$k_2 = (k_{Br_2} + k_{Br_3}K[Br^-])/(1 + K[Br^-]) \qquad (3)$$

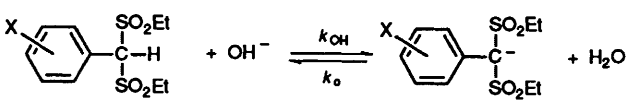
Eqns. (2) and (3) were verified by measurements over a range of concentrations of SH, $H^+$, and $Br^-$, leading to rate constants $k_{Br_2}$ and $k_{Br_3}$ for bromination of the various sulfone anions by bromine and tribromide, respectively.[18] The results are listed in Table 2.

(*b*) *Proton-transfer reactions.* A profound change in absorbance with temperature ($\Delta H^\ddagger \neq 0$) is observed at the characteristic absorption peak for each disulfone anion ($\lambda_{max}$ in Table 1) under conditions of or near thermal neutrality with respect to acid dissociation ($SH + OH^- \rightleftharpoons S^-$, $[SH] \simeq [S^-]$). Fig. 1 shows the spectral changes with temperature for the 4-nitro-anion.

Kinetic data for the proton abstraction from carbon for the various substrates may therefore be derived from spectrophotometric temperature-jump relaxation experiments. The relaxation times for the disulfones were all in the microsecond range and could conveniently be measured by the temperature-jump technique (Messanlagen instrument). A discharge of 20.5 kV from a 0.05 μF capacitor through the cell (7 mm light path, 3.5 cm$^3$ volume) raised the temperature of the solution from 20 to 25 °C in less than 5 μs. First-order relaxation absorbance–time traces were obtained and analysed by computer. Up to ten traces could easily be obtained from the same solution, leading to more reliable (averaged) values of the relaxation times. The final reaction temperature of 25 °C was applied throughout and the ionic strength of the reacting solutions was adjusted in all cases to $I$ = 0.25 mol dm$^{-3}$ (NaCl). Catalysis by hydroxide ion and buffers (substituted phenols, borax) was studied over a range of concentrations.

(*bi*) *Hydroxide catalysis.* Catalysis by hydroxide ion was studied in dilute hydroxide solutions or in very dilute solutions

**Table 3** Collected catalytic constants for the deprotonation of aryl-substituted disulfones by hydroxide ion at 25 °C



| X | p$K_a$(SH)[a] | $k_{OH}$/10$^6$ dm$^3$ mol$^{-1}$ s$^{-1}$ [b] | $k_o$/10$^4$ s$^{-1}$ |
|---|---|---|---|
| H | 12.01 | 4.49 | 4.60 |
| 4-Cl | 11.51 | 5.61 | 1.82 |
| 3-Cl | 11.35 | 11.3 | 2.54 |
| 3,4-Cl$_2$ | 10.75 | 24.5 | 1.38 |
| 3-NO$_2$ | 10.39 | 33.6 | 0.824 |
| 4-NO$_2$ | 10.08 | 35.9 | 0.431 |
| 4-CN | 10.06 | 30.9 | 0.355 |

[a] Table 1. [b] Calculated from data in Table S1 (see the text).

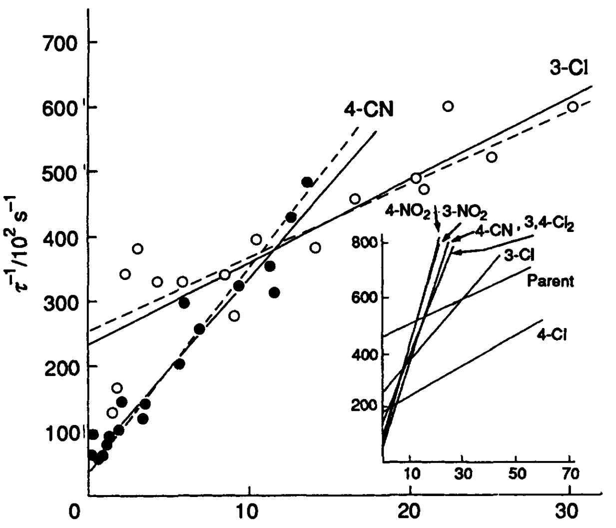
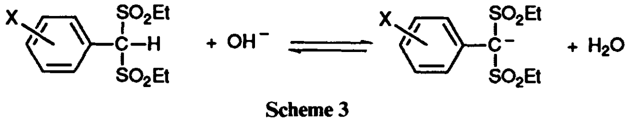


**Fig. 2** Reciprocal relaxation times plotted against hydroxide-ion concentration for the reaction between aryl-substituted disulfones and hydroxide ion (25 °C, $I$ = 0.25; data from Table S1). The total picture is seen in the insert.

of phenolate or carbonate buffers (*ca.* 10$^{-3}$ mol dm$^{-3}$); the pH of these buffers could be adjusted by addition of small amounts of NaOH or HCl. At these concentrations the catalytic contributions from the buffer were generally negligible. Since the disulfone substrates are only very sparingly soluble in water, stock solutions (0.50 mol dm$^{-3}$) were prepared in dioxane and the calculated volume of this solution was transferred to the aqueous reaction solution by micropipette, giving final substrate concentrations in the range $1 \times 10^{-4} - 4 \times 10^{4}$ mol dm$^{-3}$.

The relaxation system is represented by Scheme 3. In the



**Scheme 3**

absence of buffering of the hydroxide levels, the familiar relaxation expression given in eqn. (4) holds,[19] where $\tau$ is the

$$1/\tau = k_{OH}(C_{SH} + C_{OH}) + k_o \qquad (4)$$

observed relaxation time. In this case the relaxation time depends upon both the hydroxide ion concentration, $C_{OH}$, and that of the substrate in its protonated form, $C_{SH}$. The required rate constants, $k_{OH}$ and $k_o$, can be determined from plots of $1/\tau$ against $(C_{OH} + C_{SH})$, where $C_{SH}$ is calculated from the total substrate concentration and the hydroxide concentration, using the measured p$K_a$(SH) values.

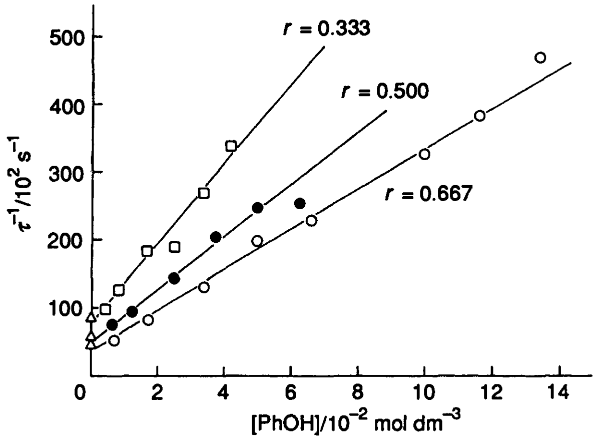


**Fig. 3** Rate–buffer plots for the phenol-catalysed relaxation of 4-nitrophenyl[bis(ethylsulfonyl)]methane in water [25 °C, $I$ = 0.25 mol dm$^{-3}$ (NaCl); data from Table S2].

In the dilute buffers, where the hydroxide concentrations are held constant, pseudo-first-order kinetics obtain and the relaxation times are independent of substrate concentrations, as in eqn. (5). The rate constants for proton transfer can then be obtained from plots of $1/\tau$ against $C_{OH}$.

$$1/\tau = k_{OH}C_{OH} + k_o \qquad (5)$$

The ratio of rate constants in Scheme 3, $k_{OH}/k_o$, equals $K_a(SH)/K_w$, and a comparison of $K_a$(SH) values determined kinetically and thermodynamically can be used as a check on the internal consistency of the two sets of measurements. In all cases, the agreement was sufficiently good to confirm that the kinetic and thermodynamic measurements correspond to the same ionisation equilibria. In view of this, the catalytic constants, $k_{OH}$ and $k_o$, were redetermined from a least-squares treatment of the data according to eqns. (4) or (5), as appropriate, but with the additional constraint that $k_{OH}/k_o = K_a(SH)/K_w$; this reduced the uncertainty associated with the intercepts ($k_o$) in some of the systems.

The observed relaxation times for the different substrates, and the conditions under which they were measured, are listed in Table S1,* and the derived catalytic constants in Table 3. Fig. 2 shows typical plots of $\tau^{-1}$/s$^{-1}$ *vs.* [OH$^-$].

(*biii*) *Buffer catalysis.* The experiments involving buffer catalysis were carried out using a buffer series of varying concentration but with a fixed buffer ratio. All solutions were made up by diluting buffer stock solutions and adjusting them to a fixed ionic strength of $I$ = 0.25 mol dm$^{-3}$ (NaCl). As most of the phenol buffers absorb strongly in the UV, kinetic measurements were restricted to the 4-nitro- and the 4-cyano-disulfones—these compounds exhibit anion absorption bands shifted towards the visible region (Table 1).

The observed rates in the buffer solutions depend upon both the buffer and hydroxide concentrations, and the relaxation time is given by eqns. (6)–(8), where BH and B$^-$ represent the

$$1/\tau = k_1 + k_{-1} \qquad (6)$$

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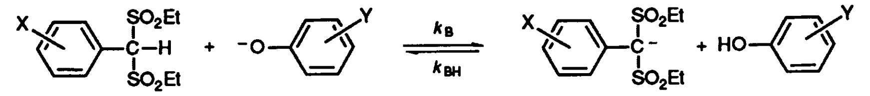
* Supplementary tables (S1 and S2) have been deposited with the British Library sup. no. 56927 (11 pp.). For details of the deposition scheme see 'Instructions for Authors (1993),' *J. Chem. Soc., Perkin Trans. 2*, 1993, issue 1.

**Table 4** Collected catalytic constants for the deprotonation of aryl-substituted disulfones by phenolates and borate at 25 °C and ionic strength $I$ = 0.25 mol dm$^{-3}$ (NaCl)



| Substituent | Catalyst | $\Delta pK_a$[a] | $k_B/10^5$ dm$^3$ mol$^{-1}$ s$^{-1}$[b] | $k_{BH}/10^5$ dm$^3$ mol$^{-1}$ s$^{-1}$[b] |
|---|---|---|---|---|
| X = 4-NO$_2$ | Y = 4-CH$_3$ | −0.18 | 2.19 | 1.45 |
| | Y = 4-CH$_3$O | −0.12 | 2.66 | 2.02 |
| | Y = H | 0.09 | 1.74 | 2.14 |
| | Y = 4-Cl | 0.68 | 0.68 | 3.24 |
| X = 4-CN | Y = 4-CH$_3$ | −0.20 | 4.55 | 2.87 |
| | Y = H | 0.07 | 1.84 | 2.16 |
| | Borate | 0.88 | 0.044 | 0.33 |

[a] $\Delta pK_a$ = p$K_a$(SH) − p$K_a$(phenol). [b] Calculated from data in Table S2 and eqn. (9).

where

$$k_1 = k_{OH}[OH^-] + k_B[B^-] \quad (7)$$

and

$$k_{-1} = k_o + k_{BH}[BH] \quad (8)$$

protonated and ionised form of the buffer. Substituting eqns. (7) and (8) into eqn. (6), and including the ratio of BH to the total buffer present, $r$ = [BH]/([BH] + [B$^-$]), we obtain eqn. (9).

$$1/\tau = k_o + k_{OH}[OH^-] + [BH]\{k_B(1 - r)/r + k_{BH}\} \quad (9)$$

This shows that at constant buffer ratio (hence constant [OH$^-$]), a plot of $1/\tau$ against [BH] gives a straight line of slope $\{k_B(1 - r)/r + k_{BH}\}$ and intercept $(k_o + k_{OH}[OH^-]$. In principle, one series of reactions is sufficient to determine $k_B$ and $k_{BH}$ for a given buffer/substrate system, as $k_B/k_{BH}$ = $K_a$(SH)/$K_a$(BH), but in practice, reactions were carried out at several different buffer ratios.

The observed relaxation times measured in the various buffers are listed in Table S2* and the derived catalytic constants in Table 4. Fig. 3 shows the results of the reactions of the 4-nitro derivative in phenol buffers.

## Discussion

*Bromination Rates.*—The rate constants for reaction of bromine with the disulfone anions are all near 1 × 10$^9$ dm$^3$ mol$^{-1}$ s$^{-1}$ and show no marked trend with substituent. They are similar to the rate constants for the corresponding brominations of nitrile-activated carbanions, $k_{Br_2}$ = 8.3 × 10$^9$ dm$^3$ mol$^{-1}$ s$^{-1}$,[3] and enolate anions derived from acetophenone and acetone, $k_{Br_2}$ = 3.2 × 10$^9$ dm$^3$ mol$^{-1}$ s$^{-1}$ and 3.1 × 10$^9$ dm$^3$ mol$^{-1}$ s$^{-1}$, respectively.[20] The values are also close to that expected for a diffusion-controlled bromination, estimated at around 5 × 10$^9$ dm$^3$ mol$^{-1}$ s$^{-1}$ for the bromination of enolate anions.[21,22]

The difference between the observed rate constants for the reaction of bromine with the disulfone anions and those expected for diffusion-controlled processes is, however, sufficiently large to suggest some chemical activation. The difference is even more marked for reactions of the tribromide ion, which is, on average, almost eight times less reactive than molecular bromine. If the reactions were wholly diffusion controlled, then the electrostatic repulsion between the tribromide and sulfone anions should lead to a reduction in the rate constant by only a factor of two; this may be calculated from the Debye–Smoluchowsky equation and is observed for brominations of enolate and cyano anions.[3,23]

The lower reactivity towards bromination of the disulfone anions compared with enolate or cyano anions does not appear to be related to differences in charge distribution—the rate constants for the aryl-substituted disulfones are not sensitive to substituent and are close to that for bis(ethylsulfonyl)methane ($k_{Br_2}$ = 1.55 × 10$^9$ dm$^3$ mol$^{-1}$ s$^{-1}$).[13] It may result from unfavourable steric interactions between the brominating species and the two sulfonyl groups. We shall see that a similar steric barrier may exist for ionisation of the carbon acid.

*Proton-transfer Reactions.*—The main purpose of the present study is to compare the proton-transfer reactions of disulfonyl-activated carbon acids with those of the so-called 'normal' acids and of other carbon acids. Acids and bases which have been termed normal by Eigen[1a] are characterised by rate processes in the thermodynamically favourable direction which are essentially diffusion controlled, *i.e.*, rate constants *ca.* 10$^{10}$ dm$^3$ mol$^{-1}$ s$^{-1}$; rate constants in the reverse direction are smaller by a factor of $10^{\Delta pK}$, where $\Delta pK$ is the difference in p$K$ between the acid and base species involved.[1a,2,24] In the immediate vicinity of $\Delta pK = 0$ there is a region ($-2 < \Delta pK < 2$) in which the proton transfer becomes partly rate determining and observed intrinsic proton-transfer rate constants between oxygen or nitrogen atoms are typically *ca.* 5 × 10$^8$ dm$^3$ mol$^{-1}$ s$^{-1}$ in aqueous solution—for example, the rate constant for proton transfer between acetic acid and propionate, $\Delta pK$ = 0.12, is 4 × 10$^8$ dm$^3$ mol$^{-1}$ s$^{-1}$.[25] Carbon acids normally show striking deviations from normal behaviour, but there is some experimental evidence that cyano-compounds and the disulfones behave much more like typical normal acids.[26] We consider this point in some detail in the remainder of the discussion.

A consequence of the diffusion-controlled rates of proton-transfer reactions of normal acids is that Brønsted plots show sharp transitions between slopes of 1 and 0 on passing from the thermodynamically unfavourable reactions (Brønsted slope 1) through the transition region near $\Delta pK$ = 0 to thermodynamically favourable reactions (Brønsted slope 0), where the rate is independent of the acid–base strength of the reaction partners. Such plots may, therefore, be used to analyse the behaviour of different substrates.

Fig. 4 shows a Brønsted plot for reaction between hydroxide and the various aryl-substituted disulfones, using data from Table 3. A reasonable correlation is observed, but it is clear that the slopes and the absolute values of the rate constants are considerably different for those expected for normal acids. The slopes for the plots of the deprotonation reactions by hydroxide and reprotonation by water correspond to $\alpha$ and $\beta$ values, respectively, of 0.5. Furthermore, the maximum observed rate constant, $k_{OH} = 3.59 \times 10^7$ dm$^3$ mol$^{-1}$ s$^{-1}$ for deprotonation of the 4-nitro-derivative, is at least two orders of magnitude below that expected for a diffusion-controlled reaction, despite a value of $\Delta pK = pK_a(SH) - pK_a(H_2O) = -5.4$, *i.e.* $\Delta G^\circ = -31$ kJ mol$^{-1}$.

In order to put these results into context, it is useful to consider them in the light of a much wider range of substrates and $\Delta pK$ values. Fig. 5 shows a Brønsted plot covering some 22 $\Delta pK$ units, including the present and earlier[13] results for disulfones and literature values for the ionisation of cyano-compounds, mainly from the work of Hibbert, Long and co-workers.[10,27] Also included for comparison are points representing the intrinsic dissociation rate constants for other carbon acids: HCN,[2] ketones and esters,[24,25] and nitro-compounds (nitromethane).[26] The dotted line represents results for typical normal acids, such as carboxylic acids and phenols,[24] with an intrinsic acid dissociation rate constant of $5 \times 10^8$ dm$^3$ mol$^{-1}$ s$^{-1}$ and a diffusion-controlled rate constant of $7 \times 10^9$ dm$^3$ mol$^{-1}$ s$^{-1}$.[24]

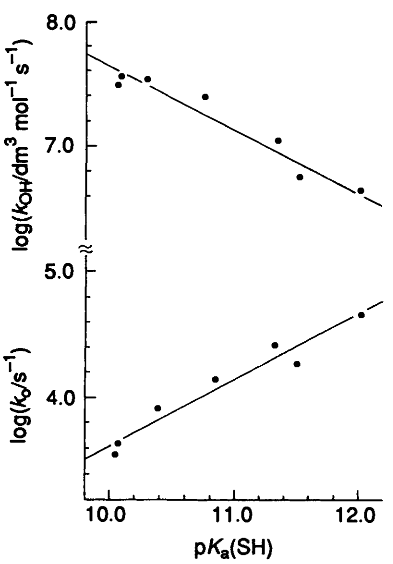
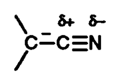
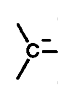


**Fig. 4** Brønsted plots for the forward and reverse reaction between aryl-substituted disulfones and hydroxide ion (data from Table 3)

Striking deviations from normal behaviour are displayed by the nitroalkanes and ketones, for which dissociation rate constants under conditions of thermoneutrality ($\Delta pK = 0$) are lower than those displayed by simple carboxylic acid or phenols by nine orders of magnitude (nitroalkanes) and six orders of magnitude (ketones, keto esters). This is attributable to the drastic electronic rearrangement accompanying proton loss for these systems.[26,28] Conversely, the ionisation of HCN, discussed in detail by Bednar and Jencks,[2] closely resembles that of normal acids: rate constants for proton transfer at $\Delta pK = 0$ to phenols are $1 \times 10^8$ dm$^3$ mol$^{-1}$ s$^{-1}$ and for thermodynamically favourable reactions involving HCN or CN$^-$ with phenolates, carboxylic acids, amines and H$^+$, are in the range $1 \times 10^9$–$4 \times 10^{10}$ dm$^3$ mol$^{-1}$ s$^{-1}$.

The kinetic behaviour of the cyano-carbon acids and the sulfones is of considerable interest, as it has been suggested that their ionisation is not accompanied by any considerable changes in bonding or shift in charge away from the carbon, *i.e.*, that their anions are true carbanions.[27] The high acidities of CN$^-$ and SO$_2$-substituted carboxylic acids, in which the polar groups are three atoms removed from the site of acidity, is consistent with the strong ability of the groups to stabilise anions electrostatically, as in the structures[27] shown below. To the extent that these effects are dominant, the kinetic behaviour of the cyano-carbon acids and disulfones should resemble that of the simple oxygen and nitrogen acids.





The results in Fig. 5 show that although they have intrinsic dissociation rates some three and four orders of magnitude,

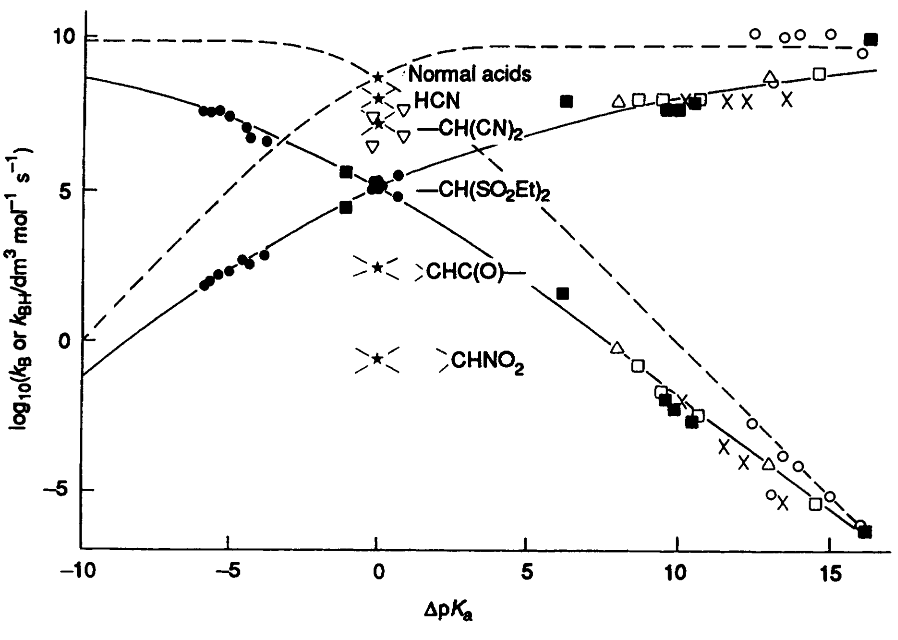


**Fig. 5** Forward and reverse rates (statistically corrected) of proton transfer from carbon acids. The various crossings of the Brønsted plots at thermoneutrality (★) refer to different types of carbon acid as indicated (see the text for references). Other designations are as follows: ● aryl-substituted disulfones, this work; ■, methyl disulfones, Bell and Cox;[13] ○, disulfones, Hibbert;[7] △, malononitrile, Hibbert, Long and Walters;[27b] ×, 1,4-dicyanobut-2-ene, Walters and Long;[27a] □, *tert*-butylmalononitrile, Hibbert and Long;[27c] ▽, bromomalononitrile, Hibbert and Long.[27c]

respectively, higher than those of the ketones, they cannot be considered as normal acids with respect to their ionisation behaviour. The intrinsic reactivity of the cyano-carbon acids, $k = 6 \times 10^6$ dm$^3$ mol$^{-1}$ s$^{-1}$, is somewhat higher than that of the aryl-substituted disulfones studied here, $k = 2 \times 10^5$ dm$^3$ mol$^{-1}$ s$^{-1}$, but is still significantly below those of HCN and the simple oxygen and nitrogen acids. Furthermore, Kresge and coworkers have shown that the protonation of the dicyanomethyl anion (from malononitrile) occurs less rapidly than its reaction with bromine and so cannot be diffusion controlled.[20,23] The differences between the cyano-carbon acids and the disulfones may reflect real differences (possibly steric in nature) in the properties of the CN and $SO_2$ groups, but any detailed interpretation is complicated by the presence of the aryl-substituent on the disulfones used to determine the reaction rates in the vicinity of $\Delta pK = 0$.

It is obvious from Fig. 5 that of the six disulfones studied by Hibbert,[7] the point for the phenyl-substituted compound is one to two orders of magnitude lower than expected from its $pK_a$. This is surprising since α-substitution of phenyl for hydrogen usually leads to acidity effects as well as higher rates of ionisation of the remaining hydrogen(s) at this carbon.[29] It should be noted here, however, that in a recent study by Bernasconi of the ionisation of nitromethane and phenylnitromethane, the introduction of a phenyl ring leads to slightly lower intrinsic rates of ionisation.[26]

Hibbert has studied the effect of a phenyl group in more detail by including cyclic disulfones as substituents, where the sulfonyl groups are less bulky ('tied-back'), and also by introducing an α-isoamyl substituent for phenyl (points not shown in Fig. 5). In both cases retardations in the rates of ionisation that are larger than expected from the $pK_a$ values are seen, but are less pronounced than for the ordinary disulfones.[30] Hibbert takes this as an indication of the involvement of steric effects from the bulky sulfonyl groups. Since the polar effect of a phenyl group is relatively small ($\sigma_I = 0.10$)[31] the carbanion stabilizing effect of phenyl is primarily due to a resonance effect, the degree of which depends on the ability of the phenyl ring to adjust (spatially) its π-system relative to the p-orbital of the carbanion. This (twisting) ability, possibly together with other conformational requirements,[32] might be severely restricted due to the presence of the sulfonyl groups.[29,30]

We learn from this discussion—and from the fact that we also saw steric effects for bromination—that our intrinsic rate data for disulfones in Fig. 5 might well be lowered by one to two orders of magnitude owing to such steric effects. An appropriate correction would therefore raise the points almost to coincide with the corresponding data for the dicyano-substituted species. However, even if this correction is adequate we would still be left with intrinsic rate data two orders of magnitude lower than for 'normal' acids, so we think it is safe to conclude that the acidifying power of both CN and $SO_2$ groups is attributable partly to a mesomeric effect and not simply to electrostatic stabilisation of the carbanion.

A Hammett $\rho$-value of 2.25 may be derived from the acid dissociation constants given in Table 1 (using $\sigma^-$-value for R = CN and $NO_2$), which may be compared with a value $\rho = 2.53$ observed for the ionisation of α,α-bis(benzylsulfonyl)-toluenes in 80% w/w DMSO–water.[10c,33] This is a very drastic reduction of $\rho$ from 12 for substituted toluenes in DMSO.[34] The difference is taken as an indication of the delocalising effect of the sulfonyl-substituents on the carbanion negative charge.[35]

The results demonstrate convincingly that there are considerable smaller structural changes accompanying proton transfer reactions of the cyano-carbon acids and the disulfones than in the corresponding reactions of ketones and nitroalkanes. There are, however, still at least two unsolved problems relating to Fig. 5. (1) Why does the point for proton transfer to hydroxide for the *methyl*-substituted disulfone studied by Bell and Cox,[13] where no steric effect is expected, fit in so well with our phenyl-substituted series? (2) Why do Hibbert's six disulfones (except the phenyl-substituted compound) in Fig. 5 appear as perfect 'normal' acids when none of the other substances investigated (apart from HCN) come even close to that classification. The answer to these questions may result from further kinetic investigations of *ad-hoc* designed series of substituted carbon acids. Work is in progress along these lines in our laboratories.

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