A Test of Leffler's Assumption for a Simple Addition Reaction in Aqueous Solution

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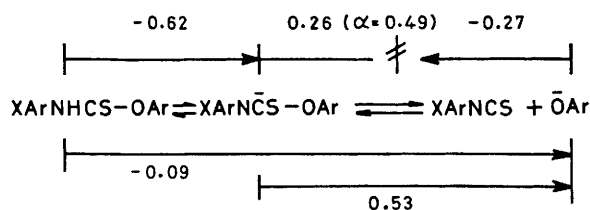*University Chemical Laboratory, University of Kent at Canterbury, Canterbury, Kent CT2 7NH, U.K.*

Substituent effects for the *N*- and *O*-aryl groups on rate and equilibrium constants for the system $ArO^- +$ Ar'NCS $\rightleftharpoons$ ArOCSNAr' in aqueous solution lead to identical Leffler–Grunwald parameters ($\alpha = \beta_F/\beta_{EQ}$) despite the marked difference in the individual β values; the α-parameter is therefore a good measure of transition-state structure for the reaction.
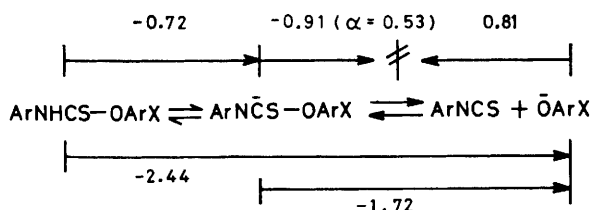
There is considerable discussion concerning the significance of the reactivity–selectivity principle.[1a–c] The Leffler–Grunwald assumption[1d,e] is a related problem and yields the parameter $\alpha = \beta_F/\beta_{EQ}$ which could be a valuable index of the transition-state relative to reactant and product.[2] While the parameter is easily obtained for proton-transfer reactions these tend to be complicated because significant changes occur at more than one bond as the reaction proceeds. Although reactions involving 'heavy-atom' reorganisation can in principle be very simple, the difficulty of measuring accurate equilibrium constants and

the variation of these with substituent has prevented research into the significance of α; moreover, it has encouraged the erroneous application of simple β_N and $\beta_{L.G.}$ values as indices of transition-state structures. If the Leffler–Grunwald assumption is valid, α is required to be the same for substituent-interaction effects *via* different paths to the reacting bond in a given reaction. That is, the electronic change in a bond 'seen' through substituent effects should be independent of the interacting path.

The approach to equilibrium of a mixture of aryl isothio-

$$-0.62 \qquad 0.26 \ (\alpha = 0.49) \qquad -0.27$$

$$XArNHCS\text{-}OAr \rightleftharpoons XArN\bar{C}S\text{-}OAr \rightleftharpoons XArNCS + \bar{O}Ar$$

$$-0.09$$

$$0.53$$

Variation of N-aryl substituent (measured against aniline pK).

$$-0.72 \qquad -0.91 \ (\alpha = 0.53) \qquad 0.81$$

$$ArNHCS\text{-}OArX \rightleftharpoons ArN\bar{C}S\text{-}OArX \rightleftharpoons ArNCS + \bar{O}ArX$$

$$-2.44$$

$$-1.72$$

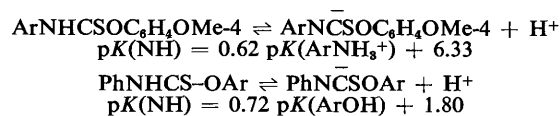Variation of O-aryl substituent (measured against phenol pK).

Scheme 1

cyanate and aryl oxide ion and the product O-aryl N-arylthio-carbamate (Scheme 1) was measured in *both* directions by using u.v. spectroscopy; allowance was made for spontaneous hydrolysis of the isothiocyanate. We confirmed the results of Sartore, Bergon, and Calmon[3] that the thiocarbamate decomposes through the isothiocyanate and not *via* any other pathway. The rate-controlling step in the decomposition of the thiocarbamate is the decomposition of its conjugate base. The present work provides data for the effect of substituents in *both* N- and O-aryl groups on equilibrium constants; rate constants and equilibrium parameters are summarised as Brønsted-type equations in Table 1 and the substituent effects are given separately in Scheme 1 for N- and O-substituent variation.
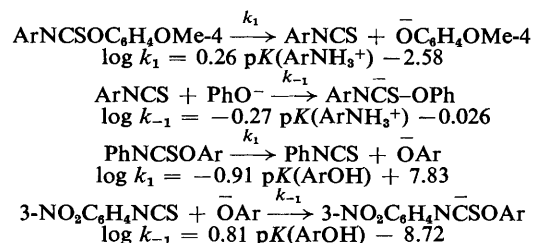
The Leffler–Grunwald parameters derived from substituent variation in the N- and O-aryl groups (0.49 and 0.53 respectively) are identical within the experimental limits. That this identity is significant is confirmed by the *gross* dissimilarity of the β_{EQ} values (0.53 and -1.72 respectively for N- and O-substituent). We therefore conclude that the Leffler assumption holds for the simple addition reaction. This result is consistent with expectation as the reaction is essentially a simple process involving major bond changes at a single bond centre, namely the CO bond. We can infer from the figures in Scheme 1 that the transition-state behaves as if it were approximately 50% between ground- and product-states. We

Table 1. Brønsted type correlations.[a]

Equilibrium constants

$$ArNHCSOC_6H_4OMe\text{-}4 \rightleftharpoons ArN\bar{C}SOC_6H_4OMe\text{-}4 + H^+$$
$$pK(NH) = 0.62 \ pK(ArNH_3^+) + 6.33$$

$$PhNHCS\text{-}OAr \rightleftharpoons PhN\bar{C}SOAr + H^+$$
$$pK(NH) = 0.72 \ pK(ArOH) + 1.80$$

Rate constants

$$ArNCSOC_6H_4OMe\text{-}4 \xrightarrow{k_1} ArNCS + \bar{O}C_6H_4OMe\text{-}4$$
$$\log k_1 = 0.26 \ pK(ArNH_3^+) - 2.58$$

$$ArNCS + PhO^- \xrightarrow{k_{-1}} ArN\bar{C}S\text{-}OPh$$
$$\log k_{-1} = -0.27 \ pK(ArNH_3^+) - 0.026$$

$$PhNCSOAr \xrightarrow{k_1} PhNCS + \bar{O}Ar$$
$$\log k_1 = -0.91 \ pK(ArOH) + 7.83$$

$$3\text{-}NO_2C_6H_4NCS + \bar{O}Ar \xrightarrow{k_{-1}} 3\text{-}NO_2C_6H_4N\bar{C}SOAr$$
$$\log k_{-1} = 0.81 \ pK(ArOH) - 8.72$$

[a] Data are for 25 °C and 0.1 M-ionic strength.

must emphasise that this statement refers to the 'solvated' species in all three cases. Only a few multiple structure-interactions have been reported where two Leffler–Grunwald parameters have been measured;[4] these reactions involve major changes at *two* bond centres and the parameters are not required to be identical as bond fission is not necessarily equally advanced in each bond.

References

1 (a) C. D. Johnson, *Tetrahedron*, 1980, **36**, 3461; (b) E. M. Arnett and R. Reich, *J. Am. Chem. Soc.*, 1980, **102**, 5892; (c) P. R. Young and W. P. Jencks, *ibid.*, 1979, **101**, 3288; (d) J. E. Leffler, *Science*, 1953, **117**, 340; (e) J. E. Leffler and E. Grunwald, 'Rates and Equilibria of Organic Reactions,' Wiley, New York, 1963.

2 D. A. Jencks and W. P. Jencks, *J. Am. Chem. Soc.*, 1977, **99**, 7948; W. P. Jencks, *Cold Spring Harbor Symp. Quant. Biol.*, 1971, **36**, 1.

3 G. Sartore, M. Bergon, and J. P. Calmon, *Tetrahedron Lett.*, 1974, 3133; *J. Chem. Soc., Perkin Trans.* 2, 1977, 650.

4 T. C. Curran, C. R. Farrar, O. Niazy, and A. Williams, *J. Am. Chem. Soc.*, 1980, **102**, 6828; T. Deacon, C. R. Farrar, B. J. Sikkel, and A. Williams, *ibid.*, 1978, **100**, 2525.