Electrophilic aromatic substitution in substituted anilines; kinetics of the reaction with 4,6-dinitrobenzofuroxan

Michael R. Crampton, Lynsey C. Rabbitt, and François Terrier

Abstract: Kinetic results are reported for reaction of aniline and six of its *N*- and ring-substituted derivatives with 4,6-dinitrobenzofuroxan (DNBF) in water – dimethyl sulfoxide mixtures. In acidic solution σ-adducts, the result of electrophilic substitution in the anilines, are formed with bonding between a ring-carbon atom of the anilines and the 7-position of DNBF. Reaction normally occurs at the 4-position of the aniline unless this carries a substituent, when reaction occurs at the 2-position. A value of 2.0 for k_H/k_D, the kinetic isotope effect, indicates that in the reaction with aniline bond formation is largely rate determining in the substitution pathway. The results allow estimates to be made for the pK_a values relating to carbon protonation of the anilines.

Key words: electrophilic substitution, σ-adducts, 4,6-dinitrobenzofuroxan, ambident reactivity of anilines.

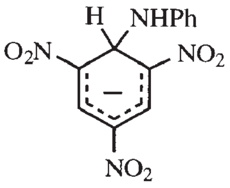
Résumé : On rapporte les données cinétiques relatives à la réaction de l'aniline (et six de ses dérivés substitués sur l'azote et sur le noyau) avec le 4,6-dinitrobenzofuroxane (DNBF) dans des mélanges formés d'eau et de diméthylsulfoxyde. En solutions acides, il se forme des adduits-σ, résultant d'une substitution électrophile sur les anilines, qui lient un atome de carbone du noyau des anilines et la position 7 du DNBF. La réaction se fait généralement en position 4 de l'aniline, à moins que cette position porte un substituant; la réaction se fait alors en position 2. Une valeur de 2,0 pour l'effet isotopique cinétique, k_H/k_D, indique que, dans cette réaction la formation de la liaison avec l'aniline constitue l'étape cinétiquement déterminante de la réaction de substitution. Les résultats permettent d'évaluer les valeurs de pK_a associées à la protonation du carbone des anilines.

Mots clés : substitution électrophile, adduits-σ, 4,6-dinitrobenzofuroxane, réactivité ambidente des anilines.

[Traduit par la Rédaction]

Aniline and its substituted derivatives usually act as nitrogen nucleophiles. Thus, reaction with 1,3,5-trinitrobenzene (1, 2) in dimethyl sulfoxide (DMSO) in the presence of a strong base gives N-bonded σ-adducts, **1**; reaction with substrates carrying good leaving groups may result in substitution leading to diphenylamine derivatives (3–5).

Nevertheless, the ambident reactivity of aniline and its derivatives has been shown in reactions with 4,6-dinitrobenzofuroxan, DNBF. Here σ-adducts have been observed involving nucleophilic attack either through nitrogen or through a ring carbon atom *para*- or *ortho*- to the amino function (6–10).



1

The high electrophilic reactivity of DNBF is well known (5, 11, 12). In fact, it has been shown to be a more powerful electrophile than the 4-nitrobenzenediazonium ion (13) or the proton (14). Previously kinetic studies have been reported of electrophilic substitutions involving reactions of DNBF with pyrroles (14), 5-substituted indoles (13), 3,4-diaminothiophene (15), 3-methoxythiophene (16), and hydroxy- and methoxy-substituted benzenes (17). In the present work, we report kinetic studies of the reactions of aniline and some *N*-substituted or ring-substituted derivatives with DNBF in water–DMSO mixtures. Measurements were made in acidic solutions where the anilines are very largely protonated. Here the results are in accord with the reactions, shown in Scheme 1, leading to the formation of carbon bonded σ-adducts. In the case of anilines **2a–e**, reaction was found to occur *para* to the amino position. However,

---

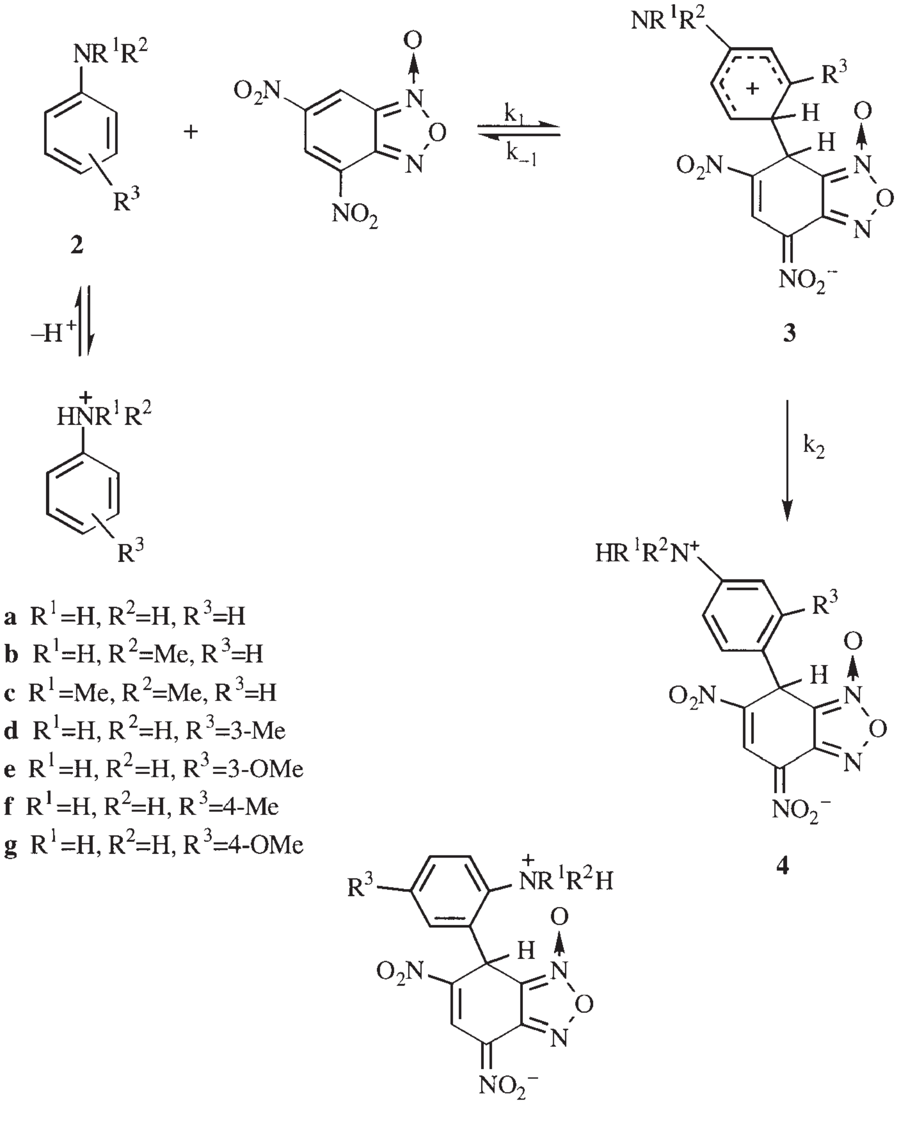
Received November 22, 1998.

This paper is dedicated to Professor Jerry Kresge in recognition of his outstanding contributions to the study of physical organic chemistry.

M.R. Crampton[1] and L.C. Rabbitt. Chemistry Department, Durham University, Durham DH1 3LE, U.K.
F. Terrier. Université de Versailles, SIRCOB, Bâtiment Lavoisier, 45 avenue des Etats-Unis, 78035 Versailles Cedex, France.

[1] Author to whom correspondence may be addressed. Telephone: +44 191 374 3130. Fax: +44 191 384 4737. e-mail: M.R.Crampton@durham.ac.uk

Scheme 1.



5

when the 4-position is blocked, reaction occurs *ortho* to the amino function to yield products **5f** and **5g**.

These reactions may be regarded as neutral nucleophile–electrophile combination reactions (18), and are examples of electrophilic substitution in the aniline ring. The powerful activating effect of the amino group towards electrophilic substitution in aromatic systems has been noted previously (19, 20). There are many examples of halogenation (21, 22) and of hydrogen exchange (23) in aniline derivatives. One of the aims of the present work was to use the reaction with DNBF to compare the reactivity of aniline with other aromatic systems.

Results and discussion

^{1}H NMR spectra have been reported previously for the products of reaction of DNBF and several amines (6–10). Our results relating to 1:1 mole ratio mixtures of DNBF and amines **2a–g** in [$^2H_6$] DMSO are given in Table 1. The spectra, showing bands at δ 5.3–5.6 and δ 8.7 for the hydrogens at the 7′ and 5′ positions of DNBF, are typical of C-adduct formation (5, 13, 14, 17), consistent with the production of **4a–e**. In 4-substituted anilines, the band due to the 7′ proton is at δ 5.8, consistent with the formation of **5f** and **g**. In solutions containing higher mole ratios of aniline to DNBF, there was NMR evidence for the kinetically controlled formation of N-bonded adducts followed by conversion to the thermodynamically more stable C-bonded adducts. In the case of aniline, **2a**, bands due to the N-bonded adduct were at δ 6.04 and 8.64, at positions similar to those reported previously (10).

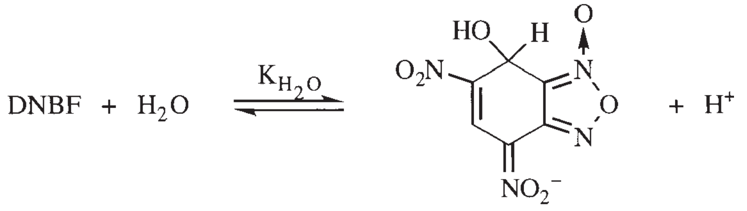
Kinetic measurements were conveniently made in water–DMSO mixtures. Most data relate to a solvent composition of 30/70 (v/v) water/DMSO, although for comparison some measurements using aniline were made in 70/30 and 50/50 (v/v) water/DMSO mixtures. All measurements were made in the presence of excess hydrochloric acid. This had the effect of reducing the concentrations of free amines to very low levels, and under these conditions there was no evidence for nucleophilic attack via the nitrogen centre of the anilines.

Table 1. ^{1}H NMR shifts for σ-adducts, **4** or **5**, in [$^2H_6$] DMSO.

Compound	H7′	H5′	Aromatic[a]	Other
DNBF	8.94	9.27		
4a	5.36	8.74	7.19 (d), 7.33 (d), *J* 8	
4b	5.38	8.74	7.30 (d), 7.37 (d), *J* 8.5	2.90 (NMe)
4c	5.39	8.74	7.40 (m)	3.12 (NMe_2)
4d	5.60	8.72	7.08 (m)	2.58 (Me)
4e	5.56	8.66	6.89 (s), 6.87 (d), 7.34 (d), *J* 7.4	3.68 (OMe)
5f	5.84	8.74	6.92 (s), 7.10 (d), 7.16 (d), *J* 8	2.20 (Me)
5g	5.84	8.74	6.53 (s), 6.95 (d), 7.18 (d), *J* 8.5	3.67 (OMe)

[a] *J* in Hz.

[1]

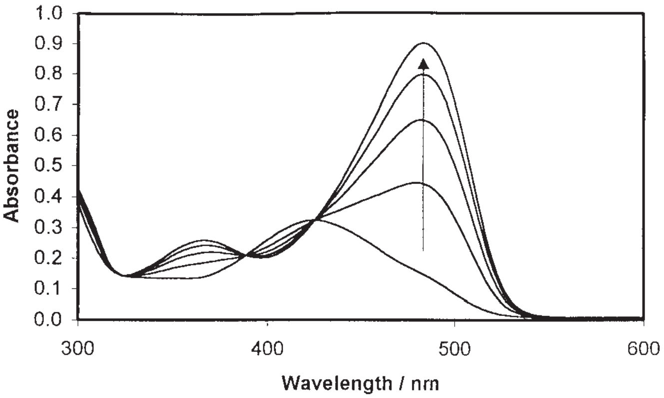


(**6**)

A further beneficial effect of the acidic media was to reduce the equilibrium concentrations of the hydroxy adduct, **6**, of DNBF which is known to form in neutral media, as shown in eq. [1].

Spectrophotometric measurements, using the absorbance of **6** at 470 nm, gave values for K_{H_2O}, defined in eq. [1], of 0.0196 ± 0.0008 mol dm^{-3} in 70% DMSO and 0.0045 ± 0.0002 mol dm^{-3} in 50% DMSO. These values are in excellent agreement with literature values of 0.019, 0.0040, and 0.00080 mol dm^{-3} in media containing 70, 50, and 30% DMSO, respectively (24).

Fig. 1. UV-vis spectra for the reaction in 30/70 (v/v) water/DMSO of DNBF, 4 × 10^{-5} mol dm^{-3}, with aniline hydrochloride 0.05 mol dm^{-3} and hydrochloric acid 0.03 mol dm^{-3}. The absorbance at 489 nm increases with time.



Reaction with aniline

The equilibrium between DNBF and **6** is established rapidly. Similarly, any adduct formation resulting from attack of aniline as a nitrogen nucleophile on DNBF will be a rapid process (3, 5). The UV/visible spectra in Fig. 1 show that in acidic solutions there is a slow reaction between DNBF and aniline, giving a band at 489 nm. In view of the NMR data, this is attributed to the C-bonded adduct **4a**. It has been reported (9, 10) that di-adducts may be formed by reaction of both N- and C-centres of an aniline molecule with two molecules of DNBF. There was no evidence for such 1:2 interaction in our systems, which contain very low, 4 × 10^{-5} mol dm^{-3}, concentrations of DNBF. Kinetic data, with concentrations of aniline hydrochloride and free hydrochloric acid in large excess of the DNBF concentration, indicated that adduct formation was an accurately first-order process. Values of k_{obs}, the measured rate constant, are in Table 2. The results show that at constant concentration of free acid, values increase linearly with the concentration of aniline hydrochloride. However, values decrease with increasing acid concentration. This observation indicates that reaction is likely to involve free aniline rather than its protonated form. Hence, we define by eq. [2] a rate constant *k*, which is related by eq. [3] to the constants for individual steps shown in the scheme. There is no evidence from NMR or UV/visible spectra of the accumulation of **3**, the intermediate in the substitution pathway. It may be shown that *k* is related to k_{obs} by eq. [4], where K_a is the acid dissociation constant of the anilinium ion. This equation allows for the small concentration of the hydroxy-adduct **6** in equilibrium with DNBF. In 70/30 (v/v) DMSO/water, the pK_a value for the anilinium ion is known to be 3.41 (25). Hence, at the acid concentrations used [H$^+$] >> K_a, allowing eq. [4] to be simplified to give eq. [5].

$$[2] \qquad \frac{-d[\mathrm{DNBF}]}{dt} = k[\mathrm{DNBF}][\mathrm{aniline}]$$

$$[3] \qquad k = \frac{k_1 k_2}{k_{-1} + k_2}$$

Table 2. Rate data for reaction of DNBF[a] with aniline in acidic solutions in 30/70 (v/v) water/DMSO at 25°C.

[Aniline H^+Cl^-]/mol dm^{-3}	[HCl]/mol dm^{-3}	$10^4\ k_{obs}/s^{-1}$[b]	$k/dm^3\ mol^{-1}\ s^{-1}$[c]
0.050	0.059	8.28	3.3
0.050	0.117	5.15	3.6
0.050	0.146	4.30	3.7
0.050	0.200	3.58	4.0
0.050	0.242	3.10	4.2
0.050	0.30	2.44	4.0
0.020	0.033	4.76	3.2
0.040	0.033	9.60	3.2
0.10	0.033	23.1	3.1
0.10	0.31	5.12	4.3

[a] DNBF concentration is 4 × 10^{-5} mol dm^{-3}.

[b] Measured at 489 nm.

[c] Calculated from eq. [5] with K_a 3.89 × 10^{-4} mol dm^{-3} and K_{H_2O} 0.0196 mol dm^{-3}.

Table 3. Isotope and solvent effects on reaction of DNBF[a] and aniline.

Vol.% DMSO	[$C_6D_5NH_3^+Cl^-$]/mol dm^{-3}	[$C_6H_5NH_3^+Cl^-$]/mol dm^{-3}	[HCl]/mol dm^{-3}	$10^4\ k_{obs}/s^{-1}$	$k/dm^3\ mol^{-1}\ s^{-1}$[b]	k_H/k_D
70	0.050	—	0.30	1.31	2.13	
	0.100	—	0.30	2.22	1.85	2.1 ± 0.1
	—	0.050	0.30	2.51	4.10	
	—	0.100	0.30	5.12	4.27	
50	0.030	—	0.030	1.90	1.17	
	0.050	—	0.030	3.10	1.15	2.0 ± 0.1
	—	0.030	0.030	3.87	2.39	
	—	0.050	0.030	5.71	2.12	
30	0.030	—	0.030	0.45	0.55	
	0.050	—	0.030	0.70	0.52	2.1 ± 0.1
	—	0.030	0.030	0.91	1.13	
	—	0.050	0.030	1.54	1.14	

[a] All measurements were made with DNBF 4 × 10^{-5} mol dm^{-3} at 25°C.

[b] Calculated from eq. [5] with values for K_a 3.89 × 10^{-4} mol dm^{-3}, 70% DMSO, ref. 25; 1.86 × 10^{-4}, 50% DMSO, ref. 15; 8.3 × 10^{-5} mol dm^{-3}, 30% DMSO, ref. 15; and values of K_{H_2O} given in the text.

Table 4. Rate data for reaction of DNBF[a] with **2b**, *N*-methylaniline, in acidic solution in 30/70 (v/v) water/DMSO at 25°C.

[*N*-Methylaniline H^+Cl^-]/mol dm^{-3}	[HCl]/mol dm^{-3}	$10^4\ k_{obs}/s^{-1}$[b]	$k/dm^3\ mol^{-1}\ s^{-1}$[c]
0.050	0.014	136	10.6
0.050	0.025	104	10.6
0.050	0.036	85	10.8
0.050	0.102	42	11.4
0.050	0.150	26	9.9
0.050	0.200	19.6	9.8

[a] DNBF concentration is 4 × 10^{-5} mol dm^{-3}.

[b] Measured at 494 nm.

[c] Calculated from eq. [5] with K_a 8.7 × 10^{-4} mol dm^{-3} and K_{H_2O} 0.0196 mol dm^{-3}.

$$[4] \qquad k_{\mathrm{obs}} = k[\text{aniline H}^+]\left(\frac{K_a}{K_a + [\mathrm{H}^+]}\right)\left(\frac{[\mathrm{H}^+]}{[\mathrm{H}^+] + K_{\mathrm{H_2O}}}\right)$$

$$[5] \qquad k = \frac{k_{\mathrm{obs}}}{K_a}\,\frac{(K_{\mathrm{H_2O}} + [\mathrm{H}^+])}{[\text{aniline H}^+]}$$

The invariance of values, in Table 2, of k with acid concentration or aniline hydrochloride concentration confirms that reaction involves free aniline rather than the anilinium ion.

The availability of pentadeuterioaniline, $C_6D_5NH_2$, allowed the evaluation of the kinetic isotope effect, k_H/k_D, on the substitution reaction. Measurements were made in media containing 70, 50, and 30% DMSO by volume and are reported in Table 3. For accuracy of comparison, measurements were made simultaneously on deuteriated and nondeuteriated systems using the multicell facility in the

Table 5. Rate data for reaction of DNBF[a] with **2c**, *N,N*-dimethylaniline, in acidic solution in 30/70 (v/v) water/DMSO at 25°C.

[*N,N*-Dimethylaniline H^+Cl^-]/mol dm^{-3}	[HCl]/mol dm^{-3}	$10^4\ k_{obs}/s^{-1}$[b]	$k/dm^3\ mol^{-1}\ s^{-1}$[c]
0.020	0.024	30.6	6.5
0.020	0.044	20.5	6.4
0.020	0.055	15.8	5.8
0.020	0.108	9.3	5.8
0.020	0.200	5.3	5.8
0.020	0.230	5.0	6.2

[a] DNBF concentration is 4×10^{-5} mol dm^{-3}.
[b] Measured at 486 nm.
[c] Calculated from eq. [5] with K_a 1.02×10^{-3} mol dm^{-3} and K_{H_2O} 0.0196 mol dm^{-3}.

Table 6. Rate data for reaction of DNBF[a] with **2d**, 3-methylaniline, in acidic solution in 30/70 (v/v) water/DMSO at 25°C.

[3-Methylaniline H^+Cl^-]/mol dm^{-3}	[HCl]/mol dm^{-3}	$10^4\ k_{obs}/s^{-1}$[b]	$k/dm^3\ mol^{-1}\ s^{-1}$[c]
0.050	0.036	56	28
0.050	0.070	34	27
0.050	0.153	18.5	28
0.050	0.200	14.2	28
0.050	0.241	11.1	27
0.050	0.300	9.3	26

[a] DNBF concentration is 4×10^{-5} mol dm^{-3}.
[b] Measured at 485 nm.
[c] Calculated from eq. [5] with K_a 2.24×10^{-4} mol dm^{-3}, and K_{H_2O} 0.0196 mol dm^{-3}.

Table 7. Rate data for reaction of DNBF[a] with **2e**, 3-methoxyaniline, in acidic solution in 30/70 (v/v) water/DMSO at 25°C.

[3-Methoxyaniline H^+Cl^-]/mol dm^{-3}	[HCl]/mol dm^{-3}	$10^4\ k_{obs}/s^{-1}$[b]	$k/dm^3\ mol^{-1}\ s^{-1}$[c]
0.010	0.090	1100	1470
0.030	0.070	3700	1350
0.030	0.17	1660	1220
0.050	0.050	7170	1280

[a] DNBF concentration is 4×10^{-5} mol dm^{-3}.
[b] Measured by stopped-flow spectrophotometry at 487 nm.
[c] Calculated from eq. [5] with K_a 8.1×10^{-4} mol dm^{-3} and K_{H_2O} 0.0196 mol dm^{-3}.

Table 8. Rate data for reaction of DNBF[a] with **2f**, 4-methylaniline, in acidic solution in 30/70 (v/v) water/DMSO at 25°C.

[4-Methylaniline]/mol dm^{-3}	[HCl]/mol dm^{-3}	$10^4\ k_{obs}/s^{-1}$[b]	$k/dm^3\ mol^{-1}\ s^{-1}$[c]
0.050	0.0142	1.63	1.10
0.050	0.0249	1.28	1.14
0.050	0.0356	1.06	1.17
0.050	0.0570	0.75	1.15

[a] DNBF concentration is 4×10^{-5} mol dm^{-3}.
[b] Measured at 485 nm.
[c] Calculated from eq. [5] with K_a 1.0×10^{-4} mol dm^{-3} and K_{H_2O} 0.0196 mol dm^{-3}.

spectrophotometer. These values, rather than the value of 3.7 dm^3 mol^{-1} s^{-1} for k_H in 70% DMSO, were used in the calculation of the isotope effect. It is known that ring-deuteriation has only a small effect on the acidity of anilinium ions (26), thus in water values are 4.71 for $C_6H_5NH_3^+$ and 4.74 for $C_6D_5NH_3^+$. We have assumed that values for K_a are unaffected by deuteriation in the DMSO–water mixtures. The overall value of *k* contains contributions from k_1, k_2, and k_{-1} as indicated in eq. [3]. It is likely that the values of k_1 and k_{-1} will show only small changes with isotopic substitution, since these involve secondary isotope effects. However, the value of k_2 that involves carbon–hydrogen bond cleavage is likely to show a primary isotope effect of ca. 7. These assumptions, together with the observed value of $k_H/k_D = 2.1$, lead to a value for k_{-1}/k_2 of 0.2 for aniline with $k_1 = 1.2k$. This indicates that, as with most electrophilic substitution reactions (19), the k_1 step, the initial attack, is largely rate determining. A similar situation was reported in reactions of

Table 9. Rate data for reaction of DNBF[a] with **2g**, 4-methoxyaniline, in acidic solution in 30/70 (v/v) water/DMSO at 25°C.

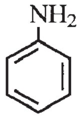
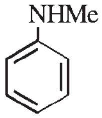
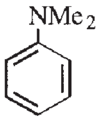
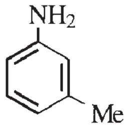
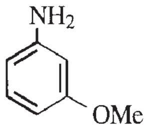
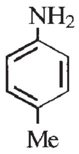
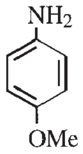
[4-Methoxyaniline H^+Cl^-]/mol dm^{-3}	[HCl]/mol dm^{-3}	10^4 k_{obs}/s^{-1}[b]	k/dm^3 mol^{-1} s^{-1}[c]
0.050	0.0142	0.62	1.24
0.050	0.0356	0.47	1.54
0.050	0.0570	0.38	1.72

[a] DNBF concentration is 4 × 10^{-5} mol dm^{-3}.

[b] Measured at 490 nm.

[c] Calculated from eq. [5] with K_a 3.39 × 10^{-5} mol dm^{-3} and K_{H_2O} 0.0196 mol dm^{-3}.

Table 10. Summary of kinetic data for reaction of DNBF with substituted anilines in 30/70 (v/v) water/DMSO at 25°C.

Aniline		pK_a[a]	λ_{max}/nm[b]	k/dm^3 mol^{-1} s^{-1}
2a		3.41	489	4.0 ± 0.7
2b		3.06	494	10.3 ± 0.6
2c		2.99	486	6.0 ± 0.8
2d		3.65	485	27 ± 1
2e		3.09	487	1300 ± 100
2f		4.00	485	1.14 ± 0.03
2g		4.47	490	1.5 ± 0.2

[a] pK_a values of the anilinium ions in 30/70 (v/v) water/DMSO from ref. 25.

[b] Absorption maxima of adducts.

DNBF with substituted indoles (13, 14). However, in reactions with 1,3,5-trimethoxybenzene, a larger isotope effect was observed showing that here proton loss from the intermediate is more kinetically significant (17).

Our results show that for substitution in aniline, the value of the isotope effect is independent of the solvent composition in the range 30–70% DMSO. The small increase in k from 1.1 dm^3 mol^{-1} s^{-1} in 30% DMSO to 4.2 dm^3 mol^{-1} s^{-1} in 70% DMSO is thus likely to reflect a similar increase in value for k_1. This may indicate slightly better solvation by DMSO than by water of the charged polarizable intermediate **3**. The value of the rate constant for attack of water on DNBF shown in eq. [1] also increases with DMSO content of the solvent (24).

Table 11. Carbon nucleophilicity of some π-excessive aromatics towards DNBF in 50/50 (v/v) water/DMSO.

Compound^a	k/dm^3 mol^{-1} s^{-1}	pK_a^{a,b}
3-Methoxythiophene	0.5	–6.5
5-Cyanoindole	1.1	–6.0
Aniline	2.3	
N,*N*-Dimethylaniline^c	3.5	(–6 to ~–5)
N-Methylaniline^c	6.0	
3-Methylaniline^c	16	(–5 to ~–4.5)
5-Bromoindole	46	–4.4
5-Chloroindole	52	–4.5
Pyrrole	520	–3.8
Indole	560	–3.5
3-Methoxyaniline^c	750	(–3)
5-Methylindole	2100	–3.3
5-Methoxyindole	2600	–2.9
N-Methylindole	3500	–2.3
1,2,5-Trimethylpyrrole	24 000	–0.5
3,4-Diaminothiophene	9×10^5	1.5–2

[a] Data from ref. 16 or from present work.

[b] pK_a values in water for protonation on carbon

[c] Values of k in 30/70 water/DMSO were multiplied by 2.3/4.0.

Reaction with substituted anilines

Data analogous to that reported in Table 2 were obtained for reaction of DNBF with the substituted anilines **2b**–**g**. Results are given in Tables 4–9. Values of k calculated from eq. [5] using the value of K_a appropriate to the particular substituted anilinium ion are summarized in Table 10.

The results show that the value of k, the rate constant for adduct formation, increases on *N*-methylation. However, further methylation to give the *N*,*N*-dimethyl derivative results in a reduction in reactivity. Successive *N*-methylations might be expected to increase reactivity by increasing the electron releasing ability of the amino group. Thus σ^+ values (27, 28) are –1.30 for *para*-NH$_2$ and –1.70 for *para*-NMe$_2$, with the NHMe group showing intermediate behaviour (29). However these σ^+ values relate to largely aqueous media, while our results were obtained in media rich in DMSO. It is known that DMSO is an extremely good hydrogen-bond acceptor (30, 31), and in this solvent the stabilization of the cationic moiety of the intermediate, **3**, will be expected to increase as the number of NH bonds available for hydrogen-bonding increases. This effect may temper the increase in electron donation expected on *N*-methylation. A similar argument may be used (25) to explain the reduced acidity of the anilinium ion, pK_a = 3.41, in DMSO–water relative to the *N*,*N*-dimethyl derivative, pK_a = 2.99.

The values of k for reaction at the 4-positions of **2d** and **2e** are considerably higher than that for aniline. Here the electron releasing effect of the 3-substituent is dominant with σ^+ values reported as –0.31 for methyl and –0.78 for methoxy (32). There may be some steric retardation here, since the substituents are *ortho* to the reaction centre.

When the 4-position is blocked, reaction occurs at the 2-position, *ortho* to the amino function. Here the values for k are reduced relative to that for aniline. These reductions probably represent a steric effect to nucleophilic attack, although steric inhibition of solvation in the intermediates leading to the adducts **5** is a possibility.

Rate constants are available (17) for reaction, in 50/50 (v/v) water/DMSO, of DNBF at the 4-position of 1,3-dimethoxybenzene (0.52 dm^3 mol^{-1} s^{-1}) and with 1,3,5-trimethoxybenzene (205 dm^3 mol^{-1} s^{-1}). Comparison of these values with data in Table 10 shows that the 4-amino group is considerably more activating, in terms of carbon nucleophilicity, than the 4-methoxy group.

Comparison with other π-excessive aromatics

It is of interest to compare our results for the nucleophilicity of aniline derivatives towards DNBF with those for other arenes. Most of the literature data refer to a solvent system of 50/50 (v/v) water/DMSO, whilst our data generally refer to 30/70 (v/v) water/DMSO. However, for aniline we have data in both media and have assumed that the solvent effect will be similar for substituted derivatives. Data are in Table 11. It has been shown previously (16) that there is an approximately linear relationship between carbon nucleophilicities towards DNBF, and pK_a values in water for carbon protonation. On the assumption that the anilines obey the same relationship, the pK_a values for C-protonation may be estimated. For aniline and its N-methylated derivative values of ca. –6 to –5 are obtained, while values for 3-methylaniline and 3-methoxyaniline are ca. –4.7 and –3, respectively. The results clearly show that in water N-protonation of the anilines, with pK_a ca. 4, is strongly favoured over ring protonation.

Experimental

4,6-Dinitrobenzofuroxan was prepared by the Drost method (33); mp 172°C (lit. (16, 33) 172–174°C). All other reagents and solvents were the purest available commercial products.

^{1}H NMR spectra were recorded using a Varian Mercury 200 MHz spectrometer. UV-vis spectra and kinetic measurements were made at 25°C with a Perkin–Elmer Lambda 2 spectrophotometer, a Shimadzu UV-2101 PC spectrometer, or an Applied Photophysics SX-17 MV stopped-flow spectrophotometer. Reported rate constants are the means of several determinations and are precise to ±5%. Potassium chloride was used to maintain ionic strength I ($\equiv (1/2)\Sigma c_i z_i^2$) 0.1 mol dm^{-3} in those solutions with lower ionic concentrations.

Acknowledgements

Financial assistance for this project from Zeneca Fine Chemicals, Huddersfield, is gratefully acknowledged.

References

1. E. Buncel and J.G.K. Webb. Can. J. Chem. **50**, 129 (1972).
2. E. Buncel and W. Eggimann. J. Am. Chem. Soc. **99**, 5958 (1977).
3. M.R. Crampton and I.A. Robotham. Can. J. Chem. **76**, 627 (1998).

4. O. Banjoko and P. Otiono. J. Chem. Soc. Perkin Trans. 2, 399 (1981).
5. F. Terrier. Nucleophilic aromatic displacement. VCH, New York. 1991.
6. R.J. Spear, W.P. Norris, and R.W. Read. Tetrahedron Lett. **24**, 1555 (1983).
7. R.W. Read, R.J. Spear, and W.P. Norris. Aust. J. Chem. **37**, 985 (1984).
8. R.W. Read and W.P. Norris. Aust. J. Chem. **38**, 435 (1985).
9. M.J. Stauss, R.A. Renfrow, and E. Buncel. J. Am. Chem. Soc. **105**, 2473 (1983).
10. E. Buncel, R.A. Renfrow, and M.J. Strauss. J. Org. Chem. **52**, 488 (1987).
11. E. Buncel, R.A. Manderville, and J.M. Dust. J. Chem. Soc. Perkin Trans. 2, 1019 (1997).
12. J.-C. Hallé, D. Vichard, M.-J. Pouet, and F. Terrier. J. Org. Chem. **62**, 7178 (1997).
13. F. Terrier, M.-J. Pouet, J.-C. Hallé, S. Hunt, J.R. Jones, and E. Buncel. J. Chem. Soc. Perkin Trans. 2, 1665 (1993).
14. F. Terrier, E. Kizilian, J.-C. Hallé, and E. Buncel. J. Am. Chem. Soc. **114**, 1740 (1992).
15. F. Terrier, M.-J. Pouet, E. Kizilian, J.-C. Hallé, F. Outurquin, and C. Paulmier. J. Org. Chem. **58**, 4696 (1993).
16. E. Kizilian, F. Terrier, A.-P. Chatrousse, K. Gzoudi, and J.-C. Hallé. J. Chem. Soc. Perkin Trans. 2, 2667 (1997).
17. F. Terrier, M.-J. Pouet, J.-C. Hallé, E. Kizilian, and E. Buncel. J. Phys. Org. Chem. **11**, 707 (1998).
18. H. Mayr. Angew. Chem. Int. Ed. **33**, 938 (1994).
19. R.O.C. Norman and R. Taylor. Electrophilic substitution in benzenoid compounds. Elsevier, Amsterdam. 1965; R. Taylor. Electrophilic aromatic substitution. Wiley, New York. 1990.
20. P.W. Robertson, P.B.D. de la Mare, and B.E. Swedlund. J. Chem. Soc. 782 (1953).
21. E. Berliner. J. Am. Chem. Soc. **72**, 4003 (1950).
22. J. Berthelot, C. Guette, P.-L. Desbene, J.-J. Basselier, P. Chaquin, and D. Masure. Can. J. Chem. **67**, 2061 (1989).
23. S. Clementi and A.R. Katritzky. J. Chem. Soc. Perkin Trans. 2, 1076 (1973).
24. F. Terrier, H.A. Sorkhabi, F. Millot, J.-C. Hallé, and R. Schaal. Can. J. Chem. **58**, 1155 (1980).
25. K. Yates and G. Welch. Can. J. Chem. **50**, 474 (1972).
26. C.F. Bernasconi, W. Koch, and H. Zollinger. Helv. Chim. Acta, **46**, 1184 (1963).
27. H.C. Brown and Y. Okomoto. J. Am. Chem. Soc. **80**, 4979 (1958).
28. S. Clementi and A.R. Katritzky. J. Chem. Soc. Perkin Trans. 2, 1077 (1973).
29. M. Charton. Prog. Phys. Org. Chem. **13**, 211 (1981).
30. M.J. Kamlet and R.W. Taft. J. Am. Chem. Soc. **98**, 377 (1976)
31. M.R. Crampton and I.A. Robotham. J. Chem. Res. Synop. 22 (1997).
32. L.M. Stock and H.C. Brown. Adv. Phys. Org. Chem. **1**, 35 (1963).
33. P. Drost. Justus Liebigs Ann. Chem. **307**, 49 (1899).