Use of the Brönsted β_{nuc} parameters in Mechanistic interpretation

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Abstract : Kinetic studies for the reactions of N1-methyl-4-nitrobenzofurazanium tetrafluoroborate **1a** with a series of 4-X-substituted anilines **2a-d** (X = OH, OMe, Me and H) have been carried out in MeCN at 20 °C. The derived second-order rate constants (k_1) have been combined with the pK_a values of the conjugate acids of the anilines **2a-d** to calculate the Brönsted parameters β_{nuc} according to the linear free-energy relationship log k_1 *vs.* pK_a. The large Brönsted β_{nuc} of 1.40 obtained suggest that the reactions proceed trough a single electron transfer (SET) mechanism. On the other hand, the finding of satisfactory correlation between the log k_1 of the reactions and the oxidation potentials (E^o) of anilines **2a-d** supports this mechanism.

Keywords: Kinetics, Linear Free Energy Relationships, Substituent Effects, and SET Mechanism.

INTRODUCTION

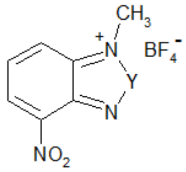
Due to their importance in synthetic applications, the reactivity and mechanism of σ-complexation [1-6] and S_NAr [7-10] reactions have been extensively investigated. In previous work, we have reported quantitative kinetic studies of nucleophilic addition reactions of N1-methyl-4-nitro-2,1,3-benzothiadiazolium tetrafluoroborate **1b** with various anilines in acetonitrile solution at 20 °C [11]. An abnormally high value β_{nuc} of 1.24 has been found. The reactions were concluded to proceed through a single electron transfer (SET) mechanism.

To obtain further systematic information into the reactivity of this class of compounds, we have extended our kinetic investigations to analogous reactions. In this paper, we report a study of the 4-nitrobenzofurazanium **1a** by various 4-X-substituted anilines **2a-d** under similar conditions to those used for **1b** in acetonitrile solution. The effect of aniline basicity on the reaction mechanism will be discussed in detail. Structure-reactivity relationships are also investigated and it is shown that the large Brönsted coefficient β_{nuc} derived in this work may be an indicator of electron transfer in nucleophilic addition mechanism.

RESULTS AND DISCUSSION

1. Kinetic Investigations

The reactions of the 4-nitrobenzofurazanium **1a** with the series of 4-X-substituted anilines **2a-d** were performed in acetonitrile solution at 20 °C (Scheme 1) under pseudo-first-order conditions using a high excess of anilines. All reactions were followed photometrically at the absorption maximum of the products **4a-d** (400 nm < λ_{max} < 475 nm) and were found to be of first-order in both reactants. In all cases, only one relaxation process



1a : Y = O
1b : Y = S

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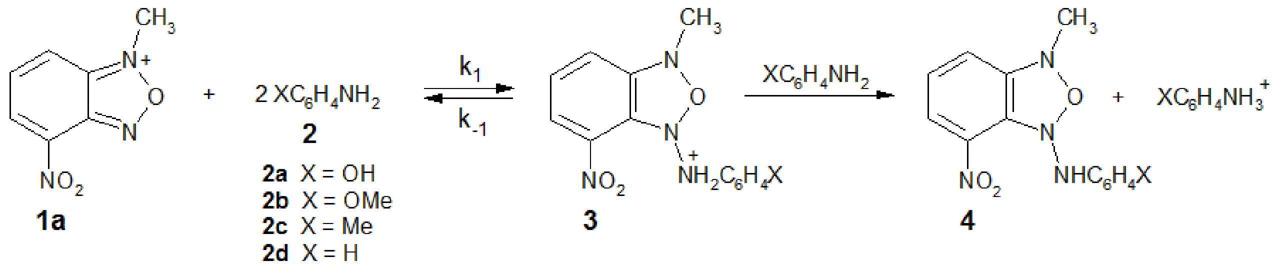


Scheme 1

corresponding to the formation of the addition products **4a-d** was observed (Figure 1), from which the pseudo-first-order rate constants (k_{obsd}) were obtained. The plots of k_{obsd} versus the concentrations of the nucleophiles were linear with intercepts near zero for all reactions of cation **1** with anilines **2a-d**. The slopes of the plots of k_{obsd} versus [aniline] gave the second-order rate constants, k_1, (Eq. (1), Figure 2), which are listed in Table I.

$$k_{obsd} = k_1 \text{ [aniline]} \qquad (1)$$

2. Effect of Aniline Basicity and Reaction Mechanism

The effect of aniline basicity on reactivity is illustrated in Figure 3 for the reactions of the 4-nitrobenzofurazanium **1a** with anilines **2a-d**. As can be seen, the Brönsted plot of log k_1 versus pK_a values of the conjugate acids of the anilines **2a-d** [12] listed in Table I is well described by a linear free energy relationship with a Brönsted coefficient β_{nuc} of 1.40, indicates that the charge is completely transferred in the rate-limiting transition state on the reaction [3].

In comparison, it is interesting to note that the β_{nuc} value determined in the present work (i.e., β_{nuc} = 1.40) is practically identical within experimental error to the one obtained (β_{nuc} = 1.24) from the

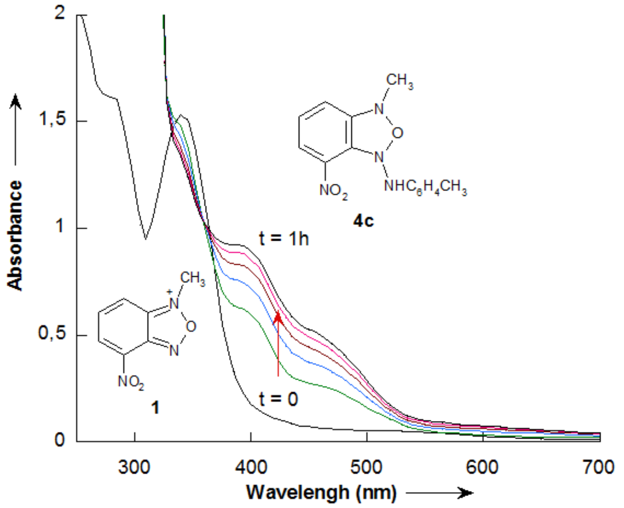


Figure 1: Time-dependence of the electronic absorption spectrum of 4-nitrobenzofurazanium **1a** (8×10^{-4} mol L^{-1}) in the presence of 4-methylaniline **2c** (10^{-2} mol L^{-1}) in acetonitrile at 20 °C.

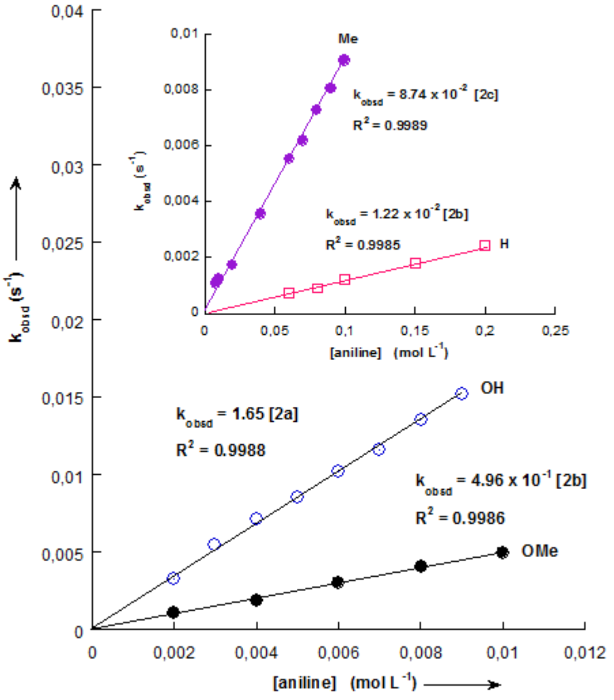


Figure 2. Determination of the second-order rate constants k_1 from the dependence of the first-order rate constant k_{obsd} on the concentration of reactions of 4-nitrobenzofurazanium **1a** with para-X-substituted anilines **2a-d** in acetonitrile solution at 20 °C.

Table I. Summary of second-order rate constants for addition reactions of 4-X-substituted anilines **2a-d** with 4-nitrobenzofurazanium **1a** in acetonitrile at 20 °C.

Substituent X	k_1 (mol^{-1} dm^3 s^{-1})	pK_a [b]	E° (V) [c]	σ^+ [d]
OH	1.65	12.10	0.76	-0.92
OMe	4.96×10^{-1}	11.80	0.79	-0.78
Me	8.74×10^{-2}	11.25	0.92	-0.31
H	1.22×10^{-2}	10.62	1.02	0

[a] Values of k_1 are determined in this work from the slope of plots of k_{obsd} *vs*. [aniline].
[b] pK_a values for anilinium ions in acetonitrile solution taken from ref [12].
[c] Oxidation potentials, E°, values in aqueous solution, were taken from ref [16].
[d] The σ and σ^+ values were taken from ref [18].

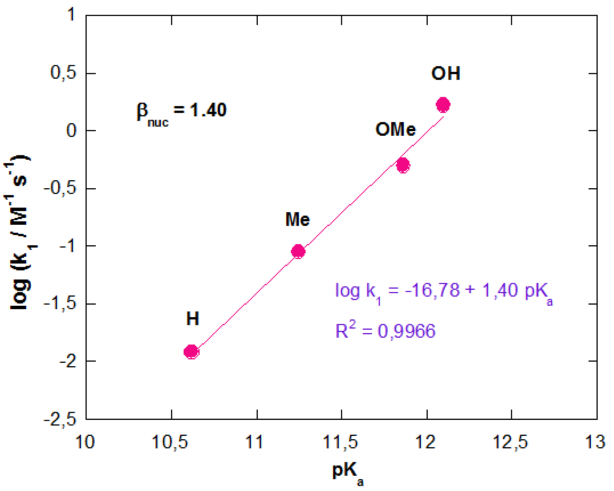
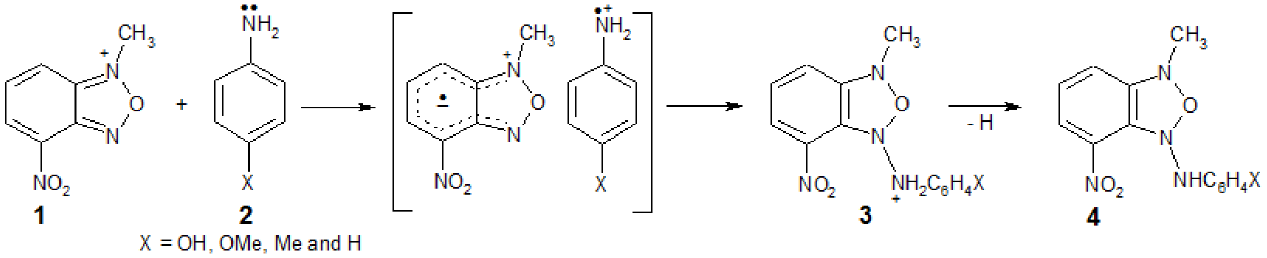


Figure 3. Brönsted plot of log k_1 *vs*. pK_a for substituted anilines **2a-d** addition to 4-nitrobenzofurazanium **1a** in acetonitrile at 20 °C.

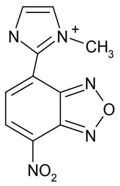
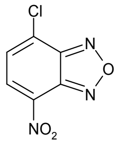
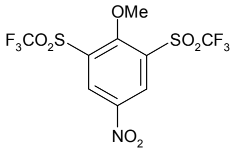
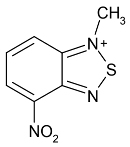
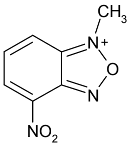
reactions of cation **1b** with the same anilines **2a-d** [11]. This observation suggests that substituting a sulfur atom of the thiadiazole ring of benzothiadiazolium cation **1b** for an oxygen atom to give **1a** does not affect dramatically the sensitivity of the rates to changes in the basicity of the aniline. It is interesting to note that β_{nuc} values close to or greater than 1have been reported for S_NAr reactions [11,13-15]. The data in Table II are illustrative in this regard.

Terrier and co-workers have discussed the origin of the abnormally high β_{nuc} values and suggested that these values are the reflection of a possible contribution of a single electron transfer process [13]. Thus, we propose the reaction scheme shown in Scheme 2, as the most probable mechanism for the present reactions.



Scheme 2. Proposed mechanistic pathway for the reaction of 4-X-substituted anilines **2a-d** with 4-nitrobenzofurazanium **1a** in CH_3CN at 20 °C.

Table II. Comparison of Brönsted β_{nuc} values for the reactions of various para-substituted anilines with some representative eletrophiles.

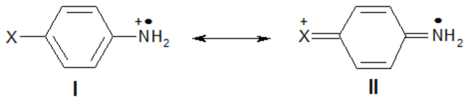
Aromatic substrate	Solvent	β_{nuc}	ref
	30 % DMSO - 70 % H_2O 80 % DMSO - 20 % H_2O	1.43 1.30	**[13]**
	DMSO	1.60	**[14]**
	DMSO	1.29	**[15]**
	CH_3CN^b	1.24	**[11]**
	CH_3CN^b	1.40	This work

^{a}T = 25 °C. ^{b}T = 20 °C.

3. Correlation log k_1 *versus* oxidation potentials E°

In order to confirm the existence of radical cation $XC_6H_4\overset{+\bullet}{N}H_2$, we have plotted the measured second order rate constants, k_1, for the reactions of 4-nitrobenzofurazanium **1a** with anilines **2a-d** determined in this work versus the oxidation potentials E° values of their radical cations reported by Jonsson and co-workers [16] (Table I). As can be seen, the relationship between log k_1 and E° is linear (Figure 4). This result is further evidence that reactions between **1a** and the anilines **2a-d** are proceeding by initial electron transfer.

Based on these findings, it seems reasonable to assume that the electron donating X-substituents interact directly through the ring π-system with the electron-deficient reaction site, the radical cation $XC_6H_4\overset{+\bullet}{N}H_2$, in the rate-determining step as shown in resonance structures **I** and **II**.



4. Analysis of Hammett Plot

To obtain additional information about the resonance effects, a Hammett plot [17] was constructed for reaction of 4-nitrobenzofurazanium **1a** with anilines **2a-d** using the data in Table I. In fact, the values of the second-order rate constants (log k_1) derived for the reaction of **1a** with anilines **2a-d** correlate linearly with Hammett's substituent constants (σ^+) [18] (Figure 5). Hence, it could be

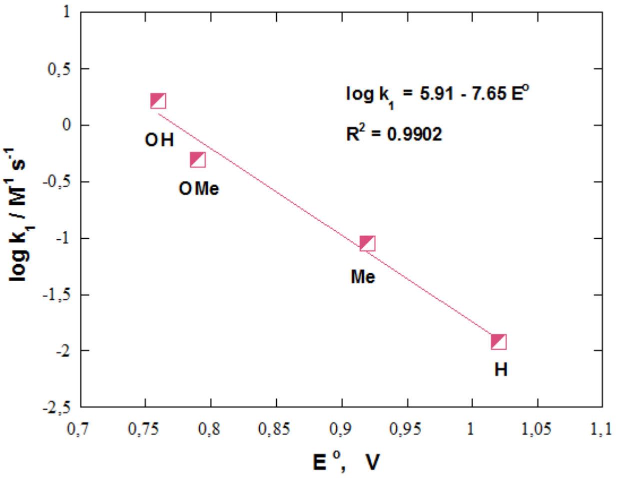


Figure 4. The influence of the oxidation potential, E°, of anilines on the rate constants of reactions of 4-nitrobenzofurazanium **1a** with **2** in acetonitrile at 20 °C. The identity of points is given in Table I.

concluded that the origin of the linear Hammett plot observed in the present work may be due to the stabilization of the transition-state through resonance between the radical moiety $XC_6H_4\overset{+\bullet}{N}H_2$ and the electron-donating substituent X. We note that, the negative ρ value obtained in the present work is clearly consistent with significant developments of positive charge at the nitrogen atom of aniline moiety in the transition state and suggest that the nucleophilic attack by aniline to form an addition intermediate is the rate-determining step.

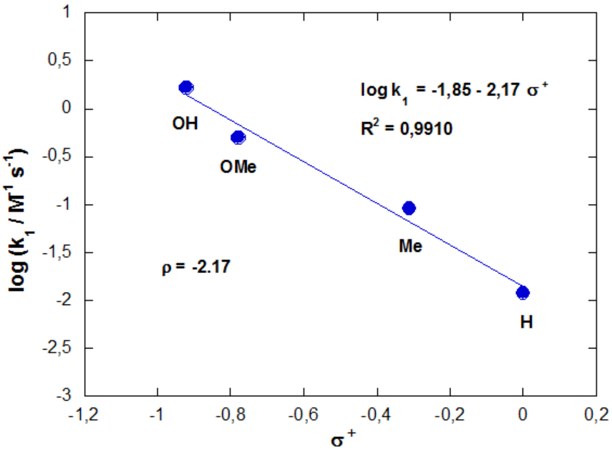


Figure 5: Hammett plot of log k_1 *vs.* σ for substituted anilines **2a-d** addition to 4-nitrobenzofurazanium **1a** in acetonitrile at 20 °C. The σ^+ values were taken from [18].

CONCLUSION

Three conclusions can be drawn from the kinetics data. First, a single electron transfer (SET) mechanism is proposed on the basis of the large Brönsted coefficient β_{nuc} of 1.40; second, the chemical evidence against a SET mechanism was supported by the linear free energy relationships (log k_1 *versus* E° values of oxidation potential constant and log k_1 *versus* Hammett's substituent constants (σ^+)) and third, the results from this study are in reasonable agreement with the idea that high Brönsted β_{nuc} values may be an indicator of SET process.

EXPERIMENTAL SECTION

1. Materials

The various anilines **2a-d** were commercially available products which were purified, as appropriate, by recrystallization or distillation prior to use. Acetonitrile (Aldrich, HPLC: 99.9%) was available of the highest quality and used without further purification.

All spectrophotometric measurements were carried out using a spectrophotometer (UV-1650 Shimadzu, Japan) equipped with a Peltier temperature controller (model TCC-240 A), which is able to keep to temperature within 0.1 K.

2. Substrates

N1-methyl-4-nitrobenzofurazanium tetrafluoroborate **1a** used in this work was carried as previously reported [1]. Analysis of the product gave the following results.

^1H NMR (300.13 MHz, CD_3CN-d3) δ_H 8.83 (1H, dd, $J_1 = 6$, $J_2 = 1.8$), 8.37 (2H,m), 4.98 (3H, s); ^{13}C NMR (75.47 MHz, CD_3CN-d3) δ_C 148.16, 142.80, 142.15,138.36, 135.76, 119.55,43.35.

3. Products analysis

Addition of 2 equivalents of 4-methoxyaniline **2b** to a solution of N1-methyl-4-nitrobenzofurazanium tetrafluoroborate **1a** (0.075 mmol) in deuterated acetonitrile resulted in the immediate disappearance of signals corresponding to **4**. Isolation of the obtained product was unattainable due to its instability. Obtained ^1H NMR spectrum presents overlapping resonance signals at averaged positions of 6.93 and 7.54 ppm corresponding to the aromatic protons of the adduct, the N-alkylated and the protonated forms of 4-methoxyaniline. The interpretation of these chemical shifts was complicated. On the other side, the singlet corresponding to the methyl group, initially present at 4.98 ppm, appears at 3.83 ppm. This decrease in the chemical shift may be due to the disappearance of the positive charge.

4. Kinetics Measurements

Kinetic measurements were performed on a conventional spectrophotometer (Shimadzu UV-visible model 1650). The thermo-electrically temperature controlled cell holder (model TCC-240 A) was maintained at 20 ± 0.1 °C. All the reactions were carried out in triplicate under pseudo-first-order conditions with a cation **1a** concentration of approximately 2×10^{-4} to 8×10^{-4} mol dm^{-3} and aniline concentrations in the range 2×10^{-3} to 2×10^{-1} mol dm^{-3}. The k_{obsd} values were determined from the slope of the plot of ln (A_∞ - A_t) vs. time. The kinetics constants measured were found to be reproducible to ± 3-5 %. Correlation coefficients of the linear regressions were usually higher than 0.9985. Measured first-order rate constants k_{obsd} obtained at aniline concentrations are given for all substrates in Tables S1 in Supporting Information, together with the derived second-order rate constants.

REFERENCES

[1] F. Terrier, in *Modern Nucleophilic Aromatic Substitution*, Wiley-VCH editor, John Wiley & Sons, Weinheim, **2013**.

[2] T. Boubaker, R. Goumont, E. Jan, F. Terrier. *Org Biomol Chem.*, **2003**, *1*, 2764-2770.

[3] E. Buncel, F. Terrier. *Org Biomol Chem.*, **2010**, *8*, 2285-2308.

[4] S. Lakhdar, R. Goumont, F. Terrier, T. Boubaker, J. M. Dust, E. Buncel. *Org Biomol Chem.*, **2007**, *5*, 1744-1751.

[5] M. R. Crampton, R. A. Lunn, D. Lucas. *Org Biomol Chem.*, **2003**, *1*, 3438-3443.

[6] D. Vichard, T. Boubaker, F. Terrier, M. J. Pouet, M. J. Dust, E. Buncel, *Can J Chem.*, **2001**, *79*, 1617-1623.

[7] J. F. Bunnett, A. V. Cartano. *J Am Chem Soc.*, **1981**, *103*, 4861-4865.

[8] J. E. Dixon, T. C. Bruice. *J Am Chem Soc.*, **1972**, *94*, 2052-2056.

[9] F. G. Bordwell, D. L. Hughes. *J Am Chem Soc.*, **1986**, *108*, 5991-5997.

[10] N. El Guesmi, T. Boubaker, R. Goumont. *Int J Chem Kinet.*, **2010**, *42*, 203-210.

[11] S. Ben Salah, T. Boubaker, R. Goumont. *Int J Chem Kinet.*, **2015**, *47*, 461-470.

[12] J. F. Coetzee, G .R. Padmanabhan. *J Am Chem Soc.*, **1965,** *87*, 5005- 5010.

[13] F. Terrier, M. Mokhtari, R. Goumont, J. C. Halle, E. Buncel. Org Biomol Chem., **2003**, 1, 1757-1763.

[14] I. Jamaoui, T. Boubaker, R. Goumont. *Int J Chem Kinet.*, **2013**, *45*, 152-160.

[15] N. El Guesmi, T. Boubaker, R. Goumont. *Prog React Kinet Mec.*, **2013**, *38*, 130-142.

[16] M. Jonsson, J. Lind, T. E. Eriksen, G. Merenyi. *J Am Chem Soc.*, **1994**, *116*, 1423-1427.

[17] L. P Hammett. in *Reaction Rates Equilibria Mechanisms* Second Edition McGraw-Hill New York **1970**.

[18] C. Hansch, A. Leo, R. W. Taft. *Chem Rev.*, **1991**, *91*, 165-195.