Water and hydroxide ion pathways in the σ-complexation of superelectrophilic 2-aryl-4,6-dinitrobenzotriazole 1-oxides in aqueous solution. A kinetic and thermodynamic study

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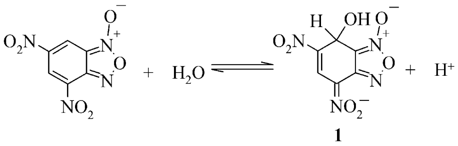
As part of our continuing studies of the highly electron-deficient nature of nitrobenzofuroxans, nitrobenzofurazans and related heterocycles, we report here a kinetic and thermodynamic study of σ-complexation for a series of 2-aryl-4,6 -dinitrobenzotriazole 1-oxides (**3a**–**e**) over a large pH range in aqueous solution. The reaction series represents a modulation in electrophilic properties of the benzotriazole moiety in formation of the corresponding hydroxy σ-adducts (**4a**–**e**). Analysis of the data has allowed dissection of observed rates into forward ($k_1^{H_2O}$, $k_2^{OH^-}$) and reverse ($k_{-1}^{H^+}$, k_{-2}) rate constants as well as the obtention of pK_a values for H_2O addition to the benzotriazole moiety. Our results reveal that **3a**–**e** are superelectrophilic compounds with respect to 1,3,5-trinitrobenzene (TNB) as a standard electron-deficient aromatic, but less superelectrophilic compared to 4,6-dinitrobenzofuroxan (DNBF). Some data pertaining to buffer catalysis of the formation and decomposition of the adducts together with solvent deuterium isotope effects for these pathways are also reported. From these results, it is concluded that adduct formation occurs *via* general base catalyzed water attack: the general bases include notably H_2O, HCO_3^-, CO_3^{2-} as well as OH^-. This contrasts with the situation for the σ-complexation of DNBF where HCO_3^- and CO_3^{2-} were found to act as nucleophilic catalysts whereas OH^- functioned as a general base catalyst. This contrasting behaviour provides further evidence that the dinitro-activated carbocyclic ring of the benzotriazoles **3a**–**e** ranks somewhat lower in electrophilic/superelectrophilic properties compared to that in DNBF. Altogether, the results provide a basis for understanding the relationship between the superelectrophilic reactivities, as evidenced by the contrasting kinetic and thermodynamic properties of the systems at hand, and the varied abilities of these substrates to react in pericyclic Diels–Alder reactions.

Introduction

The last decade has witnessed considerable interest in studies of nitrobenzofuroxans, a class of electron-deficient heteroaromatic compounds that show increased reactivity with nucleophiles in the formation of σ-bonded anionic (Meisenheimer) complexes.[1–8] The high susceptibility of 4,6-dinitrobenzofuroxan (DNBF, 4,6-dinitrobenzo[*c*][1,2,5]oxadiazole 1-oxide) to undergo σ-complexation in the absence of added base in aqueous solution is illustrative of this behaviour.[1] The pK_a for the formation of the hydroxy adduct **1** according to eqn. (1) is equal to 3.75 at 25 °C, as compared with a pK_a value of 13.37 for formation of the analogous adduct **2** of 1,3,5-trinitrobenzene (TNB),[9] the conventional reference aromatic electrophile in σ-complex chemistry.[1–8] Use of dilute alkali hydroxide solutions is in fact necessary to achieve the formation of **2** in aqueous solution (eqn. (2)). More importantly, DNBF has been found to react quantitatively at room temperature with weak nucleophiles such as anilines or hydroxy or methoxy-substituted benzenes to give stable σ-bonded adducts which are formally the products of S_EAr substitution of the benzene rings.[2–4] Similar substitutions readily occur with π-excessive heteroaromatics like pyrrole, thiophene, furan or indole derivatives. From kinetic studies of these reactions, it has been shown that DNBF is in fact more electrophilic than such strong electrophiles as benzenediazonium cations, including the *p*-nitrobenzenediazonium cation.[10]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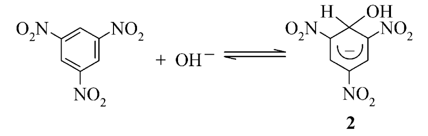
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In view of the numerous synthetic, biological and analytical applications which have derived from the discovery of the superelectrophilic character of nitrobenzofuroxans,[6–8,10–14] efforts have been made to design other families of heteroaromatic compounds that will show similar enhanced reactivity with nucleophiles in σ-complex formation and related nucleophilic aromatic substitution processes. Thus, promising results have been reported regarding the 2-aryl-4,6-dinitrobenzotriazole 1-oxides **3a**–**c**.[15,16] On the basis of ^{1}H and ^{13}C NMR studies of their reactions with such nucleophiles as ethanethiol,

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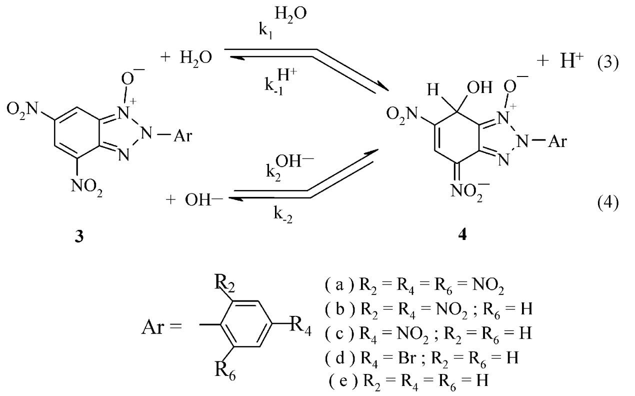
phenoxide ions and arylamines, compounds **3a**–**c** have been qualitatively ranked much closer to DNBF than to TNB on a scale of increasing electrophilicity in Meisenheimer complex formation.[16] However, no detailed kinetic and thermodynamic studies of the reactivity of these compounds has been made. In particular, it was of interest to establish whether **3a**–**c** are susceptible to covalent hydration through water attack since the importance of this pathway in the formation of the DNBF adduct **1** (eqn. (1)) has been used as a major criterion to highlight the superelectrophilic character of this substrate.[1,8]

In this paper, we report the results of a thermodynamic and kinetic study of the reactions of water and hydroxide ion with **3a**–**c** as well as with the 2-phenyl and the 2-(4′-bromophenyl) analogues **3e** and **3d** to give the hydroxide adducts **4a**–**e** according to Scheme 1 in aqueous solution. Our results reveal that **3a**–**e** are definitely somewhat less reactive than the superelectrophile DNBF but considerably more reactive than the conventional electrophile TNB. Some interesting buffer catalysis and deuterium isotope effect results will be also discussed. A few data regarding the hydroxide pathway leading to the adducts **4a**, **4c** and **4e** have been reported previously.[17] The relationship between the kinetic and thermodynamic σ-complexation results of the benzofuroxan and benzotriazole series to the observed pericyclic reactivities of these substrates is also discussed.



Scheme 1

Results

All rate and equilibrium measurements pertaining to Scheme 1 were made at 25 °C and constant ionic strength of 0.2 mol dm^{-3} maintained with KCl. Dilute hydrochloric acid solutions, various buffer solutions and dilute potassium hydroxide solutions were used to cover a pH range of 0.8–13.0. To be noted is that all pH values have been measured relative to the standard state in pure water. Accordingly the relation $[H^+] = 10^{-pH}/\gamma_\pm$ holds with $\gamma_\pm$ being the mean activity coefficient in 0.2 mol dm^{-3} KCl ($\gamma_\pm = 0.75$ at 25 °C).[1a]

pK_a values of 3a–e

In contrast with data for the covalent hydration of **3a**, **3c** and **3e** (*vide infra* Table 1),[17] the pK_a values for the σ-complexation of **3b** and **3d** according to eqn. (3) were unknown. Using appropriate buffer solutions, these pK_a's were therefore determined from the observed absorbance variations at λ_{max} of the resulting adducts **4b** and **4d** (λ_{max} = 475 nm) obtained at equilibrium as a function of pH. These actually describe clear acid–base type equilibrations, as evidenced by the observation of good straight lines with unit slopes fitting eqn. (5). From these plots (not shown), we readily obtained: $pK_a^{3b} = 7.15 \pm 0.05$, $pK_a^{3d} = 9.87 \pm 0.05$ at $I = 0.2$ mol dm^{-3}.

$$\log\frac{[\mathbf{4b,d}]}{[\mathbf{3b,d}]} = \mathrm{pH} - \mathrm{p}K_a \qquad (5)$$

pH rate profiles for the interconversion of 3a–e

Using a stopped-flow spectrophotometer, the interconversions of **3a**–**e** and **4a**–**e** were kinetically investigated under first-order conditions with a substrate or adduct concentration of 2–3 × 10^{-5} mol dm^{-3}. In agreement with the direct equilibrium approach described by Scheme 1 only one relaxation time corresponding to the formation (pH > pK_a) or decomposition (pH < pK_a) of the adducts **4a**–**e** was observed in all cases. The logarithmic values of the observed first order rate constant k_{obsd} for the combined formation and decomposition of **4a**–**e** at 25 °C are plotted in Figs. 1 and 2 as a function of pH. In the experiments where buffer catalysis was observed (*vide infra*), the k_{obsd} values used to draw the pH-rate profiles were those extrapolated to zero buffer concentration.

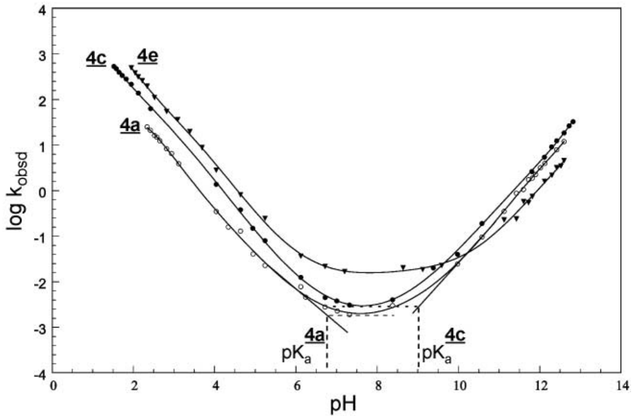


Fig. 1 pH dependence of k_{obsd} (s^{-1}) for the formation and decomposition of the adducts **4a**, **4c** and **4e** in water; T = 25 °C, I = 0.2 mol dm^{-3}.

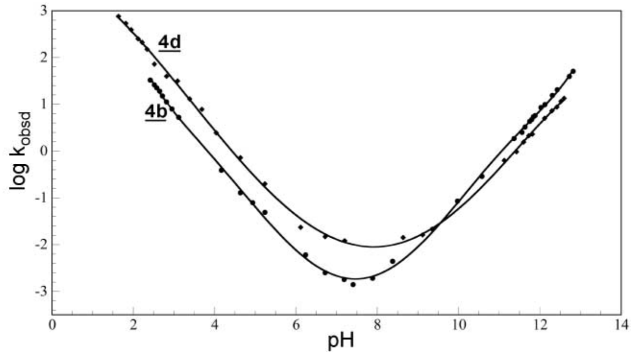


Fig. 2 pH dependence of k_{obsd} (s^{-1}) for the formation and decomposition of the adducts **4b** and **4d** in water; T = 25 °C, I = 0.2 mol dm^{-3}.

The observed rate constants at each pH are, of course, the sum of the individual first-order rate constants for formation (k_f) and decomposition (k_d) of the adducts.

$$k_{obsd} = k_f + k_d \qquad (6)$$

As shown previously in related studies of the covalent hydration of DNBF and various heterocyclic cations,[1a,18] values of k_f and k_d can be readily obtained from k_{obsd} using eqns. (7) and (8):

$$k_f = \frac{k_{obsd}}{1 + \dfrac{10^{-pH}}{10^{-pK_a}}} \qquad (7)$$

$$k_d = \frac{k_{obsd}}{1 + \dfrac{10^{-pK_a}}{10^{-pH}}} \qquad (8)$$

Table 1 Kinetic and thermodynamic parameters for the formation and decomposition of hydroxy σ-adducts in aqueous solution[a]

Adduct	pK_a	$k_1^{H_2O}/s^{-1}$	$k_{-1}^{H^+}/dm^3\ mol^{-1}\ s^{-1}$	$k_2^{OH^-}/dm^3\ mol^{-1}\ s^{-1}$	k_{-2}/s^{-1}	$K_2/dm^3\ mol^{-1}$
1[b]	3.75	3.45×10^{-2}	146	3.35×10^4	2.5×10^{-6}	1.34×10^{10}
2[c]	13.43	—	—	37.5	9.8	3.82
4a[d]	6.70	1.13×10^{-3}	4215	392	1.96×10^{-5}	2×10^7
		(6.3×10^{-4})	(10900)	(435)	(1.28×10^{-5})	
4b	7.15	6.73×10^{-4}	7050	1000	1.42×10^{-4}	7.04×10^6
			(18000)	(1010)		
4c[d]	9.00	1.80×10^{-5}	1.33×10^4	680	3.54×10^{-3}	1.92×10^5
			(3.57×10^4)	(715)		
4d[e]	9.87	4.78×10^{-6}	2.63×10^4	450	1.7×10^{-2}	2.65×10^4
4e[d]	10.73	8.3×10^{-7}	3.30×10^4	317	0.17	1860

[a] T = 25 °C; I = 0.2 mol dm^{-3} KCl. [b] Ref. 1*a*. [c] Ref. 9. [d] pK_a, $k_2^{OH^-}$ and k_{-2} values taken from ref. 17. [e] Rate and equilibrium data refer to a 90 : 10 (v/v) H_2O–DMSO mixture because of a too low solubility of the parent molecule **3d** in pure aqueous solution. Values in brackets refer to measurements in D_2O.

Each of the corresponding pH profiles, which are shown in Figs. 3 and 4 is nicely consistent with eqns. (9) and (10):

$$k_f = k_1^{H_2O} + \frac{k_2^{OH^-} K_w}{10^{-pH} \gamma_\pm} \quad (9)$$

$$k_d = \frac{k_{-1}^{H^+} 10^{-pH}}{\gamma_\pm} + k_{-2} \quad (10)$$

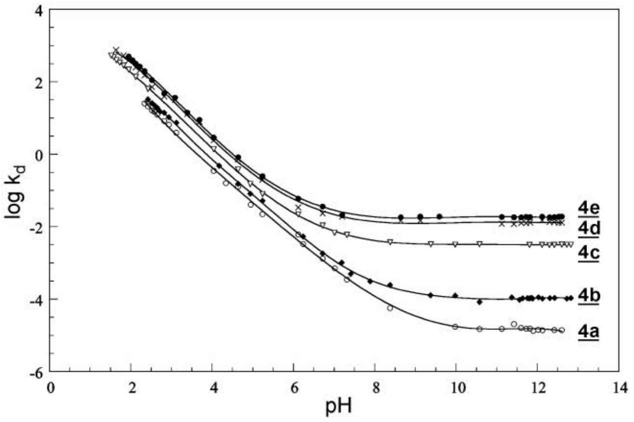


Fig. 3 pH dependence of the rate constants k_d (s^{-1}) for decomposition of **4a**–**e** in water; T = 25 °C, I = 0.2 mol dm^{-3}.

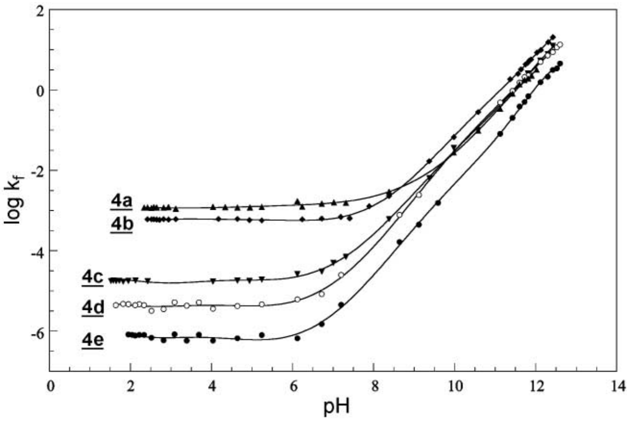


Fig. 4 pH dependence of the rate constants k_f (s^{-1}) for formation of **4a**–**e** in water; T = 25 °C, I = 0.2 mol dm^{-3}.

in which the rate constants $k_1^{H_2O}$, $k_2^{OH^-}$, $k_{-1}^{H^+}$ and k_{-2} refer to the various reactions depicted in eqns. (3) and (4). Least-squares fitting of k_f and k_d to eqns. (9) and (10) gave the parameters which are collected in Table 1.

Buffer catalysis and isotope effects

No appreciable catalysis of the interconversion of **3a**–**e** and **4a**–**e** was found to occur in buffers of $pK_a < 7$, *i.e.* the formic acid, benzoic acid, acetic acid, succinic acid and dihydrogen phosphate buffers, at least under the experimental conditions used. These are exemplified for the acetic acid–acetate buffers in Fig. 5 which refers to the *N*-picrylbenzotriazole system (**3a**). In contrast, notable catalysis was observed for the formation of the adducts **4a**, **4b** and **4c** in carbonate buffers. In these instances, only catalysis by the dianionic species CO_3^{2-} occurred, as evidenced by the finding of excellent and parallel linear plots fitting eqn. (11) on plotting k_{obsd} *vs.* the CO_3^{2-} concentration at the different pH values studied (Fig. 6).

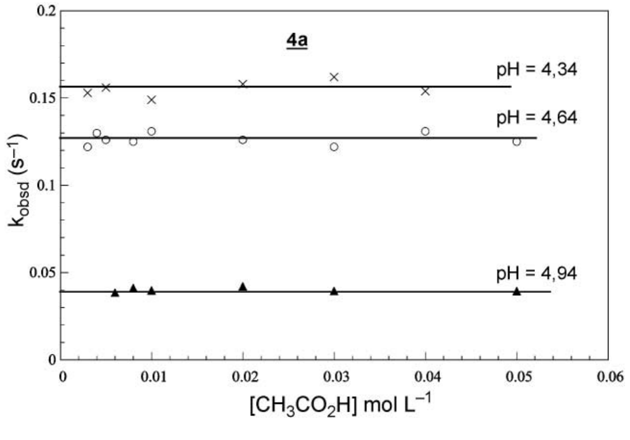


Fig. 5 Plots showing lack of dependence of k_{obsd} in acetic buffers at various pH in the *N*-picrylbenzotriazole system **3a**.

$$k_{obsd} = k_2^{OH}[OH^-] + k^{CO_3^{2-}}[CO_3^{2-}] \quad (11)$$

From the slopes of these plots, we readily obtained $k^{CO_3^{2-}}$ = 16 mol^{-1} dm^3 s^{-1} for **4a**, $k^{CO_3^{2-}}$ = 16 mol^{-1} dm^3 s^{-1} for **4b**, $k^{CO_3^{2-}}$ = 3.1 mol^{-1} dm^3 s^{-1} for **4c**. Within experimental error, the intercepts agreed well with the values of the $k_2^{OH}[OH^-]$ term, as calculated at each pH using the $k_2^{OH^-}$ values (Table 1) determined from the straight lines of slope +1 in Figs 1 and 2. Similar catalysis by HCO_3^- was observed for the **3a** and **3b** systems in bicarbonate buffers (pH = 8.38) where the formation of the adducts **4a** and **4b** is essentially complete (pH ≥ pK_a + 1.2); $k^{HCO_3^-}$ = 0.78 mol^{-1} dm^3 s^{-1} for **4a**; $k^{HCO_3^-}$ = 0.12 mol^{-1} dm^3 s^{-1} for **4b**. In the other systems, **3c**–**e**, where the decomposition pathway is largely favored in these buffers ($pK_a^{3c-e} \geq 9$), no appreciable catalysis by HCO_3^- could be observed.

Only the formation and decomposition of the most stable adduct **4a** has been studied in detail in D_2O, using dilute NaOD or DCl solutions as well as various buffer solutions. The solvent isotope effects pertaining to the different pathways involving **4a**

Table 2 Deuterium isotope effects for formation and decomposition of the hydroxy σ-adducts **1** and **4a**–**c**[a]

Adduct	$k_1^{H_2O}/k_1^{D_2O}$	$k_{-1}^{H^+}/k_{-1}^{D^+}$	$k_2^{OH^-}/k_2^{OD^-}$	k_{-2}^{H}/k_{-2}^{D}
1[b]	1.67	0.38	0.905	1.69
4a	1.79	0.386	0.90	1.53
4b	—	0.39	0.99	—
4c	—	0.372	0.95	—

[a] $T = 25$ °C; $I = 0.2$ mol dm^{-3}. [b] Ref. 1*a*.

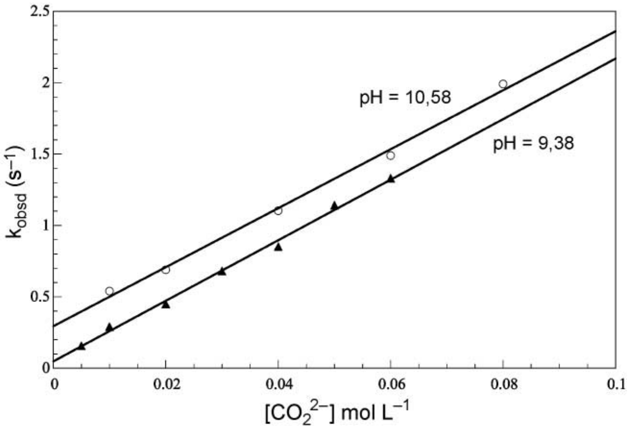


Fig. 6 Effect of carbonate concentration and pH on k_{obsd} for formation of the adduct **4a** in water; $T = 25$ °C, $I = 0.2$ mol dm^{-3}.

are given in Table 2. Also given in this Table are the $k_2^{OH^-}/k_2^{OD^-}$ and $k_{-1}^{H^+}/k_{-1}^{D^+}$ values measured, respectively, for the formation and decomposition of the adducts **4b** and **4c**

Discussion

Our study of substrates **3a**–**e**, representing an increasingly electrophilic family of electron-deficient heteroaromatic compounds, has revealed a number of interesting features, especially when compared to the known superelectrophile DNBF and the standard electrophile TNB. Salient features which derive from the results in Tables 1 and 2 and the buffer catalysis effects described in part in Figs. 5 and 6 can be highlighted under the following headings.

Relative stabilities of hydroxy adducts

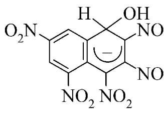
Table 1 reveals that the pK_a values for the conversion of **3a**–**e** into the adducts **4a**–**e** fall in the range 6.70–10.73. Interestingly the two most activated *N*-picryl and *N*-(2,4-dinitrophenyl) compounds, **3a** and **3b**, have pK_a values (6.70 and 7.15 respectively) which are more than six units lower than the pK_a value of TNB. While this corresponds to a considerable increase in electrophilic character from that of the common reference electrophile in σ-complex chemistry, it is rather far from being comparable to that of DNBF: the hydroxy adducts **4a** and **4b** are about 10^3 less stable than the DNBF analogue. Substituting the oxygen atom of the annelated ring of DNBF for a less electronegative *N*-phenyl group thus reduces the adduct stability. This situation is reminiscent of the one observed upon substitution of the oxygen atom for a sulfur or selenium atom in this heterocycle and it can be explained in terms of the aromatic character of the parent molecules which increases in the order O < N–Ph, and correspondingly, of the electron-withdrawing effect of the annelated ring which decreases in the order O > N–Ph.[19]

On the other hand, it is noteworthy that nitro-substitution of the N-bonded phenyl ring has a major effect on the ease of σ-complexation of the 4,6-dinitrosubstituted benzotriazole moiety as evidenced by the finding that the pK_a values increase markedly from **3a**, **3b** to the less activated *N*-phenyl substrate **3e** (pK_a = 10.73). The electrophilic character of **3e** ranks above that of TNB by only 2.70 pK units, being somewhat below that of other aromatic electrophiles like 1,3,6,8-tetranitronaphthalene (pK_a = 9.96)[20a] 1,2,3,5-tetranitrobenzene (pK_a = 9.62)[20b] or 4-nitrobenzofuroxan (pK_a = 10.32).[17]

The effect of substitution of the *N*-phenyl ring on the susceptibility of **3a**–**e** to covalent hydration calls for some additional comments. The nearly similar pK_a values of **3a** and **3b** suggest that the activating effect exerted by the picryl and 2,4-dinitrophenyl rings is largely derived from inductive/field effects rather than conjugation effects. This idea agrees with the results of a X-ray analysis which has shown that the two ring systems of **3a**, and hence of the related adduct **4a**, are in almost orthogonal orientation due to the strong steric compression of the adjacent *ortho*-nitro and *N*-oxide functions.[15a] In contrast, it is not unreasonable to assume that some conjugation between the 2-nitrogen and the *para*-substituent of the benzene ring occurs in **3c**–**e**. This would lead in the case of **3e** to some electron-donation of the phenyl ring to the heterocyclic framework, accounting for the lowest acidity of this compound.

Reactivity of 3a–e

The high susceptibility of DNBF to covalent hydration through water attack has been the major feature as a result of which this molecule has been accorded superelectrophilic properties.[1,8,21,22] Such a water reaction does not contribute at all to the formation of the TNB–hydroxide adduct **2**.[9] Interestingly, neither could a water pathway be detected in the formation of the adducts of 1,3,6,8-tetranitronaphthalene and 1,2,3,5-tetranitrobenzene **5** and **6** whose stabilities are of the same order as those of the adducts **4c**–**e**.[19,20] As a matter of fact, Table 1 reveals that a similar situation prevails for these three complexes. In the case of **4c**, for example, the first-order rate constant $k_1^{H_2O}$ for adduct formation is about 175 times lower than the first-order rate constant k_{-2} for its spontaneous decomposition. This precludes even a minor contribution of the water pathway to the formation of **4c** under the most favorable conditions where the $k_2^{OH^-}$ [OH$^-$] pathway contributes to minimal extent. In agreement with this conclusion, the pK_a value for formation of **4c** appears at the intercept between the plateau (k_{-2}) and the straight line of slope +1 ($k_2^{OH^-}$ [OH$^-$]) of the related pH-rate profile in Fig. 1.



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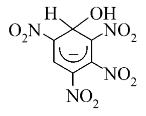

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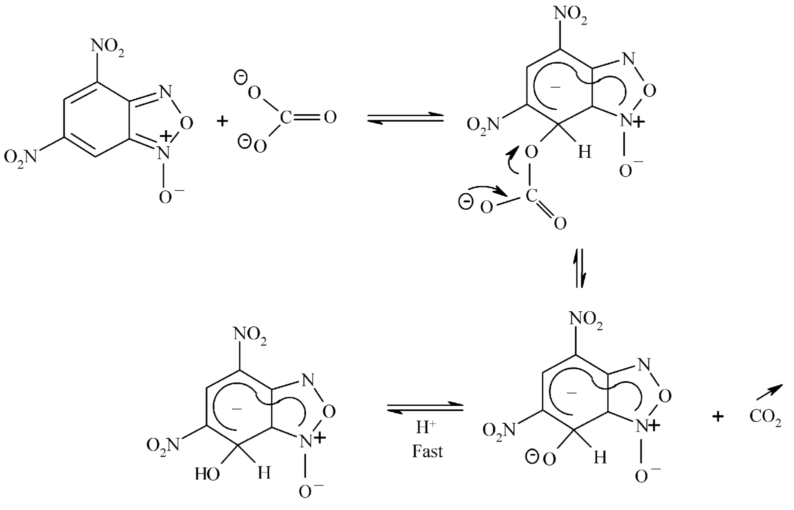
A similar situation is observed for the formation of the two less stable adducts **4d** and **4e**. In contrast, Figs. 1 and 2 show that a different situation holds for the 2,4-dinitrobenzotriazole adduct **4b** for which the k^{H_2O} and k_{-2} values are of the same order of magnitude and particularly for the picryl adduct **4a** where the $k_1^{H_2O}$ value is 40 times greater than k_{-2}. In this instance, the pK_a value for formation of **4a** is seen at the intercept of the plateau for $k_1^{H_2O}$ and the straight line of slope −1 ($k_{-1}^{H^+}$ [H$^+$]) of the pH–rate profile in Fig. 1. It remains that the $k_1^{H_2O}$ value for this electrophilic benzotriazole is 40 times lower than for DNBF. These results confirm that the 4,6-dinitrobenzotriazole series is appreciably below the 4,6-dinitrobenzofuroxan in terms of electrophilic character. Concomitantly, the pH range where the water pathway contributes predominantly to the formation of **4a** is very much reduced compared to the situation observed in the DNBF system.

Using again the data for DNBF and TNB as the references, Table 1 shows that the $k_2^{OH^-}$ rate constants for the hydroxide ion attack to the five benzotriazoles **3a**–**e** are intermediate between the two extremes, with rather moderate variations on going



Scheme 2

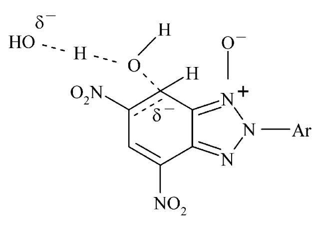
from **3a** to **3e**. Because of the especially large steric compression which exists between the two picryl and benzotriazole rings, the activating effect exerted by the picryl moiety on the susceptibility of the carbocyclic ring of **3a** to covalent hydration is reduced relative to that of the *N*-(2,4-dinitrophenyl) compound.[15a] This accounts for the observed 2.5-fold decrease in $k_2^{OH^-}$ on going from **3a** to **3b** and the absence of a linear Brönsted correlation incorporating all the compounds studied. On the other hand, it is the variations in the k_{-2} value, measuring the tendency of the adducts **4a**–**e** to undergo spontaneous decomposition, which govern the changes observed in the K_2 values. In this regard, it is noteworthy than the k_{-2} value for the most stable adduct **4a** is one order of magnitude greater than that for the DNBF adduct **1**. Then, k_{-2} increases regularly on going from **4a** to **4e**, *i.e.*, as the electron-withdrawing character of the N-bonded phenyl moiety decreases. A similar situation follows when changes are considered in the rate constant $k_{-1}^{H^+}$ for the H^+ catalyzed decomposition of **4a**–**e**.

Buffer catalysis and isotope effects

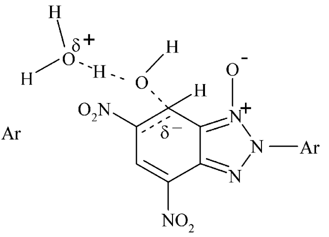
Due to the reduced contribution of the water pathway to the σ-complexation process of **3a**–**e**, the set of base catalysts involved in the formation of the adducts is restricted to OH^-, CO_3^{2-} and HCO_3^- for the *N*-picryl and *N*-(2,4-dinitrophenyl) systems, to OH^- and CO_3^{2-} for the *N*-(4-nitrophenyl) system and to OH^- for the unsubstituted and *N*-(4-bromophenyl) systems. A most interesting question is, however, whether these various catalysts act as general base or nucleophilic catalysts.

In the case of DNBF, we previously suggested that OH^- behaves as a general base catalyst on the basis that (1) the $k_2^{OH^-}$ rate constant falls nicely on the Brönsted line defined by other base catalysts such as borate, *p*-cyanophenoxide and water; (2) the observed kinetic solvent isotope effect for the reverse direction, *i.e.* k_{-2}^{H}/k_{-2}^{D} was equal to 1.69, consistent with a proton transfer being part of a rate-limiting transition state.[1a] On the other hand, the points for CO_3^{2-} and HCO_3^- showed such large positive deviations from the aforementioned Brönsted line that the catalytic contribution of these two general bases was interpreted in terms of nucleophilic catalysis (Scheme 2).[1a] This idea was in accord with the fact that DNBF is known to displace CO_2 from bicarbonate solutions.[10,12]

Considering the hydroxide reactions of the present work, no reference to a meaningful Brönsted line can be envisioned. In contrast, it is noteworthy that the measured solvent isotope effects on the $k_2^{OH^-}$ and k_{-2} pathways for the **3a**–**3c** systems are closely similar to those measured in the DNBF systems (Table 2). This suggests that we adhere to our previous reasoning and therefore to the conclusion that hydroxide ion acts as a general base catalyst for the reactions of water with **3a**–**e**. These reactions will therefore go through a transition state such as **7**. Several authors have discussed the occurrence of such hydroxide catalyzed water attack in reactions of carbonyl compounds[23–27] and evidence for a similar catalytic behaviour of OH^- has also been reported in various reaction systems, including S_NAr and related reactions.[28–32] Interestingly, our observed solvent isotope effect of $k_1^{H_2O}/k_1^{D_2O}$ = 1.79 for water attack on **3a** is also similar in magnitude to that measured for water attack on DNBF, being too large to support a transition state which would not involve rate-limiting proton transfer. This in turn favors structure **8** which represents general-base catalysed water attack with a second water molecule acting as a base catalyst. Consistent with this structure, the isotope effect $k_{-1}^{H^+}/k_{-1}^{D^+}$ is in the range of values reported for a number of examples of authentic general acid catalysis, *e.g.*, the hydrolysis of orthoesters and some acetals and ketals.[33]



7



8

Returning to the nucleophilic catalytic behaviour of CO_3^{2-} ions identified in the DNBF system, we note in Table 3 that there is a strong but regular increase in the $k_2^{OH^-}/k^{CO_3^{2-}}$ ratio on going from DNBF to **3a** to **3b** to **3c**. This decrease in the catalytic efficiency suggests that we are dealing with a loss in the ability of CO_3^{2-} to act as a nucleophilic catalyst rather than with a systematic change in the transition state structure associated with the mechanism of nucleophilic catalysis. In other words, it seems that the contribution of the nucleophilic pathway of Scheme 2 may still be operating to some extent in the case of **3a**, the strongest electrophile in the benzotriazole series, but that the general base mechanism becomes preferred in the case of **3b** and **3c**. A similar conclusion is reached for HCO_3^- from a comparison of the $k_2^{OH^-}/k^{HCO_3^-}$ ratios in Table 3.

The above results on buffer catalysis in the dinitrobenzotriazole series may be compared with corresponding data obtained previously for the archetypal superelectrophile, 4,6-dinitrobenzofuroxan (DNBF). In the latter case it was found that HCO_3^- and CO_3^{2-} act as nucleophilic catalysts in σ-complexation whereas OH^- functioned as a general base catalyst.[1a] This different behaviour provides further evidence that the dinitro-activated carbocyclic ring of the benzotriazoles

Table 3 Rate constants for catalysis of the formation of the adducts **1** and **4a–c** by carbonate and bicarbonate species[a]

Adduct	$k^{\mathrm{CO_3^{2-}}}$/dm^3 mol^{-1} s^{-1}	$k^{\mathrm{HCO_3^-}}$/dm^3 mol^{-1} s^{-1}	$k^{\mathrm{OH^-}}/k^{\mathrm{CO_3^{2-}}}$	$k^{\mathrm{OH^-}}/k^{\mathrm{HCO_3^-}}$
1[b]	2370	58	11.56	472
4a	16	0.78	24.5	502
4b	16	0.12	62.5	8330
4c	3.1	—	220	—

[a] $T = 25$ °C; $I = 0.2$ mol dm^{-3}. [b] Ref. 1*a*.

3a–e ranks somewhat lower in electrophilic/superelectrophilic properties.

Superelectrophilic *vs.* pericyclic reactivity in benzofuroxans and benzotriazoles

Recent works have highlighted the potential of benzofuroxans and benzotriazoles families to react not only as electrophilic heteroaromatics in σ-complexation and related S_NAr reactions but also in pericyclic manner as dienophiles and heterodienes. In this regard, a noteworthy finding is that whereas 4,6-dinitro and 4-nitrobenzofuroxans exhibited both types of reactivities, in contrast, in the 4,6-dinitrobenzotriazole series, only the most activated derivative, *i.e.* the picryl one, was found to react in Diels–Alder processes. In as much as the 2-(2,4,6-trinitrophenyl)-4,6-dinitrobenzotriazole 1-oxide structure is the only one which resembles DNBF in superelectrophilic behaviour, its capability to undergo Diels–Alder reactions points to a close relationship between the degree of electron-deficiency of the carbocyclic ring and the potential pericyclic reactivity of this ring. This finding suggests therefore that there is a direct relationship between superelectrophilic and pericyclic reactivities, a discovery which should be kept in mind in the design of new types of structures of inherent low aromaticity but highly prone towards pericyclic reactivity. This important conclusion concerning synthetic applications is here anchored on firmer ground based on the full kinetic and thermodynamic properties of both nitrobenzofuroxans and the triazole family of compounds.

Experimental

Materials

The benzotriazoles **3a–e** were compounds available from previous studies.[15,16] HCl and KOH solutions were prepared from Titrisol. Buffer solutions were made up from the best available commercial grades of reagents. Buffers used were formate (pH 3–4), benzoate (pH 3.6–4.3), acetate (pH 4–5.2), succinate (pH 4–5.7), phosphate (6–7.5), bicarbonate (pH 8.38), borate (pH 8.5–9.5), and carbonate (pH 9.5–10.5); solutions were prepared and their pH measured as described before.[1a]

Rate and pK_a measurements

Stopped-flow determinations were performed on an Applied Photophysics spectrophotometer, the cell compartment of which was maintained at 25° ± 0.2 °C. Other kinetic and pK_a measurements were made using a Varian Cary 1E spectrophotometer. All kinetic runs were carried out in triplicate under pseudo first-order conditions with a substrate concentration of 2 to 3 × 10^{-5} mol dm^{-3}. In the case of **2e**, the measurements were made in 90% H_2O–10% Me_2SO (v/v) to overcome solubility problems but this low Me_2SO content does not have any major influence on the results obtained, including in buffer solutions.[34] All rate constants are accurate to ± 3%.

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