Carbanion reactivity, kinetic and equilibrium studies of σ-adduct formation and elimination in the reactions of 4-nitrobenzofurazan derivatives with nitroalkane anions†

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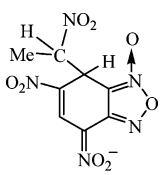
Received 1st March 2007, Accepted 22nd March 2007
First published as an Advance Article on the web 18th April 2007
DOI: 10.1039/b703154h

^{1}H NMR studies are reported of the reactions in [$^2H_6$]-DMSO of 4-nitrobenzofurazan, **2a**, and its 7-chloro- and 7-methoxy-derivatives, **2b** and **2c** respectively, with anions derived from nitromethane, **3**, nitroethane, **4**, and 2-nitropropane, **5**. The initial reactions result in σ-adduct formation by carbanion attack at the 5-position of **2a–c** and in the case of reaction of **2a** with **5** the adduct at the 7-position is also observed. These reactions may be followed by base catalysed elimination of nitrous acid to yield anionic alkene derivatives. Kinetic and equilibrium measurements of these reactions were made spectrophotometrically in methanol. The carbon nucleophilicities of the carbanions decrease in the order **3** > **4** > **5**, as also found in their reactions with benzhydrylium cations, and are much lower than the nucleophilicities of some cyano-substituted carbanions. Comparison with corresponding σ-adduct forming reactions of 1,3,5-trinitrobenzene, TNB, show that here **2** and TNB have similar electrophilicity, although the value of the intrinsic rate coefficient $k_o = 0.05$, for reaction of **2** is rather lower than that, $k_o = 0.20$, for the TNB reactions. Literature data suggest that for reaction with a variety of nucleophiles **2** and TNB show similar electrophilicities. Measurements of the rates of elimination of nitrous acid from some 5-adducts in methanol catalysed by methoxide ions are reported. Values of rate constants may be influenced both by steric requirements at the reaction centre and by the electronic effects of the 7-substituent.

Introduction

There is considerable current interest in measuring quantitatively nucleophilic and electrophilic reactivities, particularly in carbon–carbon bond forming reactions.[1,2] The nucleophilicities of many carbanions have been measured and values for some nitroalkane anions have recently been assessed by measuring rate constants for their reactions with benzhydrylium cations and quinone methides in water,[3] in DMSO[3] and in methanol–acetonitrile.[4] Conversely the electrophilicities of some superelectrophiles including 1,3,5-trinitrobenzene, TNB, and 4,6-dinitrobenzofuroxan, DNBF have been determined by measuring the rate constants for their reactions with some standard nucleophiles, including *N*-methylpyrrole and indole, in acetonitrile.[5,6]

Here we report kinetic and equilibrium results for the reactions of some nitroalkane anions with 4-nitrobenzofurazan and some 7-substituted derivatives. It is known that the nitroalkane anions may react to form anionic σ-adducts,[7] such as **1**, with DNBF[8,9] and with TNB[10] and there is one report of the reaction of 2-nitropropenide anion with 4-nitrobenzofurazan.[11] Previous reports have largely concentrated on determining the structures of the adducts formed although kinetic data are available for reactions of nitroalkane anions with TNB in methanol[12] and with DNBF in water.[8] Our results allow the comparisons both of the nucleophilicities of the nitroalkane anions and of the electrophilicities of the nitroaromatics in these σ-adduct forming reactions. A further interesting feature is that it is known[8] that in the presence of base the initially formed σ-adducts, such as **1**, may eliminate nitrous acid to give anionic alkene derivatives. We have for the first time measured rate constants for related elimination reactions in methanol.



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Our results also have relevance to studies of nucleophilic substitution of hydrogen by the vicarious mechanism.[13] There is evidence that the first step in this pathway involves σ-adduct formation[14] and that it is followed by a base-catalysed elimination process.[15] Overall the vicarious substitution mechanism allows the formation of neutral carbon–carbon bonded species.

Results and discussion

The reactions of 4-nitrobenzofurazan, **2a**, 7-chloro-4-nitrobenzofurazan, **2b**, and 7-methoxy-4-nitrobenzofurazan, **2c**, with anions derived from nitromethane, **3**, nitroethane, **4**, and 2-nitropropane, **5**, were studied.

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† Electronic supplementary information (ESI) available: Kinetic data (Tables 10–16). See DOI: 10.1039/b703154h
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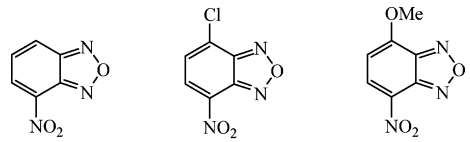


2a **2b** **2c**

^{1}H NMR measurements were made in [$^2H_6$]-DMSO in order to determine the structures of the intermediates and products produced in these reactions. Kinetic and equilibrium measurements were made in methanol to allow easy comparison with related results.[4,8,12]

^{1}H NMR results

Data for the parent molecules are in Table 1. Spectra of mixtures of nitrobenzofurazan derivatives with two molecular equivalents of nitroalkane and with two equivalents of triethylamine were recorded immediately after mixing. Subsequent changes in spectra with time were noted.

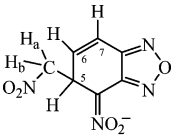
Spectra of 4-nitrobenzofurazan, **2a**, and nitromethane, **3**, measured under these conditions indicated formation of the 5-adduct, **6a**. Bands due to H5, H6 and H7 were observed at δ 4.55, 6.41 and 6.84 respectively. Owing to the chirality of C5, the geminal protons, H_a and H_b, of the added CH_2NO_2 group are diastereotopic and give separate spin-coupled bands. Shifts and coupling constants are in Table 2. The main evidence that it is the 5-adduct rather than the isomeric 7-adduct which is observed comes from the value for the shift of H6. It is known[16–18] that this value in 5-adducts will be considerably higher than in 7-adducts. For example in the 2-nitropropenide adducts, described later, shifts of H6 are δ 6.29 and 4.96 in the 5- and 7-adducts respectively. Hence the value of δ 6.41 observed with 2-nitromethane indicates that **6a** rather than its 7-isomer is formed. Spectra of **2b** and **2c** measured under the same conditions similarly indicate formation of the 5-adducts, **6b** and **6c** respectively. Shifts and coupling constants are in Table 2. In each case the initial spectra indicated extensive conversion of the nitrobenzofurazan derivative to 5-adduct and no bands due to the unreacted compounds were observed. However with **2a**, **2b** and **2c**, spectra measured after thirty minutes indicated that irreversible decomposition had occurred to give unidentified products.

Table 1 ^{1}H NMR data[a] for parent molecules in [$^2H_6$]-DMSO

	δ						
	H5	H6	H7	OMe	J_{56}	J_{67}	J_{57}
2a	8.70	7.85	8.61	—	7.2	8.8	0.8
2b	8.68	8.03	—	—	7.6	—	—
2c	8.75	7.06	—	4.21	8.6	—	—

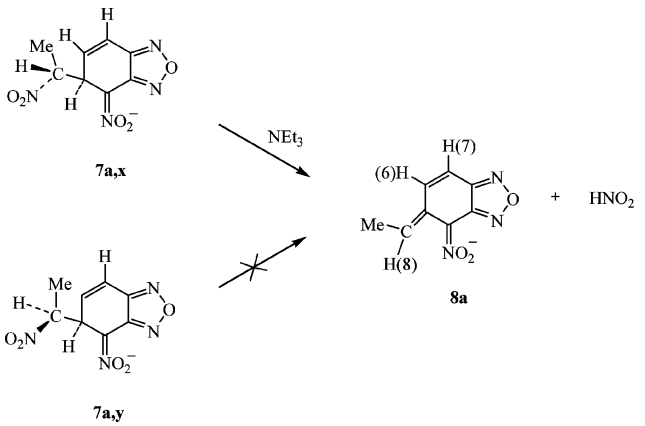
	δ		
	CH_nNO_2	Me	J_{CH-Me}
3	4.43	—	—
4	4.55	1.41	7.2
5	4.76	1.46	6.8
Triethylamine	CH_2 at 2.42	0.93	7.2

[a] Coupling constants in Hz.



6a

Spectra of **2a** with nitroethane, **4**, and triethylamine in [$^2H_6$]-DMSO initially show two sets of bands due to adducts in the intensity ratio 2 : 1. The chemical shifts, in Table 3, indicate that these are both adducts at the 5-position, and the observation of two sets of bands results from the formation of two chiral centres at C5 and Cα leading to the formation of diastereoisomeric complexes **7a**,**x** and **7a**,**y**. In Scheme 1 only one enantiomer for each is shown. With increasing time there is no evidence for isomerisation to give adducts at the 7-position. However the set of bands due to **7a**,**x** decreases in intensity and is replaced by bands attributable to **8a**, the product of elimination of nitrous acid. A quartet, J = 6.8 Hz, at δ 7.65 is observed for H8, with a doublet at δ 1.91 for the methyl group, while spin-coupled bands at δ 7.23 and 6.71 are attributed to the H6 and H7 ring hydrogens. The bands due



7a,x **7a,y** **8a**

Scheme 1

Table 2 ^{1}H NMR data[a] for 5-adducts formed from nitromethane in [$^2H_6$]-DMSO

	δ										
	H5	H6	H7	H_a	H_b	J_{56}	J_{57}	J_{67}	J_{ab}	J_{a5}	J_{b5}
6a	4.55	6.41	6.84	4.87	5.08	4.8	1.6	10	12	4	5.6
6b	4.66	6.63	—	4.86	5.16	5.2	—	—	8.2	3.2	5.6
6c	4.59	5.42	—	4.84	4.97	5.2	—	—	11.2	4	5.8

[a] Coupling constants in Hz.

Table 3 ^{1}H NMR data[a] for 5-adducts and elimination products formed with nitroethane in [$^2H_6$]-DMSO

	δ									
	H5	H6	H7	H8	Me	J_{56}	J_{57}	J_{67}	J_{58}	$J_{Me\text{-}8}$
7a, x	4.40	6.51	6.85	5.44	1.55	4.8	1.8	10.4	2.8	6.8
7a, y	4.83	6.02	6.98	5.51	1.15	4.8	1.4	10.2	4.0	6.8
7b, x	4.54	6.74	—	5.45	1.21	5.2	—	—	4.4	6.8
7b, y	4.95	6.24	—	5.46	1.21	5.4	—	—	4.0	6.8
7c, x	4.39	5.51	—	5.39	1.54	5.4	—	—	2.4	6.8
7c, y	4.87	4.98	—	5.50	1.12	5.4	—	—	4.0	6.8
8a	—	7.23	6.71	7.65	1.91	—	—	10.0	—	7.0
8b	—	7.32	—	7.62	1.91	—	—	—	—	8.0

[a] Coupling constants are in Hz.

to **7a**,**y** remain unchanged after two hours. It should be noted that from the NMR spectra it is not possible to unambiguously differentiate the structures **7a**,**x** and **7a**,**y**, so that the assignments may be reversed.

The spectra of **2b** in the presence of nitroethane and triethylamine are shown in Fig. 1. As with **2a**, two sets of bands are observed, in the ratio 1.8 : 1, attributed to the diastereoisomers **7b**,**x** and **7b**,**y** of the 5-adduct. Again the structural assignments to **7b**,**x** and **7b**,**y** may be reversed. Bands due to H6 are at δ 6.74 and 6.24, for H8 at δ 5.45 and 5.46 and for H5 at δ 4.54 (partially hidden by the methylene resonance of unreacted nitroethane) and 4.95. With time bands due to **7b**,**x** decrease in intensity coupled with the appearance of new bands attributed to the product **8b** of elimination of nitrous acid. Chemical shifts are in Table 3.

Spectra of **2c** with nitroethane and triethylamine similarly showed the initial formation of diastereoisomeric 5-adducts **7c**,**x** and **7c**,**y** in the ratio 1 : 1. However here there was no evidence for further reaction and the 5-adducts were stable for up to twenty-four hours in the presence of excess triethylamine.

It has been shown previously[11] by Terrier *et al.* that the reaction of **2a** with potassium 2-nitropropenide in [$^2H_6$]-DMSO leads to the formation of a mixture of the 5-adduct, **9a**, and the 7-adduct, **10a**, in an approximate ratio of 1 : 4. Our results obtained by generating the 2-nitropropenide ion *in situ* with triethylamine were in excellent accord with this. Spectra recorded soon after mixing gave bands due to **9a** and **10a** in a 1 : 5 ratio. After two hours only bands due to **10a** were observed. After twenty four hours the spectra showed the formation of **11a** the elimination product. These processes are summarised in Scheme 2, and shifts are in Table 4.

The spectra of **2b** in the presence of 2-nitropropane and triethylamine showed bands due to the 5-adduct, **9b**. However in this case bands due to unreacted **2b** were also present indicating that the equilibrium constant for adduct formation was lower than for reactions with nitromethane or nitroethane. With time there was no evidence for isomerisation or elimination, however bands were observed at δ 5.78 and 8.25, J = 10 Hz attributable[19] to

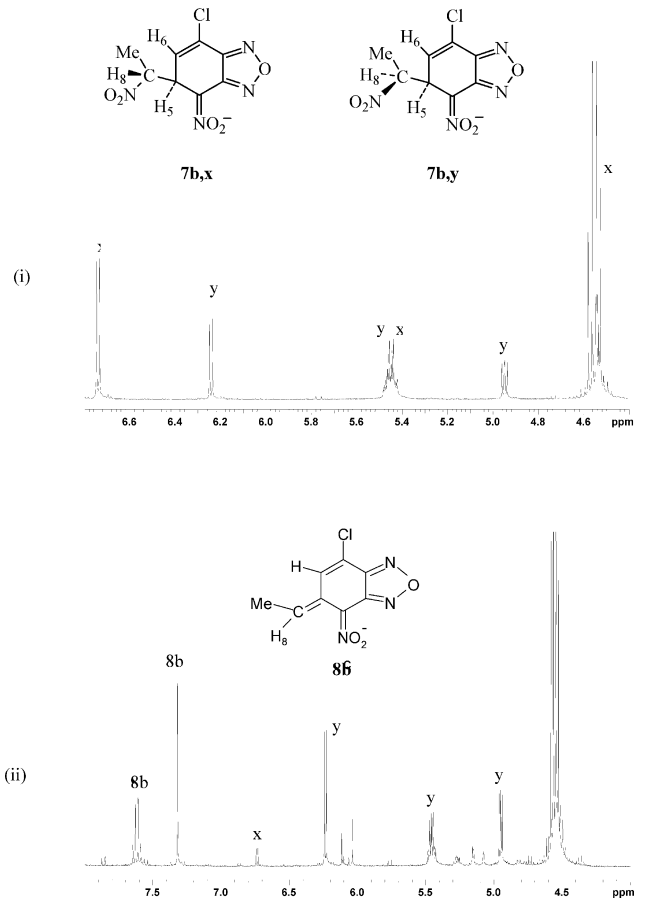


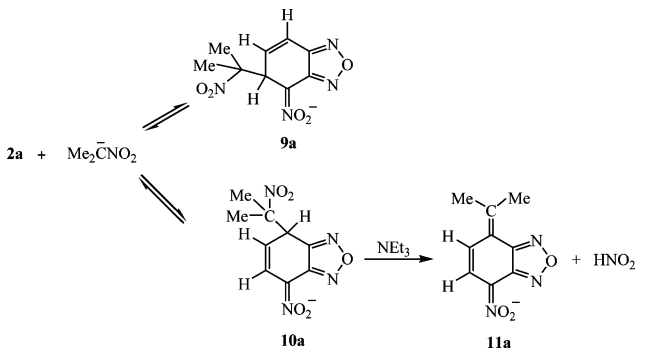
Fig. 1 ^{1}H NMR spectra, 400 MHz in [$^2H_6$]-DMSO, of 7-chloro-4-nitrobenzofurazan, 0.2 mol dm^{-3}, nitroethane, 0.5 mol dm^{-3}, and triethylamine, 1.0 mol dm^3, (i) initially and (ii) after 2 hours.

the formation of 7-hydroxy-4-nitrobenzofurazan. Formation of the hydrolysis product is likely to be due to reaction of **2b** with

Table 4 ^{1}H NMR data[a] for σ-adducts and elimination products formed with 2-nitropropane in [$^2H_6$]-DMSO

	δ							
	H5	H6	H7	Me[b]	Me[b]	J_{56}	J_{57}	J_{67}
9a	4.95	6.29	6.94	[c]	[c]	5.6	1.0	10
10a	7.09	4.96	4.58	1.51	1.45	10.4	1.6	4.4
9b	5.03	6.50	—	1.40	1.56	6.0	—	—
9c	4.94	5.24	—	1.34	1.54	6.2	—	—
11a	6.89	6.02	—	1.99	2.26	10.4	—	—

[a] Coupling constants are in Hz [b] In **9** and **10**, the methyl groups are non-equivalent due to their proximity to the chiral centre at C5. [c] Hidden by 2-nitropropane signal.



Scheme 2

hydroxide ions formed from small amounts of adventitious water present in the solvent.

In the case of **2c** bands due to the 5-adduct **9c** were observed together with bands due to unreacted parent. No change in spectrum occurred over twenty four hours. Chemical shifts are in Table 4.

Before considering the kinetic results it is useful to briefly discuss the ^{1}H NMR results. Our results show generally that adducts at the 5-position are formed initially, only in the case of reaction of 4-nitrobenzofurazan with 2-nitropropenide is the 7-adduct observed. The usual behaviour of 4-nitrobenzofurazan and its derivatives with nucleophiles is that 5-adducts are kinetically favoured while the isomeric 7-adducts are thermodynamically more stable. This reactivity pattern has been reported for reactions with methoxide ions[16,20,21] in methanol, hydroxide ions[19] in water, sulfite ions[18] in water and aliphatic amines[22] in DMSO. The explanation,[11,22] in brief, is that the 5-adducts have fewer resonance forms available to delocalise negative charge than the 7-adducts leading to lower kinetic barriers and also lower thermodynamic stabilities.

The failure to observe 7-adducts from **2a** with the anions of nitromethane and nitroethane is likely to derive from the high equilibrium constants for formation of the 5-adducts leading to slow equilibration to their more thermodynamically stable isomers coupled with alternative reaction pathways, either decomposition or elimination, for the 5-adducts. In the case of the 2-nitropropenide adduct **9a** steric interference between the added group at the five position and the adjacent NO_2^- group will reduce stability and encourage isomerisation to the thermodynamically more stable 7-adduct.

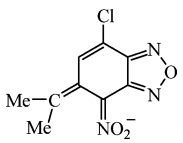
Table 5 Variation with time of the relative intensities[a] of ^{1}H NMR bands due to diastereoisomeric adducts **7b x** and **y** formed from 7-chloro-4-nitrobenzofurazan and nitroethane anion

	Ratio **x**–**y**		
[Triethylamine]/mol dm^{-3}	Initial	30 minutes	120 minutes
0.5	1.8	1.2	0.4
1.0	1.8	1.0	0.2
2.0	1.4	0.1	—

[a] The relative intensities of bands due to H6 at δ 6.74 and 6.24 were monitored in [$^2H_6$]-DMSO solutions containing **2b**, 0.2 mol dm^{-3} and nitroethane, 0.5 mol dm^{-3}.

It is interesting that in **2b** and **2c** there is no evidence for nucleophilic attack at the substituted 7-position. This can be attributed to the steric and electrostatic repulsion[19,21] between the entering carbon base and the leaving group. Makosza and co-workers[23] have found in their studies of the vicarious substitution mechanism that ring halogen atoms, while activating unsubstituted positions, protect the position they occupy against substitution.

The ^{1}H NMR results show that in the case of nitroethane adducts **7a** and **7b** only one of the diastereoisomers eliminates nitrous acid in the timescale of the experiment. Semi-quantitative results in which the triethylamine concentration was varied are in Table 5 and show that elimination is faster at higher base concentrations, consistent with a base-catalysed mechanism. Previously[8] it has been shown that adducts at the 7-position of DNBF will similarly undergo elimination. The X-ray crystal structure[9] of the 2-nitropropanide adduct shows that the hydrogen and the nitro-group to be eliminated are in a *syn*-configuration suggesting the possibility that a *syn*-elimination process is involved. In the present work the fact that only one of the diastereoisomers undergoes elimination is likely to be due to the stereoelectronic requirements of the process coupled with the very slow interconversion of the diastereoisomers. The failure to eliminate of 2-nitropropenide adducts at the 5-position may be attributed to the very unfavourable steric interactions between a methyl group and the adjacent NO_2^- group in the possible products, *e.g.* **12**.



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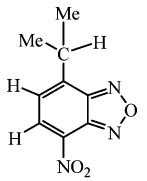
It should be noted that in attempts to replicate the vicarious substitution pathway[13–15] to give neutral products we examined the effects of acidification of the anionic elimination products **8** and **11**. The addition of concentrated hydrochloric acid to NMR tubes containing these products prepared *in situ* gave a complex series of bands with no evidence for bands expected for substitution products, such as **13** from **11a**. In a preparative experiment the presence of the anion **11a** in a reaction mixture containing **2a**, 2-nitropropane and triethylamine in DMSO was confirmed by negative electrospray mass spectrometry which showed a peak as expected at *m*/*z* 206. On the addition of aqueous hydrochloric acid a precipitate was obtained and the mass spectrum in acetonitrile was measured. Under negative electrospray conditions this showed a small peak at *m*/*z* 206 possibly corresponding to M–H for **13**. However many other bands were present at higher mass numbers

indicating the presence of a mixture of products. The extreme difficulty in achieving the carbon-protonation required to produce neutral substitution products in nitrobenzofurazan derivatives has been noted previously.[8] However it has been shown that electrochemical[24] or chemical oxidation[11] of the initially formed σ-adducts, such as **10a**, is successful in yielding neutral products.



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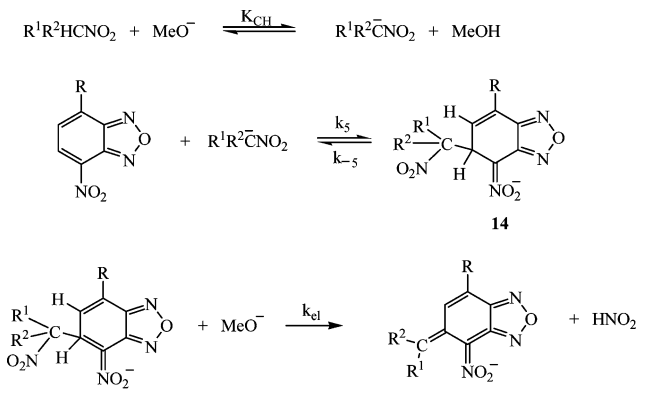

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Scheme 3

Kinetic and equilibrium measurements in methanol

These measurements were made spectrophotometrically using nitroalkane anions generated *in situ* from the parent nitroalkanes and sodium methoxide. The pK_a values of the nitroalkanes in methanol are known[12] to be 15.6, 14.2 and 13.5 for nitromethane, nitroethane and 2-nitropropane respectively allowing the equilibrium concentrations of nitroalkane anions and methoxide to be calculated. Due to the known reactions of the 4-nitrobenzofurazans with methoxide,[16,20,21] it was necessary to reduce the concentration of free methoxide ions to low values and this was done by working with [nitroalkane] $\gg$ $[MeO^-]_{stoich}$ and/or by using phenolic buffers to regulate their concentration.

4-Nitrobenzofurazan, 2a

2a shows an absorption maximum at 320 nm, $\varepsilon = 9 \times 10^3$ dm^3 mol^{-1} cm^{-1} in methanol. In the presence of anions derived from each of **3**, **4** and **5** there is a rapid reaction, measurable on the stopped-flow timescale, resulting in a shift of the maximum to longer wavelength and with increased absorbance, λ_{max} 335 nm, $\varepsilon = 1.8 \times 10^4$ dm^3 mol^{-1} cm^{-1}. Kinetic measurements were made at 25 °C with concentrations of nitroalkane and methoxide in large excess of the concentrations of **2a**. Under these conditions first order kinetics were observed and the rate constant is designated as k_{fast}. In the case of the reactions with **3** and **4** there was also a very much slower reaction, k_{slow}, again first order giving rise to an absorption band at 370 nm. With **5**, subsequent reactions were more complex and were not investigated in detail.

These processes are interpreted in terms of Scheme 3. It is known that the first step, the equilibration of the nitroalkanes with methoxide, is rapid.[12] In view of the ^{1}H NMR results and known reactivity with other nucleophiles,[18–22] the faster process which we observed is likely to form the 5-adduct and eqn (1) will apply.

$$k_{fast} = k_5[R^1R^2CNO_2^-] + k_{-5} \quad (1)$$

The shift to longer wavelength observed in the slower process is not consistent with isomerisation to give the 7-adduct since this process is not expected to involve a substantial change in absorption maximum.[18–22] However the bathochromic shift is consistent with the increased delocalisation expected on formation of the elimination product.

Results for reaction of **2a** with the nitromethane anion are in Table 6. The first five items show that k_{fast} increases linearly with increase in the carbanion concentration and gives a value for k_5 of 300 ± 20 dm^3 mol^{-1} s^{-1}. However the intercept is too low to allow calculation of a value for k_{-5}. Measurements in buffer solutions where the methoxide concentration, and hence carbanion concentrations, are very low but constant give a value for k_{-5} of (8 ± 3) × 10^{-4} s^{-1}. An alternative method for determining k_{-5} is as k_5/K_5 using the known value of k_5 and the value of K_5, 3.8 × 10^5 dm^3 mol^{-1}, calculated from amplitudes at completion of the reaction. This similarly gives a value of 8 × 10^{-4} s^{-1} for k_{-5}. The final five items in the Table refer to the slow reaction. The carbanion concentrations here are sufficiently high that initial conversion of **2a** to its 5-adduct is virtually complete. The data fit eqn (2) so that a plot of k_{slow}

$$k_{slow} = k_{el}[MeO^-] \quad (2)$$

versus methoxide concentration is linear with zero intercept, giving a value for k_{el} of 3 ± 0.3 dm^3 mol^{-1} s^{-1}. It should be noted that in the dilute solutions in methanol used in the kinetic studies the elimination reaction proceeded smoothly in this case, whereas the NMR work showed that in more concentrated solutions in DMSO other decomposition pathways prevailed.

Corresponding results for the reaction of **2a** with the nitroethane anion are available as supplementary information, ESI,† in Table 10. The values obtained for k_5, k_{-5} and K_5 are collected in Table 8. Measurement of the slow elimination reaction at 370 nm gave a value for k_{el} of 1.4 ± 0.2 dm^3 mol^{-1} s^{-1}. It was noted here that there is also a very much slower process, too slow for convenient measurement, giving rise to a further increase in absorbance at 370 nm. The ^{1}H NMR measurements show that one of the diastereoisomers of the σ-adduct **7a** suffers elimination very much more rapidly than the other. So these two processes may represent elimination reactions which occur on different timescales.

In the case of 2-nitropropane, a linear plot of k_{fast} *versus* the 2-nitropropenide concentration allowed values of k_5 and k_{-5} to be calculated. Results are in Table 11 available as ESI.†

7-Methoxy-4-nitrobenzofurazan, 2c

The parent shows a UV maximum at 375 nm, $\varepsilon = 9.1 \times 10^3$ dm^3 mol^{-1} cm^{-1}. In the presence of nitroalkane anions a fast process, k_{fast}, was observed in which the maximum shifts to 335 nm with increased absorbance. Kinetic measurements made

Table 6 Kinetic data for the reaction of nitrobenzofurazan[a] with nitromethane and methoxide in methanol at 25 °C

[Nitromethane]/ mol dm^{-3}	[NaOMe]/10^{-3} mol dm^{-3}	[MeO$^-$][b]eq/10^{-4} mol dm^{-3}	[$CH_2NO_2^-$][b]eq/ 10^{-3} mol dm^{-3}	k_{fast}[d]/s^{-1}	Ampt	K_5[e]/10^5dm^3 mol^{-1}
0.15	1.0	2.4	0.80	0.24	0.49	—
0.15	1.5	3.6	1.1	0.35	0.59	—
0.15	2.0	4.8	1.5	0.42	0.58	—
0.15	2.5	6.0	1.9	0.62	0.55	—
0.30	2.5	3.3	2.2	0.65	0.58	—
0.0010	5.0	0.54[c]	0.0011	0.0013	0.19	4.0
0.0015	5.0	0.54[c]	0.0017	0.0018	0.24	4.0
0.0020	5.0	0.54[c]	0.0024	0.0022	0.26	3.3
				k^f_{slow}/10^{-4} s^{-1}		
0.95	1.1	0.50	1.0	1.9		
0.67	1.1	0.70	1.0	2.6		
0.90	2.0	1.0	1.9	3.8		
0.67	2.2	1.4	2.0	4.8		
0.90	3.0	1.5	2.8	4.8		

[a] Concentration is 5×10^{-5} mol dm^{-3}. [b] Calculated using a value for K_{CH} of 21 dm^3 mol^{-1}. [c] Equilibrium methoxide concentration in bromophenol buffers. [d] Measured as a colour forming process at 335 nm. [e] Calculated as Ampt/(0.60-Ampt)·($CH_2NO_2^-$)eq. [f] Measured as a forming process at 370 nm.

Table 7 Kinetic data for the reaction of 7-chloro-4-nitrobenzofurazan[a] with nitroethane and methoxide in methanol at 25 °C

[Nitroethane]/ mol dm^{-3}	[NaOMe]/10^{-3} mol dm^{-3}	[MeO$^-$][b]eq/ 10^{-4} mol dm^{-3}	[$MeCHNO_2^-$][b]eq/ 10^{-3} mol dm^{-3}	k_{fast}[c]/s^{-1}	k_{slow}[d]/10^{-3} s^{-1}
0.050	2.0	0.80	1.90	0.70	1.2
0.050	3.0	1.2	2.90	1.1	1.5
0.050	4.0	1.6	3.80	1.5	1.8
0.050	5.0	2.0	4.80	1.9	2.1
0.010	5.0	1.0	4.90	1.8	1.2
0.025	5.0	4.0	4.6	(2.2)[e]	3.6

[a] Concentration is 5×10^{-5} mol dm^{-3}. [b] Calculated using a value for K_{CH} of 500 dm^3 mol^{-1}. [c] Colour forming process at 320–350 nm. [d] Colour forming process at 380 nm. [e] Some interference from methoxide reaction here.

at 375 nm are reported in Tables 12–14, available as ESI.† Values for k_5, k_{-5} and K_5 are in Table 8. It should be noted that the equilibrium constant[21] for formation of the 5-methoxy adduct is 22 dm^3 mol^{-1}, so that at the equilibrium methoxide concentrations used here there is no interference from this process. Methoxide may also add at the 7-position to give a di-methoxy adduct. However the rate constant, 14.5 dm^3 mol^{-1} s^{-1} is sufficiently small that this process[21] cannot compete kinetically with carbanion addition at the 5-position. As found from the ^{1}H NMR spectra there is no evidence for elimination from the 5-adducts to give alkene derivatives.

7-Chloro-4-nitrobenzofurazan, 2b

2b shows a UV absorption maximum at 337 nm, $\varepsilon = 1.0 \times 10^4$ dm^3 mol^{-1} cm^{-1}. Reaction with the nitroalkane anions showed a rapid process, k_{fast}, giving an increase in absorbance but with little change in λ_{max}. Kinetic measurements were made in the range 320–350 nm and values of rate constants were independent of the wavelength of measurement.

The 7-chloro derivative, **2b**, is more reactive than **2a** and the value of the equilibrium constant for formation of 5-methoxy adduct[21] is 2800 dm^3 mol^{-1}. In the case of the anions from 2-nitropropane and nitroethane it was possible to reduce the equilibrium concentrations of methoxide ions to sufficiently low levels to avoid interference from the methoxide reaction. Data for the reaction with 2-nitropropanide are in Table 15 (ESI†) and lead to values for k_5 10 ± 1 dm^3 mol^{-1} s^{-1} and k_{-5} (5 ± 1) × 10^{-3} s^{-1}. Results for reaction with the nitroethane anion are in Table 7. A linear plot of k_{obs} *versus* [$CH_3CHNO_2^-$] gives a value for k_5 of 400 ± 20 dm^3 mol^{-1} s^{-1}. Here a slow reaction, k_{slow}, giving a band at 380 nm was observed, indicating that elimination was occurring. Values of k_{slow} increase linearly with the methoxide concentration giving a value for k_{el} 12 dm^3 mol^{-1} s^{-1}.

In the case of reaction with the nitromethane anion it was not possible to avoid some interference with the methoxide addition. The analysis,[35] in Table 16 given as ESI,† leads to a value for k_5 of 1500 ± 200 dm^3 mol^{-1} s^{-1}.

Comparisons and conclusions

Nucleophilicities

Kinetic and equilibrium results in methanol are summarised in Table 8. They show that k_5 values, measuring the carbon nucleophilicities of the anions, decrease in order nitromethane > nitroethane > 2-nitropropane. Values of K_5, measuring the carbon basicities, decrease in the same order, and parallel the changes in proton basicities of the anions measured by the pK_a values. It is worth noting that changes in values of k_5 are much bigger than

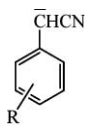
Table 8 Summary of kinetic and equilibrium data for reaction of 4-nitrobenzofurazan derivatives with nitroalkane anions in methanol at 25 °C

Parent nitroalkane	k_5/dm^3 mol^{-1} s^{-1}	k_{-5}/10^{-3} s^{-1}	K_5/dm^3 mol^{-1}	pK_a
	4-Nitrobenzofurazan, **2a**			
Nitromethane	300 ± 20	0.8 ± 0.3	(4 ± 1) × 10^5	15.6
Nitroethane	80 ± 10	1.2 ± 0.2	(6.6 ± 1) × 10^4	14.2
2-Nitropropane	2.6 ± 0.2	3.0 ± 0.3	870 ± 100	13.5
	7-Chloro-4-nitrobenzofurazan, **2b**			
Nitromethane	1500 ± 100	—	—	15.6
Nitroethane	400 ± 20	—	—	14.2
2-Nitropropane	10 ± 1	5 ± 1	(2 ± 0.5) × 10^3	13.5
	7-Methoxy-4-nitrobenzofurazan, **2c**			
Nitromethane	100 ± 10	2.5 ± 0.2	(4.0 ± 0.5) × 10^4	15.6
Nitroethane	29 ± 2	2.1 ± 0.2	(1.4 ± 0.2) × 10^4	14.2
2-Nitropropane	1.4 ± 0.1	13 ± 2	110 ± 20	13.5
	1,3,5-Trinitrobenzene[a] (TNB)			
Nitromethane	800	11	7 × 10^4	15.6
Nitroethane	34	9	380	14.2
2-Nitropropane	0.36	9	4	13.5

[a] Values from ref. 12, are for attack at an unsubstituted ring position of TNB and have not been statistically corrected.

those in k_{-5}, probably indicating a product-like transition state for these reactions.

The nucleophilic reactivity order found here, nitromethane > nitroethane > 2-nitropropane, is the same as that found in σ-adduct forming reactions of the anions with 1,3,5-trinitrobenzene,[12] and in their reactions with benzhydrylium cations[4] in methanol–acetonitrile (91 : 9, v/v). Values of rate constants for nucleophilic attack at the 5-position of 4-nitrobenzofuroxan by ring-substituted benzyl cyanide carbanions, **16**, in methanol are *ca.* 10^8 dm^3 mol^{-1} s^{-1} and are very much higher than those for the nitroalkane anions.[25] Similarly cyano-activated carbanions show considerably higher reactivities than nitro-activated carbanions in reactions with benzhydrylium cations in methanol.[4] The data available are not sufficient to allow quantitative comparisons but do suggest an overall similarity, largely independent of the electrophile, in carbanion reactivity patterns in methanol. However, as reinforced by Mayr *et al.* recently, nucleophilic reactivities are very solvent dependent so that change, *e.g.* to DMSO, results in large changes in relative nucleophilicity.[3,4]



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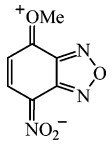
Electrophilicities

The results in Table 8 show that the reactivity order, k_5 values, for each of the nitroalkane anions is **2b** > **2a** > **2c**. The higher reactivity of **2b** than of **2a** is consistent with the inductive effect, σ_m 0.37, expected for chlorine *meta* to the reaction site at the 5-position.[26] The reduced reactivity of **2c** can be attributed to resonance stabilisation, **17**, between the nitro and methoxy groups in the parent which is lost, or partially lost, on formation of the negatively charged adduct.[18,19]



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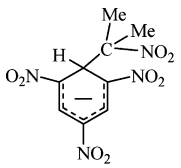
Values included in Table 8 show that the reactivity of 1,3,5-trinitrobenzene (TNB) is generally comparable to that of the 4-nitrobenzofurazans. However the relative reactivity of TNB does depend to some extent on the identity of the anion, thus for $CH_2NO_2^-$ the order is **2b** > TNB > **2a** > **2c**, for $MeCHNO_2^-$ **2b** > **2a** > TNB ∼ **2c** and for $Me_2CNO_2^-$ < **b** > **2a** > **2c** > TNB. TNB, where addition must occur at a ring-position flanked by two nitro groups, is more sterically demanding than the 4-nitrobenzofurazans and these orders may indicate some unfavourable steric interactions in the TNB-adducts, such as **18**, formed from the bulkier anions.



18

It is also useful to compare the reactivities of the nitrobenzofurazans and TNB in these reactions in terms of their intrinsic reactivities in the Marcus sense.[27–29] Logarithmic plots of rate constants *versus* equilibrium constants in Fig. 2 allow the determination of a value for the intrinsic rate coefficient, k_o, of 0.05 for reaction at the 5-position. Data for each carbanion fit essentially on the

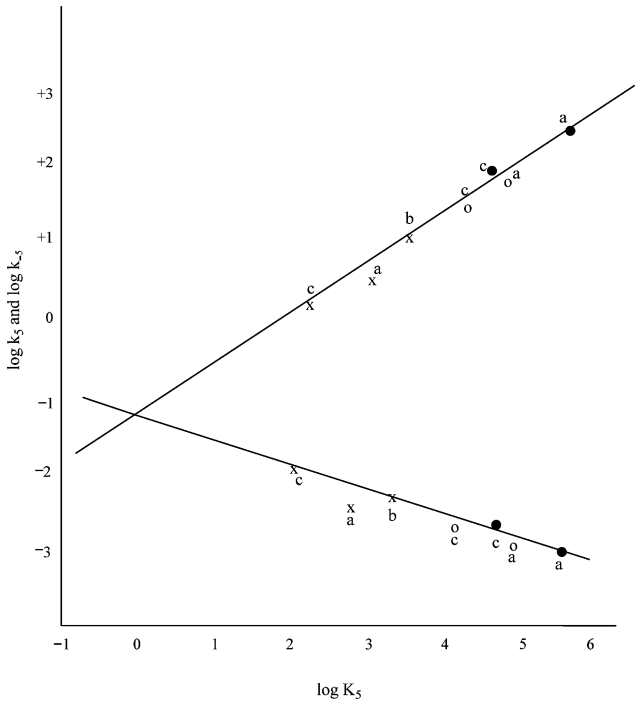
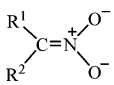


Fig. 2 Reactions of anions of nitromethane (●), nitroethane (○), and 2-nitropropane (x) at the 5-position of 4-nitrobenzofurazan a, 7-choro-4-nitrobenzofurazan b, and 7-methoxy-4-nitrobenzofurazan, c.

same straight lines. The value of 0.05 can be compared with a value of k_o, 0.20 found previously[12] for corresponding reactions of the carbanions with trinitrobenzene derivatives. Values of intrinsic rate coefficients are thought[29–32] to reflect the amount of electronic-structural reorganisation and solvent reorganisation accompanying the reaction; the more reorganisation required the lower the reactivity. The low values obtained for reaction of the nitroalkane anions, compared for example to reaction of cyano-activated carbanions,[12] reflects their structure. In methanol the anions may be represented by **19** in which the negative charge is largely on the nitro-group and will be strongly solvated. Nucleophilic attack *via* the carbon centre necessitates considerable reorganisation.



19

The lower k_o value for the nitrobenzofurazans than for the TNB derivatives may reflect the very strong solvation by methanol of the negative charge on the 4-nitro group in structure **14**. As noted previously, reaction at the 7-position of 4-nitrobenzofurazan occurs more slowly than at the 5-position but leads to more thermodynamically stable adducts. The inference is that the greater possibilities of charge delocalisation[11,22] for the 7-adducts leads to reduced intrinsic reactivity.

Terrier *et al.* [5,6] have ranked strongly electron deficient compounds using their σ-adduct forming reactions with a series of neutral nucleophiles in acetonitrile. Compared to superelectrophiles such as DNBF, TNB comes at the lower end of the electrophilicity scale. Our present results with nitroalkane anions in methanol suggest that for reaction at the 5-position the 4-nitrobenzofurazan derivatives have similar electrophilicities to TNB. However electrophilicity for reaction at the 7-position is lower than for TNB. In fact, data is available in the literature allowing the comparison of the reactivities of TNB and 4-nitrobenzofurazan with a variety of other nucleophiles in a variety of solvents. The results in Table 9 show that values of rate constants for nucleophilic attack are remarkably similar for the two compounds. This suggests that their relative electrophilicities are largely independent of the nucleophile. Nevertheless there are large differences in relative values for the reverse reactions leading to large differences in the thermodynamic stabilities of the adducts formed.

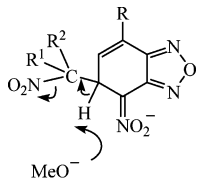
Elimination reaction

Rate constants for three reactions were measured under conditions where initial conversion of the substrates to 5-adducts, **14**, is largely complete. Values of first order rate constants increase linearly with the methoxide concentration indicating a base catalysed process. It is worth noting that no catalysis was observed from the more sterically demanding carbanions present in excess. We have no direct evidence as to the mechanism of the elimination. However it has been shown that in related eliminations in the vicarious substitution pathway[15] an E2-type process has been found. A pathway involving a transition state such as **20** would be compatible with our results. The reduction in value of k_{el} from 3 to 1.4 dm^3 mol^{-1} s^{-1} on going from the nitromethane to the nitroethane adducts of **2a** is likely to be due to increased steric congestion around the reaction centre. The increase from 1.4 to 12 dm^3 mol^{-1} s^{-1} for k_{el} for the nitroethane adducts of **2a** and **2b** will reflect the electronic influence of the chlorine atom at the 7-position.

Table 9 Comparison of the electrophilic reactivities of 4-nitrobenzofurazan, **2a**, and 1,3,5-trinitrobenzene (TNB)

		2a			TNB[a]			
Nucleophile	Solvent	k_5/dm^3 mol^{-1} s^{-1}	k_{-5}/s^{-1}	K_5/dm^3 mol^{-1}	k_f/dm^3 mol^{-1} s^{-1}	k_r/s^{-1}	K/dm^3 mol^{-1}	Ref
SO_3^{2-}	Water	3.3×10^4	0.020	1.65×10^6	3.5×10^4	125	290	18, 33
HO^-	Water	30	0.011	2700	46	13.5	3.4	19
MeO^-	Methanol	1200	8.5	140	7050	305	23	20
4-$CNC_6H_4CHCN^-$	Methanol	1.4×10^8	—	—	5×10^7	—	—	25
n-Butylamine[b]	DMSO	1.7×10^4	—	110	4.5×10^4	—	1000	22

[a] Values are for reaction at an unsubstituted ring position of TNB and have not been statistically corrected. [b] Data here for reaction of 4-nitrobenzofuroxan.



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Experimental

7-Chloro-4-nitrobenzofurazan, **2b**, 1,3,5-trinitrobenzene and the nitroalkanes **3**, **4** and **5** were the purest available commercial samples. 4-Nitrobenzofurazan, **2a**, was available from previous work.[18] 7-Methoxy-4-nitrobenzofurazan, **2c**, m.p. 113 °C (lit.[21] m.p. 115 °C) was prepared by reaction at 40 °C for one hour of **2b** with one equivalent of sodium methoxide in methanol. Solutions of sodium methoxide were prepared by dissolving clean sodium in AnalaR methanol under nitrogen. Solutions containing very low equilibrium concentrations of methoxide ions were prepared using buffers prepared from 4-bromophenol whose pK_a value[34] in methanol is 13.61. All other materials and solvents were the purest available commercial samples.

^{1}H NMR spectra [$^2H_6$]-DMSO were recorded using a Bruker Avance-400 MHz instrument. UV–visible spectra and kinetic measurements were made with an Applied Photophysics SX-17 MV stopped-flow instrument, or with Shimadzu UV-2101 PC or Perkin Elmer Lambda 2 spectrophotometers. First order rate constants, precise to ±3% were evaluated using standard methods.

Acknowledgements

We thank the Ministry of Higher Eduction, Kingdom of Saudi Arabia for funding for B.H.M.A.

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