# The versatile reactivity of 2-aryl-4,6-dinitrobenzotriazole 1-oxides in Diels–Alder type condensations and in σ-complexation — A relationship between superelectrophilicity and pericyclic reactivity

**Dominique Vichard, Taoufik Boubaker, François Terrier, Marie-José Pouet, Julian M. Dust, and Erwin Buncel**

**Abstract**: A two-pronged study of a series of 2-aryl-4,6-dinitrobenzotriazole 1-oxide substrates (**2a**–**c**) is reported: Diels–Alder type pericyclic reactivity and covalent hydration to yield Meisenheimer type hydroxy anionic σ-adducts. The most activated benzotriazole 1-oxide **2a** is found to exhibit both dienophilic and heterodienic behaviour on treatment with cyclopentadiene, providing a highly functionalized stereoselective diadduct (**7**). This diadduct is shown to be the result of two consecutive inverse demand Diels–Alder condensations proceeding through the *endo* mode with a *trans* addition of two cyclopentadiene molecules. Kinetic and thermodynamic measurements of the ease of covalent hydration of **2a**–**c** to give σ-adducts **4a**–**c** in aqueous solution indicate that the electrophilic reactivity of the 4,6-dinitrobenzotriazole 1-oxide structure is much closer to that of the superelectrophilic 4,6-dinitrobenzofuroxan (DNBF, **1a**) than that of the standard Meisenheimer electrophile 1,3,5-trinitrobenzene (TNB). The p$K_a$ values range from 6.70 for the 2-(2′,4′,6′-trinitrophenyl)-4,6-dinitrobenzotriazole 1-oxide (Pi-DNBT, **2a**) to 10.73 for the 2-phenyl-4,6-dinitrobenzotriazole 1-oxide (Ph-DNBT, **2c**). The observation that the most activated benzotriazole 1-oxide structure **2a** which resembles 4,6-dinitrobenzofuroxan (DNBF) in superelectrophilic behaviour, is the only one that undergoes Diels–Alder reactions, points to a direct relationship between superelectrophilic and pericyclic reactivity.

*Key words*: σ-complexes, arylnitrobenzotriazole 1-oxides, super-electrophiles, Diels–Alder condensations, pericyclic reactions.

**Résumé** : On a réalisé une étude d'une série de substrats 1-oxyde de 2-aryl-4,6-dinitrobenzotriazole (**2a**–**c**) et elle a été menée sur deux fronts: la réactivité péricyclique de type Diels–Alder et l'hydratation covalente conduisant à des adduits σ, des hydroxy anioniques de type Meisenheimer. On a observé que le traitement de l'oxyde de benzotriazole le plus activé (**2a**) avec du cyclopentadiène donne lieu à des comportements à la fois diénophile et hétérodiénique et qu'il permet d'obtenir un diadduit stéréosélectif hautement fonctionnalisé (**7**). On a démontré que ce diadduit résulte de deux condensations consécutives de Diels–Alder ayant des demandes inverses et qu'elles se produisent par le mode *endo* avec une addition *trans* de deux molécules de cyclopentadiène. Des mesures cinétiques et thermodynamiques de la facilité d'hydratation covalente des composés **2a**–**c** qui conduit à la formation des adduits σ correspondants (**4a**–**c**) indiquent que, en solution aqueuse, la réactivité électrophile de la structure 1-oxyde de 4,6-dinitrobenzotriazole est beaucoup plus proche de celle du 4,6-dinitrobenzofuroxane (DNBF, **1a**) superélectrophile que de celle du 1,3,5-trinitrobenzène (TNB), l'électrophile de Meisenheimer de référence. Les valeurs de p$K_a$ vont de 6,70 pour le 1-oxyde de 2-(2′4′6′-trinitrophényl)-4,6-dinitribenzotriazole (Pi-DNBT, **2a**) à 10,73 pour le 1-oxyde de 2-phényl-4,6-dinitrobenzotriazole (P-DNBT, **2c**). On a observé que la seule structure à subir des réactions de Diels–Alder est la structure la structure la plus activée du 1-oxyde de benzotriazole (**2a**), qui ressemble au 4,6-dinitrobenzofuroxnae

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*Dedicated to Professor Victor Snieckus in recognition of his contributions to Canadian chemistry.*

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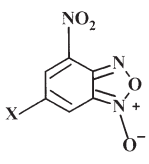
(DNBF) en comportement supe-électrophile; cette observation suggère qu'il existe une relation directe entre un comportement superélectrophile et la réactivité péricyclique.

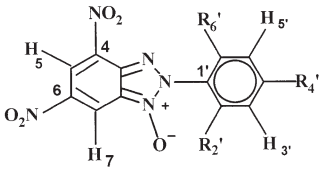
*Mots clés* : complexes-σ, 1-oxydes d'arylnitrobenzotriazole, superélectrophiles, condensations de Diels–Alder, réactions péricycliques.

[Traduit par la Rédaction]

## Introduction

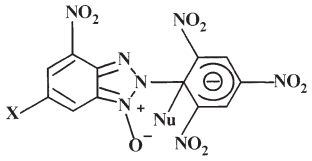
Following the discovery of the extremely strong electrophilic character of the carbocyclic ring of 4,6-dinitrobenzofuroxan (DNBF, **1a**) (1–9), we have been engaged in an effort to design analogues of **1a** in which the oxygen atom in the furoxan ring is replaced by other electron-withdrawing moieties (10, 11). We thus found that 2-(2′,4′,6′-trinitrophenyl)-4,6-dinitrobenzotriazole 1-oxide (Pi-DNBT, **2a**) is also a powerful electrophilic heterocycle that undergoes facile σ-complexation at C-7 of the carbocyclic ring with a number of nucleophiles, including weak neutral nucleophiles like water, methanol, or ethanethiol (10*a*). A contrasting feature of **2a** is that the C-1′ carbon of the picryl ring is also susceptible to reaction with nucleophiles, giving rise to an $S_NAr$ displacement reaction via the metastable σ-adduct **3a** (10, 11). The ambident (C-7 vs. C-1′) electrophilicity of **2a** (and other members of benzotriazole 1-oxides series, e.g., **2b**) has given new impetus to the study of reactivity–selectivity relationships in reactions of this and related ambident electrophiles with ambident nucleophiles (9*b*, 11).





**1a** X = $NO_2$ (DNBF)
**1b** X = H (NBF)

**2a** $R_2'$ = $R_4'$ = $R_6'$ = $NO_2$ (Pi-DNBT)
**2b** $R_2'$ = $R_6'$ = H ; $R_4'$ = $NO_2$ (NP-DNBT)
**2c** $R_2'$ = $R_4'$ = $R_6'$ = H (Ph-DNBT)

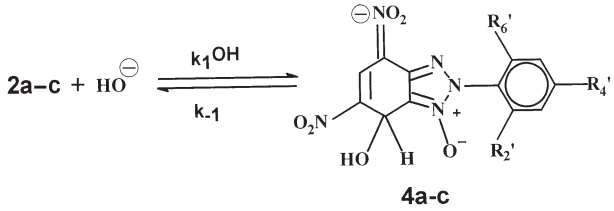


**3a**

In probing the manifold reactivity of electron-deficient heteroaromatics like **1a**, we have discovered that nitrobenzofuroxans are also remarkably versatile reagents in pericyclic reactions such as the Diels–Alder, being capable of acting as dienophiles, carbodienes, or heterodienes depending upon the experimental conditions and reaction partners employed (12). To test whether this diverse pericyclic reactivity is a reflection of the low aromaticity of the carbocyclic ring of such compounds, studies have been undertaken of the 2-aryl-4,6-dinitrobenzotriazole 1-oxides (**2a**–**c**) in which the electron-withdrawing power of the 2-aryl moiety is systematically decreased through the sequential removal of nitro groups. In this paper, we report that **2a** exhibits ambident Diels–Alder reactivity towards cyclopentadiene (Cp). This discovery opens the way to the synthesis of highly functionalized benzotriazole derivatives with defined stereochemistry. Importantly, the results point to a direct relationship between superelectrophilic and pericyclic behaviour.

So far no firm assessment of the electrophilic reactivity of **2a** or related benziotriazole systems, in terms of meaningful thermodynamic and kinetic data, has been reported. Therefore, we have carried out a kinetic and thermodynamic study of the reactions of hydroxide ion in water with the various substrates **2a**–**c** yielding the hydroxide adducts **4a**–**c** according to eq. [1]. Our results reveal that the reactivity of compounds **2a**–**c** is greater than that of the conventional Meisenheimer electrophile 1,3,5-trinitrobenzene (TNB) (9), but only that of **2a** is found to approach that of **1a**, providing further evidence of the superelectrophilic behaviour of structure **2**.

[1]

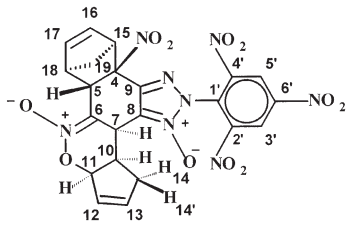


**4a-c**

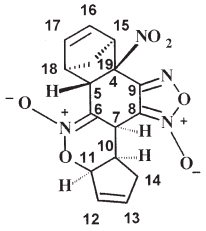
## Results

### Reaction of Pi-DNBT (2a) with cyclopentadiene

Treatment of **2a** with excess cyclopentadiene in a $CH_2Cl_2$–THF mixture at room temperature results in nearly quantitative formation of a product (5 h), which was readily isolated as a pale yellow solid after addition of pentane. $^1H$ and $^{13}C$ NMR spectra of this solid ($CD_3CN$ solvent) consisted of only one set of signals, indicating that the reaction has proceeded with a high stereoselectivity, affording only the diastereomer **7** (only one enantiomer is shown).



**7**



**8**

The proposed stereochemistry for **7** has been derived from a detailed NMR analysis which has included COSY, HETCOR, as well as *J*-modulation and NOE experiments. In particular, 2D-NOE experiments have revealed that the H-7, H-10, H-11, and

H-14 protons (but not the H-14′ proton) are located on the same side of the dihydrooxazine *N*-oxide and cyclopentene rings of **7**. The values of the related $^3J$ coupling constants ($^3J_{H7\text{-}H10}$ = 5.6, $^3J_{H10\text{-}H11}$ = 8.9 Hz) agree with the *cis* arrangement of the H-7, H-10, and H-11 protons (12*a*). On the other hand, the observation of a W-type $^4J$ coupling constant between the H-5 and H-7 protons ($^4J_{H5\text{-}H7}$ = 2.8 Hz) implies a *trans* addition of the two Cp molecules (13, 14). In accord with the strong electron-withdrawing effect of the O-$N^+$-$O^-$ fragment of the dihydrooxazine ring, both the $sp^3$ carbon C-11 and the related H-11 proton of **7** are strongly deshielded ($\delta C_{11}$ = 93.02, $\delta H_{11}$ = 5.77 ppm in $CD_3CN$) with the C-11 resonance comparing well with that of the nitro-substituted quaternary carbon C-4 ($\delta C_4$ = 93.17 ppm) (15). The close analogy between the resonances of the protons and carbons of the three carbocyclic rings of **7** with those of the related DNBF adduct **8** further supports our stereochemical assignment (Tables 1 and 2) (12*c*). Note that the stereochemistry illustrated in structure **8** was determined independently by X-ray diffraction studies. That the benzotriazole **2a** undergoes addition of 2 mol of cyclopentadiene to give the diadduct **7** was also confirmed by mass spectrometry (HRMS). Attempts to get precise information on the reaction sequence leading to **7** by carrying out similar experiments at 0°C have been unsuccessful because of solubility problems.

### Reactions of the 2-aryl-4,6-dinitrobenzotriazole 1-oxide series (2a–c) with $OH^-$

All rate and equilibrium measurements pertaining to eq. [1] were made at 25°C and constant ionic strength of 0.2 mol $dm^{-3}$ maintained with KCl. Measurements of absorbance at λ max of the σ-adducts **4a–c** (λ max ca. 470 nm) were first made at equilibrium as a function of pH. These describe clear-cut acid–base behaviour, as evidenced by the observation of excellent straight lines with unit slopes fitting eq. [2]. Here, $pK_a$ refers to the reaction of **2a–c** with water to produce **4a–c** and a proton.

$$[2] \qquad \log [\mathbf{4a\text{–}c}]/[\mathbf{2a\text{–}c}] = pH - pK_a$$

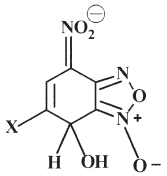
Plots are shown in Fig. 1 and yield the following $pK_a$ values: **2a** 6.70 ± 0.05, **2b** 9.0 ± 0.05, **2c** 10.73 ± 0.05. The pH ranges required for these $pK_a$ determinations were conveniently covered by using amine buffers made up from *N*-substituted aminoethane or propane sulfonic acids, namely TES, HEPES, TAPS, and CAPS which are known to be rather unreactive in nucleophilic processes (16).

Using a stopped-flow apparatus, the interconversions of **2a–c** and **4a–c** were then kinetically investigated under pseudo-first-order conditions. Solutions of the substrates (ca. $3 \times 10^{-5}$ mol $dm^{-3}$) in water containing HCl ($1 \times 10^{-3}$ mol $dm^{-3}$) were mixed with the appropriate KOH solutions ($2 \times 10^{-3}$ – $6.1 \times 10^{-2}$ mol $dm^{-3}$). In agreement with the direct equilibrium approach described by eq. [1], only one relaxation time corresponding to the complete formation of the adducts **4a–c** was observed in all cases. For each of the reactions studied, plots of $k_{obsd}$ vs. the KOH concentration afforded excellent straight lines with zero intercepts. This shows that the $k_{-1}$ pathway makes a negligible contribution so that the $k_{obsd}$ values are given by the simple eq. [3] (Fig. 2). From the slopes of these lines, values of $k_1^{OH}$ were readily determined. Then the $k_{-1}$ values could be calculated by means of eq. [4].

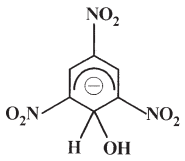
$$[3] \qquad k_{obsd} = k_1^{OH}[OH^-]$$

$$[4] \qquad k_{-1} = k_1^{OH} K_e [K_a]^{-1}$$

Values of the various rate and equilibrium parameters for the formation and decomposition of **4a–c** together with the related parameters for the DNBF adduct **5a**, the 4-nitrobenzofuroxan (NBF, **1b**) adduct **5b**, and the TNB adduct **6** are given in Table 3 for purposes of comparison.




**5a** X = $NO_2$
**5b** X = H



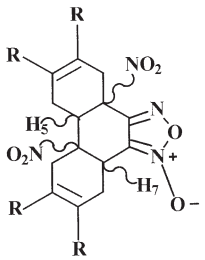

**6**

## Discussion

### The Diels–Alder reactivity of Pi-DNBT (2a)

Two main factors have long been suggested as contributing to the exceptional ease of formation and stability of adducts such as **5a** formed by reaction with the superelectrophile **1a**. The first is the combination of the strong electron-withdrawing effects of the nitro groups and the annelated furoxan ring (1–5). The result is not only a high electron deficiency at C-7 of the carbocyclic ring, and hence a high susceptibility of this ring position to nucleophilic attack, but also a high stability for the resultant σ-adducts, as a function of the high electron-delocalizing capability of the ring structure. The second factor is the relatively low aromaticity of the benzofuroxan system which is expected to favour covalent addition compared to most common aromatic and heteroaromatic systems, e.g., TNB or 3,5-dinitropyridine (9*a*, 17).

Evidence that the aromaticity factor is actually very important in determining the electrophilic reactivity of the nitrobenzofuroxan system has recently come from the discovery that DNBF is a remarkably versatile reagent in Diels–Alder reactions. We have shown that it may act as dienophile or heterodiene, depending upon the reaction partners employed and the experimental conditions (12, 18). In this regard, an early report by Kresze and Bathelt (19) that DNBF reacts to some extent with 2,3-dimethylbutadiene and 1,3-butadiene to afford the adducts **9** has remained essentially unnoticed in the literature.




**9** R = H, $CH_3$

**Table 1.** $^{13}C$ NMR data for the benzotriazole 1-oxide **2a** and the diadducts **7** and **8**.[a]

| Compound | $C_4$ | $C_5$ | $C_6$ | $C_7$ | $C_8$ | $C_9$ | $C_{10}$ | $C_{11}$ | $C_{12}$ | $C_{13}$ |
|---|---|---|---|---|---|---|---|---|---|---|
| **2a** | 137.5 | 124.2 | 144.5 | 119.9 | 125.6[b] | 136.3[b] | | | | |
| **7**[c] | 93.17 | 49.04 | 123.11 | 33.53 | 124.45 | 145.71 | 38.45 | 93.02 | 128.31 | 140.43 |
| **8**[d] | 91.27 | 47.54 | 121.82 | 32.17 | 111.35 | 152.69 | 36.61 | 91.67 | 127.52 | 139.36 |
| Compound | $C_{14}$ | $C_{15}$ | $C_{16}$ | $C_{17}$ | $C_{18}$ | $C_{19}$ | $C_{1'}$ | $C_{2',6'}$ | $C_{3',5'}$ | $C_{4'}$ |
| **2a** | | | | | | | 122.2[b] | 145.5 | 126.4 | 150.0 |
| **7**[c] | 35.34 | 55.17 | 135.40 | 142.33 | 47.45 | 47.08 | 128.3 | 147.2 (broad) | | 150.4 |
| **8**[d] | 34.60 | 54.56 | 134.27 | 141.90 | 46.11 | 46.24 | | | 124.44 | |

[a]δ in ppm relative to TMS in $Me_2SO$-$d_6$, unless otherwise specified; numbering is given in the structures **2a**, **7**, and **8** in the text.
[b]These values are based on the analysis of lone distance C—H coupling constants, allowing a complete and more reliable assignment of previously reported data (11*c*).
[c]In acetonitrile-$d_3$.
[d]Data taken from ref. 12*c*.

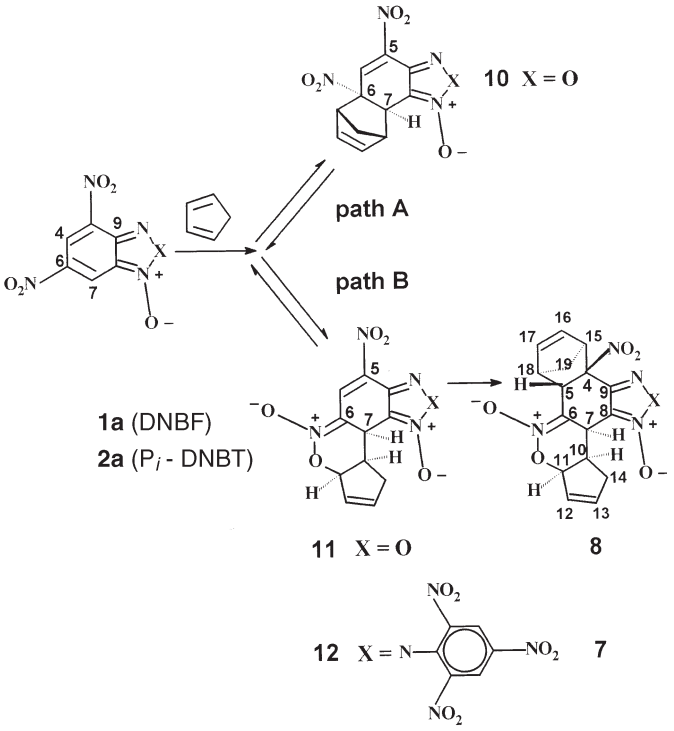
Most importantly, strong pericyclic reactivity could be observed with other highly activated nitrobenzofuroxans, e.g., the 4-nitro-6-trifluoromethylsulfonyl and 4-aza-6-nitrobenzo-furoxans for which p$K_a$ values of 2.95 and 3.8 have been measured, respectively, for water addition in aqueous solution, but not with less activated compounds such as 4-nitrobenzofuroxan itself (p$K_a$ = 10.32) (18, 20, 21)[2]. It thus appears that there is a clear correlation between the superelectrophilic and pericyclic behaviours in this series of 10 π electron heteroaromatic substrates.

Since pericyclic reactions are governed by HOMO–LUMO interactions (22) and similarly electrophile–nucleophile reactions are governed by the LUMO energy of the electrophilic partner and the HOMO energy of the nucleophilic partner (23), this observed correspondence between pericyclic and superelectrophilic reactivity follows the parallelism in the fundamental nature of both types of processes. We emphasize the salient point that *it is only the most superelectrophilic member of the series of benzotriazole 1-oxides,* ***2a****, that also displays Diels–Alder reactivity.*

In this context, our finding that **2a** reacts with cyclopentadiene (Cp) at room temperature to afford the highly functionalized stereoselective diadduct **7** supports the idea that the 4,6-dinitro-substituted carbocyclic ring of the most activated benzotriazole has a relatively low aromaticity. Interestingly, neither the *N-para*-nitrophenyl nor the *N*-phenyl analogues **2b** and **2c** which have p$K_a$ values comparable to that of NBF (**1b**) show similar pericyclic reactivity upon treatment with cyclopentadiene, thus adding to the evidence of a close relationship between the degree of electron deficiency of the carbocyclic ring and the Diels–Alder reactivity of this ring.

In the case of the reaction of **1a** with Cp, it has been clearly demonstrated that the formation of the diadduct **8** proceeds according to Scheme 1 (12*c*). Following a diastereoselective and regioselective normal electron-demand condensation leading to the formation of the monoadduct **10** under kinetic control (path A), the diadduct **8** is formed as the result of two consecutive inverse and normal electron demand processes which take place with a high stereoselectivity at the C-6—C-7 and C-4—C-5 double bonds of the carbocyclic ring. This reaction sequence is consistent with theoretical calculations which point to the activated 6,7-double bond of DNBF as being the preferred site for

**Scheme 1.**




normal as well as inverse Diels–Alder reactivity (24). Then, a second cycloaddition can take place at the remaining activated C-4—C-5 double bond of the resulting monoadduct **11**, akin to the reactivity of nitroolefins (25, 26). Although we were not able to carry out a similarly detailed study of the behaviour of **2a** at low temperatures (vide supra), it is reasonable to assume by analogy that the formation of the diadduct **7** is the result of the two-step sequence of path B in Scheme 1. That the two condensations leading to **12** and then to **7** proceed through *endo* processes with a *trans* addition of the two cyclopentadiene molecules is reminiscent of the situation which prevails in the formation of all DNBF diadducts (6*b*, 6*c*, 18, 20).

### The electrophilic character of the 2a–c series

So far, the p$K_a$ values of DNBF (3.73) (1*a*) and TNB (13.43) (26) represent the extremes in the scale of measuring

[2] F. Terrier, G. Moutiers, M. Mokhtari, and J.C. Hallé. Unpublished results.

**Table 2.** $^1$H NMR data for the diadducts **7** and **8**.[a]

| Diadduct | Solvent | H-5 | H-7 | H-10 | H-11 | H-12 | H-13 | H-14 | H-15 | H-16 | H-17 | H-18 | H-19 | Hmm′ | Coupling constants |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **7** | $CDCl_3$ | 3.49 | 4.06 | 3.98 | 5.77 | 5.95 | 6.21 | 2.41 | 4.06 | 6.38 | 6.69 | 3.49 | 1.80 | | $^2J_{14a/14b}$ = 18.0, $^2J_{19a/19b}$ = 10.2 |
| | | | | | | | | 2.16 | | | | | 1.18 | | $^3J_{11/10}$ = 8.9, $^3J_{12/13}$ = 5.8 |
| | | | | | | | | | | | | | | | $^3J_{14a/10}$ = 8.8, $^3J_{14b/10}$ = $^3J_{16/15}$ = 2.8 |
| | | | | | | | | | | | | | | | $^3J_{17/16}$ = 5.7 |
| **8**[b] | $CD_3CN$ | 3.41 | 4.32 | 4.07 | 5.78 | 5.87 | 6.21 | 2.36 | 3.84 | 6.32 | 6.68 | 3.37 | 1.73 | 9.23 | $^2J_{14a/14v}$ = 18.2, $^2J_{19a/19b}$ = 10.3 |
| | | | | | | | | 2.12 | | | | | 1.42 | | $^3J_{11/10}$ = 8.9, $^3J_{7/10}$ = 5.4 |
| | | | | | | | | | | | | | | | $^3J_{12/13}$ = 5.7, $^3J_{14a/10}$ = 8.9 |
| | | | | | | | | | | | | | | | $^3J_{17/16}$ = 5.7, $^3J_{14b/10}$ = 3.2 |
| | | | | | | | | | | | | | | | $^3J_{5/7}$ = $^3J_{5/19}$ = $^3J_{16/15}$ = 2.8 |

[a]δ in ppm relative to TMS, *J* in Hertz (Hz); numbering is given in structures **7** and **8** in the text.
[b]Data taken from ref. 12*c*.

the electron deficiency of aromatic and heteroaromatic substrates as derived from the susceptibility of these compounds to undergo covalent hydration in aqueous solution (9). In this regard, Table 3 shows that the p$K_a$ values for the three benzotriazole 1-oxides **2a–c** fall in the midrange between those of DNBF and TNB with the *N*-phenyl-substituted derivative **2c** being the weakest electrophile of the family, as expected, with a p$K_a$ value (10.73) close to that of 4-nitrobenzofuroxan (10.32). Introduction of nitro groups in the phenyl ring of **2c** has a major effect on the ease of σ-complexation of the 4,6-dinitro-substituted carbocyclic ring, as evidenced by the measurement of p$K_a$ values of 9.0 and 6.70 for formation of the hydroxy adducts **4b** and **4a** derived from the *N*-(4′-nitrophenyl) and *N*-(2′,4′,6′-trinitrophenyl) compounds **2b** and **2a**, respectively. This corresponds to a major shift in electrophilic character from that of the reference electrophile TNB, approaching in the case of **2a** the recognized superelectrophilic character of DNBF (1, 5–9). Interestingly, an X-ray analysis of **2a** has revealed that the picryl ring and the benzotriazole ring system are in an almost orthogonal orientation, due to a strong steric compression of the adjacent ortho–nitro and *N*-oxide functions (10*a*). This type of steric compression may be reasonably expected to also prevail in the corresponding adduct **4a**. Based on this, the strong activating effect exerted by the picryl ring on the susceptibility of the 4,6-dinitro-substituted carbocyclic ring of **2a** to covalent hydration must be the result of inductive and (or) field effects rather than conjugation effects.

Using again the data for the DNBF and TNB as the references, Table 3 also reveals that the $k_1^{OH}$ rate constants for the hydroxide ion attack on our three benzotriazole 1-oxides (**2a–c**) to generate the adducts **4a–c** (eq. [1]), are intermediate between the two extremes, with relatively minor variations on going from **2c** to **2a**. In fact, a most noteworthy finding is that the $k_{-1}$ values that measure the tendency of the three adducts **4a–c** to undergo spontaneous decomposition are all much lower than the value measured for the TNB adduct **6**. On the other hand, it is also of much interest that the changes in $k_{-1}$ are essentially responsible for changes in the p$K_a$ values for **2a–c**. This is clearly consistent with the idea that the Marcus intrinsic barrier for the σ-complexation process increases on going from **2c** to **2a**. This effect of nitro substitution on the intrinsic barrier may be understood as the result of charge delocalization being extensive in the resulting adducts **4a–c**, but only slightly developed at the transition state (27). In the case of **4c**, the $k_{-1}$ value is about 30-fold greater than for the mononitrobenzofuroxan adduct **5b**, suggesting that some electron donation from the monosubstituted phenyl ring to the heterocyclic framework of the benzotriazole may occur in this instance.

## Conclusions

The present work has shown definitively that the 4,6-dinitrobenzotriazole 1-oxide structure **2**, when appropriately substituted as in **2a**, can exhibit overall ambident pericyclic reactivity, i.e., normal and inverse electron demand cycloadditions take place with high stereoselectivity. This behaviour, which was found previously for **1a**, may extend to a wide range of low aromaticity heteroaromatics and investigation of the generality of such reaction is a thrust of inves-

**Fig. 1.** Variation of the ratio of ionized to non-ionized benzotriazole 1-oxides **2a**–**c** as a function of pH in aqueous solution. $T$ = 25°C, $I$ = 0.2 mol dm$^{-3}$ KCl.

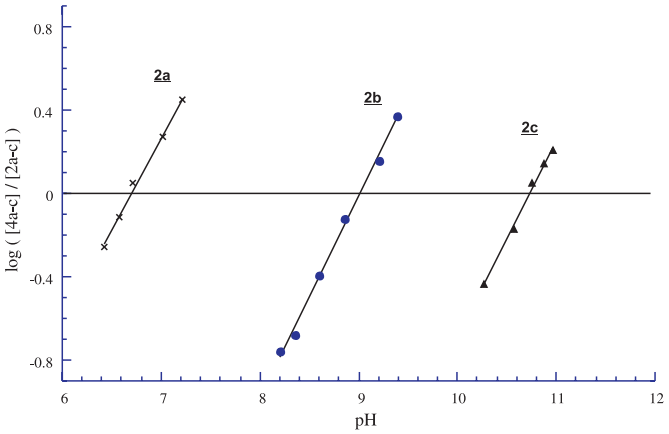



**Fig. 2.** Effect of the hydroxide ion concentration on the σ-complexation of **2a**–**c** in aqueous solution. $T$ = 25°C, $I$ = 0.2 mol dm$^{-3}$ KCl.

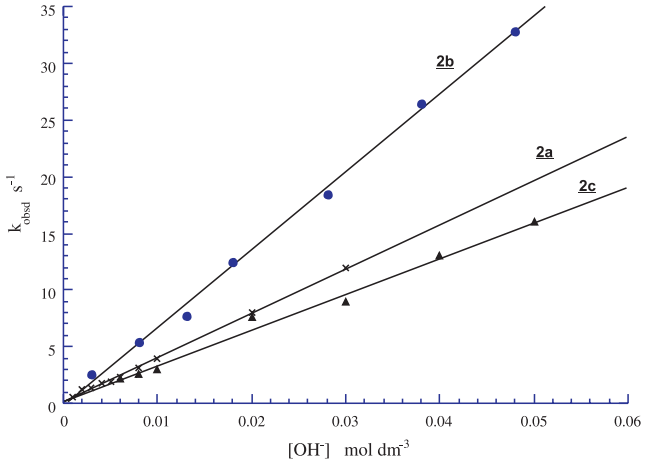



**Table 3.** Kinetic and thermodynamic parameters for the formation and decomposition of hydroxy σ-adducts ion aqueous solution.[a]

| Adduct | p$K_a$ | $k_1^{OH}$ (dm$^3$ mol$^{-1}$ s$^{-1}$) | $k_{-1}$ (s$^{-1}$) |
|---|---|---|---|
| **5a**[b] | 3.75 | 3.35 × 10$^4$ | 2.6 × 10$^{-6}$ |
| **4a** | 6.70 | 392 | 1.96 × 10$^{-5}$ |
| **4b** | 9.00 | 680 | 3.54 × 10$^{-3}$ |
| **4c** | 10.73 | 317 | 0.19 |
| **5b**[c] | 10.32 | 25 | 6 × 10$^{-3}$ |
| **6**[d] | 13.43 | 37.5 | 9.8 |

[a] $T$ = 298 K; $I$ = 0.2 mol dm$^{-3}$ KCl.
[b] Reference 1*a*.
[c] Reference 1*b*.
[d] Reference 25, $I$ = 0.1 mol dm$^{-3}$ NaCl.

tigations in our laboratories. It is also important to note that the relative ease of displacement of the picryl moiety from adducts such as **7** by nucleophiles would afford a facile route to the synthesis of functionalized triazole deriviatives of defined stereochemistry with potential pharmacological activity.

The kinetic and equilibrium data reported here show that the electrophilic character of the 4,6-dinitrobenzotriazole 1-oxide strudcture is closer to that of the nitrobenzofuroxans (i.e., **1a**, **1b**) than that of the standard aromatic electrophile TNB. This result is believed to be largely the reflection of a rleatively low aromaticity of the carbocyclic ring. Overall, the finding of a dual electrophilic and pericyclic behaviour for **2a** adds a new facet to the extremely rich chemistry of the benzotriazole 1-oxide structure (32, 33).

## Experimental

### Materials

The 4,6-dinitrobenzotriazole 1-oxides **2a** and **2b** were available from previous studies (11); the preparation of **2c** is described below. Reagent grade TES (2-*N*-[tris(hydromethyl) methyl]aminoethane sulfonic acid), HEPES (*N*-2-hydroxylethylpiperazine-*N*′-2-ethanesulfonic acid, (3-*N*-[tris(hydroxylmethyl)methyl]aminopropanesulfonic acid), and CAPS (3-[cyclohexylamino]propanesulfonic acid) were of the highest purity obtainable from commerical sources and used without further purification to prepare buffer solutions if the pH range required for the p$K_a$ determinations of **2a**–**2c**. KOH solutions were prepared from Titrisol.

### Synthesis of 2c

1-Chloro-2,4,6-trinitrobenzene (picryl chloride, 3.0 g, 0.012 mol) was dissolved in 95% ethanol (ca. 25 mL) in a 50 mL round-bottomed flask. Phenylhydrazine (2.8 g, 2.4 mL, 0.025 mol) was dripped into the stirring solution. The brick red picrylhydrazobenzene solidified in the flask, more ethanol was added (15 mL), and the suspension was stirred and warmed for 3 h. The final suspension was cooled to room temperature and the crude product collected by suction filtration, washed with dilute HCl (0.3 M), and then distilled water. The product was dried in a vacuum dry-box and recrystallized from 95% ethanol to give picrylhydrazobenzene (2.65 g, 69%), mp 179 to 180°C (lit. (29) 181°C). $R_f$ (TLC, $CH_2Cl_2$) 0.26. Picrylhydrazobenzene (0.50 g, 1.6 mmol) was cyclized in glacial acetic acid to 2-phenyl-4,6-dinitrobenzotriazole 1-oxide (**2c**) according to the method of Joshi and Deorha (30). Yield (after recrystallization from $CH_3CN$): 0.25 g, 51% (metallic, golden plates), mp 248–254°C (lit. (31) 249 to 250°C). $R_f$ ($CH_2Cl_2$) 0.36.

### Synthesis of 7

2-(2′,4′,6′-Trinitrophenyl)-4,6-dinitrobenzotriazole 1-oxide (**2a**) (86 mg, 0.197 mmol) was dissolved in a $CH_2Cl_2$–THF mixture and an excess of freshly distilled cyclopentadiene (1 mL) was added. The solution was maintained under stirring at room temperature for 5 h, then concentrated under reduced pressure. After addition of an excess of pentane, a pale yellow solid was isolated and dried under pump vacuum. Compound **7** was obtained in 92% yield (103 mg) and gave satisfactory analytical data. $^1$H NMR: 300 MHz, acetonitrile-$d_3$, see Table 2. $^{13}$C NMR: (see Table 1). FAB$^+$-MS mass spectrum (obsd). *m*/*z*: 569.1017 (reference *m*-nitrobenzyl alcohol), $C_{22}H_{14}N_8O_{11}$ requires 569.0984.

### Rate and p$K_a$ 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 p$K_a$ 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 **2c**, the measurements have been 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 discussion of the results (1*b*). All rate constants are accurate to ±3%.

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