Photochemical generation and lifetimes in water of *p*-aryloxy- and *p*-alkoxyphenylnitrenium ions

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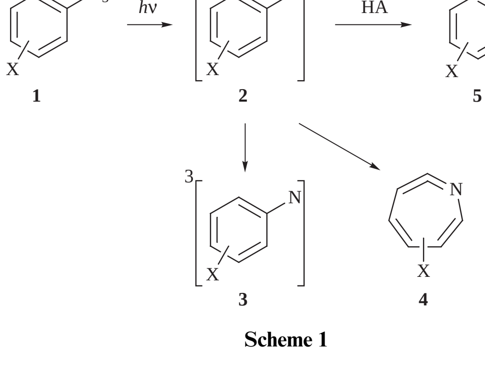
This paper describes product and flash photolysis studies following irradiation in aqueous solution of $4X–C_6H_4N_3$ [X = MeO (**12a**), EtO (**12b**), Pr^iO (**12c**), Bu^tO (**12d**), C_6H_5O (**12e**), 4-MeOC_6H_4O (**12f**), F, Cl] and 4-methoxy-1-naphthyl azide (**15**). *p*-Benzoquinone (or 1,4-naphthoquinone) is observed as a product, in yields of 70–90% with **12a**–**d**, **15**, 40% with **12e**, 26% with 4-F and 15% with 4-Cl. The quinone arises by a pathway whereby the initially-formed singlet arylnitrene is quenched by protonation by a solvent water molecule to form a nitrenium ion. Hydration of this cation at the *para* position leads through a hemiacetal (or halohydrin) to the quinone imine, whose hydrolysis results in the final quinone product. Three kinetic processes are observed, the nitrenium hydration on the μs time scale, the hemiacetal breakdown on the ms time scale, and the imine hydrolysis on the minutes time scale. The nitrenium ions have lifetimes in aqueous solution of 50 ns (4-PhO), 70 ns (4-MeOC_6H_4O), 370 ns (4-MeO), 550 ns (4-EtO), 1.25 μs (4-Pr^iO), 1.56 μs (4-Bu^tO) and 1.35 μs (4-methoxynaphthyl). A nitrenium transient is not observed with the 4-halophenyl azides, probably because the lifetime is too short for detection with ns laser flash photolysis (LFP). The alkoxyphenylnitrenium ions are argued to be better represented as oxocarbocations derived from *O*-alkylation of the quinone imine. The 4-ethoxyphenylnitrenium ion is not quenched by 0.01 mol dm^{-3} 2′-deoxyguanosine, so that $k_2(dG)$ is less than 2×10^7 mol^{-1} dm^3 s^{-1}. This contrasts with the 4-biphenylylnitrenium ion, which has a similar solvent reactivity, but reacts with $k_2(dG) = 2 \times 10^9$ mol^{-1} dm^3 s^{-1}. The localization of the positive charge in the alkoxy system is a possible explanation behind this difference.

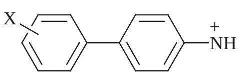
Arylnitrenium ions are a class of reactive intermediates, first extensively investigated by Gassman and co-workers,[1] that have seen increased study over the past twenty years.[2–7] This has been in part due to the implication of these species in the metabolism of carcinogenic arylamines.[8] The majority of studies of this class has been in the context of solvolysis reactions and the like, where the presence of the nitrenium intermediate is inferred on the basis of standard mechanistic criteria. Unlike the carbenium class of electrophile however, there have been virtually no successful studies of nitrenium ions in super-acid solutions,[9–11] although highly stabilized examples have been reported upon electrochemical oxidation of arylamines.[12–14] Within the past few years reports have begun to appear of arylnitrenium ions being observed with laser flash photolysis (LFP).[15–18] This approach not only shows that these species can exist, but also it provides rate constants for the various decay reactions that they can undergo.[19]

Arylnitrenes **2** are obtained photochemically upon irradiation of aryl azides **1**. They are initially formed in a singlet electronic state, and rapidly undergo reactions such as ring expansion to a didehydroazepine **4** or intersystem crossing to the triplet nitrene **3**.[20]



Scheme 1

They are however also the conjugate base of a singlet arylnitrenium ion **5**, the ground electronic state of most members of the latter class.[17,21–23] Product studies by the groups of Takeuchi[24] and Abramovitch[25] have suggested the possibility that arylnitrenes can be converted to arylnitrenium ions. Within the past few years such a reaction has been successfully applied in flash photolysis experiments for the direct observation of such cations. Examples are the biphenyl-4-ylnitrenium ion **6** (X = H),[26,27] the fluoren-2-ylnitrenium ion **7**,[26,27] a series of biphenyl-4-ylnitrenium ions **6** bearing substituents in the distal phenyl ring ranging from 4-methoxy to 4-trifluoromethyl,[28] the imidazol-2-ylnitrenium ion **8**,[29] a series of 2,3,5,6-tetrafluorophenylnitrenium ions **9**,[30] and the 2,4,6-tribromophenylnitrenium ion **10**.[31] In the case of **9** and **10**, the addition of a strong acid was necessary to trap the nitrene, but with **6**–**8** efficient protonation by solvent water molecules occurred. For the parent phenylnitrenium ion **11**, there is evidence from product studies,[27] and from quenching of singlet phenylnitrene,[31,32] that the cation does form from the nitrene in the presence of acid, although the cation has yet to be spectrally characterized.



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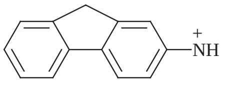

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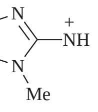

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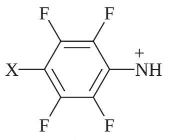

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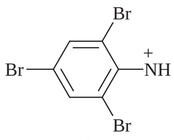

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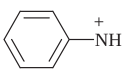

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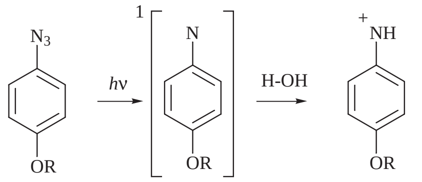
We have reported in preliminary form that the 4-methoxy- and 4-ethoxyphenylnitrenium ions **14a** and **14b** are formed in aqueous solution upon irradiation of the corresponding azides **12a** and **12b**.[33] In this paper we provide full details of this work, extending the study to the 4-isopropoxy-, 4-*tert*-butoxy-,

Table 1 Yields of benzoquinone upon irradiation of 4-alkoxy-, 4-aryloxy- and 4-halophenyl azides and rate constants for reactions of 4-alkoxyphenylnitrenium ions

4-Subst.	Yield (%)[a]	$k_w(\mu = 0)^b/s^{-1}$	$k_w(\mu = 0.5)^{c,d}/10^5\ s^{-1}$	$k_{az}(\mu = 0.5)^{d,e}/10^9\ mol^{-1}\ dm^3\ s^{-1}$
MeO	90 ± 5	$(2.7 \pm 0.2) \times 10^6$	18 ± 1	5.4 ± 0.2
EtO	79 ± 4	$(1.8 \pm 0.1) \times 10^6$	10.9 ± 0.4	5.3 ± 0.5
Pr^iO	68 ± 4	$(8.0 \pm 0.1) \times 10^5$	5.3 ± 0.3	4.0 ± 0.3
Bu^tO	87 ± 4	$(6.4 \pm 0.1) \times 10^5$	4.6 ± 0.1	4.5 ± 0.3
C_6H_5O	40 ± 3 65 ± 5[g]	$(1.9 \pm 0.2) \times 10^7$	—[f]	—[f]
ArO[h]	—[f]	$(1.4 \pm 0.1) \times 10^7$	—[f]	—[f]
F	26 ± 3	—[i]	—[i]	—[i]
Cl	15 ± 2	—[i]	—[i]	—[i]
MeONP[j]	81 ± 4[k,l]	$(7.4 \pm 0.1) \times 10^5$	5.2 ± 0.1	3.6 ± 0.2

[a] Percent yield of 1,4-benzoquinone following 254 nm irradiation in pH 4.6 1 : 1 acetic acid : sodium acetate buffer, 0.004 mol dm^{-3}. [b] First-order rate constant for decay of cation in water alone. [c] First-order rate constant for decay of cation in solvent without azide. [d] Solution was pH, 7 1 : 1 NaH_2PO_4–Na_2HPO_4, 0.002 mol dm^{-3}, containing 0.5 mol dm^{-3} $NaClO_4$. [e] Second-order rate constant for quenching of cation by azide ion. [f] Not measured. [g] Yield of phenol. [h] 4-$MeOC_6H_4O$. [i] No transient observed. [j] 4-Methoxynaphthyl. [k] Refers to 1,4-naphthaquinone. [l] Solvent contained 10% acetonitrile.

4-phenoxy- and 4-(4-methoxyphenoxy)phenyl azides **12c**–**f**, as well as to a 4-methoxy-1-naphthyl azide **15**. In addition to observing the decay reactions of the nitrenium ion, it has also proved possible to see two processes that follow, including the breakdown of a hemiacetal intermediate.



(1)

12 **13** **14**

R = **a**, Me, **b**, Et; **c**, iPr; **d**, tBu; **e**, Ph; **f**, 4-$MeOC_6H_4$

Results

Product analysis

Product analysis was performed with HPLC following 254 nm irradiation of pH 4–5 aqueous buffers containing ~1 × 10^{-4} mol dm^{-3} azide. The final product of the irradiation of **12a**–**d** is *p*-benzoquinone. The amount of this material obviously depended on irradiation time, but the yield calculated on the basis of azide reacted was, within experimental error, constant. For example, irradiation of **12d** for 15, 30 and 60 seconds consumed respectively 27, 50 and 73% of the starting material, and gave respectively yields of 80, 93 and 88% 1,4-benzoquinone.

The yields of benzoquinone obtained with the various precursors are given in Table 1. In the case of **12e**, phenol was also observed in the HPLC; its yield, like that of the quinone, was independent of irradiation time. We also examined 4-fluorophenyl and 4-chlorophenyl azide; benzoquinone was a product, although in a yield lower than those with the 4-alkoxy derivatives. The azide **15** gave the naphthalene analog, 1,4-naphthoquinone. With **12e** and the two 4-halophenyl azides, there were other peaks in the HPLC chromatogram, but these were not characterized. With **12a**–**12d** and **15**, the only peak observed in the HPLC other than the azide (and the quinone imine that is its precursor—see next section) was the quinone. We are uncertain as to the reason behind our failure to account for 100% of the azide. Irradiation in 100% acetonitrile (performed with **12b**) produced no quinone, with several unidentified peaks in the HPLC chromatogram. These peaks did not appear in the chromatogram following irradiation in water.

Slow kinetic process

Injecting immediately after irradiation gave very little of the quinone peak, but there was a large peak at a slightly shorter retention time. On repeat injection this decreased in intensity, while the peak for benzoquinone grew, becoming the only peak after one hour. Thus, while the quinone is the final product, there is a long-lived intermediate that is its precursor.

The conversion of the intermediate to the quinone could also be seen with a diode array spectrometer. With **12a**–**d**, UV spectra recorded immediately after irradiation for 30–60 seconds had a peak with λ_{max} at 255 nm. Repeat scans showed a change to the spectrum for *p*-benzoquinone, a λ_{max} at 245 nm with about 80% of the intensity of the initial absorbance. This change was identical for each of **12a**–**d** (and is also seen with **12e**, **f**), to the extent that it even occurred with the same rate constant in a solution with the same pH and buffer concentration.

This spectral change is identical to one published by Corbett in a study of the kinetics of hydrolysis of *p*-benzoquinone monoimine to benzoquinone.[34] Moreover the rate constants obtained with the azide precursors are within experimental error the same as ones calculated from equations provided by Corbett. Thus the long-lived intermediate observed with **12a**–**f** can be identified as *p*-benzoquinone monoimine. The similar intermediate with the naphthalene derivative **15** is presumably 1,4-naphthoquinone monoimine.

Fast kinetic phase

A short-lived species is detected with 248 nm LFP of solutions of **12a**–**f** and **15** in water. The intermediate forms within the 20 ns pulse width of the laser, and decays with first-order kinetics with lifetimes ($1/k_w$) ranging from 50 ns to 2 μs (see rate constants k_w in Table 1). As shown in Fig. 1A, the transient with **12b** absorbs strongly near 300 nm, with a shoulder extending out to 450 nm. This is suggested to represent a single intermediate, since the decay occurs with the same rate constant throughout. As seen by the negative ΔOD below ~310 nm, the azide precursor absorbs, distorting the spectrum of the transient.† Since the product of the decay at this stage does not absorb strongly, the true spectrum can be approximated by employing the change in optical density in the decay, *i.e.* from the reading immediately after the laser pulse to the reading at the completion of the exponential decay. Such spectra for the methoxy and *tert*-butoxy systems are shown in Fig. 1C. While the two are qualitatively similar, there is a slight difference in λ_{max}. In fact the trend is seen across the series **12a**–**d**, with λ_{max} at 305, 300, 295 and 290 nm for MeO, EtO, Pr^iO and Bu^tO respectively.

The transient spectrum for the 4-phenoxy azide **12e** shows a λ_{max} in the same region, around 295 nm, but there is now weak absorbance out into the visible (Fig. 1D). The naphthalene

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† The apparatus measures the OD after the laser pulse minus the OD at the same wavelength before the pulse. Thus, in regions where the precursor absorbs, negative ΔODs are possible and positive ODs do not represent the actual OD of the intermediate.

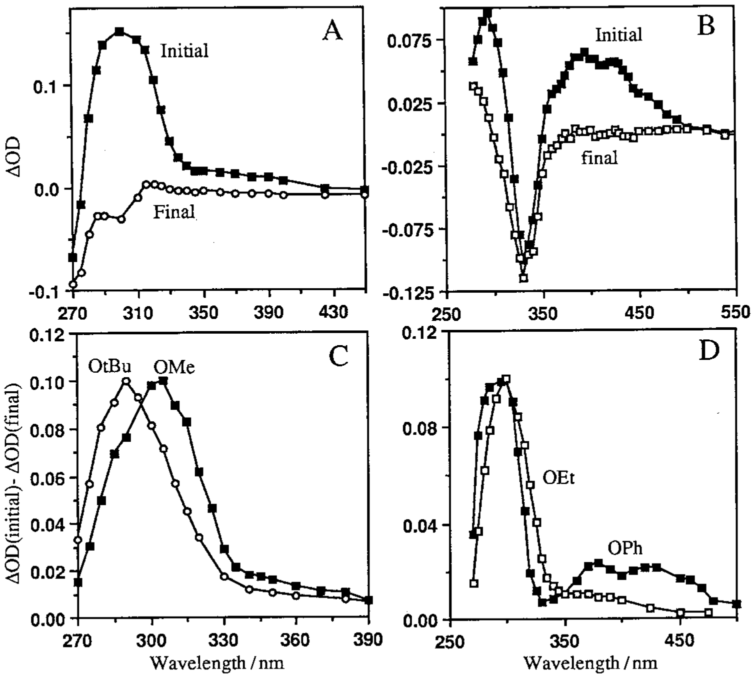

Fig. 1 Transient spectra obtained on 248 nm LFP of 4-alkoxyphenyl azides in water containing 0.002 mol dm^{-3} acetic acid : 0.002 mol dm^{-3} sodium acetate. **A**. 4-Ethoxyphenyl azide. **B**. 4-Methoxy-1-naphthyl azide. **C**. 4-Methoxyphenyl azide and 4-*tert*-butoxyphenyl azide. **D**. 4-Phenoxyphenyl azide and 4-ethoxyphenyl azide. For **A** and **B**, the '*y*' axis plots the change in optical density; the spectra marked initial were obtained immediately after the laser pulse, and the spectra marked final at a time corresponding to 10 half-lives of the first-order decay. For **C** and **D** the '*y*' axis plots the difference in the optical density between the 'initial' and 'final' reading. The data in these graphs have been normalized so that the value of '*y*' at the maximum is 0.1.

derivative **15** shows two quite strong bands decaying with the same rate constant, a broad absorbance with λ_{max} around 400 nm, and a sharper peak with λ_{max} near 300 nm (Fig. 1B). There is considerable distortion of the latter band due to the strong absorbance of the precursor below 350 nm.

These transients are quenched by sodium azide, with the observed rate constants linear in the azide concentration. Second-order rate constants for this quenching are given in Table 1.‡ The decay is accelerated in perchloric acid solutions, with plots of k_{obs} *versus* [HClO$_4$] linear up to acid concentrations of ~0.2 mol dm^{-3}, at which point k_{obs} has reached the apparatus limit of 3–4 × 10^7 s^{-1}. Second-order rate constants k_H are 2.2 × 10^8, 2.1 × 10^8, 2.0 × 10^8 and 1.5 × 10^8 dm^3 mol^{-1} s^{-1} for MeO, EtO, Pr^{i}O and Bu^{t}O respectively (at ionic strength 1.0 mol dm^{-3} with NaClO$_4$ and 20 °C). The transient from **12b** was studied in aqueous NaOH, where a first-order dependence on hydroxide ion was observed, with a rate constant k_{OH} of 8.8 × 10^8 dm^3 mol^{-1} s^{-1}. Experiments with **12b** were also carried out in a dilute pH 7 phosphate buffer containing varying concentrations of 2′-deoxyguanosine (dG). However, k_{obs} remained unchanged at 1.8 ± 0.1 s^{-1} throughout. The highest concentration of dG that was employed was 0.01 mol dm^{-3}. With the assumption that a 10% increase in k_{obs} would have been detected, the second-order rate constant for quenching by the nucleoside k_2(dG) must be less than 2 × 10^7 mol^{-1} dm^3 s^{-1}.

The alkoxy derivatives **12a**–**d** were also examined in solutions with varying acetonitrile content (Fig. 2). Fig. 2A plots the OD change that occurs in the exponential decay at the λ_{max}, normalized by dividing by the ΔOD measured in 100% water. This experiment was performed with the same laser intensity and the same concentration of azide precursor, so that the '*y*' axis effectively plots the quantum yield for formation of the intermediate relative to the quantum yield in 100% aqueous solution. As can be seen there is a regular decrease with increasing acetonitrile, until in 100% acetonitrile the intermediate is not observed.§ The first-order rate constants (Fig. 2B) increase with increasing acetonitrile content until about 70% acetonitrile, and then start to decrease.

Intermediate kinetic phase

When performed with a monitoring wavelength of 260 nm, these LFP experiments show that there is a large bleaching (negative ΔOD) at the completion of the decay. Thus, the species present at this time is much less absorbing than the precursor azide. However, recording a UV spectrum 30–60 seconds following irradiation shows a slight increase in OD at 260 nm. As discussed above this absorbance is that of the quinone imine. The implication though is that the imine is not the immediate product after the decay of the 300 nm transient, but that there is some process (or processes) that occurs at intermediate time that results in its formation. This is indeed observed with a lamp flash photolysis apparatus. A representative kinetic trace is shown in Fig. 3A. The large bleaching is observed after the ~100 µs lamp flash; this returns to a slightly positive ΔOD in an exponential fashion. Such an increase was observed with all of the azides **12a**–**f**, **15**. A detailed kinetic investigation was carried out with **12a**, with rate constants below pH 3 measured in perchloric acid solutions, and rate constants from pH 3–5 in formate and acetate buffers. Catalysis by the buffers was observed. This was not investigated in detail, with data points being obtained at low buffer concentration (0.002–0.02 mol dm^{-3}) and an extrapolation carried out to zero buffer concentration. The rate–pH profile combining the HClO$_4$ and buffer data is shown in Fig. 3B.

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‡ The azide rate constants for the 4-aryloxy compounds **12e**,**f** could not be measured accurately since the decay in the solvent was already near the limit of the apparatus. It can also be noted that the k_{az} for **12a** and **12b** are almost two-fold higher than those of our preliminary report.[33] The latter were obtained in an acetate buffer, and there was a failure to correct for protonation of the nucleophile.

§ There is a small positive ΔOD in the region 300–400 nm in 100% acetonitrile, but this does not decay over 100 µs. This is likely to also be present in the other acetonitrile-rich solutions, since there is residual absorbance at the end of the decay.

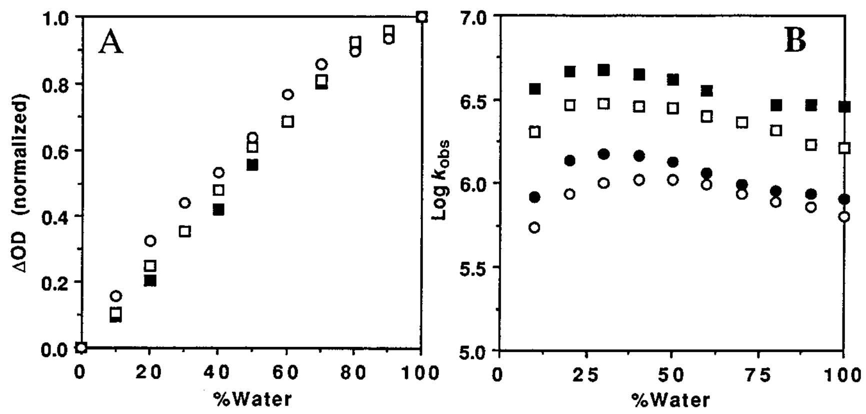


Fig. 2 Dependence on acetonitrile content of yield of transient (A) and first-order rate constant for decay (B). 4-MeO (closed squares), 4-EtO (open squares), 4-Pr^{i}O (closed circles), 4-Bu^{t}O (open circles).

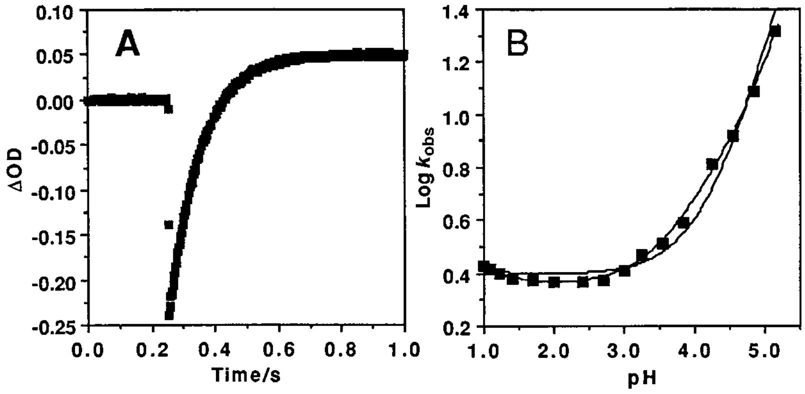
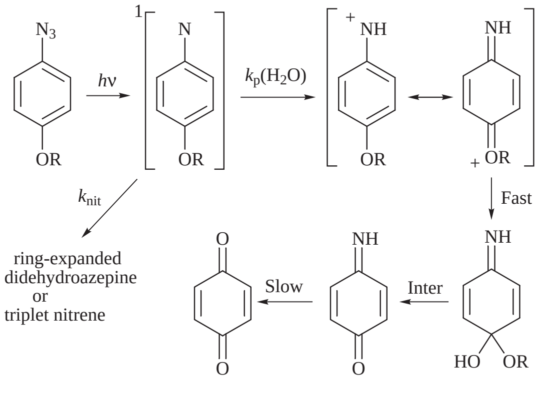


Fig. 3 (A) Absorbance change at 260 nm observed on flash lamp irradiation of **12a** in 0.005 mol dm^{-3} HOAc : 0.005 mol dm^{-3} NaOAc. (B) First-order rate constants for the absorbance increase with **12a** at 260 nm, at ionic strength 0.1 mol dm^{-3} (with NaClO$_4$) and 20 ± 1 °C. The data above pH 3 are the values extrapolated to zero buffer concentration. See Discussion section for the origins of the two curves.

Discussion

Formation of nitrenium ion

Scheme 2 depicts our proposed mechanism, with the three kinetic processes that are observed labelled as 'Fast', 'Inter' and 'Slow'. There is of course an even faster kinetic process, the decay of the singlet nitrene, which was complete well within the pulse width of our LFP apparatus. This step was observed using ps LFP in our studies with singlet biphenyl-4-yl- and fluoren-2-ylnitrenes, whose lifetimes in 20% acetonitrile are 160 and 90 ps respectively.[27] The rapid initial reactions of singlet phenylnitrene have also been recently directly observed.[31,32]



Scheme 2

As shown in Scheme 1, the singlet nitrene has several competing reaction channels, protonation to form the nitrenium ion, ring expansion to a didehydroazepine and intersystem crossing to the triplet. The protonation is the predominant pathway, since the major product is the quinone that is derived from the nitrenium ion. This protonation must occur with solvent water molecules, since the quinone is observed in the absence of added acid. Grouping the ring expansion and intersystem crossing together as k_{nit}, the ratio $k_p : k_{nit}$ can be estimated, since the quinone can not form from the k_{nit} pathways. The yields of quinone are 70–90% for **12a–d**, **15**, and 40% for **12e** (Table 1). With the assumption that the material unaccounted for is associated with one of the other pathways, the ratio $k_p : k_{nit}$ ranges from 9 : 1 to 7 : 3 for **12a–d**, **15**, and is 4 : 6 for **12e**. In every case, but particularly with the alkoxy derivatives, the protonation pathway is very competitive. As implied by the data in Fig. 2A, adding acetonitrile decreases its contribution.¶ Protonation still competes in 90% acetonitrile, but there is no nitrenium ion in the absence of water.

Identification of nitrenium ion intermediate

The intermediate observed with LFP at the completion of the 20 ns laser pulse is proposed to be a 4-alkoxy- (or 4-aryloxy)-phenylnitrenium ion. Several pieces of evidence support this interpretation.

(i) Studies with solvolytic precursors to the *N*-acetyl-4-ethoxyphenylnitrenium ion show that such nitrenium ions react with water at the 4-position, leading ultimately to *p*-benzoquinone.[7,35] Not only is the quinone formed in good to excellent

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¶ Since the data in Fig. 2A measure the relative quantum yield of nitrenium formation, this statement is true only if the quantum yield for nitrene formation from the azide is not changed with solvent composition. This has been shown to be approximately true in other systems.[27]

yield from the azide precursors, but there is kinetic evidence for both the quinone imine and the hemiacetal, the latter being the immediate product of the nitrenium ion hydration.

(ii) Arylnitrenium ions, like carbocations, are quenched by azide ion, with second-order rate constants at or very near the diffusion limit.[19,28] For biarylylnitrenium ions, this limit is ~5×10^9 dm^3 mol^{-1} s^{-1} at an ionic strength of 0.5.[28] As shown by the k_{az} data in Table 1, such behaviour is observed with the transients in this study.

(iii) The $k_{az}:k_w$ ratio for the *N*-acetyl-4-ethoxyphenylnitrenium ion is 5.4×10^2 mol^{-1} dm^{-3}, as measured by competition kinetics in a solvolysis reaction.[6,7] Taking k_{az} as 5×10^9, k_w is 9.2×10^6 s^{-1}, a factor of about nine faster than **14b**. This relatively small difference between NH and NAc is typical of arylnitrenium ions. With the biphenyl-4-yl derivatives, for example, there is a factor of 3.5 difference between NAc and NH.[18,27]

(iv) As shown in Fig. 2A, the intensity of the transient decreases with increased acetonitrile content. As discussed above, this behaviour reflects the competition between water protonation to form the nitrenium ion, and the pathways that lead to other intermediates.

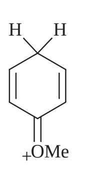
(v) The effect of substituent on k_w takes the expected form. The two aryloxy derivatives are more reactive than the alkoxy ones, with 4-methoxyphenoxy slightly more stabilized than phenoxy. In the alkoxy cations the order is 4-MeO > 4-EtO > 4-Pr^iO > 4-Bu^tO, the same order as seen previously with trialkoxy- and dialkoxy carbocations.[36,37]

Alkyl substituent effect

The quantitative alkyl order observed with the oxocarbocations was interpreted in terms of a polar effect rather than a steric one.[36,37] The same conclusion is reached here. The polar constants σ^* are 0.00 (Me), −0.10 (Et), −0.19 (Pr^i) and −0.3 (Bu^t). This predicts that there should be an incremental stabilization across the series, and this is roughly what is observed. In fact, a plot of log k_w *versus* σ^* is reasonably linear with a slope of 2.2. The steric parameters E_s are 0.00 (Me), −0.07 (Et), −0.49 (Pr^i) and −1.54 (Bu^t). These predict the same order, but they require that there be a bigger difference between OPr^i and OEt than between OEt and OMe, and an even bigger difference between OBu^t and OPr^i. This is not observed.‖

Structure and reactivity of 4-alkoxyphenylnitrenium ions

Both theory[38] and experiment[19,29,39,40] point to the idea that arylnitrenium ions are better represented as iminobenzenium ions, *i.e.* carbocations where the C–N bond is essentially a double bond. In the case of a 4-alkoxyphenylnitrenium ion, there is the additional resonance contributor shown in Scheme 2, an oxocarbocation or *O*-alkylated quinone imine structure. As we commented in our preliminary report,[33] the UV spectra of these cations are consistent with this being a major contributor. In particular the λ_{max} of 290–305 nm is quite different from those of other nitrenium ions.[15–19,27,28] However, it does approach the 285 nm λ_{max} of C4-protonated anisole **16**.[41] An additional feature seen in this study is the small decrease in λ_{max} from OMe to OBu^t. This may be associated with an even greater importance of the oxocarbocation structure as the alkyl group becomes more electron donating.



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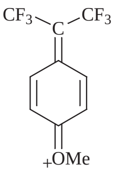

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While the alkoxyphenylnitrenium ions do have significant lifetimes in water, it might have been expected that they would be longer-lived. They have about the same lifetime as a biphenyl-4-ylnitrenium ion (as initially noted by the Novak group[6]), and yet 4-phenyl on the σ^+ scale is much less cation-stabilizing than 4-alkoxy. The 4′-methoxybiphenyl-4-ylnitrenium ion, where there is an additional phenyl ring interposed between the methoxy group and the formal N$^+$ center, has a lifetime of almost a millisecond,[28] three orders of magnitude longer. A possible explanation is that the positive charge in the 4-alkoxyphenylnitrenium ion is largely localized on the oxygen adjacent to the carbon center where the reaction with water occurs. The biphenylyl systems on the other hand are much more delocalized, as seen for example in the effects of substituents in the phenyl ring that is distant from the nitrogen.[28] An alternative way of putting this is to say that the 4-alkoxyphenylnitrenium ions are reacting as simple oxocarbocations. The Richard group has suggested that reactions of such cations have lower intrinsic barriers than ones associated with more delocalized systems.[42]

It is also interesting to note that the α,α-bistrifluoromethyl-4-methoxybenzyl cation has a lifetime in water of 100 ns,[43] only about a factor of four shorter than the 4-methoxyphenylnitrenium ion. Because of the electron withdrawing trifluoromethyl groups, the former cation is better written as the structure **17** with the positive charge largely localized at the oxygen.[44] This cation also shows the feature, highly unusual for a benzylic cation, of reacting at the ring carbon next to the oxygen leading to a quinone methide by way of a hemiacetal.[45] This sequence is obviously very similar to that seen with the alkoxyphenylnitrenium ions.

The reactivity difference that is of relevance to carcinogenicity is that with 2′-deoxyguanosine. The biphenyl-4-ylnitrenium ion reacts with this nucleoside with k_2(dG) = 2×10^9 dm^3 mol^{-1} s^{-1}, a number suggested to be close to the encounter limit.[46] Even the longer-lived 4′-methoxybiphenyl-4-ylnitrenium ion has k_2(dG) = 4×10^7 dm^3 mol^{-1} s^{-1}.[46] With each of these cations there is a significant selectivity towards dG even in the nucleophilic solvent water. For example, 0.01 mol dm^{-3} dG would trap almost 90% of the 4-biphenylylnitrenium ion, and accelerate the rate of decay by almost a factor of 10. This selectivity is not observed with a 4-alkoxyphenylnitrenium ion. In fact 0.01 mol dm^{-3} dG fails to show any acceleration of the decay, and the upper limit on k_2(dG) is 2×10^7 mol^{-1} dm^3 s^{-1}. This difference may be associated with the localization of charge in these cations. Arylnitrenium ions react with dG at the nitrenium nitrogen forming a 8-(arylamino)guanine adduct.[46,47] We speculate that in the alkoxyphenyl systems there is just too little positive charge at this site for the reaction to be initiated.

Halophenyl azides

The 4-fluoro- and 4-chlorophenyl azides give modest yields of *p*-benzoquinone on irradiation in water. This product would arise by the same mechanism as Scheme 1, with the halide as the leaving group after water addition at C4. The observation of the quinone thus demonstrates that nitrene protonation is still occurring. However, LFP with these two revealed only weak absorbances in the region 300–400 nm, with no decaying transient characteristic of a nitrenium ion. This is not surprising. As the above yields show, the actual amount of nitrenium ion that would be produced is less than that from the others. More importantly, the lifetimes of these nitrenium ions are likely too short to permit them to be detected with our apparatus. In fact,

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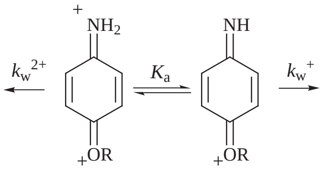
‖ The possibility that the *tert*-butyl system reacts by unimolecular cleavage of the Bu^t–O bond can be dismissed. This nitrenium ion has exactly the same dependence on acetonitrile content as that shown by the other three derivatives (Fig. 2B). Moreover, the intermediate kinetic phase, the conversion of hemiacetal to the quinone imine, is still observed, with about the same relative ΔOD as the others. The hemiacetal is not an intermediate in the unimolecular pathway.

the 4-chlorophenylnitrenium ion has a lifetime estimated by the azide clock method of only 5 ns.[7]

There is a qualitative correlation between the fraction of an arylnitrene that converts to the arylnitrenium ion by water protonation and the stability of the ion so produced, at least as measured by its lifetime. For the series 4-XC_6H_4- with X = H, 4-Cl, 4-PhO, Ph, 4-alkoxy, the lifetimes of the nitrenium ions in water are ~0.5 ns,[48] ~5 ns,[7] 50 ns, 300 ns,[27] 500–2000 ns, and the percentages of nitrenium ion formed from the nitrene are 5,[27] 15, 40, ~90[27] and 70–90. It is tempting to ascribe the latter trend to an increase in the rate constant k_p of Scheme 1 with increased nitrenium ion stability. However the constant k_{nit} will also depend on substituent, and this effect is unknown.

Alkoxynitrenium ions in acid

Quenching of a nitrenium ion by hydroxide ion, as observed with the one cation examined, is not surprising, since this simply represents the reaction with a stronger nucleophile. A faster decay is also observed in acid, where it seems unexpected that a cation would be quenched. The explanation invokes proton activation, the conversion of the nitrenium ion to an aniline dication which reacts at a greater rate [eqn. (2)]. With the assumption that equilibrium is established between the cation and dication, the observed rate constants are given by the expression $(k_w^{+2}[H^+] + k_w^{+}K_a)/([H^+] + K_a)$.



(2)

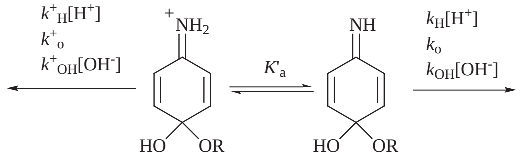
The constant k_w^{+} is the rate constant in weakly acidic and neutral solutions, and is obviously just k_w, as given in Table 1. Moving into stronger acids there is an initial linear dependence on $[H^+]$. This corresponds to the situation where the reaction begins to proceed by way of the dication, but the equilibrium has not yet begun to shift significantly to this species. The second-order rate constant k_H, the slope of a plot of k_{obs} *versus* $[H^+]$, is equal to k_w^{+2}/K_a. At even higher acidities, where the equilibrium begins to shift towards the dication, k_{obs} is expected to begin to level. With the alkoxyphenylnitrenium ions however, there is no indication of such levelling up to $HClO_4$ concentrations of 0.2 mol dm^{-3}, the point where k_{obs} becomes too fast to be accurately measured with our apparatus. With the assumption that a 10 percent deviation from linearity would be detected, K_a must be greater than 2 mol dm^{-3}. With k_H around 2×10^8 mol dm^{-3} s^{-1} for all four alkoxy nitrenium ions, k_w^{2+} is greater than 4×10^8 s^{-1}.

Some levelling was observed with the biphenyl-4-ylnitrenium ion, and curve fitting then provided $K_a = 0.8$ mol dm^{-3}, $k_w^{2+} = 6.0 \times 10^7$ s^{-1} and $k_w^{+} = 1.1 \times 10^6$ s^{-1} (at ionic strength = 1.0).[27] Thus while the 4-alkoxyphenylnitrenium ions have a similar k_w^{+} they are less easily protonated, but once protonated, more reactive. This difference may also be associated with charge delocalization. The 4-aminobiphenyl dication has the second phenyl ring where it can disperse one of the positive charges. The 4-alkoxyaniline dication will likely localize the positive charges on its oxygen and nitrogen atoms.

Hemiacetal kinetics

As discussed in the Results section, there can be no doubt that the slow kinetic process represents *p*-benzoquinone imine hydrolyzing to *p*-benzoquinone. With the fast process being due to addition of water to the nitrenium ion, the conversion of the hemiacetal to the quinone imine is left as the only reasonable reaction to account for the intermediate kinetic step. Hemiacetal breakdown is characterized by catalysis by H^+, OH^- and water (*i.e.* a pH independent reaction), as well as by buffer acids and bases.[49] The buffer catalysis was not investigated in this work, but a rate–pH profile for one system was obtained (Fig. 3B). This shows a pronounced hydroxide reaction, a pH independent region from about pH 3 to pH 2, and the beginnings of the H^+-catalyzed region from pH 2 to pH 1.

Initially we employed the simple equation $k_H[H^+] + k_o + k_{OH}[OH^-]$. As shown by the more poorly fitting curve in Fig. 3B, the correlation is not perfect. A better fit is obtained recognizing that the imine nitrogen is protonated at the more acidic pHs of Fig. 3B, so that there are actually two forms of the hemiacetal, both of which in principle can react with H^+, water and OH^- [eqn. (3)].



(3)

This gives rise to the more complicated kinetic expression [eqn. (4)]. The better fitting curve in Fig. 3B shows the result of applying this equation. The fitting provides five parameters $K'_a = 7.0 \times 10^{-5}$ ($pK'_a = 4.2$), $k_{OH} = 7.0 \times 10^9$ dm^3 mol^{-1} s^{-1}, $k^+_H = 4.1$ dm^3 mol^{-1} s^{-1}, $(k^+_o + K'_a k_H) = 2.2$ s^{-1} and $(k^+_{OH}K_w + K'_a k_o) = 5.11 \times 10^{-4}$ dm^3 mol s^{-1}. The last two parameters arise from two kinetically equivalent mechanisms, and the individual constants cannot be independently determined.

Eqn. (4) does contain a number of parameters, and thus it is not surprising that it provides a better fit to the data. There are however features that lend confidence in this model. The rate–pH profile for this hemiacetal is somewhat unusual in that the H^+-catalyzed limb is just barely apparent even in 0.1 mol dm^{-3} acid. This is typical of hemiacetals that are cationic, or like the present one, become protonated in acids, since the H^+-catalyzed breakdown of hemiacetals is slowed by electron withdrawing substituents.[50,51] The rate constant k_{OH} represents the hydroxide-catalyzed breakdown of the neutral hemiacetal. The magnitude of the number suggests that this process may be occurring by rate-limiting deprotonation of the OH group of the hemiacetal, as has been observed with other ketone hemiacetals.[52] Finally the pK'_a of 4.2 is quite consistent with the structure. The hemiacetal is 0.5 log units more basic than its quinone imine product.[34]

Conclusion

This study shows that irradiation in water of 4-alkoxyphenyl azides and 4-aryloxyphenyl azides leads to arylnitrenium ions through the solvent protonation of the initially formed singlet arylnitrene. These nitrenium ions have lifetimes in water of 400–1600 ns (alkoxy) and 50–70 ns (aryloxy). Several pieces of evidence are consistent with their structure being that of oxocarbocations—O-alkylated (or arylated) benzoquinone imines. This localization of charge may be responsible for the reactivity differences that are observed between 4-alkoxyphenylnitrenium ions and 4-biphenylylnitrenium ions, cations that are substantially more delocalized. Two kinetic processes are observed following the hydration of the 4-alkoxyphenylnitrenium ions. These represent the conversion of a hemiacetal to *p*-benzoquinone imine, followed by the hydrolysis of this species to *p*-benzoquinone.

$$k_{obs} = \frac{k^+_H[H^+]^2 + (k^+_o + K'_a k_H)[H^+] + (k^+_{OH}K_w + K'_a k_o) + (k_{OH}K'_a K_w/[H^+])}{[H^+] + K'_a} \qquad (4)$$

Experimental

The aryl azides were synthesized by diazotization of the aryl amine, followed by treatment with a large excess of sodium azide.[53,54] Where the anilines were not commercially available, they were synthesized by hydrogenation of the corresponding nitrobenzene. In cases where this was not available, it was prepared by reacting *p*-fluoronitrobenzene with the corresponding alkoxide or aryloxide.[55,56]

4-Methoxyphenyl azide, *4-ethoxyphenyl azide*, *4-fluorophenyl azide* and *4-chlorophenyl azide* were known compounds and were prepared from the commercially available anilines using the diazotization procedure described for the isopropoxy derivative below.[53,57,58]

4-Isopropoxyphenyl azide was prepared by the three step sequence. *p*-Fluoronitrobenzene (0.035 mol) was added to a solution of 4 cm^3 of previously dried isopropyl alcohol in potassium *tert*-butoxide in *tert*-butyl alcohol (40 cm^3 of solution of concentration 1 mol dm^{-3}). After stirring overnight, the solvent was removed, water added, and the solution extracted three times with diethyl ether. The combined ether fractions were washed with aqueous potassium hydroxide, and water, then dried over $MgSO_4$, and after filtration, the solvent removed to give a 76% yield of crude *4-isopropoxynitrobenzene* as a red-brown liquid: δ_H (200 MHz, $CDCl_3$, Me_4Si) 1.35 (6H, d), 4.65 (1H, sept), 6.90 (2H, d), 8.15 (2H, d).

This material was carried to the next stage without purification. The liquid (0.93 g) was dissolved in methanol (25 cm^3) and hydrogenated over 10% palladium on carbon (0.03 g), until the reaction was complete as judged by TLC. The catalyst was removed by filtration through superflow celite, anhydrous hydrochloric acid in diethyl ether was then added, and the solvents removed to give a 96% yield of *4-isopropoxyaniline hydrochloride* as a light brown solid: δ_H (200 MHz, D_2O) 1.2 (6H, d), 4.60 (1H, sept), 6.98 (2H, d), 7.24 (2H, d), 12.0 (3H, broad s).

The aniline hydrochloride (0.9 g) was dissolved in 2 mol dm^{-3} aqueous HCl, and the solution cooled to 0–5 °C. Sodium nitrite (1.23 g) in 10 cm^3 of water was slowly added, maintaining the temperature below 10 °C. After the addition was complete, the solution was stirred for a further 10 minutes, and then a saturated solution of sodium azide (10 cm^3) was added dropwise. After stirring for a further 10 minutes, the mixture was neutralized with aqueous sodium bicarbonate, followed by extraction three times with diethyl ether. After drying the ether over $MgSO_4$, filtration to remove the drying agent, the solvent was removed to give a red-brown liquid of 4-isopropoxyphenyl azide (76%). This was purified by column chromatography: δ_H (200 MHz, $CDCl_3$, Me_4Si) 1.30 (6H, d, $J = 8$ Hz), 4.45 (1H, sept, $J = 8$ Hz), 6.85 (4H, distorted doublet of doublets); ν_{max}/cm^{-1} 2105; *m*/*z* (EI, 70 eV) 177 (M^+, 14%), 149 ($M^+ - N_2$, 26), 107 ($M^+ - N_2 - C_3H_7$, 100).

4-(tert-Butoxy)phenyl azide was prepared by the same sequence, omitting the propan-2-ol in the first step. *4-(tert-Butoxy)nitrobenzene* had δ_H (200 MHz, $CDCl_3$, Me_4Si) 1.45 (9H, s), 7.03 (2H, d), 8.14 (2H, d). *4-(tert-Butoxy)aniline* was isolated as the neutral amine and had δ_H (200 MHz, $CDCl_3$, Me_4Si) 1.25 (9H, s), 3.45 (2H, broad s), 7.55 (2H, d), 6.77 (2H, d). *4-(tert-Butoxy)phenyl azide* was obtained as pale yellow oil after chromatography and had δ_H (200 MHz, $CDCl_3$, Me_4Si) 1.30 (9H, s), 6.95 (4H, distorted doublet of doublets); ν_{max}/cm^{-1} 2100; *m*/*z* (EI, 70 eV) 191 (M^+, 10%), 135 ($M^+ - C_4H_9$, 28), 107 ($M^+ - N_2 - C_4H_9$, 100), 57 ($C_4H_9^+$, 91).

4-Phenoxyphenyl azide was prepared in the two step sequence starting with commercially available 4-nitrophenyl phenyl ether. Hydrogenation as described above gave *4-phenoxyaniline*, isolated as the free amine: δ_H (200 MHz, d$_6$-DMSO) 4.95 (2H, broad s), 6.6 (2H, d), 6.8 (4H, m), 7.0 (1H, t), 7.3 (2H, t). *4-Phenoxyaniline hydrochloride* was obtained by precipitation from diethyl ether by addition of HCl in diethyl ether, and this salt converted to the azide as described above. *4-Phenoxyphenyl azide* was a pale yellow liquid with δ_H (200 MHz, $CDCl_3$, Me_4Si) 7.1 (2H, m), 7.4 (7H, m); ν_{max}/cm^{-1} 2118; *m*/*z* (EI, 70 eV) 211 (M^+, 10%), 183 ($M^+ - N_2$, 100), 77 (Ph^+, 22). (This compound has been previously reported, but no details of its preparation or characterization were given (see ref. 59).)

4-(4-Methoxyphenoxy)phenyl azide was prepared by the three step sequence. 4-Methoxyphenol (0.6 g) was deprotonated with sodium hydride (0.3 g) in 20 cm^3 of dry acetonitrile, and 4-fluoronitrobenzene (0.5 cm^3) added. After stirring at room temperature overnight, water was added, and the aqueous solution washed four times with diethyl ether. The combined ether layers were washed with aqueous HCl, aqueous bicarbonate, then dried over $MgSO_4$. After filtration and drying, *4-(4-methoxyphenyl)nitrobenzene* was obtained as an orange solid by removal of the solvent: δ_H (200 MHz, d$_6$-DMSO) 3.80 (3H, s), 6.95 (6H, m), 8.15 (2H, d). This nitrobenzene was converted to the azide following the standard procedure. *4-(4-Methoxyphenyl)phenyl azide* was obtained as a light brown solid: δ_H (200 MHz, $CDCl_3$) 3.80 (3H, s), 6.90 (8H, m); *m*/*z* (EI, 70 eV) 241 (M^+, 21%), 213 ($M^+ - N_2$, 100), 198 ($M^+ - N_2 - CH_3$, 18), 182 ($M^+ - N_2 - OCH_3$, 21).

4-Methoxy-1-azidonaphthalene was synthesized in the two step sequence from the commercially available nitro compound. *4-Methoxy-1-aminonaphthalene hydrochloride* was isolated as described above and had δ_H (200 MHz, d$_6$-DMSO) 4.0 (3H, s), 7.0 (1H, d), 7.7 (3H, m), 7.95 (1H, d), 8.25 (1H, d), 10.6 (3H, broad s). *4-Methoxy-1-azidonaphthalene* was a yellow brown oil: δ_H (200 MHz, $CDCl_3$) 4.0 (3H, s), 6.95 (2H, distorted doublet of doublets), 7.55 (2H, m), 8.05 (1H, m), 8.25 (1H, m); ν_{max}/cm^{-1} 2118; *m*/*z* (EI, 70 eV) 199 (M^+, 27), 171 ($M^+ - N_2$, 100), 156 ($M^+ - N_2 - CH_3$, 55), 140 ($M^+ - N_2 - OCH_3$, 29).

Laser flash photolysis experiments involved *ca.* 20 ns pulses at 248 nm (60–120 mJ per pulse) from a Lumonics excimer laser (KrF emission). A pulsed Xenon lamp providing monitoring light. The sample was placed in a 4 × 1 × 1 cm cuvette, irradiated with the laser on the 4 × 1 face, and monitored perpendicular so that the path length was 4 cm. The cuvette was replaced with a fresh solution after each irradiation. After passing through a monochromator, the signal from the photomultiplier tube was digitized and sent to a computer for analysis.

Conventional flash photolysis experiments were performed using an apparatus previously described,[60] with the sample being irradiated with a broad band flash lamp of *ca.* 100 μs duration.

Products analyses were performed with a Waters HPLC system using a C^{18} column with 2 cm^3 min^{-1} flow rate with a UV–visible detector set at 254 nm. Elution was carried out in the programmed mode—50:50 acetonitrile–water isocratic for 4 minutes, a linear gradient to 80:20 acetonitrile–water for the next 6 minutes, and then isocratic at the latter composition for 4 minutes. The quinone products were identified by comparison of retention times with those of authentic samples. Quantitative analyses were performed by determining the response factor of the quinone product and azide precursor at 254 nm, and correcting the peak areas of the unknown solutions. The majority of the product studies were performed with air-saturated solutions, *i.e.* without specifically removing oxygen. An early experiment with the 4-ethoxyphenyl azide compared the products under air, and in an argon saturated solution, and showed no difference.

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References

1 P. G. Gassman, *Acc. Chem. Res.*, 1970, **3**, 26.
2 R. A. Abramovitch and R. Jeyaraman, in *Azides and Nitrenes;*

Reactivity and Utility, ed. E. F. V. Scriven, Academic Press, 1984, pp. 297–354.
3 M. Novak, M. Pelecanou, A. K. Roy, A. F. Andronico, F. M. Plourde, T. M. Olefirowicz and T. J. Curtin, *J. Am. Chem. Soc.*, 1984, **106**, 5623.
4 J. C. Fishbein and R. A. McClelland, *J. Am. Chem. Soc.*, 1987, **109**, 2824.
5 M. Novak, M. J. Kahley, E. Eigen, J. D. Helmick and H. Peters, *J. Am. Chem. Soc.*, 1993, **115**, 9453.
6 M. Novak, M. J. Kahley, J. Lin, S. A. Kennedy and L. A. Swanegan, *J. Am. Chem. Soc.*, 1994, **116**, 11626.
7 M. Novak, M. J. Kahley, J. Lin, S. A. Kennedy and T. G. James, *J. Org. Chem.*, 1995, **60**, 8294.
8 See S. A. Kennedy, M. Novak and B. A. Kolb, *J. Am. Chem. Soc.*, 1997, **119**, 7654.
9 G. A. Olah and D. J. Donovan, *J. Org. Chem.*, 1978, **43**, 1743.
10 G. A. Olah, G. K. S. Prakash and M. Arvanaghi, *J. Am. Chem. Soc.*, 1980, **102**, 6640.
11 G. A. Olah, M. Arvanaghi and G. K. S. Prakash, *J. Am. Chem. Soc.*, 1982, **104**, 1628.
12 U. Svanholm and V. D. Parker, *J. Am. Chem. Soc.*, 1974, **96**, 1234.
13 D. Serve, *J. Am. Chem. Soc.*, 1975, **97**, 432.
14 A. Riecker and B. Reiser, *Tetrahedron Lett.*, 1990, **31**, 5013.
15 G. B. Anderson and D. E. Falvey, *J. Am. Chem. Soc.*, 1993, **115**, 9870.
16 R. J. Robbins, L. L.-N. Yang, G. B. Anderson and D. E. Falvey, *J. Am. Chem. Soc.*, 1995, **117**, 6544.
17 S. Srivasta and D. E. Falvey, *J. Am. Chem. Soc.*, 1995, **117**, 10186.
18 P. A. Davidse, M. J. Kahley, R. A. McClelland and M. Novak, *J. Am. Chem. Soc.*, 1994, **116**, 4513.
19 R. A. McClelland, *Tetrahedron*, 1996, **52**, 6823.
20 G. B. Schuster and M. Platz, *Adv. Photochem.*, 1992, **17**, 143.
21 S.-J. Kim, T. P. Hamilton and H. F. Schaefer, *J. Am. Chem. Soc.*, 1992, **114**, 5349.
22 D. A. Hrovat, E. E. Waali and W. T. Borden. *J. Am. Chem. Soc.*, 1992, **114**, 8698.
23 C. J. Cramer, F. J. Dulles and D. E. Falvey, *J. Am. Chem. Soc.*, 1994, **116**, 9787.
24 See H. Takeuchi, S. Hirayama, M. Mitani and K. Koyama, *J. Chem. Soc.*, *Perkin Trans. 2*, 1986, 611 and references therein.
25 R. A. Abramovitch, A. Hawi, J. A. R. Rodrigues and T. R. Trombetta, *J. Chem. Soc.*, *Chem. Commun.*, 1986, 283 and references therein.
26 R. A. McClelland, P. A. Davidse and G. Hadzialic, *J. Am. Chem. Soc.*, 1995, **117**, 4173.
27 R. A. McClelland, M. J. Kahley, P. A. Davidse and G. Hadzialic, *J. Am. Chem. Soc.*, 1996, **118**, 4794.
28 D. Ren and R. A. McClelland, *Can. J. Chem.*, 1998, **76**, 78.
29 T. A. Gadosy and R. A. McClelland, *J. Am. Chem. Soc.*, accepted for publication.
30 J. Michalak, H. B. Zhai and M. Platz, *J. Phys. Chem.*, 1996, **100**, 14028.
31 R. Born, C. Burda, P. Senn and J. Wirz, *J. Am. Chem. Soc.*, 1997, **119**, 5061.
32 N. P. Gritsan, T. Yuzawa and M. S. Platz, *J. Am. Chem. Soc.*, 1997, **119**, 5059.
33 P. Sukhai and R. A. McClelland, *J. Chem. Soc.*, *Perkin Trans. 2*, 1996, 1529.
34 J. F. Corbett, *J. Chem. Soc.* (*B*), 1969, 213.
35 M. Novak, M. Pelecanou and L. Pollack, *J. Am. Chem. Soc.*, 1986, **108**, 112.
36 S. Steenken, J. Buschek and R. A. McClelland, *J. Am. Chem. Soc.*, 1986, **108**, 2808.
37 R. A. McClelland and S. Steenken, *J. Am. Chem. Soc.*, 1988, **110**, 5860.
38 See C. J. Cramer and D. E. Falvey, *Tetrahedron Lett.*, 1997, **38**, 1515.
39 G. Kohnstam, W. A. Petch and D. L. H. Williams, *J. Chem. Soc.*, *Perkin Trans. 2*, 1984, 423.
40 S. Srivastava, J. P. Toscano, R. J. Moran and D. E. Falvey, *J. Am. Chem. Soc.*, 1997, **119**, 11552.
41 A. J. Kresge, Y. Chiang and L. E. Hakka, *J. Am. Chem. Soc.*, 1971, **93**, 6167.
42 J. P. Richard, T. L. Amyes, V. Jagannadham, Y.-G. Lee and D. J. Rice, *J. Am. Chem. Soc.*, 1995, **117**, 5198.
43 R. A. McClelland, F. L. Cozens, S. Steenken, T. L. Amyes and J. P. Richard, *J. Chem. Soc.*, *Perkin Trans. 2*, 1993, 1717.
44 J. P. Richard, *Tetrahedron*, 1995, **51**, 1535.
45 J. P. Richard, T. L. Amyes, L. Bei and V. Stubblefield, *J. Am. Chem. Soc.*, 1990, **112**, 9513.
46 R. A. McClelland, T. A. Gadosy and D. Ren, *Can. J. Chem.*, in the press.
47 S. A. Kennedy, M. Novak and B. A. Kolb, *J. Am. Chem. Soc.*, 1997, **119**, 7654.
48 J. C. Fishbein and R. A. McClelland, *Can. J. Chem.*, 1996, **74**, 1321.
49 P. E. Sorensen and W. P. Jencks, *J. Am. Chem. Soc.*, 1987, **109**, 4675 and references therein.
50 R. D. Gandour, R. A. McClelland and P. E. Sorensen, *Acta Chem. Scand.*, 1991, **45**, 558.
51 R. A. McClelland, K. M. Engell, P. Sukhai and P. E. Sorensen, *Can. J. Chem.*, 1994, **72**, 2333.
52 P. E. Sorensen, K. J. Pedersen, P. R. Pedersen, V. M. Kanagasabapathy and R. A. McClelland, *J. Am. Chem. Soc.*, 1988, **110**, 5118.
53 H. Rupe and K. v. Majewski, *Chem. Ber.*, 1900, **33**, 3405.
54 P. A. S. Smith and B. B. Brown, *J. Am. Chem. Soc.*, 1951, **73**, 2438.
55 K. Bowden and P. N. Green, *J. Chem. Soc.*, 1954, 1795.
56 G. Baddeley, N. H. P. Smith and M. A. Vickars, *J. Chem. Soc.*, 1956, 2455.
57 O. Dimroth, M. Eble and W. Gruhl, *Chem. Ber.*, 1907, **40**, 2397, 2399.
58 M. Tanno, S. Sueyoshi and S. Kamiya, *Chem. Pharm. Bull.*, 1982, 3125.
59 N. Almirante, M. Ballabio, G. Bianchetti, A. Cambiaghi and D. Pocar, *J. Chem. Res.* (*M*), 1986, 1230.
60 A. A. Allen, A. J. Kresge, N. P. Schepp and T. T. Tidwell, *Can. J. Chem.*, 1987, **65**, 1719.

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