Acid−Base Properties of Arylnitrenium Ions

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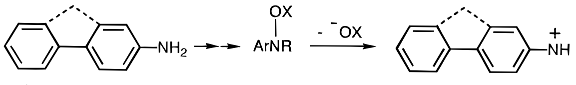
Abstract: This study uses a combination of laser flash photolysis (LFP) and product analysis to show that singlet nitrenes from the irradiation of phenyl, 4-biphenylyl, and 2-fluorenyl azide can be trapped by protonation in aqueous solutions forming nitrenium ions. With phenyl azide, the phenylnitrenium ion is indicated by the formation of ring-substituted anilines in yields of up to 50% in 1 M acids. The acidity dependence furnishes the ratio k_H:k_{exp} = 1.1, where k_H refers to H^+-trapping of singlet phenylnitrene and k_{exp} to ring expansion of this species. With k_H expected to be $2-4 \times 10^{10}$ M^{-1} s^{-1}, k_{exp} is therefore estimated as $2-4 \times 10^{10}$ s^{-1}. Protonation by solvent water also occurs, but even though the rate constant is of the order of 10^9 s^{-1}, it constitutes a minor pathway in competition with the ring expansion. LFP studies in acids reveal a transient that is assigned the structure of N-protonated 4-hydroxy-2,5-cyclohexadienone imine, the intermediate formed by water addition to the para position of the phenylnitrenium ion. With 4-biphenylyl- and 2-fluorenylnitrene, ring expansion (and intersystem crossing) occurs more slowly and protonation by water is faster, with the consequence that there are substantial yields of nitrenium ion without added acids. These nitrenium ions are detected with ns LFP, and their formation from singlet nitrene is observed with ps LFP. Combining the LFP experiments with product analysis furnishes a pK_a value of 16 for the 4-biphenylylnitrenium ion deprotonating to singlet nitrene in 20% acetonitrile. Thus singlet 4-biphenylylnitrene falls close to the category of a strong base in this solution. LFP experiments in acids show behavior consistent with N-protonation of the nitrenium ion forming an aniline dication. Kinetic analyses furnish pK_a values of 0.1 (4-aminobiphenyl dication) and 0.6 (2-aminofluorene dication) in 20% acetonitrile with 1 M ionic strength. This and other pieces of evidence are consistent with these arylnitrenium ions being better regarded as 6-iminocyclohexadienyl carbocations. Overall, arylnitrenium ions ($ArNH^+$) are very weak acids in water in their deprotonation to singlet nitrenes. They are also weak bases, accepting a proton to form the aniline dication—$^1ArN \rightleftarrows {}^1ArNH^+ \rightleftarrows (ArNH_2)^{2+}$.

Carcinogens such as 4-aminobiphenyl (**1**) and 2-aminofluorene (**2**) are generally accepted to undergo a 2-fold metabolic activation to O-acetate or O-sulfate esters **3**, followed by N−O heterolysis to an arylnitrenium ion (**4, 5**).[1]



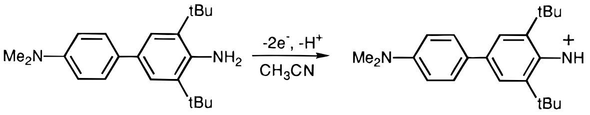
(1)

1, 4-Biphenylyl
2, 2-Fluorenyl

3, X=Ac, SO_3^-

4, 4-Biphenylyl
5, 2-Fluorenyl

The critical cellular target appears to be DNA, and indeed a covalent adduct of guanine residues has been observed *in vivo*[2] as well as in model systems.[3] In part because of this relevance to arylamine carcinogenicity a number of studies have been carried out probing the chemistry of arylnitrenium ions when formed as intermediates of solvolysis and related reactions.[4,5] In contrast to carbenium ions, however, examples of the nitrenium class that have been characterized by direct spectroscopic means are limited. There are three reports of relatively stabilized nitrenium ions produced by electrochemical two-electron oxidation of the corresponding amine. These include diarylnitrenium ions bearing stabilizing *o*- and *p*-methoxy substituents such as the bis(4-methoxyphenyl)nitrenium ion[6] and the 4-biphenylyl derivative **7**.[7] In the cases of the diarylnitrenium ions, only UV−visible absorption spectra were reported. The ion **7** was sufficiently persistent for its ^1H NMR spectrum to be recorded.



(2)

6 **7**

No nitrenium ion has been characterized as a distinct species under super acid conditions, except for the special case of cyanodiarylmethyl cations (Ar_2C^+-CN) which were considered to have significant nitrenium character ($Ar_2C=C=N^+$).[8] As implied by studies with nitrosobenzenes (e.g. **8**), one problem

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(1) (a) Miller, J. A. *Cancer Res.* **1970**, *30*, 559; **1978**, *38*, 1479. (b) Miller, E. C.; Miller, J. A. *Cancer* **1981**, *47*, 2327. Miller, E. C.; Miller, J. A. *Environ. Health Perspect.* **1983**, *49*, 3. (c) Garner, R. C.; Martin, C. N.; Clayson, D. B. In *Chemical Carcinogens*, 2nd ed.; Searle, C. E., Ed; ACS Monograph 182; American Chemical Society; Washington, DC, 1984; Vol. 1, pp 175−276. (d) Kadlubar, F. F.; Miller, J. A.; Miller, E. C. *Cancer Res.* **1977**, *37*, 805.

(2) Schut, H. A. J.; Castongauy, A. *Drug Metab. Rev.* **1984**, *15*, 753.

(3) (a) Underwood, G. R.; Price, M. F.; Shapiro, R. *Carcinogenesis* **1988**, *9*, 1817. (b) Famulok, M.; Bosold, F.; Boche, G. *Angew. Chem., Int. Ed. Engl.* **1989**, *28*, 337. (c) Novak, M.; Kennedy, S. A. *J. Am. Chem. Soc.* **1995**, *117*, 574.

(4) (a) Gassman, P. G. *Acc. Chem. Res.* **1970**, *3*, 26. (b) Gassman, P.; Hartman, G. D. *J. Am. Chem. Soc.* **1973**, *95*, 449. (c) Novak, M.; Pelecanou, M.; Roy, A. K.; Andronico, A. F.; Plourde, F. M.; Olefirowicz, T. M.; Curtin, T. J. *J. Am. Chem. Soc.* **1984**, *106*, 5623. (d) Fishbein, J. C.; McClelland, R. A. *J. Am. Chem. Soc.* **1987**, *109*, 2824. (e) Novak, M.; Kahley, M. J.; Eigen, E.; Helmick, J. S.; Peters, H. E. *J. Am. Chem. Soc.* **1993**, *115*, 9453. (f) Novak, M.; Kahley, M. J.; Lin, J.; Kennedy, S. A.; Swanegan, L. A. *J. Am. Chem. Soc.* **1994**, *116*, 11626. (g) Fishbein, J. C.; McClelland, R. A. *J. Chem. Soc., Perkin Trans. 2* **1995**, 663.

(5) See also: Abramovitch, R. A.; Jeyaraman, R. in *Azides and Nitrenes; Reactivity and Utility*; Scriven, E. F. V., Ed.; Academic Press: New York, 1984; pp 297−354.

(6) (a) Svanholm, U.; Parker, V. D. *J. Am. Chem. Soc.* **1974**, *96*, 1234. (b) Serve, D. *J. Am. Chem. Soc.* **1975**, *97*, 432.

(7) Riecker, A.; Reiser, B. *Tetrahedron Lett.* **1990**, *31*, 5013.

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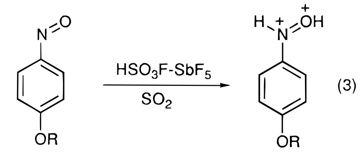
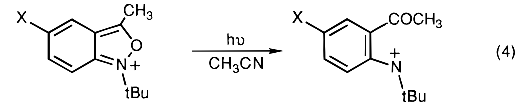
with the super acid experiments is the formation of dications (e.g. **9**) which might be viewed as N-protonated nitrenium ions.[9]



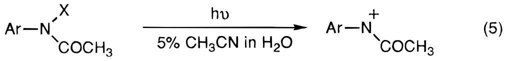
8; R = H, Me **9** (3)

Within the past two years have appeared pathways for the direct study of arylnitrenium ions using the method of laser flash photolysis (LFP). The first report came from the Falvey group and involved the photochemical ring opening in acetonitrile of **10**;[10] this has been followed by two detailed studies of this system probing aspects such as the electrophilicity of the nitrenium ions **11** and their spin multiplicity.[11,12]



10; X = Me, H, Cl, Br, NO$_2$ **11** (4)

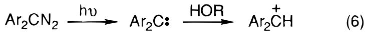
Shortly after the first Falvey paper, we reported in collaboration with the Novak group the *N*-acetyl-4-biphenylyl- and *N*-acetyl-2-fluorenylnitrenium ions (**14**, **15**), observed in aqueous acetonitrile on irradiation of precursors **12** and **13**.[13]



(5)

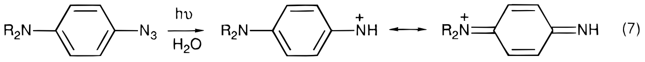
12; Ar = 4-biphenylyl, X = Cl or OSO$_3^-$
13; Ar = 2-fluorenyl, X = OCOtBu
14; 4-biphenylyl
15; 2-fluorenyl

Both the Falvey approach and our approach involved photoheterolysis—the cleavage in the excited state of a N-leaving group bond. Photoheterolytic systems have also been employed successfully for the LFP generation and study of carbenium ions.[14] A different approach that has also been successful with carbenium ions has involved the protonation of photogenerated carbenes,[15,16] as exemplified in eq 6 by the protonation by alcohols and water of diarylcarbenes **17**.[15]



$$\underset{\mathbf{16}}{Ar_2CN_2} \xrightarrow{h\nu} \underset{\mathbf{17}}{Ar_2C\!:} \xrightarrow{HOR} \underset{\mathbf{18}}{Ar_2\overset{+}{C}H} \qquad (6)$$

This raises the possibility of obtaining arylnitrenium ions through the protonation of arylnitrenes, species readily generated photochemically from aryl azides.[17] An examination of the literature shows that there is precedence. The Takeuchi group has investigated the thermolysis and photolysis of phenyl azide in the presence of acids such as acetic, trifluoroacetic, and trifluoromethanesulfonic acid and characterized the products as being consistent with a phenylnitrenium ion intermediate.[18,19] In experiments employing a biological end point, the Wild group photolyzed a series of azides derived from mutagenic arylamines and heterocyclic amines in the presence of bacterial strains.[20] They showed that there was a short-lived mutagenic intermediate and they suggested this to be the nitrenium ion. Finally there is a 25-year old study employing conventional lamp photolysis that showed that the irradiation of *p*-(dialkylamino)phenyl azides **19** in aqueous solution resulted in quantitative yields of the corresponding nitrenium ion **20**, referred to in that work as a quinonediimine **21**.[21]



19 **20** **21** (7)

Arylnitrenes also undergo other reactions very rapidly,[17] and these present a potential problem when attempting to trap by proton transfer. Somewhat to our surprise however we found that 4-biphenylyl azide and 2-fluorenyl azide photolyzed in aqueous solutions to produce high yields of the corresponding nitrenium ions (**4**, **5**) and these intermediates were detectable with LFP. This result has been reported in a preliminary communication.[22] Subsequent to this the Platz group have reported that 2,3,5,6-tetrafluorophenyl azides with a variety of substituents at the 4-position also produce nitrenium ions, in these cases when photolyzed in the presences of acids such as sulfuric acid.[23]

In this paper we provide full details of our studies of the 4-biphenylyl and 2-fluorenyl azides, and also discuss the photochemical behavior of the parent phenyl azide in aqueous acids. We in particular address the question of the acidity and basicity of the intermediate nitrenium ions, and show that these can be quantitatively assessed in some cases using the LFP kinetics.

Results

Phenyl Azide: Products in Aqueous Acid. Solutions of phenyl azide in aqueous solutions were purged with argon and irradiated at 300 nm in a Rayonet reactor. The solutions contained a mixture of HCl and NaCl so that the total ionic strength and total chloride concentration was 1 M. Four products were quantified by HPLC, 1*H*-azepin-2(3*H*)-one (**22**), 4-aminophenol (**23**), 4-chloroaniline (**24**), and 2-chloroaniline

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(8) (a) Olah, G. A.; Prakash, G. K. S.; Arvanaghi, M. *J. Am. Chem. Soc.* **1980**, *102*, 6640. (b) Olah, G. A.; Arvanaghi, M.; Prakash, G. K. S. *J. Am. Chem. Soc.* **1982**, *104*, 1628.

(9) Olah, G. A.; Donovan, D. J. *J. Org. Chem.* **1978**, *43*, 1743.

(10) Anderson, G. B.; Falvey, D. E. *J. Am. Chem. Soc.* **1993**, *115*, 9870.

(11) Robbins, R. J.; Yang, L. L.-N.; Anderson, G. B.; Falvey, D. E. *J. Am. Chem. Soc.* **1995**, *117*, 6544.

(12) Srivastava, S.; Falvey, D. E. *J. Am. Chem. Soc.* **1995**, *117*, 10186.

(13) Davidse, P. A.; Kahley, M. J.; McClelland, R. A.; Novak, M. *J. Am. Chem. Soc.* **1994**, *116*, 4513.

(14) McClelland, R. A. *Tetrahedron* In press.

(15) (a) Kirmse, W.; Kilian, J.; Steenken, S. *J. Am. Chem. Soc.* **1990**, *112*, 6399. (b) Chateauneuf, J. *J. Chem. Soc., Chem. Commun.* **1991**, 1437. (c) Belt, S. T.; Bohne, C.; Charette, G.; Sugamori, S. E.; Scaiano, J. C. *J. Am. Chem. Soc.* **1993**, *115*, 2200.

(16) (a) Schepp, N. P.; Wirz, J. *J. Am. Chem. Soc.* **1994**, *116*, 11749. (b) Kirmse, W.; Strehlke, I. K.; Steenken, S. *J. Am. Chem. Soc.* **1995**, *117*, 7007−7008.

(17) Schuster, G. B.; Platz, M. S. *Adv. Photochem.* **1992**, *17*, 143.

(18) (a) Takeuchi, H.; Takano, K. *J. Chem. Soc., Chem. Commun.* **1982**, 1254. (b) Takeuchi, H.; Takano, K. *J. Chem. Soc., Chem. Commun.* **1983**, 447. (c) Takeuchi, H.; Koyama, K. *J. Chem. Soc., Perkin Trans. 1* **1982**, 1269. (d) Takeuchi, H.; Koyama, K. *J. Chem. Soc., Perkin Trans. 1* **1988**, 1269. (e) Takeuchi, H.; Ihara, R. *J. Chem. Soc., Chem. Commun.* **1983**, 175. (f) Takeuchi, H.; Koyama, K.; Mitani, M.; Ihara, R.; Uno, T.; Okazaki, Y.; Kai, Y.; Kasai, N. *J. Chem. Soc., Perkin Trans. 1* **1985**, 677. (g) Takeuchi, H.; Takano, K. *J. Chem. Soc., Perkin Trans. 1* **1986**, 611. (h) Takeuchi, H.; Hirayama, S.; Mitani, M.; Koyama, K. *J. Chem. Soc., Perkin Trans.* I, **1988**, 521−527. See also: (i) Abramovitch, R. A.; Cooper, M.; Iyer, S.; Jeyaraman, R.; Rodrigues, J. A. R. *J. Org. Chem.* **1982**, *47*, 4819. (j) Abramovitch, R. A.; Jeyaraman, R.; Yannakopoulou, K. *J. Chem. Soc., Chem. Commun.* **1985**, 1017. (k) Abramovitch, R. A.; Hawi, A.; Rodrigues, J. A. R.; Trombretta, T. R. *J. Chem. Soc., Chem. Commun.* **1986**, 283.

(19) For another explanation see: Olah, G. A.; Ramaiah, P.; Wang, Q.; Prakash, G. K. S. *J. Org. Chem.* **1993**, *58*, 6900.

(20) (a) Wild, D.; Dirr, A. *Carcinogenesis* **1988**, *9*, 869. (b) Wild, D.; Dirr, A.; Fasshauer, I.; Henschler, D. *Carcinogenesis* **1989**, *10*, 335. (c) Wild, D.; Dirr, A. *Mutagenesis* **1989**, *4*, 446. (d) Wild, D. *Environ. Health Perspect.* **1990**, *88*, 27. (e) Sabbioni, F.; Wild, D. *Carcinogenesis*, **1992**, *13*, 709.

(21) Baetzold, R. C.; Tong, L. K. J. *J. Am. Chem. Soc.* **1970**, *93*, 1347.

(22) McClelland, R. A.; Davidse, P. A.; Hadzialic, G. *J. Am. Chem. Soc.* **1995**, *117*, 4173.

(23) Michalak, J.; Zhai, H. B.; Platz, M. S. *J. Phys. Chem.* In press.

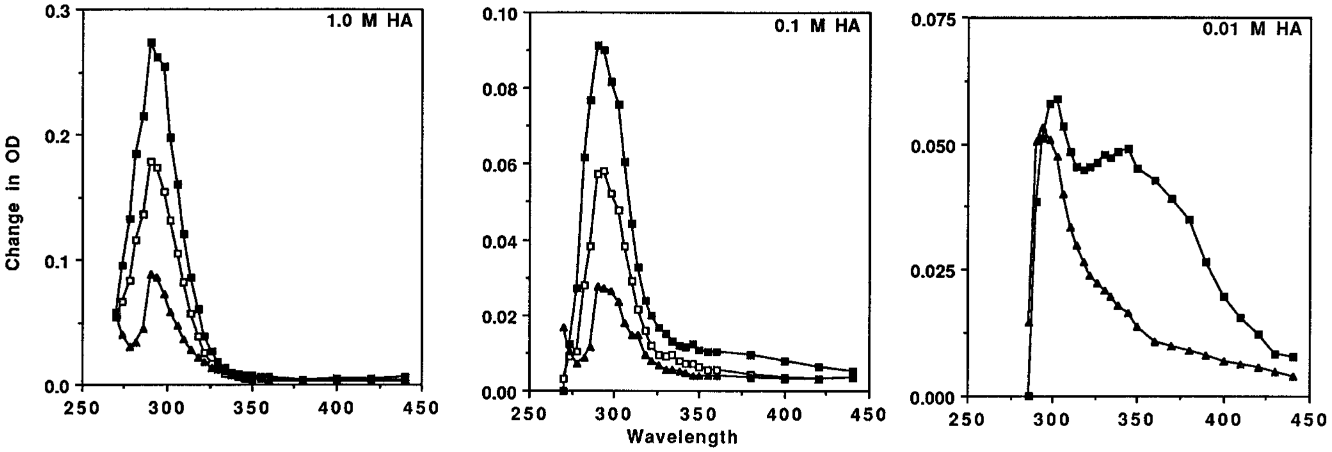

Figure 1. Absorption spectra following 248 nm irradiation of 1 × 10^{-4} M solutions of phenyl azide in aqueous $HClO_4$ solutions. Solutions were argon saturated and were irradiated under identical conditions of laser intensity and cell configuration. Ionic strength was 1.0 M maintained with $NaClO_4$, and the temperature was 20 ± 1 °C. Initial spectra (■) were obtained 100−200 ns after the laser pulse, intermediate spectra (□) at 5−5.1 μs, and final spectra (▲) at 35−40 μs.

Table 1. Product Chemical Yield[a] and Relative Quantum Yield[b] for Disappearance of Substrate for Photolysis of Phenyl Azide in Aqueous HCl + NaCl (or $HClO_4$ + $NaClO_4$) of Total Concentration 1 M (300 nm Irradiation, 5 × 10^{-5} M Substrate, Argon-Purged, 20 ± 1 °C)

	yield, %				
[HCl]	**22**[c]	**23**[d]	**24**[e]	**25**[f]	Φ_{rel}
1.00	40.1	39.0	9.3	4.2	0.97
0.75	53.5	29.2	7.6	3.7	
0.50	61.8	28.9	7.4	3.4	0.92
0.25	59.1	18.9	5.0	2.3	0.95
0.10	71.8	14.2	3.1	1.4	0.94
0.025	74.1	7.4	1.9	0.9	
0.010	79.9	5.8	1.5	0.7	0.88
0.004	78.6	5.3	1.2	0.6	
0.001	76.0	5.7	1.5	0.7	1.00
0.0003	71.8	4.8	1.3	0.6	
1.00[g]	41.1	55.2			
0.10[g]	68.7	18.6			
0.01[g]	71.8	6.8			

[a] Yields based on the percent phenyl azide consumed, for conversions of ~50%. [b] Relative to 0.001 M HCl:0.99 M HCl, and based upon the fraction of phenyl azide consumed. [c] 1*H*-Azepin-2(3*H*)-one. [d] 4-Aminophenol. [e] 4-Chloroaniline. [f] 2-Chloroaniline. [g] $HClO_4$.

(**25**). Results are given in Table 1. Control experiments demonstrated that the yields of the products were within experimental error unchanged for irradiations corresponding to 25−60% conversion. The phenyl azide was also shown to be thermally stable in all solutions for the times required for irradiation and subsequent analysis.

Examination of Table 1 reveals that the products **22**−**25** accounted for 78−100% of the total phenyl azide consumed, with the mass balance poorer in the more dilute HCl solutions. Although yields changed with changing HCl concentration, the ratio of chloroanilines to aminophenol—([**24**] + [**25**]):[**23**]—was within experimental error constant at 0.369 ± 0.026, as was also true for the ratio of 4-chloro- to 2-chloroaniline—[**24**]:[**25**] = 2.14 ± 0.07.

Also given in Table 1 are quantum yields in selected acids for the disappearance of phenyl azide relative to the quantum yield in the solution containing 0.001 M HCl. These experiments were carried out by simultaneously irradiating solutions containing the same concentration of phenyl azide (and same optical density at 300 nm) in a merry-go-round cuvette holder, such that the solutions received identical amounts of the 300-nm light. The irradiations were carried out for times corresponding on average to 35% conversion, and the relative quantum yields were calculated as the ratio of the fractions of phenyl azide consumed.

As also shown in Table 1, experiments were carried out in selected $HClO_4$ solutions. Only the two products **22** and **23** were measured here since the chloroanilines did not form in these solutions.

Experiments were also carried out in the HCl:NaCl mixtures with *N*-phenylhydroxylamine. This compound reacted thermally under acidic conditions to form **23**−**25** as the only detectable products, accounting for >96% of the reacted starting material. In these solutions where the chloride ion concentration was kept constant,[24] the yields of the three products were within experimental error independent of acid concentration. The ratio ([**24**] + [**25**]):[**23**] was 0.458 ± 0.021, and the ratio [**24**]:[**25**] was 2.35 ± 0.08.

Phenyl Azide: Laser Flash Photolysis in Aqueous Acid. These experiments were carried out with $HClO_4$ solutions of concentration 0.001−1.00 M, and representative transient spectra are shown in Figure 1. In solutions with $[HClO_4] > 0.1$, one major transient species absorbing in the region 270−320 nm was observed. The maximum absorbance was ~290 nm, although this may not be the true λ_{max} since the precursor is beginning to absorb in this region.[25] This transient decayed with single exponential kinetics, with a rate constant of $(1.3 \pm 0.1) \times 10^5\ s^{-1}$ independent of acid concentration. As illustrated by comparison of the first two panels of Figure 1, the absolute magnitude of the signal did show an acid dependence, increasing significantly with increasing acid concentration. This transient continued to be observed in the more dilute acids, but its intensity became weak, and as shown in the third panel of Figure 1, it was overlaid with a broad signal in the region from 300 to 400 nm. This absorbance decayed with reasonable first-order kinetics. The first-order rate constants were proportional to H^+ concentration, with $k_{H^+} \sim 10^8\ M^{-1}\ s^{-1}$ (based on three acids in the range 0.01−0.05 M $HClO_4$).

4-Biphenylyl Azide: Products. Photolysis of this azide in an aqueous solution containing 20% acetonitrile resulted in the formation of 4-hydroxy-4-phenyl-2,5-cyclohexadienone (**26**) as the major product. This material was isolated in good yield from a scaled-up photolysis; a sample that had been prepared

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[24] (a) For details of experiments where the reaction was carried out with varying chloride concentration see ref 24b. (b) Fishbein, J. C.; McClelland, R. A. *Can. J. Chem.* In press.

[25] For all three spectra of Figure 1 there was a large negative signal associated with bleaching of the phenyl azide at wavelengths below 270 nm.

Table 2. 4-Biphenylyl Azide Photolysis. Acetonitrile:Water Dependences of Yield of 4-Hydroxy-4-phenyl-2,5-cyclohexadienone (**26**), Relative Quantum Yield for Consumption of Substrate, ΔOD, and First-Order Rate Constant for Decay of LFP Transient at 460 nm

acetonitrile,[a] %	yield of **26**,[b] %	Φ_{rel}[c]	ΔOD(460 nm)[d]	k_{obs}(460 nm), $\times 10^6$ s^{-1}
10.0	88 ± 2		0.224 ± 0.006	2.81 ± 0.11
20.0	84 ± 3	1.00	0.212 ± 0.011	2.84 ± 0.04
30.0	73 ± 2	0.88 ± 0.05	0.188 ± 0.008	3.03 ± 0.07
40.0	66 ± 1	1.01 ± 0.12	0.163 ± 0.012	3.16 ± 0.03
50.0	57 ± 1		0.139 ± 0.007	3.37 ± 0.09
60.0	43 ± 2	1.24 ± 0.09	0.105 ± 0.005	3.35 ± 0.09
70.0	28 ± 2		0.062 ± 0.003	3.43 ± 0.09
80.0	13 ± 1	0.97 ± 0.07	0.028 ± 0.001	3.38 ± 0.12
90.0	∼1	1.14 ± 0.15	trace	
0.0			*e*	2.69 ± 0.11

[a] Percent by volume. Solutions for product studies also contained 0.002 M CH_3COOH:0.002 M CH_3COONa. [b] Measured 24 h following irradiation, and based upon the amount of 4-biphenylyl azide consumed for experiments carried out to ∼40% conversion. [c] Relative to 20% acetonitrile, and based upon the fraction of azide consumed. [d] Optical density at 460 nm measured immediately after completion of the laser pulse minus the residual optical density after complete decay. The latter was small (0.002−0.004) but finite. All solutions contained 20 μM of substrate and were irradiated under identical conditions. [e] Concentration of 4-biphenylyl azide was 1 μM.

Table 3. 4-Biphenylyl Azide Photolysis. Yield[a] of 4-Hydroxy-4-phenyl-2,5-cyclohexadienone (**26**) in 1:4 (v:v) Water−Acetonitrile, with Ionic Strength 0.5 Maintained with $NaClO_4$

conditions	yield of **26**, %	conditions	yield of **26**, %
0.1 M $HClO_4$	86.2 ± 1.1	0.050 M NaOH	43.1 ± 1.6
pH 4.5	84.8 ± 1.2	0.100 M NaOH	38.2 ± 2.1
pH 7.0	82.5 ± 0.8	0.150 M NaOH	28.5 ± 0.9
0.002 M NaOH	79.8 ± 0.9	0.200 M NaOH	23.4 ± 0.4
0.005 M NaOH	77.6 ± 0.8	0.250 M NaOH	21.7 ± 0.4
0.010 M NaOH	67.4 ± 1.4	0.300 M NaOH	21.4 ± 0.8
0.020 M NaOH	61.3 ± 0.5	0.400 M NaOH	20.8 ± 0.2
0.030 M NaOH	52.9 ± 0.6	0.500 M NaOH	21.2 ± 0.7

[a] Measured 24 h following irradiation. For the experiments where NaOH was present during irradiation, solutions were neutralized immediately following, and stood for 24 h at pH ∼5.

in a different way was also obtained from the Novak group.[26,27] Quantitative yields, as well as relative quantum yields for disappearance of starting azide, were determined by HPLC and are given in Tables 2 and 3 for photolyses carried out under a variety of conditions. Yields of **26** were independent of irradiation time for conversions up to 70%.

The ketone **26** was not the initial product of photolysis. Injections made immediately following the 0.5−1.5-min irradiations resulted in HPLC traces with a peak with a different retention time which disappeared over time with a 3−4-h half-life (at pH 5). The peak for **26** was not present in the first injection (or was very small), but grew in at the same rate as the initial peak disappeared. Such behavior had been observed previously by the Novak group (vide infra) with the precursor for **26** being assigned as 4-hydroxy-4-phenyl-2,5-cyclohexadienone imine (**27**).[27] In the experiments carried out in NaOH solutions (Table 3), the imine was present after irradiation, but did not convert to the ketone. To analyze for **26**, these solutions were therefore neutralized to pH 5 immediately after irradiation.

In the experiments with high contents of acetonitrile the amount of **26** observed was very small or negligible. The precursor **27** was also observed to a similarly small extent. In fact an excellent correlation was found between the area of the peak for the precursor **27** measured immediately after irradiation and the area of the peak for **26** measured the next day. Other peaks were observed in the HPLC, these being very small in the solutions with high water content, but increasing in intensity in the acetonitrile-rich solutions. Two of the HPLC peaks from irradiation in 100% acetonitrile were matched to authentic samples, one (∼10%) to 4-aminobiphenyl and the other (∼30%) to 4,4′-diphenylazobenzene.

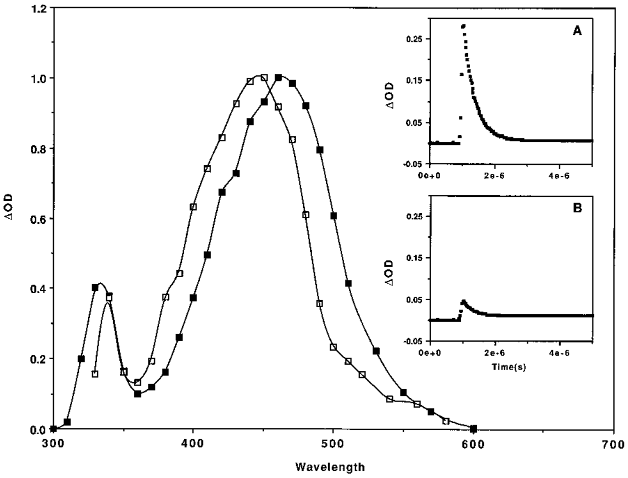

Figure 2. Absorption spectra following 248 nm irradiation of 2 × 10^{-5} M solutions of 4-biphenylyl azide (■) and 2-fluorenyl azide (□) in 1:4 (v/v) acetonitrile−water. Optical density units in the main figure have been normalized so that the maximum ΔOD is 1. The inserts show the kinetic traces at 460 nm for 4-biphenylyl azide in 1:4 acetonitrile−water (A) and 4:1 acetonitrile−water (B).

Table 4. Rate Constants for the Formation and Decay of 4-Biphenylyl- and 2-Fluorenylnitrenium Ion in 1:4 (v:v) Acetonitrile−Water (20 °C)

constant	ionic strength[a]	4-biphenylyl	2-fluorenyl
k_{app}, s^{-1}	0	6.0 ± 0.1 × 10^9	1.1 ± 0.2 × 10^{10}
k_s, s^{-1}	0	2.84 ± 0.04 × 10^6	3.4 ± 0.2 × 10^4
k_s, s^{-1}	0.5	1.85 ± 0.07 × 10^6	2.2 ± 0.2 × 10^4
k_s, s^{-1}	1.0	1.06 ± 0.02 × 10^6	1.3 ± 0.2 × 10^4
k_s, s^{-1}	0.5[b]	1.78 ± 0.04 × 10^6	2.0 ± 0.4 × 10^4
k_{Az}, M^{-1}s^{-1}	0.5[b]	5.0 ± 0.2 × 10^9	4.0 ± 0.2 × 10^9
k_{OH}(obs), M^{-1} s^{-1}	0.5	6.4 ± 0.3 × 10^7	1.05 ± 0.06 × 10^7

[a] With $NaClO_4$. [b] Solution contains 5% acetonitrile.

4-Biphenylyl Azide and 2-Fluorenyl Azide: Laser Flash Photolysis. Figure 2 shows the results of laser flash photolysis experiments in aqueous solutions containing 20% acetonitrile. With each azide, a relatively intense transient was observed, with λ_{max} around 460 nm for the biphenylyl system and 450 nm for fluorenyl. With each azide the absorbance decayed with the same rate constant across the entire spectrum from 400 to 500 nm, while the absorbance below 350 nm showed little decay on a 10-μs time scale. Rate constants were increased by the addition of azide or hydroxide, and plots of k_{obs} were linear in the concentration of the added reagent. First-order rate constants for decay in the solvent alone and second-order rate constants for the quenching by azide and hydroxide are given in Table 4.

Experiments were carried out in which the biphenylyl azide was irradiated under identical conditions in solutions of varying acetonitrile content. These showed that the initial intensity of the 460-nm transient decreased with increasing acetonitrile (compare for example the two inserts in Figure 2). Table 2 summarizes the acetonitrile dependence, for both the rate constant for the 460-nm decay and the change in optical density,

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(26) Novak, M.; Helmick, J. S.; Oberlies, N.; Rangappa, K. S.; Clark, W. M.; Swenton, J. S. *J. Org. Chem.* **1993**, *58*, 867−878.

(27) Novak, M.; Kahley, M. J.; Eiger, E.; Helmick, J. S.; Peters, H. E. *J. Am. Chem. Soc.* **1993**, *115*, 9453.

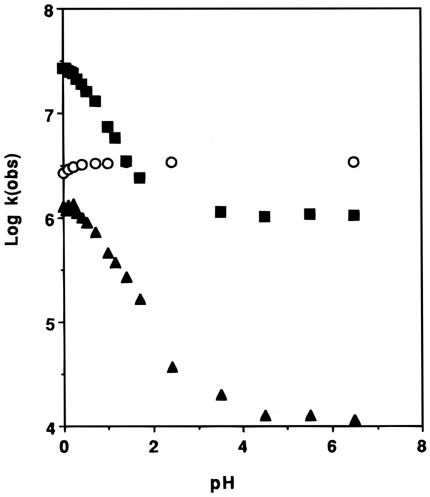


Figure 3. Rate constants for decay of nitrenium ions in acidic solutions (1:4 acetonitrile−water; 20 °C). Solutions with pH <3 contained $HClO_4$, and solutions with pH 3.5−6.5 contained dilute acetate buffer; the ionic strength in all solutions was 1.0 M, maintained with $NaClO_4$: (■) 4-biphenylyl nitrenium ion; (▲) 2-fluorenyl nitrenium ion; (○) *N*-acetyl-4-biphenylylnitrenium ion, generated from *N*-chloro precursor.

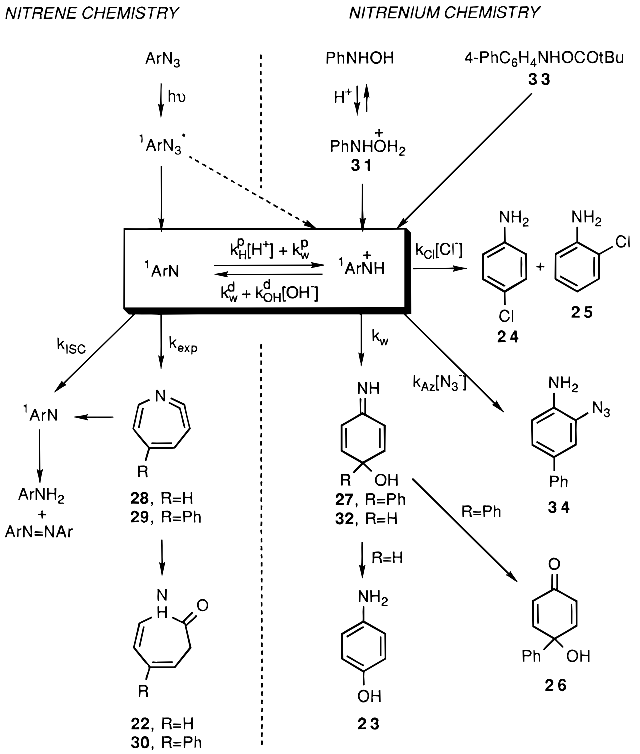
calculated as the optical density immediately after the laser pulse minus the optical density at the conclusion of the decay. As shown by the inserts to Figure 2, there is residual absorbance at 460 nm, but the amount is small. The 460-nm transient was not observed in solutions with acetonitrile content above 90%, and there was in fact only a small change in optical density above 400 nm in these solutions. The absorbance around 340 nm continued to be observed, and in fact seemed to grow in intensity (although this was not studied in detail).

Similar experiments were carried out with both azides in basic 20% acetonitrile in order to see if base had any effect on the initial intensity of the transient. These measurements could be carried out to 0.15 M NaOH with the biphenylyl azide and 0.6 M NaOH with fluorenyl before the decay of the transient became too rapid to reliably measure the initial absorbance. Within experimental uncertainty the conclusion was that the addition of base up to the above limits had no effect on the initial intensity at 460 or 450 nm.

Shown in Figure 3 are the rate constants for the decay of the two transients as a function of pH under acidic conditions. Each system showed an increase in rate below pH 3−4, with signs of leveling in the more concentrated acids. For comparison purposes, rate constants were also obtained in the same solutions for the *N*-acetyl-4-biphenylylnitrenium ion as generated from the *N*-chloro precursor.[13] These rate constants remained constant from pH 1−7, with a slight decrease in the more acidic solutions. For example, the rate constant in 1.0 M $HClO_4$ was $2.70 \pm 0.05 \times 10^6\ s^{-1}$, while in neutral 1.0 M $NaClO_4$, it was $3.35 \pm 0.07 \times 10^6$.

Since we will argue that the transient species from the azides are in a different state of protonation in acids (vide supra), we constructed a spectrum for the 2-fluorenyl system in 1.0 M $HClO_4$.[28] We found however that within the limits of our apparatus this had a very similar form and λ_{max} as the spectrum constructed without acids. There did appear to be a slightly lower initial intensity for the transient in the 1.0 M acid, the initial optical density at 450 nm in 1.0 M $HClO_4$ being about 70% of that in 1.0 M $NaClO_4$ for experiments carried out under identical conditions (substrate concentration, laser dose, etc.).

Scheme 1



The LFP experiments discussed thus far involved excitation with a laser with a ~20 ns pulse width, and in all cases the transients in the region above 400 nm were fully formed at the completion of the laser pulse. The appearance of this absorbance was however observed using a laser system with excitation at 266 nm and a ~25 ps pulse. The transients seen as the "initial" absorbances in the ns experiments grew in with good exponential kinetics with rise times in 20% acetonitrile of 90 and 160 ps for the 2-fluorenyl and 4-biphenylyl systems, respectively (Table 4). A further feature of these experiments was the absence of optical density immediately after the 25-ps pulse in the region from 400 to 700 nm where observations could be made with this equipment.

Discussion

Scheme 1 summarizes the established chemistries of arylnitrenes and arylnitrenium ions that are of relevance to this work. On the nitrene side, the key reactions from the singlet are the competing intersystem crossing to the triplet nitrene and ring expansion to a 1,2-didehydroazepine (**28**, **29**).[17] Triplet nitrenes react further to give azobenzenes and anilines by coupling and hydrogen abstraction reactions, respectively, while dehydroazepines react with nucleophiles to give azepines,[29] in the case of water an azepinone such as **22**.[18c,30] The dehydroazepines can also convert to triplet nitrene, and indeed in the absence of nucleophiles this is often the major reaction.[29,31] With singlet phenylnitrene, the predominant pathway at low temperatures (e.g. 77 K) is intersystem crossing, while in solutions at ambient temperature ring expansion to the dehydroazepine dominates.[17,32] Platz and co-workers have estimated that this ring expansion occurs with a rate constant (k_{exp}) of

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[28] This was not possible with 4-biphenylyl azide, since the decay in 1 M $HClO_4$ was too fast.

[29] See: Li, Y.-Z.; Kirby, J. P.; George, M. W.; Poliakoff, M.; Schuster, G. B. *J. Am. Chem. Soc.* **1988**, *110*, 8092 and references therein.

[30] (a) Vogel, E.; Erb, R.; Lenz, G.; Bothner, A. A. *Liebigs Ann. Chem.* **1965**, *682*, 1. (b) Doering, W. E.; Odum, R. A. *Tetrahedron* **1966**, *22*, 81.

[31] Polymerization of the dehydroazepine also occurs, and accounts for the poor mass balances in product analyses frequently observed following aryl azide photolysis.[17]

10^{10}−10^{11} s^{-1} at room temperature.[32] This same group has also established that in the case of phenyl azide the singlet phenylnitrene is the branching point for the triplet and dehydroazepine.[33]

Arylnitrenium ions are formed by ground state heterolysis reactions, either from O-protonated hydroxylamines **31** under acidic conditions[34] or from hydroxylamine esters such as the pivalate **33**. These nitrenium ions react with water at the position para to the nitrogen to give adducts such as **27** and **32**. In cases such as the parent system, rapid tautomerization gives the *p*-aminophenol. In cases such as the 4-biphenylyl system where this tautomerization is blocked, the imine can be observed but it is not stable. Several reactions occur, including imine hydrolysis and migration of R or OH to an adjacent carbon.[35] Nitrenium ions can also be trapped by external nucleophiles such as chloride and azide to give products such as **24**, **25**, and **34**.

A singlet nitrene is the conjugate base of a singlet nitrenium ion, and thus the two intermediates can in principle be linked by protonation/deprotonation. This is shown in the highlighted box in Scheme 1, with the protonation occurring by H^+ and by water, and the microscopic reverse deprotonation by water and by hydroxide ion, respectively. The acidity constant for the singlet nitrenium ion deprotonating to the singlet nitrene is thus given by the following:

$$K_a({}^1\mathrm{ArNH}^+ \rightleftarrows {}^1\mathrm{ArN}) = \frac{k_w^d}{k_H^p} = \frac{k_{OH}^d K_w}{k_w^p} \qquad (8)$$

This equation of course refers to the interconversion of the two species in their singlet electronic states. The ground state of most arylnitrenes is the triplet, calculated for example in the case of phenylnitrene to be ~20 kcal/mol more stable than the singlet.[36] Most arylnitrenium ions on the other hand are ground state singlets.[37] This is seen experimentally in their nucleophilic addition chemistry, a reaction pathway argued to be a characteristic of a singlet.[38] Theoretical calculations also show singlet ground states;[39] a recent high-level calculation for example places the singlet phenylnitrenium ion 21 kcal/mol below the triplet.[39f] An interesting consequence of the different multiplicities of the ground state nitrene and nitrenium ion is that the acidity constant of a triplet arylnitrenium ion deprotonating to a triplet arylnitrene is many orders of magnitude greater than the one that relates singlets. Based on the energy differences cited above there would be an approximately 10^{30} difference.

Trapping of Singlet Phenylnitrene by Protonation. Irradiation of phenyl azide in 1 M HCl results in 40% **22**, and slightly greater then 50% in total of the anilines **23**, **24**, and **25**. The azepinone is explained by the nitrene chemistry in Scheme 1, through water addition to the ring expanded dehydroazepine **28**. The ring-substituted anilines however are not the products from a nitrene, but are diagnostic of the presence of the phenylnitrenium ion. These same three products are formed in the ground state reaction of *N*-phenylhydroxylamine in acid, in this case in quantitative yield. Moreover, the chloroanilines: aminophenol ratios and the p-chloroaniline:o-chloroaniline ratios are very similar[40] whether phenylhydroxylamine or phenyl azide is the precursor.

The question then arises as to the immediate precursor of the nitrenium ion in the azide photolysis, that is, whether it is indeed the singlet nitrene or the excited singlet state of the phenyl azide. In the latter case, nitrenium ion would form with protonation concurrent with loss of N_2. In their study involving fluorinated phenyl azides as precursors of nitrenium ions, Platz and co-workers produced evidence for a singlet nitrene precursor by demonstrating agreement between lifetimes of this species as estimated by trapping by acid and independently by trapping with pyridine.[23] In the present case the excited singlet can be ruled out as a precursor on the basis that the relative quantum yields for disappearance of the phenyl azide are within experimental error unchanged from dilute acid to 1.0 M acid. This occurs in spite of an increase in the yield of nitrenium-derived products from 6−8% to 52%. If these products were derived from the excited state, the increasing importance of the protonation pathway would have resulted in an increase in the quantum yield, in fact an almost doubling in the 1 M acid.

Thus we conclude that the precursor to the phenylnitrenium ion is singlet phenylnitrene and that this species can be trapped by protonation. On this basis eq 9 can be written for the dependence of the products on H^+ concentration,

$$F_{\mathrm{aniline}} = \frac{\left(\frac{k_H^p}{k_{\mathrm{exp}}}\right)[H^+] + \left(\frac{k_w^p}{k_{\mathrm{exp}}}\right)}{\left(\frac{k_H^p}{k_{\mathrm{exp}}}\right)[H^+] + \left(\frac{k_w^p}{k_{\mathrm{exp}}}\right) + 1} \qquad (9)$$

where F_{aniline} is the fraction of the reacted phenyl azide that is accounted for by the aniline products **23**, **24**, and **25**. The assumptions that are made are that there is no reversal of the protonation, ring expansion, or intersystem crossing, that ring expansion is more important than intersystem crossing ($k_{\mathrm{exp}} > k_{\mathrm{ISC}}$),[17,32,41] and that the three anilines account for all of the intermediate nitrenium ion that is formed. We do not quantitatively account for all of the products from the phenyl azide, especially in the more dilute acids, but assume that this is caused by other reactions involving the dehydroazepine.[31]

The HCl product data in Table 1 were fit to eq 9 to provide values of k_H^p:k_{exp} = 1.1 ± 0.1 M^{-1} and k_w^p:k_{exp} = 0.07 ± 0.01 (see Figure 4). As will be shown singlet arylnitrenes are relatively strong bases, stronger in fact than ammonia and

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[32] Leyva, E.; Platz, M. S.; Persy, G.; Wirz, J. *J. Am. Chem. Soc.* **1986**, *108*, 3783.

[33] Marcinek, A.; Leyva, E.; Whitt, D.; Platz, M. S. *J. Am. Chem. Soc.* **1993**, *115*, 8609.

[34] (a) As in the Bamberger rearrangement. For recent references see: (b) Sone, T.; Tokudo, Y.; Sakai, T.; Shinkai, S.; Manabe, O. *J. Chem. Soc., Perkin Trans. 2* **1981**, 298. (b) Sone, T.; Hamamoto, K.; Seiji, Y.; Shinkai, S.; Manabe, O. *J. Chem. Soc., Perkin Trans. 2* **1981**, 1596. (c) Kohnstam, G.; Petch, W. A.; Williams, D. L. H. *J. Chem. Soc., Perkin Trans. 2*, **1984**, 423.

[35] For examples see refs 27, 34c, and: Biggs, T. N.; Swenton, J. S. *J. Am. Chem. Soc.* **1993**, *115*, 10416.

[36] (a) Kim, S.-J.; Hamilton, T. P.; Schaefer, H. F. *J. Am. Chem. Soc.* **1992**, *114*, 5349. (b) Hrovat, D. A.; Waali, E. E.; Borden, W. T. *J. Am. Chem. Soc.* **1992**, *114*, 8698. (c) For experimental evidence, see: Travers, M. J.; Cowles, D. C.; Clifford, E. P.; Elison, G. B. *J. Am. Chem. Soc.* **1992**, *114*, 8699. (d) Interestingly, the singlet state that has the lowest energy is an open shell species.

[37] The *N*-*tert*-butyl(2-acetyl-4-nitrophenyl)nitrenium ion recently studied by Srivasta and Falvey is an exception.[12]

[38] Anderson, G. B.; Yang, L. L.-N.; Falvey, D. E. *J. Am. Chem. Soc.* **1993**, *115*, 7254.

[39] (a) Ford, G. P.; Scribner, J. D. *J. Am. Chem. Soc.* **1981**, *103*, 4281. (b) Glover, S. A.; Scott, A. P. *Tetrahedron* **1989**, *45*, 1763. (c) Li, Y.; Abramovitch, R. A.; Houk, K. N. *J. Org. Chem.* **1989**, *54*, 2911. (d) Ford, G. P.; Herman, P. S. *J. Mol. Struct. (Theochem.)* **1991**, *236*, 269. (e) Falvey, D. E.; Cramer, C. J. *Tetrahedron Lett.* **1992**, *33*, 1705. (f) Cramer, C. J.; Dulles, F. J.; Falvey, D. E. *J. Am. Chem. Soc.* **1994**, *116*, 9787.

[40] The two ratios for [**24**]:[**25**] are within experimental error the same. The ratios for ([**24**] + [**25**]):[**23**] (0.369 ± 0.026 for PhN_3 and 0.458 ± 0.021 for PhNHOH) may be statistically different. A possible explanation is that the phenylnitrenium ion, which is very short-lived,[24b] reacts in a different state of ion pairing, or perhaps in a different vibrational state, when formed from the two precursors.

[41] This is demonstrated in the present experiments by the relatively high yield of the azepinone **22** for the non-nitrenium products.

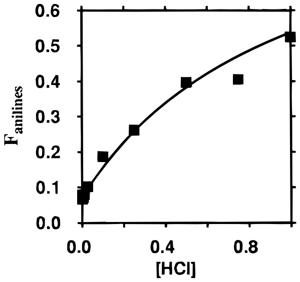


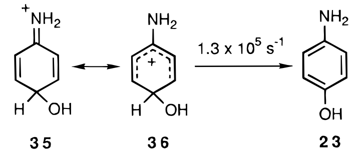
Figure 4. Yield of aniline products {%(**23** + **24** + **25**):100} as a function of HCl concentration. The points are experimental. The line has been drawn according to eq 9 using the parameters given in the text.

alkylamines. These amines are protonated by aqueous H^+ with rate constants of $2-4 \times 10^{10}$ M^{-1} s^{-1},[42] and thus k_H^p must also lie within this range. This means that k_{exp} is also $2-4 \times 10^{10}$ (with s^{-1} units), precisely in the range previously estimated by the Platz group, except with tighter limits.

One result that surprised us was the formation of a small amount of nitrenium-derived products at very low acid concentration, indicating that the solvent was sufficiently acidic to trap the singlet nitrene. Quantitatively k_w^p:k_H^p is 0.06 ± 0.02 M, which means that k_w^p is $1-2 \times 10^9$ s^{-1}. The magnitude of this rate constant indicates that singlet phenylnitrene is relatively basic, as shown by the following calculation of the upper limit on the acidity constant of the phenylnitrenium ion. This calculation uses the lower limit for k_w^p and an upper limit for k_{OH}^d of 4×10^{10} M^{-1} s^{-1}, based on data for ammonium ions and hydroxide.[42] From eq 8, $pK_a(^1PhNH^+ \rightleftarrows {}^1PhN)$ is then calculated to be greater than 12.4.

Transients Observed upon Phenyl Azide Photolysis in Acids. The transient that can be recognized from previous studies of phenyl azide is the dehydroazepine **28.**[17] This species results in a broad absorbance in the 300−400-nm region and is clearly present in the more dilute acids of our experiments. This intermediate is of course the precursor of the azepinone **22**. The dehydroazepine transient however was only seen in solutions more dilute that ∼0.1 M acid, in spite of the fact that **22** continued to form in reasonable yield in stronger acids. Although detailed kinetic experiments were not performed, the explanation appears to lie in the reaction of the dehydroazepine being H^+-catalyzed, with the decay becoming too rapid in the more concentrated acids for detection on the >20 ns time scale of our apparatus. This catalysis is not surprising since the dehydroazepine is a ketenimine, and such compounds do hydrate in a reaction that is efficiently catalyzed by acids.[43]

The new feature of our experiments is the transient at lower wavelengths. This species increases with increasing acidity in a manner similar to the aniline products, implying that it is an intermediate on the nitrenium side of Scheme 1. The phenylnitrenium ion itself can be ruled out since its lifetime in water is only 100−200 ps.[24b] Our assignment therefore is the cyclohexadiene **32**, or more particularly in the acid solutions of our studies, its conjugate acid **35.**[44] This species is the cyclohexadienyl cation (e.g. **36**) that is formed by protonating *p*-aminophenol at the carbon para to the amino group. What is being observed therefore in the decay of this transient is the deprotonation by water to form the aminophenol.[45]



(10)

4-Biphenylyl Azide: Products. The relevant data concerning the nitrenium ion in this system come from the study of the pivalate **33** by the Novak group.[27] This ester was found to undergo relatively rapid solvolysis in 5% acetonitrile−water resulting in two products. One, formed in 7% yield, retained the pivaloyl group, and was attributed to internal trapping at the stage of a nitrenium−pivalate ion pair. The other, formed in 91% yield, was the cyclohexadienone **26**. This was not an initial product; a precursor with a half-life of several hours was observed in the HPLC analysis and attributed to the imine **27**. The addition of sodium azide to the solvolysis caused no increase in the rate of reaction of **33**, but resulted in the formation of the azido adduct **34** in place of **26**. This is evidence that the intermediate 4-biphenylylnitrenium ion forms in a rate-limiting step and subsequently partitions between water and the azide ion. Quantitative analysis of the ratio of **34** to **26** provided the trapping ratio k_{az}:k_w as $(2.9 \pm 0.2) \times 10^3$ M^{-1}.

The formation of **26** in high yields, coupled with the HPLC observation of its precursor, shows that there is substantial formation of the same nitrenium ion in the photolysis of 4-biphenylyl azide. Assuming that free 4-biphenylylnitrenium ion converts quantitatively to **26**, as implied by the Novak result, 88% of the photolysis in 10% acetonitrile goes through the nitrenium pathway. This is substantially higher than observed with phenyl azide, and moreover it occurs without added acid, i.e. by a pathway involving protonation by water. As would be expected for such a pathway, the yield of **26** does decrease with decreasing water content, and by 90% acetonitrile there is little or no protonation.[46] Under these conditions, the photolysis appears to follow a similar course to that seen previously in a study in cyclohexane solvent,[29] with formation of the azo and amino derivatives.

4-Biphenylyl- and 2-Fluorenylnitrenium Ions. There is substantial evidence that the transient with λ_{max} at 460 nm in the LFP experiments with 4-biphenylyl azide is the nitrenium ion.

(i) Such an intermediate is consistent with the formation of **26**. It can be noted that experiments with varying laser intensities demonstrated that the transient absorbance was linear in the laser dose. Moreover, **26** was demonstrated to form in the same yield by HPLC analysis following laser irradiation. Thus, the laser photochemistry is the same as that observed on steady-state photolysis.

(ii) More importantly, there is an excellent linear correlation (not shown) between the initial absorbance[47] at 460 nm and the percent yield of **26** (Table 2), unequivocally demonstrating that the transient is a precursor of the product.

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(42) Eigen, M. *Angew. Chem., Int. Ed. Engl.* **1964**, *3*, 1.

(43) McCarthy, D. G.; Hegarty, A. F. *J. Chem. Soc., Perkin Trans. 2* **1980**, 579.

(44) (a) The pK_a value for protonated benzoquinone imine is 3.7.[44b] (b) Novak, M.; Martin, C. A. *J. Org. Chem.* **1991**, *56*, 1585.

(45) For previous LFP studies involving protonated aromatics see Steenken, S.; McClelland, R. A. *J. Am. Chem. Soc.* **1990**, *112*, 9648. Mathivanan, N.; Cozens, F.; McClelland, R. A.; Steenken, S. *J. Am. Chem. Soc.* **1992**, *114*, 2198. Lew, C. S. Q.; McClelland, R. A. *J. Am. Chem. Soc.* **1993**, *114*, 2198. Zhang, G.; Shi, Y.; Mosi, R.; Ho, T.; Wan. P. *Can. J. Chem.* **1994**, *72*, 2388. McClelland, R. A.; Cozens, F.; Steenken, S. *Tetrahedron Lett.* **1990**, 3821.

(46) In addition to a decreased rate of protonation associated with the lower water concentration, an added factor may be that there is insufficient water to efficiently solvate hydroxide ion, so that the ion pair $ArNH^{+} \cdot {}^{-}OH$ cannot separate.

(47) The experiments measuring this quantity reported in Table 2 were carried out in such a way that the ΔOD values represent relative quantum yields for formation of the transient.

(iii) The transient is quenched by azide ion, with k_{az}:k_w calculated from the directly measured rate constants (2.8 ± 0.1) × 10^3 M^{-1} identical to the ratio found by the Novak group. This identity is important in an additional manner since it establishes that the flash photolysis intermediate is a ground state species.

(iv) A transient with a very similar λ_{max} is observed for the *N*-acetyl-4-biphenylylnitrenium ion generated by a completely different photoreaction (eq 5).[13]

(v) The 4-biphenylylnitrenium ion **7** (eq 2), which was characterized by NMR, exhibits a λ_{max} of 502 nm.[7] The 460-nm λ_{max} observed for the parent is thus consistent, especially considering that **7** has a dimethylamino substituent in the second ring and this might be expected to increase λ_{max}.

A similar transient, albeit two orders of magnitude longer-lived, is observed on irradiation of 2-fluorenyl azide, and can be assigned to the corresponding nitrenium ion. Although product evidence is lacking with this system,[48] the similarity with the spectrum for the 4-biphenylylnitrenium ion, the efficient quenching by azide ion, and the close similarity to the spectrum of the *N*-acetyl-2-fluorenylnitrenium ion[13] place little doubt on this assignment.

Precursor of the 4-Biphenylyl- and 2-Fluorenylnitrenium Ions. As in the case of the phenyl azide, we will argue that the precursor of these nitrenium ions is the singlet nitrene. Two pieces of evidence can be cited to rule out the excited state of the azide.

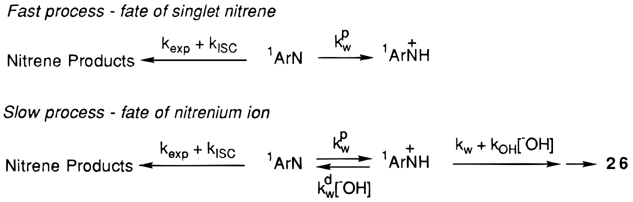
(i) In the biphenylyl system the relative quantum yield for disappearance of the substrate is essentially unchanged from 20% to 90% acetonitrile, in spite of a decrease in the yield of the nitrenium ion from 84% to almost zero. If the excited state were the precursor the loss of this photochemical pathway would surely have had an effect.

(ii) Picosecond spectroscopy with fluorene has recently showed a transition attributed to the singlet excited state near 700 nm.[49] Unless the azide substituent perturbs the system sufficiently to move the transition out of the observable region, the absence of such a transition with 2-fluorenyl azide implies that even after 25 ps the singlet excited state has lost N_2.

The rate constant for the appearance of the nitrenium ion measured in the ps experiment represents the reactions of the singlet nitrene, and is therefore equal to $k_{exp} + k_{ISC} + k_w^p$. In the case of biphenylyl this can be broken down further since k_w^p:($k_{exp} + k_{ISC} + k_w^p$) is known from the yield of the nitrenium product **26**. Thus for 20% acetonitrile k_w^p is calculated as 5 × 10^9 s^{-1} and ($k_{exp} + k_{ISC}$) as 1 × 10^9 s^{-1}. These numbers show why the amount of nitrenium ion produced by solvent protonation is so much greater with the biphenylyl system when compared to phenyl. The rate of protonation is in fact only 2.5−5 times greater for biphenylyl, but the lifetime of the singlet biphenylylnitrene with respect to ring expansion and intersystem crossing is 20−40 times longer.

Acidity of the 4-Biphenylylnitrenium Ion. In this section we will combine this value of k_w^p with a value of k_{OH}^d calculated from data obtained in base. The analysis is based on Scheme 2 where the singlet nitrene reacts by processes occurring on the ps time scale that involve partitioning between protonation to the nitrenium ion and a combination of ring expansion and intersystem crossing that results in "nitrene products". This is followed by processes occurring on the ns time scale whereby that fraction of nitrenium ion that has formed in the first step reacts with water and hydroxide leading to **26**. In competition there is deprotonation by hydroxide to the singlet nitrene which on this time scale rapidly partitions back to nitrenium ion and on to the nitrene products.

Scheme 2



The assumption that is made in this treatment is that reactions involving singlet nitrene are faster than reactions involving nitrenium ion, i.e. that ($k_{exp} + k_{ISC} + k_w^p$) > ($k_w + k_{OH}[^-OH] + k_{OH}^d[^-OH]$). Evidence that this is the case will be seen in the numbers derived below. Also noteworthy is the observation in the ns LFP experiments that the initial optical density of the nitrenium ion is unchanged even in quite concentrated base. This indicates that the quantity of nitrenium ion is still being determined by the initial partitioning of the singlet nitrene, and that on the time scale of this partitioning, reactions involving hydroxide ion and nitrenium ion are unimportant.

In terms of this model eqs 11 and 12 are derived for the rate constant for decay of the nitrenium ion and the fractional yield of the product **26**

$$k_{decay} = k_w + k_{OH}[^-OH] + (1 - \mathbf{P})k_{OH}^d[^-OH] \qquad (11)$$

$$F_{26} = \mathbf{P}\left(\frac{k_w + k_{OH}[^-OH]}{k_w + k_{OH}[^-OH] + (1 - \mathbf{P})k_{OH}^d[^-OH]}\right) \qquad (12)$$

where $\mathbf{P} = k_w^p$:($k_{exp} + k_{ISC} + k_w^p$). Equation 11 predicts a linear quenching with hydroxide ion, but the slope (k_{OH}(obs)) is equal to $k_{OH} + (1 - \mathbf{P})k_{OH}^d$ and does not represent solely nucleophilic quenching. Equations 11 and 12 contain four independent variables, **P**, k_w, k_{OH}, and k_{OH}^d. Values for **P** (0.84) and k_w (1.85 × 10^6 s^{-1}) were taken from product and LFP data in neutral solutions, and the term in [⁻OH] in the denominator of eq 12, ($k_{OH} + (1 - \mathbf{P})k_{OH}^d$) was taken as the value of k_{OH}(obs) (6.4 × 10^7 M^{-1} s^{-1}). This left one unknown, k_{OH}, and the experimental data were fit to eq 12 to obtain its value. The fit showing the good agreement of the model to the experimental data is shown in Figure 5. The value of k_{OH} so obtained was 1.4 × 10^7 M^{-1} s^{-1}, and from this value and k_{OH}(obs), the value of k_{OH}^d was obtained as 3.1 × 10^8 M^{-1} s^{-1}.

The ratio k_w^p:k_{OH}^d is 16 and is equal to the basicity constant K_b for the singlet 4-biphenylylnitrene in 20% acetonitrile−water.

$$^1\text{4-PhC}_6\text{H}_4\text{N} + \text{H}_2\text{O} \rightleftarrows {}^1\text{4-PhC}_6\text{H}_4\text{NH}^+ + {}^-\text{OH} \qquad (13)$$

This means that a hypothetical solution containing 16 M hydroxide ion is required for a 1:1 mixture of the singlet nitrene and nitrenium ion at equilibrium. In 1 M hydroxide, there is only about 5% nitrene. Using pK_w = 14.8 in 20% acetonitrile (see Experimental Section), the acidity constant for the nitrenium ion (eq 8) is calculated as 10^{-16} M. In our preliminary report we suggested that the singlet nitrene was approaching the category of a strong base in water.[22] These absolute numbers show the extent to which this is indeed true.

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(48) (a) With this azide, HPLC analysis immediately after irradiation shows a single major peak which we assign to the imine that is the fluorenyl analog of **27**. Unlike **27**, however the fluorenylimine reacts to give several new products which we have not identified. Similar observations have been made in solvolysis reactions proceeding through this nitrenium ion.[48b] (b) Novak, M. Personal communication.

(49) McGowan, W. M.; Hilinski, E. F. *J. Am. Chem. Soc.* **1995**, *117*, 9019.

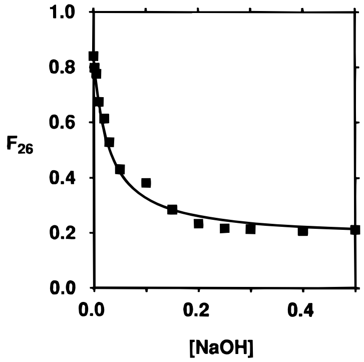
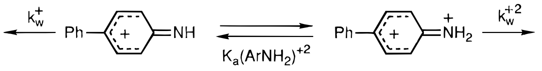


Figure 5. Yield of 4-hydroxy-4-phenyl-2,5-cyclohexadienone (**26**) as a function of NaOH concentration following irradiation of 4-biphenylyl azide. The line has been drawn on the basis of eq 12 using the parameters $\mathbf{P} = 0.84$, $k_w = 1.85 \times 10^6$ s^{-1}, $k_{OH} = 1.4 \times 10^7$ M^{-1} s^{-1}, and $k^{d}_{OH} = 3.1 \times 10^8$ M^{-1} s^{-1}.

A reviewer has suggested that the deprotonation reaction produces the ground state triplet nitrene. Such a possibility can be added to Scheme 2, through an additional pathway—^{1}ArNH$^+$ + $^-$OH → ^{3}ArN, with a rate constant defined as $^3k^{d}_{OH}$). Equation 11 is then modified by adding a further term in hydroxide ion, $^3k^{d}_{OH}[^-OH]$, and the same term is added to the denominator of eq 12. The analysis proceeds as above and results in the same value of k_{OH} plus the quantity $(1 - \mathbf{P})k^{d}_{OH} + {}^3k^{d}_{OH} = 5.0 \times 10^7$ M^{-1} s^{-1}, where the contributions from the two deprotonation pathways cannot be separated. With this model, the value of k^{d}_{OH} and acidity constant calculated above are upper limits, corresponding to the situation where the $^3k^{d}_{OH}$ term makes a negligible contribution. If deprotonation were to be occurring to the triplet nitrene, the singlet nitrene must be an even stronger base than we have calculated.

Basicity of the 4-Biphenylyl- and 2-Fluorenylnitrenium Ions. Our model to account for the kinetic behavior in acids (Figure 3) involves a mechanism where the nitrenium ion is further protonated to a more reactive dication, as illustrated in eq 14.[50] The behavior of the *N*-acetyl substituted cation is consistent with this interpretation. The amide-type nitrogen of this ion will not be protonated, at least in the solutions involved here, and indeed the rate constants do not increase. There is in fact a 20% decrease from dilute to 1 M acid which we attribute to a specific salt effect associated with replacing NaClO$_4$ with HClO$_4$.



(14)

37 **38**

According to this model,

$$k_{obs} = \frac{k_w^+ K_a(\mathrm{ArNH_2})^{2+} + k_w^{2+}[\mathrm{H^+}]}{K_a(\mathrm{ArNH_2})^{2+} + [\mathrm{H^+}]} \qquad (15)$$

and rate constants are predicted to increase at some acidity as the k_w^{2+} pathway starts occurring but then plateau as the equilibrium shifts to the dication. To fit the data to eq 16, values of k_{obs} were first corrected for the specific salt effect observed with the *N*-acetyl compound.[51] The fits to the experimental data are shown in Figure 6, and the parameters obtained in these fits are given in Table 5.

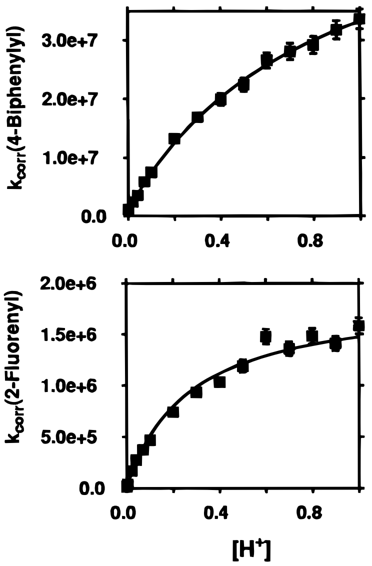


Figure 6. Corrected rate constants[51] for the decay of the 4-biphenylyl- and 2-fluorenylnitrenium ions in HClO$_4$ solutions, with ionic strength 1.0 maintained with NaClO$_4$. Curves are drawn according to eq 15 using the parameters given in the text.

Table 5. Acidity Constants for Aniline Dications, and Rate Constants for Reaction of Nitrenium Ions with Water (20% Acetonitrile−Water, 20 °C, 1 M NaClO$_4$)

constant	Ar = 4-biphenylyl	 2-fluorenyl
pK_a(ArNH$_2$)$^{2+}$	0.1	0.6
k_w^{2+} (ArNH)$^{2+}$, s^{-1}	6.0×10^7	1.9×10^6
k_w^{+}(ArNH)$^{+}$, s^{-1}	1.1×10^6	1.3×10^4
k_w^{+}(ArNAc)$^{+}$, s^{-1}	3.4×10^6	$(4.4 \times 10^4)^a$

[a] Not measured in 1 M NaClO$_4$. This number is calculated from the observed rate constant, 7.7×10^4 s^{-1} in 0.5 M NaClO$_4$, with the assumption that the effect of ionic strength is the same as it is on the *N*-acetyl-4-biphenylylnitrenium ion.

This treatment produces pK_a values of 0.1 for the 4-aminobiphenyl dication and 0.6 for the 2-aminofluorene dication. In terms of the conjugate bases, the nitrenium ions, this means that these are weakly basic species. They are however sufficiently basic to be significantly protonated in 1.0 M aqueous acid, especially the fluorenyl derivative. In terms of superacids where NMR spectroscopic detection of nitrenium ions might be possible, this will mean that the species that will be observed inevitably will be a dication. Equation 3 given in the introduction shows an example from the Olah group.

Previous experimental evidence has suggested that arylnitrenium ions are perhaps better regarded in terms of carbenium ion resonance contributors (e.g. **37**).[34c] The above basicities are fully consistent with such a structure, since these are what might be expected for an imine with a nearby positive charge. Further evidence is seen in the remarkably little difference in the absorption spectra of *N*-H and *N*-acetyl nitrenium ions, i.e. the chromophore is the cyclohexadienyl cation. Also consistent are the relatively small increases in the water rate constants (Table 5) on substituting NH in a nitrenium ion with the electron-withdrawing *N*-acetyl group.[5] Even full protonation has little effect on the spectrum and results in rate increases of only two orders of magnitude.

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(50) The constant k_w^+ is the same as k_w employed previously.

(51) Fits of eq 15 to the experimental data were significantly poorer if this was not done. The corrected rate constants were obtained by multiplying k_{obs} in each acid by the ratio k_{obs}(*N*-acetyl, 1 M NaClO$_4$):k_{obs}(*N*-acetyl), where k_{obs}(*N*-acetyl) refers to the same acid.

(52) (a) This is seen with other nitrenium ions.[52b] (b) Novak, M.; Kahley, M. J.; Lin, J.; Kennedy, S. A.; Swanegan, L. A. *J. Am. Chem. Soc.* **1994**, *116*, 11626.

The reactions of nitrenium ions with heteroatom nucleophiles also show that they are reacting as carbenium ions. This is seen not only in the nature of products, but in the reactivity patterns. Thus nitrenium ions react with azide at the diffusion limit with rate constants of 5×10^9 M^{-1} s^{-1}, the same as carbenium ions.[53] The changes seen in k_w on increasing acetonitrile content in the mixed aqueous solvents (Table 2) are also identical to what has been observed previously with carbenium ions.[54]

Summary. These studies have shown that singlet phenylnitrene, 4-biphenylylnitrene, and 2-fluorenylnitrene are relatively strong bases capable of being intercepted by protonation by H^+ and even water to give nitrenium ions in competition with other reaction channels such as intersystem crossing and ring expansion. In the case of phenylnitrene the H^+ trapping competes with a ring expansion that occurs with a rate constant of 2−4 $\times 10^{10}$ M^{-1} s^{-1}. Protonation by solvent water also occurs, but even though the rate constant is of the order of 10^9 s^{-1}, it constitutes a minor pathway in competition with the ring expansion. In the cases of 4-biphenylyl- and 2-fluorenylnitrene, ring expansion and intersystem crossing occur an order of magnitude more slowly, water protonation is faster, and there are substantial yields of nitrenium ion without added acids. In these cases the nitrenium ions are sufficiently long-lived that they are detected by ns LFP. A combination of ps LFP, ns LFP, and product analysis provides $pK_a = 16$ for the 4-biphenylylnitrenium ion deprotonating to singlet nitrene in 20% acetonitrile. Thus singlet 4-biphenylylnitrene falls close to the category of a strong base in this solution. The LFP experiments under acidic conditions show kinetic behavior consistent with protonation to a dication. Analysis of the kinetic curves furnishes the pK_a values for the dications as 0.1 (4-biphenylyl) and 0.6 (2-fluorenyl). This and other pieces of evidence are argued to be consistent with these arylnitrene ions being better regarded as imine-substituted cyclohexadienyl cations. Overall, arylnitrenium ions ($ArNH^+$) are very weak acids in water when deprotonating to singlet nitrenes and are also weak bases, accepting a proton to form the aniline dication.

Experimental Section

Flash photolysis experiments were carried out in the standard fashion with *ca.* 20 ns pulses at 248 nm (*ca.* 60 mJ per pulse) from a Lumonics excimer laser (KrF emission) and with *ca.* 25-ps pulses at 266 nm (*ca.* 4 mJ per pulse) from a Continuum YG-601-C Nd/YAG laser.

Product analyses were performed with a Waters HPLC with UV−visible detector, using a μ-Bondapak C_{18} reversed phase column. In the case of phenyl azide, the detector wavelength was 235 nm, and the eluting solvents were 0.001 M HCl and methanol. The products were eluted in the sequence **23**, **24**, **25**, **22**, and then phenyl azide by use of a gradient program beginning with 10% methanol for 10 min, then changing to 70% methanol over 15 min. In the case of 4-biphenylyl azide, the detector wavelength was 250 nm, and the eluting solvents were 0.05 M 1:1 HOAc−NaOAc and acetonitrile. The products were eluted in the sequence **26**, **27**, and 4-biphenylyl azide by use of a gradient program beginning with 40% acetonitrile for 12 min, then changing to 80% acetonitrile over 5 min. Quantitative measurements were based on the comparison of peak areas with areas obtained with authentic samples (except for the unstable **27** which was not analyzed quantitatively). The photolyses were carried out using a Rayonet Photochemical Reactor equipped with lamps operating at 300 nm. In the case of the biphenylyl system experiments were also performed following one pulse of irradiation in the LFP apparatus. These showed no difference from results obtained with the Rayonet. Solutions contained 20−100 μM substrate, and were directly injected into the HPLC for analysis. Irradiation times were of the order 0.5−1.5 min. In the case of **26** which formed slowly over time, injections were made the following day. For the experiments involving 4-biphenylyl azide in NaOH, solutions were irradiated for 0.5 min, then an amount of HCl equivalent to the NaOH was added to neutralize the solution, along with a quantity of 1:1 HOAc−NaOAc buffer to set the pH at ∼5. This solution was then allowed to stand overnight before analysis of **26**.

The pH in the mixed acetonitrile−solvents was measured using a combination electrode that had been calibrated with standard aqueous buffers, and a small empirical correction factor "Q_s" was added to the measured pH. This factor was the value required to adjust the measured pH of a solution of 0.01 M HCl to a value of 2.00. The pK_w in 20% acetonitrile was obtained from the measured pH of a 0.01 M NaOH solution, according to the equation $pK_w = pH_{measured}(0.01\ M\ NaOH) + 2.00 + Q_s$.

Phenyl azide, 4-biphenylyl azide, and 2-fluorenyl azide were known compounds and were prepared by standard routes. 4-Chloroaniline and 2-chloroaniline were commercial samples and were distilled before use. 4-Aminophenol hydrochloride was used as received. 4-Hydroxy-4-phenyl-2,5-cyclohexadienone (**26**) was obtained by irradiating at 300 nm a solution of 0.2 g of 4-biphenylyl azide in 1 L of 20% acetonitrile−water until HPLC analysis indicated less than 5% azide. The solution was then allowed to stand overnight to allow **27** to convert to **26**, at which time the solvent was completely removed, first with a rotary evaporator and then with a freeze-dryer. The remaining sample was recrystallized from ethanol−water and had NMR and melting point identical with a sample provided by Mike Novak.[26,27] 1*H*-Azepine-2(3*H*)-one (**22**) was prepared by 300-nm irradiation of a solution of 0.2 g of phenyl azide in 2 L of 0.005 M HCl. After HPLC indicated 80% conversion of the phenyl azide, the solvent was concentrated to 50 mL, and extracted with dichloromethane. The dichloromethane layer was washed with sodium bicarbonate and dried ($MgSO_4$), and after filtration the solvent was removed. The sample of **22** was then isolated by semipreparative HPLC with a reversed-phase C_{18} column and an eluting solvent of 30% methanol−70% water. The NMR of this sample−$\delta(CDCl_3)$ 2.92 (d, 2H), 5.55−5.65 (m, 1H), 5.8−5.9 (m, 1H), 6.2−6.3 (m, 2H), 8.3 (broad s, 1H)−was identical with those reported in the literature.[18a,30]

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(53) McClelland, R. A.; Kanagasabapathy, V. M.; Banait, N.; Steenken, S. *J. Am. Chem. Soc.* **1991**, *113*, 1009.

(54) McClelland, R. A.; Kanagasabapathy, V. M.; Banait, N.; Steenken, S. *J. Am. Chem. Soc.* **1989**, *111*, 3966.