Radical Cation [3 + 2] Cycloadditions of 2H-Azirines. Mechanistic Studies Concerning the Intermediate Radical Cation[†]

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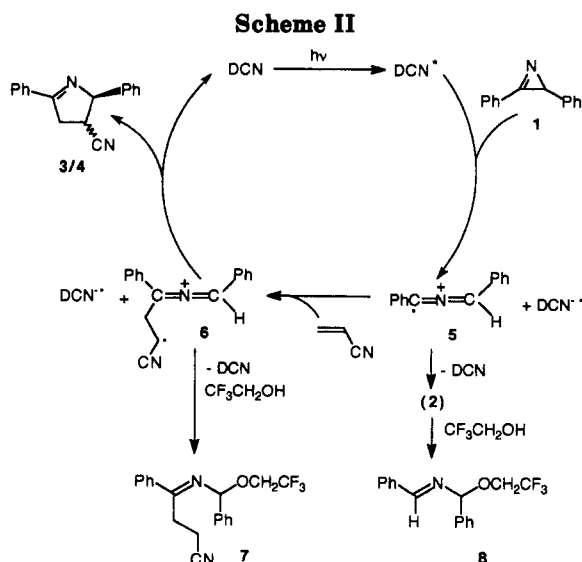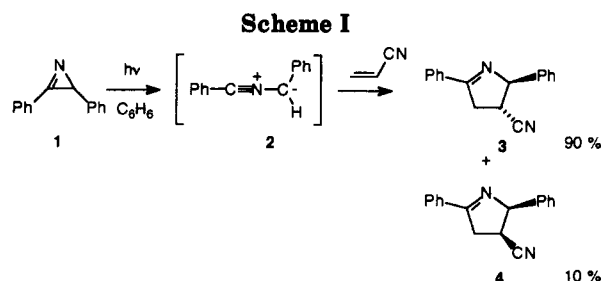
The product of the ring opening of 3-aryl-substituted azirines under conditions of photoinduced electron transfer (PET) is shown to be not a nitrile ylide but a short-lived 2-azaallenyl radical cation. This species has been investigated by pulse radiolysis and γ-radiolysis techniques. The radical cation has an absorption band with λ_{max} at 485 nm. The lifetime of the radical cation is $\tau = 1.43$ μs in *n*-butyl chloride. The rate constant for the reaction of the radical cation with the imine 9 is 7.8×10^9 M^{-1} s^{-1}. γ-Radiolysis in *n*-butyl chloride leads to the same products, i.e., an N-alkylated imidazole as in the case of PET.

Introduction

Photoinduced 1,3-dipolar cycloadditions of azirines have been known for 20 years.[2] Irradiation into the n–π* bond of an aryl-substituted azirine ring 1 (at approximately 280 nm) leads to the opening of the ring and to the formation of an ylide 2. This ylide is readily trapped with a dipolarophile like acrylonitrile forming 3 in 90% yield beside 10% of the Z-isomer 4 (Scheme I).

On the other hand, irradiation under the conditions of photoinduced electron transfer (PET)[3] leads to a different ratio of products. Irradiation of an electron acceptor, 1,4-naphthalene dicarbonitrile (DCN), with 350-nm light enables an electron transfer from the azirine to the excited sensitizer to take place. After losing one electron, the azirine ring opens. Trapping with acrylonitrile shows a complete lack of diastereoselectivity in the formation of 3/4[4] (Scheme II). This indicates that the reaction follows a path different from that in the absence of PET. In the case of similar reactions with other three-membered rings the intermediates generated under the conditions of PET have been formulated as radical cations,[5] and therefore we suggest the analogous intermediates 5.[4]

Scavenger experiments with 2,2,2-trifluoroethanol (TFE) revealed the formation of two trapping products 7 and 8

Scheme I

Scheme II

under PET conditions, whereas direct irradiation only led to the formation of 8.[4] This indicates a multistep mechanism in the case of the PET-mediated process, with 7 probably being formed from 6. To obtain more information about the nature of the postulated[4] radical cation 5, we performed time-resolved spectroscopic studies. γ-Radiation and electron-pulse radiolysis techniques were applied to obtain kinetic data about the reaction. The reaction is of interest from a synthetic point of view since heterophane compounds[6] and even a porphyrin system are accessible by this route.[7a] A complete description of the preparative results has been reported recently.[7]

[†] Radical Ions and Photochemical Charge-Transfer Phenomena (Series A). 39. Cycloadditions (Series B). 42. Series A, Part 38: Müller, F.; Mattay, J. *Chem. Ber.* 1993, *126*, 543. Series B, Part 41: see Series A, part 38.

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Figure 1. Absorption spectra upon electron-pulse radiolysis of 4 mM 2,3-diphenylazirine (1) in n-butyl chloride, deoxygenated with argon. Points were recorded at times after the end of the pulse of 2.5–2.8 μs (1), 3.5–4.0 μs (2), and 9.0–10.0 μs (3).

Experimental Section

The synthesis of the azirines has been described.[8] Solvents were of spectroscopic purity.

Preparative γ-irradiations were performed at the Max-Planck-Institut with a ^{60}Co-source. The products were identified with GC and GC–MS techniques.
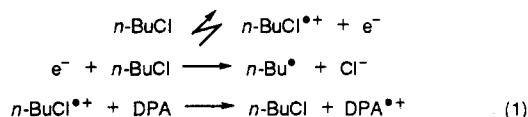
Electron-pulse radiolysis and 248-nm laser photolysis experiments were made at the Max-Planck-Institut. n-Butyl chloride was used as solvent for the pulse radiolysis and γ-radiolysis experiments. A 3-MeV van de Graaf accelerator was used that delivered 100-ns pulses with doses such that ~1–2 μM radicals were produced. The time-dependent absorption changes were digitized with Tectronix 7612 and 7912 transient recorders interfaced with a DEC LSI11/73$^+$ computer for process control and on-line preanalysis of the obtained data. The final data analysis was performed on a Microvax II connected with the LSI via Ethernet.[9]
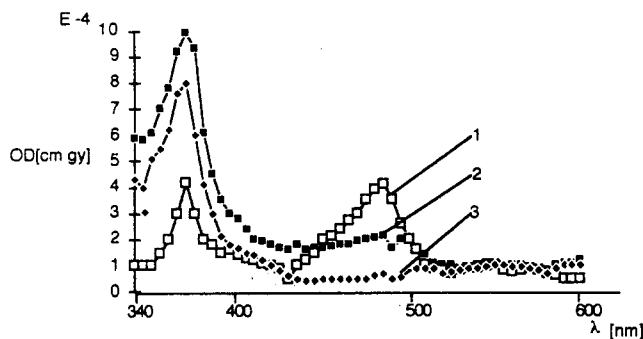
Results and Discussion

An attempt was made to generate radical cations from the azirine by photoionization with 248-nm laser light. However, in the solvent cyclohexane as well as in acetonitrile the spectra observed could be quantitatively accounted for in terms of the ylide 2, in agreement with literature data.[10,11]

Therefore, in order to generate radical cations from azirines pulse radiolysis techniques were applied using alkyl chlorides as solute.[12] Alkyl halide solvent is ionized by the radiation. The resulting solvent radical cation oxidizes the azirine 1 (2,3-diphenylazirine, DPA), leading to the 2-azaallenyl radical cation,[13] which can be compared in its reactivity and selectivity with that[14] generated with the PET process.

Electron Pulse Radiolysis Experiments. The effect of an electron pulse on a solution of DPA (1) in a halogenated solvent is shown in eq 1. A solution of 4 mM
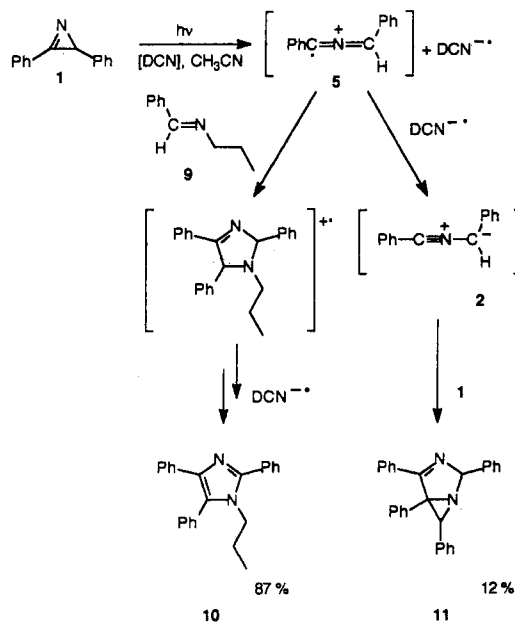
$$n\text{-BuCl} \quad \xrightarrow{\quad\quad} \quad n\text{-BuCl}^{\bullet+} + e^-$$

$$e^- + n\text{-BuCl} \longrightarrow n\text{-Bu}^\bullet + Cl^-$$

$$n\text{-BuCl}^{\bullet+} + DPA \longrightarrow n\text{-BuCl} + DPA^{\bullet+} \quad\quad (1)$$

1 in n-butyl chloride was irradiated with electron pulses. Figure 1 shows the spectrum obtained. A large peak at 370 nm and a smaller one at 485 nm are observed. The first peak has a rather long lifetime; it is assigned to the ylide.[10,11] The second peak is short lived. The lifetime obtained from the spectrum is $\tau = 1.43$ μs. The species does not react with oxygen (saturated); therefore, it is not a triplet. If the peak at 485 nm is indeed the 2-azaallenyl radical cation 5, it should be quenched selectively by the arylaldimine 9, as found by product analysis[4,7b] under PET conditions (see Scheme III).[18] Under these conditions the addition of 9 to the reactive intermediate leads (via back-electron transfer and an oxidation step) to the imidazole 10.[4,7b] A side reaction is the back-electron transfer before

Scheme III

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cycloaddtion. This results in formation of the ylide 2 which can neither form the starting azirine nor react with the imine compound, and therefore it eventually produces the diazabicyclic compound 11, as described by Padwa.[15] The absorption spectrum of the species formed on pulse radiolysis of a n-butyl chloride solution containing 20 mM 1 and 2 mM 9 is depicted in Figure 2.

As expected on the basis of these considerations the peak at 485 nm is completely quenched by the addition of imine with a concentration only 10% of that of the azirine. The ylide peak is not significantly changed by the addition of the imine 9. The investigation of the irradiated solution by means of GC–MS revealed the formation of small quantities of the imidazole 10, by comparison with the mass spectrum of an authentic sample obtained by photochemical synthesis.[4,16]

The rate constant for reaction of 5 with imine 9 was measured by observing the quenching of the 485-nm absorption as a function of [9]. The relation between k_{obsd} for decay of 5 (2 mM) and the imine concentration was linear up to 10% imine added, giving a rate constant of

(15) Padwa, A.; Dharan, M.; Smolanoff, J.; Wetmore, S. I., Jr. *J. Am. Chem. Soc.* 1973, *95*, 1954.

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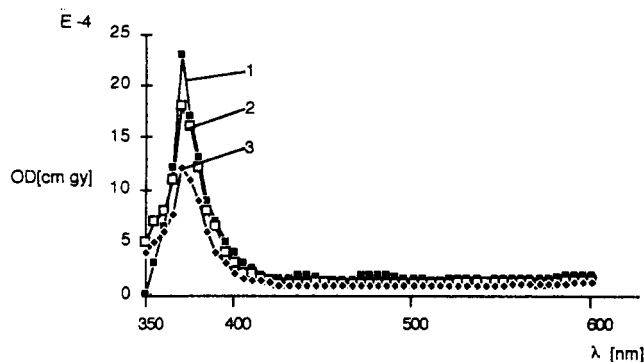
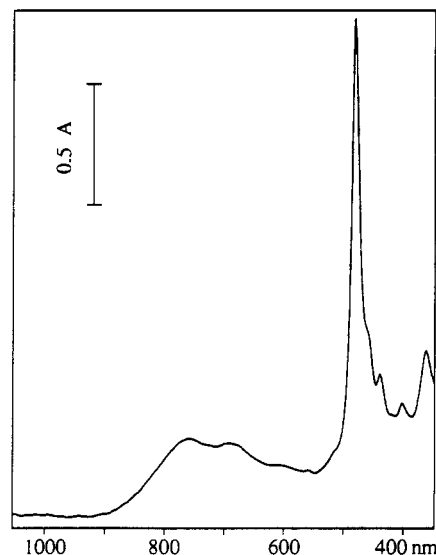**Figure 2.** Absorption spectra upon electron-pulse radiolysis of 20 mM 2,3-diphenylazirine (1) and 2 mM n-propylbenzaldimine (9) in n-butyl chloride, deoxgenated with argon. Points were recorded at times after the end of the pulse of 2.9–3.1 µs (1), 9.0–10.0 µs (2), and 90–100 µs (3).

$k = 7.8 \times 10^9$ M^{-1} s^{-1} of 5 with 9. This high rate is characteristic for diffusion-controlled reactions in n-butyl chloride. It differs remarkably from rate constants obtained for the reactions of the ylides of DPA 1[10] and 3-biphenylazirine[11] with acrylonitrile as dipolarophile, as these are $k = 1.2 \times 10^6$ M^{-1} s^{-1} and $k = 2.3 \times 10^6$ M^{-1} s^{-1}, respectively.

Product Analysis of γ-Radiation Experiments and Spectroscopy at 77 K. Under the conditions of γ-radiation the imine 9 was introduced in concentrations ≤20% of that of the azirine in order to minimize ionization of the imine as starting process for the cycloaddition.

Chloroform was used as the solvent. The maximum yield of the imidazole 10 achieved was 29%. (The yield of 10 is 87% under the conditions of preparative PET.)[4] Other halogenated solvents (n-butyl chloride, carbon tetrachloride) gave poorer yields. The formation of 10 strongly supports the idea that the reactive intermediate of the PET-controlled reaction of azirines is a radical cation. The spectroscopic investigation of species generated by γ-radiation is possible at low temperatures.[17] A solution of 30 mM 1 in a 1:1 mixture of Freons F11/F114B was irradiated with 60Co-γ-rays at 77 K, to a total dose of 500 krad. The absorption spectrum exhibits a large peak at 485 nm and a small peak at 360 nm (Figure 3). The

(17) Bally, Th.; Truttmann, L. *private communication.*
(18) One reviewer pointed to the possibility of the oxidation of 2 to 5 via single electron transfer to excited-state DCN. This pathway cannot be completely ruled out although it appears to be less probable for the following reasons: The calculated free enthalpies of electron transfer from the azirines to singlet excited DCN are negative according to the Weller equation (Müller, F. PhD-Thesis, University of Münster, 1992). Ab initio calculations indicate a spontaneous ring opening of the azirine radical cation to a linear 2-azaallenyl radical cation (cf. ref 7b). Finally, a formation of 5 via the ylide 2 would require two photons, one for the process 1 → 2, the other for the oxidation step.

Figure 3. Absorption spectra upon 60Co-γ-radiolysis of 30 mM 2,3-diphenylazirine (1) in freon at 77 K.

small peak has the same position as the ylide 2, whereas the large peak can be attributed to a 2-azaallenyl radical cation 5. This is more stable at low temperature. The occurrence of the ylide is explained either by direct formation from the excited solvent species formed by γ-radiolysis or by back-electron transfer of the radical cation.

Conclusion

It has been shown that the [3 + 2] cycloaddition of azirines under conditions of photoinduced electron transfer differs from the 1,3-dipolar cycloaddition of nitrile ylides obtained from azirines by energy transfer. The new intermediate in the first case is a 2-azaallenyl radical cation. The radical cation of 2,3-diphenylazirine 1 has been generated by two independent techniques, showing an absorption at 485 nm in both cases. Its lifetime has been measured to be $\tau = 1.43$ µs in n-butyl chloride at room temperature. Quenching with an imine as a specific substrate for radical cations enabled differentation between ylide and radical cation. The reaction of 5 with the imine 10 proceeds with $k = 7.8 \times 10^9$ M^{-1} s^{-1}. Further investigations of different azirine substrates are in progress.