# An Extremely Long-Lived Singlet 4,4-Dimethoxy-3,5-diphenylpyrazolidine-3,5-diyl Derivative: A Notable Nitrogen-Atom Effect on Intra- and Intermolecular Reactivity**

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Dedicated to Professor Waldemar Adam
on the occasion of his 70th birthday
and to Professor Masatomo Nojima
on the occasion of his 65th birthday

The central focus in chemistry is the formation and cleavage of bonds, which can be either heterolytic or homolytic. Singlet diradicals are key intermediates in homolytic processes. In general, these reactive intermediates are quite short-lived and have no chance to react intermolecularly.[1] Recent studies directed toward stabilizing singlet diradicals have provided opportunities to examine the chemistry of such electronically and structurally unique molecules. Thus, the singlet diradicals **1**,[2] **2**,[3] and **3**[4] were isolated as examples of kinetically stabilized four-membered ring systems. Inagaki and co-workers computationally predicted an isolable singlet diradical **4**.[5,6] Borden and co-workers reported on the singlet ground
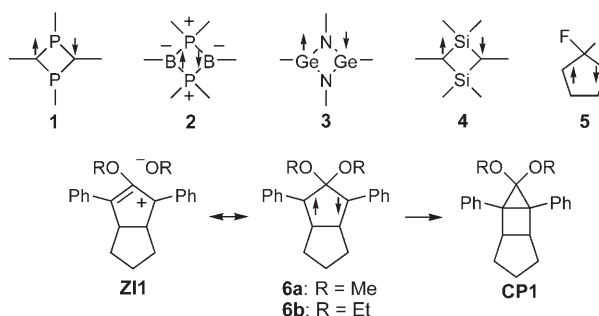
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state of 2,2-difluorocyclopentane-1,3-diyls **5**.[7] We previously studied the long-lived singlet 2,2-dialkoxy-1,3-diphenylcyclo-pentane-1,3-diyls **6** ($\tau_{6a} = 320$ ns and $\tau_{6b} = 880$ ns in benzene at 293 K), which are, to date, the longest lived five-membered singlet diradicals; they react intramolecularly to afford the ring-closure compounds **CP1** in quantitative yield.[8] In the hyperconjugative resonance structure **ZI1**, the geminal alkoxy groups are thought to stabilize the lowest energy singlet state.[8e]

In the present study, we designed the nitrogen-substituted diradical **7**, since the hyperconjugative resonance structure **ZI2** of the lowest energy singlet state of diradical **7** should be further stabilized by the electron-donating nitrogen atom as reflected by the resonance structure **ZI3**. Actually, 4,4-
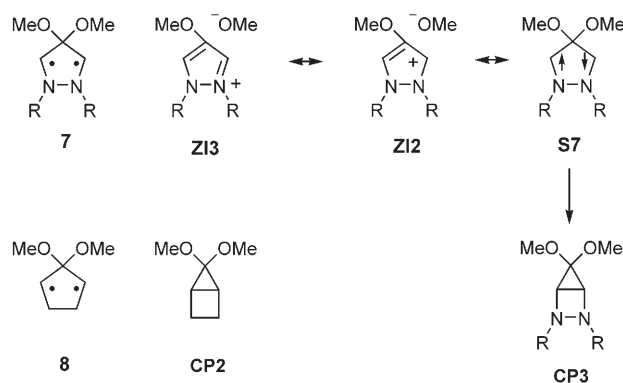
dimethoxy-1,2-dimethylpyrazolidine-3,5-diyl **7** (R = Me) was predicted to be a singlet ground-state molecule, and the singlet–triplet energy gap ($\Delta E_{ST} = E_S - E_T = -14.4$ kcal mol^{-1}) was calculated to be significantly larger than that of 2,2-di-methoxycyclopentane-1,3-diyl (**8**; $\Delta E_{ST} = -6.1$ kcal mol^{-1})[8d] at the UB3LYP/6-31G(d) level of theory.[9] Furthermore, we found, based on computation, that the energy difference between the ring-closure compound **CP3** and the singlet state of **7**, $\Delta E = E_7 - E_{CP3} = -4.0$ kcal mol^{-1}, is significantly smaller than that between 5,5-dimethoxybicyclo[2.1.0]pentane **CP2** and the singlet 2,2-dimethoxycyclopentane-1,3-diyl (**8**, $\Delta E' = E_8 - E_{CP2} = +22.1$ kcal mol^{-1}). Thus, the computational results clearly indicate that the singlet state of diradical **7** (R = Me) is energetically more stable than the ring-closure compound **CP3** (R = Me).

Here we report on the generation of the extremely long-lived singlet 4,4-dimethoxy-3,5-diphenyl-pyrazolidine-3,5-diyl derivative **9a**, which displays a lifetime of up to ca. 10 ms and inter- and intramolecular reactivity.[10] For the generation of diradical **9a**, we carried out the photodenitrogenation of the azoalkane **AZa** ($\lambda_{max} = 416$ nm, $\varepsilon = 585$ in toluene; Scheme 1). The azoalkane **AZa** was prepared from the cycloaddition of the corresponding isopyrazole with 4-phenyl-1,2,4-triazoline-3,5-dione (PTAD) as depicted in Scheme 1. First, the steady-state photolysis ($\lambda_{exc} = 360–440$ nm) of the azoalkane **AZa** was performed in toluene at room temperature in order to study the intramolecular reactivity. The clean denitrogenation was observed to afford the product of 1,2-oxygen migration **10a** (70% isolated yield). No evidence for the formation of
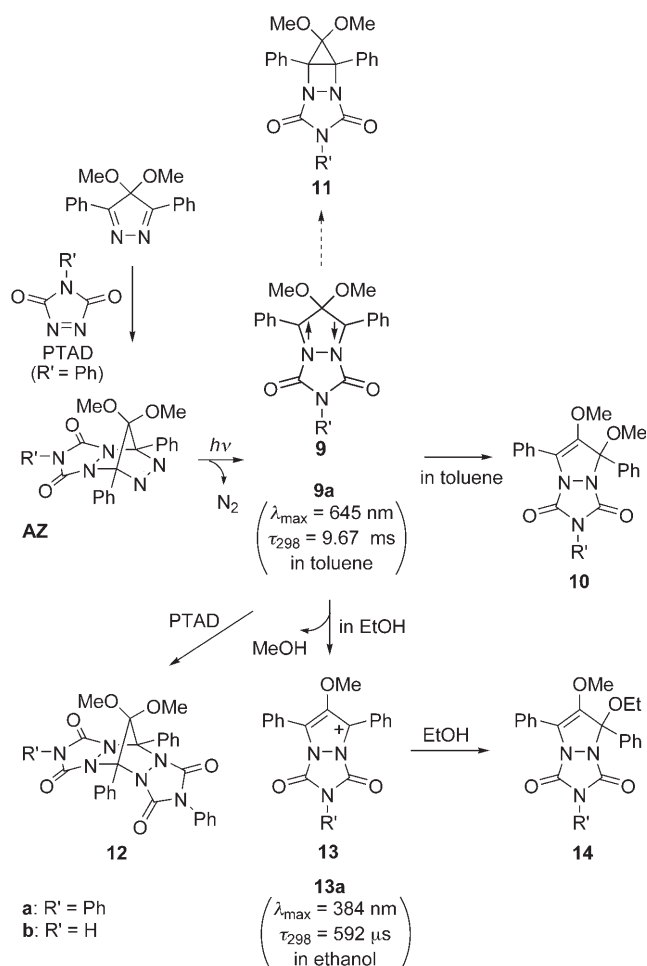
Scheme 1. Preparation of azoalkane **AZ**, the photochemical generation of singlet diradical **9**, and its intra- and intramolecular reactions.

the ring-closure product **11a** was found in the photolysate of **AZa** in [D$_8$]toluene. The result clearly indicates that 1,2-oxygen migration is an energetically more favored process than ring closure. A model ring-closure compound **11b** was calculated to be higher in energy than a model singlet-diradical **9b** and a model 1,2-migration product **10b** by 2.8 kcal mol^{-1} and 27.2 kcal mol^{-1}, respectively, at the B3LYP/6-31G(d) level of theory.

The transient absorption spectra and decay trace of the intermediate in the denitrogenation of **AZa** were measured in degassed toluene by means of laser-flash photolysis ($\lambda_{exc} = 355$ nm) at 298 K. A strong absorption was observed in the visible region ($\lambda_{max} = 645$ nm, Figure 1a), which decayed with clean first-order kinetics ($\tau_{298} = 9.67 \pm 0.07$ ms, Figure 1b). A similar absorption band ($\lambda_{max} = 630$ nm) was observed in the photolysis ($\lambda_{exc} = 380–440$ nm) of **AZa** in a 2-methyltetrahy-drofuran (MTHF) matrix at 77 K (Figure 1c), which was persistent up to ca. 120 K. The transient species was assigned to the singlet diradical **9a**, based on the following evidence: 1) The absorption maximum at around 650 nm is similar to the absorption band of singlet diradical **6** (around 600 nm); 2) The species absorbing at 630 nm was EPR-silent in a MTHF matrix at 77 K; 3) The singlet state of a model
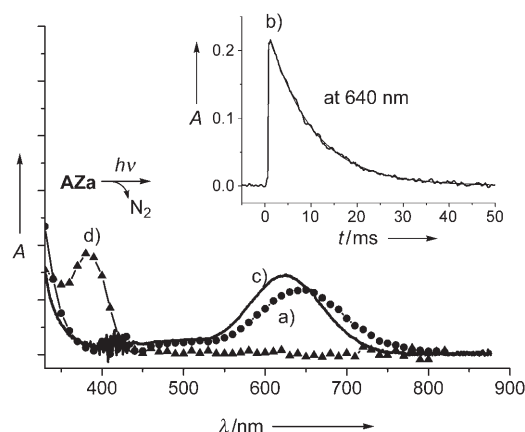
Figure 1. a) Transient absorption spectrum for the singlet diradical **9a** obtained after 5 ms of laser-flash photolysis of azoalkane **AZa** ($\lambda_{exc} = 355$ nm) at 298 K in degassed toluene. b) Transient decay trace of **9a** ($\lambda_{obs} = 640$ nm) generated by the photolysis of **AZa** at 298 K. c) Absorption spectrum of **9a** obtained after the photolysis ($\lambda_{exc} = 360$–440 nm) of **AZa** in a MTHF matrix at 77 K. d) Transient absorption spectrum for the allylic cation **13a** obtained after 8 µs of laser flash photolysis of **AZa** at 298 K in degassed ethanol.

Figure 2. a) Transient decay trace for the singlet diradical **9a** ($\lambda_{obs} = 640$ nm) generated by laser flash photolysis of **AZa** in ethanol, b) the concomitant growth of the allylic cation **13a** ($\lambda_{obs} = 380$ nm).

diradical **9b** (R′ = H) was calculated to be lower in energy than the triplet state with a significant singlet–triplet energy gap, $\Delta E_{ST} = -3.9$ kcal mol^{-1}; $S^2 = 0.77$ at the UB3LYP/6-31G(d) level of theory; 4) The calculation of the absorption maximum for the singlet state of **9b** ($\lambda_{calcd} = 710$ nm; $f = 0.14$ at the TD-UB3LYP/6-31G(d) level of theory) is in good agreement with the experimental absorption maximum.[11–12] The vertical excitation energy corresponds to the HOMO (ψ_S)→LUMO (ψ_A) electronic excitation; 5) The lifetime of the transient absorbing at 645 nm was not significantly affected by the presence of molecular oxygen; 6) The disappearance of the persistent species at 77 K was observed when PTAD was added while the sample warmed from 77 K to 120 K, at which temperature the species absorbing at ca. 630 nm is thermally stable. After careful analysis of the products formed on quenching, the PTAD adduct **12a** was isolated in 42% yield (Scheme 1).

To obtain further information on the reactivity of the extremely long-lived singlet diradical **9a**, the photodenitrogenation of **AZa** was performed in protic solvent. In toluene, the singlet diradical **9a** ($\lambda_{max} = 645$ nm) was the only detectable species. In ethanol, however, the decay of the transient absorbing at 645 nm ($\tau_{298} = 431 \pm 3$ ns) was accompanied by concomitant increasing absorption at 380 nm (Figure 1d and Figure 2). The ethanol adduct **14a** (45% yield) was obtained from the steady-state photolysis of **AZa** in ethanol at room temperature. The oxygen-migration product **10a** was intact in ethanol. Thus, the transient absorbing at ca. 380 nm is assigned to the allylic cation **13a**, $\tau_{298} = 607 \pm 18$ µs, which can be formed from the singlet diradical **9a** (Scheme 1).[13] The observed absorption maximum for **13a** was in good agreement with the computational calculation for the model allylic cation **13b** (R′ = H; $\lambda_{calcd} = 427$ nm, $f = 0.49$) at the TD-RB3LYP/6-31G(d) level of theory.

In summary, in this combined theoretical and experimental study, we found a notable effect of a nitrogen atom on the
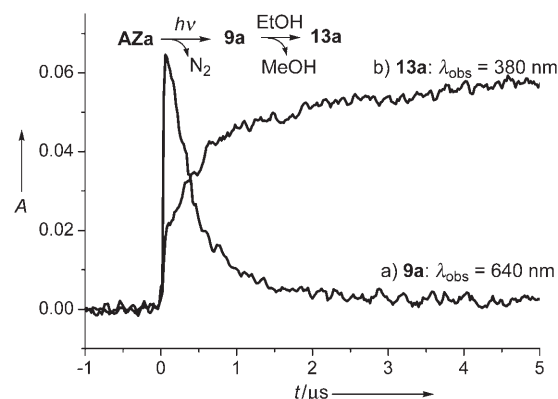
lifetime of singlet 2,2-dimethoxycyclopentane-1,3-diyls, and their intra- and intermolecular reactivity. Computationally, the nitrogen-containing singlet diradicals **7** and **9** were calculated to be lower in energy than the corresponding ring-closure compounds **CP3** and **11**. The introduction of nitrogen atoms in the five-membered ring system effectively increased the lifetime of the singlet 2,2-dimethoxypropane-1,3-diyl to the millisecond time scale. The extremely long-lived singlet 1,3-diradical was found to react intermolecularly with PTAD to afford the cycloaddition product. A 1,2-oxygen migration reaction was revealed for intramolecular reactivity. These remarkable findings should stimulate future computations and experiments on the novel reactivity of extremely long-lived singlet diradicals, especially intermolecular reactions of singlet diradicals.

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