

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/255708127>

Photochemistry of 2-Aminooxazole, a Hypothetical Prebiotic Precursor of RNA Nucleotides

ARTICLE *in* JOURNAL OF PHYSICAL CHEMISTRY LETTERS · AUGUST 2013

Impact Factor: 7.46 · DOI: 10.1021/jz401315e

CITATIONS

5

READS

38

6 AUTHORS, INCLUDING:



Rafał Szabla

Institute of Biophysics ASCR

7 PUBLICATIONS 14 CITATIONS

SEE PROFILE



Robert W. Góra

Wroclaw University of Technology

54 PUBLICATIONS 718 CITATIONS

SEE PROFILE



Andrzej L. Sobolewski

Polish Academy of Sciences

179 PUBLICATIONS 6,519 CITATIONS

SEE PROFILE

Photochemistry of 2-Aminooxazole, a Hypothetical Prebiotic Precursor of RNA Nucleotides

Rafał Szabla,[†] Deniz Tuna,[‡] Robert W. Góra,^{*,§} Jiří Šponer,^{†,||} Andrzej L. Sobolewski,[⊥] and Wolfgang Domcke^{*,‡}

[†]Institute of Biophysics, Academy of Sciences of the Czech Republic, Královopolská 135, CZ-61265 Brno, Czech Republic

[‡]Department of Chemistry, Technische Universität München, Lichtenbergstrasse 4, D-85747 Garching, Germany

[§]Theoretical Chemistry Group, Institute of Physical and Theoretical Chemistry, Wrocław University of Technology, Wybrzeże Wyspiańskiego 27, PL-50370 Wrocław, Poland

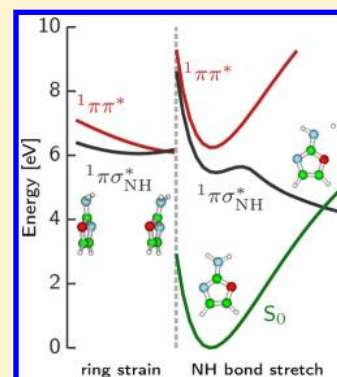
^{||}CEITEC – Central European Institute of Technology, Masaryk University, Campus Bohunice, Kamenice 5, CZ-62500 Brno, Czech Republic

[⊥]Institute of Physics, Polish Academy of Sciences, Al. Lotników 32/46, PL-02668, Warsaw, Poland

Supporting Information

ABSTRACT: 2-Aminooxazole has recently been proposed as a hypothetical precursor of RNA nucleotides on early earth. UV irradiation was considered as a crucial environmental factor in the proposed reaction sequence. We report on state-of-the-art multireference quantum-chemical calculations elucidating the possible nonradiative deactivation channels of this compound. According to our findings, the gas-phase photochemistry of 2-aminooxazole should be dominated by the photodetachment of the hydrogen atom of the NH₂ group via a $^1\pi\sigma_{\text{NH}}^*$ state leading either to ultrafast nonradiative deactivation, phototautomerization, or photodissociation of a hydrogen atom. We also identified a possible ring-opening reaction and a ring-puckering process that could occur after electronic excitation. These reactions seem to be less probable because they are driven by a higher-lying excited singlet state and are inherently slower than the hydrogen-atom dynamics.

SECTION: Spectroscopy, Photochemistry, and Excited States



Even the simplest forms of life exhibit extreme complexity in the molecular structures responsible for their functions. Then again, all of these structures consist of a rather limited group of relatively small molecules that are known as the building blocks of life. Hence, one of the most fundamental questions regarding the origins of life is why a relatively small number of specific compounds were selected in the early stages of biogenesis. It is plausible that intense and persistent UV irradiation was one of the most significant environmental factors influencing the selection in this stage. It is also well known that nucleobases and peptides are immune to long-term exposure to UV light in comparison with the multitude of other organic compounds.^{1–7} Therefore, it seems probable that the intermediates on the prebiotic routes to nucleotides were photostable as well.

Recently, Powner et al.^{8,9} suggested an efficient and selective reaction sequence leading to pyrimidine ribonucleotides under prebiotically plausible conditions via a small aromatic intermediate — 2-aminooxazole (cf. inset in Figure 1). Prolonged irradiation was one of the key factors considered by Powner et al.¹⁰ The possible radiationless decay pathways and the mechanisms of enhanced photostability of this molecule are of considerable interest in this context. In this work, we performed ab initio calculations of potential-energy surface cuts and conical intersections, revealing possible

mechanisms for radiationless deactivation via internal conversion of the title compound.

The calculated vertical excitation energies predict that the lowest-lying excited singlet state, located at ~5.5 eV at the CASPT2//CASSCF level (for details, consult the SI), is a dark $\pi\sigma_{\text{NH}}^*$ state that is repulsive with respect to the elongation of the N–H bonds of the amino group. Because the S_1 state is separated by a considerable energy gap from the higher-lying singlet states, only a large nuclear displacement might interchange their energetic order. According to Kasha's rule, the lowest-lying excited singlet state is usually reached in an ultrafast manner in a condensed-phase environment, and, therefore, the photochemistry of 2-aminooxazole should be determined primarily by this particular state. Interestingly, the discussed dark $\pi\sigma_{\text{NH}}^*$ state in 2-aminooxazole is very similar to the $\pi\sigma^*$ state observed in pyrrole.¹¹ First, the diffuse character of the σ^* molecular orbital indicates a partial Rydberg character of this state in the Franck–Condon region. The spatial extent of the electron density of this state, measured by the expectation value $\langle r^2 \rangle$, amounts to ~163 au compared with ~98 au in the ground state. Second, the $\pi\sigma_{\text{NH}}^*$ state is

Received: June 26, 2013

Accepted: August 2, 2013

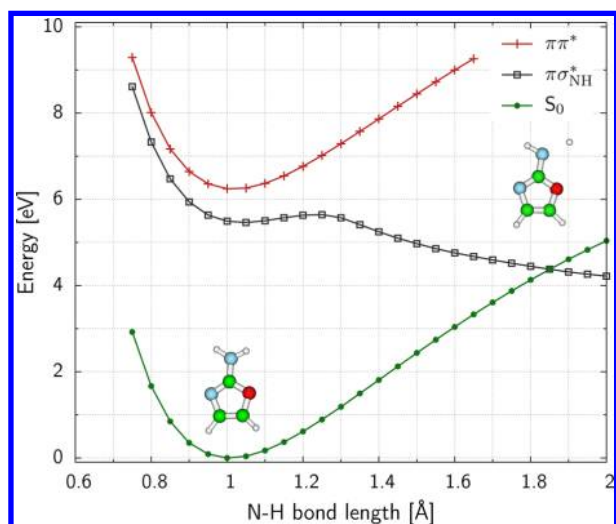


Figure 1. Potential-energy profiles along the stretching coordinate of the O-side N–H bond. The profiles were obtained by a rigid scan at the SS-CASPT2//SA-CASSCF/aug-cc-pVDZ level. The insets show the ground-state equilibrium geometry and the optimized conical intersection.

characterized by a considerable charge transfer from the aromatic ring toward the hydrogen atoms of the amino group. Hence, the S_1 state is significantly more polar ($\mu = 6.8$ D) than the electronic ground state ($\mu = 1.9$ D). It has been previously shown that such dark charge-transfer states play a crucial role in molecular mechanisms of radiationless deexcitation of heteroaromatic species.^{1,12}

The excitation energy of the optically bright $\pi\pi^*$ state is 6.25 eV at the CASPT2//CASSCF level (in C_s point-group symmetry). Our calculations show (cf. SI) that this transition is red-shifted by 0.2 eV in bulk water and the calculated wavelength of 205 nm agrees qualitatively with the experimentally determined absorption maximum of 219 nm.¹³ This transition lies within the UV–C spectral range, which is nowadays almost completely absorbed by the ozone layer. However, there was no oxygen in the atmosphere of early earth that could have reduced the amount of UV–C light reaching the surface. Furthermore, there is evidence that the sun was much more active in the ultraviolet range during the Archean age, although the total insolation was lower than that today.¹⁴

Hydrogen-transfer processes are believed to be the most important pathways ensuring the photostability of biomolecules.^{15,16} We therefore considered the two N–H internuclear distances as the reaction coordinate for 1D potential-energy

surface scans. The pathway involving the hydrogen atom, which is located cis to the oxygen atom in the aromatic ring, we call the O-side N–H scan from hereon. The second pathway we call the N-side scan. We shall focus only on the possible internal conversion channels. Although, according to El-Sayed's rules, intersystem crossing between the bright $^1\pi\pi^*$ and the $^3\pi\sigma^*$ states is, in principle, allowed, internal conversion processes related to abstraction of a hydrogen atom occur on a femtosecond time scale. Therefore, intersystem crossing cannot compete with internal conversion.^{17,18}

The potential-energy profiles obtained by a rigid scan of the O-side N–H bond (cf. Figure 1) reveal a crossing of the $\pi\sigma_{\text{NH}}^*$ surface with the ground-state surface near $R_{\text{N-H}} = 1.85$ Å. The profile determined for the N-side N–H bond is almost identical (cf. SI). However, no crossing of the optically bright $\pi\pi^*$ state and the repulsive $\pi\sigma_{\text{NH}}^*$ state can be found along the chosen reaction coordinate. Instead, the $\pi\sigma_{\text{NH}}^*$ potential-energy surface exhibits a shallow minimum in the Franck–Condon region, which reflects the “Rydbergization” of this state.¹⁹ For most of the relevant conformations, the $\pi\sigma_{\text{NH}}^*$ surface lies below the $\pi\pi^*$ surface, which has also been observed in pyrrole.^{11,16} In such cases, the photochemistry is usually dominated by the processes on the $\pi\sigma_{\text{NH}}^*$ hypersurface, which can be reached by ultrafast internal conversion from the bright $\pi\pi^*$ state. Because this particular state is repulsive with respect to the elongation of the N–H bonds, the electronically excited molecule may either interconvert to the ground state upon reaching the conical intersection or eject one of the hydrogen atoms of the amino group. In the former case, the energy of the absorbed photon is converted into vibrational motion and the original chemical constitution of the molecule is preserved.

The geometries of the conical intersections between the repulsive $\pi\sigma_{\text{NH}}^*$ state and the ground state were optimized for the O-side and N-side hydrogen-atom detachment pathways at the MR-CISD level. The $R_{\text{N-H}}$ distances calculated for both conical intersections are ~ 1.80 Å and agree well with the rigid scans. In particular, both optimized geometries are planar. The gradient-difference vector (**g**) of the conical intersection is characterized primarily by the N–H bond-stretching coordinate, while the nonadiabatic-coupling vector (**h**) is mostly characterized by an out-of-plane tilt of the respective hydrogen atom.

Our results indicate that internal conversion from the optically bright $\pi\pi^*$ state to the $\pi\sigma_{\text{NH}}^*$ state is likely to be an ultrafast process. The minimum on the crossing seam responsible for internal conversion from the optically bright state to the lowest-lying $\pi\sigma^*$ state was optimized at the MR-CISD level (cf. Figure 3 in the SI). The tuning coordinate for

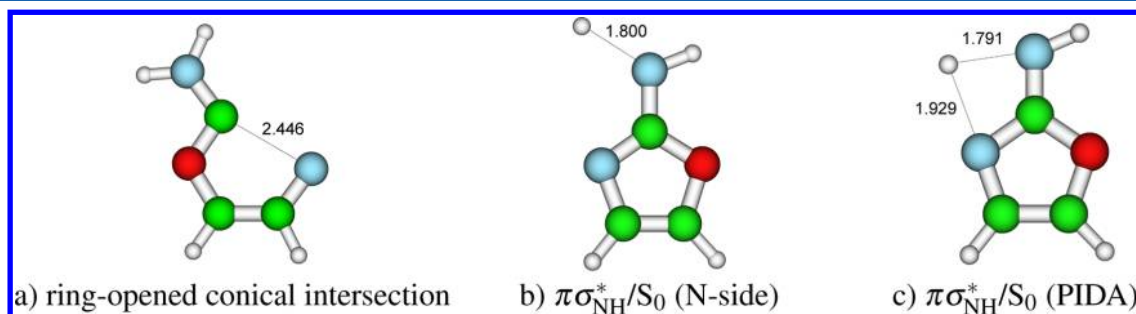


Figure 2. Optimized geometries of the remaining S_1/S_0 conical intersections obtained at the MR-CISD level. The values of the relevant internuclear distances are given in angstroms. Color coding: C, green; N, blue; O, red; H, white.

this conical intersection is composed of a set of out-of-plane molecular distortions, among which the most pronounced ones are the ring puckering of the C-2 atom and the flattening of the amino group. Only a minor distortion along these coordinates is required to reach the $\pi\pi^*/\pi\sigma^*$ conical intersection from the Franck–Condon region. The calculations indicate that the optimized conical intersection lies lower in energy than the vertical excitation energy of the $\pi\pi^*$ state and can be reached along a barrierless reaction path. Therefore, the fluorescence of the $\pi\pi^*$ state should be effectively quenched by ultrafast radiationless deactivation.

Because several cases of intramolecular phototautomerism have been suggested so far (cf. ref 20 and references cited therein), we considered the possibility that the hydrogen atom ejected from the N-side of the amino group might be transferred to the nitrogen atom of the aromatic ring. The minimum on the crossing seam responsible for this process, determined at the MR-CISD level, shows that the hydrogen atom lies midway in between the two nitrogen atoms of 2-aminooxazole (cf. Figure 2c). Thus, two different events may occur when this conical intersection is reached: either radiationless deactivation to the ground state of 2-aminooxazole or photoinduced dissociation-association (PIDA) tautomerization. The 2D potential-energy surfaces that provide insight into the latter process can be found in Figure 2 of the Supporting Information. The $\pi\sigma_{\text{NH}}^*$ state is repulsive with respect to the elongation of the N–H bond of the amino group, and for large N–H distances an intersection seam with the ground state is found. Photoexcitation of 2-aminooxazole may thus lead to one of the two tautomeric forms in their electronic ground state. The PIDA mechanism requires, however, a caging of the mobile hydrogen atom, for example, in a rare-gas matrix.²⁰

Various kinds of ring distortions have also been considered as effective funnels for radiationless deactivation in five-membered heterocycles. Thus, we investigated two mechanisms analogous to the processes suggested for pyrrole by Vazdar et al.¹⁸ The ring-puckering motion driven by the simultaneous twisting of the C=C and C=N double bonds leads to a conical intersection between the optically bright $\pi\pi^*$ state and the electronic ground state. This ring-puckered conical intersection can be reached in a barrierless manner (cf. Figure 3). The second mechanism is triggered by C=N bond cleavage and is mediated by a $\pi\sigma_{\text{CN}}^*$ state, which is repulsive with respect to this particular bond. However, to initiate this ring-opening process, the molecule needs to overcome a barrier of ~ 1.0 eV to reach the surface-crossing with the $\pi\sigma_{\text{CN}}^*$ state (cf. Figure 5 in the SI). Apart from this, the ring-opened conical intersection with the electronic ground state (geometry shown in Figure 2a) is also the highest in energy among all of the conical intersections identified in this work. Thus, it is probably of only minor importance for the radiationless deexcitation of 2-aminooxazole, similar to what was observed in the case of pyrrole.¹⁸

In conclusion, we have investigated several possible radiationless processes that may occur after photoexcitation of 2-aminooxazole, which was suggested as a potential prebiotic precursor of pyrimidine ribonucleotides. Our results indicate that the most efficient excited-state deactivation mechanisms are driven by the $\pi\sigma_{\text{NH}}^*$ state, which is repulsive with respect to the elongation of the amino N–H bonds. They may lead to either ultrafast nonradiative deactivation (including phototautomerization) or photodissociation of one of the amino hydrogen atoms. This conclusion is further supported by the apparent similarities to deactivation channels in pyrrole, which

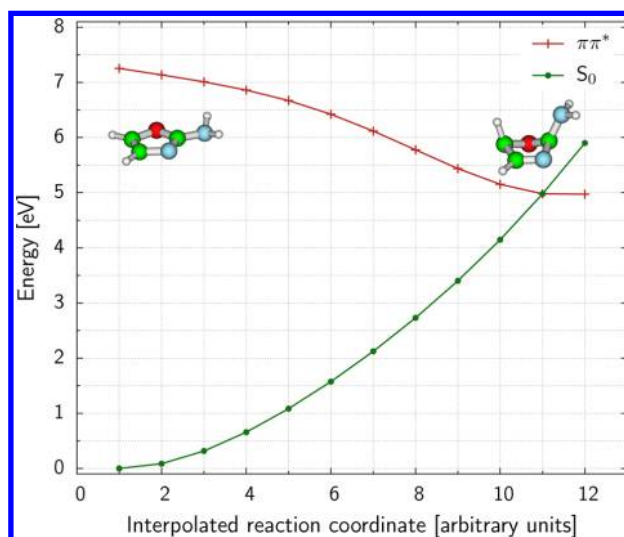


Figure 3. Potential-energy profiles along the ring-puckering motion. The profiles were obtained by linear interpolation in internal coordinates between the ground-state equilibrium geometry and the minimum-energy conical intersection at the MR-CISD/SA2-CASSCF/cc-pVDZ level.

were explored computationally¹⁶ and confirmed experimentally.¹⁷ In the condensed phase, the photodetachment will most likely be suppressed by caging effects. A similar process, in which a dissociating hydrogen atom is intercepted and subsequently returned to pyrrole by an ammonia molecule, was recently described by Zilberg et al.²¹ We have also identified a possible ring-opening process and a ring-puckering process. Both could occur after electronic excitation but seem to be less probable because they are not driven by the lowest excited singlet state and a substantial barrier is found for the ring-opening path. Therefore, 2-aminooxazole appears to exhibit enhanced photostability and could accumulate under intense hard UV irradiation, in particular, in a bulk aqueous environment. Currently, we are investigating the nonadiabatic dynamics of the suggested radiationless deactivation processes, which will provide deeper insight into the time scales and branching ratios of the photochemistry of 2-aminooxazole.

■ ASSOCIATED CONTENT

● Supporting Information

Description of the computational methodology, the PIDA mechanism, as well as the calculated vertical excitation energies, additional potential-energy surface scans, and Cartesian coordinates of the ground-state equilibrium geometry and conical intersections. This material is available free of charge via the Internet at <http://pubs.acs.org>.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: robert.gora@pwr.wroc.pl (R.W.G.); wolfgang.domcke@ch.tum.de (W.D.).

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We thank Dr. Felix Plasser for his support with the COLUMBUS 7.0 quantum chemistry package. This work was supported by a statutory activity subsidy from the Polish

Ministry of Science and Higher Education for the Faculty of Chemistry of Wrocław University of Technology to R.W.G. R.S. and J.S. were supported by the project “CEITEC - Central European Institute of Technology” (CZ.1.05/1.1.00/02.0068) from European Regional Development Fund and the Czech Grant Foundation, grant number P208/10/2302. D.T. is grateful for a Ph.D. fellowship granted by the International Max Planck Research School of Advanced Photon Science (IMPRS-APS) and for support by the TUM Graduate School. Part of the calculations was performed at the Wrocław Center for Networking and Supercomputing (WCSS).

REFERENCES

- (1) Sobolewski, A. L.; Domcke, W. The Chemical Physics of the Photostability of Life. *Europhys. News* **2006**, *37*, 20–23.
- (2) Sobolewski, A. L.; Domcke, W. Ab Initio Studies on the Photophysics of the Guanine-Cytosine Base Pair. *Phys. Chem. Chem. Phys.* **2004**, *6*, 2763–2771.
- (3) Barbatti, M.; Aquino, A. J. A.; Szymczak, J. J.; Nachtigallová, D.; Hobza, P.; Lischka, H. Relaxation Mechanisms of UV-Photoexcited DNA and RNA Nucleobases. *Proc. Natl. Acad. Sci. U.S.A.* **2010**, *107*, 21453–21458.
- (4) Kleinerann, K.; Nachtigallová, D.; de Vries, M. S. Excited State Dynamics of DNA Bases. *Int. Rev. Phys. Chem.* **2013**, *32*, 308–342.
- (5) Gustavsson, T.; Improt, R.; Markovitsi, D. DNA/RNA: Building Blocks of Life Under UV Irradiation. *J. Phys. Chem. Lett.* **2010**, *1*, 2025–2030.
- (6) Weinkauff, R.; Schermann, J.-P.; Vries, M. S. d.; Kleinerann, K. Molecular Physics of Building Blocks of Life Under Isolated or Defined Conditions. *Eur. Phys. J. D* **2002**, *20*, 309–316.
- (7) Zgierski, M. Z.; Fujiwara, T.; Lim, E. C. Conical Intersections and Ultrafast Intramolecular Excited-State Dynamics in Nucleic Acid Bases and Electron Donor-Acceptor Molecules. *Chem. Phys. Lett.* **2008**, *463*, 289–299.
- (8) Powner, M. W.; Gerland, B.; Sutherland, J. D. Synthesis of Activated Pyrimidine Ribonucleotides in Prebiotically Plausible Conditions. *Nature* **2009**, *459*, 239–242.
- (9) Powner, M. W.; Sutherland, J. D. Prebiotic Chemistry: A New Modus Operandi. *Philos. Trans. R. Soc., B* **2011**, *366*, 2870–2877.
- (10) Powner, M.; Sutherland, J.; Szostak, J. The Origins of Nucleotides. *Synlett* **2011**, *2011*, 1956–1964.
- (11) Sobolewski, A. L.; Domcke, W. Conical Intersections Induced by Repulsive $^1\pi\sigma^*$ States in Planar Organic Molecules: Malonaldehyde, Pyrrole and Chlorobenzene as Photochemical Model Systems. *Chem. Phys.* **2000**, *259*, 181–191.
- (12) Sobolewski, A. L.; Domcke, W. Ab Initio Investigations on the Photophysics of Indole. *Chem. Phys. Lett.* **1999**, *315*, 293–298.
- (13) Bödeker, J.; Burmester, K. Acylierung von 2-Amino-oxazol. *Zeit. Chem* **1987**, *27*, 258–259.
- (14) Buccino, A. P.; Mauas, P. J. D.; Lemarchand, G. A. In *UV Radiation in Different Stellar Systems*; Norris, R. P., Stootman, F. H., Eds.; Astronomical Soc Pacific: San Francisco, CA, 2004; pp 97–100.
- (15) Barbatti, M.; Ruckebauer, M.; Szymczak, J. J.; Aquino, A. J. A.; Lischka, H. Nonadiabatic Excited-State Dynamics of Polar π -Systems And Related Model Compounds of Biological Relevance. *Phys. Chem. Chem. Phys.* **2008**, *10*, 482–494.
- (16) Sobolewski, A. L.; Domcke, W.; Dedonder-Lardeux, C.; Juvet, C. Excited-State Hydrogen Detachment and Hydrogen Transfer Driven by Repulsive $^1\pi\sigma^*$ States: a New Paradigm for Nonradiative Decay in Aromatic Biomolecules. *Phys. Chem. Chem. Phys.* **2002**, *4*, 1093–1100.
- (17) Lippert, H.; Ritze, H.-H.; Hertel, I. V.; Radloff, W. Femtosecond Time-Resolved Hydrogen-Atom Elimination from Photoexcited Pyrrole Molecules. *ChemPhysChem* **2004**, *5*, 1423–1427.
- (18) Vazdar, M.; Eckert-Maksić, M.; Barbatti, M.; Lischka, H. Excited-State Non-Adiabatic Dynamics Simulations of Pyrrole. *Mol. Phys.* **2009**, *107*, 845–854.
- (19) Ashfold, M. N. R.; King, G. A.; Murdock, D.; Nix, M. G. D.; Oliver, T. A. A.; Sage, A. G. $\pi\sigma^*$ Excited States in Molecular Photochemistry. *Phys. Chem. Chem. Phys.* **2010**, *12*, 1218–1238.
- (20) Chmura, B.; Rode, M. F.; Sobolewski, A. L.; Lapinski, L.; Nowak, M. J. A Computational Study on the Mechanism of Intramolecular Oxo-Hydroxy Phototautomerism Driven by Repulsive $\pi\sigma^*$ State. *J. Phys. Chem. A* **2008**, *112*, 13655–13661.
- (21) Zilberg, S.; Kahan, A.; Haas, Y. The Photo-Dissociation of the Pyrrole-Ammonia Complex — the Role of Hydrogen Bonding in Rydberg States Photochemistry. *Phys. Chem. Chem. Phys.* **2012**, *14*, 8836–8841.