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Curious oxygen effect on photosensitized electron-transfer reactions of benzophenone oxime *O*-methyl ethers: one-way photoisomerization of an iminic double bond

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Abstract

Under an oxygen atmosphere, the *E* and *Z* isomer ratio of *N*-methoxy-4-methoxyphenyl-4′-methylphenylmethanimine (initially, $[E]/[Z]=1/1$) reached 4/96 upon irradiation (>360 nm) of 9,10-dicyanoanthracene (DCA) as a photosensitizer in acetonitrile. © 2000 Elsevier Science Ltd. All rights reserved.

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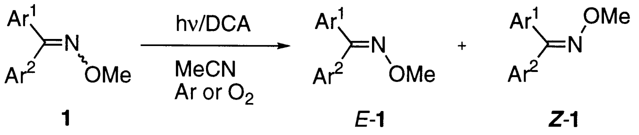
Photochemical *cis–trans* isomerizations of C=C[1] and N=N[2] double bonds have been investigated thoroughly, yet limited information is available on photoisomerization of a C=N double bond.[3] There has been virtually no report on the isomerization of a compound containing the C=N double bond derived especially from a diaryl ketone. During the course of our investigation on photosensitized electron-transfer (PET) reactions of compounds consisting of a C–N–O skeleton,[4] we found a novel oxygen-sensitive geometrical isomerization of *N*-methoxydiarylmethanimine (**1**) under the PET conditions.[5]



(1)

a $Ar^1 = p\text{-}MeOC_6H_4$, $Ar^2 = p\text{-}MeC_6H_4$
b $Ar^1 = p\text{-}CHOC_6H_4$, $Ar^2 = p\text{-}MeC_6H_4$

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Table 1
Oxidation potentials and kinetic data of the quenching of the DCA fluorescence with methanimines **1**

Compd.	$E_{1/2}^{\text{ox}}$[a] (V)	K_{sv}[b] (M^{-1})	k_q[c] (10^{10} M^{-1} s^{-1})	ΔG[d] (kJ mol^{-1})
1a	1.54	171	1.12	−11.4
1b	1.88	59.5	0.389	−3.51

[a] Half peak of oxidation potentials of **1** vs. SCE measured in dry MeCN under Ar. Supporting electrolyte: n-$Bu_4N^+ClO_4^-$.

[b] Stern–Volmer constants for the fluorescence quenching of DCA with **1**.

[c] Rate constants for the fluorescence quenching.

[d] Free energy change[6] for the electron transfer from the excited singlet state of DCA to **1**.

Fluorescence of DCA employed as a photosensitizer was quenched by **1** in MeCN at nearly diffusion-controlled rates. The oxidation potential ($E_{1/2}^{\text{ox}}$) of **1** was moderately to fairly low (<1.9 V vs. SCE) and the free energy changes (ΔG) for the electron transfer from **1** to the excited singlet state of DCA were calculated to be negative by the Rehm–Weller equation[6] employing $E_{1/2}^{\text{ox}}$ values of **1**. The photosensitized electron-transfer process is, therefore, the most probable mechanism for the fluorescence quenching of DCA. These data are summarized in Table 1.

Table 2
Photoisomerizations of *N*-methoxy-1,1-diarylmethanimines **1**[a]

Sens.	Atmosphere	Isomer ratio Compd. **1a**		Isomer ratio Compd. **1b**	
		E	*Z*	*E*	*Z*
DCA[b]	Ar	48	52	56	44
	O_2	4	96	78	22
TMK[c]	Ar	45	55	45	55
	O_2	44	56	51	49
Direct[d]	Ar	33	67	38	62
	O_2	29	71	34	66

[a] Reaction time: 3 h. Isomer ratios were determined by ^1H NMR spectra (400 MHz in MeCN-d_3).

[b] 9,10-Dicyanoanthracene.

[c] Thio-Michler's ketone.

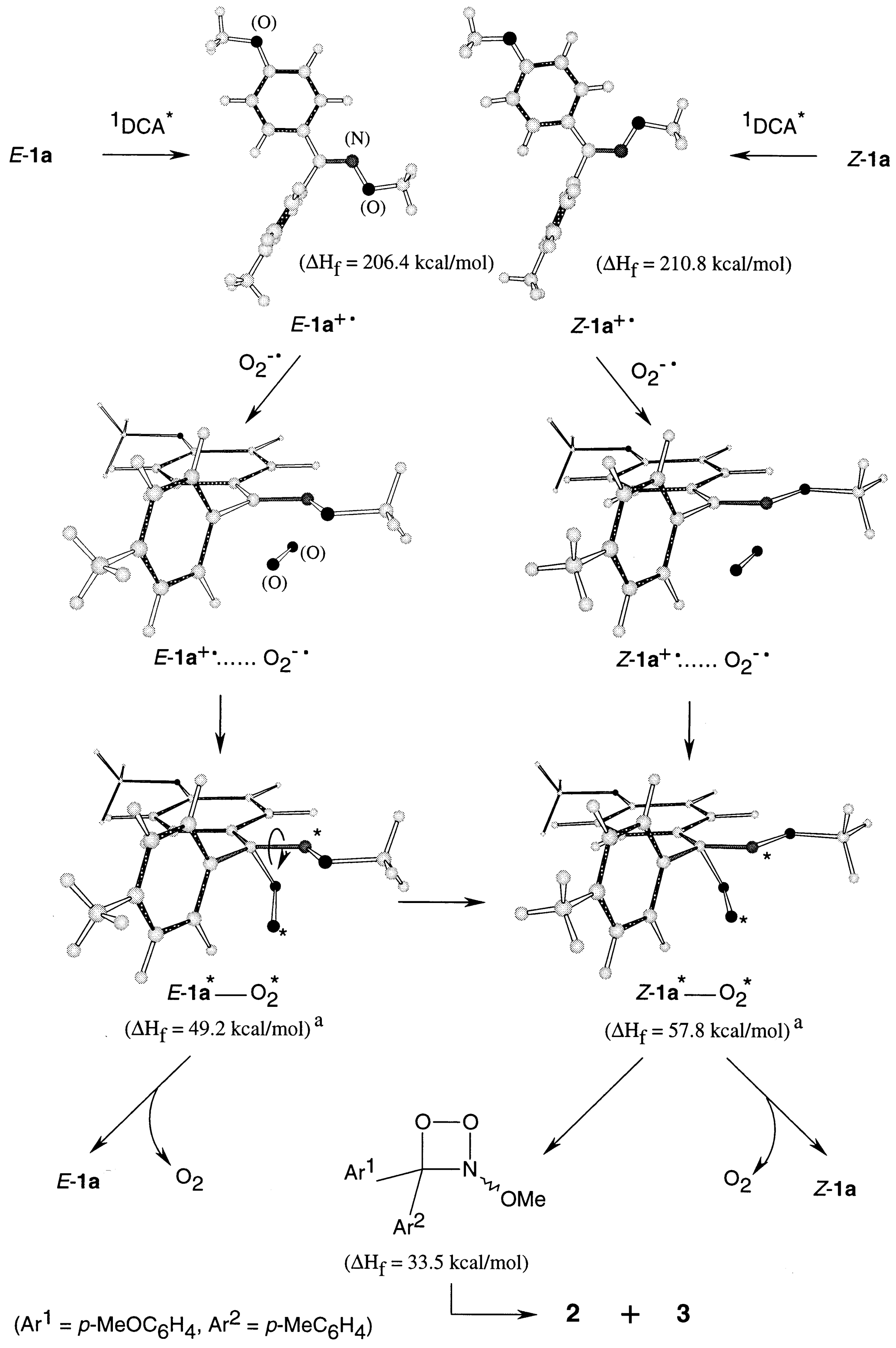
[d] $h\nu > 280$ nm.

Irradiation of **1**[7] (Eq. (1)) with or without photosensitizers gave the results as summarized in Table 2.[8] Features of the photoreactions are: (1) similar *E*/*Z* selectivities of **1a** and **1b** were observed upon direct irradiation of each under Ar. No different selectivities were observed in the reactions under O_2 from those under Ar. (2) When a typical triplet sensitizer, thio-Michler's ketone (TMK), was employed in the reactions under Ar, the ratios of *E*-**1a** and *E*-**1b** increased by ca. 10% compared to the results in the direct irradiation. In addition, the DCA-sensitized photoreaction of **1a** under Ar showed a little selectivity in geometry of **1**. (3) In DCA-sensitized photoreactions under O_2, surprisingly high geometrical selectivity in **1** was observed, especially in **1a**.[9] Moreover, diaryl ketone (**2**)[10] and methyl nitrite (**3**)[10] were detected as minor byproducts in the photoreactions of both methanimines. Note that the *Z* isomer is a major component in the PET reaction of **1a**, whereas the *E* isomer is major in the case of **1b**. By contrast, the TMK-sensitized reaction showed no such remarkable oxygen effect.

In order to elucidate the peculiar oxygen effect on the stereoselectivity under PET conditions, some control experiments were done and the results are summarized as follows: (1) no displacement of isomer ratios was observed at all in a methylene blue-sensitized photoreaction. The result rules out the participation of singlet oxygen in the photoisomerization. (2) Despite almost the same triplet energies of DCA (175 kJ mol^{-1})[11] and TMK (176 kJ mol^{-1}),[11] apparent differences in selectivity were observed in the reactions under O_2 (Table 2). This suggests that excited triplet states of **1**[3b] and/or triplet molecular oxygen are not responsible for the observed stereochemical outcome. (3) The PET reaction of **1a** employing 2,6,9,10-tetracyanoanthracene (TCA)[12] as a photosensitizer was suppressed upon irradiation for the same period (3 h) as the reaction reached the maximum isomer ratio in the DCA–PET reaction under O_2. The result suggests that a superoxide anion as an active oxygen species plays a major role in controlling the stereochemical outcome.[13] How superoxide takes part in the reaction of *E*-**1a** is considered as follows (Scheme 1). Once electron transfer between a singlet excited DCA and *N*-methoxymethanimines occurs, the resultant DCA anion radical reacts further with triplet oxygen to generate superoxide anion.[14] A mode of the interaction of these radical ion pairs is most likely to be that of a thermally allowed [π2s+π2a] cycloaddition. Accordingly, the transition state has a crisscrossed geometry as in the cycloaddition of neutral species. A similar explanation was proposed previously in the *cis* selective formation of olefins with unstable phosphorus ylides and aldehydes (a Wittig olefination).[15] In addition, a non-triplet mechanism for geometrical isomerization of olefins is already known.[16]

To explain the origin of the preferential *Z* selectivity of **1a** and *E* selectivity of **1b** in the PET reactions under O_2, we wish to propose a route to an azadioxetane via the direct interaction of the radical ion pair, i.e. an *N*-methoxymethanimine radical cation and a superoxide anion.

Energy optimized structures (the semiempirical PM3 molecular orbital calculations[17]) of radical cations of **1** are shown in Scheme 1. The *p*-methylphenyl groups in *E*- and *Z*-$\mathbf{1a}^{+\bullet}$ are inclined in 89.5 and 88.4°, respectively, against the residual molecular frameworks.[18] A positive charge and a spin are delocalized over the *p*-anisyl-C=N–O system in both *E* and *Z* isomers. Alternatively, both could be localized in the nitrogen lone pair, but this state is surely higher in energy. A spin density is the highest on the nitrogen and it is essentially a π radical similar to aminyls[19] and alkoxyaminyls.[20] Then if concerted [2s+2a] interaction of both ion radicals occurs and an azadioxetane is formed at once, it would be difficult to explain the observed stereochemistry because it isn't possible to expect so much energy difference in the isomers of azadioxetanes. Radical cation $\mathbf{1a}^{+\bullet}$ and superoxide initially make one new bond at the benzylic carbon atom at which attack of superoxide is most likely to occur. However, the attacking oxygen of the superoxide anion is discriminated in the crisscrossed geometry made up of both ion radicals, due to steric hindrance imposed on the inclined *p*-methylphenyl group in *E*-$\mathbf{1a}^{+\bullet}$ and an oxygen terminus of superoxide. In such a stepwise view, the interaction yields an intermediate 1,4-biradical. According to the Skell–Woodworth hypothesis, there is then competition between bond rotation that causes loss of *E* and *Z*, and the spin inversion necessitated for the second bond



Scheme 1. Proposed reaction mechanism with the aid of the energy-minimized structures (PM3 semiempirical MO calculations, the half electron method for open-shell compounds) of the intermediates. a: The values are those of the triplet 1,4-diradicals

formation. Perturbation of the terminal oxygen leads the methoxyaminyl π radical[20] to spin flip and concomitantly such loss of spin momentum is compensated by change of orbital momentum. That is, a proximal oxygen affects a π aminyl radical, which then causes the spin flip and the simultaneous change of an electronic configuration to a σ aminyl radical. Considering the values of ΔH_f for the energy optimized triplet *E*- and *Z*-**1a***–O_2*, the path from *E*-**1a***–O_2* to *Z*-**1a***–O_2* is apparently uphill and energetically unfavorable. Nevertheless, the subsequent large exothermic process to an azadioxetane (or a singlet biradical) would displace the equilibrium to the right. Then the second bond formation of nitrogen and oxygen in *Z*-**1a***–O_2* occurs and a proposed azadioxetane is formed. Before complete ring closure, the intermediate releases oxygen to give finally the observed preferential geometrical isomer of a C=N double bond. Byproducts **2** and **3** can be explained by decomposition of the azadioxetane. On the other hand, an interaction of the *Z*-**1a**$^{+\bullet}$ with superoxide proceeds via *Z*-**1a***–O_2* without any leakage to *E*-**1a***–O_2*. Or if any, the following spin inversion in *E*-**1a***–O_2* with a C–N bond rotation again gives rise to the formation of *Z*-**1a***–O_2* (singlet) or of the azadioxetane due to the directionality of the σ methoxyaminyl formed in the process. The root cause of the *E* selectivity of **1b** can be considered similarly.[21]

In summary, the PET reactions of the title *N*-methoxymethanimines (substituted benzophenone oxime *O*-methyl ethers) under O_2 gave rise to the unprecedented geometrical isomerization. The feature substantiates the unique PET reactivity of the oxime ethers. Further work including the isomerization of the compounds containing the C=C and C=N double bonds is in progress.

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7. *N*-Methoxymethanimines were prepared generally by a Friedel–Crafts acylation of benzoyl chloride derivatives, followed by the condensation of the ketones obtained with $NH_2OH{\cdot}HCl$, and then *O*-methylation of the oximes with MeI. A formyl group on one of the aryl groups in **1b** was introduced by a controlled chromium oxidation of 4,4′-dimethylbenzophenone. Geometrical notation of *E* about an iminic double bond of **1b** shows the opposite arrangement of *N*-methoxy and *p*-formylphenyl groups across the bond. Similarly, the notation *E* of **1a** shows the opposite relationships of *N*-methoxy and *p*-methoxyphenyl groups. The *E*/*Z* ratio of **1** was 1/1 before photoirradiation.
8. Geometrical isomers of **1a** were not separated even by high pressure liquid chromatography (HPLC) using a silica gel column eluted with 10% EtOAc in hexane. But those of **1b** were separated by HPLC with difficulty. Isomer ratios were, therefore, determined by ^{1}H NMR (400 MHz) in all experiments. Geometry of **1** was determined by NOE experiments on degree of enhancement of the peak areas of the aromatic protons upon irradiation of *N*-methoxyl signals. Experimental conditions: $[\mathbf{1}]=10^{-3}$ M. $[\mathrm{DCA}]=10^{-5}$ M. Dry MeCN solutions of samples were irradiated with a high-pressure mercury lamp [Riko® 400 W (Toshiba® glass filter L-39, >360 nm for the PET reactions; Pyrex® glass filter, >280 nm for the direct irradiation)] at <10°C in a merry-go-round apparatus (Riko® RH400-10W) after purging Ar or O_2 for 30 min in Pyrex® test tubes.

9. The value of the isomer ratio shown in Table 1 is not that in the photostationary state. We believe that it is still meaningful relevant to the term, one-way photoisomerization of the C=N double bond, according to the following experimental result and the argument below.[21] A PET reaction becomes complicated generally, when it is performed under O_2. In our preparative run of **1a** ([**1a**] $= 1.2\times10^{-2}$ M), the mixture of isomer (*E*-**1a**/*Z*-**1a** = 35/65) and benzophenone derivative were obtained in 73 and 2.6% yields, respectively, based on the starting **1a** after 4 h photoirradiation under O_2. It is considered that the *E*/*Z* PET isomerization is the major one.
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18. The values of ΔH_f for the neutral *E*- and *Z*-**1a** are 16.9 and 19.6 kcal/mol, respectively. These values for the radical cations of *E*- and *Z*-**1a** are 206.4 and 210.8 kcal/mol, respectively. By contrast, the corresponding values for the optimized structures of **1a** having the *p*-methoxyphenyl group arranged perpendicularly to the rest of the molecular framework were 218.4 and 212.2 kcal/mol for the *E*- and *Z*-**1a** radical cations, respectively. In order to avoid assigning erroneous optimized structures as the most energetically favorable ones due to the presence of multiple energy minima, the calculations were performed with starting several initial structures of **1**.
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21. About this mechanism, one of the referees pointed out that compound **1a** gave solely the *Z* isomer and **1b** gave the *E* isomer, otherwise, this reaction cannot be one-way isomerization. Actually, decomposition products were formed and coloration of the reaction mixture developed during the progress of the reaction. The analysis of the product ratio in the limit was difficult for these reasons. Concerning this reaction, we found recently a similar photoreaction of a C=C double bond. It was confirmed that one isomer isomerized perfectly to another isomer upon irradiation of DCA. Considering the importance of the proper usage of the term, one-way isomerization, in the present reaction, we believe that the reaction is where one isomer of **1** isomerizes selectively into another, similar to the reaction of the C=C double bond.