MECHANISM OF THE TRIPLET-SENSITIZED PHOTOLYSIS OF 1-[1-(1-NAPHTHYL)ETHOXY]-2-PYRIDONE AND RELATED DERIVATIVES

Asako Watanabe, Maya Matsushita, Aya Masuda, Tetsutaro Igarashi, and Tadamitsu Sakurai*

Department of Material and Life Chemistry, Faculty of Engineering, Kanagawa University, Kanagawa-ku, Yokohama 221-8686, Japan

Abstract—On irradiation at 366 nm in the presence of benzophenone, the title 2-pyridone derivatives (1) in nitrogen-saturated acetonitrile underwent sensitized decomposition to give arylaldehyde and 2-methoxypyridine in addition to the expected N–O bond cleavage products: 1-arylethanol, arylmethylketone, and 2-pyridone. A comparison of the quantum yields for the benzophenone-sensitized photolysis of 1 with those for the direct photolysis with 313 nm light led us to conclude that the former cleavage products were derived from the methyl shift in a 1-derived singlet caged radical pair, taking place in competition with the hydrogen shift in this pair as well as with the recombination and diffusive separation of this pair. Our conclusion was confirmed by deuterium isotope effects on the limiting quantum yields for 1-arylethanol (‘out-of-cage’ product) and arylaldehyde (‘in-cage’ product).

Photochemistry has continued to contribute to the development of organic reactions that are of great value from both mechanistic and synthetic points of view.\(^1\) In the course of a systematic study toward the characterization of the excited-state reactivity of bichromophoric 1-arylmethyloxy-2-pyridones,\(^2\) we found that the homolytic N–O bond cleavage of 1-benzyloxy-2-pyridones in the first singlet excited state occurs from its higher vibrational states in competition with relaxation to the fluorescent state.\(^3\),\(^4\) In addition, we also found recently that an intramolecular interaction between the two chromophores of these pyridone derivatives induces the C–O bond heterolysis in competition with the N–O bond homolysis in the singlet excited state.\(^6\) It is, thus, an interesting extension of our systematic study described above to explore the reactivity of bichromophoric 2-pyridone derivatives in the triplet excited state from a mechanistic point of view. For this extension we synthesized 1-[1-(1-naphthyl)ethoxy]-2-pyridone (1a), 1-[1-(2-naphthyl)ethoxy]-2-pyridone (1b), and 1-(1-phenylethoxy)-2-pyridone (1c) and investigated mechanism of the benzophenone (BP)-sensitized photolysis of these derivatives (Chart 1).\(^7\) On irradiation of an N\(_2\)-saturated MeCN solution of 1a (2.0×10\(^{-3}\) mol dm\(^{-3}\)) containing BP (2.0×10\(^{-2}\) mol dm\(^{-3}\)) with 366 nm light (from a 450 W high-pressure Hg lamp) at room temperature, there
appeared five new HPLC signals with retention times of 4.1 (2-pyridone, 2), 7.2 [1-(1-naphthyl)ethanol, 3a], 11.2 (1'-acetonaphthone, 4a), 7.9 (2-methoxypyridine, 5) and 11.9 min (1-naphthaldehyde, 6a), in addition to those of the starting 1a (retention time, 8.2 min) and BP (12.4 min) whose concentration remained unchanged (Scheme 1). Each product was identified by comparing its HPLC behavior with that of the corresponding authentic sample under several analytical conditions. Since the unexpected products 5 and 6a had been observed, we analyzed 1H NMR spectra of the product mixtures obtained by the 366 nm light irradiation of an N2-saturated CD3CN solution of 1a (4.0×10⁻² mol dm⁻³) in the presence of BP (2.0×10⁻² mol dm⁻³), and we were able to detect the methoxy methyl (3.56 ppm, 5) and formyl (10.38 ppm, 6a) proton signals with the area ratio of about 3:1, independent of irradiation time. Control experiments showed that irradiation of an N2-saturated MeCN solution of 1a containing no BP induced its negligible decomposition under the same conditions.

Although the formation of 5 and 6a apparently suggests that bond making between the amide carbonyl oxygen and the methyl carbon in the excited-state 1a occurs concertedely with the N–O bond cleavage to give these products, a large difference in bond dissociation energy between the N–O bond (ca. 220 kJ mol⁻¹)⁹ and the CH–CH₃ bond (ca. 310 kJ mol⁻¹)¹⁰ renders the participation of a concerted mechanism unlikely. Since BP (the first singlet excitation energy, Eₛ= 311 kJ mol⁻¹; the first triplet excitation energy, Eₜ= 289 kJ mol⁻¹)¹¹ is an excellent triplet sensitizer for the photolysis of 1 (Eₛ≈ 320 and Eₜ≈ 270 kJ mol⁻¹ for the pyridone chromophore; Eₛ≈ 380 and Eₜ≈ 250 kJ mol⁻¹ for the naphthylmethyl),²,¹¹ we are led to propose that energy transfer from BP to 1a produces the triplet excited-state 1a, the decomposition of which may generate a triplet caged radical pair. As already demonstrated in our previous studies on the triplet-sensitized photolysis of N,O-diacyl-N-phenylhydroxylamines,¹² the triplet radical pair initially formed escapes from a given solvent cage to eventually give only fragmentation products. This previous finding allows us to predict that the reaction from triplet 1a affords selectively ‘out-of-cage’ products, namely, 2-pyridone (2) and 1-(1-naphthyl)ethanol (3a). The result obtained is not consistent with our prediction and, hence, we are forced to propose a singlet caged radical pair intermediate as a precursor of 1'-acetonaphthone (4a), 2-methoxypyridine (5), and 1-naphthaldehyde (6a) in addition to 2 and 3a. The idea of ‘in-cage’ and ‘out-of-cage’ reactions was successfully applied to the interpretation of product distribution obtained...
from the direct and triplet-sensitized photolyses of \(N\)-(1-naphthoyl)-\(N\)-phenyl-\(O\)-(\(p\)-toluoyl)hydroxylamine and related hydroxylamine derivatives.\(^{12,13}\) It is, thus, reasonable to account for the appearance of 4a, 5, and 6a in terms of the reaction of the singlet caged radical pair (‘in-cage’ reaction) formed by way of the corresponding triplet radical pair and then account for the formation of 3a by the ‘out-of-cage’ reaction of this radical pair.

**Figure 1.** Relationship between \(\Phi_{3b}^{-1}\), \(\Phi_{4b}^{-1}\), and \(\Phi_{6b}^{-1}\) and \([1b]^{-1}\) in the BP-sensitized photolysis of 1b in \(N_2\)-saturated MeCN at room temperature.

It is now an important issue to estimate not only the extent (to which the ‘out-of-cage’ reaction of 1a–c-derived triplet radical pairs contributes to the overall reaction) but also the relative contribution of the ‘in-cage’ and ‘out-of-cage’ reactions of singlet radical pairs. For these two ends we determined quantum yields for formation of 3a–c, 4a–c, and 6a–c in the BP (2.0×10^{-2} mol dm^{-3})-sensitized photolysis of 1a–c (1.0–8.0×10^{-3} mol dm^{-3}) with 366 nm light, as well as those in the direct photolysis of 1a–c (2.0×10^{-3} mol dm^{-3}) with 313 nm light.\(^{14}\) As typically shown in Figure 1, any relationships between the reciprocal of the quantum yields for the sensitized reaction (\(\Phi_{3b}^{-1}\), \(\Phi_{4b}^{-1}\), and \(\Phi_{6b}^{-1}\)) and the reciprocal of the 1b concentration ([1b]^{-1}) can be approximated as being linear in the concentration range of 1b examined. Similar linear plots were obtained for the 2-pyridone derivatives 1a and 1c. The good linear relationship between \(\Phi^{-1}\) and \([1]^{-1}\) (correlation coefficient \(\gamma>0.992\)) made it possible to determine the limiting quantum yields (\(\Phi_{\text{lim}}\)), \(i.e.,\) the quantum yields extrapolated to infinite concentration of 1, the values of which were collected in Table 1. For comparison, the quantum yields of 3a–c, 4a–c, and 6a–c formed by the direct photolysis were repeatedly measured and their average values were given in the same Table. Because the ratio \(R\) of \([\Phi_{4,\text{lim}}(or \Phi_{4}) + \Phi_{6,\text{lim}}(or \Phi_{6})]\) to \([\Phi_{3,\text{lim}}(or \Phi_{3}) + \Phi_{4,\text{lim}}(or \Phi_{4}) + \Phi_{6,\text{lim}}(or \Phi_{6})]\) is a measure of the relative contribution of the ‘in-cage’ reaction vs. the ‘out-of-cage’ reaction, these \(R\) values were also estimated and summarized in Table 1. A careful
survey of substituent effects on the magnitude of $R$ for the direct and sensitized photolyses demonstrates that the ‘in-cage’ reaction giving 4 and 6 proceeds in preference to the ‘out-of-cage’ reaction affording 3 irrespective of both the excitation mode of 1 and the aryl substituent examined ($R= 0.61–0.92$). Interestingly, the relative contribution of the former reaction in the sensitized photolysis is comparable to that in the direct photolysis. If we consider that the direct photolysis of 1-arylmethyloxy-2-pyridone derivatives related to 1a–c takes place predominantly from their singlet excited states, 2–4 this interesting finding leads us to conclude that spin inversion of the 1-derived triplet radical pair to the singlet one proceeds with an extremely high efficiency without almost permitting the diffusive separation of the former radical pair.

A comparison of the magnitude of $\Phi_{4,\text{lim}}$ with that of $\Phi_{6,\text{lim}}$ (Table 1) confirms that the methyl shift in the singlet caged radical pair, leading to 5 and 6, occurs in a quantum yield comparable to the hydrogen shift in this pair, affording 2 and 4, without undergoing the steric hindrance of a methyl group. In order to elucidate the reason for the ready progress of the methyl shift, the energy-minimized conformation of 1c was determined by MM2 and PM5 calculations. 16 The conformation depicted in Figure 2 is well consistent with that determined by the X-ray structural analysis of 1c and enables the methyl carbon in this molecule to readily shift to the amide carbonyl oxygen. 17 It is likely that the singlet pyridin-2-oxyl radical/1-phenylethoxyl radical pair adopts a similar conformation to that given in Figure 2. If so, we may envisage the following four processes (1)–(4) competing in the singlet caged

Table 1. Quantum yields for formation of 3, 4, and 6 in the BP-sensitized ($\Phi_{\text{lim}}$) and direct ($\Phi$) photolyses of 1a–d and 1d–d$_2$ in MeCN at room temperature

<table>
<thead>
<tr>
<th>Compound</th>
<th>$\Phi_{3,\text{lim}}$ (3)</th>
<th>$\Phi_{4,\text{lim}}$ (4)</th>
<th>$\Phi_{6,\text{lim}}$ (6)</th>
<th>$R^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1a</td>
<td>0.21</td>
<td>0.32</td>
<td>0.17</td>
<td>0.70</td>
</tr>
<tr>
<td>1b</td>
<td>0.10</td>
<td>0.15</td>
<td>0.19</td>
<td>0.77</td>
</tr>
<tr>
<td>1c</td>
<td>0.085</td>
<td>0.47</td>
<td>0.45</td>
<td>0.92</td>
</tr>
<tr>
<td>1d</td>
<td>0.042</td>
<td>0.69</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1d–d$_2$</td>
<td>0.058</td>
<td>0.29</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1a</td>
<td>0.14</td>
<td>0.093</td>
<td>0.13</td>
<td>0.61</td>
</tr>
<tr>
<td>1b</td>
<td>0.077</td>
<td>0.16</td>
<td>0.074</td>
<td>0.75</td>
</tr>
<tr>
<td>1c</td>
<td>0.070</td>
<td>0.16</td>
<td>0.094</td>
<td>0.78</td>
</tr>
</tbody>
</table>

$^aR = (\Phi_{4,\text{lim}} + \Phi_{6,\text{lim}})/(\Phi_{3,\text{lim}} + \Phi_{4,\text{lim}} + \Phi_{6,\text{lim}})$

Figure 2. Energy-minimized conformation of 1c.
radical pair: (1) the methyl shift giving 5 and 6, (2) the hydrogen shift generating 2 and 4, (3) the escape from the cage eventually leading to 2 and 3, and (4) the recombination giving 1. Accordingly, the considerations described above led us to propose Scheme 2 that explains the observed product distribution. On purpose to obtain further information about the above competing processes, we synthesized 1-(2-naphthylmethoxy)-2-pyridone (1d) and its deuterated derivative 1-[α-(2H2)-2-naphthylmethoxy]-2-pyridone (1d-d2; the deuterium content, 98 atom%) (Chart 2) and determined the limiting quantum yields for formation of 2-naphthalenemethanol (3d, \( \Phi_{3d,\text{lim}} \)) and 2-naphthaldehyde (6d, \( \Phi_{6d,\text{lim}} \)) (Table 1) in the same way as that described above. Clearly, deuterium substitution lowered the \( \Phi_{6d,\text{lim}} \) value by a factor of 2.4 while \( \Phi_{3d,\text{lim}} \), quantum yield for the ‘out-of-cage’ product, was slightly increased by this substitution. A large decrease in the total quantum yield (\( \Phi_{3d,\text{lim}} \+ \Phi_{6d,\text{lim}} = 0.73 \rightarrow 0.35 \)) strongly suggests that the retardation of hydrogen shift in the singlet caged radical pair results in not only a great enhancement of the relative rate for the radical
pair recombination but also a slight increase of the relative rate for diffusive separation of the radical pair. Thus, the observed deuterium isotope effects on the limiting quantum yields provide additional evidence for the mechanism shown in Scheme 2.

ACKNOWLEDGMENTS
This research was partially supported by a “Scientific Frontier Research Project” from the Ministry of Education, Sports, Culture, Science and Technology, Japan.

REFERENCES AND NOTES
7. Selected data for 1a: mp 91.5–92.0 °C (EtOAc-hexane); IR (KBr) ν/cm⁻¹ = 1655; ¹H NMR (500 MHz, CDCl₃) δ = 1.93 (3H, d, J = 6.7 Hz), 5.70 (1H, dd, J = 7.0, 7.9 Hz), 6.42 (1H, q, J = 6.7 Hz), 6.63 (1H, d, J = 8.5 Hz), 6.99 (1H, d, J = 7.0 Hz), 7.13 (1H, dd, J = 7.9, 8.5 Hz), 7.45–7.63 (3H, m), 7.62 (1H, d, J = 6.7 Hz), 7.83–7.87 (2H, m), 8.41 (1H, d, J = 8.6 Hz); ¹³C NMR (125 MHz, DMSO-d₆) δ = 20.1, 81.1, 104.0, 122.5, 123.8, 125.2, 125.7, 125.9, 126.7, 128.9, 129.6, 131.5, 134.0, 135.1, 137.0, 138.4, 159.3. Anal. Calcd for C₁₇H₁₅NO₂: C, 76.96; H, 5.70; N, 5.28. Found: C, 76.98; H, 5.75; N, 5.11.
Selected data for 1b: mp 98.0–98.5 °C (EtOAc-hexane); IR (KBr) ν/cm⁻¹ = 1655; ¹H NMR (500 MHz, CDCl₃) δ = 1.81 (3H, d, J = 6.7 Hz), 5.69 (1H, dd, J = 7.0, 7.6 Hz), 5.80 (1H, q, J = 6.7 Hz), 6.64 (1H, d, J = 8.5 Hz), 6.92 (1H, d, J = 7.0 Hz), 7.14 (1H, dd, J = 7.6, 8.5 Hz), 7.47–7.52 (2H, m), 7.60 (1H, d, J = 8.2 Hz), 7.71 (1H, s), 7.78 (1H, d, J = 7.9 Hz), 7.83–7.88 (2H, m); ¹³C NMR (125 MHz, DMSO-d₆) δ = 19.9, 83.6, 104.0, 122.5, 124.5, 126.4, 126.6, 127.7, 127.8, 128.2, 128.7, 133.1, 133.6, 136.2, 137.1, 138.4, 159.2. Anal. Calcd for C₁₇H₁₅NO₂: C, 76.96; H, 5.70; N, 5.28. Found: C, 76.98; H, 5.52; N, 5.04.
Selected data for 1c: mp 58.0–59.0 °C (EtOAc-hexane); IR (KBr) ν/cm⁻¹ = 1661; ¹H NMR (500 MHz, CDCl₃) δ = 1.73 (3H, d, J = 6.1 Hz), 5.63 (1H, q, J = 6.1 Hz), 5.78 (1H, dd, J = 6.7, 7.3 Hz), 6.63 (1H, d, J = 6.7 Hz), 6.91 (1H, d, J = 6.7 Hz), 7.18 (1H, dd, J = 6.7, 7.3 Hz), 7.32–7.38 (5H, m); ¹³C NMR (125 MHz, DMSO-d₆) δ = 19.7, 83.4, 103.9, 122.5, 127.8 (2C), 128.7 (2C), 129.1, 137.2, 138.4, 138.9, 159.1. Anal. Calcd for C₁₃H₁₃NO₂: C, 72.54; H, 6.09; N, 6.51. Found: C, 72.38; H,
Analytical conditions for HPLC: 4.6×250-mm ODS column; detection wavelength, 240 and/or 220 nm; mobile phase, MeCN:H₂O = 60:40 v/v; flow rate, 0.7 mL/min.


A potassium tris(oxalato)ferrate(III) actinometer was employed to determine the quantum yields for the direct and benzophenone-sensitized photolyses of 1 at low conversions (<15%) of the starting 1a–c. A 450 W high-pressure Hg lamp was used as the light source from which 366 nm light for the sensitized photolysis was selected with Corning 0-52, Corning 7-60, and Toshiba IRA-25S glass filters and 313 nm light for the direct photolysis was isolated with a 1.0 wt% potassium carbonate solution of potassium chromate (2.0×10⁻³ mol dm⁻³), Corning 7-54, and Toshiba IRA-25S glass filters. Linear calibration curves for each product, made under the same analytical conditions, were utilized to quantify the appearance of 3, 4, and 6. All of the quantum yields are an average of more than three determinations. No attempt to determine Φ₂ and Φ₅ was made because the HPLC signals of 2 and 5 overlap strongly with those arising from the eluent and the starting 1, respectively.


MM2 and PM5 calculations were accomplished by using CAChe 5.0 for Windows available from Fujitsu Ltd, 2002.