HETEROCYCLES, Vol. 78, No. 10, 2009, pp. 2431- 2437. © The Japan Institute of Heterocyclic Chemistry
Received, 14th May, 2009, Accepted, 30th June, 2009, Published online, 1st July, 2009
DOI: 10.3987/COM-09-11756

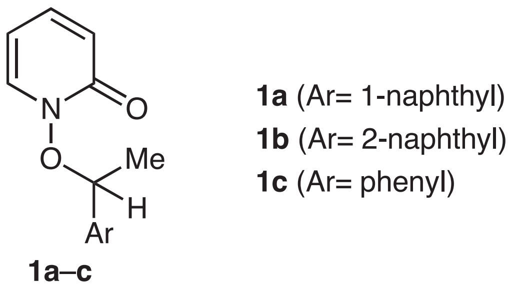
MECHANISM OF THE TRIPLET-SENSITIZED PHOTOLYSIS OF 1-[1-(1-NAPHTHYL)ETHOXY]-2-PYRIDONE AND RELATED DERIVATIVES

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).

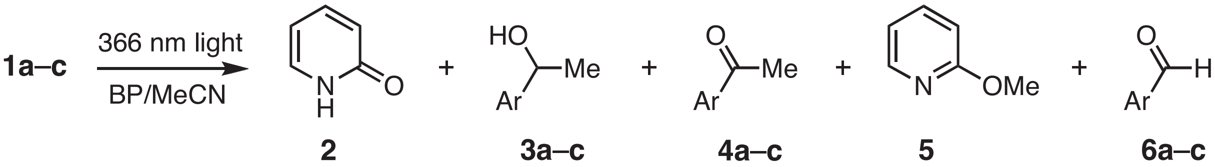
Photochemistry has continued to contribute to the development of organic reactions that are of great value from both mechanistic and synthetic points of view.[1] In the course of a systematic study toward the characterization of the excited-state reactivity of bichromophoric 1-arylmethyloxy-2-pyridones,[2–6] 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



1a–c

Chart 1

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).[8] 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 ^{1}H NMR spectra of the product mixtures obtained by the 366 nm light irradiation of an N_2-saturated CD_3CN 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 N_2-saturated MeCN solution of **1a** containing no BP induced its negligible decomposition under the same conditions.



Scheme 1

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 concertedly 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 $CH–CH_3$ bond (ca. 310 kJ mol^{-1})[10] renders the participation of a concerted mechanism unlikely. Since BP (the first singlet excitation energy, E_S= 311 kJ mol^{-1}; the first triplet excitation energy, E_T= 289 kJ mol^{-1})[11] is an excellent triplet sensitizer for the photolysis of **1** ($E_S\approx$ 320 and $E_T\approx$ 270 kJ mol^{-1} for the pyridone chromophore; $E_S\approx$ 380 and $E_T\approx$ 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.

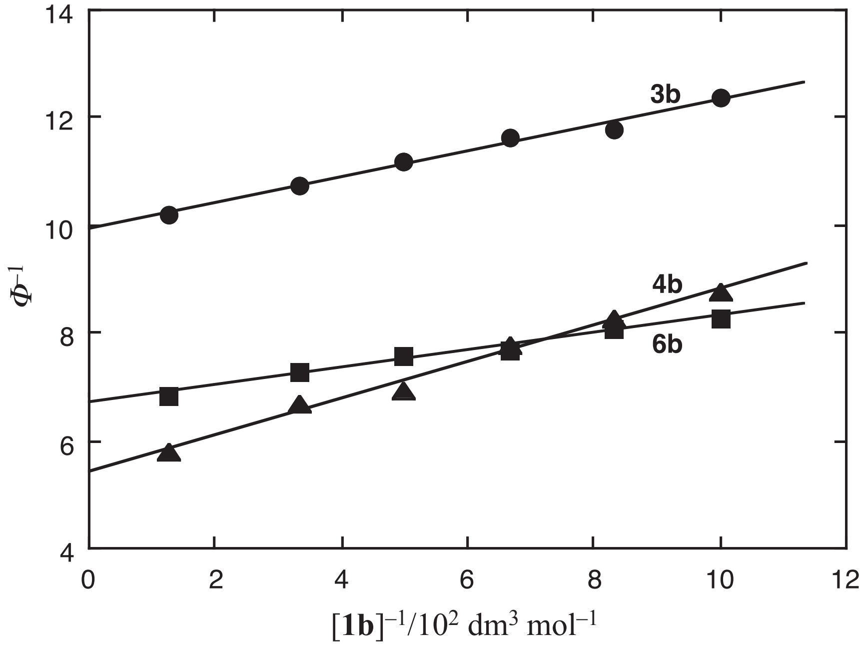


Figure 1. Relationship between Φ_{3b}^{-1}, Φ_{4b}^{-1}, and Φ_{6b}^{-1} and $[\mathbf{1b}]^{-1}$ in the BP-sensitized photolysis of **1b** in N_2-saturated MeCN at room temperature.

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 (Φ_{3b}^{-1}, Φ_{4b}^{-1}, and Φ_{6b}^{-1}) and the reciprocal of the **1b** concentration ($[\mathbf{1b}]^{-1}$) 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 Φ^{-1} and $[\mathbf{1}]^{-1}$ (correlation coefficient γ>0.992) made it possible to determine the limiting quantum yields (Φ_{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 Φ_4) + $\Phi_{6,\text{lim}}$(or Φ_6)] to [$\Phi_{3,\text{lim}}$(or Φ_3) + $\Phi_{4,\text{lim}}$(or Φ_4) + $\Phi_{6,\text{lim}}$(or Φ_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

Table 1. Quantum yields for formation of **3**, **4**, and **6** in the BP-sensitized (Φ_{lim}) and direct (Φ) photolyses of **1a**–**d** and **1d**-d_2 in MeCN at room temperatutre

Compound	$\Phi_{\mathbf{3},\mathrm{lim}}$ ($\Phi_{\mathbf{3}}$)	$\Phi_{\mathbf{4},\mathrm{lim}}$ ($\Phi_{\mathbf{4}}$)	$\Phi_{\mathbf{6},\mathrm{lim}}$ ($\Phi_{\mathbf{6}}$)	R^{a}
1a	0.21	0.32	0.17	0.70
1b	0.10	0.15	0.19	0.77
1c	0.085	0.47	0.45	0.92
1d	0.042		0.69	
1d-d_2	0.058		0.29	
1a	0.14	0.093	0.13	0.61
1b	0.077	0.16	0.074	0.75
1c	0.070	0.16	0.094	0.78

$^{a}R = (\Phi_{\mathbf{4},\mathrm{lim}} + \Phi_{\mathbf{6},\mathrm{lim}})/(\Phi_{\mathbf{3},\mathrm{lim}} + \Phi_{\mathbf{4},\mathrm{lim}} + \Phi_{\mathbf{6},\mathrm{lim}})$ or $(\Phi_{\mathbf{4}} + \Phi_{\mathbf{6}})/(\Phi_{\mathbf{3}} + \Phi_{\mathbf{4}} + \Phi_{\mathbf{6}})$

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.

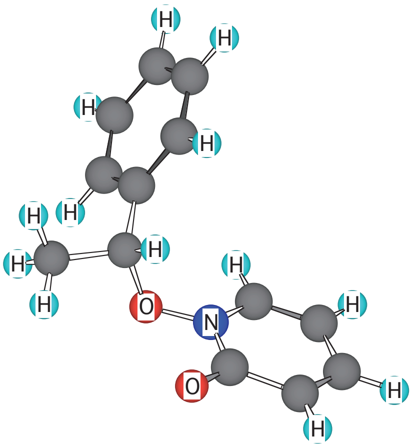
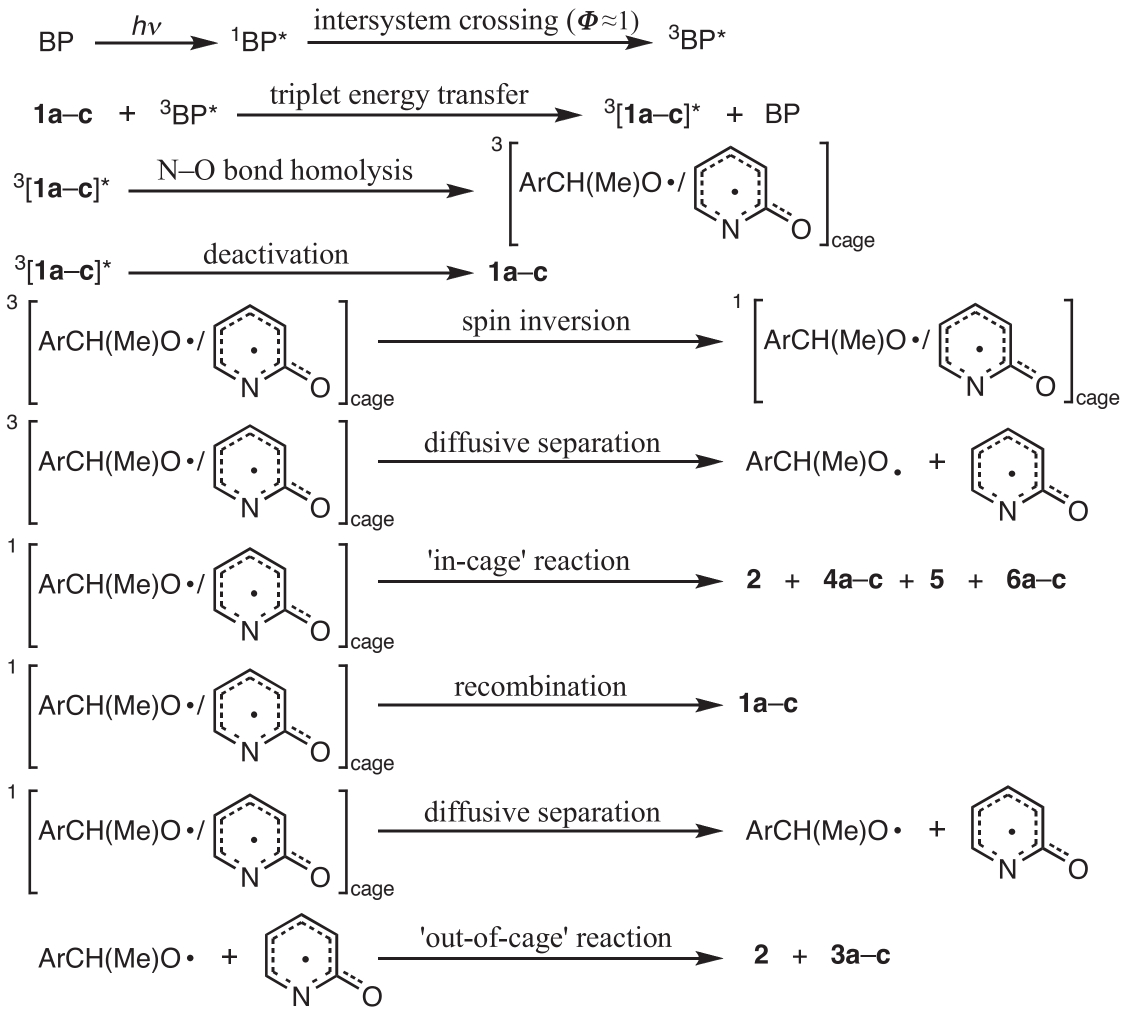


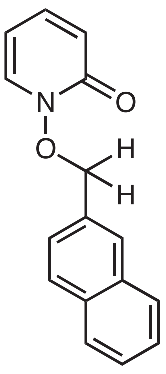
Figure 2. Energy-minimized conformation of **1c**.

A comparison of the magnitude of $\Phi_{\mathbf{4},\mathrm{lim}}$ with that of $\Phi_{\mathbf{6},\mathrm{lim}}$ (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

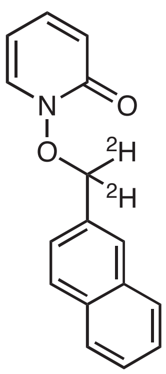


Scheme 2

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-($^2H_2$)-2-naphthylmethoxy]-2-pyridone (**1d**-d_2; the deuterium content, 98 atom%) (Chart 2) and determined the limiting quantum yields for formation of 2-naphthalenemethanol (**3d**, $\Phi_{\mathbf{3d},\mathrm{lim}}$) and 2-naphthaldehyde (**6d**, $\Phi_{\mathbf{6d},\mathrm{lim}}$) (Table 1) in the same way as that described above. Clearly, deuterium substitution lowered the $\Phi_{\mathbf{6d},\mathrm{lim}}$ value by a factor of 2.4 while $\Phi_{\mathbf{3d},\mathrm{lim}}$, quantum yield for the 'out-of-cage' product, was slightly increased by this substitution. A large decrease in the total quantum yield ($\Phi_{\mathbf{3d},\mathrm{lim}} + \Phi_{\mathbf{6d},\mathrm{lim}}$= 0.73→0.35) strongly suggests that the retardation of hydrogen shift in the singlet caged radical pair results in not only a great enhamcement of the relative rate for the radical



1d



1d-d_2

Chart 2

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

1. a) 'Synthetic Organic Photochemistry,' ed. by W. M. Horspool, Plenum, New York, 1984; b) 'Handbook of Photochemistry and Photobiology,' Vol. 2, ed. by H. S. Nalwa, American Scientific Publishers, Stevenson Ranch, 2003; c) 'Synthetic Organic Photochemistry,' ed. by A. G. Griesbeck and J. Mattay, Marcel Dekker, New York, 2005.
2. T. Sakurai, Y. Takeda, and H. Inoue, *Nippon Kagaku Kaishi*, 1984, 1.
3. T. Sakurai, T. Obana, T. Inagaki, and H. Inoue, *J. Chem. Soc.*, *Perkin Trans. 2*, 1989, 535.
4. T. Sakurai, Y. Murakata, and H. Inoue, *J. Chem. Soc.*, *Perkin Trans. 2*, 1990, 499.
5. T. Sakurai, K. Yoshikawa, and H. Inoue, *Bull. Chem. Soc. Jpn.*, 1990, **63**, 3326.
6. N. Yoshioka, C. Andoh, K. Kubo, T. Igarashi, and T. Sakurai, *J. Chem. Soc., Perkin Trans. 2*, 2001, 1927.
7. Selected data for **1a**: mp 91.5–92.0 °C (EtOAc-hexane); IR (KBr) ν/cm^{-1} = 1655; ^{1}H NMR (500 MHz, CDCl$_3$) 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); ^{13}C NMR (125 MHz, DMSO-*d*$_6$) 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 $C_{17}H_{15}NO_2$: 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; ^{1}H NMR (500 MHz, CDCl$_3$) 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); ^{13}C NMR (125 MHz, DMSO-*d*$_6$) 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 $C_{17}H_{15}NO_2$: C, 76.96; H, 5.70; N, 5.28. Found: C, 76.84; H, 5.52; N, 5.04.

   Selected data for **1c**: mp 58.0–59.0 °C (EtOAc-hexane); IR (KBr) ν/cm^{-1} = 1661; ^{1}H NMR (500 MHz, CDCl$_3$) 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); ^{13}C NMR (125 MHz, DMSO-*d*$_6$) 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 $C_{13}H_{13}NO_2$: C, 72.54; H, 6.09; N, 6.51. Found: C, 72.38; H, 6.01; N, 6.69.

8. Analytical conditions for HPLC: 4.6×250-mm ODS column; detection wavelength, 240 and/or 220 nm; mobile phase, MeCN:H_2O = 60:40 v/v; flow rate, 0.7 mL/min.
9. H. Sakuragi, M. Yoshida, H. Kinoshita, K. Utena, K. Tokumaru, and M. Hoshino, *Tetrahedron Lett*., 1978, 1529 and references cited therein.
10. Y.-R. Luo, 'Handbook of Bond Dissociation Energies in Organic Compounds,' CRC Press, Boca Raton, 2003.
11. S. L. Murov, I. Carmichael, and G. L. Hug, 'Handbook of Photochemistry,' 2nd ed., Marcel Dekker, New York, 1993.
12. a) T. Sakurai, H. Yamamoto, S. Yamada, and H. Inoue, *Bull. Chem. Soc. Jpn*., 1985, **58**, 1174; b) T. Sakurai, H. Sukegawa, and H. Inoue, *Bull. Chem. Soc. Jpn*., 1985, **58**, 2875.
13. T. Sakurai, H. Mizuno, T. Kubota, and H. Inoue, *Bull. Chem. Soc. Jpn*., 1991, **64**, 2140.
14. A potassium tris(oxalato)ferrate(III) actinometer was employed to determine the quantum yields forthe direct and benzophenone-sensitized photolyses of **1** at low conversions (<15%) of the starting **1a**–**c**.[15] 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 Φ_2 and Φ_5 was made because the HPLC signals of **2** and **5** overlap strongly with those arising from the eluent and the starting **1**, respectively.
15. C. G. Hatchard and C. A. Parker, *Proc. R. Soc. London, Ser. A*, 1956, **235**, 518.
16. MM2 and PM5 calculations were accomplished by using CAChe 5.0 for Windows available from Fujitsu Ltd, 2002.
17. J. Hartung, M. Hiller, M. Schwarz, I. Svoboda, and H. Fuess, *Liebigs Ann.*, 1996, 2091.