

Available online at www.sciencedirect.com



Chemical Physics Letters 417 (2006) 211-216



www.elsevier.com/locate/cplett

Time-resolved EPR and laser photolysis investigations of photoinduced ω -bond dissociation in an aromatic carbonyl compound having triplet π,π^* character

Minoru Yamaji^{a,*}, Susumu Inomata^a, Satoru Nakajima^b, Kimio Akiyama^b, Shozo Tero-Kubota^b, Seiji Tobita^a, Bronislaw Marciniak^c

^a Department of Chemistry, Gunma University, Tenjin-cyo, 1-5-1, Kiryu 376-8515, Japan ^b Institute of Multidisciplinary Research for Advanced Materials, Tohoku University, Sendai 980-8577, Japan ^c Faculty of Chemistry, Adam Mickiewicz University, Poznan 60-780, Poland

> Received 16 September 2005; in final form 26 September 2005 Available online 24 October 2005

Abstract

Photochemical properties of photoinduced ω -bond dissociation in *p*-phenylbenzylbenzyl phenyl sulfide (PPS) having the lowest triplet state (T₁) of π,π^* character in solution were investigated by time-resolved EPR and laser flash photolysis techniques. PPS was found to undergo photoinduced ω -bond cleavage in the excited lowest singlet state (S₁(n, π^*)) with a quantum yield (Φ_{rad}) of 0.15 for the radical formation, which was independent of excitation wavelengths. Based on the facts of the observation of the absorption spectrum of triplet PPS upon triplet sensitization of xanthone, and absence of CIDEP signal, ω -cleavage was shown to be absent in the T₁(π,π^*) state of PPS. Considering the electronic character of the excited and dissociative states of PPS, a schematic energy diagram for the ω -bond dissociation of PPS was shown.

© 2005 Elsevier B.V. All rights reserved.

1. Introduction

Photoinduced bond dissociation of aromatic carbonyl compounds has been widely documented, such as Norrish Type I and II reactions, where carbon–carbon bond fission occurs at the α - and β -positions of the carbonyl, respectively [1–19]. Recently, we have been studying a new-type photo-induced homolytic bond cleavage which occurs neither at α - nor β -position, but at the ω -position of benzophenone derivatives by using time-resolved EPR and laser photolysis techniques [20–22]. ω -Bond cleavage of benzophenone derivatives having C–S, C–Cl and C–Br bonds was characterized to occur mainly in the T₁(n, π *) state. It seems that for occurrence of ω -bond dissociation, the enthalpy of the cleaving bond must be smaller than the triplet energy. In-

* Corresponding author. Fax: +81 277 301212.

E-mail address: yamaji@chem.gunma-u.ac.jp (M. Yamaji).

deed the bond enthalpies for the breaking C–Cl, C–S and C–Br bonds in the benzophenone derivatives were smaller than the corresponding triplet energies [20–22] while *p*-hydroxymethylbenzophenone having an enthalpy for the C–O bonding larger than the triplet energy was inert to photodecomposition [20]. Interestingly, with *p*-bromomethylbenzophenone having the C–Br bond, the S₁(n, π^*) state was also shown to be reactive for ω -cleavage [21]. With *p*-benzoylbenzyl phenyl sulfide, the quantum yield for ω -cleavage was shown to depend on the excitation wavelength [22]. The reactivity of ω -bond cleavage seems to be closely related to the spin multiplicity and electronic character of the excited states, bond enthalpies and leaving groups.

In this context, ω -cleavage reactivity of aromatic ketones having the T₁ state of π,π^* character should be our next interest. When a phenyl group is introduced in benzophenone to become phenylbenzophenone, it is known that the electronic character of the T₁ state changes from n,π^*

^{0009-2614/\$ -} see front matter © 2005 Elsevier B.V. All rights reserved. doi:10.1016/j.cplett.2005.09.123

to π,π^* [1]. In the present work, reaction profiles of photoinduced ω -bond dissociation in a phenylbenzophenone derivative having a phenylthiyl moiety as a leaving group, i.e., *p*-phenylbenzoylbenzyl phenyl sulfide (PPS) are investigated by means of laser photolysis and time-resolved EPR (TR-EPR) techniques. Based on the electronic character of the excited and dissociative states of PPS, a schematic energy diagram for the ω -bond dissociation of PPS is illustrated for understanding the photochemical properties of ω -bond dissociation in solution.



2. Experimental

p-Phenylbenzoyl toluene (PBT) was synthesized by usual Friedel-Crafts acylation of toluene with *p*-phenylbenzoyl chloride. PBT was refluxed in CCl_4 in the presence of SO_2Cl_2 and dibenzoyl peroxide, providing 4-(*p*-phenylbenzoyl)benzyl chloride (PBC). *p*-Phenylbenzoylbenzyl phenyl sulfide (PPS) was synthesized by the reaction of PBC with thiophenol in the presence of K_2CO_3 in acetone. PPS was purified by repeated recrystallizations from hexane. Xanthone (XT) was recrystallized from ethanol for purification.

Acetonitirile (ACN), methanol, ethanol, butyronitrile were distilled for purification and used as solvents. ACN and butyronitrile were used for absorption measurements and TR-EPR measurements at 295 K, respectively, while a mixture of methanol and ethanol (1:1 v/v) was for phosphorescence measurement at 77 K.

Absorption and emission spectra were recorded on a Ubest 50 spectrophotometer (JASCO) and a Hitachi F-4010 fluorescence spectrophotometer, respectively.

All the samples for transient absorption measurements were degassed in a quartz cell with a 1 cm path length by several freeze-pump-thaw cycles on a high vacuum line. The concentration of PPS for direct laser photolysis was adjusted to achieve the optical density at the excitation wavelength (266, 308 or 355 nm) being ca. 0.7 in ACN. Transient absorption measurements were carried out at 295 K. A XeCl excimer laser (308 nm, Lambda Physik, Lextra 50) and third (355 nm) and fourth harmonics (266 nm) of a Nd³⁺:YAG laser (JK Lasers HY-500; pulse width 8 ns) were used as light sources for flash photolysis. The number of the repetition of laser pulsing in a sample was less than four pulses to avoid excess exposure. The details of the detection system for the time profiles of the transient absorption have been reported elsewhere [23]. The transient data obtained by laser flash photolysis was

analyzed by using the least-squares best-fitting method. The transient absorption spectra were taken with an USP-554 system from Unisoku with which one can take a transient absorption spectrum with single laser pulse.

The TR-EPR measurements were performed with a Varian E-109E X-band EPR spectrometer without field modulation as reported previously [24]. Transient EPR signals generated by the pulsed laser irradiation were detected by the diode of the EPR spectrometer and transferred to a boxcar integrator (EG&G Model 4121B) for the TR-EPR spectra. The frequency of microwave and the strength of magnetic field were measured by a microwave counter (Echo Electronics EMC-14) and an NMR field meter (Echo Electronics EFM-2000AX), respectively. The third harmonics (355 nm) of the Nd:YAG laser (Quanta-Ray INDI-40-20, Spectra Physics, 20 Hz) was used as the light source. Sample solutions for CIDEP measurements were constantly deoxygenated by Ar gas bubbling and flowed into a guartz cell in the EPR resonator. The TR-EPR measurements were carried out in butyronitrile solution $(5.0 \times 10^{-3} \text{ mol dm}^{-3})$ at 295 K.

3. Results and discussion

Fig. 1 shows absorption and phosphorescence spectra of PPS in ACN at 295 K and in a glass matrix of a mixture of methanol and ethanol (1:1 v/v) at 77 K, respectively. The absorption bands at 290 nm having a molar absorption coefficient of the order of $10^4 \text{ dm}^3 \text{ mol}^{-1} \text{ cm}^{-1}$ can be characterized due to the $S_2(\pi,\pi^*) \leftarrow S_0$ transition while that at 350 nm can be assigned to the $S_1(n,\pi^*)$ band. It was confirmed that the phosphorescence excitation spectrum of PPS agreed well with the corresponding absorption spectrum. The energy level of the lowest triplet (T_1) state of PPS was determined to be $60.4 \text{ kcal mol}^{-1}$ from the phosphorescence origin. The feature of the phosphorescence spectrum of PPS is similar to that of *p*-phenylbenzophenone whose triplet character is known to be of π, π^* [1]. Therefore, the electronic character of the T_1 state of PPS is assigned to be of π,π^* .



Fig. 1. An absorption spectrum of PPS in ACN at 295 K and a phosphorescence spectrum of PPS in a mixture of methanol and ethanol (1:1 v/v) at 77 K.



Fig. 2. Transient absorption spectra observed at 500 ns in degassed ACN (solid) and at 4.8 μ s in aerated ACN (dotted) of PPS after 266 nm laser pulsing at 295 K.

Fig. 2 shows transient absorption spectra observed after 266 nm laser pulsing in degassed and aerated ACN solutions of PPS at 295 K. The transient absorption spectrum at 500 ns obtained in the degassed solution is similar to that of triplet *p*-phenylbenzophenone, and its intensity was accelerated to decrease in the presence of dissolved oxygen. Therefore, the absorption spectrum at 500 ns is ascribed to triplet PPS. The transient absorption spectrum obtained at 4.8 µs after quenching of triplet PPS by dissolved oxygen is similar to that of the phenyl thiyl radical (PTR; $\varepsilon = 2000 \pm 100 \text{ dm}^3 \text{ mol}^{-1} \text{ cm}^{-1}$ at 450 nm [25]). Theses observations indicate that ω -bond dissociation of PPS occurs to produce PTR upon direct excitation, competing with formation of triplet PPS via intersystem crossing. The counter radical of PTR, p-phenylbenzoylbenzyl radical (PBBR) whose absorption spectrum is expected to appear around 320 nm, was not clearly seen in the wavelength region 300–700 nm. Upon 355 and 308 nm laser photolysis of PPS in ACN, it was confirmed that the absorption spectrum of PTR appeared after complete quenching of triplet PPS by dissolved oxygen.

The quantum yield (Φ_{rad}) of the radical formation upon laser pulsing of PPS was determined with the use of Eq. (1).

$$\Phi_{\rm rad} = \Delta A_{450} \varepsilon_{450}^{-1} I_{\rm abs}^{-1}, \tag{1}$$

where ΔA_{450} , ε_{450} and I_{abs} are, respectively, the absorption change at 450 nm after quenching of triplet PPS by dissolved oxygen, the molar absorption coefficient of PTR at 450 nm (2000 dm³ mol⁻¹ cm⁻¹ [25]) and the number of the photon flux of a laser pulse at the excitation wavelength. The quantity of I_{abs} was determined by using the absorption of triplet benzophenone (BP) in ACN as an actinometer [26]

$$\Delta A_{\rm T}^{\rm BP} = \varepsilon_{\rm T}^{\rm BP} \Phi_{\rm ISC}^{\rm BP} I_{\rm abs},\tag{2}$$

where ΔA_T^{BP} , ε_T^{BP} and Φ_{ISC}^{BP} are, respectively, the initial absorbance at 520 nm for the formation of triplet benzophenone obtained immediately after laser pulsing, the molar absorption coefficient of triplet BP at 520 nm in ACN (6500 dm³ mol⁻¹ cm⁻¹ [27]) and triplet yield of BP (1.0 [28]). By using Eqs. (1) and (2), the $\Phi_{\rm rad}$ values were determined to be 0.14 \pm 0.02, 0.15 \pm 0.02 and 0.16 \pm 0.02 upon 266, 308 and 355 nm laser photolyses, respectively. The obtained results show that the $\Phi_{\rm rad}$ value does not depend on the excitation wavelength.

In order to investigate ω -cleavage reactivity in the triplet state of PPS, triplet sensitization by using of xanthone (XT) was carried out. Since the triplet energy of XT (74.0 kcal mol⁻¹ [28]) is larger than that of PPS (60.4 kcal mol⁻¹), efficient triplet energy transfer is possible from triplet XT to PPS. The triplet–triplet absorption peak of XT is located at 625 nm in ACN [22,29]. When 355 nm laser photolysis was carried out in a XT (0.01 mol dm⁻³)-PPS ($5.0 \times 10^{-4} \text{ mol dm}^{-3}$) system, the intensity at 625 nm due to triplet XT decreased with a decay rate (k_{obsd}) of $8.3 \times 10^6 \text{ s}^{-1}$ (see inset in Fig. 3). The transient absorption obtained at 700 ns, when the triplet XT was completely decayed, is shown in Fig. 3. Apparently, the absorption spectrum is due to triplet PPS. After depletion of the triplet absorption spectrum, any transient



Fig. 3. A transient absorption spectrum obtained at 700 ns upon 355 nm laser photolysis of a XT (0.01 mol dm^{-3})-PPS ($5.0 \times 10^{-4} \text{ mol dm}^{-3}$) system in ACN. Inset; a temporal absorbance change at 625 nm for triplet XT.



Fig. 4. The rate (k_{obsd}) for the decay of triplet XT plotted against [PPS] upon 355 nm laser photolysis in XT (0.01 mol dm⁻³)-PPS systems in ACN at 295 K.

absorption was not seen in the wavelength region studied, 350–700 nm. The decay rates, k_{obsd} of triplet XT are plotted as a function of the concentration of PPS, [PPS] in Fig. 4. Since the plots give a straight line, the k_{obsd} can be formulated by:

$$k_{\rm obsd} = k_0 + k_{\rm q} [\rm PPS], \tag{3}$$

where k_0 and k_a , respectively, represent the decay rate of triplet XT in the absence of PPS and the rate constant for quenching of triplet XT by PPS. From the intercept and slope of the line, the values of k_0 and k_q were determined to be $3.5 \times 10^6 \text{ s}^{-1}$ and $8.3 \times 10^9 \text{ dm}^3 \text{ mol}^{-1} \text{ s}^{-1}$. The determined k_q value is close to that $(8.6 \times$ $10^9 \text{ dm}^3 \text{ mol}^{-1} \text{ s}^{-1}$) for XT sensitization of *p*-benzoylbenzyl phenyl sulfide (BBPS) having an ω -dissociative $T_1(n,\pi^*)$ state. We have reported that transient absorption due to triplet BBPS did not appear upon XT sensitization of BBPS [22]. From these observations and considerations, it is inferred that ω -bond dissociation is absent in the $T_1(\pi,\pi^*)$ state of PPS, and concluded that upon direct photo excitation of PPS, ω -cleavage proceeds in the S₁(n, π^*) state of PPS competing with the intersystem crossing to the T_1 state since the Φ_{rad} value for PPS is independent of excitation wavelength. It should be noted that the efficiency (α_{dis}) for ω -cleavage in the triplet state of benzophenone derivatives strongly depends on the electronic character, ${}^{3}(n,\pi^{*})$ or ${}^{3}(\pi,\pi^{*})$.

The above assignment of the reactive state was supported by the TR-EPR result. We tried to detect CIDEP signals from photodecomposed PPS. However, no CIDEP signal was observed upon 355 nm photolysis of PPS, whereas the transient absorption measurements clarified free radical formation. The TR-EPR result strikingly contrasts with that obtained in the photolysis of BBPS. The strong net-emissive CIDEP spectrum due to the triplet mechanism was observed upon photolysis of BBPS [22]. These results indicate that the spin multiplicity in the photocleavage process of PPS is different from that of BBPS. When the C-S bond dissociates in the singlet state of PPS, a singlet π,σ radical pair of PBBR and PTR may be initially produced in a solvent cage according to the spin conservation rule. In singlet radical pairs, geminate recombination is allowed to proceed to reform the parent molecule in the solvent cage. The rate of radical escaping from the solvent cage is considered to be smaller than that $(\sim 10^{10} \text{ s}^{-1} \text{ [30,31]})$ of geminate recombination in solution at 295 K, leading to a low escaping yield from solvent cages $(\Phi_{\rm rad} = 0.15)$. It was impossible to determine the net quantum yield (Φ_{dis}) of the C–S bond dissociation in the S₁ state by nanosecond laser spectroscopy since the geminate recombination between PBBR and PTR would be an event during the laser pulse duration (~ 8 ns) in the present system. The value of Φ_{dis} is estimated to be larger than that of $\Phi_{\rm rad}$ (0.15).

The enthalpy of the C–S bond in PPS, D(C-S) was obtained on the basis of the heat of formation ($\Delta_f H$) for PPS, PBBR and PTR computed by using a semi-empirical PM3

program contained in *MOPAC* '97, being $\Delta_f H(PPS) =$ 77.5 kcal mol⁻¹, $\Delta_f H(PBBR) =$ 76.1 kcal mol⁻¹ and $\Delta_f H$ (PTR) = 56.1 kcal mol⁻¹. The *D*(C–S) value was calculated to be 54.7 kcal mol⁻¹ for PPS by using Eq. (4).

$$\Delta_{\rm f} H({\rm PPS}) = \Delta_{\rm f} H({\rm PBBR}) + \Delta_{\rm f} H({\rm PTR}) - D({\rm C-S}) \tag{4}$$

The obtained value of D(C-S) is close to that (52.7 kcal mol⁻¹) of BBPS [22].

Based on the obtained results, a schematic energy diagram of photoexcited PPS is drawn in Scheme 1 including the C–S bond cleavage processes. The dissociation profile in the excited states of PPS can be interpreted to be a thermally activated crossing with dissociative potential surfaces leading to free radicals. The plausible dissociative potentials are of π,σ^* and π,π^* , and the energy level of the former would be located lower than that of the latter at a reaction coordinate. According to a crossing rule, excited states of π,π^* would correlate with a σ,σ^* state which leads to a pair of σ radicals whereas those of n,π^* would interact



Fig. 5. The energy diagram for the T_1 state and the correlating dissociative potential surface of PPS compared with that of BBPS.

Table 1

Quantum yields (Φ) for radical formation, efficiencies (α_{dis}) for ω -cleavage in the triplet state, triplet energies (E_T), bond enthalpies (D(C–S)) and electronic character of the T₁ states^a

Compound	Φ_{266}	Φ_{308}	Φ_{355}	α_{dis}	$E_{\rm T}~({\rm kcal~mol}^{-1})$	D(C-S) (kcal mol ⁻¹)	T ₁ character
BBPS	0.65	0.64	1.0	1.0	68.4	52.7	n,π*
PPS	0.14	0.15	0.16	0	60.4	54.7	π,π*

^a Data for BBPS are cited from [22].

with a π,σ^* state [32]. With respect to PPS, the $S_1(n,\pi^*)$ state interacts with a singlet π,σ^* potential for the C–S anti-bonding. From the fact that the transient absorption of triplet PPS was obtained upon direct excitation, it is inferred that the ω -cleaving process in the S_1 state of PPS competes with intersystem crossing from the $S_1(n,\pi^*)$ to the $T_1(\pi,\pi^*)$ state, which is an allowed transition according to the El-Sayed rule [33]. Therefore, the intersystem crossing rate of PPS may be as large as that $(1 \times 10^{11} \text{ s}^{-1} \text{ [34]})$ of benzophenone. This estimation is rationalized by the above consideration that the rate of the C–S bond fission competitive with intersystem crossing in the S_1 state may be in the magnitude of 10^{11} s^{-1} .

In the present work, although it is obvious that the ω bond enthalpy $(54.7 \text{ kcal mol}^{-1})$ in PPS is smaller than the triplet energy (60.4 kcal mol^{-1}) of PPS, it is revealed that ω -dissociation does not proceed in the T₁(π,π^*). This may be due to a large energy barrier (ΔE_{dis}) for bond dissociating between the $T_1(\pi,\pi^*)$ and a dissociative ${}^3(\sigma,\sigma^*)$ potential surface. For the case of BBPS having an ω -dissociative $T_1(n,\pi^*)$ having a unity efficiency of ω -fission (α_{dis}), the $\Delta E_{\rm dis}$ value was found to be close to zero [23]. The existence of an energy barrier can be understood by considering the difference in energy levels of triplet states and dissociative potential surfaces for PPS and BBPS (see Fig. 5). By introducing a phenyl group into BBPS, the electronic character of triplet PPS becomes of π,π^* with a lower triplet energy than that of BBPS. A dissociative potential surface, ${}^{3}(\sigma, \sigma^{*})_{PPS}$ of PPS, which can be correlated with $T_1^{\text{PPS}}(\pi, \pi^*)$, is located higher in energy than that $(^{3}(\pi,\sigma^{*})_{BBPS})$ of BBPS. Therefore, PPS has the energy barrier between the triplet state and the dissociative potential, resulting in the triplet state being inert to ω -bond dissociation. In contrast, reactivity of ω-bond cleavage in highly excited triplet states of benzophenone derivatives having C–O bonding at the ω -position was investigated by using twocolor two-laser laser photolysis technique [35]. The C-O bond cleavage was absent in the $S_1(n,\pi^*)$ and $T_1(n,\pi^*)$ states of those compounds, some of which have the triplet energies being greater than the corresponding C–O bond enthalpies, whereas that in phenoxylmethybenzophenone was found in the higher triplet state (T_n) . The difference in ω -cleavage reactivity in the highly excited triplet states was interpreted also in terms of energy barriers for electronic delocalization between the aromatic carbonyl moiety and the leaving group. It seems to be crucial for occurrence of ω -cleavage in any excited states that excited energy is efficiently distributed from the aromatic carbonyl moiety to the ω -bond according to a crossing rule (avoided crossing) [32].

4. Conclusion

By means of TR-EPR and laser flash photolysis techniques, ω -bond cleavage of PPS is characterized, and photochemical properties obtained are summarized in Table 1 along with those of BBPS. ω -Bond dissociation in PPS occurs only in the S₁(n, π^*) state independent of excitation wavelengths with a radical yield, Φ_{rad} of 0.15. Due to a large energy barrier between the T₁(π , π^*) and the ³(σ , σ^*) potential surfaces, ω -cleavage is absent in the T₁(π , π^*) state of PPS. It is considered that energy barriers for distributing the excited energy from the aromatic carbonyl moiety to the anti-bonding orbital of the leaving group may control the reactivity of ω -bond dissociation independent of electronic character of the excited states.

Acknowledgments

This work was supported by a Scientific Research Grant-in-Aid from the Ministry of Education, Culture, Sports, Science and Technology of Japan.

References

- N.J. Turro, Modern Molecular Photochemistry, Benjamin/Cummings Publishing Co, Menlo Park, CA, 1978.
- [2] H. Shizuka, Bull. Chem. Soc. Jpn. 41 (1968) 2343.
- [3] H. Shizuka, I. Tanaka, Bull. Chem. Soc. Jpn. 42 (1969) 52.
- [4] P.J. Wagner, Acc. Chem. Res. 4 (1971) 168.
- [5] F.D. Lewis, C.H. Hoyle, J.G. Magyar, J. Org. Chem. 40 (1975) 488.
- [6] G. Brunton, H.C. McBay, K.U. Ingold, J. Am. Chem. Soc. 99 (1977) 4447.
- [7] J.C. Scaiano, M.J. Perkins, J.W. Sheppard, M.S. Platz, R.L. Barcus, J. Photochem. 21 (1983) 137.
- [8] J.C. Netto-Ferreira, W.J. Leigh, J.C. Scaiano, J. Am. Chem. Soc. 107 (1985) 2617.
- [9] J.C. Scaiano, J.C. Netto-Ferreira, J. Photochem. 32 (1986) 253.
- [10] P.J. Wagner, M.J. Lindstrom, J. Am. Chem. Soc. 109 (1987) 3062.
- [11] W.G. McGimpsey, J.C. Scaiano, Can. J. Chem. 66 (1988) 1474.
- [12] J.C. Netto-Ferreira, I.G.J. Avellar, J.C. Scaiano, J. Org. Chem. 55 (1990) 89.
- [13] J.C. Scaiano, J.C. Netto-Ferreira, V.J. Wintgens, Photochem. Photobiol. A: Chem. 59 (1991) 265.
- [14] M. Hall, L. Chen, C.R. Pandit, W.G. McGimpsey, J. Photochem. Photobiol. A: Chem. 111 (1997) 27.
- [15] Y. Kaneko, S. Hu, D.C. Neckers, J. Photochem. Photobiol. A: Chem. 114 (1998) 173.
- [16] S. Jockusch, M.S. Landis, F. Beat, N.J. Turro, Macromolecules 34 (2001) 1619.

- [17] T. Suzuki, Y. Kaneko, K. Maeda, T. Arai, K. Akiyama, S. Tero-Kubota, Mol. Phys. 100 (2002) 1469.
- [18] X. Allonas, J. Lalevée, J.-P. Fouassier, J. Photochem. Photobiol. A: Chem. 159 (2003) 127.
- [19] T. Suzuki, Y. Kaneko, M. Ikegami, T. Arai, Bull. Chem. Soc. Jpn. 77 (2004) 801.
- [20] M. Yamaji, T. Yoshihara, T. Tachikawa, S. Tero-Kubota, S. Tobita, H. Shizuka, B. Marciniak, J. Photochem. Photobiol. A: Chem. 162 (2004) 513.
- [21] M. Yamaji, A. Suzuki, F. Ito, S. Tero-Kubota, S. Tobita, H. Shizuka, B. Marciniak, J. Photochem. Photobiol. A: Chem. 170 (2005) 253.
- [22] M. Yamaji, S. Inomata, S. Nakajima, K. Akiyama, S. Tobita, B. Marciniak, J. Phys. Chem. A 109 (2005) 3843.
- [23] M. Yamaji, Y. Aihara, T. Itoh, S. Tobita, H. Shizuka, J. Phys. Chem. 98 (1994) 7014.
- [24] S. Tero-Kubota, K. Akiyama, T. Ikoma, Y. Ikegami, J. Phys. Chem. 95 (1991) 766.
- [25] M. Yamaji, S. Wakabayashi, S. Ueda, H. Shizuka, S. Tobita, Chem. Phys. Lett. 368 (2003) 41.

- [26] M. Yamaji, T. Sekiguchi, M. Hoshino, H. Shizuka, J. Phys. Chem. 96 (1992) 9353.
- [27] R.V. Bensasson, J.C. Gramain, J. Chem. Soc., Faraday Trans. 76 (1980) 1801.
- [28] S.L. Murov, I. Carmichael, G.L. Hug, Handbook of Photochemistry, second edn., Revised and Expanded., Mercel Dekker, New York, 1993.
- [29] H. Okamoto, M. Yamaji, K. Satake, S. Tobita, M. Kimura, J. Org. Chem. 69 (2004) 7860.
- [30] T.W. Scott, S.N. Liu, J. Phys. Chem. 93 (1989) 1393.
- [31] Y. Hirata, Y. Niga, M. Ohta, M. Takizawa, T. Okada, Res. Chem. Intermed. 21 (1995) 823.
- [32] W.G. Dauben, L. Salem, N.J. Turro, Acc. Chem. Res. 8 (1975) 41.
- [33] S.K. Lower, M.A. El-Sayed, Chem. Rev. 66 (1966) 199.
- [34] H. Miyasaka, K. Morita, K. Kamata, N. Mataga, Bull. Chem. Soc. Jpn. 63 (1990) 3358.
- [35] X. Cai, M. Sakamoto, M. Yamaji, M. Fujitsuka, T. Majima, J. Phys. Chem. A 109 (2005) 5989.