The Fast Photochemical [2+2] Cycloaddition and Reverse Reaction of a Styrylpyrazine Amphiphile in Aqueous Dispersion

Jong-mok Park, Wanbin Zhang, Yohji Nakatsuji, Tetsuro Majima,† and Isao Ikeda*
Department of Applied Chemistry, Faculty of Engineering, Osaka University, 2-1 Yamadaoka, Suita, Osaka 565-0871
†The Institute of Scientific and Industrial Research, Osaka University, 8-1 Mihogaoka, Ibaraki, Osaka 567-0047

(Received September 9, 1999; CL-990777)

Photochemical [2+2] cycloaddition of styrylpyrazine amphiphile **1** in aqueous dispersion occurred quantitatively and much faster than that of stilbene analogue **2**. Amphiphile **1** showed intermolecular photoreversible reactivity, [2+2] cycloaddition and the reverse reaction, in aqueous dispersion with alternate irradiation at above 300 and at 254 nm as the first example for 1,2-diarylethylene in aqueous dispersion.

Photochemical [2+2] cycloaddition of 1,2-diarylethylenes,[1] especially stilbene, embedded in the hydrophobic chain of amphiphilic compounds in organized assemblies, e.g., monolayers, supported multilayers, and bilayer membranes, has been extensively studied because their reactivities can be controlled by a molecular-level geometry of the chromophores in such aggregates. In addition, the photochemical reversible reaction, [2+2] cycloaddition and the reverse reaction, of oriented chromophores in aggregates with alternate irradiation at two independent wavelengths has attracted much attention due to the possibility of its application to photomemory and on-off photoswitching systems. Although this photochromism has been well described for cinnamic acid analogues[2] and anthracene derivatives,[3] there are few reports with regard to 1,2-diarylethylenes.[1c] For realizing high performance of such devices, it should be indispensable that the photochemical reactivity is sufficiently high and selective. However, it has been recognized that stilbene amphiphiles show low photochemical [2+2] cycloaddition reactivity in multilayer assemblies[1b] and in some aqueous dispersions.[1e] And the reverse photoreaction has not been reported.

Our recent attention has been focused on the development of an amphiphile containing 1,2-diarylethylenes showing photochemical reversibility in bilayer membranes because of its availability in controlling the release of entrapped reagents in vesicles. In this paper, we describe the photochemical [2+2] cycloaddition of sodium ethyl 5-[2-(4-hexadecyloxyphenyl)ethenyl]-2-pyrazinylmethylphosphonate **1** in aqueous dispersion with irradiation at above 300 nm and the reverse reaction with irradiation at 254 nm.

Compound **1** and the stilbene analogue **2** with structures as shown in Scheme 1 revealed a single endothermic peak at 64 and 53 °C, respectively, on their DSC thermograms, which correspond to the gel to liquid crystal phase transition for bilayer membranes. This result suggests that the intermolecular interaction of **1** is stronger than that of **2** in the aggregates.

The UV-vis absorption spectrum of **1** in methanol possessing peaks at λ_{max} = 298 and 345 nm, which were well consistent with that of 2-styrylpyrazine in acetonitrile solution,[4] was changed to a spectrum possessing peaks at λ_{max} = 285 and 338 nm with overall blue-shift in the aqueous dispersion obtained by sonication, as shown in Figure 1a. The spectrum of **2** in methanol possessing peaks at λ_{max} = 306 and 322 nm was also blue-shifted to possess a peak at λ_{max} = 283 nm in aqueous dispersion, as shown in Figure 1c. The blue-shifts of the absorption spectra in the bilayer assembly are ascribed to the H-aggregation of the chromophores.[5]

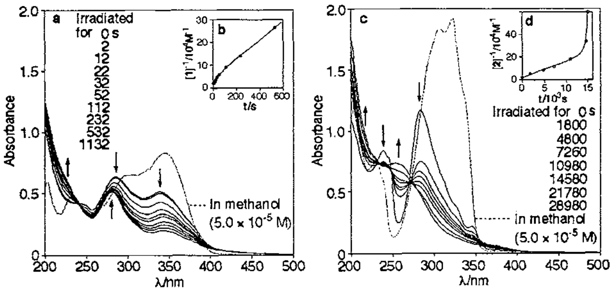
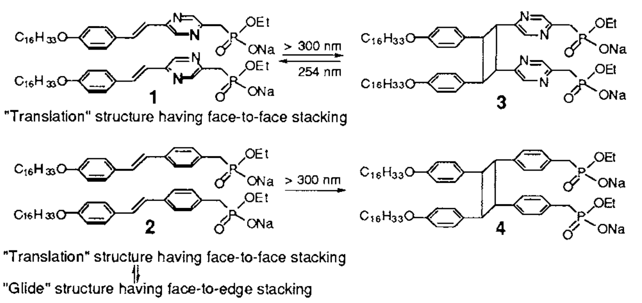


Figure 1. Electronic absorption spectra of **1** (a) and **2** (c) in aqueous dispersion (5.0 × 10^{-5} M) during the irradiation at >300 nm. Second-order kinetics of **1** (b) and **2** (d) calculated from the decrease of the absorbance at 338 nm in (a) and 283 nm in (c), respectively.

The photochemical reactivities of **1** and **2** in aqueous dispersion with irradiation at above 300 nm were examined by means of ^{1}H-NMR, UV-vis spectroscopy, and FABMS spectrometry. The aqueous dispersion of **1** (0.0125 M) or **2** (0.0089 M) obtained by sonication was irradiated under Ar atmosphere with a 500-W Xenon short-arc lamp through a pyrex glass for 2 or 4 h, respectively. ^{1}H-NMR measurements were conducted in CD_3OD after removing the water *in vacuo*.

In the case of **1**, two olefinic doublets (δ 7.63, 7.08) disappeared completely upon irradiation for 2 h, and two new symmetrical cyclobutane AA'BB' multiplets centered at 4.69 and 4.60 ppm appeared. The FABMS spectrum gave a peak of 1133 for [M+H] corresponding to the dimer. This compound was assigned to a syn head-to-head dimer (**3** in Scheme 1) based on the NMR studies of substituted cyclobutanes.[1c,1d,6] In the case of **2**, however, only 40% of the monomers were converted to the corresponding syn head-to-head dimer (**4** in Scheme 1) with even longer irradiation than in the case of **1**, for 4 h. The structure of this product was also determined by considering two symmetrical cyclobutane AA'BB' multiplets[6a,7] centered at 4.33 and 4.31 ppm and the FABMS spectrum having a peak of 1129 for [M+H] corresponding to the dimer. It is known that a mixture of *trans*-, *cis*-monomers and dimers is given in the photolysis of stilbene and azastilbenes[6b] in solution with irradiation (350 nm) at higher concentration than in the present study. Therefore, the selective dimerization in the present photoreactions of **1** and **2** in aqueous dispersion is ascribed to self-aggregation of amphiphiles **1** and **2**.

The dimerization kinetics of **1** and **2** were evaluated from the decrease of the absorbance at 338 and 283 nm, respectively, during the irradiation (Figures 1a, c). The disappearance of **1** was fairly consistent with second-order kinetics[1e,8] (the initial rate



Scheme 1.

constant: 828 $M^{-1}s^{-1}$, Figure 1b). On the other hand, the rate constant for the disappearance of **2** (the initial rate constant: 12 $M^{-1}s^{-1}$) was increasingly accelerated during the course of the irradiation (Figure 1d). The initial rate of **1** was 69 times faster than that of **2**. It is difficult to explain the remarkable difference in the initial rate only by considering the difference in the total absorption because the total absorption of **1** from 300 to 500 nm was merely 1.5 times that of **2**. Interestingly, the kinetic behavior of **2** was very similar to that of styrylthiophene amphiphiles reported by Whitten *et al.*[1d] They proposed that the low reactivity of aqueous dispersion of their amphiphiles is ascribed to the equilibration between the "glide" structure having face-to-edge stacking and the "translation" structure having face-to-face stacking, as shown in Scheme 1. They also pointed out that the acceleration of dimerization at moderate to high conversions is due to the collapse of "aggregate" excited states to "excimer". Thus, the kinetic behavior of **1** completely different from that of **2** suggests that these amphiphiles possess different stacking modes in aggregate. Based on Whitten's proposal, it is reasonably explained that amphiphile **1** forms aggregates with a "translation" structure having face-to-face stacking in aqueous dispersion, and that the dimerization of **1** in aggregates is a topochemically controlled reaction with little structural change during the photocycloaddition although no direct evidence is available at present.

This speculation on the dimerization kinetics may be supported by the multipole character of the pyrazine group of **1**. The calculation of partial charges on each atom by using INDO/S showed that the N atoms in the pyrazine group have large negative charge and C atoms have positive charge. Therefore, styrylpyrazine amphiphile **1** is expected to show much stronger interaction between the neighboring chromophores than stilbene amphiphile **2** through the multipole-multipole interaction[9] of the pyrazine moiety when **1** possesses a stacking mode as indicated in Scheme 1. This may be the main reason for formation of the "translation" structure of **1** in aqueous dispersion.

To investigate the photochromism of **1** and **2**, after irradiation at above 300 nm, additional irradiation at 254 nm was followed since the dimer **3** and **4** have relatively large absorption around 250 nm. Upon irradiation of **1** at above 300 nm for 3.0 min, the spectrum **a** changed to **b** (Figure 2A). And then the spectrum **b** changed to **c** with irradiation at 254 nm for 1.5 min. This irradiation cycle was conducted twice to change to **d** and **e** in turn. This spectral behavior is attributed to the photoreversible reaction between the photocycloaddition and photocycloreversion. However, a gradual decrease of reversibility with the repetition of the irradiation cycle was observed. This may be ascribed to side-reactions like *trans-cis* isomerization and intramolecular cyclization through the *cis*-isomer[1e] upon irradiation at 254 nm. In fact, the photostationary state composed of *trans*- (50%), *cis*-**1** (10%), and the cyclobutane dimer **3** (40%) was observed in a mixed dispersion of dimer **3** with L-α-dipalmitoyl phosphatidylcholine upon irradiation at 254 nm by ^{1}H-NMR. A similiar decrease of photochromism reproducibility had been also observed in an LB film of cinnamylideneacetic acid[2b] and in self-assembled monolayers of coumarin[2c] and anthracene.[3] This is the first case of an intermolecular reversible reaction of 1,2-diarylethylene in aqueous dispersion. On the other hand, the aqueous dispersion of **2** did not show photochemical reversibility under the same conditions (Figure 2B), although the reason for this is not clear at present.

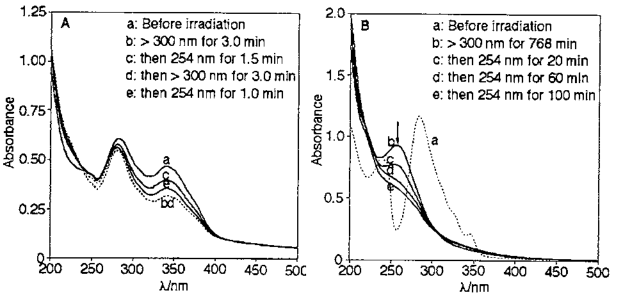


Figure 2. (A) Electronic absorption spectra of **1** (5.0×10^{-5} M) in aqueous dispersion: (a) before irradiation; (b) after irradiation for 3.0 min at >300 nm; (c) after irradiation of (b) for 1.5 min at 254 nm; (d) after irradiation of (c) for 3.0 min at >300 nm; (e) after irradiation of (d) for 1.0 min at 254 nm. (B) Electronic absorption spectra of **2** in aqueous dispersion (5.0×10^{-5} M) during the irradiation at 254 nm.

In conclusion, we have found the fast and topochemically-controlled photochemical [2+2] cycloaddition and the reverse reaction occurred in the bilayer membrane of the styrylpyrazine amphiphile. The application of this system for the release control of entrapped substances in vesicles is now under progress in our laboratory.

References and Notes

1 a) D. G. Whitten, *Acc. Chem. Res.*, **26**, 502 (1993). b) W. F. Mooney, P. E. Brown, J. C. Russell, S. B. Costa, L. G. Pedersen, and D. G. Whitten, *J. Am. Chem. Soc.*, **106**, 5659 (1984). c) F. H. Quina and D. G. Whitten, *J. Am. Chem. Soc.*, **99**, 877 (1977). d) X. Song, J. Perlstein, and D. G. Whitten, *J. Phys. Chem. A*, **102**, 5440 (1998). e) M. Shimomura, H. Hashimoto, and T. Kunitake, *Langmuir*, **5**, 174 (1989).

2 a) H. Tanaka and K. Honda, *J. Polym. Sci., Polym. Chem. Ed.*, **15**, 2685 (1977). b) A. Yabe, Y. Kawabata, A. Ouchi, and M. Tanaka, *Langmuir*, **3**, 405 (1987). c) W. Li, V. Lynch, H. Thompson, and M. A. Fox, *J. Am. Chem. Soc.*, **119**, 7211 (1997).

3 M. A. Fox and M. D. Wooten, *Langmuir*, **13**, 7099 (1997).

4 N. M. Peachey and C. J. Eckhardt, *J. Phys. Chem.*, **98**, 685 (1994).

5 M. Kasha, *Radiat. Res.*, **20**, 55 (1963).

6 a) D. A. Ben-Efraim and B. S. Green, *Tetrahedron*, **30**, 2357 (1974). b) J. Vansant, S. Toppet, G. Smets, J. P. Declercq, G. Germain, and M. V. Meerssche, *J. Org. Chem.*, **45**, 1565 (1980). c) H. Nakanishi, K. Ueno, and M. Hasegawa, *Chem. Lett.*, **1972**, 301. d) M. Hasegawa, Y. Endo, M. Aoyama, and K. Saigo, *Bull. Chem. Soc. Jpn.*, **62**, 1556 (1989).

7 a) B. S. Green and L. Heller, *J. Org. Chem.*, **39**, 196 (1974). b) H. Shechter, W. J. Link, and G. V. D. Tiers, *J. Am. Chem. Soc.*, **85**, 1601 (1963). c) H. Ulrich, D. V. Rao, F. A. Stuber, and A. A. R. Sayigh, *J. Org. Chem.*, **35**, 1121 (1970).

8 Although the kinetics in microheterogeneous medium is not simple, we adopted the second-order kinetics to compare the photo-dimerization rate of **1** and **2** in aqueous dispersion.

9 K. Takehara, Y. Oozono, S. Oda, K. Isomura, and H. Taniguchi, *Chem. Lett.*, **1990**, 5.