ZnTPPS-Sensitized Photodebromination of 2,3-Dibromo-3-phenylpropionic Acids. Electron Transfer Initiated Chain Debromination

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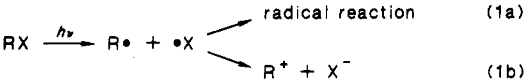
Photodebromination of 2,3-dibromo-3-phenylpropionic acids (1) sensitized with zinc tetrasodium tetrakis(sulfonatophenyl)porphyrin (ZnTPPS) has been studied in the presence of triethanolamine (TEOA) as a sacrificial reductant. An efficient debromination took place with ZnTPPS, giving cinnamic acids (or their sodium salts) in aqueous or CH_3CN solution. Electron-withdrawing substituents on the phenyl ring of the acids promote the debromination, log Φ being correlated with their reduction potentials. A similar free-energy relationship between 1 and excited metallo tetrasodium tetrakis(sulfonatophenyl)porphyrin (MTPPS; M = Sn, Cd, Zn, and H_2) implies that the reaction is initiated by a one-electron transfer from the excited ZnTPPS to dibromide. A laser flash photolysis study shows that the excited triplet porphyrin is reductively quenched by 1 with quenching rate constant $k_q = (6.5 \pm 0.2) \times 10^5\ M^{-1}\ s^{-1}$, giving $ZnTPPS^+$ and $1^{\bullet -}$. A radical chain propagation is involved in the debromination, thus leading to a quantum efficiency higher than unity with higher concentrations of TEOA or 1.

Much attention has been focused on photochemical dehalogenation of organic halides in connection with related electrochemical and thermal reactions.[1-4] For instance, the direct irradiation of aromatic and aliphatic halides results in the homolysis of the carbon–halogen bond to yield carbon and halogen radicals, which is sometimes followed by an electron transfer between the two radicals, leading to the formation of carbonium ion and halide ion (eq 1).[5] The electron-transfer step is evidenced by the formation of substitution and/or rearranged products typical of carbonium ion intermediates.[6] Sometimes, radical chain substitutions (i.e., S_{RN} reactions) take place as another type of interesting photoinitiated reaction, when an electron donor reduces excited RX* into $RX^{\bullet -}$ in the presence of a suitable nucleophile, Nu^- (eq 2 and 3).[7] Alternatively, a one-electron transfer from an excited electron donor (e.g., NADH) is shown to induce a radical chain debromination of benzyl bromide.[8]



$$RX^{\bullet -} + Nu^- \rightarrow RNu^{\bullet -} + X^- \qquad (2)$$

$$RNu^{\bullet -} + RX \rightarrow RNu + RX^{\bullet -} \qquad (3)$$

1,2-Dihalides are more susceptible to one-electron reduction and are easily dehalogenated. Recently it has been shown that the debromination of 1,2-dibromides to olefins is induced by an electron transfer from alkylviologen radical cation generated by $Ru(bpy)_3^{2+}$ photosensitization.[9] However, to the best of our knowledge, no example has been reported concerning a photosensitization system of direct electron transfer from a sensitizer to dihalides. We have also been interested in the effect of the electric charges of sensitizer and substrates on such a sensitized dehalogenation because electrostatic interaction between a sensitizer (D) and an electron acceptor (A) has been claimed to play a significant role for the forward and back electron transfers (eq 4).

$$D + A \xrightleftharpoons{h\nu/\text{electron transfer}} D^+ + A^- \qquad (4)$$

We chose a system composed of zinc tetrasodium tetrakis(*p*-sulfonatophenyl)porphyrin (ZnTPPS) as a sensitizing donor and 2,3-dibromo-3-phenylpropionic acid (1) as an electron acceptor, the formal charge of the latter being controlled by a change of pH. Herein, we report a radical chain debromination, initiated by an electron transfer from the triplet porphyrin to the dibromide, in the presence of triethanolamine (TEOA).

Experimental Section

Materials. *erythro*-2,3-Dibromo-3-phenylpropionic acid (**1b**) [*RS*-(2*l*,3*u*)-2,3-dibromo-3-phenylpropanoic acid][10b] was prepared from *trans*-cinnamic acid according to the literature method.[10a] The corresponding threo isomer 3 was obtained by the addition of Br_2 to allocinnamic acid prepared by photochemical isomerization of cinnamic acid.[11] After repeated fractional recrystallizations from hexane, the threo isomer was shown to be essentially free from its erythro isomer or allocinnamic acid on the basis of HPLC analyses. 2-Bromo-3-phenylpropenoic acid (4) was prepared by the NH_3-catalyzed dehydrobromination of methyl *erythro*-2,3-dibromo-3-phenylpropionate (*erythro*-**1c**), mp 130–132

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(1) (a) Collins, R. F. *Chem. Ind.* (*London*) **1957**, 704. (b) Cromwell, N. H.; Foster, P. W.; Wheeler, M. M. *Chem. Ind.* (*London*) **1959**, 220.

(2) (a) Beichl, G. J.; Colwell, J. E.; Miller, J. G. *Chem. Ind.* (*London*) **1960**, 203. (b) Williams, H. *Chem. Ind.* (*London*) **1960**, 900. (c) Bunce, N. J. *J. Org. Chem.* **1982**, *47*, 1948. (d) Siegman, J. R.; Hansen, J. J. *J. Org. Chem.* **1982**, *47*, 2773.

(3) (a) Foster, R. W. *Chem. Ind.* (*London*) **1960**, 1354. (b) Stevenson, D. P.; Coopinger, G. M. *J. Am. Chem. Soc.* **1962**, *84*, 149.

(4) Takagi, K.; Ogata, Y. *J. Org. Chem.* **1983**, *48*, 1966.

(5) (a) Cristol, S. J.; Mayo, G. O.; Lee, G. A. *J. Am. Chem. Soc.* **1969**, *91*, 214. (b) Cristol, S. J.; Stull, D. P.; Daussin, R. D. *J. Am. Chem. Soc.* **1978**, *100*, 6674. (c) Pienta, N. J.; Kropp, P. J. *J. Am. Chem. Soc.* **1978**, *100*, 655. (d) Purohit, P. C.; Sonawane, H. R. *Tetrahedron* **1980**, *37*, 873. (e) Cristol, S. J.; Strom, R. M. *J. Am. Chem. Soc.* **1980**, *102*, 5577.

(6) (a) Cristol, S. J.; Strom, R. M. *J. Am. Chem. Soc.* **1979**, *101*, 5707. (b) Cristol, S. J.; Opitz, R. J.; Bindel, T. H.; Dickenson, W. A. *J. Am. Chem. Soc.* **1980**, *102*, 7977. (c) Morrison, H.; Miller, A. *J. Am. Chem. Soc.* **1980**, *102*, 372. (d) Izawa, Y.; Takeuchi, M.; Tomioka, H. *Chem. Lett.* **1983**, 1297. (e) Cristol, S. J.; Dickenson, W. A.; Stanko, M. *J. Am. Chem. Soc.* **1983**, *105*, 1218.

(7) Julliard, M.; Chanon, M. *Chem. Rev.* **1983**, *83*, 425 and references therein.

(8) Fukuzami, S.; Hironaka, K.; Tanaka, T. *J. Am. Chem. Soc.* **1983**, *105*, 4722.

(9) (a) Goren, Z.; Willner, I. *J. Am. Chem. Soc.* **1983**, *105*, 7764. (b) Endo, T.; Saotome, Y.; Okawara, M. *J. Am. Chem. Soc.* **1984**, *106*, 1124. (c) Maiden, R.; Goren, Z.; Becker, J. Y.; Willner, I. *J. Am. Chem. Soc.* **1984**, *106*, 6217.

(10) (a) Grovenstein, E., Jr.; Lee, D. E. *J. Am. Chem. Soc.* **1953**, *75*, 2643. (b) Named according to the Brewster recommendation: Brewster, J. H. *J. Org. Chem.* **1986**, *51*, 4751.

(11) Grovenstein, E., Jr.; Theophilov, P. S. *J. Am. Chem. Soc.* **1955**, *77*, 3797.

°C (lit.[12] mp 131–132 °C). 3-Bromo-3-phenylpropenoic acid was obtained by the addition of HBr to phenylpropiolic acid.[13] Other *erythro*-2,3-dibromo-3-(aryl)propionic acids (i.e., *p*-tolyl,[14] *m*-bromophenyl,[15] and *m*-nitrophenyl[16]) were prepared according to the literature methods. Cetyltrimethylammonium bromide (CTAB) of the extra pure grade of Wako Pure Chemicals was used without further purification. Zinc tetrasodium tetrakis(*p*-sulfonatophenyl)porphyrin (ZnTPPS) was prepared by sulfonation of *meso*-tetraphenylporphyrin (H_2TPP) with concentrated H_2SO_4 followed by treatment with zinc acetate[17a] and purified by passing through a Sephadex G-50 column (Pharmacia Fine Chemicals) with distilled water as an eluent; ZnTPPS, $\lambda_{max}^{H_2O}$ 421, 555, and 595 nm. Similarly, CdTPPS and Sn^{IV}TPPS were prepared according to the reported methods;[17b] CdTPPS, $\lambda_{max}^{H_2O}$ 428, 567, and 607 nm; Sn^{IV}TPPS, $\lambda_{max}^{H_2O}$ 413, 549, and 588 nm. Triethanolamine (TEOA) of the extra-pure grade (Wako Pure Chemicals) was used as received.

Typical Photolysis. An aqueous solution (3 mL) of 6.7 mM sodium *erythro*-2,3-dibromo-3-phenylpropionate (**1a**), 0.12 mM ZnTPPS, and 12 mM TEOA was placed in a 1 cm × 1 cm cuvette and degassed by more than three freeze–thaw cycles ($<10^{-4}$ mmHg) or flushed by an argon stream for 30 min. The solution was photolyzed through a Corning filter 0–51 (to cut light below 355 nm) with a 150-W tungsten halogen lamp (Sylvania). Sodium cinnamate was obtained in a yield of 70% based on charged **1a** for 35-min irradiation. The absorbance of the sensitizer at the Soret band (421 nm) was >1.6. No degradation of the sensitizer occurred during the irradiation as judged by the absorbance at 421 nm. The progress of the photochemical debromination was monitored by the growth of the absorbance at around 267 nm due to cinnamate [$\lambda_{max}^{H_2O}$ 267 nm (ϵ 19 000)] by using a Hitachi 124 UV spectrophotometer. No cinnamate was observed to form on standing for 290 min at room temperature in the dark reaction of the dibromide with ZnTPPS or TEOA.

Sodium *threo*-2,3-dibromo-3-phenylpropionate (**3a**) was irradiated under reaction conditions identical with those in the case of the erythro isomer. The reaction solution after irradiation for 275 min consisted of sodium cinnamate (**2a**, trans, 9.5%), sodium allocinnamate (cis, 0.2%), and the recovered starting dibromide (90.3%). None of these products were observed under similar conditions in the absence of the light. Products were analyzed by means of a Yanagimoto GLC apparatus (Carbowax 300M) and/or a JASCO Twinkle HPLC instrument using a reversed-phase column (ODS, Fine Sil C_{18}-10) with a mixture of aqueous NaH_2PO_4 solution (pH 7.6) and methanol (2/1 in vol) as eluent. The products were monitored at 267 nm with a UV detector, and the results are shown in the text.

Irradiation of a solution of 6.7 mM **1b**, 12 mM TEOA, 2.4 μM ZnTPPS, and 130 mM toluene in 75% aqueous CH_3CN with light of >355 nm for 60 min resulted in the formation of **2b** (26%) accompanied by bibenzyl (0.6%) (based on the starting dibromide). The control experiment under similar conditions without toluene gave **2b** (62%) as the only observable product.

Reduction Potentials. Reduction potentials of substituted and unsubstituted 2,3-dibromo-3-phenylpropionic acids were measured on a Yanaco polarographic analyzer (type P-1100) with a hanging mercury drop electrode as a working electrode. A 25% aqueous CH_3CN solution of sodium salts of the dibromide ($\sim 10^{-4}$ M) containing 0.1 M tetraethylammonium perchlorate (TEAP) was bubbled with N_2 gas for 10 min and measured at a scanning range of −0.7 to −2.7 V vs SCE.

Quantum Yield Determinations. A potassium ferrioxalate actinometer[18] was used for the determinations of quantum yields on the photochemical debromination sensitized by ZnTPPS. The actinometry experiments were carried out with a monochromatized light (426 ± 10 nm) from a 150-W xenon lamp (a Hitachi fluorescence spectrophotometer, type 650-10). The incident light intensity was evaluated as 1.36×10^{-8} einstein/min. The amounts of the photolysis products were monitored by the UV spectrophotometer as described above.

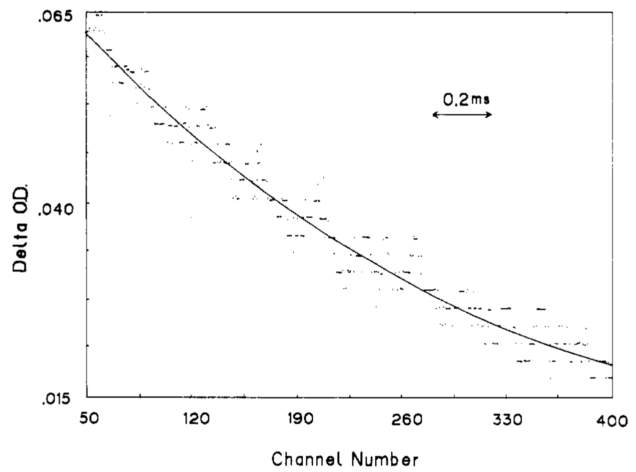

Figure 1. The computer-fitted single exponential decay of absorbance at 840 nm after its generation by a laser flash at 590 nm of an aqueous solution of 0.2 mM ZnTPPS and 40 mM **1a**: (·) experimental results; (—) computer fitting with $k_q = (6.5 \pm 0.2) \times 10^5$ M^{-1} s^{-1}.

Fluorescence Quenching Study. Fluorescence measurements were carried out with the fluorescence spectrophotometer described above. A quenching study of the porphyrin fluorescence was performed by using the dibromides **1** as quenchers. Relative fluorescence intensities of ZnTPPS at 608 nm were measured in aqueous solutions containing ZnTPPS and **1** of various concentrations; the intensities decreased with the increase in the dibromide concentration. The shape of the absorption or fluorescence spectrum of ZnTPPS was not changed by the addition of the dibromide, indicating no interaction of ZnTPPS with the quencher in the ground state.

Measurements of the Lifetimes of Excited ZnTPPS*. (A) The Excited Singlet State. The lifetimes of excited singlet ZnTPPS were measured on a Horiba time-resolved fluorescence spectrophotometer (type NAES-1100). The singlet lifetimes were determined by integrating the fluorescence intensities at over 460 nm (with a HOYA Y-46 cut filter) with a 426-nm excitation of 2.4 μM ZnTPPS in aqueous solution containing 12 mM TEOA and various concentrations (0–6 mM) of dibromide **1** under the degassed conditions. The lifetime τ of ZnTPPS^{*1} in the presence of a quencher Q is expressed as eq 5,[19] where τ_0 denotes the lifetime

$$1/\tau = 1/\tau_0 + k_q[Q] \qquad (5)$$

in the absence of Q,[20] and k_q represents the quenching rate constant.

(B) The Excited Triplet State. The dependence of the excited triplet lifetime of ZnTPPS^{*3} on the quencher concentration obeys eq 5 similarly. The lifetime of ZnTPPS^{*3} in the presence of **1** was measured on an Applied Photophysics laser kinetic spectrometer employing a laser beam emitting at 590 or 532 nm. For this purpose, a Lambda Physics FL 2002 dye laser, pumped by a Lambda Physics EMG 50 XeCl excimer laser or a Nd:YAG laser (Quanta-Ray PHS-1 prism harmonic separator), was used at 590 nm (Rhodamin 6G) or 532 nm, respectively. The analytical laser beam was carefully aligned to achieve good overlap with the exciting laser beam. Aqueous solutions containing 0.2 mM ZnTPPS and various amounts of the dibromide **1** were degassed in 1-cm cuvettes by the three freeze–thaw cycles, sealed,

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(12) Urushibara, Y.; Hirota, M. *Nippon Kagaku Zasshi* **1961**, *82*, 88.

(13) Wilson, M. A. *J. Org. Chem.* **1939**, *4*, 128.

(14) Wilson, M. A.; Woodgate, P. D. *J. Chem. Soc., Perkin Trans. 2* **1976**, 141.

(15) Buckles, R. E.; Hausman, E. A.; Wheeler, N. G. *J. Am. Chem. Soc.* **1950**, *72*, 2494.

(16) Trumbull, E. R.; Finn, R. T.; Ibene-Rasa, K. M.; Saners, C. K. *J. Org. Chem.* **1963**, *28*, 1907.

(17) (a) Shivastava, T. S.; Tsutsui, M. *J. Org. Chem.* **1973**, *38*, 2103. (b) Herrmann, O.; Mehdi, S. H.; Corsino, A. *Can. J. Chem.* **1978**, *56*, 1084.

(18) Hatchard, C. G.; Parker, C. A. *Proc. R. Soc. London, A* **1956**, *235*, 518.

(19) (a) Turro, N. J. *Modern Molecular Photochemistry*; Benjamin: Menlo Park, CA, 1978; p 121. (b) Balzani, V.; Moggi, L.; Manfrin, M. F.; Bolleta, F. *Coord. Chem. Rev.* **1975**, *15*, 321.

(20) The observed lifetime of the excited singlet ZnTPPS^{*1}, 1.7 ns, is in good agreement with the reported one.[21]

(21) Kalyanasundaram, K. *J. Chem. Soc., Faraday Trans. 2* **1983**, *79*, 1365.

Table I. Quantum Yields for ZnTPPS-Sensitized Debromination of 2,3-Dibromo-3-arylpropionic Acids[a]

	$ArCHBrCHBrCO_2R$[b]			
no.	Ar	R	solvent	quantum yield[c]
1a	C_6H_5	Na	H_2O	0.11 ± 0.02
1a	C_6H_5	Na	H_2O	0.12 ± 0.02[d]
3a[e]	C_6H_5	Na	H_2O	0.0002 ± 0.0001
1a	C_6H_5	Na	25% aqueous CH_3CN	0.055 ± 0.003
1b	C_6H_5	H	25% aqueous CH_3CN	0.021 ± 0.002
1c	C_6H_5	CH_3	25% aqueous CH_3CN	0.069 ± 0.003
	p-$CH_3C_6H_4$	Na	H_2O	0.011 ± 0.003
	m-BrC_6H_4	Na	H_2O	0.57 ± 0.03
	m-$NO_2C_6H_4$	Na	H_2O	0.66 ± 0.02

[a] A mixture of 0.12 mM ZnTPPS, 6.7 mM dibromide, and 12 mM TEOA in water (or 25% aqueous CH_3CN) was degassed by three freeze–thaw cycles and irradiated at 246 ± 10 nm with a 150-W xenon lamp. [b] Erythro dibromides were used, unless otherwise noted. [c] The yields were determined on the basis of the formation of *trans*-**2**. Incident light quanta absorbed by ZnTPPS was 1.03×10^{-8} einstein/min except for the case specified. [d] 3.4×10^{-9} einstein/min. [e] The threo isomer.

and irradiated at 590 or 532 nm. The decay of the excited triplet ZnTPPS^{*3} was monitored at 840 nm, the absorption maximum.[22] The monitoring light source was a xenon lamp, which was pulsed when necessary, filtered by a Y-52 filter to cut off the light shorter than 520 nm, and a Hamamatsu R928 photomultiplier was used as a detector. The output from the photomultiplier was received and stored as digitized data by using an Iwatsu TS-8123 storagescope. The digitized absorption decay signal was stored on a floppy disk; 512 points were collected for each decay trace, and 20 decay traces were acquired and averaged before storage on the disk. The absorption decay traces with and without quenchers were analyzed by a NEC 9801-VM microcomputer and shown to obey first-order kinetics. A typical computer-fitted decay curve is shown in Figure 1.

Similar measurements for the triplet lifetimes of H_2TPPS, CdTPPS, and Sn^{IV}TPPS were done in a 0.2 mM MTPPS aqueous solution in the presence of various amounts (0–6.0 mM) of dibromide.

Results and Discussion

Photodebromination of 2,3-Dibromo-3-phenylpropionic Acid (1) Sensitized by Zinc Tetrasodium Tetrakis(sulfonatophenyl)porphyrin (ZnTPPS). Irradiation of a deaerated 6.7 mM aqueous solution of sodium *erythro*-2,3-dibromo-3-phenylpropionate (**1a**) at >355 nm in the presence of 0.12 mM ZnTPPS as a sensitizer and 12 mM triethanolamine (TEOA) as a sacrificial reductant afforded sodium cinnamate (**2a**) as the only observable product in a nearly quantitative yield. Dibromide acid

$$\underset{\textbf{1}\ \text{(erythro)}}{PhCHBrCHBrCO_2R} \xrightarrow[\text{TEOA}]{h\nu/\text{ZnTPPS}} \underset{\textbf{2}\ \text{(trans)}}{PhCH{=}CHCO_2R} \qquad (6)$$

$$\textbf{a},\ R = Na;\ \textbf{b},\ R = H;\ \textbf{c},\ R = CH_3$$

1b and methyl ester **1c** in 25% aqueous acetonitrile were similarly debrominated photochemically to give high yields of **2b** and **2c**, respectively. The quantum efficiencies of these reactions, however, were not significantly different from each other (Table I). The quantum yields for the debromination of **1a** sensitized by ZnTPPS were shown to increase with the initial concentrations of dibromide **1a** and became greater than unity at a concentration of **1a** higher than 10 mM (Figure 2). The efficiency was enhanced more dramatically by increase of the TEOA concentration; the quantum yields became higher than 10 as shown in Figure 3. These results suggest that a radical chain reaction is involved in the present photodebromination especially at higher concentrations of the dibromide and TEOA. The operation of radical chain debromination is to be noted since the reductant TEOA is a simple and conventional amine.

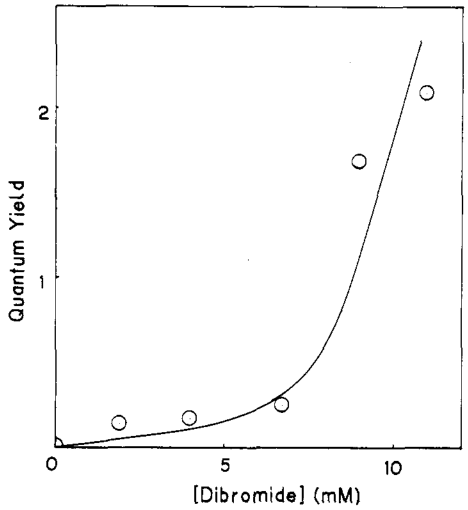

Figure 2. The dependence of the quantum yields on the concentration of dibromide for the debromination in water with initial concentrations of 2.4 μM ZnTPPS, 12 mM TEOA, and 0–30 mM **1a**.

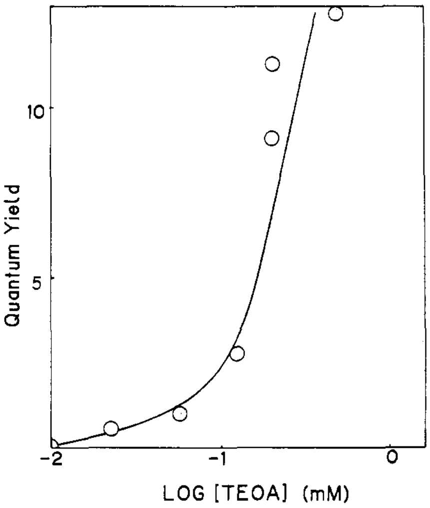

Figure 3. The dependence of the quantum yields on the concentration of triethanolamine (TEOA) for the debromination with 2.4 μM ZnTPPS and 6.7 mM **1a** in water.

In contrast to above erythro dibromide (**1**), sodium *threo*-2,3-dibromo-3-phenylpropionate (**3**) was practically inert under the photodebromination conditions in the presence of the ZnTPPS sensitizer. Prolonged irradiation of **3a** and ZnTPPS in a degassed solution resulted in 9.7% conversion affording a mixture of *trans*-cinnamate (**2a**, 98%) and allocinnamate (*cis*-**2a**, 2%). None of these products were formed from long standing in the dark.

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(22) Richoux, M.-C.; Harriman, A. *J. Chem. Soc., Faraday Trans. 1* **1982**, *78*, 1873.

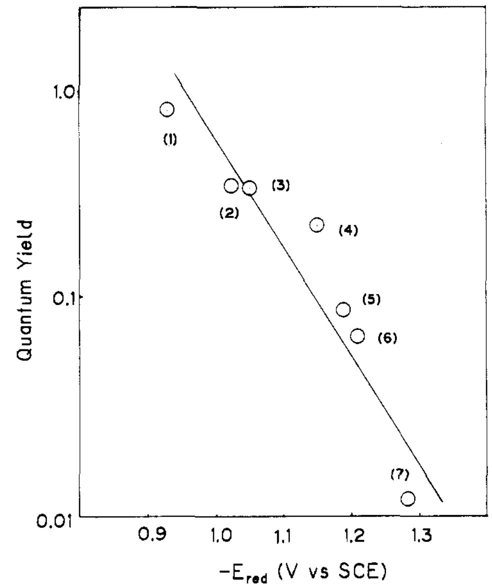

Figure 4. The substituent effect for the debromination of *erythro*-2,3-dibromo-3-arylpropionic acids in water; (1) p-$NO_2C_6H_4$-, (2) m-$NO_2C_6H_4$-, (3) m-BrC_6H_4-, (4) p-CNC_6H_4-, (5) p-ClC_6H_4-, (6) C_6H_5-, and (7) p-$CH_3C_6H_4CHBrCHBrCO_2Na$. Initial concentration: [ZnTPPS] = 2.4 μM; [dibromide] = 1.0 mM.

Furthermore, a control experiment indicated no change of cis/trans ratio during irradiation of 6.7 mM sodium *cis*- and *trans*-cinnamates (20/80 of the initial ratio) in a degassed aqueous solution involving 0.12 mM ZnTPPS and 12 mM TEOA, implying no formation of the cis isomer from *trans*-**2a**. The mechanism for the debromination of **3** will be discussed later.

Substituent Effect of 2,3-Dibromo-3-arylpropionic Acids on the Debromination. The ring substituents of 2,3-dibromo-3-arylpropionic acids affected the efficiency of the debromination significantly (Table I). Electron-withdrawing groups promoted the reaction, and the quantum efficiencies of the reaction were nicely correlated with the reduction potentials of the dibromides (E_{red}), as expected from an electron transfer of an excited ZnTPPS to **1** (Figure 4).

Sensitization Multiplicity. The lifetime of the excited singlet $ZnTPPS^{*1}$ was found to be 1.7 ns by a single photon counting method in aqueous solution (see Experimental Section). The lifetime was unchanged even when the dibromide **1a** (e.g., 6 mM) was added, indicating that the excited singlet $ZnTPPS^{*1}$ is not responsible for the debromination.

In contrast, excited triplet $ZnTPPS^{*3}$, the lifetime of which was reported to be 1.5 ms,[23] was quenched by dibromide **1a**. The quenching rate constant k_q was calculated to be (6.5 ± 0.2) × 10^5 M^{-1} s^{-1} according to eq 5 from quenching experiments with 0.2 mM ZnTPPS and 0–7.0 mM **1a** in degassed aqueous solution. Thus it is shown that excited triplet $ZnTPPS^{*3}$ is responsible for the present sensitized debromination.

Electron Transfer Quenching. As for the sensitization process, one-electron reductive quenching (eq 7) was

$$ZnTPPS^{*3} + 1 \rightarrow ZnTPPS^{\bullet+} + 1^{\bullet-} \qquad (7)$$

evidenced by the detection of $ZnTPPS^{\bullet+}$ by means of a laser flash photolysis technique. Irradiation of deaerated 30% aqueous acetonitrile solutions of 0.05 mM ZnTPPS in the absence and the presence of 5 mM **1a** without TEOA with a laser beam (532 nm) from the Nd:YAG laser resulted in the formation of $ZnTPPS^{*3}$ within 0.1 ms after the laser pulse as shown in the top spectra (λ_{max} 820 nm) in Figure 5. Both spectra (in the absence and the presence of **1a**) gradually deviated from each other. The spectrum in presence of **1a** changed in 1 ms to the one possessing an absorption maximum at around 660–700 nm, which is in agreement with the reported spectra of $ZnTPPS^{\bullet+}$ from radiolysis of ZnTPPS and N_2O.[24] When TEOA, a sacrificial reductant (12 mM), was added to the solution, the absorbance at around 700 nm at 1 ms after the irradiation decreased down to only 5.5% of that in the absence of TEOA. The result implies that $ZnTPPS^{\bullet+}$ once formed was rapidly reduced by TEOA to ZnTPPS (eq 8).

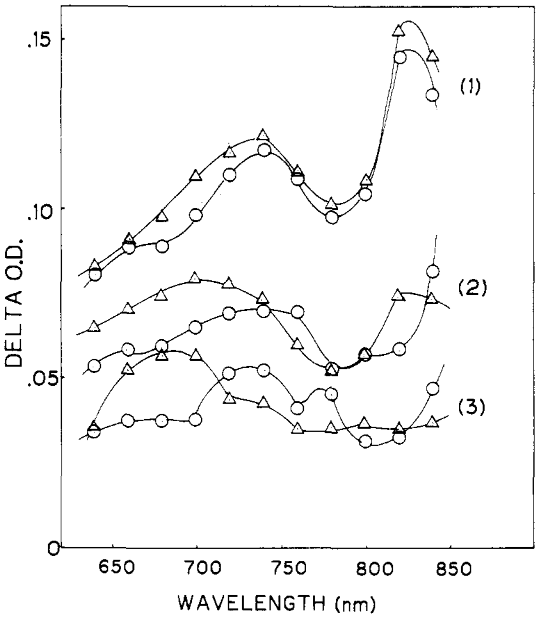

Figure 5. Absorption spectra of $ZnTPPS^*$ in the presence (△) and the absence (○) of dibromide **1a** irradiated by a Nd:YAG laser (532 nm): (1) 10 μs, (2) 500 μs, and (3) 1000 μs after the irradiation.

Table II. Quenching Rate Constants of Metallo Tetrasodium Tetrakis(sulfonatophenyl)porphyrins (MTPPS) by Sodium 2,3-Dibromo-3-phenylpropionate (1a)

M in MTPPS	k_q, M^{-1} s^{-1}	E_{ox}, V vs NHE	ΔG,[a] kcal mol^{-1}
Cd	(4.7 ± 0.6) × 10^5	0.77[b]	
Zn	(6.5 ± 0.2) × 10^5	0.90[c]	7.8
H_2	(2.7 ± 0.1) × 10^5	1.10[c]	17.1
Sn	(6.8 ± 0.5) × 10^4	1.40[b]	19.5

[a] Values calculated from an equation derived by Rehm and Weller (ref 32). [b] Harriman, A.; Richoux, M. C.; Neta, P. *J. Phys. Chem.* **1983**, *87*, 4957. [c] Cited from ref 23b.

$$ZnTPPS^{\bullet+} + TEOA \xrightarrow{e^-} ZnTPPS + TEOA^{\bullet+} \qquad (8)$$

Similarly, other metallo tetrakis(sulfonatophenyl)porphyrins (MTPPS, M = H_2, Sn(IV), and Cd) were quenched by **1a** with different efficiencies (Table II). The resulting order for the quenching rate constants is in line with the free-energy changes (ΔG) for the electron transfer between $MTPPS^{*3}$ and **1a**. The nice correlation supports the one-electron reductive quenching of $MTPPS^{*3}$ by **1a**. Thermodynamic considerations indicate that electron transfer is considerably endothermic and should not be efficient, since the oxidation potential (E_{ox}) of −1.01 V vs

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(23) (a) Kalyanasundaram, K.; Neumann-Spallart, M. *J. Phys. Chem.* **1982**, *86*, 5163. (b) Harriman, A.; Porter, G.; Walters, P. *J. Chem. Soc., Faraday Trans. 1* **1983**, *79*, 1335.

(24) Neta, P. *J. Phys. Chem.* **1981**, *85*, 3678.

SCE for $ZnTPPS^{*3}/ZnTPPS^{\bullet+}$ is lower than the $E_{1/2}$ of −1.35 and −1.21 V vs SCE for **1a** and **1b**, respectively, in 25% aqueous CH_3CN (0.1 M TEAP). The electron transfer quenching rate constant between $ZnTPPS^{*3}$ and **1a** was calculated to be $1.7 \times 10^5\ M^{-1}\ s^{-1}$ from an empirically derived equation (eq 9),[25] where ΔG and $\Delta G^{\ddagger}$ are the

$$k_q = \frac{20 \times 10^9\ M^{-1}\ s^{-1}}{1 + 0.25[\exp(\Delta G^{\ddagger}/RT) + \exp(\Delta G/RT)]} \qquad (9)$$

overall free-energy difference for eq 4 and the activation barrier for electron transfer, respectively. The calculated value is comparable with the observed one $(6.5 \pm 0.2) \times 10^5\ M^{-1}\ s^{-1}$ in Table II. In addition, the excited triplet $ZnTPPS^{*3}$ is not likely to be quenched by **1a** by an alternative way of triplet energy transfer on account of too large endothermicity for triplet energy transfer from $ZnTPPS^{*3}$ (E_T = 37 kcal/mol) to **1** (e.g., $E_T \sim 82$ kcal/mol of toluene). It is therefore reasonable to conclude that the present photosensitized debromination is initiated by one-electron transfer from $ZnTPPS^{*3}$ to **1**.

Reaction Pathways. As described above, the debromination is initiated by one-electron reduction of **1** (eq 7). Subsequent elimination of bromide ion from radical anion **1**$^{\bullet-}$ is known to be a facile process giving benzyl radicals (e.g., **5** in eq 10).[8,26,27] The quantum yields for the debromination increase with increasing concentration of dibromide **1a** and TEOA, and exceed unity (Figures 2 and 3), indicating that a radical chain reaction must be involved in the photodebromination. Inversely, the debromination efficiencies steadily decrease with decreasing TEOA concentration; the limiting quantum yield, Φ_0, extrapolated to [TEOA] = 0, where the chain reaction is of no importance, was 0.05. The profound dependence on TEOA concentration suggests a crucial role of TEOA as a chain carrier.

A likely reaction scheme, after the initial electron transfer (eq 7), is presented in Scheme I, which involves

Scheme I

$$1^{\bullet-} \rightarrow \underset{5}{Ph\dot{C}HCHBrCO_2R} + Br^- \qquad (10)$$

$$5 \rightarrow \underset{2}{PhCH{=}CHCO_2R} + Br^{\bullet} \qquad (11)$$

$$Br^{\bullet} + \underset{TEOA}{N(CH_2CH_2OH)_3} \rightarrow \underset{6}{(HOCH_2CH_2)_2N\dot{C}HCH_2OH} + HBr \qquad (12)$$

$$1 + 6 \rightarrow 1^{\bullet-} + \underset{7}{(HOCH_2CH_2)_2N^+{=}CHCH_2OH} \qquad (13)$$

$$Br^{\bullet} + 6 \rightarrow 7 + Br^- \qquad (14)$$

a radical chain sequence involving bromo radical as a chain carrier. Elimination of halide ions from radical anions, such as in eq 10, is well-known, and the following release of bromo radical (eq 11) to yield olefin seems to be very fast. The high-yield formation of **2** indicates that the elimination of bromo radical is very fast, which is also in accordance with no formation of $PhCH_2CHBrCO_2Na$ even in the presence of toluene. Intervention of bromo radical seems to be appropriate in view of the fact that bibenzyl, a radical coupling product, was formed in the photolysis of **1b** in the presence of toluene, reducing the yield of **2b** from 62% to 26%. Radical **6** formed from bromo radical and TEOA[28] is known to be a powerful reductant[29] and hence may reduce dibromide **1** to yield radical anion **1**$^{\bullet-}$ (eq 13). The reaction sequence 10–13 constitutes the propagation step, resulting in the quantum yield higher than 1.0. Reaction 14 is the termination step.

A possible two-electron reduction pathway (e.g., eq 15) might be unlikely, because the quantum efficiency is little affected by a threefold increase of the incident light quanta (Table I).

$$5 + 6 \rightarrow 2a + Br^- + 7 \qquad (15)$$

Relative Reactivity of *erythro*- and *threo*-2,3-Dibromo-3-phenylpropionic Acids. In the present photodebromination, threo dibromide **3a** is debrominated about 500 times slower than the erythro isomer **1a**. Willner et al.[9a,c] have reported similarly a large difference between *meso*- and *d,l*-1,2-dibromostilbenes (**8**) in the debromination with viologen biradical ($E_{1/2}$ = −0.90 V vs NHE), as a two-electron reducing agent, formed from alkylviologen and sodium dithionite. They[9,30] and others[31] explained the much more facile debromination of *meso*-**8** compared to the *d,l* isomer on the basis of the difference in reduction potentials between the two isomers ($\Delta E_{1/2} \sim 0.5$ V). In reference to these interpretations, the large difference in the reactivity between **1a** and **3a** might also be attributed to the differences in their reduction potentials ($\Delta E_{1/2} \sim 0.21$ V); the $E_{1/2}$ values are −1.35 and −1.56 V vs SCE for **1a** and **3a**, respectively, in 25% aqueous CH_3CN containing 0.1 M TEAP. However, our laser flash photolysis experiments revealed that one-electron reductive quenching of $ZnTPPS^{*3}$ by **1a** and that by **3a** are of the same order, i.e., $(6.5 \pm 0.2) \times 10^5\ M^{-1}\ s^{-1}$ for **1a** and $(2.9 \pm 0.1) \times 10^5\ M^{-1}\ s^{-1}$ for **3a** in aqueous solution. The k_q values, much lower than the diffusion-controlled rate ($\sim 10^{10}\ M^{-1}\ s^{-1}$), may be understood by the endoergonicity for the quenching of $ZnTPPS^{*3}$, ΔG's being +0.34 and +0.55 eV for **1a** and **3a**, respectively.[32]

These facts indicate that the apparent quantum efficiency for the debromination is governed predominantly by the subsequent chemical sequences (Scheme I) rather than the electron-transfer quenching (eq 7). Elimination of bromide ion from **1**$^{\bullet-}$ (eq 10) is competitive with a back electron from **1**$^{\bullet-}$ to $ZnTPPS^+$ (eq 16). Much less efficient

$$1^{\bullet-}\ (\text{or } 3^{\bullet-}) + ZnTPPS^{\bullet+} \rightarrow 1\ (\text{or } 3) + ZnTPPS \qquad (16)$$

debromination for **3a** suggests that most of **3a**$^{\bullet-}$ transfers an electron to $ZnTPPS^{\bullet+}$, whereas most of **1**$^{\bullet-}$ debrominates facilely. The bromide ion elimination from **1**$^{\bullet-}$ may be promoted by an anchimeric assistance of the remaining bromine atom. Erythro isomer **1** has its two bromine atoms anti to each other as the most stable conformer, and hence the transition state for bromide ion departure from **1**$^{\bullet-}$ is stabilized by a back-side assistance

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[25] Karvarnos, G. J.; Turro, N. J. *Chem. Rev.* **1986**, *86*, 401.

[26] Tanner, D. D.; Plambeck, J. A.; Reed, D. W.; Mojelsky, T. W. *J. Org. Chem.* **1980**, *45*, 5177.

[27] (a) Garst, J. F. *Acc. Chem. Res.* **1971**, *4*, 400. (b) Grimshaw, J.; Ramsey, J. S. *J. Chem. Soc. B* **1968**, 60. (c) Streitweiser, A., Jr.; Perrin, C. *J. Am. Chem. Soc.* **1964**, *86*, 4938. (d) Nadjo, L.; Saveant, J. M. *J. Electroanal. Chem.* **1971**, *30*, 41. (e) Alwair, K.; Grimshaw, J. *J. Chem. Soc., Perkin Trans. 2* **1973**, 1150.

[28] Molecular bromine or iodine oxidizes tertiary amine to give immonium salts such as **7**; (a) Fruit, R. E., Jr. *Diss. Abstr. B* **1968**, *29*, 104. (b) Donbavand, M. H.; Moeckel, H. J. *Z. Naturforsch., B: Anorg. Chem., Org. Chem.* **1974**, *29*, 742.

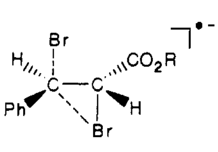
[29] (a) Griller, D.; Lossing, F. P. *J. Am. Chem. Soc.* **1981**, *103*, 1586. (b) Monserrat, K.; Foreman, T. K.; Grätzel, M.; Whitten, D. G. *J. Am. Chem. Soc.* **1981**, *103*, 6667.

[30] (a) Degani, Y.; Willner, I. *J. Am. Chem. Soc.* **1983**, *105*, 6228. (b) Willner, I.; Otvos, J. W.; Calvin, M. *J. Am. Chem. Soc.* **1981**, *103*, 3203. (c) Willner, I.; Yang, J.-M.; Otvos, J. W.; Calvin, M. *J. Phys. Chem.* **1981**, *85*, 3277. (d) Willner, I.; Degani, Y. *J. Chem. Soc., Chem. Commun.* **1982**, 761. (e) Willner, I.; Degani, Y. *Isr. J. Chem.* **1982**, *22*, 163.

[31] O'Connell, K. M.; Evans, D. H. *J. Am. Chem. Soc.* **1983**, *105*, 1473.

[32] Rehm, D.; Weller, A. *Isr. J. Chem.* **1970**, *8*, 259.

of the second bromine atom as depicted in **9**. On the other hand, a transition state for threo isomer **3** should be unstable because of the two large eclipsed groups, as in **10**. Thus, the debromination from $\mathbf{3a}^{\bullet-}$ is slowed down considerably and the competing back-electron transfer to $\mathrm{ZnTPPS}^{\bullet+}$ (eq 16) becomes predominant. The observed formation of a mixture of cis and trans olefin from **3a** suggests the radical nature of the debromination, i.e., the competitive C–C rotation and bromo radical elimination from α-bromo radical **5**. Similar cis/trans olefin ratios have been reported in the one-electron reductive radical debromination of 1,2-dibromostilbenes (**8**), i.e., *meso*-**8** gave 100% *trans*-stilbene, but *d,l*-**8** yielded a mixture of cis and trans olefin in a ratio of 0–0.04.[33]



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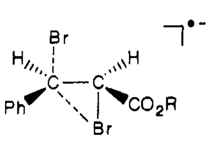

10

Effect of Charges of Sensitizer and Substrates. Many reports have dealt with the retardation of a back electron transfer; i.e., migration toward the left side in eq 4 by invoking electrostatic repulsion of donor (D) and acceptor (A) of like charge. For the present case of anionic sensitizer ZnTPPS, electrostatic repulsion may be large with anionic substrate **1a**, but smaller with the undissociated acid **1b** and ester **1c**, and hence the forward electron transfer is more favorable with **1b** and **1c**. On the other hand, a backward transfer is expected to be slowed down in all of these cases. Thus the quantum efficiency of the debromination is expected to decrease in the order **1c** ~ **1b** > **1a**. However, the observed order of **1c** ~ **1a** > **1b** was quite different from the expected order. This fact suggests that the effect of charges of sensitizer and substrates is not so significant as to control the overall debromination efficiency.

In conclusion, the present studies have demonstrated that (i) the ZnTPPS-sensitized photodebromination of **1** is initiated by a one-electron transfer from ZnTPPS^{*3} to the dibromide and (ii) the quantum efficiency for the debromination is mainly controlled by the subsequent radical chain debromination.

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[33] Mathai, I. M.; Schug, K.; Miller, S. I. *J. Org. Chem.* **1970**, *35*, 1733.

Benzyne Cyclization Route to Benzo[*c*]phenanthridine Alkaloids. Synthesis of Chelerythrine, Decarine, and Nitidine

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The alkaloids chelerythrine (**8b**) and decarine (**7c**) have been synthesized through a benzyne-mediated cyclization of *N*-(2-halobenzyl)-1-naphthylamines **4** with $\mathrm{KNH_2}$ in ammonia/ether. The 7-hydroxybenzo[*c*]phenanthridine structure **16a** proposed for the alkaloid fagaridine is questioned on the basis of comparison with a model compound (**16b**) synthesized by benzyne cyclization. For the 8,9-oxygenated alkaloids like nitidine (**8i**), this cyclization proceeded poorly, but a dramatic improvement occurred when LDA/THF at −78 °C was used instead of $\mathrm{KNH_2/NH_3}$.

The search for new and more versatile synthetic routes to benzo[*c*]phenanthridine alkaloids continues,[1] primarily because of the cytotoxic activity[2] associated with this class of compounds. In a preliminary communication,[3] it was disclosed that benzyne-mediated cyclization[4] of anils derived from ortho-halogenated benzaldehydes can be used for the synthesis of 7,8-oxygenated benzo[*c*]phenanthridines. We now report in full some applications of this route along with an important experimental modification, which enlarges its scope to the 8,9-oxygenated alkaloids.

For the synthesis of the alkaloid chelerythrine (**8b**), the bromo aldehyde **1b** was condensed with the naphthylamine **2b** (Schemes I and II). The obtained Schiff base **3b** was reduced with sodium borohydride to get **4b**. Reaction of this bromo amine with $\mathrm{KNH_2}$ gave a mixture (**6b** and **7b**), which on treatment with manganese dioxide in chloroform furnished the benzo[*c*]phenanthridine **7b** in 80% yield. Its methylation[5] afforded a product (**8b**) identical with chelerythrine chloride.[6]

Structure **7c** has been assigned[7] to the alkaloid decarine. The position of the free phenolic group was confirmed by Ishii et al.[8] by synthesizing compound **7d**, which was shown

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[1] (a) Šimânek, V. *The Alkaloids*; Academic: New York, 1985; Vol. 26, Chapter 4. (b) Ninomiya, I.; Naito, T. *Recent Developments in the Chemistry of Natural Carbon Compounds*; Akademiai Kiado: Budapest, 1984; Vol. X.

[2] Stermitz, F. R.; Larson, K. A. *J. Med. Chem.* **1973**, *16*, 939. Sethi, M. L. *J. Nat. Prod.* **1979**, *42*, 187. Suffness, M.; Dours, J. *Methods in Cancer Research*; Devita, V. J., Jr., Busch, H., Eds.; Academic: New York, 1979; Vol. 16, Chapter 3.

[3] Kessar, S. V.; Singh, M.; Balakrishnan, P. *Indian J. Chem.* **1974**, *12*, 323.

[4] (a) Kessar, S. V.; Gopal, R.; Singh, M. *Tetrahedron* **1973**, *29*, 167. (b) Kessar, S. V.; Pal, D.; Singh, M. *Tetrahedron* **1973**, *29*, 177.

[5] Bailey, A. S.; Worthing, C. R. *J. Chem. Soc.* **1956**, 4535.

[6] Sample kindly provided by Prof. R. H. F. Manske, Department of Chemistry, University of Waterloo, Ontario, Canada.

[7] Vaquette, J.; Pousset, J. L.; Paris, R. R.; Cave, A. *Phytochemistry* 1974, *13*, 1257.

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