apparent even at elevated temperatures (to 125 °C, in decalin-d_{18}). From these data, and using the Gutowsky–Holm approximation, a lower limit for E_r of ca. 22 kcal mol^{-1} was established. This value is also a lower limit for E_r of **1** since CD and CD_3 have smaller steric requirements than CH and CH_3.[13]

These findings indicate that **1** may exhibit conformational rigidity even on the laboratory time scale and suggest the possibility of separating cycloenantiomers[14] of a novel type (Figure 3), in which the direction of the ring is dictated by the conformational orientation of modified isopropyl groups, rather than by the directed sequence of bonded atoms (e.g., peptide linkages). Work is under way to test this prediction.

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(11) Cyclotrimerization produces four products from a mixture of **2** and **2**-d_{14}: **1**, **1**-d_{14}, **1**-d_{28}, and **1**-d_{42}. Given a starting mole ratio of **2**:**2**-d_{14} = 1:11, and disregarding possible isotope effects, the calculated percent product distribution is 0.06:1.9:20.9:77.1, respectively. It follows that 84% of the available protons are incorporated in **1**-d_{28}, in fair agreement with a value of 89% calculated from relative MS intensities. The relative integrated intensities of the methyl-decoupled methine proton signals indicate that the observed resonance doubling is virtually entirely due to **1**-d_{28}.

(12) Resonance doubling of the methine proton signal is consistent with C_s symmetry for **1**-d_{28}, but not with C_2 symmetry. This observation provides experimental evidence against the D_{3d} structure for **1**, in support of our calculations.[5]

(13) Mislow, K.; Graeve, R.; Gordon, A. J.; Wahl, G. H., Jr. *J. Am. Chem. Soc.* **1964**, *86*, 1733.

(14) Prelog, V.; Gerlach, H. *Helv. Chim. Acta* **1964**, *47*, 2288. Cruse, R., in Eliel, L. "Stereochemie der Kohlenstoffverbindungen"; Verlag Chemie: Weinheim, 1966; pp 215–225.

Photochemical and Chemical Reduction of Vicinal Dibromides via Phase Transfer of 4,4′-Bipyridinium Radical: The Role of Radical Disproportionation

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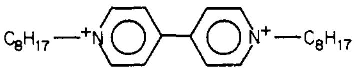
Fundamental processes in nature such as CO_2 and N_2 fixation involve multielectron reduction reactions. Yet, the primary events in these processes involve single-electron-transfer reactions. Thus, the transformation of a one-electron reductant to multielectron reducing products seems to be a basic problem. Phase-transfer catalysis[1,2] has found significant synthetic applications, including oxidations and reductions of organic substrates.[3,4] Electron acceptors might be used as electron carriers between the two phases, leading to the reduction of substrates in the organic phase. Yet, by generating a single-electron reductant in a two-phase system and designing opposite solubility properties of the disproportionation products in the two phases (eq 1), one might

$$2A^{+\cdot} \rightleftharpoons A^{2+} + A: \tag{1}$$

anticipate the transformation into a two-electron reducing product and its utilization in chemical routes.

4,4′-Bipyridinium salts (viologens) have been widely explored as electron acceptors and electron carriers.[5,6] Presently, the photosensitized reduction of these compounds is being intensively studied,[2] in particular as a means of solar energy conversion and storage.[7,8] The utilization of the photoproducts in chemical routes and in particular as a synthetic tool is an unexplored field. Among the different alkylviologens, *N*,*N*′-dioctyl-4,4′-bipyridinium dibromide (**I**), C_8V^{2+}, shows interesting solubilization properties, depending on its oxidation state.[9] The oxidized form, C_8V^{2+}, is soluble only in an aqueous media, while the reduced form, $C_8V^{+\cdot}$, due to its lipophilic character, is extracted into organic phases. Here we wish to report on the chemical and photochemical debromination of 1,2-dibromodiarylethanes to 1,2-diarylethylenes in a two-phase system. This debromination process is mediated by C_8V^{2+} (**1**), as a phase-transfer catalyst. The active species in the reduction process is the two-electron reductant C_8V, which is formed by an induced disproportionation of the singly reduced product $C_8V^{+\cdot}$ in the two-phase system.



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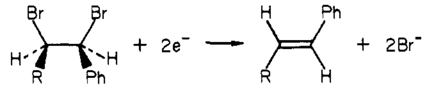
The system is composed of an aqueous sodium dithionite solution and ethyl acetate as an organic phase that includes the dibromide. Introduction of a catalytic amount of C_8V^{2+} to the deaerated system results in the blue color of $C_8V^{+\cdot}$ (in the H_2O). Upon stirring the two-phase system, the radical is extracted into the organic phase and the reduction of the dibromide to the corresponding alkene proceeds quantitatively. In such a system the reduction of dibromostilbenes **2** and **3** to the corresponding *trans*-stilbenes **4** and **5** is afforded in quantitative yields (>95%). Similarly, 1,2-dibromo-2-stilbazole (**6**) and 1,2-dibromo-4-stilbazole (**7**) undergo debromination to **8** and **9** (yield >90%). The net reaction (eq 2) corresponds to the two-electron reduction of the 1,2-dibromodiarylethane to the corresponding *trans*-diarylethylene.



(2)

2, R = Ph	**4**, R = Ph
3, R = 4-MeOPh	**5**, R = 4-MeOPh
6, R = 2-Py	**8**, R = 2-Py
7, R = 4-Py	**9**, R = 4-Py

No reduction of the dibromides occurs when C_8V^{2+} is excluded from the system. Thus, C_8V^{2+} mediates the debromination reaction, and since the molar ratio of C_8V^{2+} to the dibromide substrate is 1:15, the reducing species is recycled in the system. Similarly, the mediated reduction of the dibromides was accomplished when glucose was substituted for dithionite as the reductant in the aqueous phase.[10] Under these conditions glucose is oxidized by C_8V^{2+}, and the resulting $C_8V^{+\cdot}$ is extracted into the organic phase.

The reduction of C_8V^{2+} and the effect of added dibromostilbene on its reduction products was followed by cyclic voltammetry. The cyclic voltamogram of C_8V^{2+} shows two reversible one-electron reduction waves at $E_{1/2}^1 = -0.47$ and $E_{1/2}^2 = -0.90$ V (vs. NHE), corresponding to the formation of the radical cation $C_8V^{+\cdot}$ and the biradical C_8V. Addition of dibromostilbene to C_8V^{2+} does not affect the reversibility of the first reduction wave, while the reoxidation wave of C_8V is depleted, pointing to its rapid chemical consumption. These results indicate that the active species in the

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(1) (a) Dehmlow, E. V. "Phase Transfer Catalysis"; Verlag Chemie: Weinheim, 1980; (b) *Angew. Chem., Int. Ed. Engl.* **1977**, *16*, 493–505.

(2) Starks, C. M.; Liotta, C. "Phase Transfer Catalysis: Principles and Techniques"; Academic Press: New York, 1978.

(3) (a) Brandstrom, A.; Junggren, H.; Lamm, B. *Tetrahedron Lett.* **1972**, 3173–3176. (b) Landini, D.; Quici, S.; Rolla, F. *Synthesis* **1975**, 397–399.

(4) Herriott, A. W.; Picker, *Tetrahedron Lett.* **1974**, *16*, 1511–1514.

(5) (a) Sugimoto, T.; Miyazaki, J.; Kokubo, T.; Tanimoto, S.; Okano, M.; Matsumoto, M. *Tetrahedron Lett.* **1981**, *22*, 1119–1122. (b) Kiwi, J.; Gratzel, M. *J. Am. Chem. Soc.* **1979**, *101*, 7214–7217.

(6) (a) Kiwi, J.; Gratzel, M. *Chimia* **1979**, *33*, 289–291. (b) Willner, I.; Yang, J.-M.; Otvos, J. W.; Calvin, M. *J. Phys. Chem.* **1981**, *85*, 3277–3282. (c) Willner, I.; Ford, W. E.; Otvos, J. W.; Calvin, M. *Nature (London)* **1979**, *280*, 830–833.

(7) (a) Gratzel, M. *Acc. Chem. Res.* **1981**, *14*, 376–384. (b) Willner, I.; Laane, C.; Otvos, J. W.; Calvin, M. *Adv. Chem. Ser.* **1982**, *No. 177*, 71–95.

(8) (a) Whitten, D. G.; Russell, J. C.; Schmell, R. H. *Tetrahedron* **1982**, *38*, 2455–2487; *Acc. Chem. Res.* **1980**, *13*, 83–90. (b) Matsuo, T. *Pure Appl. Chem.* **1982**, *54*, 1693–1703.

(9) Tabushi, I. *Pure Appl. Chem.* **1982**, *54*, 1733–1736.

(10) Trudinger, P. A. *Anal. Biochem.* **1970**, *36*, 222–224.

0002-7863/83/1505-7764$01.50/0

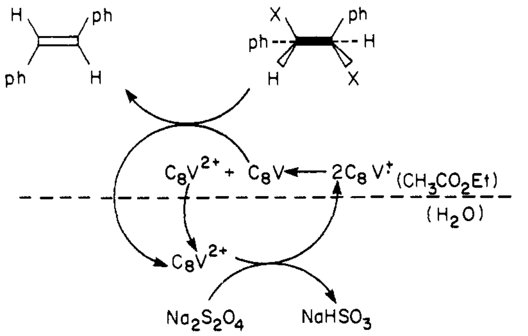

Figure 1. Reduction of 1,2-dibromostilbene in a two-phase system mediated by C_8V^{2+} (**1**).

debromination processes discussed previously is the two-electron reductant C_8V, rather than $C_8V^{+\bullet}$.

Yet, the reduction potential of dithionite and glucose in the chemical systems is only adequate for generating the one-electron reduction product $C_8V^{+\bullet}$. Therefore, the active debromination two-electron reducing agent C_8V might be formed in a disproportionation reaction (eq 3). The reduction potentials of $C_8V^{+\bullet}$

$$2C_8V^{+\bullet} \rightleftharpoons C_8V + C_8V^{2+} \qquad (3)$$

and C_8V, as well as previous studies, indicate that the comproportionation constant lies overwhelmingly toward the radical cation, $C_8V^{+\bullet}$.[11] However, such a conclusion is valid only for a homogeneous phase. The success of accomplishing the debromination reaction in the two-phase system is attributed to an induced shift in the disproportionation equilibration toward the products, C_8V^{2+} and C_8V, due to reextraction of C_8V^{2+} into the aqueous phase.

The entire scheme leading to the cyclic debromination of the dibromides is displayed in Figure 1. The formation of $C_8V^{+\bullet}$ in the aqueous phase is followed by its extraction into the organic solution. Disproportionation of $C_8V^{+\bullet}$ in the organic phase is accomplished by the reextraction of C_8V^{2+} into the aqueous phase. Consequently, the two-electron reductant, C_8V, capable of reducing the dibromides is formed. Debromination recycles the mediating electron acceptor.

The photosensitized formation of 4,4′-dipyridinium radical cations by visible light is well-known.[7,8] In these systems organometallic compounds such as ruthenium tris(bipyridine), $Ru(bpy)_3^{2+}$, or zinc porphyrins are used as sensitizers, and triethanolamine, ethylenediaminetetracarboxylic acid, EDTA, or cysteine are introduced as electron donors. Thus, in the previous systems the reducing agent solubilized in the aqueous phase could be substituted by a sensitizer and electron donor. Introduction of the sensitizer $Ru(bpy)_3^{2+}$ and the electron donor $(NH_4)_3$–EDTA into the aqueous phase yields upon illumination ($\lambda > 400$ nm) the 4,4′-bipyridinium radical $C_8V^{+\bullet}$. This radical is extracted into the organic phase and mediates the previously described debromination reaction. The sensitizer $Ru(bpy)_2^{2+}$ and the mediating electron acceptor C_8V^{2+} are present in the two-phase system in catalytic amounts. The cyclic photoreaction mediated by C_8V^{2+} corresponds to the photosynthesis of stilbene *via* oxidation of $(NH_4)_3$–EDTA by dibromostilbene.

Futhermore, our previous discussion implies that the similar debromination process should be unfavorable in a homogeneous phase due to the low availability of the active reductant C_8V. Indeed, illumination of an acetonitrile solution that includes $Ru(bpy)_3^{2+}$ as sensitizer, C_8V^{2+} as electron acceptor, triethanolamine as electron donor, and dibromostilbene does not lead to stilbene (**4**), despite the effective formation of $C_8V^{+\bullet}$.

In conclusion, we have demonstrated that the amphyphylic 4,4′-bipyridinium salt C_8V^{2+} (**1**) serves as a phase-transfer electron carrier. Photoreduction of C_8V^{2+} in the aqueous layer coupled to reactions in the organic phase might be a general approach in photosynthetic applications. The induced shift in the disproportionation equilibrium of the one-electron reduction product in the two-phase system forms a two-electron reductant having a very low reduction potential, capable of reducing a variety of 1,2-dibromides. In nature, multielectron reducing mediators are very common. Thus, similar hydrophobic–hydrophilic interactions might lead to the natural intermediates via disproportionation reactions.

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Registry No. 1, 66620-94-8; **1**·Br_2, 36437-30-6; **2**, 13440-24-9; **3**, 24533-06-0; **4**, 103-30-0; **5**, 1694-19-5; **6**, 87922-24-5; **7**, 87922-25-6; **8**, 538-49-8; **9**, 5097-93-8; $C_8V^{+\bullet}$, 87922-26-7; C_8V, 87922-27-8; $Ru(bpy)_3^{2+}$, 15158-62-0; $Na_2S_2O_4$, 7775-14-6; $(NH_4)_3$–EDTA, 15934-01-7; glucose, 50-99-7.

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(11) (a) Hunig, S.; Berneth, H. *Top. Curr. Chem.* **1980**, *92*, 1–44. (b) Hunig, S. *Pure Appl. Chem.* **1967**, *15*, 109–122. (c) Bard, A. J.; Ledwith, A.; Shine, H. J. *Adv. Phys. Org. Chem* **1976**, *13*, 155–278.

Kinetics of Long-Distance Ruthenium-to-Copper Electron Transfer in [Pentaammineruthenium histidine-83]azurin[†]

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Recent investigations have established that relatively rapid electron transfer can take place between metal centers separated by long distances (>10 Å) in proteins.[1-5] Of the systems examined to date, $a_5Ru(His\text{-}33)^{3+/2+}$–cytochrome *c* ($Fe^{3+/2+}$) (a = NH_3) is special in the sense that it involves electron transfer between metal centers in their electronic ground states.[1-3] Clearly, more studies of this sort are needed, because the dependences of the rate constant on separation distance and on the nature of the medium are critical factors that are yet to be elucidated. The purpose of this communication, therefore, is to report a fixed-site, long-distance electron-transfer experiment involving *Pseudomonas aeruginosa* azurin (Az), a blue copper protein whose structure and properties have been studied extensively.[6] For this experiment we have labeled His-83 of Az with a_5Ru^{3+} (Figure 1).

Samples of $a_5Ru(His\text{-}83)^{3+}$–Az($Cu^{2+}$) were prepared by procedures developed previously for a_5Ru^{3+} protein modification.[1,2,7,8]

[†] Dedicated to the memory of Eraldo Natonini.

(1) (a) Winkler, J. R.; Nocera, D. G.; Yocom, K. M.; Bordignon, E.; Gray, H. B. *J. Am. Chem. Soc.* **1982**, *104*, 5798–5800; (b) *Chem. Scr.* **1983**, *21*, 29–33.

(2) Nocera, D. G.; Winkler, J. R.; Yocom, K. M.; Bordignon, E.; Gray, H. B., manuscript in preparation.

(3) Isied, S. S.; Worosila, G.; Atherton, S. J. *J. Am. Chem. Soc.* **1982**, *104*, 7659–7661.

(4) McGourty, J. L.; Blough, N. V.; Hoffman, B. M. *J. Am. Chem. Soc.* **1983**, *105*, 4470–4472.

(5) McLendon, G.; Simolo, K.; Taylor, L.; Cupo, P.; Miller, J.; Muhlks, W. *Abstr. Pap.-Am. Chem. Soc.* **1983**, 186th, INOR 19.

(6) (a) "Copper Proteins"; Spiro, T. G., Ed.; Wiley-Interscience: New York, 1981. (b) Adman, E. T.; Jensen, L. H. *Isr. J. Chem.* **1981**, *21*, 8–12. (c) Freeman, H. C. In "Coordination Chemistry-21"; Laurent, J. P., Ed.; Pergamon: Oxford, 1981; pp 29–51. (d) English, A. M.; Lum, V. R.; DeLaive, P. J.; Gray, H. B. *J. Am. Chem. Soc.* **1982**, *104*, 870–871. (e) With the assistance of S. L. Mayo, several views of the azurin structure[6b] were examined by H.B.G. on a computer graphics system at the Pennsylvania State University.

(7) Yocom, K. M.; Shelton, J. B.; Shelton, J. R.; Schroeder, W. A.; Worosila, G.; Isied, S. A.; Bordignon, E.; Gray, H. B. *Proc. Natl. Acad. Sci. U.S.A.* **1982**, *79*, 7052–7055.

(8) Margalit, R.; Pecht, I.; Gray, H. B. *J. Am. Chem. Soc.* **1983**, *105*, 301–302 and references therein.

0002-7863/83/1505-7765$01.50/0