liposomes were carried out at pH 6.4 in order to maintain the monomeric state of the membrane (at higher pH values, a slow spontaneous polymerization occurs). Polymerized liposomes of **1** showed the same permeability toward sucrose at pH 6.4 as that found at pH 8.5.

Dynamic Light Scattering. Size distributions were determined with a Nicomp Model 200 laser particle sizer equipped with a 5-mW helium–neon laser at an excitation wavelength of 632.8 nm. This instrument employs digital autocorrelation to analyze the fluctuations in scattered light intensity generated by the diffusion of liposomes in solution. The measured diffusion coefficient is used to obtain the average hydrodynamic radius and, thus, the mean diameter. Samples were filtered by using a 0.45-μm HV4 Millipore filter prior to analysis.

Film Balance Experiments. Surface pressure–area isotherms were recorded by using a MGW Lauda film balance, maintained at 25 °C, and equipped with a computerized data acquisition station. All lipids were spread onto a pure water subphase (600 cm^2) that was purged with nitrogen, using a hexane/ethanol (4/1, v/v) solution. The concentrations of stock solutions of **1** and **2** that were used were 0.44 and 1.18 mg/mL, respectively. Monolayers were compressed under a nitrogen atmosphere up to the collapse point. The total quantity of lipid that was used in each experiment was 3.17 × 10^{-8} moles; the rate of compression was 60 cm^2/min.

Registry No. 1, 116405-86-8; **2**, 116405-87-9; 12-(tetrahydropyranyloxy)dodecanoic acid, 116405-88-0; 1-palmitoyl-*sn*-glycero-3-phosphocholine, 17364-16-8; 1-palmitoyl-2-(12-hydroxydodecanoyl)-*sn*-glycero-3-phosphocholine, 116405-89-1; lipoic acid anhydride, 91319-83-4.

Does a Stilbazolium Cation Adsorbing Poly(styrenesulfonate) Anion Form Micellelike Clusters?

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Abstract: Poly(styrenesulfonate) anion (PSS^{n-}) is shown to aggregate with a large number of stilbazolium cations (Stz$^+$) which undergo an electron-relay chain photoisomerization in the presence of Ru(bpy)$_3^{2+}$ sensitizer. The quantum yields for the cis-to-trans isomerization ($\Phi_{c\to t}$) were rather constant in the range of 50–110, irrespective of changing the solvent from water to acetone or of the degrees of polymerization of PSS^{n-} from 100 to 5000. Adsorption and aggregation numbers of benzyltrimethylammonium ion (BTA$^+$), an organic cationic substitute for Stz$^+$, on PSS^{n-} were determined by a methylanthracene quenching method. The results show that the thousands of Stz$^+$ ions bound to PSS^{n-} are divided into small aggregates of micellelike clusters and that their aggregation numbers are constant in the range of 80–90, irrespective of the degree of polymerization of PSS^{n-}. It was concluded that the electron-relay chain isomerization proceeds within one micellar cluster.

Interactions between polyions and organic counterions play an important role in a wide variety of biological and industrial systems.[1-4] The binding of organic materials to biopolymers or polyelectrolytes is a particularly interesting methodology to achieve artificial photosynthesis enabling a facile electron transfer between electron donors and acceptors.[5] We have reported an electron-relay chain reaction utilizing anionic micelles[6a] or colloidal silica gel surface for the Ru(bpy)$_3^{2+}$-sensitized cis-to-trans isomerization of stilbazolium cations (Stz$^+$).[6b] The resulting high quantum yields of 50–100 are suggestive of a possibility for developing a so-called photomultiplier, provided that the length of electron relay could be further increased by applying polyionic fields. Poly(styrenesulfonate) anion (PSS^{n-}), a polyelectrolyte, seems to be a good candidate for such fields with anionic sites available up to 5000. Here, we report our unexpected results that thousands of Stz$^+$ molecules bound to the anionic polymer PSS^{n-} are divided into micellelike clusters and that the electron relay is confined within one cluster.

Experimental Section

Materials. Tris(2,2′-bipyridine)ruthenium dichloride [Ru(bpy)$_3^{2+}$]-(Cl$^-$)$_2$[7] and *cis*-γ-styrylpyridine (*cis*-Stz)[8] were prepared according to the literature methods. Sodium poly(styrenesulfonates) [(PSS)Na's] were either of the standard sample grade from Pressure Chemical Co. or from Toyo Soda Manufacturing Co. β-Phenethylammonium chloride, tetramethylammonium bromide, and 9-methylanthracene of extra pure grade were used as received. Benzyltrimethylammonium chloride (BTAC) was prepared by the reaction of trimethylamine with benzyl chloride.

Preparation of *cis*-γ-Stilbazolium Poly(styrenesulfonate)[PSS^{n-}·(*cis*-Stz$^+$)$_n$]. A 0.05 M solution of *cis*-Stz in methanol (80 μL) was precisely neutralized by adding an equivalent quantity of 0.01 M poly(styrenesulfonic) acid (PSSH) in water and stored as a stock solution in the dark. The concentration of PSSH was based on the sulfonic acid group involved, and the neutralization point was checked potentiometrically. Here, the PSSH solution was obtained according to the following procedures: 50 mg of (PSS)Na in water (~1 mL) was passed through a column (17 mm i.d. × 200 mm length) packed with ca. 20 mL each of Amberlite IR and IRA and separated into fractions (ca. 10 mL). Fractions (no. 3–6) including PSSH were collected and diluted with ca. 50 mL of water to afford ca. 0.01 M PSSH solution. Its concentration was determined spectrophotometrically at 262 nm (ε 730) on a Shimadzu UV-265 spectrophotometer.

Photolysis of PSS^{n-}·(*cis*-Stz$^+$)$_n$ with Ru(bpy)$_3^{2+}$. An aqueous solution of 0.4 mM (PSS^{n-}/n)·*cis*-Stz$^+$ and 6.7 μM Ru(bpy)$_3^{2+}$ sensitizer was

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Table I Adsorption and Aggregation Numbers (N_A) of *cis*-Stz$^+$ Cation on PSS^{n-} Anion and the Quantum Yields ($\Phi_{c\to t}$) for Ru(bpy)$_3^{2+}$–Sensitized Isomerization of *cis*-Stz$^+$ in Water

	PSS$^{n-\,a}$				$\Phi_{c\to t}^{\,e}$	
no.	MW^b	polym deg (n)	adsorpn no.^{c}	aggregn no. (N_A)^d	1/1^f	3/1^f
1					1.1	
2	SDS			70	64 ± 2	
3	(2 ± 1) × 10^4	100 ± 50	82 (82%)		51	84 ± 4
4	(7 ± 3) × 10^4	360 ± 120	342 (95%)	93 ± 15	60	93 ± 7
5	3.5 × 10^5 ^{g}	1700			44 ± 4	107 ± 8
6	(5 ± 1) × 10^5	2400 ± 500	2140 (89%)	78 ± 12	44 ± 2	119 ± 4
7	(1 ± 0.2) × 10^6	4900 ± 1000	4800 (90%)	74 ± 16	66 ± 18	110 ± 1
8	1.06 × 10^6 ^{g}	5100	4350 (87%)	79 ± 8	58 ± 13	106 ± 6

[a] From Toyo Soda Manufacturing Co. unless otherwise noted. [b] Determined from viscosity measurements. [c] Number of *cis*-Stz$^+$ ions adsorbed on one polymer chain. The values in parentheses denote the percentage of Stz$^+$ ions adsorbed per available anionic sites of PSS^{n-}. [d] Aggregation number of micellelike clusters formed by the PSS$^{n-}\cdot$(BTA$^+$)$_n$ complex in H$_2$O. [e] Quantum yields for the photoisomerization of *cis*– to *trans*-Stz$^+$ irradiated at 468 ± 5 nm under argon at room temperature. Initial concentration: [PSS^{n-}/n] = [*cis*-Stz$^+$] = 0.4 mM and [Ru(bpy)$_3^{2+}$] = 6.7 μM in H$_2$O. [g] From Pressure Chemical Co. [f] Molar ratio of [*cis*-Stz$^+$]/[PSS^{n-}/n].

deaerated with argon bubbling for 10 min and irradiated with a monochromatized light (468 ± 5 nm) from a 150-W xenon lamp. The cis-to-trans isomerization was monitored with an HPLC instrument (Shimadzu LC-6A) with a column packed with Fine SIL C$_{18}$-10 using a mixture of 0.1 M aqueous NaCl and methanol (1:4, v/v) as an eluent. An aliquot (0.1 mL) was taken at appropriate time intervals and analyzed directly by means of HPLC (retention times: cis, 5.4 min; trans, 6.2 min at a flow rate of 1 mL/min). The quantum yield determination was done at the initial stage, i.e., within 30% conversion. The light intensities were determined to be 1.5 × 10^{-9} einstein/min by potassium ferrioxalate actinometer.[9] No reaction occurred without light under the same conditions.

Degree of Adsorption of Stilbazolium Ion (Stz$^+$) and Ru(bpy)$_3^{2+}$ on PSS^{n-}. The degree of adsorption of *cis*-Stz$^+$ on PSS^{n-} in H$_2$O was estimated by the zinc tetrasodium tetrasulfonatophenylporphyrin (ZnTPPS) fluorescence probe method (λ_{max} 605 ± 5 nm).[10] The fluorescence quenching study was done by changing the concentration of *cis*-Stz$^+$ quencher in deaerated aqueous solution of 0.4 mM (monomer unit concentration) (PSS)Na and 2.4 μM ZnTPPS. Figure 1 shows the case of (PSS)Na with the degree of polymerization of 5100, where the inflection point at [*cis*-Stz$^+$] = 0.35 mM indicates the degree of adsorption of *cis*-Stz$^+$ on PSS^{n-} as 87%. Other PSS^{n-}'s were examined similarly and their adsorption efficiencies are summarized in the fourth column in Table I.

The degree of adsorption of Ru(bpy)$_3^{2+}$ on PSS^{n-} was also estimated from the change of Ru(bpy)$_3^{2+}$ fluorescence intensities at 588 and 598 nm by adding PSS^{n-} ion according to the method reported by Nardo et al.[11] The dissociation equilibrium for the adsorption is expressed as eq 1, where K_d = [Ru(bpy)$_3^{2+}$][PSS^{n-}]/[Ru(bpy)$_3^{2+}\cdot$PSS^{n-}]. Solutions of

$$\mathrm{Ru(bpy)_3^{2+}\cdot PSS^{n-}} \overset{K_d}{\rightleftharpoons} \mathrm{Ru(bpy)_3^{2+} + PSS^{n-}} \qquad (1)$$

10 μM Ru(bpy)$_3^{2+}$ and various amounts (0–95.7 μM) of PSS^{n-} were prepared, and their fluorescence intensities (I) were monitored at 588 nm. The dissociation constant K_d was calculated according to the reported method.[11]

Measurement of the Aggregation Number N_A of Micellelike Clusters in the (PSS)Na-BTAC Complex [PSS$^{n-}\cdot$(BTA$^+$)$_n$]. The aggregation number, N_A, of the micellelike cluster was estimated by a Ru(bpy)$_3^{2+}$ fluorescence quenching technique using 9-methylanthracene as a quencher (Q) as developed by Turro et al.[12] The procedure is based on the fact that the fluorescence of Ru(bpy)$_3^{2+}$ is effectively quenched by a quencher in the same micelle, but is not influenced by the one in the other micelle. The ratio of the fluorescence intensities (I_0/I) in the absence and the presence of Q in the same micellelike cluster may be expressed as eq 2. Here, [Det] denotes the concentration of monomer

$$\frac{1}{\ln (I_0/I)} = \frac{1}{[\mathrm{Q}]N_A}[\mathrm{Det}] - \frac{[\text{free monomer}]}{[\mathrm{Q}]N_A} \qquad (2)$$

unit of PSS$^{n-}\cdot$(BTA$^+$)$_n$ and [free monomer] means the concentration of monomer unit without cluster formation. From a linear relationship between $\{\ln (I_0/I)\}^{-1}$ and detergent concentration, N_A can be obtained.

The following procedures were carried out in order to estimate N_A. A solution of 3.57 × 10^{-5} M Ru(bpy)$_3^{2+}$ and 2.04 × 10^{-5} M 9-methylanthracene containing various amounts (0–40 mM) of PSS$^{n-}\cdot$(BTA$^+$)$_n$ in 10% aqueous CH$_3$CN was deoxygenated by bubbling nitrogen gas, and the fluorescence intensities of Ru(bpy)$_3^{2+}$ were determined at 595 nm on excitation at 450 ± 5 nm using a Hitachi fluorescence spectrophotometer (Model 650-10).

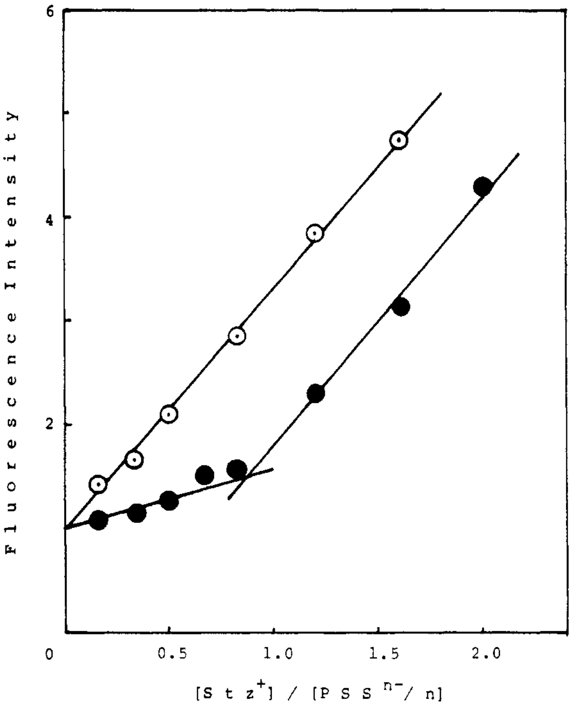
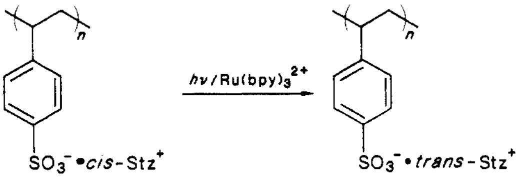


Figure 1. Stern–Volmer plots for the quenching of the fluorescence of ZnTPPS by *cis*-Stz$^+$I$^-$ in the presence (●) and the absence (⊙) of (PSS)Na in H$_2$O under argon: [PSS^{n-}/n] = 0.4 mM; [ZnTPPS] = 2.4 μM. Excited at 425 ± 5 nm and detected at 605 ± 5 nm.

Results and Discussion

Ru(bpy)$_3^{2+}$-Sensitized Photoisomerization of *cis*-Stz$^+$ Adsorbed on Poly(styrenesulfonate) Anion (PSS^{n-}). Irradiation of an equivalent mixture of *cis*-γ-stilbazolium cation (*cis*-Stz$^+$) and PSS^{n-} in the presence of Ru(bpy)$_3^{2+}$ as a sensitizer resulted in an efficient isomerization to afford *trans*-Stz$^+$ (eq 3). The



(3)

quantum yields for the cis-to-trans isomerization were much higher than unity and increased with increasing molar ratios of [Stz$^+$] to [PSS^{n-}/n]. As shown in Figure 2, the maximum quantum yield was obtained at a ratio of more than 2. The yields at the ratios

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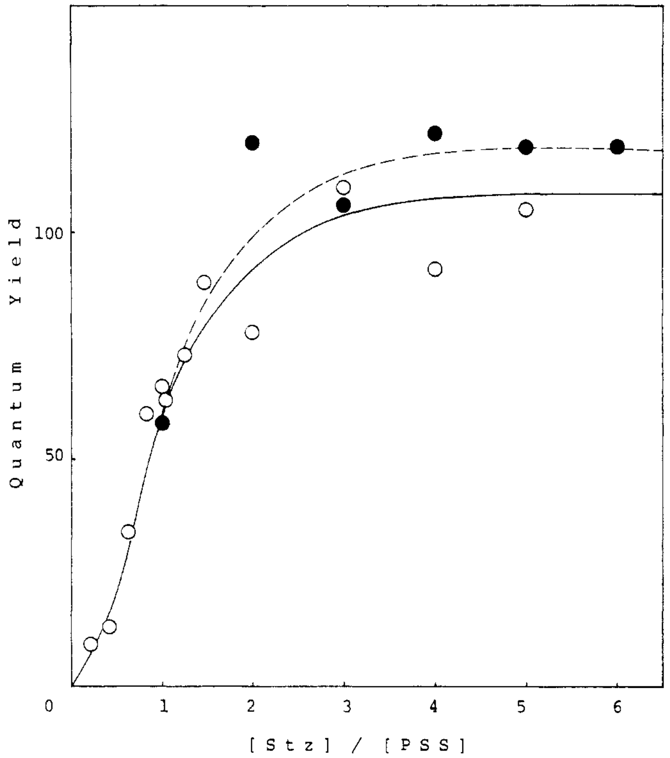


Figure 2. Dependence of the quantum yields of sensitized photoisomerization of *cis*-Stz^+ on the ratio of [*cis*-Stz^+] to [PSS^{n-}/n]; (○) for MW = (1.0 ± 0.2) × 10^6 from Toyo Soda Co. and (●) for MW = 1.06 × 10^6 from Pressure Chemical Co. conditions: [PSS^{n-}/n] = 0.4 mM; [*cis*-Stz^+] = 0–2.4 mM; in the case where the ratios were greater than unity, *cis*-γ-stilbazolium *p*-toluenesulfonate was added; [$Ru(bpy)_3^{2+}$] = 6.7 μM; irradiated at 468 ± 5 nm in water under argon.

of 1/1 and 3/1 are summarized in the last two columns in Table I. Remarkably interesting as it is, the maximum yields remain constant at around 90–110 in spite of 50-fold variation in the number of *cis*-Stz^+ molecules absorbed on a PSS^{n-} polymer chain. These observations suggest that *cis*-Stz^+ ions adsorbed on the polymer chain do not form a singly aggregated form but are divided into small aggregates, i.e., clusters. In order to verify this hypothesis, the adsorption or aggregation number of *cis*-Stz^+ ions on a PSS^{n-} polymer chain was determined as stated below.

Extent of Adsorption of *cis*-Stz^+ and $Ru(bpy)_3^{2+}$ on PSS^{n-}. The degree of adsorption of *cis*-Stz^+ ions was estimated according to the procedure reported by Whitten et al.[10] except for the use of ZnTPPS as a fluorescence probe (λ_{max} 606 nm) and summarized in the fourth column in Table I. The results show that *cis*-Stz^+ ions bind to PSS^{n-} anion sites quite efficiently (~90%) irrespective of the degrees of polymerization.

The degree of adsorption of $Ru(bpy)_3^{2+}$ ions was estimated from the dissociation constant K_d for the complex of $Ru(bpy)_3^{2+}$ and PSS^{n-} (see eq 1). The K_d values obtained were (1.88 ± 0.08) × 10^{-5} and (6.39 ± 1.16) × 10^{-5} M in the absence and the presence of β-phenethylammonium ion, respectively, as a photochemically inert substitute for *cis*-Stz^+. This means that 97% and 86% of the $Ru(bpy)_3^{2+}$ ions are complexed with PSS^{n-} anions in the absence and the presence of $PhCH_2CH_2N(CH_3)_3^+$ ion, respectively. Thus, we could safely assume that most of the *cis*-Stz^+ and $Ru(bpy)_3^{2+}$ ions added are adsorbed on the polyanion sites under the reaction conditions.

Formation of Micellelike Clusters in Stz^+-Adsorbed PSS^{n-} Polymer Anion. An electron-relay chain isomerization is undoubtedly operative in the present polyelectrolyte system, as judged from the remarkably high efficiency ($\Phi_{c\to t}$ = 50–110). The quantum yields, however, deviate considerably from the number of *cis*-Stz^+ ions adsorbed on one polymer chain of PSS^{n-} (cf. the adsorption numbers and $\Phi_{c\to t}$ in Table I). Thus, percent isomerization of Stz^+ ions on one polymer chain is ca. 26% for PSS^{n-} with *n* = 360 but only 2% for the case of *n* = 5100. These results suggest that the electron-relay chain isomerization is not widespread over the whole polymer chain of PSS^{n-}. A reasonable assumption is that the Stz^+ ions adsorbed on a polymer chain are divided into a number of small clusters and the electron relay between each cluster is inefficient. This assumption could be substantiated as stated below.

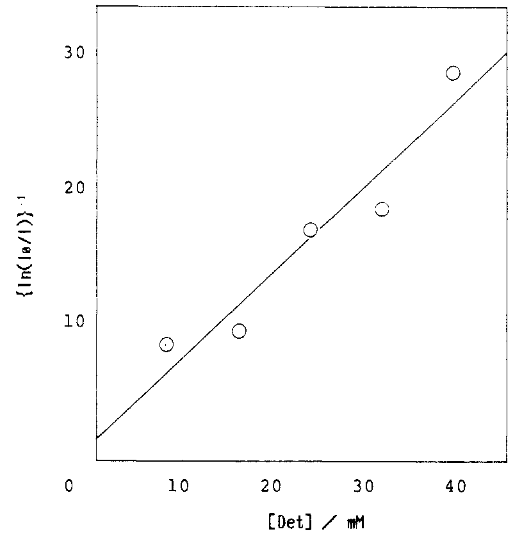
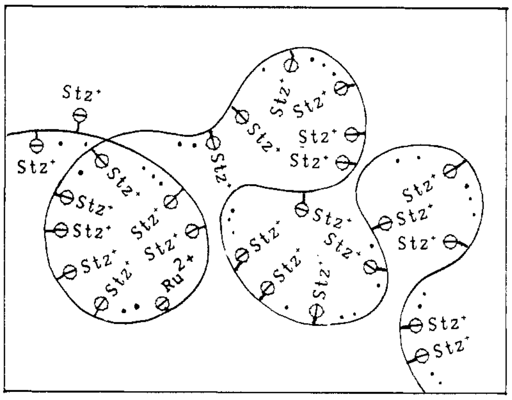


Figure 3. Plot of the reciprocal of ln (I_0/I) vs [Det] for the fluorescence quenching of $Ru(bpy)_3^{2+}$ by 9-methylanthracene in water containing 10% MeCN. [Det] is the concentration of a monomer unit of $PSS^{n-}\cdot(BTA^+)_n$, i.e., [$PSS^{n-}/n\cdot BTA$].

Scheme I. Schematic Model for Micellelike Clusters



The aggregation number N_A of Stz^+ and PSS^{n-} could be determined by the quenching of $Ru(bpy)_3^{2+}$ fluorescence with 9-methylanthracene;[1a] 10% aqueous acetonitrile was used as solvent to solubilize enough of the quencher.[13] The luminescence quenching by 9-methylanthracene was done in the presence of various amounts of the $PSS^{n-}\cdot(BTA^+)_n$ complex, BTA^+ being a photochemically inert substitute for *cis*-Stz^+. As shown in Figure 3, a linear relationship was obtained for the plot of reciprocal of ln (I_0/I) vs [Det] [i.e., [$PSS^{n-}/(BTA^+)_n$]], satisfying eq 2. The aggregation numbers thus obtained are summarized in Table I. The result shows that N_A's are constant in the range of 80–90, irrespective of the degree of polymerization (*n*). It is interesting to note the N_A values are in close coincidence with the isomerization efficiencies (Φ = 50–110). Previously, we confirmed that in a series of anionic micelle systems the electron-relay isomerization takes place in almost quantitative yields for all the Stz^+ ions adsorbed and the quantum yields were practically the same as the N_A values.[6a] Hence, the present results demonstrate that

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(13) The aqueous solution of PSS^{n-} and (*cis*-Stz^+)$_n$ ions could solubilize 9-methylanthracene; e.g., 0.248 mg of the anthracene was soluble in 100 g of an aqueous solution of 8.3 mM $PSS^{n-}\cdot$(*cis*-Stz^+)$_n$. Control experiments showed that the solubility of 9-methylanthracene was negligibly small without the two components; i.e., the solubility was less than 0.02 mg in the presence of either PSS^{n-} or Stz^+ ion.

Table II. Effect of Solvent on the Quantum Yields of Photosensitized Electron-Relay Isomerization[a]

	$\Phi_{c\rightarrow t}$		
polym deg (n)	CH_3COCH_3[b]	CH_3OH[b]	CH_3CN[b]
c	0.45		
SDS[d]	0.55		
100 ± 50	42		
360 ± 120	47		
1700	61	91	93
2400 ± 500	66		
5100			98

[a] Irradiated at 468 ± 5 nm under argon. Initial concentrations: [PSS^{n-}/n] = [*cis*-Stz$^+$] = 0.4 mM; [Ru(bpy)$_3^{2+}$] = 6.7 μM. [b] Solvents containing 10% H_2O. [c] Addition of equimolar HCl in place of PSS^{n-}. [d] SDS (sodium dodecylsulfate) was added in place of PSS^{n-}.

the poly(styrenesulfonate) anion chain and hydrophobic cation BTA$^+$ form micellelike clusters and their N_A values are in the range of 80–90, irrespective of the degree of polymerization, as depicted in Scheme I. So far, dodecyltrimethylammonium bromide and PSS^{n-} have been reported to form minimicelles, but their N_A values are less than 10.[14] Hence, the present evidence for micellelike clusters is new and quite interesting.

Effect of Solvents. To our surprise, a similar enhancement of the electron-relay isomerization was also observed in organic solvents such as acetone, methanol, and acetonitrile (Table II). The chain isomerization occurs in organic solvents as efficiently as in water. This suggests that the PSS^{n-}·(Stz$^+$)$_n$ forms micellelike clusters even in organic solvents. This is in sharp contrast to the case of typical anionic micelles; i.e., micelles do not prevail in 90% aqueous acetone as exemplified by the quantum yield of less than unity in the presence of sodium dodecylsulfate (Table II). It was, however, impossible to measure the aggregation number of PSS^{n-}·(BTA$^+$)$_n$ in the organic solvents on account of the experimental restriction that 9-methylanthracene quencher is quite soluble in the solvents.

In conclusion, the present results suggest that Stz$^+$ and PSS^{n-} form a number of divided micellelike clusters, resulting in the electron-relay chain isomerization of *cis*-Stz$^+$. This may provide an interesting model system for biopolymers and polyions.

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Registry No. PSS·*cis*-Stz, 116374-41-5; PSS·BTAC, 116350-20-0; Ru(bpy)$_3^{2+}$Cl$_2^-$, 14323-06-9.

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Mechanism of Aromatic Hydroxylation in the Fenton and Related Reactions. One-Electron Oxidation and the NIH Shift

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Abstract: Hydroxylation of substituted benzenes in the Fenton and peroxydisulfate oxidations has been studied mechanistically in relation to the NIH shift. One-electron oxidants such as Fe^{3+}, Cu^{2+}, and quinones increased the shift value effectively in aqueous or acetonitrile solutions. The shift values obtained were as high as 40–50% and dependent on both substituents (i.e., MeO $\ll$ Me, Cl, MeCO) and solvents. A high shift value was obtained also for the methoxylation, indicating unimportance of the arene oxide intermediate for the NIH shift. Oxygen reduced the shift effectively and sometimes was incorporated into product phenols with selective meta orientation. This means that oxygen abstracts a hydrogen atom from or adds to the oxycyclohexadienyl radical intermediate. It is concluded that the one-electron oxidation of the dienyl radical is the key step for the shift and its rates are dependent on substituents, oxidants, and solvents.

The NIH shift is a rearrangement of a hydrogen atom during enzymic aromatic hydroxylations,[1-3] and significantly large shift values have been reported also in model cytochrome P-450 oxidation.[4] The shift mechanism was originally understood by arene oxide intermediates,[1] but some results not compatible with the arene mechanism have also been reported.[5,6] Recently, a rearrangement via cationic intermediates has been suggested by cytochrome P-450 model study[7] or semiempirical MO calculation.[8]

As a nonenzymatic hydroxylation the Fenton oxidation is well-known and extensively studied.[9,10] Recently developed are the regioselective hydroxylation of alcohols,[11] the nonclassical[12a] or photo-Fenton reaction,[12b] efficient hydroxylation of aromatics

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