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Redox-Linked Protonation of $[Fe_4X_4(YR)_4]^{2-}$ (X,Y=S and Se; R=n-$C_{12}H_{25}$ and C_6H_4-p-t-Bu) in Aqueous Solutions

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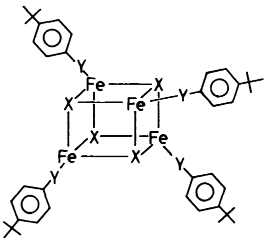
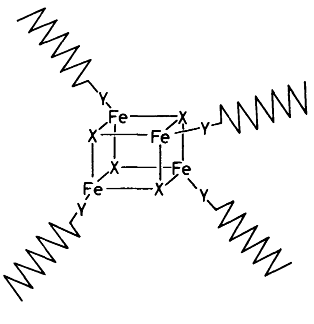
A series of $[Fe_4X_4(YR)_4]^{2-}$ (X,Y=S and Se; R=n-$C_{12}H_{25}$ and C_6H_4-p-t-Bu) were prepared as n-Bu_4N^+ salts. In aqueous Triton X-100 micellar solutions, only the reduced forms of $[Fe_4X_4(YR)_4]^{2-}$ (X,Y=S and Se; R=n-$C_{12}H_{25}$ and C_6H_4-p-t-Bu) undergo protonation reactions at the sulfur or selenium atom of the Fe_4X_4 (X=S and Se) core to exist as an equilibrium mixture of the protonated and unprotonated clusters. On the other hand, not only the oxidized but also the reduced forms of $[Fe_4X_4(YC_6H_4$-p-t-$Bu)_4]^{2-}$ (X,Y=S and Se) undergo protonation reactions in aqueous poly[2-(dimethylamino)hexanamide] (PDACA) solutions. The pK_{ox} values of $[Fe_4X_4(YC_6H_4$-p-t-$Bu)_4]^{2-}$ (X,Y=S and Se) vary depending on the terminal thiolate and selenolate ligands; 5.9 for Y=S and 6.8 for Y=Se, whereas the pK_{red} values of $[Fe_4X_4(YC_6H_4$-p-t-$Bu)_4]^{3-}$ are controlled by the core sulfur and selenium; 8.8 for X=S and 7.3 for X=Se. Such characteristic pK_{ox} and pK_{red} values suggest that the protonation takes place at the terminal sulfur or selenium atom of the oxidized clusters $[Fe_4X_4(YC_6H_4$-p-t-$Bu)_4]^{2-}$ (X,Y=S and Se), while it occurs at the sulfur or selenium atom of the Fe_4X_4 core of the reduced clusters $[Fe_4X_4(YC_6H_4$-p-t-$Bu)_4]^{3-}$ (X,Y=S and Se).

Iron–sulfur proteins containing Fe_4S_4 cores function as electron transfer catalysts in various biological redox reactions, such as photosynthesis,[1] nitrate reduction,[2] dinitrogen fixation,[3] and so on. As models of active sites of iron–sulfur proteins, the various iron–sulfur clusters with thiolate ligands have been synthesized.[4–9] The electrochemistry of those clusters[10–16] has elucidated that synthetic water soluble Fe_4S_4 clusters in aqueous solutions exhibit more positive redox potentials than water insoluble Fe_4S_4 clusters in organic solvents.[10,12,17] The redox potentials of the former, however, are still more negative than those of 4-Fe and 8-Fe ferredoxins (−0.52 to −0.73 V vs. SCE around pH 7.0) in water.[18] Such negative redox potentials of synthetic Fe_4S_4 clusters may be associated with the absence of hydrogen bondings formed between amide hydrogen of the peptide chain and sulfur of the Fe_4S_4 core and/or of the terminal cysteine residue ligated on the iron atoms in 4-Fe ferredoxins.[19–21] In accordance with this, the redox potential of $[Fe_4S_4(SCH_2CH_2CO_2)_4]^{6-}$ in water in the presence of bovine serum albumin or bovine insulin is 170—220 mV more positive than that of the cluster in water.[17] Recently, we have demonstrated that a Fe_4S_4 cluster $[Fe_4S_4(SC_6H_4$-p-n-$C_8H_{17})_4]^{2-}$ undergoes a redox-linked protonation in an aqueous micellar solution, and the protonated and unprotonated clusters exist as an equilibrium mixture below pH 10.[22] Such a redox-linked protonation of $[Fe_4X_4(Y$-n-$C_{12}H_{25})_4]^{2-}$ (X, Y=S and Se) has briefly been communicated to take place at the sulfur atom of the Fe_4S_4 core rather than the terminal thiolate sulfur on the basis of the electrochemical study in aqueous micellar solutions.[23] This paper describes the protonation behaviors of a series of $[Fe_4X_4(YC_6H_4$-p-t-$Bu)_4]^{2-}$ (**I**) as well as $[Fe_4X_4(Y$-n-$C_{12}H_{25})_4]^{2-}$ (**II**) (X, Y=S and Se) in aqueous micellar and poly[2-(dimethylamino)hexanamide] (PDACA) solutions in more detail.



I



II

(X, Y=S and Se)

Experimental

General Procedure and Materials. All manipulations were carried out under N_2 atmosphere. Solvents used for preparations and physical measurements were purified by distillations over dehydration chemicals; magnesium methoxide for MeOH, calcium hydride for MeCN, and calcium oxide for DMF. Commercially available guaranteed reagent grades of 1-dodecanethiol and p-t-butylbenzenethiol were used without purification. 1-Dodecaneselenol was obtained by the reaction of 1-bromododecane with selenourea supplied by Shinko Chemical Co., Ltd. in EtOH by the similar manner to the preparation of 1-dodecanethiol.[24] p-t-Butylbenzeneselenol,[25] $[n$-$Bu_4N]_2[Fe_4S_4(S$-t-$Bu)_4]$,[4] and $[n$-$Bu_4N]_2[Fe_4Se_4(S$-t-$Bu)_4]$[26] were prepared according to the literature. Poly[2-(dimethylamino)hexanamide] (PDACA) supplied by Toray Co., Ltd. was purified by dialysis.

Preparation of $[n$-$Bu_4N]_2[Fe_4S_4(SR)_4]$ (R=n-$C_{12}H_{25}$ and C_6H_4-p-t-Bu). To a MeOH (100 cm³) solution containing MeONa (2.43 g, 45 mmol) and 1-dodecanethiol or p-t-butylbenzenethiol (45 mmol) was added a filtered MeOH (50 cm³) solution of $FeCl_3$ (2.5 g, 15 mmol), and a MeOH (50 cm³) solution containing MeONa (0.81 g, 15 mmol) and

NaSH (0.84 g, 30 mmol) successively. After stirred for 24 h, the resulting black solution was filtered. To the filtrate was added slowly n-Bu_4NBr (4.0 g, 12 mmol) in MeOH (50 cm^3) to give a black precipitate of $[n\text{-}Bu_4N]_2[Fe_4S_4(SR)_4]$, which was collected by filtration and recrystallized from MeCN, 47% for $R=n\text{-}C_{12}H_{25}$ and 51% for $R=C_6H_4\text{-}p\text{-}t\text{-}Bu$. Found for $[n\text{-}Bu_4N]_2[Fe_4S_4(S\text{-}n\text{-}C_{12}H_{25})_4]$: C, 58.37; H, 10.37; N, 1.68%. Calcd for $C_{80}H_{172}Fe_4N_2S_8$: C, 58.51; H, 10.56; N, 1.71%. Found for $[n\text{-}Bu_4N]_2[Fe_4S_4(SC_6H_4\text{-}p\text{-}t\text{-}Bu)_4]$: C, 57.76; H, 8.28; N, 1.45%. Calcd for $C_{72}H_{124}Fe_4N_2S_8$: C, 57.74; H, 8.35; N, 1.87%.

Preparation of $[n\text{-}Bu_4N]_2[Fe_4S_4(SeR)_4]$ ($R=n\text{-}C_{12}H_{25}$ and $C_6H_4\text{-}p\text{-}t\text{-}Bu$). The selenolate ligated cluster $[n\text{-}Bu_4N]_2[Fe_4S_4(SeR)_4]$ ($R=n\text{-}C_{12}H_{25}$ and $C_6H_4\text{-}p\text{-}t\text{-}Bu$) was prepared by the ligand substitution reaction[27] of $[Fe_4S_4(S\text{-}t\text{-}Bu)_4]^{2-}$ with selenol as follows; a DMF (80 cm^3) solution containing $[n\text{-}Bu_4N]_2[Fe_4S_4(S\text{-}t\text{-}Bu)_4]$ (1.0 g, 0.84 mmol) and 1-dodecaneselenol (2.0 g, 8.0 mmol) or p-t-butylbenzeneselenol (1.8 g, 8.4 mmol) was stirred at 50 °C for 7 h, during which time N_2 gas was bubbled into the solution every 5 min to remove t-BuSH from the solution. The resulting solution was evaporated to dryness under reduced pressure. The residual solid was recrystallized from MeCN to give black crystals, 50% for $R=n\text{-}C_{12}H_{25}$ and 61% for $R=C_6H_4\text{-}p\text{-}t\text{-}Bu$. Found for $[n\text{-}Bu_4N]_2[Fe_4S_4(Se\text{-}n\text{-}C_{12}H_{25})_4]$: C, 52.07; H, 9.37; N, 1.62%. Calcd for $C_{80}H_{172}Fe_4N_2S_4Se_4$: C, 52.51; H, 9.48; N, 1.53%. Found for $[n\text{-}Bu_4N]_2[Fe_4S_4(SeC_6H_4\text{-}p\text{-}t\text{-}Bu)_4]$: C, 51.63; H, 7.44; N, 1.66%. Calcd for $C_{72}H_{124}Fe_4N_2S_4Se_4$: C, 51.31; H, 7.42; N, 1.66%.

Preparation of $[n\text{-}Bu_4N]_2[Fe_4Se_4(SR)_4]$ ($R=n\text{-}C_{12}H_{25}$ and $C_6H_4\text{-}p\text{-}t\text{-}Bu$). To a MeOH (20 cm^3) solution containing MeOLi (0.76 g, 20 mmol) and 1-dodecanethiol or p-t-butylbenzenethiol (20 mmol) was added a filtered MeOH (20 cm^3) solution of $FeCl_3$ (0.82 g, 5.0 mmol) in 10 min, followed by the addition of selenium powder (0.40 g, 5.0 mmol) rapidly. After stirred for 24 h, the resulting solution was filtered. To the filtrate was added slowly n-Bu_4NBr (1.2 g, 3.8 mmol) in MeOH (15 cm^3) to give a precipitate, which was collected by filtration, washed with MeOH, and dried in vacuo. The resulting powder was recrystallized from MeCN to give black crystals, 48% for $R=n\text{-}C_{12}H_{25}$ and 51% for $R=C_6H_4\text{-}p\text{-}t\text{-}Bu$. Found for $[n\text{-}Bu_4N]_2[Fe_4Se_4(S\text{-}n\text{-}C_{12}H_{25})_4]$: C, 52.14; H, 9.54; N, 1.50%. Calcd for $C_{80}H_{172}Fe_4N_2S_4Se_4$:C, 52.51; H, 9.48; N, 1.53%. Found for $[n\text{-}Bu_4N]_2[Fe_4Se_4(SC_6H_4\text{-}p\text{-}t\text{-}Bu)_4]$: C, 51.52; H, 7.43; N, 1.34%. Calcd for $C_{72}H_{124}Fe_4N_2S_4Se_4$: C, 51.31; H, 7.42; N, 1.66%.

Preparation of $[n\text{-}Bu_4N]_2[Fe_4Se_4(SeR)_4]$ ($R=n\text{-}C_{12}H_{25}$ and $C_6H_4\text{-}p\text{-}t\text{-}Bu$). A DMF (80 cm^3) solution containing $[n\text{-}Bu_4N]_2[Fe_4Se_4(S\text{-}t\text{-}Bu)_4]$ (1.16 g, 0.84 mmol) and 1-dodecaneselenol (2.1 g, 8.4 mmol) or p-t-butylbenzeneselenol (1.8 g, 8.4 mmol) was stirred at 50 °C for 7 h, during which time N_2 gas was bubbled into the solution. The resulting solution was evaporated to dryness under reduced pressure. The residual solid was recrystallized from MeCN to give black crystals, 45% for $R=n\text{-}C_{12}H_{25}$ and 67% for $R=C_6H_4\text{-}p\text{-}t\text{-}Bu$. Found for $[n\text{-}Bu_4N]_2[Fe_4Se_4(Se\text{-}n\text{-}C_{12}H_{25})_4]$: C, 47.39; H, 8.76; N, 1.18%. Calcd for $C_{80}H_{172}Fe_4N_2Se_8$: C, 47.63; H, 8.59; N, 1.39%. Found for $[n\text{-}Bu_4N]_2[Fe_4Se_4(SeC_6H_4\text{-}p\text{-}t\text{-}Bu)_4]$: C, 46.59; H, 6.69; N, 1.54%. Calcd for $C_{72}H_{124}Fe_4N_2Se_8$: C, 46.17; H, 6.67; N, 1.50%.

Preparation of Aqueous Micellar Solutions. A DMF (1.0 cm^3) solution of the cluster (12 μmol) was added to a stirred aqueous solution (25 cm^3, pH 5—10) containing $NaOH\text{-}H_3PO_4$ (0.1 mol dm^{-3}) and either Triton X-100 (0.025—0.5 mol dm^{-3}) or poly[2-(dimethylamino)hexanamide] (PDACA) (0.1 g). Dark brown aqueous Triton X-100 micellar or PDACA solutions thus prepared was used after filtration.

Physical Measurements. Cyclic voltammetry measurements were performed with a Hokuto Denko HA-501 potentiostat/galvanostat using a glassy carbon electrode in DMF or with a hanging mercury drop electrode (HMDE) in aqueous micellar solutions, respectively. As supporting electrolytes were used n-Bu_4NClO_4 in DMF and H_3PO_4–NaOH in aqueous solutions. A saturated calomel electrode (SCE) was used as a reference.

Results and Discussion

Redox Behaviors of $[Fe_4X_4(YR)_4]^{2-}$ (X, Y=S and Se; $R=n\text{-}C_{12}H_{25}$ and $C_6H_4\text{-}p\text{-}t\text{-}Bu$) in Aqueous Triton X-100 Micellar Solutions. Cyclic voltammograms of the present clusters show reversible $[Fe_4X_4(YR)_4]^{2-/3-}$ redox couples in the range $E_{1/2}=-0.94$ to -1.37 V vs. SCE in DMF (Table 1), where $E_{1/2}$ is approximated by the average of the cathodic and anodic peak potentials. As typical examples, the cyclic voltammograms of $[Fe_4S_4(S\text{-}n\text{-}C_{12}H_{25})_4]^{2-}$ and $[Fe_4S_4(SC_6H_4\text{-}p\text{-}t\text{-}Bu)_4]^{2-}$ are depicted in Fig. 1a and 1c. The redox potentials of synthetic Fe_4S_4 clusters as well as ferredoxins are affected significantly by the change of a medium.[10,18] The redox behaviors of synthetic Fe_4S_4 clusters in

Table 1. Electrochemical Parameters of the Clusters in DMF and in Aqueous Triton X-100 Micellar Solutions (pH 7.0)

Cluster	In DMF	In aq. micellar soln.		
	$E_{1/2}$[a]	$E_{1/2}$[a]	pK_a	$E_{1/2}$[a] at pH>pK_a
$[Fe_4S_4(S\text{-}n\text{-}C_{12}H_{25})_4]^{2-}$	−1.37	−0.59	9.1	−0.71
$[Fe_4S_4(Se\text{-}n\text{-}C_{12}H_{25})_4]^{2-}$	−1.35	−0.89	8.9	−1.04
$[Fe_4Se_4(S\text{-}n\text{-}C_{12}H_{25})_4]^{2-}$	−1.27	−0.85	7.7	−0.87
$[Fe_4Se_4(Se\text{-}n\text{-}C_{12}H_{25})_4]^{2-}$	−1.24	−0.91	7.7	−0.96
$[Fe_4S_4(SC_6H_4\text{-}p\text{-}t\text{-}Bu)_4]^{2-}$	−1.00	−0.55	8.5	−0.65
$[Fe_4S_4(SeC_6H_4\text{-}p\text{-}t\text{-}Bu)_4]^{2-}$	−0.99	−0.65	8.5	−0.67
$[Fe_4Se_4(SC_6H_4\text{-}p\text{-}t\text{-}Bu)_4]^{2-}$	−0.96	−0.78	7.5	−0.79
$[Fe_4Se_4(SeC_6H_4\text{-}p\text{-}t\text{-}Bu)_4]^{2-}$	−0.94	−0.79	7.3	−0.79

a) Values for the 2−/3− couple, V vs. SCE.

water, therefore, seem to be very important in connection with those of 4-Fe and 8-Fe ferredoxins. However, the fact that Fe_4S_4 clusters with alkanethiolate ligands such as $[Fe_4S_4(S\text{-}t\text{-}Bu)_4]^{2-}$ and $[Fe_4S_4(SCH_2CH_2CO_2)_4]^{6-}$ are subject to hydrolysis reactions in an aqueous medium[28] makes it difficult to study on the redox behaviors of synthetic Fe_4S_4 clusters in water. In order to protect the present clusters $[Fe_4X_4(YR)_4]^{2-}$ (X, Y=S and Se; R=n-$C_{12}H_{25}$ and C_6H_4-p-t-Bu) from such a hydrolysis reaction, those clusters are solubilized in an aqueous Triton X-100 micellar solution. The high stability of those clusters in this medium was confirmed by their electronic absorption spectra showing no appreciable change for 4 h under N_2. It has been reported that various surfactants strongly adsorb on solid electrodes such as glassy carbon and platinum plates and almost completely inhibit a direct electron transfer between those electrodes and the electrochemically active species in aqueous micellar solutions.[29] On the other hand, cyclic voltammograms of $[Fe_4S_4(SC_6H_4\text{-}p\text{-}n\text{-}C_8H_{17})_4]^{2-}$ solubilized in aqueous micellar and vesicle solutions have been obtained successfully[22,30] by taking advantage of a strong affinity of sulfur for an Hg electrode.[31] In accordance with this, the cyclic voltammograms of $[Fe_4S_4(S\text{-}n\text{-}C_{12}H_{25})_4]^{2-}$ and $[Fe_4S_4(SC_6H_4\text{-}p\text{-}t\text{-}Bu)_4]^{2-}$ by the use of a hanging mercury drop electrode (HMDE) clearly show the (2−/3−) redox couple at $E_{1/2}$=−0.59 and −0.55 V vs. SCE, respectively, in aqueous Triton X-100 micellar solution at pH 7.0 (Fig. 1b and 1d). A large cathodic peak current compared with anodic one of the $[Fe_4S_4(SR)_4]^{2-/3-}$ (R=n-$C_{12}H_{25}$ and C_6H_4-p-t-Bu) redox couple (Fig. 1b and 1d) suggests that adsorption of the oxidized cluster $[Fe_4S_4(SR)_4]^{2-}$ is stronger than that of the reduced species $[Fe_4S_4(SR)_4]^{3-}$ (R=n-$C_{12}H_{25}$ and C_6H_4-p-t-Bu) on the surface of an HMDE.[22,29,30] It has been shown that the adsorption of $[Fe_4S_4(SC_6H_4\text{-}p\text{-}n\text{-}C_8H_{17})_4]^{2-}$ on an Hg electrode causes the $E_{1/2}$ value of the cluster to shift cathodically by 80 mV compared with that of the free species in solutions.[30] Based on this fact, the $E_{1/2}$ values of $[Fe_4X_4(YR)_4]^{2-/3-}$ couple (X, Y=S and Se; R=n-$C_{12}H_{25}$ and C_6H_4-p-t-Bu) in aqueous Triton X-100 micellar solutions at pH 7.0 are considered to be shifted anodically by at least 150—780 mV compared with those in DMF and fall in the range −0.55 to −0.91 V vs. SCE at pH 7.0 (Table 1), which are compared to the redox potentials of 4-Fe (−0.52 to −0.67 V vs. SCE) and 8-Fe ferredoxins (−0.65 to −0.73 V vs. SCE) in water.[18] Thus, the redox potentials of Fe_4X_4 (X=S and Se) clusters are affected significantly by the extrinsic effect of the medium used.

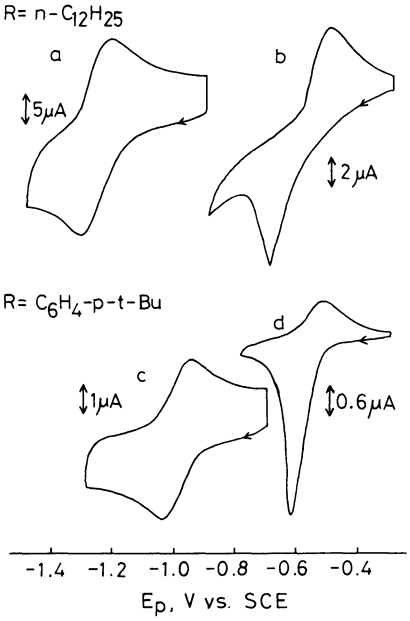


Fig. 1. Cyclic voltammograms of $[Fe_4S_4(SR)_4]^{2-}$ with a glassy carbon electrode in DMF (a, c) and with a hanging mercury drop electrode in aqueous Triton X-100 micellar solutions at pH 7.0 (b, d); scan rate 0.2 V s^{-1}.

Although the concentration of Triton X-100 (0.025—0.5 mol dm^{-3}) hardly influences the redox potentials of the present clusters, proton concentrations gave a significant effect on the redox potentials. Figure 2 shows the plots of the $E_{1/2}$ values of the present clusters vs. pH of aqueous Triton X-100 micellar solutions at 20 °C. The $E_{1/2}$ values of the $[Fe_4S_4(Y\text{-}n\text{-}C_{12}H_{25})_4]^{2-/3-}$ (Y=S (○) and Se (●) in Fig. 2a) and $[Fe_4Se_4(Y\text{-}n\text{-}C_{12}H_{25})_4]^{2-/3-}$ (Y=S (△) and Se (▲) in Fig. 2a) couples are shifted by about −55 mV/pH in the pH lower than ca. 9.0 and 7.7, respectively, while they remain constant in the pH higher than those values. Similarly, $[Fe_4S_4(YC_6H_4\text{-}p\text{-}t\text{-}Bu)_4]^{2-}$ (Y=S (○) and Se (●) in Fig. 2b) and $[Fe_4Se_4(YC_6H_4\text{-}p\text{-}t\text{-}Bu)_4]^{2-}$ (Y=S (△) and Se (▲) in Fig. 2b) display the same shifts of $E_{1/2}$ in the pH lower than ca. 8.5 and 7.3, respectively, and the $E_{1/2}$ values are constant in the pH higher than those values. The pH dependence of $E_{1/2}$ values (ca. −55.0 mV/pH) for the present clusters indicates that the redox-linked protonation of the clusters takes place and the resulting protonated cluster exists as an equilibrium mixture with unprotonated one. The electron density of $[Fe_4X_4(YR)_4]^{3-}$ (X, Y=S, Se; R=n-$C_{12}H_{25}$, C_6H_4-p-t-Bu) is apparently larger than that of $[Fe_4X_4(YR)_4]^{2-}$. The turning point of each plot in Fig. 2a and 2b, therefore, corresponds to the pK_a value of the reduced forms of the clusters, which is classified into four groups: ca. 9.0, 7.7, 8.5, and 7.3 for the $[Fe_4S_4(Y\text{-}n\text{-}C_{12}H_{25})_4]^{3-}$, $[Fe_4Se_4(Y\text{-}n\text{-}C_{12}H_{25})_4]^{3-}$, $[Fe_4S_4(YC_6H_4\text{-}p\text{-}t\text{-}Bu)_4]^{3-}$, and $[Fe_4Se_4(YC_6H_4\text{-}p\text{-}t\text{-}Bu)_4]^{3-}$ (Y=S and Se), respectively (Table 1). Thus, the pK_a values of the $[Fe_4X_4(YR)_4]^{3-}$ (X, Y=S and Se; R=n-$C_{12}H_{25}$ and C_6H_4-p-t-Bu) are controlled by the difference of the Fe_4S_4 and Fe_4Se_4 cores rather than that of the terminal sulfur and selenium atoms of the Y-n-$C_{12}H_{25}$ or YC_6H_4-p-t-Bu moiety. This result

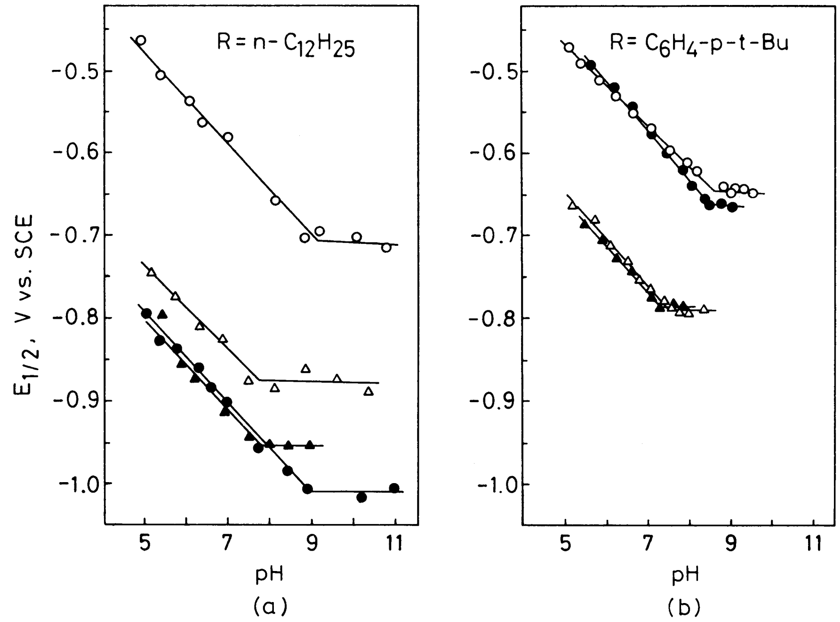
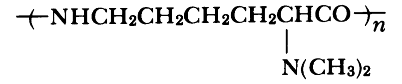


Fig. 2. Plots of the $E_{1/2}$ values of the $[Fe_4X_4(YR)_4]^{2-/3-}$ (R=n-$C_{12}H_{25}$ (a) and C_6H_4-p-t-Bu (b)) redox couples vs. pH in aqueous Triton X-100 micellar solutions at 20 °C; X,Y=S,S (○); S,Se (●); Se,S (△); Se,Se (▲).

suggests that the present redox-linked protonation takes place at the sulfur or selenium atom of the Fe_4X_4 core (X=S and Se) of $[Fe_4X_4(YR)_4]^{3-}$ (X, Y=S and Se; R=n-$C_{12}H_{25}$ and C_6H_4-p-t-Bu).

Redox Behaviors of $[Fe_4X_3(YC_6H_4$-p-t-$Bu)_4]^{2-}$ (X, Y=S and Se) in an Aqueous Poly[2-(dimethylamino)-hexanamide] (PDACA) Solution. The preceding discussion reveals that the protonation of $[Fe_4X_4(YR)_4]^{3-}$ (X, Y=S and Se; R=n-$C_{12}H_{25}$ and C_6H_4-p-t-Bu) in aqueous Triton X-100 micellar solutions takes place at the sulfur or selenium atom of the Fe_4X_4 (X=S and Se) core. The hydrophobic sphere of a nonionic Triton X-100 micelle is, however, apparently different from the environments formed by polypeptide chains of 4-Fe ferredoxins, which may be stabilized by hydrogen bondings between amide protons of peptide chains and terminal and/or core sulfur atoms. In order to introduce amide groups around the Fe_4S_4 core in a model system, poly[2-(dimethylamino)hexanamide] (PDACA) involving both amide and amino groups in the polymer chains was employed for solubilizing the clusters in aqueous solutions. The

PDACA:



$$\left[\!-NHCH_2CH_2CH_2CH_2\underset{\substack{|\\ N(CH_3)_2}}{C}HCO-\right]_n$$

electronic absorption spectrum of $[Fe_4S_4(S$-n-$C_{12}H_{25})_4]^{2-}$ in an aqueous PDACA solution (pH 7.0), however, showed a decrease of the absorption maximum at 420 nm with a half-life $t_{1/2}=1.3\times10^3$ s at 20 °C, suggesting that $[Fe_4S_4(S$-n-$C_{12}H_{25})_4]^{2-}$ slowly undergoes a hydrolysis reaction in this medium. On the other hand, the cluster in the Triton X-100 micellar solution exhibited no spectral change for 4 h under N_2. Such a difference may result from a strong hydrophobicity of Triton X-100 micelle compared with an aqueous PDACA solution. The hydrolysis of $[Fe_4S_4(S$-n-$C_{12}H_{25})_4]^{2-}$ in an aqueous PDACA solution may result in a dissociation of the terminal ligand, which is adsorbed strongly on an HMDE.[31] In fact, the cyclic voltammogram of $[Fe_4S_4(S$-n-$C_{12}H_{25})_4]^{2-}$ in an aqueous PDACA solution at pH 7.0 showed a pair of cathodic and anodic waves at $E_{pc}=-0.63$ V and $E_{pa}=-0.56$ V vs. SCE, respectively, which are consistent not only with the peak potentials but also with the appearance of those of S-n-$C_{12}H_{25}^-$ (n-Bu_4N^+ salt) in the same medium. Similarly, the redox waves due to S-n-$C_{12}H_{25}^-$ or Se-n-$C_{12}H_{25}^-$ were observed in the cyclic voltammograms of other three clusters in aqueous PDACA solutions. Thus, the 1-dodecanethiolate and -selenolate ligated clusters $[Fe_4X_4(Y$-n-$C_{12}H_{25})_4]^{2-}$ (X, Y=S and Se) undergo the ligand dissociation in aqueous PDACA solutions.

In contrast to the lability of $[Fe_4X_4(Y$-n-$C_{12}H_{25})_4]^{2-}$ in aqueous PDACA solution, $[Fe_4X_4(YC_6H_4$-p-t-$Bu)_4]^{2-}$ (X, Y=S and Se) is fairly stable in this medium, since the electronic absorption spectra of the latter except for $[Fe_4Se_4(SeC_6H_4$-p-t-$Bu)_4]^{2-}$ [32] in an aqueous PDACA solution (pH 7.0) were almost unchanged for 6 h. In fact, $[Fe_4X_4(YC_6H_4$-p-t-$Bu)_4]^{2-}$ (X, Y=S and Se) in aqueous PDACA solution at pH 7.0 exhibit each redox couple arising from the cluster ($E_{1/2}=-0.57$ for

X, Y=S, S; −0.56 for X, Y=S, Se; −0.79 for X, Y=Se, S; −0.77 V vs. SCE for X, Y=Se, Se), and the redox couple neither of SC_6H_4-*p*-*t*-Bu^- (E_{pc}=−0.70 and E_{pa}=−0.60 V) nor of SeC_6H_4-*p*-*t*-Bu^- (E_{pc}=−1.01 and E_{pa}=−0.89 V vs. SCE) was observed, indicating that $[Fe_4X_4(YC_6H_4$-*p*-*t*-$Bu)_4]^{2-}$ (X, Y=S and Se) undergoes one-electron redox reaction in aqueous PDACA solution without dissociation of the YC_6H_4-*p*-*t*-Bu^- ligand at pH 7.0. Moreover, the cyclic voltammograms of those clusters obtained even after applying the electrode potential at −1.00 V vs. SCE for 5 min exhibited only the redox waves of those clusters. The electrochemical study on the clusters in aqueous PDACA solutions, therefore, is restricted to $[Fe_4X_4(YC_6H_4$-*p*-*t*-$Bu)_4]^{2-}$ (X, Y=S and Se) in the present study.

The $E_{1/2}$ values of the $[Fe_4X_4(YC_6H_4$-*p*-*t*-$Bu)_4]^{2-/3-}$ redox couples at various pH are depicted in Fig. 3, which reveals that all the $E_{1/2}$ values for X, Y=S and Se are shifted cathodically in linear fashion with increasing the pH value in the intermediate pH range, being similar to those in aqueous Triton X-100 micellar solutions, while the values are likely to show a tendency to level off from each linear relation not only in alkaline but also in acidic sides.[33] Such characteristic pH dependence of the $E_{1/2}$ value may be interpreted in terms of protonation/deprotonation equilibria of the oxidized clusters $[Fe_4X_4(YC_6H_4$-*p*-*t*-$Bu)_4]^{2-}$ as well as of the reduced species $[Fe_4X_4(YC_6H_4$-*p*-*t*-$Bu)_4]^{3-}$ (X, Y=S and Se) in aqueous PDACA solutions, as shown in Scheme 1, where K_{ox} and K_{red} are the acid dissociation constants of the protonated species $[Fe_4X_4(YR)_4H]^-$ and $[Fe_4X_4(YR)_4H]^{2-}$ (X, Y=S and Se; R=C_6H_4-*p*-*t*-Bu), respectively, as expressed by Eqs. 1 and 2, and

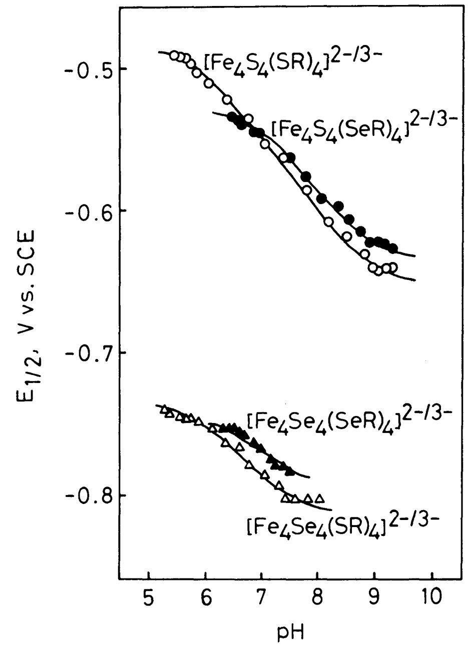


Fig. 3. Plots of the $E_{1/2}$ values of the $[Fe_4X_4(YR)_4]^{2-/3-}$ (R=C_6H_4-*p*-*t*-Bu) redox couples in aqueous PDACA solutions vs. pH at 10°C; X,Y=S,S (○); S,Se (●); Se,S (△); Se,Se (▲).

$$K_{ox} = \frac{[[Fe_4X_4(YR)_4]^{2-}][H^+]}{[[Fe_4X_4(YR)_4H]^-]} \tag{1}$$

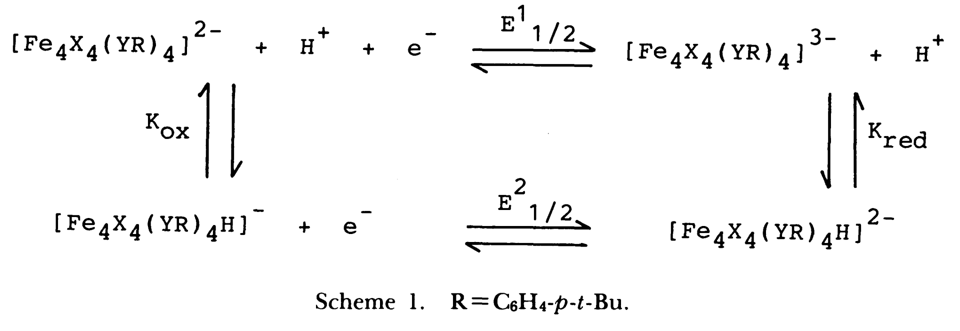
$$K_{red} = \frac{[[Fe_4X_4(YR)_4]^{3-}][H^+]}{[[Fe_4X_4(YR)_4H]^{2-}]} \tag{2}$$

$E^1_{1/2}$ and $E^2_{1/2}$ are the half-wave potentials of the redox couples of unprotonated and protonated species, respectively. The half-wave potential $E_{1/2}$ for the overall electrode reaction, therefore, can be written as Eq. 3 or 4,[34,35] where R, T, and F are the gas constant, temperature, and the Faraday constant, respectively.

$$E_{1/2} = E^1_{1/2} + \frac{RT}{F}\ln\frac{K_{ox}(K_{red} + [H^+])}{K_{red}(K_{ox} + [H^+])} \tag{3}$$

$$E_{1/2} = E^2_{1/2} + \frac{RT}{F}\ln\frac{K_{red} + [H^+]}{K_{ox} + [H^+]} \tag{4}$$

An anodic shift of $E_{1/2}$ values with increasing the proton concentration (Fig. 3) suggests that the K_{ox} value is larger than the K_{red} value (Eq. 3). Therefore, $E_{1/2}$ approaches to $E^1_{1/2}$ (Eq. 3) and $E^2_{1/2}$ (Eq. 4) under the proton concentrations being $[H^+] \ll K_{red}$ (Eq. 3) and $[H^+] \gg K_{ox}$ (Eq. 4), respectively. Thus, the redox potential $E_{1/2}$ of $[Fe_4X_4(YC_6H_4$-*p*-*t*-$Bu)_4]^{2-/3-}$ (X, Y=S and Se) in aqueous PDACA solution may be leveled off both in acidic and in alkaline regions (Fig. 3). Computer simulation curves of the $E_{1/2}$ value using Eq. 3 or 4 with the pK_{red}, pK_{ox}, and $E^1_{1/2}$ or $E^2_{1/2}$ values listed in Table 2 give reasonable agreement with the observed $E_{1/2}$ values of those clusters,[36] as shown by solid lines in Fig. 3.



Scheme 1. R=C_6H_4-*p*-*t*-Bu.

Table 2. p*K* Values of the Oxidized and Reduced Clusters in Aqueous PDACA Solution

Cluster	pK_{ox}	pK_{red}[a)]	$E^1_{1/2}$[b)]	$E^2_{1/2}$[b)]
$[Fe_4S_4(SC_6H_4\text{-}p\text{-}t\text{-}Bu)_4]^{2-}$	5.85	8.80	−0.650	−0.484
$[Fe_4S_4(SeC_6H_4\text{-}p\text{-}t\text{-}Bu)_4]^{2-}$	6.90	8.80	−0.632	−0.526
$[Fe_4Se_4(SC_6H_4\text{-}p\text{-}t\text{-}Bu)_4]^{2-}$	5.85	7.30	−0.811	−0.732
$[Fe_4Se_4(SeC_6H_4\text{-}p\text{-}t\text{-}Bu)_4]^{2-}$	6.70	7.30	−0.795	−0.744

a) Values for the 3− species. b) Values for the 2−/3− couple.

The pK_{red} values of $[Fe_4X_4(YC_6H_4\text{-}p\text{-}t\text{-}Bu)_4]^{3-}$ (Table 2) obtained from the simulation are devided into two groups; 8.8 for X=S and 7.3 for X=Se, where Y=S and Se. The close similarity of the pK_{red} values of the clusters with Fe_4S_4 and Fe_4Se_4 cores in an aqueous PDACA solution to the pK_a values of those in an aqueous Triton X-100 micellar solution also supports the view that the pK_a values in Triton X-100 micellar solutions are associated with the proton dissociation constants of the reduced species of the clusters. Thus, the protonation of the reduced clusters takes place at the sulfur or selenium of the Fe_4X_4 core (X=S and Se) both in aqueous Triton X-100 micellar and in aqueous PDACA solutions. On the other hand, the pK_{ox} values of $[Fe_4X_4(YC_6H_4\text{-}p\text{-}t\text{-}Bu)_4]^{2-}$ (Table 2) are devided into two group; 5.85 for $[Fe_4X_4(SC_6H_4\text{-}p\text{-}t\text{-}Bu)_4]^{2-}$ and 6.8±0.1 for $[Fe_4X_4(SeC_6H_4\text{-}p\text{-}t\text{-}Bu)_4]^{2-}$ (X=S and Se). This behavior indicates that pK_{ox} values are controlled by the terminal sulfur and selenium atoms in contrast to pK_{red} which depends on the core sulfur or selenium atom. Thus, the protonation of the oxidized clusters $[Fe_4X_4(YC_6H_4\text{-}p\text{-}t\text{-}Bu)_4]^{2-}$ (X, Y=S and Se) takes place at the terminal sulfur or selenium atoms in aqueous PDACA solutions. These results lead us to the conclusion that the basicities of the terminal sulfur and selenium in the oxidized clusters may be stronger than those of the core sulfur and selenium atoms, while in the reduced cluster, the basicities may be opposite; the core sulfur and selenium atoms stronger than the terminal those atoms.

References

1) D. C. Yoch, D. I. Arnon, and W. V. Sweeney, *J. Biol. Chem.*, **250**, 8330 (1975); H. Hiura, T. Kakuno, J. Yamashita, H. Matsubara, and T. Horio, *J. Biochem.*, **89**, 1787 (1981); K. T. S. Shanmugan, D. B. Buchanan, and D. E. Arnon, *Biochim. Biophys. Acta*, **256**, 477 (1972).

2) K. M. Werber and M. Mevarech, *Arch. Biochem. Biophys.*, **186**, 60 (1978); S. Seki, M. Hagiwara, K. Kudo, and M. Ishimoto, *J. Biochem.*, **85**, 833 (1979).

3) B. E. Smith, D. J. Lowe, and R. C. Bray, *Biochem. J.*, **137**, 169 (1974); M. Tanaka, M. Haniu, K. T. Yasunobu, and L. E. Mortenson, *J. Biol. Chem.*, **252**, 7093 (1977); V. Sunderson and F. M. Ausubel, *J. Biol. Chem.*, **256**, 2808 (1981).

4) B. A. Averill, T. Herskovitz, R. H. Holm, and J. A. Ibers, *J. Am. Chem. Soc.*, **95**, 3523 (1973).

5) R. H. Holm, W. D. Philips, B. A. Averill, J. J. Mayerle, and T. Herskovitz, *J. Am. Chem. Soc.*, **96**, 2109 (1974).

6) G. R. Dukes and R. H. Holm, *J. Am. Chem. Soc.*, **97**, 528 (1975).

7) R. W. Johnson and R. H. Holm, *J. Am. Chem. Soc.*, **100**, 5338 (1978).

8) G. B. Wong, D. M. Kurtz, Jr., R. H. Holm, L. E. Mortenson, and R. G. Upchurch, *J. Am. Chem. Soc.*, **101**, 3078 (1979).

9) M. A. Bobrik, E. J. Laskowski, R. W. Johnson, W. O. Gillum, J. M. Berg, K. O. Hodgson, and R. H. Holm, *Inorg. Chem.*, **17**, 1402 (1978).

10) B. V. DePamphilis, B. A. Averill, T. Herskovitz, L. Que, Jr., and R. H. Holm, *J. Am. Chem. Soc.*, **96**, 4159 (1974).

11) L. Que, Jr., J. R. Anglin, M. A. Bobrik, A. Davison, and R. H. Holm, *J. Am. Chem. Soc.*, **96**, 6042 (1974).

12) C. L. Hill, J. Renaud, R. H. Holm, and L. E. Mortenson, *J. Am. Chem. Soc.*, **99**, 2549 (1977).

13) G. Christou, P. M. Mascharak, W. H. Armstrong, G. C. Papaefthymiou, R. B. Frankel, and R. H. Holm, *J. Am. Chem. Soc.*, **104**, 2820 (1982).

14) W. H. Armstrong, P. K. Mascharak, and R. H. Holm, *J. Am. Chem. Soc.*, **104**, 4373 (1982).

15) R. E. Johnson, G. C. Papaefthymiou, R. B. Frankel, and R. H. Holm, *J. Am. Chem. Soc.*, **105**, 7280 (1983).

16) G. Christou, C. D. Garner, R. M. Miller, C. E. Johnson, and J. D. Rush, *J. Chem. Soc., Dalton Trans.*, **1983**, 2363.

17) T. C. Bruice and R. Maskiewicz, *J. Chem. Soc., Chem. Commun.*, **1978**, 703; B. Odell and P. J. Geary, *J. Chem. Soc., Dalton Trans.*, **1984**, 29.

18) C. L. Hill, J. Renaud, R. H. Holm, and L. E. Mortenson, *J. Am. Chem. Soc.*, **99**, 2549 (1977).

19) E. T. Lode, C. L. Murray, and J. C. Rabinowitz, *J. Biol. Chem.*, **251**, 1683 (1976).

20) J. C. Rabinovitz and W. V. Sweeney, *Annu. Rev. Biochem.*, **49**, 139 (1980).

21) E. Adman, K. D. Watenpaugh, and L. H. Jensen, *Proc. Natl. Acad. Sci. U.S.A.*, **72**, 4854 (1975).

22) K. Tanaka, T. Tanaka, and I. Kawafune, *Inorg. Chem.*, **23**, 517 (1984); K. Tanaka, M. Moriya, and T. Tanaka, *Inorg. Chem.*, **25**, 835 (1986).

23) M. Nakamoto, K. Tanaka, and T. Tanaka, *J. Chem. Soc., Chem. Commun.*, **1986**, 1669.

24) G. G. Urquhart, J. W. Gates, Jr., R. Connor, L. I. Smith, R. T. Arnold, and K. Stevenson, *Org. Synth.*, Coll. Vol. 3, 363 (1955).

25) T. H. Colle and E. S. Lewis, *J. Am. Chem. Soc.*, **101**, 1810 (1979).

26) G. Christou, B. Ridge, and H. N. Rydon, *J. Chem. Soc., Dalton Trans.*, **1978**, 1423.

27) L. Que, Jr., M. A. Bobrick, J. A. Ibers, and R. H.

Holm, *J. Am. Chem. Soc.*, **96**, 4168 (1974); K. Tanaka, M. Nakamoto, Y. Tashiro, and T. Tanaka, *Bull. Chem. Soc. Jpn.*, **58**, 316 (1985).

28) T. C. Bruice, R. Maskiewicz, and R. C. Job, *Proc. Natl. Sci. U.S.A.*, **72**, 231 (1975); R. C. Job and T. C. Bruice, *ibid.*, **72**, 2478 (1975).

29) Z. Kozarac and B. Cosovic, *Bioelectrochem. Bioenerg.*, **12**, 353 (1984); B. Cosovic, N. Matina, and Z. Kozarac, *J. Electroanal. Chem.*, **113**, 239 (1980); L. Pospisil, J. Kuta, E. Muller, and H.-D. Dorfler, *J. Electroanal. Chem.*, **106**, 359 (1980); F. Muller, H. Emons, and H.-D. Dorfler, *Bioelectrochem. Bioenerg.*, **10**, 279 (1983).

30) K. Tanaka, M. Masanaga, and T. Tanaka, *J. Am. Chem. Soc.*, **108**, 5448 (1986).

31) R. Parsons and P. C. Symons, *Trans. Faraday Soc.*, **64**, 1077 (1968); N. Kobayashi, A. Osawa, K. Shimizu, Y. Hayashi, H. Kimoto, and T. Fujisawa, *J. Polym. Sci., Polym. Lett. Ed.*, **15**, 137 (1977); P. J. Peerce and F. C. Anson, *J. Electroanal. Chem. Interfacial Electrochem.*, **105**, 317 (1979).

32) The electronic absorption spectrum of $[Fe_4Se_4(SeC_6H_4\text{-}p\text{-}t\text{-}Bu)_4]^{2-}$ in aqueous PDACA showed the 76% decrease of the absorptivity of the CT band at 490 nm for 6 h.

33) The cyclic voltammogram of $[Fe_4X_4(YC_6H_4\text{-}p\text{-}t\text{-}Bu)_4]^{2-}$ (X, Y=S and Se) exhibits only a (2−/3−) redox couple in the intermediate pH range (Fig. 3). When pH is higher than ca. 7.3 or 8.8 and lower than ca. 5.9 or 6.8, however, a new redox couple due to free $YC_6H_4\text{-}p\text{-}t\text{-}Bu^-$ (Y=S and Se) appeared besides a redox couple of the clusters, suggesting the partial dissociation of $YC_6H_4\text{-}p\text{-}t\text{-}Bu^-$ (Y=S and Se) in the pH range higher than ca. 7.3 or 8.8 and lower than ca. 5.9 or 6.8 in the PDACA solution.

34) M. Masanaga, S. Kuwabata, K. Tanaka, and T. Tanaka, *Chem. Lett.*, **1986**, 1531.

35) P. L. Dutton and D. F. Wilson, *Biochim. Biophys. Acta*, **346**, 165 (1974); R. S. Magliozzo, B. A. McIntosh, and W. V. Sweeny, *J. Biol. Chem.*, **257**, 3506 (1982).

36) The $E_{1/2}$ value of the $[Fe_4Se_4(SeC_6H_4\text{-}p\text{-}t\text{-}Bu)_4]^{2-/3-}$ couple observed in acid and alkaline regions is slightly deviated from computer simulation curves of the $E_{1/2}$ value, which may be due to the instability of the Fe_4Se_4 cluster with selenolate ligands, as described elsewhere.[9,32]