December, 1988] © *1988 The Chemical Society of Japan* *Bull. Chem. Soc. Jpn.*, *61*, *4385—4388 (1988)*

# The Redox Reaction by Ferrocene Derivatives Introduced to a Crown Ether in a Liquid Membrane System

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In an organic liquid membrane system, 4′-(ferrocenylcarbonylamino)benzo-18-crown-6 (FCC) dissolved in a dichloromethane membrane was found to reduce hexacyanoferrate(III) ions in the aqueous phase to hexacyanoferrate(II) ions at a rate dependent on the type of metal ion coexisting in the aqueous phase, and bound to the benzo-18-crown-6 unit of FCC.

Transport of electrons, protons, and metal ions across a biological membrane plays an essential role in the transduction of information through the biological membrane. It is known that the transport is mediated by various substances, and furthermore, the different transport systems are frequently coupled with each other.[1)]

Recently, several kinds of crown ether derivatives including "antenna" compounds, which respond to light,[2,3)] pH,[4,5)] redox reagents,[6–8)] and electrochemical potential,[9–12)] have been synthesized and investigated for the facilitated capture and transport of cations.

In the present study, 4′-(ferrocenylcarbonylamino)-benzo-18-crown-6 (FCC), composed of a ferrocene and a crown ether unit, was synthesized. Ferrocene derivatives are known as electron carriers through a lipid and liquid organic membrane in the presence of lipophilic anions. A ferrocene unit possesses a positive charge in the oxidized state and is neutral in the reduced state.[13)] 18-Crown-6 forms a complex with alkali metal ions, especially with a $K^+$ ion, and it is capable of transporting metal ions through an organic liquid membrane.[14,15)]

We examined the redox reaction of FCC solubilized in an organic liquid membrane with a redox reagent dissolved in an aqueous phase containing metal ions. The purpose of the present study is to investigate if the redox reaction of the ferrocene unit of FCC is regulated by the binding of cation with the crown ether unit of FCC, and to examine the possibility of coupled electron and metal-ion transport across an organic liquid membrane.

## Experimental

**Synthesis.** 4′-(Ferrocenylcarbonylamino)benzo-18-crown-6 was prepared according to the scheme shown in Fig. 1. Benzo-18-crown-6 was synthesized from catechol and pentaethylene glycol.[16)] An amino group was introduced to the benzene ring of benzo-18-crown-6 by a nitration and reduction reaction.[17)] Ferrocenecarbonyl chloride[18)] was coupled with 4′-aminobenzo-18-crown-6 in a *N*,*N*-dimethylformamide (DMF) solution with stirring overnight. DMF was distilled off and the residue was dried under reduced pressure. The crude product obtained was purified by eluting through a silica-gel column (95% $CHCl_3$/5% $CH_3OH$). Found: C, 59.97; H, 6.27; N, 2.30%. Calcd for $C_{27}H_{33}NO_7Fe$: C, 60.15; H, 6.18; N, 2.60%.

1,1′-Dibutylferrocene (DBF) and dibenzo-18-crown-6 (DBC) were commercially available and used as reference mediators.

**Measurement.** The electron and cation transport were measured using a U-shaped tube.[19)] The aqueous phase I (5 ml) was separated from aqueous phase II (5 ml) by an organic liquid membrane phase (20 ml) containing mediators.

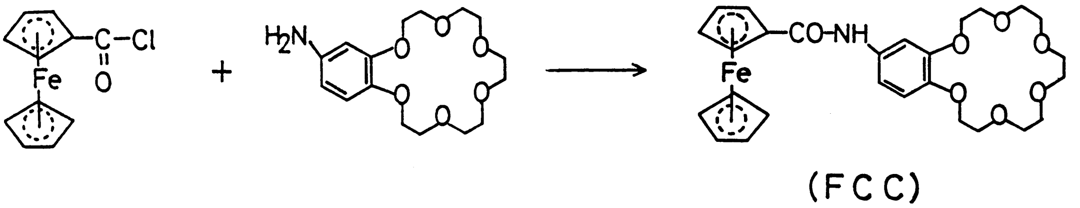
The redox capability of FCC was examined by a two-phase system composed of dichloromethane/water. The aqueous phase (5 ml) contained 1 mM potassium hexacyanoferrate(III) and 54 mM metal chloride, and the dichloromethane phase (10 ml) contained 0.3 mM FCC.

The concentration of hexacyanoferrate(III) ions was determined by measuring the absorption at 420 nm.

The cyclic voltammogram of FCC was measured in an acetonitrile solution containing 0.1 M tetrabutylammoniumhexafluorophosphate.

## Results and Discussion

The redox reaction by FCC dissolved in a dichloromethane membrane was examined by using a U-shaped tube system (Fig. 2). It was found that FCC did not extensively reduce hexacyanoferrate(III) ions in the aqueous phase I, before the addition of $Na^+$ ions. However, the concentration of hexacyanoferrate(III) ions decreased rapidly upon the addition of $Na^+$ ions to the aqueous phase I. The effect of metal ions on the



(FCC)

Fig. 1. Synthetic route of FCC.

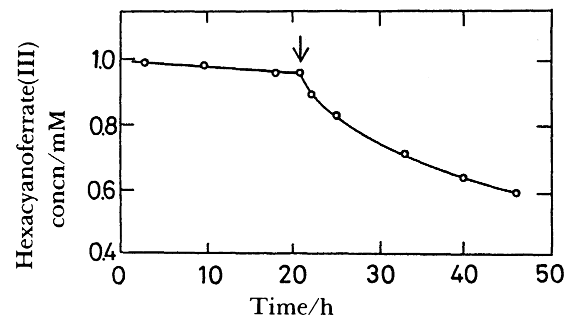


Fig. 2. Change in the concentration of hexacyanoferrate(III) ions against time in the aqueous phase I. Initial composition: aqueous phase I, 1 mM potassium hexacyanoferrate(III); aqueous phase II, 2.5 mM sodium ascorbate; organic phase M, 0.3 mM FCC in DCM. ↓: addition of 1 M NaCl.

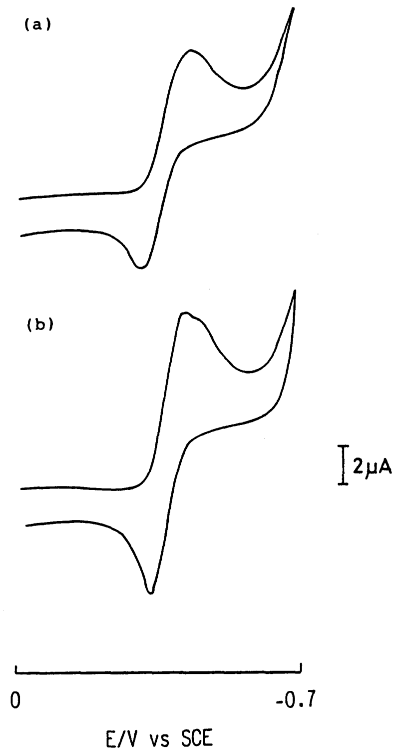


Fig. 3. Cyclic voltammograms in acetonitrile solution of FCC (a) in the absence and (b) in the presence of 1.0 equiv of $KClO_4$.

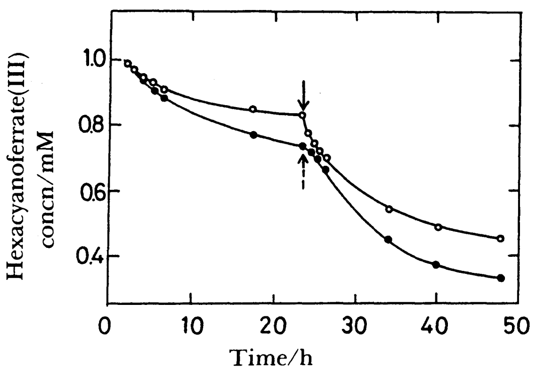


Fig. 4. Change in the concentration of hexacyanoferrate(III) ions against time in aqueous phases I (○) and II (●). Initial composition: aqueous phase I, 1 mM potassium hexacyanoferrate(III), 1 mM potassium hexacyanoferrate(II) and 54 mM $NaClO_4$; aqueous phase II, 1 mM potassium hexacyanoferrate(III), 1 mM potassium hexacyanoferrate(II) and 54 mM $KClO_4$; organic phase, 0.3 mM FCC in DCM. ↓: addition of 540 mM NaCl, ↑: addition of 540 mM KCl.

redox reaction of FCC was examined by a cyclic voltammogram (Fig. 3), and UV and NMR spectroscopies. In these measurements, no significant change was observed on the addition of a metal ion. It is therefore concluded that complexation of the crown ether unit of FCC with a metal ion does not change the redox potential or electron density of the ferrocene unit. Taken together, these experimental results show that the redox reaction by FCC is regulated by the complexation of the crown ether unit of FCC with a metal ion in the aqueous phase. However, the complexation process does not alter the redox potential of the ferrocene unit of FCC.

When 1,2-dichloroethane (DCE) was used as an organic liquid membrane, the concentration of hexacyanoferrate(III) ions did not decrease. DCE and DCM have a similar dielectric constant, however, their solubilities in water are different (0.869 g of DCE and 2.0 g of DCM are soluble in 100 g of water).[20] Therefore, the state on the water/DCM boundary region must be different from that of water/DCE, indicating that the nature of the interface between the organic phase and aqueous phase should have a strong influence on the redox reaction by FCC.

An active electron transportation with DBF driven by the different concentration of lipophilic anions between the two aqueous phases has been reported by Sinbo et al.[21] In this study, FCC was examined as a mediator of the active electron transport against redox potential driven by the selective complexation with metal ions and/or the cation transport through an organic membrane. Aqueous phases containing the same concentrations of hexacyanoferrate(III) and hexacyanoferrate(II) ions were separated by a DCM membrane containing FCC. $Na^+$ ions were added to the aqueous phase I and $K^+$ ions to the a aqueous phase II. Figure 4 shows the change in the concentration of hexacyanoferrate(III) ions in the aqueous phases I and II. In both phases, concentration of hexacyanoferrate(III) ions decreased. The decrease in the concentration of hexacyanoferrate(III) ion in the aqueous phase II containing $K^+$ ions was larger than that in the aqueous phase I containing $Na^+$ ions. This indicates that FCC failed to transport electrons across the DCM membrane.

Reduction of hexacyanoferrate(III) ions by FCC in the DCM solution was examined using a two-phase system (DCM/water). It was found that FCC in the DCM solution reduced hexacyanoferrate(III) ions in

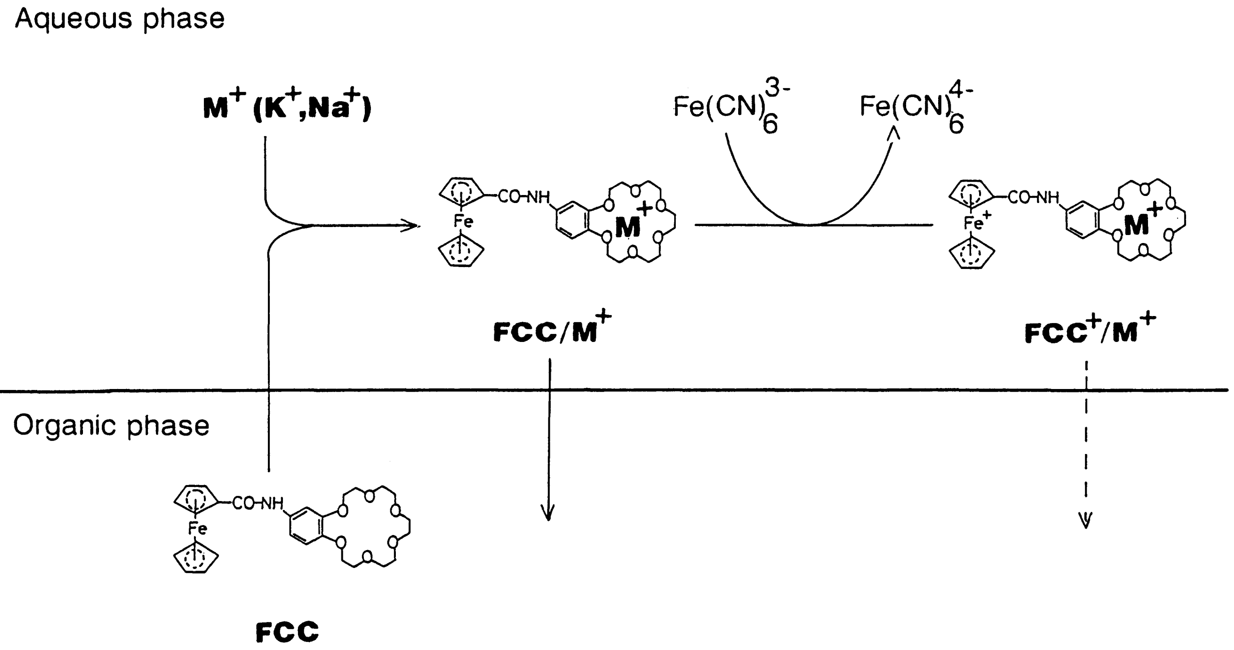


Fig. 5. The diagram of redox behavior of FCC in a liquid organic membrane system with a metal ion.

the aqueous phase containing a high concentration of either $K^+$ or $Na^+$ ions. The degree of the reduction of hexacyanoferrate(III) ions by FCC in the aqueous phase was 60% in the presence of $K^+$ ions, and 45% in the presence of $Na^+$ ions for 15 h after contacting both phases. These observations indicate that FCC reduces hexacyanoferrate(III) ions to hexacyanoferrate(II) ions in the presence of a metal ion, and that the extent of the reaction is controlled by the type of metal ion in the aqueous phase.

These experimental results can be explained by the mechanism shown in Fig. 5. The ferrocene unit of FCC in DCM solution can not be in contact with hexacyanoferrate(III) ions in the aqueous phase efficiently without metal ions. However, in the presence of metal ions, the ferrocene unit of FCC interacts with hexacyanoferrate(III) ions by complexation of the crown ether unit with a metal ion. FCC was shown to reduce hexacyanoferrate(III) ions more efficiently in the presence of a $K^+$ ion than in the presence of a $Na^+$ ion, because 18-crown-6 forms a complex with a $K^+$ ion more selectively than with a $Na^+$ ion. However the oxidized FCC ($FCC^+$) or its complex with a metal ion is so hydrophilic[22,23] that the molecule including an oxidized ferrocene unit can not diffuse freely across a DCM membrane even in the presence of lipophilic anions. This could be the reason for the failure of electron transport by FCC through an organic liquid membrane.

On the other hand, FCC was shown to transport 13.3 μmol of $K^+$ ions through DCM membrane in 12 h. This was determined by an atomic absorption method. However DBC transported 30.9 μmol of $K^+$ ions and DBF did not in the experiments using the U-shaped tube system (the aqueous phase I, 0.1 mM potassium hexacyanoferrate(III); the aqueous phase II, 0.1 mM sodium ascorbate and 300 mM KSCN; the DCM phase, 1 mM FCC, DBC, or DBF). This indicates that FCC can transport $K^+$ ions according to the concentration gradient of $K^+$ ions, when a metal ion does not exist in the aqueous phase I, in other words, the ferrocene unit of FCC is not oxidized by hexacyanoferrate(III) anions in the aqueous phase I.

Uphill transport of a picrate anion under a concentration gradient of $K^+$ ions across an organic liquid membrane has been examined using several mediators.[24] It is found that FCC showed an active transport of a picrate anion as in the case of a DBC mediator. This indicates that FCC, which is not oxidised, is active as an ionophore for $K^+$ ion in the presence of a picrate anion.

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