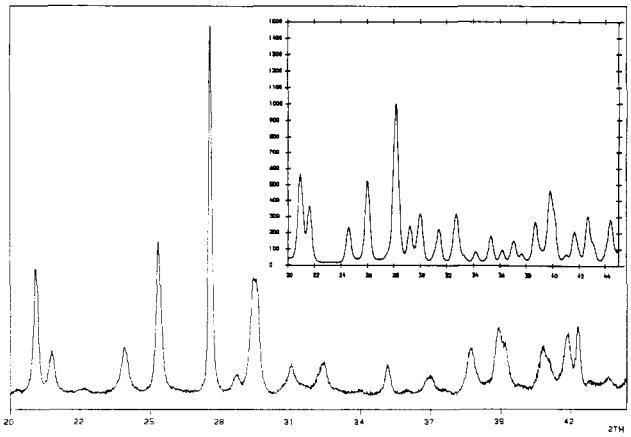

Figure 4. Powder X-ray diffraction data obtained from $MoO_2HPO_4 \cdot H_2O \cdot CH_3OH$. The inset gives the calculated pattern over the same angular range for the structure shown in Figure 3.

agreement, supporting this model. Structure determination with high-resolution powder X-ray and neutron diffraction methods is in progress.

$MoO_2HPO_4 \cdot H_2O$ has been shown to undergo reversible intercalation reactions; as such this system may provide a vehicle for the preparation of mixed inorganic–organic polymers with alternating molybdenyl phosphate and carbon-based chains.

Acknowledgment. We thank the SERC for grants in association with this work and D. B. Currie for assistance with the powder X-ray work.

Supplementary Material Available: Table SI, listing the atomic coordinates used for the calculated powder X-ray diffraction pattern in Figure 4 (1 page). Ordering information is given on any current masthead page.

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Stereoselective Electron-Transfer Reaction between Ferrocytochrome *c* and Tris(acetylacetonato)cobalt(III)

In the last decade, there has been considerable interest in electron-transfer reactions between biological molecules and transition-metal complexes,[1] because many biological molecules participating in electron-transfer reactions include transition-metal ions in their important sites. However, stereoselectivity has not been investigated yet in such electron-transfer reactions,[2] whereas high stereoselectivity is one of the important characteristic features of biological reactions. In the present work, a stereoselective electron-transfer reaction between ferrocytochrome *c* (cyt *c*(II)) and the hydrophobic tris(acetylacetonato)cobalt(III), $Co(acac)_3$, is investigated. $Co(acac)_3$ is selected here as a substrate, because

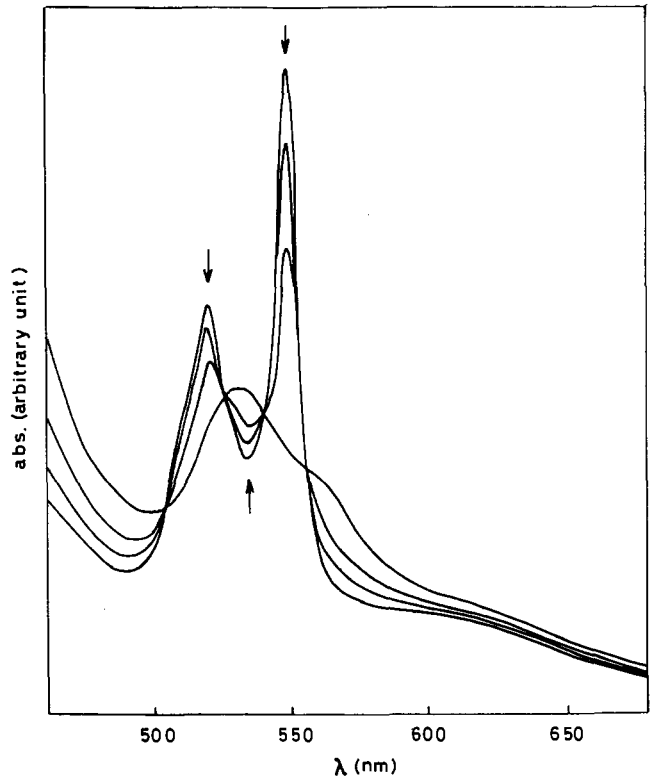

Figure 1. Absorption spectral changes in the $Co(acac)_3$ reduction by cyt *c*(II). Reaction conditions: pH 4.0,[4] μ = 0.1 M, [cyt *c*(II)] = 2.0×10^{-5} M, [$Co(acac)_3$] = 2.5×10^{-3} M. Spectra were taken at the following times (h): 0, 0.5, 2, 38.

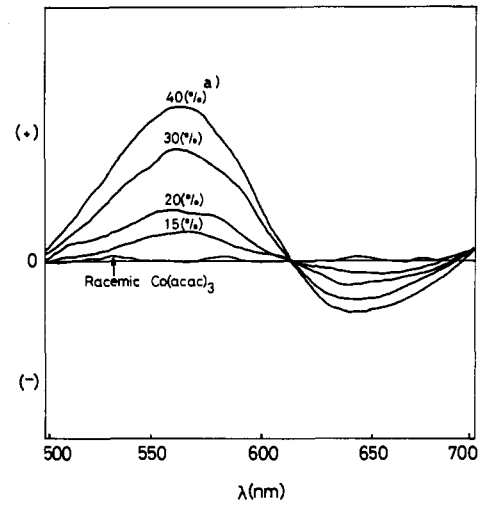

Figure 2. CD spectra of remaining $Co(acac)_3$ ((a) ethanol volume percent). Reaction conditions: pH 4.0,[4] μ = 0.1 M.

(1) For example: (a) Yandell, J. K.; Fay, D. P.; Sutin, N. *J. Am. Chem. Soc.* **1973**, *95*, 1131. (b) Hodges, H. L.; Holwerda, R. A.; Gray, H. B. *J. Am. Chem. Soc.* **1974**, *96*, 3132. (c) McArdle, J. V.; Gray, H. B.; Creutz, C.; Sutin, N. *J. Am. Chem. Soc.* **1974**, *96*, 5737. (d) Augustin, M. A.; Yandle, J. K. *Inorg. Chem.* **1979**, *18*, 577. (e) Cho, K. C.; Che, C. M.; Cheng, F. R.; Choy, C. L. *J. Am. Chem. Soc.* **1984**, *106*, 6843. (f) Peterson-Kennedy, S. E.; McGourty, M. L.; Hoffman, B. M. *J. Am. Chem. Soc.* **1984**, *106*, 5010. (g) Koller, K. B.; Hawkridge, F. M. *J. Am. Chem. Soc.* **1985**, *107*, 7412. (h) Bechtold, R.; Gardineer, B. M.; Kazmi, A.; Van Hemelryck, B.; Isied, S. S. *J. Phys. Chem.* **1986**, *90*, 3800. (i) Kjaer, A. M.; Ulstrup, J. *Inorg. Chem.* **1987**, *26*, 2052. (j) Holwerda, R. A.; Knaff, D. B.; Gray, H. B.; Clemmer, J. D.; Crowley, R.; Smith, J. M.; Mauk, A. G. *J. Am. Chem. Soc.* **1980**, *102*, 1142. (k) Butler, J.; Chapman, S. K.; Davies, D. M.; Sykes, A. G.; Speck, S. H.; Osheroff, N.; Margoliash, E. *J. Biol. Chem.* **1983**, *258*, 6400. (l) Rush, J. D.; Koppenol, W. H.; Garber, E. A. E.; Margoliash, E. *J. Biol. Chem.* **1988**, *263*, 7514.

(2) It is also noted that stereoselective electron-transfer reactions are rare in the chemistry of transition-metal complexes. For example: (a) Geselowitz, D. A.; Taube, H. *J. Am. Chem. Soc.* **1980**, *102*, 4525. (b) Popter, G. P.; Sparks, R. H. *J. Chem. Soc., Chem. Commun.* **1979**, 1094. (c) Yorozu, T.; Hayashi, K.; Irie, M. *J. Am. Chem. Soc.* **1981**, *103*, 5480. (d) Kondo, S.; Sasaki, Y.; Saito, K. *Inorg. Chem.* **1981**, *20*, 429. (e) Kaizu, Y.; Mori, T.; Kobayashi, H. *J. Phys. Chem.* **1985**, *89*, 332. (f) Sakaki, S.; Satoh, T.; Ohkubo, K. *Nouv. J. Chim.* **1986**, *10*, 145. (g) Osvath, P.; Lappin, A. G. *Inorg. Chem.* **1987**, *26*, 195. (h) Geselowitz, D. A.; Hammershoi, A.; Taube, H. *Inorg. Chem.* **1987**, *26*, 1842.

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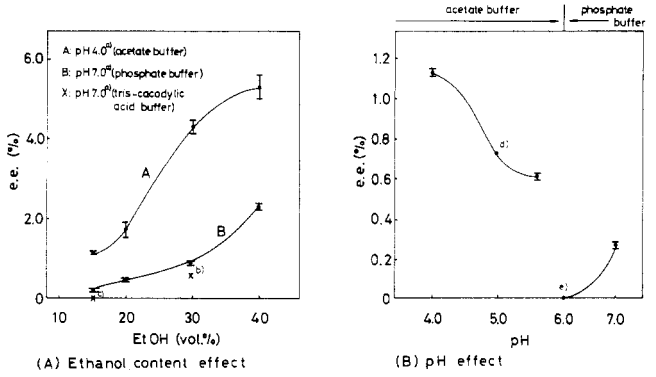

Figure 3. Dependence of stereoselectivity on ethanol content and pH ((a) See ref 4; (b) three measurements gave almost the same value (ee (%) = 0.70, 0.74, and 0.74); (c) two measurements gave zero values of the ee; (d) two measurements gave the same value; (e) three measurements gave the same value). Reaction conditions: see text.

this complex has large $\Delta\epsilon$ values in its CD spectrum[3] that are suitable for investigating a stereoselective reaction. The emphasis of this work is on presenting the first report of a stereoselective electron-transfer reaction between the protein and the transition-metal complex.

Horse heart cytochrome *c* (Sigma type VI) was used without further purification. The reduced form of cyt *c* was prepared by dithionite reduction and purified with gel filtration (Sephadex G50, 10 mm i.d. × 450 mm).[1c] All these treatments were carried out at 4 °C, and the cyt *c*(II) solution was stored under an argon atmosphere. $Co(acac)_3$ was purchased from Nakarai Chemical Co. (extra pure grade) and used after recrystallization from benzene and petroleum ether. Typical electron-transfer reactions between cyt *c*(II) (1.0×10^{-4} mol/dm^3) and $Co(acac)_3$ (2.5×10^{-3} mol/dm^3) were performed at 25 °C in 15 vol. % ethanol–water mixed solvent with the ionic strength adjusted to 0.1 M (KCl), in which phosphate buffer was used for pH 6.0 and 7.0 and acetate buffer for pH 4.0 and 5.0.[4] After the reaction (48 h), the solution was evaporated to dryness, and then the remaining $Co(acac)_3$ was dissolved into ethanol (note that cyt *c* is insoluble in ethanol).[5] CD spectra of this solution were measured with a Jasco J-500C spectropolarimeter, and the stereoselectivity (defined by the enantiomeric excess (ee)) was estimated from the obtained CD spectra.

The addition of $Co(acac)_3$ to cyt *c*(II) decreases the characteristic absorptions of cyt *c*(II) at 520 and 550 nm, and the absorption spectrum of the solution finally resembles very much the spectrum of cyt *c*(III),[6] as shown in Figure 1. The spectral change clearly shows isosbestic points. These results indicate that the electron-transfer reaction smoothly proceeds between cyt *c*(II) and $Co(acac)_3$. After the reaction, the CD spectrum of the remaining $Co(acac)_3$ exhibits a positive absorption around 570 nm and a negative one around 650 nm (typical examples are shown in Figure 2). This means that excess $\Lambda(-)$-$Co(acac)_3$ exists after the reaction[3] and cyt *c*(II) reduces $\Delta(+)$-$Co(acac)_3$ more easily than $\Lambda(-)$-$Co(acac)_3$. Although the ee observed is not very large (i.e., ee (%) = 0.28 ± 0.02 at pH 7.0 and 1.15 ± 0.02 at pH 4.0 in 15 vol. % ethanol–water mixed solvent (μ =0.1)), this is the first example of a stereoselective electron-transfer reaction between the protein and the transition-metal complex.

The ee observed is sensitive to ethanol volume percent in the ethanol–water mixed solvent;[7] as shown in Figures 2 and 3A, the stereoselectivity increases with increasing ethanol volume percent. An increase in ethanol volume percent is considered to cause some structural change around the active site, as follows. cyt *c*(II) consists of a hydrophobic core including a heme center, a solvent-exposed heme edge as its active site of the electron-transfer reaction, and a hydrophilic surface covered by unlinked COO^- and NH_3^+ groups of amino acid residues that are not used for the peptide bond.[1c] The solvent-exposed heme edge is believed to be in the hydrophobic crevice.[1c] An increase in ethanol volume percent increases the hydrophobicity of the solvent and would induce an opening of the hydrophobic crevice. Consequently, an increase in ethanol volume percent would enhance the approximation of $Co(acac)_3$ to the active site, which increases the stereoselectivity because the stereoselectivity would be mainly determined by chiral amino acid groups existing around the active site. Thus, the stereoselectivity increases with increasing ethanol volume percent.[8]

The stereoselectivity also depends on the ionic strength; the selectivity is 0.28 ± 0.02 at μ = 0.1, increases slightly to 0.35 at μ = 0.05,[9] but disappears at μ = 0.01.[10] The opening of the hydrophobic heme crevice is easier at lower ionic strength, because the hydrophilicity of the solvent increases with increasing ionic strength. This means that low ionic strength facilitates the approximation of $Co(acac)_3$ to the active site and enhances the stereoselectivity. Nevertheless, the stereoselectivity disappears at μ = 0.01. Thus, besides the crevice opening, there is another factor influencing the stereoselectivity.[8b] A coherent picture might emerge by considering that an increase in ionic strength would enhance ion-pair formation between various ions (in this case, K^+ and Cl^-) included in the solvent and amino acid residues existing on the cyt *c*(II) surface.[11] Such ion-paired amino acid residues, being less hydrophilic than the naked (not ion-paired) amino acid residues, approximate more easily to hydrophobic $Co(acac)_3$ than the naked amino acid residues and increase the stereoselectivity.[12]

(3) $\Delta(+)$-$Co(acac)_3$ exhibits CD absorptions of $\Delta\epsilon$ = 2.88 at 647 nm and $\Delta\epsilon$ = −8.11 at 574 nm: Drake, A. F.; Gould, J. M.; Mason, S. F.; Rosini, C.; Woodley, F. J. *Polyhedron* **1983**, *2*, 537.

(4) The water before mixing with ethanol has these pH values. After mixing, the pH shifts to a slightly higher value; in the phosphate or acetate buffer (μ = 0.1) pH 4.0 shifts to 4.2, pH 5.0 to 5.2, pH 6.0 to 6.3, and pH 7.0 to 7.3 (ethanol 15 vol. %), pH 7.0 shifts to 7.4 and pH 4.0 to 4.3 (ethanol 20 vol. %), pH 7.0 shifts to 7.6 and pH 4.0 to 4.5 (ethanol 30 vol. %), and pH 7.0 shifts to 7.4 and pH 4.0 to 4.8 (ethanol 40 vol. %), and in Tris–cacodylic acid buffer (μ = 0.1) pH 6.7 shifts to 6.9 (ethanol 15 vol. %) and to 7.0 (ethanol 30 vol. %).

(5) The same treatment was carried out on the solution of cyt *c* before the reaction. The resultant solution showed no CD spectrum in the wavelength region used for the measurement.

(6) Because both $Co(acac)_3$ and $Co(acac)_2$ have much smaller molar extinction coefficients in the visible region than cyt *c*, their absorptions cannot be observed well under the present experimental conditions.

(7) A similar result has been reported for stereoselective electron-transfer reactions between $[Co(en)_3]^{2+}$ and several Co(III) complexes;[2h] the stereoselectivity increases in the order water < ethylene glycol < methanol < ethanol < formamide < ethylenediamine < DMF < Me_2SO < sulfolane.

(8) (a) Not only the crevice opening but also the presence of various ions (K^+, Cl^-, and phosphate anion) would be important for the stereoselectivity, as discussed about the ionic strength effect on the stereoselectivity. (b) In the experiment investigating the effect of ethanol volume percent, the concentration of ion species is enough for ion-pair formation (μ = 0.1).

(9) (a) Slightly larger stereoselectivity at μ = 0.05 would be due to the increase in the opening of the hydrophobic crevice at μ = 0.05, because the solvent hydrophilicity decreases upon going to μ = 0.05 from μ = 0.1. This discussion is supported by a preliminary kinetic investigation.[9b] (b) A preliminary kinetic study was carried out, based on the Michaelis–Menten mechanism. When the ionic strength is increased, (μ = 0.01 to 0.1), the binding of $Co(acac)_3$ with cyt *c* increases but k_{et} (rate constant for the electron-transfer step) decreases. This result is in accordance with our observation of stereoselectivity, as follows: because the opening of the hydrophobic crevice becomes difficult at higher ionic strength, $Co(acac)_3$ approximates to a lesser extent to the active site at too high an ionic strength, which decreases k_{et} and the stereoselectivity. At too low an ionic strength, the crevice opening is easy but ion-pair formation of amino acid residues is difficult. This situation disfavors the binding of hydrophobic $Co(acac)_3$ to the hydrophilic surface of cyt *c* but favors the k_{et} step through the enhancement of approximation of $Co(acac)_3$ to the heme edge. However, the stereoselectivity decreases, because amino acid residues that are not ion-paired cannot approximate to hydrophobic $Co(acac)_3$.

(10) We decreased the ionic strength here, because an increase in ionic strength is not easy due to the hydrophobicity of $Co(acac)_3$.

(11) The similar cation binding to cyt b_5 and anion binding to cyt *c* have been reported in previous experiments. For example: (a) Reid, L. S.; Taniguchi, V. T.; Gray, H. B.; Mauk, A. G. *J. Am. Chem. Soc.* **1982**, *104*, 7516. (b) Taniguchi, I.; Funatsu, T.; Iseki, M.; Yamaguchi, H.; Yasukouch, K. *J. Electroanal. Chem. Interfacial Electrochem.* **1985**, *193*, 295. (c) Koller, K. B.; Hawkridge, F. M. *J. Am. Chem. Soc.* **1985**, *107*, 7412.

The importance of the ion-pair formation is also supported by a different experiment in which the stereoselectivity is decreased by the use of a Tris–cacodylic acid buffer instead of phosphate buffer, as shown in Figure 3A. Because the Tris–cacodylate anion does not bind with cyt *c* but the phosphate anion does bind with cyt *c*,[11c,13] the greater stereoselectivity observed in the phosphate buffer would be attributed to the binding of the phosphate anion.

An interesting pH dependence of the stereoselectivity is observed; as shown in Figure 3, the stereoselectivity is very small at pH 7.0, disappears at pH = 6.0,[4] but increases considerably as the pH is lowered from 5.6 to 4.0.[4] A pH decrease causes protonation of the COO^- group of cyt *c*(II). This protonation weakens the hydrogen bond included in cyt *c*, which would induce the opening of the heme crevice and increase the stereoselectivity similarly to the increasing ethanol volume percent.[14] The protonation is also similar, to some extent, to the ion-pair formation. Thus, the protonated amino acid residues tend to approximate to $Co(acac)_3$ more easily than the deprotonated amino acid residues, which might be the other factor enhancing the stereoselectivity.

In conclusion, the first stereoselective electron-transfer reaction between cyt *c*(II) and $Co(acac)_3$ is observed in this work.[15] An interesting dependence of stereoselectivity on such reaction conditions as ethanol volume percent of the solvent, ionic strength, and pH is found. The stereoselectivity is expected to offer new information different from the redox potential, because the redox potential would be primarily influenced by a structural change of a heme center itself but the stereoselectivity would be sensitive to the situation around the active site.

Acknowledgment. We gratefully acknowledge the Ministry of Education, Science and Culture for a Grant-in-Aid (No. 61540451) and the Department of Physics, Faculty of Science, Kumamoto University, for use of the Jasco J-500C spectropolarimeter.

Registry No. cyt *c*(II), 9007-43-6; $Co(acac)_3$, 21679-46-9.

(12) Even when the reactant is neutral, the electron-transfer reaction is considered to pass through the polarized transition state and the product is charged in many cases. Thus, the driving force of the electron-transfer reaction would be influenced by ionic strength, which would have some influence on the stereoselectivity. The relation between the stereoselectivity and the driving force of the reaction is important and an interesting issue to be examined. At the moment, we have no informative result about it, and a detailed discussion is omitted here.
(13) (a) Margalit, R.; Schejter, A. *Eur. J. Biochem.* **1973**, *32*, 492. (b) Barlow, G. H.; Hargoliash, E. *J. Biol. Chem.* **1966**, *241*, 1473.
(14) The reason that the stereoselectivity disappears at pH 6.0 is ambiguous and must be investigated in more detail.
(15) Stereoselectivity is also found in the electron-transfer reaction between cyt *c*(II) and $[Co(bpy)_3]^{3+}$. This stereoselectivity is larger than that found in this work (Sakaki, S. To be submitted for publication).

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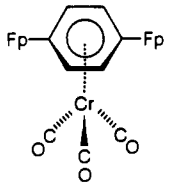
Redox-Active Phenylene-Bridged Polymetallic σ,π Complexes Containing Iron and Chromium[1]

Research in our laboratories is centered on the synthesis and characterization of new phenylene-bridged polymetallic complexes. It is our hope that such complexes will serve as models for the production of linear-chain organometallic polymers which will serve as one-dimensional electronic conductors. Our model complexes have typically contained η^1-organometallic fragments such as Fp (Fp = $(\eta^5\text{-}C_5H_5)Fe(CO)_2$) σ-bound to an arene ring, and many have had an η^6-arene coordinated in a π fashion to an "$M(CO)_3$" group (M = Cr, Mo, W), e.g.



We recently reported the synthesis and spectroscopic characterization of a representative set of these novel tri- and tetrametallic complexes and confirmed their structures by subjecting one of these compounds to a single-crystal X-ray crystallographic study.[1,2] We now wish to communicate the results of our preliminary electrochemical investigations on an extended series of the Fe/Cr complexes.

Table I. Electrochemical Data for the Oxidations of the Metalated (arene)$Cr(CO)_3$ Complexes[a]

arene[b]	$E^{o\prime}$, V[c]	arene	$E^{o\prime}$, V
1,4-C_6H_4(Cl)Fp (**1**)	+0.73	1,3-$C_6H_4Fp_2$ (**5**)	+0.45
C_6H_5Fp (**2**)	+0.64	1,4-$C_6H_4Fp_2$ (**6**)	+0.43
1,4-C_6H_4(Me)Fp (**3**)	+0.60	1,3,5-$C_6H_3Fp_3$ (**7**)	+0.28
1,4-C_6H_4(OMe)Fp (**4**)	+0.56		

[a] Complex concentrations of (5–7) × 10^{-4} M in dichloromethane/0.1 M *n*-Bu_4NPF_6; scan rate of 0.10 V s^{-1}; potentials vs SCE. [b] Fp = $(\eta^5\text{-}C_5H_5)Fe(CO)_2$. [c] Defined as the average of cathodic and anodic peak potentials.

Cyclic voltammetry at a stationary platinum-bead electrode reveals that the complexes **1**–**7**[2,3] (Table I) exhibit simple one-electron reversible oxidations in dichloromethane solution (containing 0.1 M *n*-Bu_4NPF_6, vs SCE).[6,7] These oxidation processes are diffusion-controlled and exhibit cathodic–anodic peak separations of 60–70 mV (at a scan rate of 0.1 V s^{-1}). A comparison of peak separations and wave heights with those of ferrocene[8] established the one-electron nature of these oxidations, i.e.

$$(\text{arene})Cr(CO)_3 \underset{+e^-}{\overset{-e^-}{\rightleftharpoons}} [(\text{arene})Cr(CO)_3]^{\bullet+} \qquad (1)$$

(as did controlled-potential electrolysis of **3**). These oxidations are clean and produce remarkably stable radical cations. Thus, when a representative example, $(\eta^6\text{-}1,4\text{-}C_6H_4MeFp)Cr(CO)_3$, is treated with 1 equiv of $AgPF_6$ in dichloromethane, a thermally stable but air-sensitive blue paramagnetic complex, $[(\eta^6\text{-}1,4\text{-}C_6H_4MeFp)Cr(CO)_3]^{\bullet+}PF_6^-$, is produced; i.e.[9]

$$(\eta^6\text{-}1,4\text{-}C_6H_4(Me)Fp)Cr(CO)_3 + AgPF_6 \xrightarrow{CH_2Cl_2} [(\eta^6\text{-}1,4\text{-}C_6H_4(Me)Fp)Cr(CO)_3]PF_6 + Ag \qquad (2)$$

(1) Organometallic Complexes with Electronic Bridges. 4. Part 3: Hunter, A. D.; McLernon, J. L. *Organometallics*, in press.
(2) Hunter, A. D. *Organometallics* **1989**, *8*, 1118.
(3) The $(\eta^6\text{-}1,4\text{-}C_6H_4(X)Fp)Cr(CO)_3$ complexes (X = H, Me, Cl, OMe) were synthesized from the corresponding fluoro- or chloroarene complexes by the nucleophilic displacement of fluoride or chloride by Fp^-.[4,5]
(4) Richter-Addo, G. B.; Hunter, A. D.; Wichrowska, N. Manuscript in preparation.
(5) Heppert, J. A.; Morgenstern, M. A.; Scherubel, D. M.; Takusagawa, F.; Shaker, M. R. *Organometallics* **1988**, *7*, 1715.
(6) The electrochemical cell used for the cyclic voltammetry experiments was similar to that previously described (Legzdins, P.; Wassink, B. *Organometallics* **1984**, *3*, 1811). Under the experimental conditions employed, ferrocene is reversibly oxidized in dichloromethane at +0.47 V vs SCE: cathodic–anodic peak potential separation, 60 mV; $i_{p,c}/i_{p,a}$ = 1.0; scan rate, 0.1 V s^{-1}.
(7) The complexes exhibit other oxidation waves at higher potentials, but these lead to extensive coating of the electrode surface, making analyses of these waves difficult. In addition, no reduction waves are observed in the cyclic voltammograms of these complexes up to −1.8 V vs SCE.
(8) Gagne, R. R.; Koval, C. A.; Lisensky, G. C. *Inorg. Chem.* **1980**, *19*, 2854.
(9) (a) IR (Nujol mull): ν_{CO} 2056 (s), 2034 (m), 1970 (s, br), 1930 (m, br) cm^{-1}. Compare with those of **3**: 2014 (s), 1966 (s), 1932 (s), 1862 (sh), 1850 (s), 1840 (sh), 1818 (sh) cm^{-1}. Anal. Calcd for $C_{17}H_{12}O_5PF_6CrFe$: C, 37.16; H, 2.19. Found: C, 36.84; H, 2.13. This complex exhibits an unresolved (broad) ESR signal at 298 K in dichloromethane. (b) A similar but less thermally stable complex, $[\mathbf{4}]^{\bullet+}BF_4^-$, can be prepared by the analogous reaction of **4** with $AgBF_4$ in dichloromethane.

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