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**Supplementary Material Available:** Experimental details and complete NMR spectroscopic data for **4a–e** and **5a–e** (3 pages). Ordering information is given on any current masthead page.

## Facile Nucleophilic Substitution on Coordinated $\eta^5$-Cyclopentadienyl

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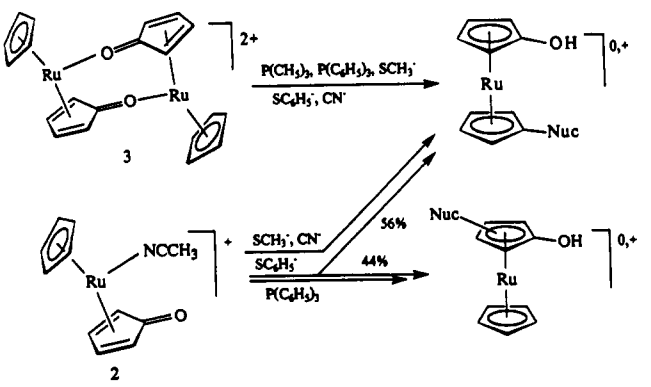
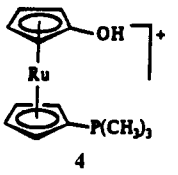
Substitution in $\eta^5$-cyclopentadienyl (Cp) is acknowledged to be difficult.[1] It is reasonable to expect that on coordination to a metal cation in the $\eta^5$ mode, this difficulty would be alleviated. There are numerous examples of nucleophilic addition to $\eta^5$-cyclopentadienyl ligands,[2] and one example[3] featuring substitution on coordinated Cp, but, even so, the examples cited involve very powerful nucleophiles such as $H^-$ or carboanions. Considerable work has also been devoted to preparing derivatives of coordinated Cp by starting with iodoferrocene and subjecting it to the action of the Cu(I) salt of the desired anions as the entering ligand.[4,5] Reactions are slow and typically require refluxing in pyridine as a solvent, for 1 h or more.

In the course of exploring the chemistry of $[Ru(\eta^5\text{-}C_5H_5)(\eta^4\text{-}C_5H_4O)]^+$ (**1**)[6] we undertook to study the action on it of a variety of nucleophiles. The experiments were done in nitromethane as solvent, at room temperature. Species **1** was introduced into the reaction solution either as the salt $[Ru(\eta^5\text{-}C_5H_5)(\eta^4\text{-}C_5H_4O)(CH_3CN)]PF_6$ (**2**)[7] or as the salt $[Ru(\eta^5\text{-}C_5H_5)(\eta^4\text{-}C_5H_4O)]_2(PF_6)_2$ (**3**).[8] With the nucleophiles $Cl^-$, $Br^-$, $I^-$, pyridine, isocyanides, thioketones, and several others, substitution at the metal center takes place, and a rough affinity order has been established.[9] But, to our astonishment, we noted that, with $P(CH_3)_3$ as the nucleophile, substitution takes place at the Cp ring, the $\eta^4$-cyclopentadienone ring ($C_5H_4O$) being reduced to $\eta^5$-hydroxycyclopentadienyl ($C_5H_4OH$), yielding

Scheme I

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With **3** as the starting material, in all cases studied thus far, substitution takes place solely on the Cp ring, but, with **2** as the starting material, in some cases substitution takes place also at the ketone (see Scheme I).

To our knowledge, facile nucleophilic substitution on coordinated $C_p$ such as we have observed with much weaker nucleophiles is unprecedented. Here we report on the reactions of **2** and **3** with $P(CH_3)_3$ and $P(C_6H_5)_3$ and give some preliminary results of the reaction of **2** and **3** with $SCH_3^-$, $SC_6H_5^-$, and $CN^-$. All reactions were carried out in $CH_3NO_2$ or $CD_3NO_2$ at room temperature under an argon atmosphere.

With equimolar amounts of each reagent (ca. 20–40 mM), in the case of the tertiary phosphines, reaction appears to be complete on mixing. By use of $^1H$ NMR spectroscopy on the product solution ($CD_3NO_2$) resulting from the action of the phosphines on **3**, reaction is found to be essentially quantitative (recovered yield as the $PF_6^-$ salts, 50–60%). The identity of the product was established by $^1H$ and $^{13}C$ NMR spectroscopies and elemental analysis, as well as by its chemical reactivity.

The $^1H$ NMR spectrum of product **5** ($P(C_6H_5)_3$ as nucleophile) features six signals (d, acetone-$d_6$, 20 °C): a multiplet pattern from 7.95 to 7.77 ppm (15 H), two apparent quartets centered at 5.20 ppm (2 H) and 4.95 ppm (2 H), two apparent triplets centered at 4.62 ppm (2 H) and 4.19 (2 H), and a broad singlet at 3.74 ppm (1 H) that is readily exchanged by deuterium. The $^1H$ NMR spectrum of **4** similarly shows that $P(CH_3)_3$ has attacked the Cp ring.[10] The absence of a sharp singlet arising from $\eta^5$-coordinated Cp, as well as the absence of the characteristic multiplet pattern of $\eta^4$-coordinated $C_5H_4O$, such as in **2** and **3**, along with the peak integrations, shows that, in both **4** and **5**, the Cp rings are monosubstituted and coordinated in a $\eta^5$ fashion. Selective homonuclear decoupling experiments show that decoupling of one of the quartets converts the other to a doublet (doublet ascribable to the coupling of the $\alpha$ and $\beta$ ring protons with $^{31}P$ of the phosphine moiety) without affecting the triplets, while decoupling of one of the triplets converts the other to a singlet without affecting the quartets. The $^{13}C$ NMR spectra support the conclusions as to the structures of **4** and **5**.

That the ketone has been reduced to an alcohol has also been established by its chemical reactivity. Both **4** and **5** readily react

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(7) **2**. 1.2 g of $[RuCp_2Br]PF_6$ and 1.4 g of $Ag_2O$ were added to 50 mL of acetonitrile, and the mixture was stirred at 70 °C for 1 h. The brownish solution was filtered, and the crude product was precipitated with diethyl ether, then dissolved in 10 mL of acetonitrile, and chromatographed with acetonitrile on an alumina column. Reduction of the volume of the solvent, under vacuum, to about 10 mL and addition of diethyl ether gave bright yellow microcrystals. After filtration the product was washed with diethyl ether and air-dried. Yield: 0.22 g (20%). Anal. Calcd for $C_{12}NOPF_6Ru$: C, 33.34; H, 2.79; N, 3.24; P, 7.16; F, 26.37. Found: 33.54; H, 2.73; N, 3.05; P, 7.42; F, 26.77. $^1H$ NMR ($\delta$, ppm, acetone-$d_6$, 20 °C): 6.49 (m, 2 H), 5.82 (s, 5 H), 4.68 (m, 2 H), 2.67 (s, 3 H). $^{13}C$ NMR ($\delta$, ppm, acetone-$d_6$, 20 °C): 182.81 (C=O), 133.8 (CN), 87.6 (CpO), 87.5 (CpO), 74.3 (Cp), 5.5 ($CH_3$). IR (KBr, $cm^{-1}$): 2325.0 (m, $\nu_{CN}$), 1698.9, 1684.5 (s, $\nu_{CO}$).
(8) **3**. 200 mg of $RuCp(C_5H_4O)Br$ was dissolved in 5 mL of nitromethane. $AgPF_6$ was added, and the mixture was stirred at room temperature for 1 h. The resulting precipitate of AgBr was removed by filtration. The solution (dark red) was treated with diethyl ether, and the solid was filtered off, washed with diethyl ether, and air-dried. Yield: 0.23 g (94%). Anal. Calcd for $C_{20}H_{18}O_2P_2F_{12}Ru_2$: C, 30.70; H, 2.32; P, 7.92; F, 29.14. Found: C, 30.74; H, 2.35; P, 7.74; F, 29.46. $^1H$ NMR ($\delta$, ppm, acetone-$d_6$, −50 °C): 6.45 (m, 2 H), 6.20 (m, 2 H), 6.09 (s, 10 H), 5.71 (m, 2 H), 5.27 (m, 2 H). IR (KBr, $cm^{-1}$): 1568.7 (s, $\nu_{CO}$).
(9) A full report on this topic, including the X-ray structures of **2** and **3**, will be submitted separately.
(10) **4**. $^1H$ NMR ($\delta$, acetone-$d_6$, 20 °C): 5.06 (q, 2 H), 5.00 (q, 2 H), 4.42 (t, 2 H), 4.33 (t, 2 H), 3.79 (b, 1 H), 2.04 (d, 9 H).
(11) Elemental analyses. Calcd for $C_{13}H_{18}OP_2F_6Ru$ (**4**): C, 33.42; H, 3.88; P, 13.26; F, 22.39. Found: C, 34.10; H, 3.85; P, 12.34; F, 23.82. Calcd for $C_{28}H_{24}OP_2F_6Ru$ (**5**): C, 51.46; H, 3.70; P, 9.48; F, 17.44. Found: C, 51.92; H, 3.69; P, 9.55; F, 17.36.

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with acyl chlorides (RCOCl) to form the corresponding esters. It is to be noted that elemental analyses of **4** and **5** give satisfactory agreement[11] with the compositions we have assigned.

The studies have been extended to other nucleophiles, and the results are summarized in Scheme I. Conversion to products as indicated is essentially quantitative, except for $CN^-$, where 25% of either **2** or **3** is found to be reduced to hydroxyruthenocene. The reactions are slower for the anionic nucleophiles than they are for the phosphines and, in the case of the former, may be governed by the rate of dissolution of the corresponding alkali-metal salts. The products were characterized by their $^1H$ NMR spectra.[12]

The activation for substitution on $\eta^5$-$C_5H_5^-$ by cyclopentadienone as coligand raises questions about the reaction mechanism. Attempts to do kinetic studies in the case of the homogeneous systems, by using $^1H$ NMR to follow the course of the reaction, failed because of the rapidity of the reactions.

Of particular interest is the role of coordinated nucleophile ($CH_3CN$ in the case of **2**) in affecting the course and the rates of the reactions.

**Acknowledgment.** Support by the National Science Founation Grant CHE8816422 is gratefully acknowledged.

(12) $^1H$ NMR spectra of the reaction products of the reaction of **3** with $SCH_3^-$, $SC_6H_5^-$, and $CN^-$, i.e. attack on the Cp ring, and **2** with P ($C_6H_5$)$_3$ and $SC_6H_5^-$, i.e. attack on the $C_5H_4O$ ring ($\delta$, ppm, nitromethane-$d_3$, 20 °C): 4.84 (b, 1 H), 4.72 (t, 2 H), 4.66 (t, 2 H), 4.57 (s, 2 H), 4.27 (t, 2 H), 2.27 (s, 3 H); 7.2-7.0 (m, 5 H), 4.70 (t, 2 H), 4.69 (t, 2 H), 4.62 (t, 2 H), 4.22 (t, 2 H); 5.38 (b, 1 H), 5.09 (t, 2 H), 4.79 (t, 2 H), 4.78 (t, 2 H), 4.38 (t, 2 H); 8.00-7.78 (m, 15 H), 5.21 (m, 1 H), 4.76 (m, 1 H), 4.57 (s, 5 H), 4.16 (m, 1 H); 7.35-7.20 (m, 5 H), 4.99 (b, 1 H), 4.91 (2d, 1 H), 4.64 (2d, 1 H), 4.59 (s, 5 H), 4.46 (2d, 1 H).

## Reactions between Cytochrome *c* and Plastocyanin Indicate That Choice of Docking Sites on Protein Surfaces May Depend on Thermodynamic Driving Force for Electron Transfer

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Various aspects of electron-transfer reactions can be examined with metalloproteins.[1] A pair of them can form multiple complexes,[2-7] and this phenomenon requires kinetic investigation. This study indicates that a protein (plastocyanin, pc) can form structurally different precursor complexes with virtually identical proteins differing in reduction potential (native and zinc-reconstituted cytochrome *c*, cyt and Zncyt).

Plastocyanin ($E°$ = 0.36 V vs NHE) has a negative patch remote (14-19 Å) from the copper atom and an electroneutral patch proximate (3-9 Å) to it.[8] Electron transfer to copper should be much more efficient from the latter than from the former;[9] the choice between the patches is often attributed simply to the charge of the other reactant.[8] Cytochrome *c* ($E°$ = 0.26 V) has a positive patch near the exposed heme edge.[10,11] In the electrostatic cyt/pc complex the heme patch abuts the remote patch,[12-22] but analysis[23-26] of dependence on ionic strength of the bimolecular rate constant $k_1$ excludes this as the reactive configuration.[27] The electron-transfer rate constant $k_2$ is large (1300 ± 200 $s^{-1}$) for the electrostatic complex, but undetectably small

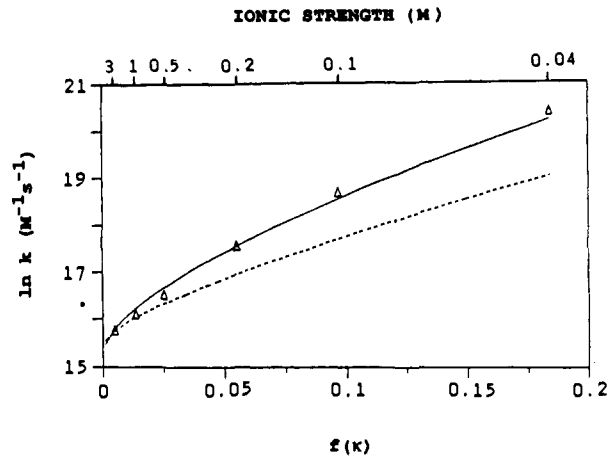


**Figure 1.** Dependence of $k_3$ on ionic strength at pH 7.0 and 25 °C. The protein parameters, function f(κ) of ionic strength, and the configuration-defining angle are explained elsewhere,[27] and $k_\infty$ = 1.5 × $10^6$ $M^{-1}$ $s^{-1}$. The fitting (—) of experimental results (Δ) yields the angle of 36°; the other curve (– –) corresponds to the angle of 86°, characteristic of cytochrome *c* binding at the proximate patch (His 87) of plastocyanin.

$$\text{cyt(II)} + \text{pc(II)} \xrightarrow{k_1} \text{cyt(III)} + \text{pc(I)} \quad (1)$$

$$\text{cyt(II)/pc(II)} \xrightarrow{k_2} \text{cyt(III)/pc(I)} \quad (2)$$

(less than 0.2 $s^{-1}$) for the complex reinforced by noninvasive covalent cross-links between the heme patch and the remote patch,[28,29] which impede protein rearrangement.[30,31]

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(28) Some evidence for this cross-linking is given in refs 14-16, 19, and 20. Our UV-vis, CD, and MCD spectra show that the covalent and electrostatic cyt/pc complexes have very similar structures,[29] and the protein orientation in the latter is known.[12-22] Moreover, plastocyanin whose carboxylate groups in the remote patch are blocked[16] cannot be cross-linked with cytochrome *c*.[29]

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