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**Authors**

Ray J. Hoobler, Marc A. Hutton, Mills M. Dillard, Michael Castellani, Arnold L. Rheingold, Anne L. Rieger, Philip H. Rieger, Thomas C. Richards, and William E. Geiger

# Synthesis, Characterization, and Crystal Structure of the ( $\eta^5\text{-C}_5\text{Ph}_5$ )Cr(CO)<sub>3</sub> Radical

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## Abstract

The reaction between Cr(CO)<sub>6</sub> and Na(C<sub>5</sub>Ph<sub>5</sub>) in refluxing diglyme yields [Na(diglyme)<sub>3/2</sub>]-[(C<sub>5</sub>Ph<sub>5</sub>)Cr(CO)<sub>3</sub>], **1**. Metathesis of **1** with [Ph<sub>3</sub>P=N=PPh<sub>3</sub>]Cl in CH<sub>2</sub>Cl<sub>2</sub> yields [Ph<sub>3</sub>P=N=PPh<sub>3</sub>]-[(C<sub>5</sub>Ph<sub>5</sub>)Cr(CO)<sub>3</sub>], **2**. Oxidation of **1** by AgBF<sub>4</sub> in THF under an argon atmosphere produces (C<sub>5</sub>Ph<sub>5</sub>)Cr(CO)<sub>3</sub>, **3**. Complexes **2** and **3** form a redox pair connected by a quasireversible one-electron process, E° = -0.69 V vs ferrocene in CH<sub>2</sub>Cl<sub>2</sub>, E° = -0.50 V in CH<sub>3</sub>CN, k<sub>s</sub> = 0.12 cm/s. ESR spectra in toluene at 90 K gave a rhombic **g**-tensor with components 2.1366, 2.0224, and 1.9953, consistent with the expected low-spin d<sup>5</sup> electronic configuration. The largest **g**-tensor component was significantly temperature dependent, suggesting an equilibrium between conformations with <sup>2</sup>A' and <sup>2</sup>A'' ground states. Crystals of **2** belong to the space group *P* $\bar{1}$  with Z = 2. The unit-cell parameters are *a* = 12.190 (3) Å, *b* = 13.019 (3) Å, *c* = 19.842 (4) Å,  $\alpha$  = 96.598 (17) °,  $\beta$  = 103.719 (17) °,  $\gamma$  = 94.322 (18) °, and V = 3021.5 (11) Å<sup>3</sup> with final values of R<sub>F</sub> = 6.72% and R<sub>wF</sub> = 7.57%. Crystals of **3**•C<sub>6</sub>H<sub>6</sub> belong to the space group *P*2<sub>1</sub>/*c* with Z = 8. The unit-cell parameters are *a* = 33.307 (9) Å, *b* = 8.978 (3) Å, *c* = 22.702 (6) Å,  $\beta$  = 91.73 (2) ° and V = 6798 (3) Å<sup>3</sup> with final values of R<sub>F</sub> = 7.69% and R<sub>wF</sub> = 7.68%.

## Introduction

Paramagnetic organometallic complexes have recently received considerable attention because of their demonstrated high reactivity and their proposed roles in a variety of important chemical reactions.<sup>2</sup> One method for isolating such compounds involves replacing a relatively small ligand in an unstable fragment with a larger ligand to prevent formation of a closed shell compound.<sup>3</sup> One such substitution expected to induce substantial molecular changes is that of the pentaphenylcyclopentadienyl ligand ( $\eta^5\text{-C}_5\text{Ph}_5$ ) used in place of the much smaller cyclopentadienyl ligand ( $\eta^5\text{-C}_5\text{H}_5$ , Cp). The  $\text{C}_5\text{Ph}_5$  ligand has been previously shown to impart stability to organometallic radicals.<sup>4</sup>

In 1974, Cotton and co-workers<sup>5</sup> suggested that the unusually long Cr-Cr bond in  $[\text{CpCr}(\text{CO})_3]_2$  might lead to the generation of  $\text{CpCr}(\text{CO})_3$  radicals under mild conditions. Work in other groups found that this dimer possessed greatly enhanced reactivity in comparison with the  $[\text{CpMo}(\text{CO})_3]_2$  dimer.<sup>6-8</sup> There were also numerous studies concerned with characterizing the radical species.<sup>9-15</sup> Recently, Baird<sup>16</sup> and Goh and co-workers<sup>17</sup> attempted to prepare an analogous monomer containing the pentamethylcyclopentadienyl ligand ( $\eta^5\text{-C}_5\text{Me}_5$ , Cp\*).<sup>18</sup> However, the product dimerized in the solid state with an exceedingly long Cr-Cr bond but in solution exhibited much greater reactivity than the  $\text{C}_5\text{H}_5$  complex. The extent of monomer formation for these complexes in room temperature solution (10% for  $[\text{CpCr}(\text{CO})_3]_2$ <sup>9,11</sup> and *ca.* 90% for  $[\text{Cp}^*\text{Cr}(\text{CO})_3]_2$ <sup>16b,c</sup>) suggested that a still larger cyclopentadienyl ligand would allow isolation of a monomeric species. The isolation of a radical of this type would permit characterization not possible with an equilibrium mixture. In addition, recent EPR work has raised interesting questions about the structure of the  $\text{CpCr}(\text{CO})_3$  radical doped in  $\text{CpMn}(\text{CO})_3$  crystals<sup>12</sup> that might be answered by structural characterization of a similar compound.

The photochemical reactivity of  $[\text{CpMo}(\text{CO})_3]_2$  has been studied extensively<sup>19</sup> with the primary photoproduct in the presence of low energy light being the  $\text{CpMo}(\text{CO})_3$  radical.<sup>19a</sup> The latter species can be studied only by fast techniques because re-combination occurs at a diffusion controlled rate.<sup>20</sup> The analogous hydridotris(pyrazolyl)borate (Tp) complex,  $\text{TpMo}(\text{CO})_3$ , has

been isolated and characterized.<sup>3c</sup> While the Tp and Cp ligands are in some ways similar, differences between them make the isolation of a cyclopentadienyl derivative desirable. Substitution of C<sub>5</sub>Ph<sub>5</sub> for C<sub>5</sub>H<sub>5</sub> has been shown to generate significant quantities of the (C<sub>5</sub>Ph<sub>5</sub>)Mo(CO)<sub>3</sub> radical in solution; however, this complex also completely dimerizes on crystallization.<sup>21</sup> We now show that the [(C<sub>5</sub>Ph<sub>5</sub>)Cr(CO)<sub>3</sub>]<sub>n</sub> system is completely monomeric. The radical is remarkably stable in the absence of air and has been characterized by a number of methods.

## Experimental Section

**General Data.** All reactions of air- and moisture-sensitive materials were performed under an argon atmosphere employing standard Schlenk techniques unless otherwise stated. Solids were manipulated under argon in a Vacuum Atmospheres glovebox equipped with a HE-493 dri-train. Diglyme, toluene, and hexanes were distilled from sodium/benzophenone ketyl under argon. Tetrahydrofuran (THF) and benzene were distilled from potassium/benzophenone ketyl under argon. Dichloromethane and CH<sub>3</sub>CN were distilled from CaH<sub>2</sub> under argon. Na[C<sub>5</sub>Ph<sub>5</sub>] was prepared according to a literature procedure or as described below.<sup>22</sup> NMR solvents were vacuum distilled from CaH<sub>2</sub> and placed under an argon atmosphere. AgPF<sub>6</sub>, AgBF<sub>4</sub>, Cr(CO)<sub>6</sub> (Strem), diglyme, [Ph<sub>3</sub>P=N=PPh<sub>3</sub>]Cl ([PPN]Cl), CDCl<sub>3</sub>, CD<sub>2</sub>Cl<sub>2</sub> (Aldrich) and all other solvents (Fisher) were used without further purification. Elemental analyses were performed by Schwartzkopf Microanalytical Laboratory, Woodside, N.Y. Infrared spectra were recorded on a Nicolet 20 DXB FTIR spectrometer. <sup>1</sup>H NMR spectra were obtained at 200.06 MHz on a Varian XL-200 NMR spectrometer equipped with a Motorola data system upgrade. UV-visible spectra were recorded on a Varian DMS-90 spectrometer.

**Electron Spin Resonance Spectra.** X-band ESR spectra were obtained using a Bruker ESP300E spectrometer at the University of Bristol. The spectrometer was equipped with a liquid nitrogen dewar and a variable temperature unit; field-frequency calibration relied on a Hewlett-Packard microwave frequency counter and the Bruker Hall probe, the offset of which was

checked from time to time with DPPH. Toluene solutions of  $(C_5Ph_5)Cr(CO)_3$  were prepared for ESR spectral studies in several ways, including the use of an argon-filled glove box, modified Schlenk techniques, and a vacuum line.

**Electrochemistry.** Electrochemical data were obtained under a nitrogen atmosphere using drybox procedures previously described.<sup>23</sup>  $CH_3CN$  and  $CH_2Cl_2$  were employed as solvents, with a supporting electrolyte of 0.1 M  $Bu_4NPF_6$ . Potentials are referred to the ferrocene/ferrocenium couple. Conversion to the S.C.E. scale requires addition of +0.46 V ( $CH_2Cl_2$ ) or +0.40 V ( $CH_3CN$ ) to these potentials. Data acquisition and treatment was as recently described.<sup>24</sup> All data were obtained with Pt working electrodes, with a Pt bead of *ca.* 1 mm radius being employed for scan rates below  $\nu = 1$  V/s, and a Pt microdisk ( $r = 247 \mu m$ ) being used for  $1 \text{ V/s} < \nu < 100 \text{ V/s}$ . A luggin probe was used to minimize resistance effects.

**X-Ray Structural Determinations.** Crystallographic data are collected in Table I. Crystals of both **2** and  $3 \cdot C_6H_6$  were sealed in capillary tubes and unit-cell parameters were obtained from the angular settings of 25 reflections. The centrosymmetric triclinic space group  $P\bar{1}$  for **2** was initially assumed and was later shown to be correct by the results of least-squares refinement. The space group for  $3 \cdot C_6H_6$  was uniquely determined by systematic absences in the reflection data. Regular crystal size and low  $\mu$ -s for both removed the need for corrections for absorption. The asymmetric unit for  $3 \cdot C_6H_6$  contains two crystallographically independent, but chemically similar, molecules of the benzene solvated radical species. All non-hydrogen atoms were refined with anisotropic thermal parameters, and hydrogen atoms were treated as idealized contributions. Phenyl rings were constrained to be rigid, planar hexagons. Atomic coordinates for **2** and  $3 \cdot C_6H_6$  are listed in Tables II and III, respectively. Bond distances and angles are collected in Tables IV and V, respectively.

All computations used the SHELXTL (5.1) software package (G. Sheldrick, Nicolet(Siemens), Madison, WI).

**Na( $C_5Ph_5$ ).** **Method 1.** This is a modification of the method of Rausch and co-workers.<sup>22a</sup> Dry toluene (500 mL) was added to a solid mixture of  $C_5Ph_5H$  (15.00 g, 33.6 mmol)

and  $\text{NaNH}_2$  (1.25 g, 32.0 mmol). The mixture was refluxed until passage of the reaction solution vapor over red litmus indicated an absence of ammonia. To ensure complete reaction, the solution was refluxed 8-12 h after paper discoloration ceased. Total reflux time was 4 d. The reaction mixture was allowed to cool to room temperature and was filtered through a frit. The resulting solid was stirred in warm benzene (4 x 20 mL, *ca.* 40-50 °C), filtered, and dried *in vacuo* to yield 12.6 g (26.9 mmol, 80%) of  $\text{Na}(\text{C}_5\text{Ph}_5)$  as a powdery white solid.

**Method 2.** Dry THF (50 mL) was added to a solid mixture of  $\text{C}_5\text{Ph}_5\text{H}$  (5.00 g, 11.2 mmol) and NaH (0.40 g, 16.8 mmol). The mixture was refluxed overnight, cooled to room temperature, and filtered via cannula to yield a deep yellow solution. The THF was removed *in vacuo* and the resulting solid dried overnight. The product contains a small amount of residual THF (*ca.* 5% by  $^1\text{H}$  NMR) most of which can be removed by refluxing the pale yellow solid in 20 mL dry benzene, followed by cooling to room temperature, and drying *in vacuo* to yield 4.78 g (10.2 mmol, 91%) of  $\text{Na}(\text{C}_5\text{Ph}_5)$  as a pale yellow solid.

**[Na(diglyme) $_{3/2}$ ][( $\text{C}_5\text{Ph}_5$ )Cr(CO) $_3$ ], 1.** Dry diglyme (100 mL) was added to a solid mixture of  $\text{Cr}(\text{CO})_6$  (3.10 g, 14.1 mmol) and  $\text{Na}(\text{C}_5\text{Ph}_5)$  (6.01 g, 12.8 mmol). After a 1.5 h reflux excess  $\text{Cr}(\text{CO})_6$  was sublimed into the reflux condenser with a heat gun. The condenser was removed and the hot solution was filtered via cannula into a second flask. Hexanes (20 mL) were added and the solution was swirled to generate a homogeneous solution. After cooling to -15 °C overnight, the solution was filtered and the resulting crystals were washed with hexanes (10 mL), to yield 8.09 g (10.0 mmol, 78%) of dark yellow crystals of 1. Occasionally, a black material co-precipitates with the product. It can be removed by recrystallization from diglyme/hexanes. Mp: 228-230°C.  $^1\text{H}$  NMR ( $\text{CDCl}_3$ )  $\delta$  3.34 (s, 9,  $\text{CH}_3$ ), 3.50-3.65 (m, 12,  $\text{CH}_2$ ), 6.90-7.20 (m, 25,  $\text{C}_6\text{H}_5$ ). Anal. Calcd. for  $\text{C}_{94}\text{H}_{92}\text{Cr}_2\text{Na}_2\text{O}_{15}$ : C, 70.05; H, 5.75. Found: C, 69.62; H, 6.07.

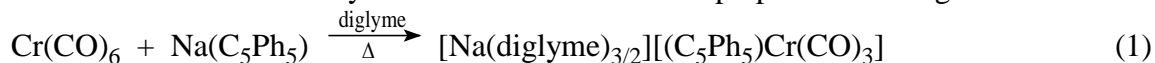
**[PPN][( $\text{C}_5\text{Ph}_5$ )Cr(CO) $_3$ ], 2.**  $[\text{Na}(\text{diglyme})_{3/2}][(\text{C}_5\text{Ph}_5)\text{Cr}(\text{CO})_3]$  (1.00 g, 1.24 mmol) and  $[\text{PPN}]\text{Cl}$  (0.69 g, 1.2 mmol) were each dissolved in 5 mL  $\text{CH}_2\text{Cl}_2$ . The solutions were combined, stirred for 20 min, filtered to remove the NaCl precipitate, and dried *in vacuo*. The

resulting yellow powder was stirred with 5 mL acetone for 5 min to dissolve any residual [PPN]Cl. The acetone was removed by cannula filtration, and the solid was dried *in vacuo*. The resulting solid was dissolved in CH<sub>2</sub>Cl<sub>2</sub> (15 mL) and layered with an equal volume of hexanes. The layers were allowed to combine in the dark producing large orange blocks of **2** in 70% yield (0.97 g, 0.87 mmol). Mp: 241-242 °C. Anal. Calcd. for C<sub>74</sub>H<sub>55</sub>CrNO<sub>3</sub>P<sub>2</sub>: C, 79.34; H, 4.95. Found C, 79.08; H, 5.08.

(C<sub>5</sub>Ph<sub>5</sub>)Cr(CO)<sub>3</sub>•C<sub>6</sub>H<sub>6</sub>, **3**•C<sub>6</sub>H<sub>6</sub>. Cold, freshly distilled THF (10 mL, -78 °C) was added with stirring to a solid mixture of [Na(diglyme)<sub>3/2</sub>][(C<sub>5</sub>Ph<sub>5</sub>)Cr(CO)<sub>3</sub>] (1.00 g, 1.24 mmol) and AgBF<sub>4</sub> (0.24 g, 1.23 mmol) cooled in a -78 °C bath. The solution was initially yellow-green and turned deep blue on warming. When the temperature exceeded 0 °C (*ca.* 2 h) the solution was filtered through Celite and the solvent was removed *in vacuo*. The dark blue-green solid was dissolved in warm benzene (20 mL, 40 °C), combined with 20 mL hexanes, and cooled to -15 °C overnight to yield 0.52 g (64%) of dark blue-green **3**•C<sub>6</sub>H<sub>6</sub>. Mp: 205 °C (dec). Visible max (C<sub>6</sub>H<sub>6</sub>) 611 nm. Anal. Calcd for C<sub>44</sub>H<sub>31</sub>CrO<sub>3</sub>: C, 80.11; H, 4.74. Found C, 79.76; H, 5.11.

## Results and Discussion

**Synthesis and Reactivity.** Reaction of Cr(CO)<sub>6</sub> and Na(C<sub>5</sub>Ph<sub>5</sub>) in refluxing diglyme yields bright yellow, crystalline [Na(diglyme)<sub>3/2</sub>][(C<sub>5</sub>Ph<sub>5</sub>)Cr(CO)<sub>3</sub>], **1**, in 75% yield (eq 1). This procedure is similar to that used by Slocum and co-workers to prepare the analogous lithio

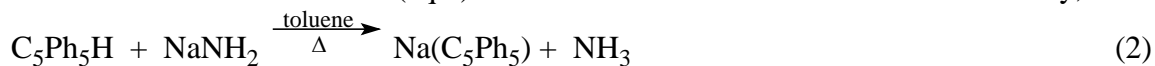


compound ([Li(diglyme)<sub>3</sub>][(C<sub>5</sub>Ph<sub>5</sub>)Cr(CO)<sub>3</sub>]).<sup>25,26</sup> The stoichiometry of **1** was established by <sup>1</sup>H NMR spectroscopy and elemental analysis. Solutions of **1** decompose in the air within minutes, while the solid requires several hours for significant decomposition to occur. Complex **1** is soluble in THF, CH<sub>2</sub>Cl<sub>2</sub>, and CH<sub>3</sub>CN. It also dissolves in benzene, although, if the solution is sufficiently concentrated, a yellow solid (presumably diglyme-free Na[(C<sub>5</sub>Ph<sub>5</sub>)Cr(CO)<sub>3</sub>])

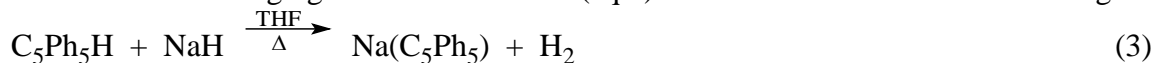


precipitates. Unlike  $\text{Na}[\text{CpCr}(\text{CO})_3]$ ,<sup>6b</sup>  $[\text{Na}(\text{diglyme})_{3/2}][(\text{C}_5\text{Ph}_5)\text{Cr}(\text{CO})_3]$  does not react with excess (50 molar equivalents) acetic acid in THF solution.

The  $\text{Na}(\text{C}_5\text{Ph}_5)$  used in the synthesis of **1** was prepared by three routes. The first was the method of Rausch and co-workers<sup>22a</sup> (eq 2) which works well in our hands. Unfortunately,



it required relatively large solvent volumes (*ca.* 100 mL toluene per gram of  $\text{Na}(\text{C}_5\text{Ph}_5)$ ) which made scaling up the reaction difficult. The reaction was modified by increasing the reactant to solvent ratio three-fold with a proportional increase in reaction time. Unfortunately, the resultant product required numerous benzene washes to remove unreacted  $\text{C}_5\text{Ph}_5\text{H}$ .<sup>27</sup> A different reaction modification involved changing the solvent to THF (eq 3). This method has several advantages



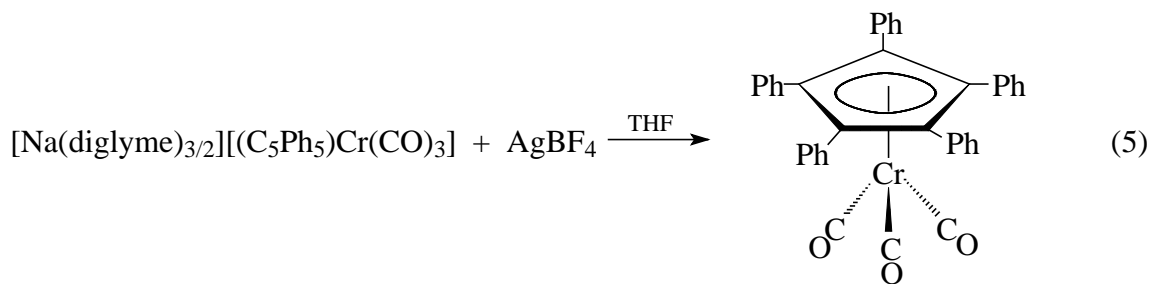
over the previously described methods: 1) much smaller solvent volumes are required, 2) the reaction time is significantly reduced, 3) contamination by residual deprotonating agent is not possible, and 4) reaction completion is easily discerned (The reactant  $\text{C}_5\text{Ph}_5\text{H}$  is only poorly soluble in refluxing THF while  $\text{Na}(\text{C}_5\text{Ph}_5)$  is quite soluble). We find this method to be the most convenient method of preparing large quantities (> 5 g) of  $\text{Na}(\text{C}_5\text{Ph}_5)$ .

Metathesis of **1** with  $[\text{PPN}]\text{Cl}$  in  $\text{CH}_2\text{Cl}_2$  solution yields  $[\text{PPN}][(\text{C}_5\text{Ph}_5)\text{Cr}(\text{CO})_3]$ , **2**, in 70% yield as large, orange blocks (eq 4). Complex **2** is soluble in dichloromethane but poorly soluble



in other solvents. Solid **2** shows no evidence of decomposition after exposure to the air for 7 days, while solutions of it decompose in several minutes.

Oxidation of THF solutions of **1** by either  $\text{AgBF}_4$  or  $\text{AgPF}_6$  under an argon atmosphere rapidly produces deep blue-green  $(\text{C}_5\text{Ph}_5)\text{Cr}(\text{CO})_3$ , **3**, in a 64% isolated yield (eq 5). The use of



freshly distilled THF is important since the presence of even minute amounts of peroxide leads to complete decomposition of the product in seconds to hours. Solutions of **3** in freshly distilled THF are stable for over a week. Complex **3** dissolves in THF,  $\text{C}_6\text{H}_6$ , toluene, and  $\text{CH}_2\text{Cl}_2$ . It is very air-sensitive, both in solution and as a solid.  $(\text{C}_5\text{Ph}_5)\text{Cr}(\text{CO})_3$  rapidly substitutes small Lewis bases, such as  $\text{PMe}_3$ ,  $\text{P}(\text{OMe})_3$ , and  ${}^t\text{BuNC}$ , for CO to yield crystalline products.<sup>28</sup>

**Infrared Spectra.** Infrared spectra of complexes **1**, **2**, and **3** were obtained in a variety of solvents and in the solid state (Table VI). The results obtained for anions **1** and **2** are similar to those reported by Darensbourg and co-workers for the  $\text{CpCr}(\text{CO})_3^-$  ion.<sup>29</sup> In coordinating solvents, the  $\text{Na}^+$  ion in **1** does not associate with the  $(\text{C}_5\text{Ph}_5)\text{Cr}(\text{CO})_3^-$  ion and a spectrum consistent with  $C_{3v}$  symmetry is obtained. In THF, the  $\text{Na}^+$  ion appears to associate with a carbonyl ligand, lowering the apparent molecular symmetry and splitting the Cr-CO *E* band. Use of the non-coordinating  $\text{PPN}^+$  ion results in solvent independent spectra, similar to the spectra of **1** in coordinating solvents.

The infrared spectrum of  $(\text{C}_5\text{Ph}_5)\text{Cr}(\text{CO})_3$ , **3**, in toluene solution shows two absorptions of intensity comparable to **2**, but shifted *ca.*  $110\text{ cm}^{-1}$  to higher energy. This is consistent with a one-electron oxidation and retention of the molecular symmetry. Thus  $(\text{C}_5\text{Ph}_5)\text{Cr}(\text{CO})_3$  exists exclusively as a monomer in solution. The Nujol mull IR spectrum of **3** displays two absorptions nearly superimposable on the solution spectrum. In contrast, the spectrum of  $[\text{CpCr}(\text{CO})_3]_2$  displays four absorptions. The fact that the mull spectrum has only two absorptions also suggests the complex is monomeric in the solid state.

**Cyclic Voltammetry of 2.** The oxidation of  $[\text{PPN}][(\text{C}_5\text{Ph}_5)\text{Cr}(\text{CO})_3]$ , **2**, was investigated in  $\text{CH}_2\text{Cl}_2$  and  $\text{CH}_3\text{CN}$  by cyclic voltammetry (CV, Figure 1). In both cases a diffusion-

controlled, one-electron oxidation was observed,  $E^\circ = -0.69$  V vs Fc in  $\text{CH}_2\text{Cl}_2$  and  $-0.50$  V in  $\text{CH}_3\text{CN}$ . No deviation from chemical reversibility was noted with scan rates above  $\nu = 0.05$  V/s, consistent with the above noted high stability of the neutral radical.

Given the relatively high resistance of  $\text{CH}_2\text{Cl}_2$  solutions, quantitative fits of CV curves to theory were restricted to the data obtained from  $\text{CH}_3\text{CN}$  solutions, the range of scan rates being 0.3 to 100 V/s. Typical values of the peak potential difference,  $\Delta E_p$ , were 78 mV with  $\nu = 10$  V/s and 102 mV with  $\nu = 50$  V/s. Finite difference digital simulations were observed to be consistent with experiment for a quasireversible one-electron transfer reaction uncomplicated by coupled chemical reactions. The electron-transfer coefficient,  $\alpha$ , is 0.50 and the standard heterogeneous charge-transfer rate,  $k_s$ , is 0.12 cm/s based on these fits. The simulations assumed equal diffusion coefficients ( $8.5 \times 10^{-6}$  cm<sup>2</sup>/s) for both **2** and **3**. The apparent  $k_s$  value required to fit the experimental curves was essentially unchanged over more than two orders of magnitude in scan rate. This suggests that the reported value is not significantly affected by errors arising from  $iR$  loss. Such errors should have become more important at high sweep rates owing to the increasingly important charging current background, and no such effect was observed.

The  $k_s$  value is about the same as that reported<sup>31</sup> for an analogous  $\pi$ -hydrocarbon complex of a metal carbonyl fragment,  $(\eta^4\text{-C}_8\text{H}_8)\text{Fe}(\text{CO})_3^{0/-}$ , but at least an order of magnitude below that reported for the oxidation of ferrocene.<sup>32</sup> We ascribe no special significance to the lower  $k_s$  value of **2/3**, since, among other reasons, the electrode dependence of the value was not tested.<sup>33</sup> Among the possible factors limiting the charge-transfer rate are solvent dynamics and ion-pairing changes.

The voltammetry of **2** was investigated in  $\text{CH}_2\text{Cl}_2$  as a function of temperature, using  $[\mathbf{2}] = 1.2$  mM. The purpose of this experiment was to search for evidence of dimerization at low temperatures, in light of a report showing that the metal-metal bonded dimer  $[\text{CpCr}(\text{CO})_3]_2$  is favored under such conditions.<sup>12d</sup> At temperatures as low as 223 K, no deviation from chemical reversibility was noted for the oxidation of **2**, showing that no dimerization occurred after its

one-electron oxidation to **3**. Hence, it can be concluded that the 17-electron radical **3** is quite robust with respect to dimerization, even at significantly reduced temperatures.

The  $E^\circ$  value for  $\mathbf{2} \rightleftharpoons \mathbf{3} + e^-$  in  $\text{CH}_2\text{Cl}_2$ , -0.69 V, may be compared with that reported for the Cp analogue in the same medium, -0.83 V.<sup>12d</sup> The shift of +140 mV shift in the pentaphenylcyclopentadienyl complex is consistent with previous observations that the phenyl substituents result in a moderate stabilization of low oxidation states in  $\eta^5\text{-C}_5\text{R}_5$  complexes.<sup>4e,f</sup>

**Molecular Structure.** Crystal structures of  $[\text{PPN}][(\text{C}_5\text{Ph}_5)\text{Cr}(\text{CO})_3]$  and  $(\text{C}_5\text{Ph}_5)\text{Cr}(\text{CO})_3 \cdot \text{C}_6\text{H}_6$  are displayed in Figure 2. Bond distances and angles are listed in Tables IV and V. For both compounds, bond lengths within the cyclopentadienyl ligand are normal for a coordinated  $\text{C}_5\text{Ph}_5$  ligand. The phenyl ring torsion angles (Table VII) do not appear to vary systematically between the compounds. The  $(\text{C}_5\text{Ph}_5)\text{Cr}(\text{CO})_3$  radical crystallizes with two conformers in the unit cell with the torsion angles representing the only significant differences between them. These results, in conjunction with the reports of other  $\text{C}_5\text{Ph}_5$  containing complexes,<sup>22,25c,34</sup> suggest that intermolecular packing forces are the dominant factor in determining torsion angles in coordinated  $\text{C}_5\text{Ph}_5$  ligands.

In each case, the metal is centered 1.86 Å beneath the  $\text{C}_5$  ring. In the anion **2**, the OC-Cr-CO angles are close to 90°, and similar to those predicted<sup>35</sup> and found in isoelectronic  $\text{CpMn}(\text{CO})_3$ <sup>38</sup> and  $\text{Cp}^*\text{Mn}(\text{CO})_3$ .<sup>12c</sup> The corresponding angles in  $[\text{Me}_4\text{N}][\text{CpCr}(\text{CO})_3]$  are also close to 90°; however, they differ slightly from the expected values, due to interaction between one CO and the  $\text{Me}_4\text{N}^+$  cation.<sup>37</sup>

Two significant differences between the structures of **2** and  $\mathbf{3} \cdot \text{C}_6\text{H}_6$  include changes in the Cr-C(O) bond lengths and the OC-Cr-CO bond angles. As expected, oxidation of the anion leads to a lengthening of the Cr-CO bond. While the OC-Cr-CO bond angles in the anion are very close to 90°, those in the radical are significantly different as has been predicted by Fortier and coworkers.<sup>12c</sup> The two conformers of  $\mathbf{3} \cdot \text{C}_6\text{H}_6$  are very similar and differ by only small amounts in some of the bond length and angle values.

**ESR Spectra.** The spectrum of  $(C_5Ph_5)Cr(CO)_3$  in a toluene glass in the temperature range 77-110 K shows the characteristic pattern expected for a rhombic  $g$ -tensor. The measured  $g$ -tensor components are given in Table VIII. The low-field feature (width at half height *ca.* 30 G at 90 K) broadens as the temperature increases and disappears into the baseline above 120 K. The central feature (*ca.* 16 G wide at 90 K) also broadens, but remains detectable up to about 150 K; the high-field feature (*ca.* 12 G wide at 90 K) remains well-defined up to about 140 K, but broadens at higher temperatures. The spectrum was found to be very sensitive to the quality of the glass. Rapidly frozen samples often showed many extra features; however, when the sample was thawed and slowly re-cooled, the extra features disappeared, leaving only the canonical three.

The experimental  $g$ -tensor is characteristic of a low-spin  $d^5$  system<sup>38?</sup> and is very similar to that obtained for  $CpCr(CO)_3$  (2.1339, 2.0353, 1.9969)<sup>12b</sup> and  $(C_5Me_5)Cr(CO)_3$  (2.1215, 2.0192, 1.9973).<sup>12c</sup> Fortier and coworkers<sup>12c</sup> concluded that the ground state of  $CpCr(CO)_3$  is  $^2A'$ , whereas that of  $(C_5Me_5)Cr(CO)_3$  is  $^2A''$ . The spectroscopic distinction between the two symmetries lies in the orientations of the  $g$ -tensor principal axes relative to the molecular axes, information not available from a frozen solution spectrum.

As shown in Table VIII,  $g_1$  is significantly temperature-dependent, whereas  $g_2$  and  $g_3$  remain constant within the experimental uncertainty. This behavior suggests that, in frozen toluene, there is a temperature-dependent equilibrium between the conformations giving  $^2A'$  and  $^2A''$  ground states. At the temperature of our experiments, the lifetimes of these conformations are apparently long enough that a superposition of the spectra of the two conformers is observed. At higher temperatures, the lifetimes decrease and the spectrum broadens and eventually becomes undetectable. In order to rationalize the observation of a single low-field feature, the centers of the two components must differ by less than the linewidth, *ca.* 30 G, suggesting that the  $g_1$  values for the two conformers differ by no more than about 0.02. Furthermore, the energy difference must be quite small, on the order of 1-2 kJ/mol, in order to account for the appearance of both conformers and for the temperature coefficient.

Spectra of liquid solutions showed a wide range of features which depended to some extent on the method of sample preparation. The isotropic features as a group always had an integrated intensity less than 1% of that of the frozen  $(C_5Ph_5)Cr(CO)_3$  spectrum. The isotropic features included: (1) A 1:1:1 triplet at  $g = 1.9830 \pm 0.0003$ ,  $A = 5.00 \pm 0.07$  G; this resonance appeared only for samples which were prepared under or otherwise exposed to  $N_2$ . This result is reminiscent of the  $g = 1.98$  resonance observed by Curtis and coworkers<sup>40</sup> for  $TpMo(CO)_3$  in toluene at room temperature. Isotropic g-values less than g are inconsistent with low-spin  $d^5$  systems but are expected for the +3 or +5 oxidation states of chromium or molybdenum. Given our results, it would be surprising if the ESR spectrum of  $TpMo(CO)_3$  was observable at room temperature, and it is likely that the reported spectrum is that of a minor oxidation product. (2) Single resonances at  $g = 2.005 \pm 0.001$ ; these features were quite sharp and are consistent with organic radicals with no hyperfine structure, possibly including  $C_5Ph_5$ . (3) A resonance at  $g = 2.026 \pm 0.002$  or  $2.020 \pm 0.001$  was seen in most samples; however, the two features never occurred together. (4) Similarly, a resonance occurred at  $g = 2.0144 \pm 0.0002$  or  $2.0116 \pm 0.0003$  in many samples, but never at both positions. (5) Finally, one sample showed a broad feature at  $g = 2.04$ .

The feature at  $g = 2.026$  is reminiscent of the  $g = 2.025$  resonance observed in benzonitrile solutions of  $[CpCr(CO)_3]_2$  and originally assigned to  $CpCr(CO)_3$ .<sup>10</sup> This assignment was rejected by Morton and coworkers;<sup>12b</sup> the resonance is now believed to be due to a PhCN substitution product. The reaction with benzonitrile apparently goes to completion and the  $g = 2.025$  resonance has a corresponding frozen solution spectrum.<sup>41</sup> The resonances of type 3, 4, and 5 are very weak and do not correspond to any detectable features in the frozen solution spectrum. Nonetheless, the type 3, 4, and 5 features are most likely due to reaction with adventitious traces of various nucleophiles in the sample preparations.

**Summary.** The compounds  $[Na(diglyme)_{3/2}][(C_5Ph_5)Cr(CO)_3]$ ,  $[PPN][(C_5Ph_5)Cr(CO)_3]$ , and  $(C_5Ph_5)Cr(CO)_3$  have been prepared and characterized. The former two complexes have spectroscopic and crystallographic properties similar to the analogous  $C_5H_5$  and  $C_5Me_5$

compounds. The 17-electron radical  $(C_5Ph_5)Cr(CO)_3$  is thermally stable and has been structurally characterized. ESR measurements suggest that in frozen solutions  $(C_5Ph_5)Cr(CO)_3$  exists in two conformations with  $^2A'$  and  $^2A''$  ground states differing in energy by only 1-2 kJ/mol. The oxidized and reduced forms of the complex  $(C_5Ph_5)Cr(CO)_3^{0,-}$  constitute a redox pair with a quasireversible charge transfer,  $E^\circ = -0.69$  V vs Fc in  $CH_2Cl_2$ .

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**Supplementary Material Available.** For  $[PPN][(C_5Ph_5)Cr(CO)_3]$  and  $(C_5Ph_5)Cr(CO)_3$ , respectively as follows: Tables 1S-2S, anisotropic thermal parameters, Tables 3S-4S, hydrogen-atom coordinates (10 pages). An ORTEP drawing of  $[PPN][(C_5Ph_5)Cr(CO)_3]$  is provided. Ordering information is given on any current masthead page.

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**Table I. Crystal Data for [PPN][( $\eta^5$ -C<sub>5</sub>Ph<sub>5</sub>)Cr(CO)<sub>3</sub>] (2) and ( $\eta^5$ -C<sub>5</sub>Ph<sub>5</sub>)Cr(CO)<sub>3</sub> (3•C<sub>6</sub>H<sub>6</sub>)****(a) Crystal Parameters**

	[PPN][( $\eta^5$ -C <sub>5</sub> Ph <sub>5</sub> )Cr(CO) <sub>3</sub> ]	( $\eta^5$ -C <sub>5</sub> Ph <sub>5</sub> )Cr(CO) <sub>3</sub> •C <sub>6</sub> H <sub>6</sub>
formula	C <sub>74</sub> H <sub>55</sub> CrO <sub>3</sub> P <sub>2</sub>	C <sub>38</sub> H <sub>25</sub> CrO <sub>3</sub> •C <sub>6</sub> H <sub>6</sub>
formula weight	1120.21	659.72
crystal system	triclinic	monoclinic
space	$P\bar{1}$	$P2_1/c$
<i>a</i> , Å	12.1903(28)	33.307(9)
<i>b</i> , Å	13.0185(28)	8.978(3)
<i>c</i> , Å	19.8417(42)	22.702(6)
$\alpha$ , deg	96.598(17)	-----
$\beta$ , deg	103.719(17)	91.73(2)
$\gamma$ , deg	94.322(18)	-----
<i>V</i> , Å <sup>3</sup>	3021.5(11)	6798(3)
<i>Z</i>	2	8
cryst dimens, mm	0.36 x 0.37 x 0.46	0.38 x 0.40 x 0.40
cryst color	golden yellow	dark green
<i>D</i> (calc), g cm <sup>-3</sup>	1.216	1.289
$\mu$ (MoK $\alpha$ ), cm <sup>-1</sup>	2.81	3.58
temp, K	297	297

**(b) Data Collection**

diffractometer	Nicolet R3m	
monochromator	graphite	
radiation	MoK $\alpha$ ( $\lambda$ = 0.71073 Å)	
2 $\theta$ scan range, deg	4-50	4-42
data collected ( <i>h</i> , <i>k</i> , <i>l</i> )	$\pm 15$ , $\pm 16$ , $+24$	$\pm 33$ , $+8$ , $+22$
reflns. collected	10,986	8006

indpt. rflns	10,649	7188
indpt obsvd rflns	6820 ( $n = 5$ )	3418 ( $n = 4$ ) ( $F_o \geq n\sigma(F_o)$ )
std. rflns	3 std/197 rflns	3 std/197 rflns
var. in stds.	< 1	;2

**(c) Refinement**

$R(F)$ , %	6.72	7.69
$R(wF)$ , %	7.57	7.68
$\Delta/\sigma(\max)$	0.027	0.026
$\Delta(\rho)$ , eÅ <sup>-3</sup>	1.061	0.60
$N_o/N_v$	11.2	9.47
GOF	1.521	1.473

**Table II. Atomic coordinates ( $\times 10^4$ ) and isotropic thermal parameters ( $\text{\AA}^2 \times 10^3$ ) for [PPN][ $(\text{C}_5\text{Ph}_5)\text{Cr}(\text{CO})_3$ ]**

	x	y	z	U*
Cr	56.7(6)	9961.5(5)	2374.6(4)	30.1(2)
P(1)	6615(1)	5033(1)	3807(1)	37(1)
P(2)	5013(1)	6517(1)	3141(1)	38(1)
N	5560(4)	5604(3)	3511(2)	49(2)
C(1)	-663	10569	1377	30
C(2)	-961	9477	1276	30
C(3)	76	8982	1375	28
C(4)	999	9776	1536	30
C(5)	552	10761	1550	28
C(6)	1278(4)	10310(4)	3105(3)	44(2)
O(6)	2066(4)	10555(4)	3589(2)	72(2)
C(7)	-351(4)	8886(4)	2798(2)	37(2)
O(7)	-610(3)	8187(3)	3066(2)	58(2)
C(8)	-676(4)	10807(4)	2870(3)	38(2)
O(8)	-1131(4)	11363(3)	3185(2)	59(2)
C(11)	-2468(3)	11317(3)	1486(2)	49(2)
C(12)	-3227	12057	1349	73(3)
C(13)	-2988	12863	985	81(3)
C(14)	-1989	12927	758	67(3)
C(15)	-1230	12186	895	46(2)
C(16)	-1469	11381	1259	37(2)
C(21)	-2819(3)	9163(2)	394(2)	42(2)
C(22)	-3857	8575	85	56(2)
C(23)	-4192	7724	381	57(2)

C(24)	-3490	7461	986	53(2)
C(25)	-2452	8048	1295	45(2)
C(26)	-2116	8899	1000	34(2)
C(31)	856(3)	7372(2)	1766(1)	41(2)
C(32)	935	6310	1654	49(2)
C(33)	318	5721	1029	59(3)
C(34)	-376	6193	517	62(2)
C(35)	-455	7255	630	50(2)
C(36)	161	7844	1254	34(2)
C(41)	3110(3)	10043(3)	2117(1)	59(2)
C(42)	4227	9965	2074	73(3)
C(43)	4444	9461	1467	58(2)
C(44)	3543	9035	904	50(2)
C(45)	2427	9113	948	42(2)
C(46)	2210	9617	1554	35(2)
C(51)	1169(3)	12577(2)	2182(2)	42(2)
C(52)	1770	13548	2248	51(2)
C(53)	2445	13741	1789	62(2)
C(54)	2518	12961	1264	65(3)
C(55)	1917	11990	1198	50(2)
C(56)	1242	11798	1657	33(2)
C(61)	6605(3)	3249(3)	4464(2)	72(3)
C(62)	6166	2255	4521	102(4)
C(63)	5191	1776	4033	97(4)
C(64)	4655	2290	3488	88(3)
C(65)	5094	3284	3431	67(3)
C(66)	6069	3763	3920	42(2)

C(71)	7903(3)	3899(2)	3069(2)	46(2)
C(72)	8659	3800	2642	57(2)
C(73)	9075	4668	2395	60(2)
C(74)	8735	5635	2575	61(2)
C(75)	7979	5734	3001	51(2)
C(76)	7562	4866	3248	38(2)
C(81)	6927(3)	6163(3)	5110(2)	60(2)
C(82)	7570	6751	5728	82(3)
C(83)	8752	6869	5866	89(4)
C(84)	9292	6399	5385	95(4)
C(85)	8650	5811	4767	74(3)
C(86)	7468	5693	4629	42(2)
C(91)	6263(3)	8222(3)	2865(2)	53(2)
C(92)	6928	9174	3059	66(3)
C(93)	7186	9649	3752	74(3)
C(94)	6781	9170	4252	82(3)
C(95)	6116	8218	4058	66(3)
C(96)	5858	7744	3364	44(2)
C(101)	3833(3)	6701(2)	1783(2)	48(2)
C(102)	3471	6387	1063	59(2)
C(103)	3903	5544	757	61(2)
C(104)	4697	5015	1172	58(2)
C(105)	5059	5330	1893	50(2)
C(106)	4627	6173	2198	37(2)
C(111)	3281(3)	7657(2)	3417(2)	49(2)
C(112)	2238	7754	3579	58(2)
C(113)	1632	6896	3727	59(2)



C(114)	2068	5940	3712	59(2)
C(115)	3111	5843	3549	45(2)
C(116)	3718	6701	3402	37(2)

\* Equivalent isotropic  $\mathbf{U}$  defined as one third of the trace of the orthogonalized  $\mathbf{U}_{ij}$  tensor

**Table III. Atomic Coordinates ( $\times 10^4$ ) and isotropic thermal parameters ( $\text{\AA}^2 \times 10^3$ ) of  $(\text{C}_5\text{Ph}_5)\text{Cr}(\text{CO})_3 \cdot \text{C}_6\text{H}_6$**

	x	y	z	U*
Cr	1213.2(5)	6161.7(21)	5080.2(8)	43.0(7)*
Cr'	3786.8(5)	8300.5(20)	8272.4(8)	38.4(7)*
C(1)	1214(3)	4067(12)	5578(5)	33(4)*
C(2)	1597(3)	4734(12)	5681(4)	34(4)*
C(3)	1783(3)	4860(12)	5125(5)	36(4)*
C(4)	1521(3)	4209(11)	4681(5)	36(4)*
C(5)	1166(3)	3734(11)	4975(5)	35(4)*
C(6)	1093(4)	7572(16)	5643(5)	60(6)*
O(6)	1003(3)	8470(12)	5976(4)	107(5)*
C(7)	1426(3)	7801(14)	4689(5)	58(5)*
O(7)	1570(3)	8812(11)	4477(4)	89(5)*
C(8)	681(4)	6472(14)	4880(5)	58(5)*
O(8)	334(3)	6635(11)	4777(5)	102(5)*
C(11)	529(2)	3744(8)	5991(3)	56(4)
C(12)	279	3094	6400	69(4)
C(13)	442	2215	6854	70(4)
C(14)	855	1986	6899	77(4)
C(15)	1106	2636	6490	55(4)
C(16)	942	3515	6036	32(3)
C(21)	1565(2)	5882(8)	6691(3)	52(3)
C(22)	1740	6165	7245	66(4)
C(23)	2129	5674	7379	68(4)
C(24)	2343	4900	6958	68(4)
C(25)	2168	4617	6403	52(4)

C(26)	1779	5108	6270	35(3)
C(31)	2343(2)	6775(7)	5207(3)	47(3)
C(32)	2736	7207	5100	62(4)
C(33)	2990	6247	4805	54(4)
C(34)	2852	4855	4617	56(4)
C(35)	2459	4423	4724	45(3)
C(36)	2205	5383	5019	39(3)
C(41)	1771(2)	5130(7)	3705(3)	50(3)
C(42)	1857	4866	3117	56(4)
C(43)	1781	3471	2868	65(4)
C(44)	1618	2339	3207	65(4)
C(45)	1532	2602	3795	52(3)
C(46)	1609	3997	4044	41(3)
C(51)	626(2)	3403(7)	4185(3)	56(4)
C(52)	321	2554	3919	75(4)
C(53)	223	1168	4153	76(4)
C(54)	431	632	4652	66(4)
C(55)	736	1482	4917	59(4)
C(56)	834	2867	4684	35(3)
C(1')	3928(3)	6255(11)	7777(4)	30(4)*
C(2')	3742(3)	5854(11)	8324(5)	33(4)*
C(3')	4005(3)	6334(11)	8800(4)	32(4)*
C(4')	4342(3)	7057(11)	8554(4)	24(4)*
C(5')	4306(3)	7004(11)	7931(4)	26(4)*
C(6')	3224(4)	8530(14)	8213(5)	54(5)*
O(6')	2890(3)	8657(11)	8150(4)	84(4)*
C(7')	3867(3)	9914(16)	8786(5)	51(5)*

O(7')	3908(3)	10887(11)	9100(4)	95(5)*
C(8')	3778(3)	9649(15)	7662(5)	52(5)*
O(8')	3757(3)	10511(10)	7284(4)	80(4)*
C(11')	3415(2)	6293(7)	6938(3)	50(3)
C(12')	3274	5720	6400	66(4)
C(13')	3499	4661	6105	59(4)
C(14')	3865	4175	6348	58(4)
C(15')	4006	4748	6886	52(3)
C(16')	3781	5807	7182	31(3)
C(21')	3079(2)	5336(7)	8758(3)	43(3)
C(22')	2744	4425	8818	61(4)
C(23')	2708	3112	8492	67(4)
C(24')	3007	2711	8106	64(4)
C(25')	3342	3622	8045	45(3)
C(26')	3378	4934	8372	36(3)
C(31')	3835(2)	4565(7)	9594(3)	50(3)
C(32')	3783	4218	10186	63(4)
C(33')	3833	5318	10616	65(4)
C(34')	3935	6765	10454	55(4)
C(35')	3987	7112	9862	42(3)
C(36')	3937	6012	9432	34(3)
C(41')	4870(2)	6718(6)	9337(3)	44(3)
C(42')	5190	7248	9686	52(4)
C(43')	5333	8692	9605	69(4)
C(44')	5154	9606	9174	54(4)
C(45')	4834	9077	8826	45(3)
C(46')	4691	7633	8907	36(3)

C(51')	4502(2)	8119(8)	6969(3)	42(3)
C(52')	4795	8451	6563	52(3)
C(53')	5195	8087	6688	55(4)
C(54')	5302	7392	7219	59(4)
C(55')	5010	7061	7625	41(3)
C(56')	4610	7425	7500	30(3)
Cs(1)	602(3)	7008(12)	2340(4)	95(5)
Cs(2)	769	6378	2852	90(5)
Cs(3)	885	7287	3326	73(4)
Cs(4)	834	8827	3286	93(5)
Cs(5)	667	9456	2774	96(5)
Cs(6)	551	8547	2300	89(5)
Cs(7)	2099(4)	5334(12)	1439(5)	127(6)
Cs(8)	1978	4690	903	115(6)
Cs(9)	2257	3945	564	121(6)
Cs(10)	2656	3846	761	135(7)
Cs(11)	2777	4490	1297	144(7)
Cs(12)	2498	5235	1636	140(7)

\* Equivalent isotropic  $U$  defined as one third of the trace of the orthogonalized  $U_{ij}$  tensor

Cs refers to the lattice benzene molecules.

**Table IV. Bond lengths (Å) in [PPN][ $(C_5Ph_5)Cr(CO)_3$ ] and  $(C_5Ph_5)Cr(CO)_3 \cdot C_6H_6$** 

	[PPN][ $(C_5Ph_5)Cr(CO)_3$ ]	$(C_5Ph_5)Cr(CO)_3$	
		<u>Conformer A</u>	<u>Conformer B</u>
Cr-C(1)	2.227(1)	2.194(11)	2.212(10)
Cr-C(2)	2.229(1)	2.244(10)	2.205(10)
Cr-C(3)	2.240(1)	2.233(10)	2.243(10)
Cr-C(4)	2.236(1)	2.237(11)	2.240(9)
Cr-C(5)	2.214(1)	2.198(11)	2.244(9)
Cr-CNT	1.860(1)	1.860(3)	1.863(3)
Cr-C(6)	1.802(5)	1.852(14)	1.888(13)
Cr-C(7)	1.816(5)	1.870(12)	1.873(14)
Cr-C(8)	1.818(5)	1.842(13)	1.839(13)
C(1)-C(2)	1.427(1)	1.425(14)	1.452(14)
C(2)-C(3)	1.446(1)	1.427(15)	1.438(14)
C(3)-C(4)	1.422(1)	1.440(15)	1.427(14)
C(4)-C(5)	1.436(1)	1.441(15)	1.415(13)
C(1)-C(5)	1.434(1)	1.404(15)	1.461(13)
C(6)-O(6)	1.180(6)	1.151(17)	1.125(15)
C(7)-O(7)	1.169(7)	1.140(16)	1.134(17)
C(8)-O(8)	1.160(7)	1.182(16)	1.157(16)

**Table V. Bond Angles (°) in [PPN][(C<sub>5</sub>Ph<sub>5</sub>)Cr(CO)<sub>3</sub>] and (C<sub>5</sub>Ph<sub>5</sub>)Cr(CO)<sub>3</sub>•C<sub>6</sub>H<sub>6</sub>**

	[PPN][(C <sub>5</sub> Ph <sub>5</sub> )Cr(CO) <sub>3</sub> ]	(C <sub>5</sub> Ph <sub>5</sub> )Cr(CO) <sub>3</sub>	
		<u>Conformer A</u>	<u>Conformer B</u>
C(6)-Cr-C(7)	88.7(2)	83.3(6)	94.7(5)
C(7)-Cr-C(8)	89.9(2)	98.2(5)	87.6(6)
C(6)-Cr-C(8)	86.0(2)	80.8(6)	83.3(5)
Cr-CO (avg)	178.9(5)	176.5(11)	177.6(11)
P(1)-N-P(2)	150.9(3)		

**Table VI. Infrared Spectral Data for (C<sub>5</sub>Ph<sub>5</sub>)Cr(CO)<sub>3</sub><sup>0/1-</sup> Complexes**

<u>Complex</u>	<u>Solvent</u>	<u><math>\nu(\text{C4O})</math> (cm<sup>-1</sup>)<sup>a</sup></u>	<u>Reference</u>
Na[(C <sub>5</sub> H <sub>5</sub> )Cr(CO) <sub>3</sub> ]	THF	1897, 1793, 1743	29
[Na(HMPA) <sub>x</sub> ][(C <sub>5</sub> H <sub>5</sub> )Cr(CO) <sub>3</sub> ] <sup>b</sup>	THF	1895, 1778	29
[Na(dg) <sub>3/2</sub> ][(C <sub>5</sub> Ph <sub>5</sub> )Cr(CO) <sub>3</sub> ] <sup>c</sup>	CH <sub>3</sub> CN	1892, 1783	this work
	CH <sub>2</sub> Cl <sub>2</sub>	1891, 1783	this work
	THF	1896, 1802, 1757	this work
[PPN][(C <sub>5</sub> Ph <sub>5</sub> )Cr(CO) <sub>3</sub> ] <sup>d</sup>	CH <sub>3</sub> CN	1893, 1783	this work
	CH <sub>2</sub> Cl <sub>2</sub>	1891, 1781	this work
	THF	1895, 1792	this work
	Mull	1888, 1790, 1775	this work
(C <sub>5</sub> H <sub>5</sub> )Cr(CO) <sub>3</sub>	CO Matrix	1986, 1910, 1902	30
(C <sub>5</sub> Me <sub>5</sub> )Cr(CO) <sub>3</sub>	Toluene	1994, 1895	16
(C <sub>5</sub> Ph <sub>5</sub> )Cr(CO) <sub>3</sub>	Toluene	2005, 1901	this work
	THF	2005, 1897	this work
	Mull	1998, 1885	this work

<sup>a</sup>All bands are strong.

<sup>b</sup>HMPA = hexamethylphosphoramide

<sup>c</sup>dg = diglyme

<sup>d</sup>PPN = bis(triphenylphosphine)iminium cation



**Table VII. Phenyl Ring Torsion Angles (Deg)**

$(C_5Ph_5)Cr(CO)_3$				
<u>Phenyl</u>	<u>[PPN][<math>(C_5Ph_5)Cr(CO)_3</math>]</u>	<u>Conformer A</u>	<u>Conformer B</u>	
1	42.0	52.8	66.0	
2	51.8	47.6	49.4	
3	52.7	52.6	48.2	
4	61.5	46.6	51.7	
5	59.3	54.3	43.3	
Ave	53.5	50.8	51.7	

**Table VIII. ESR Parameters for (C<sub>5</sub>Ph<sub>5</sub>)Cr(CO)<sub>3</sub>**

T, K	$g_1$	$g_2$	$g_3$
77	2.1387(4)	2.0225(3)	1.9952(2)
90	2.1366(3)	2.0224(2)	1.9953(2)
100	2.1345(4)	2.0224(3)	1.9954(2)
110	2.1327(5)	2.0220(4)	1.9954(2)
130	---	2.0214(16)	1.9957(3)

## Figure Captions

Figure 1. Circles: Cyclic voltammetry scan of 0.8 mM **2** in CH<sub>3</sub>CN/0.1 M Bu<sub>4</sub>NPF<sub>6</sub> with charging current subtracted;  $\nu = 0.3$  V/s; T = 296 K; working electrode = 0.7 mm Pt disk. Solid line: Finite difference simulation of quasireversible charge transfer, chemically reversible system;  $n = 1e^-$ ;  $k_s = 0.12$  cm/s; diffus coeff =  $8.5 \times 10^{-6}$  cm<sup>2</sup>/s;  $\alpha = 0.5$ .

Figure 2. Molecular structure and labeling scheme for (C<sub>5</sub>Ph<sub>5</sub>)Cr(CO)<sub>3</sub><sup>0,-</sup>.

Figure 3. X-Band ESR spectrum of (C<sub>5</sub>Ph<sub>5</sub>)Cr(CO)<sub>3</sub> in toluene at 90 K.

Supplementary Material

for

Synthesis, Characterization, and Crystal Structure of the

$(\eta^5\text{-C}_5\text{Ph}_5)\text{Cr}(\text{CO})_3$  Radical

by

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### Figure Caption

This is the molecular structure and labling scheme for [PPN][(C<sub>5</sub>Ph<sub>5</sub>)Cr(CO)<sub>3</sub>]. Figure 2 shown in the text is the ORTEP drawing of (C<sub>5</sub>Ph<sub>5</sub>)Cr(CO)<sub>3</sub>.

**Table 1S. Anisotropic thermal parameters ( $\text{\AA}^2 \times 10^3$ ) for [PPN][ $(\text{C}_5\text{Ph}_5)\text{Cr}(\text{CO})_3$ ]**

	$U_{11}$	$U_{22}$	$U_{33}$	$U_{23}$	$U_{13}$	$U_{12}$
Cr	30(1)	28(1)	32(1)	5(1)	7(1)	0(1)
P(1)	34(1)	33(1)	42(1)	8(1)	6(1)	6(1)
P(2)	34(1)	35(1)	44(1)	10(1)	8(1)	4(1)
N	39(3)	44(2)	67(3)	20(2)	11(2)	16(2)
C(1)	31	29	31	8	7	8
C(2)	29	29	31	6	7	-2
C(3)	31	24	28	3	3	2
C(4)	28	33	28	3	4	-1
C(5)	27	23	34	5	7	-1
C(6)	40(3)	45(3)	44(3)	6(2)	7(3)	-2(2)
O(6)	51(3)	97(3)	49(2)	-4(2)	-12(2)	-7(2)
C(7)	42(3)	36(3)	35(3)	5(2)	12(2)	6(2)
O(7)	66(3)	50(2)	63(2)	27(2)	18(2)	3(2)
C(8)	43(3)	32(3)	40(3)	10(2)	9(3)	-2(2)
O(8)	77(3)	47(2)	62(3)	-1(2)	35(2)	15(2)
C(11)	36(3)	52(3)	53(3)	-4(3)	4(3)	10(3)
C(12)	44(4)	81(5)	80(5)	-14(4)	-4(3)	30(3)
C(13)	77(5)	60(4)	82(5)	-6(4)	-29(4)	36(4)
C(14)	75(5)	42(3)	69(4)	13(3)	-16(4)	13(3)
C(15)	52(3)	40(3)	37(3)	8(2)	-6(3)	9(3)
C(16)	34(3)	32(3)	38(3)	-3(2)	-3(2)	6(2)
C(21)	38(3)	43(3)	41(3)	3(2)	4(3)	3(2)
C(22)	35(3)	71(4)	53(3)	2(3)	-1(3)	2(3)
C(23)	35(3)	67(4)	58(4)	-17(3)	11(3)	-15(3)
C(24)	46(3)	52(3)	56(4)	3(3)	15(3)	-17(3)

C(25)	41(3)	45(3)	46(3)	8(2)	8(3)	-9(2)
C(26)	32(3)	35(2)	33(3)	-6(2)	9(2)	-1(2)
C(31)	43(3)	33(3)	51(3)	10(2)	15(3)	7(2)
C(32)	59(4)	39(3)	57(4)	13(3)	25(3)	16(3)
C(33)	74(4)	26(3)	86(5)	4(3)	39(4)	10(3)
C(34)	81(5)	40(3)	60(4)	-16(3)	16(4)	6(3)
C(35)	62(4)	40(3)	44(3)	-1(2)	8(3)	3(3)
C(36)	33(3)	33(2)	34(3)	4(2)	8(2)	2(2)
C(41)	34(3)	73(4)	60(4)	-17(3)	7(3)	2(3)
C(42)	33(3)	94(5)	78(5)	-17(4)	3(3)	2(3)
C(43)	39(3)	62(4)	79(4)	11(3)	24(3)	15(3)
C(44)	43(3)	50(3)	61(4)	10(3)	19(3)	11(3)
C(45)	40(3)	48(3)	41(3)	7(2)	16(3)	10(2)
C(46)	28(3)	32(2)	43(3)	10(2)	5(2)	3(2)
C(51)	43(3)	36(3)	48(3)	3(2)	14(3)	2(2)
C(52)	50(3)	36(3)	65(4)	-6(3)	15(3)	-0(3)
C(53)	48(4)	37(3)	95(5)	5(3)	14(4)	-10(3)
C(54)	70(4)	46(3)	87(5)	14(3)	38(4)	-9(3)
C(55)	60(4)	36(3)	60(4)	9(3)	29(3)	-4(3)
C(56)	30(3)	27(2)	40(3)	7(2)	5(2)	4(2)
C(61)	104(6)	52(4)	54(4)	15(3)	9(4)	1(4)
C(62)	173(9)	62(5)	75(5)	34(4)	32(6)	-1(5)
C(63)	132(8)	44(4)	126(7)	17(4)	57(6)	-10(5)
C(64)	78(5)	51(4)	125(7)	-6(4)	22(5)	-22(4)
C(65)	52(4)	46(3)	96(5)	8(3)	9(4)	-4(3)
C(66)	42(3)	38(3)	48(3)	2(2)	16(3)	0(2)
C(71)	51(3)	41(3)	45(3)	3(2)	10(3)	7(3)

C(72)	62(4)	44(3)	66(4)	-4(3)	24(3)	5(3)
C(73)	55(4)	64(4)	64(4)	-0(3)	28(3)	-0(3)
C(74)	59(4)	54(3)	80(4)	18(3)	35(4)	4(3)
C(75)	47(3)	39(3)	73(4)	12(3)	24(3)	11(3)
C(76)	32(3)	44(3)	37(3)	6(2)	2(2)	7(2)
C(81)	63(4)	65(4)	51(4)	4(3)	14(3)	12(3)
C(82)	106(6)	85(5)	50(4)	-7(4)	15(4)	18(5)
C(83)	117(7)	73(5)	58(4)	-10(4)	0(5)	-23(5)
C(84)	75(5)	117(6)	73(5)	-16(5)	4(4)	-30(5)
C(85)	48(4)	95(5)	66(4)	-12(4)	6(4)	-7(4)
C(86)	45(3)	36(3)	43(3)	8(2)	7(3)	2(2)
C(91)	44(3)	52(3)	63(4)	11(3)	15(3)	-5(3)
C(92)	47(4)	66(4)	84(5)	22(4)	13(4)	-9(3)
C(93)	49(4)	55(4)	110(6)	13(4)	8(4)	-16(3)
C(94)	84(5)	63(4)	83(5)	-9(4)	7(4)	-16(4)
C(95)	71(4)	62(4)	61(4)	5(3)	15(4)	-8(3)
C(96)	37(3)	39(3)	56(3)	9(2)	11(3)	4(2)
C(101)	50(3)	47(3)	48(3)	9(3)	11(3)	3(3)
C(102)	63(4)	62(4)	50(4)	17(3)	9(3)	2(3)
C(103)	58(4)	76(4)	44(3)	7(3)	12(3)	-14(3)
C(104)	59(4)	58(4)	60(4)	1(3)	24(3)	1(3)
C(105)	42(3)	48(3)	62(4)	4(3)	16(3)	3(3)
C(106)	34(3)	37(3)	39(3)	10(2)	9(2)	-2(2)
C(111)	50(3)	51(3)	50(3)	15(3)	13(3)	14(3)
C(112)	52(4)	70(4)	54(4)	18(3)	4(3)	31(3)
C(113)	40(3)	94(5)	47(3)	13(3)	15(3)	20(3)
C(114)	49(4)	69(4)	56(4)	5(3)	15(3)	-3(3)



C(115)      44(3)      47(3)      45(3)      10(2)      13(3)      7(3)

C(116)      35(3)      40(3)      36(3)      11(2)      4(2)      6(2)

The anisotropic temperature factor exponent takes the form:  $-2\pi^2(h^2a^2U_{11} + \dots + 2hka^*b^*U_{12})$

**Table 2S. Anisotropic thermal parameters ( $\text{\AA}^2 \times 10^3$ ) for  $(\text{C}_5\text{Ph}_5)\text{Cr}(\text{CO})_3$** 

	$U_{11}$	$U_{22}$	$U_{33}$	$U_{23}$	$U_{13}$	$U_{12}$
Cr	40(1)	42(1)	47(1)	1(1)	-0(1)	1(1)
Cr'	42(1)	32(1)	41(1)	-2(1)	-3(1)	6(1)
C(1)	23(7)	42(8)	33(8)	1(6)	-4(6)	2(6)
C(2)	29(7)	37(8)	37(7)	3(6)	4(6)	8(6)
C(3)	37(7)	27(7)	44(8)	-4(7)	5(6)	3(6)
C(4)	51(8)	22(7)	34(7)	-5(6)	-10(6)	8(6)
C(5)	22(7)	27(7)	55(9)	-3(7)	3(6)	-4(6)
C(6)	74(10)	67(11)	39(9)	-4(8)	5(7)	16(9)
O(6)	166(11)	89(9)	65(7)	-16(7)	6(7)	44(8)
C(7)	51(8)	72(10)	51(8)	17(8)	3(7)	-9(7)
O(7)	94(8)	67(8)	105(8)	27(7)	18(6)	-12(7)
C(8)	56(9)	40(9)	76(10)	13(8)	-11(8)	7(8)
O(8)	61(7)	84(8)	158(10)	-8(7)	-27(7)	10(7)
C(1')	29(6)	29(7)	32(7)	-0(6)	1(5)	3(6)
C(2')	31(7)	25(7)	43(8)	-1(6)	8(6)	-0(6)
C(3')	32(7)	14(7)	48(8)	-1(6)	-11(6)	8(6)
C(4')	6(6)	34(7)	33(7)	5(6)	-5(5)	5(5)
C(5')	18(6)	22(7)	37(7)	3(6)	1(5)	5(5)
C(6')	46(9)	51(9)	65(9)	6(8)	15(8)	5(8)
O(6')	33(5)	84(8)	137(9)	4(7)	7(6)	12(6)
C(7')	37(8)	68(11)	48(9)	-6(8)	-15(7)	12(8)
O(7')	117(9)	62(8)	104(9)	-40(7)	-36(7)	30(7)
C(8')	38(8)	62(10)	55(9)	2(8)	1(7)	11(8)
O(8')	105(8)	58(7)	77(7)	31(6)	20(6)	18(6)

The anisotropic temperature factor exponent takes the form:  $-2\pi^2(h^2a^2U_{11} + \dots + 2hka^*b^*U_{12})$

**Table 3S. H-Atom coordinates ( $\times 10^4$ ) and isotropic thermal parameters ( $\text{\AA}^2 \times 10^3$ ) for [PPN][((C<sub>5</sub>Ph<sub>5</sub>)Cr(CO)<sub>3</sub>)]**

	x	y	z	U
H(11)	-2633	10763	1737	80
H(12)	-3915	12013	1505	80
H(13)	-3510	13372	890	80
H(14)	-1824	13481	507	80
H(15)	-542	12230	739	80
H(21)	-2588	9748	191	80
H(22)	-4341	8756	-332	80
H(23)	-4907	7319	168	80
H(24)	-3720	6875	1189	80
H(25)	-1968	7867	1712	80
H(31)	1280	7778	2196	80
H(32)	1413	5985	2006	80
H(33)	372	4991	952	80
H(34)	-800	5788	87	80
H(35)	-933	7580	277	80
H(41)	2961	10390	2534	80
H(42)	4847	10258	2461	80
H(43)	5212	9407	1438	80
H(44)	3693	8689	487	80
H(45)	1807	8820	560	80
H(51)	704	12445	2498	80
H(52)	1720	14085	2609	80
H(53)	2859	14409	1834	80
H(54)	2983	13093	948	80

H(55)	1967	11453	837	80
H(61)	7276	3578	4800	80
H(62)	6535	1901	4896	80
H(63)	4888	1092	4072	80
H(64)	3984	1961	3152	80
H(65)	4726	3638	3057	80
H(71)	7616	3301	3238	80
H(72)	8893	3134	2518	80
H(73)	9596	4600	2102	80
H(74)	9021	6233	2405	80
H(75)	7744	6400	3125	80
H(81)	6114	6083	5015	80
H(82)	7198	7075	6059	80
H(83)	9194	7273	6291	80
H(84)	10106	6480	5480	80
H(85)	9022	5487	4436	80
H(91)	6086	7896	2388	80
H(92)	7207	9504	2715	80
H(93)	7643	10304	3886	80
H(94)	6958	9497	4729	80
H(95)	5837	7889	4401	80
H(101)	3536	7282	1994	80
H(102)	2924	6750	777	80
H(103)	3654	5327	262	80
H(104)	4994	4435	962	80
H(105)	5606	4967	2178	80
H(111)	3698	8248	3315	80

H(112)	1938	8412	3590	80
H(113)	914	6963	3839	80
H(114)	1651	5350	3813	80
H(115)	3411	5185	3539	80

**Table 4S. H-Atom coordinates ( $\times 10^4$ ) and isotropic thermal parameters ( $\text{\AA}^3 \times 10^3$ ) for  $(\text{C}_5\text{Ph}_5)\text{Cr}(\text{CO})_3$**

	x	y	z	U
H(11)	417	4349	5679	80
H(12)	-5	3252	6369	80
H(13)	270	1768	7135	80
H(14)	968	1381	7211	80
H(15)	1390	2479	6521	80
H(21)	1298	6220	6599	80
H(22)	1593	6698	7535	80
H(23)	2250	5869	7760	80
H(24)	2611	4562	7050	80
H(25)	2315	4084	6114	80
H(31)	2168	7435	5411	80
H(32)	2831	8165	5230	80
H(33)	3261	6544	4732	80
H(34)	3027	4194	4414	80
H(35)	2364	3465	4594	80
H(41)	1824	6090	3877	80
H(42)	1969	5645	2883	80
H(43)	1840	3290	2463	80
H(44)	1566	1378	3035	80
H(45)	1420	1823	4029	80
H(51)	694	4357	4024	80
H(52)	178	2923	3576	80
H(53)	13	583	3970	80
H(54)	363	-322	4812	80

H(55)	879	1113	5260	80
H(11')	3261	7022	7142	80
H(12')	3022	6055	6233	80
H(13')	3402	4267	5734	80
H(14')	4020	3447	6145	80
H(15')	4258	4414	7054	80
H(21')	3104	6239	8982	80
H(22')	2539	4702	9083	80
H(23')	2478	2486	8533	80
H(24')	2982	1807	7881	80
H(25')	3548	3345	7780	80
H(31')	3801	3808	9298	80
H(32')	3713	3223	10297	80
H(33')	3798	5080	11023	80
H(34')	3970	7522	10750	80
H(35')	4057	8108	9751	80
H(41')	4772	5725	9393	80
H(42')	5313	6618	9982	80
H(43')	5553	9056	9845	80
H(44')	5252	10600	9118	80
H(45')	4711	9706	8530	80
H(51')	4227	8370	6883	80
H(52')	4721	8929	6197	80
H(53')	5396	8315	6408	80
H(54')	5578	7142	7305	80
H(55')	5084	6583	7991	80