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Electron-Transfer Oxidation by Phase-Separating Reagents

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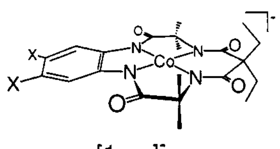
Introduction

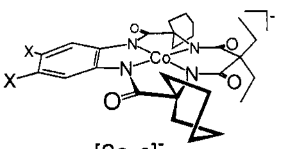
Soluble electron-transfer oxidants are a widely used reagent class in chemistry.[1] Many consist of transition metal complexes where the transition metal is quite toxic[2] and the ligands are readily released or oxidatively degraded.[3,4] New strategies are needed for developing soluble, nondegradable, metal-based oxidants where the spent reagent can be easily and quantitatively collected for recharging and reuse.[5−7] Ligands are important determinants of the properties of metal-based oxidants, such that systematic ligand variation is a powerful tool for achieving targeted reagent behavior.[8] In several case studies[9,10] based on macrocyclic ligands as in [**1a**−**c**]$^-$, we have overcome a primary obstacle to producing long-lived, recyclable, homogeneous metal-based oxidants, namely, the sensitivity of most ligands to oxidative degradation. Robust ligands have been achieved employing an iterative ligand refinement approach[8] such that metal-based oxidants developed from the ligands do not degrade rapidly in use[9] and are easily modified for selectivity control. Here we illustrate the use of ligand design to produce aliphatic hydrocarbon soluble metal-based oxidants that precipitate quantitatively following electron transfer. The metal-based oxidant is neutral, an uncommon situation, such that its one-electron-reduced product is an anion. The challenge of producing oxidants that would precipitate quantitatively once discharged was made more interesting by the fact that electron-transfer oxidants with significant aliphatic hydrocarbon solubility have not been developed for routine use.

Experimental Section

Physical Measurements. ^{1}H NMR spectra were measured on an IBM NR/300 FT-NMR spectrometer. FTIR spectra were taken on a Mattson 5000 FTIR spectrometer while UV/vis spectra were obtained using a Hewlett-Packard HP8452A spectrophotometer. Elemental analyses were performed by Midwest Microlab, Indianapolis, IN. Electrochemical measurements were performed in CH_2Cl_2 (supporting electrolyte 0.1 M [n-Bu_4N][PF_6], Fluka puriss) under N_2 in a three-compartment cell using a glassy carbon disk working electrode, a Pt wire counter electrode, and a sodium chloride saturated calomel electrode (SSCE) reference electrode, using an EG&G Model 273 potentiostat/galvanostat. Electrospray ionization mass spectra (ESI-MS) were obtained using a Finnigan MAT SSQ700 mass spectrometer with an Analytica of Branford electrospray ionization interface. Electrospray voltages of 2400−3400 V were utilized. EPR spectra were measured on a Bruker ER300 spectrometer in CH_2Cl_2 at approximately 4 K.



[1a-c]$^-$



[3a-c]$^-$

X = H(a), OCH_3(b), Cl(c)

Syntheses. The macrocyclic ligands H_4[**2a**] (X = H), H_4[**2b**] (X = OCH_3), and H_4[**2c**] X = Cl were synthesized as described in the Supporting Information. These were metalated according to methods described in the literature[10] to give the corresponding lithium salts [Li]-[**3a**−**c**]. The crude lithium salts from the metalation process were metathesized with [NMe_4]Cl in water, from which [NMe_4][**3a**]·H_2O, [NMe_4][**3b**], or [NMe_4][**3c**] precipitated in analytically pure form as a purple solid. Anal. Calcd (found) for $C_{31}H_{48}N_5O_5Co$ [NMe_4][**3a**]·H_2O: C, 59.13 (59.00); H, 7.68 (7.44); N, 11.12 (11.02). For $C_{33}H_{50}N_5O_6Co$ [NMe_4][**3b**]: C, 59.01 (58.84); H, 7.50 (7.43); N, 10.43 (10.50). For $C_{31}H_{44}N_5O_4Cl_2Co$ [NMe_4][**3c**]: C, 54.72 (54.72); H, 6.52 (6.77); N, 10.29 (10.06). UV/vis (CH_2Cl_2) λ_{max}/nm (ϵ/M^{-1} cm^{-1}): [NMe_4][**3a**] 518 (8900); [NMe_4][**3b**] 520 (11 000); [NMe_4][**3c**] 516 (7800). IR (Nujol, cm^{-1}): [NMe_4][**3a**] 1627, 1590, 1574; [NMe_4][**3b**] 1625, 1580, 1550; [NMe_4][**3c**] 1628, 1572, 1560. ^{1}H NMR (($CD_3)_2CO$) (all resonances are singlets): δ [NMe_4][**3a**] 15.8 (4H), 11.1 (4H), 8.4 (4H), 4.3 (2H), 3.5 (12H, [NMe_4]$^+$), 2.6 (2H), 0.2 (4H), −2.0 (6H), −7.0 (2H), −9.1 (4H), −24.3 (2H); [NMe_4][**3b**] 16.2 (4H), 11.2 (6H, OCH_3), 9.4 (4H), 7.2 (4H), 3.0 (2H), 2.5 (12H, [NMe_4]$^+$), 1.4 (2H), −0.4 (4H), 1.7 (2H), −2.5 (6H), −10.4 (4H); [NMe_4][**3c**] 14.1 (4H), 11.4 (4H), 7.5 (4H), 3.8 (2H), 2.8 (12H, [NMe_4]$^+$), 1.9 (2H), −1.0 (4H), −3.1 (6H), −9.1 (2H), −10.3 (4H). ESI-MS m/z: [**3a**]$^-$ 537.2; [**3b**]$^-$ 597.1; [**3c**]$^-$ 605.1.

Synthesis of Co(κ^4-2b), 3b. [NMe_4][**3b**] (0.100 g, 0.16 mmol) was dissolved in H_2O (50 mL), then cyclohexane (25 mL) containing Br_2 (0.010 mL, 0.19 mmol) was added, and the mixture was shaken vigorously for 1 min. The deep blue cyclohexane layer was removed and dried over $MgSO_4$. The solvent was removed under vacuum, yielding a blue solid, which was recrystallized by diffusion of pentane into a benzene solution (0.029 g, 27%). **3b**·C_6H_6 (X = OCH_3). Anal. Calcd (found) for $C_{35}H_{44}N_4O_6Co$: C, 62.22 (62.49); H, 6.56 (6.84); N, 8.29 (8.65). UV/vis (cyclohexane): λ_{max}/nm (ϵ/M^{-1} cm^{-1}): 630 (15 000). IR: (Nujol, cm^{-1}) 1696, 1614, 1595. EPR: $g = 2.58, 2.21, 2.04$.

Crystal Structure Determination. Crystals of [NMe_4][**3a**]·H_2O were obtained by the slow evaporation of acetone from a water and acetone solution of [NMe_4][**3a**] in air. A green-black prismatic crystal (0.80 × 0.25 × 0.25 mm) was used for X-ray measurements on a Rigaku AFC7R diffractometer with graphite-monochromated Mo $K\alpha$ radiation. The data were collected at 21 °C using the $\omega-2\theta$ scan technique to $2\theta_{max} = 45.0°$. Of the 10 129 reflections which were collected, 9581 were unique ($R_{int} = 0.022$). The intensities of three representative reflections, measured after every 150 reflections, increased by 0.6% over the course of data collection. A linear correction factor was applied to the data to account for this phenomenon. An

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Table 1. Crystallographic Data for [NMe$_4$][3**a**]·H$_2$O

empirical formula	$C_{34}H_{52}O_5N_5Co$
fw	669.75
space group	$P2_1/c$ (No. 14)
a, Å	11.817(7)
b, Å	16.33(1)
c, Å	36.679(6)
β, deg	96.55(3)
V, Å^3	7030(6)
Z	8
ρ_{calcd}, g/cm^3	1.265
temp, °C	21
μ, cm^{-1}	5.34
λ, Å	0.710 69
R^a	0.060
$R_w{}^b$	0.057

^{a} $R = \Sigma||F_o| - |F_c||/\Sigma|F_o|$. ^{b} $R_w = [(\Sigma w(|F_o| - |F_c|)^2/\Sigma w(F_o{}^2)]^{1/2}$.

empirical absorption correction was applied. The data were corrected for Lorentz and polarization effects. The structure was solved by direct methods[11] and expanded using Fourier techniques.[12] Non-hydrogen atoms were refined anisotropically. Hydrogen atoms were included but not refined. The final cycle of full-matrix least-squares refinement was based on 5445 observed reflections ($I > 3\sigma(I)$) and 812 variable parameters and converged (largest parameter shift was 0.04 times its esd) with $R = 0.060$ and $R_w = 0.057$. Neutral atom scattering factors[13] and anomalous dispersion terms[14] were included. All calculations were performed using teXsan[15] from Molecular Structure Corporation. Crystal data and experimental details are given in Table 1. The crystal is composed of two independent Co(III) complexes with virtually identical bond lengths and angles.

Results and Discussion

We have previously described the neutral, planar, four-coordinate cobalt complexes, **1a**−**c**, which exhibit appreciable solubility in aromatic hydrocarbons (solubility of **1c** in benzene, ca. 60 mM).[10] The innovation described here arises from the significant increase in solubility in aliphatic hydrocarbons that accompanies the replacement of the two sets of *gem*-dimethyl groups of **1a**−**c** with the pentamethylene units of **3a**−**c**. The one-electron-reduced Co^{III} forms, [**3a**−**c**]$^-$, are completely insoluble in aliphatic hydrocarbons. Since both **3a**−**c** and [**3a**−**c**]$^-$ are highly colored, the former blue and the latter purple, the progress of any oxidation can be visually monitored by the loss of the intense blue color in solution that is accompanied by the formation of a purple solid.

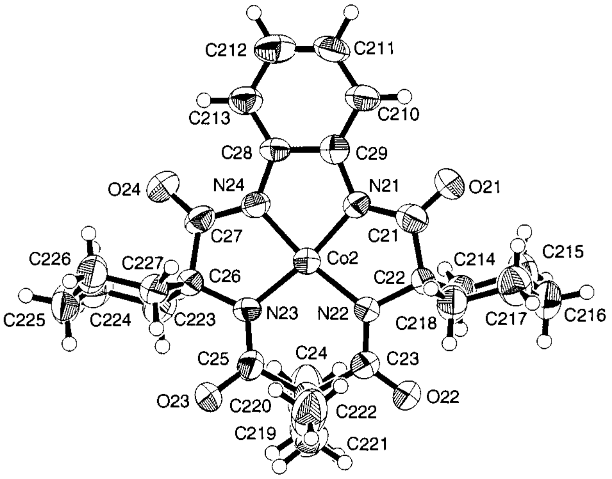

Figure 1. Molecular structure of [**3a**]$^-$ (molecule 2, see Experimental Section): ORTEP drawing with non-hydrogen atoms drawn to encompass 50% of electron density. Selected bond lengths (Å): Co2−N21, 1.804(6); Co2−N22, 1.841(6); Co2−N23, 1.836(6); Co2−N24, 1.815(6); N24−C28, 1.378(9); N21−C29, 1.403(9); C28−C29, 1.432(10); C28−C213, 1.36(1); C29−C210, 1.40(1); C213−C212, 1.43(1); C210−C211, 1.37(1); C211−C212, 1.35(1).

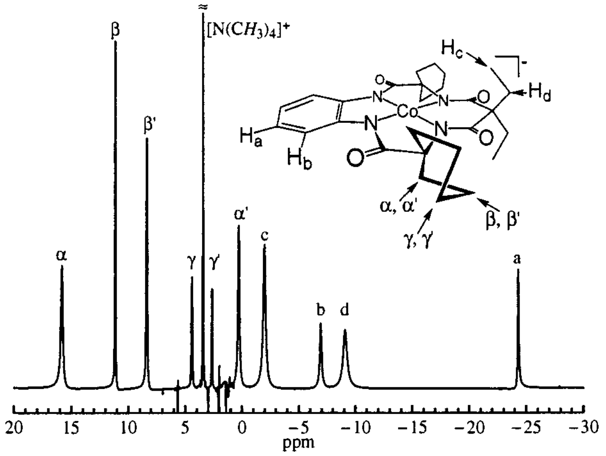

Figure 2. ^{1}H NMR spectra of [NMe$_4$][**3a**] in acetone-d_6 at 22 °C, with diamagnetic signals suppressed/inverted.

The syntheses of the starting materials, [**3a**−**c**]$^-$, are based on adaptations of published procedures.[10,16,17] The single-crystal X-ray structure of [**3a**]$^-$ shows a planar four-coordinate Co^{III} ion, as has been found for Co^{III} complexes with related ligands,[10,18] Figure 1; only one of two independent molecules in the unit cell is shown. Both cyclohexane rings are found in a chair conformation, and the bond distances and angles are as expected from related structures.[10,18] The paramagnetic ^{1}H NMR spectrum of [**3a**]$^-$ with diamagnetic resonances suppressed,[19] Figure 2, exhibits well-resolved, paramagnetically shifted signals spread over a 40 ppm window, as has been observed for other $S = 1$ cobalt(III) complexes with related ligands.[10,18,20] The formulations of the [**3a**−**c**]$^-$ salts are also supported by ESI mass spectrometry and by other characterization techniques. Each of the [**3a**−**c**]$^-$ ions shows a reversible redox process in the cyclic voltammogram; $E°$/V vs NHE [**3a**]$^{0/-}$, 0.98; [**3b**]$^{0/-}$, 0.58; [**3c**]$^{0/-}$, 1.14. Thus, this small series of aromatic ring substituted macrocycles provides a driving force differential (ca. 0.6 V) for use in a variety of oxidations. The $E°$ values for [**3a**−**c**]$^-$ determine which oxidants can be used to give **3a**−**c**. The neutral species shows EPR signals (CH_2Cl_2, 4 K) at $g = 2.58$, 2.21, and 2.04, which are due to coupling between the $S = 1$ Co^{III} center and the organic radical of the oxidized ligand.[20] The solubility of **3b** in cyclohexane was determined by visible spectroscopy to be 7.4 ± 1 mM. While

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the other members of the series, **3a** and **3c**, are similarly quite cyclohexane soluble, greater reactivity has made it difficult to obtain quantitative alkane solubility information. In contrast, the solubility of **1c** in cyclohexane is less than 0.2 mM.

We have studied the reaction of cyclohexane solutions of **3a**−**c** with different types of oxidizable substrates to obtain proof-of-concept examples. Our initial studies involved molecules which upon oxidation gave 1:1 charge-transfer salts with [**3a**−**c**]$^-$. All of the following reactions were carried out on a small scale (<10 mg of Co reagent) in cyclohexane and were performed by adding an excess of the substrate (1.05 equiv) to the Co reagent. The reaction of decamethylferrocene, (Cp_2*Fe), with each Co reagent gave a fine purple precipitate, [Cp_2*Fe]-[**3a**−**c**], which could be isolated quantitatively by centrifugation. **3b** has an insufficient driving force to oxidize ferrocene, (Cp_2-Fe), but **3a** and **3c** react with ferrocene to give a fine purple precipitate, [Cp_2Fe][**3a**,**c**], which was separated quantitatively by centrifugation. The reaction of **3a**−**c** and *N*,*N*,*N*′,*N*′-tetramethyl-*p*-phenylenediamine gave the Wurster's Blue radical cation salts, [$WB^\bullet$][**3a**−**c**], which show absorbances due to Wurster's Blue radical cation and to the Co^{III} anion in their UV/vis spectra (CH_2Cl_2). The EPR spectrum of [$WB^\bullet$][**3c**] (CH_2Cl_2, 4 K) shows only the diagnostic $g = 2.00$ signal of the organic radical.[21] The reaction of **3c** with tetraphenylporphyrinatomagnesium forms a charge-transfer salt, [$MgTPP^\bullet$][**3c**], which shows absorbances due to the metalloporphyrin π-radical cation,[22] and to the Co^{III} anion in its UV/vis spectrum (CH_2-Cl_2). In each of these cases described above, a UV/vis titration indicated a 1:1 stoichiometry for the reaction. The resulting solids from some of these reactions were characterized spectroscopically (UV/vis, ^1H NMR, and FTIR) to show that the integrity of the Co macrocylic species was maintained completely through the oxidation/reduction process. The ESI-MS of the anions of the precipitated reagents are identical to those of the Co^{III} starting materials. The resulting Co^{III} species could be reoxidized quantitatively to give the neutral, blue species.

Oxidative coupling reactions were also studied. Cyclohexane solutions of thiophenol were oxidized by **3a**−**c** to give diphenyl disulfide, confirmed by ^1H NMR of the solution phase, with the Co^{III} anion, [**3a**−**c**]$^-$, precipitating quantitatively from solution, presumably with a proton as the countercation. Also tributyltin hydride was oxidized to form the bis(tributyltin) dimer, again with quantitative precipitation of the spent oxidant. As with the charge-transfer salts, the macrocyclic complex remains intact in these precipitated species.

Finally, we have examined the oxidation of hydroquinone, an oxidation which has been typically carried out in organic solvents with lead tetraacetate, or in water with Cr^{VI}.[23] Hydroquinone was oxidized by 2 equiv of **3c** to give quinone. This reaction proceeds despite the formal potential of **3c** being 200 mV lower than that for the hydroquinone to quinone reaction.[24] ^1H NMR studies are consistent with the intermediacy of hydroquinone-derived species bound to the metal center,[10] suggesting an inner-sphere oxidation mechanism.

We are in the process of further studying the chemistry of the unique aliphatic hydrocarbon soluble electron-transfer oxidants reported here. The concept of designing reagents to undergo phase changes upon reaction to facilitate recovery could have broad utility in reagent design for all classes of reactions as chemistry moves toward more environmentally benign technologies.

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Supporting Information Available: Synthetic procedures for the ligands H_4**2a**−**c**, a table of selected bond lengths and angles for the two independent molecules in the unit cell of [NMe_4][**3a**]·H_2O, a table of characterization data for the charge-transfer salts formed using the Co reagents, and UV/vis spectra for the Wurster's Blue charge transfer salt forming reaction (5 pages). An X-ray crystallographic file, in CIF format, for compound [NMe_4][**3a**]·H_2O is available on the Internet only. Ordering and access information is given on any current masthead page.

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