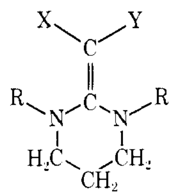

6, X = Ph; Y = CN; R = CH_2Ph
7, X = Ph; Y = CN; R = CH_3
8, X = p-$NO_2C_6H_4$; Y = CN; R = CH_2Ph
9, X = p-$NH_2C_6H_4$; Y = CN; R = CH_2Ph

N-methyl resonance at −125 °C ($\Delta G^{\ddagger} = 7.4$ kcal/mol). The low π-electron barriers in the six-membered compounds are at least partly due to increased ground-state strain, but improved stabilization of the zwitterionic transition state may also contribute.

Models and simple strain-energy calculations indicate that the aryl group must be nearly orthogonal to the double bond on passage over the steric barrier, and the para substituent must influence this barrier by the loss of conjugation in the transition state. Thus the steric barrier in **8** is considerably raised ($\Delta G^{\ddagger} = 13.9$ kcal/mol) whereas no π-electron barrier can be measured. In **9**, on the other hand, the π-electron barrier is raised and the steric barrier is lowered compared to **6**. The rotations past the two barriers now occur with similar rates, and the exchange system is quite complex. Precise rate constants could therefore not be evaluated but an approximate steric barrier of 9.5 kcal/mol (T_c ca. −75 °C) could be calculated.

It might be argued that the AB spectra given by **6**, **8**, and **9** could be caused by pyramidal ring nitrogen atoms exhibiting slow inversion rather than by twisted double bonds. Against this interpretation speaks the x-ray structure[5] and also the observation that the ring N-CH_2 resonances in **6** and **8** appear as sharp triplets throughout the region of broadening of the benzylic proton resonances.

Acknowledgment. We are grateful to the Swedish Natural Science Research Council and to the Royal Physiographic Society of Lund for financial support.

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Received December 1, 1976

A Water-Stable Cu(III) Complex

Sir:

The ability of cupric salts to form intensely colored products in the presence of oxalodihydrazide and certain aldehydes and ketones was first noted by Nilsson[1] and developed into a sensitive analytical method for copper by Gran and coworkers.[2,3] Frieden et al.[4] recognized that the intense color was produced only in the presence of molecular oxygen and proposed that these copper complexes might serve as good models for "blue" copper proteins[5] as well as the oxygen-transport protein, hemocyanin.[6] In an effort to determine whether an oxygenation process is indeed responsible for the intense coloration of the copper–bis(oxalodihydrazide) system, Clark and coworkers[7] solved the crystal structure of the violet complex formed with acetaldehyde. The copper is coordinated to a macrocyclic ligand formed by condensation reactions between 6 mol of acetaldehyde and 2 mol of oxalodihydrazide, but a liganded oxygen molecule is clearly not present (Figure 1). No systematic chemical and spectroscopic characterizations of these complexes have heretofore been published. In this paper, we demonstrate that oxygen and other oxidizing agents convert copper to the trivalent state and that it is a Cu(III) complex which is responsible for the unusually high absorptivity (ϵ_{540} = 29 500 M^{-1} cm^{-1})[2,7] in this system.

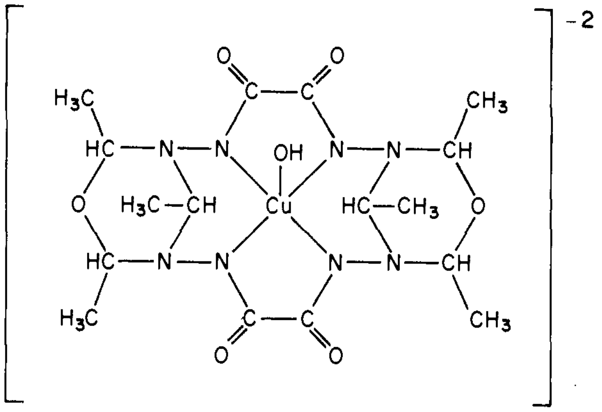

Figure 1. Disodium *bcde*-[7,9,16,18,19,20-hexamethyl-8,17-dioxa-1,2,5,6,10,11,14,15-octaazatricyclo[13.3.$1^{6,10}$]eicosane-3,4,12,13-tetronato(4−)-N^2,N^5,N^{11},N^{14}]-*a*-hydroxocuprate(III), hereafter designated [Cu(III) macrocycle], based on the x-ray crystallographic study of Clark et al.[7] and this work.

Under anaerobic conditions, oxalodihydrazide (0.59 g, 5.0 mmol) was added to a solution of copper(II) sulfate pentahydrate (0.25 g, 1.0 mmol) in 20 mL of water. Ammonium hydroxide (3 mL, 45 mmol) was added with stirring, and, after all of the oxalodihydrazide had dissolved, acetaldehyde (3 mL, 50 mmol) was added. Upon shaking in air, the solution became intensely violet. This was filtered, applied to a Bio-Rad AG 1-X8 anion-exchange column (6.5 × 85 cm, 100–200 mesh, 4.1-equiv capacity, Cl^-/OH^- form) and eluted (0.5 mL/min) with 0.02 M NaCl adjusted to pH 8 with NaOH. The mixture separated into three components, one light band followed by two very intensely colored bands. The visible absorption spectrum of the middle band was identical with that of the compound reported by Clark et al.[7] This band was collected, freeze-dried, dissolved in a minimum amount of water at pH 8, and passed down a column containing Sephadex G-15 (5 × 100 cm, 650-g dry wt). The violet band was collected and freeze-dried. Anal. Calcd. for $Na_2C_{16}H_{25}CuN_8O_7 \cdot 8H_2O$): C, 27.64; H, 5.96; N, 16.12; Cu, 9.14; found: C, 26.55; H, 5.10; N, 17.13; Cu, 7.81. Similar to Clark et al.,[7] we have not been able to obtain good elemental analyses and our crystallization attempts have thus far been unsatisfactory. The violet compound, however, migrates as a single component in both TLC and electrophoresis at pH 8. Upon lowering the pH, the UV-vis spectrum (Figure 2) changes isosbestically ($pK_a \simeq 5$) with a concomitant decrease in the electrophoretic mobility, which is consistent with protonation of the original dinegative anion. The ^1H NMR spectrum (Figure 3) consists of two quartets and two doublets of relative areas 1:2:6:3, thus accounting for all of the proton resonances expected from the structure shown in Figure 1.

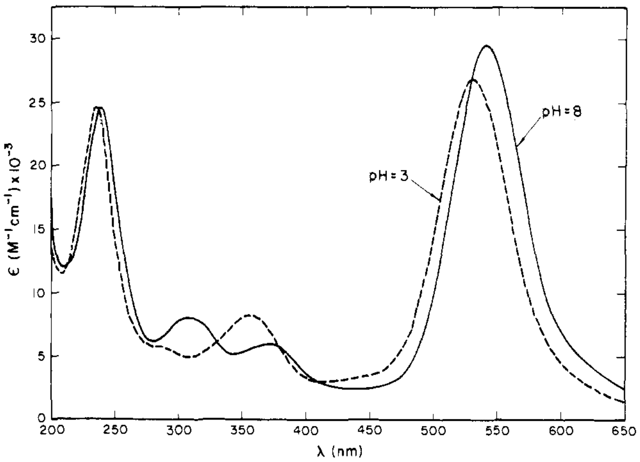

Figure 2: The electronic absorption spectrum of [Cu(III) macrocycle] at pH 8 (——) and pH 3 (- - -). The spectrum at pH 8 is normalized to ϵ_{540} = 29,500 M^{-1} cm^{-1}, a value taken from ref 2 and 7.

The nature of the oxidation process, the conversion of the orange anaerobic Cu(II) solution (λ_{max} 460 nm; ϵ_{460} = 190 M^{-1} cm^{-1}) to the violet mixture, was followed by the increase in absorbance at 540 nm and loss of EPR signal upon addition of ferricyanide (Figure 4). The titration is completed upon addition of ~1 equiv of ferricyanide, indicating that production of the violet complexes involves a one-electron oxidation. Both ferricyanide and air oxidation are accompanied by a >95% loss of EPR signal at room and liquid nitrogen temperatures.

The above observations strongly suggest the production in aqueous solution of chemically stable complexes of Cu(III). A one-electron oxidation process converts the orange solution possessing characteristic Cu(II) EPR parameters into EPR silent, NMR active material. This is the behavior expected for the production of Cu(III) with a spin-paired, d^8 electronic configuration. The complexes exhibit unusual stability; for example, no significant decomposition occurs during isolation by ion-exchange chromatography even for elution times of several weeks. Complexes of substitution labile Cu(I) or Cu(II) would be expected to dissociate under these conditions, whereas square-pyramidal Cu(III) should be relatively inert. The stabilization of this high oxidation state of copper is made possible by the strong electron-donating ability of the deprotonated amide nitrogens and the near-square-planar coordination of the macrocyclic ligand, which is a favorable geometry for d^8 metal ion systems.

The identification of the Cu(III) oxidation state in this system is supported by its similarity to other Cu(III)-amide species which have recently been characterized, including Cu(III)-bis(biuret),[8] -bis(oxamide),[8] and -tetraglycine.[9] Notably, each complex consists of four nitrogen donors lying in a plane about the central metal ion. The Cu(II) complexes can be readily oxidized (0.5-0.65 V)[8-10] to their respective diamagnetic Cu(III) forms possessing intense (5000-8500 M^{-1} cm^{-1}) UV-vis spectra. Calculations are presently being performed to determine the origin of these absorptions and of the dramatically high extinction coefficients (ϵ_{540} = 29 500 M^{-1} cm^{-1}) of [Cu(III) macrocycle] (Figure 2).

The Cu(III) assignment is further supported by the short Cu-N bond lengths reported in the crystal structure determination by Clark et al.[7] Whereas Cu(II)-N (amide) bond lengths are 1.94 ± 0.01 Å in $K_2[Cu(biuret)_2]\cdot 4H_2O$ and 1.92 ± 0.01 Å in Cu(II)-peptide complexes,[11] the average Cu-N distance for [Cu(III) macrocycle] is only 1.86 ± 0.01 Å. A similar pattern is observed in the copper dithiocarbamates in which the Cu(III)-S bonds are ~0.08 Å shorter than the same bonds in the Cu(II) species.[12]

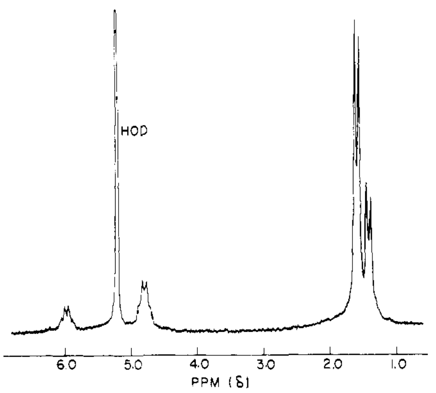

Figure 3: The 100-MHz ^{1}H NMR spectrum of [Cu(III) macrocycle] at pH 7 in D_2O. External TMS was used as a reference.

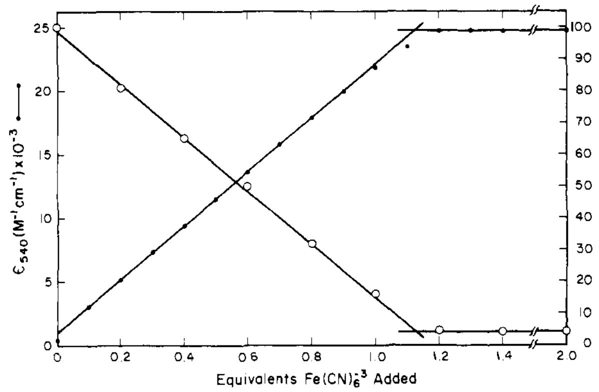

Figure 4: Spectrophotometric (●) and EPR (○) titration of the Cu(II) mixture (10^{-3} M) with potassium ferricyanide (10^{-1} M) under anaerobic conditions; the estimated accuracy of the stoichiometry is ±10%.

Clark et al.[7] reported an axial water molecule 2.74 Å from the copper atom. This was consistent with their identification of the species as a dinegative ion in solution and their assumption that it contained Cu(II) coordinated to four deprotonated nitrogens. As our data have indicated a +3 oxidation state for the copper in this complex, it is likely that the axial ligand is a hydroxyl ion at neutral pH as shown in Figure 1. Although the observed pK_a of 5 is lower than would be expected for a coordinated water in this system, we see no alternative explanations consistent with the data.

Acknowledgments. We are grateful to the U.S. Public Health Service, National Institutes of Health, for support of this research under Grant GM 18865. We wish to thank Drs. George R. Clark, Brian W. Skelton, and T. Neil Waters for making available their new paper on the crystallography of this complex prior to its publication. We express our appreciation to Dr. David K. Roe (Department of Chemistry, Portland State University) for electrochemical experiments[10] and helpful discussions of this work.

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An upper limit to the oxidation potential is established in that $K_3[Fe(CN)_6]$, $E^\circ[Fe(III)/Fe(II)] = 0.36$ V, may be used as the oxidant in the production of the Cu(III) species. The lack of electrode activity found in this system is a common occurrence; for example, at pH 7 the ethylenediaminetetraacetate complexes of cobalt(II), nickel(II), zinc(II), and manganese(II) show neither oxidative nor reductive waves in polarographic measurements ("Handbook of Analytical Chemistry", L. Meites, Ed., McGraw-Hill, San Francisco, Calif., 1963, pp 5-72).

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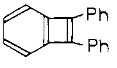
Received February 8, 1977

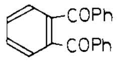
Oxidation of Tetraphenylbenzo[1,2:4,5]dicyclobutadiene with Molecular Oxygen in the Presence and Absence of Solvent to Afford Benzocyclobutadiene Oxide and *o*-Quinomethide, Respectively. Conversion of the Latter into Stable Methylenecyclohexa-1,3-diene

Sir:

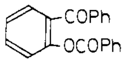
Oxidation of 1,2-diphenylbenzocyclobutadiene (I) with molecular oxygen in boiling benzene to *o*-dibenzoylbenzene (II) and *o*-benzoylphenyl benzoate (III) has been reported.[1] The formation of III suggests that this reaction involves an oxidation process with one oxygen atom. Because 1,3-diphenylisobenzofuran peroxide (IV) of similar structure to **8**,



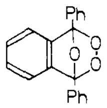
I



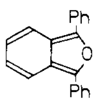
II



III



IV

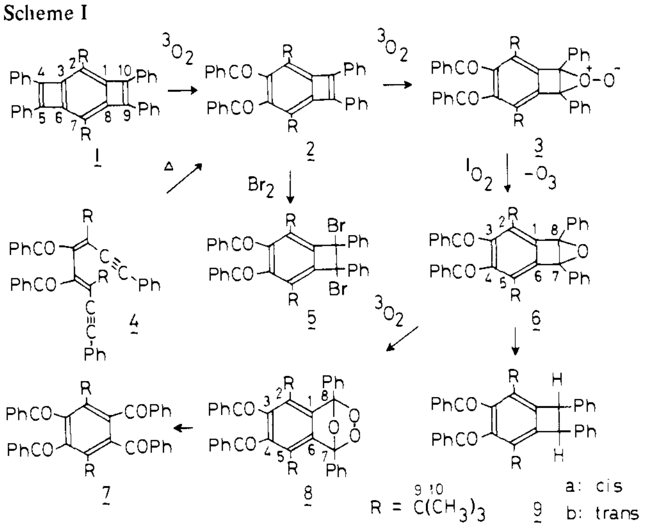


V

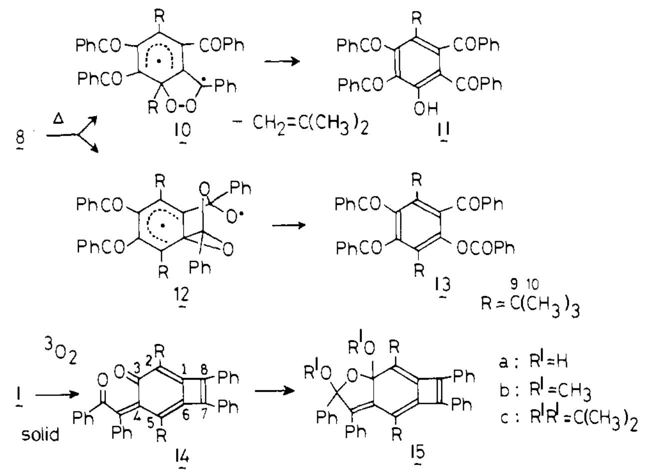
which was prepared by photooxidation of 1,3-diphenylisobenzofuran (V), can easily be converted into II and III,[2] a possible pathway of the oxidation of I is that which proceeds successively via V and IV. To clarify the pathway of the oxidation of benzocyclobutadiene, we studied the oxidation of the title benzocyclobutadiene (**1**) and found that the oxidation of **1** with molecular oxygen in the presence of solvent affords benzocyclobutadiene oxide (**6**) and that **6** is further oxidized to its peroxide (**8**) which can easily be converted into tetrabenzoylbenzene (**7**) (Scheme I), tetrabenzoylphenol (**11**), and tribenzoylphenyl benzoate (**13**) (Scheme II). We also found that the oxidation of **1** with molecular oxygen in solid state affords *o*-quinomethide (**14**), which is easily converted into stable methylenecyclohexa-1,3-dienes (**15a–c**).

Stirring a suspension of **1**[3] in MeOH under O_2 atmosphere at room temperature for 1 h afforded **6** (96%): mp (N_2 atmosphere) 287-288 °C; ν_{max}[4] 1670 cm^{-1}; λ_{max} 266 nm (ϵ 43 700), 280 (sh) (33 800), 335 (sh) (4900); ^{1}H NMR δ 0.93 (s, 18 H), 6.8-7.9 ppm (m, 20 H); ^{13}C NMR[5] δ 32.6 (C_{10}), 35.3 (C_9), 57.7 (C_7), 131.9 (C_2), 137.6 (C_1), 152.3 ppm (C_3). No solvent effect for this oxidation was observed, and almost the same results were obtained when the oxidations were carried out in acetone, CCl_4, and petroleum ether. Hydrogenation of **6** over Pd/C afforded *cis*-diphenylbenzocyclobutane (**9a**) (46%): mp 204-206 °C; ^{1}H NMR δ 5.26 ppm (s, 2 H). $NaBH_4$ reduction of **6** gave **9a** (68%) and its trans isomer (**9b**, 12%): mp 206-207 °C; ^{1}H NMR δ 4.42 ppm (s, 2 H).

Scheme I



Scheme II



The oxidation of **1** to **6** probably proceeds via dibenzoylbenzocyclobutadiene (**2**), since **2** which was prepared (not isolated) by heating (*E,Z*)-4,5-dibenzoylocta-1,7-diyne-3,5-diene (**4**)[3b] under reflux in mesitylene under N_2 atmosphere for 1 h turned to **6** immediately by exposing to air. Although **2** was too air sensitive to isolate, it was isolated as dibromo derivative (**5**, 75%), mp 229-230 °C. Because the oxidation of **1** was also performed in the dark, triplet oxygen ($^3O_2$) would be the oxygenation reagent. A plausible pathway of the formation of **6** is as follows. Perepoxide of a triplet state, initially formed by the attack of $^3O_2$ to the 4,5 positions of **1**, turns to a singlet state by spin inversion.[6] This perepoxide of the singlet state gives **2** via a dioxethane intermediate.[6] Perepoxide **3** of a singlet state, which is formed by the same manner as described above, reacts with singlet oxygen ($^1O_2$) evolved during the oxidation process[6] to afford **6** and ozone.[7]

Although both the oxidation reactions of **1** and **2** were not quenched by a radical scavenger, 2,6-di-*tert*-butyl-4-methylphenol, these reactions were quenched by a singlet oxygen scavenger, 1,4-diaza[2.2.2]bicyclooctane (Dabco).[8] The quenching results by Dabco are similar to those obtained for the oxidation of strained acetylene with molecular oxygen.[6]

Although **6** was stable in crystalline state at room temperature, a solution of **6** in benzene absorbed oxygen gradually even in the dark, affording, after 24 h, isobenzofuran peroxide (**8**, 50%). By photooxidation in tetrahydrofuran, however, **6** was converted into **8** in 72% yield within 1 h: mp 134-135 °C; ν_{max} 1670, 1650, 1220, 1070 cm^{-1}; λ_{max} 255 nm (ϵ 27 200), 263 (sh) (25 300); ^{1}H NMR δ 0.95 (s, 18 H), 7.50 ppm (br s, 20 H); ^{13}C NMR δ 32.9 (C_{10}), 37.6 (C_9), 112.5 (C_7), 134.3 (C_2), 138.5 (C_1), 142.7 ppm (C_3). A plausible pathway of the