[Contribution from the Department of Chemistry of the University of Illinois, Urbana, Illinois, and the Department of Chemistry of the University of California, Los Angeles, Calif.]

Reactivity of Organic Hydroxy Groups β to the Coördination Site in Cobalt(III) Complexes[1]

By William C. Drinkard, H. Frederick Bauer and John C. Bailar, Jr.

Received December 3, 1959

The new compounds bis-N-hydroxyethyldiethylenetriamine[2] cobalt(III) chloride, tri-(thiocyanato)-di-N-hydroxyethyldiethylenetriamine[2] cobalt(III) and trinitro-(di-N-hydroxyethyldiethylenetriamine)[2]-cobalt(III) are reported. A new synthesis of tris-(N-hydroxyethylethylenediamine)[2]-cobalt(III) ion is reported and its properties are compared to those recorded in the literature. The unusual inertness of the organic β-hydroxy groups is discussed.

Keller and Edwards[3] have described the preparation of tris-(N-hydroxyethylethylenediamine)-cobalt(III) chloride and have noted that the organic hydroxy groups are quite inert. The work reported here grew out of attempts to use these hydroxy substituents as functional groups in polymer formation. The $[Co(etolen)_3]Cl_3$ obtained by Keller and Edwards was an orange, crystalline solid, but that prepared in this study was dark red.

Difficulty was encountered in the preparation of $[Co(etolen)_3]^{+3}$ ion by the direct air oxidation of the cobalt(II)–amine mixture.[3] Repeated attempts to prepare the complex by this method resulted in a *ca.* 17% yield of tris-(ethylenediamine)-cobalt(III) ion. No other product could be isolated. The $[Co(en)_3]Cl_3$ was identified by elemental analysis and by comparison of its infrared spectrum with that of a known sample of the ethylenediamine complex. These large yields of the $[Co(en)_3]^{+3}$ ion were obtained even though the hydroxyethylethylenediamine had been recrystallized as the hydrochloride and twice distilled at reduced pressure. Only the middle fraction was taken in each distillation. Determination of the equivalent weight of the purified N-hydroxyethylethylenediamine indicates the absence of ethylenediamine in it. The absence of ethylenediamine also was shown by failure to isolate $[Co(en)_3]Cl_3$ when $[Co(etolen)_3]Cl_3$ was prepared by displacement of ammonia from $[Co(NH_3)_6]Cl_3$. Addition of known amounts of ethylenediamine to the reaction mixture in the latter case allowed the ready isolation of $[Co(en)_3]Cl_3$.

By displacement of ammonia from $[Co(NH_3)_6]Cl_3$ by N-hydroxyethylethylenediamine, a dark red compound is produced. The uncatalyzed reaction occurs extremely slowly in aqueous solution at steam-bath temperatures, but addition of activated carbon to the hot mixture results in a rapid evolution of ammonia. The resulting product is very soluble in water and ethanol and can be recovered only as a glass by evaporation of the water in vacuum. The last traces of water are removed in vacuum over phosphorus(V) oxide. The product is deliquescent.

Of the large number of anions tried, only $[Cr(NH_3)_2(SCN)_4]^-$ was found to precipitate the $[Co(etolen)_3]^{+3}$ ion from water solution. The salt precipitates as a purple-red powder which is only slightly soluble in water.

The cobalt(III) complex of N-hydroxyethyldiethylenetriamine was prepared by displacement of ammonia from $[Co(NH_3)_6]Cl_3$. The chloride of this ion is also dark red, deliquescent and very soluble in water and ethanol.

Attempts to make the hydroxy group of $[Co(etolen)_3]Cl_3$ and $[Co(etoldien)_2]Cl_3$ react with nitric acid, thionyl chloride, benzoyl chloride and acetyl chloride were equally as unsuccessful as for the compound reported by Keller and Edwards.[3] The complexes were dissolved or suspended in the reagent in question and refluxed for several hours. The reagent was then evaporated and the solid residue dried in vacuum and analyzed. Analyses showed no change in composition. Reaction with dimethyldichlorosilane resulted in reduction of the cobalt to the plus two state and decomposition of the complex.

The lack of a structural change in the ligand on coördination was shown by recovery and identification of the amine. Cobalt was precipitated from the complexes of N-hydroxyethylethylenediamine and N-hydroxyethyldiethylenetriamine by treatment of the aqueous solutions with hydrogen sulfide. The amines were recovered and analyzed as the hydrochlorides.

Because it is felt that the complete lack of reactivity of $[Co(etolen)_3]Cl_3$ and $[Co(etoldien)_2]Cl_3$ is associated with the charge field about the ion, the neutral complexes $[Co(dietoldien)(SCN)_3]$ and $[Co(dietoldien)(NO_2)_3]$ were prepared and their reactivity investigated. Attempts to effect reactions of the organic hydroxy groups in these compounds with acetyl chloride, benzoyl chloride, thionyl chloride, phenyl isocyanate and nitric acid resulted in decomposition of the complexes. Thus, no conclusions could be drawn concerning the behavior of the organic ligand in the initial compound.

Experimental

N-Hydroxyethyldiethylenetriamine and Di-N-hydroxyethyldiethylenetriamine.—These compounds were obtained commercially from the Rohm and Haas Company and used without further purification.

---

[1] Most of this research was supported by Contract AF 33(616)-3209 with the Materials Laboratory of Wright Air Development Center, Wright-Patterson Air Forces Base, Ohio. Reproduction of this paper in whole or in part is permitted for any purpose of the United States Government. The paper for the most part is based on a portion of a thesis submitted by William C. Drinkard to the Graduate College of the University of Illinois in partial fulfillment of the requirements for the degree of Doctor of Philosophy, 1956.

[2] The following abbreviations for the ligands will be used: N-hydroxyethyldiethylenetriamine, $HOCH_2CH_2NHCH_2CH_2NHCH_2CH_2NH_2$ = etoldien, di-N-hydroxyethyldiethylenetriamine, $HOCH_2CH_2NHCH_2CH_2NHCH_2CH_2NHCH_2CH_2OH$ = dietoldien, N-hydroxyethylethylenediamine, $HOCH_2CH_2NHCH_2CH_2NH_2$ = etolen, ethylenediamine, $NH_2CH_2CH_2NH_2$ = en.

[3] R. N. Keller and L. J. Edwards, This Journal, **74**, 215 (1952).

N-Hydroxyethylethylenediamine.—Because [Co(en)$_3$]Cl$_3$ was isolated from reactions involving direct air oxidation, the amine was purified carefully to assure the absence of ethylenediamine in the starting material. Two procedures were used for purification of the Eastman White Label compound:

1. The amine was distilled twice through a Vigreux column. The distillate was then redistilled from solid sodium hydroxide and finally distilled from calcium hydride. Only the middle fraction was taken in each distillation.
2. The commercial amine was converted to the dihydrochloride and recrystallized from water. The dry salt was mixed with an excess of solid sodium hydroxide and the free amine distilled from this mixture. The distillate was redistilled from calcium hydride. Only the middle fraction was taken in each distillation.

An equivalent weight of 52.8 was determined for the purified amine by titration with hydrochloric acid using a Beckman Model GS *p*H meter. The theoretical equivalent weight is 52.07.

Tris-N-hydroxyethylethylenediamine-cobalt(III) Chloride. Displacement Reaction.—A solution of 5.34 g. of [Co(NH$_3$)$_6$]Cl$_3$ (0.02 mole) and 6.24 g. of N-hydroxyethylethylenediamine (0.06 mole) in 50 ml. of water was heated on the steam-bath and 0.5 g. of activated carbon (Norite) was added. Ammonia was evolved rapidly. When the odor of ammonia was no longer present, the hot solution was filtered and evaporated in vacuum over sulfuric acid. A dark red glass resulted. The last traces of water were removed in vacuum at 105° over P_2O_5.

Anal. Calcd. for $CoC_{12}H_{36}N_6O_3Cl_3$: C, 30.2; H, 7.5; N, 17.6. Found: C, 31.15; H, 7.59; N, 17.30.

Addition of excess alcohol to solutions of [Co(etolen)$_3$]Cl$_3$, prepared by the displacement reaction, did not result in the precipitation of [Co(en)$_3$]Cl$_3$.

Direct Air Oxidation.—A mixture of 9.6 g. of $CoCl_2 \cdot 6H_2O$ (0.04 mole), 21.6 g. of N-hydroxyethylethylenediamine (0.2 mole), 40 ml. of water, 2.0 ml. of concentrated hydrochloric acid and 0.2 g. of activated carbon (Norite) was oxidized by a stream of air at steam-bath temperatures for 5 hr. The hot mixture was filtered and the solution was added to 300 ml. of ethanol. A yellow precipitate weighing 1.65 g. was formed on standing. The compound formed orange needles when recrystallized from ethanol–water. The infrared spectrum of the compound is the same as that of a known sample of [Co(en)$_3$]Cl$_3$.

Anal. Calcd. for $CoC_6H_{24}N_6Cl_3$: C, 20.85; H, 6.95; N, 24.40; Cl, 30.8. Found: C, 21.03; H, 7.14; N, 23.91; Cl, 30.7.

Tris-(N-hydroxyethylethylenediamine)-cobalt(III) Tetrathiocyanatodiamine Chromate (III).—A solution of NH$_4$[Cr(NH$_3$)$_2$(SCN)$_4$] (saturated at 25°) was added to a solution of [Co(etolen)$_3$]Cl$_3$ until precipitation was complete. The red-purple precipitate was filtered, washed with water and dried.

Anal. Calcd. for $CoCr_3C_{24}H_{54}O_3S_{12}$: C, 21.8; H, 4.1; N, 25.4. Found: C, 21.47; H, 3.92; N, 25.49.

Bis-(N-hydroxyethyldiethylenetriamine)-Cobalt(III) Chloride.—A solution of 26.6 g. of [Co(NH$_3$)$_6$]Cl$_3$ (0.1 mole) and 29.4 g. of N-hydroxyethyldiethylenetriamine (0.2 mole) in 150 ml. of water was warmed on the steam-bath and 0.5 g. of activated carbon (Norite) was added. Ammonia was evolved rapidly. When the odor of ammonia was no longer present the solution was filtered and the water was evaporated in vacuum over sulfuric acid. A red glass resulted. Attempts to crystallize the compound were unsuccessful due to its extreme solubility in water and ethanol and insolubility in other common solvents.

Anal. Calcd. for $CoC_{12}H_{34}N_6O_2Cl_3$: C, 31.4; H, 7.4; N, 18.3. Found: C, 31.19; H, 7.42; N, 18.65.

Trinitro-(di-N-hydroxyethyldiethylenetriamine)-cobalt-(III).—A solution of 20.2 g. of Na$_3$[Co(NO$_2$)$_6$] (0.05 mole) and 9.5 g. of di-N-hydroxyethyldiethylenetriamine (0.05 mole) in 50 ml. of water was warmed on the steam-bath at 60–70° for 30 minutes and allowed to stand overnight. The brown-red crystals of product were filtered and washed with water, ethanol and acetone.

Anal. Calcd. for $CoC_8H_{21}N_6O_8$: C, 24.8; H, 5.4; N, 21.6. Found: C, 24.29; H, 5.37; N, 21.30.

Trithiocyanato-(di-N-hydroxyethyldiethylenetriamine)-cobalt(III).—A solution of 3.88 g. of trinitro-(di-N-hydroxyethyldiethylenetriamine)-cobalt(III) (0.01 mole) dissolved in 100 ml. of water was mixed with 3.00 g. of potassium thiocyanate (0.03 mole) in 25 ml. of water. The solution was warmed on the steam-bath and 4 ml. of concentrated hydrochloric acid added. Gas was evolved and on cooling, dark red crystals of the product separated. These were filtered, washed with a small amount of water and dried.

Anal. Calcd. for $CoC_{11}H_{21}N_6O_2S_3$: C, 31.2; H, 4.95; N, 19.8. Found: C, 29.29; H, 4.83; N, 19.95.

Recovery of N-Hydroxyethylethylenediamine from [Co(etolen)$_3$]Cl$_3$.—Hydrogen sulfide was bubbled through a solution of 19.0 g. of [Co(etolen)$_3$]Cl$_3$ (0.04 mole) in 100 ml. of water until precipitation of CoS was complete. The cobalt sulfide was removed by filtration and the filtrate was cleared by treatment with activated carbon (Norite). The solution was evaporated to an oil on the steam-bath. After dissolving this residue in 25 ml. of ethanol, the solution was made acid with concentrated hydrochloric acid and diluted to 10 ml. with absolute ethanol. The oil which precipitated was crystallized by stirring.

Anal. Calcd. for $C_4H_{14}N_2OCl_2$: C, 28.2; H, 7.9; N, 16.5. Found: C, 28.96; H, 8.06; N, 16.40.

Discussion

The isolation of relatively large quantities of [Co(en)$_3$]Cl$_3$ after air oxidation of a mixture of a cobalt(II) chloride and N-hydroxyethylethylenediamine indicates that cleavage of a C–N bond has occurred. Ethylenediamine has been shown to be absent in the N-hydroxyethylethylenediamine used by equivalent weight determination and by failure to isolate [Co(en)$_3$]Cl$_3$ when [Co(etolen)$_3$]Cl$_3$ is prepared from [Co(NH$_3$)$_6$]Cl$_3$ by displacement of ammonia. The calculated equivalent weight of N-hydroxyethylethylenediamine is 52.07. The value found was 52.7. This value was not lowered even after drying over CaH$_2$. If ethylenediamine were present in the initial N-hydroxyethylethylenediamine in the concentration indicated by the amount of [Co(en)$_3$]Cl$_3$ isolated, the amine would contain 8% ethylenediamine and an equivalent weight of 49.8 would be found. Although it is not possible to isolate [Co(en)$_3$]Cl$_3$ after the displacement of ammonia from [Co(NH$_3$)$_6$]Cl$_3$ by pure N-hydroxyethylethylenediamine, the addition of 5% ethylenediamine results in a 31% recovery of the added ethylenediamine as [Co(en)$_3$]Cl$_3$.

It is interesting to observe that for each mole of cobalt(II) oxidized, 0.7 of a mole of ethylenediamine was isolated as [Co(en)$_3$]Cl$_3$. No case was observed in which the number of moles of ethylenediamine isolated was greater than the number of moles of Co(II) oxidized.

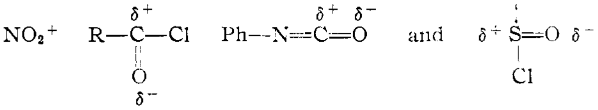
The preparation of [Co(etolen)$_3$]Cl$_3$ by air oxidation has been reported previously. The product was isolated as orange needles in 10–20% yield after recrystallization from ethanol–water. On the other hand, the alternate method of preparation discussed in the present study produced an extremely soluble, deliquescent red compound which could not be recrystallized from ethanol–water. [Co(etoldien)$_2$]Cl$_3$ has physical properties very similar to those of [Co(etolen)$_3$]Cl$_3$. The addition of a solution of NH$_4$[Cr(NH$_3$)$_2$(SCN)$_4$] to an aqueous solution of [Co(etolen)$_3$]Cl$_3$, prepared by ammonia displacement from [Co(NH$_3$)$_6$]Cl$_3$, resulted in the precipitation of [Co(etolen)$_3$] [Cr(NH$_3$)$_2$(SCN)$_4$]$_3$. No such product could be isolated from the material obtained by the direct oxidation procedure after $[Co(en)_3]Cl_3$ had been removed by dilution with ethanol.

It is also interesting that all compounds reported here have a distinct red color. It is generally found that the coördination of six nitrogens about a cobalt(III) ion results in a yellow compound. The unusual shift to red would indicate an extensive effect of the OH group on the metal ion. This interaction is also supported by the very large change in reactivity of the hydroxy group toward organic reagents. None of the reagents tested were found to attack the hydroxy group.

It seems unlikely that direct coördination of the OH to cobalt has occurred. This would imply that cobalt may assume a coördination number of nine in $[Co(etolen)_3]^{+3}$ and eight in $[Co(etoldien)_2]^{+3}$. Complexes showing various, large coördination numbers would not be expected to have stabilities comparable to that of $[Co(en)_3]Cl_3$, as is observed here. It is equally as unlikely that cobalt(III) retains its coördination number of six by coördination of OH leaving a free amine group. Such a free amine would be as reactive as a free hydroxy group.

Inspection of molecular models suggests that if the two nitrogens of each of the three N-hydroxyethylethylenediamines are coördinated to the metal, the three free hydroxy groups will be in a very favorable position for hydrogen bond formation with the hydrogen of the coördinated nitrogen atom. The strong inductive effects resulting from the hydrogen bond may distort the field of the nitrogen with a resulting shift in spectrum.

The lack of chemical reactivity of the hydroxy group is not surprising in view of the mechanism generally accepted for attack by the reagents investigated. The functional groups of the attacking molecules may be represented as



$$NO_2^+ \quad \mathrm{R}-\underset{\underset{\delta^-}{\mathrm{O}}}{\overset{\delta^+}{\mathrm{C}}}-\mathrm{Cl} \quad \mathrm{Ph}-\mathrm{N}=\overset{\delta^+}{\mathrm{C}}=\overset{\delta^-}{\mathrm{O}} \quad \text{and} \quad \delta^+\ \underset{\mathrm{Cl}}{\overset{\mathrm{Cl}}{\mathrm{S}}}=\mathrm{O}\ \delta^-$$

The reaction is initiated by the attack of the positive center of the reagent on an electron pair of the hydroxy oxygen. Models show the oxygen of the OH lies close to the cobalt(III) ion. Such a position places it in the large positive field of the cobalt. The activation energy necessary for the approach of a positive center into the positive field of the ion would be large and attack would be greatly hindered or prevented.

[CONTRIBUTION FROM THE DEPARTMENT OF CHEMISTRY, UNIVERSITY OF NOTRE DAME, NOTRE DAME, INDIANA]

Metal Binding of the Benzimidazoles[1]

BY THOMAS J. LANE, C.S.C., AND KENNETH P. QUINLAN[2]

RECEIVED JUNE 8, 1959

The acid dissociation constants have been determined potentiometrically for benzimidazole, 2-methylbenzimidazole and 2-ethylbenzimidazole in solutions of ionic strength 0.16 M ($NaNO_3$) at 4 ± 1, 25 ± 0.1 and 35 ± 0.1°. The changes in enthalpy, ΔH^0, were found to be 8.7, 9.8 and 9.3 kcal./mole, respectively. Formation constants have been determined for copper(II) with benzimidazole by the Bjerrum potentiometric method in solutions of the same ionic strength at the three above temperatures. An upper limit of the value of the formation constant for copper(II) and 2-methylbenzimidazole at 4° is reported. The formation constants for cadmium with benzimidazole and 2-methylbenzimidazole have been determined by the polarographic method in 50% aqueous ethanol at 25 ± 0.1°. Results indicate that the benzene portion of the benzimidazole hinders coördination with copper(II). Formation constants of copper(II) with 2-hydroxymethylbenzimidazole and 1-methyl-2-hydroxymethylbenzimidazole show that the unsaturated nitrogen is the active site in the substituted benzimidazoles.

Introduction

No formation constants have been reported for metal complexes of benzimidazole and its alkylated derivatives although the substituted benzimidazoles have been thoroughly studied as analytical reagents[3-5] and as part of the Vitamin B_{12}[6] molecule.

Freiser[4] has postulated that the benzene part of the substituted benzimidazoles exhibits steric effects in the chelation of metallic ions. A comparison of the difference in the stability constants of the imidazoles[7] with those of the benzimidazoles may give conclusive evidence that the benzene portion of the molecule is sterically hindering the coördination.

It has been assumed that coördination with the substituted benzimidazoles takes place through the unsaturated nitrogen. Freiser's[8] infrared study on the chelates of the derivatives of benzimidazole seems to substantiate this assumption. A study of the steric effect of the methyl group on the stability constants of 2-hydroxymethylbenzimidazole and 1-methyl-2-hydroxymethylbenzimidazole was undertaken to show which of the two nitrogen atoms in the benzimidazole is coördinating.

Experimental

Materials, Apparatus and Solutions.—Benzimidazole, 2-methylbenzimidazole and 2-ethylbenzimidazole were obtained from the Aldrich Chemical Company, Inc., Milwaukee, Wisconsin. The compounds were recrystallized at least three times before use and then purity was established by analysis and melting points.

---

[1] Presented at the 135th meeting of the American Chemical Society, Boston, Mass., 1959.

[2] The paper was abstracted from the Ph.D. thesis of Kenneth P. Quinlan, Notre Dame University, 1959.

[3] R. G. Charles and H. Freiser, *Anal. Chim. Acta*, **11**, 1 (1954).

[4] W. D. Johnston and H. Freiser, *ibid.*, **11**, 301 (1954).

[5] J. L. Walter and H. Freiser, *Anal. Chem.*, **25**, 127 (1953).

[6] M. T. Davies, P. Mamalis, V. Petrow, B. Sturgeon, G. H. Beaven, E. R. Holiday and E. A. Johnson, *J. Pharm. Pharmacol.*, **4**, 448 (1952).

[7] Y. Nozaki, F. R. N. Gurd, R. F. Chen and J. T. Edsall, THIS JOURNAL, **79**, 2123 (1957).

[8] T. R. Harkins, J. L. Walter, O. E. Harris and H. Freiser, *ibid.*, **78**, 260 (1956).