Cantaurus, Vol. 9, 23-26, May 2001 © McPherson College Division of Science and Technology

The Synthesis and Characterization of Co(AcBcyclam)PF_6

Jonas Lichty

ABSTRACT

The Co^{2+} complex of 4, 11 – diacetato – 1, 4, 8, 11 – tetraazabicyclo[6.6.2]hexadecane (Co(AcBcyclam)PF_6 or simply Co^{III}**L**) has been synthesized. Due to the air – sensitivity of the Co^{II}**L** complex, the low spin diamagnetic Co^{III}**L** complex was prepared by chemical oxidation of the Co^{II}**L** complex. The Co^{II}**L** complex was then characterized by mass spectrometry, infrared absorption, elemental analysis, UV – VIS absorption, NMR, conductance measurements and an X-ray crystal structure, all of which helped to confirm the structure (FIGURE 2) of the complex as formulated. In addition, the structure of the complex was also confirmed by comparison with data from similar Co complexes.

Keywords: *cross – bridged ligands, tetraazamacrocycle, Cobalt, macrobicycle*

INTRODUCTION

Co^{II} and Co^{III} complexes are the standard for modern coordination chemistry[1]. Complexes made with new ligands and these metals can be compared to the properties of the large database of known Co^{II} and Co^{III} complexes. In this case, the new ligand will be an ethylene cross-bridged tetraazamacrocyle. This ligand, prepared by Dr. Tim Hubin and colleagues at the California Institute of Technology, was synthesized using a glyoxal – tetraazamacrocyle condensation reaction.[2,3]

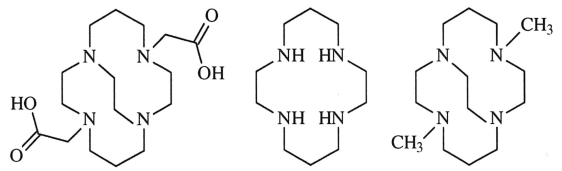


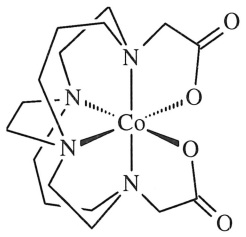
Figure 1

The ethylene cross bridge gives these ligands unique characteristics. They are extremely basic and some of them have been described as "proton sponges".[2,5,6] Proton sponges are difficult to complex with some metal ions under protic conditions because of the competition between protons and the metal ions for the nitrogen donors[7]. Previous studies[4,5,7,8] have shown that this problem can be overcome by eliminating protons from the reaction media. In doing so, a variety of transition metal complexes can be synthesized using these ligands.

Another unique characteristic of these complexes is their kinetic inertness in unfavorable conditions.[7,8] The "fixing" in place of donor atoms as a result of the multiple connections between them and the ligand because of the ethylene cross – bridge could be a logical explanation for the stability of these complexes. As a result of this, the stepwise dissociation can be slowed or prevented.

The long-term goal of studies involving these types of ligands is for the development of improved MRI contrast agents[9]. MRI contrast agents utilize Gd^{3+} because it has a high magnetic moment because it has seven unpaired electrons.[2] As a result of this; it modulates the magnetic properties of water[2]. However, as previously mentioned, this study involves Co so that comparisons can be made with the vast library of Co complexes. Theoretically, the more open coordination sites there are to interact with water, the better the resolution.[3] However, at the same time, the Gd^{3+} must be held in place firmly enough by the ligand so that it does not come off under physiological conditions because Gd^{3+} is toxic to humans.[3] Presently, the ligands used for MRI contrasting agents have only one open coordination site on Gd^{3+} to interact with water.[2] Cross – bridged tetraazamacrocycles such as **L** and $\mathbf{L_3}$ leave more (3) open coordination sites on the Gd^{3+}, and at the same time provide exceptional kinetic stability.[9] Both of these aspects make them potentially ideal candidates for MRI contrasting agents.

This particular study will look at how adding carboxyl ate pendant arms to cross – bridged tetraazamacrocycles affects the physical and chemical properties (mass spec, IR, elemental analysis, UV-Vis, X – ray crystal structure, NMR, and conductance) of their Co^{II} and Co^{III} complexes.



Co(AcBcyclam)PF_6

Figure 2

MATERIALS AND METHODS

$CoCl_2$ (99.99%) and NH_4PF_6 (99%) were purchased from Aldrich Chemical Company and used as received. HPLC grade methanol and acetonitrile were purchased from Fisher Scientific and used as received. Dr. Tim Hubin provided the ligand.

Quantitative Technologies, Inc performed elemental analyses. Mass spectra were measured by the Analytical Service of the University of Kansas on a VG ZAB HS spectrometer equipped with a xenon gun. The matrices used were NBA (nitrobenzyl alcohol) and TG/G (thioglycerol/glycerol). The University of Kansas NMR lab recorded NMR spectra with a Bruker DRX 400 spectrometer. UV-VIS absorption was measured at McPherson College on a Spectronic Genesys 2 spectrophotometer. FT-IR was done at McPherson College on a Nicolet 320 Avatar. Conductivity was measured using 1mM solutions at room temperature on a type 700 conductivity meter by Chemtrix at McPherson College.

Complex Synthesis. The AcBcyclam ligand (**L**) (7.30×10^{-4}, .250 g) was suspended in 40 ml 4:1 acetonitrile: methanol solution in a 100 ml roundbottom flask. Helium was then bubbled through the ligand solution as it was being stirred for one hour to degas the solution. The reaction vessel was then left under helium pressure and $CoCl_2$ (7.30×10^{-4} mol, .095g) was added. The $CoCl_2$ dissolved quickly into a yellow solution. The reaction was then stirred overnight. The following day the brown liquid was filtered through filter paper into a beaker. The solvent was then evaporated in the hood over the weekend, leaving only 15 – 20 ml of solvent, many brown/red crystals ($Co^{2+}\mathbf{L}^{2-}$), and a course gray/brown precipitate, possibly KCl (K from impure ligand, and Cl from $CoCl_2$). Two samples of the crystals were taken. One was for X-ray crystallography and the other for mass spec. Next, everything (crystals, precipitate, solvent) was dissolved in about 10 ml of H_2O, leaving a brown liquid. Then 6-8 ml of concentrated HCl was added and air was bubbled through the mixture over the weekend, as it was being stirred. Three days later, the H_2O was not quite evaporated, so 20 ml of methanol along with Na_2SO_4 (drying agent) was added. The beaker was then covered with parafilm and stirred overnight, leaving a red/purple liquid. The following day the purple solution was pipetted off of the Na_2SO_4 into a roundbottom flask. The Na_2SO_4 was then rinsed with methanol. The methanol was then added to the solution. Next, 5 eq (.607 g) NH_4PF_6 was dissolved in the methanol, and then added to the solution through a Kimwipe filter. After being shaken thoroughly a purple solid began to precipitate from solution ($[\mathbf{CoL}]^+[PF_6]^-$). The round bottom flask was then placed in the refrigerator overnight to complete the precipitation. The following day the solution was filtered with suction through a fine glass frit, and then the precipitate was washed with methanol. The precipitate was left on the frit for an additional five minutes to dry it. The suction was then removed and a Kimwipe was placed over the top of the funnel, which was then left to air-dry overnight. The product was then tested for purity by dissolving it in CH_3CN (PF_6 salts should be soluble). A white solid was discovered, which was subsequently removed by filtration through Celite. The purified complex was then obtained by way of ether precipitation from acetonitrile solution.

$$CoCl_2 + \mathbf{LH_2} \xrightarrow[He]{MeOH/MeCN} Co^{II}\mathbf{L}$$

$$Co^{II}\mathbf{L} \xrightarrow{O_2,\ HCl,\ H_2O} [Co^{III}\mathbf{L}]Cl$$

$$[Co^{III}\mathbf{L}]Cl \xrightarrow[MeOH]{NH_4PF_6} [Co^{III}\mathbf{L}][PF_6] + NH_4^+ + Cl^-$$

Figure 3 . Complex Synthesis

RESULTS AND DISCUSSION

Analytical calculations for the purified complex ($C_{16}O_4H_{28}N_4CoPF_6$) were: C 35.31%, H 5.19%, N 10.29%. The percentages found were: C 35.32%, H 5.26%, N 10.31%. The infrared spectrum showed (using KBr pellet): 3429 cm^{-1}, (H_2O); 2919 cm^{-1}, (C – H stretches); 2361 cm^{-1}, (C=O); 834 cm^{-1}, (PF_6). FAB^+ mass spectra in CH_3CN (NBA matrix) exhibited a peak at m/z = CoL^+ (399.4) for both the Co^{II} as well as the final Co^{III} complex. The ^1H NMR integrated for the correct number of hydrogens, but due to the extreme complexity of the spectrum, the signals were not assigned. ^{13}C NMR (500 Mhz, CD_3CN) showed: 177.441 ppm (C=O), 69.040 (CH_2CO_2H), 64.942 (CH_2 bridge), 57.869, 57.632, 57.067, 56.426 (CH_2 macrocycle) and 22.110 (propylene). All of these results help to confirm the structure of the complex as formulated.

Conductance of the complex was measured to make sure that the electrolyte type matched what the formulated compound was meant to be. The ionization (displacement of PF_6^- by solvent) of these complexes in solution correlates with the solvent dielectric constant.[8] The molar conductance of the complex in water (.001M) was Λ_0 = 79.5 $ohm^{-1}cm^2mole^{-1}$. The molar conductance in acetonitrile was Λ_0 = 92.4 $ohm^{-1}cm^2mole^{-1}$. Literature values for a 1:1 electrolyte in acetonitrile are 120 – 160 $ohm^{-1}cm^2mole^{-1}$, and for 2:1 are 220 – 300 $ohm^{-1}cm^2mole^{-1}$. For water, literature values for a 1:1 electrolyte are 118 – 131 $ohm^{-1}cm^2mole^{-1}$, and for 2:1 are 235 – 273 $ohm^{-1}cm^2mole^{-1}$.[10] The experimental values were slightly low, but what did dissociate was obviously 1:1. Acetonitrile has a low dielectric constant, so it was the control, in effect. Water is the more important media since we are concerned with physiological conditions. Water also has a high dielectric constant. So if the pendant arms dissociate at all, they should do it in water. Since the value for water was about the same as that for

acetonitrile the conclusion that the pendant arms stay attached in aqueous solution can be made.

Electronic Structure. The complex is low spin d^6 and diamagnetic, as evidenced by the sharp proton and carbon NMR spectra, indicating electronic structures typical of octahedral amine Co^{III} complexes.[11] So, magnetic moment calculations were not necessary.

An interesting property of Co^{III} complexes is that their electronic spectra can be used to estimate the ligand field strengths of the ligands in the complexes.[12] The ligand field strength represents the strength of the metal – donor bonds. The energy of the lowest energy absorption band ($^1A_{1g} \rightarrow {}^1A_{2g}$) plus the Racah parameter C = 3800 cm^{-1} for Co^{3+} can be taken as Δ_o.[12,13] This has been calculated for the complex, and the result is: $\Delta_o = 24{,}040\ cm^{-1}$. The value for *cis* – $[CoL_2]^+[CO_3]^-$ was determined[13] as $\Delta_0 = 23{,}030\ cm^{-1}$. This value illustrates the fact that the ligand field strength of this ethylene cross – bridged tetraazamacrocycle is very similar to, and possibly even slightly higher than that of unbridged analogs. The values for both the synthesized complex and the complexes listed above take Δ_o to be C (3800 cm^{-1}) plus the energy of the lowest absorption. In each of the electronic spectra only two absorptions are seen. This energy is actually an average of the $E(^1T_{1g})$ and $A(^1T_{1g})$ state energies, whose separate absorptions are not well enough resolved to distinguish.[11]

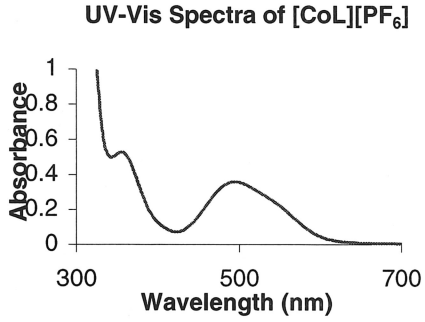


Figure 3

The more accurate energy should be assigned to the lowest energy band arising from the $A(^1T_{1g})$ state only.[11] This is significant because it means that the reported energies are slightly higher than the true values, since they average in the higher energy $E(^1T_{1g})$ state. However, both complexes show only two absorptions [the absorption maxima and extinction coefficients are: λ_{max}= 494 nm (72 L m^{-1} cm^{-1}) and λ_{max}= 355 nm (106 L m^{-1} cm^{-1})] so we can compare their values. The striking similarity tells us that the addition of the cross - bridge has not affected the ligand field strength of the complex, even though it made it more rigid.

The value for $CoL_3Cl_2^+$ has been determined as Δ_o = 20,470 cm^{-1}. The field strength of carboxylate arms is higher than that of Cl^-. As a result of this, in the Cl complex all three peaks are visible, instead of only two, so the ligand field strength will be lower because the value for the lowest absorption band is used, rather than the average of the lowest two. In addition, the ligand field strength of the $CoL_3Cl_2^+$ should be expected to be lower because Co-Cl bonds typically have weaker ligand field strengths than Co-O bonds.

The X-ray crystal structure confirms the structure predicted in Figure 2. The unit cell contained two nearly identical cations, two Cl^- anions, and four H_2O's. The 6-coordinate Co^{3+} (as evidenced by the presence of the Cl^- anion) complex shows the nearly ideal octahedral geometry expected for Co^{3+} complexes. That is, the trans-donor bonds are near 180° and the cis-donor bonds are near 90°. Bond distances are as expected for Co^{3+} with these donor atoms.[14]

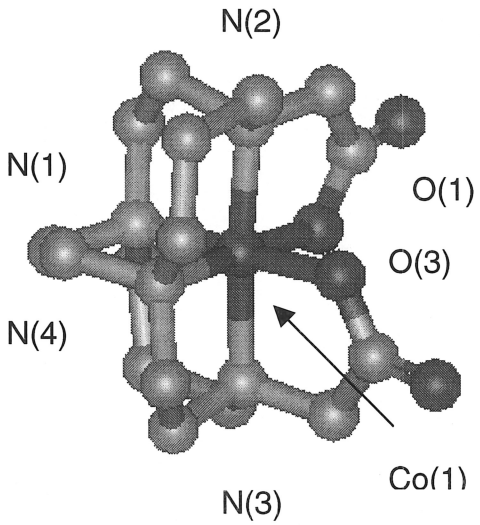


Figure 4. X-Ray Crystal Structure

Table 1. Selected Bond Lengths (Angstroms)

Co1-O1 = 1.888	
Co1-O3 = 1.911	
Co1-N4 = 1.960	
Co1-N1 = 1.965	
Co1-N3 = 1.980	
Co1-N2 = 1.983	

Table 2. Selected Bond Angles (degrees)

O1-Co1-O3 = 90.8	N4-Co1-N3 = 88.4
O1-Co1-N4 = 177.9	N1-Co1-N3 = 94.7
O3-Co1-N4 = 89.0	O1-Co1-N2 = 86.7
O1-Co1-N1 = 90.7	O3-Co1-N2 = 89.1
O3-Co1-N1 = 177.2	N4-Co1-N2 = 95.4
N4-Co1-N1 = 89.6	N1-Co1-N2 = 88.6
O1-Co1-N3 = 89.5	N3-Co1-N2 = 175.0
O3-Co1-N3 = 87.7	

CONCLUSIONS

From the elemental analysis we can conclude that the synthesized Co^{3+} complex of 4, 11-diacetato-1, 4, 8,

11-tetraazabicyclo[6, 6, 2]hexadecane was pure. From the UV-Vis we can conclude that AcBcyclam is a strong field ligand. The CMR, Mass Spec, and IR have all been assigned. The Co(AcBcyclam)PF_6 complex is the first AcBcyclam complex to give an NMR, as a result of its being diamagnetic. The X-ray crystal structure confirms the geometry predicted in Figure 2.

ACKNOWLEDGEMENTS

I would like to thank Dr. Tim Hubin for all of his guidance in various aspects of the project, and for providing many of the materials needed for this project. In addition, I thank the Stine Committee for funding this project. Also, I thank Dr. Steven J. Archibald of the University of Hull (U.K.) Department of Chemistry for the X-ray crystal structure. Lastly, I would like to thank Dr. David VanderVelde of the University of Kansas for the NMR data.

LITERATURE CITED

(1) *Advanced Inorganic Chemistry*, 5th Ed., Cotton, F.A.; Wilkinson, G.; Wiley and Sons, New York, 1988.

(2) Weisman, G.R.; Rogers, M.E.; Wong, E.H.; Jasinski, J.P.; Paight, E.S. *J. Am. Chem. Soc.* **1990**, *112*, 8604.

(3) Weisman, G.R.; Wong, E.H.; Hill, D.C.; Rogers, M.E.Reed, D.P.; Calabrese, J.C. *J. Chem. Soc., Chem. Commun.* **1996**, 947.

(4) Hubin, T.J.; McCormick, J.M.; Alcock, N.W.; Busch, D.H.; Clase, N.J. *Inorg. Chem.* **1999**, *38*, 4435.

(5) Hubin, T.J.; McCormick, J.M.; Alcock, N.W.; Busch, D.H. *Submitted*, **2000**.

(6) Bencini, A.; Bianchi, A.; Bazzicalupi, C.; Ciampolini, M.; Fusi, V.; Micheloni, M.; Nardi, N.; Paoli, P.; Valtancoli, B. *Supramol. Chem.* **1994**, *3*, 41.

(7) a) Hubin, T.J.; McCormick, J.M.; Collinson, S.R.; Alcock, N.W.; Busch, D.H. *J. Chem. Soc., Chem. Commun.* **1998**,1675. b) Busch, D.H.; Collinson, S.R.; Hubin, T.J.; *Catalysts and Methods for Catalytic Oxidation,* WO 98/39098, Sept. 11, 1998. c) Busch, D.H.; Collinson, S.R.; Hubin, T.J.; Labeque, R.; Williams, B.K.; Johnston, J.P.; Kitko, D.J.; Burkett-St. Laurent, J.C.T.R.; Perkins, C.M. *Bleach Compositions*, WO 98/39406, Sept. 11, 1998.

(8) Hubin, T.J.; McCormick J.M.; Collinson, S.R.; Buchalova, M.; Perkins, C.M.; Alcock, N.W.; Kahol, P.K.; Raghunathon, A.; Busch, D.H. *J. Am. Chem. Soc.* **2000**, *122*, 2520.

(9) Hubin, T.J.; Meade, T.J. *in prepararation*, **2000**.

(10) Angelici, R.J. *Synthesis and Techniques in Inorganic Chemistry,* University Science Books: Mill Valley, CA. **1986**, 213, and references therein.

(11) Hubin, T.J.; Alcock, N.W.; Clase, H.J.; Seib,L.L.; Busch, H.B. *in preparation*, **1999**.

(12) a) Wentworth, R.A.D.; Piper, T.S. *Inorg. Chem.* 1965, 4, 709. b) Wentworth, R.A.D.; Piper, T.S. .*Inorg. Chem.* **1965**, *4*, 1524.

(13) Hung, Y.; Martin, L.Y.; Jackels, S.C.; Tait, A.M.; Busch, D.H. *J. Am. Chem. Soc.* **1977**, *99*, 4029.

(14) Allen, F.H.; Orpen, A.G.; Taylor, R. *J. Chem. Soc. Dalton Trans.* **1989**, S1-S83.