76-21,179

NELSON, Harold Christopher, 1946-
Cu(II) COORDINATION COMPOUNDS WITH NUCLEIC ACID CONSTITUENTS.

City University of New York, Ph.D., 1976
Chemistry, inorganic

Xerox University Microfilms, Ann Arbor, Michigan 48106

Cu(II) Coordination Compounds with Nucleic Acid Constituents

A Dissertation
Submitted to
The Graduate Faculty of the Department of Chemistry
The City University of New York

In Partial Fulfillment
of the Requirements for the Degree of
Doctor of Philosophy

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by
Harold C. Nelson
May 17, 1976

This manuscript has been read and accepted for the Graduate Faculty in Chemistry in satisfaction of the dissertation requirement for the degree of Doctor of Philosophy.

5-17-76
date

Chairman of Examining Committee

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Abstract

Cu(II) COORDINATION COMPOUNDS WITH
NUCLEIC ACID CONSTITUENTS

by

Harold C. Nelson

Adviser: Professor Juan F. Villa

A series of new Cu(II) coordination compounds with 5X-Uracil (X= H, NO_2, and I), 6Y,2S-Uracil (Y= H, NH_2, CH_3, and C_3H_7), 2,4-Dithiouracil, 8Z-Guanosine (Z= H, and Br), Deoxyguanosine(d-Guanosine), 2Q-Cytosine (Q= O, and S), Xanthosine, Cytidine, Inosine, Adenosine, 5'-CMP, 5'-AMP, and 5'-GMP were prepared and characterized by elemental analysis, IR, visible absorption spectroscopy, variable temperature magnetic susceptibility (12 - 500°K), and electron paramagnetic resonance at 77 and 300°K.

It was observed that bidentate chelation at the expense of monodentate coordination appeared to be the preferred mode of bonding in coordination complexes of copper(II) with these nucleic acid constituents. This type of bonding appeared to be general for pyrimidine and purine moieties and involved adjacent oxygen (sulfur) and nitrogen atoms on the ring or nitrogen (oxygen) and phosphate oxygen when nucleotides were considered. Generally, stoichiometries

2:1 ligand to metal were preferred although 1:1 stoichiometries, with and without bridging between metal centers, were seen. A trimeric d-guanosine-copper(II) complex was also prepared.

In the uracil (cytosine) complexes, the effect of replacing a keto oxygen on C(2) with a thio sulfur interchanged the preference for coordination between N(1) (N(3)) for keto to N(3) (N(1)) for thio. Also EPR data demonstrated the square planar (distorted octahedral) geometry for all these systems. However, it was noted, that the introduction of bonding sulfur atoms in coordinating ligands distorted this bonding towards a C_{2v} or T_d disposition about the metal center with a concomitant lowering of the d-d band maximum. The ground state term in all cases was seen to be $^2B_{1g}(d_{x^2-y^2})$.

Ligand field strengths for the distorted octahedral complexes varied as:

> 2S-Cytosines > Cytosine > 5X-Uracils > 6Y,2S-Uracils > 2,4-Dithiouracil > 8Z-Guanosines > 2'-Deoxyguanosine > Inosine > Cytidine > Xanthosine > Adenosine; 5'-AMP > 5'-GMP > 5'-CMP.

Magnetic susceptibility and EPR data showed that sulfur coordination appeared to predispose the complexes to polymeric interactions ($-2J \geq 1400 cm^{-1}$) as did the introduction of ribose and phosphoribose functions on the pyrimidine or purine bases. Also, the magnetic data suggested that the cooperative phenomenon responsible for the ferromagnetism ob-

served in a number of these complexes, appeared to be enhanced according to the following series:

Nucleosides > 5'-CMP > Uracil

and suggested an ordering capability of the sugar group.

Recognition of the sugar group by copper(II) was seen for d-guanosine but not for guanosine (and presumably for d-ribosides and not ribosides, in general), and is postulated to operate through the 3'OH group of the d-guanosine.

Acknowledgements

To Dr. Juan F. Villa for giving me the opportunity of working with him on this project. He was always available for consultation and his comments provided me with the insight and understanding to tackle the problems and questions that continuously arose during this work. He was a source of great energy and intellect, and appeared to have an infinite capacity for working and sharing with others. I will feel blessed if my future collaborations provide one-half the excitement and warm personal interactions I have experienced with Juan F. Villa during my graduate career.

To my parents, Irene and Harold, for their unending love and encouragement; they gave me everything I could wish for throughout my life. I love them both.

To Miss Ngarling Khoe and Mr. Leonard Zyzyck for their help with some computer programming.

To Professor Fiztgerald Bramwell of Brooklyn College for allowing me the use of his EPR spectrometer during the final weeks of this work.

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Introduction

Nucleic acids are long polymer molecules, the backbones of which consist of repeated sequences of phosphate and sugar molecules resembling links in a chain. There are two main types of nucleic acids according to the sugar molecule present: RNA with ribose and DNA with deoxyribose. Attached to the sugar links in the backbone are two kinds of purines, adenine and guanine; and two kinds of pyrimidines, cytosine and thymine ($5CH_3$-uracil) in DNA, or cytosine and uracil in RNA, Fig. 1. DNA and sometimes RNA are comprised of two polymer chains hydrogen bonded in a special complementary way: guanine to cytosine and adenine to thymine (in DNA) or adenine to uracil (in RNA).

25 years ago, nucleic acids were implicated in the transmission of hereditary characteristics through genetic coding, and in the direction of cell metabolism (e.g., protein synthesis, enzymatic catalysis, etc.). In the early 1950s, the work conducted by Hershey and Chase[1,2] proved conclusively that DNA served as the physical basis for hereditary. Their experiments showed that the component of T2 bacteriophages incorporated into E. coli host cells was DNA and not the protein coats. The synthesis of new bacteriophages was accompanied by rapid and extensive changes in the metabolism of the host cell and the normal synthesis of respiratory and adaptive enzymes, and of native RNA, ceased.

A capacity for directing the activities of the cells

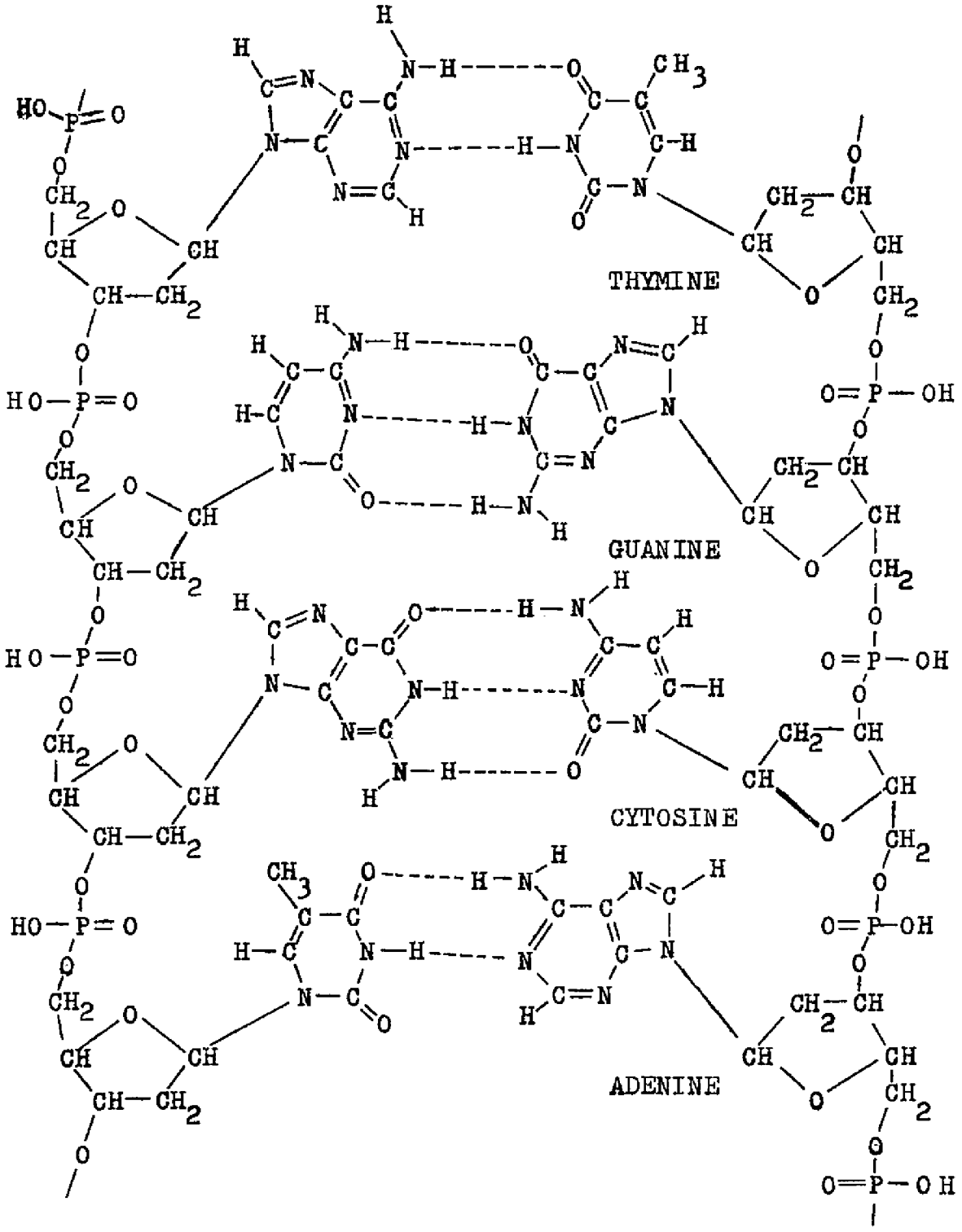


Fig. 1. Diagram of a section of a DNA molecule showing pairing of bases on parallel polynucleotide chains.

seems to be characteristic of RNA as well as DNA. Free RNA isolated from Tobacco Mosaic Virus is capable by itself of infecting tobacco plants with mosaic disease and causing the plant cells to support production of complete virus particles. Similar infective properties have been demonstrated in purified RNA from a wide variety of RNA viruses, for example, poliomyelitis [3,4] and in purified DNA from the bacterial DNA virus ØX 174.[5-7]

The evidence from viruses therefore indicates that in spite of their chemical differences, DNA and RNA are equally capable of assuming control of the activities of the cell. In the normal, uninfected cell, however, this control seems to be vested mostly in DNA while the role of RNA is one of transmission of the genetic information within the cell (i.e., the transcription and translation processes).

Metal ions have been implicated in a wide variety of biological processes including biological oxidations and reductions, charge carriers, enzyme activators, and control mechanisms.[8,9] Their interactions with nucleic acids and their constituents have been reviewed recently,[10-12] and their role in the replication, translation, and transcription of nucleic acids is well documented.[9]

The role that Cu(II) ions play in biochemical processes involving amino acids, enzymes, and proteins,[13] as well as its influence on activities involving nucleic acids[14-19] has been an area of active research. Currently, the nature

of the binding of Cu(II) to DNA is being eagerly explored because of the Cu(II) induced reversible unwiding of DNA.[20-23]

The ability of metal ions to stabilize the DNA double helix was first discovered by Shack, et al.,[23] and elucidated by Dove and Davidson,[24] who found that T_m, the "melting temperature", or the temperature at which DNA unwinds into single strands, increased linearly with the logarithm of ionic strength. Here the negatively charged phosphate groups on adjacent nucleotides are neutralized to a larger degree at higher ionic strengths, and the driving force to unwind is removed. However, this stabilization is not a universal characteristic of all metal ions. Cu(II) has been shown to lower the T_m of DNA[20,22] far more effectively than any other metal ion studied to date. The reason for the differences in behavior of the metal ions studied with respect to DNA can readily be explained by differences in binding tendencies. Ions like Mg(II) and Co(II) bind to phosphate, stabilizing the ordered structure by the counter-ion effect, while Cu(II) (and to a lesser extent Cd(II)) bind not only to phosphate, but to base as well. Binding to base competes with the hydrogen-bonding of the double helix and therefore helps to destroy it. The rewinding of cooled DNA solutions in the presence of Cu(II) and an optimum concentration of electrolyte[21] can be explained in a similar fashion. Here the ability of the bases to recognize

each other and to reform native DNA is attributed to the ability of copper ions to form cross-links between the DNA strands while in the denatured state. Only a few such cross-links between the bases are required to maintain the single strands in close proximity, so that under favorable conditions,[21] the double helix can be regenerated.

To date, solution studies have provided the vast majority of data on metal interactions with nucleic acids and nucleic acid constituents and Weser[11] has reviewed some of the instrumental approaches commonly employed. Studies on solid complexes of pyrimidines, purines, and nucleic acids with metal ions, however, are sorely lacking and very much needed from several points of view. First, studies involving solid adducts eliminate problems that inevitably arise when solution work is employed. Solids are the only systems that can be used to unequivocally locate coordinations sites (e.g., by X-ray crystallography or IR spectroscopy). Second, to work with solids eliminates the uncertainty in relation to the species being studied. This is not true for solution studies where the integrity of the complex under investigation is unclear due to the possibility of generating systems of various stoichiometries that persist in solution. Third, in order to better understand the forces that operate between metal ions and systems of a more complex nature (e.g., amino acid-metal ion-RNA, as presumed in protein intermediates or

protein-metal ion-substrate, as in catalases), the trends in bonding and stoichiometry that exist between metal ions and the small units comprising DNA and RNA must first be elucidated. Only then can solution studies involving higher-order systems provide beneficial information concerning the forces found on the atomic level between the metal ion and its immediate environment.

Specific Aims

It will become evident from the literature review that there is a lack of information and of a systematic characterization of the bonding, electronic and magnetic properties of coordination compounds of the nucleic acid components, and of the Lewis base behavior, in general, of these nucleic acid constituents. The biological importance of these coordination compounds prompted us to undertake this investigation in order to elucidate the coordination abilities these nucleic acid components have towards Cu(II) and to understand the resulting bonding. Our specific aims were to elucidate the interactions between Cu(II) and nucleic acid components as they form solid coordination compounds. Of special interest will be to determine the capability of forming coordination compounds with a representative variety of these ligands, to observe any trends in the stoichiometries of the compounds formed as well as the preferred sites of coordination employed by the ligands, to find the pH necessary for complexation to occur, and to

carry out a full characterization of these solid coordination compounds by means of vibrational, electronic, and EPR spectral and magnetic susceptibility measurements. Cu(II) was chosen as the metal ion because of its ubiquitous presence in many biological processes, and its capability of being utilized as a simple magnetic probe.

Historical Background

Nucleic acid components offer a multitude of sites that can coordinate as Lewis bases towards metal ions. For example, the simple 5'-thymidylic acid molecule (5'-TMP), Fig.1, has 3 sites on the ring, 2 sites on the sugar, and 1 or more sites on the phosphate group available for bonding. Bonaccorsi, et al.,[25] noted that deprotonated purine bases offer a variety of nucleophilic sites which may not greatly differ in their electronic properties. Therefore, when such

Table I

Selected pK_as of Purine and Pyrimidine Bases (by potentiometry at 25°C)

Base	Ionization Site	Reaction	pK_a
Adenine	N(9)	$HL \rightleftharpoons H^+ + L^-$	9.88[26]
	N(1)	$H_2L^+ \rightleftharpoons H^+ + HL$	4.22[26]
Cytosine	N(1)-C(2)O	$HL \rightleftharpoons H^+ + L^-$	12.16[27]
	N(3)	$H_2L^+ \rightleftharpoons H^+ + HL$	4.58[26], 4.60[27]
Guanine	N(9)	$HL^- \rightleftharpoons H^+ + L^{-2}$	12.3[29]*
	N(1)	$H_2L \rightleftharpoons H^+ + HL^-$	9.2[29]
	N(7)	$H_3L^+ \rightleftharpoons H^+ + H_2L$	3.3[29]
Thymine	N(3)-C(4)O/N(1)-C(2)O	$H_2L \rightleftharpoons H^+ + HL^-$	9.90[28], 9.94[27]
Uracil	N(3)-C(4)O/N(1)-C(2)O	$H_2L \rightleftharpoons H^+ + HL^-$	9.46[28], 9.45[27], 9.43[26]

* Hydrogen electrode

heterocycles are treated with electrophiles a number of products may result. However, Izatt, et al.,[10] recently reviewed the stabilities of various complexes of nucleic acid constituents with protons and various metal ions, and their compilation suggests that a particular type of site (e.g., base nitrogen, sugar or phosphate oxygen) might be preferred at a particular pH, but that the exact site used is a matter of conjecture. These results are borne out by the known pK_as of some of these nucleic acid components, Table I. Here a high pK_a implies a high coordinating ability. For example, in adenine, coordination at N(9) is expected, while in uracil, the similarity of the pK_as of N(1) and N(3) make it unclear as to which site would be preferred for metal coordination.

The two sections that follow deal with some of the chemical aspects of solid transition metal coordination compounds of pyrimidine and purine bases, their nucleosides and nucleotides that have appeared in the literature through early 1976. There have been reviews[10,11,30] dealing with the general area of transition metal ion-nucleic acid component interaction, but none has dealt with the solid coordination compounds.[31,32] It is hoped that the present survey reflects the large amount and diversified character of the work that has been done and is being done in this field.

Pyrimidines

Thymine

The first 1:1 solid adducts of thymine and 1-acetylthymine with Hg(II) were reported by Hoffer[33-35] while the first 2:1 (ligand/metal)adducts of thymine with Hg(II) were reported by Fox, et al.[35] These reports gave only synthetic routes to product formation with no chemical properties of the complexes. The first crystal structure of a transition metal complex with thymine, bis(1-methylthymine)Hg(II), was given by Kosturko, et al.[37] This complex was prepared at moderately high pH in aqueous solution. The coordination around Hg(II) is a highly distorted octahedron with the two deprotonated N(3) atoms bonded linearly at 2.04°A and the O(2), O(2)', O(4), and O(4)' atoms bonded in a trans arrangement at approximately 3°A.

Silver-thymine compounds have been prepared and used[36,39] as intermediates for the synthesis of nucleosides. These preparations were carried out in basic solutions with $AgNO_3$ as the starting agent but the products were not well characterized.

Recently, the first example of binding of a pyrimidine base through N(1) was given in a crystal structure determination of an anionic thymine complex with Cu(II) by Kistenmacher, et al.,[40] (aquo)(diethylenetriamine)(thyminato)Cu(II) bromide, $Cu(H_2O)(C_4H_{13}N_3)(C_5H_5N_2O_2)Br$. The coordination sphere about the Cu(II) ion is approximately square pyramidal with the tridentate diethylenetriamine

ligand and the N(1) of the thymine monoanion occupying the four equatorial sites; the coordination sphere is completed by an axially bonded water molecule at 2.465Å. No evidence for a significant axial Cu-O(2) interaction was found. This type of interaction has been noted in N(3) bonded cytosine and cytidine complexes,[41-44] which have a Cu-O(2) distance of about 2.8Å.

The structure of an unusual complex, $K_2Pd_2Cl_6 \cdot 4$(1-propylthymine), made by mixing aqueous solutions of K_2PdCl_4 and 1-propylthymine has been determined by X-ray diffraction[45] and shown to contain $(Pd_2Cl_6)^{-2}$ dimers. However, no evidence for direct dimer base bonding was found.

To date no metal complexes with thymidine and thymidine nucleotides have been characterized by standard chemical analysis, but some[35,46] have been prepared with Hg(II) and used to form intermediates necessary for organic syntheses.

Cytosine

The first unequivocal case of copper-pyrimidine bonding was reported by Carrabine and Sundaralingam[44,47] when the crystal structure of $Cu(cytosine)_2Cl_2$ was determined. The preparation of this compound was essentially the same as that previously reported by Melzer[48] who cited a 5% yield of a 1:1 adduct in addition to a 71% yield of the 2:1 cytosine-copper complex. The coordination about the Cu(II) ion is a very distorted octahedron,[44] with the two chloride ions at 2.29Å and the two N(3) atoms of the cytosine bases

at 1.96Å in a trans square planar arrangement. The two O(2) atoms complete the coordination sphere but are only weakly coordinated, 2.81Å (average) away from the Cu(II) ion.

A series of compounds with the general formula $Cu(L)_4(ClO_4)_2 \cdot nH_2O$, where for L = cytosine, n = 2, and for L = cytidine, n = 4, have been prepared recently.[49] Although crystallographic parameters were given, no base bonding sites were reported.

A novel protonated complex of cytosine was reported by Kindberg and Amma,[50] bis(cytosinium)tetrachloropalladinate(II). The brick red complex was formed by adding equimolar amounts of K_2PdCl_4 and cytosine together at pH 1 (HCl). Here the structure consists of discrete $(PdCl_4)^{-2}$ ions and protonated cytosine rings in a complex network of hydrogen bonds. Each ring is hydrogen bonded to five different square planar $(PdCl_4)^{-2}$ ions and the only contact made between the metal and the ring is through hydrogen bonding via the chloride ion. The polyatomic anion preserves its monomeric integrity, unlike what occurs in the previously presented thymine complex.[45]

Recently, ternary Cu(II) complexes with cytosine and cytidine, and an amino acid (or Shiff base) have been prepared[42,51-54] and their structures determined by X-ray crystallography. The structure of these compounds might be similar to those systems were substantial interactions between nucleic acid, protein, and metal ion should occur (in many instances, enzymes are well known to be activated

by metal ions[55,56]. In the copper(II) glycylglycine complex with cytosine[52] and cytidine,[42] the molecular conformations of the two complexes are nearly identical. The coordination geometry about the copper ion is approximately square planar with the tridentate glycylglycine dianion and the N(3) of the cytosine or cytidine occupying the four coordination sites. Furthermore, the exocyclic oxygen atom, O(2), on the cytosine or cytidine residues is axially located 2.7Å (average) away from the Cu(II) ion, extending qualitatively the coordination geometry to square pyramidal. The presence of this Cu-O(2) interaction in all known square planar copper(II) complexes of cytosine[44,52,54] or cytidine[42] suggests that this type of interaction may be important in the binding of Cu(II) to cytosine residues in nucleic acids. In the Cu(II)-Schiff base complex with cytosine,[54] ((N-salicylidene-N'-methylethylenediamine)(cytosine)copper (II)) nitrate monohydrate, $Cu((C_{10}H_{13}N_2O_2)(C_4H_5N_3O_1))NO_3 \cdot H_2O$, the primary coordination sphere about the copper ion is approximately octahedral with the tridentate Shiff base and N(3) of the neutral cytosine constituting the basal plane. The O(2) of the cytosine ligand and one of the oxygen atoms of the nitrate group are axially located 2.772 and 2.806Å away, respectively, from the Cu(II) ion.

A 1:1 complex of Hg(II) and 5-fluorocytosine,[35] $Hg(C_4H_1N_3O_1F_1)$, has been reported. The complex was prepared by refluxing mercuric acetate and 5-fluorocytosine in methyl

alcohol. The product was poorly characterized. Weiss and Venner[57] noted that Co(II) and Ni(II) only weakly coordinate with cytosine yielding adducts of various stoichiometries, however, these adducts were not characterized.

A series of 1:1 complexes of various transition metal ions with 5'-cytidylic acid[58,59] (5'-CMP), 5'-cytidine diphosphate[60] (5'-CDP), and 5'-cytidine triphosphate[60-62] (5'-CTP) have been isolated and characterized. Ogawa and Sakaguchi[59] prepared crystalline complexes of 5'-CMP with Zn (II), Pb(II), Co(II), Cd(II), and Mn(II). The general procedure employed was to mix aqueous solutions of the metal nitrates with aqueous solutions of the ligands, acidify with dilute HNO_3, and heat gently at 60°C for 10 minutes. Usually, 1:1 stoichiometries were obtained except with Ag(I) and Hg(II) which yielded 2:1 and 3:2 metal to ligand ratios, respectively. Infrared characterization was made by comparing the spectra of the metal complexes with those of the free acid, and alkaline and alkaline earth salts of 5'-CMP. In all instances, metal coordination through the phosphate group was suggested from the infrared absorption band near 980 cm^{-1}. In addition, coordination by the cytosine ring moiety to Hg(II), Co(II), Zn(II), and Cd(II) was assumed from the spectral changes in the 1700-1600 cm^{-1} region.

De Pamphilis and Cleland[60] successfully isolated stable complexes of Cr(III) with a variety of diphospho- and triphosphonucleotides, including 5'-CDP and 5'-CTP, by heating the nucleotides with aqueous chromium(III)

perchlorate at 80°C and pH 3 for 12 minutes and purifying the complexes by ion exchange methods. These complexes, which are stable at acid pH, can be used as dead end inhibitors for elucidating enzyme kinetic mechanisms.[60,63] In the tri- and diphosphate complexes, Cr(III) is bound to all phosphates in each case; no evidence for metal-pyrimidine or metal-sugar bonding is given. The remaining coordination positions are presumably taken up by water. For chromium (III)-5'-adenosine triphosphate, Cr(III)-5'-ATP, a magnetic moment of 3.83 BM was reported at room temperature, consistent with a mononuclear complex. An axial EPR spectrum ($g_{\perp}$=1.97 and $g_{\parallel}$=4.70) was recorded. De Pamphilis and Cleland were also able to isolate a series of Cr(III) complexes having the general formulas: $(Cr(NH_3)_x(H_2O)_y(Z)_z)\ Z_q$, where Z = Br, x = 2, y = 2, z = 2, and q = 1; Z = Cl, x = 3, y = 1, z = 2, and q = 1; Z = Cl, x = 4, y = 1, z = 1, and q = 2. By simply heating these chromium(III) complexes with 5'-ATP and 5'-adenosine diphosphate (5'-ADP) a new series of Cr(III)-ammine-nucleotide complexes could be generated. During the heating process the Br or Cl leaves the coordination sphere, but NH_3 remains. Coordination positions not occupied by NH_3 or nucleotide contain H_2O. The monodentate nature of the nucleotides is implied. The visible absorption spectra of the Cr(III) compounds mentioned above contained two bands, one in the 382-430 nm and the other in the 516-610 nm region. The colors of these com-

plexes were red, green, violet, and red violet. These absorptions are characteristic of formation of inner sphere coordination complexes of Cr(III). Electronic spectra of $Cr(H_2O)_6^{+3}$ in acidic solutions at 100°C with nucleotide were also interpreted for the presence of dimeric and trimeric species. The absorption at 340 nm appears to be a measure of polymers of this type.

Lastly, Dale, et al.,[62,64] have developed a relatively simple synthesis to generate a series of 5-mercurithio derivatives of CTP, dCTP, ATP, and 2'-deoxyuridine-5'-triphosphate (dUTP) which are excellent substrates for polymerases. The general procedure is to prepare the mercuriacetate derivative of the nucleotide first and then convert it to the active mercurithio form by addition of an appropriate mercaptan. The activity of these mercurithio derivatives is due, in part, to the fact that mercury addition by this procedure occurs at C(5) for pyrimidine residues and C(8) for purine residues where addition: (1) does not interfere with the normal Watson-Crick hydrogen bonding potential of the bases and (2) does not alter the normal "anti" nucleoside conformation found in natural polynucleotides.

Uracil

Zn(II), Ag(I), and Cu(II) complexes with uracil have various therapeutic potential as antimicrobial agents[65-66]

and for alleviating viral manifestations.[67] The stoichiometries are 1:1 in the case of Ag(I) complexes, and 2:1 (ligand/metal) in the case of Cu(II) and Zn(II). Also Ag(I) and Hg(II) complexes with uracil and 5X-uracils (X = Br, I, C_2H_5, and NO_2) have been employed as intermediates for organic syntheses.[33,35,38,39,68-72] These intermediate complexes have not been characterized except for elemental analysis.

Gel'fman and Kustova have studied the reactions of Ag(I)[73] and Pd(II)[74] with 5-fluorouracil and isolated adducts of various stoichiometries. Pd(II) diammine and dichloro complexes with 5-fluorouracil[74] were shown to have a trans square planar configuration by means of IR spectroscopy. In addition, a 5-fluorouracil (neutral form) bridged dimer of Pd(II) with NH_3 and Cl was postulated on the basis of elemental analysis.

The structures of bis(uracil)mercuric chloride, $Hg(C_4H_4N_2O_2)_2Cl_2$, and bis(dihydrouracil)mercuric chloride, $Hg(C_4H_6N_2O_2)_2Cl_2$, have been determined by Carrabine and Sundaralingam.[75] The translucent crystals were prepared by slow evaporation of a 2:1 ligand to $HgCl_2$ solution (pH = 4). The quantities of uracil and dihydrouracil used were 10mmoles and 1mmole, respectively, in a total of 2ml of solution. Both complexes involve two long trans Hg-O(4) bonds (2.8Å), two long Hg-Cl bonds (3.06Å) and two short Hg-Cl bonds (2.3Å). The octahedrally bound Hg atoms are

held together by Cl bridges, and the O(2) atoms are involved in intermolecular hydrogen bonding between ligand molecules. Mansy and Tobias[76] have recently used IR and Raman spectroscopy to fingerprint uridine mercuriated at C(4)O, C(5), and N(3) in aqueous solution.

The pH of the complexing medium seems to play an important role in determining where Hg(II) will coordinate. It appears that under acidic, neutral, and basic conditions, Hg(II) will bond to uracil residues preferentially at C(4)O,[75] C(5),[62,64] and N(3),[77] respectively.

Metal-UMP[78] (Metal- 5'adenylic acid) and Metal-UTP[61] (Metal-5'adenosine triphosphate) complexes have been isolated. Although no work was done to characterize the Fe(III)-UTP complexes[61] further, the UMP complexes of Zn(II), Ag(I), Pb(II), and Cd(II)[78] (the Ag(I) complex was 1:3 ligand/metal) were characterized by elemental analysis and IR spectroscopy. The general procedure used to prepare these complexes was to add a solution of the metal nitrate to a solution of Na_2UMP, heat gently and allow it to evaporate slowly at a pH between 4.8 and 6.8. The IR data indicated that in all cases coordination was through the phosphate group and in the case of Pb(II) and Ag(I) also through the C(4) or C(2) carbonyl group.

2-thiouracil and its 6-alkyl homologues were shown to have enhanced antithyroid activity,[79,80] and much interest has been generated in an effort to prepare metal complexes

with these ligands.[81-86] Libermann[81,82] was the first to report the formation of a metal complex when a series of 6- and 5,6-substituted 2-thiouracils were reacted with Co(II), Zn(II), Fe(II), Mn(II), and Cu(II) (Ce(II) did not react). The complexes were generated by mixing a saturated solution of the ligand with a solution of the metal salt (usually the chloride or sulfate). In the case of Cu(II), the complexation with 2-thiouracil led to a drop in the filtrate pH. On the basis of this observation and solubility constant limits, a 1:1 complex with 2-thiouracil involving the C(2)S and C(4)O was postulated. Similar bidentate chelation is presumed for the other metal complexes, however, their stoichiometries were not given. The nature of the metal interaction in 2:1 (ligand/metal) complexes of 6X-2-thiouracil (X=H, C_3H_7) has not been clearly elucidated. Weber[84] presumed that the ligand was monodentate and involved the C(2)S or C(4)O when complexed with Cu(II).

Khullar and Agarwala[85,86] have done detailed spectroscopic work on complexes made with a variety of metal ions and 2-thiouracil. In all cases, except Pt(II), the data shows that the coordination is simultaneously via S and N atoms. A large amount of work on solid complexes of 2,4-dithiouracil with transition metal ions has recently emerged.[87-89] Dimer and trimer metal complexes have been postulated on the basis of elemental analysis and spectroscopic evidence. In all cases, coordination through an

S and N atom were postulated from IR data and very often polymeric species involving a bridging dithiouracil ligand were presumed from solubility and IR measurements. In particular, the Cu(II) complex involved a tridentate form of the ligand which permitted extensive, random polymerization throughout the crystal lattice.

Lastly, a crystal structure determination of chlorobis (2-thiouracil)Cu(I) dimethylformamide solvate was recently reported.[90] This compound was prepared by the addition of solid 2-thiouracil to 0.2M $CuCl_2$ at 70°C. The insoluble product was recrystallized from DMF to give yellow octahedral crystals. Apparently a redox reaction ensued reducing Cu(II) to Cu(I). The structure is nearly planar with Cu(I) trigonally coordinated by two C(2)S atoms and the chloride ion. The DMF is filling a gap in the crystal lattice. The C-S distance of 1.60Å (average) and the C-O distance of 1.22Å (average) indicate the existence of double bonds.

It becomes apparent from the discussion that there are a variety of possible bonding modes (i.e., monodentate, bidentate, and tridentate) as well as possible bonding sites found in solid complexes of metal ions with nucleic acid constituents. The actual bonding site(s) used by these ligands was shown to be a function of reaction conditions (i.e., pH, temperature, reagent stoichiometries, etc.). A compilation of the bonding sites found in solid

transition metal compounds containing pyrimidine residues is given in Table II.

Table II

Ligand Bonding Sites Found in Solid Transition Metal Coordination Compounds of Pyrimidine Residues

	Ligand	Bonding Site(s)	Metals	pH
A)	1. Thymine	--**		
	2. 1-methy thymine	N(3)[37]	Hg(II)	Basic
		N(1)[40]	Cu(II)	Basic
	3. Thymidine	--		
	4. TMP*	--		
	5. TDP*	--		
	6. TTP*	--		
B)	1. Cytosine	N(3)[44,52,54]	Cu(II)	--***
	2. Cytidine	N(3)[42]	Cu(II)	--
	3. CMP	Ring/Phosphate[59]	Hg(II), Co(II), Zn(II), Cd(II)	Acidic
		Phosphate[59]	Pb(II), Mn(II), Ag(I)	Acidic
	4. CDP	α,β Phosphates[60]	Cr(III)	Acidic
	5. CTP	α,β,γ Phosphates[60]	Cr(III)	Acidic
		C(5)[62,64]	Hg(II)	Neutral
C)	1. Uracil	C(4)O[75]	Hg(II)	Acidic
	2. 2-thiouracil	C(2)S[90]	Cu(I)	--
	3. Uridine	--		
	4. UMP	Ring/Phosphate[78]	Zn(II), Cd(II), Ag(I), Pb(II)	Acidic
	5. UDP*	--		
	6. UTP	C(5)[62,64]	Hg(II)	Neutral

* Abbreviations: TMP (5'-thymidine monophosphate)
TDP (5'-thymidine diphosphate)
TTP (5'-thymidine triphosphate)
UDP (5'-uridine diphosphate)

** Indicates no transition ion coordination compounds isolated to date.

*** Indicates that the information regarding pH conditions employed was not determined or undeterminable.

Purines

Purinic ligands provide a variety of complexation modes when combining in acidic, neutral, or basic solutions and crystallographic and other studies have shown them to possess the capability to use a number of sites for bonding. In addition, these ligands have been found in complexes involving one, two, and three metal centers.

The earliest reports of solid adducts with purine residues were a Au(III) complex with guanine[91] and a series of metal(II) complexes with 5'-adenylic acid[92] (5'-AMP) and 2,8-dichloroadenine.[93] Although the metal complexes were not well characterized both monomer[91,92] and trimer[92] stoichiometries were assumed on the basis of chemical analysis.

The purine bases have been the basis for much of the information accrued on metal-nucleic acid base complexes. Adenine has been studied more extensively than any purine base to date.

Adenine

Venner and Weiss have contributed heavily to the syntheses of metal complexes with purine residues especially with adenine and substituted adenines.[94-98] These authors and others,[61,78,82,91-93,96,99-113] however, have not proceeded with further chemical characterization of these coordination complexes.

Colaitis and Brigando[114-120] have synthesized several cobalt complexes with adenine and adenosine and have studied their electronic properties using UV-Vis and IR spectroscopy, and magnetic susceptibility measurements.

Complexes with adenine[114,118] having the general stoichiometry $M(L)(OH)_2 \cdot nH_2O$, where M = Co(II), (I), or Co(III), (II), were isolated and a spectral study performed. Compound (I) was prepared by adding a solution of NaOH slowly with stirring to an equimolar mixture of $CoCl_2$ and adenine under N_2 and collecting the rose-colored precipitate that falls out at pH 7.4. Compound (II), a dark brown-green product, was prepared by air oxidation of a basic solution of (I). Magnetic measurements were performed over the range 79-271°K. Compound (I) had an effective moment of 4.64BM indicating 3 unpaired electrons, while (II) had an effective moment of 2.77BM indicating 2 unpaired electrons. The charge on the ligands was established by means of the UV bands at 268nm of neutral adenine in compound(I), and at 260nm of anionic adenine in compound(II). Compound (I) shows 2 absorptions in the visible region at about 510 and 350nm, while in compound (II) only 1 absorption near 350nm was seen. On the basis of visible absorption and magnetic susceptibility data, the electronic configurations for compounds (I) and (II) were postulated as $4s4p^3$ and $3d4s4p^2$, respectively. In both cases chelation to the adenine moiety through N(10) and N(7) was presumed on the basis of IR

spectroscopy from a large perturbation of the out-of-plane vibrations of the N(10) amino hydrogens. The remaining two coordinate bonds were from the hydroxyl groups.

Polynuclear complexes with adenine[115,117,118], adenosine[116,118-120], and ATP[116] have been synthesized and characterized. The conditions for formation of a particular stoichiometry with any of the ligands depend on temperature as well as heating time. The typical preparation consisted of mixing adenine with $Co(NH_3)_5Cl_2$ in an aqueous solution with heating. Two series of trimetallic Co(III) complexes were obtained, one with 2 adenines and the other with 3. In all cases the ligand is in the anionic form (from UV measurements) with the Co(III) octahedrally coordinated. Bridging ligands are assumed to be NH_2 or NH_2 and OH groups, and the purine ligand is presumed to bind through the amino nitrogen N(10) and N(7) on the basis of IR data. A plateau at about 580nm in the visible spectra is consistent with octahedrally coordinated Co(III) complexes. A Co(III)-ATP dimer was also synthesized and characterized.[116]

Reactions of heavy metals with purine residues have been suggested for sequencing of nucleic acids by electron microscopy and X-ray crystallography,[62,121] for possible use in the elucidation of enzyme mechanisms,[60] and as an effective method of precipitation for nucleic acid constituents.[100]

Gibson, et al.,[100] synthesized a series of potassium

salts of Au(III) adducts with various adenine nucleotides by reacting mixtures containing various amounts of chloroauric acid, $HAuCl_4$, at various pH+pCl with the desired nucleotide. Brown adducts were isolated by addition of ethanol and appeared to be polymerized because of N→Au←N bridges. The potassium salts of gold-adenine nucleotides are rather soluble, yet the gold adducts with adenine and adenosine are insoluble.

The preparation and properties of a large series of Cr(III) complexes with nucleotides was reported by DePamphilis and Cleland,[60] and a discussion of the synthesis and characterization of 7-mercuriacetate derivatives of 7-deazaATP[62] was described in the previous section on pyrimidine nucleotide complexes (p.16).

The report that certain platinum complexes[122-124] have antitumor and antibacterial activity has prompted interest in synthesizing platinum complexes with nucleic acid constituents. Theophanides, et al.,[125,126] have isolated and characterized a series of complexes having the general formula, trans-$(Pt(Purine)_2X_2)$, where the purine is adenine, adenosine and acetyladenosine, and X is Cl and Br. The halide ion was shown to be in the first coordination sphere by conductivity, halide titration, and IR data. The general procedure[126] used to prepare the complexes was to dissolve the ligand (6:1 ligand to metal) in an HX acid solution with K_2PtX_4 with gentle heating. Yellow products appeared within

3-5 hours. The synthesis of the acetyladenine complexes required dissolution of ligand in a non-aqueous solvent like DMF or acetonitrile and a longer heating time. Attempts to substitute the halide ion with NO_3 or ClO_4 were unsuccessful. All systems were diamagnetic at room temperature. The band at 262nm in the UV spectrum of adenosine shifts in position to the 255-300nm range upon complexation. A <u>trans</u> configuration is presumed on steric grounds and from a sharp peak in the far IR at 340cm^{-1}. The binding site used is N(1) or N(7); participation by N(10) was ruled out because of the presence of the free N-H stretch at about 3300cm^{-1} and NH_2 deformation at 1600cm^{-1} in the IR spectrum. The lone pair of electrons of the $-NH_2$ group in the acetyladenosine is not available for bonding with the metal because it participates in the ring, as shown by the high C-N stretching frequency

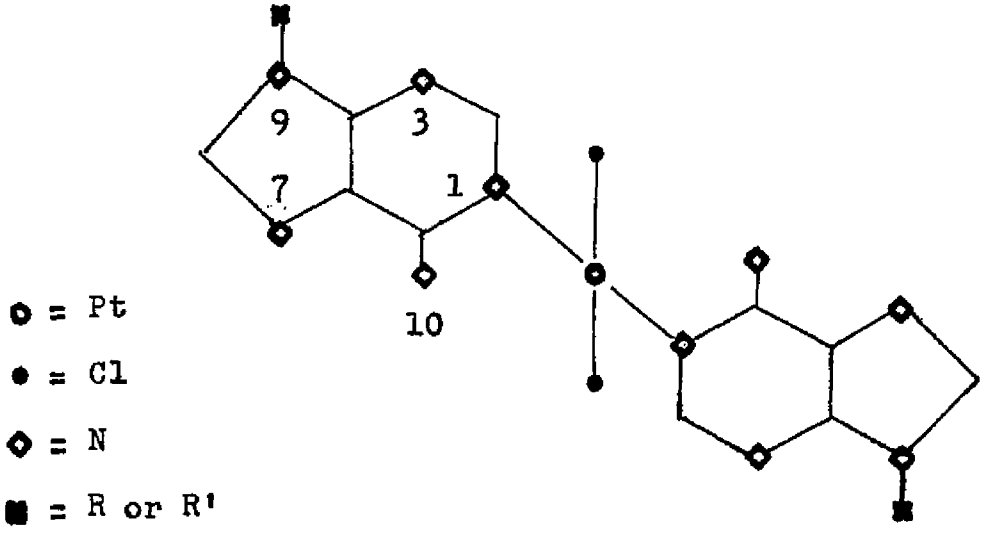


Fig.2.- Possible structure of the platinum-dipurine complex with the metal linkage through N(1). A linkage through N(7) is also possible. R=H, $-COCH_3$, R'= D-ribose (adenosine) or R=H, $-COCH_3$, R'=H (adenine)[125-6]; X=Cl, Br

of the C-NH_2 vibration at 1215cm^{-1}. Also, IR measurements showed that the sugar hydroxyls do not interact with the metal. NMR data support N(1) or N(7) binding. Possible structures for the trans platinum complexes are shown in Fig. 2.

Roos, et al.,[127] used mass spectrometry to elucidate the binding capability and bonding sites of a series of nucleoside analogues (including 9-methyladenine and 9-methylguanine) to cis- and trans- $Pt(amine)_2Cl_2$ complexes. The general synthetic procedure was to react equimolar quantities of the platinum-amine complex and ligand for about 14 days and then reduce the volume by a factor of 10 to obtain the product. The mass spectrum yielded extremely useful information concerning binding capacity: in the cis isomer the 9-methyladenine ligand appears to be monodentate, while the 9-methylguanine appears to be bidentate. The efficacy of cis-$Pt(amine)_2Cl_2$ complexes against tumors might be the result of preferential and selective bidentate binding of the guanine residues[128] in tumor DNA to the platinum complex thereby disrupting DNA synthesis leading to tumor death. Supporting evidence for the N(7)-N(10) bidentate capability of guanine residues comes from phtoelectron spectroscopy measurements[129] on complexes of various purine residues with the $Pt(amine)_2Cl_2$ systems. These results, however, are in contrast with NMR studies by Kong and Theophanides[130] where data reveal only N(7) binding by guanosine, inosine, and xanthosine in $(Pt(A)_2(L)_2)Cl_2$ compounds, where L = nucleoside and A = NH_3,

1/2 en, and pyridine.

IR studies with metal-adenine and metal-adenine nucleotide complexes[131-133] have helped elucidate coordination sites on the ligand. The metal nucleotide complexes (1:1 generally) are prepared in acidic solution by mixing equimolar amounts of the Na_2nucleotide and metal nitrate salts. ATP yielded Th(IV) and Ag(I) products containing metal to ligand mole ratios of 1:2 and 3:1, respectively.[133] The areas of interest in the IR are the 1600-1700cm^{-1} region (the adenine ring) and the 900-1200cm^{-1} region (the phosphate group(s)). Comparison to the free nucleotide and/or sodium salts of the nucleotide are generally used as the basis of comparison. Hg(II), Cd(II), and Pb(II) appear to shift the ring C = N stretching frequency from 1690cm^{-1} to 1705cm^{-1} upon complexation with little change in the 900-1200cm^{-1} region. These results suggest coordination exclusively via the nitrogen atoms on the purine ring and is consistent with the high complexation tendency of these metals with nitrogen bases. Although evidence[133] suggests that N(1) is protonated during complexation, the particular site of coordination on the adenine moiety has still to be determined in these complexes. Fe(III), Al(III), UO_2(II), ZrO(II), Ag(I), and Th(IV) coordination appears to alter absorptions in the 900-1200cm^{-1} region indicating phosphate interaction.

A large amount of crystallographic work with adenine[134-144]

and its nucleoside analog, 9-methyladenine[145-150] has been reported over the last few years, and a short crystallographic review by Sletten[30] on copper(II) complexes with purines has appeared recently. In addition, adenine has been incorporated in a series of mixed ligand complexes with ethylenediamine,[151,152] Schiff bases,[153] amino acids,[51] and 2,2'-bipyridine.[154] The first reported crystallographic determinations of metal complexation with adenosine,[155] 5'-AMP,[156] and 5'-ADP[157] have been elucidated only a short time ago.

Dimeric Cu(II) complexes with the copper acetate[158] and copper succinate[159] structure have been prepared with both the neutral[137,141] and anionic[136] adenine. The basic dimeric unit of these complexes is shown in Fig.3, where the purine ligand bonds via N(3) and N(9), and N(7) may[137,141] or may not[125] be protonated. The apical ligands may vary. The coordination around each Cu(II) ion approaches a square pyrimidal geometry

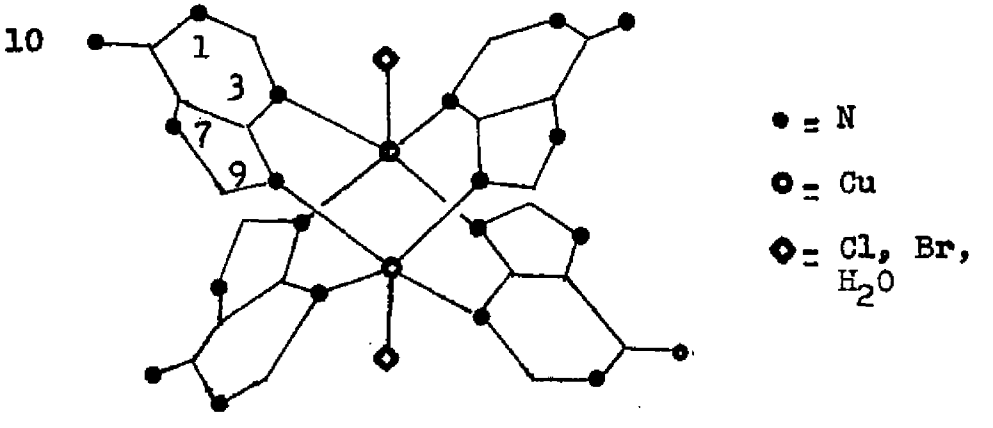


Fig.3. - Cu(II)-purinic dimer unit having the copper acetate structure. Purine may be adenine or hypoxanthine; apical ligand may be Cl, Br, H_2O.

with a Cu-Cu distance of about 2.950Å. Recent magnetic measurements on a number of these systems[154,160-164] (including hypoxanthine) strongly suggest that the anti-ferromagnetic coupling observed is due almost exclusively to spin pairing via a superexchange mechanism[165] through the π system of the bridging ligand. The strength of the spin pairing is markedly influenced by the charge on the bridging ligand and not in the apical ligand. For example, the anionic, inner complex, $Cu_2(Ad)_4(H_2O)_2$, and the neutral complex, $Cu_2(AdH)_4(H_2O)_2$, have the same Cu-Cu distance (2.95Å), yet the exchange parameter, 2J, is different for each being -210[162] and -302[164] cm^{-1}, respectively. 2J represents the energy difference between the singlet and first excited triplet state; the negative sign means the singlet state is the ground state. Table III contains the magnetic parameters (including 2J) found in solid Cu(II) dimer complexes with purinic ligands. Data on a new series of halogen bridged (halogen = F, Br, Cl(anhydrous)) Cu(II) guaninium dimers[220] are also included. Jezowska-Trzebiatowska and Kozlowski[168] have related the character of this bridge to the hyperfine coupling constants found from EPR measurements for $Cu_2(Ad)_4(H_2O)_2$ and $Cu_2(AdH)_4Cl_4$.

The retention of purine bridges even in the presence of halide ions, which themselves function as excellent bridges, indicates a high preference for the dinuclear configuration under these conditions. However, the crystal structure of a novel trinuclear Cu(II) complex with adenine and halogen

Table III

Magnetic Parameters Found in Solid Cu(II) Purinic Dimers

Basic Cu(II) Dimer Unit***	$-2J$ (cm^{-1})	g_{xy}	g_z	g_{av}**	A_z (G)	A_{xy} (G)	E (cm^{-1})	D (cm^{-1})	Cu-Cu_o Distance (Å)
1. Adenine (LH) $(Cu(LH)_2X)_2$									
$X=H_2O$ [163]	300±60	2.05	2.22	-	21*	95*	.03	.110	2.951 [137]
H_2O [164]	302	-	-	-	-	-	-	-	
H_2O [222]	300±60	2.045	2.27	-	-	-	-	.111	
$X=Cl$ [168]****	-	2.065	2.30	2.24	-	58	-	.083	3.066 [141]
Cl [221]	275	2.049	2.29	-	-	-	-	.112	
Cl [213]*****	-	2.05	2.17	-	-	-	-	.094	
			2.23					.096	
$X=Br$ [213]*****	-	2.05	2.17	-	-	-	-	.094	-
			2.23					.096	
Br [221]	280	2.046	2.27	-	-	-	-	.115	
$(Cu(L)_2X)_2$									
$X=H_2O$ [222]	160±60	-	-	-	-	-	-	.121	2.949 [136]
H_2O [168]****	-	2.053	2.50	2.20	-	48	-	.115	
H_2O [163]	160±60	2.05	2.19	-	21*	87*	.03	.121	
H_2O [162]	210	2.03	-	-	-	70	-	.125	
2. Guanine (LH) $(Cu(LH_2)_2X_3)_2$									
$X=Cl$ [185]	99	-	2.20	2.18	-	-	-	.023	3.7 [185]
Cl [220]	99	2.11	2.01	2.07	-	-	-	.08	
Cl [183]	82.6±1	-	-	2.12	-	-	-	-	3.575 [183]

Table III (Cont'd)

Basic Cu(II) Dimer Unit***	-2J (cm^{-1})	g_{xy}	g_z	g_{av}**	A_z (G)	A_{xy} (G)	E (cm^{-1})	D (cm^{-1})	Cu-Cu_o Distance (Å)
Cl(anhydrous)[220]	55	-	-	2.10	-	-	-	.050	-
F[220]	15	2.19	2.01	2.14	-	-	-	.018	-
Br[220]	310	-	-	-	-	-	-	.30	-
3. Hypoxanthine (LH)									
$(Cu(LH)_2X)_2$									
X=Cl[166]	240	2.051	2.28	-	-	-	-	.096	3.024[197]
Br[221]	245	2.049	2.28	-	-	-	-	.097	-
$(Cu(L)_2X)_2$									
$X=H_2O$[222]	265	2.047	2.27	-	-	-	-	.102	-

* $1G=0.933 \times 10^{-4} cm^{-1}$
** g represents the relative spin and orbital contributions to the total angular momentum of the electron.
*** the counterion and waters of hydration omitted for convenience.
**** A value given unqualified.
***** range of g and D values given only.

bridges was reported by DeMeester, et al.,[134] Fig. 4. The trinuclear complex was isolated from a 2M HCl solution.

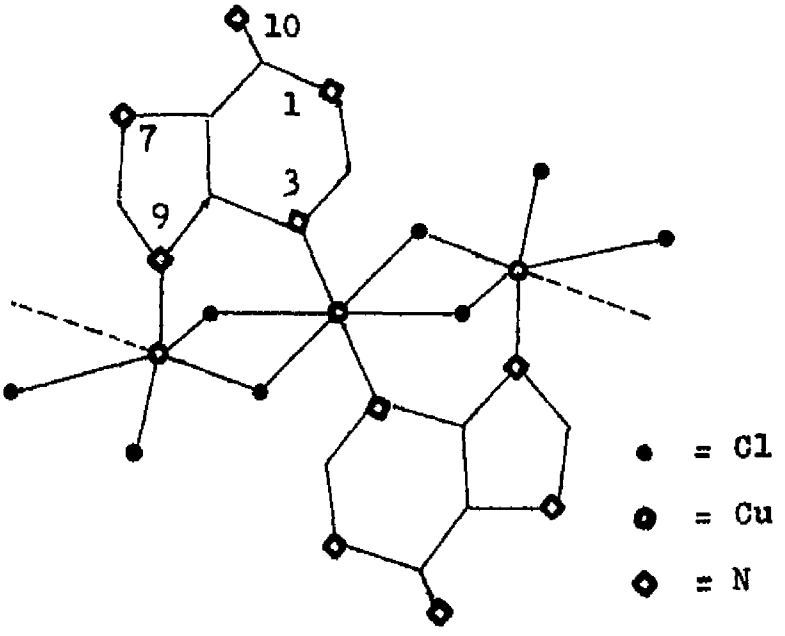


Fig.4. - Crystal structure of $Cu_3Cl_8(AdH_2)_2 \cdot 4H_2O$.[134]

The adenine carries a net positive charge, as it is protonated at both N(1) and N(7). The metal ion separation has increased to 3.479Å. The central copper ion can be considered six-coordinate with four bridging chloride ions, and two N(3) atoms from the bridging adeninium ions completing the octahedron. The terminal copper ions are effectively five-coordinate with four chloride ions, and an N(9) atom from the bridging adeninium ion completing the square pyramid. All the magnetic data on this complexare consistent with a magnetically dilute system with no Cu-Cu interactions since the magnetic moment at room temperature is 1.86BM and the

EPR spectrum merely shows a signal in the g = 2 region.[134,168]

With zinc and cobalt, adenine residues are found to form complexes that bind through N(7),[138] and N(1) and N(7).[148] The latter complex consists of infinite chains in which tetrahedrally coordinated cobalt ions are linked by 9-methyladenine bridges. This is the first example of metal-N(1) bonding reported to date. The site preference for mononuclear complexes, however, appears to be N(9),[140,143] or N(7)[146,156] if the 9 position is bound to another group in the free ligand (e.g., a sugar group[156] or a methyl group[146]).

The crystal structure determination of an osmium(IV) ester of adenosine[155] is of considerable interest since it shows no coordination through any nitrogen atom in the adenine ring. The brown complex of bis(pyridine)(adenosine) osmate(IV) was prepared by dissolving $OsO_3(py)_2$ and adenosine in a small volume of water-pyridine (2:1 v/v) and kept for several hours at 4°C in the dark. The osmium ion binds as an osmate ester to the 2'-3' <u>cis</u> diol of the adenosine sugar molecule, and the entire complex assumes an octahedral coordination with the two osmyl groups <u>trans</u> to one another. The ability of osmium to bind exclusively with the 2'-3' <u>cis</u> diol function in the ribose moiety is interesting since Berger, <u>et al.</u>,[167] reported that in the presence of the copper acetate dimer RNA polymerase was able to "recognize" ribonucleotides (as opposed to deoxyribonucleotides). Presumably, the Cu-Cu distance is about

the right size to accomodate the cis 2'-3' oxygen atoms of the ribose sugar with the result that the metal complex is oriented in a fashion more favorable for action by the polymerase than the uncomplexed ribonucleotide.

Lastly, a series of mixed ligand complexes of adenine residues with some nitrogenous chelates[51,151-154,168] has been prepared and characterized in the hope of elucidating the effects of specific interligand interactions[151-153] on a metal's selectivity toward a particular nucleic acid base as well as the role metal ions play in protein synthesis.[51]

Kistenmacher, et al.,[151,152] utilized a stereospecific reaction[169] which exhibits base selectivity and proceeds only in the presence of adenine. The reaction is

$$\text{trans-}(Co(en)_2Cl_2)^{+1} + \text{adenine} \rightarrow \text{cis-}(Co(en)_2Cl(\text{adenine}))^{+2} + Cl^-$$

where en is the bidentate ethylenediamine ligand.

The structure of cis-$(Co(en)_2Cl(\text{adenine}))Br_2$[152] was carried out. The coordination about the Co(III) is approximately octahedral with the six coordination sites occupied by the four nitrogen atoms of the two ethylenediamine molecules, the chloride ion, and the N(9) of the adenine anion. The adenine ring has positioned itself in such a way as to maximize the hydrogen bonding to the N(11) and N(13) atoms of the ethylenediamine ligands, and to minimize the intramolecular repulsion with the ethylenediamine ligands or the

chloride ion. It seems that intramolecular hydrogen bonds are important features that indeed play a role in determining the molecular conformation of the complex ion, and may play an important role in the future understanding of metal-promoted recoiling of nucleic acids.[170]

Sakaguchi and Tanno prepared[171] and studied[51] the ternary coordination complex, adenine-glycylglycine-Cu(II) which can be used as a simple model compound for the investigation of nucleic acid-protein-metal ion interaction. Blue single crystals of the complex were obtained by dissolving Cu(II)-glycylglycinate and adenine in 30% aqueous ethanol in a 1:1 mole ratio with gentle heating for 30 minutes followed by slow evaporation at room temperature. Tomita, et al.,[223] have determined the crystal and molecular structure of this compound and have shown that the geometry is square pyramidal with atoms N(1), N(4) and O(8) of the glycylglycine anion and N(9) of the adenine molecule in the plane and the water molecule axially located approximately 2.3Å from the metal. This 4 + 1 geometry has been seen in many copper systems[134, 136,137,141] although the 4 + 2 geometry was considered the preferred conformation until recently.

Guanine

Numerous synthetic conditions for metal-purine complexes have been developed including those with guanine[91,96,172-175] and guanine residues,[172] but spectroscopic methods have only

recently been employed in an effort to characterize them.[127,130,139,176-186]

Sundaralingam and Carrabine[44] performed an X-ray determination, which was later reconfirmed by Declercq, et al.,[182] on the dimeric trichloroguaninium copper(II) complex, $(Cu(GuanH_2)Cl_3)_2 \cdot 2H_2O$. Yellow brown crystals of the complex were prepared by dissolving 1·1 mmoles of guanine in an excess of concentrated HCl and adding this solution to an aqueous solution of 4·7 mmoles of $CuCl_2 \cdot 2H_2O$. The resulting solution is allowed to boil for 25 minutes with a concomitant decrease in volume at which time precipitation begins. The complex in the hydrated form is undoubtedly the one prepared by Venner and Weiss[95] when they reported the synthesis of (Guanine)$CuCl_2 \cdot HCl$. The chlorine-bridged complex, consisting of two units related by a center of inversion, is shown in Fig. 5. The penta-coordinate copper ion is bonded directly to the N(9) of the guaninium moiety and four chloride ions

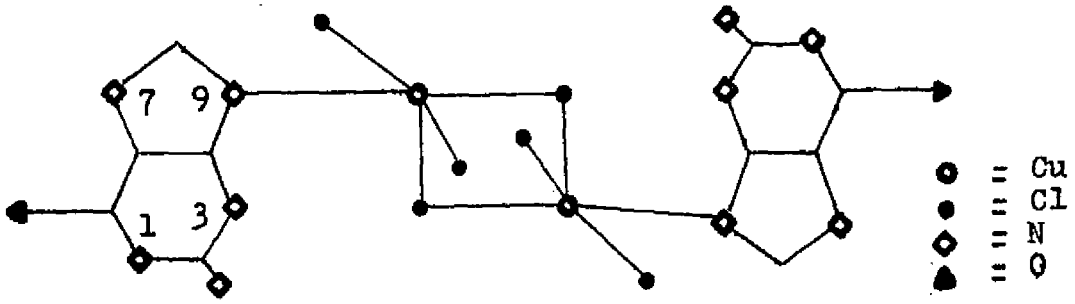


Fig. 5. - Crystal structure of the dimeric trichloroguaninium copper(II) complex.[44]

approaching a trigonal bipyramid arrangement. The guanine ring is protonated at both N(3) and N(7). The apparent

preferential binding of copper to N(9) does not preclude N(3) or N(7) binding in cases where N(9) is blocked,[127,180,184] but the lack of involvement of the amino group in either proton or metal binding indicates that this group is unlikely to participate in metal binding. Indeed, crystal structures for copper with adenine (see Table IV at the end of this section) and cytosine (see Table II at the end of the previous section on pyrimidines) support this contention.

The X-ray crystal structure of the zinc trichloroguaninium complex has been determined,[139] but is composed of discrete, monomeric units. The complex was prepared according to the method of Weitzel and Spher[173] by slow evaporation of a 2:1 mixture of zinc chloride and guanine in acid solution. Here the zinc is tetrahedrally coordinated to three chloride ions and an N(9) bound guanine residue protonated at N(3) and N(7).

Villa,[185] and later Drake, et al.,[183] studied the magnetic properties of the trichloroguaninium copper(II) dimer, Fig. 5. Variable temperature susceptibility measurements[183] from 293 to 1.6°K were conducted on a powdered sample of the complex. After correcting for a small amount of monomeric impurity a near perfect fit to the modified Van Vleck equation[187-190] for exchange coupled dimers was obtained with $2J = -82.6 cm^{-1}$ and $g = 2.12$. The sign of 2J, the energy separation between the ground state and first excited triplet state, indicates that the singlet configuration for the dimer is the ground

state with an excited state 82.6cm^{-1} higher in energy. The large Cu-Cu separation of 3.58Å precludes spin interactions through space since direct orbital overlap over this distance is extremely small. The interaction must therefore occur via superexchange through the chloride bridge. Although the EPR spectrum at 77°K is poorly resolved due to dipolar interactions caused by the significant population of the triplet excited state, a "half field" band from the $\Delta M_s = \pm 2$ transition of a triplet species was observed around 1500G at X-band frequency.[183,185]

DeMeester, et al.,[184] reported the X-ray crystal structure of a Co(III) complex with 5'-guanylic acid (5'-GMP), $(Co(GMP)(H_2O)_5) \cdot 3\ H_2O$. The structural determination indicates exclusive binding of the metal ion to N(7). The remaining 5 positions of the octahedrally coordinated cobalt ion are taken up by water molecules. There is no phosphate interaction at all. This result contrasts those obtained by Ogawa and Sakaguchi[191] on a very similar complex with a smaller number of coordinated water molecules. They suggested coordination via a nitrogen atom in the ring and an oxygen atom in the phosphate group on the basis of IR measurements. Apparently, the loss of water resulted in a transformation in the molecular crystal with the result that ring and phosphate coordination to the metal could be construed from IR data.

Hypoxanthine, Xanthine, and Theophylline

Although these purinic systems are not actual constituents of nucleic acids they are very similar to the biological purines. The amount of synthetic work on these and related systems[91,94,96-98,102,173,174,192-196] is more extensive than the work performed in order to characterize their metal complexes.[130,131,147,184,197-213]

Sletten determined the crystal structure of a dimeric Cu(II) complex with neutral hypoxanthine, $(Cu(HypoH)_2Cl)_2Cl_2 \cdot 6H_2O$.[197] The deep turquoise dimeric complex was prepared from an HCl (pH 4) solution of hypoxanthine and cupric chloride in 2:1 molar proportions.[174] The coordination about the copper ions is approximately square pyramidal with two N(3) and two N(9) atoms from the four neutral hypoxanthine molecules comprising the plane around each copper(II) ion with a chloride ion completing the geometry in the apical position. Its structure is analogous to the Cu-Adenine complex, Fig. 3, with a Cu-Cu distance of 3.024Å and is 0.042Å shorter than the corresponding distance in the adenine analog.[141] Chemically the "bite" of hypoxanthine and adenine should be almost identical. Although crystal structures of inner complexes with adenine[136,137] where the apical ligand is water rather than a chloride ion have been determined, a similar complex with hypoxanthine has not been characterized.

Goodgame and Waggett[213] have examined the copper-hypoxanthine dimer where the axial ligand is Cl and Br and

analyzed them in terms of an S = 1 spin configuration for spin coupled Cu(II) ions. Villa, et al.,[166,221] have carried the magnetic measurements further and extracted 2J values from EPR measurements for $(Cu(LH)_2X)_2X_2$, where LH=neutral adenine and neutral hypoxanthine and X = Cl and Br. These values are given in Table III, p. 31. Here the apical ligand apparently has little influence on the coupling mechanism which is through the hypoxanthine residues. The smaller magnitude of 2J values noted here as compared to those for the analogous adenine complexes[221] are most likely the result of a favorable electronic system in the adenine residues as compared to the hypoxanthine residues. This allows a more effective coupling to occur. The axial and briding ligands and not the Cu-Cu separation are critical factors since overlap between metal orbitals is not expected to be important at a distance of approximately 3Å.

Coordination by hypoxanthine residues where N(9) is blocked with methyl or sugar groups is more relevant to biological systems since in naturally occuring nucleosides and nucleotides N(9) is blocked by a ribose function. Also, since N(3) has never been used by itself as a complexation site (See Table IV at the end of this section, p. 45) and N(1) is protonated, complexation with N(7) becomes the most likely site for coordination. The proximity of C(6)O to N(7) does not preclude chelation of a metal with either of these two sites in N(9) substituted hypoxanthines. In fact, chelation

with both sites has been implicated on the basis of photoelectron spectroscopy measurements,[129] to explain the strong anti-tumor activity of cis-($Pt(NH_3)_2Cl_2$).

Crystal structures of an N(7) bound Cu(II) complex with 9-methylhypoxanthine[147] as well as 1:1 metal complexes of 5'-IMP (hypoxanthosine monophosphate or inosine monophosphate) with Co(II),[184,210] Ni(II),[210,214] Zn(II),[211] and Mn(II)[215] have been reported. The 1:1 metal nucleotide complexes are generally prepared by mixing equimolar amounts of the disodium salt of the ligand with the metal nitrate in water and adjusting the pH to between 3 and 6.

Aoki,[210] and Clark and Orbell[214] reported that the coordination geometries about the nickel and cobalt ions are similar to the ($Co(GMP)(H_2O)_5$)$\cdot 3H_2O$ complex,[184] octahedrally coordinated by the five oxygen atoms of the five water molecules and the N(7) atom of the hypoxanthine ring of IMP. A notable feature of the metal coordination in these complexes is that the metal is not directly attached to the phosphate oxygen atoms[184,210,214,215] as is found in the crystal structure of calcium thymidylate[216] and disodium ATP.[217] Reports of simultaneous metal-phosphate and metal-nitrogen bonding have been reported with Co(II) and Ni(II)[201] with IMP, however, the overall stoichiometries contained fewer water molecules than those reported by other experimenters.[184,210,214]

The crystal structure of the tetrahedrally distorted polymer, $(Zn(IMP))_n$,[211] indicates a different type of bonding where the Zn(II) ion is coordinated by one N(7) atom from one IMP molecule and three oxygen atoms from three different IMP molecules. A structure of the type (M(nucleotide) $(H_2O)_5$) is very likely to exist in solutions as well as in the solid state, but the polymeric structure of the zinc complex cannot, of course, be retained to a large extent in dilute solutions. However, with very large molecules such as nucleic acids, local conditions may approximate those in the solid state in that from the viewpoint of an individual metal ion a set of potential ligand atoms is spatially relatively fixed, though not completely rigid. Therefore, the base binding and the apparent capability of zinc for multiple phosphate bonding to the exclusion of coordinated water may be significant pointers to behavior in more complex systems.

Lastly, crystallographic works involving theophylline have just recently been reported[203,205-207] by Kistenmacher, et al., to elucidate how interligand hydrogen bonds may in some cases impart selectivity to the reaction of metal complexes of ethylenediamine,[205-207] or Schiff bases[203] with purine or pyrimidine bases, their nucleosides and nucleotides. Particularly, in trans-(theophyllinatochlorobis (ethylenediamine)Co(III)) chloride dihydrate[207] the geometry about the metal center in the cation is a distorted

octahedron with the four nitrogen atoms from the two ethylenediamine ligands constituting the basal plane and the chloride ion and N(7) from the theophylline monoanion completing the coordination sphere in the axial positions. The Co-Cl, Co-N (ethylenediamine), and Co-N(7) distances agree well with their analogues in the cis-(adeninatochlorobis(ethylenediamine)-Co(III))bromide complex reported by Kistenmacher.[152]

The formation of interligand hydrogen bonds among the ternary metal-purine or metal-pyrimidine complexes with ethylenediamine[205-207] or Schiff bases[203] seems to play an important role in the stabilization of these complexes. Also, the ability of the nucleic acid bases to form such interactions may influence the site at which metal coordination takes place. The variety of exocyclic functions displayed by the four common purine bases may, therefore, be employed to direct metal binding to a specific site by a suitable choice of other ligands in the coordination sphere.

A compilation of the ligand bonding sites found in solid transition metal coordination compounds containing purine residues is given in Table IV.

Table IV

Ligand Bonding Sites Found in Solid Transition Metal Coordination Compounds of Purine Residues

	Ligand	Bonding Site(s)	Metals	pH
A)	1. Adenine	N(9)[51,223]	Cu(II)	---***
		N(3)-N(9)[136,141]	Cu(II)	---
		N(9)[140]	Co(II)	---
		N(1) or N(7)[126]	Pt(II)	---
		N(9)[151,152]	Co(III)	Basic
		N(7)-N(10)[117]	Co(II), Co(III)	Basic
		N(3)-N(9)[134,137]	Cu(II)	Acidic
		N(9)[143]	Cu(II)	Acidic
		N(7)[138]	Zn(II)	Acidic
	2. 9-methyladenine	N(1) and N(7)[148]	Co(II)	---
		N(7)[127,145]	Pt(II)	---
		N(7)[153]	Cu(II)	Basic
		N(7)[146]	Cu(II)	Acidic
	3. Adenosine	N(1) or N(7)[126]	Pt(II)	Acidic
		2'-3' ribose oxygens[155]	Os(IV)	---
	4. N(10) acetyladenosine	N(1) or N(7)[126]	Pt(II)	Acidic
	5. AMP	N(7)[156]	Ni(II)	Acidic
		Phosphate[132]	Ag(I), Fe(III), Al(III), UO_2(II), ZrO(II)	Acidic
		Ring/Phosphate[132]	Pb(II), Cd(II)	Acidic
	6. ADP	α,β Phosphates[60]	Cr(III)	Acidic
	7. ATP	Phosphate[133]	Fe(III), UO_2(II)	Acidic
		Ring[133]	Hg(II)	Acidic
		α,β,γ Phosphates[60]	Cr(III)	Acidic
	8. 7-deaza ATP	C(7)[62]	Hg(II)	Acidic
B)	1. Guanine	N(9)[44]	Cu(II)	Acidic
		N(9)[139]	Zn(II)	Acidic

Table IV (cont'd)

	Ligand	Bonding Site(s)	Metals	pH
	2. 9-methyl-guanine	N(7)-O(6)[180] N(7)-N(10)[127]	Cu(II) Pt(II)	--- ---
	3. Guanosine	N(7)[186]	Pt(II)	---
	4. GMP	N(7)[184] Ring/Phosphate[191]	Co(III) Cu(II), Pb(II), Zn(II), Cd(II), Ni(II), Co(II), MN(II)	Acidic Acidic
	5. GDP*	α, β Phosphates[60]	Cr(III)	Acidic
	6. GTP*	α, β, γ Phosphates[60]	Cr(III)	Acidic
C)	1. Xanthine	N(9)[202] N(7)[209] C(8)[209]	Co(III) Ru(III), Ru(II) Ru(III), Ru(II)	Acidic Acidic Acidic
	2. Xanthosine	---**		
	3. XMP*	---		
	4. XDP*	---		
	5. XTP*	α, β, γ Phosphates[60]	Cr(III)	Acidic
D)	1. Hypoxanthine	N(3)-N(9)[197]	Cu(II)	Acidic
	2. 9-methylhypo-xanthine	N(7)[147]	Cu(II)	---***
	3. Inosine	---		
	4. IMP	N(7)/Phosphate[211] N(7)[184] N(7)[210,214] N(7), Phosphate, Ribose oxygens[200]	Zn(II) Co(III) Co(III), Ni(II) Cd(II)	Acidic Acidic Acidic Acidic
	5. IDP*	---		
	6. ITP*	α, β, γ Phosphates[60]	Cr(III)	Acidic
E)	1. Theophylline	N(7)[205-207] N(7)[203,180]	Co(III) Cu(II)	--- Basic

Table IV (cont'd)

* Abbreviations: GDP (5'-guanosine diphosphate)
GTP (5'-guanosine triphosphate)
XMP (5'-xanthosine monophosphate)
XDP (5'-xanthosine diphosphate)
XTP (5'-xanthosine triphosphate)
IDP (5'-inosine diphosphate)
ITP (5'-inosine triphosphate)

** Indicates no transition ion coordination compounds isolated to date.

*** Indicates that the information regarding pH conditions employed was not determined or undeterminable.

Electron Paramagnetic Resonance

Systems containing unpaired electrons can usually be studied by electron paramagnetic resonance (EPR). This technique is one in which "flipping" between Zeeman magnetic states is seen as an absorption of energy. The energies required to induce this flipping are found in the radio-frequency range and two frequencies are commonly employed in EPR measurements: 9.5 GHz (X-band) and 35 GHz (Q-band). X-band frequencies were used in this work.

The EPR spectra will distinguish the presence of copper(I) or copper(II) vs. copper(I) (no signal), the presence of monomeric copper(II) systems vs. coupled copper(II) systems (e.g., dimers, trimers, etc.), and the geometry about the coordinated copper(II) ion. Specific copper(II) spin systems are discussed below.

The Cu(II) System: a $3d^9$ ion

Case I: Magnetically Dilute System. Monomer with S = 1/2.

The magnetic moment μ_e of a single unpaired electron in a Cu(II) ion is given by

$$\mu_e = -g\beta S \qquad (1)$$

Here g is a dimensionless constant called the electron g factor (or Landé g factor), β is the electronic Bohr magneton, equal to $e\hbar/2mc$, where -e and m are the charge

and the mass of the electron, c is the speed of light, and S is the spin angular momentum quantum number of the electron.

The interaction between the electron's magnetic moment and an applied field H is represented by the Hamiltonian (2) which becomes (3) using eq. (1).

$$\hat{H} = -\mu_e \cdot H \tag{2}$$

$$\hat{H} = g\beta H \cdot S \tag{3}$$

Because $S = 1/2$ for the unpaired electron and because of the quantization of the spin angular momentum when a magnetic field is applied along the z-direction, there will be two possible m_s spin states, $\pm 1/2\hbar$, Fig. 6. The splitting in energy between these two levels increases as H increases and their slopes determine g, Fig. 7.

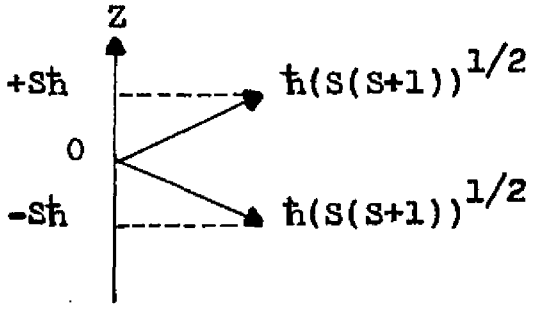


Fig. 6. Allowed values for the z component of the spin angular momentum, m_s, for $S = 1/2$.

Application of an oscillating magnetic field perpendicular to the applied field H (obtained, in this case, with

electromagnetic radio-frequency radiation) induces transitions provided that the frequency ν is such that the resonance condition

$$h\nu = g\beta H \qquad (4)$$

is satisfied. In equation(4), h is Planck's constant and

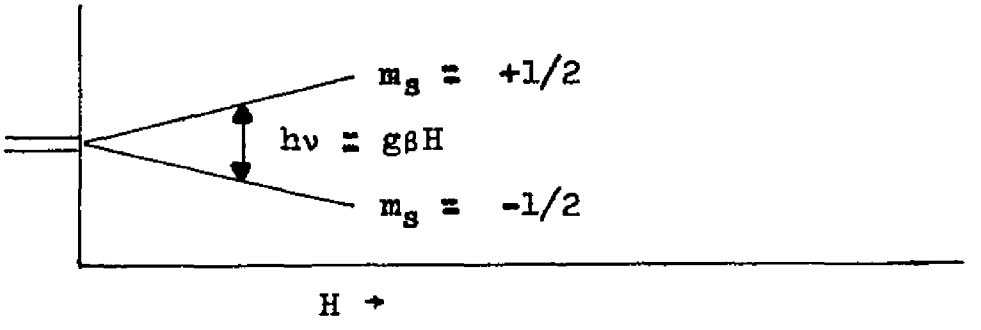


Fig. 7. Energy levels for S = 1/2. Zeeman effect in an applied field H along the z-axis with an allowed transition $h\nu = g\beta H$.

xy and z subscripts are appropriate when the molecular z-axis is perpendicular or parallel, respectively, to the external field H and there is environmental anisotropy between the z-axis and the xy plane (as is usual with Cu(II)). In a randomly oriented sample (i.e., a polycrystalline sample as used here) two transitions would be observed since there will be crystallites with their z-axes along the external field and some with their x,y axes along the external field. In terms of spin states, the resonance condition is allowed for magnetic dipole

transitions when $\Delta M_s=1$. Therefore, for uncoupled copper(II) compounds with axially distorted octahedral symmetry (environment along xy plane ≠ environment along z-axis) transitions at about 2900 and 3200G are typically observed. In this case, g_z will be greater than g_{xy} and in the range of 2.3 and 2.1, respectively. Hyperfine coupling constants (which result from interaction of the unpaired electron spin with the nuclear spin of the copper(II) ion) result in parallel and perpendicular splittings for A_z and A_{xy} of approximately 130 and 20G, respectively.

Case II: Magnetically Condensed Systems. Dimer with S = 1.

When two copper(II) nuclei are contained in the same molecule two total spin states, S = 1 and 0, are generated; these are the triplet state with $m_s = \pm 1, 0$ and the singlet state with $m_s = 0$, respectively. The S = 0 level is non-magnetic and does not contribute to the EPR spectrum. Even at zero external magnetic fields, the non-cubic symmetry of Cu(II) will introduce anisotropies in the m_s levels as shown in Fig. 8. Axial distortions are reflected in the ZFS (zero field splitting) parameter D, the energy separation between $m_s = 0$ and ± 1 levels, while any rhombic distortions will reflect themselves in E, the splitting between the ± 1 levels. Fig. 8 shows the expected transitions for the S = 1 state under axial symmetry (E = 0). Here the solid lines represent allowed

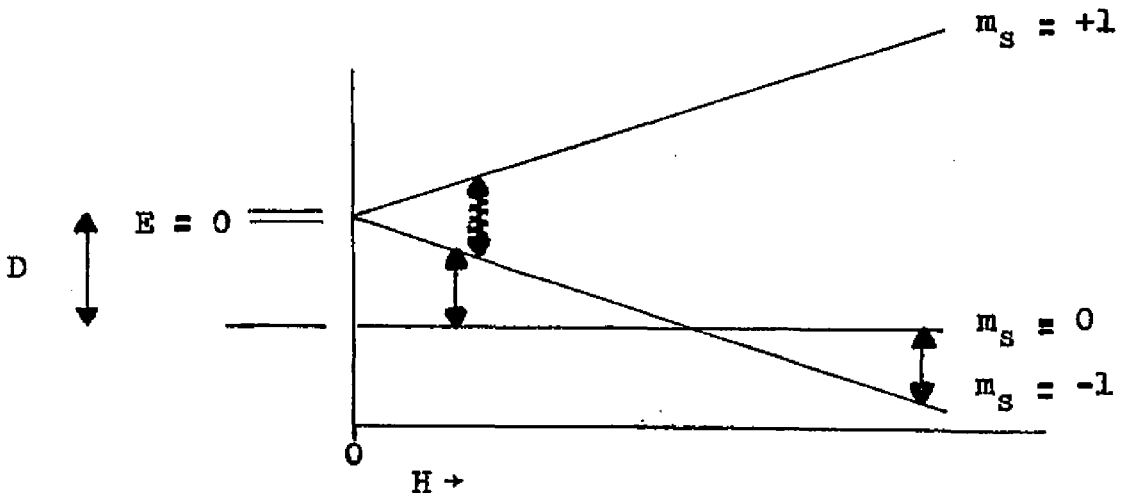


Fig. 8. Energy levels and allowed (↑) and forbidden (⇑) transitions for an axial S = 1 system with the external magnetic field along the z-axis.

transitions, $\Delta M_s = \pm 1$; the dashed line represents the $\Delta M_s = \pm 2$ spin forbidden transition. This transition becomes partially allowed at low fields (below 2000G) because of mixing of the m_s spin states. Since this $\Delta M_s = \pm 2$ transition normally appears at one-half the field position (3000G) of a $\Delta M_s = \pm 1$ transition it is sometimes called the half-field band or H_{MIN} (the minimum resonance position in the EPR spectrum). It is understood that a similar diagram will hold for the x,y oriented molecules, yielding overall four full-field transitions, called the low and high field parallel and low and high field perpendicular bands. Since H_{MIN} is much less anisotropic only one band is observed at half fields, making a total of five bands that will normally be observed.

Excluding hyperfine and quadrupole interactions for simplicity, an axial S = 1 spectrum can be interpreted in terms of the axial effective spin Hamiltonian given by eq. (5),[224] where all the terms have their usual meanings.

$$\hat{H} = g_z \beta H_z \cdot S_z + g_{xy} \beta H_{xy} \cdot S_{xy} + D(S_z^2 - 1/3S(S+1)) \quad (5)$$

The resonance positions of the $\Delta M_s = \pm 1$ transitions have been calculated by Wasserman, et al.[225] for randomly oriented samples from the Hamiltonian in (5) and are given in eqs.(6), where subscripts 1 and 2 refer to low and high field, respectively.

$$\begin{aligned} (H_{xy})_1^2 &= (1/g_{xy}\beta)^2 \, (h\nu(h\nu - D)) \\ (H_{xy})_2^2 &= (1/g_{xy}\beta)^2 \, (h\nu(h\nu + D)) \\ (H_z)_1^2 &= (1/g_z\beta) \quad |h\nu - D| \\ (H_z)_2^2 &= (1/g_z\beta) \quad |h\nu + D| \end{aligned} \quad (6)$$

The value of the ZFS constant, $|D|$, can be calculated from the half-field band using eq.(7)[226] and the g value obtained from the full-field spectrum (assuming coincidence of the D and g tensors).

$$D_{exptl} = (.75(h\nu)^2 - (2g\beta H_{MIN})^2)^{1/2} \quad (7)$$

$$g_{av} = 1/3 \, (g_z + 2g_{xy})$$

Typically, for coupled copper(II) systems (dimers) with D values of approximately 0.15cm^{-1}, $(H_{xy})_1$, $(H_{xy})_2$, $(H_z)_1$, and $(H_z)_2$ are generally observed at about 2000, 4300, 1500, and 5300G, respectively. Under conditions of temperature normally employed, hyperfine interactions are not usually observed for these copper(II) dimers.

Case III: Systems with S> 1.

Here each case is special and will depend dramatically on many variables such as the value of S and D, and the radio frequency used. Figure 9 shows the splitting diagram corresponding to S = 3/2 (a trimer). As can be observed,

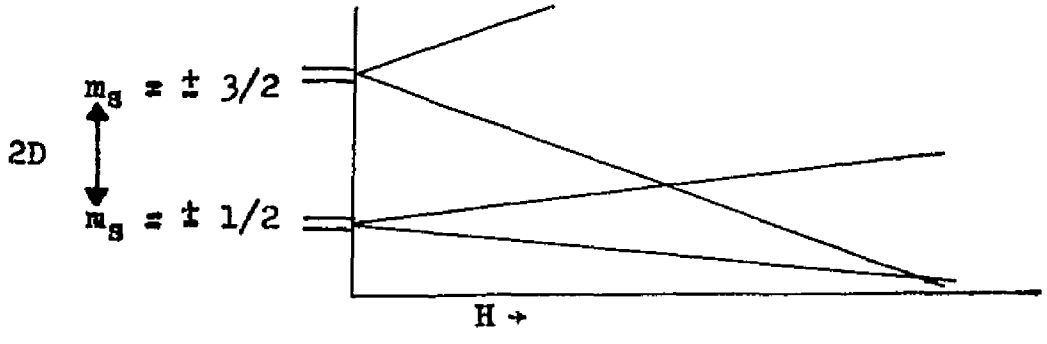


Fig. 9. Energy levels for an axial S = 3/2 system with the external magnetic field along the z-axis.

with small values of D there are three allowed transitions (+3/2⇔+1/2, +1/2⇔-1/2, -1/2⇔-3/2), but as the value of D gets larger, it is possible to end up with an effective ground state with S = 1/2 and its corresponding single transition. In some cases extensive dipolar coupling will

broaden these signals to such an extent that these transitions may not be observed. The complexity and variety of possibilities is staggering and standard texts such as Carrington and McLachlan,[227] Abragam and Bleany,[228] and Ayscough[229] should be referred to for further details.

Paramagnetic Susceptibilities

Variable temperature magnetic susceptibility measurements allow the distinction between magnetically dilute copper(II) systems vs. magnetically coupled copper(II) systems (dimers, trimers, etc.), as well as a means to measure the type, magnitude, and extent of the interactions.

The classical theory of paramagnetism was developed by Langevin[230-1] at the turn of the century on the assumption that each atom is a little permanent magnet, and that these atomic magnets tend to line up parallel to an applied field, but that the alignment is resisted by thermal agitation of the atoms.

The expression deduced by Langevin for the molar para-

$$\chi_m = N \mu^2 \beta^2 / 3kT \qquad (8a)$$

$$\chi_m = C/T \qquad (8b)$$

magnetism is eq. (8a) where N is Avogadro's number, μ is the magnetic moment expressed in Bohr magnetons, β is the Bohr magneton, k is Boltzman's constant, and T is the absolute temperature. Actually, eq. (8b) had previously been established on empirical grounds by Curie[232] and is known as Curie's Law.

Van Vleck,[187] using a simple quantum mechanical treatment, generated eq. (9) which can then be applied to various models with different degrees of approximation. This equation sums over a Boltzman distribution of particles in the energy levels populated. In eq. (9) the subscripts n, j, m

refer to the principal, rotational, and magnetic quantum numbers, respectively; the superscripts 0, 1, 2 refer to

$$\chi = N \sum_{njm} ((W^{(1)2}_{njm}/kT) - 2W^{(2)}_{njm}) \exp(-W^{0}_{njm}/kT) \; / \sum_{njm} \exp(-W^{o}_{njm}/kT) \quad (9)$$

zeroth, first, and second order, corrections to the energy W respectively; all other terms have their usual meanings. Eq.(8) is obtained from eq.(9) if second order, orbital angular momentum and spin-orbit coupling effects are neglected. Consideration of second order effects adds an additional term which is usually independent of temperature called temperature independent paramagnetism (TIP) and consideration of the other two effects are usually lumped in deviations from 2.0023 of the Landé g factor. For Cu(II) this factor is always greater than the free electron value because the spin-orbit coupling constant is negative and the magnitude will depend on the ligand field geometry surrounding it. So far the treatment has been for so-called magnetically dilute Cu(II) complexes, that is, where interactions among magnetic centers is non-existent.

One usual way to account for magnetic interactions (when the temperature intercept of a $1/\chi$ vs. T plot is non-zero) is to include a correction for T in eq.(8). The expression that results is called the Curie-Weiss Law and is given in eq.(10):

$$\chi_m = C \; / \; (T-\phi) \quad (10)$$

Here the Weiss constant, ϕ, is a measure of the degree of departure from a perfectly isolated paramagnetic system in two ways.

First, ϕ reflects the effects of strong coupling between magnetic ions near each other - the so-called Heisenberg exchange interactions. This effect can be transmitted through space(dipolar exchange) or through ligands that intervene between the magnetic ions(superexchange). The effect of the Heisenberg exchange could be one of anti-parallel coupling(antiferromagnetic exchange) or parallel coupling(ferromagnetic exchange). Antiferromagnetic and ferromagnetic behaviour are easily characterized by magnetic susceptibility measurements since the former leads to lower moments as the temperature is dropped while the latter leads to higher moments as the temperature is dropped. Second, ϕ measures long distance effects(10Å) that influence the magnetic character of the ion being studied. These "lattice interactions" or "domains" can also yield ferromagnetic or antiferromagnetic behaviour.

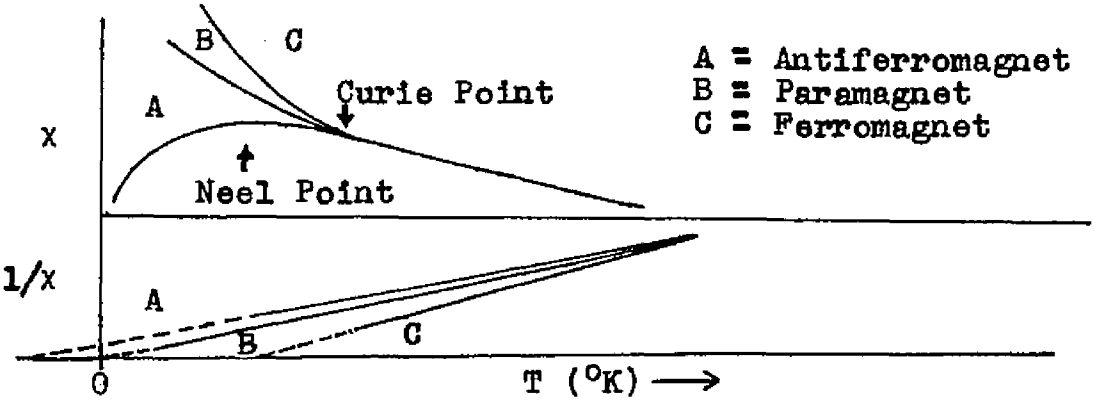


Fig. 10 Idealized χ vs. T and $1/\chi$ vs. T plots for three classes of magnetic systems.

Fig. 10 illustrates idealized χ vs. T and $1/\chi$ vs. T plots for various types of magnetic behaviour. The temperature intercepts, ϕ, for the $1/\chi$ vs. T plots for the three magnetic classes considered here can be related to paramagnetic Curie behaviour($\phi = 0^{\circ}K$), antiferromagnetic behaviour ($\phi < 0^{\circ}K$), and ferromagnetic behaviour($\phi > 0^{\circ}K$). When these interactions(either close or long range) become appreciable in energy compared to kT, the χ and $1/\chi$ plots deviate considerably from ideality, and extrapolation to the temperature axis becomes more doubtful. More sophisticated treatments become necessary that can account for strong nearest neighbor interactions such as those found in dimer, trimer, tetramer, and polymer systems.

A. Copper(II) Dimer

When the interaction is essentially between two Cu(II) ions within a dimer the Hamiltonian(11) is a good description of the system where 2J is the energy separation

$$\hat{H} = -2JS_1 \cdot S_2 \qquad (11)$$

between the triplet (S = 1) and singlet (S = 0) state. Summation over all the magnetic spin states in eq. (9) yields:

$$\chi = Ng^2\beta^2/3kT \left[(1+1/3\exp(-2J/kT))^{-1} \right] + N\alpha \qquad (12)$$

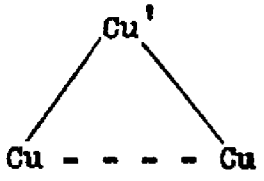
where all the terms have their usual meaning and N α is the TIP term. A negative value of 2J indicates a singlet ground state. A modified Van Vleck expression, eq.(13), where the Weiss constant, ϕ, is incorporated has been used to account for interdimer coupling throughout the lattice.

$$\chi = Ng^2\beta^2/3k(T-\phi)\ (1+1/3\exp(-2J/kT))^{-1} + N\alpha \qquad (13)$$

A very complete theoretical treatment on dimeric systems can be found in a series of papers by Wojciechowski.[233-5]

B. Copper (II) Trimer

Sinn and Harris,[236] utilizing a treatment similar to the one employed for dimer systems, developed an expression for the susceptibility per gram ion of copper(II) in a trimer having the following geometry



$$\chi = Ng^2\beta^2/12kT\left[\frac{\exp(-2J/kT)+\exp(-2J_{CuCu}/kT)+10\exp(J/kT)}{\exp(-2J/kT)+\exp(-2J_{CuCu}/kT)+2J\exp(J/kT)}\right]+N\alpha \qquad (14)$$

where $J_{CuCu'}=J_{Cu'Cu}=J$. The agreement of experimental results with eq. (14) is best when J_{CuCu} is small or zero and should therefore describe a linear or bent trimer more

satisfactorily than a triangular trimer where the coupling between all three pairs of copper ions becomes comparable.

C. Copper(II) Tetramer

A simple magnetic state configuration was developed by this laboratory to explain the magnetic behavior of systems with four interacting copper(II) ions. The illustration depicted in Fig. 11 is an approximation to the interaction between four copper(II) ions (two sets of dimeric copper(II) units). The degeneracy of each spin manifold is 2S+1, and

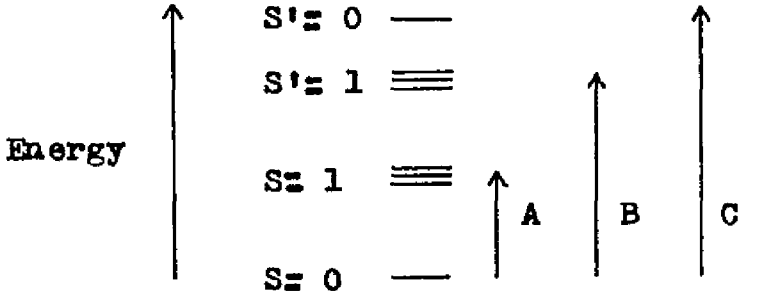


Fig. 11 Proposed magnetic state configuration of two interacting dimer units in one series of complexes studied.

the labels A, B, and C refer to the energy separation from the singlet ground state to the S=1, S'=1, and S'=0 manifolds, respectively. Using eq. (9), an expression for the susceptibility of the above model was obtained and is shown in eq. (15)

$$\chi = Ng^2\beta^2/2kT\left[\frac{\exp(-A/kT)+\exp(-B/kT)}{1+3\exp(-A/kT)+3\exp(-B/kT)+\exp(-C/kT)}\right]+ N\alpha \quad (15)$$

Equation (15) is different in form from one used by other authors[237-8] in describing tetramer systems in that an S=2 state was disregarded as being too high in energy.

D. Copper(II) Straight-Chain Polymer

Susceptibility data for the Ising model for antiferromagnetic interactions in linear chains can be described using eqs. (16) developed by Fischer.[239]

$$\chi_{xy} = Ng^2\beta^2/8J\left[\tanh(J/kT)+(J/kT)\ \mathrm{sech}^2\ (J/kT)\right] \qquad (16a)$$

$$\chi_z = (Ng^2\beta^2/4kT)\ \exp(2J/kT) \qquad (16b)$$

$$\chi_{av} = 1/3(\ \chi_z + 2\ \chi_{xy}\ ) \qquad (16c)$$

Indeed, the tendency of copper(II) to form linear chains appears to be quite common,[240-3] and related to the tendency of the copper(II) ions to be surrounded by four atoms at short distances with two additional atoms at longer distances.[244] Other models have been developed in an effort to describe the magnetic behavior found in polymeric systems having very specific features, however, their specificity puts a limitation on the number of systems that can be characterized successfully by them. These models have been discussed elsewhere.[245]

Experimental Section

I. Spectral and Magnetic Measurements

A. EPR Measurements

The room temperature and 77°K X-band EPR spectra of polycrystalline samples of the complexes were obtained using a Varian Assocates HFE-12 and EM-500 spectrometers. A dual rectangular cavity of TE_{104} mode and an unloaded Q of 7500 was used with a modulation frequency of 100KHz in each case. The spectra at 77°K were recorded using a quartz liquid nitrogen dewar. In all cases the magnetic field sweep was 0 to 10,000G. The magnetic field was pre-calibrated using a proton NMR probe yielding an uncertainty of about ±0.1G (completely negligible considering the width of our absorptions). DPPH was used as the internal standard. Scan times ranged from 4 minutes to 2 hours, depending on the filters used. High purity quartz EPR tubes (0.3cm ID) were used as sample holders with about 100mg samples.

B. Bulk Magnetic Susceptibility Measurements

The magnetic susceptibilities were obtained in the range 12-500°K, using a Faraday balance setup and $HgCo(SCN)_4$ as the standard.[246] The sample support used for all temperatures was a 50-50 quartz-nylon fibre as described by Nelson and Villa.[247-8] Samples sizes from 2 to 20mg were used

and introduced into specially made high purity quartz buckets (8mm x 3mm; ID = 2mm). The results reflect a maximum error of 1μg for every weight change, leading to a systematic error in the gram susceptibility for the smallest sample measured of about 0.5% and 0.05% at room temperature and 12°K, respectively. Considerably smaller systematic errors are obtained as the sample size increases. Temperatures in the range 12-300°K were measured by means of a gold-chromel (0.07% Fe) thermocouple and in the 12-30°K region with a H_2 gas gauge. Temperature variability was obtained using an Air Products and Chemical Inc. (Allentown, Pa.) Duplex Closed-Cycle Refrigerator System, CSW-202, coupled to a Faraday shroud with a sample chamber ID of 1.5". Helium gas at 1 atmosphere pressure was used as the heat exchanger between sample and cryostat. Temperatures in the range 300-500°K were measured by means of a copper-constantan thermocouple using a variable temperature heating element mounted on a 75cm x 2cm glass finger. A remote controlled Cahn G-2 Electrobalance (Ventron Instruments Corporation, Paramount, Calf.) allowed changes in weight of 0.5μg to be observed. Maximum field strengths of 7KG were used for the variable temperature runs below room temperature while field strengths of up to 15KG were used for measurements at and above room temperature. Field dependence studies at room temperature were made at 3 different field strengths: 3, 8 and 15KG. A Model 4600,

4" water cooled adjustable gap electromagnet (Alpha Scientific Incorporated, Haywood, Calf.) with specially constructed tapered pole pieces for Faraday measurements[249] was used. The electromagnet was powered by an Alpha, Model #3002-1, current regulated power supply (Alpha Scientific Incorporated) and calibrated by a Bell 640 Instrumental Gaussmeter (F.W.Bell Incorporated, Columbus, Ohio). Measurements made out-of-field were accompanied by a shut down of magnet power to assure zero magnetic field. The gram susceptibility was obtained according to the Faraday method from eq.(17)[249]

$$\chi_s = \chi_r(W_r(\Delta W_s - Buc) \;/\; W_s(\Delta W_r - Buc)) \qquad (17)$$

where the subscripts s and r refer to sample and reference, respectively, W is the actual weight employed, ΔW is the change in weight (i.e., weight in the field minus weight out of the field), Buc is the diamagnetic correction of the bucket used to hold sample and reference, and χ_r is the gram susceptibility of a suitable reference at a specified temperature. The molar susceptibility is obtained by multiplying eq.(17) by the molecular weight of the sample; that is

$$\chi_m = \chi_s \cdot MW \qquad (18)$$

The corrected molar susceptibility χ_{mc} used in all the fitting procedures for the models discussed subsequently, is found by subtracting the diamagnetic correction of the molecule (metal plus ligand) and the TIP contribution of the metal ion from (18)

$$\chi_{mc} = \chi_m - DIAC - TIP \qquad (19)$$

Here DIAC is the diamagnetic correction of the complex obtained using Pascal's constants[250] (except in those complexes having sulfur-containing ligands where the corrections were made from the susceptibility data of the free ligand) and TIP is the temperature independent paramagnetism correction obtained from the expression $TIP = N\Delta g\beta^2/\lambda = 60 \times 10^{-6}$ cgsu.[251] Molar susceptibilities and effective magnetic moments were calculated from the raw data by means of our "CALSUS" computer program. This program automatically incorporates into the calculations appropriate Pascal's constants for DIAC and a TIP for the system under study. Several other Fortran IV computer programs in our possession ("DIMFIT", "TETRAMER", "ISING", "TRIMER") give a least-squares best fit of the experimental data to a theoretical equation (corrected for a range of % monomer impurity in appropriate cases) in order to extract the magnetic parameters g, 2J, and ϕ.

C. Visible Absorption Measurements

The visible/near-infrared spectra (25,000 - 8,300cm^{-1}) were obtained as Nujol mulls on Watman #1 filter paper mounted on a specially constructed wood support in a Beckman DK-2A spectrophotometer with a tungsten source and lead sulfide detector.

D. Infrared Measurements

The infrared spectra (4,000 - 660cm^{-1}) were obtained as KBr pellets on a Perkin Elmer Model 21 IR spectrophotometer with NaCl optics. Comparison of spectra run as pellets and mulls (Nujol and fluorolube) was made to assess the effect of grinding and compaction on the resolution of sample spectra. In all instances, the spectra and resolution obtained were comparable. KBr pellets of 0.1mm width were prepared by grinding a 1% mixture of complex (or ligand) and oven-dried infrared grade KBr (Mallinckrodt Chemical Works, St. Louis, Mo.) followed by evacuation and compression in a specially constructed stainless steel unthreaded die with a cylindrical insert at 16,000 lbs for 30 minutes. The spectra were calibrated using the 1603.2cm^{-1} absorption of a 0.05mm polystyrene film.

II. Synthetic Aspects

A. Solvents

The water used was purified by distillation. The methanol and ethanol were commercially available and used without purification from Commercial Solvents Corporation, Terre Haute, Ind., and Fisher Scientific Co., Fairlawn, N. J., respectively.

B. Solutions

The hydrochloric acid and nitric acid solutions used were prepared from reagent grade acids supplied by Fisher Scientific Co.. The sodium hydroxide solution was prepared from sodium hydroxide pellets and all copper(II) salt solutions were prepared without further purification from reagent grade salts, both from J. T. Baker Chemical Co., Phillipsburg, N. J.

C. Ligands

All ligands were commercially available from Nutritional Biochemical Corp., Cleveland, Ohio and used without further purification.

D. pH Measurements

pH readings were performed with alkacid test ribbon obtained from Fisher Scientific Co..

E. Qualitative Test for Cu(II)

Low susceptibility measurements on complexes containing

sulfur ligands prompted us to conduct a simple qualitative redox test to detect Cu(II). A positive test for Cu(II) would indicate that the low susceptibilities observed were not due to the reduction of Cu(II) to Cu(I) by the ligand.

All the complexes containing sulfur ligands were subjected to the redox test[252] that is outlined below and summarized by the following expression:

$$2Cu(II) + 4I^{-1} \xrightarrow[H_2SO_4]{N_2} 2CuI + I_2 \xrightarrow[I^{-1}]{Starch} I_3^{-1}$$

(purple complex)

A purple coloration of the mixture then is only possible if Cu(II) is present. The complexes are dissolved in a minimum amount of 6M H_2SO_4 under N_2 and the pH adjusted to 4 with 3M NaOH. To this solution 25ml of 0.1M KI solution and 10ml of 1% starch solution are added and the color change observed. The KI, soluble potato powder, and H_2SO_4 were commercially available and obtained from J. T. Baker Chemical Co.. In all complexes tested a positive test for Cu(II) was obtained.

F. Elemental Analyses

The chemical analyses for C, H, and N were carried out by PCR, Inc., Gainsville, Florida. The results of the analyses were interpreted by means of our stoichiometry

fitting computer program "LIGFIT". All stoichiometries reported were consistent within a 1% error limit to the chemical analysis and were self-consistent in terms of the charges, ligands, and metal.

G. Preparation of the Coordination Compounds

Four pH ranges were used in all the complexation attempts initially with copper(II): 2, 5, 8, and 10. Non-aqueous and partially aqueous solvents were employed when aqueous systems failed to produce products that isolated or analyzed well. Ligand to metal stoichiometries were generally 2:1 in the syntheses, and the concentrations of the reactants were always less than 0.1M.

1. $Cu(5NO_2\text{-Uracil})_2 \cdot 2H_2O$: A solution of 0.400 g (2.5 mmoles) of $5NO_2$-uracil was placed in 20 mlof water heated to 65°C in a hot water bath. Addition of 15 drops of 10% NaOH solution yielded, upon moderated swirling, a clear yellowish solution; pH about 7. The base fortified solution was added slowly in small (3 ml) increments along the side of a test tube containing 5 ml (1.25 mmoles) of copper acetate solution previously heated to 65°C. Each addition was accompanied by rapid swirling and the reaction mixture was kept at about 65°C at all times. After addition of 5 ml a distinct greenish cast and suspension was

detected; pH about neutral. A copious bluish-green well formed precipitate settled out after the completion of all additions; final pH 7. The mixture was kept an additional 15 minutes at 65°C in a hot water bath, and then cooled for 30 minutes in an icewater bath. The green product was collected on a Buchner plate and dried in an oven at 90°C. Anal. Calcd. for $CuC_8H_{10}N_6O_{10}$: C, 23.40; H, 2.44; N, 20.40. Found: C, 23.44; H, 1.99; N, 19.95.

2. $Cu(5I\text{-Uracil})_2 \cdot H_2O$: The green 5I-uracil complex was prepared in a fashion similar to the $5NO_2$-uracil complex except that 21 drops of 10% NaOH solution was used. Anal. Calcd. for $CuC_8H_8N_4O_5I_2$: C, 17.35; H, 1.08; N, 10.02. Found: C, 17.34; H, 1.27; N, 9.42.

3. $Cu(Uracil)_2 \cdot H_2O$: A solution of 0.5495 g (5 mmoles) of uracil was prepared in 50 ml of 20% ethanol with swirling at 60°C. Freshly prepared $Cu(OH)_2$ (5 mmoles) was added to this solution and the mixture was heated under reflux for one hour at which time a dark green jade solution resulted. The solution was allowed to stir at room temperature for three more hours and then was concentrated to approximately 40 ml volume at which time a pale green precipitate developed. The product was filtered and washed with ethanol and water. The product deepened in color after washing with water. The product was oven dried at 75°C.

Anal. Calcd. for $CuC_8H_8N_4O_5$: C, 31.58; H, 3.51; N, 18.42. Found: C, 31.51; H, 3.46; N, 18.36.

4. $Cu(2S\text{-Uracil})_2 \cdot 3H_2O$: A solution of 0.3024 g (2.5 mmoles) of 2-thiouracil was prepared in 20 ml of water at 70°C. The pH of the solution was brought above 10 by the addition of 20 drops of 10% NaOH solution. The base fortified solution was added in small portions (4 ml) to 5 ml of copper acetate solution (1.25 mmoles) at 70°C with constant swirling. Initially, a black turbid mixture developed which changed to a pea-green and finally to a yellow color; pH neutral after the final addition. The mixture was heated for ten minutes in a hot water bath then cooled under tap water and placed in an ice-bath for 20 minutes. The mixture was gravity filtered and dried in an open oven at 90°C. The yellow-brown flakes that resulted were ground up and placed in a desiccator for three days at which time the product took on its present lime-green hue. Anal. Calcd. for $CuC_8H_{12}N_4O_5S_2$: C, 25.84; H, 3.25; N, 15.07. Found: C, 26.16; H, 2.39; N, 15.00.

5. $Cu(6CH_3\text{-}2S\text{-Uracil})_2 \cdot 2H_2O$: A solution of 0.1258 g (1 mmole) of $6CH_3$-2S-uracil was prepared in 100 ml of methanol at 55°C. A solution of 0.0866 g of $CuCl_2 \cdot 2H_2O$ (0.5 mmoles) in 10 ml of methanol was added dropwise to

the ligand solution with constant stirring. A light yellow solution formed immediately and turned cloudy after the addition was complete. Heating three additional minutes yielded a light yellow precipitate. The mixture was allowed to concentrate to 50 ml, cooled to room temperature and suction filtered. The product was washed with methanol and dried in an open oven at 80°C. Anal. Calcd. for $CuC_{10}H_{14}N_4O_4S_2$: C, 31.45; H, 3.70; N, 14.67. Found: C, 31.86; H, 3.50; N, 15.55.

6. $Cu(6C_3H_7\text{-}2S\text{-}Uracil)_2 \cdot 4H_2O$: A saturated solution of $6C_3H_7$-2S-uracil was prepared in 100 ml of water at room temperature. Three drops of 10% NaOH solution were added to the ligand solution to raise the pH to 8. With constant swirling dropwise addition of 3 ml of 0.01M $CuSO_4 \cdot 5H_2O$ solution resulted in a turbid purple mixture; pH 7. Two drops of 10% NaOH solution were added to the mixture raising the pH to 8 and yielding a light green-yellow solution. Two ml of the $CuSO_4$ solution were added followed by 2 drops of 10% NaOH yielding a light, green-yellow solution as before; pH 8. An additional 1 ml of the $CuSO_4$ solution was added which resulted in a light green mixture (not purple as before). Two ml more of the $CuSO_4$ solution were added, followed by 2 drops of the 10% NaOH. The mixture was dark yellow at this point. Finally, 2 ml of $CuSO_4$ solution were added slowly. The mixture developed a turbid,

muddy green appearance. The mixture was stirred at room temperature and after 24 hours a faint yellow product separated out. The product was filtered, washed with water and oven dried at 90°C. Anal. Calcd. for $CuC_{14}H_{26}N_4O_6S_2$: C, 35.48; H, 5.53; N, 11.82. Found: C, 35.68; H, 5.81; N, 11.16.

7. $Cu(6NH_2\text{-}2S\text{-}Uracil)_2 \cdot 3CH_3OH$: A solution of 0.1446 g of $6NH_2$-2S-uracil was prepared in 100 ml of methanol at 55°C. A solution of 0.0866 g $CuCl_2 \cdot 2H_2O$ (0.5 mmoles) in 10 ml of methanol was added dropwise to the ligand solution with constant swirling. After addition of $CuCl_2$ was complete, the solution became milky-yellow. The mixture was allowed to concentrate to one-half its original volume with stirring at 50°C. The mixture was removed and cooled to room temperature and the light yellow product was suction filtered, washed with methanol and oven dried at 80°C. Anal. Calcd. for $CuC_{11}H_{20}N_6O_5S_2$: C, 29.76; H, 4.54; N, 18.93. Found: C, 29.30; H, 3.72; N, 18.61.

8. $Cu(Di\text{-}S\text{-}Uracil)(OH) \cdot H_2O$: A mixture of 0.1635 g (1 mmole) of dithiouracil was prepared in 80 ml of water at 65°C. Complete dissolution could not be affected with 20 drops of 10% NaOH solution and the mixture was filtered. To the clear, yellow ligand solution (pH 10) 4 ml of 0.25M $Cu(NO_3)_2 \cdot 3H_2O$ (1 mmole) was quickly added with

stirring. An immediate green-brown product developed and the mixture was heated for an additional 15 minutes. During this time the mixture turned yellow-brown and then to its final orange color. The product was filtered, washed with copious amounts of water and oven dried at 85°C. Anal. Calcd. for $Cu_1C_6H_4N_2O_2S_2$: C, 19.88; H, 2.50; N, 11.60. Found: C, 19.22; H, 1.56; N, 11.84.

9. Cu(AMP).$2H_2O$: A solution of 0.3395 g (1 mmole) of 5'-AMP was prepared in 40 ml of water at 55°C by addition of 8 drops of 10% NaOH solution; pH 7. To the ligand solution 0.5 mmoles of $Cu(NO_3)_2.3H_2O$ in 5 ml of solution was added with stirring and the light blue cloudy mixture that developed (pH 3) was allowed to heat gently until the final volume was 35 ml. A pale green product separated out and the mixture was allowed to concentrate at room temperature over a two day period. The shiny, light green product was filtered, washed with water and methanol and oven dried at 80°C. The product when crushed lost its luster and had the consistency of talcum powder. Anal. Calcd. for $CuC_{10}H_{16}N_5O_9P_1$: C, 27.00; H, 3.63; N, 15.75. Found: C, 26.72; H, 4.25; N, 16.31.

10. Cu(CMP).$6H_2O$: Freshly prepared $Cu(OH)_2$ (5 mmoles) was added quickly with stirring to 50 ml of an aqueous solution containing 0.3231 g (1 mmole) of 5'-CMP at 50°C, (pH 4). A turbid, light blue mixture developed (pH 6)

which was allowed to concentrate to one-half its original volume at 65°C. After removal from the hot plate, the solvent was allowed to evaporate slowly for two days. The product was filtered, washed with water and oven dried at 85°C. Anal. Calcd. for $CuC_9H_{24}N_3O_{14}P_1$: C, 21.93; H, 4.87; N, 8.53. Found C, 20.96; H, 3.94; N, 8.94.

11. $Cu(GMP).5H_2O$: A solution of 0.5 mmoles of $Cu(NO_3)_2.3H_2O$ in 5 ml of water was added with stirring to 40 ml of an aqueous solution at 60°C containing 0.3553 g (1 mmole) of 5'-GMP (pH 7). A slight green product developed and the mixture was allowed to heat an additional 15 minutes at which time one-half of the supernatant was poured off and 15 ml of water added. The mixture was allowed to stand 2 days at room temperature then gravity filtered (suction ineffective) and oven dried at 80°C. Anal. Calcd. for $CuC_{10}H_{22}N_5O_{13}P_1$: C, 23.33; H, 4.31; N, 13.61. Found: C, 22.48; H, 3.70; N, 14.38.

12. $Cu_3(Deoxyguanosine)_2(OH)_4.4H_2O$: A basic solution of 2'-deoxyguanosine, prepared by adding 20 drops of 10% NaOH solution to 20 ml of water at 69°C containing 0.5010 g (2 mmoles) of ligand (pH 10), was added to 4 ml of a 0.25M $Cu(Ac)_2.H_2O$ solution at 68°C with swirling in small (5 ml) increments. After the third addition a cloudy green mixtured developed; final pH 10. The mixture was

placed in an ice bath for 20 minutes, gravity filtered and the dark product oven dried at 85°C. Anal. Calcd. for $Cu_3C_{20}H_{36}N_{10}O_{16}$: C, 27.83; H, 4.20; N, 16.23. Found: C, 27.79; H, 3.52; N, 15.92.

13. $Cu(Guanosine)_2 \cdot 4H_2O$: A basic solution of guanosine, prepared by adding 25 drops of 10% NaOH solution to 20 ml of water heated to 65°C containing 0.7071 g (2.5 mmoles) of ligand (pH 10), was added in small increments (4 ml) with constant swirling to 5 ml of 0.25M $Cu(Ac)_2 \cdot H_2O$ solution (1.25 mmoles). After the final addition the green gel initially formed was transformed to a turbid light green mixture (pH 8) and allowed to heat an additional 10 minutes. The mixture was placed in an ice bath for 20 minutes, filtered and oven dried at 85°C. Anal. Calcd. for $CuC_{20}H_{32}N_{10}O_{14}$: C, 34.31; H, 4.61; N, 20.01. Found: C, 34.52; H, 4.26; N, 19.34.

14. $Cu(8Br\text{-}Guanosine)_2 \cdot 3H_2O$: A basic solution of 8Br-guanosine, prepared by adding 20 drops of 10% NaOH solution to 35 ml of water at 55°C containing 0.9165 g (2.5 mmoles) of ligand, was added with stirring to a solution prepared by adding 0.2500 g (1.25 mmoles) of $Cu(Ac)_2 \cdot H_2O$ in 10 ml of water at 55°C. The addition was performed in one portion. A light green mixture developed (pH 8) which was cooled to room temperature under running tap water,

suction filtered, washed with water and oven dried at 90°C. Anal. Calcd. for $CuC_{20}H_{28}N_{10}O_{13}Br_2$: C, 28.60; H, 3.36; N, 16.68. Found: C, 28.26; H, 3.14; N, 17.20.

15. $Cu(Cytosine)_2Cl_2$: A solution, prepared by addition of 0.1260 g of $CuCl_2.2H_2O$ to 20 ml of methanol, was added with stirring to a cytosine solution, prepared by addition of 0.0928 g of ligand to 60 ml of methanol at 50°C. After 5 minutes of heating a turbidity developed in the dark green solution at which time the mixture was removed from the hot plate. Within a short period of time a light blue product appeared that was gravity filtered, washed with methanol and oven dried at 95°C. Anal. Calcd. for $CuC_8H_{10}N_6O_2Cl_2$: C, 26.94; H, 2.83; N, 23.57. Found: C, 26.97; H, 3.06; N, 23.67.

16. Cu(2S-Cytosine)Cl_2: Dropwise addition of 4 ml of a methanol solution containing 0.0229 g of $CuCl_2.2H_2O$ to 20 ml of a methanol solution containing 0.0175 g of 2-thiocytosine at 65°C yielded a fluffy, light yellow mixture that was heated for 5 minutes. After removal from the hot plate, a room temperature mixture of the light yellow product was filtered, washed with methanol, and oven dried at 90°C. The dried product was dirty yellow in appearance. Anal. Calcd. for $CuC_4H_5N_3S_1Cl_2$: C, 18.36; H, 1.93: N, 16.07. Found: C, 17.94; H, 2.12; N, 16.75.

17. $Cu(2S\text{-}Cytosine)_2 \cdot 2H_2O$: An acidic solution of 2-thiocytosine, prepared by addition of 0.3138 g of ligand (2.5 mmoles) to 20 ml of water at 65°C acidified with 25 drops of 10% HCl solution, was added in small portions (5 ml) to 5 ml of 0.25M $Cu(Ac)_2 \cdot H_2O$ solution (1.25 mmoles) with constant swirling. Initially, a black solution developed which changed to a yellow, lime-green viscous mixture after the ligand additions completed. The mixture was allowed to heat an additional 15 minutes, and after cooling in an ice-bath for 20 minutes, the orange-yellow, gel-like mixture was suction filtered and washed with water. The product was oven dried and stored over P_2O_5. After 2 days the color of the product changed from orange to brown. Anal. Calcd. for $CuC_8H_{12}N_6O_2S_2$: C, 27.28; H, 3.41; N, 23.87. Found: C, 26.47; H, 3.06; N, 23.78.

18. $Cu(Adenosine)(OH) \cdot 1/2\ H_2O$: A basic solution of adenosine, prepared by adding 0.6702 g (2.5 mmoles) of ligand to 20 ml of water at 66°C containing 20 drops of 10% NaOH solution (pH 10), was added to 5 ml of 0.25M $Cu(Ac)_2 \cdot H_2O$ (1.25 mmoles) in small portions (5 ml) with constant swirling. A green viscous mixture (pH 7) resulted after the last addition and was allowed to heat an additional 10 minutes in a hot water bath at 65°C. The mixture was suction filtered (after immersion in an ice-bath for 15 minutes), and oven dried at 85°C. The crushed product was

dark green. Anal. Calcd. for $Cu_1C_{10}H_{14}N_5O_{5.5}$: C, 33.75; H, 3.97; N, 19.69. Found: C, 34.06; H, 4.13; N, 18.93.

19. Cu(Xanthosine)(OH).$2H_2O$: A basic straw-colored solution of xanthosine, prepared by adding 0.4998 g (2.5 mmoles) of ligand to 20 ml of water at 69°C containing 15 drops of 10% NaOH solution (pH 10), was added is small increments (4 ml) to 5 ml of 0.25M $Cu(Ac)_2.H_2O$ solution with constant swirling. A light green mixture developed (pH 6) and was allowed to heat an additional 10 minutes in a hot water bath at 65°C after which time the mixture was placed in an ice bath for 20 minutes. The green product was gravity filtered and oven dried at 85°C. Anal. Calcd. for $Cu_1C_{10}H_{16}N_4O_9$: C, 30.04; H, 4.03; N, 14.02. Found: C, 29.22; H, 3.47; N, 13.82.

20. Cu(Inosine)(OH).H_2O: A basic solution of inosine, prepared by adding 0.6807 g (2.5 mmoles) of ligand to 20 ml of water heated to 65°C containing 20 drops of 10% NaOH solution; pH 10, was added to 5 ml of 0.25M $Cu(Ac)_2.H_2O$ solution at 65°C in small increments (5 ml) with constant swirling. A dull, blue-green mixture developed immediately; final pH 9. The mixture was heated for 180 minutes in a hot water bath at 65°C, cooled in an ice bath for 20 minutes, and gravity filtered. The dark green product was oven dried at 90°C. Anal. Calcd. for $Cu_1C_{10}H_{14}N_4O_7$: C, 32.83;

H, 3.86; N, 15.32. Found: C, 31.99; H, 3.77; N, 15.37.

21. Cu(Cytidine)(OH).$2\frac{1}{2}H_2O$: A basic solution of cytidine, prepared by adding 0.6051 g (2.5 mmoles) of ligand to 20 ml of water heated to 68°C containing 30 drops of 10% NaOH solution; pH 10, was added to 5 ml of 0.25M $Cu(Ac)_2 \cdot H_2O$ at 68°C in small increments (5 ml) with constant swirling. A light blue mixture developed after the first addition; pH 7. Subsequent additions imparted a green caste to the mixture. The final addition transformed the mixture to a clear deep blue solution, pH>10. The volume was concentrated to 10 ml on a hot plate and the solution allowed to evaporate slowly at room temperature. After 1 month the hard blue film that resulted was dissolved in 10 ml of hot water. Slow evaporation over a 4 month period yielded a light green-blue product that was suction filtered, washed with water and methanol, and oven dried at 90°C. Anal. Calcd. for $Cu_1C_9H_{18}N_3O_{8.5}$: C, 30.12; H, 4.78; N, 11.71. Found: C, 29.45; H, 4.04; N, 11.21.

22. Attempts at Complex Formation

In addition to the ligands found in the complexes mentioned previously, a large variety of other pyrimidine and purine ligands were tested under the same reaction conditions outlined at the beginning of this section. Attempts to

synthesize copper(II) complexes failed with the following ligands:

Pyrimidines

1. 5X-Uracil, X=CH_3, Br, F, NH_2, CH_3CO
2. 6X-Uracil, X=CH_3, NH_2
3. 6Aza-uracil, Diazauracil
4. Uridine, Deoxyuridine
5. Thymine, Thymidine

Purines

1. Guanine, 6Cl-guanine, 8Aza-guanine, 6Mercapto-guanine, 8Br-guanine
2. Adenine, 8Aza-adenine
3. 3'-Deoxyadenosine
4. 3'-dAMP, 3',5'-cyclic AMP
5. 5'-IMP

Results and Discussion

The compounds prepared during this investigation have been grouped by the criterion of similar composition and similar ligand group into five different sections. The data pertinent to these compounds will then be presented and discussed in the corresponding section below.

A. $Cu(5X\text{-Uracil})_2 \cdot n\ H_2O$, where X = H, I, NO_2 and n = 1, 1, and 2, respectively; $Cu(6X,2S\text{-Uracil})_2 \cdot n$ solvent, where X = H, NH_2, CH_3, C_3H_7 and n solvent = $3H_2O$, $3CH_3OH$, $2H_2O$, and $4H_2O$, respectively; Cu(2,4-Dithiouracil)(OH)$\cdot H_2O$.

Complexes of the pyrimidine bases have been very elusive up to now because of their small pK_as and reported weak Lewis base behavior,[253] however, two new series of 2:1 ligand to Cu(II) coordination compounds with 6X,2S-Uracil, where X = H, NH_2, CH_3, and C_3H_7, and 5X-Uracil, where X = H, NO_2, and I, have been isolated as a result of this work. This shows that 2S-uracil acts as a good Lewis base and readily coordinates to Cu(II). Recently, Villa and Nelson[254] reported the syntheses and spectroscopic properties of two members of the series corresponding to $Cu(5X\text{-Uracil})_2 \cdot nH_2O$, where X = I, and NO_2 and n = 1 and 2, respectively. Again, the Cu(II)-substituted uracil interactions have been shown to be real and stable, and this represents the preparation and characterization of the first simple coordination compounds of the 5-sub-

stituted uracils. In addition to the uracil and thiouracil complexes, a novel complex with 2,4-dithiouracil has also been isolated.

Complete tabulations of the major IR bands for all ligands and complexes in the NaCl range (3500 - 700cm^{-1}) are given in Tables VII and VIII. The assignments given in the tables were arrived at by interpolation among the IR spectra of the free uracil, 2S-uracil, and 2,4-dithiouracil and by direct comparison to previous published IR analyses for uracil[255] and 2,4-dithiouracil.[89] The coordination sites were determined by comparison between free ligand and coordinated ligand.

The main area of interest is the region between 1700 and 800cm^{-1} where the following bands are located (all in cm^{-1}): ν C(2)O, 1730; ν C(4)O, 1690; δ N(1)H, 1510; δ N(3)H, 1420; ν thioamide I, 1560; ν thioamide II, 1230; and ν thioamide III, 860.

The changes in the spectra are dramatic upon coordination. For the 6X,2S-uracil and 2,4-dithiouracil complexes, δN(3)H decreases in intensity or completely disappears from the spectra pointing to N(3) deprotonation and concomitant coordination. The C(2)S moiety, as monitored by thioamide bands I-III, is also used for coordination since there are changes in position, intensity or both in several of these bands. ν C(4)O remains unchanged in intensity and only slightly shifted in position (combination band with ν C=C); δ N(1)H also remains constant in intensity and position. This is in-

dicative that C(4)O and N(1) are not used as coordination sites. The presence at 3425 and 3335cm^{-1} of the asymmetric and symmetric NH stretching modes, respectively, for the -NH_2 group, governed by the following expression:[256] νNH_2 (sy.) = 345.54 + 0.876 νNH_2(asy.) precludes coordination at the NH_2 postion in the 6NH_2,2S-uracil complex. However, for the 5X-uracil complexes, ν C(2)O and δ N(1)H disappear from the spectra, while ν C(4)O and δ N(3)H remain constant, indicating that the bonding sites in these compounds are C(2)O and N(1). The high frequency area, from 3600 to 2800cm^{-1}, contains several bands which can be assigned to ν N(X)H and νOH. The decrease in intensity of the ν N(X)H bands in this region corroborates the assignment of ring nitrogen deprotonation and coordination. Although IR data points to a large reduction in thioamide bands I-III for the 2,4-dithiouracil complex, involvement of C(2)S and/or C(4)S cannot be discriminated from the IR data. However, owing to the complete insolubility of this complex in most organic and inorganic solvents, a polymeric type structure is possible and coordination through both C(2)S and C(4)S is suggested. Magnetic evidence will be presented later that supports this contention for a polymeric interaction. Therefore, a shift in the bonding sites is observed from N(3)/C(2)S in the 6X,2S-uracil, and 2,4-dithiouracil complexes to N(1)/C(2)O in the 5X-uracil complexes. Although simultaneous coordination via N and S in mono-[85,86] and dithiouracil[87-9] metal complexes has been recently postulated, the

exact nature of the coordination has never been elucidated. Weber's contention[84] for monodentate coordination in 2S-uracil appears, therfore, unwarranted in light of the results presented here. The coordination found in the 5X-uracil metal complexes contrasts the monodentate bonding at C(4)O[75] and N(3)[77] of uracil with Hg(II).

Several inferences may be drawn from these results. First, nucleic acid bases act as donors towards transition metal ions. This donor property would allow them to interact with metals during transcription and/or translation processes[9] as well as processes involving nucleic acids (e.g., biological oxidations and reductions, charge carriers, enzyme activators, and control mechanisms[8,9]). Second, these nucleic acid bases behave as chelating agents. This suggests that they can also function as the coordinating (chelating) sites at RNA by metal complexes such as the cis-$Pt(amine)_2Cl_2$[122-4,128-9] complexes used as anticarcinogens. Since the N(1) chelating site is substituted by ribose in RNA (Fig. 1), the chelating ability of the uracil nucleotides is expected to be: 2,4-dithiouracil > 2S-uracil > uracil. Also since N(3) is involved in hydrogen bonding, the incorporation of 2S-uracil for uracil in RNA should allow a more effective disruption of the hydrogen bonding by metal ions like Cu(II) with a concomitant alteration in the functional capabilities possessed by these polynucleotides.

Complete tabulations of the visible-near IR bands in the 25,000 - 8,300 cm^{-1} region and EPR absorptions for all com-

plexes are given in Tables V and VI, respectively, at the end of Section E. The magnetic susceptibility data and $1/\chi$ vs. ^{T} plots of the 5X-uracils, and 6X,2S-uracil and 2,4-dithiouracil complexes are given in Tables XIII and XIV and Figures 12 and 13, respectively.

The range of the d-d transition band maxima for the 5X-uracils is: 15,400 - 14,700 cm^{-1}, and is consistent with tetragonally distorted octahedral Cu(II) complexes of approximate D_{4h} symmetry and can be assigned to the $^{2}E_{g}$ $(d_{xz,yz})$ $\longleftarrow$ $^{2}B_{1g}$ $(d_{x^2-y^2})$ transition. The transition to the $^{2}E_{g}$ level is usually[257] degenerate with the one to the $^{2}B_{2g}$ set, while the transition to the $^{2}A_{1g}$ level is at much higher energies, outside our spectrometer range or masked by ligand to ligand transitions. Similar ranges of the value of the d-d transition have been observed for approximately D_{4h} Cu(II) complexes having the O_4N_2 chromophores.[258-9]

The range of the d-d transition band maxima for the 6X, 2S-uracil and 2,4-dithiouracil complexes, 13,300 - 10,800 cm^{-1}, suggests a change in the geometry around the Cu(II) ion, from a tetragonally distorted D_{4h} symmetry (as seen for the 5X-uracil complexes) to a trigonally (rhombic) distorted configuration with approximate C_{2v} symmetry. In the latter case, the large size of the S atoms induces a symmetry low enough to allow d-d transitions from the $^{2}A_{1g}$ $(d_{x^2-y^2})$ ground state to either the $^{1}B_{1g}$ or $^{1}B_{2g}$ excited states. It should be noted that the electronic absorptions observed were very broad and may consist of two overlapping semi-degenerate tran-

sitions. Resolution of these bands could probably be attained only at temperatures below 20°K, but the new information would probably still be consistent with approximate C_{2v} symmetry. Furthermore, it is well known[259] that the ability of Lewis bases to coordinate to Cu(II) is in the order S > N > O and EPR measurements[260] suggest that the σ Cu-S bond is twice as covalent as the σ Cu-N bond. This indicates that in going from the O_2N_2 chromophore (in the 5X-uracils) to the S_2N_2 chromophore (in the 6X,2S-uracils and 2,4-dithiouracil), the overall ligand field strength and distortions from approximate D_{4h} symmetry increase with a concomitant splitting of the d levels and a lowering of the d-d transitions observed. An alternative explanation for the position of the d-d transition band maxima in these 6X, 2S-uracil and 2,4-dithiouracil complexes might be a change of coordination number upon complexation which effectively changes the site symmetry about the Cu(II) from distorted octahedral to tetrahedral or trigonal bipyramidal geometry. However, our EPR data unequivocally show the ground state to be $^2B_{1g}$ ($d_{x^2-y^2}$) since $g_z > g_{xy}$, precluding the possibility of these coordination number changes upon complexation. It is also unreasonable to postulate a loss in coordination number when the ligand changes from bidentate to tridentate as is expected for the 2,4-dithiouracil complex.

Information regarding the magnitude and nature of the magnetic interactions in these complexes was determined by variable temperature magnetic susceptibility measurements.

The results for the 5X-uracil, and 6X,2S-uracil and 2,4-dithiouracil series are plotted in Figures 12 and 13, respectively. As can be seen from the variation of the inverse susceptibility with temperature and the value of the temperature intercept, ϕ, both series display antiferromagnetic interactions (Fig. 10), however, the nature of these interactions is not the same in all cases.

For the $5NO_2$-uracil complex, a linear least squares plot of the experimental points allowed extraction of a temperature intercept, ϕ, of $-7.9^{\circ}K$ which is a measure of the interdimer interactions. The experimental data for the complex was then fitted to the Van Vleck equation for exchange coupled dimers according to eq. (12). Theoretical best fit values to g and -2J were 2.11 and $6.2cm^{-1}$, respectively. The value of -2J indicates that the overall exchange is rather weak and should manifest as a deviation from linearity only at temperatures below $12^{\circ}K$. The experimental EPR g value obtained was 2.16 and points to the correctness of the magnetic model used. The value of ϕ in the denominator of eq. (13) allows one to calculate the magnitude of the intradimer interactions within the $5NO_2$-uracil complex and leads to a -2J value of $0.1cm^{-1}$ (approximately zero) implying that lattice interactions (interdimer interactions) constitute the major pathway for the antiferromagnetic coupling with no localized dimeric interactions per se. A fit to the Ising model, eq. (16), was also acceptable but not as good as the Van Vleck model, indicating that our proposition of a lattice interac-

tion is correct.

The 5I-uracil complex was fitted to the Ising model for antiferromagnetically coupled straight chain polymers. The parameters g and -2J obtained from the theoretical best fit were 2.08 and 111cm^{-1}, respectively, as well as a 16% contribution from a monomer species. Therefore, these data suggest that the 5I-uracil complex is comprised of linear chains with 12 metal ions (molecular formulas) coupled in a moderately strong antiferromagnetic fashion with an essentially uncoupled ion at each end of the chain (average: 16% of total), Fig. 14. The antiferromagnetic coupling of the single $d_{x^2-y^2}$ electron on adjacent copper(II) centers can proceed via a superexchange mechanism[261] involving the d_{xz} and d_{yz} orbitals of adjacent metal centers and the π system of the 5I-uracil anion. The water molecules complete the dis-

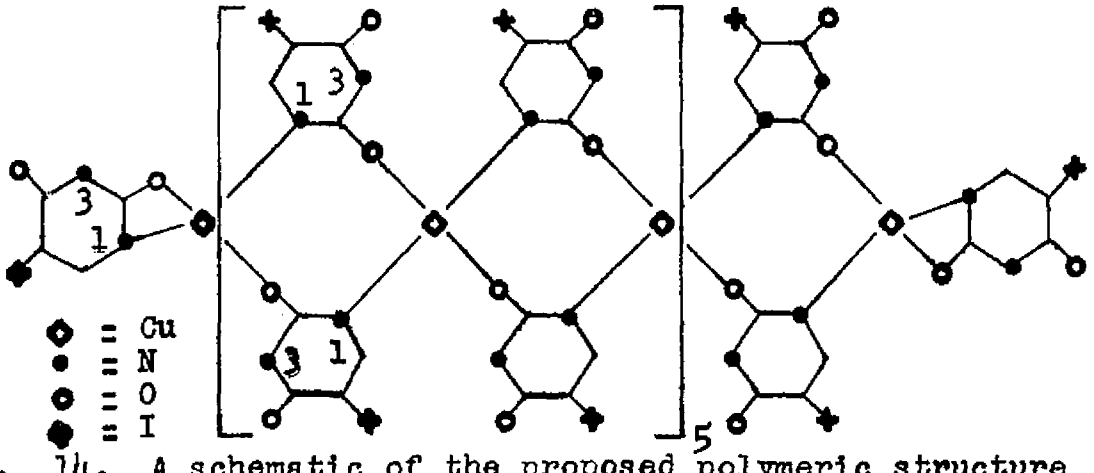


Fig. 14. A schematic of the proposed polymeric structure for the Cu-5I-uracil complex. Here the 5I-uracil anion acts as a bridging ligand connecting two adjacent metal centers.

torted octahedral geometry. The model suggests a long range interaction (larger and more extensive presumably than the

$5NO_2$-uracil system), however, the role the substituent at the 5 position plays in both these systems is uncertain. Apparently, their incorporation allows a more effective orientation between metal centers whereby long-range lattice interactions predominate at the expense of relatively short-range dimeric interactions. The experimental g value obtained was 2.13 and points to the correctness of the magnetic model used.

The magnetic data for the unsubstituted uracil complex did not fit any of the magnetic models outlined earlier and the curvature of the $1/\chi$ vs. T plot (Fig. 12) prompted a field dependence study at room temperature. The results of the study at three field strengths are shown in Table IXX and clearly demonstrate the ferromagnetic nature (Fig. 10) of the complex. At the highest field strength the coupling of spins in the lattice is broken and the individual spins are forced to align in the field direction leading to lower susceptibilities and lower effective magnetic moments. At lower external field strengths the ability to develop domains of spins is enhanced and leads to higher susceptibilities and higher effective magnetic moments. This cooperative phenomenon is the basis of the ferromagnetic interaction observed and can be ascribed to an ordering throughout the lattice.

It is noteworthy to point out that the 5X-uracil complexes display a lattice involvement of spin centers and suggests that the substituent at the 5 position is important in

determining the specific mode employed even though it is not possible at this time to determine if its involvement is electronic, steric, or a dual effect. In fact, Gel'man and Kustova[74] postulated a bridged interaction between a Pd(II) ammine dimer with 5F-uracil acting as the bridging ligand, however, only on the basis of elemental analysis. The EPR data for the 5X-uracils support the interactions postulated since they display the $\Delta M_s = \pm 2$ spin forbidden transition at half field, H_{MIN}, at approximately 1500G. This band is, in itself, enough proof of magnetic interactions in Cu(II) systems. The 5I-uracil complex is an exception showing no H_{MIN}. Apparently, the multiatom interaction in the case of the 5I-uracil complex yields several bands in the H_{MIN} region and precludes the resolution of any band in this case.

The 6X,2S-uracil complexes were all fitted to the Van Vleck dimer expression for exchange coupled dimers, eq. (12), and plots of $1/\chi$ vs. T are shown in Fig. 13 for this series. It was observed that the effective magnetic moment was very low at room temperature for every member in the series and magnetic measurements below room temperature would have given no useful information. In all cases, only data above room temperature were obtained. The curves appear essentially flat as the temperature is increased indicating little change in the susceptibilities over a large temperature range. A close inspection of Fig. 13 and of the magnetic data tabulation for these complexes in Table XIV shows them to be, as

mentioned before, very strongly coupled with effective magnetic moments due almost entirely to small amounts of monomeric impurities that are always present. A theoretical best fitting procedure was difficult in each case because very small changes in g values and/or % monomer impurity corrections used led to drastic changes in the molar susceptibilities. Also, the absolute values of the susceptibilities are so small, that they are very difficult to obtain and utilize with a high degree of accuracy. Therefore, we restricted our calculations to determining a lower limit for the exchange interaction parameter, -2J, for these complexes as shown in Table VI. Typically, -2J is 1400cm^{-1} and indicates a triplet excited state far removed from the singlet ground state. EPR signals for these coupled systems were weak as expected since the triplet state, the only magnetic state, is virtually unpopulated in relation to the ground state, but EPR absorptions characteristic of coupled systems were observed at approximately 1500G, corresponding to H_{MIN}, and at 5300G and 3700G, corresponding to the high field parallel and perpendicular transitions, respectively. EPR absorptions for these complexes are given in Table VI. Indeed, calculations based on a Boltzman distribution between ground and excited states showed that weak triplet state bands should be observed.

The 1/X vs. T data found for the 2,4-dithiouracil complex is given in Table XIV and plotted in Fig. 13. The fit to the Ising model for straight chain polymers was excellent

yielding respective values for the magnetic parameters g and $-2J$ of 2.02 and 700cm^{-1}. The criterion used to determine a best fit was a minimization of the standard deviation between calculated and experimental g values. A standard deviation in g of 0.0317 was obtained. The 9% monomer correction found implies an average chain length of 22 complex units which is more extensively coupled (lower effective magnetic moment) and polymerized than the 5I-uracil complex. This data, along with all the electronic, magnetic, and solubility data, strongly suggests that both S atoms are used in the coordination of Cu(II) nuclei and strongly supports the IR evidence for tridentate bonding by the ligand. This conclusion is in agreement with the bonding mode proposed very recently on a similar Cu(II) complex with 2,4-dithiouracil by Agarwala and Khullar.[89]

The EPR spectrum observed for this system was consistent with a triplet species approximately 700cm^{-1} above the ground state and displayed a half field transition, H_{MIN}, at approximately 1600G and a weak high field parallel transition at approximately 5400G. A proposed structure consistent with all the spectroscopic data for the 2,4-dithiouracil complex is shown in Fig. 15.

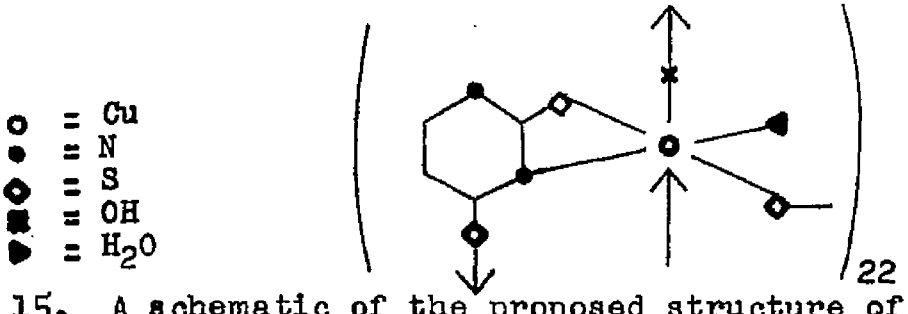


Fig. 15. A schematic of the proposed structure of the polymeric Cu(II) complex with 2,4-dithiouracil.

Table VII

IR Data For 6X,2S-Uracil and 2,4-Dithiouracil Ligands and Their Complexes (cm^{-1})

Free Ligand 2S-Uracil (LH)	Complexed Ligand $Cu(L)_2 \cdot 3H_2O$	Assignment
3470 m	3420 m	νOH H_2O
3106 s	3106 m	νCH &
2940 s,sp	2940 m	νNH
1701 s	1704 s,sh	νC(4)O &
1686 s	1684 s,sp	νC=C
1623 m	1633 m	δOH H_2O
-	1623 m,sh	νC=C
1558 s	1558 m	TAB I
	1535 m	
1524 w,sh	1524 w,sh	δN(1)H
1449 w,sp	1437 w	ν ring
1416 m,sp	1416 w,sh	δN(3)H
1391 vw,sp	1385 vw	δCH in-plane
1238 m,sp	1272 s	TAB II
	1238 w	
1211 s	1211 s	
1171 s,sp	1174 w	
1155 m	1155 w	
1068 w	1068 w	
1000 w	1000 w	ν ring
909 w	909 w	ν ring
890 w,bd	890 w,bd	
835 m,sp	835 w,sp	TAB III
	820 w,bd	
758 w,bd	758 w,bd	

Table VII (Cont'd)

Free Ligand 6CH_3,2S-Uracil (LH)	Complexed Ligand $Cu(L)_2 \cdot 2H_2O$	Assignment
3420 vw	3420 m	νOH H_2O
3125 s 2941 m	3030 w,sh 2890 m,bd	νCH & νNH
1639 s,bd	1656 s	νC(4)O & νC=C
-	1629 m	δOH H_2O
1558 s	1558 s,bd 1535 m,sh	TAB I
1524 w,sh	1500 w,sh	δN(1)H
1435 m,sh	1437	ν ring
1420 m	-	δN(3)H
1381 w	1385 w	δCH
1348 m,sp	1355 w	ν ring
1239 w 1199 s,sp 1190 s,sp 1186 w,sh 1166 s	1244 w 1193 m,sp 1186 w,sh 1166 s	TAB II
1040 w	1040 w,bd	ν ring
958 w	956 w,bd	ν ring
929 w	917 w	ν ring
870 w,bd 838 m,bd - 805 w,bd	882 w,bd 836 w 822 w,bd 795 vw	TAB III

Table VII (Cont'd)

Free Ligand $6C_3H_7,2S$-Uracil (LH)	Complexed Ligand $Cu(L)_2 \cdot 4H_2O$	Assignment
3450 w	3450 m	νOH H_2O
3125 m,bd 2941 m	3077 w 2976 w 2890 sh	νCH & νNH
1656 s	1656 s	νC(4)O &ν C=C
1629 m,sp	1635 sh	δOH H_2O
1558 s,bd	1570 w 1541 m	TAB I
1500 w,sh	1490 m	δN(1)H
1445 m	1441 m	ν ring
1416 w,sh	-	δN(3)H
1393 w	1385 w	δCH in-plane
1333 w	1340 w	ν ring
1279 w 1241 m 1190 s 1163 m	1272 m 1230 w,sh 1208 m,bd 1166 w	TAB II
1010 w	1015 w,bd	ν ring
960 w	953 w	ν ring
935 w	-	
885 w 861vw 818 m,bd 785 w	876 vw 858 vw 820 w,bd -	TAB III

Table VII (Cont'd)

Free Ligand $6NH_2$,2S-Uracil (LH)	Complexed Ligand $Cu(L)_2 \cdot 3CH_3OH$	Assignment
3425 w	3400 m	νNH_2 (asy.) & νH_2O
3335 w,sh	3335 w,sh	νNH_2 (sy.)
3135 m	3106 w,bd	νCH & νNH
	3049 w,bd	
2941 m	2907 m,bd	
1639 s	1653	$\nu C(4)O$, $\nu C=C$, & δNH_2
-	1630 m	δOH H_2O
1558 s	1558 m,sh	TAB I
	1543 s	
1500 w,sh	1500 w,sh	$\delta N(1)H$
1425 m,bd	1437 m,bd	ν ring
1405 w,sh	-	
1381 w,sp	1385 w	δCH in-plane
1348 m	1355 w	ν ring
1299 w	1295 w	-
1239 w,sp	1241 w,bd	TAB II
1199 s,sp	-	
1190 s,sp	1185 m,bd	
1166 s	1166 s	
1041 sh	-	ν ring
929 w	916 vw	ν ring
870 w,bd	864 vw	TAB III
838 m	836 vw	
806 w,bd	799 vw	
789 w	-	

Table VII (Cont'd)

Free Ligand 2,4-Dithiouracil (LH)	Complexed Ligand $Cu(L)(OH).H_2O$	Assignment
-	3425 m	νOH H_2O
3106 m	-	νCH & νNH
3012 m	-	
2924 m	-	
1610 s,sp	-	νC=C
1572 s	1563 w,sh	TAB I
1546 m,sp	1543 m,sp	δN(1)H
1493 m,sp	1493 vw	TAB I
1412 w	-	δN(3)H
1366 w	1366 w	ν ring
-	1381 s	TAB II
1252 m,sp	-	
-	1299 m	
1235 s	-	
1211 s	1188 m	
1126 vs	1155 m,bd	TAB III
1096 w	1092 vw	
980 w,sp	-	ν ring
859 w,sp	-	δCH out-of-plane
791 sh	806 w,bd	TAB IV
779 w,bd	778 w,sh	

Table VIII

IR Data For 5X-Uracil Ligands and Their Complexes (cm^{-1})

Free Ligand Uracil (LH)	Complexed Ligand $Cu(L)_2 \cdot H_2O$	Assignment
-	3597 w	νOH H_2O
3144 s,sp	3141 m,bd	νNH
3012 s	3012 s,bd	ν CH in-plane
1721 s,sp	1718 m,bd	ν C(2)O
1669 s	1678 s,bd	ν C(4)O
-	1597 m	δOH H_2O
1511 w,sp	1511 vw	δN(1)H
1420 m,sp	1420 m,sp	δN(3)H
1235 m,bd	1238 m,bd	ν ring
1217 w,sh	1215 w,sh	δ CH in-phase
1092 w,bd 1000 w	1092 w,bd 1002 w	ν ring
990 w	990w	ν , δ ring
758 w	758 w	ν ring

Table VIII (Cont'd)

Free Ligand 5I-Uracil (LH)	Complexed Ligand $Cu(L)_2 \cdot H_2O$	Assignment
3311 sh	3370 sh 3246 m	νOH H_2O
3125 m	3125	νNH
3067 s	3030 m	νCH in-plane
2857 m	2841 m	νCH out-of-plane
1748 s	1736 w,sh	νC(2)O
1700 s	1690 s,sh	νC(4)O
1650 s,bd	1640 s,bd	δOH H_2O
1608 s,sp	1603 s,sp	νC=C in-plane
1506 w	-	δN(1)H
1471 m,sp	1460 m	ν ring
1433 m,sp	1429 m	δN(3)H
1397 w	1397 w	δCH in-plane
1323 m,sp	1319 m	-
1214 s	1211 s	ν ring
1136 s	1131 s	-
992 w	992 vw	ν, δ ring
935 m	935 w	-
773 m	772 w,bd	ν, δ ring
753 s,sp	753 m	δCH
725 m	725 m	ν, δ ring

Table VIII (Cont'd)

Free Ligand $5NO_2$-Uracil (LH)	Complexed Ligand $Cu(L)_2 \cdot 2H_2O$	Assignment
3270 sh	3450 s	νOH H_2O
3160 w,sh	3160 sh	νNH
3086 s,bd	3049 m,bd	νCH in-plane
2841 m,sh	2874 m	νCH out-of-plane
1724 s,bd	-	νC(2)O
1685 s,bd	1685 s,sp	νC(4)O
1620 m	1600 m	δOH H_2O
-	1567 s	νNO (asy.)
1524 s,bd	-	δN(1)H
1497 sh	1497 m	ν ring
1453 m	1440 w,sh	δN(3)H
1412 s	1429 m,sp	ν ring
1359 s	1355 m	δ CH in-plane
1323 s	1323 s	ν C-NO_2
1232 s,bd	1292 s,bd	νNO (sym.)
1121 w	1199 w	ν ring
1002 w 978 m,bd 858 sh	1019 w 1007 w 861 w	ν ring
824 s,bd	-	δNO_2
779 w	775 w	ν, δ ring

Table XIII

Variable Temperature Molar Susceptibilities and Effective Magnetic Moments For 5X-Uracil Complexes

Compound	Temp (^{o}K)	χ (exp) ($\times 10^{-6}$)	$1/\chi$ (exp) ($\times 10^{4}$)	χ (calc) ($\times 10^{-6}$)	$1/\chi$ (calc) ($\times 10^{4}$)	Moment (exp)	Moment (calc)	Std. Dev. Between g values
$Cu(NO_2\text{-}U)_2 \cdot 2H_2O$	298.0	1488	672.0	1452	688.8	1.88	1.86	0.0316
	239.0	1835	544.8	1792	588.0	1.87	1.85	
	179.0	2461	406.4	2365	422.8	1.88	1.84	
	142.0	3051	327.7	2956	338.3	1.86	1.83	(Dimer)
	100.0	4163	240.2	4144	241.3	1.82	1.82	
	76.8	5101	196.0	5340	187.3	1.77	1.81	
	68.8	5889	169.8	5932	168.6	1.80	1.81	
	58.3	6861	145.7	6945	144.0	1.79	1.80	
	43.0	9055	110.4	9252	108.1	1.76	1.78	
	33.0	11780	84.9	11820	84.6	1.76	1.77	
	28.0	12300	76.9	13710	72.9	1.71	1.75	
	12.0	27810	36.0	27410	36.5	1.63	1.62	
$Cu(I\text{-}U)_2 \cdot H_2O$	298.0	1028	972.9	1130	885.2	1.57	1.64	0.0987
	234.0	1211	826.0	1305	766.1	1.51	1.56	
	159.0	1543	648.0	1567	638.1	1.40	1.41	
	118.0	1809	552.8	1744	573.2	1.31	1.28	(Ising)
	60.7	2534	394.7	2322	430.7	1.11	1.06	
	52.3	2866	348.9	2545	392.9	1.09	1.03	
	43.0	3222	310.4	2912	343.4	1.05	1.00	
	36.0	3621	276.2	3323	300.9	1.02	0.98	
	28.0	4186	238.9	4052	246.8	0.97	0.95	
	20.6	5077	197.0	5232	191.1	0.91	0.93	
	16.3	5815	172.0	6411	156.0	0.87	0.91	
	12.0	7105	140.8	8434	118.6	0.83	0.90	

Table XIII (Cont'd)

Variable Temperature Molar Susceptibilities and Effective Magnetic Moments For 5X-Uracil Complexes

Compound	Temp (°K)	χ (exp) (x10^{-6})	1/χ (exp) (x10^{4})	χ (calc) (x10^{-6})	1/χ (calc) (x10^{4})	Moment (exp)	Moment (calc)	Std. Dev. Between g values
$Cu(U)_2 \cdot H_2O$	297.0	1320	757.8	-	-	1.78	-	-
	215.0	1555	643.2	-	-	1.64	-	
	169.0	1738	575.3	-	-	1.54	-	
	122.0	1987	503.2	-	-	1.40	-	
	79.1	2352	425.2	-	-	1.22	-	
	65.3	2545	392.9	-	-	1.16	-	
	56.5	2701	370.3	-	-	1.11	-	
	44.9	2954	338.6	-	-	1.03	-	
	34.3	3149	317.6	-	-	0.93	-	
	27.3	3322	301.0	-	-	0.86	-	
	18.7	3567	280.3	-	-	0.73	-	
	15.0	3707	269.8	-	-	0.67	-	
	12.0	3980	251.3	-	-	0.62	-	

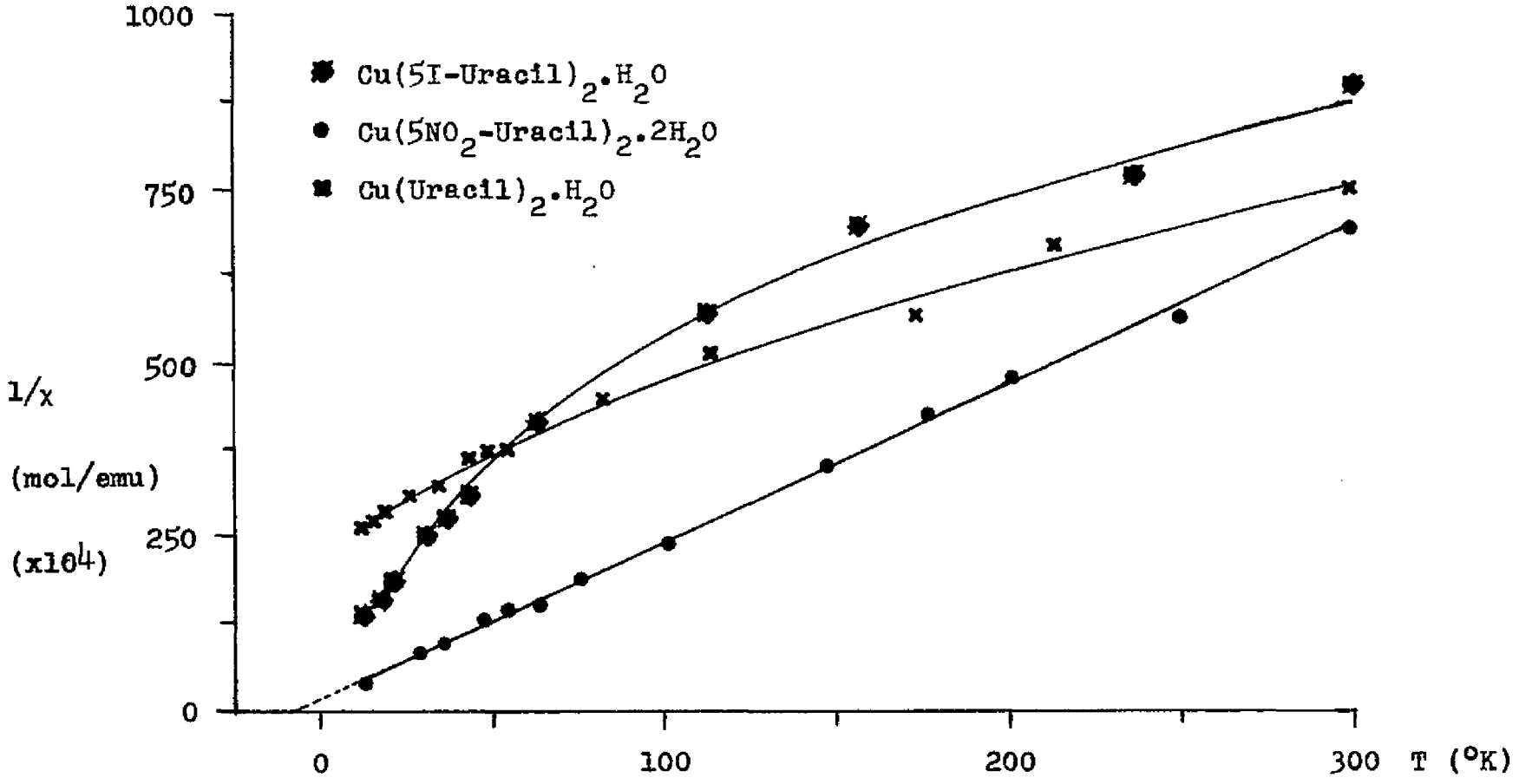


Figure 12. Inverse susceptibility vs. temperature for 5X-uracil complexes. Solid lines represent theoretical best fits to Ising model (X=I), and dimer model ($X=NO_2$); experimental best fit for X=H.

Table XIV

Variable Temperature Molar Susceptibilities and Effective Magnetic Moments For 6X,2S-Uracil and 2,4-Dithiouracil Complexes

Compound	Temp (°K)	χ (exp) (x10^{-6})	1/χ (exp) (x10^{4})	χ (calc) (x10^{-6})	1/χ (calc) (x10^{4})	Moment (exp)	Moment (calc)	Std. Dev. Between g values
Cu(Dithiouracil)(OH).H_2O	294.0	315.9	3166	332.4	3008	0.86	0.88	0.0318
	321.0	313.0	3195	320.4	3121	0.90	0.91	
	347.0	309.9	3227	311.1	3214	0.93	0.93	
	365.0	309.9	3227	305.7	3271	0.95	0.94	(Ising)
	384.0	307.6	3251	300.8	3325	0.97	0.96	
	422.0	298.9	3346	292.9	3415	1.00	0.99	
	450.0	288.7	3464	288.4	3468	1.02	1.02	
	463.0	292.0	3425	286.6	3489	1.04	1.03	
Cu(6C_3H_7,2S-Uracil)$_2$.$4H_2O$	293.0	138.6	7216	150.4	6651	0.57	0.59	0.117
	323.0	152.8	6546	145.8	6861	0.63	0.61	
	349.0	144.3	6932	143.8	6955	0.63	0.63	
	372.0	156.1	6407	143.4	6975	0.68	0.68	(Dimer)
	395.0	146.6	6820	144.0	6944	0.68	0.67	
	424.0	150.4	6649	146.1	6843	0.71	0.70	
	471.0	136.2	7341	151.9	6584	0.72	0.76	
Cu(2S-Uracil)$_2$.$3H_2O$	299.0	117.7	8493	118.0	8476	0.53	0.53	0.162
	324.0	122.5	8164	113.5	8810	0.56	0.54	
	354.0	111.2	8996	109.0	9177	0.56	0.56	
	404.0	94.7	1056	102.9	9717	0.55	0.58	(Dimer)

Table XIV (Cont'd)

Variable Temperature Molar Susceptibilities and Effective Magnetic Moments For 6X,2S-Uracil and 2,4-Dithiouracil Complexes

Compound	Temp (°K)	χ (exp) (x10^{-6})	1/χ (exp) (x10^{4})	χ (calc) (x10^{-6})	1/χ (calc) (x10^{4})	Moment (exp)	Moment (calc)	Std. Dev. Between g values *
Cu(6NH_2,2S-Uracil)$_2$·3CH_3OH	289.0	4.19	238700	60.00	16670	0.099	0.118	-
	315.0	15.79	63330	60.00	16670	0.199	0.123	
	351.0	16.73	59770	60.00	16670	0.216	0.130	
	373.0	15.79	63330	60.00	16670	0.216	0.134	(Dimer)
	405.0	17.39	57500	60.00	16670	0.238	0.140	
	433.0	23.00	43480	60.00	16670	0.283	0.144	
	460.0	18.93	52830	60.00	16670	0.264	0.149	
Cu(6CH_3,2S-Uracil)$_2$·2H_2O	297.0	2.69	371700	5.34	187300	0.080	0.113	-
	313.0	8.86	112900	7.25	138000	0.149	0.135	
	346.0	13.80	72460	12.34	81070	0.196	0.185	
	372.0	20.70	48310	17.42	57410	0.248	0.228	(Dimer)
	418.0	25.60	39060	28.47	35130	0.293	0.309	

* Fixed g values used

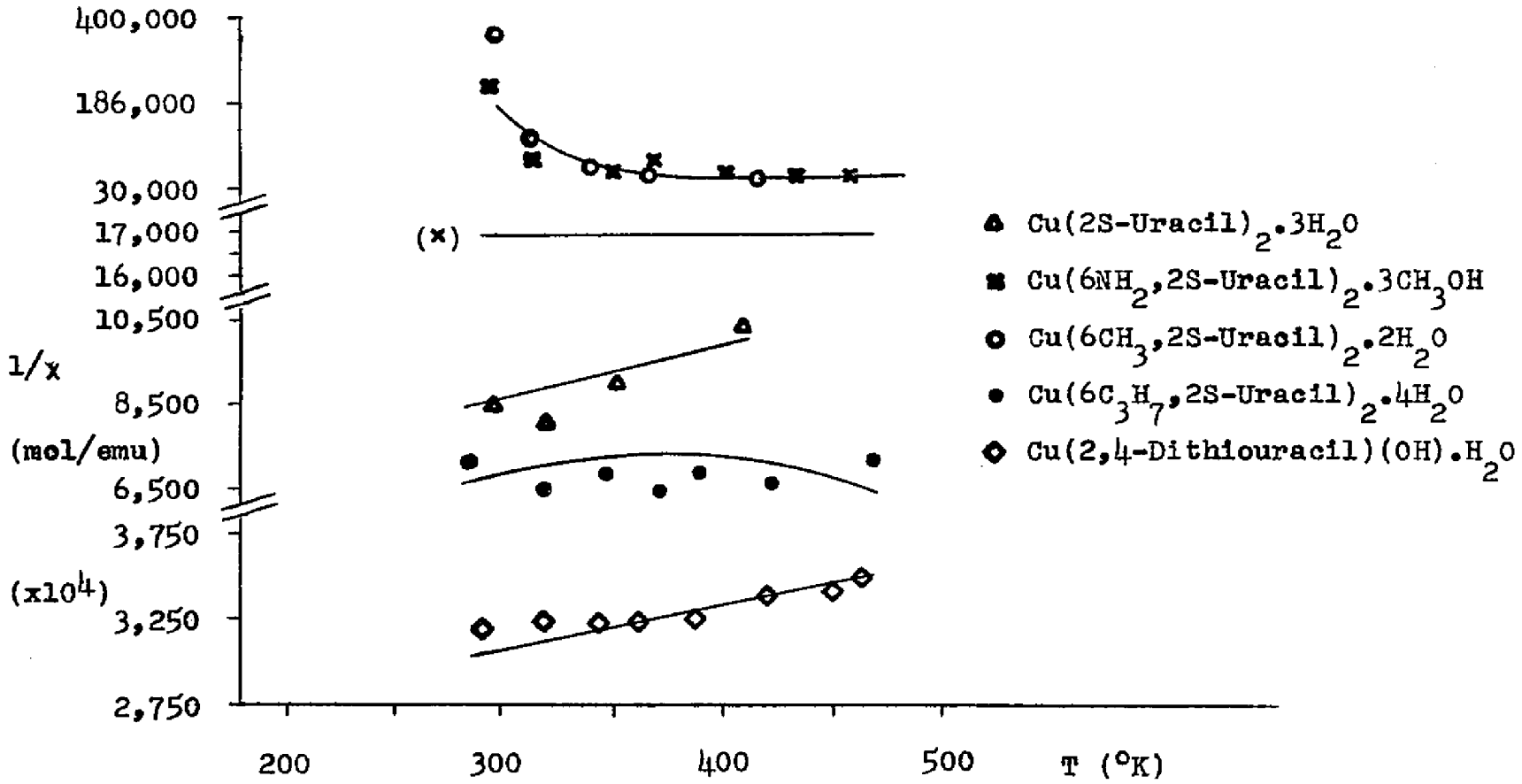


Figure 13. Inverse susceptibility vs. temperature for 6X,2S-uracil complexes and 2,4-dithiouracil complex (DTU). Solid lines represent theoretical best fits to Ising model (DTU), and to dimer model (X=H, NH_2, CH_3, C_3H_7).

B. $Cu(Cytosine)_2Cl_2$; $Cu(2S\text{-}Cytosine)Cl_2$; $Cu(2S\text{-}Cytosine)_2.2H_2O$.

The first series of Cu(II) coordination compounds with 2S-cytosine, $Cu(2S\text{-}cytosine)Cl_2$ and $Cu(2S\text{-}cytosine)_2.2H_2O$, were prepared and characterized. This shows that 2S-cytosine acts as a Lewis base, and like the uracil and thiouracil systems described in Section A, substantiates the evidence that metal coordination compounds with pyrimidine bases can be formed and isolated. A complex previously prepared and examined by X-ray crystallography by Carrabine and Sundaralingam[44,47], $Cu(cytosine)Cl_2$, was also prepared and studied here.

A complete tabulation of the major IR bands for these complexes is given in Table IX. Assignment of these bands was made by interpolation between cytosine and 2S-cytosine and by direct comparison to previously published data for cytosine[262-3] and 2S-cytosine.[264] The coordination sites were determined by comparison between free ligand and coordinated ligand.

The main area of interest is the region between 1700 and 800cm^{-1} where the following bands (cm^{-1}) are located: for cytosine, $\nu C(2)O$, 1661; δNH_2, 1706; $\delta N(1)H$, 1520; $\nu C\text{-}N$ (ring), 1466, 1362; and for 2S-cytosine, δNH_2, 1656; $\delta N(1)H$, 1543, ν thioamide I, 1225; ν thioamide II, 800. A second area of interest lies between 3600 and 2800, where $\nu N(X)H$ at 3150, νOH at 3100, and νNH_2 (asy. and sy.) at 3400 are located.

For the cytosine complex $\nu C(2)O$ decreases in intensity

pointing to C(2)O coordination. The ring vibrations are dramatically reduced in intensity and point to a large perturbation. However, the presence of δNH_2 at 1678cm^{-1} and δN(1)H at 1520cm^{-1} precludes their involvement in coordination and suggests N(3) as the site of complexation. The presence of the νNH_2 (asy. and sy.) at 3425 and 3333cm^{-1}, respectively, is further evidence for the non-involvement of the NH_2 group. This indicates C(2)O and N(3) coordination and is in agreement with the known[44,47] bonding sites for this complex. In addition, the X-ray structure determination[44,47] uncovered additional coordination by the two chloride counterions completing a distorted octahedron around Cu(II).

Both 2S-cytosine ligands coordinate differently from the cytosine but similarly to each other. The reduction in intensity and shift to lower energy of δN(1)H at 1543cm^{-1} coupled with the sharp reduction of the high frequency νNH at 3120cm^{-1} points to N(1) coordination. The involvement of the NH_2 group is ruled out since δNH_2 at 1650cm^{-1} and νNH_2 (out-of-plane) at 3333cm^{-1} are present in both complexes. The severe reduction of thioamide bands I and II at 1230 and 800cm^{-1}, respectively, points unequivocally to C(2)S coordination. Therefore, the coordination is via C(2)S and N(1).

It is interesting to note that within the pyrimidine coordination compounds studied, in the uracil (cytosine) series, the effect of replacing a keto oxygen on C(2) with a thio sulfur is to interchange the preference for coordination between N(1) (N(3)) for keto to N(3) (N(1)) for thio. The implica-

tion is that substantial electronic changes are encountered in these pyrimidine systems leading to specificity in bonding when the replacement of O by S has been affected and points to a possible means of selectivity in bonding and biological function. As N(1) is coordinated to a sugar moiety in DNA and RNA (leaving open only the N(3) site for coordination), the complexation ability of Cu(II) with these macromolecules is expected to follow the order: cytosine > 2S-cytosine.

The range of the d-d transition band maxima for these complexes is 16,400 - 15,200cm^{-1} (Table V). The absorptions can be assigned to the $^2E_g \leftarrow {}^2B_{1g}$ transitions in an axially distorted octahedral Cu(II) system. An interesting feature is the shift to higher energies (blue shift) of approximately 400cm^{-1} upon replacing oxygen by a sulfur donor in the chloride complexes. It is apparent that the thio group in the plane effects a larger ligand field than does the keto group and a high binding affinity for Cu(II). Similar blue shifts have recently been reported[265] in comparisons of Cu(II) complexes with peptides and sulfhydryl peptides. This comparison, however, can only be made if the crystal structures of these complexes are known, that is, if the overall coordination geometry around Cu(II) remains otherwise the same. As will be apparent, in light of the EPR and magnetic susceptibility data, the coordination geometry does change between the cytosine and 2S-cytosine, with a probable substitution of O atoms or chloride ions in the coordination sphere by S atoms from the 2S-cytosine ligands. These substitutions by S atoms

are expected to introduce distortions away from planarity (in the xy plane) and away from pseudo D_{4h} symmetry.

The EPR data for the cytosine and 2S-cytosine complexes are given in Table VI. Full field absorptions at 2990 and 3208G yielding values of $g_z = 2.23$ and $g_{xy} = 2.08$, point to an axial distortion about the copper(II) center for the cytosine complex ($g_z > g_{xy}$). The EPR spectra of both 2S-cytosine complexes were unusual and similar as they did not show parallel or perpendicular hyperfine coupling but only one very broad band which is indicative of dipolar coupling between copper(II) centers with axial symmetry. However, the spectra of these systems can be explained as if they originated from monomeric species similar to the polymers.

The tabulated magnetic susceptibility data for these systems are given in Table XV. Plots of $1/\chi$ vs. T for these systems are shown in Fig. 16. The cytosine complex was fitted to the Van Vleck equation for exchange-coupled dimers, eq. (12), and yielded theoretical best fits to g and -2J of 2.07 and 6.2cm^{-1}, respectively. As can be seen the agreement between theory and experiment is excellent and the small standard deviation in the g values of 0.0155 points to the correctness of the magnetic model employed for this system. As before with the $5NO_2$-uracil complex, the nature of the exchange interaction was elucidated by substituting $\phi = -3^{\circ}K$, obtained from a linear least squares fit of the experimental $1/\chi$ data as a function of temperature, into eq. (13). The results demonstrated that the exchange energy 2J approached zero (1.6

cm^{-1}) indicating that the interactions found in this complex are of a lattice type and not between discrete Cu(II) dimers and may well proceed by a mechanism similar to that found in the $5NO_2$-uracil complex. A good fit to the Ising model for antiferromagnetically exchange-coupled, straight-chained polymers was also obtained indicating that the interactions are of a polymeric nature throughout the lattice. The magnitude of this polymeric interaction was small (approximately $7cm^{-1}$) and is apparently of a dipolar nature.

Both 2S-cytosine complexes were fitted to the Van Vleck dimer equation, eq. (12), with small amounts of monomeric impurity corrections (approximately 4%). The $1/\chi$ vs. T plots clearly demonstrate the small magnitude of susceptibility as well as the almost imperceptible change in susceptibility as the temperature is varied through a large range. The general characteristic of these plots is reminiscent of those found for the complexes containing sulfur ligands mentioned before in Section A. Since small changes in g and % monomeric impurity corrections had drastic effects on the values of -2J, lower limits to this parameter were calculated only and found to be $1400\pm200cm^{-1}$. Again, these 2J values are very similar to those obtained in the complexes coordinated via an S stom and indicates an extremely strong coupling in these systems.

The EPR spectra of the 2S-cytosine complexes were very weak and similar to each other displaying an H_{MIN} at approximately 1480G and having high field parallel and perpendicular transitions at about 4400G. These data are consistent

with spin coupled S = 1 Cu(II) systems and is further support for exchange interactions that occur principally through coupling within a dimer unit rather than through the lattice.

Table IX

IR Data For 2X-Cytosine Ligands and Their Complexes (cm^{-1})

Free Ligand Cytosine (LH)	Complexed Ligand $Cu(LH)_2Cl_2$	Assignment
3425 s	3378 s	νNH_2 (asy.)
3333 s	3330 m	νNH_2 (sy.)
3185 s	3185 s,bd	νNH, νCH
2809 s	2907 w	-
1678 m	1678 m	δNH_2
1661 s	1656 m	δ C(2)O
1634 s,sh	1629 s	ν C=C
1520 s	1520 s	δ N(1)H
1466 s	1466 w,sp	ν ring
	1462 w,sp	
1362 s,sp	1362 w,sp	
1276 s	1263 w	δ CH out-of-plane
1235 s	1235 w,sp	ν ring
1096 w	1098 w	ν ring
779 s,bd	779 w,sh	ν, δ ring
	775 m	

Table IX (Cont'd)

Free Ligand 2S-Cytosine (LH)	Complexed Ligand $Cu(LH)Cl_2$	Assignment
3333 s,bd	3289 s,bd	νNH_2 (asy. & sy.)
3125 m	3145 w,bd	νNH, νCH
1656 s,sh	1656 s,sh	δNH_2
1639 s 1567 s	1639 m 1558 sh	$\nu C{=}C$, $\nu C{=}N$
1543 m	1541 w	$\delta N(1)H$
1502 m	1502 w	ν ring
1302 s 1226 s 1176 s	1309 m,bd 1232 m,bd 1176 w	TAB I
1080 w	1089 w,bd	ν ring
923 w	921 vw	-
853 w 799 m,bd	- 785 vw	TAB II

Table IX (Cont'd)

Free Ligand 2S-Cytosine (LH)	Complexed Ligand $Cu(L)_2 \cdot 2H_2O$	Assignment
-	3480	νOH H_2O
3430 s 3333 s	3311 s,bd	νNH_2 (asy. & sy.)
3125 m	3125 w,bd	νNH, νCH
1656 s,sh	1656 s	δNH_2
1639 s 1567 s	1639 s 1558 sh	νC=C, νC=N
1543 sh	-	δN(1)H
1502 m	1502 w	ν ring
1302 s 1225 s 1176 s	1302 w,bd 1225 w,bd 1181 w	TAB I
1080 w,bd	-	ν ring
923 w	912 vw	-
853 w 799 m,bd	- 790 sh	TAB II

Table XV

Variable Temperature Molar Susceptibilities and Effective Magnetic Moments For 2X-Cytosine Complexes

Compound	Temp (°K)	χ (exp) (x10^{-6})	1/χ (exp) (x10^{4})	χ (calc) (x10^{-6})	1/χ (calc) (x10^{4})	Moment (exp)	Moment (calc)	Std. Dev. Between g values
Cu(Cytosine)$_2$Cl$_2$	299.0	1330	752.0	1395	716.7	1.78	1.83	0.0155
	204.0	1917	521.6	2010	497.5	1.77	1.81	
	151.0	2583	387.2	2684	372.6	1.77	1.80	
	95.0	4056	246.6	4192	238.5	1.76	1.78	(Dimer)
	78.5	4930	202.8	5034	198.6	1.76	1.78	
	64.2	5892	169.7	6100	163.9	1.74	1.77	
	54.7	6938	144.1	7102	140.8	1.74	1.76	
	44.9	8328	120.1	8552	116.9	1.73	1.75	
	36.1	10440	95.7	10470	95.5	1.74	1.74	
	25.5	14070	71.1	14340	69.7	1.69	1.71	
	18.0	19870	50.3	19320	51.8	1.69	1.67	
	12.0	26340	38.0	26340	38.0	1.59	1.59	
Cu(S-Cytosine)Cl$_2$	291.0	140.4	7122	116.2	8602	0.57	0.52	0.669
	327.0	133.6	7487	112.4	8894	0.59	0.54	
	356.0	122.4	8172	111.1	9004	0.59	0.56	
	403.0	73.7	13570	111.7	8956	0.49	0.60	(Dimer)
Cu(S-Cytosine)$_2$ .2H$_2$O	290.0	188.7	5299	171.3	5838	0.66	0.63	0.254
	339.0	185.7	5385	158.6	6307	0.71	0.66	
	367.0	158.4	6311	154.1	6489	0.68	0.67	
	403.0	144.5	6918	150.9	6629	0.68	0.70	(Dimer)
	445.0	118.7	8423	150.0	6667	0.65	0.73	

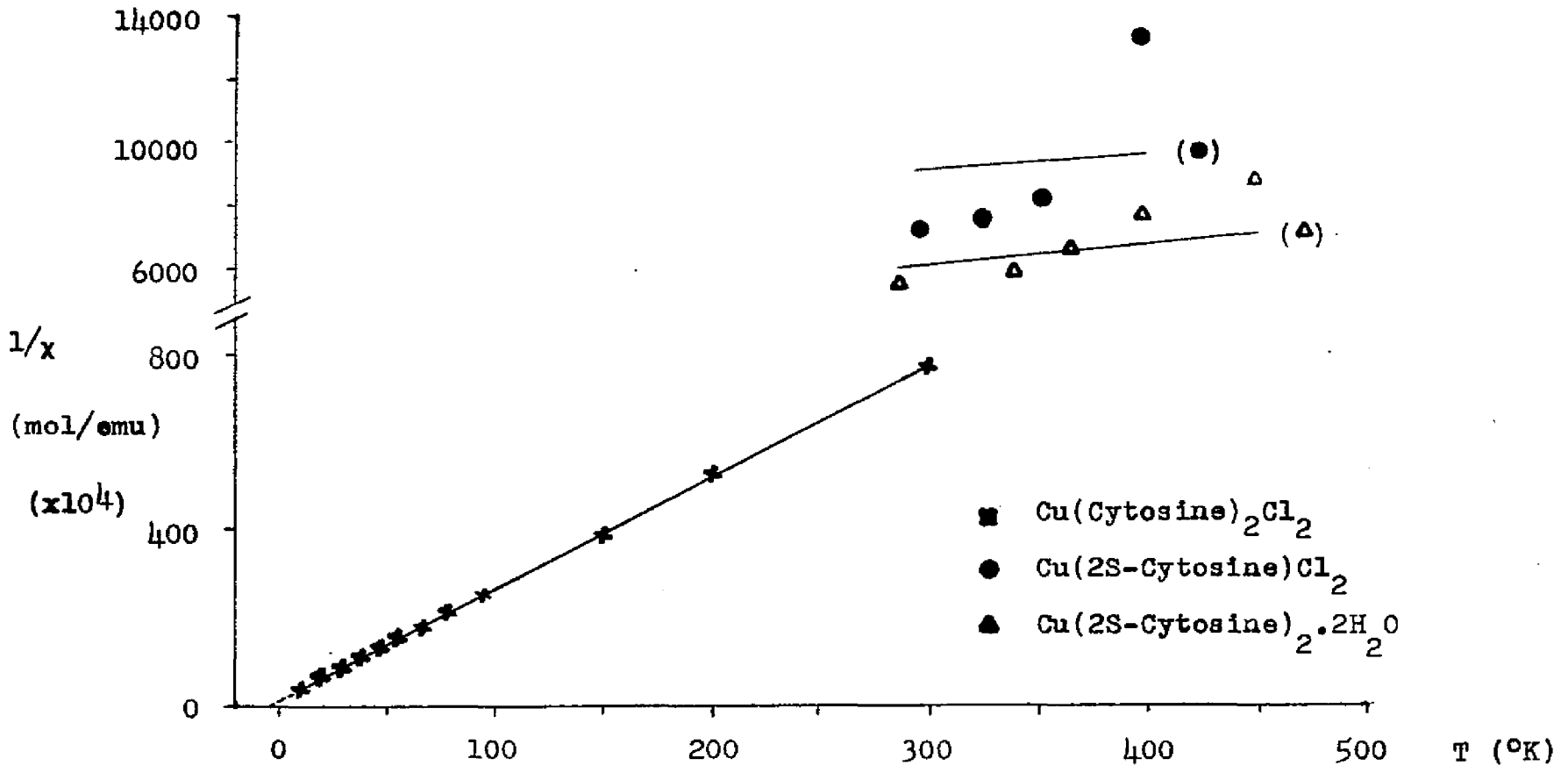


Figure 16. Inverse susceptibility vs. temperature for 2X-cytosine complexes. Solid lines represent theoretical best fits.

C. $Cu(L)(OH).xH_2O$, where L = cytidine, adenosine, xanthosine, and inosine; and x = 2, 1/2, 2, and 1, respectively.

The first series of hydroxyl-bridged Cu(II) nucleoside complexes and the first report of metal complexes with xanthosine and inosine are given here, demonstrating that metal nucleoside interactions are real and do not involve sugar coordination.

Tabulations of the major bands in the IR for cytidine, adenosine, xanthosine, and inosine and their complexes are given in Table XI. IR band assignments were arrived at by interpolation among the spectra of the free ligands as well as by reference to previously published data on these ligand systems.[266-71] The coordination sites were determined by comparison between free ligand and coordinated ligand.[272-5]

The main areas of interest (cm^{-1}) are: νOH (bridging), 3500; νNH_2 (asy. and sy.), 3350; δNH_2, 1650; ν C(6)O, 1710; νC(2)O, 1650; δ N(1)H, 1535; δ N(3)H, 1520; ν ribose (deg.), 1130 - 1000; ν ribose (sy.), 890 - 840; δ OH (bridging), 950.

For the cytidine complex C(2)O involvement is seen as the carbonyl stretch at 1639cm^{-1} is dramatically reduced, however, no evidence for NH_2 participation is seen since the band at 1655cm^{-1} is present in both ligand and complex. The exclusion of amino nitrogen coordination is also evidenced by the presence of the νNH_2 stretch (asy. and sy.) at 3356cm^{-1}. Ring participation at N(3) is supported by the

perturbation of the ring vibrations at 1600, 1502, and 1433 cm^{-1} to lower frequencies. Exclusion of sugar involvement is borne out by the presence of both the degenerate and symmetric ribose stretches at 1134, 1096, 1054, and 980, and 859cm^{-1}, respectively, in both free and coordinated ligand. Conclusive proof for the presence of bridging OH groups results from the work of Ferraro and Walker[272] who interpreted the IR spectra of a large series of OH-bridged Cu(II) complexes of 1,10-phenanthroline and 2,2'-bipyridyl. They showed that in spite of the broad and strong absorption of the water band present at approximately 3500cm^{-1} in the hydrated complexes, a shoulder very often appeared on the high-frequency side of this water band and was assigned to the OH stretch in the bridging OH groups. Strong evidence was also presented for the assignment at 950cm^{-1} for the bending OH vibration in these hydroxyl-bridged copper(II) dimers. In light of these results, hydroxyl bridging for the cytidine complex was concluded from the presence of a shoulder at 3550cm^{-1}; no absoprtion at 950cm^{-1} was observed, however.

The involvement of the C(2)O and N(3) atoms in the cytidine complex suggests that they are the preferred sites for complexation to the cytosine moiety since this pyrimidine ring coordinates at those sites regardless of the presence of the ribose group.

In the adenosine complex, evidence for complexation at N(1), N(3), or N(7) comes from the perturbation of the ring stretching modes at 1605, 1572, and 902cm^{-1}. In adenosine,

NH ring stretching absorptions are not present and cannot be used to locate the exact site of ring nitrogen coordination. However, considering the results of crystallographic and other spectroscopic studies on adenosine and $9CH_3$-adenine (an adenosine analog), Table IV, and the relative acidity of N(1) and N(7) (N(7) has the proton in neutral adenine), the coordination site can be assigned as N(7). Involvement of NH_2 in coordination is precluded by the presence in ligand and complex of νNH_2 (asy. and sy.) at 3333cm^{-1} and δNH_2 at 1656cm^{-1}. As with the cytidine complex, no evidence for sugar involvement is seen as both the degenerate and symmetric ribose stretches in the region 1120 - 1030cm^{-1} and 860 - 840cm^{-1}, respectively, are present. As previously described above, a high-frequency shoulder at 3550cm^{-1} supports OH bridging in this complex.

For the xanthosine complex carbonyl oxygen participation is evidenced by the drastic reduction of the νC(6)O and νC(2)O at 1712 and 1689cm^{-1}, respectively. Nitrogen involvement at N(1) and N(3) is precluded by the presence of δN(1)H and δN(3)H at 1535 and 1524cm^{-1}, respectively. Support for OH bridging in this complex comes from the high-frequency shoulder at 3538cm^{-1}. No evidence for sugar involvement in the complex is found as both the degenerate and symmetric ribose stretches at 1114 - 970cm^{-1} and 901 - 870cm^{-1} are unchanged upon complexation.

The IR data for the inosine complex points to C(6)O coordination as the νC(6)O is lost at 1712cm^{-1} upon complexa-

tion. This assignment is corroborated by the reduced intensity of the combination band (νC(6)O and ν ring) at 1695cm^{-1}. The δ N(1)H at 1535cm^{-1} precludes the participation of N(1) as a bonding site in the complex. Support of OH bridging in this complex comes from the δ OH (bridging) at 943cm^{-1} found in the complex; the high-frequency shoulder of ν OH (bridging) was not observed because of the extreme broadness of the absorptions in that region. The degenerate and symmetric sugar stretches found in both the ligand and complex at 1121 - 1040cm^{-1} and 890 - 870cm^{-1}, respectively, suggest no bonding through the ribose oxygens.

The data clearly show that for all the nucleoside complexes discussed here, ribose sugar involvement in metal complexation with Cu(II) is not found. This is interesting in light of the work of Berger and Eichhorn[167] where the 2',3' cis diol function was implicated as the pathway for the "recognition" of RNA polymerase by $Cu(Ac)_2$, however, there is no evidence in the solid state to support this contention.

The bonding through the maximum number of carbonyl oxygen atoms available in the xanthosine and inosine complexes at the exclusion of ring nitrogens is without precedent (see Tables II and IV) in Cu(II) complexes with nucleosides,[42] however, this selectivity in binding, at the expense of chelation, may result from the complexation pH required in this work. Evidence for the pronounced effect pH has on selectivity in site coordination has been found in the recent work by Hadjiliadis and Theophanidis[276] with solid Pt(II)

complexes of inosine and guanosine.

A complete tabulation of the visible and near IR absorption bands for these complexes is given in Table V. The range of the d-d band maxima is: 15,600 - 14,200cm^{-1} and can be assigned to the $^2E_g \leftarrow {}^2B_{1g}$ transition for tetragonally distorted octahedral Cu(II) complexes. Further support for a distorted octahedral complex is seen from the low-energy shoulders at 13,500 - 12,700cm^{-1} for all these systems (except adenosine) which can be assigned to the $^2B_{2g}(d_{xy}) \leftarrow {}^2B_{1g}$ $(d_{x^2-y^2})$ transition. The characteristic axial EPR signals observed ($g_z > g_{xy}$) for all these complexes is futher support for tetragonally distorted octahedral coordination in these systems. The relative positions of the d-d absorptions in these complexes suggest that the average ligand field strength of the ligands decreases in the order: inosine > cytidine > xanthosine > adenosine. The range of positions of these absorptions also suggests that the OH bridging occurs in plane and not out of plane, since the latter arrangement about copper(II) leads to distortions towards T_d and/or C_{2v} symmetry and a concomitant lowering in energy of the d-d band maximum.

A tabulation of the variable temperature magnetic susceptibility data is given in Table XVI and plots of $1/\chi$ vs. T are shown in Fig. 17 for these complexes. Attempts to fit the static magnetic susceptibility data to the magnetic models previously described were unsuccessful in all cases. Inspection of the $1/\chi$ vs. T plots suggested that the curvature found for all four complexes is the result of a cooperative

phenomenon that is manifested throughout the entire temperature range studied. This prompted a field dependence study at room temperature with these systems and the results are given in Table IXX. In all cases, a field dependence on the molar susceptibilities and effective magnetic moments at low field strengths were higher than expected while the molar susceptibilities and effective magnetic moments at high field strengths were lower than expected as is typical for ferromagnetically coupled systems.

These results indicate that the mere presence of a non-bonded ribose moiety in these systems induces the cooperative phenomenon to occur in these polymeric complexes and suggests that this is probably the result of more favorable crystal packing or intermolecular hydrogen bonding since, as previously discussed, the ribose group is not actually employed in bonding to the metal ion. There are several examples[277-8] in the literature where Cu(II) coordination compounds behave in an analogous fashion as that observed here, but these are the first recorded cases of ferromagnetism in any metal complex of a nucleic acid base nucleoside. It would be interesting to try to elucidate the nature of these ferromagnetic lattice interactions, but this extension of this work will have to wait until more theoretical developments are made in this field. Supporting evidence for the presence of spin-spin coupling in these systems is obtained from EPR data. In all cases, the presence of H_{MIN} signals at approximately 4500G and 5300G, respectively, is consistent with a coopera-

tive phenomenon leading to coupling between spin centers. The D and g values obtained from the spectra of these coupled species are consistent with the proposed geometry of these complexes and have typical values of $0.14cm^{-1}$ and 2.13, respectively. The EPR data obtained for these nucleoside complexes is tabulated in Table VI.

Table XI

IR Data For Nucleoside Ligands and Their Hydroxyl-bridged Complexes (cm^{-1})

Free Ligand Cytidine (LH)	Complexed Ligand $Cu(L)(OH).2H_2O$	Assignment
-	3550 sh	νOH (bridging)
3497 w	3497 m,sh	νOH H_2O
3367 s 3295 s	3356 s,bd	νNH_2 (asy. & sy.), νOH H_2O
3247 s,bd 3105 m	3185 - 3090 m,bd	νOH
2941 m	2907 w	νCH_2
1655 m,sh	1656 m,sh	δNH_2
1639 s,bd	-	ν C(2)O
1600 s,bd	1596 m,sh	ν C=C
1502 s	1493 w	ν ring
1433 w,sp	1439 vw	ν C-N
1292 s	1282 m,bd	δ CH out-of-plane
1247 w	-	ν ring
1214 m	1205 m,bd	$\nu C\text{-}NH_2$
1134 m,bd 1099 s,bd 1053 s,bd 982 m,bd	1134 w,sh 1096 s,bd 1054 m,bd 980 w	ν ribose (deg.)
942 m,bd	943 vw	-
870 m,sp 853 m,sp 838 w	859 w,bd	ν ribose (sy.)
790 s	785 m,bd	δ ring wag

Table XI (Cont'd)

Free Ligand Adenosine (LH)	Complexed Ligand $Cu(L)(OH).1/2H_2O$	Assignment
-	3540 sh	νOH (bridging)
3430 s 3333 s	3356 s,bd	νNH_2 (asy. & sy.), νH_2O
3205 s	3205 s	νOH
2941 s	2924 m	νCH_2
1656 s	1656 s	δNH_2
1605 s	1603 m	ν ring
1572 s,sp	1577 m,bd	νC=C, νC=N
1477 s	1479 w	ν ring
1333 s	1333 w	-
1302 s	1289 w	-
1208 s	1208 w	$\delta C-NH_2$
1125 s 1106 s 1055 s 1035 s	1118 s,bd 1105 s,bd 1055 m 1020 m,bd	ν ribose (deg.)
902 s	898	ν ring
857 w 842 m	859 w,sh -	ν ribose (sy.)
793 m 765 s	785 m	δ ring wag

Table XI (Cont'd)

Free Ligand Xanthosine (LH)	Complexed Ligand Cu(L)(OH).$2H_2O$	Assignment
-	3538 sh	νOH (bridging)
3497 s,sp	3484 s,sp	νOH H_2O
3289 s 3125 s	3257 s,bd 3155 m,sh	νCH, νNH, νOH
2959 m	2959 w	νCH_2
1712 vs	1712 w,sh	νC(6)O
1689 vs	1689 w,sh	νC(2)O
1658 m,sh	1658 sh	ν ring
1608 w	-	ν ring
1535 w	1535 w	δN(1)H
1524 w	1524 w	δN(3)H
1462 w,sp	1462 w,sp	-
1302 w 1175 m,sp 1147 w	- 1176 w,bd -	ν ring
1114 m 1079 s 1046 m 978 m	1129 m,bd 1075 s 1053 m 980 m	ν ribose (deg.)
916 w	918 vw,sh	ν ring
901 w 872 w	- 862 w	ν ribose (sy.)

Table XI (Cont'd)

Free Ligand Inosine (LH)	Complexed Ligand Cu(L)(OH).H_2O	Assignment
3500 w	3500 s,bd	νOH H_2O
3333 m 3086 s	3401 m,bd 3125 m,bd	νCH, νNH, νOH
2924 s	2933 w,sh	
1712 vs	1718 w,sh	νC(6)O
1695 s	1686 w,sh	ν ring
-	1618 s	δH_2O
1595 m,sp	-	ν ring
1535 m	1535 m	δN(1)H
1429 m 1225 m 1170 w 1135 s	1420 1220 w,bd - 1131 sh	ν ring
1121 m 1082 vs 1047 m 980 m	1116 m 1080 s 1046 bd 980 w	ν ribose (deg.)
-	943 w	νOH (bridging)
894 m 874 m	896 w 867 w	ν ribose (sy.)

Table XVI

Variable Temperature Molar Susceptibilities and Effective Magnetic Moments For Hydroxyl Bridged Nucleoside Complexes

Compound	Temp (°K)	χ (exp) (x10^{-6})	1/χ (exp) (x10^{4})	χ (calc) (x10^{-6})	1/χ (calc) (x10^{4})	Moment (exp)	Moment (calc)	Std. Dev. Between g values
Cu(Xanthosine)(OH).2H_2O	292.0	2272	440.2	-	-	2.31	-	-
	204.0	2546	392.7	-	-	2.05	-	
	151.0	2719	367.8	-	-	1.82	-	
	96.7	3049	328.0	-	-	1.54	-	
	71.7	3397	294.3	-	-	1.40	-	
	66.0	3540	282.5	-	-	1.37	-	
	55.3	3852	259.6	-	-	1.31	-	
	44.9	4201	238.1	-	-	1.23	-	
	33.7	4786	208.9	-	-	1.14	-	
	24.9	5642	177.3	-	-	1.06	-	
	15.7	7083	141.2	-	-	0.95	-	
	12.0	8304	120.4	-	-	0.90	-	
Cu(Adenosine)(OH).1/2H_2O	298.0	1789	559.0	-	-	2.07	-	-
	204.0	2176	459.6	-	-	1.89	-	
	152.0	2520	396.8	-	-	1.76	-	
	98.3	3091	323.5	-	-	1.57	-	
	73.5	3576	279.7	-	-	1.46	-	
	64.2	3717	269.0	-	-	1.39	-	
	54.7	4049	247.0	-	-	1.34	-	
	43.0	4482	223.1	-	-	1.25	-	
	34.9	5044	198.3	-	-	1.19	-	
	23.7	6047	165.4	-	-	1.08	-	
	17.5	7167	139.5	-	-	1.01	-	
	12.0	8589	116.4	-	-	0.91	-	

Table XVI (Cont'd)

Variable Temperature Molar Susceptibilities and Effective Magnetic Moments For Hydroxyl Bridged Nucleoside Complexes

Compound	Temp (°K)	χ (exp) ($\times 10^{-6}$)	$1/\chi$ (exp) ($\times 10^{4}$)	χ (calc) ($\times 10^{-6}$)	$1/\chi$ (calc) ($\times 10^{4}$)	Moment (exp)	Moment (calc)	Std. Dev. Between g values
Cu(Cytidine)(OH).21/2H_2O	298.0	1173	852.8	-	-	1.68	-	-
	202.0	1551	644.6	-	-	1.59	-	
	151.0	1826	547.6	-	-	1.49	-	
	101.0	2337	428.0	-	-	1.38	-	
	75.7	2830	353.4	-	-	1.31	-	
	66.0	3177	314.7	-	-	1.30	-	
	52.9	3696	270.6	-	-	1.26	-	
	43.0	4381	228.3	-	-	1.23	-	
	34.3	5380	185.9	-	-	1.22	-	
	24.3	7554	132.4	-	-	1.22	-	
	17.5	11850	84.4	-	-	1.29	-	
	12.6	15360	65.1	-	-	1.25	-	
Cu(Inosine)(OH).H_2O	300.0	951	1051.9	-	-	1.52	-	-
	200.0	1240	806.4	-	-	1.41	-	
	149.0	1511	661.7	-	-	1.35	-	
	100.0	1905	525.0	-	-	1.24	-	
	72.9	2303	434.3	-	-	1.16	-	
	66.0	2420	413.3	-	-	1.14	-	
	55.3	2702	370.1	-	-	1.10	-	
	45.5	3132	319.3	-	-	1.07	-	
	36.1	3745	267.0	-	-	1.04	-	
	25.5	4737	211.1	-	-	0.99	-	
	18.1	5960	167.8	-	-	0.93	-	
	13.2	7716	129.6	-	-	0.91	-	

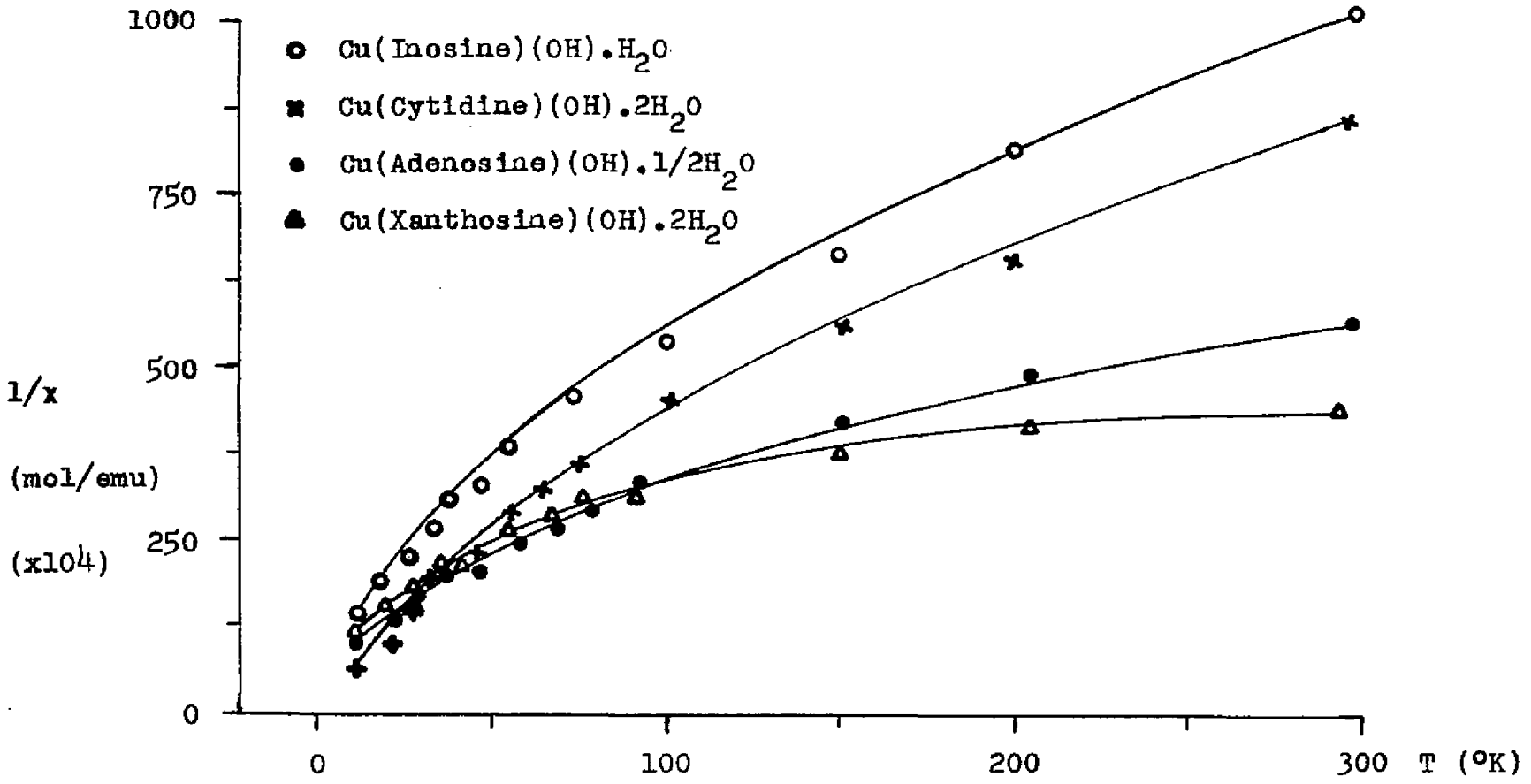


Figure 17. Inverse susceptibility vs. temperature for hydroxyl bridged nucleoside complexes. Solid lines represent experimental best fits.

D. $Cu(8X\text{-Guanosine})_2.nH_2O$, where X = H and Br, and n = 4 and 3, respectively; $Cu_3(Deoxyguanosine)_2(OH)_4.4H_2O$.

This series of compounds represents the first record of Cu(II) complexation with guanosines and deoxyguanosine and represents only the second account of a trimeric copper(II) complex with a nucleic acid constituent.

A tabulation of all the major IR bands for these complexes is given in Table X. The assignments given in the tables were arrived at by reference to previously published data[256,279] on these systems.[266-71,280-1] The bonding sites were determined by comparison between free ligand and coordinated ligand.

The main areas of interest in the 8X-guanosine and d-guanosine systems are between 3500 and 2800cm^{-1} and between 1800 and 800cm^{-1} where the following bands (cm^{-1}) appear: νOH (bridging), 3500; νNH (asy. and sy.), 3330; ν C(6)O, 1730; δNH_2 (def.), 1690; ν ring, 1640; δN(1)H, 1520; ν ribose and d-ribose (deg.), 1130, 1080, 1050, 1030; δOH (bridging), 957; ν ribose and d-ribose (sy.), 900, 870.

For both 8X-guanosine systems the νC(6)O at about 1720 cm^{-1} is sharply reduced in intensity and points to C(6)O coordination. Participation by the $C(2)NH_2$ group in both complexes is precluded by the presence in the free and complexed ligand of νNH_2 (asy. and sy.) at approximately 3370cm^{-1} and by δNH_2 (def.) at 1690cm^{-1}. The complete loss of δN(1)H at approximately 1510cm^{-1} points to N(1) coordination. Ring

participation in both complexes is supported by the diminution in ring stretches at approximately 1540, 1600, and 1640 cm^{-1} (combination with H_2O). No evidence for sugar involvement in the complexation is found as the degenerate and symmetric ribose stretches at approximately 1120, 1080, 1050, and 1010cm^{-1}, and 900 and 880cm^{-1}, respectively, are present in both ligand and complex. For the d-guanosine trimer, the high frequency shoulder at 3550cm^{-1} in the complex supports OH bridging in the complex. This assignment is corroborated by the presence of a weak absorption at 957cm^{-1} in the complex that is not present in the free ligand. The absorptions at 3495 and 957cm^{-1}, respectively, are assigned to the stretching and bending OH (bridging) vibrations in the complex. The νC(6)O is completely lost and points to C(6)O coordination. The reduction in intensity of δN(1)H at 1525cm^{-1}, corroborated by the reduction of ν ring at 1656 and 1637cm^{-1} (combination band with H_2O), suggests N(1) involvement. The participation by C(2)NH_2 is evidenced by the loss of δNH_2 at 1689cm^{-1} and νNH_2 (asy. and sy.) at 3420 and 3333cm^{-1}, respectively, in the coordination compound. The 2'-deoxyribose (d-ribose) oxygen is presumed to be involved to some extent as the intensity of both the degenerate d-ribose stretches at 1075 and 1031cm^{-1}, and the symmetric d-ribose stretches at 883 and 865cm^{-1} are lost. It appears then that for the guanine moiety, complexation via C(6)O and N(1) is preferred and maintained regardless of the type of sugar residue attached to it. Apparently, the only difference in behavior between ribo- and

deoxyriboguanosine complexes is the unusual coordination ability that the single 3'OH group possesses. Therefore, it is highly probable that the recognition of deoxyribo- as opposed to ribonucleotides during the replication process of DNA by specific metal ions such as Mg(II) (but not Mn(II)), occurs via the actual coordination of the 3'OH group to the metal ion. The results of the coordination found for the d-guanosine complex are interesting in light of the work performed by Berger and Eichhorn[167] who postulated that the "recognition" of ribonucleotides (as opposed to deoxyribonucleotides) by RNA polymerase in the presence of $Cu(Ac)_2$ was the result of a more favorable orientation of the metal-nucleotide complex, and that the favorable orientation resulted from the complexation of copper(II) to the 2' and the 3' oxygen atoms of the ribose sugar. However, the results with copper(II) and deoxyguanosine in the solid state presented here do not support this postulate since complexation occurs at the deoxyribose sugar in spite of the absence of the 2'OH group. It should be mentioned that the specific binding sites utilized by the nucleic acids, including the 3'OH group, in biological processes, will depend on the specific metal ion used.

A tabulation of the absorption bands for all the complexes in the visible-near IR region is given in Table V. The d-d band maxima are in the vicinity of $14,300 cm^{-1}$ and can be ascribed to the $^2E_g \leftarrow {}^2B_{1g}$ transition in distorted octahedral copper(II) complexes. It is unusual that the three com-

plexes absorb in the same region, but this can be rationalized since the IR data point to identical coordination sites at the guanine moiety in all three compounds (and possibly the replacement of H_2O by 3'OH coordination in the deoxyguanosine complex). Also, the EPR data, Table VI, points to very similar coordination spheres as evidenced by the similarity of their g values (approximately 2.13). The characteristic features of the EPR spectra indicates a $d_{x^2-y^2}$ ground state for all these complexes (i.e., $g_z > g_{xy}$) which corroborates the transition assigned for the visible absorption.

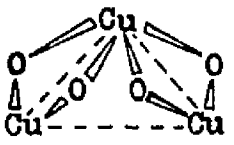
The magnetic susceptibility data for all three complexes is given in Table XVIII and the plots of $1/\chi$ vs. T are shown in Fig. 19. Attempts to fit the 8X-guanosine complexes to the magnetic models described earlier did not yield satisfactory results and the curvature of the $1/\chi$ vs. T plots suggested a field dependence of the susceptibilities at room temperature, the results of which are shown in Table IXX. The results can be interpreted in terms of ferromagnetically coupled systems, yielding higher susceptibilities and effective magnetic moments at low external magnetic fields and lower susceptibilities and effective magnetic moments at high external magnetic fields. Again the presence of the ribose function has been apparently to allow an extensive degree of lattice interactions to occur. Half field and full field EPR signals at 1500, 1800, and 5100G for the guanosine complexes corroborate the interpretation of a ferromagnetically ordered

state, and the spin-coupling required accounts for the EPR absorptions observed. The Br-guanosine complex, however, did not exhibit any full-field or half-field EPR signals as expected for this coupled complex, but as pointed out previously spin-spin coupling may be so extensive and strong that absorptions consistent with magnetically coupled spin centers may broaden these signals and preclude an observation of them.

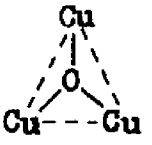
The trimer was fitted to the theoretical trimer expression developed previously by Sinn and Harris,[236] eq. (14), yielding the following best fit parameters: $g = 2.00$, $-2J = -58cm^{-1}$, and $-2JJ = -52cm^{-1}$, where $-2J$ and $-2JJ$ have the same meaning as $-J$ and $-J_{CuCu}$, respectively, in eq. (14). The data indicates antiferromagnetic coupling of relatively low intensity, with similar coupling between terminal copper(II) ions ($-2JJ$) and central and terminal copper(II) ions ($-2J$). The fit to the theoretical expression was excellent with a value for the standard deviation of the experimental g values from the theoretical g values of 0.11, and a plot of $1/\chi$ vs. T for the trimer is shown is Fig. 19.

There have been several reports [282-7] of oxygen-bridged trinuclear copper(II) complexes that exhibit varying degrees of antiferromagnetic behavior, and the hydroxyl-bridged analogs are expected to exhibit similar properties. The molecular structures[288-90] for a representative number of these oxygen-bridged complexes have revealed only two kinds of trinuclear copper(II) clusters. Both consist of triangular ar-

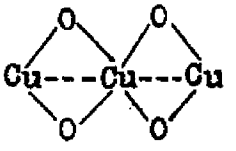
rays (I and II) of copper(II) ions but differ in the kind of bridging oxygen atoms, the shape of the triangle (isosceles I or equilateral II), and the degree of exchange coupling between copper(II) ions.



I



II



III

Complexes of type I exhibit subnormal room temperature magnetic moments greater than approximately 1BM per copper ion; that is, there is still some population of the spin 3/2 state by the three electrons of the Cu_3 core at room temperature. The magnetic behavior of type I complexes with a few exceptions has been characterized[286,288,291] by using the trimer model described previously in the theoretical section.

Complexes of type II, however, exhibit complete spin pairing, so that only the spin doublet state ($S = 1/2$) is populated at room temperature. All type II complexes examined to date by X-ray diffraction have shown the copper(II) ions to be positioned at the corners of an equilateral triangle. Recently, the first report on an additional type of trinuclear copper(II) complex having a spin-doublet ground state in which the copper ions are arranged in a strict linear fashion and joined by bridging oxygen atoms was given,[292] III. This complex had a reduced magnetic moment at room tem-

perature (approximately 1.1BM per copper ion) that was constant down to 35°K.

IR data support hydroxyl bridging between copper(II) centers, and the similarity of the exchange parameters 2J and 2JJ suggest comparable Cu-Cu and Cu-Cu' distances (I and II). This precludes model III from further consideration. Since there are four hydroxyl bridges in the complex, model I was chosen as the most probable structure.

The magnetic moment of 1.5BM at room temperature for our trimer suggests appreciable population of the S = 1/2 and 3/2 states. This accounts for the full-field EPR signals (S = 1/2 at 2940 and 3240G) and the half-field EPR signals (S = 3/2 at 1300, 3800, and 5400G). Visible spectroscopy suggests a distorted six-coordinate complex about each copper ion in the trimer, and the presence of four hydroxyl bridges, two bidentate deoxyguanosine anions chelating the terminal copper ions (with complex involvement by the d-ribose sugar oxygen), and four lattice waters can be accomodated about each copper ion in a fashion similar to that depicted in I.

The evidence presented, therefore, is consistent with a bent copper(II) trimer where two bidentate deoxyguanosine ligands chelate both terminal copper ions, and is the first report of the synthesis and magnetic and spectral characterization of a copper(II) nucleoside trimer to date. The magnetic data obtained here is particularly interesting when compared to similar data for the only other trimer complex of

copper(II) with a nucleic acid base, $Cu_3Cl_8(AdH_2)_2 \cdot 4H_2O$,[134] Fig. 4. In the latter complex, an S = 1/2 spectrum as well as a normal room temperature moment was exhibited,[154] consistent with a magnetically dilute copper(II) system. A crystal structure determination of the copper(II) trimer studied in this work may provide a clue as to the role substituents at the 9 position of purinic-like nucleic acid constituents play in the bonding, and spectral and magnetic properties of trimeric metal complexes of nucleic acid bases.

A possible structure for this complex based on the spectroscopic and magnetic data presented is shown in Fig. 20.

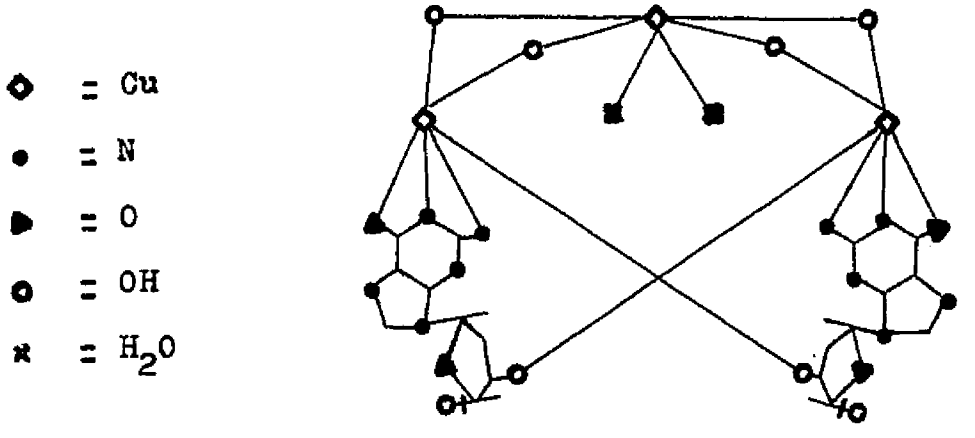


Fig. 20. A schematic of the proposed structure for the copper(II) complex with deoxyguanosine, Cu_3(d-guanosine)$_2(OH)_4 \cdot 4H_2O$.

Table X

IR Data For d-Guanosine and 8X-Guanosine Ligands and Their Complexes (cm^{-1})

Free Ligand Guanosine (LH)	Complexed Ligand $Cu(L)_2.4H_2O$	Assignment
-	3500 sh	νOH H_2O
3497 s	3425 s	νNH_2 (asy.)
3333 s	3333 s	νNH_2 (sy.)
3226 s	3226 s	νOH
2874 m,bd	2941 m	νCH_2
1730 s,sp	1736 w,sh	νC(6)O
1689 s	1695 s	δNH_2
1639 s 1628 s 1600 sh	1639 s 1621 s 1600 s	ν ring, δ H_2O
1533 m	1531 w	ν ring
1501 m	-	δN(1)H
1425 m 1393 m	1408 w 1393 w	ν ring
1129 s 1080 s,bd 1048 m,bd 995 m	1129 s 1082 s,bd 1048 m,bd 995 m	ν ribose (deg.)
916 m	916	ν ring
898 w 880 w	897 w 878 w	ν ribose (sy.)

Table X (Cont'd)

Free Ligand 8Br-Guanosine (LH)	Complexed Ligand $Cu(L)_2 \cdot 3H_2O$	Assignment
3534 sh	3534 s	νOH H_2O
3425 s,bd	3333 s,bd	νNH_2 (asy. & sy.)
3185 s	3175 m,bd	νOH
2959 s	2941 sh	νCH_2
1706 s	1706 m,sh	νC(6)O
1695 s,sp	1695 s,sp	δNH_2
1667 s	1667 m,sh	δ ring & δH_2O
1608 s,bd	1608 s,bd	
1563 m,sh	1558 vw,sh	
1515 m	-	δN(1)H
1471 m,sp	1464 m,sh	ν ring
1464 m	1458 m	
1427 m	-	
1121 s	1116 m	ν ribose (deg.)
1082 s	1080 m	
1048 m	1048 m	
1029 m	1025 m	
920 m	916 w	ν ring
908 m	906 w	ν ribose (sy.)
880 m	880 w	

Table X (Cont'd)

Free Ligand d-Guanosine (LH)	Complexed Ligand $Cu_3(L)(OH)_4 \cdot 4H_2O$	Assignment
-	3550 w,sh	νOH (bridging)
3472 m,sh	3472 m,sh	νOH H_2O
3420 s 3333 s	3340 m,bd	νNH_2 (asy. & sy.)
3226 s	3205 m	νOH
2959 m	2941 m	νCH_2
1727 m	-	νC(6)O
1689 vs	-	δNH_2
1656 s,sp 1637 m 1567 m	1656 m,sp 1639 s 1570 m	ν ring & δH_2O
1525 m	1522 w	δN(1)H
1488 w 1416 w	1493 w 1420 w	ν ring
1125 m 1075 m 1055 s 1031	1125 m - 1055 m -	ν ribose (deg.)
-	957 w	δOH (bridging)
927 w,sp	940 w,bd	ν ring
883 w 865 w	- -	ν ribose (sy.)

Table XVIII

Variable Temperature Molar Susceptibilities and Effective Magnetic Moments For d-Guanosine Trimer and 8X-Guanosines

Compound	Temp (°K)	χ (exp) (x10^{-6})	1/χ (exp) (x10^{4})	χ (calc) (x10^{-6})	1/χ (calc) (x10^{4})	Moment (exp)	Moment (calc)	Std. Dev. Between g values
Cu_3(d-Guanosine)$_2$	299.0	994	1006.1	949	1054.1	1.51	1.54	0.114
	204.0	1247	802.0	1241	805.2	1.42	1.43	
$(OH)_4.4H_2O$	153.0	1435	696.8	1422	703.3	1.32	1.33	
	106.0	1676	596.5	1868	535.2	1.26	1.19	(Trimer)
	80.2	1910	523.6	2119	472.0	1.17	1.11	
	70.0	2064	484.4	2302	434.3	1.14	1.08	
	59.5	2303	434.2	2547	392.7	1.10	1.05	
	49.2	2675	373.8	2871	348.3	1.06	1.03	
	39.9	3224	310.2	3251	307.6	1.02	1.01	
	30.5	4167	240.0	3884	257.4	0.97	1.01	
	22.4	5645	177.2	4756	210.3	0.92	1.01	
	17.5	7208	138.7	5663	176.6	0.89	1.00	
Cu(Guanosine)$_2$ $.4H_2O$	297.0	2410	415.0	-	-	2.40	-	-
	206.0	2813	355.5	-	-	2.16	-	
	154.0	3153	317.2	-	-	1.98	-	
	104.0	3492	286.3	-	-	1.71	-	
	81.9	4014	249.1	-	-	1.63	-	
	66.0	4320	231.5	-	-	1.52	-	
	55.3	4651	215.0	-	-	1.44	-	
	43.7	5118	195.4	-	-	1.34	-	
	34.3	5755	173.8	-	-	1.26	-	
	26.1	6880	145.4	-	-	1.20	-	
	15.0	9002	110.1	-	-	1.04	-	
	12.0	10280	97.3	-	-	1.00	-	

Table XVIII(Cont'd)

Variable Temperature Molar Susceptibilities and Effective Magnetic Moments
For d-Guanosine Trimer and 8X-Guanosines

Compound	Temp (°K)	χ (exp) ($\times 10^{-6}$)	$1/\chi$ (exp) ($\times 10^{4}$)	χ (calc) ($\times 10^{-6}$)	$1/\chi$ (calc) ($\times 10^{4}$)	Moment (exp)	Moment (calc)	Std. Dev. Between g values
$Cu(Br\text{-}Guanosine)_2 \cdot 3H_2O$	296.0	1090	917.5	-	-	1.61	-	-
	205.0	1462	683.8	-	-	1.56	-	
	153.0	1638	610.5	-	-	1.42	-	
	105.0	2195	455.5	-	-	1.36	-	
	82.4	2604	384.0	-	-	1.32	-	
	69.4	2868	348.6	-	-	1.27	-	
	58.3	3140	318.5	-	-	1.22	-	
	49.7	3649	274.0	-	-	1.21	-	
	38.6	4274	234.0	-	-	1.15	-	
	29.9	5291	189.0	-	-	1.13	-	
	20.6	6918	144.5	-	-	1.07	-	
	16.3	8192	122.1	-	-	1.04	-	
	12.0	10160	98.4	-	-	0.99	-	

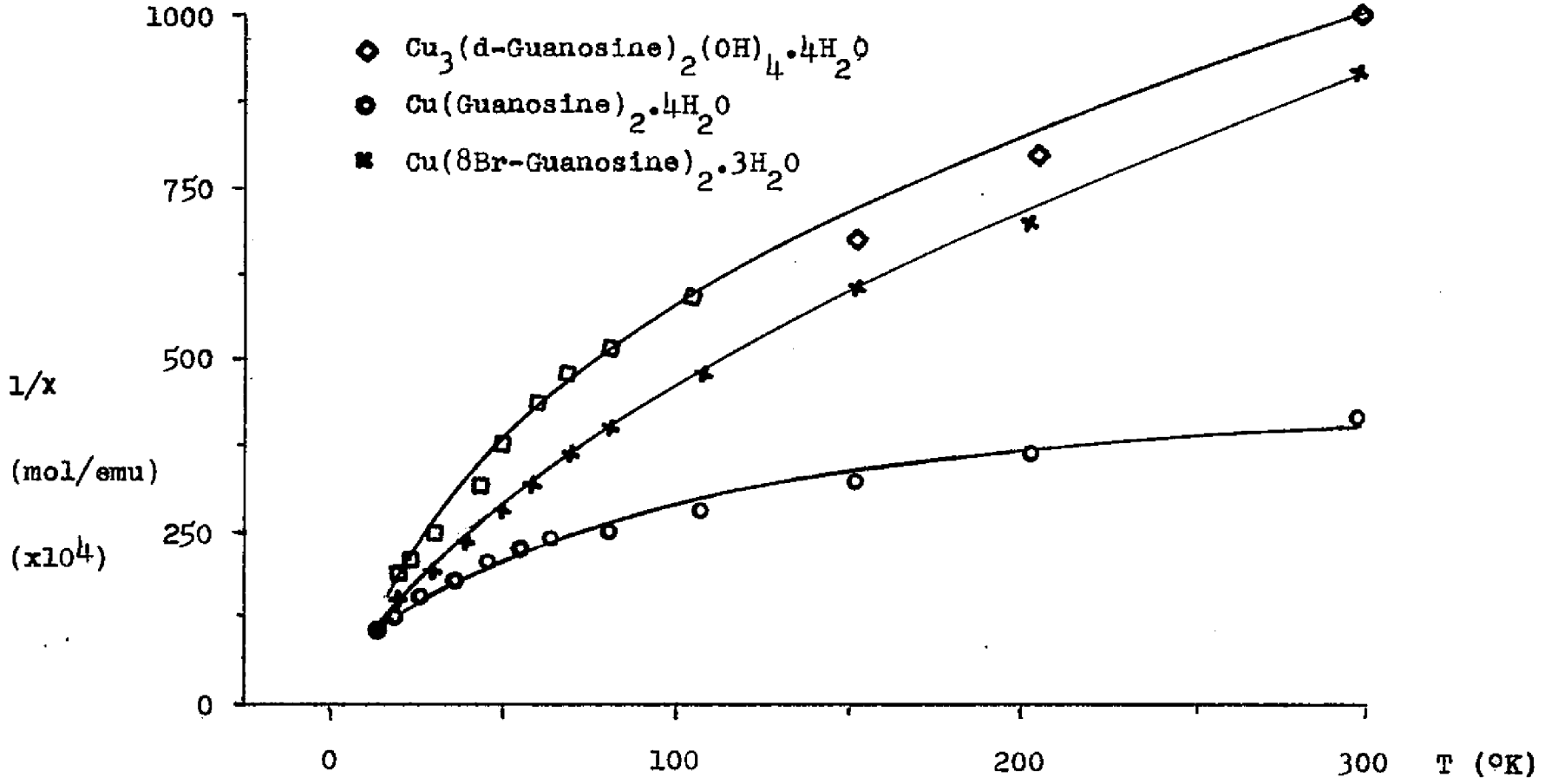


Figure 19. Inverse susceptibility vs. temperature for guanosine complexes. Solid line for d-guanosine complex represents theoretical best fit to trimer equation. Solid lines for two remaining complexes represent experimental best fits.

E. $Cu(L).nH_2O$, where L = 5'-Guanylic Acid(GMP), 5'-Adenylic Acid(AMP), and 5'-Cytidylic Acid(CMP), and n = 5, 2, and 6, respectively.

The preparation and complete spectral and magnetic characterization of the first series of copper(II) compounds with AMP, GMP, and CMP are reported here, and are shown, in all instances, to bond through the ring and phosphate positions.

A tabulation of the major IR bands of CMP, GMP, and AMP, and their complexes is given in Table XII. The IR assignments were arrived at by reference to previously published data on these systems.[266-71,280-1] The bonding sites were determined by comparison between free ligand and coordinated ligand.

The areas of interest in the IR for these systems are similar to those of the previously discussed compounds; the specific bands of interest are (cm^{-1}): νNH_2 (asy. and sy.), 3300; νC(2)O, 1742, ν C(6)O, 1704; δNH_2, 1640; δ N(1)H, 1540; ν ring, 1600; νP=O (free), 1240; $\nu P{=}O(OH)_2$, 960; νPO_3 (sy.), 980; νPO_3 (asy.), 1100; ν ribose (asy.), 1130, 1065, 1010, and 960; ν ribose (sy.), 870, and 840.

For the CMP complex C(2)O and N(3) involvement is suggested from the diminution and shift of ν C(2)O at 1742 to $1712cm^{-1}$ and virtual loss of ν ring at $1534cm^{-1}$. Participation by the $C(4)NH_2$ function is ruled out by the νNH_2 (asy. and sy.) at 3356 and $3289cm^{-1}$ present in both free and coordinated ligand, as well as the δNH_2, also present in both

ligand and complex at 1656cm^{-1}. Reduction in the ν ring at 1689 and 1230cm^{-1} supports ring coordination. Evidence for phosphate involvement in coordination comes from the reduction, shift to lower energies, and loss of the $\nu P{=}O$ (free) and $\nu P{=}O(OH)_2$ at 1266 and 969cm^{-1}, respectively. The appearance of the asymmetric and symmetric νPO_3 at 1104 and 986 cm^{-1} confirms this assignment. Ribose involvement is precluded since the degenerate and symmetric ν ribose at 1124, 1071, 1044, and 969cm^{-1}, and 853 and 842cm^{-1}, respectively, are found unchanged in intensity and only slightly shifted from the free ligand positions. The data points to ring participation at C(2)O and N(3), and phosphate coordination.

For the GMP coordination compound the dramatic reduction of ν C(6)O and the loss of δN(1)H at 1704 and 1555cm^{-1}, respectively, point to ring participation at C(6)O and N(1). The involvement of $C(2)NH_2$ in complexation is precluded by the presence of νNH_2 (asy. and sy.) in ligand and complex at 3448cm^{-1}. The ring vibrations at 1355 and 1235cm^{-1} are reduced as expected upon coordination. Evidence for phosphate involvement comes from the reduction and shift to lower energies of $\nu P{=}O$ (free) at 1235cm^{-1} and loss of $\nu P{=}O(OH)_2$ at 963 cm^{-1}. The asymmetric and symmetric phosphate absorptions at 1109 and 984cm^{-1}, respectively, confirm phosphate involvement. No evidence for sugar coordination is present as the ν ribose (deg.) at 1130, 1073, 1046, and 963cm^{-1}, and the ν ribose (sy.) at 890cm^{-1} are virtually unaffected in intensity and position in going from ligand to complex. The

data support C(6)O, N(1), and phosphate coordination to the copper(II).

For the AMP complex, evidence for ring nitrogen coordination comes from the loss of $\nu C{=}C$ and $\nu C{=}N$ at 1706 and 1689 cm^{-1} upon complexation. Non-involvement of the $C(6)NH_2$ is evidenced by the presence in both ligand and complex of νNH_2 (asy. and sy.) at 3360 and 3250cm^{-1}, respectively, and δNH_2 at 1656cm^{-1}. Evidence for phosphate involvement is seen in the loss in intensity and shift to lower energies of $\nu P{=}O$ (free) at 1222cm^{-1} and the loss of $\nu P{=}O(OH)_2$ at 938cm^{-1} upon complexation. Support for this assignment comes from the appearance of νPO_3 (asy. and sy.) in the complex at 1120 and 985cm^{-1}, respectively. The results point to ring and phosphate coordination. No evidence for sugar participation is seen as the degenerate ribose stretching frequencies at 1143, 1071, 1044, and 975cm^{-1}, and the symmetric ribose stretching frequencies at 899 and 867cm^{-1} are virtually unchanged in intensity or position after coordination. The data do not distinguish between N(1), N(3), or N(7) coordination. However, using the same arguments presented in Part C for the adenosine complex, N(7) coordination is presumed. The data support N(7) and phophate coordination to copper(II).

The IR data then for the three nucleotide complexes discussed clearly demonstrate the involvement of both ring and phosphate positions in coordination to copper(II).

A complete tabulation of the visible-near IR absorption bands for these complexes is given in Table V and can be as-

signed to the $^2E_g \leftarrow {}^2B_{1g}$ transition in distorted octahedral copper(II) complexes (or conceivably to the $^2E \leftarrow {}^2B_1$ transition in C_{4v} symmetry). The range of the d-d band maxima is: 13,500 - 15,750cm^{-1} and suggests the following order of ligand field strengths: AMP > CMP > GMP.

The full-field EPR data for these complexes is given in Table VI and supports the assumption of axial distortion in these systems (i.e., $g_z > g_{xy}$). The values of g_z are 2.30 (approximate), 2.35, and 2.38 for AMP, CMP, and GMP, respectively, suggesting the distortion from octahedral symmetry as: GMP > CMP > AMP. This is the same trend determined from the electronic spectra of these complexes. For the AMP complex, the g_z resonance is not actually seen and is presumed to lie under the average absorption at 3080G. Also, the correlation between distortions from octahedral symmetry (as seen in the shifts in the d-d band maxima), and g_z must be made with caution as the chromophore about copper(II) is presumably not the same throughout the series, but suggests similar bonding characteristics within the series.

The static magnetic susceptibility data for these complexes is given in Table XVII and plots of $1/\chi$ vs. T are given in Fig. 18. Theoretical best fits were attempted and the AMP and GMP compounds successfully fitted to the modified tetramer expression, eq. (15). The best fit values obtained for the parameters A, B, C, and g were 118, 12, 2cm^{-1} and 2.03 and 130, 14, 2cm^{-1} and 2.08 for the AMP and GMP complexes, respectively. Inspection of Fig. 18 and the fact

that the standard deviation in the g values obtained experimentally and theoretically was on the order of 0.06, clearly demonstrates the excellence in the tetramer model in light of the approximations made. Therefore, these tetramer systems are magnetically described in terms of a singlet ground state with another singlet state $2cm^{-1}$ above it, and slightly higher in energy two excited triplet states - one at approximately $13cm^{-1}$ and the other at approximately $125cm^{-1}$. Other spin states, such as S = 2, etc., if at all present would be at much higher energies according to the data and do not contribute significantly to the magnetic properties of these complexes.

Attempts to fit the CMP data to any of our theoretical models did not give good fits. These results and the curvature of the $1/\chi$ vs. T plot for this system (Fig. 18) prompted a field dependence study, Table IXX. The results are most striking here since the CMP complex has an unusually high susceptibility and effective magnetic moment at low external field strengths. The results point to ferromagnetic coupling of the type seen for the uracil, and hydroxyl-bridged nucleoside complexes. This type of ferromagnetic field dependence in a nucleotide complex is without precedence. Further support for magnetic coupling (ferromagnetic in the CMP complex and antiferromagnetic in the AMP and GMP complexes) comes from the half field EPR data, Table VI, where the presence of H_{MIN} is seen in all cases at around 1500G except in the ferromagnetic CMP complex. The lack of an H_{MIN}

signal in the CMP system can be attributed to dipolar broadening of the bands in this extraordinarily strongly coupled Cu(II) compound.

The magnetic data suggest that in the solid state, the metal nucleotide complexes are highly associated. In fact, recent crystal structure determinations[282] of Co(II)CMP and Cd(II)CMP as well as the crystal structure of Cd(II)IMP[200], clearly demonstrate the highly associative and polymeric nature of these nucleotide complexes. Furthermore, the association phenomenon shown towards Cu(II) in this work corroborates the work of Burger and Eichhorn[293] where dimeric Cu(II) coordination compounds with AMP were postulated to exist in solution, and suggests that biological processes involving metal ion interactions with nucleic acid constituents might indeed proceed via a multi-centered pathway involving clusters of two or more metal complexes with these ligands.

Table XII

IR Data For Nucleotide Ligands and Their Complexes (cm^{-1})

Free Ligand CMP (LH)	Complexed Ligand $Cu(L).6H_2O$	Assignment
-	3490 m	$\nu OH\ H_2O$
3356 m	3356 m,bd	νNH_2 (asy.)
3289 m	3240 sh	νNH_2 (sy.)
3106 m	3140 - 3070 bd	νCH, νNH, νOH
2941 m,bd	2874 sh	νCH_2
1742 s	1712 w,sh	$\nu C(2)O$
1689 sh	1689 w,sh	δNH_2
-	1656 s	δH_2O
1534 s	1524 vw,sh	ν ring
1511 vw	-	ν ring
-	1493 w	
1475 vw,sp	1471 sh	
1276 m	1289 w,bd	$\delta C\text{-}NH_2$
1266 s	1208 w	νPO (free)
1229 m	-	ν ring
1209 m		
1124 s	1130 s,bd	ν ribose (deg.)
1071 s	1060 s,bd	
1044 m,sp	1040 s	
969 s	969 m	
-	1104 s	νPO_3 (asy.)
-	986 s	νPO_3 (sy.)
969 s,bd	-	$\nu PO(OH)_2$ (combina.)
853 w,sh	853 vw	ν ribose (sy.)
842 w	842 vw	
797 m,bd	-	ν ring

Table XII (Cont'd)

Free Ligand AMP (LH)	Complexed Ligand $Cu(L).2H_2O$	Assignment
3378 w	3378 s	$\nu OH\ H_2O$
3360 s	3356 s	νNH_2 (asy.)
3250 s	3270 s	νNH_2 (sy.)
3184 s	3184 s,bd	νCH, νNH, νOH
3030 s	3030 s,sh	νCH_2
1706 s	-	$\nu C{=}C$
1689 s	1689 sh	δNH_2
1656 m,sp	1656 s,bd	δH_2O
1613 m	1603 m	ν ring
1539 w,sp	1539 vw,bd	
1475 w,sp	1479 vw,bd	
1420 m,sp	1425 w	
1222 s	-	νPO (free)
1188 m,sh	-	ν ring
1143 s	1145 s,sh	ν ribose (deg.)
1071 s	1075 s	
1044 s	1050 s	
975 w	-	
-	1120 s	νPO_3 (asy.)
-	980 m	νPO_3 (sy.)
938 s	943 sh	$\nu PO(OH)_2$
924 s	929 sh	ν ring
899 w,sh	899 sh	ν ribose (sy.)
867 w	867 sh	

Table XII (Cont'd)

Free Ligand GMP (LH)	Complexed Ligand Cu(L).5H_2O	Assignment
3448 s,bd 3200 s,bd	3378 s,bd 3230 s,bd	νOH, νH_2O, νCH, νNH, νNH_2 (asy. & sy.)
2924 s,bd	2959 m,sh	νCH_2
1704 s	1704 vw,sh	νC(6)O
1689 s,sh	1689 s,sh	δNH_2
1653 m,sh	1653 s	δH_2O
1639 m,sh 1597 w	1639 w,sp 1597 sh	ν ring
1525 m	-	δN(1)H
1462 m,sh 1408 m 1355 s,bd	1462 w,sp 1408 w 1365 w,sp	ν ring
1235 s,bd	1235 w,sh	νPO (free)
1130 s,sh 1073 s 1040 s 963 s	1145 w,sh 1075 s 1045 m,sh 975 w	ν ribose (deg.)
-	1109 s	νPO_3 (asy.)
-	984 s	νPO_3 (sy.)
963 s,bd	-	$\nu PO(OH)_2$
890 w,bd	890 w,bd	ν ribose (sy.)
775 w	778 w	δCH out-of-plane

Table XVII

Variable Temperature Molar Susceptibilities and Effective Magnetic Moments For Nucleotide Complexes

Compound	Temp (°K)	χ (exp) ($\times 10^{-6}$)	$1/\chi$ (exp) ($\times 10^{4}$)	χ (calc) ($\times 10^{-6}$)	$1/\chi$ (calc) ($\times 10^{4}$)	Moment (exp)	Moment (calc)	Std. Dev. Between g values
$Cu(GMP).5H_2O$	295.0	1488	671.9	1326	754.4	1.87	1.77	0.0715
	204.0	1991	502.3	1825	548.0	1.80	1.73	
	154.0	2445	409.0	2315	432.0	1.74	1.69	
	106.0	3018	331.4	3146	317.9	1.60	1.63	(Tetramer)
	84.1	3629	275.5	3785	264.2	1.56	1.60	
	70.0	4138	241.6	4373	228.7	1.52	1.56	
	58.9	4744	210.8	5000	200.0	1.49	1.53	
	48.6	5438	183.9	5789	172.8	1.45	1.50	
	39.9	6400	156.3	6696	149.3	1.43	1.46	
	29.3	7852	127.3	8261	121.1	1.36	1.39	
	23.0	9425	106.1	9485	105.4	1.32	1.32	
	16.9	11590	86.3	10700	93.5	1.25	1.20	
$Cu(AMP).2H_2O$	295.0	1382	723.4	1274	784.8	1.81	1.73	0.0519
	205.0	1709	585.0	1752	570.9	1.67	1.69	
	153.0	2452	407.9	2250	444.4	1.73	1.66	
	101.0	3257	307.0	3178	314.6	1.62	1.60	(Tetramer)
	81.3	3647	274.2	3789	263.9	1.54	1.57	
	71.7	4056	246.6	4190	238.6	1.53	1.55	
	61.3	4591	217.8	4746	210.7	1.50	1.53	
	49.2	5427	184.3	5640	177.3	1.46	1.49	
	39.9	6277	159.3	6625	150.9	1.42	1.45	
	30.5	7787	128.4	8068	123.9	1.38	1.40	
	21.4	10180	98.3	10120	98.8	1.32	1.32	
	15.0	12440	80.4	11850	84.4	1.22	1.20	

Table XVII (Cont'd)

Variable Temperature Molar Susceptibilities and Effective Magnetic Moments For Nucleotide Complexes

Compound	Temp (°K)	χ (exp) ($\times 10^{-6}$)	$1/\chi$ (exp) ($\times 10^{4}$)	χ (calc) ($\times 10^{-6}$)	$1/\chi$ (calc) ($\times 10^{4}$)	Moment (exp)	Moment (calc)	Std. Dev. Between g values
$Cu(CMP).6H_2O$	295.0	2545	392.9	-	-	2.46	-	-
	205.0	3073	325.5	-	-	2.25	-	
	156.0	3487	286.8	-	-	2.09	-	
	101.0	4156	240.6	-	-	1.84	-	
	81.3	4548	219.9	-	-	1.73	-	
	72.3	4884	204.8	-	-	1.69	-	
	58.9	5308	188.4	-	-	1.59	-	
	49.8	5662	176.6	-	-	1.51	-	
	41.7	6259	159.8	-	-	1.45	-	
	33.0	7081	141.2	-	-	1.37	-	
	21.7	8660	115.5	-	-	1.23	-	
	18.1	9577	104.4	-	-	1.18	-	
	12.0	12170	82.2	-	-	1.09	-	

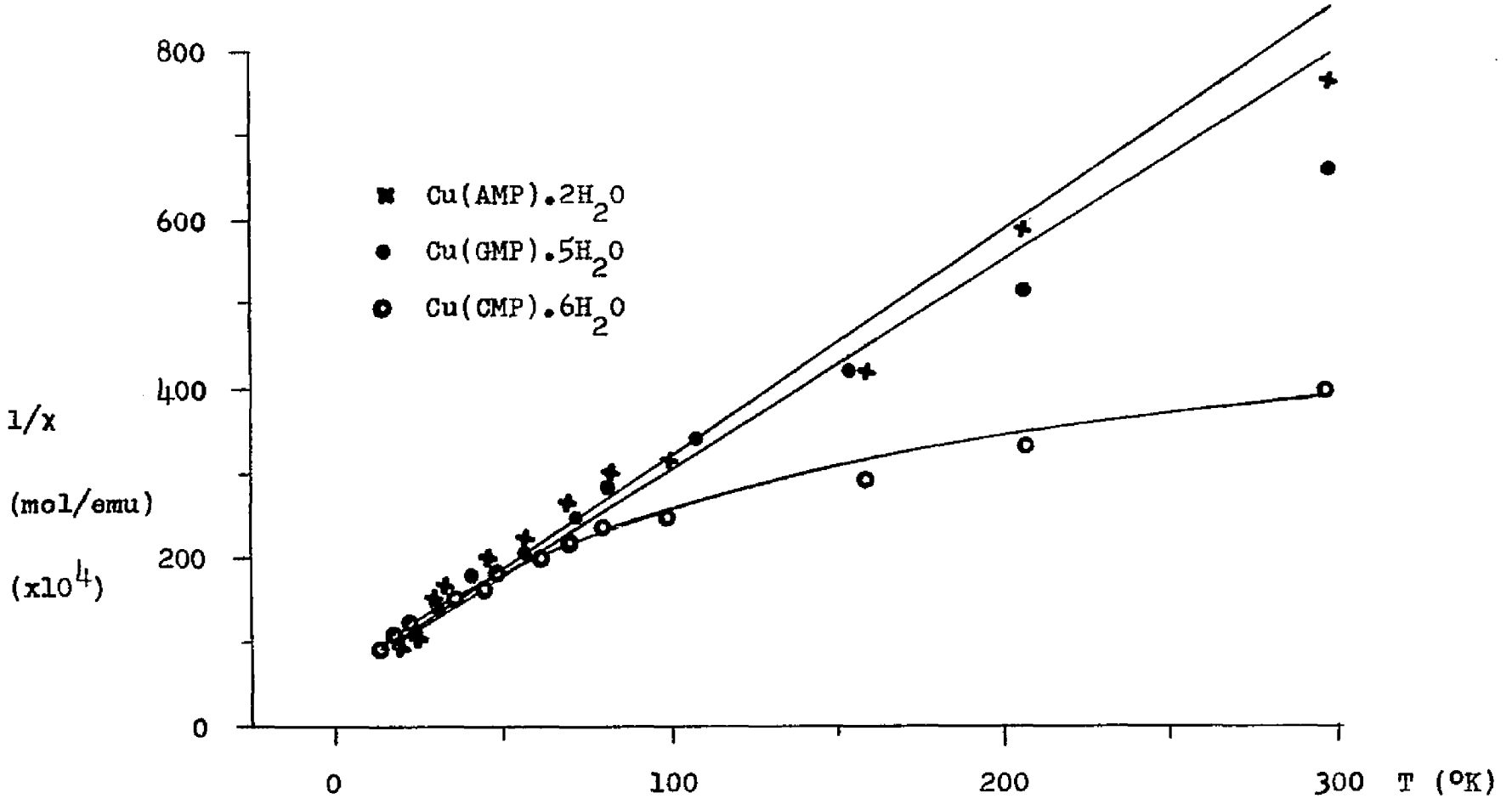


Figure 18. Inverse susceptibility vs. temperature for nucleotide complexes. Solid lines represent theoretical best fits to tetramer equation for all systems shown (except CMP complex).

Table V

Visible Absorption and Physical Constant Data For Complexes

Compound	Color	Dec. pt., °C	E_{max}, cm^{-1}	
$Cu(Uracil)_2 \cdot H_2O$	Pale green	160-165	15,380	
$Cu(5I\text{-}Uracil)_2 \cdot H_2O$	Light green	115-120	14,710	12,900 sh
$Cu(5NO_2\text{-}Uracil)_2 \cdot 2H_2O$	Blue green	188-193	15,390	12,900 sh
$Cu(2S\text{-}Uracil)_2 \cdot 3H_2O$	Pea green	180-184	11,770	
$Cu(6NH_2,2S\text{-}Uracil)_2 \cdot 3CH_3OH$	Pale yellow	202-206	13,330	
$Cu(6CH_3,2S\text{-}Uracil)_2 \cdot 2H_2O$	Pale yellow	215-219	10,750	
$Cu(6C_3H_7,2S\text{-}Uracil)_2 \cdot 4H_2O$	Pale yellow	218-223	10,810	
$Cu(2,4\text{-}Dithiouracil)(OH) \cdot H_2O$	Brick orange	270-275	11,430	
$Cu(Cytosine)_2Cl_2$	Blue	155-159	16,000	
Cu(2S-Cytosine)Cl	Brown green	160-164	16,390	
$Cu(2S\text{-}Cytosine)_2 \cdot 2H_2O$	Pea green	150-155	15,150	

Table V (Cont'd)

Compound	Color	Dec. pt., °C	E_{max}, cm^{-1}	
$Cu(Guanosine)_2 \cdot 4H_2O$	Pale green	180-184	13,890	
$Cu(8Br\text{-}Guanosine)_2 \cdot 3H_2O$	Light green	160-165	14,290	
$Cu_3(d\text{-}Guanosine)_2(OH)_4 \cdot 4H_2O$	Dark green	142-147	14,290	
$Cu(Xanthosine)(OH) \cdot 2H_2O$	Green	112-118	14,490	13,160 sh
$Cu(Cytidine)(OH) \cdot 2H_2O$	Blue green	126-130	14,930	13,510 sh
$Cu(Inosine)(OH) \cdot H_2O$	Green	116-120	15,630	12,740 sh
$Cu(Adenosine)(OH) \cdot 1/2H_2O$	Green	115-122	14,180	
$Cu(GMP) \cdot 5H_2O$	Pale green	115-119	13,500	
$Cu(AMP) \cdot 2H_2O$	Pale green	118-123	15,770	
$Cu(CMP) \cdot 6H_2O$	Light blue	120-125	13,510	

Table VI

EPR Field Positions and Calculated Magnetic Parameters*

Compound**	ν (GHz)	H_{MIN}	$(H_z)_1$	$(H_z)_2$	$(H_{xy})_1$	$(H_{xy})_2$	H_{av}	g_z	g_{xy}	g_{av}
$Cu(Ura)_2.H_2O$	9.524	1600	-	-	-	-	-	-	-	-
	9.524		-		-		3325	-	-	2.05
$Cu(5I\text{-}Ura)_2.H_2O$	9.524	-	-	-	-	-	-	-	-	-
	9.298		2965		3210		-	2.24	2.07	2.13
$Cu(5NO_2\text{-}Ura)_2.2H_2O$	9.525	1260	1450	-	-	-	-	-	-	-
	9.525		2925		3280		-	2.33	2.08	2.16
$Cu(2S\text{-}Ura)_2.3H_2O$	9.329	-	1482	5000	4100	2150	-	2.26	2.06	2.13
	9.296		2645		3140		-	2.51	2.12	2.38
$Cu(6NH_2,2S\text{-}Ura)_2.3CH_3OH$	9.332	-	1590	-	3750	-	-	-	-	-
	9.298		2800		3190		-	2.37	2.08	2.18
$Cu(6CH_3,2S\text{-}Ura)_2.2H_2O$	9.331	-	1660	-	-	4150	-	-	-	-
	9.298		2760		3175		-	2.41	2.09	2.20
$Cu(6C_3H_7,2S\text{-}Ura)_24H_2O$	9.522	750	1120	5100	-	-	-	-	-	-
	9.522		2725		3190		-	2.50	2.13	2.38
Cu(2,4-Dithioura)(OH).H_2O	9.524	1580	1700	5100	-	-	-	-	-	-
	9.524		3075		3295		-	2.21	2.07	2.12
$Cu(Cyto)_2Cl_2$	9.524	-	-	-	-	-	-	-	-	-
	9.319		2990		3208		-	2.23	2.08	2.13

Table VI(Cont'd)

Compound	A_z (G)	B_{xy} (G)	/D/ (cm^{-1})	-2J (cm^{-1})	g (best fit)	-ø (^oK)	Monomer Corr. (%)	Magnetic Model
$Cu(Ura)_2 \cdot H_2O$	-	-	0.072	-	-	-	-	-
	-	-						
$Cu(5I\text{-}Ura)_2 \cdot H_2O$	-	-	-	110.7	2.08	-	17	Ising
	160	8						
$Cu(5NO_2\text{-}Ura)_2 \cdot 2H_2O$	-	-	0.165	6.2	2.11	7.9	0	Dimer
	-	-						
$Cu(2S\text{-}Ura)_2 \cdot 3H_2O$	-	-	0.180	1400 ±200	2.15	-	3	Dimer
	-	-						
$Cu(6NH_2,2S\text{-}Ura)_2 \cdot 3CH_3OH$	-	-	0.160	1400 ±200	2.18	-	0	Dimer
	125	-						
	110	-						
$Cu(6CH_3,2S\text{-}Ura)_2 \cdot 2H_2O$	-	-	0.140	1400 ±200	2.18	-	0	Dimer
	150	-						
	125	-						
$Cu(6C_3H_7,2S\text{-}Ura)_2 \cdot 4H_2O$	-	-	0.200	1400 ±200	2.00	-	5	Dimer
	-	-						
$Cu(2,4\text{-}Dithioura)(OH) \cdot H_2O$	-	-	0.047	700	2.02	-	9	Ising
	-	-						
$Cu(Cyto)_2Cl_2$	-	-	-	6.2	2.07	3.0	0	Dimer
	-	-						

Table VI(Cont'd)

Compound	ν (GHz)	H_{MIN}	$(H_z)_1$	$(H_z)_2$	$(H_{xy})_1$	$(H_{xy})_2$	H_{av}	g_z	g_{xy}	g_{av}
$Cu(2S\text{-}Cyto)Cl_2$	9.524	1500	1600	5100	-	-	-	-	-	-
	9.318		-		-		3157	-	-	2.11
$Cu(2S\text{-}Cyto)_2.2H_2O$	9.525	1475	-	5060	-	-	-	-	-	-
	9.298		-		-		3145	-	-	2.11
$Cu(Guano)_2.4H_2O$	9.294	1490	1800	4900	-	-	-	-	-	-
	9.280		2950		3230		-	2.25	2.05	2.12
$Cu(8Br\text{-}Guano)_2.3H_2O$	9.254	-	-	-	-	-	-	-	-	-
	9.526		2965		3294		-	2.30	2.07	2.15
$Cu_3(d\text{-}Guano)_2(OH)_4.4H_2O$	9.521	1300	-	4860	-	3800	-	-	-	-
	9.293		2940		3240		-	2.26	2.05	2.12
$Cu(Xantho)(OH).2H_2O$	9.523	1460	-	4900	-	-	-	-	-	-
	9.280		2875		3190		-	2.31	2.08	2.16
$Cu(Cyti)(OH).2H_2O$	9.524	1450	1600	5210	-	4450	-	-	-	-
	9.323		2850		3255		-	2.34	2.05	2.15
$Cu(Ino)(OH).H_2O$	9.526	1520	-	5300	-	4500	-	-	-	-
	9.278		2940		3205		-	2.25	2.07	2.13
$Cu(Adeno)(OH).1/2H_2O$	9.523	900	-	5100	-	-	-	-	-	-
	9.319		2958		3250		-	2.25	2.05	2.12
$Cu(GMP).5H_2O$	9.523	1580	-	-	-	-	-	-	-	-
	9.324		2795		3155		-	2.38	2.11	2.20

Table VI(Cont'd)

Compound	A_z (G)	B_{xy} (G)	/D/ (cm^{-1})	-2J (cm^{-1})	g (best fit)	-ø (^oK)	Monomer Corr. (%)	Magnetic Model
$Cu(2S\text{-}Cyto)Cl_2$	- -	- -	0.054	1400 ±200	2.05	-	3	Dimer
$Cu(2S\text{-}Cyto)_2.2H_2O$	-	-	0.093	1400 ±200	2.06	-	6	Dimer
$Cu(Guano)_2.4H_2O$	- 180	- 30	0.082	-	-	-	-	-
$Cu(8Br\text{-}Guano)_2.3H_2O$	- 165	- 35	-	-	-	-	-	-
$Cu_3(d\text{-}Guano)_2(OH)_4.4H_2O$	- 175	- 13	0.161	J=58.0 JJ=52.0	2.00	-	0	Trimer
$Cu(Xantho)(OH).2H_2O$	- 155	- -	0.103	-	-	-	-	-
$Cu(Cyti)(OH).2H_2O$	- 135 150	- 15 35	0.110	-	-	-	-	-
$Cu(Ino)(OH).H_2O$	- 170	- 10	0.084	-	-	-	-	-
$Cu(Adeno)(OH).1/2H_2O$	- 185	- 30	-	-	-	-	-	-
$Cu(GMP).5H_2O$	- -	- -	0.150	A=130 B= 14 C= 2	2.08	-	0	Tetramer

Table VI(Cont'd)

Compound	ν (GHz)	H_{MIN}	$(H_z)_1$	$(H_z)_2$	$(H_{xy})_1$	$(H_{xy})_2$	H_{av}	g_z	g_{xy}	g_{av}
$Cu(AMP).2H_2O$	9.525	1450	2210	5100	2340	-	-	-	-	-
	9.308		-		-		3080	-	-	2.16
$Cu(CMP).6H_2O$	9.525	-	-	-	-	-	-	-	-	-
	9.526		2900		3285		-	2.35	2.07	2.26

Table VI (Cont'd)

Compound	A_z (G)	B_{xy} (G)	/D/ (cm^{-1})	-2J (cm^{-1})	g (best fit)	-ø (^oK)	Monomer Corr. (%)	Magnetic Model
$Cu(AMP).2H_2O$	- -	- -	0.107	A=118 B= 12 C= 2	2.03	-	0	Tetramer
$Cu(CMP).6H_2O$	- -	- -	-	-	-	-	-	-

* All field positions in gauss and result from best resolved spectra; 1 and 2 refer to low and high, respectively; data for coupled systems given before monomer systems. For monomer systems, perpendicular and parallel field positions entered under "low" headings.

** First letters of the ligand used in identifying compounds.

Table IXX

Field Dependent Molar Susceptibility and Effective Magnetic Moment Measurements at 294°K

Compound	Field Strength 3KG		Field Strength 8KG		Field Strength 15KG	
	χ ($\times 10^{-6}$)	μ	χ ($\times 10^{-6}$)	μ	χ ($\times 10^{-6}$)	μ
Cu(Xanthosine)(OH).$2H_2O$	3874	3.93	2272	2.31	2003	2.18
Cu(Cytidine)(OH).$2H_2O$	3448	2.86	3108	2.69	1393	1.81
Cu(Adenosine)(OH).$1/2H_2O$	2389	2.37	1583	1.93	1292	1.74
Cu(Inosine)(OH).H_2O	2987	2.66	2845	2.58	1008	1.54
Cu(Guanosine)$_2$.$4H_2O$	1935	2.14	1814	2.06	1306	1.77
Cu(Br-Guanosine)$_2$.$3H_2O$	3670	2.95	1074	1.59	866	1.43
Cu(Uracil)$_2$.H_2O	3030	2.68	1320	1.78	1168	1.66
Cu(CMP).$6H_2O$	5227	3.52	3098	2.69	2474	2.42

Concluding Remarks

The scope of this work, in terms of systems studied and spectroscopic techniques employed was ambitious, but deliberately so in an effort to extract as much information on solid coordination compounds of copper(II) with nucleic acid constituents as possible. Specific ligands and sets of ligand systems were chosen in order to observe trends and be able to make generalities about the bonding and electronic and magnetic properties of solid copper(II)-nucleic acid constituent compounds. The following observations can be made about bonding sites, bonding modes and stoichiometries, and electronic and magnetic properties of the solid copper(II) coordination compounds of pyrimidines, purines, their nucleosides and nucleotides:

1. The ability to form Cu(II) coordination compounds with nucleic acid constituents is established and pronounced. It is seen that all the nucleic acid constituents - pyrimidines, purines, their nucleosides and nucleotides - react to form stable coordination compounds with copper(II).

2. Bidentate chelation at the expense of monodentate coordination appears to be the preferred mode of bonding in coordination complexes of nucleic acid constituents with copper(II). This type of bonding appears to be general for pyrimidine and purine moieties and involves adjacent oxygen

(sulfur) and nitrogen atoms on the ring. In addition, phosphate oxygen coordinates when nucleotide systems are considered. Exclusive phosphate or sugar bonding is not found in these complexes.

3. In the uracil (cytosine) complexes, the effect of replacing a keto oxygen on C(2) with a thio sulfur interchanges the preference for coordination between N(1) (N(3)) for keto to N(3) (N(1)) for thio. This type of selectivity used for chelation sites in keto- and thio-containing nucleic acid ligands may be general for pyrimidine and purine systems alike.

4. Generally, 2:1 ligand to metal stoichiometries are preferred although 1:1 stoichiometries, with and without bridging between metal centers, are seen. Trimeric metal stoichiometries are rare.

5. EPR data demonstrate the tetragonally distorted octahedral geometry preferred by these copper(II) complexes. However, the introduction of bonding sulfur atoms in coordinating ligands distorts this bonding towards a C_{2v} or T_d disposition about the metal center with a concomitant lowering of the d-d band maximum. The ground state term in all complexes is seen to be $^2B_{1g}(d_{x^2-y^2})$.

6. Ligand field strengths for these distorted octahedral geometries vary as:

2S-Cytosines > Cytosine > 5X-Uracils > 6Y,2S-Uracils > 2,4-Dithiouracil > 8Z-Guanosines > Inosine > Cytidine >

Xanthosine > Adenosine; AMP > GMP > CMP.

7. Sulfur coordination appears to predispose the complexes to polymeric interactions ($-2J \geq 1400\ cm^{-1}$) as does the introduction of ribose and phosphoribose functions on the pyrimidine or purine base.

8. Ferromagnetism, a relatively rare type of magnetic ordering, is seen in several Cu(II) coordination compounds reported here.

9. Magnetic data suggest that the cooperative phenomenon responsible for the ferromagnetism observed in a number of these complexes, appears to be enhanced according to the following series:

Nucleosides > CMP > Uracil

and suggests the possibility of an ordering capability of the sugar group.

10. Recognition of the sugar by copper(II) is seen for deoxyguanosine but not for guanosine (apparently, d-ribosides but not ribosides) and is assigned to operate through the 3'OH group of the sugar.

Future Studies

1. Mixed-Nucleic Acid Base Complexes

To date there have been no reports of solid coordination compounds involving two different nucleic acid constituents to the same metal ion. The synthesis and spectroscopic characterization of these systems can be of importance in elucidating the role of metal ions in the replication process of DNA.

In order for DNA to replicate, it must unwind and synthesize two new half helices.[294] The potential importance of metal ions in this process is seen *in vitro* from the reversible unwinding of DNA by Cu(II)[21] and Zn(II),[295] and the effect of metal ions on the ability to alter the hydrogen bonding between the two strands of the DNA helix was briefly touched upon in the Introduction. Furthermore, metal ions like Mg(II), Mn(II), Zn(II), and Co(II) are also required *in vivo* by two of the most important enzymes for DNA synthesis: DNA polymerase[296] and the terminal deoxynucleotidyl transferase.[297]

It can be concluded from *in vitro* and *in vivo* studies, therefore, that transition metal ions are necessary for DNA replication and, in some instances, metal ions help to maintain the halves of the double helix close to each other. This requires metal coordination to two different nucleic acid components, one on each half of the double helix.

2. Ternary Complexes

Transition metal complexes containing a nucleic acid base and an amino (or Schiff base or amine) have only recently been prepared[42,51-54,151-54,168,171,203,205-7,223] and are good model systems to those where substantial interactions between nucleic acid, protein, and metal should occur. This type of interaction is vital for the processes of transcription and translation of genetic material. In transcription, metal ions like Mg(II), Mn(II), and Co(II) are essential for catalyzing the reaction,[9] while other metals like Cu(II) and Zn(II) act as partial inhibitors.[298] The transcription process requires the presence of a template (1/2 of a DNA helix), a supply of ribonucleotide triphosphate, and RNA polymerase enzyme. In the translation process, however, a sequence of three nucleic acid bases (codons) in the m-RNA is interpreted by t-RNA (anticodon), after which the anticodon proceeds to line up particular amino acids for the synthesis of proteins. Again metal ions such as Mg(II), Ca(II), and Mn(II) are required,[299] and the possibility for interaction between metal ion, nucleic acid base, and amino acid (or peptide) is obvious.

Metal ion-bridged complexes between a purine or pyrimidine moiety of a coenzyme and an aromatic amino acid residue may occur in biological systems including metal-ion-dependent enzyme systems, nucleic acid-protein interactions, or synaptosomes[300] (which contain biogenic aromatic amines,

ATP, and several metal ions), however, only recently[301] has an attempt been made to demonstrate that an interaction between a naturally occuring constituent, tryptophan and ATP with various transition metal ions (i.e., indole-metal-purine) is possible.

These examples clearly demonstrate the need to elucidate the interactions between metal ion, nucleic acid base, and peptide and it is hoped that the work presented here on metal interactions between nucleic acid constituents in the solid state will assist in this quest.

APPENDIX

```
C     THIS PROGRAM IS DESIGNED TO FIT 6 LIGANDS ABOUT A CENTRAL METAL
C     ATOM CALCULATE THE C,H,N,M ANALYSIS RESULTING FROM THE COMBINATION
C     AND COMPARE THE ANALYSIS TO THAT FOUND EXPERIMENTALLY.IF THE
C     DIFFERENCE BETWEEN THE FOUND C,H,N,M AND THE EXPERIMENTAL VALUE
C     ARE WITHIN SPECIFIED LIMITS THE LIGAND COMBINATION,ITS C,H,N,M
C     ANALYSIS AND MW ARE PRINTED OUT.UP TO 200 RESULTS ARE POSSIBLE.IF
C     THE NUMBER OF POSSIBLE COMBINATIONS EXCEEDS THIS THE EXECUTION IS
C     TERMINATED.THE COMBINATIONS THAT ARE FOUND ARE SORTED TO GIVE THE
C     FITS IN DECREASING ORDER.
C         DATA CARDS
C          #1 COLUMNS 1-60 HEADING,INFORMATION ABOUT THE JOB,61-64 MAX
C             % C,65-68 MAX %H,69-72 MAX %N,73-76 MAX %CU,DIFFERENCE
C             ALLOWED IN CALCULATED AND EXPERIMENTAL RESULTS.80 NUMBER
C             OF LIGANDS.IF COLUMNS 61-80 ARE LEFT BLANK THE FOLLOWING
C             INFORMATION IS USED IN THE PROGRAM,
C                   61-64=1.00
C                   65-68=1.00
C                   69-72=1.00
C                   73-76=5.00
C                      80=6
C          #2-3 THE NEXT SET OF CARDS ARE IN PAIRS.EACH LIGAND HAS TWO
C             CARDS.THE FIRST CONTAINS THE NAME OF THE LIGAND COLUMNS
C             1-76,COLUMNS 77-80 CONTAIN THE CHARGE.THE PROGRAM IS
C             DESIGNED TO MAINTAIN CHARGE NEUTRALITY.IF THE METAL IS NOT
C             USED AS A LIGAND A CHARGE OF +2 IS ASSUMED
C             THE SECOND CARD CONTAINS THE NUMBER OF EACH ELEMENT TO BE
C             FOUND IN THE LIGAND,
C                   COLUMNS   1-5=C
C                             6-10=H
C                            11-15=N
C                            16-21=CU
C                                26-30=CL
C                            26-30=CL
C                            31-35=BR
C                            36-40=S
C                            41-45=I
C                            46-50=F
C         LAST CARD.THE LAST CARD CONTAINS THE ATOMIC WEIGHT OF THE
C             METAL AND THE %C,H,N AND CU FOUND EXPERIMENTALLY.IF THE
C             %CU IS NOT KNOWN ENTER THE ATOMIC WEIGHT OF THE METAL,IF
C             THE %CU IS KNOWN LEAVE THE AWM BLANK
C                   COLUMNS  1-5=AWM
C                           6-10=%C
C                          11-15=%H
C                          16-20=%N
C                          21-25=%CU
C     THIS PROGRAM WAS WRITTEN BY L.A.ZYZYCK 1/30/74.GOOD LUCK
0001        DIMENSION CL(10,6),AW(10),TAW(6),A(6),IHEAD(20),ILIG(19),ICH(6),ST
           1ORE(200,11),NUM(200),TMIN(200),HLD(11)
0002        AW(1)=12.01                                                    C
0003        AW(2)=1.008                                                    H
0004        AW(3)=14.01                                                    N
0005        AW(4)=63.55                                                    CU
0006        AW(5)=16.00                                                    O
0007        AW(6)=30.97                                                    P
0008        AW(7)=79.90                                                    BR
```

```
0009            AW(8)=32.00                                                    S
0010            AW(9)=126.9                                                    I
0011            AW(10)=19.00                                                   F
0012         60 READ(5,2,END=100)(IHEAD(I),I=1,15),CC,CH,CN,CCU,NL
0013          2 FORMAT(15A4,4F4.0,3X,I1)
0014            IF(CC.GT.0.0) GO TO 200
0015            CC=1.0
0016        200 IF(CH.GT.0.0) GO TO 201
0017            CH=1.0
0018        201 IF(CN.GT.0.0) GO TO 202
0019            CN=1.0
0020        202 IF(CCU.GT.0.0) GO TO 203
0021            CCU=5.0
0022        203 IF(NL.GT.0) GO TO 204
0023            NL=6
0024        204 WRITE(6,3)(IHEAD(I),I=1,15),CC,CH,CN,CCU,NL
0025          3 FORMAT(15A4,'%C=',F4.2,'%H=',F4.2,'%N=',F4.2,'%CU=',F4.2,1X,'#OF L
                 1IGANDS=',I1)
0026            INT=0
0027            DO 17 I=1,NL
0028            READ(5,72)(ILIG(J),J=1,19),ICH(I)
0029         72 FORMAT(19A4,I4)
0030            WRITE(6,19)I                                                    9
0031         19 FORMAT(1X,' LIGAND NO. ',I1)                                    1
0032            WRITE(6,18)(ILIG(J),J=1,19),ICH(I)
0033         18 FORMAT(4X,19A4,1X,' CHARGE ',I4)
0034            READ(5,10)(CL(J,I),J=1,10)                                      14
0035         10 FORMAT(10F5.0)                                                  3
0036            WRITE(6,20)CL(1,I),CL(2,I),CL(3,I),CL(4,I),CL(5,I),CL(6,I),CL(7,I)
                 1,CL(8,I),CL(9,I),CL(10,I)                                     16
0037         20 FORMAT(10X,'C',F5.2,'H',F5.2,'N',F5.2,'CU',F5.2,'O',F5.2,'CL',F5.2  17
                 1,'BR',F5.2,'S',F5.2,'I',F5.2,'F',F5.2)                        18
0038         17 CONTINUE                                                        19
0039            READ(5,11)AWM,PC,PH,PN,PCU                                      20
0040         11 FORMAT(5F5.0)                                                   21
0041            WRITE(6,29)                                                     22
0042         29 FORMAT(1X,' EXP. ANALYSIS ')                                    23
0043            WRITE(6,13)PC,PH,PN,PCU,AWM                                     24
0044         13 FORMAT(1X,' %C= ',F5.2,2X,' %H= ',F5.2,2X,' %N= ',F5.2,2X,'%CU= ',  25
                 1F5.2,'AWM=',F6.2)                                             26
0045            NE=0
0046            WRITE(6,52)
0047         52 FORMAT(2X,'%C',7X,'%H',5X,'%N',6X,'%CU',6X,'MW',6X,'1',4X,'2',4X,'
                 13',4X,'4',4X,'5',4X,'6',/)
0048            DO 14 J=1,NL
0049            DO 14 I=1,10
0050         14 CL(I,J)=CL(I,J)*AW(I)
0051            DO 15 I=1,NL
0052            SUM=0.0
0053            DO 16 J=1,10
0054         16 SUM=CL(J,I)+SUM
0055         15 TAW(I)=SUM
0056            TEST=0.0
0057            DO 22 N=1,7
0058            DO 22 M=1,7
0059            DO 22 L=1,7
```

```
0060              DO 22 K=1,7
0061              DO 22 JN=1,7
0062              DO 22 IN=1,7
0063              A(6)=IN-1
0064              A(5)=JN-1
0065              A(4)=K-1
0066              A(3)=L-1
0067              A(2)=M-1
0068              A(1)=N-1
0069              SUM=0.0
0070              DO 24 I=1,NL
0071           24 SUM=SUM+A(I)*ICH(I)
0072              IF(AWM.NE.0.0) GO TO 410
0073              GO TO 411
0074          410 SUM=SUM+2.
0075          411 IF(SUM.NE.0.0) GO TO 22
0076              TESTMW=0.0
0077              TESTC=0.0
0078              TESTH=0.0
0079              TESTN=0.0
0080              TESTCU=0.0
0081              DO 30 J=1,NL
0082              TESTC=CL(1,J)*A(J)+TESTC
0083              TESTH=CL(2,J)*A(J)+TESTH
0084              TESTN=CL(3,J)*A(J)+TESTN
0085              TESTCU=CL(4,J)*A(J)+TESTCU
0086           30 TESTMW=TAW(J)*A(J)+TESTMW
0087              TESTMW=TESTMW+AWM
0088              IF(TESTMW-TESTM)32,22,32
0089           32 TESTM=TESTMW
0090              TPC=(TESTC/TESTMW)*100.0
0091              TPH=(TESTH/TESTMW)*100.0
0092              TPN=(TESTN/TESTMW)*100.0
0093              TPCU=(TESTCU/TESTMW)*100.0
0094              TDC=TPC-PC
0095              TDC=ABS(TDC)
0096              IF( CC-TDC)22,41,41
0097           41 TDH=TPH-PH
0098              TDH=ABS(TDH)
0099              IF( CH-TDH)22,42,42
0100           42 TDN=TPN-PN
0101              TDN=ABS(TDN)
0102              IF( CN-TDN)22,43,43
0103           43 TDCU=TPCU-PCU
0104              TDCU=ABS(TDCU)
0105              IF(CCU-TDCU)22,44,44
0106           44 INI=INI+1
0107              WRITE(6,50)TPC,TPH,TPN,TPCU,TESTMW,(A(I),I=1,NL)
0108           50 FORMAT(4(F6.2,2X),F7.2,1X,6F5.1)
0109              NUM(INT)=INI
0110              TMIN(INI)=((TDH**2+(TDC/12)**2+(TDN/14)**2)**0.5
0111              STORE(INI,1)=TPC
0112              STORE(INI,2)=TPH
0113              STORE(INI,3)=TPN
0114              STORE(INI,4)=TPCU
0115              STORE(INI,5)=TESTMW
```

```
0116              DO 301 J=1,NL
0117              KT=J+5
0118            301 STORE(INT,KT)=A(J)
0119              NET=NET+1
0120              IF(NET-200)22,61,61
0121             22 CONTINUE
0122              IF(INT.EQ.0) GO TO 412
0123              DO 302 K=1,INT
0124              DO 310 I=K,INT
0125              IF(TMIN(I).GT.TMIN(K)) GO TO 310
0126              HOLD=TMIN(I)
0127              TMIN(I)=TMIN(K)
0128              TMIN(K)=HOLD
0129              IHOLD=NUM(I)
0130              NUM(I)=NUM(K)
0131              NUM(K)=IHOLD
0132            310 CONTINUE
0133            302 CONTINUE
0134              WRITE(6,403)
0135            403 FORMAT(1X,' SORTED BY MIN=(TDH**2+(TDC/12)**2+(TDN/14)**2)**0.5')
0136              DO 304 I=1,INT
0137              WRITE(6,55)(STORE(NUM(I),J),J=1,KT),TMIN(I)
0138             55 FORMAT(4(F6.2,2X),F7.2,1X,6F5.1,2X,F6.4)
0139              IF(TMIN(I).EQ.TMIN(I+1)) GO TO 304
0140              WRITE(6,402)
0141            402 FORMAT('**********************************************************
                 1**********')
0142            304 CONTINUE
0143            412 WRITE(6,405)
0144              GO TO 60
0145             61 WRITE(6,62)(A(I),I=1,NL)
0146             62 FORMAT(1X,' THE NUMBER OF POSSIBILITIES IS GREATER THAN 200,EXECUT
                   ION TERMINATED AT',6F5.0)
0147              WRITE(6,405)
0148              GO TO 60
0149            100 CONTINUE
0150              WRITE(6,51)
0151            405 FORMAT(1H1,' LIGFIT II ')
0152             51 FORMAT(1X,' IF THIS IS THE ONLY OUTPUT GIVE UP')
0153              STOP
0154              END
```

```
    HCN-105-2          CU-AMP                                    %C=1.00%H=1.00%N=1.00%CU=5.00 #OF LIGANDS=6
LIGAND NO. 1
    CU                                                                                    CHARGE    2
        C 0.0 H 0.0 N 0.0 CU 1.000 0.0 CL 0.0 BR 0.0 S 0.0 I 0.0 F 0.0
LIGAND NO. 2
          ANP                                                                             CHARGE   -2
        C10.00H12.00N 5.00CU 0.0 O 7.00CL 1.00BR 0.0 S 0.0 I 0.0 F 0.0
LIGAND NO. 3
        AMP                                                                             CHARGE   -1
        C10.00H13.00N 5.00CU 0.0 O 7.00CL 1.00BR 0.0 S 0.0 I 0.0 F 0.0
LIGAND NO. 4
        NITRATE ION                                                                     CHARGE   -1
        C 0.0 H 0.0 N 1.00CU 0.0 O 3.00CL 0.0 BR 0.0 S 0.0 I 0.0 F 0.0
LIGAND NO. 5
       HYDROXIDE ION                                                                    CHARGE   -1
        C 0.0 H 1.00N 0.0 CU 0.0 O 1.00CL 0.0 BR 0.0 S 0.0 I 0.0 F 0.0
LIGAND NO. 6
        WATER                                                                           CHARGE    0
        C 0.0 H 2.00N 0.0 CU 0.0 O 1.00CL 0.0 BR 0.0 S 0.0 I 0.0 F 0.0
EXP. ANALYSIS
%C= 26.72   %H=  4.26   %N= 16.31  %CU=  0.0 AWM= 63.54
%C        %H      %N       %CU       MW        1     2     3     4     5     6

27.00     3.63    15.75     0.0     444.79    0.0   0.0   1.0   0.0   1.0   1.0
27.00     3.63    15.75     0.0     444.79    0.0   1.0   0.0   0.0   0.0   2.0
27.72     3.64    17.25     4.89   1299.83    1.0   0.0   3.0   1.0   0.0   4.0
27.34     3.75    17.01     4.82   1317.85    1.0   0.0   3.0   1.0   0.0   5.0
26.97     3.85    16.78     4.76   1335.87    1.0   0.0   3.0   1.0   0.0   6.0
 SORTED BY MIN=(TDH**2+(TDC/12)**2+(TDN/14)**2)**0.5
26.97     3.85    16.78     4.76   1335.87    1.0   0.0   3.0   1.0   0.0   6.0   0.4136
**********************************************************************************
27.34     3.75    17.01     4.82   1317.85    1.0   0.0   3.0   1.0   0.0   5.0   0.5171
**********************************************************************************
27.72     3.64    17.25     4.89   1299.83    1.0   0.0   3.0   1.0   0.0   4.0   0.6244
**********************************************************************************
27.00     3.63    15.75     0.0     444.79    0.0   0.0   1.0   0.0   1.0   1.0   0.6357
**********************************************************************************
27.00     3.63    15.75     0.0     444.79    0.0   1.0   0.0   0.0   0.0   2.0   0.6357
**********************************************************************************
```

```
$JOB            NELSON
CDATA IMPUT ALTERNATE A HEADING CARD WITH A DATA CARD PLUG IN VALUES IN THE
CORDER GIVEN IN STATEMENT# 3 FORMATED AS F5.0 R=REFERENCE, S=SAMPLE, AND D=DELTA
CFW=MOLECULAR WEIGHT HG CO(SCN)4 IS USED AS THE REFERENCE THE EQUATION IS A
CPROPORTION SO PLUG IN RELATIV E WEIGHTS.  THE EXPONENT FOR THE TEMPERATURE
CINDEPENDENT PARAMAGNETIC CORRECTION(TIP) AND THE DIAMAGNETIC CORRECTION(DIA) IS
CINCLUDED IN THE PROGRAM(10-6) USE A NEGATIVE SIGN FOR BUCKET CONTRIBUTION(BUC)
CPRINTOUT:  THE MAGNETIC SUSCEPTIBILITY IS GIVEN BY XMC.  THE TEMPERATURE IS THE
CDATA POINT 1.
C
C
C     SET OF DATA CARDS CONSISTS OF
C         1ST CARD: HEADING CARD COL 1-72
C         2ND CARD: NO. OF EXP. POINTS OBTAINED
C         3RD CARD: WTR,WTS,DWTR,BUC,FW,CR
C         4TH CARD: NO. OF ATOMS OF DIFF. ELEMENT THAT COMPOUND HAS
C      5TH CARD    TEMP,DWTS
C
C
 1          DIMENSION  IHEAD(18),DIAC(75),ITAB(75)
 2          REAL*8 WTR,DWTR,BUC,WTS,DWTS
 3          TIP=60.
 4          TIPE=TIP*1.E-6
 5          DIAC(1)=1.0
 6          DIAC(2)=6.8
 7          DIAC(3)=14.9
 8          DIAC(4)=22.5
 9          DIAC(5)=35.0
10          DIAC(6)=35.7
11          DIAC(7)=13.3
12          DIAC(8)=40.0
13          DIAC(9)=5.0
14          DIAC(10)=15.0
15          DIAC(11)=32.0
16          DIAC(12)=10.4
17          DIAC(13)=12.8
18          DIAC(14)=12.8
19          DIAC(15)=12.8
20          DIAC(16)=12.8
21          DIAC(17)=9.1
22          DIAC(18)=23.4
23          DIAC(19)=34.6
24          DIAC(20)=50.6
25          DIAC(21)=18.9
26          DIAC(22)=30.2
27          DIAC(23)=32.0
28          DIAC(24)=36.8
29          DIAC(25)=51.9
30          DIAC(26)=51.4
31          DIAC(27)=13.0
32          DIAC(28)=31.0
33          DIAC(29)=40.1
34          DIAC(30)=29.5
35          DIAC(31)=12.0
36          DIAC(32)=2.93
37          DIAC(33)=6.0
38          DIAC(34)=4.61
39          DIAC(35)=5.57
40          DIAC(36)=1.54
41          DIAC(37)=2.11
```

```
      DIAC(38)=4.61
      DIAC(39)=-1.73
      DIAC(40)=3.36
      DIAC(41)=6.3
      DIAC(42)=20.1
      DIAC(43)=30.6
      DIAC(44)=44.6
      DIAC(45)=15.0
      DIAC(46)=23.0
      DIAC(47)=37.3
      DIAC(48)=26.3
      DIAC(49)=43.0
      DIAC(50)=20.9
      DIAC(51)=74.0
      DIAC(52)=4.2
      DIAC(53)=9.2
      DIAC(54)=18.5
      DIAC(55)=10.0
      DIAC(56)=15.9
      DIAC(57)=13.0
      DIAC(58)=13.5
      DIAC(59)=33.0
      DIAC(60)=20.0
      DIAC(61)=30.0
      DIAC(62)=46.0
      DIAC(63)=-5.5
      DIAC(64)=-10.6
      DIAC(65)=-0.8
      DIAC(66)=-1.8
      DIAC(67)=-8.2
      DIAC(68)=-0.24
      DIAC(69)=-3.9
      DIAC(70)=-4.1
      DIAC(71)=-4.1
      DIAC(72)=105.
      DIAC(73)=128.
      DIAC(74)=13.
      DIAC(75)=194.
    1 READ(5,200,END=100)(IHEAD(I),I=1,18)
  200 FORMAT(18A4)
      WRITE(6,3000)(IHEAD(I),I=1,18)
 3000 FORMAT(1H1,1X,18A4,/)
      READ(5,400)N
  400 FORMAT(I2)
      READ(5,700)WTR,WTS,DWTR,BUC,FW,CR
  700 FORMAT (6F10.4)
      L=1
      RATIO=DWTR/WTR
      WRITE(6,5000)FW,TIP,CR,RATIO
 5000 FORMAT(4X,'FORMULA WT. =',F12.4,//,4X,'INDEPENDENT PARAMAGNETIC CO
     $RRECTION =',F11.4,//,4X,'CR =',F11.4,//,4X,'RATIO =',F11.4,//,T7,'
     $WT.',T19,'DIFF. IN',T35,'WT.',T47,'DIFF. IN',T61,'BUCKET',T77,'DIA
     $',T90,'TEMP',T105,'XMC',T119,'UEFF',/,T5,'OF REF',T19,'WT. REF',T3
     $1,' OF SAMPLE',T45,'WT. SAMPLE',T58,'CONTRIBUTION',T104,'X 10**6',
     $//)
      ZZ=CR*1.E-6*WTR/(DWTR-BUC)/WTS
      READ(5,900)(ITAB(I),I=1,75)
  900 FORMAT(36I2,/,39I2)
      SUM=0.
      DO 13  I=1,75
```

```
 97   13     SUM=SUM+ITAB(I)*DIAC(I)
 98          DIA=-SUM
 99          DIAE=DIA*1.E-6
100   2      READ(5,800)T,DWTS
101   800    FORMAT(F10.2,F10.4)
102          XG=ZZ*(DWTS-BUC)
103          XM=XG*FW
104          XMC=XM-TIPE-DIAE
105          IF(XMC.LT.0.0)GO TO 99
106          UEFF=2.84*SQRT(XMC*T)
107          XMC=XMC*1.E06
108          WRITE(6,7000)WTR,DWTR,WTS,DWTS,BUC,DIA,T,XMC,UEFF
109   7000   FORMAT(1H ,2X,F9.4,T17,F10.4,T31,F10.4,T45,F10.4,T59,F10.4,T73,F10
             $.4,T87,F10.4,T99,F15.3,T116,F10.4,//)
110   3      L=L+1
111          IF(L.GT.N)GO TO 1
112          GO TO 2
113   99     XMC=XMC*1.E06
114          WRITE(6,1500)WTR,DWTR,WTS,DWTS,BUC,DIA,T,XMC
115   1500   FORMAT(1H ,2X,F9.4,T17,F10.4,T31,F10.4,T45,F10.4,T59,F10.4,T73,F10
             $.4,T87,F10.4,T99,F12.3,T113,'INCOR. DATA',//)
116          GO TO 3
117   100    STOP
118          END

       $DATA
```

CU(GMP).5H2O HCN-104-2 12/9/75

FORMULA WT. = 514.7700

INDEPENDENT PARAMAGNETIC CORRECTION = 60.0000

CR = 16.3300

RATIO = 0.0367

WT. OF REF	DIFF. IN WT. REF	WT. OF SAMPLE	DIFF. IN WT. SAMPLE	BUCKET CONTRIBUTION	DIA	TEMP	XMC X 10**6	UEFF
8.9765	0.3295	9.2348	0.0145	-0.0445	-259.1899	295.0000	1488.208	1.8817
8.9765	0.3295	9.2348	0.0375	-0.0445	-259.1899	204.0000	1990.707	1.8098
8.9765	0.3295	9.2348	0.0583	-0.0445	-259.1899	154.0000	2445.141	1.7427
8.9765	0.3295	9.2348	0.0845	-0.0445	-259.1899	106.0000	3017.553	1.6062
8.9765	0.3295	9.2348	0.1125	-0.0445	-259.1899	84.1000	3629.290	1.5690
8.9765	0.3295	9.2348	0.1358	-0.0445	-259.1899	70.0000	4138.336	1.5286
8.9765	0.3295	9.2348	0.1635	-0.0445	-259.1899	58.9000	4743.520	1.5012
8.9765	0.3295	9.2348	0.1953	-0.0445	-259.1899	48.6000	5438.277	1.4600
8.9765	0.3295	9.2348	0.2393	-0.0445	-259.1899	39.9000	6399.582	1.4351
8.9765	0.3295	9.2348	0.3058	-0.0445	-259.1899	29.3000	7852.457	1.3622
8.9765	0.3295	9.2348	0.3778	-0.0445	-259.1899	23.0000	9425.492	1.3223
8.9765	0.3295	9.2348	0.4770	-0.0445	-259.1899	16.9000	11592.790	1.2571
8.9765	0.3295	9.2348	0.6828	-0.0445	-259.1899	11.3000	16089.060	1.2109

CORE USAGE OBJECT CODE= 4784 BYTES,ARRAY AREA= 672 BYTES,TOTAL AREA AVAILABLE= 18528 BYTES

DIAGNOSTICS NUMBER OF ERRORS= 0, NUMBER OF WARNINGS= 0, NUMBER OF EXTENSIONS= 0

COMPILE TIME= 0.11 SEC,EXECUTION TIME= 0.02 SEC, WATFIV - JUL 1973 V1L4 12.24.14 SATURDAY 20 MAR 76

```
      $JOB          NELSON
      C     TESTED FOR CU(AC)2 ON JULY21ST,1975 WORKS
      C      THE LAST CARD IN THE DATA DECK MUST BE A BLANK CARD
      C     INPUT IS UNFORMATTED, DATA CARDS CONTAIN:
      C           (CARD 1) HEADING
      C           (CARD 2) NUMBER OF X VALUES; VALUE OF G
      C           (ALL OTHER CARDS) X VALUE; TEMPERATURE
      C
      C
      C     TO FIND ONLY THE J VALUE WITHOUT CALCULATING DELTA,
      C     MAKE THE FOLLOWING CHANGES:
      C           JUST BEFORE LINE 10 (D1=D ), INSERT: GOTO 500
      C
 1          DIMENSION HEADER(20)
 2          COMMON /FIND/ OD,OJ
 3           COMMON XT(3,100),N,G,ALPHA
      C     XT(1,?)=EXPERIMENTAL X; XT(2,?)=TEMPERATURE; XT(3,?)=CALCULATED X
 4    1000  CONTINUE
 5          READ(5,140,END=2000) HEADER
 6    140   FORMAT(20A4)
 7          READ, N, G
 8          IF (N.EQ.0) GO TO 2000
 9           READ,((XT(I,J),I=1,2),J=1,N)
10          DO 50 J=1,N
11           XT(1,J)=XT(1,J)/10**6
12    50    CONTINUE
      C     INITIALIZE
13          OJ=100000
14          OD=OJ
15          D=1000
16           Q=0
17           CALL FINDJ(D,Q,0)
18            Q=-Q
19           GOTO 500
20    10     D1=0
21           Q1=0
22          OD1=OD
23           OJ1=OJ
24           CALL FINDD(D,Q)
25           CALL FINDJ(D,Q,1)
26          OLDSUM=OD
27           IF(OD.GT.OD1) GOTO 500
28          OLDSUM=OJ
29           IF(OJ.GT.OJ1) GOTO 500
30           IF (D.GT.D1) GOTO 500
31           IF( N.EQ.N1) GOTO 500
32           GOTO 10
33    500   WRITE(6,200) HEADER,N,G,OLDSUM,Q,D
34    200   FORMAT(1H1,20A4,//,T10,'N =',I4,//,T10,'G =',F10.7,//T5,'SUM SQ ='
           $,E14.7,//,T10,'J =',F10.4,//,T6,'DELTA =',F12.5////T13,'T',T37,'EX
           $P X',T62,'CALC. X',T88,'EXP 1/X',T113,'CALC. 1/X',/)
35           DO 205 I=1,N
36           EX=1/XT(1,I)
37           CX=1/XT(3,I)
38    205     WRITE(6,210) XT(2,I),XT(1,I),XT(3,I),EX,CX
39    210   FORMAT(1X,T6,F12.4,T32,6PF12.4,T58,F12.4,T84,0PF12.4,T114,F12.4,/)
40    21     WRITE(6,135)
41    135    FORMAT(1H1)
42           GO TO 1000
43    2000  STOP
```

```
      END

      FUNCTION F(I,X)
C
C     F(I,X) CHANGES THE VALUE OF X AS FOLLOWS:
C           IF I=0, X=X/2 ;
C           IF I=1, X=X+10 ;
C           IF I=2, X=X-1 ;
C           IF I=3, X=X+0.1
C
      IF (I-2) 1,2,3
3     F=X+.1
      RETURN
2     F=X-1.
      RETURN
1     IF (I) 4,4,5
4     F=X/2.
      RETURN
5     F=X+10.
      RETURN
      END

      SUBROUTINE FINDJ(D,Q,MODE)
       COMMON  XT(3,100),N,G,ALPHA
      COMMON /FIND/ OD,OLDSUM
      IQ=1
10     SUM=0.0
       DO 20 I=1,N
       T=XT(2,I)
      ALPHA=.000060
      XT(3,I)=.3755*G*G/T/(3+EXP(Q/T/.6951)+EXP((Q+D)/T/.6951)*MODE)
     $+ALPHA
        SUM=SUM+(XT(3,I)-XT(1,I))**2
      SUMP=SUM
20     CONTINUE
      IF(SUMP.GE.OLDSUM) GOTO 30
       OLDSUM=SUMP
      Q=F(IQ,Q)
      GOTO 10
30     IF(IQ.EQ.3) RETURN
       IF (IQ.EQ.2) IQ=3
      IF (IQ.EQ.1) IQ=2
      IF (IQ.EQ.0) IQ=1
       OLDSUM=SUMP
      Q=F(IQ,Q)
       GOTO 10
       END

      SUBROUTINE FINDD(D,Q)
       COMMON  XT(3,100),N,G,ALPHA
      COMMON /FIND/ OLDSUM,OJ
       IQ=0
10     SUM=0.0
       DO 20 I=1,N
       T=XT(2,I)
      ALPHA=0.00006
      XT(3,I)=.3755*G*G/T/(3+EXP(Q/T/.6951)+EXP((Q+D)/T/.6951))+ALPHA
```

```
 90           SUM=SUM+(XT(3,I)-XT(1,I))**2
 91          SUMP=SUM
 92    20     CONTINUE
 93          IF (SUMP.GE.OLDSUM) GOTO 30
 94          OLDSUM=SUMP
 95           D=F(IQ,D)
 96           GOTO 10
 97    30     IF(IQ.EQ.3) RETURN
 98           IF (IQ.EQ.2) IQ=3
 99           IF(IQ.EQ.1)IQ=2
100          IF (IQ.EQ.0) IQ=1
101          OLDSUM=SUMP
102           D=F(IQ,D)
103           GOTO 10
104           END

     $DATA
```

CU(CYTOSINE)2CL2 DIMFIT USING G VALUE SET AT 2.07

N = 12

G = 2.0699990

SUM SQ =0000000000000000

J = -6.2000

DELTA = 1000.00000

T	EXP X	CALC. X	EXP 1/X	CALC. 1/X
299.0000	1329.8060	1395.1920	751.9888	716.7468
204.0000	1917.3010	2009.9990	521.5662	497.5125
151.0000	2582.5540	2683.9550	387.2134	372.5842
95.0000	4055.6000	4192.4560	246.5726	238.5236
78.5000	4930.3620	5034.4870	202.8248	198.6299
64.2000	5891.5200	6100.4160	169.7355	163.9232
54.7000	6938.2710	7101.8520	144.1281	140.8083
44.9000	8327.8930	8552.1260	120.0784	116.9300
36.1000	10444.6000	10472.8700	95.7432	95.4847
25.5000	14073.2400	14339.3600	71.0568	69.7381
18.0000	19872.5900	19318.9000	50.3205	51.7628
12.0000	26335.0300	26335.7800	37.9722	37.9711

```
C   MAIN PROGRAM
C
C
C      THIS PROGRAM IS NAMED AFTER MY FATHER, KHOE TJHIE CHIM
C     THIS PROGRAM IS DESIGNED TO FIND THE G FACTOR,J,X(CAL),AMU(CAL)
C     X(CAL) IS ASSUMED TO BE EQUAL TO X(EXP)+NALPHA AT BEGINNING OF PROGRAM
C     G IS DECIDED TO BE BETWEEN A RANGE OF GMIN-GMAX
C     J IS DECIDED TO BE BETWEEN A RANGE OF JMIN-JMAX
C     NALPHA-THE CORRECTION FACTOR FOR X IS GIVEN
C     G IS FOUND THROUGH FORMULA GIVEN.  THE STD DEV. IS FOUND
C     OF THE G VALUES.   THE NEW FOUND STD DEV IS THEN COMPARED TO THE
C     FORMER FOUND ONE.  THE G AND J VALUE WITH THE LEAST STD. DEV.
C     ARE DECIDED TO BE THE VALUES WE WANTED
C     THE LAST CARD IN THE DATA DECK SHOULD BE A CARD WITH  0 IN THE 2ND COLUMN
C
C
0001          DIMENSION  X(25),XCAL(25),AMU(25),AMUC(25),GG(25),DEV(25),T(25),
             $PING(6,3),W(25)
0002          REAL    K,JMIN,JMAX,J,NALPHA,KEEPJ
0003          DATA  K,C,B,AVO/1.38E-16,1.9862E-16,9.273E-21,6.022E23/
0004          DATA  GMIN,GMAX/2.00,2.10/
0005          RAT=AVO*B*B/K/3.
0006    1      READ(5,1000)N,SMAX,SMIN,NALPHA,Z,COUNT,DD
0007    1000  FORMAT(I2,F18.2,F10.2,F10.2,F5.2,F5.2,F5.2)
0008           IF(N.EQ.0)STOP
0009          READ(5,111)PING
0010    111    FORMAT(16A4)
0011          DO 66 I=1,N,1
0012          READ(5,2)T(I),X(I)
0013     2     FORMAT(F10.2,F10.4)
0014          W(I)=(X(I)-NALPHA)*1.E-6
0015     66   CONTINUE
0016     444   WRITE(6,333)PING
0017     333   FORMAT(1H1,4X,18A4)
0018          WRITE(6,3000)SMIN,SMAX,GMIN,GMAX,NALPHA,N,Z
0019    3000  FORMAT(1H0,9X,'JMIN =',F12.5,//,10X,'JMAX = ',F12.5,//,10X,'GMIN =
             $',F12.5,//,10X,'GMAX =',F12.5,//,10X,'NALPHA = ',F12.5,//,10X,'N =
             $',I3,//,10X,'Z =',F6.2,//)
0020          WRITE(6,4000)
0021    4000  FORMAT(1H0,10X,'TEMP',9X,'X(EXP)',13X,'X(CAL)',14X,'AMU(EXP)',12X,
             $'AMU(CAL)',15X,'% DEV IN X',//)
C      SET J'S LIMIT
0022          JMIN=SMIN*C
0023          JMAX=SMAX*C
0024          J=JMIN
0025          OLDEV=100000.
0026          A=0.
0027          Z00=1.-Z
C      FIND G TO BE WITHIN G LIMIT, FIXING Z VALUE, VARYING J
0028     17   DO 20  I=1,N
0029          DIM=1.+0.333*EXP(-J/K/T(I))
0030          SKY=RAT/T(I)
0031          SHIP=0.125*Z00/T(I)/DIM+SKY*Z
0032          GG(I)=SQRT(W(I)/SHIP)
0033     20    CONTINUE
0034     40   CALL  DDEV(GG,STDEV,N,BARG)
```

```
0035              IF (BARG.LT.GMIN)GO TO 30
0036              IF(BARG.GT.GMAX)GO TO 30
0037              IF(STDEV.GT.OLDEV)GO TO 30
0038              OLDEV=STDEV
0039              FBARG=BARG
0040              A=FBARG*FBARG
0041              KEEPJ=J
0042              IF (OLDEV.LE.0.0010)GO TO 222
0043           30 J=J+1.E-16
0044              IF(J.GT.JMAX)GO TO 222
0045              GO TO 17
                C     FINALLY THE DECIDED G AND J VALUES ARE OBTAINED
0046          222 IF(A.EQ.0.)GO TO 350
0047              DO 100  I=1,N
0048              DIM=1.+0.333*EXP(-KEEPJ/K/T(I))
0049              ER=0.125*A/T(I)/DIM*ZOO
0050              XCAL(I)=(ER+RAT/T(I)*A*Z)*1.E6*NALPHA
0051              AMU(I)=2.828*SQRT(X(I)*T(I))
0052              AMUC(I)=2.828*SQRT(XCAL(I)*T(I))
0053              DEV(I)=ABS(XCAL(I)-X(I))/XCAL(I)*100.
0054              WRITE(6,7000)T(I),X(I),XCAL(I),AMU(I),AMUC(I),DEV(I)
0055          7000 FORMAT(1H ,9X,F6.2,3X,F12.4,7X,F12.4,8X,F12.4,8X,F12.4,8X,F12.4,10
                   $X,F11.4,/)
0056          100 CONTINUE
0057              KEEPJ=KEEPJ/C
0058              WRITE(6,8000)KEEPJ,FBARG,OLDEV
0059          8000 FORMAT(1H0,10X,'ABSOLUTE VALUE OF 2J = ',F12.5,//,10X,'G = ',F12.5
                  $,//,10X,'STD. DEV. BETWEEN G VALUES FOUND =',F15.5,//)
0060            457 Z=Z+DD
0061              IF(Z.GT.COUNT)GO TO 1
0062              GO TO 444
0063            350 WRITE(6,351)
0064            351 FORMAT(' CANNOT FIND G & J VALUES, POSSIBILITY: NOT A DIMER')
0065              GO TO 457
0066              END
```

```
FORTRAN IV G LEVEL  21                DDEV              DATE = 76080        11/44/19            PAGE 0001

0001                SUBROUTINE DDEV(GG,STDEV,N,BARG)
0002                DIMENSION  GG(N)
0003                VAR=0.
0004                SUMG=0.
0005                DO 200  I=1,N
0006            200 SUMG=SUMG+GG(I)
0007                EN=N
0008                BARG=SUMG/EN
0009                DO 300  I=1,N
0010            300 VAR=VAR+(GG(I)-BARG)**2
0011                STDEV=SQRT(VAR/(EN-1.))
0012                RETURN
0013                END
```

CU(CYTOSINE)2CL2 DIMFIT OUTPUT ZERO % IMPURITY

JMIN = -50.00000

JMAX = 10.00000

GMIN = 2.00000

GMAX = 2.10000

NALPHA = 60.00000

N = 12

Z = 0.0

TEMP	X(EXP)	X(CAL)	AMU(EXP)	AMU(CAL)	% DEV IN X
299.00	1329.8069	1344.6858	1783.2371	1793.1853	1.1065
204.00	1917.3018	1937.9072	1768.6406	1778.1189	1.0633
151.00	2582.5549	2589.4780	1766.0073	1768.3728	0.2674
95.00	4055.6079	4053.0156	1755.3713	1754.8098	0.0640
78.50	4930.3594	4873.2500	1759.3542	1749.1353	1.1719
64.20	5891.5195	5915.2344	1739.2434	1742.7405	0.4009
54.70	6926.2695	6898.1328	1740.9460	1737.1558	0.4369
44.90	8327.8945	8328.9180	1729.2986	1729.4048	0.0123
36.10	10444.5977	10238.6602	1736.5156	1719.3108	2.0114
25.50	14073.2500	14143.9258	1694.1294	1698.3777	0.4997
18.00	19872.5977	19332.6719	1691.3865	1668.2507	2.7928
12.00	26335.0273	27147.2383	1589.7786	1614.1079	2.9919

ABSOLUTE VALUE OF 2J = -4.68709

G = 2.02968

STD. DEV. BETWEEN G VALUES FOUND = 0.01547

```
      $JOB   NOARLING  KNOE
      C      TRIMER SYSTEM
     1       DIMENSION  X(25),W(25),T(25),G(25),TITLE(3,6)
     2       REAL  NALPHA,K,KEEPG1,KEEPY1,KEEPZ1,M,MM
     3       DATA     BETA,NALPHA,K,AVO,C/9.273E-21,60.E-6,1.38E-16,6.022E23,1.
            $9802E-16/
     4       DATA  GMIN,GMAX/2.00,2.30/
     5       K=AVO*BETA*BETA/12./K
     6       S=K*4.
     7   1   READ(5,111,END=9000)TITLE
     8   111 FORMAT(18A4)
     9       READ(5,222)N,YMIN,YMAX,ZMIN,ZMAX,MM,M
    10   222 FORMAT(I2,8A,6F10.4)
    11       DO 100   I=1,N
    12       READ(5,333)T(I),X(I)
    13   333 FORMAT(2F10.4)
    14   100  W(I)=X(I)*1.E-6*NALPHA
    15       RANGE=1.
    16   4325 WRITE(6,444)TITLE
    17   444 FORMAT(1H1,4A,18A4)
    18       WRITE(6,555)YMIN,YMAX,ZMIN,ZMAX,GMIN,GMAX,NALPHA,N,M
    19   555 FORMAT(1H0,9X,'JMIN =',F12.5,/,10X,'JMAX =',F12.5,/,10X,'JJMIN =',
            $F12.5,10X,'JJMAX=',F12.5,/,10X,'GMIN =',F12.5,/,10X,'GMAX=',F12.5,
            $/,10X,'NALPHA =',F12.5,/,10X,'N =',I2,/,10X,'M =',F6.3,//)
    20       WRITE(6,666)
    21   666 FORMAT(1H0,10X,'TEMP',9X,'X(EXP)',13X,'X(CAL)',14X,'AMU(EXP)',12X,
            $'AMU(CAL)',15X,'% DEV IN X',//)
    22       OLDDEV=10000.
    23       Y=YMIN
    24   307  ZZ=ZMAX
    25       Z=ZMIN
         C
    26   500 DO 200  I=1,N
    27       PEACH=K*T(I)/C
    28        APPLE=Y/PEACH
    29       PEAR=Z/PEACH
    30       GRAPE=EXP(-2.*APPLE)
    31       TOMATO=EXP(-2.*PEAR)
    32       B=(GRAPE+TOMATO+10.*EXP(APPLE))/(GRAPE+TOMATO+2.*EXP(APPLE))
    33       A=K/T(I)*(1.-4)
    34       DAISY=S/T(I)*M
    35       G(I)=SQRT(W(I)/(A*B+DAISY))
    36    200  CONTINUE
         C
    37       CALL  DDEV(G,STDEV,N,BARG)
    38        IF(BARG.GT.GMAX.OR.BARG.LT.GMIN)GO TO 300
    39        IF(STDEV.GT.OLDEV)GO TO 300
    40   700  OLDEV=STDEV
    41       KEEPG1=BARG
    42       KEEPY1=Y
    43       KEEPZ1=Z
    44   300 Z=Z+RANGE
    45       IF(Z.LE.ZZ)GO TO 500
    46   900  Y=Y+2.
    47       IF(Y.LE.YMAX)GO TO 307
         C   END OF LOOP
    48       IF(OLDDEV.EQ.10000.)GO TO 1999
    49       DO  218   I=1,N
    50       PEACH=K*T(I)/C
    51       APPLE=KEEPY1/PEACH
```

```
      PEAR=KEEP21/PEACH
      GRAPE=EXP(-2.*APPLE)
      TOMATO=EXP(-2.*PEAR)
      B=(GRAPE+TOMATO+10.*EXP(APPLE))/(GRAPE+TOMATO+2.*EXP(APPLE))
      A=R/T(I)*KEEPG1*KEEPG1*(1.-M)
      DAISY=S/T(I)*KEEPG1*KEEPG1*M
      W(I)=(A*B+DAISY*ALPHA)*1.E6
      AMU=2.82*SQRT(X(I)*T(I))
      AMUC=2.82*SQRT(W(I)*T(I))
      DEV=ABS(W(I)-X(I))/X(I)*100.
      WRITE(6,7000)T(I),W(I),X(I),AMU,AMUC,DEV
7000   FORMAT(1H ,9X,F6.2,3X,F12.4,7X,F12.4,3(8X,F12.4),10X,F11.4,/)
218    CONTINUE
      WRITE(6,8000)KEEP1,KEEP2,KEEPG1,OLDEV
8000  FORMAT(1H0,10X,'J =',F12.4,/,10X,' JJ=',F12.4,/,10X,'G = ',F12.4,/
     1,10X,'STD. DEV BTWN G VALUES FOUND=',F15.5,///)
      M=M+0.01
      IF(M.LE.MM)GO TO 4325
      GO TO 1
1999     WRITE(6,7080)
7080  FORMAT(/,10X,'CANNOT FOUND BEST J AND JJ VALUES',/,10X,'POSSIBILIT
     1Y: 1.NOT A TRIMER SYSTEM,2. TRY  ANOTHER J &JJ VALUES',///)
      M=M+0.01
      IF(M.LE.MM)GO TO 4325
      GO TO 1
C
9000    STOP
      END


      SUBROUTINE  DDEV(C,STDEV,N,BARC)
       DIMENSION  C(N)
      VAR=0.
      SUMC=0.
      DO  200    I=1,N
200    SUMC=SUMC+C(I)
      EN=N
      BARC=SUMC/EN
      DO 300     I=1,N
300    VAR=VAR+(C(I)-BARC)**2
      STDEV=SQRT(VAR/(EN-1.))
      RETURN
      END

      DATA
```

TRIMER TEST POINTS (AFTER SINN AND HARRIS)

JMIN = -100.00000
JMAX = 50.00000
JJMIN = 0.00000 JJMAX= 5.00000
GMIN = 2.00000
GMAX= 2.30000
NALPHA = 0.00006
N = 5
M = 6.000

TEMP	X(EXP)	X(CAL)	AMU(EXP)	AMU(CAL)	% DEV IN X
325.00	1154.9870	1151.8000	1752.6410	1732.6300	2.2705
292.50	1268.4790	1238.0000	1701.1940	1722.0080	2.4620
261.50	1398.9830	1368.3990	1691.6930	1710.4930	2.2350
230.40	1550.0320	1625.0000	1731.9040	1696.9300	3.9980
200.00	1704.9640	1733.0000	1664.9200	1680.2140	1.8456

J = -22.0000
JJ= 5.0000
G = 2.0087
STD. DEV BTWN G VALUES FOUND= 0.03159

CORE, USAGE OBJECT CODE= 5240 BYTES, ARRAY AREA= 472 BYTES, TOTAL AREA AVAILABLE= 18528 BYTES

DIAGNOSTICS NUMBER OF ERRORS= 0, NUMBER OF WARNINGS= 0, NUMBER OF EXTENSIONS= 0

COMPILE TIME= 0.09 SEC, EXECUTION TIME= 0.75 SEC, WATFIV - JUL 1973 V1L4 13.43.10 MONDAY 5 APR 76

$STOP

```
**  END  -                DATE= 3/27/76   CLOCK=15.00.19   ACCOUNTING TIME=     4.43 SECONDS;   MAX REGION USED=   128K  **

      $JOB            NELSON
      C     TETRAMER SYSTEM
      C     FIND BEST A,B,C,G
 1          DIMENSION  A(25),B(25),T(25),AMU(25),AMUC(25),PING(6,3),G(25)
 2          REAL  K,NALPHA,KEEPA1,KEEPA2,KEEPB1,KEEPB2,KEEPC1,KEEPC2,KEEPG1,
           $KEEPG2
 3          DATA  BETA,NALPHA,SK,AVO,Y/9.273E-21,60.E-6,1.38E-16,6.022E23,
           $1.98E-16/
 4          DATA  GMIN,GMAX/2.00,2.3/
 5          K=SK/AVO/BETA/BETA
 6    11    READ(5,111,END=9000)PING
 7    111   FORMAT(18A4)
 8          READ(5,222)N
 9    222   FORMAT(I2)
10          READ(5,333)AMIN,AMAX,BMIN,BMAX,CMIN,CMAX
11    333   FORMAT(6F10.4)
12          DO  10  I=1,N
13          READ(5,444)T(I),X(I)
14    444   FORMAT(2F10.4)
15    10    B(I)=X(I)*1.E-6*NALPHA
16          WRITE(6,555)PING
17    555   FORMAT(1H1,9X,18A4)
18          WRITE(6,666)N,GMIN,GMAX,AMIN,AMAX,BMIN,BMAX,CMIN,CMAX
19    666   FORMAT(1H0,9X,'N=',I2,/,9X,'GMIN=',F10.4,//,9X,'GMAX=',F10.4,/,9X,
           $'AMIN =',F12.4,5X,'AMAX =',F12.4,/,5X,'BMIN =',F12.4,5X,'BMAX =',F
           $12.4,/,5X,'CMIN =',F12.4,5X,'CMAX =',F12.4,//)
20          WRITE(6,777)
21    777   FORMAT(1H0,10X,'TEMP',9X,'X(EXP)',13X,'X(CAL)',14X,'AMU(EXP)',12X,
           $'AMU(CAL)',15X,'% DEV IN X',//)
22          OLDEV=5000.
23          DC=2.
24          DA=2.
25          DB=2.
26    8954  C=CMIN
27    1000  CC=-C/SK*Y
28          B=BMIN
29    2000  BB=-B/SK*Y
30          A=AMIN
31    3000  AA=-A/SK*Y
32          DO  20  I=1,N
33          W=EXP(AA/T(I))
34          V=EXP(BB/T(I))
35          Z=EXP(CC/T(I))
36          FREE=(1.+3.*W+3.*V+Z)/(W+V)
37          DUM=B(I)*T(I)*R
38          FREDUM=DUM*FREE
39          G(I)=SQRT(FREDUM)
40    20    CONTINUE
41          CALL DDEV(G,STDEV,N,BARG)
42          IF(BARG.GT.GMAX.OR.BARG.LT.GMIN)GO TO 4000
43          IF(STDEV.GE.OLDEV)GO TO 4000
44          OLDEV=STDEV
45          KEEPG1=BARG
46          KEEPA1=A
47          KEEPB1=B
48          KEEPC1=C
49    4000  A=A+DA
50          IF(A.LE.AMAX) GO TO 3000
51          B=B+DB
52          IF (B.LE.BMAX) GO TO 2000
```

```
      C=C+DC
      IF(C.LE.CMAX) GO TO 1000
C     LOOP ENDS HERE
      IF (OLDEV.EQ.5000.)GO TO 7000
5431  K=KEEPG1*KEEPG1/R
      AA=-KEEPA1/SK*Y
      BB=-KEEPB1/SK*Y
      CC=-KEEPC1/SK*Y
      DO  30  I=1,N
      W=EXP(AA/T(I))
      V=EXP(BB/T(I))
      Z=EXP(CC/T(I))
      Q(I)=K/T(I)*(W+V)/(1.+3.*W+3.*V+Z)
      J(I)=(Q(I)+NALPHA)*1.E6
      AMU(I)=2.828*SQRT(X(I)*T(I))
      AMUC(I)=2.828*SQRT(Q(I)*T(I))
      DEV=ABS(Q(I)-X(I))/X(I)*100.
      WRITE(6,888)T(I),X(I),Q(I),AMU(I),AMUC(I),DEV
30    CONTINUE
      WRITE(6,8888)KEEPA1,KEEPB1,KEEPC1,KEEPG1,OLDEV
888   FORMAT(1H ,9X,F6.2,3X,F12.4,/X,F12.4,3(8X,F12.4),10X,F11.4,/)
8888  FORMAT(1H0,10X,'A=',F15.5,/,10X,'B=',F15.5,/,10X,'C=',F15.5,/,10X,
     $'G =',F12.4,/,10X,'STD. BTWN G VALUES FOUND',F15.5,//)
      GO TO 11
7000  WRITE(6,999)
999   FORMAT(2X,'CANNOT FIND BEST A,B,C,G VALUES. TRY LARGER VALUES FOR
     $A,B,C')
      GO TO 11
9000  STOP
      END


      SUBROUTINE  DDEV(C,STDEV,N,BARC)
      DIMENSION  C(N)
      VAR=0.
      SUMC=0.
      DO 200   I=1,N
  200   SUMC=SUMC+C(I)
      EN=N
      BARC=SUMC/EN
       DO 300   I=1,N
  300   VAR=VAR+(C(I)-BARC)**2
      STDEV=SQRT(VAR/(EN-1.))
      RETURN
      END


$DATA
```

```
      CU(GMP).5H2O    TEHAMER FIT

      N=12
     GMIN=    2.0000

     GMAX=    2.3000
     AMIN =     50.0000     AMAX =    150.0000
 BMIN =      6.0000     BMAX =     14.0000
 CMIN =      0.0000     CMAX =     10.0000


       TEMP        X(EXP)          X(CAL)          AMU(EXP)        AMU(CAL)        % DEV IN X

      295.00      1488.2080       1325.6010       1873.7940       1768.4650       10.9264
      204.00      1990.7050       1824.7790       1802.1780       1725.4380        8.3350
      154.00      2445.1380       2314.8910       1735.3670       1688.5150        5.3268
      106.00      3017.5520       3145.8410       1599.4090       1633.0530        4.2514
       84.10      3629.2890       3785.0620       1562.3850       1595.5620        4.2921
       70.00      4138.3350       4372.8320       1522.0930       1564.6220        5.6664
       58.90      4743.5190       4999.7770       1494.8130       1534.6600        5.4023
       48.60      5438.2730       5788.5070       1453.8770       1499.9630        6.4402
       39.90      6399.5780       6695.7070       1429.0290       1461.7180        4.6273
       29.30      7852.4570       8260.6090       1356.4870       1391.2940        5.1978
       23.00      9425.4920       9465.3160       1316.7250       1320.8970        0.6347
       16.90     11592.7800      10696.1900       1251.7460       1202.3670        7.7340

       A=      130.00000
      B=       14.00000
      C=        2.00000
      G =      2.0824
      STD. BTWN G VALUES FOUND        0.07149

CORE USAGE       OBJECT CODE=    5328 BYTES,ARRAY AREA=     672 BYTES,TOTAL AREA AVAILABLE=   18528  BYTES

DIAGNOSTICS        NUMBER OF ERRORS=       0, NUMBER OF WARNINGS=       0, NUMBER OF EXTENSIONS=       0

COMPILE TIME=     0.09 SEC,EXECUTION TIME=     4.29 SEC,  WATFIV - JUL 1973 V1L4      15.00.18    SATURDAY     27 MAR 76

      $STOP
```

```
C      THIS IS THE ISING PROGRAM,FIT FOR COMPOUNDS THAT ARE
C            POLYMERS
C    TESTING OF THIS PHOGRAM IS MADE ON FEB. 4, 1976
C      J IS INPUT AS IT IS, NO CHANGE OF SIGN IS NEEDED
C      Z,COUNT IS THE RANGE OF FRACTION OF MONOMERS ALLOWED
C     THIS PROGRAM CANNOT BE WORKED ON WATFFIVE EXTRA TIME IS NEEDED
C
C
C    MAIN PROGRAM
C
C
0001          DIMENSION  X(25),AMU(25),XCAL(25),AMUC(25),GG(25),DEV(25),T(25),
             $PING(6,3),Q(25)
0002          REAL  K,JMIN,JMAX,J,NALPHA,KEEPJ
0003          DATA  K,C,H,AVO/1.38E-16,1.9862E-16,9.273E-21,6.022E23/
0004          DATA  GMIN,GMAX/1.90,2.35/
0005          CON=AVO*B*B/12.
0006     1     READ(5,888,END=9000)N,SMAX,SMIN,NALPHA,Z,COUNT
0007     888  FORMAT(I2,F18.4,2F10.4,F5.2,F5.2)
0008          READ(5,111)PING
0009     111   FORMAT(18A4)
0010          DO 66  I=1,N,1
0011          READ(5,2)T(I),X(I)
0012     2    FORMAT(F10.2,F10.4)
0013          Q(I)=(X(I)-NALPHA)*1.E-6
0014     66   CONTINUE
0015      444     WRITE(6,333)PING
0016     333   FORMAT(1H1,4X,18A4)
0017          WRITE(6,3000)SMIN,SMAX,GMIN,GMAX,NALPHA,N,Z
0018     3000  FORMAT(1H0,9X,'JMIN =',F12.5,//,10X,'JMAX = ',F12.5,//,10X,'GMIN =
             $',F12.5,//,10X,'GMAX =',F12.5,//,10X,'NALPHA = ',F12.5,//,10X,'N =
             $',I3,//,10X,'Z=',F6.2,//)
0019          WRITE(6,4000)
0020     4000  FORMAT(1H0,10X,'TEMP',9X,'X(EXP)',13X,'X(CAL)',14X,'AMU(EXP)',12X,
             $'AMU(CAL)',15X,'% DEV IN X',//)
0021          JMIN=SMIN*C
0022          JMAX=SMAX*C
0023          J=JMIN
0024          OLDEV=100000.
0025          A=0.
0026          ZOO=1.-Z
C
C     FIND G TO BE WITHIN G LIMIT, VARYING J
0027     17    DO 113 I=1,N,1
0028          RK=J/K/T(I)
0029          EX=EXP(2.*RK)
0030          ZIP=TANH(RK)
0031          W=ZIP+RK-RK*ZIP*ZIP
0032          POLY=CON/K/T(I)*EX+CON/J*W
0033          RAT=Z*CON*4./K/T(I)
0034          WET=ZOO*POLY+RAT
0035          GG(I)=SQRT(Q(I)/WET)
0036     113       CONTINUE
C
0037     40    CALL  DDEV(GG,STDEV,N,BARG)
0038          IF(BARG.LT.GMIN)GO TO 30
```

```
0039              IF(BARG.GT.GMAX)GO TO 30
0040              IF(STDEV.GT. OLDEV) GO TO 30
0041              OLDEV=STDEV
0042              FBARG=BARG
0043              A=FBARG*FBARG
0044              KEEPJ=J
0045              IF(OLDEV.LE.0.001)GO TO 222
0046        30     J=J+1.E-16
0047               IF(J.GT.JMAX)GO TO 222
0048              GO TO 17
0049        222    IF(A.EQ.0.)GO TO 350
                  C
                  C     FINALLY THE DECIDED G AND J VALUES ARE OBTAINED
0050              DO 157  I=1,N
0051               RK=KEEPJ/K/T(I)
0052              EX=EXP(2.*RK)
0053              ZIP=TANH(RK)
0054               W=ZIP+RK-RK*ZIP*ZIP
0055              POLY=CON/K/T(I)*EX+CON/KEEPJ*W
0056              RAT=Z*CON*4./K/T(I)
0057              WET=ZOO*POLY+RAT
0058              XCAL(I)=A*1.E06*WET+ALPHA
                  C
0059              AMU(I)=2.828*SQRT(X(I)*T(I))
0060              AMUC(I)=2.828*SQRT(XCAL(I)*T(I))
0061              DEV(I)=ABS(XCAL(I)-X(I))/XCAL(I)*100.
0062              WRITE(6,7000)T(I),X(I),XCAL(I),AMU(I),AMUC(I),DEV(I)
0063        7000  FORMAT(1H ,9X,F6.2,3X,F12.4,7X,F12.4,8X,F12.4,8X,F12.4,8X,F12.4,10
                 $X,F11.4,/)
0064        157     CONTINUE
0065               KEEPJ=KEEPJ/C
0066              WRITE(6,8000)KEEPJ,FBARG,OLDEV
0067        8000  FORMAT(1H0,10X,'ABSOLUTE VALUE OF 2J = ',F12.5,//,10X,'G = ',F12.5
                 $,//,10X,'STD. DEV. BETWEEN G VALUES FOUND =',F15.5,//)
0068        457    Z=Z+0.01
0069               IF(Z.GT.COUNT)GO TO 1
0070              GO TO 444
0071         350     WRITE(6,214)
0072        214   FORMAT(1X,'CANNOT FIND G & J VALUES,POSSIBILITY: NOT A POLMER',/)
0073              GO TO 457
0074        9000    STOP
0075              END
```

CU(CYTOSINE)2CL2 ISINGFIT 0% IMPURITY

JMIN = -50.00000

JMAX = 10.00000

GMIN = 1.90000

GMAX = 2.35000

NALPHA = 60.00000

N = 12

Z= 0.0

TEMP	X(EXP)	X(CAL)	AMU(EXP)	AMU(CAL)	% DEV IN X
299.00	1329.8069	1350.0596	1783.2371	1796.7651	1.5001
204.00	1917.3018	1944.6995	1768.6406	1781.2327	1.4088
151.00	2582.5549	2597.1079	1766.0073	1770.9763	0.5604
95.00	4055.6079	4059.9810	1755.3713	1756.3179	0.1077
78.50	4930.3594	4878.4414	1759.3542	1750.0667	1.0642
64.20	5891.5195	5916.8945	1739.2434	1742.9849	0.4289
54.70	6928.2695	6895.3008	1740.9460	1736.7986	0.4781
44.90	8327.8945	8317.8359	1729.2986	1728.2539	0.1209
36.10	10444.5977	10214.2227	1736.5156	1717.2576	2.2554
25.50	14073.2500	14088.6406	1694.1294	1695.0554	0.1092
18.00	19872.5977	19246.6563	1691.3865	1664.5356	3.2522
12.00	26335.0273	27114.5586	1589.7786	1613.1365	2.8750

ABSOLUTE VALUE OF 2J = -2.16972

G = 2.03485

STD. DEV. BETWEEN G VALUES FOUND = 0.01695

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