1979

Stereoselective coordination of [beta]-(2-pyridyl)-[alpha]-alanine to transition metal ions

Stephen Ronald Ebner
Iowa State University

Recommended Citation

Ebner, Stephen Ronald, "Stereoselective coordination of [beta]-(2-pyridyl)-[alpha]-alanine to transition metal ions " (1979). *Retrospective Theses and Dissertations*. 7201.
https://lib.dr.iastate.edu/rtd/7201

INFORMATION TO USERS

This was produced from a copy of a document sent to us for microfilming. While the most advanced technological means to photograph and reproduce this document have been used, the quality is heavily dependent upon the quality of the material submitted.

The following explanation of techniques is provided to help you understand markings or notations which may appear on this reproduction.

1. The sign or "target" for pages apparently lacking from the document photographed is "Missing Page(s)". If it was possible to obtain the missing page(s) or section, they are spliced into the film along with adjacent pages. This may have necessitated cutting through an image and duplicating adjacent pages to assure you of complete continuity.
2. When an image on the film is obliterated with a round black mark it is an indication that the film inspector noticed either blurred copy because of movement during exposure, or duplicate copy. Unless we meant to delete copyrighted materials that should not have been filmed, you will find a good image of the page in the adjacent frame.
3. When a map, drawing or chart, etc., is part of the material being photographed the photographer has followed a definite method in "sectioning" the material. It is customary to begin filming at the upper left hand corner of a large sheet and to continue from left to right in equal sections with small overlaps. If necessary, sectioning is continued again—beginning below the first row and continuing on until complete.
4. For any illustrations that cannot be reproduced satisfactorily by xerography, photographic prints can be purchased at additional cost and tipped into your xerographic copy. Requests can be made to our Dissertations Customer Services Department.
5. Some pages in any document may have indistinct print. In all cases we have filmed the best available copy.

University
Microfilms
International

300 N. ZEEB ROAD, ANN ARBOR, MI 48106
18 BEDFORD ROW, LONDON WC1R 4EJ, ENGLAND

8000126

EBNER, STEPHEN RONALD
STEREOSELECTIVE COORDINATION OF
BETA-(2-PYRIDYL)-ALPHA-ALANINE TO TRANSITION
METAL IONS.

IOWA STATE UNIVERSITY, PH.D., 1979

University
Microfilms
International 300 N. ZEEB ROAD, ANN ARBOR, MI 48106

Stereoselective coordination of β-(2-pyridyl)-α-alanine to transition metal ions

by

Stephen Ronald Ebner

A Dissertation Submitted to the
Graduate Faculty in Partial Fulfillment of the
Requirements for the Degree of
DOCTOR OF PHILOSOPHY

Department: Chemistry
Major: Inorganic Chemistry

Approved:

Signature was redacted for privacy.

In Charge of Major Work

Signature was redacted for privacy.

For the Major Department

Signature was redacted for privacy.

For the Graduate College

Iowa State University
Ames, Iowa

1979

TABLE OF CONTENTS

GENERAL INTRODUCTION

During recent decades, the stereochemistry of coordination compounds has been a field of intense research by chemists of many different specializations. This area has attracted the attention of biochemists attempting to understand the role of metal ions in the action of metalloenzymes, inorganic chemists investigating the electronic structure of coordination compounds, investigators of macromolecular compounds studying the part played by catalysts in stereoselective and stereospecific polymerizations, and finally, organic chemists using asymmetric induction in complexes to effect asymmetric syntheses.

A particular case of stereoselectivity, namely enantioselectivity, is the major concern in the work presented here. By enantioselectivity we mean that there is a difference in the interaction of a chiral molecule (or structure) with two optical isomers. This enantioselectivity is observed in the different equilibrium constants for the formation of bis amino acidato metal ion complexes where the amino acidato ligands are different enantiomers; i.e., equilibrium constants for the reactions,

$$M(\underline{L}\text{-}A)^{+} + \underline{L}\text{-}A^{-} \rightleftharpoons M(\underline{L}\text{-}A)_2 \qquad K_2 \tag{1}$$

$$M(\underline{L}\text{-}A)^{+} + \underline{D}\text{-}A^{-} \rightleftharpoons M(\underline{L}\text{-}A)(\underline{D}\text{-}A) \qquad K_X \tag{2}$$

are different. This indicates that the stabilities of the meso complex, M(L-A)(D-A), and the bis complex, $M(L\text{-}A)_2$, are different.

Stereoselectivity has been detected in the parent and mixed complexes of a small number of amino acids, particularly histidine and substituted histidines.[1] With Co(II), Ni(II) and Zn(II), stereoselectivity was found in the neutral bis complexes, the *meso* complex M(L-His)(D-His), being favored in all cases. With copper(II), however, the neutral bis complex did not show any stereoselectivity in its formation constants, although some stereoselectivity was detected in the protonated species such as $[Cu(His)_2H]^+$. The observed effects were explained in terms of interligand repulsions due to electrostatic and steric interactions.

The synthetic amino acid β-(2-pyridyl)-α-alanine, $^+H_3NCH(CH_2C_5H_4N)CO_2^-$ (PyalaH), is a tridentate analogue of histidine with a pyridine group in place of the imidazole. Previous work has shown that $Pyala^-$ binds to transition metal ions to form $M(Pyala)_2$ with some enantioselectivity depending upon the chirality of the $Pyala^-$ ligand.[2] Formation constants for the binding of L-PyalaH and D,L-PyalaH with Cu(II), Ni(II), Co(II) and Zn(II) were determined by potentiometric titration. In all cases, the formation constant for M(L-Pyala)(D-Pyala), eq. 2, was larger than that for $M(L\text{-}Pyala)_2$, eq. 1. The difference between K_x

and K_2 indicates that M(L-Pyala)$^+$ complexes bind D-Pyala$^-$ more favorably than they do L-Pyala$^-$. The higher stability of the M(L-Pyala)(D-Pyala) complexes compared to M(L-Pyala)$_2$ or M(D-Pyala)$_2$ was rationalized by assuming that the bis(pyridylalanine) complexes were predominantly octahedral and that they preferred a geometry in which all equivalent groups of the two ligands were trans to each other, in order to minimize steric repulsion.[2] Therefore, the most stable structures (Figure 1) for M(D-Pyala)$_2$, or M(L-Pyala)$_2$, and M(L-Pyala)(D-Pyala) were thought to be 1c and 1e, respectively, with 1e being preferred over 1c.

Our purpose was to determine the major isomers of M(D-Pyala)$_2$ and M(L-Pyala)(D-Pyala) to shed some light on the origins of the stereoselectivity observed. Of the techniques available, the most useful were visible, circular dichroism, optical rotatory dispersion, infrared, ^{13}C and ^{1}H NMR spectroscopy and x-ray crystallography.

In the present work, stereoselectivity was examined in both labile and nonlabile transition metal complexes. Diastereomers of the kinetically stable complexes of Co(III) and Cr(III) can be isolated and characterized most easily for two reasons. First, the complex present in solution can be crystallized without fear of isomerization. Second, the isomers of the Co(III) and Cr(III) complexes have

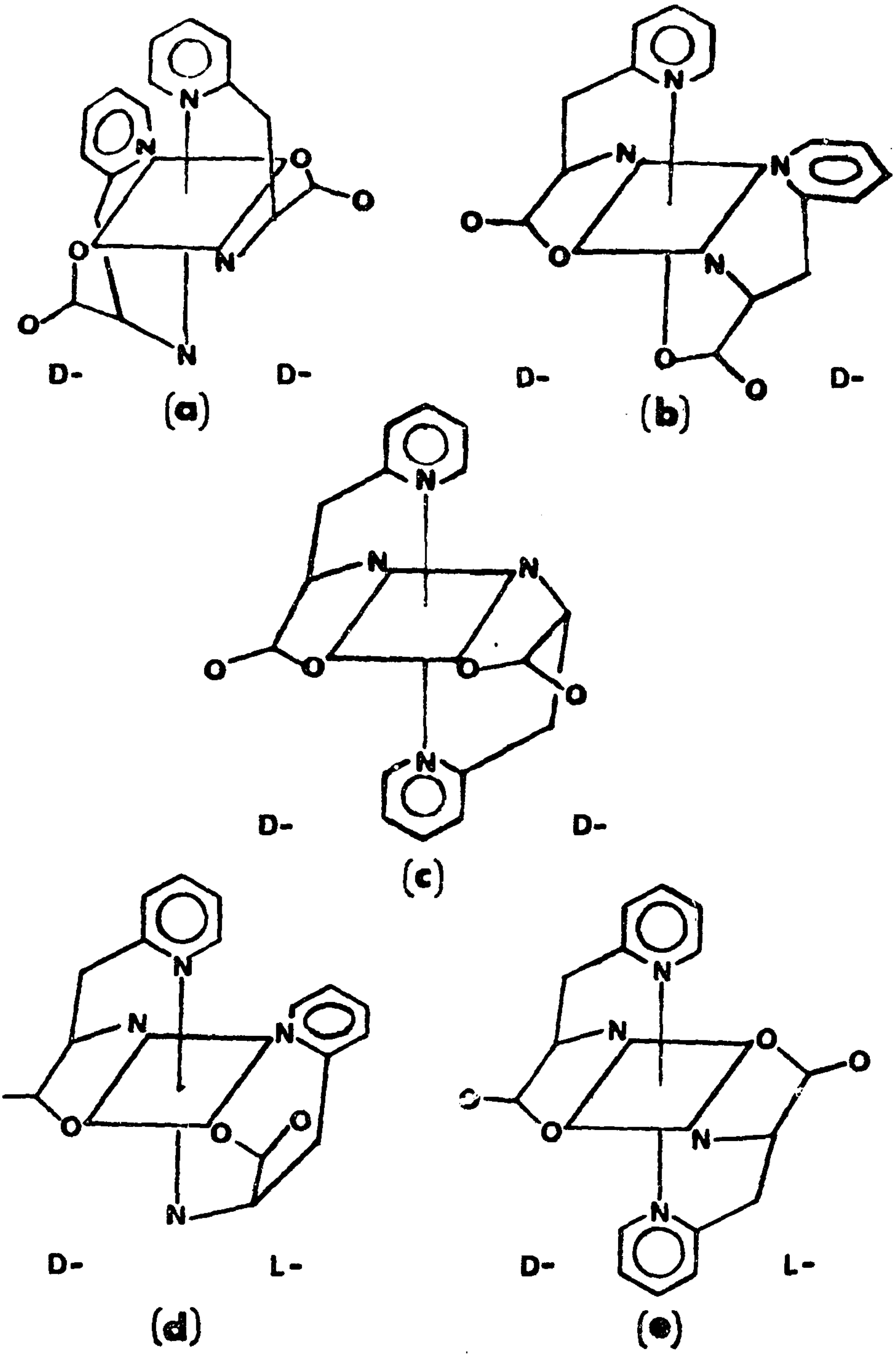


Figure 1. The five possible geometrical isomers of M(Pyala)$_2$ obtained from reaction of a metal ion with *D*,*L*-PyalaH: (a) *trans*-carboxylate, (b) *trans*-amino, (c) *trans*-pyridyl, (d) all-*cis* and (e) all-*trans*

characteristic spectra that can be associated with a particular structure.

By investigating the labile complexes of Ni(II), Cu(II) and Zn(II), the stereoselective effect was examined as a function of the metal ion itself. The influence of ionic radius and the necessity for octahedral coordination may be studied.

Explanation of Dissertation Format

The material in this dissertation was arranged so that a minimum of rewriting was required for preparation of a manuscript for publication. Each section constitutes an article which has been submitted for journal publication. References to figures apply only to those contained within that section. The literature cited in the General Introduction and Summary appear in the final list of references.

SECTION I. PREPARATION, STRUCTURE, AND SPECTRAL CHARACTERIZATION OF bis[D-β-(2-pyridyl)-α-alaninato]cobalt(III), Co(D-Pyala)$_2^+$

INTRODUCTION

The synthetic amino acid, β-(2-pyridyl)-α-alanine, $^{+}H_3NCH(CH_2C_5H_2N)CO_2^-$, (PyalaH), is a tridentate analog of histidine with a pyridine group in place of the imidazole. In earlier work, it was shown that $Pyala^-$ binds to transition metal ions to form $M(Pyala)_2$ with some enantioselectivity depending upon the chirality of the $Pyala^-$ ligand.[1] Where the ligand is present as only one enantiomer, *e.g.*, *D*-$Pyala^-$, the octahedral M(*D*-Pyala)$_2$ complexes may exist in three geometric isomeric forms (Figure 1). In the present study, we prepared the Co(III) complex Co(*D*-Pyala)$_2^+$ for the purpose of establishing the most stable isomer of this complex.

All three isomers of the Co(ligand)$_2^+$ complexes have been isolated for the tridentate ligands *L*-histidinate,[2,3] *L*-2,3-diaminopropionate,[4] and *L*-2,4-diaminobutyrate.[5] The trans-imidazole isomer was the major structural form of Co(*L*-his)$_2^+$. It was suggested that because of steric hindrance the imidazole groups prefer to occupy trans positions in octahedral $M(his)_2$ complexes.[6] Because of the similarity of $Pyala^-$ to his^-, Co(*D*-Pyala)$_2^+$ might be expected to prefer the trans-pyridyl structure. However, as reported herein, the trans-carboxylate structure is the most stable form. This complex was fully characterized by its IR, ^1H NMR, visible, ORD and CD spectra.

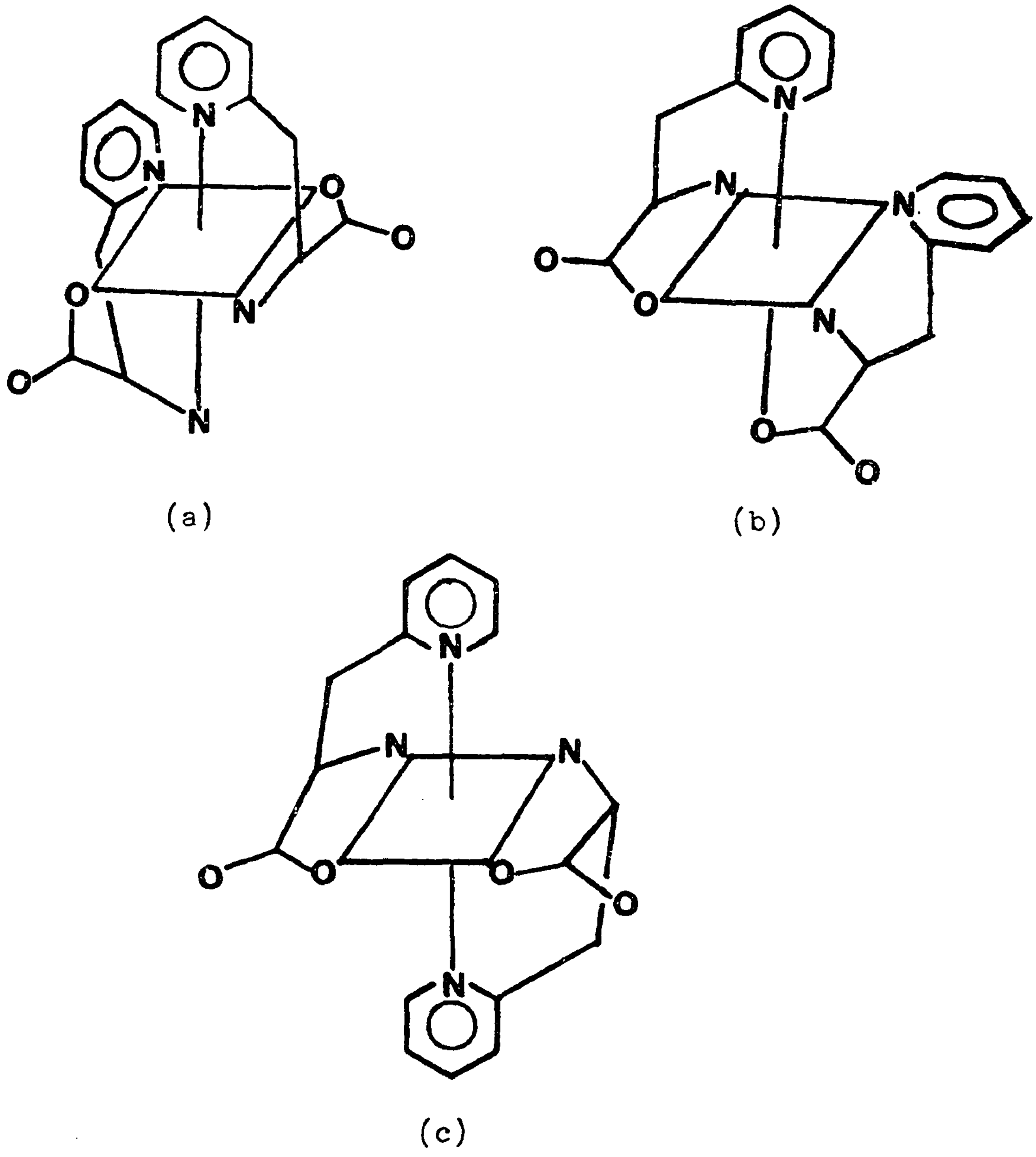


Figure 1. The three possible isomers of $Co(Pyala)_2^+$ ion. These are (a) *trans*-carboxylate, (b) *trans*-amino and (c) *trans*-pyridyl

EXPERIMENTAL SECTION

Materials. Racemic β-(2-pyridyl)-α-alanine (PyalaH) was prepared and resolved as described previously.[7] $[Co(NH_3)_4CO_3]NO_3$,[8a] $[Co(NH_3)_6](NO_3)_3$,[8b] and $Na_3[Co(CO_3)_3]\cdot 3H_2O$ [8c] were prepared according to literature methods.

Preparation of bis-[D-β-(2-pyridyl)-α-alaninato]-cobalt(III) Nitrate Hemihydrate, $[Co(D\text{-}Pyala)_2]NO_3\cdot 1/2H_2O$. The $[Co(NH_3)_4CO_3]NO_3$ (0.75 g, 3.0 mmol) and D-PyalaH (1.00 g, 6.0 mmol) were dissolved in 40 ml of distilled water and 0.3 g of activated charcoal was added. The solution was stirred at 85°C for 20 hrs. The charcoal was filtered from the hot solution and washed with boiling water. The filtrate and wash solution were combined and evaporated to dryness. The glassy solid that formed was redissolved in a minimum of 80:20/MeOH:H_2O and loaded on a column (2.25 x 70 cm) of basic alumina (200 ml). The bands were eluted with 80:20/MeOH:H_2O at 1 drop/4 sec. Of the bands which separated, only one contained more than a few mg of material when evaporated to dryness. This component eluted first from the column and was red-violet in color. After evaporating the solution to 1 ml, 9 ml of methanol were added. Upon standing overnight, red-violet crystals formed. They were filtered from the solution and vacuum dried. The yield was 44%. Anal. calcd for $[Co(C_8H_9N_2O_2)_2]NO_3 \cdot 1/2H_2O$: C, 41.75; H, 4.16; N, 15.21. Found: C, 41.55; H, 4.13; N, 15.39.

No crystals could be isolated from the other bands eluted from the column. NMR, visible and CD spectra indicated that these components were not isomers of $[Co(\underline{D}\text{-Pyala})_2]^+$.

The complex was also prepared by adding $Co(NO_3)_2 \cdot 6H_2O$ (0.87 g, 3.0 mmol) to 50 ml of water containing D-PyalaH (1.0 g, 6.0 mmol) and NaOH (6.0 mmol). After stirring for 15 minutes, 0.5 ml of 30% H_2O_2 was added. The solution was allowed to stand for 2 hrs and then was evaporated to dryness. The solid formed was dissolved in 80:20/MeOH:H_2O and chromatographed as above. Yield of the trans-carboxylate $[Co(\underline{D}\text{-Pyala})_2]NO_3 \cdot 1/2H_2O$ was 29%.

In a preparation similar to that above $[Co(NH_3)_6](NO_3)_3$ (1.04 g, 3.0 mmol), D-PyalaH (1.0 g, 6.0 mmol) and NaOH (6.0 mmol) were dissolved in 50 ml of water. Activated charcoal (0.5 g) was added, and the solution was stirred at 60°C for 2 hrs. The charcoal was filtered from the hot solution and the filtrate was evaporated to dryness. The residue was dissolved in 80:20/MeOH:H_2O and chromatographed as described above. The trans-carboxylate $[Co(\underline{D}\text{-Pyala})_2]NO_3 \cdot 1/2H_2O$ was the only isomer isolated. Yield based on total cobalt was 24%.

Freshly prepared $Na_3[Co(CO_3)_3] \cdot 3H_2O$ (0.54 g, 1.5 mmol) was added to a solution of D-PyalaH (1.0 g, 3.0 mmol) and

HNO_3 (6.0 mmol) in 50 ml of H_2O. After the initial foaming subsided, 0.5 g of activated charcoal was added. The solution was heated to 60°C for 2 hrs, then stirred at ambient temperature for 16 hrs. The charcoal was filtered from the solution and washed with hot water until the filtrate was colorless. The solution was evaporated to dryness, dissolved in 80:20/MeOH:H_2O and chromatographed as described previously. One band formed and was identified as trans-carboxylate $[Co(\underline{D}\text{-Pyala})_2]NO_3 \cdot 1/2H_2O$. Yield was 53% (based on total Co).

Spectra. The infrared spectrum was recorded on a KBr disk using a Beckman IR 4250 spectrophotometer. The visible, optical rotatory dispersion and circular dichroism spectra were recorded at room temperature using a Jasco ORD/UV/CD-5 spectrophotometer. The ^1H NMR spectrum was measured on a Varian Associates HA-100 spectrometer in 99.7% deuterium oxide *vs* *t*-butyl alcohol ($\delta = 1.23$) as an internal standard.

Crystal Data. A crystal of dimensions 0.1 x 0.1 x 0.5 mm was mounted on a glass fiber with Duco cement and subsequently attached to a standard gonimeter head. From four preliminary ω-oscillation photographs taken on an automated four-circle X-ray diffractometer at various χ and ϕ settings, nine independent reflections were selected and their coordinates were input to the automatic indexing program ALICE.[9] The resulting reduced cell and reduced cell scalars indicated an orthorhombic crystal system. Orthorhombic *m m m* symmetry was confirmed by inspection of the three axial ω-oscillation photographs. Observed layer line separations agreed well with those predicted for the cell by the indexing program.

A least-squares refinement of the lattice constants based on the ±2θ measurements of thirteen reflections on a previously aligned four-circle diffractometer (graphite-monochromated Mo K_α radiation, $\lambda = 0.70954$ Å) at 25°C, yielded $a = 9.248(1)$, $b = 18.439(4)$, and $c = 21.697(5)$ Å.

Collection and Reduction of X-ray Intensity Data. Data were collected at 25°C using an automatic four-circle diffractometer designed and built in the Ames Laboratory.[10] All data in two octants and with a 2θ sphere of 50° (sin $\theta/\lambda = 0.596$ Å^{-1}) were measured using an ω step-scan technique.

As a general check on electronic and crystal stability, the intensities of three standard reflections were remeasured every 75 reflections. These standards did not vary significantly throughout the entire data collection period. A total of 4168 reflections were recorded in this manner. Examination of the data revealed systematic absences for $hk\ell$: $h + k = 2n + 1$ and 00ℓ: $\ell = 2n + 1$, thus uniquely defining the space group as $C222_1$.

The measured intensities were corrected for Lorentz and polarization effects, but no absorption correction was made ($\mu = 10.24$ cm^{-1}). The minimum and maximum transmission factors were 0.88 and 0.92. The estimated variance in each intensity was calculated by $\sigma_I^2 = C_T + K_t C_B + (0.03\ C_T)^2 + (0.03\ C_B)^2$ where C_T and C_B represent the total and background count, respectively, K_t is a counting time constant, and the factor 0.03 represents an estimate of nonstatistical errors. The standard deviations in the structure factor amplitudes were obtained by the method of finite differences.[11] Equivalent reflections for which $|F_o| > 3\sigma F_o$ were retained and averaged. This yielded 1646 independent reflections which were used in subsequent calculations.

Solution and Refinement of the Structure. The position of the cobalt atom was obtained by analysis of a three-dimensional Patterson function. The remaining atoms were found by successive structure factor[12] and electron density map calculations.[13] The positional parameters for all non-hydrogen atoms and their anisotropic thermal parameters were refined by a full-matrix least-squares procedure,[12] minimizing the function $\sum\omega(|F_o|-|F_c|)^2$, where $\omega = 1/\sigma_F^2$, to a final conventional residual index of $R = \sum||F_o|-|F_c||/\sum|F_o| = 0.062$. Examination of observed and calculated structure factors revealed no appreciable extinction effects. The scattering factors used were those of Hanson *et al.*[14] modified for anomalous dispersion.[15]

The solution and refinement of the structure were completed without attempting to refine the absolute configuration of the cation. The final structure of the optically active cation was based on the known[1] configuration of D-Pyala$^-$.

The final positional and thermal parameters are listed in Table I. The standard deviations were calculated from the inverse matrix of the final least-squares cycle.[16]

Table I. Final atomic parameters

(a) Final positional parameters and their estimated standard deviations (in parentheses)[a]

Atom	x	y	z
Co	5598.6 (11)	2547.4 (5)	4002.0 (5)
O1	4385 (7)	2760 (3)	3327 (3)
O2	3367 (8)	3699 (4)	2846 (3)
O3	6748 (6)	2351 (3)	4707 (2)
O4	6919 (7)	1599 (4)	5499 (3)
O5	1675 (9)	848 (4)	4691 (3)
O6	9722 (10)	1063 (6)	4218 (5)
O7	1761 (11)	1254 (6)	3773 (4)
O8[b]	3364 (13)	5000	5000
N1	4952 (9)	3469 (4)	4331 (3)
N2	7316 (8)	3055 (4)	3672 (3)
N3	4082 (8)	2016 (4)	4435 (3)
N4	6053 (8)	1627 (4)	3580 (3)
N5	1038 (11)	1058 (5)	4221 (5)
C1	4090 (10)	3450 (5)	3271 (4)
C2	4734 (10)	3931 (5)	3771 (4)
C3	6147 (11)	4274 (5)	3578 (5)
C4	7422 (10)	3760 (5)	3513 (4)
C5	8732 (11)	4060 (6)	3325 (5)
C6	9971 (13)	3639 (6)	3272 (5)
C7	9868 (11)	2908 (6)	3442 (4)
C8	8550 (9)	2637 (5)	3639 (4)

---

[a] The positional parameters are presented in fractional unit cell coordinates (x 10^4).

[b] The y and z positional parameters were not varied.

Table I. (Continued)

Atom	x	y	z
C9	6272 (10)	1823 (5)	5051 (4)
C10	4885 (10)	1483 (5)	4831 (4)
C11	5273 (11)	818 (5)	4445 (4)
C12	6021 (10)	961 (5)	3834 (4)
C13	6578 (11)	356 (5)	3536 (5)
C14	7149 (14)	437 (6)	2949 (5)
C15	7069 (13)	1095 (5)	2660 (4)
C16	6525 (13)	1685 (6)	2984 (4)

(b) Final thermal parameters (x 10^4) and their estimated standard deviations (in parentheses)[c]

	β_{11}	β_{22}	β_{33}	β_{12}	β_{13}	β_{23}
Co	47.9 (12)	15.0 (3)	10.3 (2)	0.7 (6)	-1.2 (4)	-0.3 (2)
O1	74 (7)	20 (2)	13 (1)	4 (3)	-3 (3)	-1 (1)
O2	104 (9)	30 (2)	17 (2)	10 (4)	-5 (4)	5 (2)
O3	60 (7)	20 (2)	12 (1)	0 (3)	-3 (2)	1 (1)
O4	84 (9)	36 (3)	12 (1)	1 (4)	-4 (3)	6 (2)
O5	122 (11)	41 (3)	19 (2)	5 (5)	2 (4)	6 (2)
O6	100 (13)	65 (5)	50 (4)	-15 (6)	-18 (6)	24 (4)
O7	192 (15)	69 (5)	15 (2)	-54 (8)	6 (5)	-2 (2)
O8	114 (16)	37 (4)	36 (4)	---	---	-2 (3)
N1	95 (10)	14 (2)	12 (2)	7 (4)	2 (4)	0 (2)
N2	74 (10)	21 (2)	11 (2)	-1 (4)	4 (3)	0 (2)

---

[c] The β_{ij} are defined by: $T = \exp\{-(h^2\beta_{11} + k^2\beta_{22} + \ell^2\beta_{33} + 2hk\beta_{12} + 2h\ell\beta_{13} + 2k\ell\beta_{23})\}$.

Table I. (Continued)

	β_{11}	β_{22}	β_{33}	β_{12}	β_{13}	β_{23}
N3	55 (9)	19 (2)	16 (2)	0 (4)	-1 (3)	2 (2)
N4	53 (9)	21 (2)	12 (2)	1 (4)	0 (3)	-1 (2)
N5	125 (14)	27 (3)	22 (2)	-22 (5)	4 (5)	0 (2)
C1	50 (11)	21 (3)	14 (2)	2 (4)	3 (4)	3 (2)
C2	69 (12)	20 (3)	13 (2)	-4 (5)	-1 (4)	1 (2)
C3	54 (12)	18 (3)	26 (3)	-1 (5)	10 (5)	6 (2)
C4	59 (11)	22 (3)	12 (2)	-6 (5)	-1 (4)	2 (2)
C5	69 (13)	30 (4)	20 (3)	-17 (6)	0 (5)	4 (3)
C6	92 (13)	34 (4)	17 (2)	-3 (6)	1 (5)	1 (3)
C7	87 (13)	30 (3)	13 (2)	-2 (6)	1 (4)	0 (2)
C8	47 (9)	25 (3)	17 (2)	13 (5)	3 (4)	-5 (2)
C9	68 (12)	21 (3)	13 (2)	3 (5)	4 (4)	4 (2)
C10	65 (10)	19 (3)	14 (2)	0 (5)	-2 (4)	3 (2)
C11	106 (15)	19 (3)	14 (2)	-1 (5)	0 (5)	2 (2)
C12	72 (12)	16 (2)	15 (2)	3 (5)	-2 (4)	-1 (2)
C13	71 (12)	23 (3)	19 (2)	2 (5)	-5 (5)	-10 (2)
C14	154 (19)	30 (4)	23 (3)	10 (7)	-11 (7)	-10 (3)
C15	147 (18)	25 (3)	13 (2)	2 (6)	-2 (5)	-7 (2)
C16	99 (14)	33 (4)	12 (2)	-5 (6)	-5 (5)	-3 (2)

RESULTS

Description and Discussion of the Structure. The crystal structure consists of discrete bis-[D-β-(2-pyridyl)-α-alaninato]cobalt(III) cations, $Co(D\text{-}Pyala)_2^+$, and nitrate anions. The atomic labeling of the structure is shown in Figure 2. The cobalt atom is coordinated to the carboxylate oxygen atom, the amino nitrogen atom and the pyridine nitrogen atom of each $D\text{-}Pyala^-$ ion in a slightly distorted octahedral arrangement. The configuration may be termed trans-carboxylate according to the convention noted in the Introduction (Figure 1).

The interatomic distances and angles are given in Tables II and III. A comparison between the two $D\text{-}Pyala^-$ groups shows that corresponding bond lengths and angles do not differ significantly. (The difference in each case is less than three times the standard deviation.) The bond distances observed within the ligands compare quite well with those for similar groups in either D-histidinato-L-histidinato-cobalt(III) bromide,[17] or carbonatotetrakis(pyridine)-cobalt(III) perchlorate.[18] Two types of C-O distances in the carboxylate groups are evident. The C-O distances of the coordinated oxygen atoms (1.31(1) and 1.30(1)Å) are significantly longer than those in the uncoordinated "carbonyl-type" oxygen atoms (1.23(1) and 1.21(1)Å), as has been observed in other amino acid complexes.[19-21] The Co-N(amino) and Co-O

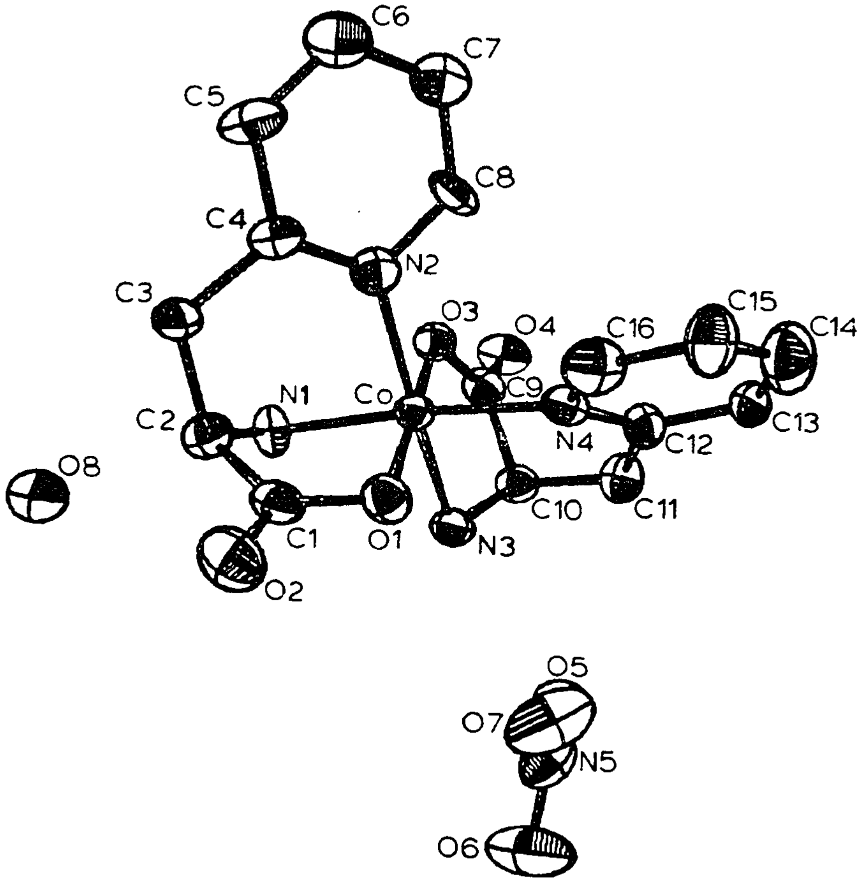


Figure 2. The structure of $[Co(\underline{D}\text{-Pyala})_2]NO_3 \cdot 1/2H_2O$

Table II. Interatomic distances (Å) and their estimated standard deviations (in parentheses)

Co-O1	1.887(6)	Co-O3	1.898(5)
Co-N1	1.938(7)	Co-N3	1.952(7)
Co-N2	1.978(7)	Co-N4	1.973(7)
O1-C1	1.31(1)	O3-C9	1.30(1)
O2-C1	1.23(1)	O4-C9	1.21(1)
O1-O2	2.230(9)	O3-O4	2.214(8)
C1-C2	1.52(1)	C9-C10	1.51(1)
N1-C2	1.50(1)	N3-C10	1.50(1)
C2-C3	1.51(1)	C10-C11	1.53(1)
C3-C4	1.52(1)	C11-C12	1.52(1)
C4-C5	1.39(1)	C12-C13	1.39(1)
C5-C6	1.39(2)	C13-C14	1.39(1)
C6-C7	1.40(1)	C14-C15	1.37(1)
C7-C8	1.39(1)	C15-C16	1.39(1)
C8-N2	1.38(1)	C16-N4	1.37(1)
N2-C4	1.35(1)	N4-C12	1.35(1)
N5-O5	1.24(1)	O5-O6	2.12(1)
N5-O6	1.22(1)	O5-O7	2.13(1)
N5-O7	1.24(1)	O6-O7	2.15(1)
N1-O8	3.497(9)		
N3-O5	3.15(1)		
N3-O7	2.94(1)		

Table III. Bond angles (deg) and their estimated standard deviations (in parentheses)

01-Co-03	177.2(3)		
N1-Co-N4	172.1(3)	N3-Co-N2	171.4(3)
01-Co-N1	85.4(3)	03-Co-N3	85.4(3)
01-Co-N2	95.7(3)	03-Co-N4	95.2(3)
01-Co-N3	92.9(3)	03-Co-N1	92.5(3)
01-Co-N4	86.8(3)	03-Co-N2	86.1(3)
N1-Co-N2	88.1(3)	N3-Co-N4	86.9(3)
N1-Co-N3	92.4(3)	N2-Co-N4	93.9(3)
Co-01-C1	113.5(6)	Co-03-C9	114.5(5)
Co-N1-C2	104.0(5)	Co-N3-C10	104.4(5)
Co-N2-C4	127.4(6)	Co-N4-C12	126.1(6)
Co-N2-C8	114.8(6)	Co-N4-C16	116.1(6)
01-C1-02	123.2(9)	03-C9-04	123.2(8)
01-C1-02	114.9(8)	03-C9-C10	114.7(7)
02-C1-C2	121.9(8)	04-C9-C10	122.1(8)
C1-C2-N1	107.4(7)	C9-C10-N3	109.2(7)
N1-C2-C3	110.3(8)	N3-C10-C11	109.1(7)
C1-C2-C3	112.6(8)	C9-C10-C11	108.0(8)
C2-C3-C4	115.9(7)	C10-C11-C12	116.5(7)
C3-C4-N2	121.4(8)	C11-C12-N4	121.7(8)
C3-C4-C5	117.1(8)	C11-C12-C13	115.8(8)
C4-C5-C6	121.3(9)	C12-C13-C14	118.8(9)
C5-C6-C7	117(1)	C13-C14-C15	120(1)
C6-C7-C8	119(1)	C14-C15-C16	118.9(9)
C7-C8-N2	122.9(9)	C15-C16-N4	122.1(9)
C8-N2-C4	117.7(8)	C16-N4-C12	117.7(8)
N2-C4-C5	121.4(9)	N4-C12-C13	122.3(8)
05-N5-06	119(1)	05-N5-07	119(1)
06-N5-07	122(1)		

bond distances are comparable to those found in other cobalt(III) complexes,[17,19-21] and the Co-N(pyridine) bond distances are similar to those reported in other cobalt(III) structures.[18,22] The corresponding N(amino)-Co-N(pyridine), N(amino)-Co-O and N(pyridine)-Co-O bond angles for the two ligands differ only slightly (up to 1.2°). Distortions from ideal octahedral geometry are apparent by comparison of angles around the cobalt atom. Deviations from 90° occur for all angles and range from 1.9 to 5.7°. These differences are best explained by considering the constraints imposed upon the coordination geometry by the chelate ring sizes. The small angles (both 85.4(3)°) in the 5-membered amino acidate chelate rings are consistent with other values reported for cobalt(III) complexes.[20-32] The six-membered rings have the smallest deviations from 90° as was also found for the D-histidinato-L-histidinatocobalt(III) ion.[17] The pyridine rings seem to repel each other, as suggested by the expansion of the O1-Co-N2, O3-Co-N4 and N4-Co-N2 angles and contraction of the N2-Co-O3 and N4-Co-O1 angles.

A small difference in the bonding of the two D-Pyala$^-$ ions is seen when considering the pyridine rings. The distances from the cobalt atom to the least-squares planes of the pyridine rings are 0.09 and 0.32 Å (Table IV). Also the Co-N2 and Co-N4 bonds make angles of 2.6 and 9.3° with the plane of their respective pyridine rings. Similar

Table IV. Equations of least-squares planes[a]

Plane 1: N2-C4-C5-C6-C7-C8

$$0.22919\ X + 0.23315\ Y + 0.94504\ Z - 10.4 = 0$$

Atom	D[b]	Atom	D
N2	-0.0056	C2[c]	0.0266
C4	-0.0061	C3[c]	0.0778
C5	0.0149	Co[c]	0.0887
C6	-0.0120		
C7	0.0004		
C8	0.0085		

Plane 2: N4-C12-C13-C14-C15-C16

$$0.91075\ X + 0.19490\ Y + 0.36406\ Z - 8.47207 = 0$$

Atom	D	Atom	D
N4	0.0387	C10[c]	-0.0085
C12	-0.0269	C11[c]	-0.2256
C13	-0.0105	Co[c]	0.3201
C14	0.0357		
C15	-0.0234		
C16	-0.0136		

Plane 3: N5-O5-O6-O7

$$0.00542\ X + 0.93598\ Y + 0.35201\ Z - 5.05479 = 0$$

Atom	D
N5	0.0002
O5	0
O6	0
O7	0

---

[a] Planes are defined as $C_1X + C_2Y + C_3Z + C_4 = 0$ where X, Y, and Z are cartesian coordinates.

[b] D = distance (A) of the given atom from the fitted plane.

[c] These atoms were not included in the calculation of the plane.

displacements of the cobalt atom with respect to the plane of the ring have been observed in other pyridine-containing cobalt(III) complexes.[18,33] The dihedral angle between the least-squares planes of the two pyridine rings is 53.2°. Neither of these least-squares planes is coincident with the plane defined by N1-N2-N3-N4-Co. The dihedral angles between N1-N2-N3-C4-Co and the planes of the rings are 33.7° (for ring containing N2) and 39.8° (for ring containing N4).

The nitrate ion has average N-O distances of 1.23(1) Å and average O-N-O angles of 120(1)°, all of which are normal for this ion.

The water molecule, O8, forms no close contacts to the rest of the structure. The nearest approach of the oxygen atom, O8, is to the amino nitrogen N1. This distance (3.497(9) Å) is considerably longer than the sum of the van der Waals radii for an N•••O contact (3.07 Å).[34]

Hydrogen bonding does not appear to play a major role in stabilizing this crystal structure. Neither the closest contacts nor the associated angles indicate anything but very weak hydrogen bonding. The interaction most favorable for hydrogen bond formation would be between N3 and O7 (2.94(1) Å). However, the N5-O7-N3 angle is 98.6°, somewhat less than the 120° expected, and more importantly, assuming an N-H bond length of 1.05 Å places the hydrogen a distance of 2.45 Å from O7.

The packing of the eight cations and anions in the unit cell is shown in Figure 3.

Discussion. Attempts were made by several different methods to prepare all three isomers of $Co(\underline{D}\text{-Pyala})_2^+$. However, only the trans-carboxylate isomer (Figure 1a) was isolated from all preparative methods. These include mixing Co(II) salts with $\underline{D}\text{-Pyala}^-$ and subsequently oxidizing the metal ion to Co(III) and reacting $\underline{D}\text{-Pyala}^-$ with $[Co(NH_3)_4CO_3]NO_3$, $[Co(NH_3)_6](NO_3)_3$ or $Na_3[Co(CO_3)_3]\cdot 3H_2O$. In an attempt to isomerize the trans-carboxylate isomer, the complex was heated with charcoal in boiling water for 24 hours. Only starting material and some decomposition remained after this treatment. Similar treatment of an analogous complex, (D-asparato)(L-2,4-diaminobutyrato)-cobalt(III) produced an equilibrium mixture of isomers.[35] The three isomers of L-histidinatoiminodiacetatocobalt(III) were found to isomerize in water without any catalyst at 80°C.[36] Since trans-carboxylate $Co(\underline{D}\text{-Pyala})_2^+$ did not produce a mixture of isomers under similar conditions, we believe that this is the most stable form.

The infrared spectrum of trans-carboxylate $[Co(\underline{D}\text{-Pyala})_2]NO_3\cdot 1/2H_2O$ exhibited strong NH_2 stretching absorptions at 3218 and 3100 cm^{-1}. The NH_2 deformation mode was observed at 1610 cm^{-1}. The intense CO_2^- asymmetric stretching absorption appeared at 1670 cm^{-1}, compared to

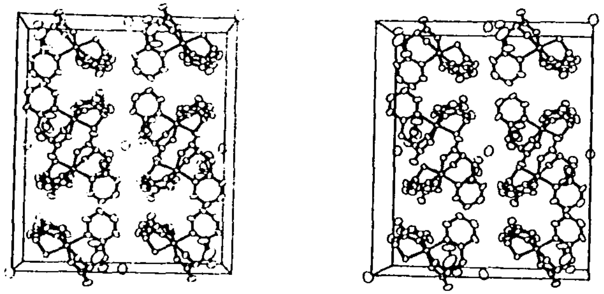


Figure 3. Stereoscopic view of the unit cell with the b axis horizontal and the c axis vertical

1650 cm^{-1} reported for the bis(histidinato)cobalt(III) ion.[3] The presence of the nitrate anion was detected as a sharp peak at 1385 cm^{-1}.

The visible, ORD and CD spectra of the trans-carboxylate isomer are given in Figure 4. These spectra are very similar to those of the analogous isomers of bis(L-2,3-diaminopropionato)cobalt(III) ion,[4] bis(L-2,4-diaminobutyrato)-cobalt(III) ion[5] and bis(L-histidinato)cobalt(III) ion.[2] The splitting in the lowest energy spin-allowed d-d band was used to assign the correct geometry to the complex before the crystal structure had been solved. Two components were seen in this band with the less intense shoulder appearing at shorter wavelengths as in the previously mentioned complexes.[2-5] The CD spectrum is very similar to the inverse of the spectra of the L-histidinato, L-2,3-diaminopropionato and L-2,4-diaminobutyrato cobalt(III) complexes.[2,4,5] This result confirms the original assignment, which was based on the Clough-Lutz-Jirgenson rule,[1] of the D configuration to the free D-PyalaH ligand.

The ^{1}H NMR spectrum of the diamagnetic complex is consistent with its C_2 symmetry which implies two equivalent D-$Pyala^-$ groups. In free D-PyalaH, the α and β protons show an ABX pattern. The α proton occurs as four peaks of equal intensity centered at $\delta = 4.13$, and the β protons occur as three peaks centered at $\delta = 3.33$ with the lowest field peak

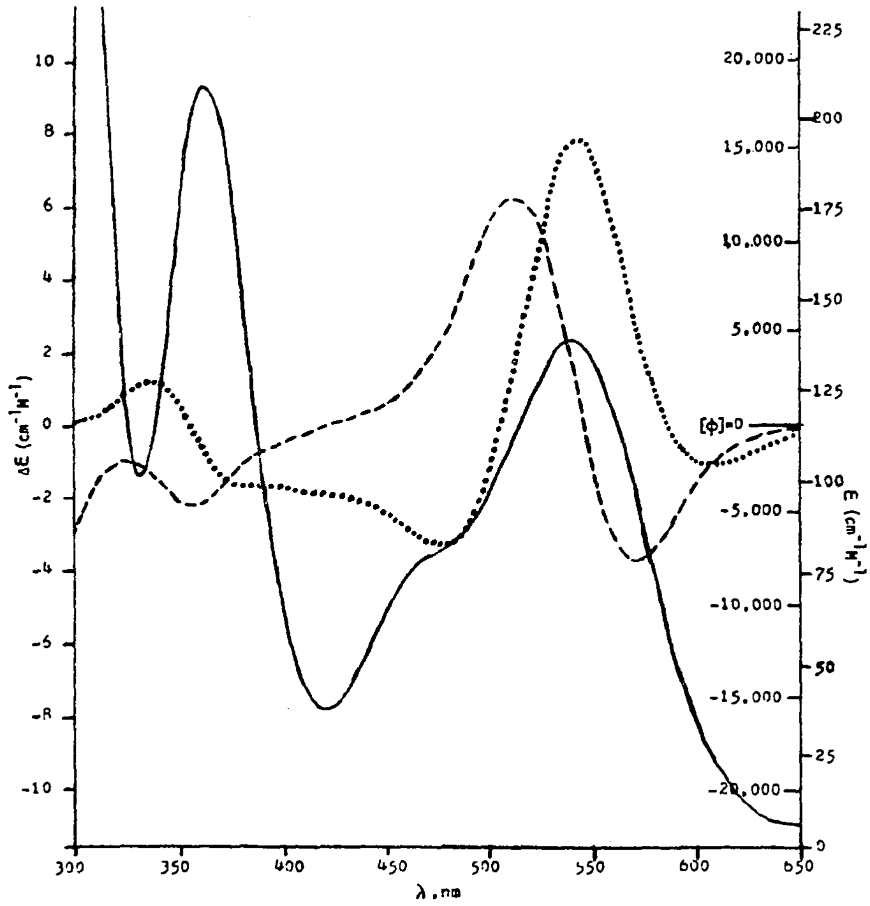


Figure 4. Absorption (——), molar rotation (•••) and CD (---) spectra of trans carboxylate Co(D-Pyala)$_2^+$ ion in aqueous solution

being the most intense. Upon coordination to cobalt(III), the α proton is shifted upfield and the β protons shifted downfield, as in the case of L-histidine. The shifts are such that both α and β protons absorb at $\delta = 3.91$ ppm and appear as a sharp singlet with no splitting. The position of the pyridine protons also differs from that observed in the uncoordinated ligand. The most noticeable shift occurs for the protons on carbons 8 and 16 in Figure 2. D-PyalaH shows a set of complex peaks assigned to this proton at 8.36 - 8.50 ppm, with the remaining pyridine protons at 7.22 - 7.89 ppm. Coordination in the trans-carboxylate structure shifts the C8 and C16 protons upfield to where they are no longer distinguishable from the other ring protons at 7.22 - 8.14 ppm. This shift is not unexpected when the structure of the complex is considered, since this proton occupies a position over the other pyridine ring and is thus shielded.

CONCLUSION

When L-histidine, L-2,3-diaminopropionic acid or L-2,4-diaminobutyric acid is coordinated to cobalt(III), all three possible isomers are separated.[2-5] In the case of L-histidine the major isomer is the trans-imidazole which accounted for more than 75% of the products.[2] Since the imidazole and pyridine rings are sterically very similar, the distribution of isomers based on repulsion of the rings alone was expected to be similar for $Co(L\text{-his})_2^+$ and $Co(D\text{-Pyala})_2^+$. However, we observe the formation of the trans-carboxylate isomer of $Co(D\text{-Pyala})_2^+$ almost exclusively, and our other studies indicate that this is the thermodynamically most stable isomer. The reason for this stability may be related to the stabilities of similar amino-acid cobalt complexes. Thus, only a small amount of the trans N isomer of bis(L-asparato)cobalt(III) anion could be prepared.[37] Likewise, little of the analogous trans N isomer was found in the equilibrium mixtures of (D-asparato)(L-2,4-diaminobutyrato)cobalt(III)[35] and L-histidinoiminodiacetatocobalt(III).[36] Only 6% of the trans-N(amino) isomer of $Co(L\text{-his})_2^+$ and none of this isomer of $Co(L\text{-his})(D\text{-his})^+$ could be isolated.[2] Our results support these findings since the trans-amino isomer of $Co(D\text{-Pyala})_2^+$ could not be isolated. This suggests that α-amino nitrogens avoid being trans to each other in all of these complexes.

Reasons for the absence of the trans-pyridyl isomer of Co(D-Pyala)$_2$ are not as obvious. Indeed, many factors may contribute to its instability. The weaker coordination of pyridine compared to imidazole (the difference in log K_f values for several transition metal ions is about 1.0) may cause the pyridine to preferentially assume a position trans to the amino-nitrogen. The greater π-acceptor ability of the pyridine group trans to the strongly donating amino group may also add to the stability of the trans-carboxylate structure (Figure 1). Finally, molecular models of the trans-pyridyl structure show that the α-hydrogen of the pyridine ring points into the π-cloud of the carboxylate group of the other ligand. Repulsion between the α-hydrogen and carboxylate group may also destabilize this structure. This repulsion would be much smaller in Co(L-his)$_2^+$, where the α-hydrogen of the smaller imidazole ring does not point directly into the π-cloud of the carboxylate group. Thus, electronic as well as steric factors may be responsible for the destabilization of the trans-amino and trans-pyridyl structures.

REFERENCES

1. Rechani, P. R.; Nakon, R.; Angelici, R. J. Bioinorg. Chem. 1976, 5, 329.
2. Bagger, S.; Gibson, K.; Sorenson, C. S. Acta Chem. Scand. 1972, 26, 2503.
3. Zompa, L. J. Chem. Comm. 1969, 783.
4. Freeman, W. A.; Liu, C. F. Inorg. Chem. 1968, 7, 764.
5. Freeman, W. A.; Liu, C. F. Inorg. Chem. 1970, 9, 1191.
6. Ritsma, J. H.; Van de Grampel, J. D.; Jellinek, F. Rec. Trav. Chim. 1969, 88, 411.
7. Bedell, S. A.; Rechani, P. R.; Angelici, R. G.; Nakon, R. Inorg. Chem. 1977, 16, 972.
8. a) Angelici, R. J. "Synthesis and Technique of Inorganic Chemistry"; W. B. Saunders Company: Philadelphia, 1969.

   b) Fernelius, W. C. "Inorganic Synthesis", Vol. II; McGraw-Hill Company: New York, 1946.

   c) Holtzclaw, H. F. "Inorganic Synthesis", Vol. III; McGraw-Hill Company: New York, 1946
9. Jacobson, R. A. J. Appl. Cryst. 1976, 9, 115.
10. Rohrbaugh, W. J.; Jacobson, R. A. Inorg. Chem. 1974, 13, 2535.
11. Lawton, S. L.; Jacobson, R. A. Inorg. Chem. 1968, 7, 2124.
12. Busing, W. R.; Martin, K. O.; Levy, H. A. "ORFLS, A Fortran Crystallographic Least Squares Program"; U. S. Atomic Energy Commission Report ORNL-TM-305: Oak Ridge National Laboratory, Oak Ridge, Tenn., 1962.
13. Hubbard, C. A.; Quicksall, C. O.; Jacobson, R. A. "The Fast Fourier Algorithm and the Programs, ALFF, ALFFDP, ALFFPROJ, ALFFT, and FRIEDEL"; U. S. Atomic Energy Commission Report IS-2625: Iowa State University and Institute for Atomic Research, Ames, Iowa, 1971.

14. Hanson, H. P.; Herman, F.; Lea, J. D.; Skillman, S. Acta Crystallogr. 1960, 17, 1040.

15. Templeton, D. H. "International Tables for X-Ray Crystallography", Vol. III; Kynoch Press: Birmingham, England, 1962, pp. 215-216, Table 3.3.2C.

16. Busing, W. R.; Martin, K. O.; Levy, H. A. "ORFFE, A Fortran Crystallographic Function and Error Program"; U. S. Atomic Energy Commission Report ORNL-TM-306: Oak Ridge National Laboratory, Oak Ridge, Tenn., 1964.

17. Thorup, N. Acta Chem. Scand. 1977, A31, 203.

18. Kaas, K.; Sorenson, A. M. Acta Crystallogr. 1973, B29, 113.

19. Buckingham, D. A.; Cresswell, P. J.; Dellaca, R. J.; Dwyer, M.; Gainsford, G. J.; Marzelli, L. G.; Maxwell, I. E.; Robinson, W. T.; Sargeson, A. M.; Turnbull, K. R. J. Amer. Chem. Soc. 1974, 96, 1713.

20. Halloran, L. J.; Caputo, R. E.; Willett, R. D.; Legg, J. I. Inorg. Chem. 1975, 14, 1762.

21. Anderson, B. F.; Buckingham, D. A.; Gainsford, G. J.; Robertson, G. B.; Sargeson, A. M. Inorg. Chem. 1975 14, 1658.

22. Bartlett, M. W.; Dunitz, J. D. Helv. Chim. Acta 1971, 54, 2753.

23. Barnet, M. T.; Freeman, H. C.; Buckingham, D. A.; Hsu, I.; van der Helm, D. Chem. Comm. 1970, 367.

24. Liu, C. F.; Ibers, J. A. Inorg. Chem. 1969, 8, 1911.

25. Watson, W. H.; Johnson, D. R.; Celap, M. B.; Kamberi, B. Inorg. Chim. Acta 1972, 6, 591.

26. Herak, R.; Prelesnik, B.; Manojlovic-Muir, L.; Muir, K. W. Acta Crystallogr. 1974, B30, 229.

27. Gillard, R. D.; Payne, N. C.; Robertson, G. B. J. Chem. Soc. (A) 1970, 2579.

28. Corradi, A. B.; Palmieri, C. G.; Nardelli, M.; Pellinghelli, M. A.; Tani, M. E. V. J. C. S. Dalton 1973, 655.

29. Svetich, G. W.; Voge, A. A.; Brushmiller, J. G.; Berends, E. A. *J. C. S. Chem. Comm.* *1972*, 701.

30. Weakleim, H. A.; Hoard, J. L. *J. Amer. Chem. Soc.* *1959*, 81, 549.

31. Nagao, R.; Marumo, F.; Saito, Y. *Acta Crystallogr.* *1972*, B28, 1852.

32. Voss, K.; Angelici, R. J. *Inorg. Chem.* *1978*, 17, 1922.

33. Bailey, N. A.; Higson, B. M.; McKenzie, E. D. *J. C. S. Dalton* *1975*, 1105.

34. Bondi, A. *J. Phys. Chem.* *1964*, 68, 441.

35. Watabe, M.; Kawaai, S.; Yoshikawa, S. *Bull Chem. Soc. Japan* *1976*, 49, 1845.

36. Watabe, M.; Zama, M.; Yoshikawa, S. *Bull. Chem. Soc. Japan* *1978*, 51, 1354.

37. Hosaka, K.; Nishikawa, H.; Shibata, M. *Bull. Chem. Soc. Japan* *1969*, 42, 277.

SECTION II. PREPARATIONS AND SPECTRAL CHARACTERIZATIONS OF THE β-(2-pyridyl)-α-alanine COMPLEXES: *trans*-Amino $Co(\underline{D}\text{-Pyala})_2^+$, Racemic all-*cis* $Co(\underline{D}\text{-Pyala})(\underline{L}\text{-Pyala})^+$ AND *trans*-Carboxylate $Cr(\underline{D}\text{-Pyala})_2^+$

INTRODUCTION

This study is part of an investigation into the origins of the stereoselectivity observed in the chelation of β-(2-pyridyl)-α-alanine, $^{+}H_3NCH(CH_2C_5H_4N)CO_2^-$, PyalaH, to transition metal ions.[1] When the Pyala$^-$ ligands were allowed to have either the D or L configuration, five different geometrical isomers of the $M(Pyala)_2^+$ complexes are possible as indicated in Figure 1. Four of these, a-d, are optically active and the fifth, e, is a meso complex.

Recently, the trans-carboxylate Co(D-Pyala)$_2^+$ complex (Figure 1a) was isolated and characterized.[2] It was suggested that this form was the most stable isomer since several different methods of preparation produced this complex as the major species, and attempts to convert it to other isomers were unsuccessful. We have now separated and fully characterized a second isomer, trans-amino Co(D-Pyala)$_2^+$, that was formed in very low yield in the preparation of the trans-carboxylate complex.

The complexes formed in the reaction of racemic ligand, D,L-PyalaH, have also been isolated and identified. The structures of the resulting complexes are compared with those reported for analogous complexes of histidine.[3]

Finally, the more labile chromium(III) complexes of D-Pyala$^-$ have also been studied and the results compared with the related histidine complexes.[4]

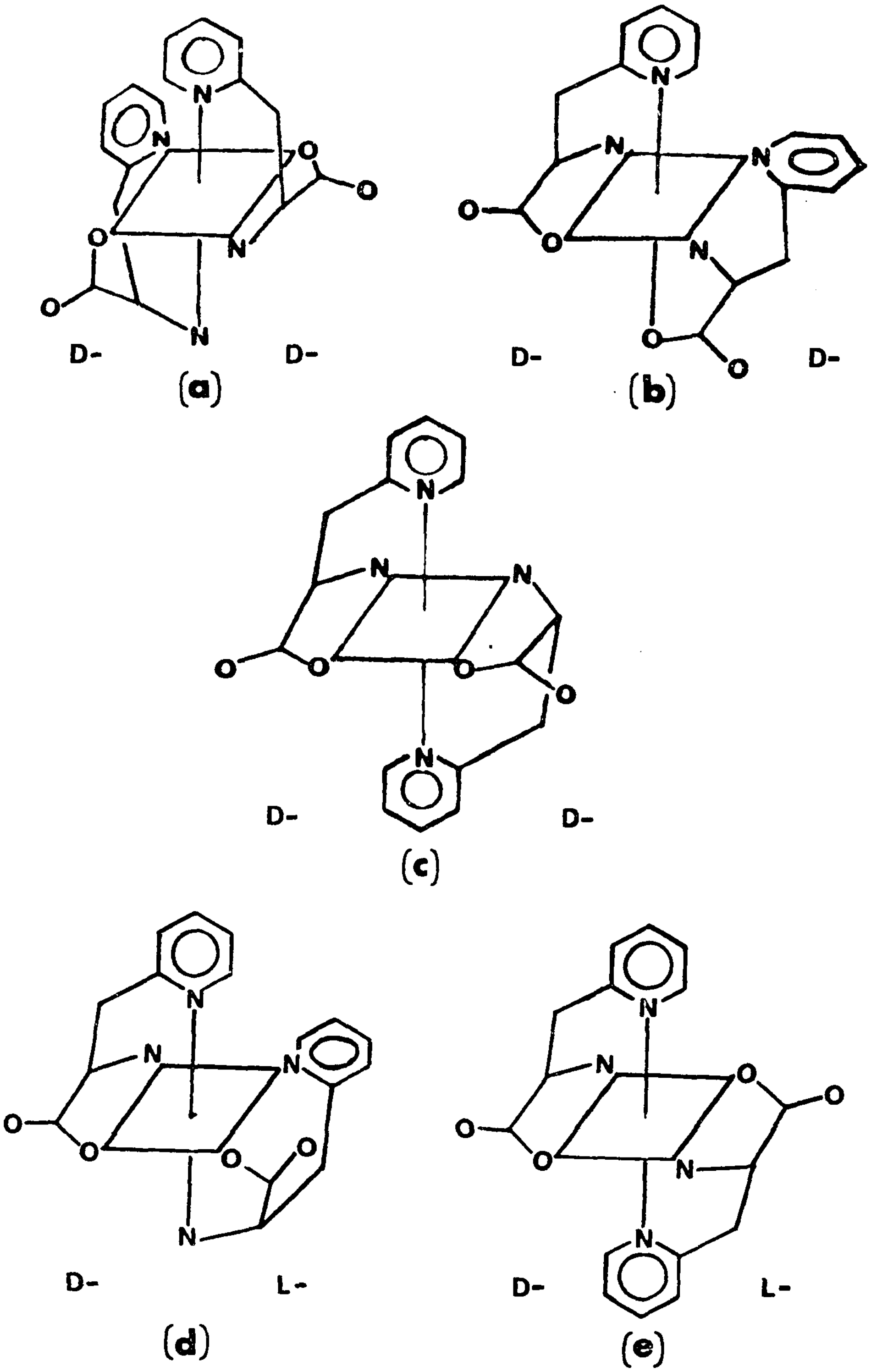


Figure 1. The five possible geometrical isomers from the reaction of cobalt(III) with D,L-PyalaH: (a) trans-carboxylate, (b) trans-amino, (c) trans-pyridyl, (d) all-cis and (e) all-trans

EXPERIMENTAL SECTION

Materials. Racemic β-(2-pyridyl)-α-alanine was prepared and resolved as described previously.[5]

Preparation of trans-amino bis-[D-β-(2-pyridyl)-α-alaninato]cobalt(III) Nitrate, $[Co(D\text{-}Pyala)_2]NO_3\cdot 1\frac{1}{2}H_2O$. The complex was prepared by adding $Co(NO_3)_2\cdot 6H_2O$ (1.75 g, 6.0 mmol) to 20 ml of water containing D-PyalaH (2.0 g, 12.0 mmol) and NaOH (12.0 mmol). After stirring for 15 minutes, PbO_2 (0.75 g, 3.1 mmol) was added, and the resulting mixture was heated to 70°C for one hour. The unreacted PbO_2 was filtered from the solution, which was subsequently loaded on a column (1.8 x 42 cm) of Dowex 50W-X8 in the Na^+ form. The column was washed with 200 ml of water to remove ligand decomposition products. Elution with 0.1 M $NaNO_3$ at 1 drop/2 sec for one week gave three bands. The first complex eluted was trans-carboxylate $Co(D\text{-}Pyala)_2^+$ which was identified by its visible, circular dichroism and ^1H NMR spectra.[2] The yield was 46% based on the $Co(NO_3)_2\cdot 6H_2O$ starting material.

The second band was evaporated to 10 ml and a layer of absolute ethanol (∿20 ml) was added. The $NaNO_3$ that precipitated from the aqueous phase as the layers diffused together was filtered from the solution. The filtrate was evaporated to 5 ml and a layer of ethanol (∿10 ml) was added once again.

This caused precipitation of most of the remaining $NaNO_3$. The solution was filtered, evaporated to dryness, and dissolved in a minimum of boiling 95% ethanol. A layer of acetone (∿15 ml) was floated on top of the ethanol solution. Upon allowing the acetone to diffuse into the ethanol, red crystals precipitated. These were filtered from the solution and vacuum dried. The yield of the trans-amino complex was 4%. Anal. calcd for $[Co(\underline{D}\text{-Pyala})_2]NO_3 \cdot 1\frac{1}{2}H_2O$: C, 40.18; H, 4.43; N, 14.64; Co, 12.32. Found: C, 40.24; N, 4.45; N, 14.27; Co, 12.48.

Crystals were obtained from the third band, after removing the $NaNO_3$ as described above, by evaporation to 1 ml adding a layer of acetone and cooling. Carbon, hydrogen and nitrogen analyses of these crystals as well as their circular dichroism spectrum indicated that this complex was not an isomer of $Co(\underline{D}\text{-Pyala})_2^+$, and it was not characterized further.

Preparation of racemic all-cis-$[Co(\underline{D}\text{-Pyala})(\underline{L}\text{-Pyala})]NO_3 \cdot H_2O$. This complex was prepared according to several different procedures. Those methods in which $[Co(NH_3)_6](NO_3)_3$, $[Co(NH_3)_4CO_3]NO_3$ and $Na_3[Co(CO_3)_3] \cdot 3H_2O$ were used as starting material have been reported previously,[2] and the only change was in using D,L-PyalaH instead of D-PyalaH. The method involving oxidation of cobalt(II) nitrate to the cobalt(III) complex was also similar to that reported,[2] but PbO_2 (0.38 g, 1.6 mmol) was used as the oxidizing agent instead of hydrogen peroxide.

Separation of the isomeric cobalt(III) complexes was achieved chromatographically on basic alumina in 90:10/MeOH:H_2O. After eight hours, three bands were eluted separately from the column. The first band was red-violet in color and was identified by its visible and ^1H NMR spectra[2] as a racemic mixture of trans-carboxylate $Co(\underline{D}\text{-Pyala})_2^+$ and $Co(\underline{L}\text{-Pyala})_2^+$. The lack of any optical activity in its circular dichroism spectrum verified the presence of equal amounts of the enantiomers, $Co(\underline{D}\text{-Pyala})_2^+$ and $Co(\underline{L}\text{-Pyala})_2^+$. The lowest yield, 7.6%, was obtained from the reaction solution in which cobalt(II) was oxidized to cobalt(III) with PbO_2. The highest yield, 10%, was isolated from the reaction of $Na_3[Co(CO_3)_3]\cdot 3H_2O$ with $\underline{D},\underline{L}$-PyalaH.

The third band was red in color and was identified by its visible and ^1H NMR spectra as a racemic mixture of the trans-amino complex, $Co(\underline{D}\text{-Pyala})_2^+$ and $Co(\underline{L}\text{-Pyala})_2^+$. Since the enantiomers were formed in equal amounts, no circular dichroism was observed. The yields of this complex were always very small (<1%).

The second band eluted from the column was red-violet in color and yielded the major product. The solution containing the red-violet complex was evaporated to a small volume (∿1 ml) and a layer (2-3 ml) of ethanol was added.

The crystals that formed were filtered, washed with 95% ethanol and vacuum dried. The highest yield obtained of this all-cis [Co(D-Pyala)(L-Pyala)]$NO_3 \cdot H_2O$ complex was 26% from the reaction of $Na_3[Co(CO_3)_3] \cdot 3H_2O$ with D,L-PyalaH. The lowest yield, 20%, was isolated from the oxidation of cobalt(II) to cobalt(III) with PbO_2. The ratio of the yield of all-cis [Co(D-Pyala)(L-Pyala)]$NO_3 \cdot H_2O$ to that of trans-carboxylate $[Co(D\text{-}Pyala)_2]NO_3 \cdot 1/2H_2O$ and $[Co(L\text{-}Pyala)_2]NO_3 \cdot 1/2H_2O$ was a constant, 2.6, for each reaction. Anal. calcd for $[Co(C_8H_9N_2O_2)_2]NO_3 \cdot H_2O$: C, 40.95; H, 4.30; N, 14.92. Found: C, 41.22; H, 4.34; N, 14.92.

Preparation of tris(D-β-(2-pyridyl)-α-alaninato]-chromium(III) monohydrate, $[Cr(D\text{-}Pyala)_3] \cdot H_2O$, and bis-[D-β-(2-pyridyl)-α-alaninato]chromium(III) chloride, $[Cr(D\text{-}Pyala)_2]Cl$. The $CrCl_3 \cdot 6H_2O$ (0.80 g, 3.0 mmol) and D-PyalaH (1.0 g, 6.0 mmol) were dissolved in 20 ml of water and a methanol solution of $(n\text{-}Bu)_4N^+OH^-$ was added dropwise until the pH was 6.0. The green solution turned violet after stirring for 2 hrs at 55°C. This solution gave different products when treated in each of the following two ways.

A) The aqueous solution was evaporated under reduced pressure to about 10 ml and allowed to stand at room temperature. After three days, pink crystals of $[Cr(D\text{-}Pyala)_3] \cdot H_2O$ formed. They were filtered from the solution and recrystallized from boiling water. Anal. calcd for $Cr(C_8H_9N_2O_2)_3 \cdot H_2O$: C, 50.97; H, 5.17; N, 14.86. Found: C, 50.89; H, 5.32; N, 14.66.

B) The reaction solution was evaporated to dryness and the solid was dissolved in methanol. This solution was chromatographed on basic alumina (125 ml, column 1.9 x 55 cm) and eluted with methanol at 1 drop/2 sec. One violet band formed and was eluted from the column after 6 hrs. The solution was evaporated to 5 ml and stored at -40°C. Attempts to obtain crystals of the violet $[Cr(\underline{D}\text{-Pyala})_2]Cl$ complex were unsuccessful.

Spectra. The visible, optical rotatory dispersion and circular dichroism spectra were recorded at room temperature using a Jasco ORD/UV/CD-5 spectrophotometer. The proton nmr spectra were recorded on a Varian Associates HA-100 spectrometer in 99.7% deuterium oxide *vs*. t-butyl alcohol ($\delta = 1.23$) as an internal standard.

RESULTS

Discussion. There are five possible geometrical isomers of the bis[β-(2-pyridyl)-α-alaninato)cobalt(III) ion, $Co(Pyala)_2^+$ (Figure 1). Three of these geometries (a-c) require the two ligands in the complex to have the same absolute configuration, while in the remaining two geometries (d and e) the ligands must be of opposite absolute configuration. Of the five geometrical isomers that may form when D,L-Pyala⁻ is used in the reactions, four are optically active, (a-d), and may have both enantiomers present, (only one enantiomer of each pair is shown in Figure 1), while the all-trans structure (Figure 1e) is a meso complex.

Trans-amino[Co(D-Pyala)$_2$]NO$_3$·1½H$_2$O. Of the three possible geometrical isomers (Figure 1a-c) that may form upon coordination of two D-Pyala⁻ groups to cobalt(III), two have been isolated and characterized. These are the trans-carboxylate[2] and trans-amino $Co(D\text{-}Pyala)_2^+$ complexes. The visible, ORD and CD spectra of the trans-amino complex are given in Figure 2. These spectra compare quite well with those of the trans-amino isomers of bis(L-2,3-diaminopropionato)cobalt(III) ion,[6] bis(L-2,4-diaminobutyrato)-cobalt(III) ion[7] and bis(L-histidinato)cobalt(III) ion.[3] The lowest energy d-d transition exhibits a shoulder on the long wavelength side of the band which is characteristic of the trans-amino structure. The circular dichroism spectrum

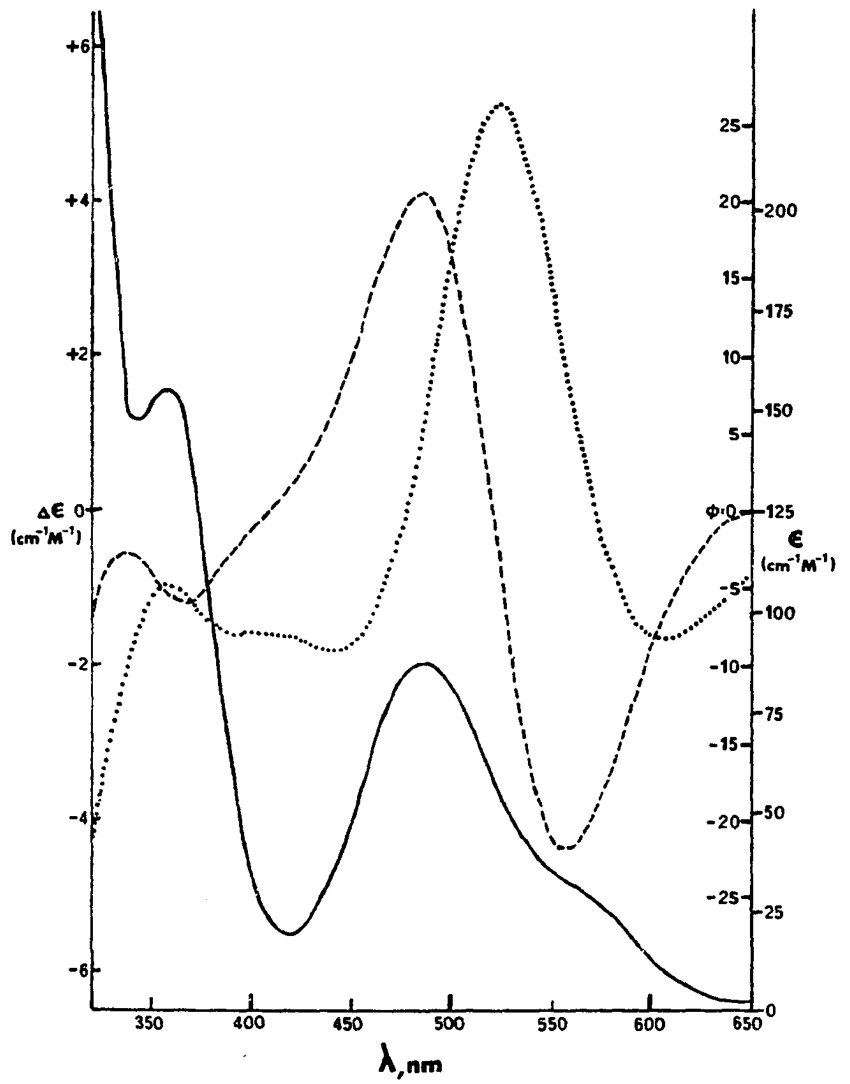


Figure 2. Absorption (——), molar rotation (•••), and circular dichroism (---) spectra of *trans*-amino Co(D-Pyala)$_2^+$ ion in aqueous solution

is similar to the inverse of the spectra of the L-histidinato, L-2,3-diaminopropionato and L-2,4-diaminobutyrato cobalt(III) trans-amino complexes.[3,6,7]

The ^{1}H NMR spectrum of the trans-amino Co(D-Pyala)$_2^+$ complex is consistent with its C_2 symmetry which requires two equivalent D-Pyala$^-$ groups. In free D-PyalaH, the α proton was observed as four peaks of equal intensity centered at δ = 4.13, and the β protons occurred as three peaks centered at δ = 3.33 with the lowest field peak being the most intense. Upon deprotonation and coordination to cobalt(III) in the trans-amino structure, the α proton was shifted upfield and the β protons were shifted downfield, such that the α and β proton patterns overlap. Four peaks of unequal intensity were observed from δ = 3.97 to 4.22 ppm. This differs from the spectrum of the trans-carboxylate isomer which exhibited only a sharp singlet at δ = 3.91 ppm.

The peak positions in the aromatic region of the spectrum for the trans-amino complex differ from those of either the uncoordinated ligand or the trans-carboxylate isomer. The D-PyalaH showed peaks which resemble a doublet (δ = 8.46 ppm), a triplet (δ = 7.79 ppm) and an overlapping doublet and triplet (δ = 7.22 - 7.44 ppm). The coordinated pyridine in the trans-amino complex showed the following pattern: overlapping triplet and doublet (δ = 8.07 ppm); doublet (δ = 7.66 ppm) and triplet (δ = 7.34 ppm). These shifts can be compared with those observed for trans-carboxylate Co(D-Pyala)$_2^+$: triplet (δ = 7.99 ppm); doublet (δ = 7.90 ppm); doublet (δ = 7.62 ppm); and triplet (δ = 7.40 ppm). Upon expansion further splitting can be observed in all three spectra due to coupling of nonadjacent hydrogens of the ring. The most easily assigned peak is that from the proton on the carbon adjacent to the pyridine nitrogen (δ = 8.46 ppm in the D-PyalaH). The doublet observed for this proton was shifted to 8.07 ppm in the trans-amino complex and to 7.90 ppm in the trans-carboxylate structure. These shifts parallel those reported for the analogous proton of histidine upon coordination to cobalt(III).[3]

Racemic all-cis [Co(D-Pyala)(L-Pyala)NO$_3$·H$_2$O. Three bands were separated from the reaction mixture by column chromatography when the racemic ligand, D,L-Pyala$^-$, was coordinated to cobalt(III). The order of elution was: racemic trans-carboxylate (Co(D-Pyala)$_2^+$ and Co(L-Pyala)$_2^+$); racemic all-cis Co(D-Pyala)(L-Pyala)$^+$; and racemic trans-amino (Co(D-Pyala)$_2^+$ and Co(L-Pyala)$_2^+$). The racemic all-cis complex (Figure 1d) was the major product of all the preparations.

The visible spectrum of racemic all-cis [Co(D-Pyala)-(L-Pyala)]NO$_3$·H$_2$O in water is shown in Figure 3. The broad band at 502 nm identifies the structure as being all-cis

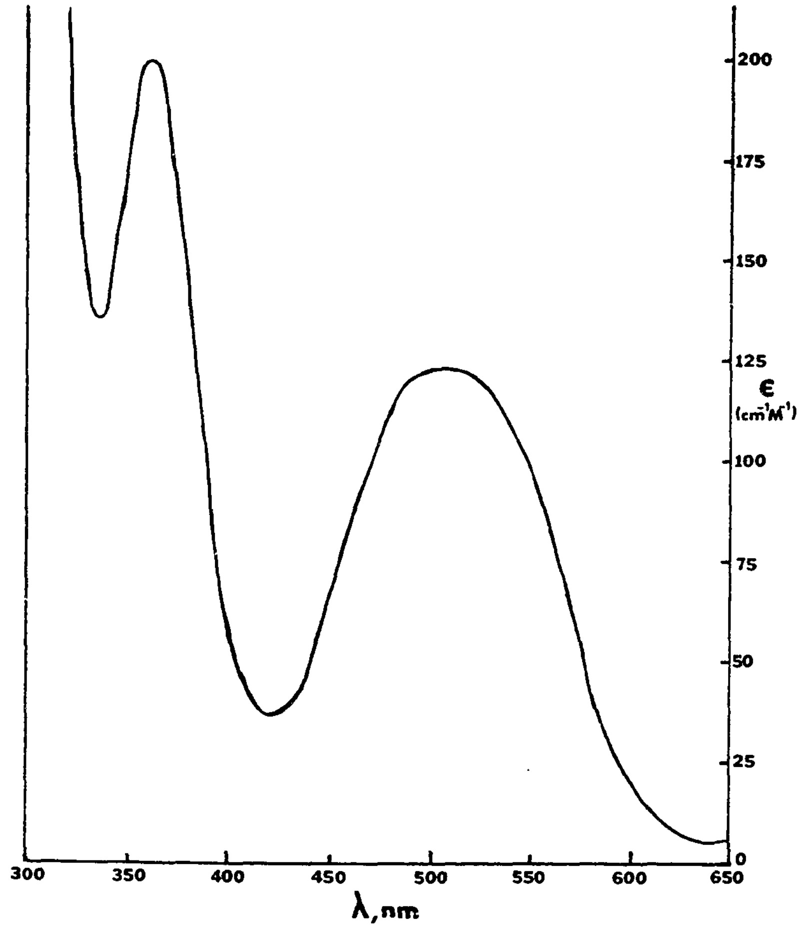


Figure 3. The absorption spectrum of racemic all-<u>cis</u> Co(<u>D</u>-Pyala)(<u>L</u>-Pyala)$^+$ ion in aqueous solution

because of its similarity to the analogous histidinato complex.[3]

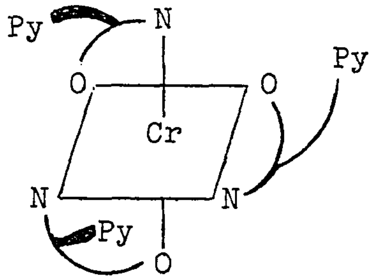
The ^{1}H NMR spectrum of the racemic all-cis complex is composed of two Pyala$^-$-type spectra. This was not evident in the methine and methylene patterns since the chemical shift of all six of these protons was equal, and only one slightly broadened peak was observed at $\delta = 3.91$ ppm. However, the aromatic region consisted of a number of patterns from which the presence of two different pyridine rings could be identified. The patterns observed for these protons (ignoring coupling of $J < 2$ Hz) were: doublet ($\delta = 8.48$); triplet ($\delta = 8.09$); triplet ($\delta = 7.86$); doublet ($\delta = 7.67$); doublet ($\delta = 7.45$) and triplet ($\delta = 7.10$ ppm).

<u>Facial [Cr(D-Pyala)$_3$]·H$_2$O and trans-carboxylate [Cr(D-Pyala)$_2$]Cl.</u> When an aqueous solution of chromium(III) and D-Pyala$^-$ was left standing at room temperature, the tris amino acid complex, [Cr(D-Pyala)$_3$]·H$_2$O, precipitated. If an aqueous solution containing only trans-carboxylate Cr(D-Pyala)$_2^+$ was allowed to stand at room temperature for three days, precipitation of [Cr(D-Pyala)$_3$]·H$_2$O occurred also. Presumably, an equilibrium between the bis complex, Cr(D-Pyala)$_2^+$ and the tris complex, Cr(D-Pyala)$_3$, was established in solution, and because of its very low

solubility (less than 1 mg/10 ml H_2O) [Cr(D-Pyala)$_3$]·H_2O precipitated.

The infrared spectrum of [Cr(D-Pyala)$_3$]·H_2O is similar to that of other tris amino acid chromium(III) complexes.[8,9] Stretching absorptions for $-NH_2$ were observed from 3130 to 3310 cm^{-1}. Three strong absorptions were observed from 1598 to 1690 cm^{-1} in the $-CO_2^-$ stretching region.

The visible and circular dichroism spectra of the complex in DMSO are given in Figure 4. The maxima and extinction coefficients are comparable to values reported for Cr(amino acidato)$_3$ complexes isolated previously.[8-13] The maxima for an aqueous solution of the complex are 379 nm (ε = 102 cm^{-1} M^{-1}) and 518 nm (ε = 81 cm^{-1} M^{-1}). Because of the similarity of the circular dichroism spectra of [Cr(D-Pyala)$_3$]·H_2O to those of the tris amino acid chromium(III) complexes reported previously,[11] the configuration of the complex can be assigned as Λ-fac as shown below:



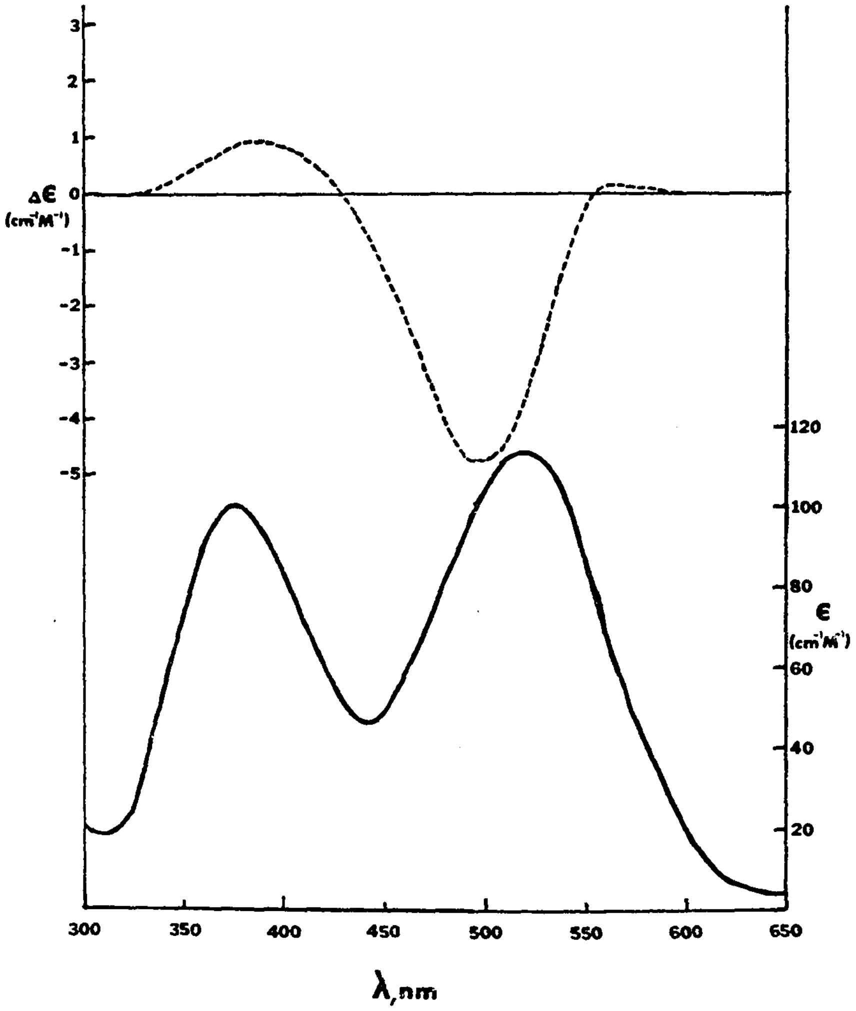


Figure 4. The absorption (——) and circular dichroism (---) spectra of Λ-<u>fac</u> [Cr(<u>D</u>-Pyala)$_3$]·H_2O in DMSO

The circular dichroism spectrum of [Cr(D-Pyala)$_3$]$\cdot$H$_2$O in H$_2$O has maxima at 406 nm ($\Delta\varepsilon$ = +0.24 cm^{-1} M^{-1}) and 517 nm ($\Delta\varepsilon$ = -0.83 cm^{-1} M^{-1}).

The trans-carboxylate Cr(D-Pyala)$_2^+$ complex was separated from any decomposition products and any remaining tris complex by column chromatography on basic alumina in methanol. Storage of the purple trans-carboxylate complex in methanol at 0°C prevented its conversion to [Cr(D-Pyala)$_3$]$\cdot$H$_2$O. The infrared spectrum of trans-carboxylate Cr(D-Pyala)$_2^+$ showed a sharp peak at 1635 cm^{-1} indicating that both carboxylate groups are coordinated. The coordination of the four nitrogen donors is inferred by the positions of the maxima in the visible and circular dichroism spectra. These are comparable to the CrN$_4$O$_2$ chromophore as described below.

Structural assignments can be made when both the cis-O and trans-O isomers of a CrN$_4$O$_2$ complex are isolated, since the cis-O isomer usually has maxima at higher energy than the trans-O isomer. In addition, the trans-O isomer may show a splitting of the $A_{2g}\rightarrow T_{2g}$ band further supporting the structural assignments. This splitting was observed in Cr(D-Pyala)$_2^+$ (Figure 5) and led to its assignment as trans-carboxylate. The similarity of the spectra of trans-carboxylate Cr(D-Pyala)$_2^+$ (λ_{max}: 382, 420 sh, 536 nm) and trans-O Cr(en)$_2$(OAc)$_2^+$ (λ_{max}: 373, 420 sh, 535 nm)[14] is

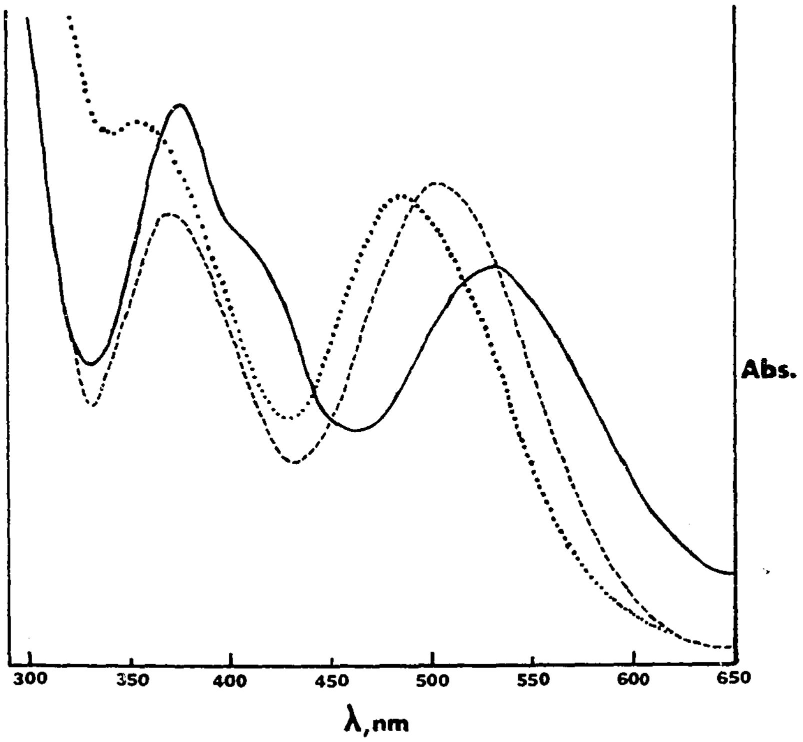


Figure 5. The absorption spectra of trans-carboxylate $Cr(\underline{D}\text{-Pyala})_2^+$ ion (——), trans-carboxylate $Cr(\underline{L}\text{-His})_2^+$ ion (---) and trans-imidazole $Cr(\underline{L}\text{-His})_2^+$ ion (•••) in aqueous solution

further support for this structural assignment. The assignments of the trans-carboxylate and trans-imidazole Cr($\underline{L}$-His)$_2^+$ isomers, reported previously, were based on the positions of the maxima in their visible spectra.[4]

The inverse of the circular dichroism spectra of the two isomers of Cr($\underline{L}$-His)$_2^+$ along with the recorded spectrum of trans-carboxylate Cr($\underline{D}$-Pyala)$_2^+$ are given in Figure 6. The similarity of the curves for the trans-carboxylate isomers is evident. The same structural assignment for the two isomers of Cr($\underline{L}$-His)$_2^+$ was obtained by this CD comparison as was made based on their visible spectra. Although the shape of the CD curves is very similar, the spectrum of trans-carboxylate Cr($\underline{D}$-Pyala)$_2^+$ is shifted to longer wavelengths than that of trans-carboxylate Cr($\underline{L}$-His)$_2^+$. This can be explained by noting the higher position of imidazole as compared to pyridine in the spectrochemical series.[15]

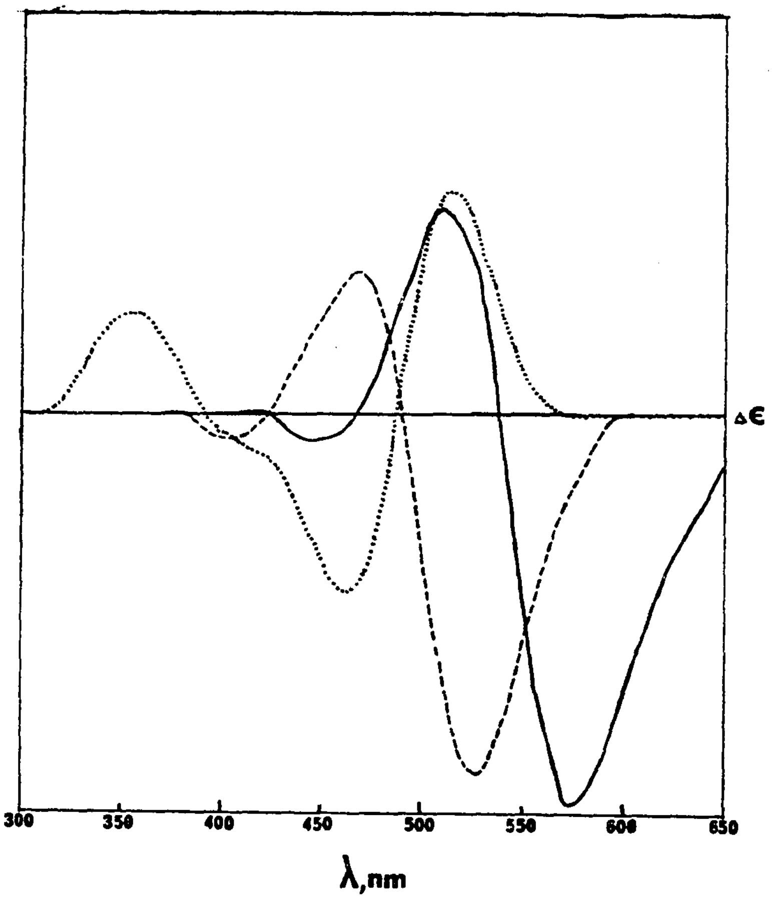


Figure 6. The circular dichroism spectrum of trans-carboxylate Cr(D-Pyala)$_2^+$ ion (——) in aqueous solution, the inverse of the circular dichroism spectra of trans-carboxylate Cr(L-His)$_2^+$ ion (---) and trans-imidazole Cr(L-His)$_2^+$ ion (•••) in aqueous solution

CONCLUSION

Previously, we isolated and identified the trans-carboxylate isomer of $Co(\underline{D}\text{-}Pyala)_2^+$. Since this complex did not isomerize in the presence of charcoal at 80°C to either the trans-amino or trans-pyridyl structure, the trans-carboxylate configuration was presumed to be the most stable isomer.[2] The present study supports this conclusion, since trans-amino $Co(\underline{D}\text{-}Pyala)_2^+$ isomerizes to the trans-carboxylate structure when left standing in water at room temperature for three weeks. Heating the trans-amino isomer at 80°C for 12 hours in the presence of activated charcoal gave a mixture of trans-carboxylate to trans-amino in a ratio of 14 to 1. In the trans-carboxylate structure (Figure 1a), the amino nitrogen atom occupies a position trans to the pyridine nitrogen atom. In the trans-amino structure (Figure 1b), the amino nitrogen atoms are, of course, mutually trans, and in the trans-pyridyl structure (Figure 1c), the pyridine nitrogens occupy trans positions. The percentage of each isomer present in the reaction solution (trans-carboxylate > trans-amino > trans-pyridyl), and the isomerization of the trans-amino complex to the trans-carboxylate isomer suggest several possible rules, governing the stability of these complexes, which may be applicable to other cobalt(III) systems. <u>First, the amino nitrogens avoid occupying trans positions</u>. This conclusion was also reached by Watabe _et al._, who found only small amounts of the trans N isomer in equilibrium mixtures of (_D_-aspartato)(_L_-2,4-diaminobutyrato)cobalt(III)[16] and (_L_-histidinato)(iminodiacetato)cobalt(III).[17] Also, only a small amount of the analogous trans N isomer of bis(_L_-aspartato)cobalt(III) anion could be prepared.[18] Only 6% of the trans N(amino) isomer of $Co(\underline{L}\text{-His})_2^+$ and none of this isomer of $Co(\underline{L}\text{-His})(\underline{D}\text{-His})^+$ could be isolated.[3] _Second, the pyridyl nitrogens avoid being trans to each other_. This generalization is not documented by other work because few complexes containing only two pyridine groups have been studied. A third possible rule which is suggested by the complexes in the present study and which we are investigating further is that the amino nitrogen prefers to occupy a position trans to the pyridine group.

In the reactions of cobalt(III) with _D_,_L_-PyalaH, there was a preference for the formation of the all-cis isomer. Small amounts of the trans-carboxylate and trans-amino isomers were also isolated, but none of the trans-pyridyl or all-trans complex was found. The ratio of racemic all-cis $Co(\underline{D}\text{-Pyala})(\underline{L}\text{-Pyala})^+$ to racemic trans-carboxylate was 2.6 to 1 for all of the different preparations used. Thus, the all-cis structure seems to be the most stable complex formed. There appears to be a decrease in steric interaction in the all-cis structure, compared to the trans-carboxylate structure, since the angle between the planes of the pyridine rings has increased from about 30° in trans-carboxylate to about 60° in all-cis. Thus, the repulsion between the pyridine groups is probably less in the all-cis complex than in the trans-carboxylate isomer.

According to the above generalizations, the absence of the all-trans complex (Figure 1e) would not be unexpected since the amino groups occupy positions trans to one another as do the pyridine groups. The absence of the trans-pyridyl isomer and the small amount of the trans-amino complex formed in the reactions are also in accord with the above rules.

It was reported earlier,[4] that trans-carboxylate $Cr(\underline{L}\text{-His})_2^+$ was unstable in aqueous solution and isomerized to the trans-imidazole isomer. Because of the similarity of $Pyala^-$ to histidinate, the $Cr(\underline{D}\text{-Pyala})_2^+$ complex might be expected to undergo isomerization similar to the $Cr(\underline{L}\text{-His})_2^+$ complexes. But, only trans-carboxylate $Cr(\underline{D}\text{-Pyala})_2^+$ was formed in the reaction solution (excluding $[Cr(\underline{D}\text{-Pyala})_3]\cdot H_2O$), and it was found not to isomerize even in the presence of activated charcoal. Thus, trans-carboxylate $Cr(\underline{D}\text{-Pyala})_2^+$ appears to be the most stable isomer.

The reasons for the stability of the trans-carboxylate $Cr(\underline{D}\text{-Pyala})_2^+$ structure may be analogous to those given above for the $Co(\underline{D}\text{-Pyala})_2^+$ complexes. Evidence for π bonding from chromium(III) to pyridine has been reported,[19] and may play a role in determining the preferred structure. The weak σ-donor donor ability and possible π-bonding of the pyridine may favor a strong σ-donor, such as the amino nitrogen, in a position trans to it. It may be noted that the imidazole group of histidine is a stronger σ-donor and a much weaker π-acceptor[15] than the pyridine group of D-Pyala$^-$. This may be the reason that the trans-imidazole structure seems to be the most stable configuration of $Cr(L\text{-}His)_2^+$ while the trans-carboxylate structure seems to be the most stable configuration of $Cr(D\text{-}Pyala)_2^+$.

REFERENCES

1. Rechani, P. R.; Nakon, R.; Angelici, R. J. Bioinorg. Chem. 1976, 5, 329.
2. Ebner, S. R.; Jacobson, R. A.; Angelici, R. J. Inorg. Chem. 1979, 18, 765.
3. Bagger, S.; Gibson, K.; Sorensen, C. S. Acta Chem. Scand. 1972, 26, 2503.
4. Hoggard, P. E.; Schmidtke, H. H. Proc. Int. Conf. Coord. Chem. 16th 1974, 1.26.
5. Bedell, S. A.; Rechani, P. R.; Angelici, R. J.; Nakon, R. Inorg. Chem. 1977, 16, 972.
6. Freeman, W. A.; Liu, C. F. Inorg. Chem. 1968, 7, 764.
7. Freeman, W. A.; Liu, C. F. Inorg. Chem. 1970, 9, 1191.
8. Mizuochi, H.; Urhara, A.; Kyuno, E.; Tsuchiya, R. Bull. Chem. Soc. Japan 1971, 44, 1555.
9. Vieles, P.; Bonniol, A. J. Chim. Phys. Physicochim. Biol. 1973, 70, 348.
10. Gillard, R. D.; Laurie, S. H.; Price, D. C.; Phipps, D. A.; Weick, C. F. J. Chem. Soc. Dalton Trans. 1974, 1385.
11. Oki, H. Bull. Chem. Soc. Japan 1977, 50, 680.
12. Oki, H.; Takashi, Y. Bull. Chem. Soc. Japan 1977, 50, 2288.
13. Bhaqwat, V.; Sharma, V.; Poonie, N. S. Ind. J. Chem. 1977, 15A, 46.
14. Garner, C. S.; House, D. A. Trans. Met. Chem. 1970, 6, 59.
15. Sundberg, R. J.; Martin, R. B. Chem. Rev. 1974, 74, 471.
16. Watabe, M.; Kawaai, S.; Yoshikawa, S. Bull. Chem. Soc. Japan 1976, 49, 1845.

17. Watabe, M.; Zama, M.; Yoshikawa, S. *Bull. Chem. Soc. Japan* **1978**, 51, 1354.

18. Hosaka, K.; Nishikawa, H.; Shibata, M. *Bull. Chem. Soc. Japan* **1969**, 42, 277.

19. Glerup, J.; Monsted, O.; Schaffer, C. E. *Inorg. Chem.* **1976**, 15, 1399.

SECTION III. PREPARATION AND SPECTRAL CHARACTERIZATION OF SOME MIXED LIGAND COBALT(III) COMPLEXES OF THE FORM [Co(L-Pyala)(A)], A = L-HISTIDINATE, L- OR D-ASPARTATE, OR IMINODIACETATE

INTRODUCTION

The preparation and characterization of the most stable cobalt(III) complexes containing the optically active tridentate ligand β-(2-pyridyl)-α-alanine, $^{+}H_3NCH(CH_2C_5H_4N)CO_2^-$, (PyalaH), have been reported.[1,2] The most stable isomers were found to be all-cis Co(D-Pyala)(L-Pyala)$^+$ and trans-carboxylate Co(D-Pyala)$_2^+$. The absence or instability of the other possible isomers suggested several rules which may apply to other cobalt(III) complexes. First, amino nitrogens avoid occupying trans positions. Second, pyridine groups also avoid being trans to each other. In addition, there was evidence to suggest that the most favorable position for the amino nitrogen atom was trans to a pyridine donor. These observations could not be completely rationalized by considering ligand steric interactions, which suggested that electronic factors, such as σ donor and π acceptor abilities, may play important roles in determining the most stable isomer of these cobalt(III) complexes.

We have now prepared and characterized a number of mixed ligand complexes of the type Co(L-Pyala)(A), where A = L-histidinate, L- or D-aspartate or iminodiacetate, in order to determine their preferred geometries and to understand the factors which contribute to these preferences.

The complexes were identified by their visible, circular dichroism and ^{1}H NMR spectra.

EXPERIMENTAL SECTION

Materials. L-histidine, L- and D-aspartic acid, and iminodiacetic acid were purchased from Aldrich Chemical Company. Racemic β-(2-pyridyl)-α-alanine (PyalaH) was prepared and resolved as described previously.[3]

Isomers of [Co(L-Pyala)(L-His)]NO_3. To a hot solution (ca. 60°C) containing L-PyalaH (0.5 g, 3.0 mmol), L-histidine (0.47 g, 3.0 mmol) and NaOH (0.24 g, 6.0 mmol) in 15 ml of water, $Co(NO_3)_2 \cdot 6H_2O$ (0.87 g, 3.0 mmol) was added. After mixing for 15 min, PbO_2 (0.36 g, 1.5 mmol) was added and the stirring and heating continued for 1 hr. The solution was filtered, cooled to room temperature and loaded on a column (2.4 x 80 cm, 350 ml) of Dowex 50W-X8 resin which was in the sodium form. Any uncharged or anionic species produced in the reaction were washed from the column with 250 ml of water. Separation of the Co(III) complexes was achieved by eluting with 0.05 M $NaNO_3$ at a rate of 1 drop/4 sec. Eight colored bands formed, three red-violet, two red, and three orange in order of elution from the column. The first red-violet band was eluted after twelve days, and the last orange band, on the forty-second day. Each band was evaporated to 20 ml and a layer (100 ml) of absolute ethanol was added. As the two layers diffused together, $NaNO_3$ precipitated. The solution was filtered, evaporated to

5 ml and another layer (20 ml) of absolute ethanol added. More $NaNO_3$ precipitated from the solution as the layers mixed. The solution was filtered and evaporated to dryness under reduced pressure to give a solid. This solid was dissolved in D_2O and the ^1H NMR taken. Those spectra which contained either pyridine or imidazole protons in the aromatic region, but not both, were identified by matching their ^1H NMR, visible and circular dichroism spectra with those reported for the isomers of $Co(\underline{D}\text{-Pyala})_2^+$[1,2] and $Co(\underline{L}\text{-His})_2^+$.[4] In this way the following assignments were made (% yield based on Co^{II} starting material in parentheses): Band 1, trans-carboxylate $Co(\underline{L}\text{-His})_2^+$ (8.5); Band 3, trans-carboxylate $Co(\underline{L}\text{-Pyala})_2^+$ (23.7); Band 4, trans-imidazole $Co(\underline{L}\text{-His})_2^+$ (26.0); Band 6, trans-amino $Co(\underline{L}\text{-His})_2^+$ (4.3); Band 8, trans-amino $Co(\underline{L}\text{-Pyala})_2^+$ (3.0).

Two of the bands (2,5) which showed peaks for both pyridine and imidazole protons in their ^1H NMR spectra were crystallized from 1 ml of water to which a layer of 9 ml of ethanol had been added. These were identified as I (band 2, yield 19.5%) and III (band 5, yield 3.5%). Complex II (band 7) could not be crystallized. Anal. calcd for $[Co(C_8H_9N_2O_2)(C_6H_8N_3O_2)]NO_3\cdot H_2O\cdot 1/4C_2H_5OH$: C, 37.07; H, 4.40; N, 17.89. Found (I): C, 36.91; H, 4.34; N, 17.82. Anal. calcd for $[Co(C_8H_9N_2O_2)(C_6H_8N_3O_2)]NO_3\cdot 2H_2O$: C, 35.31; H, 4.44; N, 17.64. Found (III): C, 35.49; H, 4.01; N, 17.57.

Isomers of [Co(L-Pyala)(L-Asp)]. The mixture of isomers was obtained by a procedure similar to that described above, using L-aspartic acid instead of L-histidine. A column (1.8 x 70 cm, 175 ml) of Dowex 50W-X8 resin which was in the sodium form was used to separate the isomers. Three bands were eluted with water, while a fourth, consisting of the isomers of $Co(L\text{-}Pyala)_2^+$, stuck to the top of the column. The first band contained a mixture of the anionic bis-aspartato cobalt(III) complexes, $Co(L\text{-}Asp)_2^-$.[5] The second (IV) and third (VI) bands which were purple and red in color, proved to be two of the isomers of [Co(L-Pyala)(L-Asp)]. These bands were each separately evaporated to 2 ml under reduced pressure and a layer (10 ml) of absolute ethanol was added. As the two layers diffused together, crystals were formed. Anal. calcd for $[Co(C_8H_9N_2O_2)(C_4H_5NO_4]\cdot H_2O$: C, 38.62; H, 4.32; N, 11.26. Found (IV): C, 38.59; H, 4.83; N, 11.11. Anal. calcd for $[Co(C_8H_9N_2O_2)(C_4H_5NO_4)]\cdot 1\frac{1}{2}H_2O$: C, 37.71; H, 4.48; N, 10.99. Found (VI): C, 37.85; H, 4.57; N, 11.24.

Isomers of [Co(L-Pyala)(D-Asp)]. These isomers were obtained by a method similar to that described above. Of the three possible isomers only two were isolated. The meridional isomer (VII) was eluted first from the column followed by the facial isomer (IX). Anal. calcd for $[Co(C_8H_9N_2O_2)(C_4H_5NO_4)]\cdot H_2O\cdot \frac{1}{4}C_2H_5OH$: C, 39.02; H, 4.59;

N, 10.92. Found (VII): C, 39.20; H, 4.89; N, 10.93. Anal. calcd for $[Co(C_8H_9N_2O_2)(C_4H_5NO_4)]\cdot H_2O$: C, 38.62; N, 4.32; N, 11.26. Found (IX): C, 38.44; H, 4.61; N, 11.11.

Isomers of [Co(L-Pyala)(IMDA)]. The same procedure was used as described above. Only one of the three possible isomers was separated and crystallized (X). One of the two meridional isomers (XI) and the facial (XII) isomer were not obtained. Anal. calcd for $[Co(C_8H_9N_2O_2)(C_4H_5NO_4)]\cdot \frac{1}{2}H_2O$: C, 39.58; H, 4.15; N, 11.54. Found (X): C, 39.83; H, 4.25; N, 11.64.

Alternate methods of preparation using either $[Co(NH_3)_4CO_3]NO_3$, $[Co(NH_3)_6](NO_3)_3$ or $Na_3[Co(CO_3)_3]\cdot 3H_2O$ with L-PyalaH and IMDA or L- or D-$AspH_2$ as starting materials were performed as described previously.[1] The results are listed in Table I. Other products that also formed in these reactions included the isomers of Co(L-Pyala)$_2^+$, Co(L-Asp)$_2^-$, Co(D-Asp)$_2^-$ and Co(IMDA)$_2^-$.

Spectra. Visible and circular dichroism spectra were measured with a Jasco ORD/UV/CD-5 spectrophotometer in aqueous solution. The ^1H NMR spectra were recorded on a Varian Associates HA-100 spectrometer in 99.7% deuterium oxide *vs* *tert*-butyl alcohol ($\delta = 1.23$ ppm) as an internal standard.

Table I. Product yields in various preparations of Co(L-Pyala)(A) mixed complexes

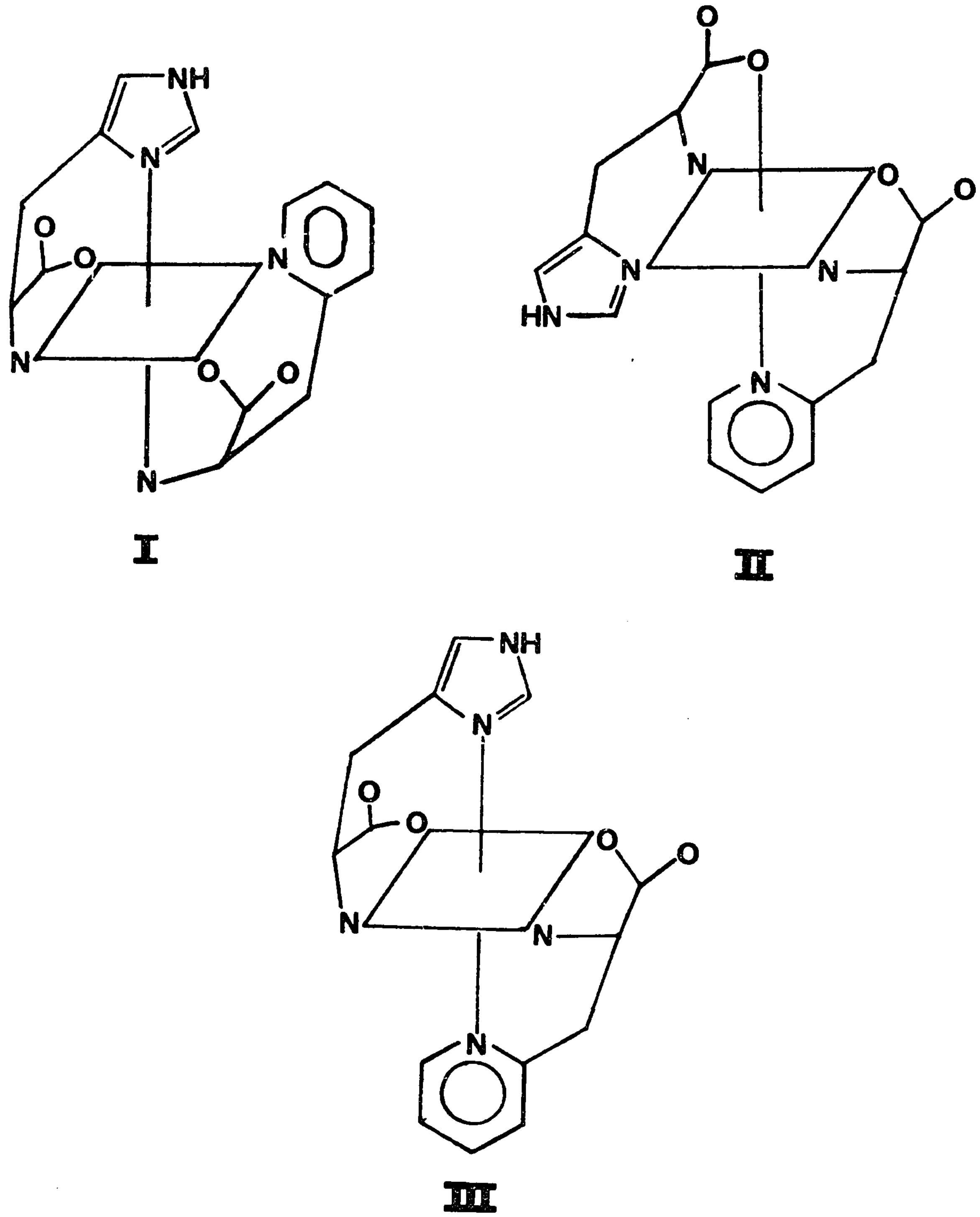
Ligand	Product	Starting Material			
		$Co(NO_3)_2 \cdot 6H_2O$	$[Co(NH_3)_4CO_3]NO_3$	$[Co(NH_3)_6](NO_3)_3$	$Na_3[Co(CO_3)_3] \cdot 3H_2O$
L-Aspartic Acid	IV	21	21	26	22
	V	N.O.[a]	N.O.	N.O.	N.O.
	VI	24	N.O.	N.O.	2
D-Aspartic Acid	VII	19	21	28	26
	VIII	N.O.	N.O.	N.O.	N.O.
	IX	40	N.O.	12	3
Iminodiacetic Acid	X	47	62	36	46
	XI	N.O.	N.O.	N.O.	N.O.
	XII	N.O.	N.O.	N.O.	N.O.

[a] Not observed.

RESULTS AND DISCUSSION

Isomers of [Co(L-Pyala)(L-His)]NO_3. The three isomers of Co(L-Pyala)(L-His)$^+$ are shown in Figure 1. All three of these complexes were separated by column chromatography from the analogous isomers of Co(L-Pyala)$_2^+$ and Co(L-His)$_2^+$. Only structures I and III could be obtained in crystalline form. The yield of each complex based on the number of moles of Co(II) starting material was: I, 19.5%; II, unknown; III, 3.5%. Of the nine structures that may form in the reaction mixture (three isomers for each of the following complexes: Co(L-Pyala)$_2^+$, Co(L-Pyala)(L-His)$^+$, and Co(L-His)$_2^+$) only one, trans-pyridyl Co(L-Pyala)$_2^+$, was not obtained. Previous attempts[1,2] to prepare this complex were also unsuccessful.

Structural assignments of the isomers of Co(L-Pyala)(L-His)$^+$ were based on the similarity of their visible and circular dichroism spectra to those of Co(L-Pyala)$_2^+$ and Co(L-His)$_2^+$. The visible spectra (Figure 2) are similar for analogous isomers with the extinction coefficients increasing within each series in the order Co(L-His)$_2^+$ < Co(L-Pyala)(L-His)$^+$ < Co(L-Pyala)$_2^+$. The band that appears at longer wavelength is not shifted by changing the ligand; however, the band in the high energy region experiences a shift of about 10 nm when an imidazole nitrogen is replaced by a pyridine nitrogen donor in the coordination sphere of the



I

II

III

Figure 1. Isomers of Co(L-Pyala)(L-His)$^+$: I, trans-carboxylate; II, trans-amino; III, trans-rings

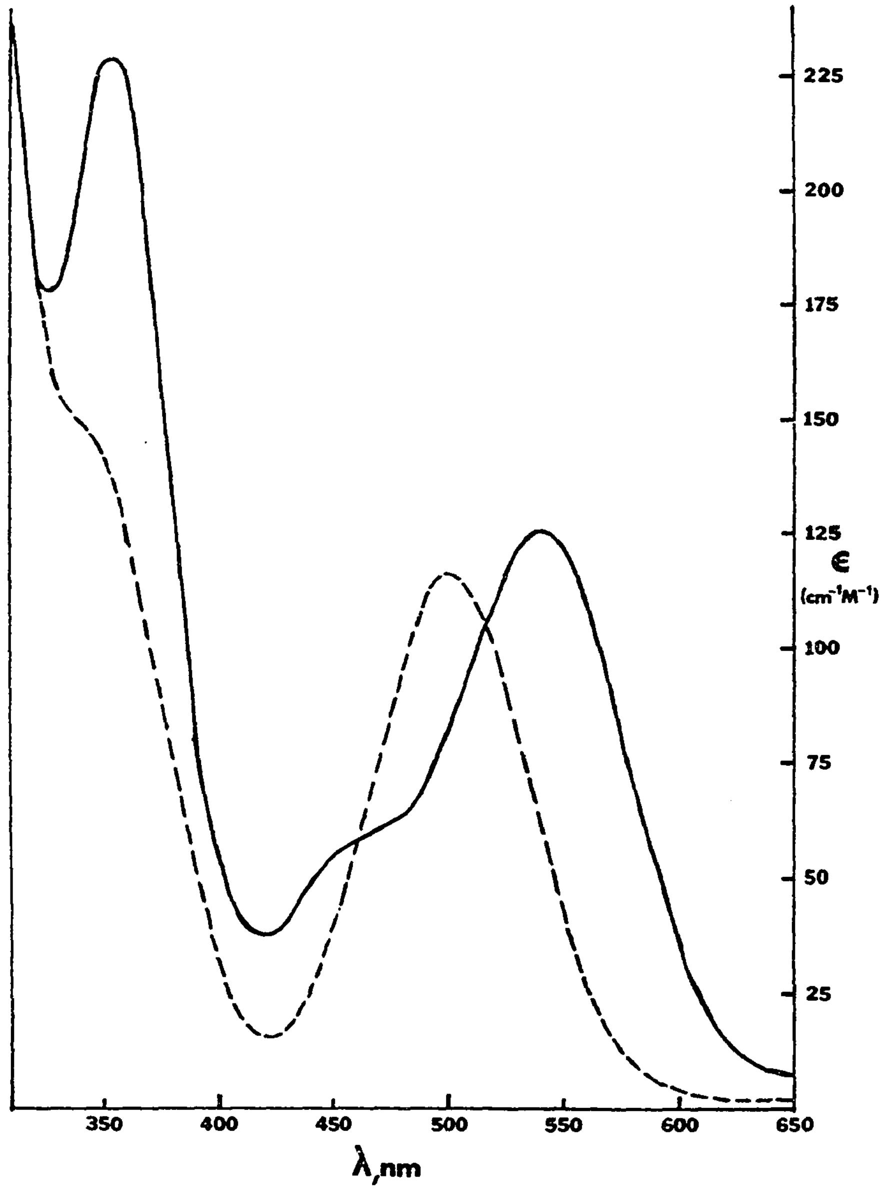


Figure 2. The visible spectra of I (——) and III (---)

cobalt(III), (trans-carboxylate isomers: Co(L-His)$_2^+$, 344 nm; Co(L-Pyala)(L-His)$^+$, 354 nm; Co(L-Pyala)$_2^+$, 364 nm).

The circular dichroism spectrum of I (Figure 3), is similar to those of the trans-carboxylate isomers of Co(L-Pyala)$_2^+$ [1] and Co(L-His)$_2^+$.[4] For these complexes, $\Delta\varepsilon$ increases in the same order as was observed for the extinction coefficients in the visible spectra. There is a difference, however, in the CD spectrum of III compared to that observed for trans-imidazole Co(L-His)$_2^+$. A positive absorption appears at 538 nm followed by a negative peak at 478 nm for III, whereas trans-imidazole Co(L-His)$_2^+$ shows a negative band at 525 nm and a positive band at 475 nm. This change in the CD spectrum may be due to the added asymmetry about the cobalt center caused by the substitution of a pyridine for an imidazole group. The difference in donor ability of these two nitrogen atoms (the difference in log K_f for several transition metal ions is 1)[6] as well as the lesser strain in the amino-pyridine chelate ring may account for these differences.

Interpretation of the ^{1}H NMR spectra of the Co(L-Pyala)(L-His)$^+$ complexes is difficult because of the large degree of overlap between the protons of each ligand. Structure I shows a number of complex patterns at (number of H's in parentheses): 3.48-3.64 (1), 3.84-4.04 (5), 7.27-7.67 (4) and 7.96-8.16 ppm (2). The imidazole protons,

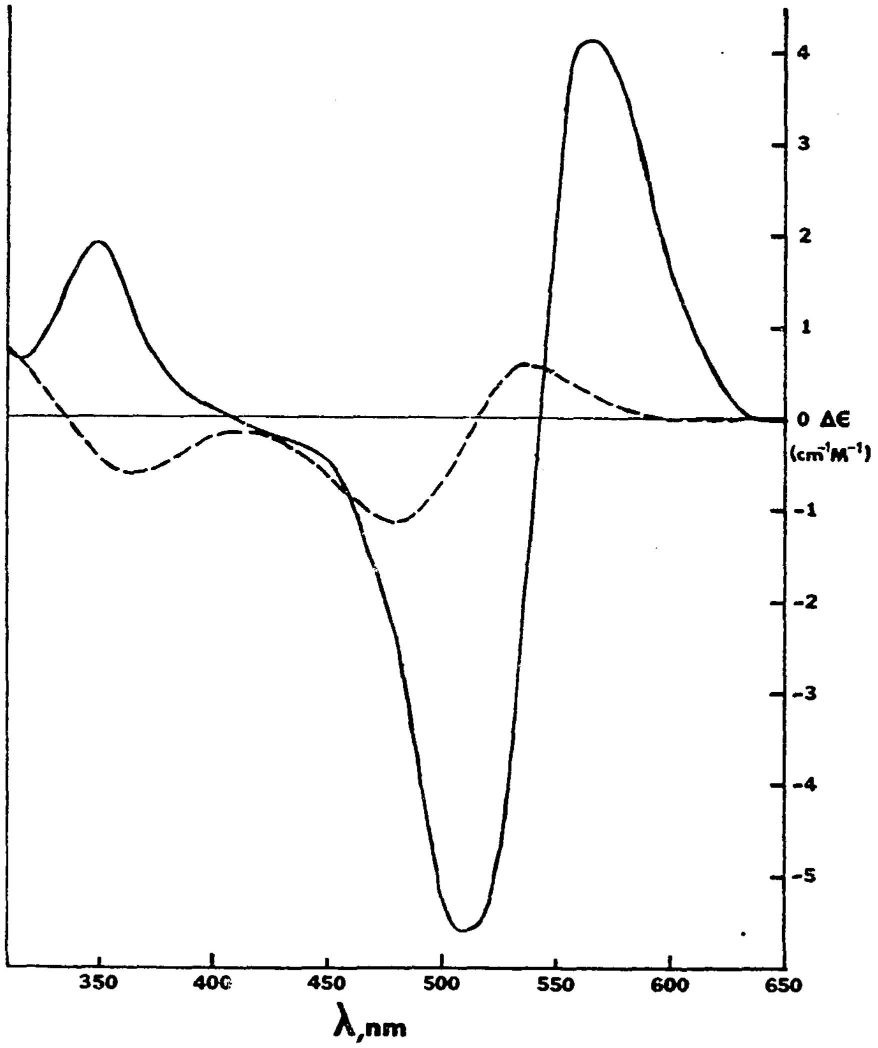


Figure 3. The circular dichroism of I (——) and III (---)

which can be distinguished from the pyridine peaks because their absorptions are sharper ($J \sim 1.5$ Hz), occur at 7.30 and 7.50 ppm. The analogous protons occur at 7.41 and 7.82 ppm in trans-carboxylate Co(L-His)$_2^+$, which has a structure similar to I. From an inspection of molecular models, the shift from 7.82 to 7.50 ppm in the proton on the carbon atom adjacent to the coordinated nitrogen atom of the imidazole ring may be rationalized. Because of the larger size of the pyridine ring, the imidazole proton is thrust deeper into the shielding region of the pyridine ring. The ethanol reported in the analysis of trans-carboxylate [Co(L-Pyala)(L-His)]$NO_3 \cdot H_2O \cdot \frac{1}{4} C_2H_5OH$ was observed as a triplet at 1.16 ppm, with the quartet which should be at 3.60 ppm overlapping with the ligand protons.

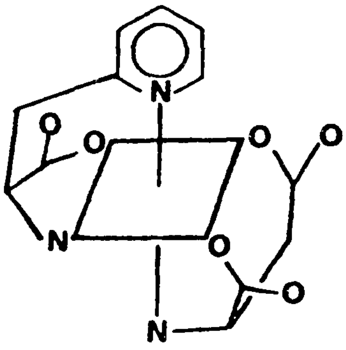
Structure II has complex patterns with much overlap between the protons of the ligands at: 3.38-3.78 (2), 3.89-4.11 (2), 4.18-4.36 (2), 7.13-7.34 (2), 7.38-7.57 (1), 7.74-8.00 ppm (3). The imidazole protons fall within these complex patterns at 7.28 and 7.91 ppm. These protons occur at 7.26 and 7.93 ppm in trans-amino Co(L-His)$_2^+$.

Although the ^{1}H NMR spectrum of III is simpler in the aromatic region, the methine and methylene protons of the L-histidinate and L-Pyala$^-$ ligands overlap extensively. If small couplings ($J < 2$ Hz) are ignored, the spectrum of III is: 3.41, singlet (2); 3.84, complex (4); 7.23, singlet (1);

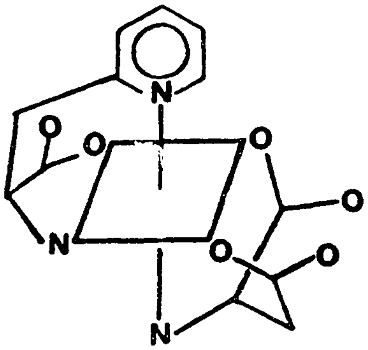
7.62, triplet (2); 7.86, singlet (1); 7.89, triplet (1); and 8.41 ppm, doublet (1). The absorptions at 7.23 and 7.86 ppm are assigned to the imidazole protons. The values reported[4] for the analogous protons in trans-imidazole $Co(L\text{-}His)_2^+$ were 7.31 and 7.93 ppm.

Isomers of [Co(L-Pyala)(L-Asp)] and [Co(L-Pyala)(D-Asp)]. The possible isomers of [Co(L-Pyala)(L-Asp)] and [Co(L-Pyala)(D-Asp)] are shown in Figure 4. Both series of mixed complexes are composed of two meridional and one facial arrangement of nitrogen donor atoms about the cobalt(III) center. The isomers are denoted by considering the 5-membered glycinato N and O atoms. The two mer isomers for the L-series are denoted by trans O_5 cis N_5 (IV) and cis O_5 trans N_5 (V). Similarly, the three isomers of [Co(L-Pyala)(D-Asp)] are designated by mer-cis O_5 cis N_5 (VII), trans O_5 trans N_5 (VIII) and fac (IX).

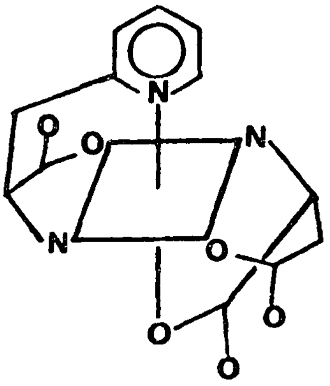
Figures 5 and 6 show the visible absorption spectra of the isolated complexes. These spectra may be compared to those for [Co(L-His)(L- or D-Asp)],[7] [Co(L-2,4-dba)(L- or D-Asp)][8] and [Co(L-orn)(L- or D-Asp)].[9] The isomers of [Co(L-Pyala)(L-Asp)], IV and VI, are assigned as trans O_5 cis N_5 and fac because of the similarity of their visible spectra to those of the analogous isomers of the complexes of L-Histidinato, L-2,4-diaminobutyrato and L-ornithine.



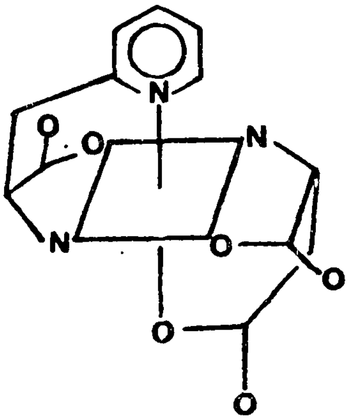
IV



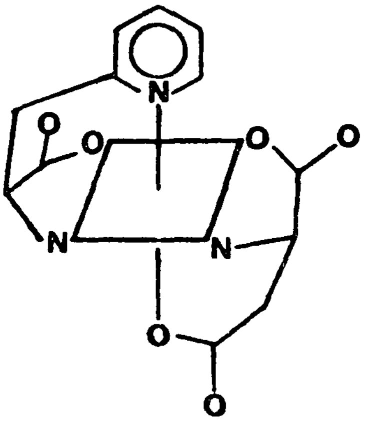
VII



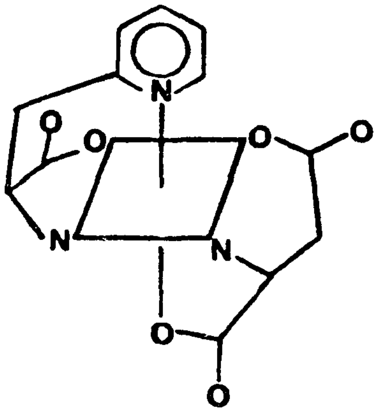
V



VIII



VI



IX

Figure 4. Isomers of [Co(L-Pyala)(L-Asp)]: IV, trans O_5 cis N_5; V, cis O_5 trans N_5; VI, L-fac. Isomers of [Co(L-Pyala)(D-Asp)]: VII, mer cis O_5 cis N_5; VIII, trans O_5 trans N_5; IX, D-fac

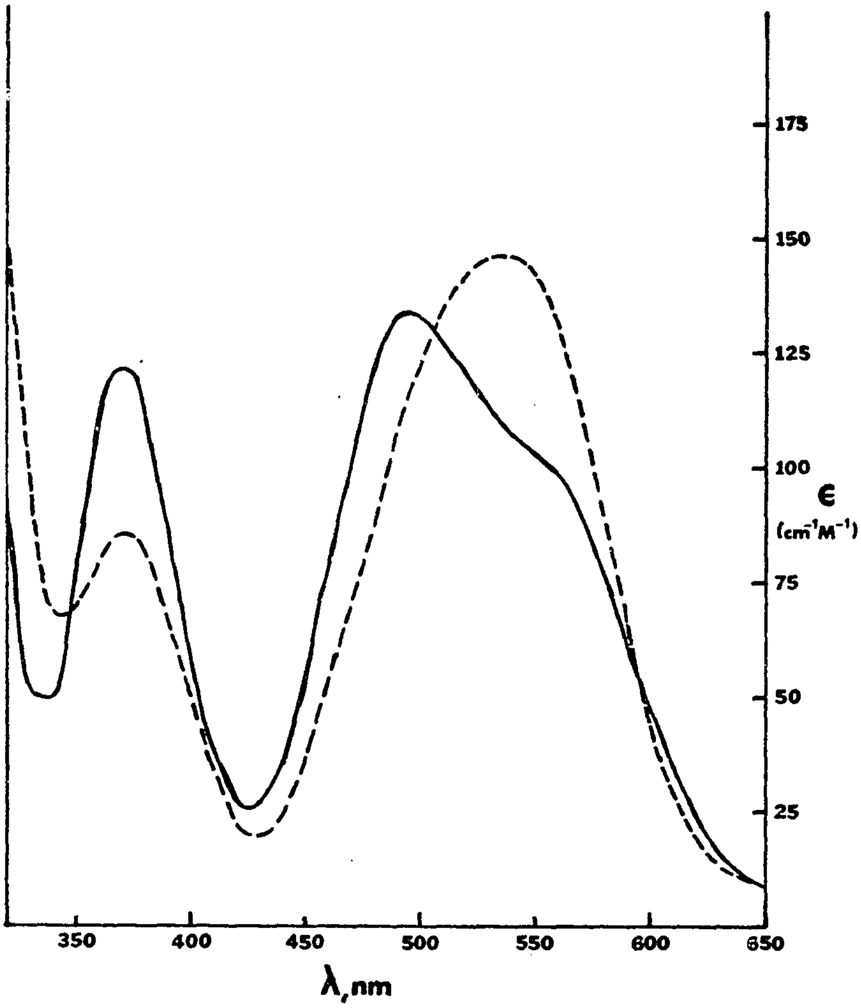


Figure 5. The visible spectra of IV (——) and VI (---)

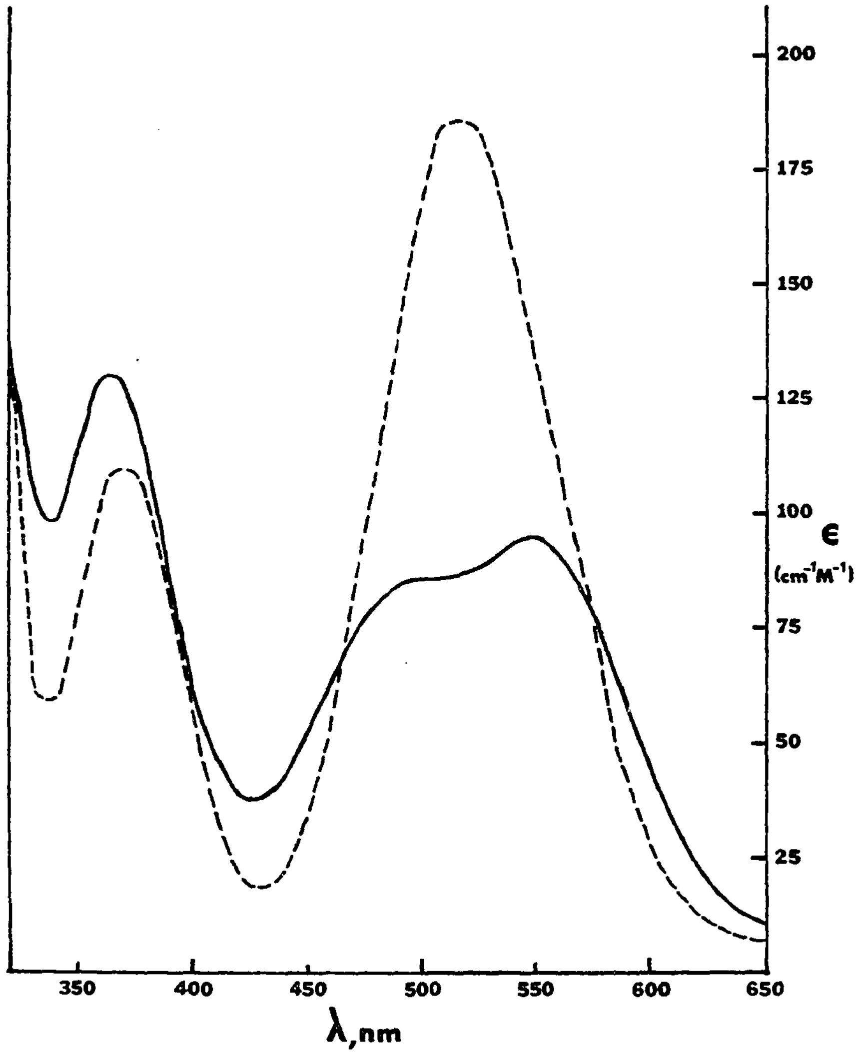


Figure 6. The visible spectra of VII (——) and IX (---)

Likewise, VII and IX, which are isomers of [Co(L-Pyala)(D-Asp)] are assigned as mer cis O_5 cis N_5 and fac.

Figures 7 and 8 show the CD spectra of IV, VI, VII and IX. The CD spectrum of IV is similar to the reported spectra for the trans O_5 cis N_5 isomers of [Co(L-His)(L-Asp)],[7] [Co(L-2,4-dba)(L-Asp)] [10] and [Co(L-orn)(L-Asp)].[9] Likewise, the CD spectrum of VI can be compared to that of the facial isomers of the cobalt(III) complexes of L-histidinato, L-2,4-diaminobutyrato and L-ornithine with L-aspartate. The two isomers of [Co(L-Pyala)(D-Asp)], VII and IX, can be assigned because of the similarity of their CD spectra to the mer cis O_5 cis N_5 and fac isomers of previously reported analogs containing L-histidinate,[7] L-ornithinate,[9] or L-2,4-diaminobutyrate.[11]

The coordination of L-Pyala$^-$, in place of L-His, L-2,4-dba and L-orn in the four complexes isolated, IV, VI, VII and XI, caused an increase in the magnitude of the CD peaks. A positive band also appeared at about 580 nm in the CD spectra of the two meridional isomers, IV and VII, which was not present in the L-His, L-2,4-dba, or L-orn complexes.

The general similarity of the CD spectra of IV to VII and VI to IX seems to indicate that the arrangement of the donor atoms about the cobalt(III) center makes the major contribution to the CD spectra of these complexes. The

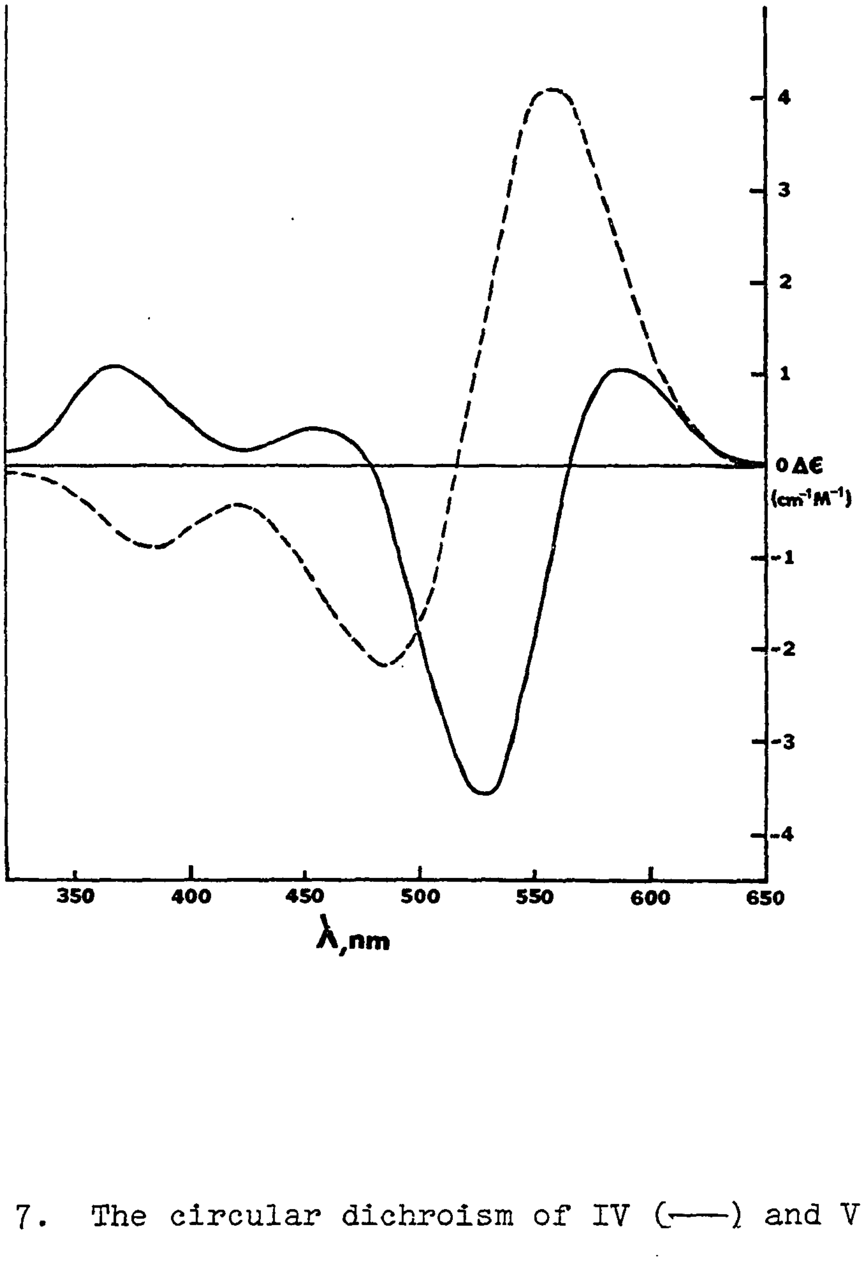


Figure 7. The circular dichroism of IV (——) and VI (---)

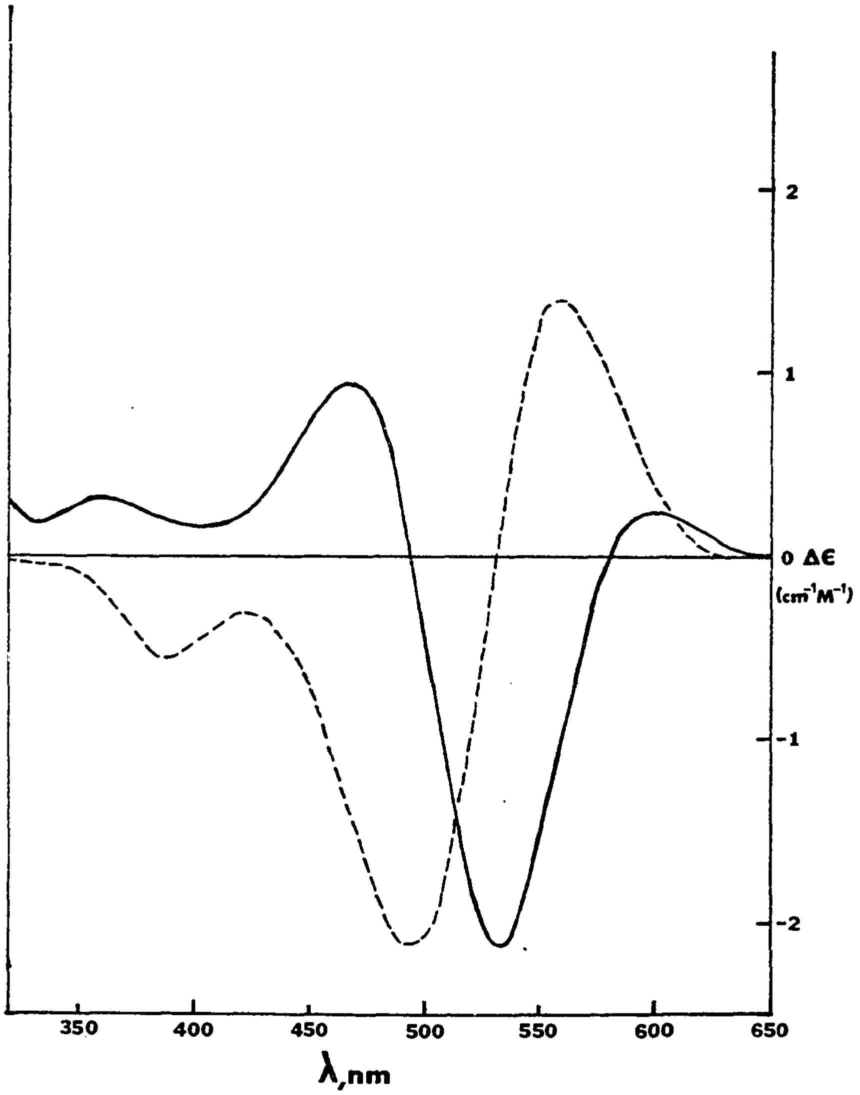


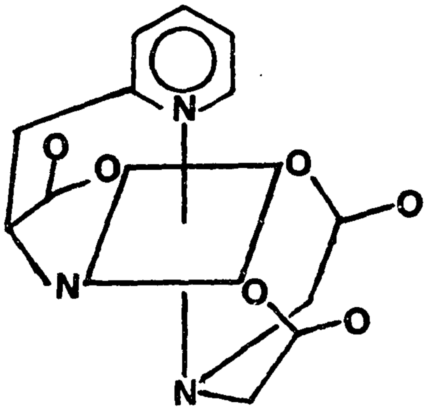
Figure 8. The circular dichroism of VII (——) and IX (---)

absolute configuration of the aspartate anion makes only a minor contribution.

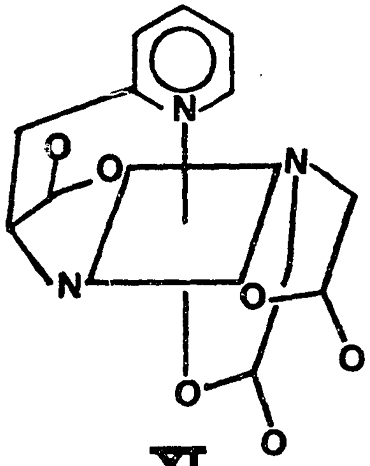
The ^{1}H NMR spectra of these isomers, IV, VI, VII and IX had overlapping complex patterns from 2.65-5.00 corresponding to the two methine and four methylene protons of the two ligands. The aromatic region was less complex and is given below (the patterns reported are without considering small couplings, $J < 2$Hz; t = triplet, d = doublet)
IV, 7.60 ppm, t and d (2); 8.07 ppm, t (1); 8.59 ppm, d (1);
VI, 7.44 ppm, t and d (2); 7.92 ppm, t (1); 8.18 ppm, d (1);
VII, 7.58 ppm, t and d (2); 8.05 ppm, t (1); 8.72 ppm, d (1);
IX, 7.40 ppm, t and d (2); 7.91 ppm, t (1); 8.19 ppm, d (1).
The ethanol which appeared in the analysis of VII was also detected in the ^{1}H NMR as a triplet at 1.16 ppm, and a quartet at 3.60 ppm.

Isomer of [Co(L-Pyala)(IMDA)]. Figure 9 shows the three possible isomers of [Co(L-Pyala)(IMDA)]. The two meridional isomers, X and XI, are denoted cis N and trans N by considering the position of the amino group of L-Pyala$^-$ in relation to the nitrogen atom of IMDA.

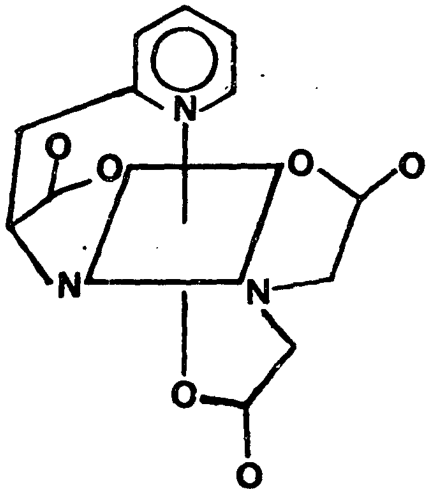
Figure 10 shows the visible and circular dichroism spectra of the sole isomer of [Co(L-Pyala)(IMDA)] that was isolated. The absorption spectrum is similar to that reported for the cis N isomer of [Co(L-His)(IMDA)].[12] Cis N [Co(L-His)(IMDA)] and X have a shoulder on the high energy



X



XI



XII

Figure 9. Isomers of [Co(L̲-Pyala)(IMDA)]: X, mer cis N; XI, trans N; XII, fac

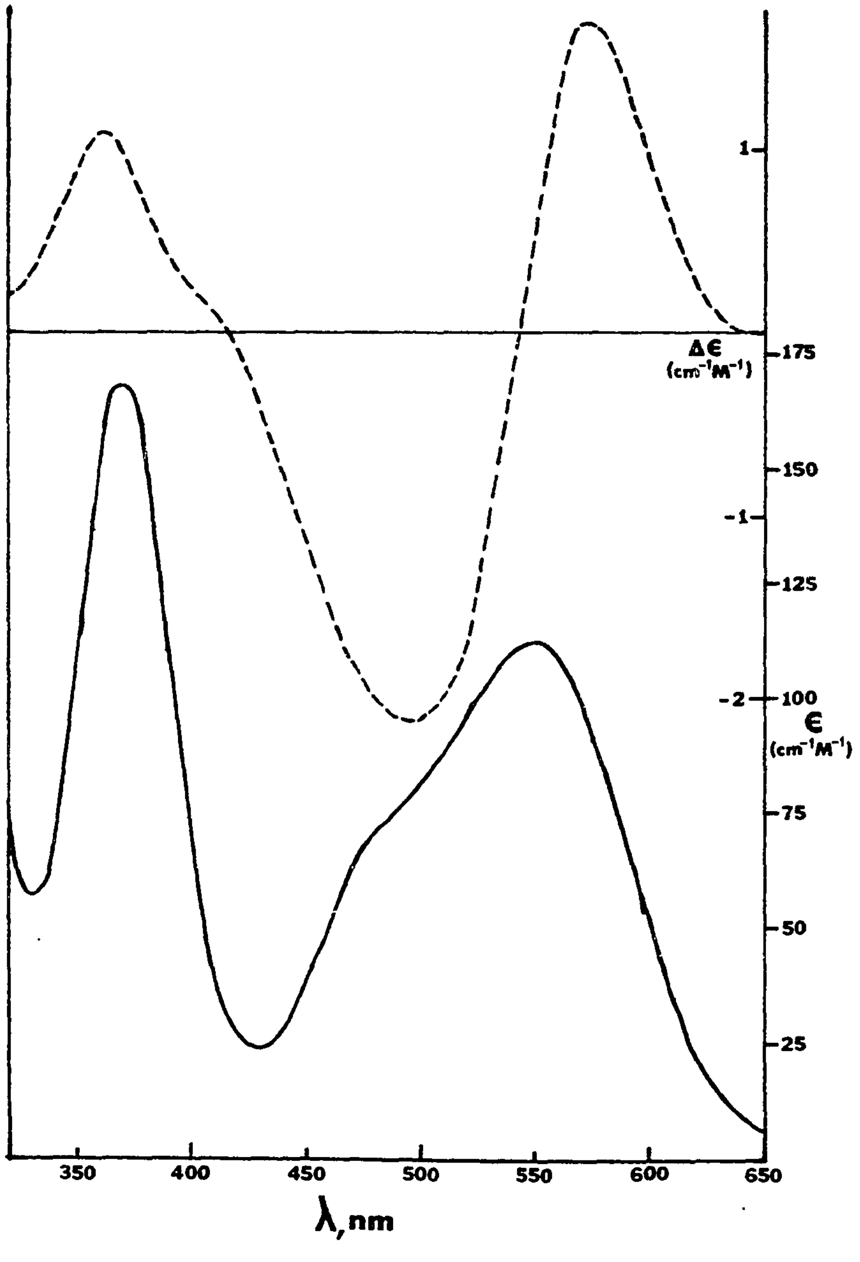


Figure 10. The visible (——) and circular dichroism (---) spectra of X

side of the first absorption band which is characteristic of this isomer. The CD spectrum also compares favorably with that of the cis N [Co(L-His)(IMDA)] complex. The coordination of the L-Pyala$^-$ ligand in place of L-His caused an increase in $\Delta\varepsilon$ as was noted for the isomers of [Co(L-Pyala)(L-Asp)] and [Co(L-Pyala)(D-Asp)]. It appears that this increase in $\Delta\varepsilon$ is due to the L-Pyala$^-$ ligand, since this is the only difference between the cis N isomers of [Co(L-Pyala)(IMDA)] and [Co(L-His)(IMDA)].

The ^{1}H NMR spectrum of cis N [Co(L-Pyala)(IMDA)] exhibited the following absorptions: 3.51 ppm, doublet (1); 3.57 ppm, doublet (1); 3.74 ppm, singlet (3); 4.23 ppm, doublet (1); 4.34 ppm, doublet (1); 7.55 ppm, doublet and triplet (2); 8.01, triplet (1); 8.92, doublet (1). The doublets, 3.51, 3.57, 4.23 and 4.34 ppm, were assigned to the four protons of the IMDA ligand. The two protons on each carbon were inequivalent and thus, split each other. The coupling constants, 17 Hz and 18 Hz, were within the normal range observed for two protons on the same carbon split by each other. The singlet at 3.74 ppm consisted of both the α and β protons of the L-Pyala$^-$ ligand; no splitting was observed because the chemical shifts of these three protons were the same, as was also found in trans-carboxylate $Co(D\text{-}Pyala)_2^+$.[1] The remaining peaks were assigned to the aromatic protons of the pyridine ring.

CONCLUSION

Previously, several rules governing the stability of cobalt(III) complexes such as those described in the Introduction, were proposed. These rules were: (1) amino groups prefer not to be trans to each other; (2) pyridine groups also prefer not to be trans to each other; and (3) amino groups prefer to occupy positions trans to pyridine groups. These rules may be applied to the results of the present study, with the exception of (2), which does not apply because no complexes containing more than one pyridine ring were investigated.

The major isomer of the mixed ligand complex Co(L-Pyala)(L-His)$^+$ was I. This structure has the amino group occupying the position trans to the pyridine group, which is in accordance with the above rules for the preferred isomer. Only low yields of II (which has trans amino groups) and III were observed.

The four reactions involving L-aspartic acid (Table I) produced two isomers. The major product in three of these reactions was IV. This arrangement of the donor atoms, with the amino and pyridine groups mutually trans, is in agreement with (1) and (3), given above. The other isomer isolated was VI, which follows rule (1) but not (3).

The reactions forming Co(L-Pyala)(D-Asp) gave product distributions similar to those observed for L-aspartic acid.

In three of the four reactions, the major isomer was VII. This structure has the amino group trans to the pyridine group, in accordance with (1) and (3). The other isomer isolated, IX, did not follow rule (3).

Only one isomer of Co(L-Pyala)(IMDA) was isolated. The structure of this isomer, X, is predicted to be the most stable by the rules presented above, since it has the amino and pyridine group occupying trans positions.

The results presented for the Co(III) mixed complexes of L-His, L- or D-Asp and IMDA with L-Pyala suggest that in general the major isomer formed is in agreement with the rules given in the Introduction. It seems that the isomer preferences observed must be due, at least in part, to electronic factors, such as σ donor and π acceptor donor atom properties.

The substitution of L-Pyala$^-$ for L-His, L-orn or L-2,4-dba caused an increase in ε and $\Delta\varepsilon$. This was also observed in the bis(pyridylalaninato)cobalt(III) complexes and seems to be characteristic of the Pyala$^-$ ligand. Reasons for the increase in ε and $\Delta\varepsilon$ are not clear, but the more rigid conformation imposed on the ligand by the planar pyridine ring and the weaker pyridine nitrogen donor may be important. Nevertheless, the shapes of the CD curves, *i.e.*, number and signs of the transitions, were similar enough to assign structures to the complexes isolated.

REFERENCES

1. Ebner, S. R.; Jacobson, R. A.; Angelici, R. J. Inorg. Chem. 1979, 18, 765.

2. Ebner, S. R.; Angelici, R. J. submitted for publication.

3. Bedell, S. A.; Rechani, P. R.; Angelici, R. J.; Nakon, R. Inorg. Chem. 1977, 16, 972.

4. Bagger, S.; Gibson, K.; Sorensen, C. S. Acta Chem. Scand. 1972, 26, 2503.

5. Legg, J. I.; Neal, J. A. Inorg. Chem. 1973, 12, 1805.

6. Sillen, L. G.; Martell, A. E. "Stability Constants of Metal-Ion Complexes", The Chemical Society, Burlington House: London, 1964, Special Publication No. 17 and 25.

7. Watabe, M.; Yano, H; Yoshikawa, S. Bull. Chem. Soc. Japan 1979, 52, 61.

8. Watabe, M.; Onuki, K.; Yoshikawa, S. Bull. Chem. Soc. Japan 1975, 48, 687.

9. Watabe, M.; Onuki, K.; Yoshikawa, S. Nippon Kagaku Kaishi 1977, 12, 1833.

10. Watabe, M.; Yoshikawa, S. Bull. Chem. Soc. Japan 1975, 48, 2185.

11. Watabe, M.; Kawaai, S.; Yoshikawa, S. Bull. Chem. Soc. Japan 1976, 49, 1845.

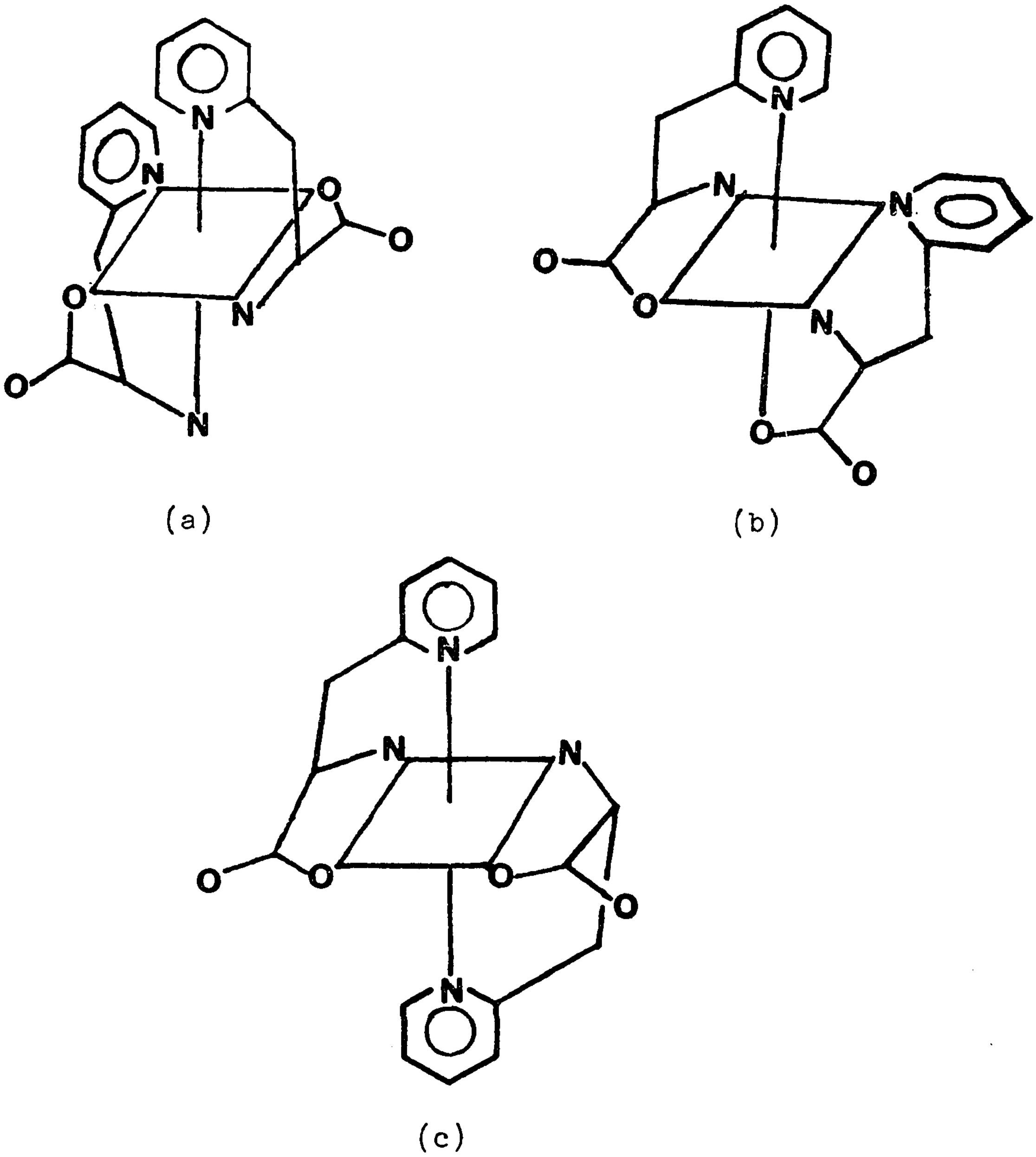
12. Watabe, M.; Zama, M.; Yoshikawa, S. Bull. Chem. Soc. Japan 1978, 51, 1354.

SECTION IV. PREPARATION, STRUCTURE AND SPECTRAL CHARACTERIZATION OF bis[D-β-(2-pyridyl)-α-alaninato]nickel(II), Ni(D-Pyala)$_2$

INTRODUCTION

Earlier work has shown that β-(2-pyridyl)-α-alanine, $^{+}H_3NCH(CH_2C_5H_4N)CO_2^{-}$, (PyalaH), binds to transition metal ions to form $M(Pyala)_2$ with a large degree of enantioselectivity.[1] For example, the formation constant for Ni(D-Pyala)(L-Pyala) is nine times larger than that for $Ni(D\text{-}Pyala)_2$. Our purpose was to examine this stereoselective effect in greater depth.

When only one enantiomer of the ligand is present, *e.g.*, D-Pyala^{-}, the resulting octahedral $M(D\text{-}Pyala)_2$ complexes may exist in any of three geometrical isomers (Figure 1). We have reported the preparation and structure of the most stable complex of cobalt(III), $Co(D\text{-}Pyala)_2^{+}$, which has the trans-carboxylate configuration (Figure 1a).[2] The cis arrangement of the pyridine rings was surprising since it was believed that sterically these groups should occupy trans positions. Indeed, the trans-imidazole was found to be the observed structure for the bis complexes of L-histidine with Co(II),[3] Ni(II)[4,5] and Co(III).[6] In the present study we extended our investigations to the labile Ni(II) complex in solution and in the crystalline state to further explore the factors which determine the most stable structures of the $M(Pyala)_2$ complexes.



(a)

(b)

(c)

Figure 1. The three possible isomers of Ni(D-Pyala)$_2$. These are (a) trans-carboxylate, (b) trans-amino and (c) trans-pyridyl

EXPERIMENTAL SECTION

Materials. Racemic β-(2-pyridyl)-α-alanine (PyalaH) was prepared and resolved as described previously.[7] Nickel carbonate was purchased from Allied Chemical.

Preparation of bis-[D-β-(2-pyridyl)-α-alaninato]-nickel(II) Dihydrate, $[Ni(D\text{-}Pyala)_2]\cdot 2H_2O$. To an aqueous solution of D-PyalaH (1.0 g, 6.1 mmol), powdered $NiCO_3$ (0.36 g, 3.0 mmol) was added, and the mixture was heated (60°C) and stirred for two hrs. The dark blue solution was allowed to cool to room temperature and the unreacted $NiCO_3$ was filtered from the liquid. The volume was reduced to about 3 ml under reduced pressure. Slow evaporation over phosphorus pentoxide in a desiccator yielded well-formed deep blue crystals suitable for X-ray analysis. More crystals were obtained by allowing a layer of ethanol to diffuse into the aqueous phase. The yield was 54%. Anal. calcd for $[Ni(C_8H_9N_2O_2)_2]\cdot 2H_2O$: C, 45.21; H, 5.22; N, 13.18. Found: C, 44.93; H, 5.37; N, 13.21.

Spectra. Infrared spectra were recorded on a KBr disk and on a D_2O solution of the complex using a Beckman IR 4250 spectrophotometer. The visible and circular dichroism spectra from 650 to 350 nm were recorded on aqueous solutions at room temperature using a Jasco ORD/UV/CD-5 spectrophotometer. At wavelengths longer than 650 nm, the visible spectrum was measured with the Cary Model 14 spectrophotometer.

Crystal Data. $[Ni(C_8H_9N_2O_2)_2]\cdot 2H_2O$, mol. wt. 425.08, monoclinic $P2_1$, a = 14.942(4), b = 12.091(2), c = 10.090(2) Å, β = 90.3(3)°, V = 1815.58 $Å^3$, P_c = 1.556 g/cm^3, Z = 4, μ = 11.1 cm^{-1} for Mo-K_α.

A crystal of the title compound of dimensions 0.2 x 0.2 x 0.3 mm was mounted on a glass fiber and subsequently placed on a goniometer head. From four preliminary ω-oscillation photographs at various χ and ϕ settings, 15 independent reflections were input to the automatic indexing program ALICE.[8]

The resulting reduced cell and reduced cell scalars indicated P_{2_1} (monoclinic) symmetry, which was confirmed by inspection of axial ω-oscillation photographs. The observed layer spacings on these photographs were equal within experimental error to those predicted for this cell by the indexing program. The lattice constants were obtained from a least squares refinement based on the precise $\pm 2\theta$ ($|2\theta| > 30°$) measurement of seventeen strong independent reflections. At 27°C using Mo-K_α (λ = 0.70954 Å), they are a = 14.942(4), b = 12.091(2), c = 10.090(2) Å and β = 90.3(3)°.

Collection and Reduction of X-ray Intensity Data. The data were collected at 27°C with graphite monochromated Mo-K_α radiation on an automated four circle diffractometer designed and built at Ames Laboratory and previously described by Rohrbaugh and Jacobson.[9] All data (7275 reflections) within a 2θ sphere of 50° ($\sin\theta/\lambda = 0.596$ Å^{-1}) in the $hk\ell$, $hk\bar{\ell}$, $h\bar{k}\bar{\ell}$, $\bar{h}\bar{k}\ell$ were measured using an ω-stepscan technique.

As a general check on electronic and crystal stability, the intensities of three standard reflections were measured every seventy-five reflections. These standard reflections were not observed to have varied significantly throughout the data collection period (∿6 days). Examination of data revealed systematic absences of 0k0 reflections for $k = 2n + 1$, thus uniquely defining the space group $P2_1$.

The intensity data were corrected for Lorentz and polarization effects; no absorption correction was made since the transmission factors were 0.76 ± 0.04. The estimated error in each intensity was calculated by $\sigma_I^2 = C_T + K_tC_B + (0.03\ C_T)^2 + (0.03\ C_B)^2$ where C_T, K_t and C_B represent the total count, a counting time factor and background count, respectively, and the factor 0.03 represents an estimate of nonstatistical errors. The estimated deviations in the structure factors were calculated by the finite difference method.[10] Equivalent data were averaged and yielded 5957 reflections with $I_o > 3\sigma(I)$ which were retained for structural solution and refinement.

Solution and Refinement of the Structure. The positions of the two nickel atoms in the asymmetric unit were obtained from an analysis of a standard sharpened three-dimensional Patterson function. The remaining nonhydrogen atoms were found by successive structure factor and electron density map calculations.[11] The atomic positional parameters were refined using anisotropic thermal parameters by a block matrix least squares procedure,[12] with final refinement using a full matrix least squares procedure, and minimizing the function $\sum\omega(|F_o|-|F_c|)^2$, where $\omega = 1/\sigma(F)^2$ to a conventional discrepancy factor of $R = \sum||F_o|-|F_c||/\sum|F_o| = 0.084$. The scattering factors were those of Hanson *et al.*,[13] modified for the real and imaginary parts of anomalous dispersion.[14]

The solution and refinement of the structure were completed without attempting to refine the absolute configuration of the molecule. The final structure of the optically active molecule was based on the known[1] configuration of *D*-Pyala$^-$.

The final positional and thermal parameters for one of the two molecules in the asymmetric unit are listed in Table I. The standard deviations were calculated from the inverse matrix of the final least squares cycle.

Table I. Final atomic parameters

(a) Final positional parameters and their estimated standard deviations (in parentheses)[a]

Atom	x	y	z
Ni[b]	58.0 (6)	0.0	2142.6 (8)
O1	-656 (5)	-882 (5)	747 (7)
O2	-1046 (8)	-809 (7)	-1363 (9)
O3	867 (4)	-1345 (4)	2494 (5)
O4	1189 (5)	-2575 (7)	4051 (6)
N1	799 (6)	343 (5)	435 (7)
N2	-750 (5)	1398 (5)	1772 (6)
N3	-680 (5)	-793 (7)	3615 (9)
N4	806 (4)	863 (7)	3572 (7)
C1	-576 (9)	-505 (7)	-433 (11)
C2	81 (9)	377 (8)	-618 (9)
C3	-308 (10)	1539 (8)	-596 (8)
C4	-904 (7)	1827 (6)	570 (8)
C5	-1537 (8)	2678 (7)	407 (10)
C6	-2056 (7)	3039 (7)	1475 (10)
C7	-1889 (6)	2605 (9)	2684 (11)
C8	-1221 (6)	1747 (8)	2828 (9)
C9	735 (6)	-1770 (8)	3593 (8)
C10	-1 (7)	-1278 (10)	4445 (11)
C11	391 (10)	-433 (12)	5408 (9)
C12	906 (6)	488 (11)	4846 (10)
C13	1531 (11)	1038 (16)	5686 (14)

---

[a] The positional parameters are presented in fractional unit cell coordinates (x 10^4).

[b] The y positional parameter was not varied.

Table I. (Continued)

Atom	x	y	z
C14	2036 (9)	1936 (19)	5199 (29)
C15	1887 (7)	2297 (13)	3920 (20)
C16	1263 (6)	1735 (10)	3106 (14)
Ni2	4950.1 (7)	7270.6 (9)	7134.2 (9)
O21	3802 (6)	9840 (6)	9048 (6)
O22	5681 (5)	8145 (5)	5731 (6)
O23	4143 (5)	8624 (4)	7482 (6)
O24	6123 (7)	8047 (6)	3588 (7)
N21	4194 (7)	6920 (6)	5463 (8)
N22	5761 (5)	5881 (5)	6754 (6)
N23	4197 (5)	6410 (6)	8605 (8)
N24	5706 (5)	8081 (7)	8587 (7)
C21	5908 (7)	5419 (6)	5558 (8)
C22	6555 (6)	4582 (6)	5412 (9)
C23	7025 (6)	4209 (8)	6449 (10)
C24	6873 (6)	4684 (9)	7675 (10)
C25	6240 (6)	5511 (8)	7809 (9)
C26	5360 (9)	5732 (7)	4372 (10)
C27	4920 (10)	6883 (7)	4381 (9)
C28	5604 (9)	7772 (8)	4565 (9)
C29	3744 (7)	5506 (8)	8134 (13)
C210	3102 (8)	4975 (10)	8887 (17)
C211	2960 (8)	5339 (11)	10185 (21)
C212	3471 (8)	6254 (10)	10719 (12)
C213	4092 (6)	6756 (9)	9851 (9)
C214	4269 (8)	9032 (8)	8585 (9)
C215	4986 (7)	8596 (8)	9486 (9)
C216	4585 (8)	7735 (10)	10418 (9)

Table I. (Continued)

Atom	x	y	z
OW1	2203 (11)	2265 (10)	314 (16)
OW2	3266 (7)	1929 (10)	8505 (14)
OW3	1753 (8)	5355 (8)	3484 (13)
OW4	2764 (10)	4961 (10)	5436 (14)

(b) Final thermal parameters (x 10^4) and their estimated standard deviations (in parentheses)[c]

	β_{11}	β_{22}	β_{33}	β_{12}	β_{13}	β_{23}
Ni	48.9 (4)	52.2 (7)	75.7 (9)	-13.4 (5)	-7.4 (5)	7.4 (6)
O1	97 (5)	47 (4)	165 (9)	-8 (3)	-59 (6)	8 (5)
O2	180 (9)	123 (8)	200 (12)	70 (7)	-126 (9)	-87 (8)
O3	52 (3)	67 (4)	88 (6)	-11 (3)	-1 (3)	4 (4)
O4	99 (5)	122 (7)	99 (7)	45 (5)	-13 (4)	26 (6)
N1	94 (5)	45 (4)	86 (7)	-7 (4)	26 (5)	-4 (4)
N2	65 (4)	50 (4)	81 (6)	-8 (3)	-12 (4)	-9 (4)
N3	43 (3)	113 (8)	179 (11)	5 (4)	10 (5)	77 (8)
N4	40 (3)	99 (7)	104 (8)	2 (4)	5 (4)	-32 (6)
C1	127 (9)	37 (5)	161 (14)	32 (6)	-69 (9)	-46 (8)
C2	144 (10)	55 (6)	86 (9)	26 (7)	9 (8)	-9 (6)
C3	180 (11)	57 (6)	67 (8)	53 (7)	7 (8)	6 (6)
C4	99 (7)	35 (5)	84 (8)	7 (4)	-28 (6)	-4 (5)
C5	102 (7)	38 (5)	142 (11)	-1 (5)	-45 (7)	-10 (6)
C6	75 (6)	62 (6)	131 (11)	1 (5)	-20 (6)	-2 (7)
C7	56 (5)	88 (8)	162 (13)	-10 (5)	15 (6)	-8 (8)

---

[c] The β_{ij} are defined by: $T = \exp\{-h^2\beta_{11} + k^2\beta_{22} + \ell^2\beta_{33} + 2hk\beta_{12} + 2h\ell\beta_{13} + 2k\ell\beta_{23})\}$.

Table I. (Continued)

	β_{11}	β_{22}	β_{33}	β_{12}	β_{13}	β_{23}
C8	58 (5)	86 (7)	119 (10)	-7 (5)	-4 (5)	1 (7)
C9	57 (5)	77 (7)	92 (9)	6 (4)	-12 (5)	8 (6)
C10	68 (6)	130 (11)	133 (12)	25 (6)	31 (7)	72 (10)
C11	141 (11)	152 (13)	67 (9)	58 (10)	22 (8)	28 (9)
C12	60 (5)	165 (12)	110 (11)	50 (6)	-28 (6)	-79 (10)
C13	107 (11)	249 (23)	219 (19)	122 (14)	-109 (13)	-167 (18)
C14	57 (7)	250 (25)	572 (59)	62 (10)	-93 (16)	-326 (36)
C15	42 (5)	162 (16)	400 (34)	-19 (7)	20 (10)	-196 (22)
C16	49 (5)	118 (10)	289 (23)	-26 (6)	43 (9)	-114 (13)
Ni2	66.7 (6)	39.0 (6)	85.3 (11)	-9.3 (5)	-24.1 (6)	2.3 (6)
O21	130 (6)	75 (5)	100 (7)	10 (5)	12 (5)	-16 (5)
O22	108 (5)	39 (4)	108 (7)	-10 (3)	-3 (5)	-1 (4)
O23	99 (4)	47 (4)	87 (6)	0 (3)	-22 (4)	1 (4)
O24	149 (7)	84 (6)	113 (8)	30 (5)	36 (6)	18 (5)
N21	116 (6)	52 (5)	124 (10)	3 (4)	-74 (7)	-2 (5)
N22	63 (4)	43 (4)	90 (7)	-6 (3)	-7 (4)	6 (4)
N23	53 (4)	56 (5)	143 (10)	-1 (3)	-25 (5)	17 (5)
N24	71 (4)	83 (6)	116 (8)	-17 (4)	-24 (5)	-16 (6)
C21	95 (6)	39 (5)	76 (8)	-4 (4)	-12 (5)	9 (5)
C22	61 (5)	43 (5)	132 (10)	-8 (4)	9 (6)	8 (6)
C23	52 (5)	95 (8)	127 (11)	-7 (5)	7 (6)	-18 (8)
C24	50 (4)	103 (9)	133 (11)	9 (5)	-8 (5)	29 (8)
C25	47 (4)	96 (7)	95 (9)	-1 (5)	-12 (5)	1 (7)
C26	152 (10)	51 (6)	112 (11)	32 (7)	-59 (8)	-12 (7)
C27	160 (11)	46 (6)	89 (10)	23 (7)	-70 (9)	-17 (6)
C28	131 (9)	52 (6)	82 (9)	46 (6)	4 (7)	11 (6)
C29	57 (5)	60 (7)	265 (20)	-10 (5)	-48 (8)	60 (10)
C210	61 (6)	83 (9)	292 (23)	9 (6)	-24 (9)	62 (13)
C211	55 (6)	92 (11)	359 (35)	12 (6)	-15 (12)	112 (17)

Table I. (Continued)

	β_{11}	β_{22}	β_{33}	β_{12}	β_{13}	β_{23}
C212	72 (6)	120 (11)	193 (16)	12 (7)	-6 (8)	82 (11)
C213	66 (5)	98 (8)	111 (10)	8 (5)	-18 (6)	46 (8)
C214	106 (7)	58 (7)	90 (10)	-11 (5)	-1 (7)	6 (7)
C215	74 (6)	83 (7)	103 (10)	-28 (5)	-21 (6)	-6 (7)
C216	98 (7)	126 (11)	88 (10)	-31 (7)	-37 (7)	25 (9)
OW1	268 (13)	92 (9)	490 (27)	-13 (10)	205 (16)	-35 (13)
OW2	123 (7)	234 (15)	474 (27)	102 (9)	165 (12)	223 (17)
OW3	150 (8)	124 (9)	357 (21)	50 (7)	-149 (11)	-81 (11)
OW4	236 (12)	121 (10)	378 (23)	41 (10)	-161 (14)	-26 (13)

RESULTS

Description and Discussion of the Structure. The asymmetric unit of the crystal contains two molecules of bis[D-β-(2-pyridyl)-α-alaninato]nickel(II). In each molecule the nickel is octahedrally coordinated to two nitrogen atoms and an oxygen atom of each D-Pyala$^-$ group (Figure 2). Since the structures of the two molecules in the asymmetric unit are identical, only one set of bond distances and angles are given here (Table II and III). The arrangement of the donor atoms about the nickel ion confers the trans-amino configuration (structure 1b in Figure 1) upon the complex according to the convention used in the Introduction.

A comparison of the corresponding bond distances and angles between the two D-Pyala$^-$ ligands shows only small differences which are within the accuracy of the determination. The bond lengths observed within the ligands compare quite well with other similar amino acid groups.[2,15] The average Ni-N(amino) and Ni-O distances of 2.084(7) Å and 2.062(6) Å correspond with those found in other octahedral complexes of nickel(II) involving amino-nitrogen or carboxylate oxygen atoms.[15-19] The Ni-N(pyridine) distances (ave. 2.108(7) Å) are very similar to values reported for other structures containing a nickel-pyridine bond (ave. 2.111 Å).[20-22]

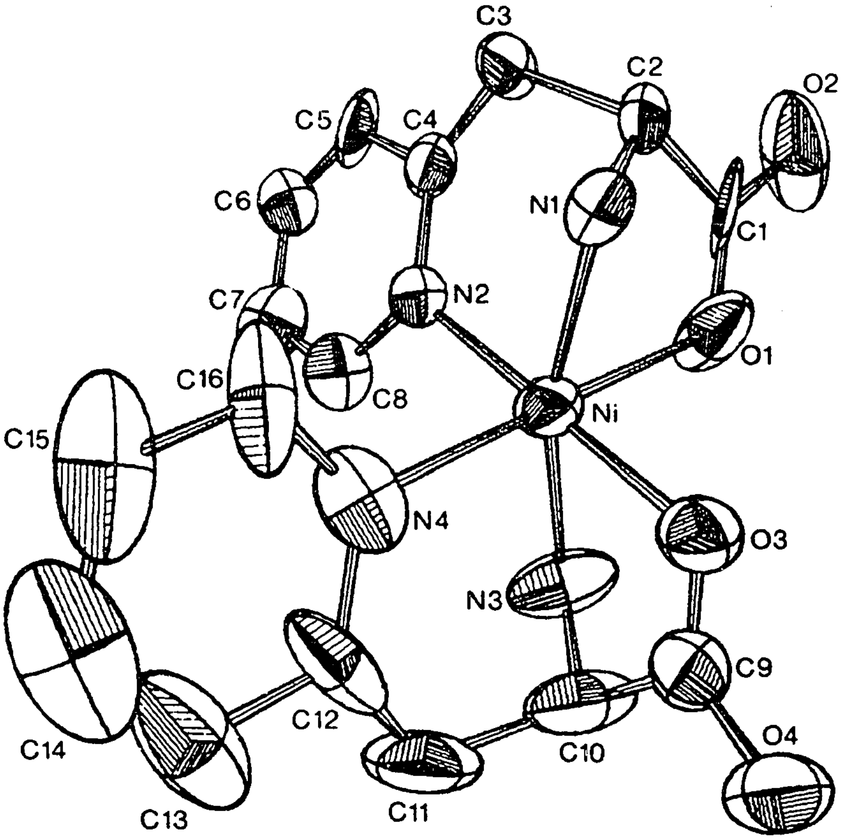


Figure 2. The structure of Ni(D-Pyala)$_2$·2H$_2$O. The water molecules are not shown

Table II. Interatomic distances (Å) and their estimated standard deviations (in parentheses)

Ni-O1	2.066(6)	Ni-O3	2.058(6)
Ni-N1	2.087(7)	Ni-N3	2.081(7)
Ni-N2	2.111(7)	Ni-N4	2.105(7)
C1-O1	1.28(1)	C9-O3	1.24(1)
C1-O2	1.23(1)	C9-O4	1.27(1)
O1-O2	2.211(10)	O3-O4	2.217(8)
C1-C2	1.46(2)	C9-C10	1.52(1)
N1-C2	1.51(1)	N3-C10	1.44(1)
C2-C3	1.52(1)	C10-C11	1.53(2)
C3-C4	1.51(1)	C11-C12	1.47(2)
C4-C5	1.41(1)	C12-C13	1.43(2)
C5-C6	1.40(1)	C13-C14	1.41(3)
C6-C7	1.35(1)	C14-C15	1.38(3)
C7-C8	1.45(1)	C15-C16	1.42(2)
C8-N2	1.34(1)	C16-N4	1.34(1)
N2-C4	1.34(1)	N4-C12	1.37(1)
N1-Ow1	3.127(14)	Ow3-Cw4	2.532(14)
N21-Ow4	3.190(17)	O2[a]-Ow3	2.776(9)
O4-Ow3[b]	2.698(9)	O2[a]-Ow1	3.076(16)
O21[b]-Ow2	2.706(13)	Ow1-Ow2[c]	2.449(16)

---

[a] Symmetry operation: -x, 1/2 + y, -z

[b] Symmetry operation: x, y - 1, z

[c] Symmetry operation: x, y, z - 1

Table III. Bond angles (deg) and their estimated standard deviations (in parentheses)

N1-Ni-N3	163.6(3)		
O1-Ni-N4	178.6(3)	O3-Ni-N2	178.9(2)
O1-Ni-O3	90.9(2)	N2-Ni-N4	91.7(3)
O1-Ni-N1	79.2(3)	O3-Ni-N3	79.8(3)
O1-Ni-N2	89.7(2)	O3-Ni-N4	87.7(3)
O1-Ni-N3	88.6(3)	O3-Ni-N1	89.4(3)
N1-Ni-N2	89.8(3)	N3-Ni-N4	91.2(3)
N1-Ni-N4	100.7(3)	N3-Ni-N2	101.2(3)
Ni-O1-C1	113.8(6)	Ni-O3-C9	113.0(5)
Ni-N1-C2	102.1(6)	Ni-N3-C10	103.3(5)
Ni-N2-C4	124.8(6)	Ni-N4-C12	122.6(7)
Ni-N2-C8	114.2(5)	Ni-N4-C16	114.9(7)
O1-C1-O2	123.4(13)	O3-C9-O4	124.0(8)
O1-C1-C2	116.0(8)	O3-C9-C10	117.3(8)
O2-C1-C2	120.4(12)	O4-C9-C10	118.7(8)
C1-C2-N1	111.6(8)	C9-C10-N3	109.9(8)
N1-C2-C3	106.7(8)	N3-C10-C11	111.7(9)
C1-C2-C3	114.5(11)	C9-C10-C11	110.1(9)
C2-C3-C4	116.6(8)	C10-C11-C12	117.6(7)
C3-C4-N2	120.8(8)	C11-C12-N4	123.7(9)
C3-C4-C5	118.1(8)	C11-C12-C13	117.9(13)
C4-C5-C6	120.7(8)	C12-C13-C14	120.1(16)
C5-C6-C7	118.1(9)	C13-C14-C15	118.7(12)
C6-C7-C8	119.9(9)	C14-C15-C16	119.9(17)
C7-C8-N2	120.3(8)	C15-C16-N4	120.6(15)
C8-N2-C4	120.3(8)	C16-N4-C12	122.1(10)
N2-C4-C5	120.5(9)	N4-C12-C13	118.5(14)

The corresponding N(amino)-Ni-N(pyridine), N(amino)-Ni-O and N(pyridine)-Ni-O bond angles for each of the two ligands differ only slightly. Distortions from ideal octahedral geometry about the nickel atom are readily apparent. The largest deviations occur for N(amino)-Ni-O in the five-membered chelate ring (ave. 79.4(3)°) and N1-Ni-N4, N3-Ni-N2 (ave. 101.0(3)°). The remainder of the angles about the nickel ion are very near the expected values of 90° or 180°. The departure of the N(amino)Ni-O angles in the five-membered chelate rings from the ideal value is the result of the invariant distance between the N(amino) and O(carboxylate) donor atoms in the ligand itself. Freeman[15] noted that if one imagines a triangle whose corners are M, N(amino) and O(carboxylate), then the constancy of the N···O distance requires that the angle N-M-O decrease if the sides M-N and M-O are lengthened. Indeed, a plot of the angle N-M-O vs. the average M-donor bond length yielded a straight line from distances of 2.0 Å (angle of 84°) to 2.5 Å (angle of 64°). If the present structure is compared to that for $Co(\underline{D}\text{-Pyala})_2^+$, this generalization is shown to hold true for the $\underline{D}\text{-Pyala}^-$ ligand. The corresponding average distances and angles are: Co-N(amino), 1.947(7) Å, Co-O, 1.893(6) Å, N-Co-O, 85.4(3)°; Ni-N(amino), 2.084(6) Å, Ni-O, 2.062(6) Å, N-Ni-O, 79.5(3)°. The angle found in the amino acid five-membered chelate ring (N-Ni-O) is very close to that found in the structure of bis(histidino)nickel(II) (79.7(5)°) which has equal numbers of Ni(D-His)$_2$ and Ni(L-His)$_2$ both in the trans-imidazole configuration.[23] In the present structure, the large angles N1-Ni-N4 and N3-Ni-N2 seem to be a consequence of the smaller N-Ni-O five-membered chelate ring angle.

The distances from the nickel atom to the least-squares planes of the pyridine rings are -0.25 and -0.30 Å. These are similar to the displacement of the cobalt atom from one of the pyridine rings in Co(D-Pyala)$_2^+$ (0.32 Å).[2] The dihedral angle between the least-squares planes of the two pyridine rings is 89.3°. Neither of these planes is coincident with the plane defined by O1-O3-N2-N4-Ni, but make dihedral angles with it of 58.7° (for ring containing N2) and 60.6° (for ring containing N4). As can be seen from Table IV, the least-squares plane derived from atoms Ni-O1-O3-N2-N4 is very well-defined. (The largest deviation is -0.01 Å). Contrary to this is the fact that the other two planes defined by the coordination sphere and containing N1 and N3 show much larger deviations (Plane 2, -0.14 Å; Plane 3, 0.11 Å). This is at least in part a consequence of the small bite of the five-membered amino acid ring.

Figure 3 illustrates the packing of molecules in the crystal lattice. Hydrogen bonding both within and between the asymmetric units stabilizes the crystal structure. Very

Table IV. Equations of least-squares planes[a]

Plane 1: Ni-O1-O3-N2-N4

$$- 0.63211\ X - 0.30453\ Y + 0.71252\ Z - 1.47256 = 0$$

Atom	D[b]	Atom	D
Ni	0.0070	N2	-0.0099
O1	0.0065	N4	0.0065
O3	-0.0103		

Plane 2: Ni-N1-N2-N3-O3

$$0.56757\ X + 0.54161\ Y + 0.62009\ Z - 1.31177 = 0$$

Atom	D	Atom	D
Ni	0.0833	N3	-0.1375
N1	-0.1362	O3	0.1094
N2	0.0809		

Plane 3: Ni-N1-N3-N4-O1

$$0.62692\ X - 0.77293\ Y + 0.09761\ Z - 0.36158 = 0$$

Atom	D	Atom	D
Ni	-0.0903	N4	-0.0519
N1	0.1099	O1	-0.0761
N3	0.1084		

---

[a] Planes are defined as $C_1X + C_2Y + C_3Z + C_4 = 0$ where X, Y and Z are cartesian coordinates.

[b] D = distance (Å) of the given atom from the fitted plane.

Table IV. (Continued)

Plane 4: N2-C4-C5-C6-C7-C8

$$0.69496\ X + 0.69489\ Y + 0.18479\ Z - 0.7148 = 0$$

Atom	D	Atom	D
N2	0.0151	C7	0.0192
C4	-0.0121	C8	-0.0192
C5	0.0151	Ni[c]	-0.2502
C6	-0.0180		

Plane 5: N4-C12-C13-C14-C15-C16

$$-\ 0.71939\ X + 0.61850\ Y + 0.31612\ Z - 0.91761 = 0$$

Atom	D	Atom	D
N4	-0.0101	C15	0.0107
C12	0.0038	C16	0.0027
C13	0.0092	Ni[c]	-0.3033
C14	-0.0164		

---

[c] These atoms were not included in the calculation of the plane.

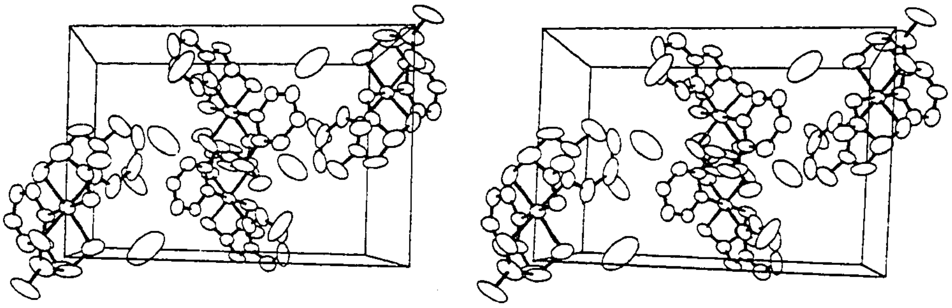


Figure 3. View of the unit cell with the a axis horizontal and the c axis vertical

strong interactions occur between water molecules (Ow1···Ow2, 2.45(2) Å; Ow3···Ow4, 2.53(1) Å) with weak and strong bonds between the water and Ni(D-Pyala)$_2$ molecules. The N-H···O interactions appear to be weak (3.13(1) and 3.19(2) Å) with a much stronger carboxylate-water interaction (2.698(9), 2.776(9) and 2.706(13) Å).

Discussion. It is of interest to know whether the amino acid, D-Pyala$^-$, in Ni(D-Pyala)$_2$ retains its tridentate nature in solution or becomes a bidentate ligand. Two techniques are available for distinguishing the atoms in the coordination sphere of the nickel(II) ion. It has been noted previously[1] that log K_1 (7.1) for the binding of Pyala$^-$ to nickel(II) is 1.9 units larger than for 2-(2'-aminoethyl)-pyridine (5.2), suggesting coordination of the carboxylate group to the nickel(II) ion. This value for Pyala$^-$ (7.1) is also larger than those reported for glycine (5.9) and phenylalanine (5.2) indicating that the pyridine nitrogen adds to the coordinating ability of Pyala$^-$. Complexation through only the carboxylate oxygen and pyridine nitrogen atoms seems unlikely since a less favorable seven-membered chelate ring would be formed.

The rule of average environment, first proposed by Jorgensen,[24] has been used quite extensively by investigators of nickel(II) complexes containing oxygen and nitrogen donors. Since the spectra of the nickel complexes for any given combination of n amine and 6-n oxygen donor atoms are similar, the number of each type of donor atom can be estimated. The visible spectrum of Ni(D-Pyala)$_2$•2H$_2$O in water is shown in Figure 4. The maxima of the complex (563, 780, 962 nm) agree very well with those of an NiN_4O_2 chromophore (*e.g.*, Ni(en)(gly)$_2$; 561, 781, 952 nm).[25] These comparisons suggest that the ligands in Ni(D-Pyala)$_2$ are tridentate in solution, as well as in the solid state.

The infrared spectrum of the crystals in the KBr disk compares quite well with other bis(amino acidato)nickel(II) complexes.[26] The asymmetric and symmetric N-H stretching absorptions of the coordinated amine appear at 3290 and 3242 cm^{-1}, respectively. Coordination through the carboxylate group is indicated by the position of the asymmetric and symmetric $-CO_2^-$ stretches at 1600 and 1405 cm^{-1}. The M-N stretch occurs at 342 cm^{-1} with the M-O band lying outside the range of the instrument. The infrared solution spectrum taken in D_2O has the $-CO_2^-$ stretches in the same position as in the KBr disk spectrum.

As has been shown, the nickel(II) ion is coordinated to the carboxylate oxygen atom, the amino nitrogen atom and the pyridine nitrogen atom of each D-Pyala$^-$ ligand. To determine which of the three geometrical isomers of the bis-complex predominates in solution, the circular dichroism

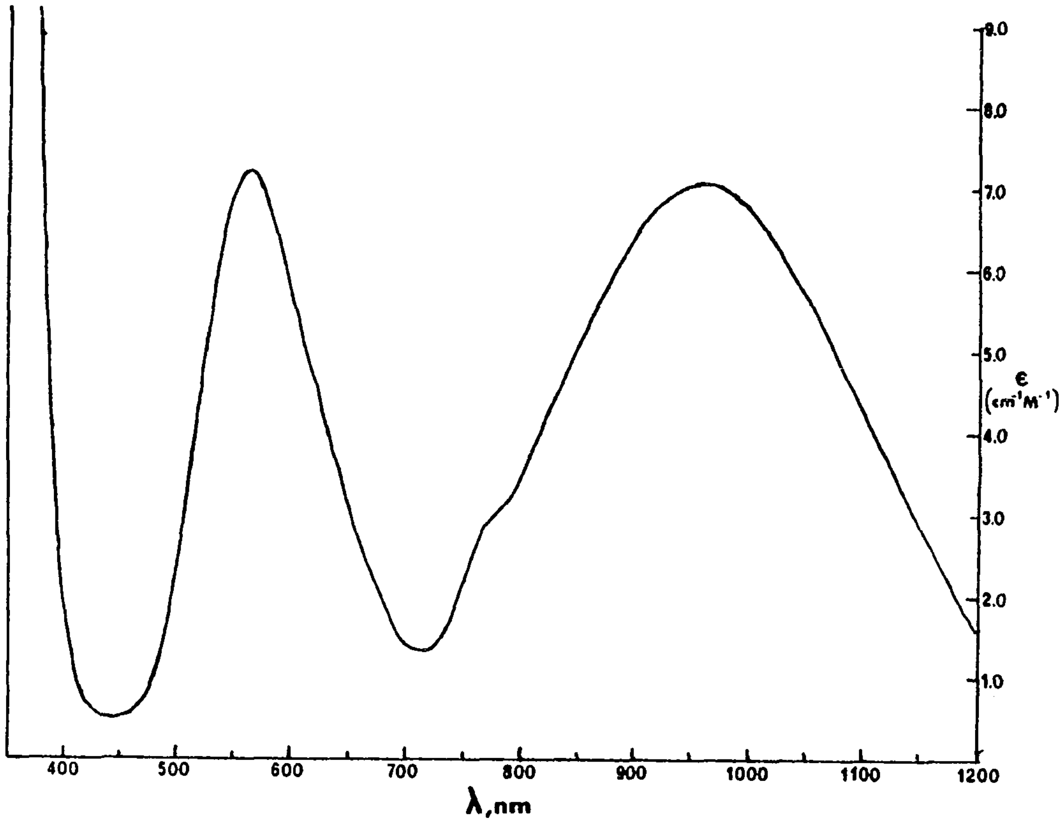


Figure 4. Absorption spectrum of trans-amino Ni(D-Pyala)$_2$·2H$_2$O in water

was taken for comparison with other bis(amino acidato)-nickel(II) complexes. The CD spectrum of an aqueous solution of the complex [Ni(D-Pyala$_2$]·2H$_2$O along with those of Na$_2$[Ni(D-Asp)$_2$]·5H$_2$O and the inverse of [Ni(L-His)$_2$]·H$_2$O are shown in Figure 5.

Contributions to the optical activity of these three complexes arise from (1) the vicinal effect of the asymmetric carbon, (2) the conformational effect of the chelate rings formed, and (3) the overall configuration of the complex. The first contribution should be similar to those for other amino acids, *e.g.*, Ni(D-ala)$_2$, and is expected to be small.[27] Although there are more chelate rings formed in these tridentate amino acid complexes, when compared to bidentate amino acid complexes, the same conformation (δ for D enantiomer) is imposed on the amino acid ring because of the steric requirements of the ligand. This contribution is also expected to be small and very similar in the histidinate, asparate and Pyala$^-$ complexes. Thus, the major contribution arises from the overall configuration imposed on the complex by the particular geometrical isomer that is formed. The circular dichroism curves for Ni(D-Pyala)$_2$, Na$_2$[Ni(D-Asp)$_2$] and Ni(D-His)$_2$ (equal to the inverse of Ni(L-His)$_2$) should be very similar if the arrangements of the chelate rings in the complexes are the same.

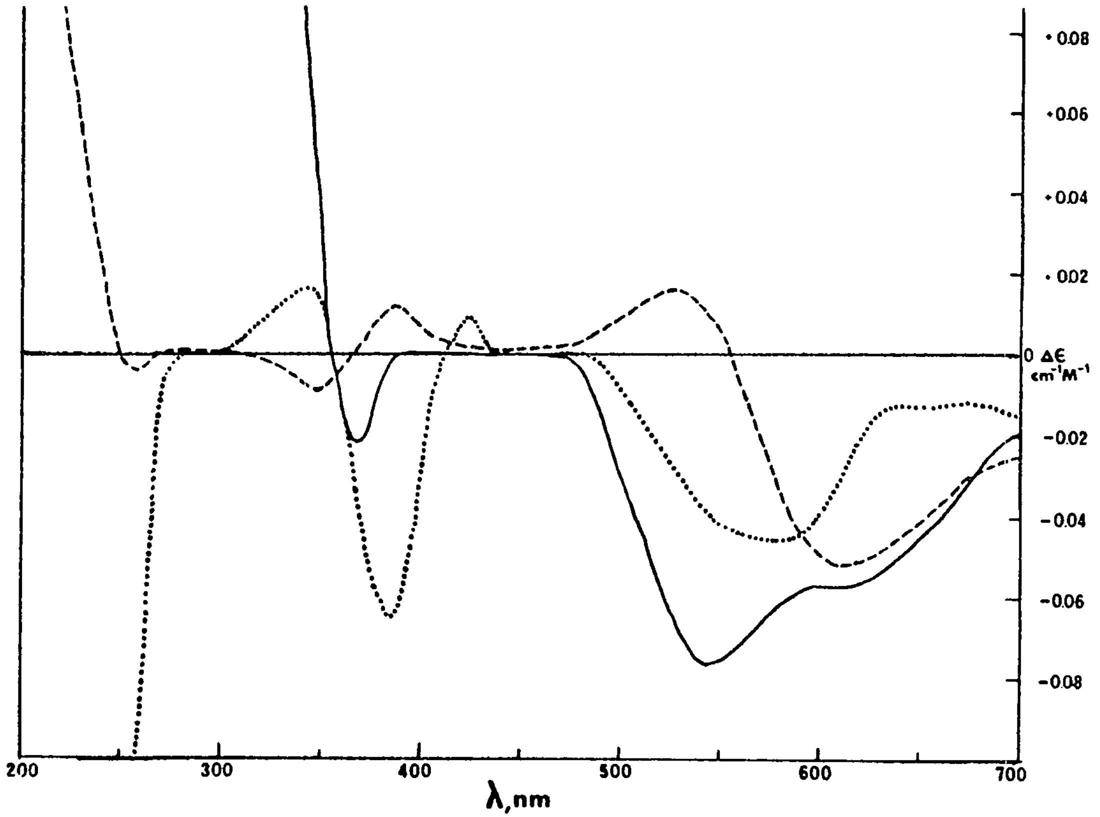
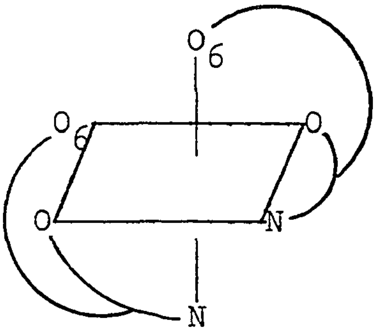


Figure 5. Circular dichroism spectra of (——) $Ni(\underline{D}\text{-Pyala})_2\cdot 2H_2O$, with (---) the inverse of $Ni(\underline{L}\text{-His})_2\cdot H_2O$ and (•••) $Na_2[\underline{D}\text{-Asp})_2]\cdot 5H_2O$ (x5) taken from ref. 27

It has been suggested that the trans-imidazole configuration is the predominant isomer of Ni(L-His)$_2$ in aqueous solution.[27,28] In Figure 5 it can be seen that the circular dichroism spectrum of Ni(D-Pyala)$_2$ differs considerably from the inverse of the Ni(L-His)$_2$ spectrum (this should be equal to the CD of Ni(D-His)$_2$). Both spectra have two maxima in the long wavelength region (450 - 700 nm); however, the maxima for Ni(D-Pyala)$_2$ are of the same sign (neg.) while those of Ni(D-His)$_2$ are of opposite sign (one positive and one negative). This suggests that the structure of Ni(D-Pyala)$_2$ differs from that of Ni(D-His)$_2$ in aqueous solution.

Based on the signs of the maxima and shape of the circular dichroism spectrum, a predominance of the trans O_5 cis N_5 isomer of Ni(D-Asp)$_2^-$,



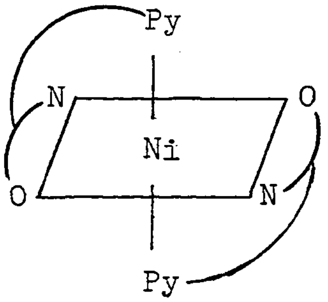
in aqueous solution was suggested.[27] The arrangement of the chelate rings in trans O_5 cis N_5 Ni(D-Asp)$_2^-$ is the same as in trans-carboxylate Ni(D-Pyala)$_2$ (Figure 1a). The large difference between the circular dichroism spectra of

Ni(D-Pyala)$_2$ and Ni(D-Asp)$_2^-$ suggests that Ni(D-Pyala)$_2$ does not have the analogous trans-carboxylate structure (Figure 1a). This conclusion leaves the trans-amino configuration as the most likely isomer in solution, as well as in the solid state.

CONCLUSION

Although it is not clear why Ni(D-Pyala)$_2$ adopts the trans-amino structure in the solid state and presumably also in solution, it appears that in the limited number of crystal structures of other octahedral 2:1 amino acid complexes of nickel(II), the majority also has the trans-amino configuration. This is in contrast to the related Co(D-Pyala)$_2^+$ complex whose most stable structure is the trans-carboxylate.

Assuming the trans-amino isomer of Ni(D-Pyala)$_2$ to be the most stable in solution, the higher formation constant for Ni(D-Pyala)(L-Pyala) as compared to Ni(D-Pyala)$_2$[1] may be readily rationalized. A preference for trans-amino groups requires that the pyridyl groups be cis to each other in Ni(D-Pyala)$_2$. On the other hand, Ni(D-Pyala)(L-Pyala) with trans-amino groups would have the structure,



in which the bulky pyridyl groups are trans to each other, which could favor the formation of this complex over Ni(D-Pyala)$_2$.

REFERENCES

1. Rechani, P. R.; Nakon, R.; Angelici, R. J. *Bioinorg. Chem.* *1976*, 5, 329.

2. Ebner, S. R.; Jacobson, R. A.; Angelici, R. J. *Inorg. Chem.* *1979*, 18, 765.

3. Harding, M. M.; Long, H. A. *J. Chem. Soc. A* *1968*, 2554.

4. Candlin, R.; Harding, M. M. *J. Chem. Soc. A* *1970*, 384.

5. Led, J. J.; Grant, D. M. *J. Amer. Chem. Soc.* *1977*, 99, 5845.

6. Bagger, S.; Gibson, K.; Sorenson, C. S. *Acta Chem. Scand.* *1972*, 26, 2503.

7. Bedell, S. A.; Rechani, P. R.; Angelici, R. J.; Nakon, R. *Inorg. Chem.* *1977*, 16, 972.

8. Jacobson, R. A. *J. Appl. Cryst.* *1976*, 9, 115.

9. Rohrbaugh, W. J.; Jacobson, R. A. *Inorg. Chem.* *1974*, 13, 2535.

10. Lawton, S. L.; Jacobson, R. A. *Inorg. Chem.* *1968*, 7, 2124.

11. Hubbard, C. A.; Quicksall, C. O.; Jacobson, R. A. "The Fast Fourier Algorithm and the Programs ALFF, ALFFDP, ALFFPROJ, ALFFT and FRIEDEL"; U. S. Atomic Energy Commission Report IS-2625; Iowa State University and Institute for Atomic Research, Ames, Iowa, 1971.

12. Lapp, R. L.; Jacobson, R. A. "ALL, A Generalized Crystallographic Least Squares Program"; U. S. DOE Report, 1979, in preparation.

13. Hanson, H. P.; Herman, F.; Lea, J. D.; Skillman, S. *Acta Cryst.* *1960*, 17, 1040.

14. Templeton, D. H. "International Tables for X-ray Crystallography"; Vol. III, Table 3.3.2c, The Kynoch Press, Birmingham, England, 1962, p. 215-216.

15. Freeman, H. C. *Advances in Protein Chemistry Vol. 22*; Academic Press: New York, 1967, p. 257.

16. Van der Helm, D.; Hossain, M. B. *Acta Cryst.* *1969*, *B25*, 457.

17. Guha, S. *Acta Cryst.* *1973*, B29, 2167.

18. Freeman, H. C.; Guss, J. M. *Acta Cryst.* *1968*, B24, 1133.

19. Freeman, H. C.; Guss, J. M. *Acta Cryst.* *1972*, B28, 2090.

20. Madaule-Aubrey, F.; Brown, G. M. *Acta Cryst.* *1968*, B24, 745.

21. Elder, R. C. *Inorg. Chem.* *1968*, 7, 2316.

22. Hamm, D. J.; Bordner, J.; Schreiner, A. F. *Inorg. Chim. Acta* *1973*, 7, 637.

23. Fraser, K. A.; Harding, M. M. *J. Chem. Soc. A* *1967*, 415.

24. Jorgensen, C. K. *Acta Chem. Scand.* *1956*, 10, 887.

25. Chow, S. T.; McAuliff, C. A. *Prog. Inorg. Chem.* *1975*, 19, 51.

26. a) Lane, T. J., C. S. C.; Durkin, J. A.; Hooper, R. J. *Spectrochimica Acta* *1964*, 20, 1013.

    b) Nakagawa, I.; Hooper, R. J.; Walter, J. L., C. S. C.; Lane, T. J., C. S. C. *Spectrochimica Acta* *1965*, 21, 1.

    c) Jackovitz, J. F.; Walter, J. L., C. S. C. *Spectrochimica Acta* *1966*, 22, 1393.

    d) Jackovitz, J. F.; Durkin, J. A.; Walter, J. L., C. S. C. *Spectrochimica Acta* *1967*, 23A, 67.

    e) Inomata, Y.; Inomata, T.; Moriwaki, T.; Walter, J. Walter, J. L. *Spectrochimica Acta* *1973*, 29A, 1933.

27. Haines, R. A.; Reimer, M. *Inorg. Chem.* *1973*, 12, 1482.

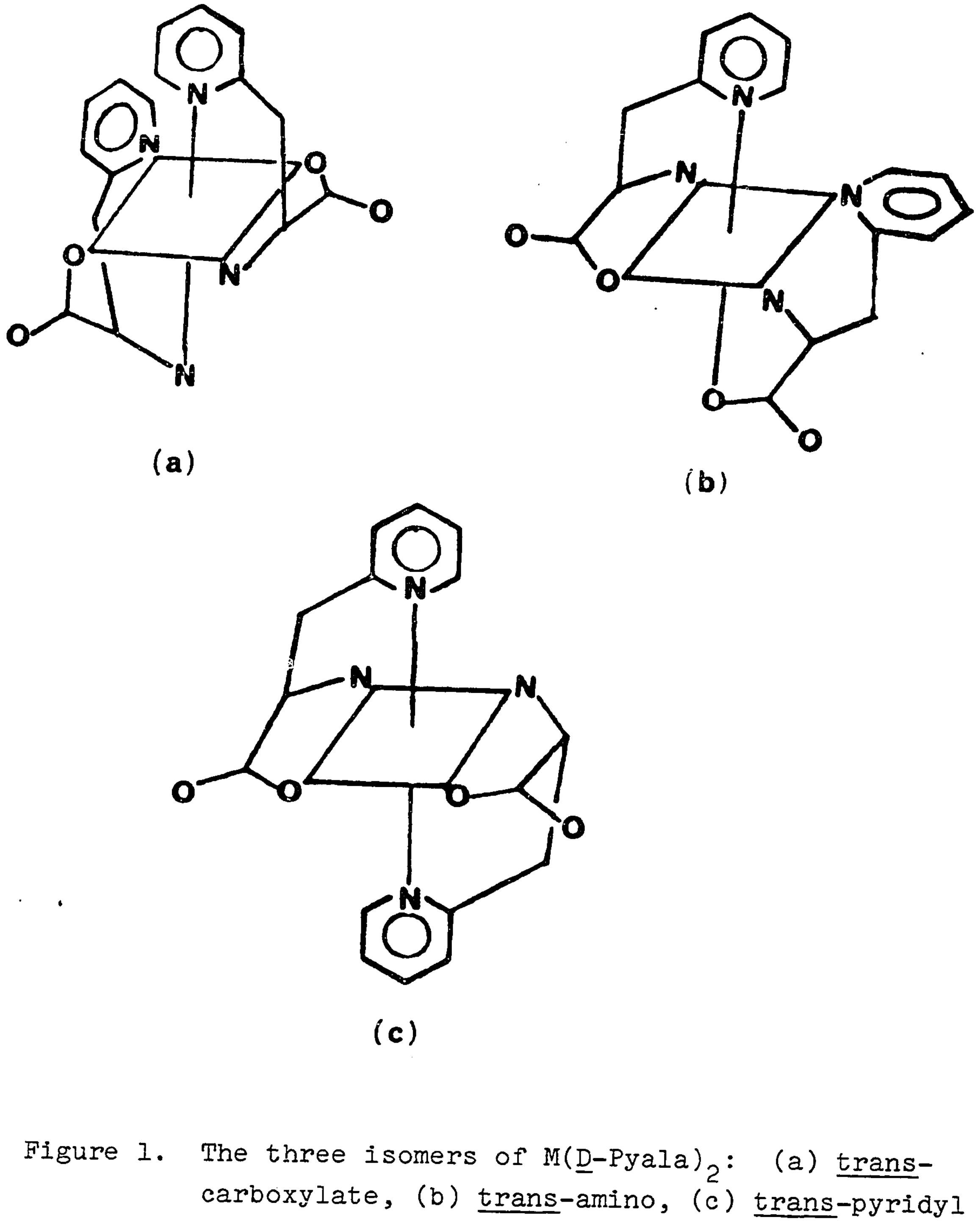
28. Led, J. J.; Grant, D. M. *J. Amer. Chem. Soc.* *1977*, 99 5845.

SECTION V. PREPARATION AND CHARACTERIZATION OF THE COPPER(II) AND ZINC(II) COMPLEXES OF D-β-(2-pyridyl)-α-alaninate AND THEIR CONDENSATION PRODUCTS WITH ACETONE

INTRODUCTION

Potentiometric studies have shown that β-(2-pyridyl)-α-alanine, $^{+}H_3NCH(CH_2C_5H_4N)CO_2^-$, (PyalaH), binds to transition metal ions to form $M(Pyala)_2$ with a large degree of enantioselectivity.[1] Formation constants for the binding of L-Pyala⁻ or D,L-Pyala⁻ with Cu(II), Ni(II), Co(II) and Zn(II), which were determined by potentiometric titration, showed that the mixed complexes, M(L-Pyala)(D-Pyala), were more stable than the bis complexes, $M(L\text{-}Pyala)_2$.

We have been investigating the origins of this stereoselective effect by considering the possible structures of the complexes and determining the most stable species. Previous investigations[2,3] have shown that the most stable complex of cobalt(III), $Co(D\text{-}Pyala)_2^+$, has the trans-carboxylate configuration (Figure 1a). The structure[4] of $[Ni(D\text{-}Pyala)_2]\cdot 2H_2O$ was determined from x-ray diffraction data and was found to be the trans-amino isomer (Figure 1b). In this report, we extend these studies to include the D-Pyala⁻ complexes of Cu(II) and Zn(II).



(a)

(b)

(c)

Figure 1. The three isomers of M(*D*-Pyala)$_2$: (a) *trans*-carboxylate, (b) *trans*-amino, (c) *trans*-pyridyl

EXPERIMENTAL SECTION

Materials. Racemic β-(2-pyridyl)-α-alanine was prepared and resolved as described previously.[5] $Zn(OH)_2$ was prepared by the method of Dietrich and Johnston.[6] $Cu(OH)_2$ was prepared according to the literature method.[7] The preparation of $[Ni(\underline{D}\text{-Pyala})_2]\cdot 2H_2O$ was reported previously.[4]

Preparation of bis[D-β-(2-pyridyl)-α-alaninato)]-copper(II) Dihydrate, $Cu(\underline{D}\text{-Pyala})_2\cdot 2H_2O$. To an aqueous solution containing 1.0 g (6.0 mmol) of D-PyalaH in 20 ml H_2O, 3.0 mmol of freshly prepared $Cu(OH)_2$ was added. The mixture was stirred at 80°C for 2 hrs, after which the solution was a deep blue color. The unreacted $Cu(OH)_2$ was filtered from the solution, which was then evaporated under reduced pressure to 2 ml. A layer of absolute ethanol (38 ml) was floated on top of the aqueous phase and the two layers were allowed to diffuse together. The blue crystals that formed were filtered from the mother liquor, washed with 1 ml of cold ethanol, and dried under vacuum. The mother liquor was blue-green in color. It was evaporated to dryness and the solid that formed was dissolved in 5 ml of water. A yellow color was extracted from the aqueous phase with EtOAc (10 ml, twice), leaving a blue solution. The blue aqueous phase was evaporated under reduced pressure to 1 ml and 19 ml of absolute ethanol was added. The two phases were allowed to diffuse together, and the resulting solution was cooled to -40°C, which yielded more of the deep blue crystals. The yield of Cu(D-Pyala)$_2$•2H$_2$O based on the moles of Cu(II) in the starting material was 79.2%. Anal. calcd for Cu(C$_8$H$_9$N$_2$O$_2$)$_2$•2H$_2$O: C, 44.70; H, 5.16; N, 13.03. Found: C, 44.76; H, 5.26; N, 13.01.

Preparation of bis[D-β-(2-pyridyl)-α-alaninato]zinc(II), [Zn(D-Pyala)$_2$]. The ligand, D-PyalaH (1.0 g, 6.0 mmol) was dissolved in 20 ml of H$_2$O and Zn(OH)$_2$ (0.3 g, 3.0 mmol) was added. This solution was stirred at 60°C for 16 hrs. The unreacted Zn(OH)$_2$ was filtered from the solution, which was then evaporated to 1 ml. A layer of absolute ethanol (19 ml) was added and allowed to diffuse into the aqueous phase. The white crystals that formed were filtered, washed with cold ethanol and vacuum dried. The yield of Zn(D-Pyala)$_2$, based on Zn(II) starting material, was 83%. Anal. calcd for Zn(C$_8$H$_9$N$_2$O$_2$)$_2$: C, 48.56; H, 4.58; N, 14.16. Found: C, 48.39; H, 4.58; N, 14.18.

Preparation of [Ni(aib-D-Pyala)]•H$_2$O. The [Ni(D-Pyala)$_2$]•2H$_2$O[4] (1.0 g, 2.4 mmol) was dissolved in 15 ml of methanol, 15 ml of acetone was added, and the solution was refluxed for 32 hrs. At the end of this period, the solution was colorless and a purple precipitate was formed. The solid was filtered, washed with cold water and vacuum dried. Yield of [Ni(aib-D-Pyala)]·H_2O was 98%. Anal. calcd for [Ni($C_{22}H_{26}N_4O_4$)]·H_2O: C, 54.24; H, 5.79; N, 11.50. Found: C, 54.34; H, 5.95; N, 11.37.

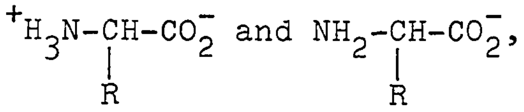
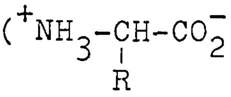
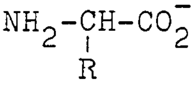
Preparation of Cu(aib-D-Pyala)·4½H_2O. The blue crystals of [Cu(D-Pyala)$_2$]·$2H_2O$ (1.0 g, 2.4 mmol) were dissolved in 125 ml of methanol, and 10 ml of acetone were added. After refluxing for 92 hrs, the solution was evaporated to 2 ml, and 10 ml of acetone was floated on top of the colored phase. Blue-green crystals formed as the layers diffused together. These crystals were filtered from the mother liquor, washed with acetone, and redissolved in a minimum of 95% ethanol (∿3 ml). A layer of acetone (10 ml) was added and the phases allowed to diffuse together, causing precipitation of the complex as deep blue crystals. The crystals were air dried, because they lost their luster and became crumbly if dried under vacuum. Analysis of the vacuum dried crystals indicated that four molecules of water had been lost. The yield of Cu(aib-D-Pyala)·4½H_2O was 55%. Anal. calcd for [Cu($C_{22}H_{26}N_4O_4$)]·4½H_2O: C, 47.60; H, 6.36; N, 10.09. Found: C, 47.45; H, 6.29; N, 10.16.

Preparation of [Zn(aib-D-Pyala)]·1½H_2O. After dissolving [Zn(D-Pyala)$_2$] (1.0 g, 2.5 mmol) in 10 ml of water, 10 ml of acetone was added and the solution was allowed to stand at room temperature. White crystals began forming after four days. More crystals were allowed to precipitate for two weeks, at which time the crystals were filtered from the solution. The fluffy white crystals were dissolved in boiling water, and precipitated by cooling to 10°C. The crystals were filtered from the mother liquor and dried under vacuum. The yield of $[Zn(aib\text{-}\underline{D}\text{-}Pyala)]\cdot 1\frac{1}{2}H_2O$ was 23%. Anal. calcd for $[Zn(C_{22}H_{26}N_4O_4)]\cdot 1\frac{1}{2}H_2O$: C, 52.55; H, 5.81; N, 11.14. Found: C, 52.59; H, 5.74; N, 11.13.

Spectra. Infrared spectra were recorded in KBr disks or D_2O solutions using a Beckman IR 4250 spectrophotometer. Visible and circular dichroism spectra were recorded at room temperature using a Jasco ORD/UV/CD-5 spectrophotometer. The ^1H NMR spectra were measured on a Varian Associates HA-100 spectrometer in 99.7% deuterium oxide *vs*. *tert*-butyl alcohol (δ 1.23) as an internal standard. The ^{13}C NMR spectrum was recorded on a Jeol FX90Q spectrometer in D_2O with dioxane (67.00 ppm) as an internal standard.

RESULTS AND DISCUSSION

$Cu(D\text{-}Pyala)_2 \cdot 2H_2O$. The first and second stability constants, log K_1 and log K_2, for the interaction of D-Pyala$^-$ with copper(II) are 8.26 and 6.83,[1] respectively. The corresponding values for 2-(2'-aminoethyl)pyridine are 7.3 and 5.6.[8] Log K_1 and log K_2 values for phenylalanine are 7.93 and 6.90.[9] The larger value of log K_1 for D-Pyala$^-$ would seem to indicate that the first D-Pyala$^-$ ion chelates through all three groups, the amino and pyridine nitrogen atoms and the carboxylate oxygen atom. Log K_2 for D-Pyala$^-$ is very close to that for phenylalanine suggesting that the second D-Pyala$^-$ group may coordinate like a simple amino acid, through its amino nitrogen and carboxylate oxygen atoms.

The infrared spectrum of the complex $Cu(D\text{-}Pyala)_2 \cdot 2H_2O$ was taken in D_2O as well as in a KBr disk. The antisymmetric $-CO_2^-$ stretching frequency in D_2O for D-PyalaH was shifted from 1611 cm^{-1} to 1570 cm^{-1} when the pD was raised to 10.0. These values are comparable to those reported for other amino acids of the forms  $^+H_3N\text{-}\underset{\displaystyle R}{\underset{|}{CH}}\text{-}CO_2^-$ and $NH_2\text{-}\underset{\displaystyle R}{\underset{|}{CH}}\text{-}CO_2^-$, respectively.[10] Upon formation of the complex $Cu(D\text{-}Pyala)_2$, this band is shifted to 1598 cm^{-1}. This value is similar to others reported for bidentate amino acids coordinated to copper(II) through their amino and carboxylate groups.[10-12] Similar shifts have been reported for the copper(II)-*L*-histidine system ( $^{+}NH_3-\underset{R}{\underset{|}{C}}H-CO_2^-$, pD = 2.5, 1622 cm^{-1};  $NH_2-\underset{R}{\underset{|}{C}}H-CO_2^-$, pD = 10.2, 1578 cm^{-1}; $-NH_2$ and $-CO_2^-$ coordinated, 1592 cm^{-1}).[13]

When the pyridyl ring nitrogen is complexed with a metal, the ring breathing mode shifts from about 995 cm^{-1} (uncomplexed) to 1015 cm^{-1} (complexed).[14] The IR spectrum of *D*-PyalaH in KBr showed this band at 977 cm^{-1}. In the complex $Cu(\underline{D}\text{-Pyala})_2 \cdot 2H_2O$, it was shifted to 1015 cm^{-1} which may indicate coordination through the pyridine group.

The use of ^1H NMR spectroscopy for the elucidation of metal ion binding sites is a well-established technique.[15] The copper(II) ion, being paramagnetic, causes proton relaxation effects and selectively broadens the signals of protons near the binding sites. Since there is rapid exchange between complexed and free ligand, only a trace of paramagnetic copper(II) is used to cause the broadening of proton signals in proximity to the binding sites. Figure 2 shows the results obtained when increasing amounts of copper(II) were added to a D_2O solution of *D*-Pyala$^-$ at pD 10.0. The signal for the methine proton at 3.73 ppm (quartet, X portion of ABX spin pattern) was broadened by

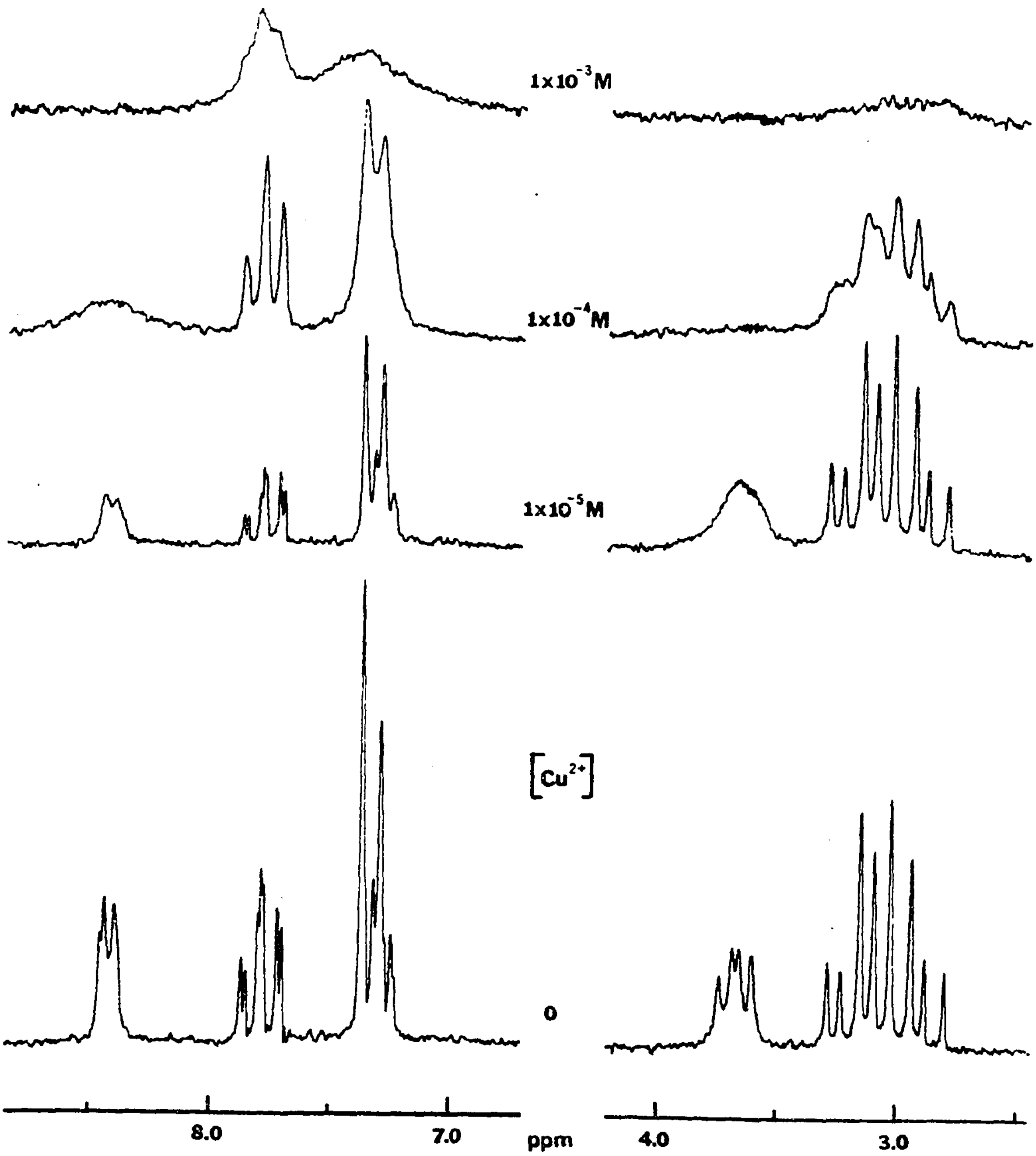


Figure 2. ^{1}H NMR spectra of D-PyalaH (0.4 M) at pD 10.0 in the presence of 0, 10^{-5}, 10^{-4} and 10^{-3} M copper(II) ion

the addition of small amounts of copper(II). The initial line width for the quartet, measured at half-height, went from 16 Hz at zero copper(II) concentration to 22 Hz at 1×10^{-5} $\underline{M}$ copper(II). At 10^{-4} and 10^{-3} $\underline{M}$ copper(II), the peak was lost in the baseline. The signal for the methylene protons, adjacent to the methine, were a pair of overlapping quartets at 3.08 ppm (AB portion of ABX spin pattern). These were broadened at the higher copper(II) concentrations due to a proximity effect. This is analogous to $\underline{L}$-α-aminobutyric acid, where the signal for the β-methylene group was broadened in the presence of 2×10^{-4} M copper(II) at pD 7.6.[16]

The signal for the ortho proton of the pyridine ring at 8.44 ppm (doublet, if small couplings, $J < 2$ Hz, are ignored) was broadened when small amounts of copper(II) were added. The initial line width for the doublet went from 9 Hz at zero copper(II) concentration to 13 Hz at 1×10^{-5} M copper(II), and 40 Hz at 1×10^{-4} M copper(II). The para and meta protons of the pyridine ring at 7.78 ppm and 7.32 ppm, respectively, were only slightly broadened, as observed for the methylene protons.

These results may be compared with those observed for (S)-β-(2-pyridylethyl)-$\underline{L}$-cysteine, in which broadening of the α-methine group indicated glycine type chelation through the amino and carboxylate groups, while the pyridyl nitrogen atom was eliminated as a binding site because the ring protons were not broadened even at 1×10^{-3} M copper(II) concentration.[14] However, the broadening of the α-methine and ortho pyridine protons in the present case suggests that D-Pyala$^-$ is tridentate in binding to copper(II).

Further evidence regarding the structure of Cu(D-Pyala)$_2$ was provided by visible absorption and circular dichroism spectra, which are shown in Figure 3. Visible absorption spectra of 1:2 complexes of copper(II) and amino acids, which are bound through one amino nitrogen and one carboxylate oxygen atom, exhibit a maximum near 620 nm, as typified by L-alanine.[17] Displacement of an apical water molecule in Cu(gly)$_2$ with imidazole causes an increase in ε (45 to 62 cm^{-1} M^{-1}), with no change in the maximum.[18] The absorption maximum of Cu(D-Pyala)$_2$·2H$_2$O in aqueous solution (Figure 2) occurs at 613 nm with an ε of 85 cm^{-1} M^{-1}. The similarity between the maximum of Cu(D-Pyala)$_2$ and other bis(amino acidato)copper(II) complexes implies that two D-Pyala$^-$ ions bind through their amino nitrogen and carboxylate oxygen atoms to form an N_2O_2 chromophore about the copper(II) center. The larger ε value for Cu(D-Pyala)$_2$ than for the bis(amino acidato)copper(II) complexes (ε are between 40 and 60 cm^{-1} M^{-1}) suggests an apical interaction of the pyridine group with the copper(II) ion, which is consistent with the ^{1}H NMR studies.

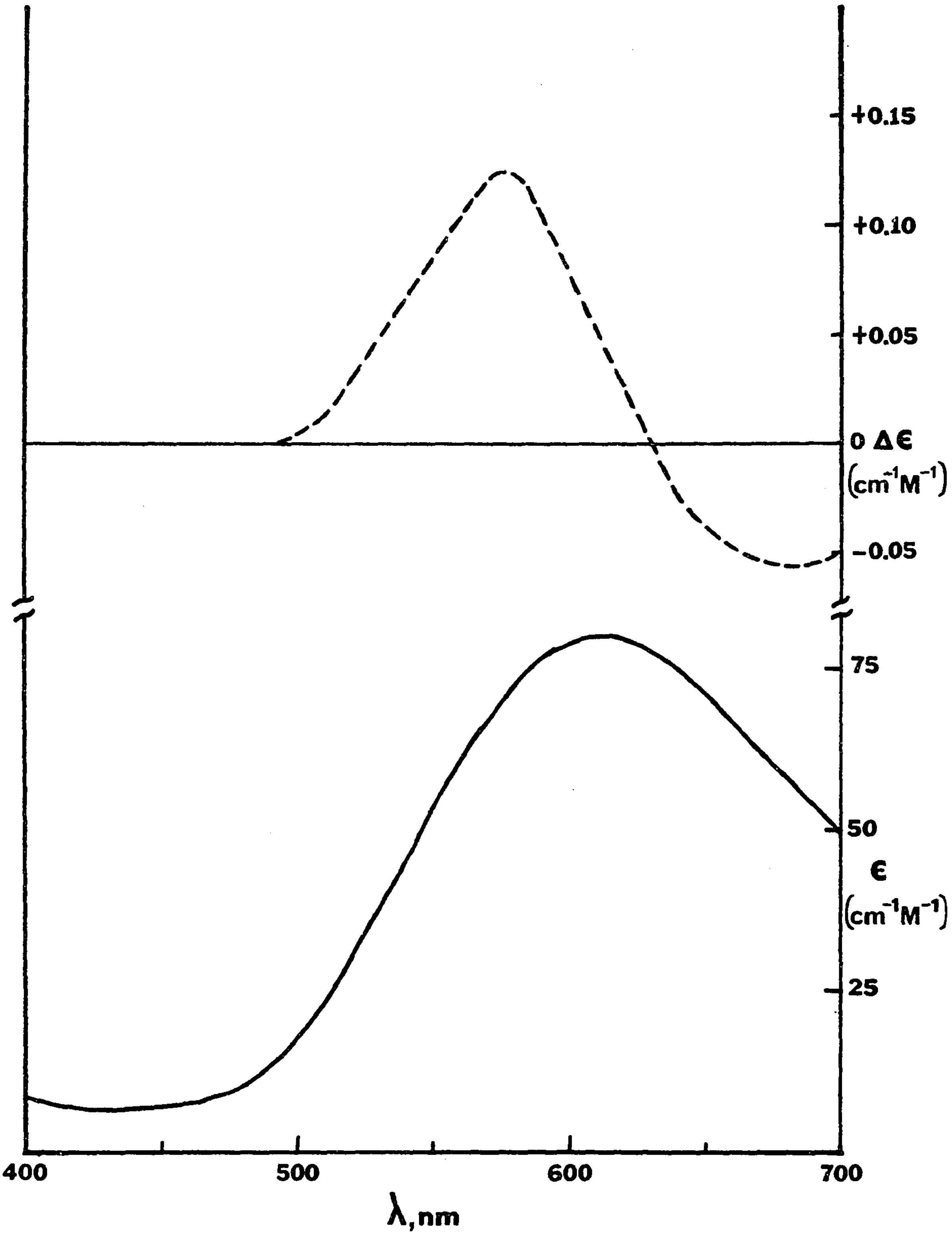
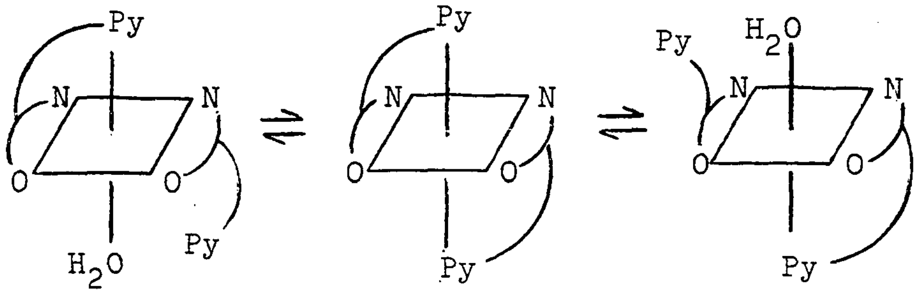


Figure 3. The visible (——) and CD (---) spectra of $Cu(\underline{D}\text{-Pyala})_2\cdot 2H_2O$ in aqueous solution

The inverse of the CD spectra of bis(L-amino acidato)-copper(II) complexes show a small negative peak ($\Delta\varepsilon < -0.05$) around 700 nm and a more intense positive band with a maximum between 580 and 640 nm.[17,19-22] The CD spectrum of Cu(D-His)$_2$, which is equal to the inverse of the CD spectrum of Cu(L-His)$_2$, had a large negative maximum at 690 nm ($\Delta\varepsilon = -0.52$) with a less intense positive peak at 570 nm ($\Delta\varepsilon = +0.03$).[19] It was proposed, that one histidinate was bound to copper(II) primarily through the amino and imidazole nitrogen atoms, with weaker apical chelation by the carboxylate group. The second histidinate was proposed to be bidentate and was coordinated to copper(II) through the amino nitrogen atom and carboxylate oxygen atom. The chelate plane was composed of three nitrogen and one oxygen donors. The CD spectrum of Cu(D-Pyala)$_2 \cdot 2H_2O$ in aqueous solution lies between that of the simple bidentate amino acids and the CD spectrum of Cu(D-His)$_2$. The positions of the maxima are similar to those of Cu(L-His)$_2$, but the intensities of the absorptions are much less.

The structure which best fits all of the results is one in which one D-Pyala$^-$ ion is tridentate, while the second is bidentate (structure I). Exchange of the coordinated pyridine group could occur through an intermediate (structure II) in which both ligands become tridentate with a trans-pyridyl structure.



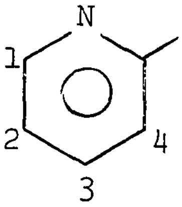
I II I

Zn(D-Pyala)$_2$. The first and second stability constants, log K_1 and log K_2, for the interaction of D-Pyala$^-$ with zinc(II) are 4.93 and 4.12,[1] respectively, whereas the values for phenylalanine are 4.29 and 4.1.[9] This suggests that at least one of the D-Pyala$^-$ ligands in Zn(D-Pyala)$_2$ is tridentate.

The infrared spectrum of Zn(D-Pyala)$_2$ was taken in D_2O as well as in KBr disk. The asymmetric $-CO_2^-$ stretching frequency, which occurs at 1570 cm^{-1} for D-Pyala$^-$ in D_2O, was shifted to 1592 cm^{-1} upon complex formation with zinc(II). This shift is similar to that reported for the zinc(II) complex of D,L-alanine in D_2O (1575 cm^{-1}, deprotonated and uncoordinated; 1592 cm^{-1}, deprotonated and coordinated to Zn(II)).[10] In a KBr pellet, Zn(D-Pyala)$_2$ showed bands at 3360-3159 cm^{-1} for the coordinated NH_2 stretches, and strong absorptions at 1611 and 1590 cm^{-1} corresponding to the $-NH_2$ scissors and $-CO_2^-$ asymmetric stretching modes. These values are comparable to those reported for bis(amino acidato)zinc(II) complexes in which the amino nitrogen and carboxylate oxygen atoms are coordinated.[23-25]

The ^1H NMR spectral data for D-PyalaH and its 2:1 zinc(II) complex in D_2O are presented in Table I. The

Table I. ^1H NMR spectra of D-PyalaH and its complexes in D_2O



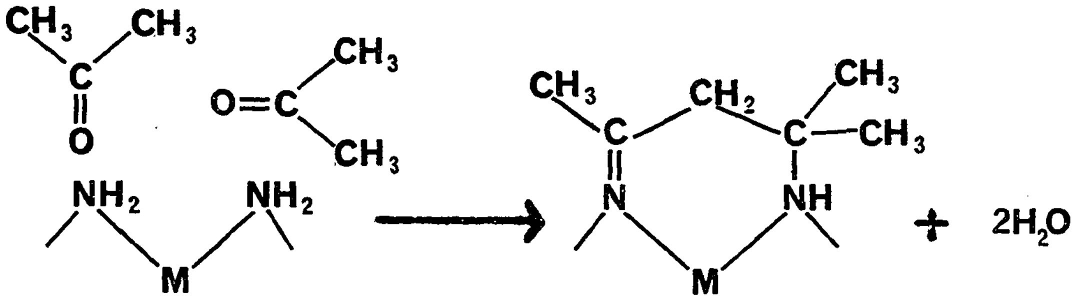
	pyridine moiety				alanine moiety	
	1 (d)[a]	2 (t)	3 (t)	4 (d)	CH	CH_2
D-PyalaH pD = 7.0	8.44	7.28	7.78	7.32	4.12	3.38
D-Pyala$^-$ pD = 10.0	8.44	7.28	7.78	7.32	3.73	3.22
Zn(D-Pyala)$_2$	8.11	7.18	7.78	7.25	3.87	3.35

[a] First order splitting ($J < 2$ Hz).

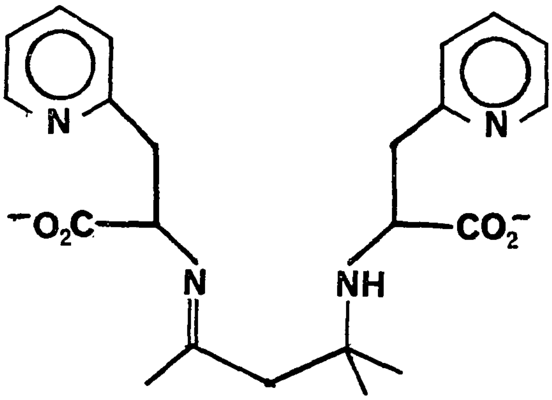
alanine moiety of D-PyalaH at pD 7.0 and 10.0 consisted of an ABX pattern, with a quartet for the methine proton and a pair of overlapping quartets for the methylene protons. The pyridine protons exhibited first and second order splitting, but the second order coupling constants are only about 2 Hz. Ignoring second order coupling, the spectra at pD 7.0 and 10.0 are: 1, doublet; 2, triplet; 3, triplet; 4, doublet. Deprotonation results in an upfield shift of the C-H and CH_2 resonances due to inductive and magnetic anisotropic effects.[26] The methine proton, which is closest to the deprotonation site (the amino group), showed the largest upfield shift. The protons of the pyridine moiety were not affected by increasing the pD from 7.0 and 10.0 (pK_a is 3.89 for pyridine nitrogen).[1] In the zinc(II) complex, the pyridine resonances, particularly that of the ortho proton, lay upfield from those observed in the spectra of D-PyalaH and D-$Pyala^-$. This shift suggests that the pyridine nitrogen atom is coordinated to zinc(II). That the amino group is also coordinated is implied by noting that the alanine resonances lie between those observed for free D-PyalaH at pD 7.0 and 10.0, where the amino group is protonated and deprotonated, respectively. These shifts are similar to those observed when L-histidine coordinates to zinc(II).[10] Coordination of the amino and carboxylate groups is also supported by ^{13}C NMR data. The α carbon and carboxylate carbon atoms were shifted from 57.25 and 182.01 ppm in D-Pyala$^-$ to 53.78 and 180.01 ppm, respectively, in Zn(D-Pyala)$_2$. A large change was also observed for the β carbon atom upon coordination, 43.11 ppm in D-Pyala$^-$, 38.45 ppm in Zn(D-Pyala)$_2$. The pyridine ^{13}C resonances in the zinc(II) complex occurred at 158.12, 148.53, 139.76, 126.38 and 123.29 ppm.

The ^{13}C NMR, ^{1}H NMR and IR spectra, as well as the formation constants for Zn(D-Pyala)$_2$, suggest tridentate chelation of the D-Pyala$^-$ molecules. Crystal structures of zinc(II) amino acid complexes have shown that the preferred geometry about the metal ion center is either regular or distorted octahedral.[27,28] The absence of any water in the crystals of Zn(D-Pyala)$_2$ suggests that the metal ion is coordinated to the amino nitrogen, pyridine nitrogen and carboxylate oxygen atoms of each D-Pyala$^-$ molecule in the solid state. Although the data obtained in solution implies that the same type of structure occurs in water, it is not possible to assign the structure to one of the three expected isomers (Figure 1).

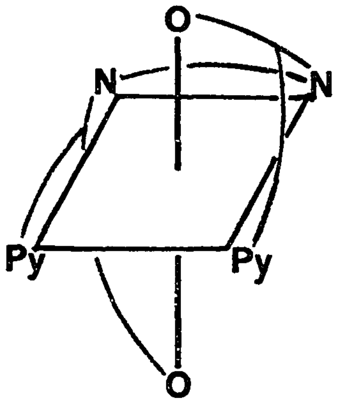
Condensation Products. The direct condensation of metal-amine complexes with acetone has been investigated in depth by Curtis.[29] We find that the reaction of M(D-Pyala)$_2$ with acetone results in the formation of the complexes in which a three carbon bridge links amine and imine donor groups.



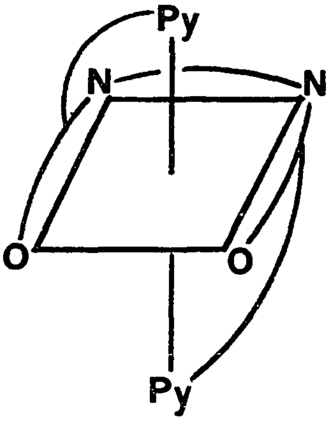
In the present case, the amine groups are part of the D-Pyala⁻ ligand, and the product formed, D,D-4,6,6-trimethyl-2,8-bis(2'-picolyl)-3,7-diazanon-3-enedioic acid, (aib-D-Pyala), is shown below:



The two possible structures for M(aib-D-Pyala) are, trans-carboxylate (III) or trans-pyridyl (IV).



III



IV

Ni(aib-D-Pyala)$\cdot H_2O$. Only one N-H stretching band at 3200 cm^{-1} was observed in the infrared spectrum of N(aib-D-Pyala)$\cdot H_2O$ in a KBr disk, compared to the two absorptions at 3305 and 3260 cm^{-1} for the $-NH_2$ groups of [Ni(D-Pyala)$_2$]$\cdot 2H_2O$.[4] Other nickel(II) complexes containing an N-H group showed a similar band.[29,30] Three intense bands were observed at 1667, 1641 and 1595 cm^{-1} in the spectrum of Ni(aib-D-Pyala)$\cdot H_2O$. In D_2O, the band at 1595 cm^{-1} remained unchanged suggesting that this is the CO_2^- asymmetric stretching mode. The sharp band at 1667 cm^{-1} is most likely the coordinated imino stretch, since this compares favorably with that found for the condensation product of acetone with bis[2-(2'-aminoethyl)pyridine)]di-isothiocyanatonickel(II),[31] at 1668 cm^{-1}. The band at 1641 cm^{-1} may be due to the water of crystallization.

The visible and CD spectra of Ni(aib-D-Pyala)·H_2O in methanol are given in Figure 4. The absorption maximum at 556 nm is similar to that observed for [Ni(D-Pyala)$_2$]·$2H_2O$, 563 nm, and suggests that the same chromophore is present in both complexes, namely NiN_4O_2. However, [Ni(aib-D-Pyala)]·H_2O has a more pronounced shoulder at about 630 nm than was observed in the spectrum of [Ni(D-Pyala)$_2$]·$2H_2O$.

The circular dichroism spectrum of Ni(aib-D-Pyala)·H_2O showed a positive band at 614 nm and two negative bands at 535 and 374 nm. There are also three transitions in the CD spectrum of [Ni(D-Pyala)$_2$]·$2H_2O$, but the signs and intensities of these bands differ from those shown for Ni(aib-D-Pyala)·H_2O. This is probably due to a number of factors, including the addition of another chelate ring, formation of an asymmetric nitrogen and most likely a different arrangement of donor atoms about the nickel center. Whether Ni(aib-D-Pyala)·H_2O has structure III or IV cannot be established on the basis of the spectral results.

Attempts to reduce the imino group with $NaBH_4$, $NaBH_3CN$, and Pd/c with H_2 in water or alcohol were unsuccessful.

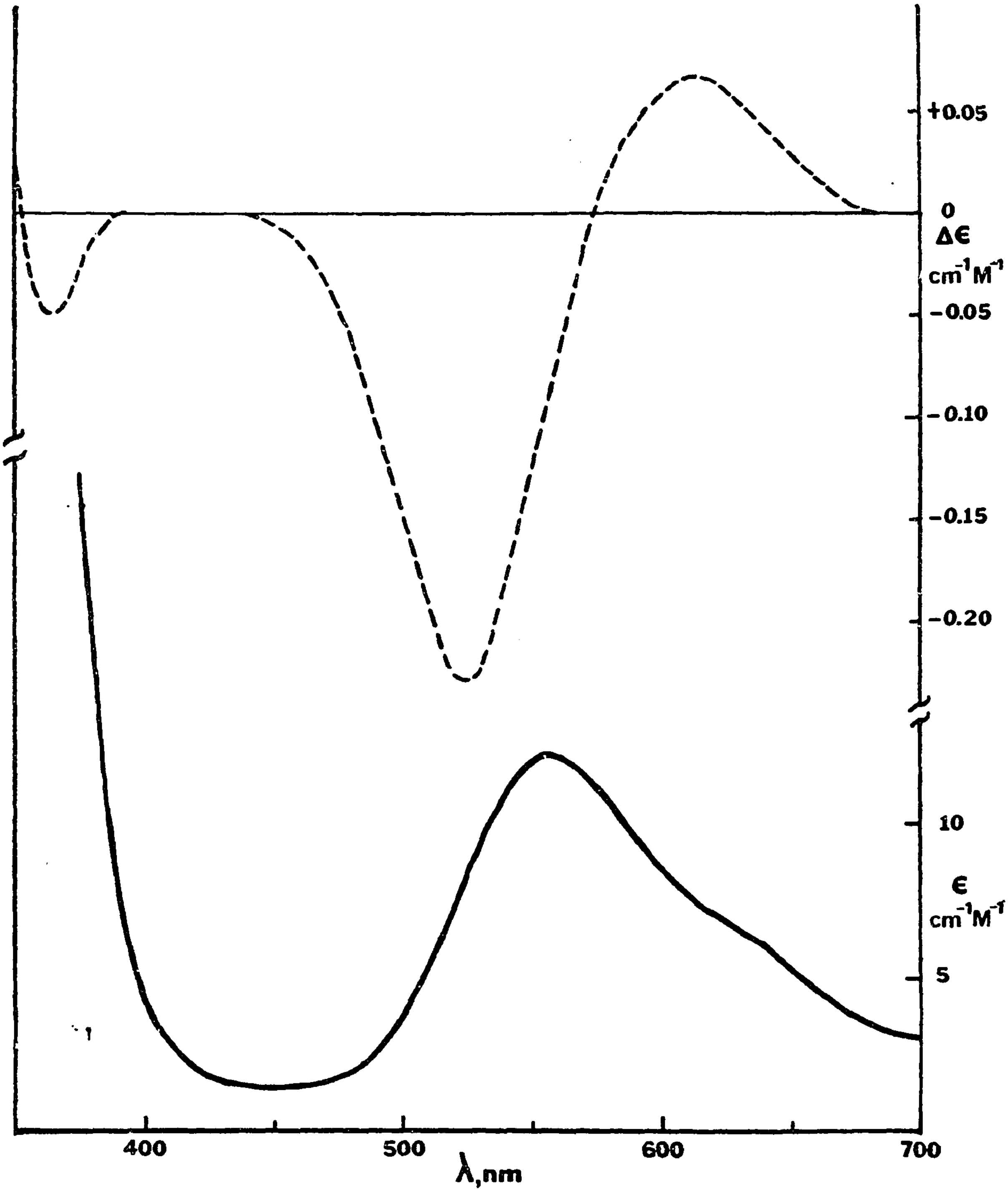


Figure 4. The visible (——) and CD (---) spectra of Ni(aib-D-Pyala)·H_2O in methanol

Cu(aib-D-Pyala)·4½H_2O. Crystals of this complex lost four molecules of water when dried under vacuum. However, the infrared spectrum remained the same, implying that no change in coordination to the copper(II) ion occurred.

The infrared spectrum of Cu(aib-D-Pyala)·4½H_2O has one N-H absorption at 3140 cm^{-1}. This band was observed at 3120 cm^{-1} in similar complexes prepared by Curtis.[30] Three bands were found in the C=N and CO_2^- region as was observed in the nickel(II) analog. The absorption at 1662 cm^{-1} may be assigned to the C=N stretch by comparison with similar copper(II) complexes such as those prepared by Curtis[30] and Rastogi and Pachauri.[32] The band at 1598 cm^{-1} may be assigned to the $-CO_2^-$ asymmetric stretching mode since in D_2O this band remained unchanged. The band at 1635 cm^{-1} is of unknown origin and may be from the water of crystallization.

The visible and CD spectra of Cu(aib-D-Pyala)·4½H_2O in methanol are given in Figure 5. The absorption maximum, 614 nm, is nearly identical with that observed for [Cu(D-Pyala)$_2$]·2H_2O, 613 nm. However, the extinction coefficient for Cu(aib-D-Pyala)·4½H_2O (119 cm^{-1} M^{-1}) is greater than that for [Cu(D-Pyala)$_2$]·2H_2O (85 cm^{-1} M^{-1}).

The CD spectrum of Cu(aib-D-Pyala)·4½H_2O differs from that of [Cu(D-Pyala)$_2$]·2H_2O in both the shape of the curve and size of $\Delta\varepsilon$. The reasons for this are probably similar to those given above for the nickel(II) complexes. The

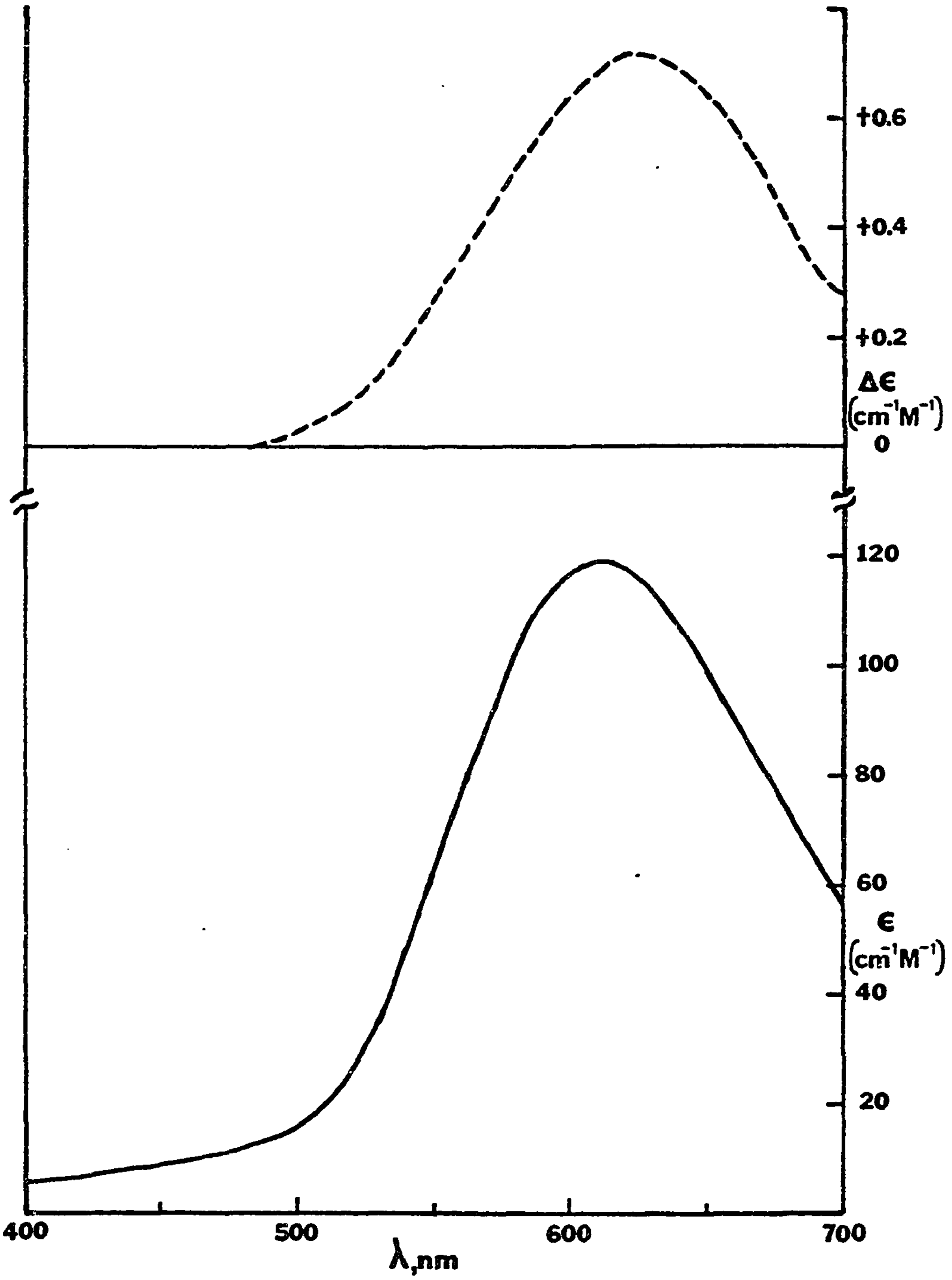


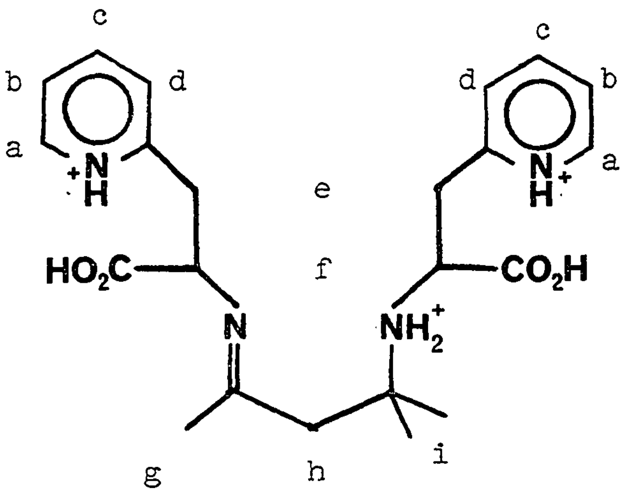
Figure 5. The visible (——) and CD (---) spectra of Cu(aib-D-Pyala)·4½H_2O in methanol

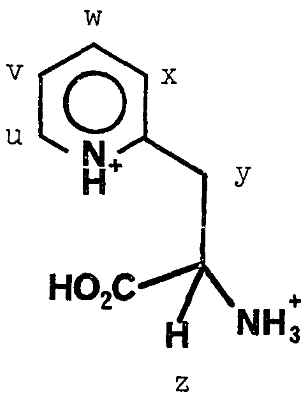
arrangement of the donor atoms about copper(II) in Cu(aib-D-Pyala) (structure III or IV) is not known.

Zn(aib-D-Pyala)·1½H_2O. The infrared spectrum of this complex in a KBr disk exhibited an NH stretch at 3212 cm^{-1} which may be compared with the $-NH_2$ stretches observed for Zn(D-Pyala)$_2$ at 3360 and 3255 cm^{-1}. The C=N stretch occurred at 1666 cm^{-1} and the asymmetric carboxylate stretch was at 1593 cm^{-1}. The infrared spectrum of the complex in D_2O showed the $-CO_2^-$ stretch at 1591 cm^{-1}, similar to that observed in the solid state.

The ^1H NMR spectrum of Zn(aib-D-Pyala)·1½H_2O was taken in 1 M D_2SO_4 because of its low solubility in water, and is reported in Table II. The appearance of peaks at 1.43, 2.26 and 3.18 ppm indicated that the diacetone amino-imine bridge was present. The pyridine region for Zn(aib-D-Pyala) was quite different from that of Zn(D-Pyala)$_2$. The positions of the pyridine peaks in Zn(aib-D-Pyala) were similar to those of D-PyalaH$_3^+$ in 1 M D_2SO_4, suggesting that the pyridyl group is protonated and not coordinated to Zn(II). It is not possible to determine if the remaining donor atoms are coordinated to Zn(II) in 1 M D_2SO_4. No structural assignment could be made from the data available.

Table II. ^1H NMR of D-PyalaH and Zn(aib-D-Pyala)·1½H_2O in 1 M D_2SO_4/D_2O





Shift (ppm)	Splitting (ignoring J < 2 Hz)[a]	No. of H's	Assignment
Zn(aib-D-Pyala)·1½H_2O			
1.43	s	6	i
2.26	s	3	g
3.18	s	2	h
3.78	d	4	f
4.62	c	2	e
8.05	t	2	b
8.09	d	2	d
8.63	t	2	c
8.79	d	2	a
D-PyalaH$_3^+$			
3.82	d	2	y
4.70	t	1	z
8.06	t	1	v
8.12	d	1	x
8.64	t	1	w
8.78	d	1	u

[a] s = singlet, d = doublet, t = triplet, c = complex.

REFERENCES

1. Rechani, P. R.; Nakon, R.; Angelici, R. J. Bioinorg. Chem. 1976, 5, 329.
2. Ebner, S. R.; Jacobson, R. A.; Angelici, R. J. Inorg. Chem. 1979, 18, 765.
3. Ebner, S. R.; Angelici, R. J. Submitted for publication to Inorg. Chem.
4. Ebner, S. R.; Helland, B. J.; Jacobson, R. A.; Angelici, R. J. Submitted for publication to Inorg. Chem.
5. Bedell, S. A.; Rechani, P. R.; Angelici, R. J.; Nakon, R. Inorg. Chem. 1977, 16, 972.
6. Dietrich, H. G.; Johnston, J. J. Amer. Chem. Soc. 1927, 49, 1419.
7. Lepore, A. Anales asoc. quim. y farm. Uraguary 1946, 48, 5; Chem. Abstr. 1949, 43, 7361h.
8. Sillen, L. G.; Martell, A. E. "Stability Constants of Metal-Ion Complexes", Special Publications No. 17 and 25, The Chemical Society, Burlington House, London, 1964 and 1971.
9. Brookes, G.; Pettit, L. D. J. Chem. Soc. Dalton Trans. 1977, 1918.
10. Carlson, R. H.; Brown, T. L. Inorg. Chem. 1966, 5, 268.
11. Sarkar, B.; Wigfield, Y. J. Biol. Chem. 1967, 242, 5572.
12. Nakamoto, K. "Infrared and Raman Spectra of Inorganic and Coordination Compounds", Wiley, New York, N.Y., 1978, 3rd ed.
13. Kruck, T.; Sarkar, B. Can. J. Chem. 1973, 51, 3563.
14. Fish, R. H.; Windle, J. J.; Gaffield, W.; Scherer, J. R. Inorg. Chem. 1973, 12, 855.
15. Nakamoto, K.; McCarthy, P. J. "Spectroscopy and Structure of Metal Chelate Compounds", Wiley, New York, N.Y., 1968.

16. McCormick, D. B.; Sigel, H.; Wright, L. D. Biochim. Biophys. Acta 1969, 184, 318.

17. Tsangaris, J. M.; Martin, R. B. J. Amer. Chem. Soc. 1970, 92, 4255.

18. Walker, W. R.; Shaw, Y. L.; Li, N. C. J. Coord. Chem. 1973, 3, 77.

19. Wilson, E. W., Jr.; Kasperian, M. H.: Martin, R. B. J. Amer. Chem. Soc. 1970, 92, 5365.

20. Wilson, E. W., Jr.; Martin, R. B. Inorg. Chem. 1971, 10, 1197.

21. Hawkins, C. J.; Wong, C. L. Aust. J. Chem. 1970, 23, 2237.

22. Yasui, T. Bull. Chem. Soc. Japan 1965, 38, 1746.

23. Inomata, Y.; Inomata, T.; Moriwaki, T.; Walter, J. L. Spectrochim. Acta 1973, 29A, 1933.

24. Jackovitz, J. F.; Walter, J. L. Spectrochim. Acta 1966, 22, 1393.

25. Jackovitz, J. F.; Durkin, J. A.; Walter, J. L. Spectrochim. Acta 1967, 23A, 67.

26. Spiesecke, H.; Schmeider, W. G. J. Chem. Phys. 1961, 35, 722.

27. Freeman, H. C. Adv. Protein Chem. 1967, 22, 257.

28. Chow, S. T.; McAuliffe, C. A. Prog. Inorg. Chem. 1975, 19, 51.

29. Curtis, N. F. Coord. Chem. Rev. 1968, 3, 3.

30. Curtis, N. F. J. Chem. Soc. Dalton Trans. 1974, 347.

31. Curtis, N. F. J. Chem. Soc. Dalton Trans. 1974, 91.

32. Rastogi, D. K.; Pachauri, P. C. Ind. J. Chem. 1977, 15A, 47.

SUMMARY

In an effort to understand the preferred stereochemistries of $M(Pyala)_2$ complexes, a series of $Pyala^-$ complexes with different metal atoms were prepared. Initially, cobalt(III) complexes of D-$Pyala^-$ and D,L-$Pyala^-$ were investigated. Five geometrical isomers are possible for the coordination of D,L-$Pyala^-$ to Co(III) (Figure 1). In an attempt to isolate all of these isomers and identify the most stable complex, several different cobalt starting materials were used including $[Co(NH_3)_4CO_3]NO_3$, $[Co(NH_3)_6](NO_3)_3$, $Na_3[Co(CO_3)_3]\cdot 3H_2O$ and $Co(NO_3)_2\cdot 6H_2O$. The most stable isomer was found to be all-cis $Co(L\text{-}Pyala)(D\text{-}Pyala)^+$. The all-cis structure was preferred over trans-carboxylate $Co(D\text{-}Pyala)_2^+$ (or $Co(L\text{-}Pyala)_2^+$), which was the favored configuration of the $Co(D\text{-}Pyala)_2^+$ complex. The systematic absence or isolation in low yields of certain structural types for $Co(D\text{-}Pyala)_2^+$ and $Co(L\text{-}Pyala)(D\text{-}Pyala)^+$, suggested several rules governing the stability of the cobalt(III) complexes. First, amino nitrogen atoms prefer not to be trans to each other. Second, pyridine nitrogen atoms also prefer not to occupy trans positions. Third, the amino nitrogen prefers the position trans to the pyridine nitrogen. These rules could not be rationalized by steric arguments which consider the bulkiness of the pyridine group as the determining structural

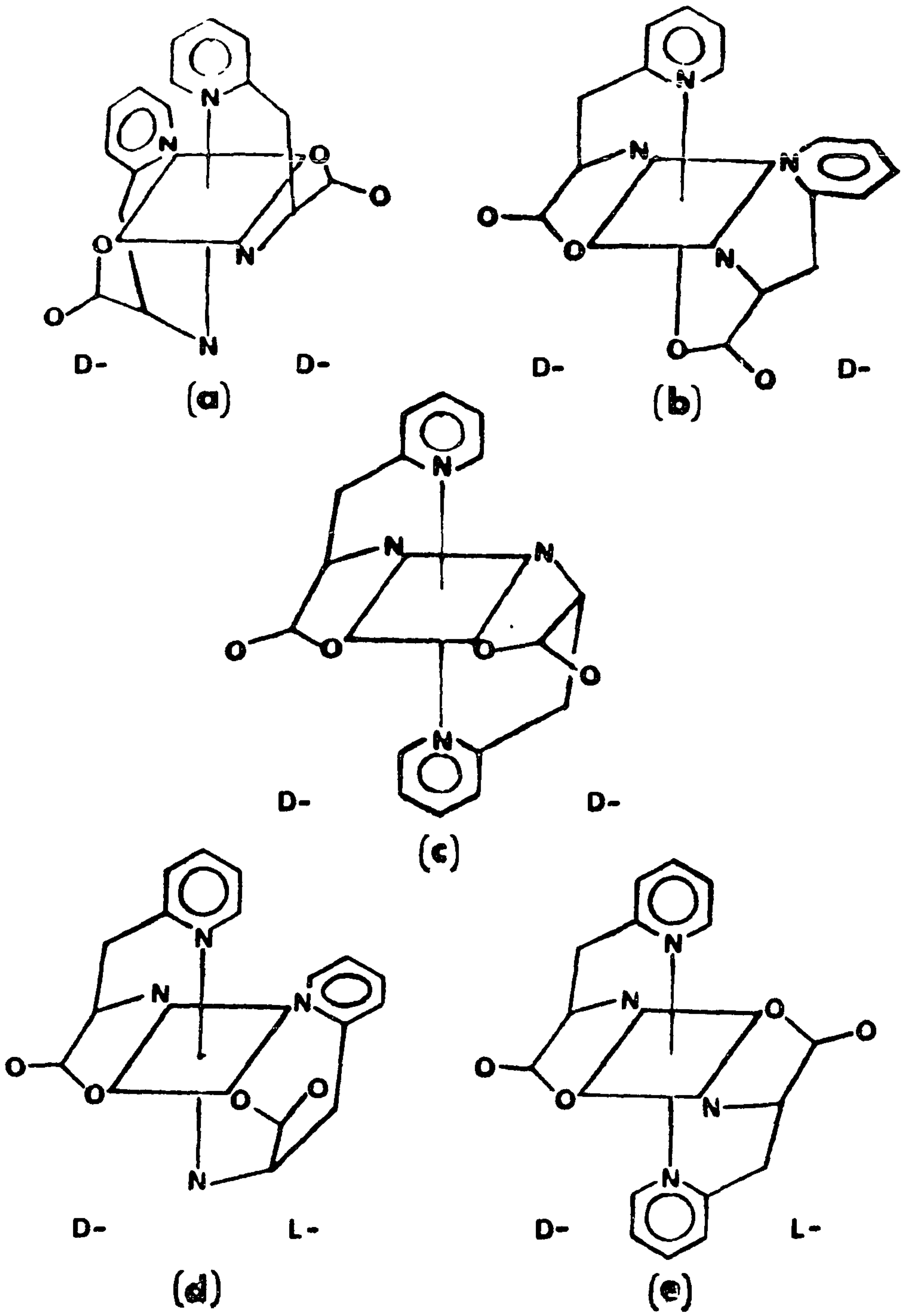


Figure 1. The five possible geometrical isomers of $M(Pyala)_2$ obtained from reaction of a metal ion with D,L-PyalaH: (a) trans-carboxylate, (b) trans-amino, (c) trans-pyridyl, (d) all-cis and (e) all-trans

factor. This implied that the positions of the coordinating groups are determined by electronic effects, such as π acceptor and σ donor strengths. This work was extended to include several mixed complexes of the type Co(L-Pyala)(A) where A = L-histidinate, D- or L-aspartate, or iminodiacetate. The major species in each of the reaction solutions was generally that predicted by the above rules. Therefore, these rules may be applicable to a range of cobalt(III) complexes.

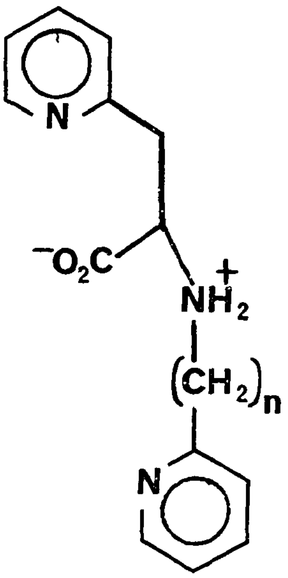
The preferred configuration of Ni(D-Pyala)$_2$ appears to have trans amino nitrogens (1b), contrary to the structure proposed previously based on formation constants, where the pyridine groups were assumed to be trans (1c).[2] A preference for trans amino groups requires that the pyridine groups be cis to each other. The greater stability of Ni(D-Pyala)(L-Pyala) may be due to structure 1e, in which the bulky pyridine groups are trans to each other, as are the amino groups.

Previously, the four nitrogen donors of D-Pyala$^-$ were throught to lie in the same plane around Cu(II).[2] The present work has shown that this is probably not the case, and the proposed structure of Cu(D-Pyala)$_2$ has trans pyridine nitrogens (1c).

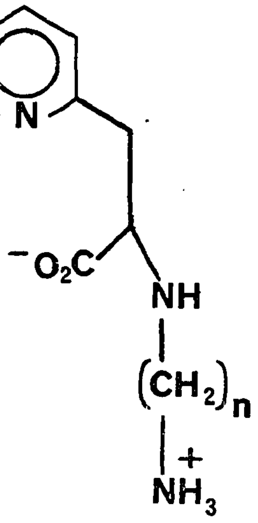
The rules derived from cobalt(III) studies could not be generalized to include the labile metal ion complexes of D-Pyala$^-$. The implications are that both electronic and steric factors may be important in determining the most stable structure. The radius of the metal ion as well as d orbital occupancy may also be influential.

The work described here has triggered several ideas for future studies. Isolation and characterization of other transition metal complexes of D-Pyala$^-$, such as Mn(II), Fe(II), Fe(III), Co(II), Pd(II), Pt(II) and Cd(II), will aid in determining the properties of the metal ion that influence the most stable structure. Relatively few amino acid complexes of lanthanide metals have been reported, although interesting visible and circular dichroism spectra are observed in these complexes.[3] Isolation and characterization of these lanthanide complexes could prove interesting.

The present work has also suggested several possible ligands which will aid in determining the origins of the stereoselective effect. Two of the more promising possibilities are shown below. These are designed with the hope

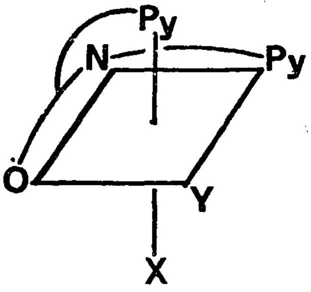


I



II

that their coordination to the metal ion will be predetermined by the donor groups, for example, the rules governing the cobalt(III) complexes suggest that I would preferentially coordinate to Co(III) as shown below:



III

The coordination of an amino acid would also be determined by the rules with the amino nitrogen occupying position x and carboxylate oxygen occupying position y. The steric interaction between the side chain of the amino acid and the pyridine rings can be studied by comparing the stability of III with the D- and L- forms of the amino acid.

LITERATURE CITED

1. Ritsma, J. H., Thesis, University of Groningen, Netherlands, 1973.

2. Rechani, P. R.; Nakon, R.; Angelici, R. J. *Bioinorg. Chem.* *1976*, 5, 329.

3. Katzin, L. I. *Coord. Chem. Rev.* *1970*, 5, 279.

ACKNOWLEDGEMENTS

I wish to thank Dr. Robert J. Angelici who instigated this work and whose guidance kept me from falling astray. I am deeply indebted to Larry A. Meiske and Man Sheung Ma for hours of valuable discussion. A special thanks to Mrs. Sue Musselman who typed and organized this dissertation. And finally, I am deeply grateful to my loving wife, Coleen, who was always there in time of need.