Contribution from the Department of Chemistry,
Iowa State University, Ames, Iowa 50011

Synthesis and Spectral Characterization of the Mixed-Ligand Complexes [*N*-(Carboxymethyl)-L-β-(2-pyridyl)-α-alaninato][amino acidato]cobalt(III), Co(*N*-Cm-L-Pyala)(AA)

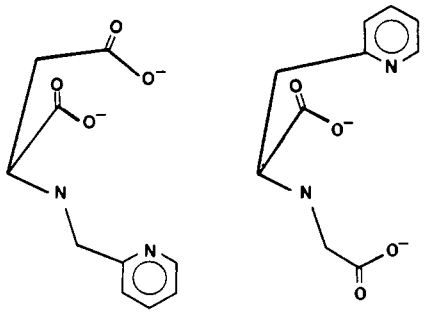
LARRY A. MEISKE and ROBERT J. ANGELICI*

Received March 13, 1980

A series of mixed-ligand complexes of the form Co(*N*-Cm-L-Pyala)(AA) was prepared by H_2O_2, PbO_2, or $K_2S_2O_8$ oxidation of Co(II) to Co(III) in the presence of the tetradentate ligand *N*-(carboxymethyl)-L-β-(2-pyridyl)-α-alaninate, *N*-Cm-L-Pyala^{2-}, and a bidentate amino acidate, AA$^-$ (where AA$^-$ is one of the following: glycinate, α-aminoisobutyrate, D,L-alaninate, D-threoninate, D-, L-, and D,L-valinate, D-asparaginate). The facial $Co^{III}N_3O_3$ isomer in which the *N*-carboxymethyl group of *N*-Cm-L-Pyala^{2-} is coordinated trans to the pyridyl group was obtained for all the amino acidates above, except for L-valinate. The meridional $Co^{III}N_3O_3$ isomer, in which the amino nitrogen of the amino acidate is coordinated trans to the pyridyl group of *N*-Cm-L-Pyala^{2-}, was also obtained for all the amino acidates listed above but in much lower yields than the facial isomer. The distribution of isomers is discussed in terms of a combination of electronic, structural, and steric factors. It is suggested that if steric factors (interaction of bulky groups) are absent, the facial isomer is structurally preferred, while if steric factors are present, the meridional isomer is preferred. Circular dichroism spectra of the meridional complexes were resolved into contributions from the optically active portion of the amino acidate chelate ring (*Y*) and from the rest of the molecule (*X*). In addition, the visible, ^{13}C NMR, ^1H NMR, and circular dichroism spectra of the complexes are discussed.

Introduction

The preparation and characterization of the mixed-ligand $Co^{III}N_3O_3$ complexes containing the tetradentate *N*-(2-pyridylmethyl)-L-aspartate, PLASP^{2-}, and a bidentate amino acidate, AA$^-$, have been reported previously.[1,2] The only isomer isolated for the various amino acidates was the facial $Co^{III}N_3O_3$ isomer shown in Figure 1a in which the β-CO_2^- group of PLASP^{2-} is coordinated trans to the pyridyl group. The bidentate amino acidate is coordinated with its amino group trans to the α-CO_2^- of PLASP^{2-} and its α-CO_2^- group trans to the secondary amino group of PLASP^{2-}. We suggested that coordination as in Figure 1a would be electronically favored since the amino nitrogens (and pyridyl nitrogen) are coordinated trans to oxygens (carboxylate groups).[1,2] This is consistent with other results, which indicate that amino nitrogens avoid trans positions[3] and that for $ML_3L'_3$ systems the facial isomers should be favored.[4] We also noted that steric factors (interactions of the amino acidate chelate ring and the pyridyl group of PLASP^{2-}) do not appear to play a large role in determining the overall geometry of the Co(PLASP)(AA) complexes.[2] Finally, we concluded that coordination as in Figure 1a would give the least strained bond angle around the secondary amino nitrogen of PLASP^{2-} and would be favored over the more strained structures in which the pyridyl group is trans to the α-CO_2^- of PLASP^{2-}.



We have also reported the preparation and characterization of the mixed-ligand Co(*N*-Cm-L-Pyala)(D-Thr) complex, where *N*-Cm-L-Pyala^{2-} is *N*-(carboxymethyl)-L-β-(2-pyridyl)-α-alaninate (see above) and D-Thr$^-$ is the bidentate amino acidate D-threoninate.[5] We found that the major isomer is the facial isomer shown in Figure 2a. A second isomer that has the meridional geometry as shown in Figure 2c was also isolated but in lower yield. We concluded that the formation of the meridional isomer in the *N*-Cm-L-Pyala^{2-} case and not in the PLASP^{2-} case is due to the greater flexibility of the *N*-carboxymethyl chelate ring as compared to that of the *N*-pyridylmethyl chelate ring.[3]

In order to study further the effect of electronic and structural factors on the overall geometries of $Co^{III}N_3O_3$ complexes, we prepared a series of complexes of the type Co(*N*-Cm-L-Pyala)(AA) where AA$^-$ is one of the following: glycinate, Gly$^-$; α-aminoisobutyrate, α-AIBA$^-$; D,L-alaninate, D,L-Ala$^-$; D-threoninate, D-Thr$^-$; D and L and D,L-valinate, Val$^-$, D-asparaginate, D-AsN$^-$. Their structures and trends in their visible, CD, and NMR spectra are compared to those reported for the Co(PLASP)(AA) complexes.

Experimental Section

Materials. All amino acids were purchased from Aldrich or Eastman Chemicals and were used without further purification. The ligand *N*-Cm-L-PyalaH$_2$ was prepared as previously reported.[6]

Preparation of the [*N*-(Carboxymethyl)-L-β-(2-pyridyl)-α-alaninato][amino acidato]cobalt(III), Co(*N*-Cm-L-Pyala)(AA), Complexes. The method of preparation, yields, and elemental analyses of each Co(*N*-Cm-L-Pyala)(AA) complex are given in Table I.

Method A. This procedure, which uses excess hydrogen peroxide to oxidize Co(II) to Co(III) in the presence of *N*-Cm-L-Pyala^{2-} and AA$^-$, has been described previously.[5] All reactions were carried out with use of 2.5 mmol of *N*-Cm-L-Pyala^{2-}, 2.5 mmol of AA$^-$, 2.5 mmol of $CoSO_4 \cdot 7H_2O$, and activated carbon (0.1 g). The less soluble facial isomer of Co(*N*-Cm-L-Pyala)(AA) precipitated during the reaction and was filtered off with the activated carbon. The reddish pink isomer was separated from the carbon by stirring the carbon and product mixture with 100 mL of water and filtering off the carbon. This was repeated until the filtrate was colorless. All filtrates were combined and reduced to near dryness under vacuum to give a reddish pink solid.

(1) Meiske, L. A.; Jacobson, R. A.; Angelici, R. J. *Inorg. Chem.* **1980**, *19*, 2028.
(2) Meiske, L. A.; Angelici, R. J. *Inorg. Chem.* **1980**, *19*, 3783.
(3) Ebner, S. R.; Angelici, R. J. *Inorg. Chem.* **1980**, *19*, 1031.
(4) Burdett, J. K. *Adv. Inorg. Chem. Radiochem.* **1978**, *21*, 113.
(5) Meiske, L. A.; Jacobson, R. A.; Angelici, R. J. *Inorg. Chem.* **1981**, *20*, 1794.
(6) Bedell, S. A.; Rechani, P. R.; Angelici, R. J.; Nakon, R. *Inorg. Chem.* **1977**, *16*, 972.

0020-1669/82/1321-0731$01.25/0

Table I. Syntheses, Yields, and Elemental Analyses of Co(*N*-Cm-L-Pyala)(AA) Complexes

complex	method of prepn	% yield	formula		anal. % C	% H	% N
I, *fac*-[Co(*N*-Cm-L-Pyala)(Gly)]·H_2O	C	56	$C_{12}H_{14}N_3O_6Co·H_2O$	theory	38.62	4.29	11.26
				found	38.63	4.50	11.19
II, *fac*-[Co(*N*-Cm-L-Pyala)(D,L-Ala)]·$^1/_2H_2O$	B	31	$C_{13}H_{16}N_3O_6Co·^1/_2H_2O$	theory	41.28	4.50	11.11
				found	41.50	5.16	11.24
III, *fac*-[Co(*N*-Cm-L-Pyala)(α-AIBA)]·$^1/_2H_2O$	A	9	$C_{14}H_{18}N_3O_6Co·^1/_2H_2O$	theory	42.87	4.86	10.74
	C	31		found	43.23	4.63	10.64
IV, *fac*-[Co(*N*-Cm-L-Pyala)(D-Thr)]·H_2O	A	15	$C_{14}H_{18}N_3O_7Co·H_2O$	theory	40.30	4.80	10.07
				found	40.36	5.14	10.05
V, *fac*-[Co(*N*-Cm-L-Pyala)(D-Val)]	A	30	$C_{15}H_{20}N_3O_6Co$	theory	45.35	5.42	10.58
	C	40		found	45.18	5.27	10.52
VI, *fac*-[Co(*N*-Cm-L-Pyala)(D-Val)][a]	A	25[b]	$C_{15}H_{20}N_3O_6Co$	theory	45.35	5.04	10.58
				found	45.07	5.04	10.48
VII, *fac*-[Co(*N*-Cm-L-Pyala)(D-AsN)][a]	C	22[b]	$C_{14}H_{17}N_4O_7Co$	theory	39.08	4.42	13.03
				found	38.62	4.85	13.68
VIII, *mer*-[Co(*N*-Cm-L-Pyala)(D,L-Ala)]·$2H_2O$	B	5	$C_{13}H_{16}N_3O_6Co·2H_2O$	theory	38.78	4.94	10.37
				found	38.60	5.05	10.32
IX, *mer*-[Co(*N*-Cm-L-Pyala)(α-AIBA)]·$^1/_2H_2O$	A	18	$C_{14}H_{18}N_3O_6Co·^1/_2H_2O$	theory	42.87	4.86	10.74
	C	<1		found	42.95	4.88	10.70
X, *mer*-[Co(*N*-Cm-L-Pyala)(D-Thr)]·$^1/_2H_2O$	A	7	$C_{14}H_{18}N_3O_7Co·^1/_2H_2O$	theory	41.19	4.66	10.30
				found	41.87	4.79	10.30
XI, *mer*-[Co(*N*-Cm-L-Pyala)(D-Val)]·$^1/_2H_2O$	A	1	$C_{15}H_{20}N_3O_6Co·^1/_2H_2O$	theory	42.46	5.42	9.91
				found	42.39	5.19	9.95
XII, *mer*-[Co(*N*-Cm-L-Pyala)(L-Val)]·H_2O	A	13	$C_{15}H_{20}N_3O_6Co·H_2O$	theory	43.38	5.30	10.12
				found	43.62	5.50	10.32
XIII, *mer*-[Co(*N*-Cm-L-Pyala)(D,L-Val)]·H_2O	A	32[b]	$C_{15}H_{20}N_3O_6Co·H_2O$	theory	43.38	5.30	10.12
				found	43.64	5.47	10.15

[a] Isolated with use of D,L-AA^- in the synthesis. [b] Based on total D- and L-AA^-.

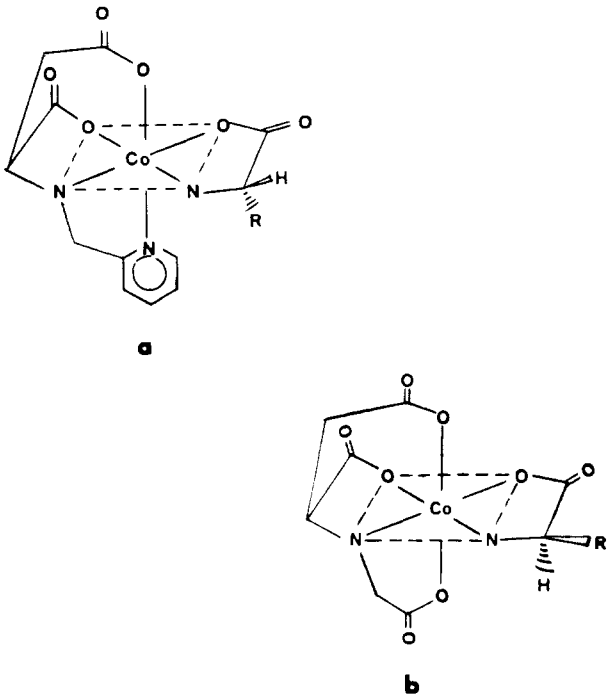


Figure 1. (a) The facial isomer of Co(PLASP)(L-AA) and (b) the cis-N,cis-O_5 isomer of Co(*N*-Cm-L-Asp)(D-AA).

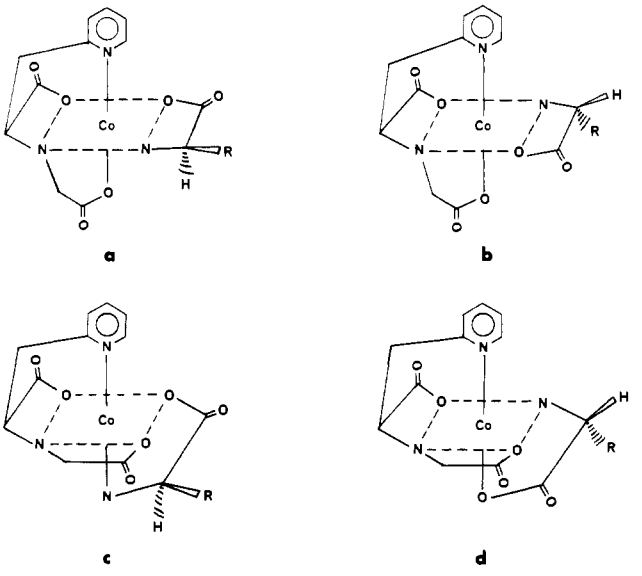


Figure 2. The four possible geometrical isomers of [Co(*N*-Cm-L-Pyala)(D-AA)]: (a) *fac*; (b) *mer*-*N*-Cm-CO_2^-; (c) *mer*-AA^- amino; (d) *mer*-$AA^-CO_2^-$.

This solid was filtered, washed with MeOH, and then vacuum-dried. Identification of the reddish pink solid as the facial isomer was based on its visible spectrum.

The original filtrate from the reaction mixture was reduced to near dryness (5–10 mL) and placed on a Dowex 50W-X8 ion-exchange column (2.5 × 65 cm, 200–400 mesh) in the Na^+ form. The column was eluted with water to give, usually, two bands; the first off contained the meridional isomer, salts, and unreacted materials; the second contained any remaining facial isomer. The solution from band two containing the facial isomer was reduced to near dryness in a rotary evaporator to give a reddish pink solid. The band containing the meridional isomer was reduced to 5 mL and placed on an acidic alumina column. (The size of the column depended upon the yield of the meridional isomer; for amounts of less than 0.1 g a 1.9 × 50 cm column was used, while a column 2.5 × 65 cm was used for amounts greater than 0.1 g as for the Co(*N*-Cm-L-Pyala)(L-Val) complex.) The meridional complex was eluted with a 75:25 MeOH–H_2O solvent to give two bands. Band one contained salts and decomposition products while band two contained the purple meridional isomer. The purple band was collected and reduced under vacuum to near dryness. Next a large volume (100–150 mL) of absolute ethanol was added to cause precipitation. The resulting solid was filtered and washed with acetone. The meridional product, identified by its visible spectrum, can be recrystallized for analysis by dissolving in a minimum volume of water and adding a volume of ethanol equal to 4–5 times that of water to force precipitation.

Method B, Preparation of [Co(*N*-Cm-L-Pyala)(D,L-Ala)]. This procedure uses PbO_2 to oxidize Co(II) to Co(III) in the presence of *N*-Cm-L-$Pyala^{2-}$ and D,L-Ala^- and is similar to the synthesis described for Co(PLASP)(D,L-Val).[2] *N*-Cm-L-$PyalaH_2$ (0.056 g, 2.5 mmol), D,L-AlaH (0.20 g, 2.5 mmol), $CoSO_4·7H_2O$ (0.70 g, 2.5 mmol), and 5 mL of 1 N NaOH were dissolved in 50 mL of water, and PbO_2 (0.35

Table II. Visible Absorption Maxima for Co(*N*-Cm-L-Pyala)(AA) Complexes in Water

complex	λ, nm	ε, cm^{-1} M^{-1}	λ, nm	ε, cm^{-1} M^{-1}	λ, nm	ε, cm^{-1} M^{-1}
I	522	153			367	120
II	521	155			368	117
III	521	164			369	127
IV	522	159			369	131
V	520	167			368	119
VI[a]	520	169			368	125
VII[a]	520	168			370	127
VIII	546	194	474	105	373	194
IX	543	191	474	104	371	197
X	545	177	472	96	370	184
XI	544	182	472	99	372	186
XII	543	186	474	101	371	189
XIII	544	177	472	97	371	184

[a] Isolated from the reaction using D,L-AA^-.

g, 1.5 mmol) was added. After the solution was heated at 70 °C for 45 min, 2.5 mL of 1 N H_2SO_4 was added, and the solution was filtered. The filtrate was reduced under vacuum until a reddish pink precipitate formed. This was filtered and found to be the facial isomer by its visible spectrum. The remaining solution was reduced to 1–2 mL and placed on a Dowex 50W-X8 column in the Na^+ form. The facial and meridional isomers were chromatographed and isolated as described in Method A.

Method C. The ligands *N*-Cm-L-PyalaH_2 (0.056 g, 2.5 mmol) and AAH (2.5 mmol) and $CoSO_4 \cdot 7H_2O$ (0.70 g, 2.5 mmol) were placed in 10 mL of water. Next 7.5 mL of 1 N NaOH was added to give a brown solution of pH 9. After the solution was stirred for 5 min, activated carbon (0.1 g) was added. This was followed by the addition of a solution of $K_2S_2O_8$ (0.4 g, 1.5 mmol) in 15 mL of water. At this point each reaction was treated somewhat differently. Each product discussed below was identified by its visible spectrum.

In the synthesis of the α-$AIBA^-$ complexes, the solution was heated for 1 h at 60 °C and filtered to give a deep reddish purple solution. The solution was reduced to 10–15 mL and placed on a 2.5 × 65 cm Dowex 50W-X8 column in the Na^+ form. Elution with water gave two bands. The first band contained the meridional isomer, which was further purified by chromatography on an acidic alumina column as described in Method A. The second band containing the facial isomer was reduced to near dryness, and ~150 mL of ethanol was added to cause precipitation. The precipitate was filtered off and vacuum-dried.

The facial D-AsN^- complex was prepared as described for the α-$AIBA^-$ complex above with use of D,L-AsN^- in the synthesis. A trace of the meridional isomer was isolated and identified by its ^{13}C NMR spectrum.

For the synthesis of the D-Val^- complexes, the reaction solution was stirred for 1 h at room temperature to give the facial isomer as a reddish pink precipitate mixed with the activated charcoal. The facial isomer and carbon were filtered off. The filtrate was reduced to 5–10 mL to give more of the facial isomer, which was filtered and washed with 30 mL of water. Reduction of this second filtrate followed by chromatography on Dowex 50W-X8 in the Na^+ form as for the α-$AIBA^-$ complex above failed to yield any of the meridional isomer. The facial isomer and carbon were extracted with water (100 mL) and filtered. This was repeated until the filtrate was clear. The solutions containing the facial isomer were combined and reduced to near dryness. The solid was filtered, washed with MeOH, and dried under vacuum.

In the synthesis of the Gly^- complex the reaction solution was stirred for 1 h at room temperature and filtered to give a deep purple solution characteristic of the meridional isomer. This solution was placed on a rotary evaporator, and when it was heated, a reddish pink precipitate, which was identified by its visible spectrum to be the facial isomer, formed. The facial isomer was filtered off. The filtrate was reduced to 5–10 mL and chromatographed on Dowex 50W-X8 in the Na^+ form. Upon elution with water two bands formed. The first was purple, but no solid resembling the meridional isomer was isolated from it. The second band contained more of the facial isomer.

Isomerization of *mer*-Co(*N*-Cm-L-Pyala)(α-AIBA). Upon standing for several weeks at room temperature, an aqueous solution of the meridional α-$AIBA^-$ isomer was chromatographed on Dowex 50W-X8 in the Na^+ form to give two bands. Band one contained the major product and was identified by its visible spectrum as the meridional isomer. The visible spectrum of band two showed it to be *fac*-Co(*N*-Cm-L-Pyala)(α-AIBA).

A sample of the meridional isomer (~0.1 g) was placed in 10 mL of water and heated at ~60 °C for 1 h. The solution was cooled to room temperature and chromatographed on Dowex 50W-X8 in the Na^+ form to give two bands. The first band off the column was the meridional isomer while the second band was the facial isomer. Each isomer was identified by its visible spectrum.

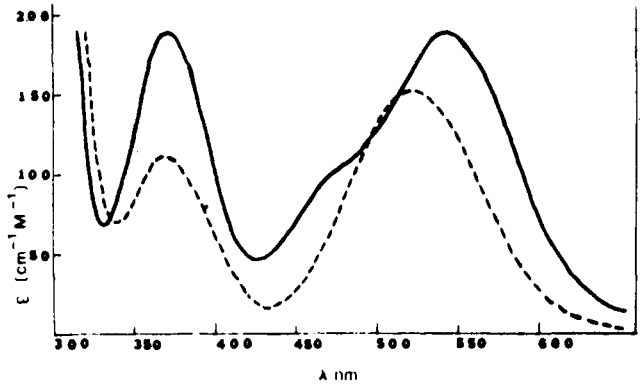


Figure 3. Visible spectra of *mer*-[Co(*N*-Cm-L-Pyala)(D-Thr)]·$^1/_2H_2O$ (—) and *fac*-[Co(*N*-Cm-L-Pyala)(D-Thr)]·H_2O (- - -) in water.

Spectra. Visible spectra were recorded at room temperature in water on a Cary Model 14 spectrophotometer, while the circular dichroism spectra were measured in water at room temperature with use of a Jasco ORD/UV/CD-5 spectrophotometer. Proton NMR spectra were recorded at room temperature on a Jeol FX90Q Fourier transform NMR spectrometer in 99.7% deuterium oxide, with *tert*-butyl alcohol (δ 1.23) as an internal standard. The ^{13}C NMR spectra were also recorded on the above NMR spectrometer in either 99.7% deuterium oxide or 70% H_3PO_4 (aqueous), with 1,4-dioxane (67.0 ppm downfield from Me_4Si) as an internal standard.

Results and Discussion

The four possible geometric isomers of the Co(*N*-Cm-L-Pyala)(D-AA) complex are shown in Figure 2. The structure in Figure 2a has a facial arrangement of oxygen atoms while the three structures in Figure 2b–d have a meridional arrangement of oxygen atoms. For the differentiation of the various meridional isomers, the terms *N*-Cm-CO_2^-, AA^- amino, and $AA^-CO_2^-$ following the word *mer* in Figure 2 are used to denote which group is coordinated trans to the pyridyl group of *N*-Cm-L-$Pyala^{2-}$. It should be noted that the term meridional isomer will be used throughout the rest of this paper to refer to the *mer*-AA^- amino isomer in Figure 2c.

Visible Spectra of the Co(*N*-Cm-L-Pyala)(AA) Complexes. Figure 3 shows visible spectra of *mer*-[Co(*N*-Cm-L-Pyala)(D-Thr)]·$^1/_2H_2O$ and *fac*-[Co(*N*-Cm-L-Pyala)(D-Thr)]·H_2O. These spectra are typical of the other Co(*N*-Cm-L-Pyala)(AA) complexes whose maxima are presented in Table II. The visible spectra of the facial isomers with their two symmetrical peaks at 520 ± 1 nm ($\epsilon \approx 160$) and 368 ± 2 nm ($\epsilon \approx 125$)

Table III. Circular Dichroism Maxima and Minima for the Co(*N*-Cm-L-Pyala)(AA) Complexes in Water

	band I				band II	
complex	λ, nm	$\Delta\epsilon$[a]	λ, nm	$\Delta\epsilon$	λ, nm	$\Delta\epsilon$
I	554	+4.19	488	−2.60	350	+0.77
II	555	+4.10	490	−2.67	352	+0.78
III	557	+4.30	488	−2.27	353	+0.82
IV	555	+4.82	488	−2.17	353	+0.87
V	557	+4.99	488	−2.02	352	+0.89
VI[b]	557	+5.05	488	−2.12	352	+0.94
VII[b]	557	+3.63	488	−1.82	353	+0.76
VIII	555	−0.13	465	−1.50	380	+0.34
IX	554	+0.06	468	−1.80	375	+0.36
X	553	+1.22	465	−2.37	370	+0.68
XI	554	+0.83	464	−1.86	372	+0.50
XII	545	−0.83	460	−1.57	376	+0.11
XIII	545	−0.14	465	−1.65	375	+0.36

[a] Units for $\Delta\epsilon$ are $cm^{-1}\ M^{-1}$, and an estimate of experimental error in $\Delta\epsilon$ is $\pm 0.05\ cm^{-1}\ M^{-1}$ for band I of the facial isomer. All others are approximately $\pm 0.1\ cm^{-1}\ M^{-1}$. [b] Isolated from the procedure using D,L-AA$^-$ in the synthesis.

are comparable to those reported for the facial Co(PLASP)(AA) mixed-ligand complexes, which have two symmetrical peaks at 513 ± 4 and 370 ± 3 nm.[1,2] Since the absorption maxima and extinction coefficients for the facial complexes listed in Table II are so similar, they are all assigned the structure of the facial isomer shown in Figure 2a. Visible spectra of the meridional isomers in Table II are comparable to those of other meridional $Co^{III}N_3O_3$ complexes reported previously.[3,5,7] Since the X-ray structure analysis of the *mer*-[Co(*N*-Cm-L-Pyala)(D-Thr)]·$^1/_2H_2O$ showed the structure of this complex to be that shown in Figure 2c and the spectra of all the meridional isomers in Table II are so similar, they are all assigned this structure.[5] The shoulder (~474 nm) on the high-energy side of the peak at ~544 nm is typical of other reported complexes having imidazole or pyridine coordinated trans to an amino group.[3,7]

Circular Dichroism Spectra of the Co(*N*-Cm-L-Pyala)(AA) Complexes. Circular dichroism spectra in water of various *fac*-Co(*N*-Cm-L-Pyala)(AA) complexes are shown in Figure 4 and are typical of the spectra of the other facial isomers isolated; their minima and maxima are listed in Table III. Since the CD spectrum of the facial complex isolated from the reaction using D,L-Val$^-$ is identical (within experimental error) with that of the *fac*-Co(*N*-Cm-L-Pyala)(D-Val) complex isolated using optically pure D-Val$^-$, the complex is formulated as *fac*-Co(*N*-Cm-L-Pyala)(D-Val). This assignment is consistent with the proton NMR spectra of the two complexes (see below). Thus the formation of *fac*-Co(*N*-Cm-L-Pyala)(D-Val) appears to be stereoselective since it is the only facial isomer isolated when D,L-Val$^-$ is used in the synthesis.

The spectra of the facial isomers can be divided into two major bands (Table III) with band I in the 450–600-nm region and band II in the 320–400-nm region. The positive peak at ~555 nm and negative peak at 488 nm of band I are very similar in shape to the positive and negative peaks of band I of the cis-N,cis-O_5 Co(*N*-Cm-L-Asp)(AA) complexes (Figure 1b), where *N*-Cm-L-Asp^{3-} is the tetradentate *N*-(carboxymethyl)-L-aspartate ligand.[8] It should be noted, however, that the intensities of band I differ considerably for these two complexes with Co(*N*-Cm-L-Pyala)(AA) having $\Delta\epsilon$ values of ~+5.00 (554 nm) and ~−2.50 (488 nm) and Co(*N*-Cm-L-Asp)(AA) having $\Delta\epsilon$ values of ~+2.00 (580 nm) and ~−0.80 (490 nm).

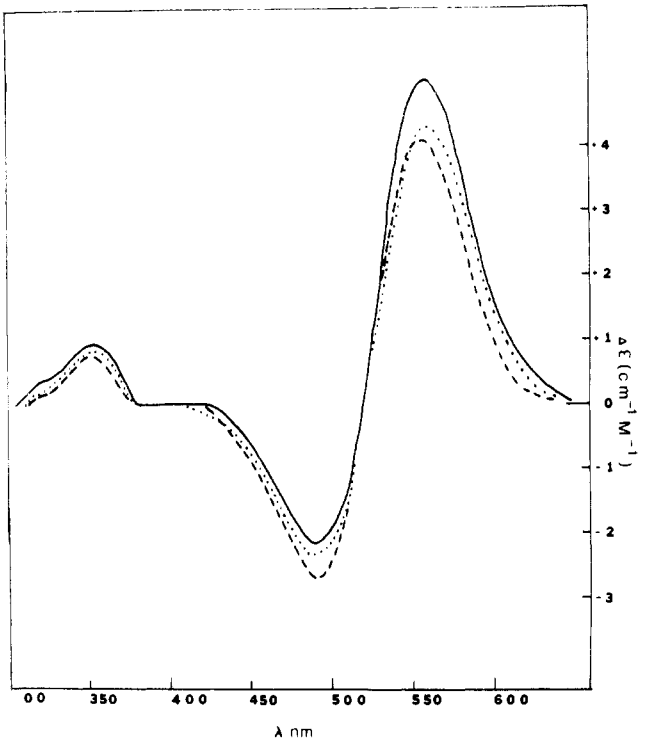


Figure 4. Circular dichroism spectra of various facial Co(*N*-Cm-L-Pyala)(AA) complexes in water: D-Val$^-$ (—); α-AIBA$^-$ (···); Gly$^-$ (- - -).

A comparison of the *fac*-Co(*N*-Cm-L-Pyala)(α-AIBA) circular dichroism spectrum to that of *fac*-Co(PLASP)(α-AIBA)[2] (Figure 1a) shows that both have a positive peak at ~550 nm, but the PLASP^{2-} complex has a positive peak at 495 nm while the *N*-Cm-L-Pyala^{2-} complex has a negative peak at 488 nm. Similar differences are observed in comparisons of the other *fac*-Co(*N*-Cm-L-Pyala)(AA) CD spectra to the corresponding *fac*-Co(PLASP)(AA) circular dichroism spectra.

Band II consists of one positive peak at ~352 nm. This peak remains fairly constant for all the facial complexes in Table II.

In Figure 5 are shown circular dichroism spectra in water of the various meridional Co(*N*-Cm-L-Pyala)(AA) complexes; their minima and maxima are given in Table III. As in the case of the facial isomers, the CD spectra of the meridional isomers can be divided into two bands, with band I in the 600–400-nm region and band II in the 400–320-nm region.

For the CD spectra (Figure 5) of the meridional complexes containing D,L-Val$^-$, α-AIBA$^-$, and D,L-Ala$^-$ (where the terms D,L-AA refer to complexes containing equal amounts of the two diastereomers Co(*N*-Cm-L-Pyala)(L-AA) and Co(*N*-Cm-L-Pyala)(D-AA)), band I consists of a large negative peak at ~460 nm. The small negative or positive peak at ~550 nm is of the same magnitude as experimental error (±0.1) and will not be discussed. Band I of the meridional complexes containing D-Val$^-$ and D-Thr$^-$ consists of two peaks, one positive at ~554 nm and one negative at ~465 nm, while for the L-Val$^-$ complex band I has a negative peak at 465 nm but it also has a negative peak at 545 nm instead of a positive peak as for the D-amino acidates. Band II of the meridional isomers consists of a broad peak at ~370 nm. The intensity of this peak remains constant for the α-AIBA$^-$, D,L-Val$^-$, and D,L-Ala$^-$ complexes but varies for the L-Val$^-$, D-Val$^-$ and D-Thr$^-$ complexes.

As noted previously, differences in the CD spectra of the Co(PLASP)(AA) complexes were attributed to changes at the α-carbon of the amino acidate.[2] Their CD spectra were re-

(7) Watabe, M.; Zama, M.; Yoshikawa, S. *Bull. Chem. Soc. Jpn.* **1978**, *51*, 1354.
(8) Colomb, G.; Bernauer, K. *Helv. Chim. Acta* **1977**, *60*, 459.

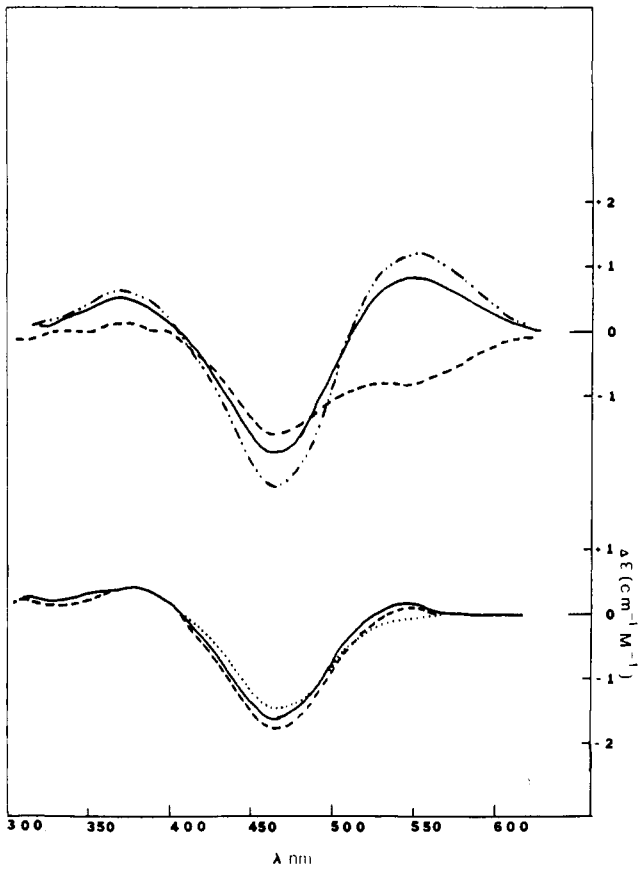


Figure 5. Circular dichroism spectra of various meridional Co(*N*-Cm-L-Pyala)(AA) complexes in water. Lower spectra: α-AIBA⁻ (---); D,L-Val⁻ (—); D,L-Ala⁻ (···). Upper spectra: D-Val⁻ (—); D-Thr⁻ (-··-); L-Val⁻ (---).

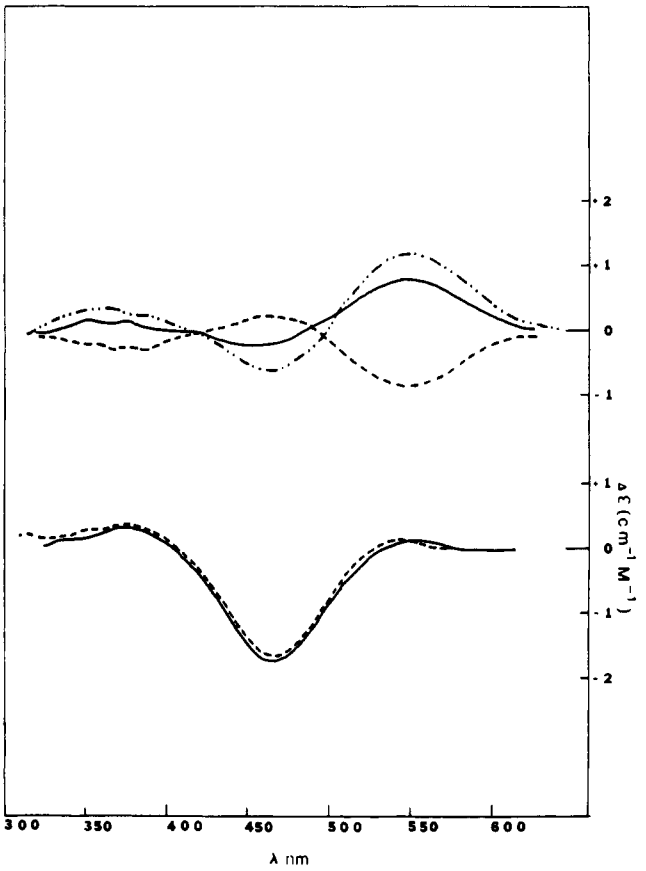


Figure 6. Lower spectra: circular dichroism *X* term from {*mer*-[Co(*N*-Cm-L-Pyala)(D-Val)] + *mer*-[Co(*N*-Cm-L-Pyala)(L-Val)]}/2 (—) and the CD spectrum for *mer*-[Co(*N*-Cm-L-Pyala)(D,L-Val)]·H_2O (---). Upper spectra: *Y* terms calculated from *mer*-[Co(*N*-Cm-L-Pyala)(AA)] − *mer*-[Co(*N*-Cm-L-Pyala)(α-AIBA)]·$^1/_2H_2O$ for D-Val⁻ (—), D-Thr⁻ (-··-), and L-Val⁻ (---).

solved into two contributions, one associated with the optically active portion of the amino acidate chelate ring (*Y*) and the other with the rest of the molecule (*X*). Similarly, the differences in the overall shapes and intensities of the CD spectra for the meridional isomers of Co(*N*-Cm-L-Pyala)(AA) must be related to changes at the α-carbon of the amino acidates. Therefore, the CD spectra of the meridional isomers can also be resolved into *X* and *Y* terms. With use of the same argument as presented for the Co(PLASP)(AA) CD spectra[2] and has been used in other systems,[9] the value of $\Delta\epsilon$ at a given wavelength in the CD spectrum of a *mer*-Co(*N*-Cm-L-Pyala)(AA) complex can be expressed as

$$X + Y_{\text{D or L}} = \text{CD}[\text{Co}(N\text{-Cm-L-Pyala})(\text{D- or L-AA})] \quad (1)$$

If it is assumed that $Y_D = -Y_L$, then

$$X = \{\text{CD}[\text{Co}(N\text{-Cm-L-Pyala})(\text{L-AA})] + \text{CD}[\text{Co}(N\text{-Cm-L-Pyala})(\text{D-AA})]\}/2 \quad (2)$$

The *X* value calculated with use of CD data for the pair *mer*-Co(*N*-Cm-L-Pyala)(D-Val) and *mer*-Co(*N*-Cm-L-Pyala)(L-Val) is given in Figure 6 and is identical (within experimental error) with that observed for the *mer* complex obtained from the reaction of D,L-Val⁻. This means that *mer*-Co(*N*-Cm-L-Pyala)(D,L-Val) is formed, and there is no stereoselective formation of either the D-Val⁻ or the L-Val⁻ *mer* complex (in contrast to the *fac* isomer).

It should be noted that the CD spectra of D,L-Val⁻, D,L-Ala⁻, and α-AIBA⁻ (Figure 5) are nearly identical (within experimental error) with that of the calculated *X* term. Thus, as in the case of the facial Co(PLASP)(AA) complexes, the assumption that *X* is essentially equal to the observed spectrum of *mer*-Co(*N*-Cm-L-Pyala)(α-AIBA) can also be made. A comparison of the *X* terms for *fac*-Co(PLASP)(AA) and *mer*-Co(*N*-Cm-L-Pyala)(AA) shows no similarity between the two since the *X* term for the $PLASP^{2-}$ complexes[2] has two positive peaks at 545 and 495 nm while that of the *mer*-*N*-Cm-L-$Pyala^{2-}$ complexes has only a negative peak at ~470 nm.

Calculated *Y* terms for the D-Val⁻, L-Val⁻, and D-Thr⁻ meridional complexes using eq 1 and assuming *X* is equal to the observed CD spectrum of *mer*-Co(*N*-Cm-L-Pyala)(α-AIBA) are given in Figure 6. An examination of the *Y* curves for D-Val⁻ and L-Val⁻ shows that to a first approximation the assumption of $Y_D = -Y_L$ in formulating eq 2 is valid. The *Y* term for the D-amino acidates has a positive peak at ~550 nm while the L-amino acidate has a negative peak at ~550 nm. This trend has been observed before for the *Y* terms of the *fac*-Co(PLASP)(AA) complexes where the *Y* term of a D-AA^- has a positive peak in the 520-nm region and an L-AA^- has a negative peak at ~520 nm.

Attempts to calculate *X* and *Y* terms from the CD spectra of the facial Co(*N*-Cm-L-Pyala)(AA) complexes gave unreliable values because of the small differences in the CD spectra of the complexes with different amino acids (see Figure 4 and Table III). It should be noted however, that the *Y* term at ~550 for the D-Val⁻ and D-Thr⁻ complexes would be positive since these two D-AA^- complexes have a higher $\Delta\epsilon$ at 550 nm than the corresponding facial α-$AIBA^-$ complex.

^{1}H NMR Spectra of the Co(*N*-Cm-L-Pyala)(AA) Complexes. Proton NMR spectra of the various Co(*N*-Cm-L-

(9) Liu, C. T.; Douglas, B. E. *Inorg. Chem.* **1964**, *3*, 1356. Job, R. In "Stereochemistry of Optically Active Transition Metal Compounds"; American Chemical Society: Washington, D. C., 1980; ACS Symp. Ser. No. 119, pp 273–287.

Table IV. ^{1}H Chemical Shifts of Various Co(*N*-Cm-L-Pyala)(AA) Complexes in 99.7% D_2O[a]

		δ(*N*-Cm-L-Pyala^{2-})						δ(AA$^-$)		
isomer	AA$^-$	α-H[b]	β-H[b]	*N*-Cm-H[c]	2-py	3-py[d]	4-py	α-H	β-H	γ-H
fac	Gly$^-$	3.9 m	3.9 m	3.60 d 4.34 d	8.13 d	7.55 m	8.03 t	3.54 s		
fac	D,L-Ala$^-$	3.9 m	3.9 m	3.59 d . . .	8.0 m	7.47 m	8.0 m	4.24 t	1.48 d	
fac	α-AIBA$^-$	3.9 m	3.9 m	3.56 d 4.37 d	8.0 m	7.50 m	8.0 m		1.47 s 1.50 s	
fac	D-Thr$^-$	3.9 m	3.9 m	3.60 d 4.33 d	8.12 d	7.46 m	7.98 t	3.54 d	4.4 m	1.27 d
fac	D-Val$^-$	3.9 m	3.9 m	3.57 d 4.40 d	8.0 m	7.50 m	8.0 m	3.58 d	2.33 m	0.97 d[e] 1.05 d
fac	D-Val$^-$	3.9 m	3.9 m	3.57 d 4.40 d	8.0 m	7.55 m	8.0 m	3.58 d	2.33 m	0.97 d[e] 1.05 d
fac	D-AsN$^-$	3.9 m	3.9 m	3.59 d 4.37 d	8.41 d	7.50 m	7.99 t	3.78 m	2.91 m	
mer	D,L-Ala$^-$	4.1 m	4.1 m	3.65 s	8.97 d[f] 8.92 d	7.58 m	8.04 t		1.51 d 1.54 d	
mer	α-AIBA$^-$	4.0 m	4.0 m	3.62 s	9.03 d	7.63 m	8.09 t		1.52 s	
mer	D-Thr$^-$	4.0 m	4.0 m	3.62 s	8.99 d	7.61 m	8.07 t	3.62 d	4.4 m	1.37 d
mer	D-Val$^-$	4.0 m	4.0 m	3.61 s	9.01 d	7.60 m	8.07 t	3.73 d	2.36 m	0.94 d[e] 1.15 d
mer	L-Val$^-$	4.0 m	4.0 m	3.63 s	8.97 d	7.61 m	8.08 t	3.76 d	2.44 m	0.90 d[e] 1.16 d
mer	D,L-Val$^-$	4.0 m	4.0 m	3.63 s	8.96 d 9.02 d	7.64 m	8.08 t	3.72 d 3.76 d	2.5–2.2	0.90 d[e] 0.94 d 1.16 d
mer	L-Pro$^-$	4.0 m	4.0 m	3.61 s	8.96 d	7.62 m	8.08 t	4.22 m	1.8–3.3 m[g]	
	N-Cm-L-PyalaH$_2$	4.15 q	3.66 m	3.78 s	8.69 d	7.92 m	8.49 t			

[a] The center of each peak (or peaks) is given, and the multiplicity is given by s = singlet, d = doublet, t = triplet, q = quartet, and m = multiplet. [b] The resonances for the α- and β-hydrogens overlap, and the value given represents the center of the multiplet. [c] The coupling constant for the doublets given in this column is 18 Hz. [d] This multiplet consists of an overlapping doublet and triplet. [e] $J = 7$ Hz each doublet. [f] $J = 5$ Hz each doublet. [g] This region includes the β-, γ-, and δ-protons of the prolinate ligand.

Table V. ^{13}C NMR of the Co(*N*-Cm-L-Pyala)(AA) Complexes in D_2O[a]

	N-Cm-L-Pyala^{2-}					*N*-Cm-L-Pyala^{2-}					AA$^-$			
complex	α-CO_2^-	*N*-Cm-CO_2^-	α-C	β-C	*N*-Cm-CO_2^-	1	2	3	4	5	α-CO_2	α-C	β-C	γ-C
I	184.9	183.5	66.6	35.4	57.5	157.3	150.9	142.0	129.4	126.3	186.6	47.6		
II	183.8	183.0	66.5	35.4	56.8	158.0	151.0	141.2	128.8	125.2	188.2	54.5	18.1	
				35.5	57.1							54.8	18.4	
III	183.8	182.9	66.5	35.5	57.1	157.9	150.6	141.2	128.9	125.2	189.8	62.1	27.3	
													28.7	
IV[b]	185.3	183.9		35.5		157.0	151.0	142.2	129.5	126.5	185.5		64.8	18.7
V[b]	185.3	183.9	66.6	35.4		157.4	150.0	142.2	129.8	126.2	186.9	64.8	30.3	16.5, 18.5
VII[c]	183.7	183.2	66.7	35.5	56.9	157.6	152.5	141.1	128.5	124.8	184.3	55.2	35.6	175.3
N-Cm-L-PyalaH$_2$	171.4	171.2	60.7	33.8	48.5	151.7	146.6	142.4	128.3	126.1				
VIII	183.1	182.8	59.2	30.8	49.1	156.4	153.1	140.9	127.9	125.0		54.9	18.3	
				30.9	49.4		153.4					55.4	18.6	
IX	183.1	182.8	59.1	30.9	49.3	156.4	153.3	140.9	127.9	125.0	187.9	62.2	27.0	
													27.7	
X	183.2	182.8	59.1	30.1	49.7	156.4	153.5	140.9	127.9	125.0	184.0	66.6	64.3	19.2
XI[d]	183.2	182.8	59.1	30.9	49.6	156.4	153.5	140.9	127.9	125.0	185.9	64.5	30.4	15.8, 18.5
XII	183.2	182.9	59.3	30.8	49.3	156.4	153.3	140.9	127.8	125.0	185.7	64.1	30.2	15.5, 18.6
XIII	183.2	182.8	59.1	30.8	49.3	156.4	153.3	140.9	127.9	125.0	185.9	64.1	30.2	15.5, 15.8
		182.9	59.3	30.9	49.6		153.5					64.5	30.4	18.5, 18.6
XIV[e]	183.0	182.8	58.9	30.8	49.3	156.5	153.2	140.9	127.8	125.1	186.9	66.3	47.8	25.0, 29.2

[a] The chemical shifts are given dowfield from Me_4Si with dioxane used as an internal reference at 67.0 ppm. [b] In 70% H_3PO_4(aq). [c] Isolated with use of D,L-AsN$^-$ in the synthesis. [d] Chemical shifts are from the ^{13}C NMR spectrum of the *mer*-D,L-Val$^-$ complex minus those of the L-Val$^-$ complex. [e] *mer*-Co(*N*-Cm-L-Pyala)(L-Pro).

Pyala)(AA) complexes and *N*-Cm-L-PyalaH$_2$ in 99.7% deuterium oxide are given in Table IV. The chemical shifts of the *N*-Cm-L-Pyala^{2-} portion for both the facial and meridional isomers are explained in detail in a previous paper.[5] The major difference between the *N*-Cm-L-Pyala^{2-} chemical shifts in the meridional and facial isomers is in the 2-pyridyl protons and the *N*-carboxymethyl protons. In the facial isomers the 2-proton ($\delta \sim 8.0$) is positioned over the amino acidate carboxylate plane and is shielded relative to the meridional 2-proton ($\delta \sim 9.0$), which is nearly in the plane of the amino acidate carboxylate group and is deshielded. An examination of the chemical shifts of the 2-pyridyl proton for the facial isomer shows that they do not remain constant from one amino acidate to another. In the Gly$^-$, D-Thr$^-$, and D-AsN$^-$ complexes, the doublet of the 2-proton is shifted downfield relative to that of the other complexes in which the doublet overlaps with the triplet of the 4-proton. In the facial isomer the 2-pyridyl proton is situated over the π cloud of the amino acidate CO_2^- group. In the case of a D-amino acidate the CO_2^- is bent away from the 2-hydrogen, while in that of an L-amino

acidate it is bent toward the 2-hydrogen. Thus any changes in the bending of the amino acidate chelate ring will cause a change in the chemical shifts of the 2-proton. This has also been noted for the 2-pyridyl proton in the Co(PLASP)(AA) complexes.[2]

The deshielding of the 2-proton (δ 8.41) of the facial D-AsN$^-$ complex relative to the other facial isomers is presumably due to the presence of a polar amide group near the 2-proton. This deshielding by the AsN$^-$ R group is similar to that found in the Co(PLASP)(L-AsN) complexes where the polar amide group is near the 2-pyridyl proton of PLASP^{2-}.[2] Thus, the assignment of the complex isolated from the reaction of D,L-AsN$^-$ as *fac*-Co(*N*-Cm-L-Pyala)(D-AsN) is consistent with the proton NMR data. Further evidence for this assignment is given in the discussion of the ^{13}C NMR spectrum of the D-AsN$^-$ complex, to be presented below.

The splitting of the *N*-carboxymethyl protons of the facial isomers is similar to the splitting observed for the *N*-pyridylmethyl protons of the *fac*-Co(PLASP)(AA) complexes previously reported.[2] It should be noted that no splitting is observed for the meridional *N*-carboxymethyl protons, which occur as a broad singlet. The difference in the *N*-carboxymethyl protons in the meridional and facial isomers may be due to the magnetic anisotropy of the C–N bonds of the secondary amino nitrogen of the *N*-Cm-L-Pyala^{2-} and/or the difference in position of the C–N bonds in the two isomers. This has been noted before in other Co(III) complexes containing poly(aminocarboxylate) ligands.[10]

The amino acidate α-H chemical shifts of the facial Co(*N*-Cm-L-Pyala)(D-AA) isomers are comparable to those of the corresponding Co(PLASP)(L-AA) complexes. This seems reasonable since the α-H of the amino acidate in *fac*-Co(*N*-Cm-L-Pyala)(D-AA) and that in Co(PLASP)(L-AA) are in similar environments. In the PLASP^{2-} complex the α-H is in the vicinity of the β-CO_2^- and in the *N*-Cm-L-Pyala^{2-} complex it is in the vicinity of the *N*-carboxymethyl carboxylate.

^{13}C NMR Spectra of the Co(*N*-Cm-L-Pyala)(AA) Complexes. The ^{13}C NMR spectra of the free ligand *N*-Cm-L-PyalaH$_2$ and the various Co(*N*-Cm-L-Pyala)(AA) complexes in D_2O and 70% H_3PO_4 (aqueous) are assigned in Table V. The chemical shifts of the *N*-Cm-L-Pyala^{2-} ligand in the facial complexes remain constant and do not seem to be affected by the amino acidate. This is also true for the *N*-Cm-L-Pyala^{2-} fragment of the meridional complexes. The chemical shifts of the *fac*-Co(*N*-Cm-L-Pyala)(AA) complexes are comparable to those reported for the facial Co(PLASP)(AA) complexes.[2]

All the various carbon resonances for the *fac*-Co(*N*-Cm-L-Pyala)(D-AsN) complex occur as distinct singlets (protons are broad-band decoupled), and no evidence for the presence of the other diastereomer was found. This is consistent with the proton NMR and CD spectral assignment of the complex as *fac*-Co(*N*-Cm-L-Pyala)(D-AsN).

Discussion of Isomer Distribution. Of the 4 possible isomers of Co(*N*-Cm-L-Pyala)(AA), only the *fac*- (Figure 2a) and the *mer*-AA$^-$ amino (Figure 2c) were obtained. We[1,3] and others[7] had noted previously that amino groups avoid coordinating trans to each other in certain Co(III) complexes, and this may be the reason for structures 2a and 2c to be favored over 2b and 2d, which have trans-amino groups.

Strain in the *N*-Cm-L-Pyala$^-$ ligand should be greater in the *mer* than the *fac* isomer. Coordination of the *N*-carboxymethyl CO_2^- group trans to the pyridyl group in the facial isomer should produce little strain in the C–N–C bond angle. This has been noted in the Introduction for the Co(PLASP)(AA) complexes and is consistent with the coordination of polydentate ligands such as ^-O_2C–CH_2–NH–CH_2–CO_2^- and IMDA^{2-}, reported previously.[1,11-14] In the facial mode of coordination the glycinate chelate rings of IMDA^{2-} are 90° to each other, and there is very little strain in the C–N–C angle. However, in the meridional Co(*N*-Cm-L-Pyala)(AA) complexes coordination of the *N*-carboxymethyl CO_2^- trans to the α-CO_2^- of *N*-Cm-L-Pyala^{2-} produces considerable strain in the C–N–C angle. The X-ray structure analysis of *mer*-[Co(*N*-Cm-L-Pyala)(D-Thr)]·$^1/_2H_2O$ showed[5] that the 120° C–N–C bond angle is severely distorted from the ideal tetrahedral value. Similar C–N–C angular strain has been found in the meridional coordination of the glycinate chelate ring of other polydentate ligands in the same plane.[11-14] Thus, the facial isomer of Co(*N*-Cm-L-Pyala)(D-AA) appears to be structurally favored over the meridional isomer.

However, the *mer* is a stable isomer. Aqueous solutions of *mer*-Co(*N*-Cm-L-Pyala)(α-AIBA) on standing at room temperature for several weeks or on heating a 60 °C for 1 h yield solutions with substantial amounts of both the *fac* and *mer* isomers. The somewhat unexpected stability of the *mer* isomer may be due to the presence of an amino group trans to the pyridine, which in other amino–pyridine complexes of Co(III) appears to be a favorable stereochemistry.[3,15] This favorable electronic factor may offset the unfavorable strain energy in this isomer.

The isolation of the facial isomers of D-Val$^-$, D-Thr$^-$, D,L-Ala$^-$, D-AsN$^-$, and Gly$^-$ in higher yields than the meridional isomers suggests that the facial isomers of D-amino acidates are preferred over the corresponding meridional isomers. It should be noted, however, that the lower solubilities of the facial isomers may be responsible for their higher yields. These facial complexes also appear to be sterically favored. In the cases of D-Val$^-$, D-Thr$^-$, D-AsN$^-$, and possibly the Gly$^-$ complexes, the chelate ring is bent down and away from the pyridine ring, which would minimize repulsion between the pyridine ring and the α-CO_2^- and α-C groups. This bending would be caused by the bulky R groups of the D-amino acidates favoring the equatorial rather than the axial position.

Although the facial isomer appears to be preferred, the meridional isomer (Figure 2c) cannot be ignored since it was isolated for all the amino acidates except Gly$^-$. In the case of the Co(*N*-Cm-L-Pyala)(L-Val) complex, the meridional isomer is the only one isolated, and there was no evidence for the facial isomer. In *fac*-Co(*N*-Cm-L-Pyala)(L-Val) the chelate ring would be bent upward toward the pyridine; an examination of models indicates that there would be considerable steric interaction between the α-CO_2^- of L-Val$^-$ and the 2-hydrogen of the pyridyl ring. Thus, it appears the meridional isomer of Co(*N*-Cm-L-Pyala)(L-Val) is sterically favored over the facial. It should be noted that, since *fac*-Co(*N*-Cm-L-Pyala)(D-Val) was the only facial isomer isolated from the reaction using D,L-Val$^-$, the formation of this complex appears to be stereospecific.

Acknowledgment. The authors thank the National Institute of General Medical Sciences for support of this research through Grant GM12626. We thank the National Science Foundation for support of the purchase of the Jeol FX90Q NMR spectrometer.

Registry No. I, 79953-38-1; II, 79953-39-2; III, 79953-40-5; IV, 77027-86-2; V, 79953-41-6; VII, 79953-42-7; VIII, 79982-49-3; IX, 79982-53-9; X, 79982-50-6; XI, 79982-51-7; XII, 79982-52-8; XIII, 80008-80-6; XIV, 79970-15-3.

(10) Legg, J. I.; Cooke, D. W. *Inorg. Chem.* **1965**, *4*, 1576; **1966**, *5*, 595.
(11) Halloran, L. J.; Caputo, R. E.; Willett, R. D.; Legg, J. I. *Inorg. Chem.* **1975**, *14*, 1762.
(12) Weakliem, H. A.; Hoard, J. L. *J. Am. Chem. Soc.* **1959**, *81*, 549.
(13) Corradi, A. B.; Palmieri, C. G.; Nardelli, M.; Pellinghelli, M. A.; Tani, M. E. V. *J. Chem. Soc., Dalton Trans.* **1973**, 655.
(14) Bernauer, K. *Top. Curr. Chem.* **1976**, *65*, 1.
(15) Ebner, S. R.; Angelici, R. J. *Inorg. Chem.* **1980**, *19*, 1347.