Infrared Spectra of Amino Acids and Their Metal Complexes. II. Geometrical Isomerism in Bis(amino acidato)copper(II) Complexes[1]

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Abstract: The infrared spectra of crystalline glycine, L- and DL-alanine, DL-α-amino-*n*-butyric acid, L- and DL-valine, L- and DL-leucine, L- and DL-isoleucine, L- and DL-phenylalanine, and the corresponding bis(amino acidato)-copper(II) complexes are investigated. The vibrational modes which principally contribute to the observed frequencies in the spectrum of the complex are empirically assigned by comparison with the spectrum of the corresponding amino acid and through analogies with a Urey–Bradley force-field analysis of metal–glycine complexes.[3] Frequencies attributable to copper–ligand stretching vibrations are cataloged for complexes whose geometries have been elucidated by X-ray crystallography, and the data are used to develop a vibrational criterion that allows discrimination between the cis and trans configurations of the copper complexes. Employing this criterion, stereochemistries of a number of bis(amino acidato)copper(II) complexes of previously undetermined geometries are inferred. The two forms of bis-DL-phenylalaninatocopper(II) appear to be verifiably the first example of geometrical isomerism in a racemic bis(amino acidato)copper(II) complex.

The first example of cis–trans isomerism in complexes of the kinetically labile cupric ion was reported by Tomita,[4] who suggested that while bisglycinatocopper(II) monohydrate adopts a cis configuration, the dihydrate of this complex exists as the trans isomer. The structure of the monohydrate was subsequently confirmed by Weissenberg projection[5] and complete three-dimensional[6] X-ray analyses, but a similar refinement of the structure of the trans dihydrate is not available. Gillard, *et al.*,[7] prepared light blue platelets and dark blue prismatic crystals of bisalaninatocopper(II), and they concluded that these represent trans and cis modifications, respectively. Contemporary X-ray diffraction measurements[8–10] have verified these conclusions, and the alanine complexes form the sole unequivocal example of this novel isomerism in Cu(II) systems.

Recognizing that confirmed reports of such isomers are rare, the possibility that structural characterization of a large number of (amino acidato)copper(II) complexes will reveal geometrical isomerism to be a more general phenomenon is intriguing. Moreover, an investigation of the principal structural features of these complexes is important, since they may mediate physiological copper transport[11] and since such knowledge is prerequisite to understanding the detailed role which copper plays in the catalysis of amino acid ester hydrolyses[12] and the factors determining copper binding in metalloenzymes, like ceruloplasmin.[13] Although several groups, particularly Freeman and coworkers,[14] have directed an exhaustive effort at X-ray structural characterization of amino acid complexes, it is clear that the time and expense involved in these studies makes the development of efficient determinative techniques desirable. Intensity variations in diffuse reflectance spectra[15,16] and optical activity effects in circular dichroic spectra[17] of bis(amino acidato)copper(II) complexes have been suggested as alternative methods, but the evidence provided is oblique and sometimes conflicting. For instance, the visible diffuse reflectance spectra of the monohydrates of both bis-L-isoleucinatocopper(II) and bis-L-valinatocopper(II) have been taken to indicate cis conformations for these materials,[15] while Gillard and Laurie regard circular dichroism measurements as unequivocally establishing trans geometries,[17] although the state of hydration is unclear in the latter study. The present investigation is devoted to exploring correlations between features appearing in the infrared spectra of a number of α-amino acid complexes of Cu(II) and their structures in order to establish a vibrational criterion that discriminates geometrical isomers of square-planar complexes containing these ligands.

Experimental Section

A. Preparation of Complexes. (1) *cis*-Bisglycinatocopper(II) Monohydrate. The monohydrate was prepared by the method described by Tomita,[4] and the product was purified by recrystallization from water.

(2) *trans*-Bisglycinatocopper(II) Dihydrate. The dihydrate was obtained by heating a suspension of the monohydrate in aqueous solution for approximately 24 hr. The precipitate was filtered

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(9) R. D. Gillard, R. Mason, N. C. Payne, and G. B. Robertson, *Chem. Commun.*, 155 (1966).
(10) R. D. Gillard, R. Mason, N. C. Payne, and G. B. Robertson, *J. Chem. Soc. A*, 1864 (1969).
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(12) R. J. Angelici and B. E. Leach, *J. Amer. Chem. Soc.*, **89**, 4605 (1967); **90**, 2499, 2504 (1968).
(13) See, for example, W. E. Blumberg in ref 11, p 49.
(14) A thorough review of this work is found in H. C. Freeman, *Advan. Protein Chem.*, **22**, 258 (1967).
(15) T. Yasui and Y. Shimura, *Bull. Chem. Soc. Jap.*, **39**, 604 (1966).
(16) S. Laurie, *Aust. J. Chem.*, **20**, 2609 (1967).
(17) R. D. Gillard and S. H. Laurie, *Chem. Commun.*, 489 (1969).

from solution and air-dried. Washing with organic solvents may cause conversion back to the monohydrate. Alternatively, this complex may be prepared according to the method described by Mauthner and Suida.[18]

(3) Bis-DL-alaninatocopper(II) Monohydrate. The complex was prepared by a method similar to that described by Neuberg, *et al.*[19] The anhydrous compound was obtained by heating the monohydrate *in vacuo* at 100° for several hours. Prolonged heating of the monohydrate in a potassium bromide matrix above 100° produced a complex exhibiting the identical spectrum.

(4) *cis*- and *trans*-Bis-L-alaninatocopper(II). The optically active copper complexes were prepared as previously described by Gillard, *et al.*[7] The light blue or trans form of the complex was dissolved in a minimum amount of water and concentrated with stirring until excess solid was in equilibrium with the saturated solution. After stirring this suspension for several days, the dark blue or cis form was filtered from the solution and air-dried. Washing with organic solvents may convert this material to the light blue form.

(5) *trans*-Bis-DL-α-amino-*n*-butyratocopper(II), Bis-L- and -DL-valinatocopper(II), Bis-L- and -DL-leucinatocopper(II), and Bis-L- and -DL-isoleucinatocopper(II) Monohydrate. These compounds were also prepared by the method described by Neuberg, *et al.*[19] Anhydrous bis-L-isoleucinatocopper(II) was obtained by heating the corresponding monohydrate *in vacuo* at 100° for several hours.

(6) Bis-L- and -DL-Phenylalaninatocopper(II). The two forms of the racemic complex were synthesized by the methods previously described by Laurie.[16] Alternatively, the cis form may be prepared by heating a suspension of the complex as described in (4) above. The complex prepared with L-phenylalanine was synthesized in an analogous manner.

B. Spectral Measurements. The infrared spectra were recorded in the 4,000–200-cm^{-1} region using a Perkin-Elmer Model 621 grating infrared spectrophotometer equipped with an air-dryer accessory. This instrument was calibrated using known frequencies of water vapor and polyethylene, and frequencies are accurate to better than 1 cm^{-1}. The spectra in the 4,000–400-cm^{-1} region were measured as KBr pellets that were carefully dried for all anhydrous compounds. Spectra of Nujol mulls supported on CsI plates were also measured in the 4,000–200-cm^{-1} region, and these were in good agreement with those observed using the potassium bromide disk technique.

Because we initially hoped to obtain information about the structures of the copper complexes in aqueous solution as well as in the solid state and because of the importance of Raman data in framing arguments regarding geometrical isomerism, we attempted to measure their Raman spectra using Hg-arc excitation (Cary 81) and He–Ne and Ar^+ laser excitation (Spex Model 1400 spectrometer). These attempts were unsuccessful because of solution absorption of both the exciting and Raman-shifted light. Infrared spectroscopy of H_2O and D_2O solutions of the complexes also met with little success.

Results

The infrared spectra of all amino acids and their complexes were measured in the region from 4000–200 cm^{-1}, but only the region below 800 cm^{-1} is generally recorded in the tables. Although we believe this to be the first comprehensive vibrational study of α-amino acidato complexes of a single metal ion, the spectra of some of the racemic amino acids and their copper complexes have been disparately reported.[3,7,20–28] In the region above 800 cm^{-1}, the frequency and assignment agreement with these studies is sufficiently precise to preclude tabulation, though the differences between the spectra of the DL- and L-amino acids are often striking (presumably arising from hydrogen-bonding effects). Data from this region will be cited only insofar as they pertain to structural features, but the complete spectra are available from the authors. The low-energy measurements, for which the advantages of improved instrumentation are clearly evidenced, are discussed below.

A. Complexes of Known Geometry. The infrared spectra of glycine, bisglycinatocopper(II) monohydrate, and bisglycinatocopper(II) dihydrate are tabulated in Table I and are in agreement with previous studies.[3,20]

Table I. Infrared Spectra (800–200 cm^{-1}) of Glycine and Copper(II)–Glycine Complexes

gly[a,b]	*trans*-$Cu(gly)_2 \cdot 2H_2O$	*cis*-$Cu(gly)_2 \cdot H_2O$	Assignments
696 (s)	737 (m)	741 (s)	COO^- bend
	640 (m)	664 (s)	NH_2 rock
606 (m)	580 (m)	575 (w)	COO^- wag
502 (s)	545 (w)	557 (m)	COO^- rock
		532 (sh)	
	477 (w)	471 (w)	Cu–N asym str
		454 (w)	Cu–N sym str
354 (s)	376 (m)	376 (w)	CCN bend, out-of-plane ring def
	334 (ms)	330 (ms)	Cu–O asym str
		277 (ms)	Cu–O sym str

[a] The following abbreviations will be used sporadically for the ligands: gly, glycine; ala, alanine; leu, leucine; ile, isoleucine; val, valine; pro, proline; α-ABA, α-amino-*n*-butyric acid; phe, phenylalanine. [b] Intensity designations in the tables: vs, very strong; s, strong; ms, medium strong; m, medium; w, weak; br, broad; sh, shoulder. All frequencies are in cm^{-1}. Other abbreviations used are: asym, asymmetric; sym, symmetric; str, stretch; def, deformation.

The assignments for glycine are based on a Urey–Bradley force-field analysis,[20] and the assignments for the copper complexes are obtained from a similar normal coordinate analysis.[3] We follow Condrate and Nakamoto[3] in assigning the metal–nitrogen stretching frequencies to lines at 477 cm^{-1} in the *trans*-bisglycinatocopper(II) dihydrate and at 471 and 454 cm^{-1} in the *cis*-bisglycinatocopper(II) monohydrate. The metal–oxygen stretching frequencies for these complexes are assigned at 334 cm^{-1} and at 330 and 277 cm^{-1}, respectively. Other workers[21,22] have utilized a cruder normal coordinate analysis to suggest that the latter frequencies should be assigned to the copper–nitrogen modes and that the copper–oxygen frequencies appear below 200 cm^{-1}. The several lines of evidence leading to a preference for the former set of assignments have been summarized.[3] Additionally, Raman spectra of the glycine complexes of Zn(II), Cd(II), and Hg(II) in aqueous solution[1,23] contain strong polarized bands at *ca.* 450 cm^{-1} that are most reasonably attributed to the respective metal–nitrogen stretching modes, while no Raman shifts in the region below 200 cm^{-1} are observed. The occurrence of water librations and intermolecular modes between 200 and 100 cm^{-1} in solid-state amino acid complexes presents a further complication to the

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(27) I. Nakagawa, R. J. Hooper, J. L. Walter, and T. J. Lane, *Spectrochim. Acta*, **21**, 1 (1965).
(28) J. F. Jackovitz and J. L. Walter, *ibid.*, **22**, 1393 (1966).

Table II. Infrared Spectra (800–200 cm^{-1}) of DL-Alanine, L-Alanine, and Their Biscopper(II) Complexes

DL-Ala[a]	Cu-(DL-ala)$_2$·H_2O	Cu(DL-ala)$_2$	L-Ala	*trans*-Cu(L-ala)$_2$	*cis*-Cu(L-ala)$_2$	Assignments
790 (sh)						
768 (ms)	787 (m)	787 (m)	770 (ms)	786 (m)	776 (m)	COO^- bend
		768 (ms)		768 (m)	768 (m)	
	726 (m)	714 (m)		707 (m)	719 (ms)	
	662 (m)	669 (m)		669 (m)	685 (m)	NH_2 rock
				616 (w)	648 (m)	
643 (s)	620 (w)	602 (m)	645 (s)	602 (m)	628 (m)	COO^- wag
541 (vs)	578 (s)	573 (s)	539 (s)	572 (s)	566 (ms)	COO^- rock
	563 (s)				549 (ms)	H_2O wag for the
	525 (m)				529 (m)	monohydrate and skeletal def
495 (w)			481 (w)			NH_3^+ torsion
	490 (w)	493 (w)		484 (w)	483 (m)	Cu–N asym str
					411 (m)	Cu–N sym str
		398 (sh)		397 (m)	400 (m)	CCCN asym def,
408 (s)	404 (m)	382 (m)	408 (s)	385 (w)		out-of-plane
		366 (sh)		360 (m)	374 (w)	ring def
	348 (ms)	333 (m)		332 (m)	325 (ms)	Cu–O str
323 (m)	319 (ms)	321 (sh)	320 (w)	319 (w)	309 (ms)	CCCN def
295 (m)		287 (w)	290 (m)	298 (m)		
279 (w)		273 (w)	276 (w)	276 (w)	276 (ms)	Skeletal def Cu–O sym str of cis complex
257 (w)	244 (w)	236 (w)	257 (w)	258 (vw)	255 (sh)	In-plane def
208 (vs)			206 (m)		225 (w)	Skeletal torsion

[a] Abbreviations as in Table I.

assignment of bands in this range to metal–oxygen stretches. The association of a particular frequency with a normal mode is meaningful only to the degree that the mode dominates the potential energy distribution. Indeed, the bands characterized above as metal–oxygen modes contain sizable contributions from the metal–nitrogen stretching motions and ring deformations, but the lines at *ca.* 450 cm^{-1} correspond to almost pure metal–nitrogen stretching.[3]

The spectra of DL-alanine, L-alanine, and several alaninatocopper(II) complexes are recorded in Table II. The spectrum of DL-alanine is in reasonable agreement with that of Fukushima, *et al.*,[24] though greater detail is evident, and the assignments for this molecule and for L-alanine are based on the vibrational analysis and deuteration studies reported by those workers. The infrared spectra of Cu(DL-ala)$_2$·H_2O, *trans*-Cu(L-ala)$_2$, and *cis*-Cu(L-ala)$_2$ have been measured in the characterization of these complexes,[7] but assignments were not attempted and the region below 700 cm^{-1} was not recorded for *cis*-Cu(L-ala)$_2$. The spectrum of Cu(DL-ala)$_2$ has also been reported,[25] but our data and assignments are at variance with that study in the region between 750 and 200 cm^{-1}. The frequency assignments for the Cu(II) complexes are made by comparison with the alanine spectrum and through analogies with the assignments adopted for the cis and trans glycine complexes. Absorptions which appear in the spectra of the complexes between 480 and 495 cm^{-1} are designated as Cu–N asymmetric stretches, since these frequencies are close to those observed in the glycine complexes and since bands in this position in the spectra of the zwitterionic amino acids have been shown through deuteration to be NH_3^+ torsional modes. The symmetric copper–nitrogen stretching mode of the cis isomer is assigned to a band at 411 cm^{-1} that is not found in the spectra of the other alanine complexes. The asymmetric Cu–O stretches are measured at similar frequencies to analogous motions in the glycine complexes (325–250 cm^{-1}), but the designation of the symmetric copper–oxygen mode in the cis complex is complicated by the occurrence of alanine skeletal deformations in the region in which this mode is expected to occur. The enhanced intensity of the absorption at 276 cm^{-1} in the spectrum of the cis complex and its proximity to the corresponding vibration in *cis*-Cu(gly)$_2$·H_2O (277 cm^{-1}) indicate an assignment of this peak to the symmetric Cu–O stretch.

Table III. Infrared Spectra (800–200 cm^{-1}) of DL-α-Amino-*n*-butyric Acid and Bis(DL-α-ABA)copper(II)

DL-α-ABA[a]	*trans*-Cu(DL-α-ABA)$_2$	Assignments
754 (w)	779 (s)	COO^- scissors
689 (vw)	711 (ms)	
658 (m)	655 (w)	NH_2 rock and
638 (w)	624 (m)	COO^- wag
542 (vs)	583 (ms)	COO^- rock
504 (vw)	555 (sh)	
	498 (w)	Cu–N str
471 (w)		NH_3^+ torsion
419 (ms)	412 (ms)	CCCN asym def
374 (w)	400 (sh)	
344 (w)	341 (ms)	CCCN def
	341 (ms)	Cu–O str
303 (m)	309 (w)	CCCN def and
230 (m)	233 (m, br)	skeletal torsion

[a] Abbreviations as in Table I.

An incomplete (single-projection) crystal structure determination of bis-DL-α-amino-*n*-butyratocopper(II) shows that the unit cell is centrosymmetric,[29] and for an anhydrous square-planar complex of a racemic amino acid, only a trans configuration possesses a center of symmetry. The infrared spectra of DL-α-amino-*n*-butyric acid and the complex are recorded in Table III.

(29) A. J. Stosick, *J. Amer. Chem. Soc.*, 67, 362 (1945).

Table IV. Infrared Spectra (800–200 cm^{-1}) of DL-Isoleucine, L-Isoleucine, and Their Copper(II) Complexes

DL-ile[a]	$Cu(DL\text{-ile})_2 \cdot H_2O$	L-ile	*cis*-$Cu(L\text{-ile})_2 \cdot H_2O$	$Cu(L\text{-ile})_2$	Assignments
798 (ms)	799 (m)	788 (w)	798 (m)	801 (s)	
					COO^- scissor
772 (ms)	779 (w)	769 (m)	778 (m)	776 (m)	
741 (vw)	759 (w)	749 (w)	719 (w)	753 (vw)	
					CH_2 rock
718 (m)	720 (m)	710 (s)			
690 (s)	695 (sh)	672 (m)	692 (m)	690 (m)	
					COO^- wag
766 (m)	668 (m)	667 (sh)	646 (vw, br)	649 (m)	
601 (vw)		555 (s)	590 (s)	570 (m)	COO^- rock and H_2O
540 (s)	578 (m)	535 (s)	571 (ms)	461 (m)	libration
	529 (w)		526 (m)		
485 (w)	480 (w)	487 (w)	496 (w)	498 (w)	Skeletal def
	468 (w)		471 (w)	464 (w)	Asym cu–N
450 (s)	430 (w)	440 (s)	420 (w)	430 (w)	Skeletal deformation
	409 (w)		407 (sh)	407 (w)	Sym Cu–N str
365 (vs, br)	379 (sh)	390 (s)	391 (m)	385 (w)	
					Skeletal def
		368 (w)			
	345 (w)		342 (m, sh)	344 (sh)	Asym Cu–O str
313 (w)	308 (s, br)	339 (ms)	312 (s)	320 (s, br)	
					Skeletal def
		310 (m)			
	285 (w, sh)		298 (w)	320 (s, br)	Sym Cu–O str
265 (w)	255 (w)	237 (m)	261 (w)	250 (w)	Chelate ring def
237 (w)					and skeletal def

[a] Abbreviations as in Table I.

The infrared spectra of L- and DL-isoleucine and three copper(II) complexes containing these ligands are tabulated in Table IV. Figure 1 shows the spectral region from 1800 to 200 cm^{-1} for L-isoleucine and $Cu(L\text{-ile})_2 \cdot H_2O$, and the quality of these spectra is representative of those reported in this investigation. The assignments for the amino acid conform to those reported earlier,[26] as do the band designations for $Cu(DL\text{-ile})_2 \cdot H_2O$ above 500 cm^{-1}. Again, the interpretations of the metal–ligand stretching region for this complex disagree with the previous work[26] because they are based on conflicting vibrational analyses of the spectra of the glycinato complexes. The spectra of the other two isoleucine complexes are reported here for the first time. As discussed below, the observation of both asymmetric and symmetric metal–ligand stretching modes is indicative of a cis disposition of binding groups. Subsequent to the completion of this vibrational investigation, we became aware of an X-ray determination of the crystal structure of $Cu(L\text{-ile})_2 \cdot H_2O$[30] which shows that this is a pseudo-square-planar cis complex with the pentacoordinate copper attached to a water molecule in addition to the two bidentate ligands.

The only other bis(α-amino acidato)copper(II) complex whose structure has been determined is bis(DL-prolinato)copper(II) dihydrate, which exists in a trans configuration.[31] The infrared spectra of proline, $Cu(DL\text{-pro})_2 \cdot 2H_2O$, and several other proline complexes are discussed in detail in paper III of this series,[32] with particular attention to the effects of hydration on spectral features.

(30) C. M. Weeks, A. Cooper, and D. A. Norton, Medical Foundation of Buffalo, Inc., Buffalo, N. Y., 14203. We appreciate receiving a preprint of this work prior to publication.
(31) A. M. Mathieson and H. K. Welsh, *Acta Crystallogr.*, **5**, 599 (1952).
(32) A. W. Herlinger and T. V. Long, *J. Amer. Chem. Soc.*, **92**, 6481 (1970).

B. Complexes of Unknown Geometry. The infrared spectra of racemic and optically active valine and leucine and their complexes are listed in Tables V and VI, respectively. The assignments for both DL- and

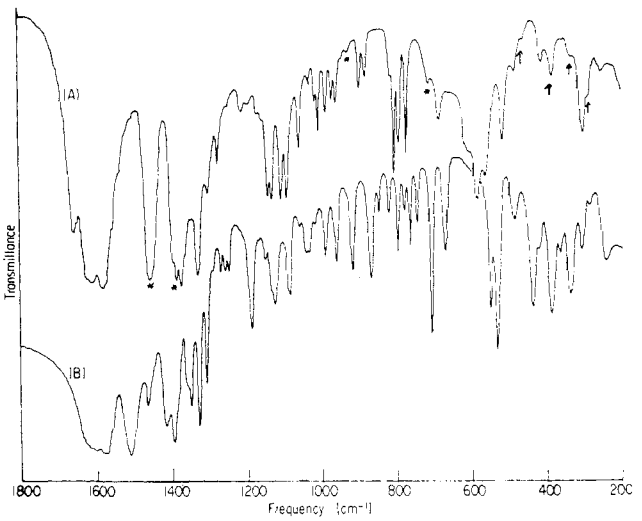

Figure 1. Infrared spectra (1800–200 cm^{-1}) of (a) $Cu(L\text{-ile})_2 \cdot H_2O$, as Nujol mull on CsI plates (Nujol bands starred), and (b) L-ile, as CsI pellet. Metal–ligand bands are indicated by arrows.

L-valine and their complexes are those suggested by Nakagawa, *et al.*,[27] for the racemic amino acid and $Cu(DL\text{-val})_2$, except in the metal–ligand stretching regions. The spectra of L- and DL-leucine and their complexes above 600 cm^{-1} may be similarly assigned.[28]

The spectra of phenylalanine and its complexes are found in Table VII.[16] The vibrational spectra of L- and DL-phenylalanine are empirically assigned by comparison with the spectrum of alanine given above

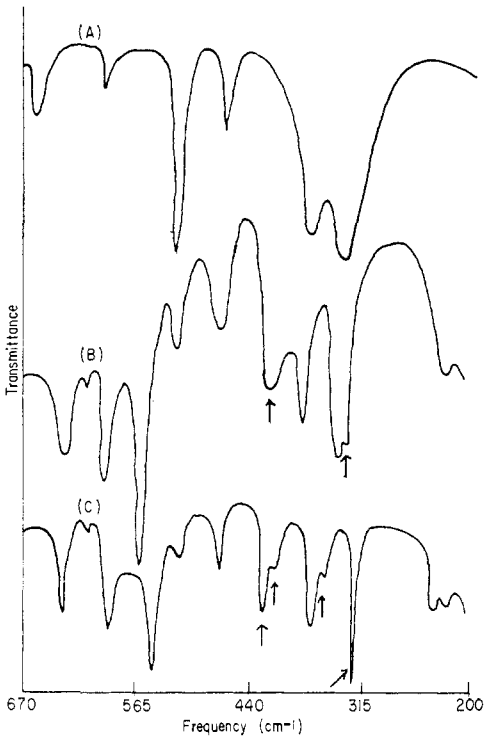

Figure 2. Far-infrared spectra (700–200 cm^{-1}) of (a) DL-phe, (b) blue, scaly form of Cu(DL-phe)$_2$, and (c) blue-violet, needle-like form of Cu(DL-phe)$_2$. Metal–ligand bands are indicated by arrows.

and the spectra of monosubstituted benzenes.[33] The spectral frequency designations for Cu(L-phe)$_2$ and the two forms of Cu(DL-phe)$_2$ lines are determined by analogy to the spectra of the free amino acids and the bis-alaninatocopper(II) complexes. Partial spectra of the DL species (from 700 to 200 cm^{-1}) are shown in Figure 2.

(33) D. H. Whiffen, *J. Chem. Soc.*, 1350 (1956).

Table V. Infrared Spectra (800–200 cm^{-1}) of DL-Valine, L-Valine, and Their Copper(II) Complexes

DL-val[a]	Cu(DL-val)$_2$	L-val	Cu(L-val)$_2$	Assignments
775 (s)	774 (s)	774 (s)	768 (s)	
				COO$^-$ scissor
752 (vw)	768 (s)	752 (m)		
683 (s)	737 (s)	716 (s)	726 (m)	
				COO$^-$ wag
665 (sh)	670 (vw)	662 (s)	670 (s)	
	640 (m)		639 (w)	
				NH_2 rock
			625 (m)	
536 (vs)	578 (s)	541 (vs)	576 (s)	
				COO$^-$ rock
			530 (w)	
	491 (m)	484 (sh)	482 (m)	
				Skeletal def
473 (m)	474 (sh)	469 (w)	469 (m)	
	450 (w)		446 (w)	Cu–N str.
424 (m)	399 (s, br)	427 (m)	404 (m)	
		398 (m)	388 (m)	Skeletal def
364 (s)	345 (sh)	373 (m)	372 (w)	
	331 (s)		351 (m)	Cu–O str
		335 (m)	336 (w)	
278 (m)	315 (sh)	290 (m)	308 (m)	Skeletal def
		280 (sh)		(CCCN def)
216 (m)	228 (m)	231 (m)	228 (m)	

[a] Abbreviations as in Table I.

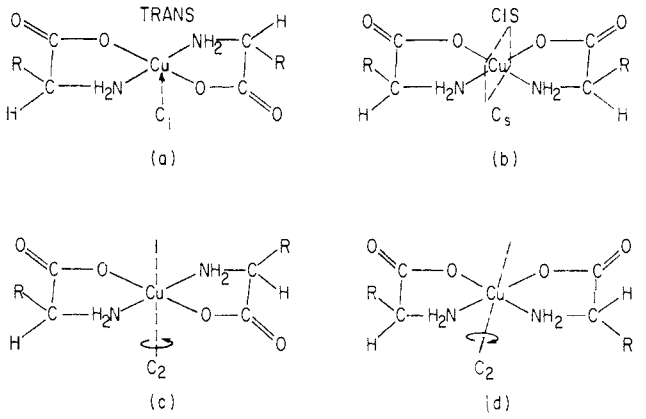

Figure 3. Geometries of square-planar complexes formed from racemic (a, trans; b, cis) and optically active (c, cis; d, trans) amino acids (after Laurie[16]).

The far-infrared spectrum of the blue, scaly form of Cu(L-phe)$_2$ exhibits a single Cu–N stretch at 401 cm^{-1} and a Cu–O absorption at 340 cm^{-1}. Corresponding peaks appear in the spectrum of the blue Cu(DL-phe)$_2$ at 416 and 328 cm^{-1}, respectively. The spectrum of the blue-violet, needle-like form of Cu(DL-phe)$_2$ is generally more complex than that of the blue form, and two bands that are ascribable to metal–ligand motions are found in both the 400–500- and the 300–400-cm^{-1} ranges. The relatively low frequencies at which the copper–phenylalanine modes occur probably indicate that significant mixing of both modes with skeletal deformations occurs.

Table VI. Infrared Spectra (800–200 cm^{-1}) of DL-Leucine, L-Leucine, and Their Anhydrous Copper Complexes

DL-leu[a]	Cu-(DL-leu)$_2$	L-leu	Cu(L-leu)$_2$	Assignment
773 (s)	788 (w)		787 (s)	CH_2 rock
759 (sh)	762 (m)	768 (m)	765 (m)	
713 (vw)	727 (m)	732 (sh)	716 (m)	
		719 (w)		COO$^-$ scissor
683 (s)	668 (sh)	666 (s)	667 (s)	COO$^-$ wag
666 (sh)			654 (ms)	and
			646 (sh)	NH_2 rock
	655 (m, br)		655 (m, br)	(complexes)
			634 (vw)	
534 (s)	579 (s)	534 (s)	569 (ms)	COO$^-$ rock
	488 (w)		476 (w)	Cu–N str
451 (sh)	452 (w)	454 (sh)		
438 (s)	437 (w)	439 (s)	436 (m)	
398 (s)	397 (sh)	400 (s)	392 (m)	CC_3 sym def
363 (ms)	388 (m)	363 (m)	375 (sh)	and CCCN def
348 (ms)	351 (s)	339 (m)	340 (ms)	
	328 (m)		316 (m)	Cu–O str
279 (vw)	309 (sh)	278 (vw)		Skeletal def
218 (ms)		218 (ms)		

[a] Abbreviations as in Table I.

Discussion

X-Ray crystallographic investigations of bis(amino acidato)copper(II) complexes[10,14,30] have shown the amino acids to be bidentately coordinated to the metal, forming square-planar or pseudo-square-planar arrangements in which the chelate rings may be situated either cis or trans. Examination of the molecular symmetries of possible complexes suggests that the

Table VII. Infrared Spectra of DL-Phenylalanine, L-Phenylalanine, and Their Anhydrous Complexes

L-phe[a]	Cu(L-phe)$_2$	DL-phe	Cu(DL-phe)$_2$ (blue-violet)	Cu(DL-Phe)$_2$ (blue)	Assignments
778 (m)	784 (s)	774 (w)	770 (vw)	782 (vw)	CC str
744 (s)	754 (s)	745 (m)	756 (m)	750 (m)	COO^- scissor and
	743 (s)			745 (sh)	C–H out-of-plane def
720 (sh)	720 (s)				
698 (s)	697 (vs)	697 (s)	702 (s)	700 (s)	Out-of-plane phenyl def
	673 (s)				
670 (m)	640 (w)	676 (w)	644 (m)	642 (w)	
	633 (m)				COO^- wag and
	621 (w)		618 (vw)	617 (vw)	NH_2 rock (complexes)
	613 (w)				
602 (w)	584 (w)	604 (w)	595 (m)	595 (w)	
					In-plane phenyl def
	578 (w)				
	555 (vs)		547 (m)	555 (m)	COO^- rock
523 (s)	516 (w)	521 (s)	519 (w)	517 (w)	
					Skeletal def
467 (m)	467 (ms)	471 (m)	473 (w)	464 (w)	
	401 (m)		422 (m)	416 (w)	Asym Cu–N str
	393 (sh)		412 (w)		Sym Cu–N str
374 (sh)	381 (w)	374 (s)	370 (w)	378 (w)	
					Skeletal def
362 (s)		337 (s)		339 (w)	
	340 (ms)		358 (w)	328 (w)	Asym Cu–O str
			324 (m)		Sym Cu–O str
323 (w)	323 (w, sh)				Skeletal def
	288 (vw)		232 (vw)		Skeletal or chelate ring
	240 (w)		222 (vw)	223 (vw)	def

[a] Abbreviations as in Table I.

infrared activity of metal–ligand stretching frequencies can be used to discriminate between isomeric forms. Figure 3 shows the geometry and molecular symmetry for the complexes formed from optically active and racemic amino acids within a square-planar molecular model that ignores axial coordination and chelate-ring nonplanarity. The trans isomer of the racemic complex (a) belongs to the C_i point group for which only the asymmetric copper–ligand stretching vibrations are infrared active, while the cis isomer, complex b, belongs to the noncentrosymmetric C_s molecular point group for which both asymmetric and symmetric metal–ligand stretching vibrations are active. Both the *cis*- and the *trans*-bis(amino acidato)copper(II) complexes formed from optically active amino acids, c and d, belong to the C_2 molecular point group, and the geometries of these complexes are best differentiated by noting the local centrosymmetry of the binding groups about the metal atom of the trans complex. For the optically active complexes, local symmetry may dictate the activity of the copper–ligand stretching vibrations. Thus, for cis complexes, asymmetric and symmetric Cu–N and Cu–O stretching modes are expected to be infrared active, while the spectra of trans complexes should exhibit only asymmetric vibrations. The validity of this criterion has been demonstrated for a number of glycinato complexes,[3,21] and similar considerations have been used to predict the configurations of several metal–isoleucine chelates,[26] but low-frequency vibrational assignments in that study differ with those proposed above.

The minor deviations in metal–ligand distances and intraring geometry of bis(α-amino acidato)copper(II) complexes whose crystal structures have been determined[10,30,34] suggest that the far-infrared criterion cited above for the glycine complexes may be extended to other amino acid complexes. Moreover, the metal–ligand frequencies should lie proximate to the bisglycinatocopper(II) values, and the assignments given above are based on this. The Cu–O and Cu–N stretching frequencies measured for complexes of known configurations are summarized in Table VIII

Table VIII. Copper–Ligand Stretching Frequencies (cm^{-1}) of Complexes Whose Structures Have Been Determined by X-Ray Diffraction

Complex	ν(Cu–N) Asym	ν(Cu–N) Sym	ν(Cu–O) Asym	ν(Cu–O) Sym
Trans complexes				
Bisglycinatocopper(II) dihydrate	477		334	
Bis-L-alaninatocopper(II)	484		332	
Bis-DL-α-amino-*n*-butyrato-copper(II)	498		341	
Bis-DL-prolinatocopper(II)-dihydrate	498		319	
Cis complexes				
Bisglycinatocopper(II) monohydrate	471	454	330	277
Bis-L-alaninatocopper(II)	483	411	325	276
Bis-L-isoleucinatocopper(II) monohydrate	471	407	342	298

and seem to bear out both expectations. For the trans complexes, only the asymmetric stretching modes are infrared active at *ca.* 475 cm^{-1} (Cu–N) and *ca.* 330 cm^{-1} (Cu–O), but two stretching modes for each linkage appear for the cis complexes. The L-isoleucine complex is included in Table VIII, although the X-ray determination that confirmed the prediction of a cis geometry for this chelate was not available until after completion of our investigation. While the

(34) H. C. Freeman in ref 11, p 95.

Table IX. Copper–Ligand Stretching Frequencies (cm^{-1}) and Predicted Local Geometries about the Copper(II) Ion

Complex	ν(Cu–N)	ν(Cu–O)	Geometry
1. Bis-DL-alaninatocopper(II) monohydrate	490	348	Trans
2. Bis-DL-alaninatocopper(II)	493	333	Trans
3. Bis-DL-isoleucinatocopper(II) monohydrate	468, 409	345, 285	Cis
4. Bis-DL-valinatocopper(II)	450	331	Trans
5. Bis-L-valinatocopper(II)	446	351	Trans
6. Bis-DL-leucinatocopper(II)	488	328	Trans
7. Bis-L-leucinatocopper(II)	476	316	Trans
8. Bis-DL-prolinatocopper(II)	510	330	Trans
9. Bis-DL-phenylalaninatocopper(II) (blue, scaly)	416	328	Trans
10. Bis-DL-phenylalaninatocopper(II) (blue violet, needles)	422, 412	358, 324	Cis
11. Bis-L-phenylalaninatocopper(II)	401	340	Trans

correct geometry of this moiety is predicted using the vibrational criterion, the circular dichroism spectrum has been interpreted as establishing a trans configuration.[17]

The configurations inferred for 11 amino acid chelates are presented in Table IX. The data for complexes formed both by optically active and racemic amino acids have been included, since the crystal forces leading to the stereoselection of the cis configuration in the solid could differ. Thus, only the trans configuration of the anhydrous and hydrated forms of DL-alaninatocopper(II) could be prepared, although geometrical isomerism is observed for optically active chelates formed from either the D- or L-amino acids.[7-10] In the region below 600 cm^{-1}, the spectra of the anhydrous Cu(DL-ala)$_2$ complex and *trans*-Cu(L-ala)$_2$ are virtually identical. The unit cell parameters of the monoclinic Cu(DL-ala)$_2$ have been determined by electron diffraction, and this compound was ascribed a trans configuration on the basis of peak positions in Patterson space.[35]

The Cu(DL-ile)$_2\cdot OH_2$ appears to be a cis complex like Cu(L-ile)$_2\cdot OH_2$, and the metal–ligand frequencies are very close to those found for the optically active chelates. It may be that the stabilization of the relatively unusual cis configuration intimately depends on a first-coordination-sphere interaction with a single water molecule, leading to an extensive hydrogen-bonding network and efficient packing.[30] It would appear that in the isoleucine case such factors may be more important than crystal energy terms arising from the difference in chelate ring geometries. The copper–amino acid stretching frequencies do not appear to be otherwise sensitive to hydration effects,[32] and the anhydrous bis-DL-prolinatocopper(II) complex exhibits the two modes expected for a trans geometry at only slightly higher frequencies than found in the trans dihydrate.

Trans geometries are found for anhydrous complexes prepared with both DL- and L forms of valine and leucine. Yasui and Shimura[15] interpret the diffuse reflectance spectrum of Cu(DL-val)$_2$ in terms of this conformation also, but a hydrated form of Cu(L-val)$_2$ is taken to be cis. The latter complex could be stabilized by forces similar to those existing in crystals of Cu(ile)$_2\cdot OH_2$, but our attempts to synthesize a hydrated valine complex that exhibited a cis ligand arrangement were unsuccessful.

The possible existence of geometrical isomerism in DL-phenylalanine complexes is intriguing,[16] since no other cases of such stereoselective effects are known in racemic (amino acidato)copper(II) compounds. Moreover, the molecular symmetries of the cis and trans complexes approach idealized C_s and C_i symmetries, respectively, and the reliance on local symmetry arguments is not so severe as in the optically active complexes. As predicted by Laurie[16] from intensity effects in the electronic absorption spectra and from differences in the infrared spectra above 700 cm^{-1}, the blue, scaly form of Cu(DL-phe)$_2$ does appear to be the trans isomer, while the blue-violet, needle-like material exhibits four copper–ligand bands and verifiably adopts a cis configuration. The similarity of the infrared spectrum of Cu(L-phe)$_2$ to that of the trans DL isomer argues for an analogous conformation.

At the inception of this study it was hoped that some indication as to the nature of intercomplex interaction through copper's fifth and sixth coordination positions might be evident in the vibrational spectra. An examination of the complete spectra does not reveal characteristics that can unambiguously be differentiated from hydration effects. However, the appearance of a strong peak at 1648 cm^{-1} in the spectrum of *cis*-Cu(L-ala)$_2$ that is not found in the spectrum of the trans isomer may be related to the intercomplex copper–carbonyl oxygen interaction which is apparent from the X-ray diffraction investigation.[9,10] For the DL-phenylalanine isomers, which are also anhydrous, analogous effects are not observed in the carboxylate stretching region, and one may assert, in lieu of a crystal structure determination, that the packing of the bulky phenyl rings rather than fifth- and sixth-coordination-position interactions may be responsible for the observed isomerism. For the *cis*-bisglycinatocopper(II) monohydrate, a carbonyl–copper interaction similar to that in the *cis*-alanine complex is known to occur,[6] and a strong absorption does appear at 1674 cm^{-1} which is not found in the spectrum of the corresponding dihydrate. This band may arise from the water that is also known to be coordinated,[6] however, and a similar peak is found at 1650 cm^{-1} in the dihydrate of Cu(DL-prol)$_2$.[32] In the proline complex the fifth and sixth coordination sites are occupied by the water molecules,[36] and the 1650-cm^{-1} peak com-

(35) A. V. Ablov, L. F. Chapurina, K. A. D'yakon, and V. Ya. Ivanova, *Russ. J. Inorg. Chem.*, 11, 1407 (1966).

pletely vanishes on dehydration. Similarly, the strong band measured at *ca.* 1660 cm^{-1} in the monohydrato isoleucine complexes probably arises from the bending mode of *coordinated* water in both species. Interestingly, the absence of an absorption in this region for $Cu(gly)_2 \cdot 2H_2O$ may indicate that the water molecules exist in the lattice of this crystal rather than coordinated to the copper ion.[36]

Acknowledgment. We appreciatively acknowledge several conversations with Professor C. R. Hare of the University of Miami that stimulated our interest in the problem discussed in this manuscript.

(36) The bending mode of lattice water should appear in the range 1600–1630 cm^{-1} (see K. Nakamoto, "Infrared Spectra of Inorganic and Coordination Compounds," Wiley, New York, N. Y., 1963, p 156), and in $Cu(gly)_2 \cdot 2H_2O$ it is assigned to a very strong absorption at 1608 cm^{-1}, unresolved from the NH_2 scissors.

Laser-Raman and Infrared Spectra of Amino Acids and Their Metal Complexes. III. Proline and Bisprolinato Complexes

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Abstract: The laser-Raman spectra of DL-proline and L-proline in the solid state and in aqueous solutions of pH 1.0, 6.0, and 11.0 are investigated, and bands characteristic of the cationic, zwitterionic, and anionic forms of the amino acid residue are discriminated. The infrared spectra of solid DL-proline and L-proline have been measured in the region between 4000 and 200 cm^{-1} and the infrared and Raman spectra of proline in D_2O solutions are also reported. Vibrational modes that principally contribute to the observed frequencies are empirically assigned on the basis of spectral changes resulting from N-deuteration and pH variation and through comparison with a Urey–Bradley force-field analysis of glycine[2] and with the spectrum of pyrrolidine.[3] The infrared spectra of anhydrous, monohydrato, and dihydrato forms of the bis-DL-prolinatocopper(II) complex and the dihydrate of bis-DL-prolinatonickel(II) were carefully examined in order to infer structural differences in these complexes and to detail the effects of variable hydration on their infrared spectra. Similarities in the positions of the metal–nitrogen and metal–oxygen stretching modes indicate that the trans configuration is maintained in all four complexes, and spectral features resulting from removal of the groups occupying axial coordination positions are discussed. Contrasting with this result for the DL-proline complexes, the anhydrous and hydrated forms of bis-L-prolinatocopper(II) appear to adopt cis geometries.

The molecular structure of bis-DL-prolinatocopper(II) dihydrate as determined by Mathieson and Welsh[4] using X-ray diffraction techniques is interesting because it presumably closely resembles the coordinated species in aqueous solution.[5,6] The copper ion is located in a tetragonally distorted octahedral environment with the prolines bidentately coordinated in a trans configuration and with two water molecules bonded axially.[4] This complex can apparently be dehydrated to form $Cu(DL\text{-}pro)_2 \cdot H_2O$[7] and $Cu(DL\text{-}pro)_2$, and the effects on the vibrational spectra of the series of complexes of variable hydration and, concomitantly, of groups occupying the fifth and sixth coordination positions, can be examined. Laurie[8] has noted the possible hazards in employing vibrational criteria that ignore these effects to distinguish geometrical isomers of Cu(II)–amino acid complexes. However, the perturbations on the spectra due to such structural changes in the metal–ligand stretching regions are minimal, and the previously developed criterion[9] based on symmetry arguments regarding the number of Cu–N and Cu–O stretching absorptions appears to be valid (at least for this test case). Identification of metal–ligand and chelate ring modes in $Ni(DL\text{-}pro)_2 \cdot 2H_2O$, $Cu(DL\text{-}pro)_2$, $Cu(DL\text{-}pro)_2 \cdot H_2O$, $Cu(DL\text{-}pro)_2 \cdot 2H_2O$, $Cu(L\text{-}pro)_2$, and $Cu(L\text{-}pro)_2 \cdot XH_2O$ is based on a comparison with spectrum of the free amino acid and on analogies to the spectrum of bisglycinatocopper(II) monohydrate.[9,10] Utilizing our vibrational criterion[9] and through comparison of the spectra with that of *trans*-$Cu(pro)_2 \cdot 2H_2O$ it is concluded that the complexes formed from the racemic amino acids adopt a trans structure. The present study also shows that copper(II) complexes synthesized with the optically active amino acid are cis isomers, and the recent suggestion[11] that stereoselective crystal packing effects operate to stabilize this configuration for bis-L-prolinato complexes is most probably correct.

The spectral study of the metal complexes necessitated a comprehensive investigation and assignment of the

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