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Metal Isotope Effects on the Vibrational Spectra of Polymeric Metal Complexes. V.[1] Infrared Spectra of Bis(L- and DL-phenylalaninato)copper(II)

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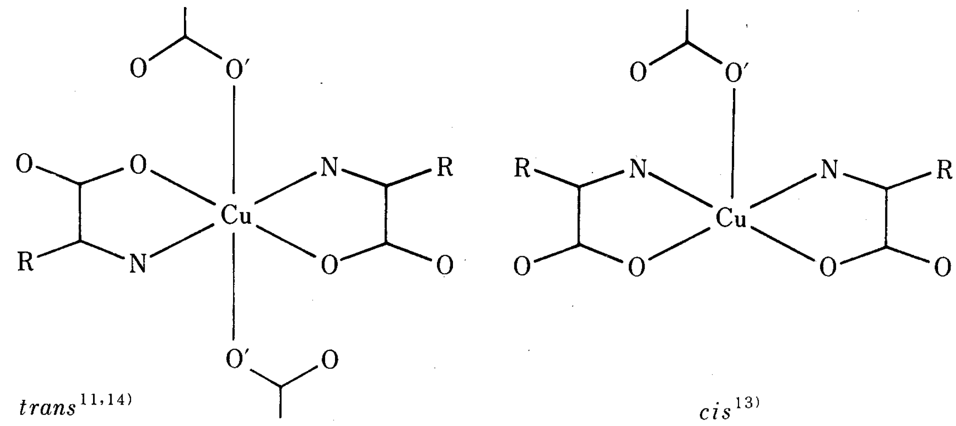
The infrared spectra of bis(L- and DL-phenylalaninato)copper(II) and their *N*-deuterated analogues have been recorded in the region between 4000 and 200 cm^{-1}. The vibrational assignments of the Cu-ligand stretching vibrations have been made by means of the metal isotope technique, ^{63}Cu and ^{65}Cu substitution. Three bands of *trans*-bis(L-phenylalaninato)copper at 400, 380, and 339 cm^{-1} shift appreciably on ^{63}Cu–^{65}Cu substitution. The blue isomer of bis(DL-phenylalaninato)copper also shows three copper isotope-sensitive bands at 380, 340, and 328 cm^{-1}, analogous to those of *trans*-bis(D-alaninato)- and (L-phenylalaninato)copper. However, the blue-violet isomer of the DL complex shows only two sensitive bands at 370 and 322 cm^{-1}, as in the case of *cis*-bis(D-alaninato)copper. Frequency shifts on *N*-deuteration suggest that one of the Cu–N stretching vibrations is at higher frequency than the Cu–O stretching vibrations for bis(L-phenylalaninato)copper, but this frequency order is reversed for the two isomers of bis(DL-phenylalaninato)copper.

Keywords——IR spectra; aminoacid; phenylalanine; isomerism; bis(L-phenylalaninato)-copper; bis(DL-phenylalaninato)copper; ^{63}Cu–^{65}Cu substitution; isotope shift; deuteration; *trans-cis*

As fundamental complexes of metallo-proteins and -enzymes, aminoacid-copper complexes have already received considerable attention in relation to their biological activities[2,3] and the role of copper *in vivo*.[4] Among them, isomers of bis(DL-phenylalaninato)copper, Cu(DL-phe)$_2$, have been structurally investigated by means of electron spin resonance (ESR)[5] and infrared (IR)[6,7] spectroscopy. In these investigations, a monomeric model has frequently been adopted.[6,7] According to the X-ray analyses,[8-13] however, most copper-aminoacid complexes take complicated polymeric structures in the solid state. Since *trans*-bis(L-phenylalaninato)copper, Cu(DL-phe)$_2$, takes the polymeric structure shown in Fig. 1,[14] the monomeric model seems clearly inappropriate. In the previous paper,[15] it was reported that polymeric *trans*- and *cis*-bis(D-alaninato)copper, Cu(D-ala)$_2$, show three and two bands appreciably sensitive to ^{63}Cu–^{65}Cu substitution, respectively. The present paper shows that the IR spectra of Cu(L-phe)$_2$ and an isomer of Cu(DL-phe)$_2$ are consistent with those of *trans*-Cu(D-ala)$_2$ and the IR spectrum of the other isomer of Cu(DL-phe)$_2$ is consistent with that of *cis*-Cu(D-ala)$_2$.

Experimental

Materials——Commercially available L- and DL-phenylalanines (Ishizu Seiyaku) were recrystallized several times from water. *N*-Deuterated L- and DL-phenylalanines were obtained from the purified L- and DL-phenylalanines by the usual exchange reaction with heavy water (Merck, AG., 99%). Cu(L-phe)$_2$ and two isomers of Cu(DL-phe)$_2$ were prepared from the purified L- and DL- phenylalanines according to the method of Laurie.[16] A blue isomer (α-form), α-Cu(DL-phe)$_2$, prepared at room temperature was converted by heating on a boiling water bath into a blue-violet isomer (β-form), β-Cu(DL-phe)$_2$. For the preparation of *N*-deuterated complexes, Cu(L-phe-d_2)$_2$ and Cu(DL-phe-d_2)$_2$, anhydrous cupric acetate was reacted with the *N*-deuterated ligands in heavy water. The IR spectra of Cu(L-



trans[11,14]

cis[13]

Fig. 1. Polymeric *trans* and *cis* Structures for Cu(D-ala)$_2$ and Cu(L-phe)$_2$

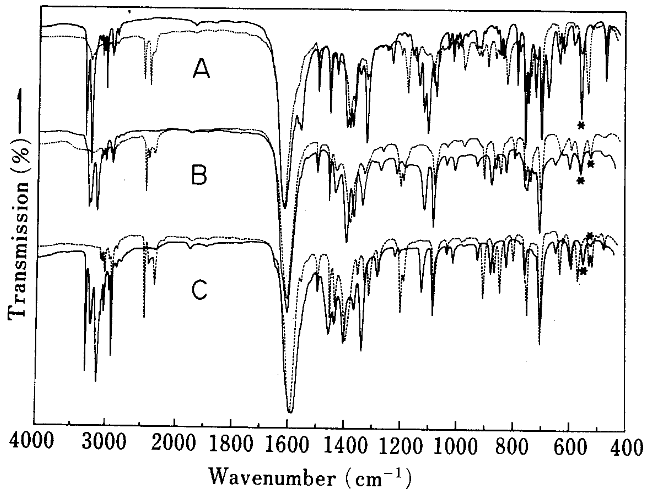


Fig. 2. IR Spectra of Cu(L-phe)$_2$, and α- and β-Cu(DL-phe)$_2$ in the Region above 450 cm^{-1}

A, Cu(L-phe)$_2$ (——) and Cu(L-phe-d_2)$_2$ (----); B, α-Cu(DL-phe)$_2$ (——) and α-Cu(DL-phe-d_2)$_2$ (----); C, β-Cu(DL-phe)$_2$ (——) and β-Cu(DL-phe-d_2)$_2$ (----).

phe)$_2$, and α- and β-Cu(DL-phe)$_2$ in the region above 680 cm^{-1} coincided with those reported by Laurie.[16] The complexes containing copper isotopes were obtained from isotopic cupric acetates which were prepared from ^{63}CuO and ^{65}CuO (Oak Ridge National Lab., U.S.A.) in the manner described in the previous papers.[15,17,18] The yield was about 30 mg of the complexes from 7 mg of the isotopic CuO. The IR spectra of the complexes containing copper isotopes coincided with those of the complexes containing copper of natural abundance except for the copper isotope shifts. The isotopic purities were 99.89% for ^{63}CuO and 99.70% for ^{65}CuO.

Measurements——The IR spectra were recorded on a JASCO DS-403G IR spectrophotometer (4000—200 cm^{-1}). The measurements were made with solid samples in Nujol and hexachlorobutadiene (Merck, AG., Uvasol) mulls. The frequencies were calibrated by the standard absorptions of polystyrene, indene and water vapor. For measuring small shifts of band centers on ^{63}Cu and ^{65}Cu (^{63}Cu–^{65}Cu) substitution, the scale of the frequency was expanded ten times over the desired frequency region, and the measurements were repeated at least three times to check the reproducibility of the spectra.

The IR spectra in the region above 500 cm^{-1} of Cu(L-phe)$_2$, Cu(DL-phe)$_2$, and their *N*-deuterated analogues are shown in Fig. 2, and parts of the expanded spectra in Fig. 3.

Vibrational Assignments and Discussion

The Region between 4000 and 500 cm^{-1}

No bands in the region above 500 cm^{-1} show an appreciable isotope shift on ^{63}Cu–^{65}Cu substitution except for some bands asterisked in Fig. 2 which show a small shift of less than 0.5 cm^{-1}. This small shift may be caused by a small contribution of the Cu-ligand stretching vibrations to the vibrations of phenylalaninates, and all the bands of Cu(L-phe)$_2$, and α- and β-Cu(DL-phe)$_2$ in this region were assigned to the vibrations of phenylalaninates. By referring to the frequency shifts on *N*-deuteration and the assignments of previous authors,[6,7] most of the bands were tentatively assigned to individual vibrations of phenylalaninates. By analogy

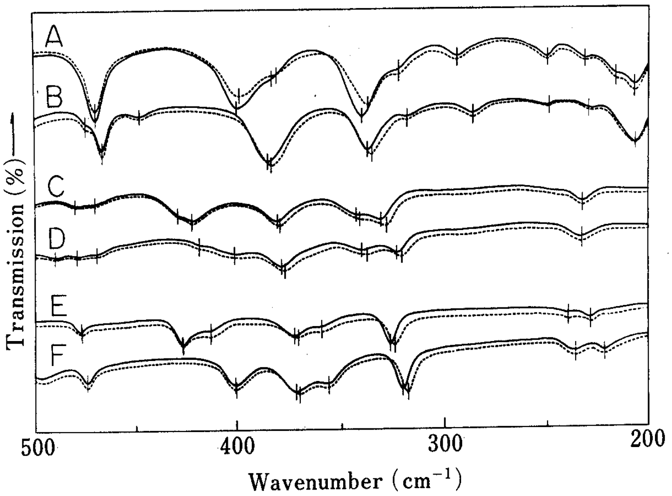


Fig. 3. Expanded IR Spectra of Cu(L-phe)$_2$, and α- and β-Cu(DL-phe)$_2$ in the Region between 500 and 200 cm^{-1}

A, ^{63}Cu(L-phe)$_2$ (——) and ^{65}Cu(L-phe)$_2$ (----); B, ^{63}Cu(L-phe-d_2)$_2$ (——) and ^{65}Cu(L-phe-d_2)$_2$ (----); C, α-^{63}Cu(DL-phe)$_2$ (——) and α-^{65}Cu(DL-phe)$_2$ (----); D, α-^{63}Cu(DL-phe-d_2)$_2$ (——) and α-^{65}Cu(DL-phe-d_2)$_2$ (----); E, β-^{63}Cu(DL-phe)$_2$ (——) and β-^{65}Cu(DL-phe)$_2$ (----); F, β-^{63}Cu(DL-phe-d_2)$_2$ (——) and β-^{65}Cu(DL-phe-d_2)$_2$ (----).

with *trans*- and *cis*-Cu(D-ala)$_2$,$^{15)}$ small differences of the IR spectra among three complexes were assumed to be caused by differences of the conformation of phenylalaninates. The IR spectra of the three complexes in this region give no clue to the structure of the coordination around the Cu atom.

The Region between 500 and 200 cm^{-1}

Bis(L-phenylalaninato)copper (II)——According to the X-ray analysis,$^{14)}$ the structure of Cu(L-phe)$_2$ resembles that of *trans*-bis(L-alaninato)copper(II).$^{11)}$ The copper coordination is a distorted octahedron including a *trans* square plane with two additional weak bonds (Cu–O′, see Fig. 1). Since the copper atom occupies a symmetry site, C$_1$, in this environment, six Cu-ligand stretching vibrations are infrared-active. However, two Cu–O′ bonds are so long that their stretching vibrations are probably in the region below 200 cm^{-1}.

Three band-centers of Cu(L-phe)$_2$ at 400, 380 and 339 cm^{-1} shift appreciably on ^{63}Cu–^{65}Cu substitution as shown in Fig. 3. These bands can undoubtedly be assigned to the vibrations including displacements of the copper atom. On *N*-deuteration, the 400 cm^{-1} band shifts to the lower frequency region by about 20 cm^{-1} and hides the 380 cm^{-1} band, whereas the 339 cm^{-1} band unshifts. Accordingly, we assigned the 400 cm^{-1} band to a Cu–N stretching vibration and the 380 and 339 cm^{-1} bands to the Cu–O stretching vibrations. It is consistent with the case of *trans*-Cu(D-ala)$_2$$^{15)}$ that three bands of Cu(L-phe)$_2$, two Cu–O and one Cu–N stretching bands, show an appreciable shift on ^{63}Cu–^{65}Cu substitution. The assignments based on the above discussion are summarized in Table I together with the observed frequencies, approximate intensities and isotope shifts on ^{63}Cu–^{65}Cu substitution.

α- and β-Bis(DL-phenylalaninato)copper(II)——No X-ray analysis has yet been carried out for α- and β-Cu(DL-phe)$_2$ to date. Herlinger *et al.*$^{6)}$ concluded that the α- and β-forms were monomeric *trans*- and *cis*-conformations (C_i and C_s models), respectively, because the symmetric Cu–O and Cu–N stretching bands were missing in the IR spectrum of α-Cu(DL-phe)$_2$ as opposed to that of β-Cu(DL-phe)$_2$. However, by analogy with Cu(L-phe)$_2$$^{14)}$ and Cu(L-ala)$_2$,$^{11)}$ it seems likely that the two isomers of Cu(DL-phe)$_2$ take polymeric structures, not monomeric structures.

As shown in Fig. 3, the bands of α-Cu(DL-phe)$_2$ at 380, 340 and 328 cm^{-1} show appreciable isotope shift on ^{63}Cu–^{65}Cu substitution. Further, the 328 cm^{-1} band is replaced by a band at 320 cm^{-1} while the 380 and 340 cm^{-1} bands remain almost unshifted on *N*-deuteration. We assigned the 380 and 340 cm^{-1} bands to the Cu–O stretching vibrations and the 328 cm^{-1} band to a Cu–N stretching vibration. The number of copper isotope-sensitive bands for α-Cu(DL-phe)$_2$ is consistent with those for *trans*-polymeric Cu(L-phe)$_2$ and Cu(D-ala)$_2$.$^{15)}$

For the β-form, two completely different assignments have been reported to date as

TABLE I. Observed Frequencies, Metal Isotope Shifts and Assignments for *trans*-Cu(L-phe)$_2$ and Its *N*-Deuterated Analogues in the Region between 500 and 200 cm^{-1}

trans-Cu(L-phe)$_2$				*trans*-Cu(L-phe-d_2)$_2$		
ν[a]	$\Delta\nu_m$[b]	Assign.[c] Herlinger *et al.*[6]	Assign.[c] Present study	ν[a]	$\Delta\nu_m$[b]	Assign.[c] Present study
470 w	0	δskel	δskel	466 w	0	δskel
—[d]	—	—[e]	ν_sCu–NH$_2$	448 vw	0	ν_sCu–ND$_2$
400 w	1.2	ν_aCu–NH$_2$	ν_aCu–NH$_2$	385 w	1.5	ν_aCu–ND$_2$
380 sh	>1	δskel	ν_sCu–OOC	—[d]	—	ν_sCu–OOC
339 w	2.5	ν_aCu–OOC	ν_aCu–OOC	336 w	2.0	ν_aCu–OOC
320 sh	*ca.* 0	δskel	δskel	316 vw	0	δskel
292 vw	0	δskel	δskel	284 vw	0	δskel
249 vw	0	δskel or δring	δskel	247 vw	0	δskel
230 vw	0	—[e]	δskel	229 vw	0	δskel
215 sh	*ca.* 0	—[e]	δskel	—[d]	—	δskel
207 w	0	—[e]	δskel	206 w	0	δskel

a) w, weak; vw, very weak; sh, shoulder.
b) Shifts of band center on ^{63}Cu–^{65}Cu substitution.
c) ν, stretching; δ, deformation.
d) Hidden by a neighboring band.
e) Not reported.

TABLE II. Observed Frequencies, Metal Isotope Shifts and Assignments for α-Cu(DL-phe)$_2$ and Its *N*-Deuterated Analogues in the Region between 500 and 200 cm^{-1}

α-Cu(DL-phe)$_2$				α-Cu(DL-phe-d_2)$_2$		
ν[a]	$\Delta\nu_m$[b]	Assign.[c] Herlinger *et al.*[e]	Assign.[c] Present study	ν[a]	$\Delta\nu_m$[b]	Assign.[c] Present study
479 w	0	δskel	δskel	478 vw	0	δskel
469 sh	*ca.* 0	—[d]	δskel	468 sh	*ca.* 0	δskel
430 sh	*ca.* 0	δskel	ν_sCu–NH$_2$	415 sh	*ca.* 0	ν_sCu–ND$_2$
421 w	0	ν_aCu–NH$_2$	δskel	400 vw	0	δskel
380 w	1.0	δskel	ν_sCu–OOC	378 w	1.5	ν_sCu–OOC
340 sh	>1	δskel	ν_aCu–OOC	337 vw	2.0	ν_aCu–OOC
328 w	2.5	ν_aCu–OOC	ν_aCu–NH$_2$	320 w	2.2	ν_aCu–ND$_2$
230 vw	0	δskel	δskel	229 vw	0	δskel

a) w, weak; vw, very weak; sh, shoulder.
b) Shifts of band center on ^{63}Cu–^{65}Cu substitution.
c) ν, stretching; δ, deformation.
d) Not reported.
e) Assuming a *trans*-monomeric model.[6]

shown in Table III. One was carried out by assuming a *trans* monomeric square model,[7] whereas the other was based on a *cis* monomeric square model.[6] Because of the ambiguity of the previous assignments, isotope labeling studies seemed essential.

The IR spectrum of β-Cu(DL-phe)$_2$ is similar to that of α-Cu(DL-phe)$_2$ as seen in Fig. 3. However, β-Cu(DL-phe)$_2$ shows only two appreciably copper isotope-sensitive bands at 370 and 322 cm^{-1} whereas α-Cu(DL-phe)$_2$ shows three. On *N*-deuteration, the 370 cm^{-1} band remains almost unshifted but the 322 cm^{-1} band shifts to a lower frequency region by about

TABLE III. Observed Frequencies, Metal Isotope Shifts and Assignments for β-Cu(DL-phe)$_2$ and Its *N*-Deuterated Analogues in the Region between 500 and 200 cm^{-1}

β-Cu(DL-phe)$_2$					β-Cu(DL-phe-d_2)$_2$		
ν[a]	$\Delta\nu_m$[b]	Assign.[c] Herlinger *et al.*[f]	Assign.[c] Inomata *et al.*[g]	Assign.[c] Present study	ν[a]	$\Delta\nu_m$[b]	Assign.[c] Present study
474 vw	0.2	δskel	Benzene ring	δskel	472 w	0	δskel
424 w	0.2	ν_aCu–NH$_2$	δskel	ν_sCu–NH$_2$	400 w	0.2	ν_sCu–ND$_2$
415 sh	*ca.* 0	ν_sCu–NH$_2$	—[e]	δskel	—[d]	—	δskel
370 vw	1.8	δskel	ν_aCu–NH$_2$	ν_aCu–OOC	369 w	1.5	ν_aCu–OOC
360 vw	0	ν_aCu–OOC	δskel	ν_sCu–OOC	357 w	0	ν_sCu–OOC
322 w	2.3	ν_sCu–OOC	δskel	ν_aCu–NH$_2$	316 w	2.2	ν_aCu–ND$_2$
236 vw	0	δskel	—[e]	δskel	232 vw	0	δskel
225 vw	0	δskel	—[e]	δskel	218 vw	0	δskel

a) w, weak; vw, very weak; sh, shoulder.
b) Shifts of band center on ^{63}Cu–^{65}Cu substitution.
c) ν, stretching; δ, deformation.
d) Hidden by a neighboring band.
e) Not reported.
f) Assuming a *cis*-monomeric model.[6]
g) Assuming a *trans*-monomeric model.[7]

10 cm^{-1}. By referring to these isotope shifts, the former can be assigned to a Cu–O stretching vibration and the latter to a Cu–N stretching vibration. It should be mentioned that the number of copper isotope-sensitive bands for β-Cu(DL-phe)$_2$ is in agreement with that of *cis*-polymeric Cu(D-ala)$_2$.[15]

By referring to the frequency shifts on *N*-deuteration and the assignments for related complexes,[15,17,18] the remaining bands of α- and β-Cu(DL-phe)$_2$ in the region between 500 and 200 cm^{-1} were tentatively assigned to skeletal deformation or Cu-ligand stretching vibrations involving little displacement of the Cu atom.

Our assignments are entirely different from those reported by previous authors[6,7] as summarized in Tables II and III. This point suggests that the conventional methods used by the previous authors[6,7] are frequently ineffective for assigning metal-ligand stretching vibrations and give ambiguous assignments for complicated metallo-aminoacids. In contrast, the shifts on ^{63}Cu–^{65}Cu substitution permit the unambiguous assignment of the vibrations including displacement of the copper atom.

The Cu-phenylalaninate stretching frequencies of α- and β-Cu(DL-phe)$_2$ are not very different from each other as can be seen in Tables II and III. As discussed above, the number of copper isotope-sensitive bands suggests that α- and β-Cu(DL-phe)$_2$ take the *trans*- and *cis*-polymeric structures, respectively. The Cu–N stretching frequencies of Cu(L-phe)$_2$ are higher by about 70 cm^{-1} than those of α- and β-Cu(DL-phe)$_2$, whereas the Cu–O stretching frequencies are comparable with one another. This result is of interest, suggesting that the Cu–N binding forces are probably weakened by changing the ligand from L-phenylalanine to DL-phenylalanine.

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