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# Metal Isotope Effects on the Vibrational Spectra of Polymeric Metal Complexes. I. Infrared Spectra of $[\mathrm{Bis(L\text{-}asparaginato)copper(II)}]_n$

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The infrared spectra of $[\mathrm{bis\text{-}(L\text{-}asparaginato)copper(II)}]_n$ and its isotopic complexes containing copper and hydrogen isotopes have been measured in the region between 4000 and 200 cm$^{-1}$. By referring to the isotope shifts on $^{63}$Cu and $^{65}$Cu substitution, two bands at 359 and 318 cm$^{-1}$ have been assigned to metal-ligand stretching vibrations. The frequency shifts on *N*,*N'*-deuteration revealed that the Cu–N stretching frequency is larger than the Cu–O stretching frequency.

**Keywords**——infrared spectra; polymeric metal complex; $[\mathrm{bis\ (L\text{-}asparaginato)\text{-}copper(II)}]_n$; metal isotope effect; $^{63}$Cu and $^{65}$Cu substitution; L-asparagine monohydrate; metal-ligand stretching

Much interest has been centered on polymeric metal complexes in relation to their roles in cancer chemotherapy and their biological activity.1) Among them, complexes including amino acids and related compounds may be of interest in relation to the role of metals *in vivo* and have already received considerable attention from many investigators.2–5) However, in contrast with monomeric metal complexes of amino acids, their vibrational spectra have rarely been investigated in detail because of their complicated structures. In the present work, $[\mathrm{bis(L\text{-}asparaginato)copper(II)}]_n$, $[\mathrm{Cu(asp)_2}]_n$, was studied as a model of polymeric metal complexes including amino acids. Metal-ligand stretching frequencies of $[\mathrm{Cu(asp)_2}]_n$ were assigned by using the metal isotope technique which has been shown to be effective for identifying vibrations involving the displacement of a metal atom.6,7) In addition to this technique, the frequency shifts on *N*,*N'*-deuteration were useful for making assignments.

## Experimental Results

**Materials**——Commercially available L-asparagine monohydrate (asp·$H_2O$, Wako Junyaku) was purified several times by crystallization from water. Deuterated L-asparagine monohydrate(asp-$d_5$·$D_2O$) was obtained from the purified asp·$H_2O$ by exchange reaction with heavy water (Merck, AG., 99%). $[\mathrm{Cu(asp)_2}]_n$ was prepared from the purified asp·$H_2O$ according to the method of Stephans *et al.*8) For the preparation of *N*,*N'*-deuterated complexes, anhydrous cupric acetate was reacted with the purified asp·$H_2O$ in heavy water. The precipitate was filtered, washed with heavy water and dried under reduced pressure. For the preparation of complexes containing metal isotopes, $^{63}$CuO and $^{65}$CuO (Oak Ridge National Lab., USA) were converted into the corresponding cupric acetates by reaction with dilute acetic acid on a milligram scale. The cupric acetates were reacted with the asp·$H_2O$ in water and the resulting solides were washed with water and dried under reduced pressure. The yield was about 40 mg of both complexes. The chemical purity of each complex containing isotopes was checked by comparing its IR spectrum with that of the complex containing metal of natural abundance. The isotopic purities were 99.89% for the $^{63}CuO$ and 99.70% for the $^{65}CuO$.

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

The IR spectra in the region above 400 $cm^{-1}$ of asp·$H_2O$, $[Cu(asp)_2]_n$ and their deuterated analogs are shown in Fig. 1, and parts of the expanded spectra are shown in Fig. 2.

## Assignments and Discussion

### In the Region above 530 $cm^{-1}$

According to neutron diffraction analysis,[9] asparagine takes a zwitter-ion structure in the monohydrate crystal. In this structure, the group vibrations of amino acids and primary amides can be expected to resemble those of asparagine. By referring to the frequency shifts on deuteration and the IR spectra of related compounds, for example alanine,[10] glycine[11] and acetamide,[12,13] we tentatively assigned these group vibrations as summarized in Table I.

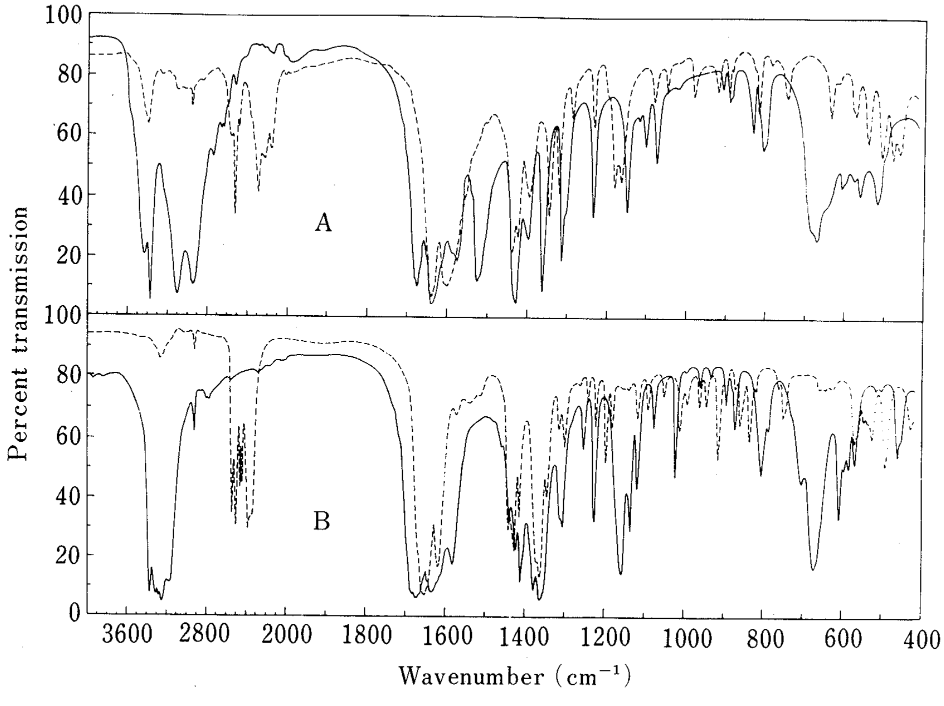

Fig. 1. IR Spectra of Asp·$H_2O$ and $[Cu(asp)_2]_n$ in the Region above 400 $cm^{-1}$

A: asp·$H_2O$ (——) and asp-$d_5$·$D_2O$ (----); B: $[^{NA}Cu(asp)_2]_n$ (——) and $[^{NA}Cu(asp\text{-}d_4)_2]_n$ (----).

Upon complex formation, the $-NH_3^+$ group of asp·$H_2O$ is replaced by the $-NH_2$ group.[8,9] Except for the spectral change caused by this replacement, the IR spectrum in this region of $[Cu(asp)_2]_n$ is expected to be similar to that of asp·$H_2O$, and the ligand absorptions can be assigned to individual vibrations as shown in Table I by referring to the frequency shifts on *N,N'*-deuteration and the assignments of asp·$H_2O$ and monomeric amino acid complexes.[14-16] However, there are some noteworthy spectral changes upon complex formation. One of them is the spectral difference between asp·$H_2O$ and $[Cu(asp)_2]_n$ in the region between 3500 and 2800 $cm^{-1}$. A band at 1520 $cm^{-1}$ of asp·$H_2O$, assigned to the $-NH_3^+$ symmetrical deformation vibration, vanishes upon complex formation. Two bands of asp-$d_5$·$D_2O$ assigned to the $COO^-$

TABLE I. Infrared Frequencies and Assignments for Asp·$H_2O$ and $[Cu(asp)_2]_n$ in the Region above 530 $cm^{-1}$

| asp·$H_2O$ | asp-$d_5$·$D_2O$ | $[Cu(asp)_2]_n$ | $[Cu(asp\text{-}d_4)_2]_n$ | Assignments c) |
|---|---|---|---|---|
| 3443 s | 2175 m | 3375 vs | 2549 s | $\nu NH_2$ ($ND_2$) or<br>$\nu NH_3^+$ ($ND_3^+$) or<br>$\nu H_2O$ ($D_2O$) |
| 3377 vs | 2237 m | 3319 vs | 2515 s | |
| 3103 vs | 2302 s | 3285 vs | 2409 m | |
| 2951 vs | 2493 m | 3255 vs | 2447 s | |
| | 2535 s | 3175 vs | 2387 s | |
| | 2570 m | | 2349 s | |
| | 2956 w | 2925 w | 2924 w | $\nu CH_2$ or $\nu CH$ |
| 1680 vs | 1643 vs | 1678 vs | 1655 vs | $\nu C{=}O$ |
| 1643 vs | 1605 vs | 1640 vs | 1624 s | $\nu_a COO^-$ |
| —a) | 1184 m | 1586 s | 1199 m, 1183 w | $\beta NH_2$ ($ND_2$) |
| 1580 s | 1169 m | —b) | —b) | $\delta_d NH_3^+$ ($ND_3^+$) |
| 1527 s | 1082 w | —b) | —b) | $\delta_s NH_3^+$ ($ND_3^+$) |
| 1430 vs | 1442 s | 1418 s | 1426 m | $\nu CN$ |
| | 1428 s | 1443 m, 1426 s | 1443 m, 1430 m | $\delta CH_2$ |
| 1401 m | 1400 m | 1380 s, 1365 vs | 1375 sh, 1366 vs | $\nu_s COO^-$ |
| 1363 s | 1351 s | —a) | 1346 m | $\delta CH$ |
| 1316 s | 1326 m | 1321 sh, 1306 m | 1318 w, 1302 m | $\omega CH_2$ |
| 1306 sh | 1290 w | —a) | 1265 vw | $t CH_2$ |
| 1236 m | 1235 w | 1254 w, 1226 m | 1245 w, 1224 m | $\nu$skel |
| 1151 m | 925 w | 1158 s | 914 m | $\rho NH_2$ ($ND_2$) |
| 1104 m | 749 m | —b) | —b) | $\rho NH_3^+$ ($ND_3^+$) |
| —b) | —b) | 1135 m | 835 m, 750 m | $t NH_2$ ($ND_2$) |
| 1075 m | 1051 w | 1119 m, 1077 w | 1118 w, 1053 w | $\nu$skel |
| 911 w | 984 w | 961 w, 935 w | 962 w, 945 w | $\nu$skel |
| 894 w | 898 w | 896 w | 896 w | $\nu$skel |
| 834 m | 822 m | 872 m | 859 m | $\rho CH_2$ |
| 808 m | 480 m | 804 m | 525 m | $\tau NH_2$ ($ND_2$) |
| 685 sh | 461 m | 669 s | 490 m | $\omega NH_2$ ($ND_2$) |
| 670 vs | 639 m | 702 w | 646 vw | $\delta$skel |
| —b) | —b) | 606 s | 430 m | $\omega NH_2$ ($ND_2$) |
| 604 m | 574 w | 594 sh | 568 m | $\delta$skel |
| 573 m | | 582 m | 561 sh | $\delta$skel |
| 558 m | 542 m | 567 m | 545 vw, 535 sh | $\delta$skel |

a) Hidden by a neighboring band.
b) Not expected.
c) $\nu$: stretching; $\beta$: bending; $\delta$: deformation; $\omega$: wagging; $\rho$: rocking; $t$: twisting; $\tau$: torsion.
d) Not expected for $[Cu(asp)_2]_n$ and $[Cu(asp\text{-}d_4)_2]_n$.

stretching vibrations undergo a high frequency shift by about 10—20 $cm^{-1}$ upon complex formation in spite of the fact that the $-COO^-$ group coordinates to the Cu atom. The corresponding shift for the undeuterated compounds is not obvious because of the interference of the $NH_2$ and $NH_3^+$ group and water vibrations.

In the region above 530 $cm^{-1}$, no band shows appreciable shifts on $^{63}Cu$ and $^{65}Cu$ substitution. This result indicates that none of the vibrations in this region involve displacements of the Cu atom.

## In the Region between 530 and 200 $cm^{-1}$

By analogy with the IR spectra of amino acid complexes,14—16) the Cu-ligand stretching vibrations can be expected in this region. Strictly speaking, all the copper-ligand stretching vibrations of $[Cu(asp)_2]_n$ should be infrared-active because the Cu atom is in a tetragonally distorted octahedral environment and occupies a $C_1$ site.9) However, since the carboxyl oxygen and the $\alpha$-amino nitrogen atoms of each ligand coordinate to the copper atom in a *trans* square planar configuration and the two Cu–O′ bonds are almost colinear with the normal to the coordination square plane,9) it is a reasonable approximation to classify the Cu-ligand

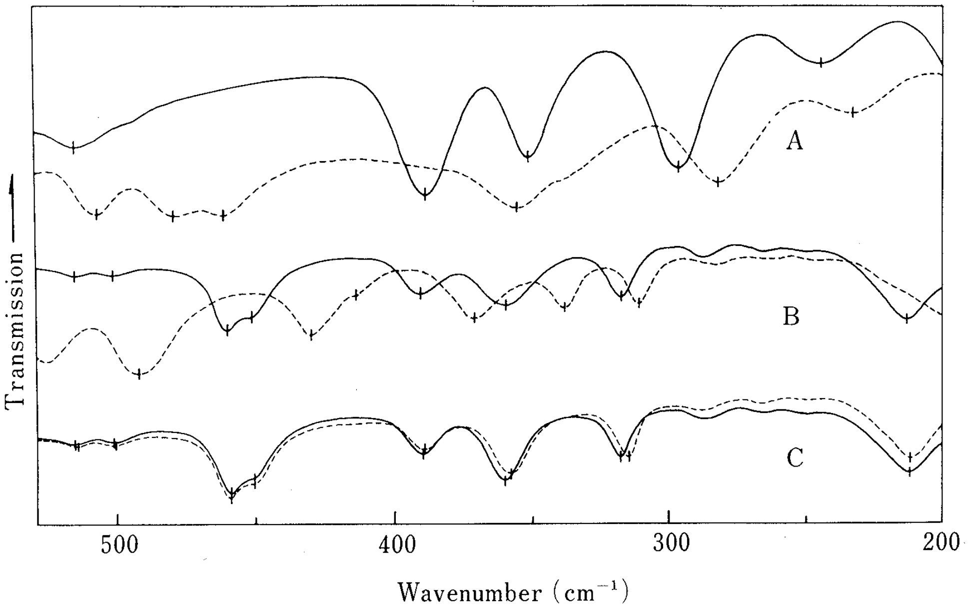

Fig. 2. IR Spectra of Asp·$H_2O$ and $[Cu(asp)_2]_n$ in the Region between 530 and 200 cm$^{-1}$

A: asp·$H_2O$ (——) and asp-$d_5$·$D_2O$ (----); B: $[^{NA}Cu(asp)_2]_n$ (——) and $[^{NA}Cu(asp\text{-}d_4)_2]_n$ (----); C: $[^{63}Cu(asp)_2]_n$ (——) and $[^{65}Cu(asp)_2]_n$ (----).

stretching vibrations into symmetrical and asymmetrical modes for the Cu atom. The latter can be expected to be relatively strong in the IR spectrum and to be sensitive to $^{63}Cu$ and $^{65}Cu$ substitution, in contrast with the symmetrical modes.

$[Cu(asp)_2]_n$ shows strong bands at 459, 450, 391, 360, 318 and 212 cm$^{-1}$ in this region. On simple comparison with the IR spectra of asp·$H_2O$ and $[Cu(asp)_2]_n$, the 391, 360 and 318 cm$^{-1}$ bands seem to correspond to the ligand bands at 390, 352 and 296 cm$^{-1}$, respectively. The 459 and 450 cm$^{-1}$ bands seem to appear newly upon complex formation and might be due to the Cu-ligand stretching vibrations. In contrast with expectation, these bands remain almost unshifted on $^{63}Cu$ and $^{65}Cu$ substitution, but are replaced by two bands at 427 and 411 cm$^{-1}$ on *N*,*N'*-deuteration. This result strongly indicates that the 459 and 450 cm$^{-1}$ bands require displacement not of the Cu atom, but of the nitrogen atoms. Thus, these bands should be assigned to skeletal deformation vibrations of the ligands. The frequency difference of these vibrations between asp·$H_2O$ and $[Cu(asp)_2]_n$ may be caused by coupling with the Cu–N stretching vibration and/or the structure change of asparagine upon complex formation. The 318 and 360 cm$^{-1}$ bands show 2.1 and 1.5 cm$^{-1}$ shifts, respectively, on $^{63}Cu$ and $^{65}Cu$ substitution, and are assigned to vibrations involving displacement of the Cu atom. On *N*,*N'*-deuteration, the 318 cm$^{-1}$ band shows a relatively small isotope shift, but the 360 cm$^{-1}$ band is replaced by a band at 327 cm$^{-1}$. Accordingly, the former was assigned to the Cu–O asymmetrical stretching vibration and the latter to Cu–$NH_2$ asymmetrical stretching vibration. The 391 and 212 cm$^{-1}$ bands are unaffected by the $^{63}Cu$ and $^{65}Cu$ substitution, but are replaced by bands at 369 and below 200 cm$^{-1}$ on *N*,*N'*-deuteration, respectively, and were assigned to skeletal deformation vibration of the ligands.

The symmetrical modes of the Cu-ligand stretching vibration are expected in this region. The bands caused from these vibrations are expected to be weak and to show small isotope shifts on $^{63}Cu$ and $^{65}Cu$ substitution, since these vibrations include a small displacement of the Cu atom. Thus, two very weak bands at 514 and 500 cm$^{-1}$, which display relatively small isotope shifts on $^{63}Cu$ and $^{65}Cu$ substitution, as shown in Table II, may be assigned to symmetrical Cu-ligand stretching vibrations. However, the observed magnitude of the metal isotope shifts of these two bands is also compatible with their assignment to skeletal deformation

TABLE II. Infrared Frequencies, Isotope Shifts and Assignments in the Region below 530 $cm^{-1}$

| $asp \cdot H_2O$ | $asp\text{-}d_5 \cdot D_2O$ | $[^{63}Cu(asp)_2]_n$ | $\Delta\nu_m$ [b] | $\Delta\nu_h$ [c] | Assignments [d] |
|---|---|---|---|---|---|
| 515 m | a) | | | | $\delta$skel |
| | | 514.3 vw | 0.7 | e) | $\delta$skel or $\nu_s$Cu-ligand |
| | | 499.7 vw | 0.2 | e) | $\delta$skel or $\nu_s$Cu-ligand |
| 390 m | 350 m | 458.9 m | 0.1 | 31 | $\delta$skel |
| 352 m | 337 sh | 450 sh | ~0 | 39 | $\delta$skel |
| 296 m | 282 m | 390.6 w | 0.2 | 22 | $\delta$skel |
| | | 359.6 m | 1.5 | 22 | $\nu_a$Cu–$NH_2$ |
| | | 317.6 w | 2.1 | 6 | $\nu_a$Cu–OOC |
| 244 w | 233 w | 211.6 m | ~0 | e) | $\delta$skel |

a) Hidden by the $N'D_2$ wagging and torsional bands.
b) Shifts of band center on $^{63}Cu$ and $^{65}Cu$ substitution.
c) Shifts on deuteration.
d) $\nu$: stretching; $\delta$: deformation.
e) Not observed, since the corresponding band of $[Cu(asp\text{-}d_4)_2]_n$ is not observed or is hidden by a neighboring band.

vibrations with slight contributions by the Cu-ligand stretching vibrations. Throughout the investigated region, no band assignable to the Cu–O′ stretching vibration was observed. The Cu–O′ bond-lengths are too long for their stretching vibrations to be observed in the region above 200 $cm^{-1}$. The assignments discussed above are summarized together with the isotope shifts in Table II.

As discussed above, it is often dangerous to attempt to identify the Cu-ligand stretching vibrations only by comparing the IR spectra of the complex and the ligand. However, $^{63}Cu$ and $^{65}Cu$ substitution is very useful as a means to assign vibrations that include displacement of a Cu atom of a complicated complex such as $[Cu(asp)_2]_n$, although such substitution is ineffectively for Cu-ligand stretching vibrations that do not include displacements of a Cu atom. The Cu-ligand stretching frequencies obtained in this study do not agree well with those of the related complexes reported by Walter *et al.*,[15-17] and comprehensively by Herlinger *et al.*,[18,19] and the results of these authors also differ from each other. Although Walter *et al.* carried out normal coordinate analysis by assuming a monomeric chelate model, it seems desirable to re-examine their assignments by using the metal isotope technique. The Cu–O and Cu–N asymmetrical stretching frequencies of $[Cu(asp)_2]_n$ are lower by about 40 and 80 $cm^{-1}$ than the Cu–O and Cu–N antisymmetric stretching frequencies of *cis*-Cu(glycine)$_2 \cdot H_2O$, respectively, although the Cu-ligand bond lengths of $[Cu(asp)_2]_n$ and Cu(glycine)$_2 \cdot H_2O$ are not very different from each other.[9,20] These Cu-glycine stretching frequencies are comparable with those of Cu(glycine)$_2 \cdot 2H_2O$, whose structure was estimated to be *trans*-monomeric by analogy with the structure of Ni(glycine)$_2 \cdot 2H_2O$.[14,21] It is of interest that the Cu-ligand stretching frequencies of $[Cu(asp)_2]_n$ are also much lower than those of *trans*-Cu(glycine)$_2 \cdot 2H_2O$, which has the same coordinating number and *trans*-structure as $[Cu(asp)_2]_n$. This frequency difference may reflect the structure difference between the monomeric and polymeric structure through a complicated vibrational coupling.

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## References and Notes

1) A. Yokoyama and M. Chikuma, *Kagaku* (Kyoto), Special Issue 68, "Bioinorganic Chemistry (II)" ed. by H. Tanaka, S. Nakahara, and S. Fukui, Kagakudojin, Kyoto, 1976, pp. 157—175.
2) A.J. Charlson, K.E. Trainor, and E.C. Watton, *J. Proc. Roy. Soc., New South Wales*, **108**, 6 (1975).
3) D.R. Williams, *J. Chem. Soc., Dalton*, **1973**, 1064.

4) B.B. Misra, S.D. Sharma, and S.K. Gupta, *J. Mag. Res.*, **16**, 193 (1974).
5) H. Yokoi, *Bull. Chem. Soc., Jpn.*, **47**, 639 (1974).
6) K. Nakamoto, *Angew. Chem.*, **84**, 755 (1972).
7) Y. Saito, J. Takemoto, B. Hutchinson, and K. Nakamoto, *Inorg. Chem.*, **11**, 2003 (1972).
8) F.S. Stephans, R.S. Vagg, and P.A. Williams, *Acta Cryst.*, **B31**, 841 (1975).
9) M. Ramanadham, S.K. Sikka, and R. Chidambaram, *Acta Cryst.*, **B28**, 3000 (1972).
10) K. Machida, A. Kagayama, and Y. Saito, *J. Raman Spectrosc.*, **7**, 188 (1978).
11) K. Machida, A. Kagayama, Y. Saito, and Y. Kuroda, *Spectrochim. Acta*, **33A**, 569 (1977).
12) T. Uno, K. Machida, and Y. Saito, *Bull. Chem. Soc., Jpn.*, **42**, 897 (1969).
13) T. Uno, K. Machida, and Y. Saito, *Spectrochim. Acta*, **27A**, 833 (1971).
14) J.R. Kincaid and K. Nakamoto, *Spectrochim. Acta*, **32A**, 277 (1976).
15) J.F. Jackovitz, J.A. Durkin, and J.L. Walter, C.S.C., *Spectrochim. Acta*, **23A**, 67 (1967).
16) J.L. Walter, C.S.C. and R.J. Hooper, *Spectrochim. Acta*, **25A**, 647 (1969).
17) J.F. Jackovitz and J.L. Walter, C.S.C., *Spectrochim. Acta*, **22**, 1393 (1966).
18) A.W. Herlinger, S.L. Wenhold, and T.V. Long II, *J. Am. Chem. Soc.*, **92**, 6474 (1970).
19) A.W. Herlinger and T.V. Long II, *J. Am. Chem. Soc.*, **92**, 6481 (1970).
20) H.C. Freeman and M.R. Snow, *Acta Cryst.*, **17**, 1463 (1964).
21) H.C. Freeman and J.M. Guss, *Acta Cryst.*, **B24**, 1133 (1968).