The Crystal Structure of Bis-(L-tyrosinato)copper(II)*

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The crystal structure of bis-(L-tyrosinato)copper(II), CuC₁₈H₂₀N₂O₆, has been determined and refined by the least-squares method using three-dimensional X-ray data. The crystals are orthorhombic, space group $P_{2_12_12_1}$, Z=4, with a=13.049 (7), b=22.227 (8), c=6.078 (3) Å. Diffractometer intensity data were collected for all unique reflections with sin θ/λ less than 0.61 Å⁻¹, using Ni-filtered copper radiation. The final R=4.2% for all 2012 data. The estimated standard deviations of C, N and O coordinates are between 0.003 and 0.006 Å. Coordination of the copper ion is distorted square pyramidal, with ligands in the *trans* configuration. Conformations of the two crystallographically independent tyrosyl residues differ. One of the phenolic rings is located beneath the base of the copper coordination pyramid at a distance slightly greater than 3 Å. This conformation was also observed in the crystal structure of the copper(II) chelate of glycyl-L-leucyl-L-tyrosine. It is interpreted as supporting the hypothesis of a weak interaction between the π -electron system of the phenolic ring and the copper(II) ion.

Introduction

As part of a study of the interactions between transition metal ions and amino acids and peptides, we have determined the crystal structure of the copper(II) chelate of L-tyrosine (CUTY). Previously it was reported (Van der Helm & Franks, 1968; Franks & Van der Helm, 1971) that a possible weak interaction had been observed between chelated copper(II) ions and the phenolic portion of tyrosyl residues in the structure of the copper(II) chelate of glycyl-L-leucyl-L-tyrosine, CUGLT. This behavior could have had at least two possible causes: (1) a weak interaction between the copper ion and the aromatic π -electron system, or (2) structure-specific effects, such as packing requirements. The implications of a weak interaction, if verified, would prove useful in elucidating the mechanism of certain oxidase enzymes. In order to further examine the possibility of an interaction, we are determining the crystal structures of several related compounds. The copper(II) chelate of L-phenylalanine, CUPA, has been reported (Van der Helm, Lawson & Enwall, 1971) and the structure determination of CUTY is the subject of the present communication.

Experimental

Single crystals of CUTY were obtained by slow aqueous diffusion of cupric acetate and L-tyrosine at room temperature. Deep blue, thin plates [plate face is (010) plane] appeared at the surface of the tyrosine after 2–3 days. Crystals thus obtained were quite stable; the solution, however, showed slow decomposition after

10-20 days. As the crystals were not appreciably soluble in common solvents, no recrystallization was accomplished.

Crystallographic data (Table 1) and integrated Xray intensity data were collected, at room temperature, on a G.E.-XRD 5 diffraction unit equipped with a SPG single-crystal orienter, scintillation counter and pulse-height analyzer. The 2012 data, comprising all unique reflections with $2\theta \le 140$, were collected by using Ni-filtered Cu K α radiation ($\lambda = 1.5418$ Å) and θ -2 θ scans. This corresponds to a resolution of 0.82 Å. For 193 scans, the intensity was not visibly distinguishable from the background; these were tagged as unobserved and assigned an intensity equal to $\frac{1}{5}$ of the background at the location of the expected reflection. Lorentz, polarization and absorption corrections ($\mu =$ 21.4 cm⁻¹) were applied to the data. For the absorption correction, the program of Coppens, Leiserowitz & Rabinovich (1965) was used with 216 sampling points. This program uses the numerical integration method of Gauss.

Table 1. Crystallographic data

Formula: Cu(C₉H₁₀NO₃)₂ F.W. 423.91 Systematic absences: h00, h = 2n + 10k0, k=2n+100l, l=2n+1Space group P212121 $a = 13.049 \pm 0.007$ Å $b = 22 \cdot 227 \pm 0.008$ $c = 6.078 \pm 0.003$ (determined by least-squares fit to the 2θ values of 28 reflections) Z = 4 $\rho_c = 1.60 \text{ g.cm}^{-3}$ $\rho_0 = 1.58 \text{ g.cm}^{-3}$ (measured by flotation, at 24°C, in a CCl₄-CH₃I mixture) Crystal dimensions: $0.6 \times 0.1 \times 0.03$ mm

F(000) = 876.

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Structure determination and refinement

A sharpened Patterson synthesis was calculated. The positions of the copper atom were determined from the Harker sections, while 11 nonhydrogen atoms were also located. These atoms were used in a structure factor calculation. The subsequent Fourier synthesis vielded the positions of the remaining nonhydrogen atoms. Block-diagonal least-squares refinement of these atoms using isotropic thermal parameters converged to an $R = (\sum ||kF_o| - |F_c|| / \sum |kF_o|$ of 0.11. All hydrogen atoms, excepting the two hydroxyl hydrogens, were located from a difference Fourier. The hydrogen atom coordinates used in the further refinement were calculated from geometrical considerations and were not refined. They were given isotropic thermal parameters, which were $\frac{1}{2}$ Å² larger than those of the atoms to which they are attached. All nonhydrogen atoms were given anisotropic thermal parameters. The observed structure factors were corrected for the anomalous dispersion of copper: $\Delta f' = -1.862$, $\Delta f'' = 0.604$ (Cromer & Lieberman, 1969). Least-squares refinement of the nonhydrogen atoms, using all the data, was terminated when all parameter shifts were less than 0.1 of the corresponding calculated standard deviations. The final R, based on the final parameters (Tables 2 and 3), is 0.042 for all data, and 0.034 when the unobserved reflections are excluded. A final difference Fourier showed a number of peaks between -0.3 and +0.3e.Å⁻³.

Table 3. Hy	drogen at	om parameter	rs
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Atomic coordinates are $\times 10^3$.

	x	У	z	B
$H(1)_{1}$	332	55	- 96	2.4
$H(1)_{2}$	433	73	- 212	2.4
H(3)	240	90	-332	2.2
$H(5)_{1}$	429	149	- 461	2.2
$H(5)_{2}$	309	172	- 547	2.2
H(9)	181	210	- 268	3.4
H(11)	489	179	- 109	3.0
H(13)	163	272	53	3.5
H(15)	469	236	222	3.1
$H(2)_{1}$	389	- 145	- 443	2.6
$H(2)_{2}$	467	-111	- 596	2.6
H(4)	532	-175	-310	2.6
H(6) ₁	680	-110	- 263	3.2
H(6) ₂	645	-119	- 533	3.2
H(10)	679	- 10	- 91	3.1
H(12)	561	-35	-730	3.2
H(14)	682	99	- 157	3.3
H(16)	560	73	- 739	3.3

The atomic scattering factors for Cu^{2+} , N, C and O were taken from *International Tables for X-ray Crystallography* (1962). The scattering factors for the hydrogen atoms were those of Stewart, Davidson & Simpson (1965). The quantity minimized in the leastsquares refinement was $\sum w(|kF_o| - |F_c|)^2$, where $|/w = |kF_o|/P$ for $|kF_o| \le P$, and $|/w = P/|kF_o|$ for $|kF_o| > P$, with P = 30 electrons, giving maximum weight to those reflections which were determined most accurately. A previously described logical routine (Van der Helm &

Table 2. Atomic coordinates $(\times 10^4)$ and thermal parameters

The temperature factor is expressed in the form $\exp \left[-(h^2b_{11}+k^2b_{22}+l^2b_{33}+hkb_{12}+hlb_{13}+klb_{23})\times 10^{-4}\right]$. Standard deviations for the last digit given in parentheses.

	x	у	z	b_{11}	b22	b33	b23	b13	b12
Cu	3886.3 (4)	-326.6(2)	-3358.6 (9)	38.0 (3)	11.4 (1)	93 (1)	- 6·2 (8)	-7(1)	5.1 (4)
N(1)	3712 (3)	512 (1)	- 2265 (5)	41 (3)	10 (1)	69 (8)	-9 (4)	1 (8)	-2(2)
Ô(1)	3425 (2)	-5(1)	-6128(5)	42 (2)	11 (1)	72 (8)	-6(4)	-16(7)	7 (2)
Ō(3)	2747 (3)	786 (1)	-7754 (5)	48 (2)	14 (1)	104 (8)	10 (4)	-43 (7)	-2(2)
$\mathbf{C}(1)$	3107 (3)	532 (2)	-6108(7)	26 (2)	12(1)	70 (10)	-8(4)	15 (8)	-9(2)
C(3)	3116 (3)	870 (2)	- 3901 (7)	28 (2)	9 (1)	88 (10)	-9 (5)	2 (9)	-1(2)
C(5)	3507 (4)	1513 (2)	-4191 (8)	70 (4)	10 (1)	94 (10)	-6 (6)	19 (11)	-4(3)
C(7)	3392 (4)	1897 (2)	-2130(7)	45 (3)	8 (1)	153 (14)	8 (6)	35 (10)	-8(3)
C(9)	2447 (4)	2165 (2)	-1653 (9)	51 (3)	14 (1)	169 (12)	-4 (8)	- 36 (14)	-1(3)
C(11)	4193 (4)	1995 (2)	- 724 (8)	39 (3)	14 (1)	134 (12)	7 (6)	13 (10)	-2(3)
C(13)	2340 (4)	2522 (2)	184 (10)	41 (3)	15 (1)	244 (16)	-22 (7)	26 (13)	3 (3)
C(15)	4104 (4)	2356 (2)	1149 (8)	39 (3)	11 (1)	195 (14)	-1 (6)	22 (11)	-11 (3)
C(17)	3163 (4)	2623 (2)	1570 (9)	50 (3)	9 (1)	145 (12)	4 (7)	4 (13)	-8(2)
O(5)	3026 (3)	2985 (1)	3425 (6)	58 (2)	13 (1)	186 (10)	- 38 (6)	37 (10)	-1(2)
N(2)	4373 (3)	-1125(2)	-4531 (6)	40 (2)	12(1)	84 (9)	-4 (5)	4 (8)	-4(2)
O(2)	4374 (3)	-0651(1)	-523(5)	48 (2)	13 (1)	74 (8)	-10(4)	1 (7)	16 (2)
O(4)	5308 (3)	-1384(2)	900 (5)	66 (3)	16(1)	112 (8)	11 (4)	-1(8)	18 (2)
C(2)	4941 (4)	-1108(2)	- 702 (7)	44 (3)	12(1)	97 (12)	12 (6)	2 (10)	-3(3)
C(4)	5228 (4)	-1306(2)	- 3061 (7)	42 (3)	11 (1)	95 (12)	-1(6)	-8 (10)	8 (2)
C (6)	6239 (4)	-1002(2)	- 3808 (7)	41 (3)	15 (1)	157 (13)	6 (6)	5 (12)	6 (3)
C(8)	6191 (3)	-316 (2)	- 4089 (6)	26 (2)	15 (1)	150 (10)	-1(7)	26 (10)	4 (3)
C(10)	6546 (4)	71 (2)	- 2422 (8)	38 (3)	16 (1)	132 (11)	-10 (6)	6 (11)	-3(3)
C(12)	5868 (4)	-67(2)	-6051 (7)	50 (3)	15(1)	103 (11)	- 27 (6)	8 (10)	-1(3)
C (14)	6571 (4)	694 (2)	-2797 (8)	39 (3)	16 (1)	172 (15)	- 24 (7)	- 16 (11)	-9(3)
C (16)	5879 (3)	549 (2)	- 6410 (9)	40 (3)	16 (1)	172 (14)	7 (7)	-18 (12)	-12 (3)
C (18)	6263 (4)	927 (2)	-4790 (9)	28 (3)	16(1)	252 (15)	11 (7)	1 (12)	-2(3)
O (6)	6306 (3)	1541 (2)	- 5222 (7)	50 (3)	15 (1)	422 (15)	21 (6)	- 50 (12)	-8(2)

Table 4. Observed and calculated structure factors

The values of $|10kF_o|$, $|10F_c|$ and calculated phase angles, in centicycles, are given. Unobserved reflections are indicated by a star.

E FO FC AL E FO FC AL E I We G Le O 5 77 EO 25 2 4 4 441 610 G 6 74 76 50 3 3 21411659 C 7 27 12 254 4 1 6 24G 317 50 8 300 295 5G 52 4	FO FC AL K FO FC AL K FN FC AL 56 74 11 5 167 544 69 10 159 164 78 43 326 18 6 163 198 3 11 224 223 47 23 122 24 7 36 21 414 12 347 144 43 07 202 15 6 38 72 248 13 64 45 41	E FO FC FG FL K FD FC 19 367 360 70 322 322 64 4 322 322 20 184 147 35 1C 171 181 42 332 342 345 21 147 11 7C 11 172 161 44 6 210 217 22 66 76 72 12 313 316 347 365 345	IL E PO FC AL E FC FC AL 13 IO 448 507 51 2 157 154 6 15 II 64 74 75 3 242 287 56 15 I2 IO3 LIT 80 4 184 186 71 18 I3 175 144 14 5 136 114 3	E FO FC AL S FO FC AL E FO FC H 12 92 81 27 18 144 142 81 9 73 85 24 H 8 6 19 178 177 29 10 246 243 74 0 71 65 5C H 11 (17 29 10 246 243 74 1 57 55 12 C 218 216 49 12 107 114 74
B 24 33 C 4 254 251 25 6 3 10 291 286 50 10 178 175 50 7 1 12 330 347 50 ₩ 1 L 0 6 27 14 174 171 5C 1 405 414 24 4 16 204 211 50 2 425 604 24 10 1	64 364 26 4 190 158 22 14 227 217 45 56 156 19 10 32 78 78 49 15 182 224 29 44 253 32 11 152 126 4C 16 250 246 50 49 8C 45 12 184 198 72 17 210 230 20 45 169 28 13 228 24C 56 18 246 241 49	23 168 177 77 13 462 467 50 8 223 730 24 47 43 16 14 152 154 59 9 0106 117 P* 4 L* 4 15 216 225 58 10 261 270 0 554 347 C 16 38 71 29 11 168 166 1 262 278 20 17 372 377 11 16 275 213	71 14 175 185 66 6 176 179 18 17 15 F4 102 17 7 236 239 63 16 16 220 227 85 8 201 207 69 14 17 35 54 998 9 91 125 59 16 18 14 22 9 1	2 25 57 27 28 1 365 368 77 13 55 48 74 3 67 60 90 2 287 290 97 14 28 30 74* 4 187 184 37 3 239 245 72 15 156 166 75 5 72 76 38 4 768 362 94 1* 13 1* 1 6 211 211 25 5 38 62 294 214 75
18 158 151 50 3 560 487 24 21 1 20 146 162 0 4 764 746 25 12 1 22 38 44 50 522 210 25 13 1 24 50 47 59 6 241 227 74 14 5	46 141 67 14 215 267 74 19 265 304 12 OL 10C 28 15 291 291 52 2C 61 7C 56 96 157 74 16 151 154 84 21 52 94 14 51 53 37 17 27C 262 49 22 55 65 91	2 329 335 1 10 62 35 21 13 60 55 3 277 301 21 14 161 166 40 14 344 344 4 429 433 9 20 83 90 90 15 206 150 5 441 437 15 23 142 160 57 16 212 311	4 19 56 67 8 11 107 102 28 4 20 227 723 99 12 205 213 50 15 21 27 51 10 13 127 178 23 11 H= 7 L= 4 14 127 179 93 4 343 44 50 14 171 73 33	H= 10 L= C 6 14 16C 64 1 274 215 48 0 244 243 C 7 215 237 51 2 216 310 7e 1 1.4 1.4 2.4 2.6 7 7 8.6 7 7.4 83 55 2 2.22 2.22 C 9 58 105 1.5 4 1.45 1.45 71
Hen C Le 1 8 766 786 24 He 1 E 73 112 25 9 403 404 75 0 3 2 227 721 45 1011401167 25 1 2' 3 155 881 74 11 251 745 75 2 2'	Le 7 19 219 233 48 C 38 8 256 22 224 24 26 27 157 161 55 1 267 290 4 76 256 95 89 2 Le 6 2 273 217 26 15 208 24 0 69 61 45 3 110 115 46	7 140 171 7 27 24 16 416 18 236 233 8 206 213 14 14 5 t+ 4 19 31 59 9 114 102 87 0 12 50 27 50 20 173 179 10 34 55 458 1 401 410 25 21 147 148	1 141 144 16 16 147 14 14 144 14 16 16 147 17 17 17 17 12 14 146 16 17 17 12 14 146 146 15 16 14 147 14 14 146 14 14 146 14 14 14 146 14	4 262 243 C 10 72 56 28 5 162 16 71 5 211 214 45 12 67 6 78 5 147 146 51 5 211 214 45 12 67 6 7 13C 13G 93 6 37 18 498 13 15C 148 7 8 51 65 54 7 216 227 45 14 132 110 7 9 163 156 79
4138418420 50 12 445 516 24 3 1 51013 467 25 13 275 276 75 4 4 6 20 84 449 14 67 56 75 5 14 7 60 31 24 15 181 144 75 6 4 9 354 784 45 16 52 40 75 7 1	#2 171 66 1 185 14C 55 4 216 215 56 95 90 26 2 261 91 5 711 3C7 26 95 90 26 2 261 91 5 711 3C7 26 91 140 62 3 33 349 4 6 148 <td>11 271 216 74 7 176 174 75 22 28 46 1 12 79 43 64 7 171 334 35 He 6 Le 4 13 144 145 74 4 448 454 33 0 96 86 14 215 734 50 5 575 547 55 1 171 176 14 215 274 50 5 6 176 187 38 2 289 292 1</td> <td>10 5 203 205 24 C 393 340 75 6 159 161 60 1 228 263 48 C 7 65 54 60 2 176 183 45 12 8 123 133 84 3 12* 142 57 10 9 49 45 5 47 76 34 6</td> <td>P P1 64.5C 15.102 95.23 10 PR P3.5C 9 1PC 1P4.45 16.146 174.98 11.50 57.C 1C 11P 11P.45 16.146 174.98 11.50 57.C 1C 11P 11P.45 16.146 174.02 12.107 101.14 11 11P.45 17.7 14.20 12.107 101.14 101.14 11 197.158 50.18 131.135 93.18 14.14 137.33 12 132.374.67 110.147 131.135 93.18 14.14 147.33</td>	11 271 216 74 7 176 174 75 22 28 46 1 12 79 43 64 7 171 334 35 He 6 Le 4 13 144 145 74 4 448 454 33 0 96 86 14 215 734 50 5 575 547 55 1 171 176 14 215 274 50 5 6 176 187 38 2 289 292 1	10 5 203 205 24 C 393 340 75 6 159 161 60 1 228 263 48 C 7 65 54 60 2 176 183 45 12 8 123 133 84 3 12* 142 57 10 9 49 45 5 47 76 34 6	P P1 64.5C 15.102 95.23 10 PR P3.5C 9 1PC 1P4.45 16.146 174.98 11.50 57.C 1C 11P 11P.45 16.146 174.98 11.50 57.C 1C 11P 11P.45 16.146 174.02 12.107 101.14 11 11P.45 17.7 14.20 12.107 101.14 101.14 11 197.158 50.18 131.135 93.18 14.14 137.33 12 132.374.67 110.147 131.135 93.18 14.14 147.33
9 224 628 24 17 213 206 74 8 1 10 543 544 50 18 37 23 24 H= 2 11 544 825 21 19 134 155 75 C 11 12 298 278 50 20 149 151 74 1 6	92 184 42 6 35 4C 91 4 77 727 71 L= C 7 472 434 46 10 124 147 51 GC 146 5 163 163 11 217 217 21 L 6 165 163 32 11 217 217 21 L E E 10 9 162 144 12 714 202	16 154 146 45 7 417 47 47 3 161 167 17 753 756 71 # 416 441 35 4 778 781 18 173 176 53 6 167 6 6 6 7 16 4 78 5 4 78 78 19 146 145 66 17 147 166 33 6 189 466	11 1C 3# 17 94# 5 77 69 41 12 11 24 24 84 85 253 24 80 13 24 25 25 95 9 16 13 153 171 78 P 196 185 40 13 153 171 78 P 196 185 40	13 243 245 50 C 71 7C 74 15 143 143 C 14 764 365 50 1 16C 176 52 16 17 L 2 15 792 24 56 7 17 16 15 16 12 5C 16 792 241 49 7 16 85 52 1 109 101 4
13 725 730 24 21 78 77 75 25 14 191 200 50 22 137 144 75 100 15 264 250 75 21 114 121 27 4 65 16 203 285 99 24 214 214 74 5 55 17 76 6 249 29 72 65 25 6 4	27 491 0 10 56 42 44 13 141 161 21 20 494 49 11 207 206 46 14 243 244 68 25 689 49 12 23 87 86 15 199 211 9 1 48 527 49 17 127 141 55 16 230 222 81 25 406 0 14 28 43 109 17 13 89 88	20 85 72 56 11 116 111 19 7 234 238 21 107 106 77 12 261 262 16 8 358 380 P= 4 t= 5 17 216 214 33 9 274 277 0 387 383 25 14 259 278 6 10 288 290 1 154 165 27 14 122 126 31 119 169 1	11 14 283 285 1 9 16 174 15 12 15 228 224 67 1C 157 148 4 15 16 249 258 6 11 124 128 12 13 17 186 186 69 17 29 1C5 78 16 18 255 261 1 13 145 138 55	17 96 101 99 4 200 70 3 2 198 197 34 18 199 205 50 5 25 62 12 3 207 209 88 19 224 220 90 6 277 272 3 4 221 225 37 20 51 88 50 7 52 43 77 5 212 210 94 19 10 14 1 8 201 75 6 7 4 35 10 14
18 199 134 99 26 263 256 75 7 5 19 #2 79 75 27 186 187 24 # 4 20 243 242 C ++ 1 t + 1 9 6 21 236 236 75 011171129 75 1C 24	16 577 40 14 26 47 558 18 135 134 80 76 648 0 16 55 84 35 10 70 70 76 648 0 16 55 84 35 10 70 70 76 648 0 16 55 75 70	2 414 414 41 14 75 131 45 12 260 257 3 214 217 1 17 34 73 949 13 67 88 4 446 425 43 14 112 57 73 14 26 78 5 383 173 87 19 48 48 5 131 151 75	A 19 193 204 60 H= 8 L= 6 5 H= 7 L= 5 C 71C 204 0 7 0 105 118 75 1 107 67 76 1 7 0 70 7 2 2 177 175 97	C 36 41 25* C 76 95 95 7 234 239 C 1 135 134 49 1C 217 224 3 8 39 31 12 2 219 222 54 11 22 42 18 9 237 256 9 2 76 3C3 46 12 233 229 45 10 43 45 3
23 230 221 74 2 431 406 24 12 56 24 246 244 94 3 655 635 92 13 2 25 169 110 75 4 337 26 94 14 27 26 217 216 C 5 19C 800 76 15 14	4 5(8) 50 2 211 218 34 2 215 275 RC 75 240 50 2 257 41 3 346 346 29 35 218 70 4 156 275 41 9 346 29 35 218 70 4 158 196 26 4 141 206 47 57 141 40 5 126 157 24 3 126 157 26	7 174 381 82 21 166 17 195 183 8 214 215 86 171 195 183	i 3 277 283 75 4 131 137 53 i 4 132 137 283 75 4 137 137 53 i 4 112 107 85 5 245 254 6 3 5 275 258 64 6 73 7C 28 3 6 5 66 14 7 16C 142 93 <td>4 214 216 42 14 29 17 064 17 16 17 16 19 36 4 214 216 42 14 29 17 064 12 17 16 19 36 4 215 375 48 15 59 56 57 13 39 54 25 7 257 271 33 16 35 46 57 14 13 14 1 7 277 373 51 14 11 14 4 5 33 32 744</td>	4 214 216 42 14 29 17 064 17 16 17 16 19 36 4 214 216 42 14 29 17 064 12 17 16 19 36 4 215 375 48 15 59 56 57 13 39 54 25 7 257 271 33 16 35 46 57 14 13 14 1 7 277 373 51 14 11 14 4 5 33 32 744
27 68 68 74 6 543 350 44 10 4 H= 0 L= 2 7 596 595 93 17 22 0 786 758 50 8 796 795 67 18 1 1 669 614 24 9 57 56 76 19 2 2 649 615 50 10 278 75 75 7 20 1	55 34 0 6 64 58 36 6 218 216 68 26 225 0 7 26 33 36 7 109 119 21 27 65 59 9 154 164 72 8 157 201 63 38 5 505 44 3 54 67 8 36 42 689 22 133 40 1 167 171 24 10 181 179 64	11 101 103 61 2 346 340 9 He 6 Le 5 12 279 215 42 3 199 210 67 0 266 763 13 104 102 49 4 298 253 21 1 371 367 14 45 63 41 5 195 153 63 2 215 216 15 155 165 46 41 6 164 168 20 1 3 166 258	7 33# 327 72 8 25 44 51 5 8 215 221 4 5* 9 t* C 4 9 329 222 73 1 167 179 75 5 10 246 246 3 2 183 181 25 6 11 207 267 74 182 29 25	9 765 260 16 C 372 287 C 1 213 206 94 10 273 255 6.0 1 95 79 82 2 127 135 93 11 2745 242 92 2 37 240 10 3 170 174 5 12 716 122 2 37 240 10 3 170 174 5 12 716 122 2 37 240 10 3 170 174 5 12 716 126 3 74 85 90 4 140 130 74 13 140 145 140 140 14 140 140 140 140 140 140 140 140 140 140 140 140 140 140 140 140 140 140 140
9 219 121 74 11 AA 115 78 21 22 4-301 771 50 12 325 513 60 22 5 5 162 324 74 13 177 731 66 23 32 6 24 31 500 14 501 510 76 24 13	34 221 0 213401377 24 11 106 10C 70 58 35 5C 7 32 341 24 12 3C 15 92 35 15 17 74 12 3C 15 92 55 15 17 17 74 14 15 86 98 12 14 15 86 98 1 15 16 91 14 15 86 98 1 15 17 14 15 86 98 1	16 31 54 64+ 7 212 211 51 4 38 44+ 17 134 141 37 8 355 161 7 51 158<	C* 12 144 155 17 4 231 235 25 6 13 73 91 74 5 335 256 25 6 14 67 62 13 6 457 57 25 16 14 67 62 13 6 455 57 25 15 27 12 92+ 7 26 72 16	14 77 75 488 5 34 42 788 6 01 21 26 15 177 157 9 6 31 60 11 7 30 74 10 16 35 101 128 7 14 55 30 8 71 71 84 17 35 56 8 77 71 70 9 79 76 64
7 204 212 24 13 416 45 51 25 2 8 510 522 14 579 127 71 26 1 9 97 91 75 17 255 557 59 H= 2 10 29 1 C 18 290 298 83 0 10 11 424 449 75 19 68 65 14 1 7	37 27 49 6 827 KC2 74 15 278 221 72 27 13 509 7 141 162 75 H= 3 L H= 7 L+ 1 9 66 172 74 C 44 27 25 67 161 74 9 121 121 74 1 121 112 59 9C 193 52 1C 645 61C 75 2 153 154 66	0 [73 100 49 11 36 15 404 8 534 135 4 1 103 95 38 12 222 221 33 9 61 36 2 245 288 49 13 65 7C 14 10 200 199 4 3 93 88 89 14 202 227 72 11 103 173 4 36 29 466 15 124 125 7 12 116 157	13 15 74 74 40 8 136 27 25 16 14 7 14 6 9 37 6 240 14 0 32 31 430 10 462 457 24 3 1 323 322 75 11 36 7 740 6 7 70 85 52 12 432 417 24	IF 10: 112 72 9 9 96 114 19 10 136 125 85 19 27 64 56 10 119 125 61 11 130 139 57 20 89 51 89 11 95 20 11 μ= 13 L= 4 H= 10 L= 2 12 144 162 59 0 77 47 C0 C 1C1 1C7 5C 13 156 157 18 1 90 91 67
12 340 332 0 20 180 174 79 2 56 13 515 533 75 21 141 131 26 3 13 14 102 46 C 22 150 145 50 4 7 15 665 672 75 23 258 249 20 5 10 16 37 34 69 34 69 34 106 1 64 10	67 572 58 11 547 516 75 3 200 278 67 78 170 79 12 557 535 75 4 291 290 61 50 725 11 12 757 72 727 5 241 235 69 81 371 53 14 355 157 75 6 126 159 57 14 66 75 15 16 75 65 75 6 126 159 57	5 117 106 51 16 233 225 25 13 240 241 6 35 47 29 17 129 128 6 14 89 88 7 153 156 56 18 17 129 6 16 18 18 18 7 153 156 56 18 17 129 6 16 158 139 7 153 156 56 16 175 129 6 16 154 130	1 1 248 245 71 11 32 72 75 1 4 148 152 34 14 45 65 25 1 5 250 211 72 14 32 41 244 5 5 50 94 31 16 22 27 24 7 14 144	1 229 300 30 ++ 11 1+ 5 2 59 40 17 7 53 76 35 C 24 24 24 3 88 96 60 7 23 24 242 71 1 73 80 77 4 26 23 11+ 4 211 222 73 2 52 92 67 5 151 154 50
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Nicholas, 1970) was also used to optimize the refinement. The list of observed and calculated structure factors is shown in Table 4.

Description and discussion of the structure

A projection of the structure down the c axis is shown in Fig. 1. The chelate molecules form infinite chains around screw axes parallel to the c axis. Perpendicular to these chains the crystal is stabilized by two strong hydrogen bonds (2.62 and 2.71 Å). No other hydrogen bonding occurs in the structure.

The tyrosine residues form two five-membered chelate rings with the copper atom. The residues are *trans* with respect to each other. The copper coordination is square pyramidal. The bond distances and bond angles for the copper coordination are given in Figs. 1, 2 and 3. While the Cu-N distances are similar and compare well with the literature value (2.00 Å),



Fig. 1. Projection of the structure down the c axis.

the Cu–O distances in the basal plane differ considerably (1.925 and 1.973 Å), and the Cu–O(1) distance is significantly shorter than the average value (1.98 \pm 0.012 Å) given by Freeman (1967). The basal plane of the square pyramid is tetrahedrally distorted (Table 5, Fig. 4), while the copper ion is displaced 0.11 Å from this plane toward the top of the pyramid. The two chelate rings are not planar (Planes 2 and 3, Table 5). The nitrogen atoms show the largest deviations (0.22 and 0.65 Å) from the least-squares planes through the carboxylic acid groups. The bond angles in the rings are given in Fig. 3. The nonplanarity of the rings is the result of a rotation around the C^{α}-C' bond, by 11.2° for the C(3)-C(1) bond and -29.3° for the C(4)-C(2)



Fig. 2. Intramolecular distances. The estimated standard deviation for the last digit is given in parentheses.

Table 5. Least-squares planes

The equations of the planes are expressed in the form Ax+By+Cz=D, where x, y and z are fractional coordinates and D is the distance from the origin in Å. The method of Schomaker, Waser, Marsh & Bergman (1959) was used to calculate the least-squares planes.

	Plane	Atoms		A	В	С	D	
	1	N(1), O(1), N(2), O(N(1), O(1), N(2), O(2)		6.686	-1.284	5.039	
	2	O(1), O(3), C(1), C(3)	3)	11.946	7.563	-1.306	4.894	
	3	O(2), O(4), C(2), C(4)	1)	10.418	13.383	0.054	3.677	
	4	C(7), C(9), C(11), C(C(15), C(17)	(13),	3.470	17.783	- 3.268	5.241	
	5	C(8), C(10), C(12), C C(16), C(18)	C(14),	12.102	-1.854	- 2 ·215	8.450	
	⊿(1)	⊿(2)		⊿(3)		⊿(4)		⊿(5)
N(1)	0∙099 Å	O(1) −0·006 Å	O(2)	0∙006 Å	C(5)	0∙035 Å	C(6)	0.130 Å
O(1)	<i>−</i> 0·098	O(3) - 0.006	O(4)	0.006	C(7)	0.002	C(8)	0.007
N(2)	0.098	C(1) 0.017	C(2)	−0 ·016	C(9)	-0.002	C(10)	-0.002
O(2)	<i>−</i> 0·099	C(3) - 0.005	C(4)	0.004	C(11)	-0.003	C(12)	0.004
Cu	-0.110	N(1) 0·223	N(2)	-0.652	C(13)	- 0.005	C(14)	-0.007
O(3')	<i>—</i> 2·477	Cu −0.060	Cu	−0.084	C(15)	-0.003	C(16)	-0·017
					C(17)	0.007	C(18)	0.019
					O(5)	-0.002	O(6)	0.053
							Cu	- 2.942

bond. The larger rotation around the C(4)-C(2) bond is reflected in the observation that all bond angles in the chelate ring formed by molecule *B* are smaller than those in the one formed by molecule *A*.

The thermal motion of the atoms in the amino acid residues, observed in the present structure (Figs. 4 and 5), is considerably less than the motion found in the copper chelate of L-phenylalanine. The largest thermal motion is observed for O(6) with 6.57 and 2.66 Å² for the temperature factors along the major and minor axes. The bond distances and bond angles in two tyrosine residues are shown in Figs. 2 and 3. The dimensions of the two residues are quite similar. The valence angles of the C^{β} atoms are significantly greater (113.4 and 115.6°) than the tetrahedral value. This was also observed for one of the phenylalanine residues in CUPA, and in the structure of the potassium salt of L-tyrosine-O-sulfate (Fries & Sundaralingam, 1971). The other distances and angles are normal.



Fig. 3. Bond angles with estimated standard deviations. Other angles at Cu: $O(3')-O(1)=90\cdot 8$ (1); $N(1)-O(2)=95\cdot 0$ (1); $O(3')-N(1)=104\cdot 3$ (1); $N(1)-N(2)=168\cdot 0$ (1); $O(3')-O(2)=89\cdot 8$ (1); $O(1)-N(2)=96\cdot 7$ (1); $O(3')-N(2)=87\cdot 6$ (1); $O(1)-O(2)=179\cdot 3$ (1).

The conformation of N and C^{γ} about the C^{α}-C^{β} bond is described by the torsional angle X¹ (Edsall, Flory, Kendrew, Liquori, Némethy, Ramachandran & Scheraga, 1966). It is found that C^{γ} occurs only for values of X¹ close to 60, 180 and 300°, conformations I, II and III respectively (Ramachandran & Sasisekharan, 1968).

For amino acids with aromatic side chains, conformation II seems to be the most common (Pieret, Durant, Griffé, Germain & Debaerdemaeker, 1970). Conformation III has been observed in 3,4-dihydroxy-L-phenylalanine (Becker, Thathachari & Simpson, 1970) and in the two phenylalanine residues in CUPA. Residue A in the present structure also has this conformation, with the result that the phenyl group points away from the chelation side. Position I has been observed in L-phenylalanine-HCl (Gurskaya, 1964), in L-tyrosine-O-sulfate (Fries & Sundaralingam, 1971) and in CULGLT (Franks & van der Helm, 1971). This conformation is observed for residue B in the present structure and allows the phenyl group to be positioned below the base of the square pyramidal copper coordination, as was similarly observed in the CUGLT structure.

The phenyl group of residue *B* is approximately parallel to the basal plane of the metal coordination (Fig. 5, Table 6). There are two close approaches between the Cu²⁺ ion and carbon atoms of the phenyl group [C(8): 3.04 Å and C(12): 3.11 Å] (Fig. 4, Table 6). Similar observations were made for both tyrosine residues in the CUGLT structure. The close approaches, as observed, are believed to constitute interactions between the Cu²⁺ ion and the phenyl group. It is interesting to note that these interactions do not occur in the CUPA structure. The possible inferences, regarding enzyme mechanisms, of these observations will be published elsewhere.

The basal plane of the square pyramidal copper coordination is tetrahedrally distorted (Fig. 5, Table 5). These distortions (0.10 Å) are similar to those observed in CUGLT, while more than eight times those in the structure of CUPA. It may well be that this distortion is related to the postulated interaction between the Cu²⁺ ion and the phenyl group.

Both aromatic rings are planar (Table 5, Planes 4 and 5). The exocyclic atoms C(6) and O(6) in residue *B*, however, show large displacements (0.13 and 0.05

Table 6.	Comparison	of CUTY	and	CUGLT
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The notations follow the conventions of Edsall, Flory, Kendrew, Liquori, Némethy, Ramachandran & Scheraga (1966).

	CL	JTY	CU	GLT
	Mol. A	Mol. <i>B</i>	Mol. A	Mol. B
Angle between basal plane and phenyl group $Cu-C^{\gamma}$ distance $Cu-C\delta$ distance		24° 3·04 Å 3·11	21° 3·34 Å 3·27	18° 3·21 Å 3·17
four atoms from basal plane	0.09	8 Å	0·155 Å	0·125 Å
X ¹ angle X ² angle	295·2° 99°/278°	52·5° 99°/274°	54° 90°/281°	59° 84°/274°



Fig. 4. Stereodiagram (Johnson, 1965) of the structure. The view is along the normal of the phenyl group of residue B.



Fig. 5. Stereodiagram. The view is 80° rotated from the one shown in Fig. 4.

Å respectively) from the least-squares plane through the six atoms of the aromatic ring system; the convex side of the aromatic ring is presented to the basal plane of the metal coordination (Plane 5).

All intermolecular distances less than 3.5 Å are listed in Table 7.

Table 7. Intermolecular distances less than 3.5 Å

N(1)	O(1 ⁱ)	3·086 Å	4	N(2)	O(3 ⁱ)	3.063	Å (C)
N(1)	O(3 ⁱ)	3.468	(<i>C</i>)	O(2)	O(3 ⁱ)	3.096	- (-)
N(1)	C(1 ⁱ)	3.392		O(2)	$C(1^i)$	3.268	
N(1)	O(3 ^{iv})	3.079		O(2)	$C(3^i)$	3.430	
O(1)	O(3 ⁱ)	3.092	(<i>C</i>)	O(2)	$O(1^{iv})$	3.276	
C(3)	$O(1^i)$	3.253		O(4)	$N(2^{iv})$	3.087	
C(15)	O(4 ⁱⁱ)	3.415		C(10)	$C(12^{v})$	3.477	
C(15)	$C(5^{iv})$	3.484		Cù	O(1 ⁱ)	3.388	
C(17)	O(4 ¹¹)	3.351		Cu	$O(3^i)$	2.391	(C)
O(5)	C(18 ⁱⁱⁱ)	3.439		Cu	$C(1^i)$	2.974	. ,
O(5)	O(6 ⁱⁱⁱ)	2.709	(H)				
O(5)	O(4 ⁱⁱ)	2.620	(H)				

The small letter in parentheses indicates that one of the following operations has to be applied to the coordinates given in Table 2:

$i \frac{1}{2} - x, -y, \frac{1}{2} + z$	iv x, y, $1+z$
ii $1-x, \frac{1}{2}+y, \frac{1}{2}-z$	$v 1\frac{1}{2} - x, -y, \frac{1}{2} + z$
iii $-\frac{1}{2}+x, \frac{1}{2}-y, -z$	

The letter H indicates hydrogen bonds, and the letter C, distances occurring in the metal coordination.

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