Chiral Supramolecular Assemblies Derived from the Insertion of a Segmental Ligand into a Copper-Tyrosine Framework

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The use of a predisposed 4,4-bipyridine segmental ligand in copper-tyrosine chiral complex self-assembly processes allows the preparation of a new type of complex $\{[Cu_2(tyrosine)_2(4,4\text{-bipyridine})\cdot 2H_2O]\cdot 2ClO_4\}_n$, which results in the fine tuning of network structure and stereo conformation.

The construction of metal-organic molecular coordination frameworks by metal coordination-directed self-assembly processes has become an area of intense research in recent years.[1−4] The network structures and properties of these coordination supramolecules can be fine-tuned by a systematic change of the organic linking ligands.[5−7] However, the study of metal-amino acid chiral supramolecular assemblies is less popular and the synthesis of these assemblies with a mixture of organic ligands is a significant challenge.

Among the natural amino acids, phenylalanine with hydroxyl group(s) plays an important role in biological systems.[8] Tyrosine has also been known to be located at the active sites of a series of metal proteins and to act as an important part in the protein factors.[9−13] On the other hand, copper is a bioelement and an active site in several metalloenzymes and proteins.[14] The blue copper proteins have received considerable interest because of their unusual spectral and structural properties. The geometry around copper in blue proteins is intermediate between tetrahedral and square planar and several model systems have been developed to study the molecular structure with the electronic group state of those complexes.[15−17] Hence, copper-amino acid complexes, especially aromatic amino acid ones, are of great interest, not only due to their importance in biological systems but also because of their remarkable properties derived from stacking, hydrogen bonding, and metal-aromatic ring interactions.[18] In the course of our studies on this structure-function relationship, we report here the synthesis and crystal structures of two copper(II) coordination polymers with tyrosine as ligand $[Cu(Tyr)_2]_n$ (**1**) and $\{[Cu_2(Tyr)_2(4,4\text{-bipy})\cdot 2H_2O]\cdot 2ClO_4\}_n$ (**2**) (Tyr = tyrosine; 4,4-bipy = 4,4-bipyridine), where 4,4-bipy acts as an inserting component that has a subtle effect on the structural characteristics of the copper-tyrosine complex by self-assembled control. The synthesis and the structures of the polymers provide a new insight into understanding the mode of action of copper(II)-tyrosine complexes and are important not only for coordination chemistry but also for biochemistry.

Complex **1** was obtained by slow evaporation of solutions prepared by mixing tyrosine and Cu^{II} perchlorate in methanol/water with a metal-to-ligand molar ratio of 1:1. Figure 1 shows the crystal structure of the biologically relevant complex **1** formed between Cu^{II} and tyrosine. The geometry around the Cu^{II} ion can be described as square pyramidal. Two tyrosine molecules chelate the Cu^{II} ion through the nitrogen and oxygen atoms forming two five-membered rings with the Cu^{II} ion located in the center of the N_2O_2 square plane. There are two kinds of coordination modes of tyrosine molecule in complex **1**: chelating, which leaves one oxygen atom of the carboxyl group free, and exobidentate bridging, with a μ-carboxyl group linking adjacent Cu^{II} ions through the oxygen atom at the vertex of the square pyramid giving rise to a one-dimensional right-handed chiral chain structure generated by a 2_1 operation (Figure 2). The angles between the axial Cu−O bond and the four equatorial bonds in the square plane lie in the range of 85.3−95.7°. All Cu−N and Cu−O bond lengths are normal (1.92 Å to 2.00 Å) except for the axial Cu−O bond (2.36 Å). The phenyl-bound hydroxyl group of the bridging tyrosine hydrogen-bonds with that of the non-bridging tyrosine and the free oxygen atom of the carboxyl

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group, which connects the adjacent chiral chains to form a three-dimensional supramolecular assembly.

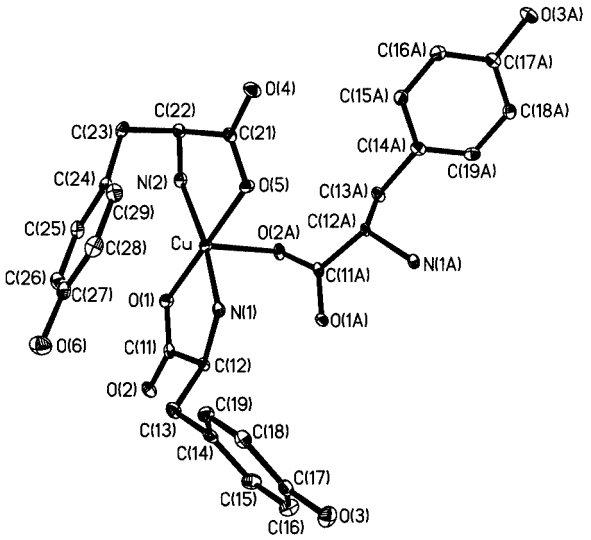

Figure 1. Coordination environment of **1**; the asymmetric unit is shown with ellipsoids at 30% probability; hydrogen atoms have been omitted for clarity

In order to insert an organic ligand into the chiral chains of the copper(II)-tyrosine assembly, 4,4-bipy was added to the reaction mixture of copper(II) and tyrosine; complex **2** was obtained. The structural subunit of complex **2** contains two copper ions(Figure 3), each of which is coordinated to one tyrosine molecule, one water molecule of crystallization and one 4,4-bipy molecule. The coordination geometry of Cu^{II} in **2** is also square pyramidal: the oxygen atom of the water molecule lies at the vertex of the square pyramid and four donor atoms — a nitrogen atom from 4,4-bipy, an oxy-

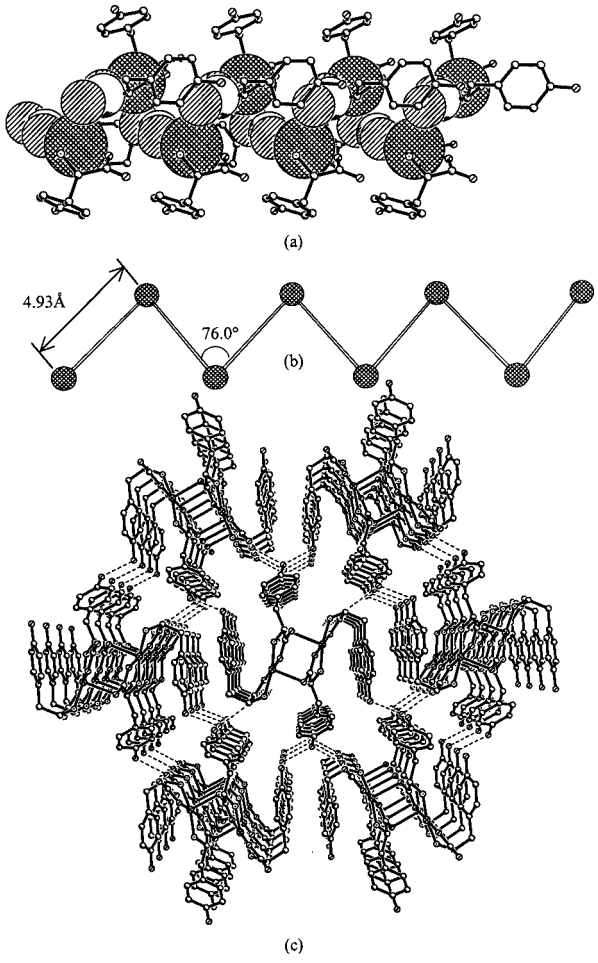

Figure 2. (a) Perspective view of the chiral chain structure of **1**; the Cu^{II} and bridging carboxyl are represented by larger circles; (b) 1-D chiral chain connectivity in **1**; the circles represent the $Cu(Tyr)_2$ unit; (c) stacking of the chiral chains of **1** viewed down the *a* axis

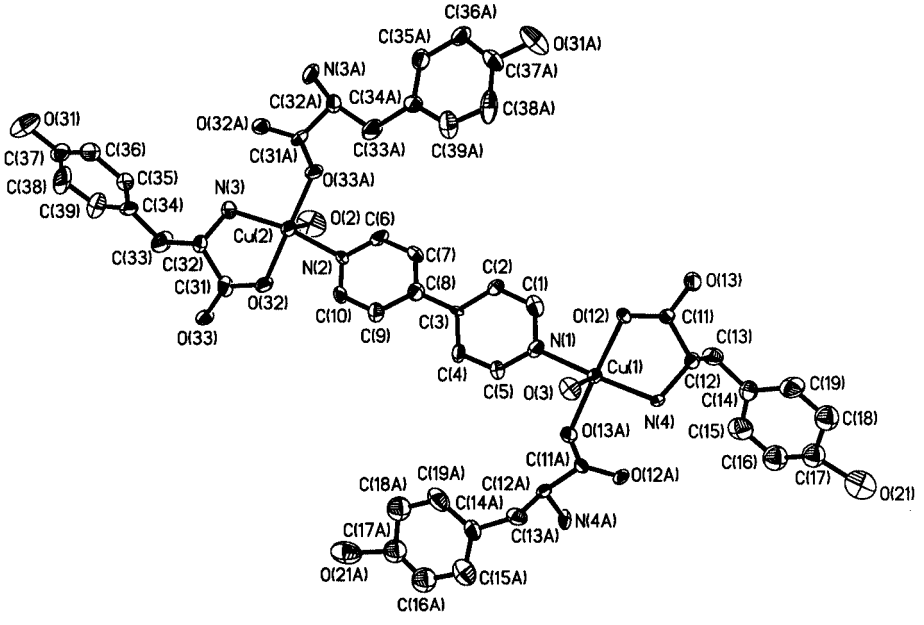

Figure 3. Coordination environment of **2**; the asymmetric unit is shown with ellipsoids at 30% probability; hydrogen atoms and the perchlorate anion have been omitted for clarity

gen atom from the μ-carboxyl group and the chelated N and O atoms — form the N_2O_2 square plane. The angles between the bond of the axial oxygen with Cu^{II} and the equatorial bonds ranges from 87.6 to 97.3°, while the bond lengths are similar to those in complex **1**. Similar to complex **1**, the tyrosine in complex **2** coordinates to Cu^{II} ion in a bidentate fashion through N and O donor atoms and a μ-carboxyl group links adjacent Cu^{II} ions (Figure 4). The adjacent subunits are related by a 2_1 operation to form an infinite chiral chain structure similar to complex **1**. The N(1) and O(1) atoms in complex **1** are replaced by a nitrogen atom from 4,4-bipy and an oxygen atom from the bridging carboxyl group in complex **2**, respectively, and the 4,4-bipy ligand bridges the adjacent chiral Cu-Tyr chains to form the extended two-dimensional plane. These 2-D sheets are stacked through hydrogen bonding between the ClO_4^- counterion and the free phenol hydroxyl groups and between the counterion and crystal water. Although both chiral chain structures in **1** and **2** are similar topologically, the Cu−Cu−Cu angle and the distance between adjacent Cu atoms in the same chain are different, as shown in Figure 2 and Figure 4 (76.0° and 4.93 Å in **1**, 141.6° and 5.35 Å in **2**) due to the different coordination position of the oxygen atom of the bridging carboxyl of tyrosine (it is axial in complex **1** and equatorial in complex **2**). We believe that the presence of the 4,4-bipy ligand in **2** is responsible for the subtle tuning of the chiral chain structure, forming a square-planar geometry in the self-assembly process with amino acids.[15,19] The Cu^{II} ion acts as a kind of Lewis acid[20] and can therefore bind Lewis bases, such as the oxygen atom of the bridging carboxyl group in complex **1** and a water molecule of crystallization in complex **2**, in its free axial coordination site.

In conclusion, the use of a 4,4-bipy segmental ligand in Cu-Tyr complex self-assembly processes allows the preparation of a new type of complex $\{[Cu_2(Tyr)_2(4,4\text{-bipy})\cdot 2H_2O]\cdot 2ClO_4\}_n$. This modification of the ligand environment has a considerable effect on the solid-state structure

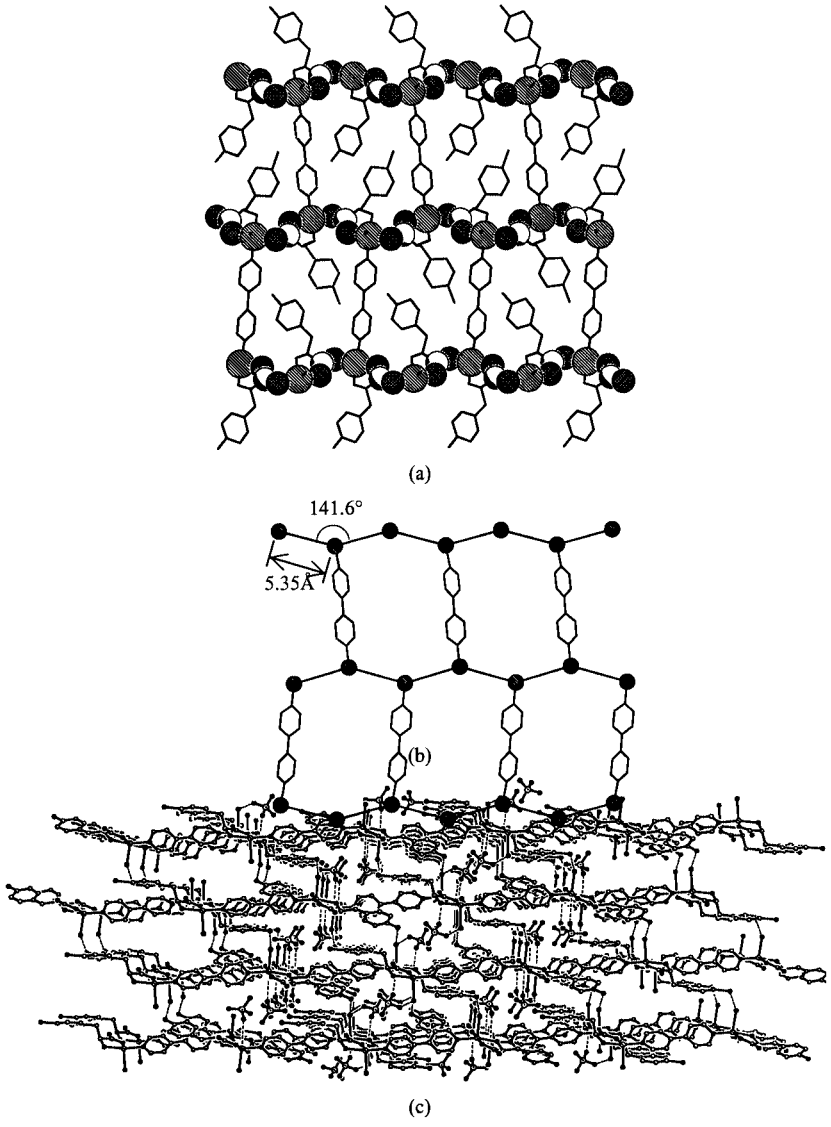

Figure 4. (a) perspective view of the 2-D sheet of **2**; the Cu^{II} and bridging carboxyl are represented by larger circles; (b) 2-D network connectivity in **2**; the filled circles represent the $Cu(Tyr)\cdot H_2O$ unit; (c) stacking of 2-D sheets of **2**

of Cu-Tyr complexes, thus leading to the fine tuning of the structural and stereo conformation.

Experimental Section

Synthesis of $[Cu(Tyr)_2]_n$ (1): A 1.0 M aqueous solution of NaOH was carefully added dropwise to a suspension of L-tyrosine (181 mg, 1.0 mmol) in 10 mL water, with vigorous stirring, until ligand dissolved. The solution was then mixed with a solution of copper perchlorate (576 mg, 1.0 mmol) in 10 mL methanol. The reaction mixture was stirred overnight to give a blue solution, which was then filtered. Blue needle-shaped crystals of $[Cu(Tyr)_2]_n$ (**1**) suitable for X-ray diffraction analysis were obtained after several days' evaporation at room temperature. Yield: 136 mg (64% for tyrosine). $C_{18}H_{20}CuN_2O_6$ (423.9): calcd. C 50.96, H 4.75, N 6.61; found C 50.47, H 4.66, N 6.82.

Synthesis of $\{[Cu_2(Tyr)_2(4,4\text{-bipy})\cdot 2H_2O]\cdot 2ClO_4\}_n$ (2): This complex was synthesized as for complex **1**. 4,4-Bipyridine (156 mg, 1.0 mmol) was added after the overnight reaction step and the mixture was stirred for another 4 h. Single crystals of complex **2** suitable for X-ray diffraction analysis were obtained by evaporation of the filtered mixture at room temperature after two weeks. Yield: 190 mg (43% for tyrosine). $C_{23}H_{32}Cl_2Cu_2N_4O_{16}$ (818.5): calcd. C 38.24, H 3.67, N 6.37; found C 38.86, H 3.68, N 6.62.

X-ray crystallography: The intensity data were collected on a Bruker CCD diffractometer with graphite-monochromated Mo-K_α radiation ($\lambda = 0.71073$ Å) at room temperature. All of the calculations were performed on an HP computer by using the SHELXTL-PL version 5.10 package. The structures were solved by direct methods and refined by full-matrix least-squares (Table 1).[21]

Crystal Data for 1: Blue needle, dimensions 0.25 × 0.20 × 0.10 mm, $C_{18}H_{20}CuN_2O_6$, M_r = 423.90, orthorhombic, space group $P2_12_12_1$; a = 6.0753(12) Å, b = 12.948(3) Å, c = 22.037(4) Å, V = 1733.4(6) Å^3; $\rho_{calc.}$ = 1.624 g/cm^3, Z = 4; $F(000)$ = 876; μ(Mo-K_α) = 1.300 mm^{-1}; 2340 reflections collected, 2340 reflections observed ($|F_0| \geq 2\sigma|F_0|$); R_1 = 0.0397; wR_2 = 0.1004.

Table 1. Crystallographic data for complexes **1** and **2**

	1	**2**
Mol. formula	$C_{18}H_{20}N_2O_6Cu$	$C_{28}H_{32}N_4O_{16}Cu_2Cl_2$
Mol. wt.	423.90	878.56
Crystal system	Orthorhombic	Monoclinic
Space group	$P2_12_12_1$	$P2_1$
a (Å)	6.0753(12)	8.4341(6)
b (Å)	12.948(3)	10.1027(8)
c (Å)	22.037(4)	20.9444(15)
β (deg)	90.00	97.449(2)
V (Å^3)	1733.4(6)	1769.6(2)
Z	4	2
D_c (g·cm^{-3})	1.624	1.649
μ (mm^{-1})	1.300	1.430
R_1 [$I < 2\sigma(I)$][a]	0.0397	0.0782
wR_2 (all data)[b]	0.1107	0.2308

[a] $R_1 = \|\|F_0| - |F_c\|/|F_0|$. [b] $wR_2 = [w(F_0^2 - F_c^2)^2/w(F_0^2)^2]^{1/2}$.

Crystal Data for 2: Blue plate, dimensions 0.30 × 0.30 × 0.20 mm, $C_{28}H_{32}Cl_2Cu_2N_4O_{16}$, M_r = 878.56, monoclinic, space group $P2_1$; a = 8.4341(6) Å, b = 10.1027(8) Å, c = 20.9444(15) Å, β = 97.449(2)°, V = 1769.6(2) Å^3; $\rho_{calc.}$ = 1.649 g/cm^3, Z = 2; $F(000)$ = 896; μ(Mo-K_α) = 1.430 mm^{-1}; 5643 reflections collected, 4318 reflections observed ($|F_o| \geq 2\sigma(|F_o|)$); R_1 = 0.0782; wR_2 = 0.1840. CCDC-176587 and CCDC-176588 contain the supplementary crystallographic data for this paper. These data can be obtained free of charge at www.ccdc.cam.ac.uk/conts/retrieving.html [or from the Cambridge Crystallographic Data Centre, 12, Union Road, Cambridge CB2 1EZ, UK; Fax: (internat.) +44-1223/336-033; E-mail: deposit@ccdc.cam.ac.uk].

Acknowledgments

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