Crystal Structure of [Aib-COCO-Aib]Cu₂: A Unique Example of Modular Self-Assembly†

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Design of supramolecular systems[1] by metal-ion-directed self-assembly of individual components with the ultimate aim of generating new molecular materials[2] is an area of current interest.

We report here that C_2 symmetric core oxalo retro-bispeptides show a unique property of self-assembly, with Cu(II) ions, using the core −NH−CO−CO−NH− unit as the anchor, into highly organized, rigid, two-dimensional molecular arrays interlinked *via* the terminal carboxylate units and demonstrate this with the crystal structure of [Aib-COCO-Aib]Cu₂.

The uptake of two copper atoms by a single −NH−CO−CO−NH− (N,N′-disubstituted oxamide) unit, when tethered to a COOH group *via* a quaternary carbon, to produce modules having a unique tetracyclic array of atoms, wherein a vacant ligand site promotes self-assembly to novel structures, constitutes, in our opinion, an original finding having wide ramifications.[3]

Core oxalo retro-bispeptide dicarboxylic acid **1**,[4] generated from its methyl ester,[5] yielded in nearly quantitative yields, on treatment with Cu(II) salts, a blue violet complex, which, on the basis of FAB mass and analytical data, was assigned the structure Cu₂L where L = retro-bispeptide ligand **1** (Figure 1).

† Dedicated to Professor S. Ranganathan on the occasion of his 60th birthday.
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(1) Lehn, J.-M. *Angew. Chem., Int. Ed. Engl.* **1990,** *29,* 1304. Vogtle, F. *Supramolecular Chemistry;* Wiley: Chichester, England, 1991. Lehn, J.-M. *J. Coord. Chem.* **1992,** *27,* 3.
(2) Stumpf, H. O.; Pei, Y.; Kahn, O.; Sletten, J.; Renard, J. P. *J. Am. Chem. Soc.* **1993,** *115,* 6738 and references cited therein.
(3) X-ray crystallographic studies of several peptides having the oxalamide unit (NH−CO−CO−NH), recently carried out by us (Karle, I.; Ranganathan, D.; Shah, K.; Vaish, N. K. *Int. J. Pept. Protein Res.* **1994,** *43,* 160), have consistently shown that the "bicyclo[3.3.0]octane" motif (i) arising out of pseudo C_5 intramolecular hydrogen bonding forms the cornerstone for the self-assembly of these peptides. The structural similarity between i and the binuclear module ii which organizes to generate the network presented here is striking.

(i)   (ii)

(4) HO-Aib-COCO-Aib-OH (**1**): A solution of MeO-Aib-COCO-Aib-OMe⁵ (1 mmol) in MeOH (~4 mL) was admixed with cold aqueous NaOH (2 N, 4 mL) and stirred at room temperature for 4 h. The reaction mixture was concentrated to half the volume in vacuo (without heating) and cooled in ice, its pH was adjusted to pH 3 with cold 2 N H₂SO₄, and the precipitated bis acid was filtered, washed with ice cold water, and crystallized from hot aqueous MeOH; yield 98%; mp 263−264 °C; FAB MS, *m/z* 261 (MH)⁺, 283 (M + Na)⁺. [Aib-COCO-Aib]Cu₂: To the disodium salt of **1** prepared in situ by admixture with aqueous NaHCO₃, was added 2 equiv of cupric nitrate in water. The precipitated turquoise blue solid was filtered, washed with water, and crystallized from hot water as blue violet crystals: yield 95%; mp >350 °C.
(5) Ranganathan, D.; Vaish, N. K.; Shah, K.; Roy, R.; Madhusudanan, K. P. *J. Chem. Soc., Chem. Commun.* **1993,** 92.

(1)
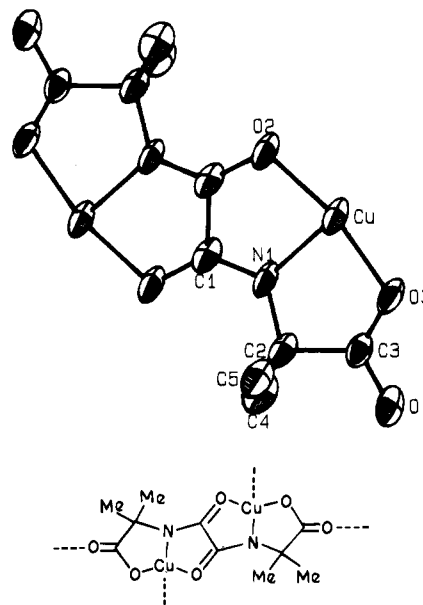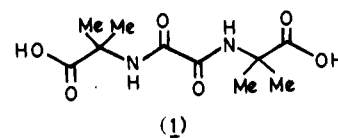
a molecular block of the Cu(II) complex

Figure 1. ORTEP and structural representations of a single repeating unit (module) of [Aib-COCO-Aib]Cu₂.

The X-ray crystal structure[6] of this complex revealed a unique supramolecular two-dimensional structure arising from modular self-assembly. The ORTEP diagram of a single repeating module is presented in Figure 1. The self-assembly of these modules, projected down the *b*-axis, generated the two-dimensional network shown in Figure 2, wherein the layers are separated by 6.4 Å with a nearest contact value of 3.3 Å. The layers are held together by van der Waals forces. The modular assembly along the *b*-axis exhibits regular features. The inter-copper vector is perpendicular to this axis, and this factor naturally leads to two different orientations for the module, the dihedral angle between the planes being 114.1°. The exquisite two-dimensional array arising from the above arrangement is shown in Figure 3, a noteworthy and potentially useful aspect of which is the presence of regular, alternate voids formed out of four interconnected modules, which when viewed in a three-

(6) (a) X-ray structure analysis of [Aib-COCO-Aib]Cu₂ (C₁₀H₁₂O₆N₂-Cu₂): $M = 383.3$; blue violet crystal (0.3 × 0.8 × 0.2 mm³). Monoclinic system of space group $P2_1/c$ with unit cell dimensions $a = 10.031(4)$ Å, $b = 6.134(3)$ Å, $c = 13.385(5)$ Å, $\beta = 126.83(11)°$, $V = 659.3$ Å³, $Z = 2$, $\varrho_{calcd} = 1.9308$ g cm⁻³, $\varrho_{obsd} = 1.9324$ g cm⁻³, $F(000) = 384$, $\mu = 41.9$ cm⁻¹. One crystal free of cracks, selected by examination under microscope, was mounted on the goniometer head of an Enraf-Nonius single-crystal X-ray diffractometer for data collection at ambient temperature. Cu Kα radiation ($\lambda = 1.5418$ Å) with graphite monochromator was used. Twenty-five reflections were used to determine the unit cell and the orientation matrix, and three strong reflections from this list were chosen for intensity control. An $\omega - 2\theta$ scan mode in the range $2° < \theta < 60°$ was selected, and the data was collected for a total of 1254 reflections with $h = 0-11$, $k = 0-6$, $l = -14$ to 14 with a maximum scan time of 1 min/reflection with a check on orientation every 1 h of X-ray exposure time. The crystal was stable to X-rays during the entire data collection with practically no loss of intensity. Lorentz and polarization corrections were applied. The structure was solved using an Enraf-Nonius Molen/VAX package (6b) by a combination of Patterson, difference Fourier, and full matrix least-squares methods (F refinements), $w = 1/(\sigma^2(F) + 0.04F^2)$. The overall $R = 0.056$, and weighted $R_w = 0.045$. The structure has a center of inversion with half the molecule consisting of C₅H₆NO₃Cu being the asymmetric unit. (b) *MOLEN, An interactive structure solution procedures* Enraf-Nonius: Delft, The Netherlands, 1990.
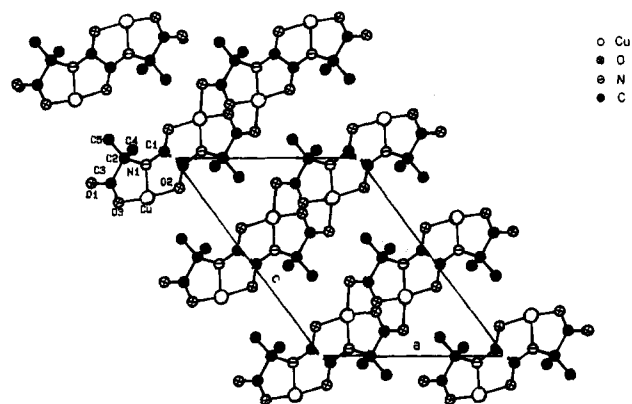
Figure 2. Stacking profile of the layers in the two-dimensional network of [Aib-COCO-Aib]Cu₂.
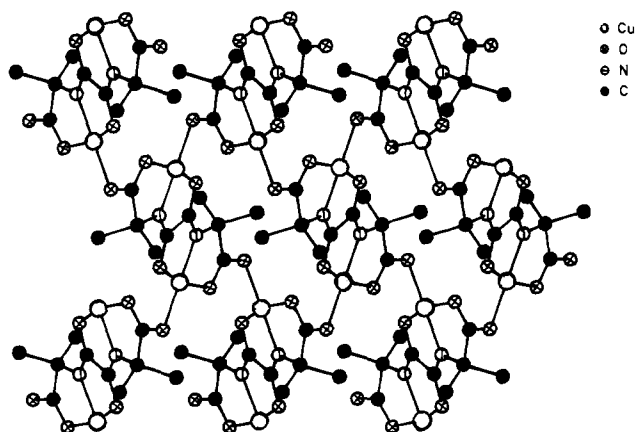

Figure 3. The supramolecular architecture arising from linkage of each module to four neighbors creating alternating voids.
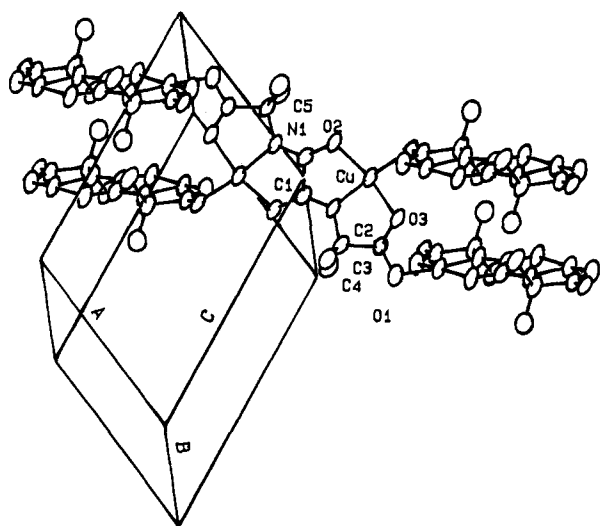

Figure 4. The orientation of modules with respect to the unit cell axes of the crystal, showing the connectivity of one module to four others of the same orientation forming a pentameric motif.

dimensional arrangement are seen as forming channels of 6.3—6.6 Å diameter. The arrangement within a unit cell framework, shown in Figure 4, clearly summarizes the genesis of the supramolecular framework by regular docking of the modular units. A necessary consequence of this assembly is that while each module [$Cu_2N_2O_2C_2$] is rigorously planar, the resulting Cu—N1—O1—O2—O3 unit exhibits slight distortion (~0.1 Å) arising from deviation of the O3; further, while the inter-copper distance in each module is 5.155 Å, the inter-copper distance between two proximate modules in the supramolecular network
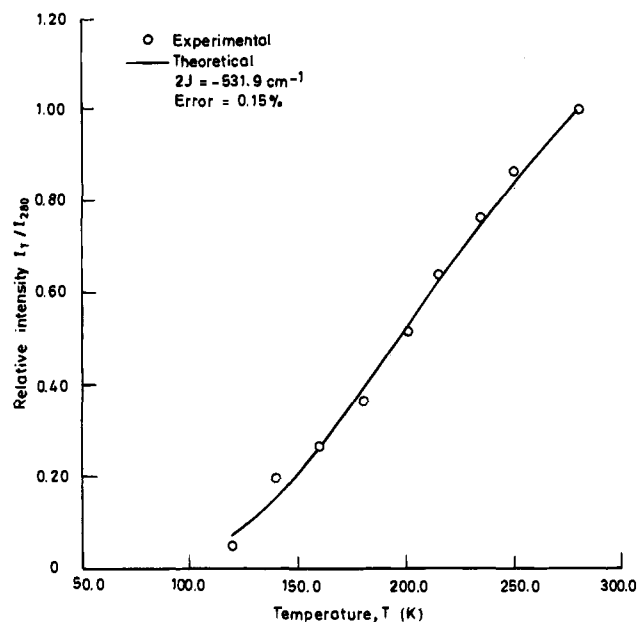

Figure 5. The experimental (O) and calculated (—) relative temperature dependence of the integrated EPR intensities of [Aib-COCO-Aib]Cu₂ in the temperature region 70—280 K.

is 4.551 Å. This results in intramodular exchange coupling as well as intermodular exchange.

Recent studies[7] have brought out a correlation between binuclear copper complexes of the type described here and large magnetic exchange coupling in antiferromagnetically coupled systems. The modular assembly presented here exhibits this profile.

EPR intensity and magnetic susceptibility studies in the temperature range 4.2—300 K have shown fortuitously that intermodular exchange coupling is not significant in the 120—280 K region, a domain of relevance pertaining to the assessment of the above correlation. EPR intensity measurements in the region 120—280 K were interpreted using a simple singlet—triplet model for the representation shown in Figure 1. The result presented in Figure 5 is noteworthy from diverse perspectives. The experimentally determined values match exceptionally well with that simulated from theory based on the metal profile presented in individual modules. The large value of $2J$ (-531.9 cm^{-1}) is in excellent agreement with expectations.

Supplementary Material Available: Tables of bond angles, bond distances, least-squares planes, general displacement parameter expressions, and positional parameters and, Figures A and B showing projections of the copper complex in a view direction respectively parallel and perpendicular to the molecular plane of the core oxalamide motif (9 pages); listing of observed and calculated structure factors (11 pages). This material is contained in many libraries on microfiche, immediately follows this article in the microfilm version of the journal, and can be ordered from the ACS; see any current masthead page for ordering information.

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(7) Kahn, O. *Angew. Chem., Int. Ed. Engl.* **1985**, *24*, 834. Vardaguer, M.; Julve, M.; Gleizes, A.; Kahn, O. *Nouv. J. Chim.* **1985**, *9*, 325. Okawa, H.; Matsumoto, N.; Koikawa, M.; Takeda, K.; Kida, S. *J. Chem. Soc., Dalton Trans.* **1990**, 1383. Cornia, A.; Fabretti, A. C.; Ferraro, F.; Gatteschi, D.; Giusti, A. *J. Chem. Soc., Dalton Trans.* **1993**, 3363.