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Tetra(μ_3-hydroxo) bridged copper(II) tetranuclear cubane complexes: synthesis, crystal structure, and DNA binding studies

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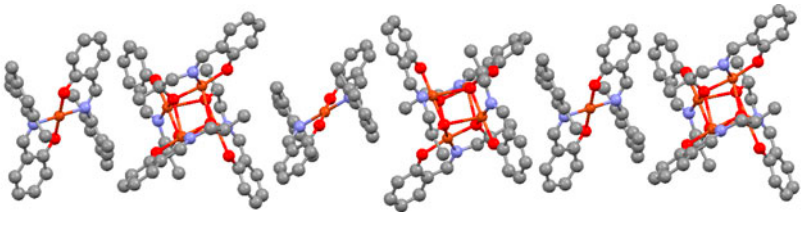

The tridentate Schiff base H_2L was synthesized by the condensation of equimolar amount of 1-amino-2-propanol and salicylaldehyde. The reaction of H_2L with an equimolar amount of Cu $(CH_3COO)_2{\cdot}H_2O$ in methanol leads to the formation of the tetranuclear Cu_4L_4, **1**. However, reaction of equimolar amount of H_2L, copper(II) acetate, and 2,4,6-trimethylaniline in methanol forms a mixture of products which includes a discrete mononuclear complex $Cu(L')_2$, **2m** (where HL′ is a bidentate ligand), in addition to the tetranuclear Cu_4L_4 species, **2c**. In both tetranuclear cubane species, the tridentate H_2L is both a chelating and a bridging ligand, after deprotonation of the enolic and the phenolic OH. The copper(II) centers are five-coordinate with a [N, O_4] donor set from the ligands. The coordination geometry about each copper is distorted square pyramidal with one nitrogen and two oxygen from one ligand and two oxygen from adjacent ligands in the next unit of the cubane. In mononuclear **2m**, the ligand is bidentate and the coordination geometry around copper(II) is square planar. The absorption spectra strongly suggest that tetranuclear **1** interacts with CT-DNA.

Keyword: Copper complex; Tridentate Schiff base; Tetranuclear; Cubane; DNA binding

1. Introduction

The synthesis of polynuclear complexes (clusters) by spontaneous self-assembly of organic ligands and transition metal ions has attracted much interest due to their relevance to bioinorganic chemistry [1–3], molecular magnetic materials [4–6], and coordination

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chemistry [6–10]. In the self-assembly process, the constituent ligands and metals play important roles in the formation of metallo polynuclear clusters.

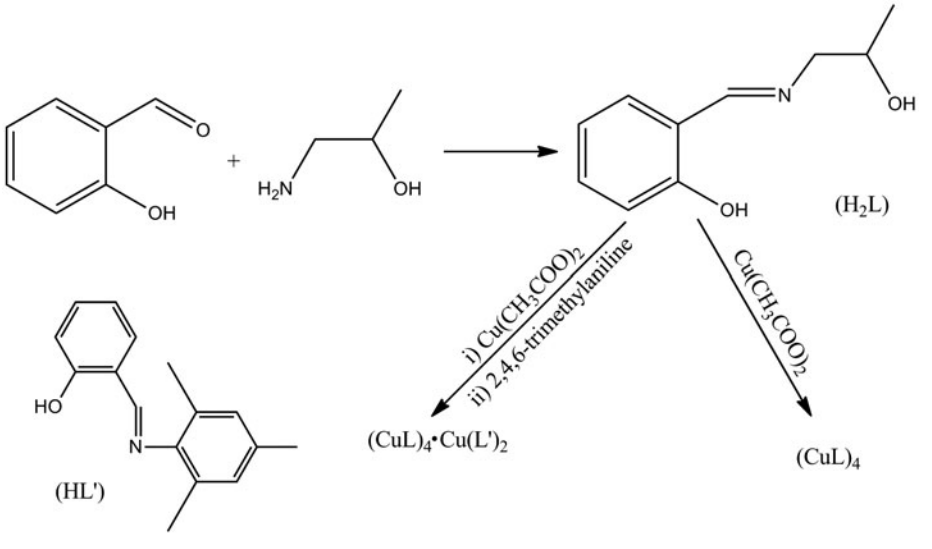
Polynuclear copper(II) complexes are of particular interest from both structural and functional points of view. The most common ligands used for the construction of polynuclear copper(II) complexes are tridentate Schiff base ligands. The coordination sites of Cu(II) ion are blocked by the tridentate Schiff base ligand, and to saturate the coordination number of the copper ion, a bridging ligand (halides, pseudo-halides, oxalate, etc.) and/or μ-bridging alkoxo and phenoxo oxygen (self-assembly process) are used [10–15]. However, dianonic tridentate Schiff base ligands can form polynuclear complexes such as cubane-type structures by a self-assembly process [10, 16–18]. Among them, tetranuclear copper complexes with Cu_4L_4 cores have been studied extensively. All complexes containing such cores have the same structural framework with four Cu(II) ions at the corners of a tetrahedron around the central μ-bridging hydroxo, alkoxo, or phenoxo oxygen donors [18–20]. The cubane complexes are attractive due to their interesting physical properties, including luminescence, superparamagnetism, and antiferromagnetic properties [21, 22] together with their potential to serve as biomimetic models for enzymes such as carbon monoxide dehydrogenase and superoxide dismutase, in addition to their nuclease activities [3, 23, 24]. Interaction between polynuclear copper(II) complexes and DNA has attracted much interest due to their importance in cancer therapy and molecular biology [25–27].

Herein, we report the synthesis, spectroscopic characterization, structural analysis, and DNA interaction of some new copper(II) complexes derived from the [N, O_2] donor, H_2L, and NO, HL′ donor Schiff base ligands (scheme 1).

2. Experimental

2.1. *Reagents*

All chemicals were used as supplied by Merck and Fluka without purification.



Scheme 1. Synthesis of 1 and 2.169 × 98 mm (300 × 300 DPI).

2.2. *Physical measurements*

Infrared spectra were taken with an Equinox 55 Bruker FT-IR spectrometer using KBr pellets from 400 to 4000 cm^{-1}. Absorption spectra were determined in methanol using a GBC UV–Visible Cintra 101 spectrophotometer with 1 cm quartz cuvette from 200 to 800 nm at 25 °C. Elemental analyses (C, H, N) were performed using a CHNS-O 2400II PERKINELMER elemental analyzer.

2.3. *DNA binding*

The interaction of **1** with calf thymus CT-DNA was studied in Tris–HCl buffer (5.5 mM Tris–HCl, pH 7.2) containing 50 mM NaCl at room temperature. The solution was subsequently kept for over 24 h at 4 °C. The resulting, somewhat viscous, solution was clear and particle-free. The CT-DNA in the buffer mixture gave a ratio of UV absorbance at 260 and 280 nm of 1.8 : 1, indicating that the DNA was sufficiently free of protein [28]. The DNA concentration was measured from its absorption intensity at 260 nm using the molar absorption coefficient (ε) value of 6600 M^{-1} cm^{-1} [29]. The stock solutions of complexes were freshly prepared by first dissolving the complexes in DMF and then diluting them with the buffer. The amount of DMF was kept at 10% (by volume) for each set of experiments and had no effect on experimental results. Absorption spectral titration experiments were performed while maintaining a constant complex concentration and varying the nucleic acid concentration. This was achieved by dissolving an appropriate amount of the metal complex (25 μM) and DNA stock solutions (0–80 μM) while maintaining the total volume constant (1 mL). The spectral band exhibited hypochromism without a shift in the band position and was recorded after the successive addition of CT-DNA. The Tris–HCl buffer was used as a blank to make preliminary adjustments. The intrinsic binding constants (K_b) of the complexes to CT-DNA were determined from the spectral titration data using the following equation [30]:

$$[\mathrm{DNA}]/(\varepsilon_a - \varepsilon_f) = [\mathrm{DNA}]/(\varepsilon_b - \varepsilon_f) + 1/K_b(\varepsilon_b - \varepsilon_f) \quad (1)$$

where [DNA] is the concentration of the bases of CT-DNA, and the apparent absorption coefficients ε_a, ε_f, and ε_b correspond to A_{obs}/[DNA], the absorbance for the free Cu(II) complex (unbound) and the absorbance for the fully-bound complex, respectively. *A* plot of $[\mathrm{DNA}]/(\varepsilon_a - \varepsilon_f)$ *versus* [DNA] gave a slope $1/(\varepsilon_b - \varepsilon_f)$ and an intercept $1/K_b(\varepsilon_b - \varepsilon_f)$. The value of K_b was determined from the ratio of the slope to the intercept.

2.4. *X-ray crystallography*

Diffraction images were measured at 200 K on a Nonius Kappa CCD diffractometer using Mo Kα radiation with a graphite monochromator ($\lambda = 0.71073$ Å), and data are extracted using the *DENZO/SCALEPACK* package [31]. The structures were solved by direct methods with SIR92 [32]. The structures were refined on F^2 by full-matrix least-squares using the CRYSTALS program package [33]. Atomic coordinates, bond lengths and angles, and displacement parameters have been deposited at the Cambridge Crystallographic Data Center. Crystallographic details for **1** and **2** are summarized in table 1.

Table 1. Crystallographic data of **1** and **2**.

Compound	**1**	**2**
Chemical formula	$C_{40}H_{44}Cu_4N_4O_8$	$C_{40}H_{44}Cu_4N_4O_8{\cdot}C_{32}H_{32}CuN_2O_2$
Formula weight	963.00	1503.16
Temperature (K)	200	200
Crystal system	Monoclinic	Monoclinic
Space group	*C2/c*	*C2/c*
Z	4	4
Unit cell dimensions		
a (Å)	25.5926(6)	34.7662(6)
b (Å)	7.3265(2)	9.8119(1)
c (Å)	22.5504(5)	21.0656(3)
α (°)	90	90
β (°)	110.9673(9)	112.0669(8)
γ (°)	90	90
V (Å^3)	3948.32(17)	6659.55(17)
F (0 0 0)	1968	3100
D_{Calc} (g cm^{-3})	1.620	1.499
Crystal size (mm)	0.26 × 0.16 × 0.11	0.44 × 0.11 × 0.07
μ (mm^{-1})	2.18	1.64
θ range (°)	2.9–27.5	2.6–27.5
Limiting indices	$-33 \le h \le 33$	$-44 \le h \le 44$
	$-9 \le k \le 9$	$-11 \le k \le 12$
	$-29 \le l \le 29$	$-27 \le l \le 27$
No. reflections measured	35,909	69,692
No. independent reflections	4529	7609
R_{int}	0.053	0.049
No. parameters	319	421
$R[F^2 > 2\sigma(F^2)]$	0.036	0.032
$wR(F^2)$ (all data)	0.085[a]	0.084[b]

[a] $w = 1/[\sigma^2(F^2) + (0.04P)^2 + 7.4P]$, where $P = (\max(F_o^2, 0) + 2F_c^2)/3$.
[b] $w = 1/[\sigma^2(F^2) + (0.05P)^2 + 5.85P]$, where $P = (\max(F_o^2, 0) + 2F_c^2)/3$.

2.5. *Syntheses*

2.5.1. Synthesis of Schiff base (H_2L). The tridentate Schiff base H_2L was synthesized by a general method [10, 34] using the condensation of 1-amino-2-propanol (5 mmol, 0.40 mL) and salicylaldehyde (5 mmol, 0.45 mL) in methanol (30 mL) at room temperature. The resulting solution was stirred for 2 h, and the bright yellow solution containing the Schiff base ligand (H_2L) was used for synthesis of the complexes without further purification. The IR spectrum of H_2L shows a characteristic strong band at 1634 cm^{-1} (ν(C=N)).

2.5.2. Synthesis of [Cu_4L_4], 1. Cu_4L_4 was prepared by a general method [35–37]. A methanolic solution of $Cu(CH_3COO)_2{\cdot}H_2O$ (5 mmol, 0.988 g) was added to a stirred solution of the Schiff base ligand and the solution stirred for 3 h. The resulting green precipitate was collected by filtration, washed with ethanol, and dried in air. The green solid was recrystallized from dichloromethane/2-propanol (2 : 1 v/v). Green needle-shaped crystals of Cu_4L_4 suitable for X-ray analysis appeared at the bottom of the vessel upon slow evaporation of the solvent and were washed with ethanol and dried in air. The yield was 78%. Anal. Calcd for $C_{40}H_{44}Cu_4N_4O_8$: C, 49.89; H, 4.61; N, 5.82. Found: C, 50.03; H, 4.70; N, 5.74. IR (KBr, cm^{-1}): υC=N=1602. Electronic spectra in DMF solvent: λ_{max} = 637 nm (d–d).

2.5.3. Synthesis of $[Cu_4L_4][Cu(L')_2]$, 2. This complex was prepared by a similar procedure to that used for **1**. A methanolic solution of $Cu(CH_3COO)_2 \cdot H_2O$ (5 mmol, 0.988 g) was added to a stirred solution of H_2L. To this solution, 2,4,6-trimethylaniline was added and stirring was continued for 3 h. The resulting green precipitate was collected by filtration, washed with ethanol, and dried in air. It was recrystallized from dichloromethane/2-propanol (2 : 1 v/v). Green needle-shaped crystals of $[Cu_4L_4][Cu(L')_2]$ suitable for X-ray analysis were obtained by slow evaporation of the solvent and were washed with ethanol and dried in air. The yield was 61%. Anal. Calcd for $C_{40}H_{44}Cu_4N_4O_8$, $C_{32}H_{32}CuN_2O_2$: C, 57.53; H, 5.10; N, 5.59. Found: C, 57.75; H, 5.32; N, 5.44. IR (KBr, cm-1): υC=N=1602. Electronic spectra in DMF solvent: λ_{max} = 637 nm (d–d).

For comparison, the corresponding reaction of $Cu(CH_3COO)_2$ with the Schiff base ligand in the presence of monodentate neutral ligands (X) such as H_2O, pyrazole, and imidazole were studied under the same conditions. It was found that CuLX complexes were not formed, with the exception of Cu_4L_4, analogous to **1**.

3. Results and discussion

3.1. *Synthesis and characterization of the complexes*

The synthesis of **1** and **2** are schematically represented in scheme 1. The tridentate Schiff base H_2L was obtained by *in situ* condensation of 1-amino-2-propanol and salicylaldehyde at room temperature. Reacting copper(II) acetate monohydrate with equimolar H_2L in methanol leads to the formation of tetranuclear **1**. The tridentate Schiff base H_2L, which can adopt both chelating and bridging modes, undergoes deprotonation at two sites during the reaction and the dianionic form of the ligand, L^{2-}, coordinates to the metal center through the imine nitrogen, deprotonated phenolic, and alkoxo oxygen. By a self-assembly process, four such [CuL] building blocks form the cubane tetranuclear **1**. This could be due to the fact that, in tetranuclear **1**, the interaction between the bridging alkoxo and the Cu ion is stronger than those between neutral ligands such as H_2O, pyrazole and imidazole, and the Cu center [10, 38]. However, in the reaction of an equimolar amount of copper(II) acetate, tridentate Schiff base ligand H_2L, and 2,4,6-trimethylaniline in methanol, **2** forms instead. In **2**, there is a discrete mononuclear complex, **2m**, in addition to the tetranuclear Cu_4L_4 cubane, **2c**. The addition of 2,4,6-trimethylaniline to the methanolic solution of the Schiff base ligand H_2L and $Cu(CH_3COO)_2 \cdot H_2O$ prevents self-assembly. 2,4,6-Trimethylaniline does not coordinate to Cu in **2c**, likely due to the aniline nitrogen being a weaker donor than the alkoxo oxygen of L^{2-}. However, in addition to the formation of the tetranuclear complex **2c**, the new mononuclear complex **2m**, with bidentate Schiff base ligand, (L′) was obtained, where the $NCH_2C(CH_3)H(OH)$ part of the original tridentate H_2L has been substituted by $NC_6H_2(CH_3)_3$.

The IR spectrum of free H_2L shows bands at 1270 and 1634 cm^{-1}, which are assigned as υC–O and υC=N, respectively. In the free Schiff base, the frequency of hydroxyl groups (phenol and alcohol) were observed at ~3200–3400 cm^{-1} due to intramolecular hydrogen bonding between OH and the imine group in the Schiff base. The disappearance of this band in IR spectra of complexes is indicative of the fact that OH has been deprotonated and is coordinated to copper. In **1** and **2**, the strong υC=N shifts to 1602 cm^{-1}, which indicates the coordination of the imine nitrogen to copper. The υC–O band in **1** and **2** is shifted

~30 cm^{-1} toward higher energies compared with the free ligand, consistent with coordination of the deprotonated Schiff base to copper ion [10, 16, 18].

3.2. *Crystal structures*

The structures of **1** and **2** both contain a tetrameric Cu_4L_4 cubane species. In **2**, in addition to Cu_4L_4, **2c**, there is also a discrete mononuclear complex, **2m**. The molecular structures of **1** and **2** are shown in figures 1 and 2, respectively. The ORTEP representations of the unit cell of **1** and **2** are shown in supplementary figure and figure 3, respectively. Both compounds crystallize in the monoclinic space group *C2/c* and there are four molecules in the unit cell. Selected bond lengths and angles as well as interatomic distances are summarized in table 2.

In both tetranuclear cubane complexes, the tridentate L^{2-} is both chelating and bridging after double deprotonation of the enolic and the phenolic OH. The dianionic form L^{2-} coordinates through the imine nitrogen, deprotonated phenolic, and alkoxo oxygen. By self-assembly, four such monomeric CuL entities eventually are linked through alkoxo bridges to produce the tetranuclear cubane core. Here, all four alkoxo oxygen are located at the four corners of the cube and bridged the metal centers in a μ^3-fashion (figures 1 and 2). The cubic core contains two crystallographically independent metal ions, and the two sets of metal ions are related by the crystallographic two-fold axis passing through the middle of Cu1–Cu1* and Cu2–Cu2* vectors. The adjacent Cu···Cu distances are 3.108(4)–3.6154(9)

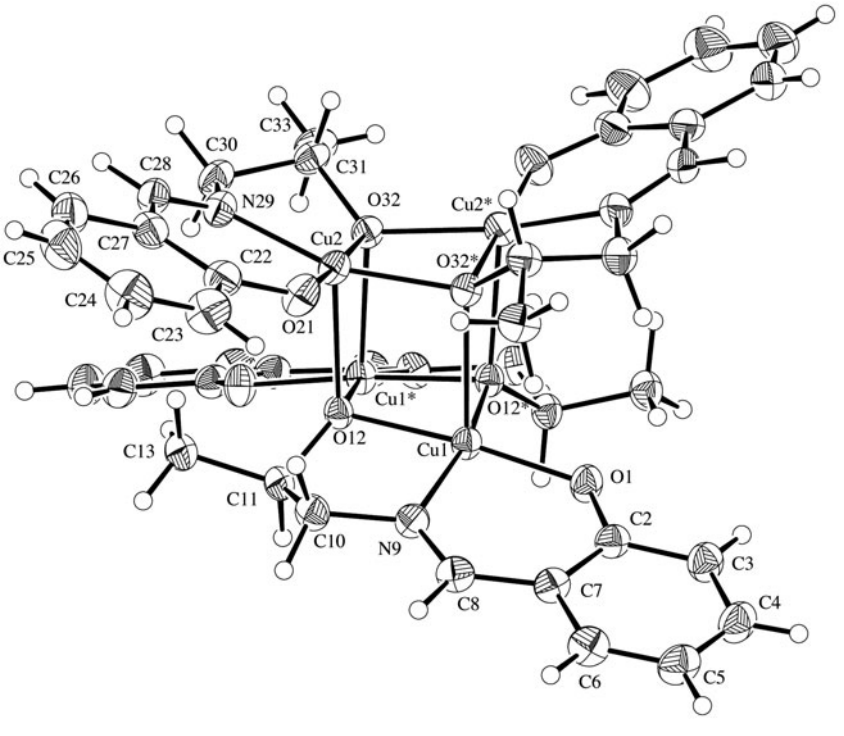


Figure 1. The molecular structure of tetranuclear cubane **1** with labeling of selected atoms.

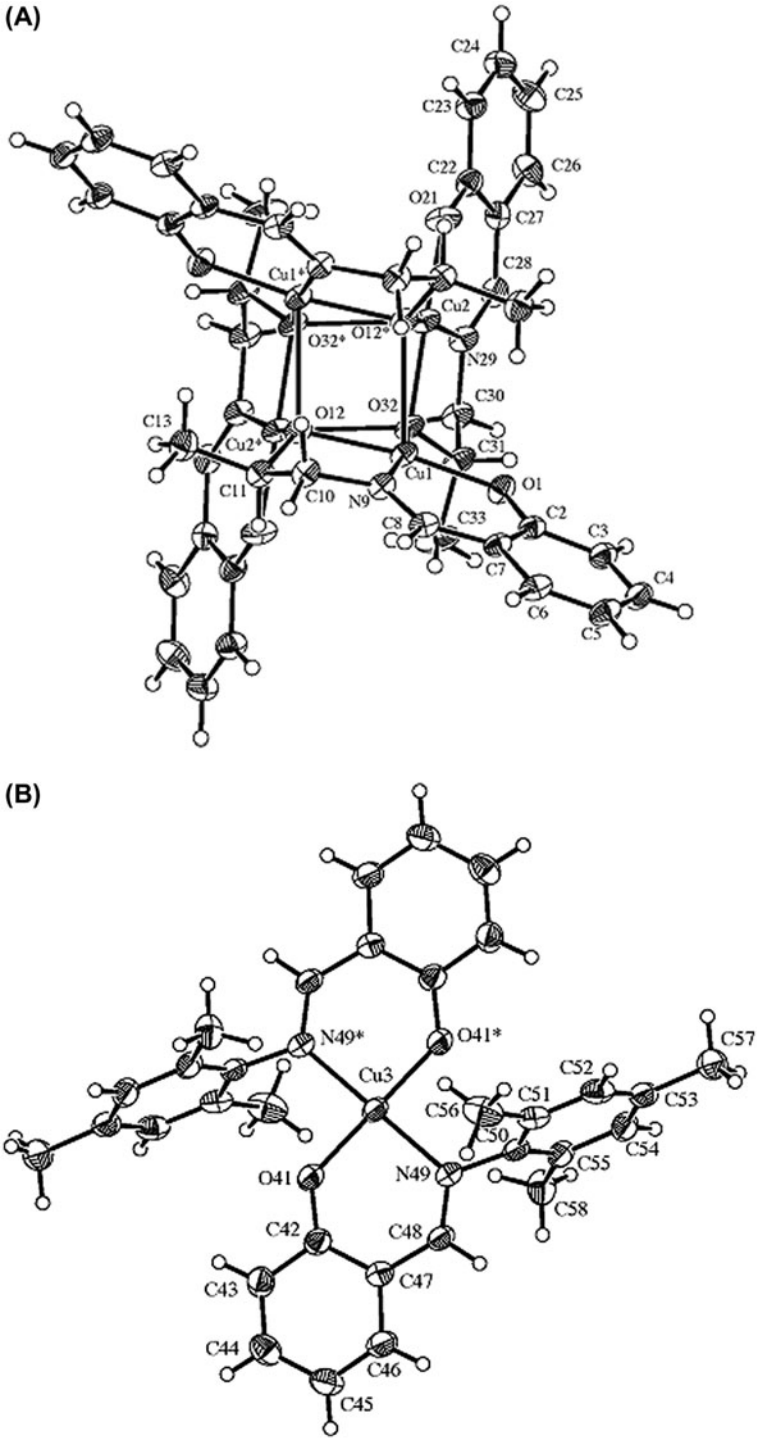


Figure 2. The molecular structure of **2c** (A) and **2m** (B) with labeling of selected atoms.

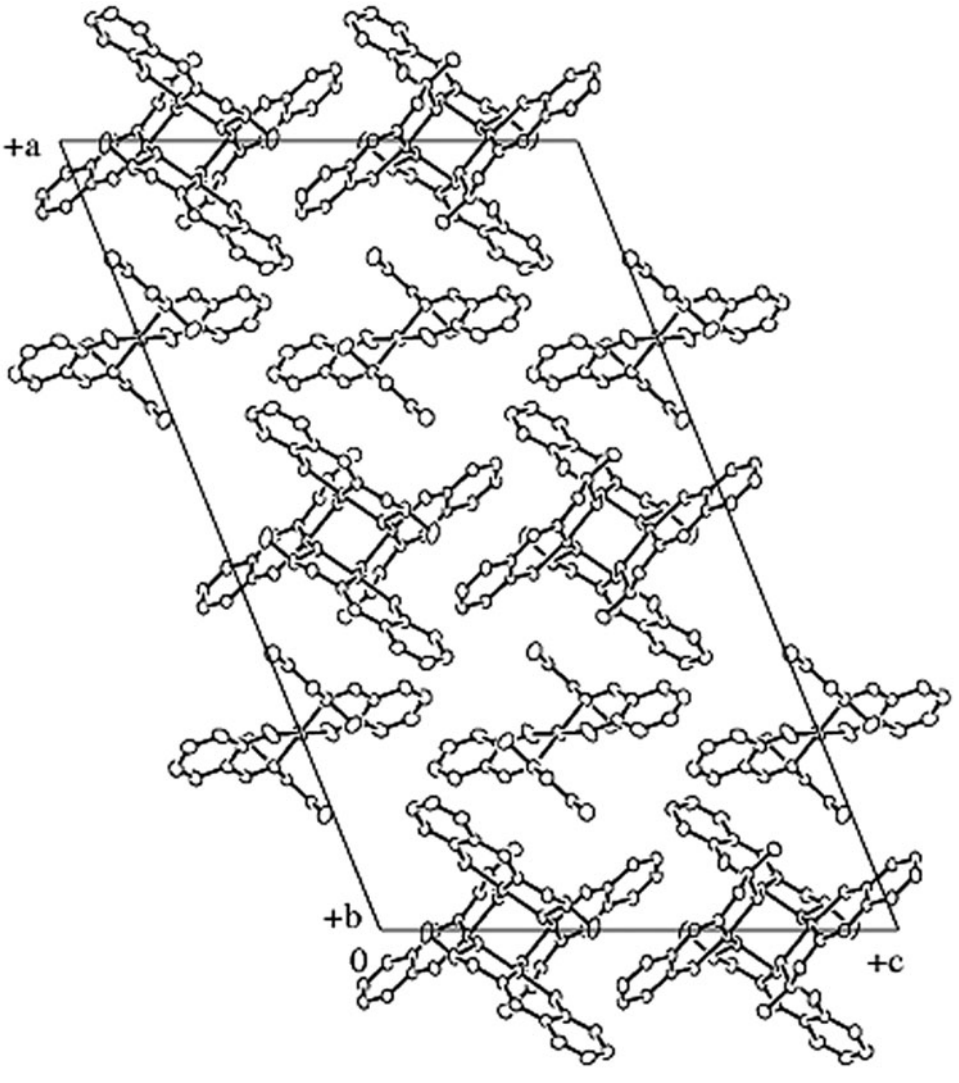


Figure 3. Unit cell packing diagram of **2** projected down the *b* axis; anisotropic displacement ellipsoids show 30% probability levels. Hydrogen have been deleted for clarity.

Å, which are comparable with values of similar compounds [16, 22, 39, 40]. All copper(II) centers are five-coordinate with a [N, O_4] donor set from the Schiff base ligands. Coordination geometry about each copper ion is essentially square pyramidal with one nitrogen and two oxygen from a ligand and two oxygen from the next unit of the cubane. Based on the bond lengths between copper and coordinating atoms (i.e., four bonds with short distances (1.8891(19)–1.9795(17) Å in **1** and 1.8948(15)–1.9808(14) Å in **2c**) and bonds with longer distances (2.3569(18)–2.3770(19) Å in **1** and 2.4277(15)–2.4477(14) Å in **2c**), the basal planes for Cu1 and Cu2 are regarded as O1–N9–O12–O12* and O21–N29–O32–O32* (in **1**) and O1–N1–O12–O32* and O21–N29–O12*–O32 (in **2c**), respectively. Cu1 and Cu2 in both tetranuclear species deviate from the corresponding mean planes by 0.118 and

Table 2. Selected bond lengths (Å) and angles (°) in **1** and **2**[a].

Complex **1**			
Cu1–O32*	2.3770(19)	O32*–Cu1–O1	104.11(8)
Cu1–O12*	1.9763(16)	O12*–Cu1–O1	98.23(7)
Cu1–O1	1.8933(18)	O32*–Cu1–N9	109.97(8)
Cu1–O12	1.9795(17)	O12*–Cu1–N9	161.65(9)
Cu1–N9	1.940(2)	O1–Cu1–O12	174.51(8)
N9–C8	1.284(4)	O1–Cu1–N9	94.21(9)
Cu1···Cu2*	3.3256(4)	O32*–Cu2–N29	160.99(9)
Cu1···Cu1*	2.9389(6)	O12–Cu2–N29	109.77(8)
Cu1···Cu2	3.2846(5)	O21–Cu2–O32	176.88(9)
Cu2···Cu2*	2.9312(6)	O32–Cu2–N29	94.08(9)
Complex **2c**			
Cu1–O12*	2.4477(14)	O12*–Cu1–O1	110.02(6)
Cu1–O1	1.8948(15)	O12*–Cu1–N9	108.88(6)
Cu1–N9	1.9328(16)	O1–Cu1–O12	172.58(6)
Cu1–O12	1.9808(14)	O32–Cu1–N9	170.06(7)
Cu1–O32	1.9655(13)	O12–Cu1–O32	88.46(6)
C8–N9	1.290(3)	O32*–Cu2–N29	111.97(6)
Cu1···Cu2*	3.0662(3)	O12*–Cu2–N29	166.17(7)
Cu1···Cu2	3.1517(3)	O21–Cu2–N29	94.17(7)
Cu1···Cu1*	3.468(4)	O32*–Cu2–O21	101.46(6)
Cu2···Cu2*	3.384(5)	O21–Cu2–O32	178.39(6)
		N29–Cu2–O32	84.61(6)
Complex **2m**			
Cu3–O41	1.8744(19)	O41*–Cu3–O41	180
Cu3–N49	2.0057(19)	N49*–Cu3–N49	180
C48–N49	1.291(3)	O41*–Cu3–N49	88.57(8)
		O41–Cu3–N49	91.43(8)

[a]Symmetry codes: for **1** and **2c**, $-x + 3/2, y, -z + 3/2$; for **2m**, $-x + 1/2, y + 3/2, -z + 1$.

0.035 Å, toward the apical ligand, similar to that observed in other copper cubane complexes [7, 20, 22, 40]. The coordination spheres of the copper ions in **1** and **2c** are best described as a distorted square pyramid according to the Addison parameter τ values of 0.12–0.15. The parameter τ is defined as $\tau = (\alpha - \beta)/60$, $\alpha > \beta$, where α and β are the largest angles, with $\tau = 1$ for a regular trigonal bipyramid and $\tau = 0$ for a regular square pyramid [41].

The Cu–O and Cu–N bond lengths in the equatorial plane are 1.9055(11)–1.9732(11) and 1.9276(12)–1.9424(14) Å, respectively (table 1). The lengths of the bonds between the copper ions and the donor sites (O, N, O) of the tridentate ligands are within the range of values normally found for such systems [10, 42–44]. The apical oxygen show longer Cu–O (alkoxo) bond lengths than the equatorial oxygen, being in agreement with the literature values for similar compounds [16, 22, 40]. Elongation of the Cu–O axial bonds is due to a pseudo-Jahn–Teller distortion of the d^9 copper center.

The bridging bond angles of Cu–O(alkoxo)–Cu in **1** and **2c** are 86.2(3)–112.1(3)° and 86.2(3)–112.1(3)°, respectively (table 2), which are similar to other reported alkoxo-bridged cubane complexes [16, 22, 40]. It is evident from the different Cu–O body diagonal distances as well as from the unequal metal–metal distances (table 2) that the cubane core is not a regular one, but distorted.

Complexes **1** and **2c** are isomers. The geometry coordination around the copper(II) ion in **1** and **2c** is very similar with only small discrepancies among the corresponding bond

lengths and angles of the two cubane complexes. Although in both complexes the tridentate ligand has similar coordination, in **1**, the planes of phenol rings of the four Schiff base ligands are roughly parallel to each other, while in **2c**, there are two pairs of parallel ligand planes which are perpendicular to each other.

The crystal structure of **2** (figure 2) indicated two independent parts, namely, **2c**, which is a discrete tetranuclear $[Cu_4L_4]$ and **2m**, the mononuclear complex, $[Cu(L')_2]$. In the Schiff base ligand (L'^-), the $NCH_2C(CH_3)H(OH)$ part of original tridentate ligand (H_2L) has been lost and replaced by $NC_6H_2(CH_3)_3$. H_2L', after deprotonation of the enolic OH is bidentate, forming a six-membered chelate ring with the Cu(II) center. The coordination geometry around copper(II) ion in **2m** is four-coordinate square-planar. The structure of **2m** is very similar to complexes which were synthesized directly from reaction of copper(II) and bidentate Schiff base ligands [35, 44].

In **2**, the Cu–N(imino) and Cu–O(phenoxo) bond distances for the two crystallographically different copper(II) centers (**2m** and **2c**) are very similar. However, the bond length Cu–O(alkoxo) in tetranuclear **2c** is longer than the Cu–O(phenoxo) bond distances in both complexes (table 2). This could be due to the fact that in **2c**, the alkoxo-bridged interaction with copper ions are weaker than the terminal phenoxo interaction with the Cu centers. The four donors around Cu(II) in **2m** form a slightly distorted square-planar trans-$Cu(N_2O_2)$ geometry. Elongation of the displacement parameters of O, perpendicular to the plane, might suggest some packing disorder of units that are not precisely planar. The chelating N9–Cu3–O1 angle is 92.76(4)° and the non-chelating O1–Cu3–N9* angle is 87.24(4)°. The Cu3–O1 and Cu3–N9 bond lengths are 1.8309(9) and 1.9068(10) Å, respectively, in agreement with analogous square-planar Cu(II) complexes [10, 35, 44–47]. The pendant phenyl rings ($C_6H_2(CH_3)_3$) of the Schiff base ligands are on the opposite sides of the molecular plane.

3.3. *DNA binding studies*

3.3.1. Absorption spectral studies of CT-DNA with 1. UV–Visible spectroscopy experiments were performed to study the interaction of **1** and **2** with DNA keeping the complex concentration constant (25 μM) and varying the concentration of CT-DNA (0–80 μM). The change in absorbance at 260 nm was used to evaluate the intrinsic binding constant K_b. The absorption spectra of **1** in the presence of CT-DNA are shown in figure 4. From figure 4, it is clear that hyperchromicity (increase of absorbance) of the DNA occurs at 265 nm without a shift in the band position upon the addition of CT-DNA.

The copper(II) complexes can bind to double-stranded DNA in a range of binding modes on the basis of their structure, charge, and the type of ligands. Hypochromism (decrease of absorbance) indicates a strong interaction between complexes and CT-DNA mainly through groove binding [44]. Non-covalent intercalative binding of the complex to the DNA helix can lead to large hyperchromism due to the strong π–π stacking interaction between the aromatic moiety of the complex and the base pairs of DNA [48–52]. Complex **1** binds to DNA through intercalation and resulted in hyperchromism due to the strong π–π stacking interaction between the aromatic chromophore of the complex and the base pairs of DNA [52–54].

Analysis of the spectral data using equation (1) in the presence of DNA (figure 4) gave a binding constant, K_b, of $(4.50 \pm 0.26) \times 10^3$ M^{-1} for **1**. The K_b values are lower than that observed for the classical intercalator ethidium bromide, EB (~10^6 M^{-1} [55]), $[CuL1](ClO_4)_2$

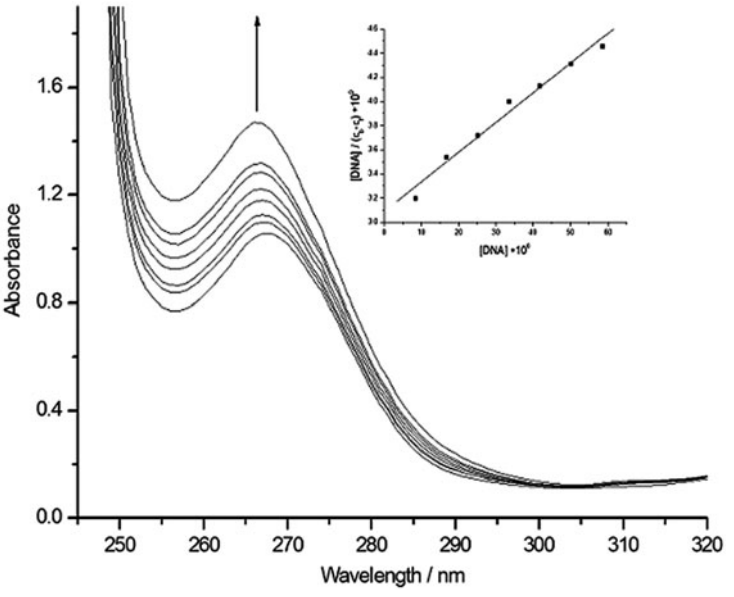


Figure 4. Absorption spectra of **1** (25 μM) in Tris–HCl buffer (pH 7.2) with increase in the molar ratio of DNA to complex (0–80 μM). Arrow shows the absorbance changing upon the increase of DNA concentration. The inset shows plot of $[DNA]/(\varepsilon_a - \varepsilon_f)$ vs. [DNA] for titration of CT-DNA with the complex.

$(2.6 \times 10^4\ M^{-1}$ [56], L1 = *N*,*N*′-bis-pyridin-2-ylmethyl-butane-1,4-diimine), and $[Cu(bpy)_2(pic)](pic)$ $(2.6 \times 10^4\ M^{-1}$ [57], pic = picrate), indicating that the complexes bind DNA with less affinity. However, the K_b value for **1** is comparable to that observed for other copper(II) complexes such as $[CuL_2]$ $(1.55 \times 10^3\ M^{-1}$ [58], HL = N-(3-hydroxybenzyl)-leucine acid), $[Cu(bpy)(Gly)Cl]\cdot 2H_2O$, $1.84 \times 10^3\ M^{-1}$, $[Cu(dpa)(Gly)Cl]\cdot 2H_2O$, $3.10 \times 10^3\ M^{-1}$ [59], [Cu(L)(bpy)Cl] (HL = (E)-3-(2-hydroxyphenylimino)-N-*o*-tolylbutanamide), $1.55 \times 10^3\ M^{-1}$ [60] $[Cu2(\mu\text{-}Cl)_2(O\text{-}2\text{-}alkoxyethylpyridine\text{-}2\text{-}carboximidate)_2Cl_2]$, where alkoxy = methoxy, ethoxy, and butoxy, 1.52×10^3, 5.59×10^3, and $6.36 \times 10^3\ M^{-1}$, respectively [61].

From the binding constant value, it is clear that **1** had moderate interaction with CT-DNA. However, in the absence or presence of an oxidizing agent, **1** exhibited no nuclease activity.

4. Conclusion

We have synthesized two tetranuclear copper(II) cubane complexes. The complexes were structurally characterized using single crystal X-ray crystallography. The complexes had cubane Cu_4O_4 core in which copper and oxygen were present at alternating vertices. Coordination geometry about each copper ion was essentially square pyramidal. In **2**, there was a discrete mononuclear complex in addition to Cu_4L_4 cubane. The coordination geometry around copper(II) in mononuclear **2m** was square planar. Complex **1** bound to DNA through intercalation and resulted in hypochromism due to the stacking interaction between the aromatic chromophore of the complex and the base pairs of DNA.

Supplementary material

The deposition numbers of the studied complexes, **1** and **2**, are CCDC 976217 and 976218, respectively. These data can be obtained free-of-charge via www.ccdc.cam.ac.uk/data_request/cif, by emailing data-request@ccdc.cam.ac.uk, or by contacting the Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge CB2 1EZ, UK; Fax: +44 1223 336033.

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Disclosure statement

No potential conflict of interest was reported by the authors.

Supplemental data

Supplemental data for this article can be accessed here [http://dx.doi.org/10.1080/00958972.2015.1048688].

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