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Supramolecular Assemblies with Calix[6]arenes and Copper Ions: from Dinuclear to Trinuclear Linear Arrangements of Hydroxo–Cu(II) Complexes

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Complexation of copper(II) by calix[6]arene-based ligands bearing either two or three *N*-benzylimidazole coordinating arms under basic conditions has been studied. Whereas the tris(imidazole) derivative stabilizes dicationic 5-coordinate aqua complexes in a mononuclear state with an intracavity bound guest, in the presence of hydroxide ions, the latter undergo dimerization. An X-ray structure revealed decoordination of one imidazole arm and formation of a bis(hydroxo) bridged Cu(II) core with a square-planar geometry for both metal centers sandwiched by two empty calixarene cavities. Upon methanolysis, the dinuclear complex underwent an unexpected rearrangement leading to the clean formation of a trinuclear complex. X-ray diffraction analyses of this novel species revealed a trinuclear core constructed around a central Cu(II) ion that is doubly bridged through either methoxide or hydroxide anions to two Cu(II) ions hold by two calixarene units. The same complex could be directly synthesized by reacting the ligand with copper(II) perchlorate in a 2:3 ratio in the presence of base. In solution, the tetrahydroxo Cu_3 complex was characterized by UV–vis and ^1H NMR spectroscopies and displayed an electron paramagnetic resonance (EPR) signal only below 100 K that accounts for a $S = {}^1/_2$ fundamental state. Formation of the same di- and trinuclear species was observed with a calix[6]arene-based bis(imidazole) ligand, which demonstrates the generality of the reaction schemes. All these results emphasize the versatility of the calix[6]arene scaffold for the stabilization of metal complexes with various nuclearities.

Introduction

With the aim of developing a supramolecular system that mimics the hydrophobic environment at the copper site of enzymes,[1−3] we have studied the coordination chemistry of copper(I) and copper(II) with a tris(imidazole) ligand that has been built on a calix[6]arene scaffold at the level of its small rim. Complexation of Cu(I) and Cu(II) by this N_3 ligand under neutral conditions, that is, in the absence of a base, led to the formation of mono- and dicationic species, respectively. On one hand, the Cu(I) complex behaved as a receptor for small neutral coordinating molecules such as CO and nitriles, leading to tetrahedral species.[4] On the other

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(1) Review of bioinorganic enzymology: *Chem. Rev.* **1996**, *96*, 2237−3042.

(2) (a) Kaim, W.; Rall, J. *Angew. Chem., Int. Ed.* **1996**, *35*, 43−60. (b) Solomon, E. I.; Chen, P.; Metz, M.; Lee, S.-K.; Palmer, A. E. *Angew. Chem., Int. Ed.* **2001**, *40*, 4570−4590.

(3) For recent reviews on Cu-enzyme modeling, see (a) Hatcher, L. Q.; Karlin, K. D. *J. Biol. Inorg. Chem.* **2004**, *9*, 669−683. (b) Lewis, E. A.; Tolman, W. B. *Chem. Rev.* **2004**, *104*, 1047−1076. (c) Mirica, L. M.; Ottenwaelder, X.; Stack, T. D. P. *Chem. Rev.* **2004**, *104*, 1013−1045.

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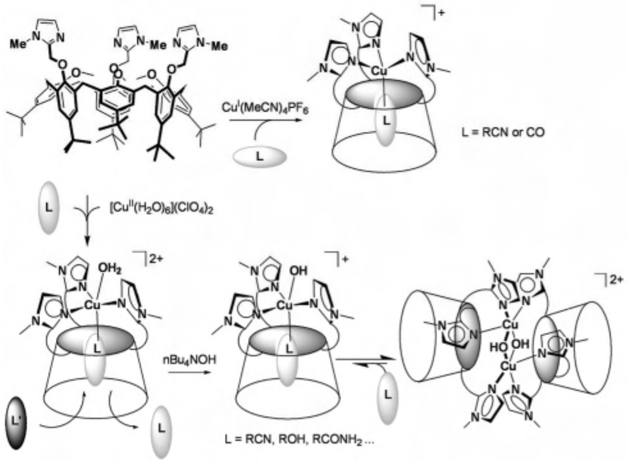
Scheme 1. Cu(I) and Cu(II) Coordination by the Tridentate *N*-Methylimidadole-Based Calix[6]ligand



hand, the dicationic Cu(II) complex was 5-coordinate with the selective endo binding of a small organic ligand (such as a nitrile, an alcohol, or an amide) and a capping water molecule as a fifth donor[5] (Scheme 1). Wanting to synthesize a basic derivative of this Cu(II) complex, we discovered that deprotonation of this capping water ligand leads to an equilibrated mixture of mononuclear and dinuclear hydroxo complexes. The X-ray structure of the latter revealed the self-inclusion of one imidazole arm into the hydrophobic calixarene cavity, allowing each copper ion to remain 5-coordinate in a square-based pyramidal environment.[6]

To preclude this self-inclusion process, we designed calix[6] ligands that present N-benzylimidazole arms in place of the N-methyl ones and explored the consequences such a small modification in the ligand design could have on the Cu(II) coordination chemistry. In this paper, we describe the synthesis and coordination behavior of two novel ligands, one N_2, the other N_3, with Cu(II) under basic conditions. Surprisingly, the ligands behaved similarly, leading to dinuclear hydroxo complexes that could be converted under specific conditions into interesting and novel trinuclear species that proved to be quite stable in the specific environment provided by the *N*-benzylimidazole−calix[6]arene systems.

Experimental Section

All solvents and reagents were obtained commercially. Tetrahydrofuran (THF) was distilled from sodium/benzophenone under argon, and acetonitrile was distilled from calcium hydride under argon. IR spectra were recorded with a Perkin-Elmer Spectrum One spectrometer. Elemental analysis was performed at the Institut des Substances Naturelles, Gif sur Yvette, France. ^{1}H NMR spectra were recorded on a Bruker ARX 250 spectrometer. Electron paramagnetic resonance (EPR) spectra were recorded using a Bruker Elexys spectrometer (X-band). Fitting of the EPR spectra was performed with Xepr & Xsophe suite (Bruker). The UV−vis spectra were recorded on a Jasco V-570 spectrophotometer.

Safety Note: Caution! Although we have not encountered any problems, it is noted that perchlorate salts of metal complexes with organic ligands are potentially explosive and should be handled only in small quantities with appropriate precautions.

5,11,17,23,29,35-Hexa-*tert*-butyl-37,39,41-trimethoxy-38,40,-42-tris[(1-benzyl-2-imidazolyl)methoxy]calix[6]arene (2). Under an argon atmosphere, a solution of $X_6Me_3H_3$ (5,11,17,23,29,35-hexa-*tert*-butyl-37,39,41-trimethoxycalix[6]arene-38,40,42-triol) (400 mg, 0.394 mmol) in a dry THF/*N*,*N*-dimtheylformamide (DMF) (7:1) mixture (16 mL) was introduced into a flask containing NaH (60% in oil, washed with pentane; 460 mg, 11.5 mmol). The mixture was stirred for 20 min at room temperature, and 2-chloromethyl-1-benzylimidazole hydrochloride[7] (560 mg, 2.3 mmol) was slowly added. After the solution was refluxed (90 °C) for 3 days, water was poured into the solution. The product was extracted with CH_2Cl_2. The organic layer was washed twice with water, dried with Na_2SO_4, and finally dried under vacuum. The crude product was recrystallized in a CH_2Cl_2/MeCN mixture to give **2** as a white powder (405.6 mg, 68%): mp >260 °C. NMR ^{1}H (250 MHz, $CDCl_3$) $\delta = 0.74$ (s, 27H, *t*Bu), 1.35 (s, 27H, *t*Bu), 2.05 (s, 9H, OCH_3), 3.18 (d, $J = 15$ Hz, 6H, Ar-αCH_{eq}), 4.45 (d, $J = 15$ Hz, 6H, Ar-αCH_{ax}), 4.98 (s, 6H, OCH_2), 5.41 (s, 6H, CH_2Bn), 6.58 (s, 6H, ArH), 6.91 (s, 3H, ImH), 7.02 (s, 3H, ImH), 7.20 (s, 6H, ArH), 7.16−7.32 (m, 15H, BnH). Anal. Calcd for $C_{102}H_{120}N_6O_6{\cdot}H_2O$: C, 79.34; H, 7.96; N, 5.44. Found: C, 79.24; H, 8.04; N, 5.14.

5,11,17,23,29,35-Hexa-*tert*-butyl-37,38,39,41-tetramethoxy-40,42-bis[(1-benzyl-2-imidazolyl)methoxy]calix[6]arene (2′). Under an argon atmosphere, a solution of $X_6Me_4H_2$ (5,11,17,23,29,35-hexa-*tert*-butyl-37,38,39,41-tetramethoxycalix[6]arene-40,42-diol)[8] (192 mg; 0.186 mmol) in a dry THF/DMF (7:1) mixture (8 mL) was introduced into a flask containing NaH (60% in oil, washed with pentane (150 mg, 3.75 mmol). The mixture was stirred for 20 min at room temperature, and 2-chloromethyl-1-benzylimidazole hydrochloride (183 mg, 0.750 mmol) was slowly added. After the solution was refluxed (90 °C) for 2 days, water was poured into the solution. The product was extracted with CH_2Cl_2. The organic layer was washed twice with water, dried with Na_2SO_4, and finally dried under vacuum. The crude product was purified by column chromatography (silica gel, CH_2Cl_2/MeOH mixture, 96:4) and dissolved in CH_3CN. After one night in the freezer, the precipitate was filtered and dried under vacuum to give **2′** (185 mg, 71%): mp >260 °C. NMR ^{1}H (250 MHz, $CDCl_3$) $\delta = 0.85$ (s, 18H, *t*Bu), 0.90 (s, 9H, *t*Bu), 1;35 (s, 18H, *t*Bu), 1.41 (s, 9H, *t*Bu), 2.05 (s, 3H, OMe), 2.41 (s, 6H, OMe), 3.25 (d, $J = 15$ Hz, 2H, Ar-αCH_{eq}), 3.25 (d, $J = 16$ Hz, 2H, Ar-αCH_{eq}), 3.32 (d, $J = 16$ Hz, 2H, Ar-αCH_{eq}), 3.56 (s, 3H, OMe), 3.59 (d, $J = 16$ Hz, 2H, Ar-αCH_{eq}), 4.40 (d, $J = 16$ Hz, 2H, Ar-αCH_{ax}), 4.43 (d, $J = 15$ Hz, 2H, Ar-αCH_{ax}), 4.49 (d, $J = 16$ Hz, 2H, Ar-αCH_{ax}), 5.04 (s, 4H, OCH_2), 5.46 (s, 4H, CH_2Bn), 6.67 (s, 2H, ArH), 6.74 (s, 4H, ArH), 6.96 (d, $J = 1$ Hz, 2H, ImH), 7.08 (d, $J = 1$ Hz, 2H, ImH), 7.20−7.33 (m, 16 H, BnH/ArH). Anal. Calcd for $C_{92}H_{112}N_4O_6{\cdot}2H_2O$: C, 78.59; H, 8.32; N, 3.99. Found: C, 78.69; H, 8.62; N, 3.55.

$[Cu(2)(H_2O)_2](ClO_4)_2$ (3). To a solution of **2** (55.0 mg, 36 μmol) in THF (0.5 mL) under an inert atmosphere was added a

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(4) Blanchard, S.; Le Clainche, L.; Rager, M.-N.; Chansou, B.; Tuchagues, J.-P.; Duprat, A. F.; Le Mest, Y.; Reinaud, O. *Angew. Chem., Int. Ed.* **1998**, *37*, 2732−2735. Rondelez, Y.; Sénèque, O.; Rager, M.-N.; Duprat, A. F.; Reinaud, O. *Chem. Eur. J.* **2000**, *6*, 4218−4226.

(5) (a) Le Clainche, L.; Giorgi, M.; Reinaud, O. *Inorg. Chem.* **2000**, *39*, 3436−3437. (b) Le Clainche, L.; Rondelez, Y.; Sénèque, O.; Blanchard, S.; Campion, M.; Giorgi, M.; Duprat, A. F.; Le Mest, Y.; Reinaud, O. *C. R. Acad. Sci., Sér. IIc* **2000**, *3*, 811−819.

(6) Izzet, G.; Frapart, Y.-M., Prangé, T.; Provost, K.; Michalowicz, A.; Reinaud, O. *Inorg. Chem.* **2005**, *44*, 9743−9751.

(7) Birker, P. J. M. W. L.; Godefroi, E. F.; Helder, J.; Reedijk, J. *J. Am. Chem. Soc.* **1982**, *104*, 7556−7560.

(8) Otsuka, H.; Araki, K.; Shinkai, S. *J. Org. Chem.* **1994**, *59*, 1542−1547.

stoichiometric amount of $Cu(ClO_4)_2(H_2O)_6$ (36 μmol) dissolved in THF (0.5 mL). The mixture was stirred for 20 min. Acetonitrile (1 mL) was then added to the blue solution, which became green. The solution was concentrated to 1 mL and filtered on Celite, and the solvents were removed under vacuum. The solid was redissolved in THF (0.5 mL) and precipitated with pentane (4 mL). The resulting light-green powder was dried under vacuum. (57 mg, 87%): mp 205 °C (decomp). IR (KBr, cm^{-1}) 2961, 2905, 2869, 1482, 1457, 1363, 1293, 1184, 1108, 1004, 876, 714, 623 (ClO_4). Anal. Calcd for $C_{102}H_{124}Cl_2CuN_6O_{16}{\cdot}3H_2O$: C, 65.84; H, 6.93; N, 4.52, Found: C, 65.57; H, 6.67; N, 4.51.

$[Cu(2)(OH)]_2(ClO_4)_2$ (4). Under argon, dry THF (3 mL) containing $Cu(ClO_4)_2(H_2O)_6$ (8.5 mg, 22.9 μmol) was added to **2** (35.0 mg, 22.9 μmol). The cobalt blue-green solution was stirred for 20 min. A stoichiometric amount of NBu_4OH was then added to the reaction mixture via a 0.1 M solution in THF/MeOH 9:1 (v/v) (230 μL, 23.0 μmol), and the solution was stirred for 20 min. Pentane (3 mL) was then added to the solution, which became cloudy. The mixture was quickly centrifuged, and after removal of the precipitates, the solution was evaporated under reduce pressure to give a pale purple powder that was finally washed with pentane and dried under vacuum (33 mg, 82%). IR (KBr, cm^{-1}) 2960, 2906, 2868, 1482, 1456, 1362, 1289, 1184, 1104, 1001, 875, 623 (ClO_4); in CH_2Cl_2 solution, $\nu_{OH} = 3658$ and 3597 cm^{-1}. Anal. Calcd for $[Cu(C_{102}H_{120}N_6O_6)(OH)]_2(ClO_4)_2{\cdot}3H_2O$: C, 70.69; H, 7.21; N, 4.85. Found: C, 70.41; H, 7.21; N, 4.38.

$[Cu_3(2)_2(OMe(H))_4](ClO_4)_2$ (5). Purple complex **4** (33 mg, 9.6 μmol) was dissolved in methanol. A green solid precipitated out of the solution within a few minutes. It was collected by centrifugation, washed twice with methanol, and dried overnight under vacuum. This green solid (**5a**) turned blue after being exposed to air for 1 week to provide **5b** (20 mg, 3.8 μmol, 59% based on Cu). Compound **5** could be also obtained through the reaction of dicationic complex **3** with Et_3N (3 equiv vs Cu) in $MeOH{:}CH_2Cl_2$ 9:1 (v/v). After 2 days of stirring, the green precipitate was collected (**5a**; 62% vs Cu) and dried in the air to provide **5b**. Compound **5** could also be synthesized directly from **2**: under argon, dry THF (1 mL) containing $Cu(ClO_4)_2(H_2O)_6$ (11.25 mg, 29 μmol) was added to **2** (30 mg, 19 μmol). The blue solution was stirred for 20 min, Et_3N (39 mM solution, 100 μL, 39 μmol) was added to the reaction mixture, the dark green solution was stirred for 30 min, and the solvent was reduced to half the volume. MeOH (5 mL) was then added to the solution and a green solid precipitated within a few minutes. It was collected by centrifugation, washed twice with methanol, and dried overnight under vacuum (20 mg, 60% vs Cu). This green solid (**5a**) turned blue after being exposed to air for 1 week to quantitatively provide **5b**. The transformation of **5a** into **5b** was monitored by UV−vis spectroscopy (see Figure 2). Reacting **5a** with water in solution to provide **5b** was not as efficient as the slow solid-state exchange since it led to partial decomposition of the trinuclear core. The purity of the samples was also checked by ^{1}H NMR spectroscopy: when it contained dinuclear species, four resonances instead of two in the high-field region were observable and quantifiable (compare Figures 2 and 4). When the sample contained organic impurities, other resonances in the aromatic and *t*Bu region were observed. When it contained ill-defined Cu(II) complexes, it was extremely broad, due to the paramagnetism of Cu(II) and/or fast exchange processes. Single crystals of **5a** were obtained upon slow diffusion of MeOH into a CH_2Cl_2/MeCN solution of freshly prepared **5a**. Single crystals of **5b** were obtained upon slow diffusion of pentane into a CH_2Cl_2/PhCN solution of **5b**. Spectroscopic data of the products isolated after synthesis were identical to those recorded on the collected single crystals (UV−vis, EPR, and NMR; see Figures 2 and 4). Mp 220 °C (decomp). IR (KBr, cm^{-1}): 2961, 2905, 2868, 1482, 1456, 1362, 1289, 1185, 1104, 1008, 876, 712, 623 (ClO_4); in CH_2Cl_2 solution, $\nu_{OH} = 3654$ cm^{-1}. Anal. Calcd for $[Cu_3(C_{102}H_{120}N_6O_6)_2(OH)_4](ClO_4)_2{\cdot}5H_2O$: C, 68.08; H, 7.11; N, 4.67. Found: C, 68.10; H, 7.02; N, 4.58.

$[Cu(2')(OH)]_2(ClO_4)_2$ (4′). Starting from complex **2′** (30 mg, 21 μmol) and following the procedure described above for **4**, complex **4′** was obtained as a pale purple powder (24 mg, 55%): mp 235 °C (decomp). IR (KBr, cm^{-1}) 2957, 2927, 2867, 1482, 1461, 1362, 1290, 1203, 1185, 1107, 1003, 875, 716, 623 (ClO_4). Anal. Calcd for $[Cu(C_{92}H_{112}N_4O_6)(OH)]_2(ClO_4)_2{\cdot}3H_2O$: C, 70.07; H, 7.25’ N, 3.55. Found: C, 69.89; H, 7.25; N, 3.43.

$[Cu_3(2')_2(OMe(H))_4](ClO_4)_2$ (5′). The procedure was the same as the one described for **5**. Starting from 24 mg (7.7 μmol) of complex **4′**, complex **5′** was isolated as a green solid that turned blue after being exposed to air for 1 week, hence providing **5b′** (12 mg, 3.7 μmol; 72% vs Cu). The transformation of **5a′** into **5b′** was monitored by UV−vis spectroscopy (see Figure 2). Mp 255 °C (decomp). IR (KBr, cm^{-1}) 2961, 2905, 2868, 1482, 1462, 1292, 1201, 1184, 1107, 1010, 875, 712, 623 (ClO_4). Anal. Calcd for $[Cu_3(C_{92}H_{112}N_4O_6)_2(OH)_4](ClO_4)_2{\cdot}2CH_2Cl_2$: C, 64.62; H, 7.06; N, 3.24. Found: C, 64.81; H, 6.86; N, 3.25.

X-ray Studies: (A) $[Cu(2)(OH)]_2(ClO_4)_2$ (4). Data recordings were made at the synchrotron DCI facility in Orsay (France). Crystals were found to be unstable in air; they were rapidly fished out from their mother liquor with a cryoloop, mounted on the goniometer head of the diffraction device (MAR Research 345 Image Plate), and frozen under a cold nitrogen stream. Data sets consist of 100 frames, 3° rotation each (exposure time 6 s/frame). Frames were processed with the DENZO/HKL package.[10] The structure was solved by use of the SnB[11] program. Refinements were processed first with SHELXL and then with SHELXH[12] programs. Constraints on 1,2- and 1,3-bond distances were applied throughout the refinement cycles as well as flat ring constraints for the benzene and imidazole rings. Hydrogen atoms were introduced in calculated positions with their isotropic thermal factor riding on that of the bonded atom. In addition to the two perchlorate counterions, a molecule of pentane was observed. Four additional individual peaks located at H-bond distances were interpreted as putative water molecules.

(B) $[Cu_3(2)(OMe(H))_4](ClO_4)_2$ (5a) and $[Cu_3(2)(OH)_4](ClO_4)_2$ (5b). Diffraction data were measured on a Bruker-Nonius KappaCCD diffractometer.[13] Crystals were unstable in air and were rapidly fished out from their mother liquor with a cryoloop and frozen under a cold nitrogen stream. Data sets consist of 645 ($\Phi + \Omega$) frames, 1° rotation each (exposure time 60 s/frame) and 200 frames for **5a** and 1° rotation each (exposure time 30 s/frame) for **5b**. Frames were processed with the DENZO/HKL package. The structures were solved by direct methods and refined with SHELXL.[12] Hydrogen atoms (experimentally found or theoretically positioned) were introduced in the calculation with their isotropic thermal factors riding on that of the bonded atom but not refined.

Complex **5a** cocrystallized with two methanol solvent molecules of occupancy 0.5 and a disordered water molecule split on four partially occupied sites. Some *t*Bu were also split on two distinct sites with equal occupancies because of static disorders. Finally,

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(9) Le Clainche, L. Ph.D. Thesis, Paris VI University, 2000.

(10) Otwinowsky, Z.; Minor, W. *Methods Enzymol.* **1997**, *276*, 307−326.

(11) Miller, R.; Gallo, S. M.; Khalak, H. G.; Weeks, C. M. *J. Appl. Crystallogr.* **1994**, *27*, 613−621.

(12) Sheldrick, G. M. SHELXL97. Program for the refinement of crystal structures, University of Göttingen: Göttingen, Germany, 1997.

(13) Bruker-Nonius. Kappa CCD Reference Manual; Nonius B. V., P.O. Box 811, 2600 Av., Delft, The Netherlands, 1998.

Table 1. Comparison of EPR Parameters and UV−Vis Data of Dicationic Cu(II) Complexes[a]

cosolvent (20% v/v)	**3**[b]				corresponding N-methyl derivative[c]			
	$A_{\|\|}$, 10^{-4} cm^{-1}	$g_{\|\|}$	$g_{\perp}$	λ_{max}, nm (ϵ, mol^{-1}·L·cm^{-1})	$A_{\|\|}$, 10^{-4} cm^{-1}	$g_{\|\|}$	$g_{\perp}$	λ_{max}, nm (ϵ, mol^{-1}·L·cm^{-1})
	143	2.328	2.071	717 (74)	162	2.29	2.07	644 (38)
MeCN	140	2.312	2.065	745 (98)	135	2.31	2.07	758 (34)
EtOH	136	2.300	2.063	698 (45)	146	2.30	2.06	685 (32)
DMF	137	2.325	2.062	749 (80)	140	2.31	2.07	749 (43)
acetamide[d]	136	2.320	2.059	672 (45)	145	2.31	2.07	688 (52)
solid	146	2.307	2.053		162	2.28	2.07	

[a] EPR parameters, obtained at X band, 9.4 GHz, 100 K; UV−vis data, obtained in CH_2Cl_2; dicationic Cu(II) complexes: based on *N*-methyl (see Figure 1) and *N*-benzyl calix[6]tris-imidazole ligands. [b] Values obtained after simulation of the spectra. [c] See ref 5a and 9. [d] Ca. 10 molar equiv.

Table 2. Data Processing and Refinement Statistics for **4**, **5a**, and **5b**

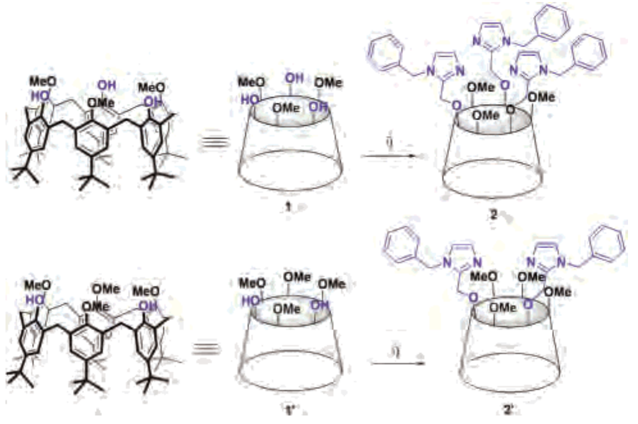
compound	**4**	**5a**	**5b**
formula (asymmetric unit)	$C_{105.5}H_{126}Cl_1Cu_1N_6O_{12}$	$C_{104.5}H_{129.5}Cl_1Cu_{1.5}N_{62}O_{14.5}$	$C_{111}H_{129}Cl_7Cu_{1.5}N_7O_{13}$
mol wt	1769.19	1832.4	2112.78
space group	triclinic; $P\bar{1}$ ($Z = 2$)	triclinic; $P\bar{1}$ ($Z = 2$)	triclinic; $P\bar{1}$ ($Z = 2$)
params			
a (Å)	17.341(2)	15.346(3)	17.170(2)
b (Å)	23.216(2)	16.798(3)	18.771(2)
c (Å)	30.088(2)	22.227(6)	21.888(3)
α (deg)	68.94(8)	87.283(9)	106.777(5)
β (deg)	86.57(9)	83.533(9)	92.097(5)
γ (deg)	77.22(8)	76.486(9)	108.334(9)
vol (Å^3)	11021	5534.3	6348.04
temp (K)	110	193	223
no. of reflns measd	55 260	112 146	44 206
resolution limits (Å)	20−1.07	22.13−0.79	20.77−0.84
completeness (%)	90.2	95.6	91.2
R_{sym} (%) overall	6.5	6.6	5
no. of independent reflns	18 487	22 831	20 492
no. of obsd reflns[a]	14 548	18 333	15 692
R factor (obsd *F* data)	0.0702	0.1021	0.1016
R factor (all *F* data)	0.0787	0.1231	0.1252
R factor (obsd F^2 data)	0.2263	0.2678	0.2855
no of params	2262	1178	1397
min/max (e$^-$) in last electron density	−0.29/+0.45	−0.77/+0.9	−0.55/+1.15
CCDC deposit no.	262287	268478	268477

[a] Criteria for observation: $F \geq 2\sigma(F)$.

one of the two linking bridges between the copper atoms was found to be a mixture of hydroxide and methoxide anions that were assigned occupancy factors equal to 0.5 each.

Complex **5b** cocrystallized with a disordered water molecule and four $CHCl_3$, two of them being disordered and split on several sites. The ClO_4 counterion was also split on several sites because of static disorder. The H-atoms of the bridging hydroxides were found experimentally through a last Fourier difference before the last refinements. Final statistics for **4**, **5a**, and **5b** are given in Table 2.

Scheme 2. Syntheses of Bi- and Tridentate Calix[6]ligands **2** and **2′** [a]



[a] (i) 2-chloromethyl-1-benzyl-1*H*-imidazole hydrochloride, NaH, THF/DMF.

From Mononuclear to Dinuclear Cu(II) Complexes

The tris- and bis(N-benzylimidazole)-based ligands (named **2** and **2′**, respectively) were synthesized from the tris- and tetramethylated calix[6]arene derivatives (**1** and **1′**; Scheme 2) by reaction of the free phenol functions with *N*-benzyl-2-chloromethylimidazole in the presence of excess NaH.

Reaction of N_3 ligand **2** with 1 equiv of copper(II) perchlorate led to the formation of the corresponding aqua complex **3**. EPR and UV−vis spectroscopies indicate that complex **3** is sensitive to the presence of small coordinating molecules but not large ones. According to these EPR and UV−vis features (Table 1), which are very similar to those reported for the closely related N-methyl derivative,[5] this complex can then be described as a 5-coordinate mononuclear species $[Cu(\mathbf{2})(L)(OH_2)]^{2+}$ that behaves as a selective molecular receptor for small neutral ligands L with a capping water ligand, as illustrated in Scheme 1 with the N-methyl ligand. Reaction of aqua complex **3** with 1 equiv of NBu_4-OH in a THF/MeOH (99:1 v/v) mixture yielded a new green species that turned to purple upon the addition of a nonpolar solvent such as pentane.

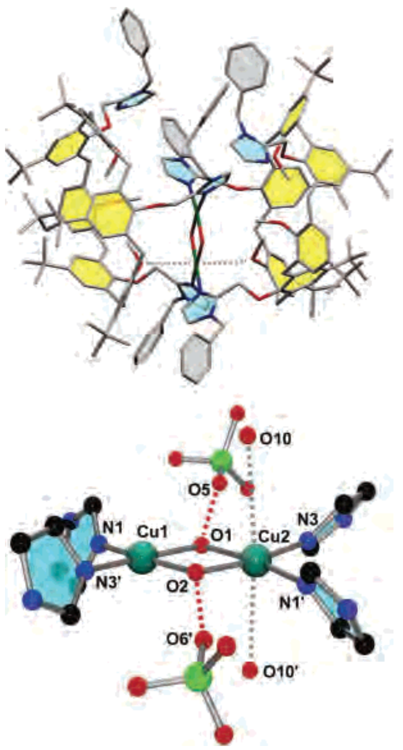


Figure 1. Top: crystal structure of dinuclear hydroxo-complex **4**. Hydrogen atoms, perchlorate counterions, and solvent of crystallization have been omitted for clarity. Bottom: view of the copper centers.

Table 3. Selected Interatomic Distances and Angles for Complex **4**

distance (Å)		angle (deg)	
Cu1−O1	1.900(4)	O1−Cu1−O2	77.31(16)
Cu1−O2	1.932(4)	O1−Cu1−N3′	170.73(15)
Cu1−N3′	1.970(5)	O1−Cu1−N1	93.87(18)
Cu1−N1	1.980(5)	O2−Cu1−N3′	93.71(17)
Cu1···Cu2	3.002(2)	O2−Cu1−N1	170.89(16)
O1···O2	2.394(9)	N3−Cu1−N1	95.19(19)
O1···O5	2.899(9)	Cu1−O1−Cu2	103.35(18)
Cu2−O1	1.927(3)	O1−Cu2−O2	76.96(16)
Cu2−O2	1.921(4)	O1−Cu2−N1′	93.72(19)
Cu2−N1′	1.977(5)	O1−Cu2−N3	170.98(15)
Cu2−N3	1.984(5)	O2−Cu2−N1′	170.14(17)
Cu2−O10	3.109(4)	O2−Cu2−N3	95.22(18)
Cu2−O10′	3.220(4)	N4−Cu2−N3	94.30(2)
O2−O6′	2.831(5)	Cu1−O2−Cu2	102.36(18)

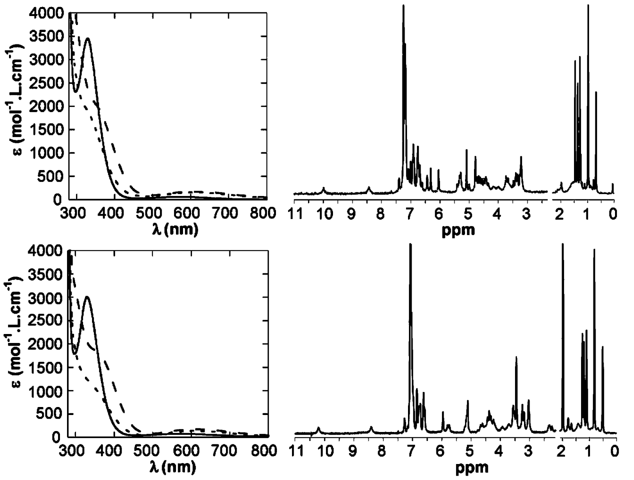


Figure 2. Left: UV−vis spectra (CH_2Cl_2) of the di- and tri-nuclear hydroxo Cu(II) complexes. Solid line, complexes **4** (top) and **4′** (bottom); dashed lines, complexes **5** (top) and **5′** (bottom) before (short dashes) and after (long dashes) addition of MeOH (5% v/v). Right: ^{1}H NMR (300 K, $CDCl_3$) spectra of dinuclear complexes **4** (top) and **4′** (bottom) based on the calix[6]ligands. The intensity of the spectra in the 0−2 ppm area has been divided by a factor of 3. The two imidazole resonances are 8.42, 9.98 for **4** and 8.41, 10.19 for **4′**.

X-ray Diffraction Analysis of a ($Cu^{II}OH)_2$ Complex. Single crystals of cupric complex **4** were grown out of this purple solution. The molecular structure (Figure 1and Table 3) shows a classical[14] dinuclear bis(μ-hydroxo) complex with two Cu(II) ions in a square-planar geometry at a distance $d(Cu1 \cdots Cu2) = 3.00$ Å. The Cu_2O_2 core is located between two calix[6] ligands that are stacked head to head in a cone conformation. Each copper is coordinated by two imidazole arms belonging to two different calixarene units [$d(Cu-N)_{avg} = 1.98$ Å] and by two bridging hydroxides [$d(Cu-O)_{avg} = 1.92$ Å]. As a result, one benzylimidazole arm of each calixarene unit does not coordinate the copper center and is projected away from the calixarene cavity, forming a hydrophobic microenvironment around the metal centers. In contrast, two out of the three methoxy groups of each calixarene point toward the center of the macrocycle in order to fill the cavity. On each side of the metal core, the oxygen atom of one of these methoxy groups is in weak axial interaction with Cu2 [$d(Cu2 \cdots O5)$ and $d(Cu2 \cdots O6) = 3.11$ and 3.21 Å, respectively]. Finally, each perchlorate anion points toward a hydroxo ligand at a hydrogen-bond distance [$d(O \cdots O) = 2.83$ and 2.90 Å].

Spectroscopic Characterization of the Dinuclear Hydroxo−Cu(II) Complexes. The UV−vis spectrum of hydroxo−Cu(II) complex **4** in THF (Figure 2) presented a weak absorption at 575 nm ($\epsilon = 70$ $M^{-1} \cdot cm^{-1}$) corresponding to a d−d transition. This value is characteristic of a copper ion in a tetragonal geometry.[15] It also displayed an intense absorption at 328 nm ($\epsilon = 3500$ $M^{-1} \cdot cm^{-1}$) assignable to a charge-transfer transition $OH \rightarrow Cu^{II}$. Whereas this dinuclear complex was EPR-silent even in a coordinating solvent such as MeCN, it presented a sharp ^{1}H NMR spectrum in $CDCl_3$ (Figure 2) with most resonances in the diamagnetic region. Such behavior is characteristic of a strong antiferromagnetic coupling between the two copper centers as classically observed for bis(hydroxo) bridged Cu(II) complexes. When the bidentate ligand **2′** was used to coordinate Cu(II) in place of the tridentate ligand **2**, the same species was obtained under the same experimental conditions: the reaction of **2′** with 1 equiv of copper(II) perchlorate and subsequent

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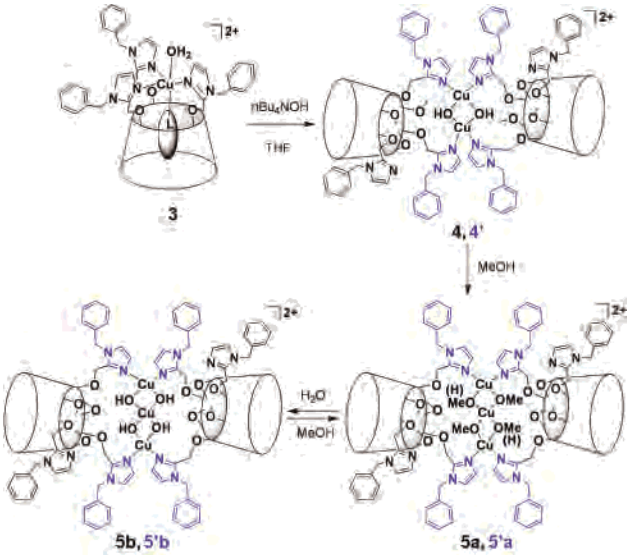
(14) (a) Kitajima, N.; Koda, T.; Hashimoto, S.; Kitagawa, T.; Moro-oka, Y. *J. Am. Chem. Soc.* **1991**, *113*, 5664−5671. (b) Kitajima, N.; Fujisawa, K.; Fujimoto, C.; Moro-oka, Y.; Hashimoto, S.; Kitagawa, T.; Toriumi, K.; Tatsumi, K.; Nakamura, A. *J. Am. Chem. Soc.* **1992**, *114*, 1277−1291. (c) Spencer, D. J. E.; Reynolds, A. M.; Holland, P. L.; Jazdzewski, B. A.; Duboc-Toia, C.; Le Pape, L.; Yokota, S.; Tachi, Y.; Itoh, S.; Tolman, W. B. *Inorg. Chem.* **2002**, *41*, 6307−6321. (d) Lam, B. M. T.; Halfen, J. A.; Young, V. G., Jr.; Hagadorn, J. R.; Holland, P. L.; Lledós, A.; Cucurull-Sánchez, L.; Novoa, J. J.; Alvarez, S.; Tolman, W. B. *Inorg. Chem.* **2000**, *39*, 4059−4072. (e) Mukherjee, J.; Mukherjee, R. *Inorg. Chim. Acta* **2002**, *337*, 429−438. (f) Zhang, C. X.; Liang, H.-C.; Kim, E.-I.; Shearer, J.; Helton, M. E.; Kim, E.; Kaderli, S.; Incarvito, C. D.; Zuberbühler, A. D.; Rheingold, A. L.; Karlin, K. D. *J. Am. Chem. Soc.* **2003**, *125*, 634−635.

(15) Hathaway, B. J.; Billing, D. E. *Coord. Chem. Rev.* **1970**, *5*, 143−207.

Scheme 3. Formation of Di- and Trinuclear Hydroxo Complexes[a]



[a] With ligand **2′**, the black-colored *N*-benzylimidazolyl arm is replaced by a methyl group.

addition of 1 equiv of a strong base (nBu_4NOH) led, in an apolar medium, to a purple complex **4′**. It was EPR-silent and presented UV−vis [$\lambda_{max} = 330$ nm (3000 $M^{-1}\cdot cm^{-1}$) and 575 nm (70 $M^{-1}\cdot cm^{-1}$)] and NMR signatures characteristic of the dinuclear bis(hydroxo) Cu(II) complex (Figure 2 and Scheme 3).

Hence, the absence of one benzylimidazole group did not seem to modify the chemical behavior of the hydroxo−Cu(II) species in this system whose geometry appears to be essentially controlled by the calix[6]arene scaffold bearing two imidazole arms at the small rim. In these complexes, the Cu(II) centers can reversibly interact with a coordinating solvent as testified by the color change (from purple to green or blue) in the presence of DMF or MeCN. However, the dinuclear core remains strongly bound, as almost no EPR signal could be detected in coordinating solvents. This was somewhat disappointing as we have previously showed that the addition of a small coordinating guest to a solution containing the dinuclear hydroxo complex based on the N-methyl tris(imidazole) calix[6] ligand could partially break the hydroxo bridge to yield a 5-coordinate mononuclear species (Scheme 1). Actually, such a mononuclear hydroxo species has never been detected with the N-Bn ligands. Whereas this is readily understandable for ligand **2′** that lacks one binding arm, in the case of tridentate **2**, such a reluctance to yield a mononuclear hydroxo complex may stem from the higher steric hindrance with the N-Bn substituents in place of N-Me, which either destabilizes the 5-coordinate species or protects and stabilizes (thanks to the microhydrophobic environment) the Cu_2OH_2 core.

From Dinuclear to Trinuclear Cu(II) Complexes

When methanol was added to a THF solution containing the purple Cu(II) dinuclear complexes obtained either with the di- or the tridentate BnIm ligand (**4** and **4′**, respectively), the solution immediately turned green and a new compound precipitated, leaving within a few minutes a colorless solution. The resulting solid green complexes turned slowly blue when dried in the air. Their elementary analyses showed a 3:2:2 copper/ligand/perchlorate ratio. Infrared spectroscopy confirmed the presence of 1 equiv of perchlorate/calixarene ligand. The same complex could be directly obtained through the reaction of the ligand, copper(II) perchlorate, and Et_3N in a 2:3:4 ratio in THF/MeOH.

X-ray Diffraction Analysis. Depending on the conditions in which they were grown, two different kinds of single crystals could be obtained with the tridentate ligand. In one case, crystals were grown out of a dichloromethane/acetonitrile mixture by slow diffusion of methanol. In the other case, the crystallization was performed by slow diffusion of pentane into a chloroform solution containing a small quantity of benzonitrile. Both molecular structures (**5a** and **5b**) are very similar and display a trinuclear Cu(II) core sandwiched between two calixarene scaffolds (Figure 3 and Table 2). The three Cu(II) ions are linearly arranged in a square planar geometry with a slight trigonal distortion for Cu1 and two terminal imidazole ligands on each side arising from two different calixarene units. Once again, one of the imidazole arms lies uncoordinated at the small rim of the cones. The structures actually differ from each other by the nature of the bridging anions. In the crystal grown in the presence of methanol (**5a**), the three copper centers are bridged by either four methoxide anions or two hydroxide and two methoxide (see Experimental Section) with a central symmetry around Cu2. The other structure (**5b**) displays four hydroxide bridging ligands. Finally, the three methoxy groups of the calixarene are oriented toward the center of the cavity, one of them being in weak interaction with the central copper [$d(\mathrm{Cu2}\cdots\mathrm{O}) = 3.01$ and 2.90 Å]. Distances and angles around the metal centers for both X-ray structures are reported in Table 4.

Spectroscopic Characterization of the Trinuclear Hydroxo−Cu(II) Complexes. The UV−vis spectra of the hydroxo−Cu_3 complexes (pale blue hydrated form) with the tris- and bis(imidazole) ligands showed in CH_2Cl_2 a d−d transition at 609 nm ($\epsilon = 160$ $M^{-1}\cdot cm^{-1}$) for **5b** and 612 nm ($\epsilon = 140$ $M^{-1}\cdot cm^{-1}$) for **5b′** and a charge-transfer OH → Cu^{II} at ca. 330 nm. In both cases, addition of MeOH to the CH_2Cl_2 solution led to a slight increase and red shift of the charge-transfer transition with no change of the d−d transition. This substantiates the exchange of the hydroxo bridges (form b) for methoxo ones (form a) (Figure 3). The solid and solution (CH_2Cl_2) EPR spectra of trinuclear complexes **5** and **5′** presented a very weak intensity at 100 K. However, at lower temperatures, the intensity of the spectra drastically increased, showing an axial signal with a well-resolved hyperfine splitting for the parallel component (Figure 4). At 10 K, double integration of the signals indicated one unpaired electron *per* molecule with a half-saturation power of 25 mW, which is about 2 orders of magnitude higher than for mononuclear complex **3**. Hence, all this suggests that trinuclear complexes **5** and **5′** have a $S = {}^1/_2$ ground state with the half-occupied orbital centered on one copper. The trinuclear complexes (**5b** and **5b′**) were characterized by ^1H NMR spectroscopy as well. As in the

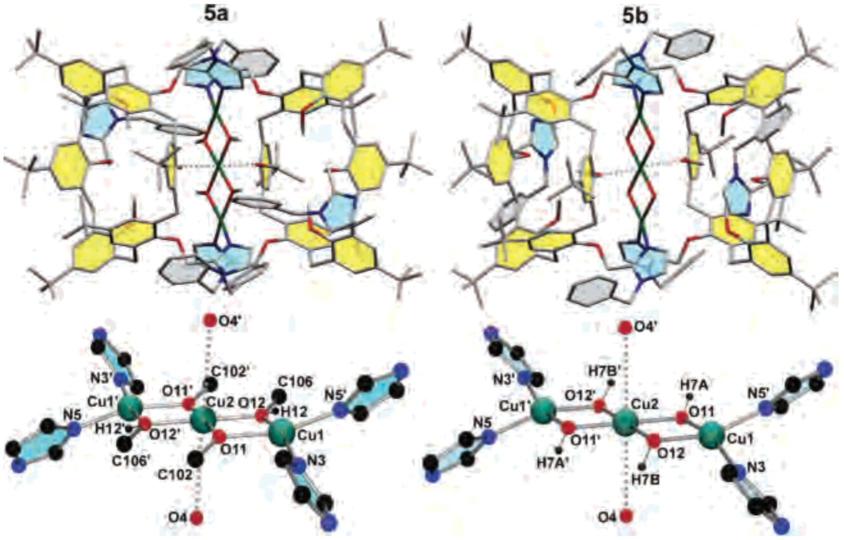


Figure 3. Crystal structure of the trinuclear complexes based on ligand **2** (left, **5a**; right, **5b**). Hydrogen atoms, perchlorate counterions, and solvent of crystallization have been omitted for clarity. Bottom: corresponding enlarged views of the copper centers. The atoms labeled with a prime are not present in the asymmetric unit and are centrosymmetric of the atoms of the asymmetric unit.

Table 4. Selected Interatomic Distances and Angles for $[Cu_3(\mathbf{2})(OMe(H))_4](ClO_4)_2$, **5a**, and $[Cu_3(\mathbf{2})(OH)_4](ClO_4)_2$, **5b**

distance (Å)		angle (deg)	
		5a	
Cu1−O11	1.946(4)	O11−Cu1−O12	77.95(18)
Cu1−O12	1.930(4)	O11−Cu1−N3	96.76(17)
Cu1−N3	1.972(3)	O11−Cu1−N5	163.33(15)
Cu1−N5	1.975(3)	O12−Cu1−N3	166.70(15)
Cu1⋯Cu2	2.9545(5)	O12−Cu1−N5	93.28(15)
Cu2−O11	1.906(4)	N3−Cu1−N5	94.66(14)
Cu2−O12	1.880(4)	O11−Cu2−O12	80.19(17)
Cu2−O4	3.009(3)	O11−Cu2−O12	99.81(17)
O11⋯O12	2.438(6)	O11−Cu2−O11	180
		O12−Cu2−O12	180
		Cu1−O11−Cu2	100.2(2)
		Cu1−O12−Cu2	101.7(2)
		5b	
Cu1−O11	1.927(4)	O11−Cu1−O12	81.39(16)
Cu1−O12	1.907(4)	O11−Cu1−N3	160.72(16)
Cu1−N3	1.992(4)	O11−Cu1−N5	93.93(17)
Cu1−N5	1.975(4)	O12−Cu1−N3	94.72(16)
Cu1⋯Cu2	2.9195(6)	O12−Cu1−N5	162.92(17)
Cu2−O11	1.939(4)	N3−Cu1−N5	94.85(17)
Cu2−O12	1.915(4)	O11−Cu2−O12	80.89(16)
Cu2−O4	2.825(3)	O11−Cu2−O12	99.11(16)
O11⋯O12	2.500(5)	O11−Cu2−O11	180
		O12−Cu2−O12	180
		Cu1−O11−Cu2	98.11(18)
		Cu1−O12−Cu2	99.61(17)

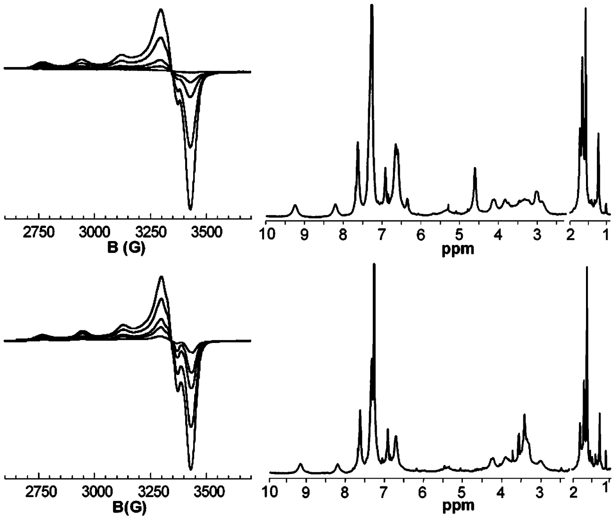


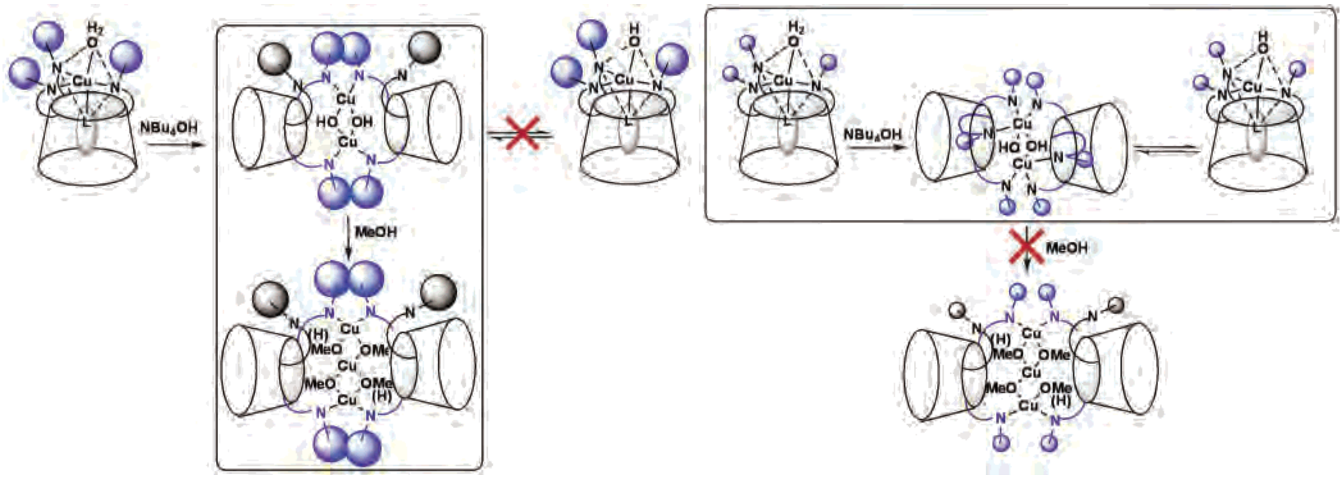
Figure 4. Left: EPR spectra (X band, 9.6 GHz) of the trinuclear complexes in CH_2Cl_2 at various temperatures (from 100 K for the weakest signal to 20 K for the most intense). Top, **5**, $A_{\|} = 182.7 \times 10^{-4}$ cm^{-1}, $g_{\|} = 2.274$, $A_{\perp} = 21.7 \times 10^{-4}$ cm^{-1}, $g_{\perp} = 2.052$; bottom, **5′**, $A_{\|} = 185.5 \times 10^{-4}$ cm^{-1}, $g_{\|} = 2.269$, $A_{\perp} = 18.5 \times 10^{-4}$ cm^{-1}, $g_{\perp} = 2.052$. The parameters were obtained by simulation. Identical, although somewhat broader spectra were obtained with solid samples. Right: ^{1}H NMR signatures ($CDCl_3$, 300 K) of the trinuclear hydroxo complexes (top, **5**; bottom, **5′**). The intensity of the spectra in the 1−2 ppm area has been divided by a factor of 2. The two imidazole resonances are 8.22, 9.26 for **5** and and 8.23, 9.20 for **5′**.

case of the dinuclear complexes, most resonances lie in the diamagnetic region. Some broader peaks, however, were detectable at higher and lower field (28, 35, and −4 ppm, for example, with the tridentate ligand), which are reminiscent of some paramagnetism (Figure 4).

Discussion

Whereas the tridentate N-benzylimidazole ligand allows the stabilization of a mononuclear 5-coordinate dicationic aqua−Cu(II) complex, the corresponding hydroxo species undergoes dimerization. The resulting dinuclear bis(hydroxo) complex presents a $Cu_2(OH)_2$ core where each Cu(II) ion lies in a 4-coordinate square planar environment, leaving one imidazole arm uncoordinated with a calix[6]arene still in a cone conformation. As a matter of fact, an analogous dinuclear complex can be readily obtained when a bidentate calix[6] ligand is used in place of the tridentate one. Interestingly, these dinuclear cores spontaneously rearrange in the presence of methanol into trinuclear Cu(II) complexes (Schemes 3 and 4). The structural reorganization occurring in this reaction is probably initiated by the substitution of the hydroxide bridging donors by methoxide ligands as observed in one of the X-ray structure of the trinuclear complex. Once the trinuclear core forms, the copper complex precipitates, which allows its isolation. In the solid state, slow retro substitution of the methoxo for hydroxo groups

Scheme 4. Comparative Coordination Behavior of the N-Benzyl (left) and N-Methyl (right) Derivatives of the Imidazole-Based Calix[6]ligands



proceeds, yielding a complex that is stable enough to be characterized in solution in a noncoordinating solvent. To our knowledge, no tetrahydroxo Cu_3 complexes have been so far described in the literature. A survey of the Cambridge Structural Database yielded 18 examples of linear trinuclear cupric complexes.[16,17] Most of them are based on a polydentate ligand with an O-donor leading to the endogenous bridging of the Cu(II) ions.[16] In only three cases, such a trinuclear core has been obtained with exogenous bridging anions.[17] Beside two exceptions,[17b,c] a $S = {}^1/_2$ ground state has been reported, as in our case. However, little information[16f,18] is available on the solution studies and spectroscopic characterization of these trinuclear cores, possibly due to their instability in solution.

This propensity of the calixarene-based Cu(II) complexes to form multinuclear species is related to both the highly basic and the bridging character of the hydroxide ligand. Indeed, the π-basic aromatic walls of the calixarene structure along with the phenolic oxygen atoms disfavor the endo coordination of anionic ligands.[19,20] Hence, the host properties of the calixarene structure are favorable to the inclusion of a polarized neutral organic ligand thanks to CH$-\pi$ interactions and possible hydrogen bonding to the oxygen atoms surrounding the first coordination sphere. As a result, in the absence of hydroxide, the host properties of the calixarene cavity allows the stabilization of mononuclear 5-coordinate Cu(II) complexes with a water molecule completing the square-based pyramidal edifice. Due to the disfavored coordination of anionic ligands in the calixarene cone, deprotonation of this water ligand gives rise to dinuclear hydroxo complexes that are classical thermodynamic sinks in Cu(II) chemistry (Scheme 4). With the less sterically encumbered N-methylimidazole-based ligand, this dinuclear hydroxo complex remains 5-coordinate thanks to the self-inclusion of one imidazole arm. The latter being only weakly bound in the apical position, it can be partially displaced by a good guest ligand such as acetamide, leading to a mononuclear 5-coordinate hydroxo complex.[6] With the ligands bearing N-benzyl groups, such a mono/dinuclear equilibrium for the hydroxo complexes was not observed. In contrast, the dinuclear hydroxo species could be readily converted into the much more rare trinuclear tetrahydroxo$-$Cu(II) core that, in turn, could not be stabilized by the N-methyl ligand (Scheme 4). Such contrasting behavior related to the nature of the N$-$R substituents that are far away from the first coordination sphere is quite remarkable. It may be related to sterical interactions between these R groups and the calixarene skeleton, which induces some extra energetic cost when the three arms are coordinated to the same metal ion.[21]

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(16) (a) Epstein, J. M.; Figgis, B. N.; White, A. H.; Willis, A. C. *J. Chem. Soc., Dalton Trans.* **1974**, *18*, 1954−1961. (b) Baker, W. A., Jr.; Helm, F. T. *J. Am. Chem. Soc.* **1975**, *97*, 2295−2296. (c) Matsumoto, N.; Nishida, Y.; Kida, S.; Ueda, I. *Bull. Chem. Soc. Jpn.* **1976**, *49*, 117−121. (d) Chiari, B.; Piovesana, O.; Tarantelli, T.; Zanazzi, P. F. *Inorg. Chem.* **1985**, *24*, 4615−4619. (e) Ferguson, G.; Langrick, C. R.; Parker, D.; Matthes, K. *J. Chem. Soc., Chem. Commun.* **1985**, 1609−1610. (f) Veit, R.; Girerd, J.-J.; Kahn, O.; Robert, F.; Jeannin, Y. *Inorg. Chem.* **1986**, *25*, 4175−4180. (g) Curtis, N. F.; Gainsford, G. J.; Morgan, K. R. *Aust. J. Chem.* **1988**, *41*, 1545−1555. (h) Smolander, K.; Leisto, K. *Inorg. Chim. Acta* **1990**, *169*, 151−155. (i) Sillanpää, R.; Rissanen, K. *Acta Chem. Scand.* **1990**, *44*, 1013−1017. (j) Myllyviita, S.; Sillanpää, R.; Kolnaar, J. J. A.; Reedijk, J. *J. Chem. Soc., Dalton Trans.* **1995**, *13*, 2209−2213. (k) Kannan, S.; Pillai, M. R. A.; Droege, P. A.; Jurisson, S.; Barnes, C. L. *Inorg. Chim. Acta* **1997**, *254*, 397−400. (l) Higgs, T. C.; Spartalian, K.; O'Connor, C. J.; Matzanke, B. F.; Carrano, C. J. *Inorg. Chem.* **1998**, *37*, 2263−2272. (m) Cronin, L.; Mount, A. R.; Parsons, S.; Robertson, N. *J. Chem. Soc., Dalton Trans.* **1999**, *12*, 1925−1928. (n) Bu, X.-H.; Du, M.; Shang, Z.-L.; Zhang, R.-H.; Liao, D.-Z.; Shionoya, M.; Clifford, T. *Inorg. Chem.* **2000**, *39*, 4190−4199. (o) Song, Y.; Gamez, P.; Roubeau, O.; Lutz, M.; Spek, A. L.; Reedijk, J. *Eur. J. Inorg. Chem.* **2003**, 2924−2928.

(17) (a) Cronin, L.; Walton, P. H. *Inorg. Chim. Acta* **1998**, *269*, 241−245. (b) Gutierrez, L.; Alzuet, G.; Real, J. A.; Cano, J.; Borras, J.; Castineiras, A. *Inorg. Chem.* **2000**, *39*, 3608−3614. (c) Gutierrez, L.; Alzuet, G.; Real, J. A.; Cano, J.; Borras, J.; Castineiras, A. *Eur. J. Inorg. Chem.* **2002**, 2094−2102.

(18) Journaux, Y.; Lloret, F.; Kahn, O. *Inorg. Chem.* **1990**, *29*, 3048−3051.

(19) (a) Darbost, U.; Zeng, X.; Rager, M.-N.; Giorgi, M.; Jabin, I.; Reinaud, O. *Eur. J. Inorg. Chem.* **2004**, 4371−4374. (b) Sénèque, O.; Rager, M.-N.; Giorgi, M.; Prangé, T.; Tomas, A.; Reinaud, O. *J. Am. Chem. Soc.* **2005**, *127*, 14833−14840.

(20) When the anisol units of a calixarene are π-metalated, the cavity becomes more acidic and can host anions. See Staffilani, M.; Hancock, K. S. B.; Steed, J. W.; Holman, K. T.; Atwood, J. L.; Juneja, R. K.; Burkhalter, R. S. *J. Am., Chem. Soc.* **1997**, *119*, 6324−6335.

(21) Strong conformational couplings between the metal center and the calix[6]arene structure have been highlighted in other instances. See ref 19b and Rondelez, Y.; Sénèque, O.; Rager, M.-N.; Duprat, A.; Reinaud, O. *Chem. Eur. J.* **2000**, *6*, 4218−4226.

Conclusion

The flexibility of the calixarene ligands allows the stabilization of various geometries and nuclearities, with possible severe rearrangement of the coordination sphere. The hydrophobic environment due to the presence of the calixarene structure can be tuned at the level of the small rim by introduction of more or less bulky substituents on the coordinating arms, which drives the nuclearity of the basic Cu(II) complexes. Hence, unusual trinuclear complexes can be reproducibly obtained, stabilized, and studied in solution. The versatility of calix[6]arenes as a scaffold for the coordination of metal ions is nicely illustrated by this study: on one hand, its high flexibility allows very impressive structural changes of the metal coordination site, and on the other hand, the macrocycle imposes geometric constraints and microenvironments that allow the stabilization of unusual metal arrangements, such as these tetrahydroxo−$Cu(II)_3$ cores. Such a feature is actually quite reminiscent of metalloproteins, whose structuring imposes the nuclearity and geometry of the metal core.

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Supporting Information Available: Crystallographic data (CIF). This material is available free of charge via the Internet at http://pubs.acs.org.

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