One-step Template Synthesis and Solution Structures of Bis(macrocyclic) Octaamine Dicopper(II) Complexes

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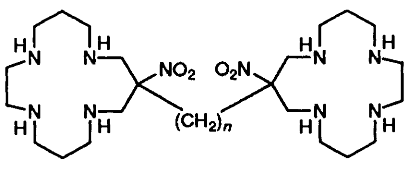
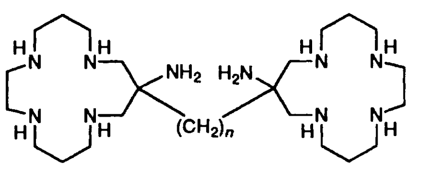
The template reaction of (1,10-diamino-4,7-diazadecane)copper(II) with formaldehyde, dinitroalkanes $(NO_2CH_2)_2(CH_2)_n$ (n = 2–4) and base in MeOH yielded 1,n-bis(10-nitro-1,4,8,12-tetraazacyclopentadecyl)alkanes with n = 2, 3 or 4 respectively, co-ordinated to copper(II) in reasonable yields (*ca.* 30%). The nitro substituents may be reduced with Zn–HCl and the metal-free bis(pendant amino tetraazamacrocyclic) compounds isolated in *ca.* 25% yield. The synthesis and spectroscopic properties of the dicopper(II) complexes with nitro substituents and of the bis(pendant amine) metal-free compounds are reported. The similar template reaction of (1,9-diamino-3,7-diazanonane)copper(II) with 1,4-dinitrobutane yielded the corresponding dicopper(II) complex of the bis(14-membered) $(CH_2)_2$-linked bis(pendant nitro) bis(macrocyclic) ligand. The dicopper(II) complexes of the bis(pendant nitro) macrocycles do not exhibit any coupling in their EPR spectra irrespective of the size of the bridge. This is in contrast to other dicopper(II) complexes of $(CH_2)_2$-linked bis(macrocyclic) ligands. The solution structures of the dicopper(II) complexes of the $(CH_2)_2$-linked 14-membered macrocycles and the compound prepared by a similar template reaction with 1,2-diaminoethane instead of 1,4-dinitrobutane were compared using a combination of molecular mechanics calculations and simulation of the EPR spectra. This reveals a stretched conformation for the dicopper(II) complex resulting from the formaldehyde–dinitrobutane template reaction and a face-to-face conformation of that from the formaldehyde–ethylendiamine template reaction.

The interest in dinuclear transition-metal complexes is primarily based on the important role played by multimetallic sites of metalloproteins.[1–4] The synthesis of co-ordination compounds derived from multinucleating ligands and the determination of their structures and physical properties is largely motivated by their possible use as relatively simple model compounds for bioinorganic systems and/or their application as catalysts. The most important method for the determination of molecular structures is undoubtedly X-ray crystallography. However, there are often difficulties in obtaining X-ray-quality crystals. In addition, the result of a crystal structure analysis might not be relevant in terms of the structure predominantly present in solution. The combination of molecular mechanics calculations with experimental results from spectroscopic studies is an important alternative for the determination of structures.[5,6] The use of molecular mechanics with EPR spectroscopy of weakly coupled dicopper(II) systems (MM-EPR) is one such technique.[7]

Macrocyclic systems are often used to increase the stability of metal complexes, to influence metal-ion selectivity and to stabilize uncommon oxidation states.[8–10] These effects are largely the result of the high degree of preorganization of these systems. However, the synthesis of macrocyclic compounds is often tedious and based on multistep reactions where side products of the cyclization step may only be prevented through high-dilution techniques. Template condensations, where the sites to be linked may be selectively activated and preorganized by the co-ordination centre, and where the formation of large rings may be reduced through chelate-ring formation, often lead to the desired product in a few high-yielding steps.[8,11–13] The template reaction reported here is an extension of the formaldehyde–nitroalkane condensation of (diamino-diaza)-copper(II) complexes[14] to the synthesis of the dicopper(II) complexes of the bis(pendant) nitro bis(macrocyclic) compounds L^1–L^3 and their reduction to the corresponding bis(pendant) amino metal-free L^4–L^6.



	n
L^1	2
L^2	3
L^3	4



	n
L^4	2
L^5	3
L^6	4

The detailed spectroscopic analysis of the dinuclear copper(II) complexes of L^1–L^3 reveals that there is no coupling between the copper(II) centres. This is in contrast to observations with other $(CH_2)_2$-linked bis(macrocyclic) dicopper(II) complexes.[15–17] Of special interest is the

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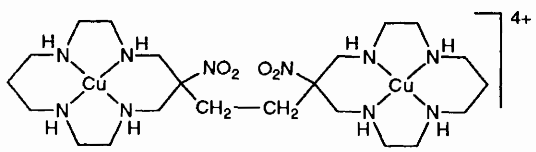
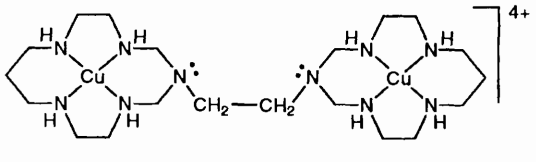
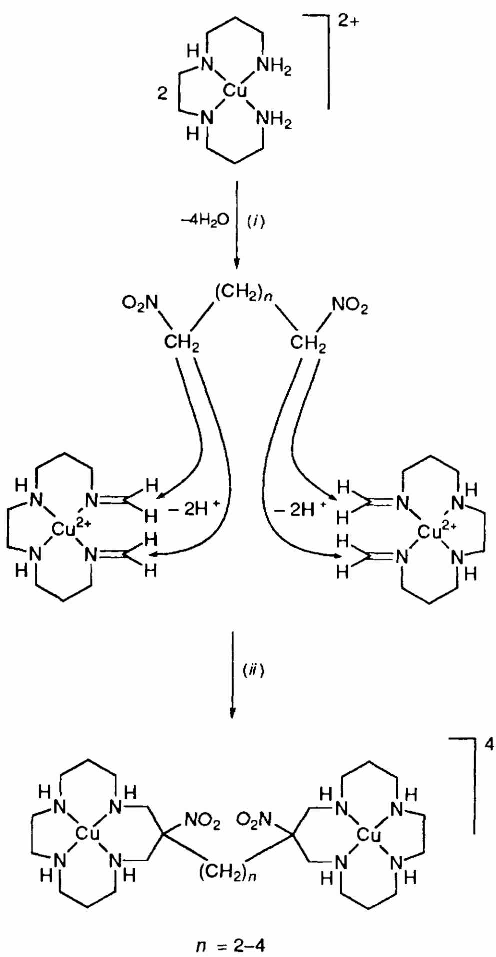


$[Cu_2L^7]^{4+}$



$[Cu_2L^8]^{4+}$



Scheme 1 (*i*) Base, 4HCHO; (*ii*) base

structurally related bis(14-membered macrocyclic) dicopper(II) complex $[Cu_2L^8]^{4+}$ which exhibits weak coupling in the EPR spectrum. For an adequate comparison of the solution structures (MM-EPR) of the dicopper(II) complexes of the bis(macrocyclic) compounds, obtained by the template reaction using 1,4-dinitrobutane and ethane-1,2-diamine, L^7 was prepared and the solution structures of $[Cu_2L^7]^{4+}$ and $[Cu_2L^8]^{4+}$ were determined. The comparison of the two structures represents the first determination of solution structures with the MM-EPR approach applied to molecules with a wide variety of different conformers, resulting from the flexibility of the alkyl bridge, and where electrostatic interactions between the two copper(II) centres are of some importance.

Results and Discussion

Syntheses.—Addition of formaldehyde and nitroalkanes to copper(II) complexes of open-chain tetraamines produces the co-ordinated macrocycles *via* imine intermediates.[18] The two condensation reactions leading to the bis(macrocyclic) product are consecutive reactions (see Scheme 1), and the two copper(II) centres are at a distance where the influence of one site on the condensation of the other is minimal (see solution structures). The successful condensation of two open-chain tetraamines to a bis(macrocyclic) compound co-ordinated to copper(II) was identified by elemental analyses, the characteristic stretching modes of the nitro groups, the macrocyclic nature of the products shown by the stability of the corresponding copper(II) complexes in acidic aqueous solution and by the expected spectroscopic properties of the dicopper(II) complexes and their reduced free macrocycles (see Experimental section and Table 1). The side products of the template condensation have not been fully analysed but the second band could be identified as the starting material (UV/VIS 545 nm, IR, unstable in acidic aqueous solution) and the third band seems to consist of the expected monomacrocyclic intermediate (UV/VIS 568 nm, characteristic IR stretching modes of the nitro groups, stable in acidic aqueous solution).

Comparison of the formaldehyde–dinitroalkane template reaction and the template reaction of *cis*-co-ordinated primary amines with formaldehyde and diamines leading to $[Cu_2L^8]^{4+}$ type bis(macrocyclic) complexes[15] reveals two important differences in the application of these template reactions to the preparation of bis(macrocyclic) complexes. The template synthesis of bis(macrocyclic) copper(II) complexes with ligands of the type of L^8 (1,3,5-triazapentane 'cap'; 3,3′ bridge) is only feasible for 14-membered macrocyclic products. Only tricyclic mononuclear complexes were identified in attempts to prepare the corresponding bis(15-membered) bis(macrocyclic) species.[*,19] The formaldehyde–nitroalkane template reaction, on the other hand, is applicable to the preparation of macrocycles with hole sizes from 13 to 16.[14] Furthermore, the metal-free compounds from the formaldehyde–amine template condensation[21–23] with 1,3,5-triazapentane 'caps' are particularly unstable and therefore basically useless for extensive co-ordination chemistry. Although the metal-free compounds resulting from the formaldehyde–nitroalkane condensation decay in neutral or basic aqueous solution, the pendant amine reduction products are generally stable.[24,25] The formaldehyde–dinitroalkane template reaction is a simple and efficient route for the preparation of bis(macrocyclic) octaamines with variable ring sizes and chain lengths of the alkyl bridge. The metal-free compounds may be obtained by reduction of the pendant nitro groups to bis(macrocyclic) compounds with pendant amines.

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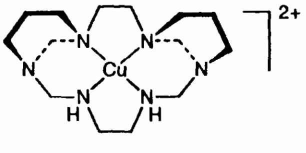
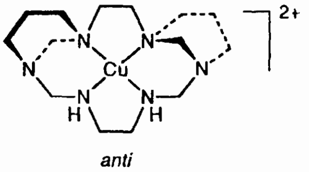
[*] All attempts to synthesize the NCH_2CH_2N-linked 15-membered bis(macrocyclic) dicopper(II) complexes failed and yielded, as described in the literature,[19] the isomeric mixture of a tricyclic mononuclear copper(II) complex. The *syn* and *anti* isomers were separated on a column of cation-exchange resin (SP Sephadex C25, Na^+ form) and characterized by X-ray structural analyses.[20]



syn



anti

Table 1 Electronic transitions and spin-Hamiltonian parameters for the copper(II) macrocyclic complexes

Complex	Electronic transition[a] $\tilde{\nu}$/cm^{-1} (ε/dm^3 mol^{-1} cm^{-1})	Spin-Hamiltonian parameters[b]					
		g_{iso}	$g_{\perp}$	$g_{\parallel}$	A_{iso}	$A_{\perp}$	$A_{\parallel}$
$[CuL^9]^{2+}$	17 480 (124)	2.11	2.05	2.22	78	21	191
$[Cu_2L^1]^{4+}$	17 513 (119)	2.11	2.05	2.22	78	20	191
$[Cu_2L^2]^{4+}$	17 513 (123)	2.11	2.05	2.22	78	20	191
$[Cu_2L^3]^{4+}$	17 513 (117)	2.11	2.05	2.22	78	20	191
$[CuL^{10}]^{2+}$	19 600 (78)	2.09	2.04	2.19	84	26	201
$[Cu_2L^7]^{4+}$	19 570 (77)	2.09	2.04	2.19	84	25	201
$[Cu_2L^8]^{4+}$	19 800 (79)	—	2.04[c]	2.28[c]	—	35[c]	120[c]

[a] Aqueous solution; ε values for ditopic complexes were determined per metal ion. [b] A Values in 10^{-4} cm^{-1}. [c] Determined from the DISSIM simulation.

Spectroscopy.—The spectroscopic properties of the dinuclear copper(II) complexes are assembled in Table 1, where data of the mononuclear complexes $[CuL^9]^{2+}$ and $[CuL^{10}]^{2+}$ (L^9 = 10-methyl-10-nitro-1,4,8,12-tetraazacyclopentadecane; L^{10} = 6-methyl-6-nitro-1,4,8,11-tetraazacyclotetradecane) appear for comparison. The d–d transitions and spin-Hamiltonian parameters of the dicopper(II) compounds synthesized in the formaldehyde–nitroalkane template reaction are typical for two independent (well separated) chromophores. The EPR and, with less accuracy due to inferior resolution, the electronic spectra indicate that the two sites each are, as expected, identical. From comparison with the spectroscopically and structurally thoroughly analysed $[CuL^9]^{2+}$ and $[CuL^{10}]^{2+}$, and from a series of $Cu^{II}N_4$ chromophores with variable geometries[14,26] it follows that the geometries of the two copper(II) sites are each tetragonally distorted octahedral with a small tetrahedral twist of φ = 12° (square planar, φ = 0°; tetrahedral, φ = 90°) in the central CuN_4 plane for the 15-membered and with a nearly planar CuN_4 arrangement for the 14-membered macrocyclic chromophores. From the fact that the EPR spectra of $[Cu_2L^n]^{4+}$, n = 1–3 or 7, are not coupled it emerges that the Cu $\cdots$ Cu separation of these complexes is larger than that of $[Cu_2L^8]^{4+}$ which shows a typical EPR spectrum of a weakly coupled dicopper(II) system.[15]

Solution Structures.—A simple and efficient method based on the combination of molecular mechanics calculations and EPR spectroscopy was developed for the determination of solution structures of dipole–dipole-coupled dinuclear copper(II) complexes.[7] For comparision of the solution structures of the dicopper(II) compounds resulting from the dinitrobutane template reaction with these resulting from the ethylenediamine template reaction we had to choose the bis(14-membered macrocyclic) dicopper(II) complexes $[Cu_2L^7]^{4+}$ and $[Cu_2L^8]^{4+}$ because the bis(15-membered macrocyclic) ones are not available in the latter case. The calculated structures of the 15-membered bis(macrocycles) resulting from the dinitrobutane- and ethylenediamine-based condensations reveal differences similar to those of the 14-membered bis(macrocyclic) dicopper(II) complexes discussed here.

Molecular mechanics calculations. Owing to the flexibility of the alkyl bridge and that of the macrocycle chelate rings, the energy surfaces of $[Cu_2L^7]^{4+}$ and $[Cu_2L^8]^{4+}$ have an exceedingly large number of minima. The conformational search may be simplified by separating the analysis of the chromophores from that of the bridges between the macrocyclic units. For the analysis of the copper(II) chromophores the spectroscopic properties may be used in combination with molecular mechanics calculations for the determination of their structures.[6] The spectroscopic parameters of the two bis(macrocyclic) complexes $[Cu_2L^7]^{4+}$ and $[Cu_2L^8]^{4+}$, and those of the corresponding mononuclear complex $[CuL^{10}]^{2+}$, are, with the exception of the A-tensor parameters of $[Cu_2L^8]^{4+}$, which are reduced by coupling of the two copper(II) centres, very similar (see Table 1). The structural properties of the CuN_4 chromophores of the bis(macrocyclic) complexes are therefore assumed to be very similar to those of the related mononuclear $[CuL^{10}]^{2+}$ system, for which both solid-state and solution structures [based on an MM-AOM (combination of molecular mechanics and angular overlap model) analysis] were determined.[26] As expected, the conformations of the chromophores remain nearly unchanged during structural optimization by molecular mechanics calculations when the well established structure of the mononuclear $[CuL^{10}]^{2+}$ is used as the starting model. Thus, the conformational search may be reduced to the analysis of a 1,4-bis(macrocyclic ligand)-substituted ethane system. The ethane bridge may be bound as an axial or equatorial substituent to the six-membered chelate rings in the chair conformation of the two macrocyclic ligand complexes at each end. A thorough molecular mechanics analysis reveals that, both with an axial and an equatorial disposition of the ethyl bridge, there are two low-energy orientations of the CuN_4 planes which both have an anti-periplanar torsion around the C–C bond of the ethyl bridge: a stretched conformation with a +synclinal and a −synclinal torsion of the terminal C–C(N) bonds for $[Cu_2L^7]^{4+}$ ($[Cu_2L^8]^{4+}$) of the butane fragment, and a face-to-face conformation with the two torsions being +synclinal. For both these conformations, axial substitution to the chair conformation of the six-membered chelate ring is found to be energetically favoured. For both bis(macrocyclic) dicopper(II) species investigated, $[Cu_2L^7]^{4+}$ and $[Cu_2L^8]^{4+}$, this leads to two low-energy conformers (see SCHAKAL plots below).

Electrostatic terms might be of considerable importance in the energetics of the dinuclear systems discussed here since repulsion of the cationic copper(II) sites might favour the stretched conformers. In addition to the general problem of determining charge distributions in co-ordination compounds, the question arises as to how much of the charges is neutralized by axial co-ordination of anions. The effects of ion pairing may be determined by the Fuoss equation.[27] However, the approximation of spherical symmetry for the dinuclear species certainly is an oversimplification, and the error of the assumed cation–anion distance r (cubic term in the Fuoss equation) might be rather large. To avoid the problem of calculating rather insecure ion-aggregation constants for all different conformers, the charge dependences of the total energy of the two lowest-energy conformers each of $[Cu_2L^7]^{4+}$ and $[Cu_2L^8]^{4+}$ have been determined (see Fig. 1). It emerges that the stretched conformer of $[Cu_2L^7]^{4+}$ is favoured with a charge per copper(II) centre larger than 1.4, and the face-to-face conformation of $[Cu_2L^8]^{4+}$ is favoured with a charge per copper(II) centre less than 1.8. There is only a small variation of structural parameters as a function of the charges per copper(II) site. When the charges were varied between 1.4 and 1.8 the differences in the orientation of the two copper(II) chromophores were smaller than *ca.* 5° for the angular geometry and smaller than *ca.* 0.25 Å for the Cu $\cdots$ Cu distance. Similar to

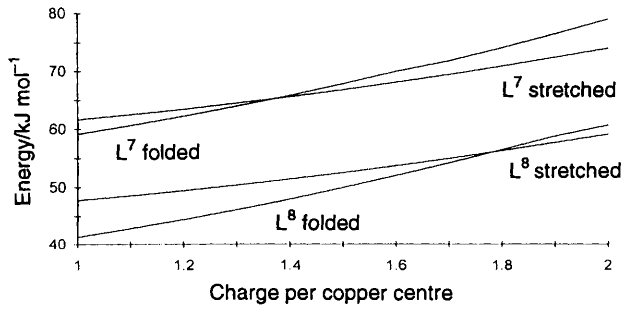


Fig. 1 Total strain energy (electrostatic interactions included) of $[Cu_2L^7]^{4+}$ and $[Cu_2L^8]^{4+}$ as a function of charge neutralization by perchlorate anions (for charge distributions see text)

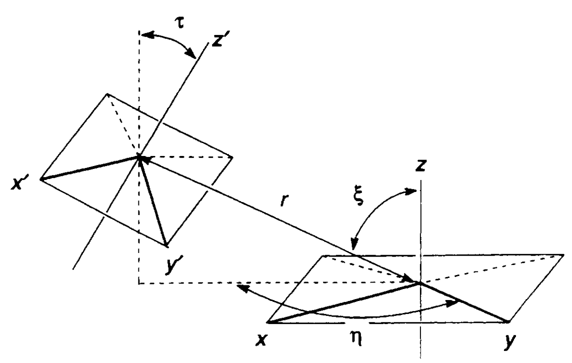


Fig. 2 Definition of the structural parameters used for the simulation of the EPR spectra

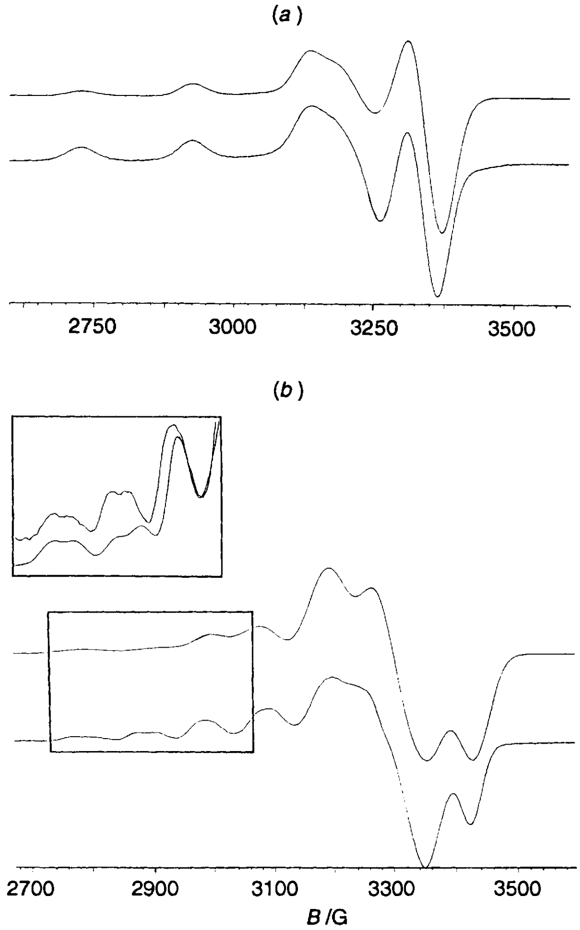


Fig. 3 Experimentally determined (bottom) and DISSIM-simulated (top) EPR spectra of (*a*) $[Cu_2L^7]^{4+}$ at 9.303 GHz (stretched conformation; MM and DISSIM, $\zeta = 75°$, $\tau = 0°$, $\eta = 35°$ and $r = 9.1$ Å) and (*b*) $[Cu_2L^8]^{4+}$ at 9.469 GHz (face-to-face conformation; MM, $\zeta = 87°$, $\tau = 49°$, $\eta = 41°$ and $r = 7.1$ Å; DISSIM, $\zeta = 90°$, $\tau = 44.5°$, $\eta = 49°$ and $r = 6.7$ Å). [Insert to (*b*) shows an expansion of the simulated spectrum (top) as well as that calculated using a smaller linewidth (bottom)]

results with other transition-metal compounds[28-30] the charge distribution (after partial neutralization by ion pairing) does not seem to be a critical problem.*

Clearly, the assumptions leading to the results presented in Fig. 1 are too severe to allow any quantitative interpretation. Also, the difference in the ligand systems of L^7 and L^8, both in terms of steric and electronic effects, might lead to slightly different charge distributions and ion-pairing effects. However, a preference for the face-to-face form of $[Cu_2L^8]^{4+}$ and for the stretched form of $[Cu_2L^7]^{4+}$ by 5–10 kJ mol^{-1} might be realistic.

MM-EPR approach. The results presented in the preceding section indicate that, owing to the neglect of solvation and the crude approximations involved in the determination of ion pairing, electrostatic interactions and conformational equilibria, the accuracy of the computed structures is less than satisfactory. As we have shown with other systems, the general way to get highly accurate solution structures is to combine the results from molecular mechanics calculations with experimental data related to structural parameters.[6,7,26] We have shown that the appropriate method to solve structural problems of weakly coupled dicopper(II) systems is to combine molecular mechanics calculations with the simulation of experimentally determined EPR spectra.[7] This is because the spin-Hamiltonian parameters are strongly dependent on the Cu ⋯ Cu distance and the orientation of the two *g*-tensors (see Fig. 2). The Cu ⋯ Cu distance and the three angles ζ, τ and η defining the relative orientation of the two chromophores were determined from the molecular mechanics-minimized structures and used as starting values for simulations of the EPR spectra. Only small variations of the parameters were necessary to get a good fit between experimental and simulated spectra. The simulation of the EPR spectrum of $[Cu_2L^8]^{4+}$ leads to a typical spectrum of two weakly coupled copper(II) centres, while that of $[Cu_2L^7]^{4+}$ simulated with the unchanged geometric parameters of the MM calculation did not show any sign of coupling. In Fig. 3 the experimentally determined EPR spectra of $[Cu_2L^7]^{4+}$ and $[Cu_2L^8]^{4+}$ are compared with the simulated ones, and SCHAKAL[31] plots of the four conformers that were considered, stretched and face-to-face conformations each of $[Cu_2L^7]^{4+}$ and $[Cu_2L^8]^{4+}$, are given in Fig. 4.

The spectral simulations indicate that, as predicted by the molecular mechanics calculations, $[Cu_2L^7]^{4+}$ exists in solution in the stretched conformation while for $[Cu_2L^8]^{4+}$ the face-to-face structure predominates. Also, despite the crude approximations in terms of ion pairing and charge distributions, the simplified conformational search procedure and the neglect of solvation, the structural information obtained by the force-field calculations is rather accurate and only small modifications of the structural parameters were necessary to obtain a good fit of the EPR spectra. However, this should not hide the fact that it was necessary to gain security in the structural interpretation by combining the force-field calculations with the EPR spectral simulations. A notable point is that the experimentally

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* Calculations have been carried out for total charges per Cu of 2, with 2 for Cu and 0 for N, with 1 for Cu and 0.25 for N, with 0 for Cu and 0.5 for N; for total charges of 1.6 per Cu, with 1.6 for Cu and 0 for N, with 0.80 for Cu and 0.2 for N, with 0 for Cu and 0.4 for N; for total charges per Cu of 1, with 1 for Cu and 0 for N, with 0.5 for Cu and 0.125 for N, with 0 for Cu and 0.25 for N. The corresponding strain-energy differences differ just by a maximum of 0.4 kJ mol^{-1} for the same total charge.

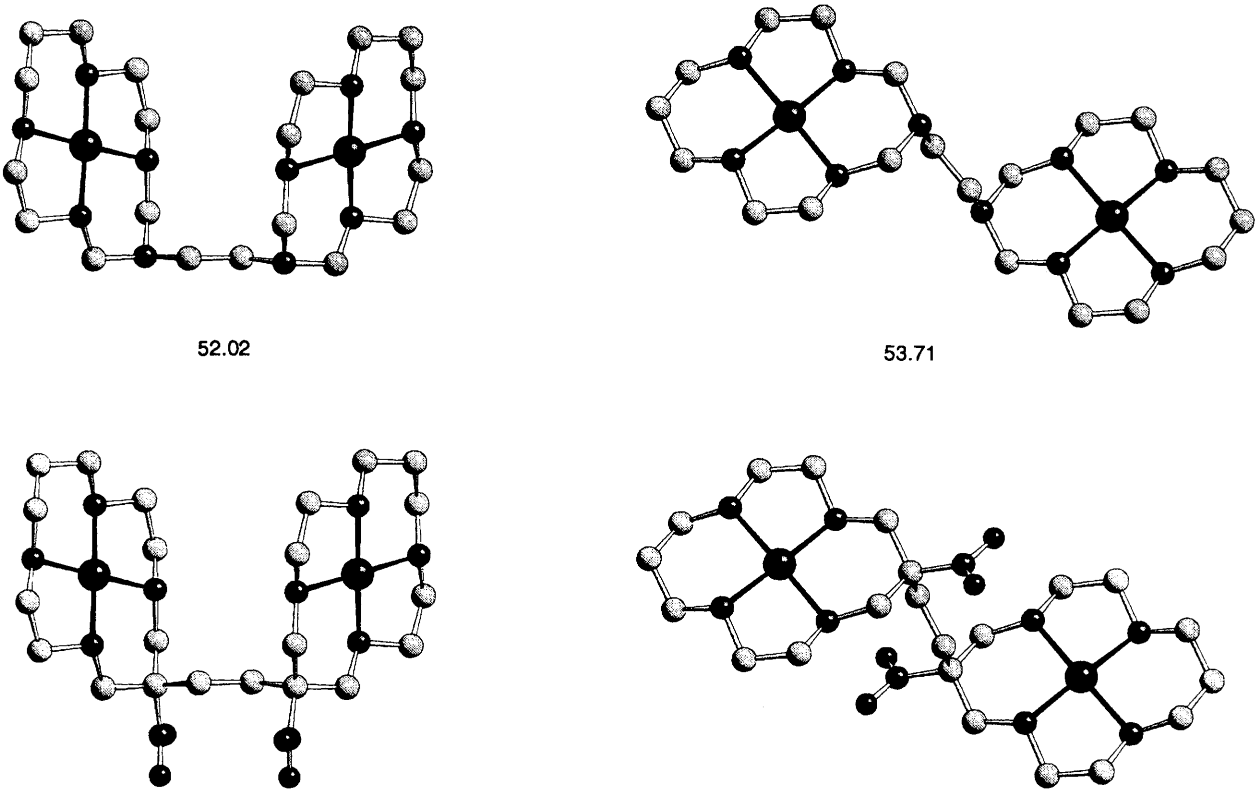
52.02 53.71 69.95 68.09

Fig. 4 The SCHAKAL[31] plots of the stretched and face-to-face conformers of $[Cu_2L^7]^{4+}$ and $[Cu_2L^8]^{4+}$ [the structures and total strain energies E/kJ mol^{-1}, including the coulomb energy, are for a charge per copper(II) site of 1.6; the structures are based on the molecular mechanics optimization and are slightly different from those obtained from the spectral simulations]

determined EPR spectra indicate that, in contrast to other systems where more than one species was detected in solution,[7] in both cases investigated here only one structure each seems to be present in solution, *viz.* the energy difference between the stretched and face-to-face structures is close to or larger than approximately 10 kJ mol^{-1}. This does not emerge from the molecular mechanics analysis.

The full analysis of the weakly coupled EPR spectrum of $[Cu_2L^8]^{4+}$ in comparison with the uncoupled spectrum of $[Cu_2L^7]^{4+}$ using the MM-EPR method demonstrates that (*i*) small structural changes in the ligand system can lead to very different conformations, (*ii*) there is no reason to suppose without a quantitative analysis that any system favours a stretched conformation due to steric hindrance or electrostatic repulsion and (*iii*) the use of the simplified formula[32] for the direct calculation of the $Cu\cdots Cu$ distance from an EPR spectrum is only possible in the special case of coplanar chromophores and therefore not of any use for structure determinations.

Experimental

CAUTION: Perchlorate salts are potentially explosive and should be handled with care.

Materials.—All reagents used were of analytical purity. 1,4-Dinitrobutane, 1,5-dinitropentane and 1,6-dinitrohexane were prepared and purified according to published procedures.[33] The complex $[Cu_2L^8][ClO_4]_4$ was obtained as described in the literature.[15]

Syntheses.—Copper(II) *complexes.* [1,2-*Bis*(10-*nitro*-1,4,8,12-*tetraazacyclopentadecyl*)*ethane*]*dicopper*(II) *tetraperchlorate-hydrate* $[Cu_2L^1][ClO_4]_4\cdot H_2O$, [1,3-*bis*(10-*nitro*-1,4,8,12-*tetraazacyclopentadecyl*)*propane*]*dicopper*(II) *tetraperchlorate hydrate* $[Cu_2L^2][ClO_4]_4\cdot H_2O$, [1,4-*bis*(10-*nitro*-1,4,8,12-*tetraazacyclopentadecyl*)*butane*]*dicopper*(II) *tetraperchlorate hydrate* $[Cu_2L^3][ClO_4]_4\cdot H_2O$ *and* [1,2-*bis*(6-*nitro*-1,4,8,11-*tetraazacyclotetradecyl*)*ethane*]*dicopper*(II) *tetraperchlorate hydrate* $[Cu_2L^7][ClO_4]_4\cdot H_2O$. To a solution of $Cu(NO_3)_2\cdot 3H_2O$ (4.1 g, 17 mmol) and 1,10-diamino-4,7-diazadecane (95%, 2.96 g, 17 mmol) {for $[Cu_2L^7][ClO_4]_4\cdot H_2O$, 1,9-diamino-3,7-diazanonane (97%, 2.80 g, 17 mmol)} in MeOH (200 cm^3) were added the dinitroalkane (8.5 mmol) (1,4-dinitrobutane, 1.27 g; 1,5-dinitropentane, 1.38 g; 1,6-dinitrohexane, 1.50 g), formaldehyde (37% aqueous solution, 10 cm^3, 133 mmol) and NEt_3 (1.7 cm^3). The solution was refluxed (55 °C) for 2 h and then diluted with water to 2 l (a small fraction of a solid, impure product, shown by chromatography redissolved) and sorbed onto a column of cation-exchange resin (SP Sephadex C25, Na$^+$ form, 4 × 15 cm). Elution with aqueous 0.2 mol dm^{-3} $NaClO_4$ separated three fractions (an open-chain and two macrocyclic side products); the main product was eluted with 0.5 mol dm^{-3} $NaClO_4$. The products precipitated after concentration of the solution to *ca.* half volume under reduced pressure. Filtration, washing with EtOH and air-drying yielded 2.34, 2.58, 2.63, 3.01 g (2.20, 2.38, 2.40, 2.85 mmol; 26, 28, 28, 34%) of $[CuL^1][ClO_4]_4\cdot H_2O$, $[Cu_2L^2][ClO_4]_4\cdot H_2O$, $[Cu_2L^3][ClO_4]_4\cdot H_2O$ and $[Cu_2L^7][ClO_4]_4\cdot H_2O$ respectively (Found: C, 27.05; H, 4.90; N, 12.45. Calc. for $C_{24}H_{54}Cl_4Cu_2N_{10}O_{21}$: C, 26.50; H, 5.00; N, 12.90. Found: C, 27.05; H, 5.15; N, 12.45. Calc. for $C_{25}H_{56}Cl_4Cu_2N_{10}O_{21}$: C, 27.25; H, 5.10; N, 12.70. Found: C, 28.00; H, 5.25; N, 12.45. Calc. for $C_{26}H_{58}Cl_4N_{10}O_{21}$: C, 28.00; H, 5.25; N, 12.55. Found: C, 25.30; H, 4.95; N, 13.20. Calc. for $C_{22}H_{50}Cl_4Cu_2N_{10}O_{21}$: C, 24.95; H, 4.75; N, 13.20%). IR: $\nu_{asym}(NO_2)$ 1550, 1548, 1544, 1549; $\nu_{sym}(NO_2)$ 1352, 1350, 1352, 1334 cm^{-1}, respectively for $[Cu_2L^1]^{4+}$, $[Cu_2L^2]^{4+}$, $[Cu_2L^3]^{4+}$ and $[Cu_2L^7]^{4+}$.

Metal-free compounds. 1,2-*Bis*(10-*amino*-1,4,8,12-*tetraazacyclopentadecyl*)*ethane decahydrochloride trihydrate* $L^4 \cdot 10HCl \cdot 3H_2O$, 1,3-*bis*(10-*amino*-1,4,8,12-*tetraazacyclopentadecyl*)*propane decahydrochloride trihydrate* $L^5 \cdot 10HCl \cdot 3H_2O$ *and* 1,4-*bis*(10-*amino*-1,4,8,12-*tetraazacyclopentadecyl*)*butane decahydrochloride trihydrate* $L^6 \cdot 10HCl \cdot 3H_2O$. The complex $[Cu_2L^n][ClO_4]_4 \cdot H_2O$, n = 1, 2 or 3 (0.96, 0.98, 1.00 g; 0.9 mmol each), in water (250 cm^3) was added dropwise to a suspension (50 cm^3) of zinc powder (*ca.* 2 g) in 1 mol dm^{-3} HCl. The dark blue colour of each drop disappeared with evolution of H_2 before more product is added. More Zn and/or 3 mol dm^{-3} HCl were added when the reaction slowed down. Then the excess of Zn and Cu produced were filtered off, the pH adjusted to 2 (2 mol dm^{-3} NaOH), the solution diluted with water to 1 l and sorbed onto a column of cation-exchange resin (Dowex 50W × 2, H^+ form, 3 × 10 cm). Zinc ions were eluted with 1 mol dm^{-3} HCl [identified as $Zn(OH)_2$] before the macrocyclic compounds were eluted in two fractions with 3 and 6 mol dm^{-3} HCl each [identified as copper(II) complexes]. The two fractions containing amines were each concentrated under reduced pressure to *ca.* 10 cm^3. Addition of EtOH (*ca.* 50 cm^3) precipitated white products which were washed with a little EtOH then Et_2O and dried *in vacuo*. The products eluted with 6 mol dm^{-3} HCl were shown to be the hydrochlorides of L^4, L^5 and L^6. Yields: 0.18, 0.18, 0.20 g (0.21, 0.20, 0.23 mmol; 23.2, 22.2, 25.4%). NMR (D_2O): ^1H, L^4, δ 2.20 (s, 4 H), 2.23 (m, 8 H) and 3.15–3.65 (m, 32 H); L^5, δ 1.63 (m, 2 H), 1.90–2.20 (m, 12 H) and 3.15–3.65 (m, 32 H); L^6, δ 1.55 (m, 4 H), 1.95 (m, 4 H), 2.15 (m, 8 H) and 3.05–3.70 (m, 32 H); ^{13}C, L^5, δ 26.1, 29.5, 44.3, 46.8, 49.0, 55.9 and 58.5; L^6, δ 26.7, 36.1, 45.6, 48.1, 50.5, 56.2 and 58.8; L^7, δ 24.5, 26.1, 35.3, 44.0, 46.8 and 49.0 (Found: C, 32.20; H, 8.15; N, 14.45. Calc. for $C_{24}H_{72}Cl_{10}N_{10}O_3$: C, 31.90; H, 8.05; N, 15.50. Found: C, 32.75; H, 8.05; N, 15.00. Calc. for $C_{25}H_{74}Cl_{10}N_{10}O_3$: C, 32.75; H, 8.15; N, 15.25. Found: C, 33.25; H, 8.10; N, 14.75. Calc. for $C_{26}H_{76}Cl_{10}N_{10}O_3$: C, 33.55; H, 8.20; N, 15.05%).

Physical Methods.—Infrared spectra (KBr pellets) were measured with a Perkin Elmer 16PC FT-IR instrument, UV/VIS spectra with a Varian Cary IE spectrophotometer and EPR spectra [10^{-3} mol dm^{-3} dimethylformamide–water (1:2); frozen solutions] with a Bruker ESP 300E instrument (ER 041 XK X-band microwave bridge). The spin-Hamiltonian parameters were determined by simulation of the spectra with the computer program EPR50F.[34] The spin-Hamiltonian parameters and the relative orientation of the chromophores of the dipole–dipole-coupled dinuclear copper(II) complexes were determined by simulating the $\Delta M_s = 1$ resonances with the computer program DISSIM.[35] Considering the fact that the DISSIM simulations do not include the g and A strain on the linewidths, the quality of the simulations are not as high as those for mononuclear complexes computed by EPR50F, but reproduction of the resonance field positions is attainable. Proton and ^{13}C NMR spectra at 200 and 50.32 MHz, respectively, were obtained with a Bruker AS 200 instrument with 3-trimethylsilylpropionate as internal reference. Molecular mechanics calculations were performed with MOMEC[36] with a published force field[37] and, for the metal-independent N–C–N bond angle a force constant of 0.450 mdyn rad^{-1} (dyn = 10^{-5} N) and a strain-free bond angle of 1.911 rad. The plots of the calculated structures were produced with SCHAKAL.[31]

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