Triangular tricopper(I) clusters supported by donor-substituted triazacyclohexanes†

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Triazacyclohexanes (R_3TAC, **1a–i**) with pyridyl or thioether functionalities (R) in the N-substituents react with three equivalents of CuX (X = Cl (**2**), Br (**3**) or I (**4**)) in MeCN to give the triangular tri-copper clusters [$R_3TAC(CuX)_3$] (R = 2-pyridylmethyl (**2a**, **3a**), 5-^{t}butyl-2-pyridyl (**3b**), 2-(3-phenylpropylthio)ethyl (**3c**), 2-(2-ethyl-butylthio)ethyl (**3d**), 2-(4-heptylthio)ethyl (**2e**, **3e**), 2-(1-heptylthio)ethyl (**3f**), 2-(2,4,6-trimethyl-benzylthio)ethyl (**3g**), 2-(*o*-methyl-benzylthio)ethyl (**3h**) and 2-(*o*-fluoro-benzylthio)ethyl (**2i**, **3i**, **4i**)). The thioether complexes are stable towards air and water. The bromide bridge in the clusters can be replaced by chloride (**2c**, **e**, **f**, **i**) or iodide (**4c**, **e**, **f**, **i**) by the reaction of a dichloromethane solution of the cluster with aqueous NaI or AgCl, respectively. Crystal structures of **2a**, **3a**, **3b**, **2e**, **3h** and **4i** show triangular halide-bridged Cu_3 clusters capped by the triazacyclohexane and stabilised by the coordination of one pyridyl or thioether arm to each copper atom. DFT calculations confirm the NMR assignments and reveal the electronic structure of the copper triangle.

Introduction

Copper-containing oxidases have gained importance during the last decade with the elucidation of some of their crystal structures. Trinuclear copper centres are present in many of the blue copper oxidases such as ascorbate oxidase, ceruplasmin and laccase. The trinuclear copper cluster is the active site of these enzymes, where O_2 is reduced to water in a four electron process. The active site is located next to a fourth copper atom, a T1 or blue copper, which mediates the electron transfer from the oxidised substrate to the trinuclear copper cluster site.[1]

In our research, we have focused on reproducing well-defined triangular tri-copper complexes. We have previously shown that a triazacyclohexane can act as a bridging ligand between copper atoms.[2] The highly sensitive and insoluble complexes could not be studied further. Kickelbick *et al.*[3] have described the two complexes shown in Fig. 1 where the triangular array of three Cu(I) atoms mutually bridged by bromides is stabilised by the coordination of an ether or amine functionality at the N-substituent of the triazacyclohexane. Both of these complexes were still not soluble without decomposition so that no solution chemistry or properties were reported. In this paper, we report the syntheses and characterisation of more stable and soluble complexes with pyridyl or thioether donor groups.

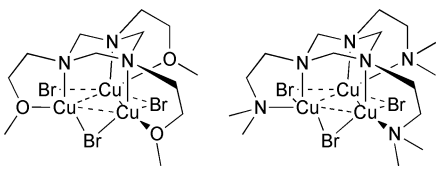
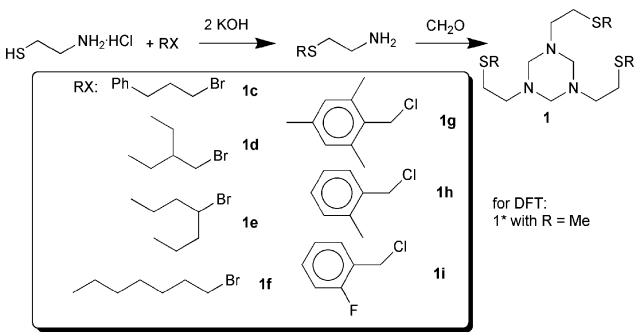


Fig. 1 Previously reported triangular tri-copper clusters.[3]

Results and discussion

Synthesis

The pyridylmethyl and alkylthioethyl substituted triazacyclohexanes were prepared from the corresponding amines and formaldehyde as shown in Scheme 1. **1a**, previously described as oil, was found to crystallise after long storage and was characterised by X-ray crystallography as shown in Fig. 2. The other triazacyclohexanes were isolated as viscous oils.



Scheme 1 Synthesis of the thioether ligands **1c-i**.

Copper(I) halides react readily in acetonitrile in a 3 : 1 ratio with **1** to give the triangular tri-copper complexes **2–4** (Scheme 2). Best results were obtained for the bromides **3** where the product precipitates or even crystallises shortly after the addition of **1** to the acetonitrile solution of CuBr. The chlorides **2** and iodides **4**

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† Electronic supplementary information (ESI) available: Plots for structures not shown in the article, DFT results including a typical input file, additional orbital contour plots and xyz files for optimised structures and calculated ^{1}H and ^{13}C NMR shifts. CCDC reference numbers 707388–707395. For ESI and crystallographic data in CIF or other electronic format see DOI: 10.1039/b819268e

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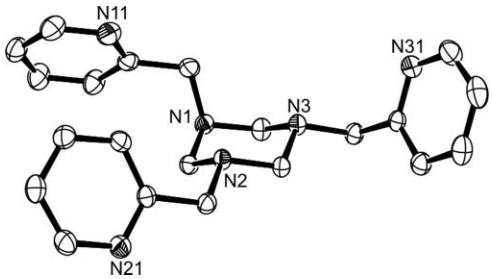


Fig. 2 Thermal ellipsoid (50%) plot of ligand **1a**. Hydrogen atoms omitted for clarity.

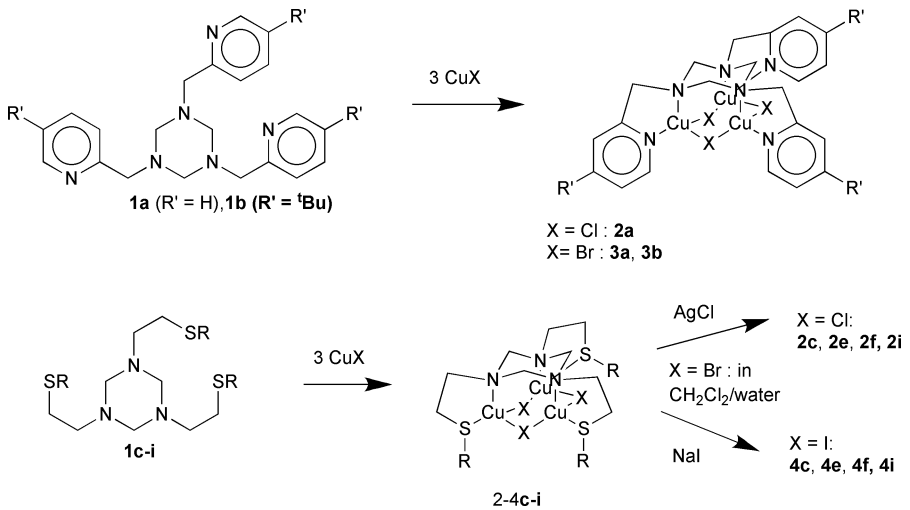
can also be obtained from the bromides **3** by halide exchange in dichloromethane–water with *in situ*-generated AgCl or NaI, respectively. The pyridylmethyl complexes are intense yellow while all thioether complexes are colourless. All complexes gave satisfactory elemental analyses with the exception of **2c**, **f** which may contain traces of fine particles of Ag or AgCl that could not be removed. However, ESI-MS and NMR showed the purity of the solutions even in these cases.

The donor substituents on the triazacyclohexane ligands were varied to improve the solubility of the clusters. A *tert*-butyl group in the pyridylmethyl-substituted complex **3b** improved the solubility relative to **3a** at the cost of substantial synthetic effort. Variation of the thioether substituent was much easier, especially for longer alkyl chain substituents in **1e**, **f**, which gave complexes of good solubility (>0.1 M) in chlorinated hydrocarbon solvents. Among the aromatic thioether substituents tested, *ortho*-fluorobenzyl in **1i** gave the best solubility for the complexes with the additional advantage of a ^{19}F NMR handle for future investigations. The use of wet solvents containing several equivalents of water per cluster was found to further improve the solubility.

All complexes tolerate air in the solid state, at least for a short time, and are unaffected by water. Solutions of the pyridylmethyl-substituted complexes **2a**, **3a** and **3b** are readily oxidised to green solutions on contact with air while all thioether substituted complexes tolerate air, even in solution, for extended periods before turning green or yellow (**4**).

NMR and ESI-MS characterisation

All complexes are soluble enough in polar solvents like MeCN or $MeNO_2$ to be characterised by NMR spectroscopy. The ^{t}Bu-pyridylmethyl-subtituted complex **2b** and the thioether-substituted complexes are also soluble in halogenated hydrocarbons (chloroform, fluorobenzene, dichloromethane, dichloroethane or *o*-dichlorobenzene). Apart from small NMR shifts upon coordination relative to the free ligand, the most characteristic change is observed for the ring protons: the broad singlet for the equatorial and axial proton in free triazacyclohexane becomes two separate doublets as is generally observed for triazacyclohexane complexes.[4] Assignment of the two ring positions was possible by 1D NOESY and, in some cases, ROESY *e.g.* irradiation at the 6-py position in **3b** (8.6 ppm) in $PhNO_2$ led to NOE enhancement of signals at 4.0 and 3.1 ppm in a 2 : 1 ratio as expected for the closer equatorial and axial position, respectively, based on the structure shown later. $^1J_{CH}$ coupling constants were determined for a few complexes. While, in most cases, the resolution did not allow the extraction of different coupling constants for the equatorial and axial ring C–H bonds, in the case of the highly soluble **4e**, a doublet of doublets was observed with 141 and 153 Hz coupling. Weak ^{13}C satellites at about 153 Hz around the well-isolated ^1H signal at 4 ppm allowed an assignment of the larger coupling constant to the equatorial hydrogen. DFT optimised C–H bonds also show this difference (1.098 Å (eq) and 1.113 Å (ax)) and the weaker axial C–H bond indicates involvement in the $Cu–N_{TAC}$ interaction. Surprisingly, and especially for the pyridylmethyl-substituted complexes, the two ring proton signals were difficult to observe, being broadened and shifted depending upon the solvent, temperature and concentration, and even coalescing to a single, broad peak at elevated temperatures. 1D ROESY spectroscopy confirmed that chemical exchange was occurring between the two ring positions. Due to the large size of the complexes, 1D NOESY also gave strong correlation signals but of the same sign as correlation due to dipolar NOE. The mechanism of this surprising fast exchange of the equatorial and axial ring positions is currently under detailed experimental and computational investigation and



Scheme 2 Synthesis of the complexes.

will be published later. An analogous process in the thioether substituted complexes occurs much slower or not at all and clean pairs of doublets for the ring protons are observed in ^{1}H NMR spectra in halogenated solvents. A variable-temperature study on **3f** showed some evidence of a dynamic process within the thioether arm but no exchange of the ring hydrogen positions. This slow conformational exchange also leads to complex ^{1}H NMR patterns for the S–CH_2CH_2–N bridge in the thioether complexes.

The Cu_3 cluster complexes could be characterised by electrospray mass spectrometry in acetonitrile or fluorobenzene solution. All complexes $[LCu_3X_3]$ show a common pattern of the highest mass signal for $[LCu_3X_2]^+$ (thus [M – X]) and two major signals for the loss of one and two CuX to give $[LCu_2X]^+$ and $[LCu]^+$. The isotope pattern and high-resolution mass confirm these assignments. A typical spectrum for **3f** is shown in Fig. 3. No ion for the complete cluster (or proton or sodium adduct) was found for samples in acetonitrile solution. A solution of **3b** in the less polar fluorobenzene gave a signal for the complete cluster at about 0.1% of the intensity of the major ion $[LCu_2X]^+$ ($[LCu_3X_2]^+$ also observed). Interestingly, in several cases of $[LCu_3Br_3]$ complexes, ESI-MS also showed ions for fragments containing chloride in place of a bromide. This chloride must come from a facile substitution from ubiquitous chloride in the MS instrument. No bromide containing ions were detected in the mass spectra of the products of halide exchange reactions. This proves there was complete exchange.

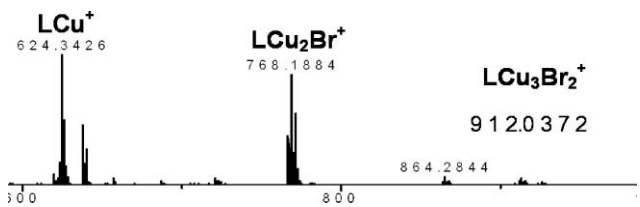


Fig. 3 ESI-MS of **3h**.

Description of crystal structure

Crystals suitable for X-ray crystallography were grown for **2a**, **3a**, **3b**, **2e**, **3h** and **4i**. The crystals of **3h** were very poor but still gave a reasonable structure to allow comparison to the other structures, at least for bond distances to copper. An even poorer structure for **3i** confirms the connectivity and a coordination environment around copper similar to **3h** or **4i**. Sample molecular structures are shown in Fig. 4–7. Two different crystal types were obtained for **3a**—one

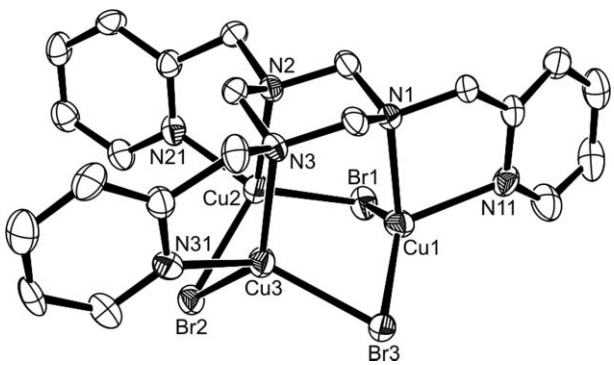


Fig. 4 Thermal ellipsoid (50%) plot of the *asym* conformer found for **3a-A**. Hydrogen atoms omitted for clarity.

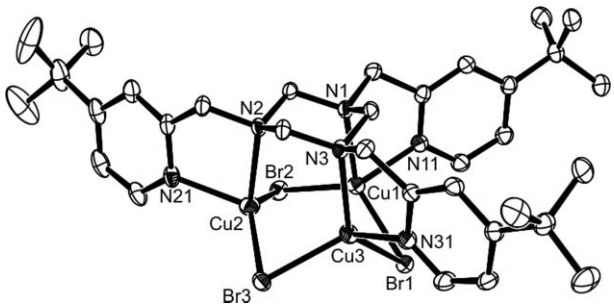


Fig. 5 Thermal ellipsoid (50%) plot of **3b**. Hydrogen atoms omitted for clarity.

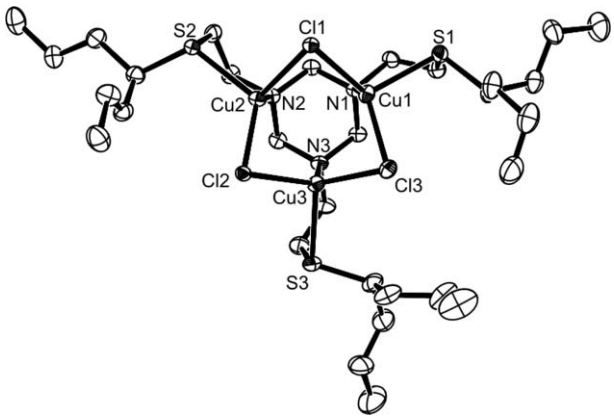


Fig. 6 Thermal ellipsoid (20%) plot of **2e**. Hydrogen atoms omitted for clarity.

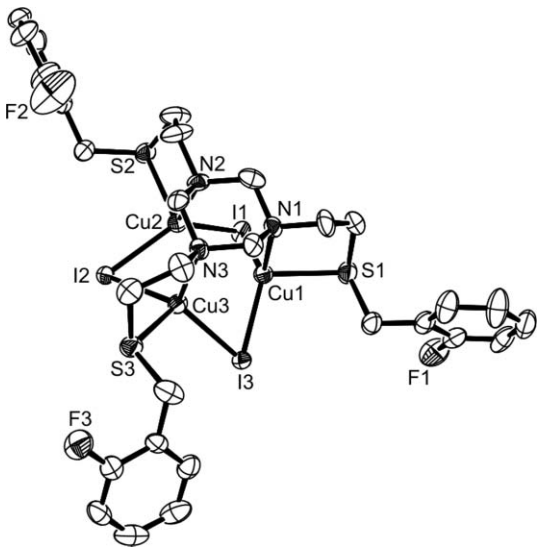


Fig. 7 Thermal ellipsoid (50%) plot of **4i**. Hydrogen atoms omitted for clarity.

solvent-free structure **3a-A** and a second, **3a-B**, with MeCN in the lattice and two independent molecules of different conformations. The crystal structure for **2a** was isostructural to the latter with two conformers. The two conformers are shown in Fig. 8. One is nearly C_3 symmetric (*sym*) with the three pyridyl arms pointed in a trikelion fashion and all three halide bridges at a similar distance from the Cu_3 plane. The other (*asym*) does not have this symmetry and has two pyridyl groups pointed at each other and one of the

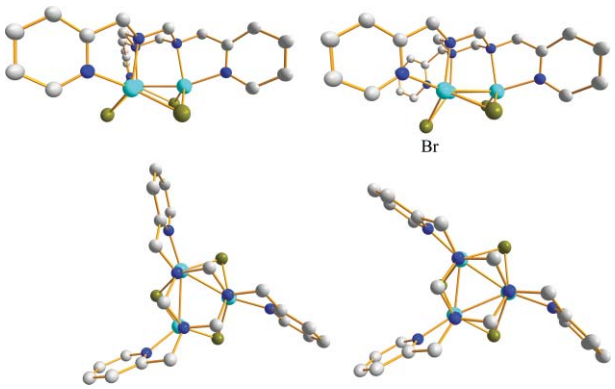


Fig. 8 Two conformers found in the triangular clusters shown in **2a**: nearly C_3 symmetric (left) with all halide bridges at a similar distance from the Cu_3 plane (*sym*) and asymmetric (right) with the halide labelled "Br" about twice as far below the Cu_3 plane than the other two halide bridges (*asym*).

halide bridges about twice as far below the Cu_3 plane than the other two halide bridges. A similar asymmetric structure is found in the other crystal form of **3a** and in **3b**. This asymmetry in the halide bridges is much less pronounced in the thioether complexes as well as in the amine and ether complexes of Kickelbick. Our DFT calculations described below found minima with an even larger asymmetry in the halide bridge (for both pyridyl and thioether substituents) as well as another minimum with symmetrical halide bridges (for the thioether substituent at almost the same energy). Thus, bending of the halide bridge along the Cu–Cu axis has a rather soft energy potential and can be influenced by crystal packing effects. This structural lability of the halide bridge may also aid the facile substitution of the bridge by another halide.

The copper–copper distances are in the range of 2.8–2.9 Å for the pyridyl complexes and 2.9–3.0 Å for the thioether complexes and indicate a trend of increasing distance with stronger donors compared to the weaker donor complexes of Kickelbick[3] (Cu–Cu distance 2.79 Å with amine donor and 2.67 Å with ether). These distances are in the range observed for weak "cuprophilic" closed-shell interactions.[5]

The average distances from copper to the donor atoms shown in Table 1 are not unusual compared to other copper complexes. Noticeable is the trend for the bond distance to the triazacyclohexane nitrogen atoms. The Cu–N distances are longer than 2.21 Å for pyridyl complexes (as for Kickelbick's amine and ether complexes) and shorter than 2.20 Å for thioether complexes.

DFT calculations

The pyridylmethyl-substituted complexes **2a** and **3a** and methylthioethyl-substituted complexes **2***, **3*** and **4*** were investigated by DFT calculations on the RI-BP86/TZVP level with ZORA and COSMO solvent corrections using the ORCA[6] programme. Reasonable agreement of the optimised structure with the crystal structures (bond distances to copper within 0.1 Å of X-ray data) and of the calculated NMR shifts with the observed shifts (except for **4*** where the basis set used for iodine was not suitable for property calculations) were found. As expected for weak dispersion interactions, our DFT calculations give the largest deviation from the experiment in the Cu–Cu contacts which are optimised at about 2.6 Å. The difference in the triazacyclohexane to copper bond distances between the complexes with the soft thioether substituent and the harder substituents is well reproduced by the DFT calculations (about 2.15 Å for thioether and 2.20 Å for pyridyl complexes). Calculation

Table 1 Average bond lengths (standard deviation of average) and elevation Δ of the halide bridge X below the Cu_3 plane in Å. Donor = N(pyridyl) or S(thioether). *For comparison the corresponding distances from DFT optimisation are given in italics*

		Cu–Cu	Cu–X	Cu–N_{TAC}	Cu–Donor	Δ
2a	*sym*	2.87(8)	2.31(7)	2.25(1)	2.07(2)	1.21, 0.96, 0.89
	sym, DFT	*2.62*	*2.36*	*2.21*	*2.03*	*1.87, 0.95, 0.72*
	asym	2.84(6)	2.31(4)	2.27(2)	2.08(4)	1.55, 0.76, 0.70
	asym, DFT	*2.57*	*2.41*	*2.18*	*2.04*	*1.68, 1.48, 0.90*
	asym, DFT, no VDW	*2.63*	*2.38*	*2.22*	*2.05*	*1.78, 1.06, 0.86*
3a	*sym*	2.86(7)	2.44(7)	2.23(1)	2.10(1)	1.36, 1.08, 0.98
	asym	2.80(7)	2.44(3)	2.24(1)	2.10(3)	1.73, 0.82, 0.80
	asym, other cell	2.87(10)	2.44(3)	2.22(1)	2.11(4)	1.59, 0.87, 0.81
	asym, DFT	*2.56*	*2.49*	*2.20*	*2.05*	*2.03, 0.76, 0.71*
	asym, DFT, no VDW	*2.59*	*2.49*	*2.21*	*2.05*	*1.95, 1.01, 0.87*
3b	*asym*	2.89(10)	2.44(4)	2.23(1)	2.11(2)	1.53, 1.02, 0.67
2e		2.98(10)	2.29(3)	2.19(1)	2.38(1)	1.04, 0.95, 0.80
2*	*DFT*	*2.63*	*2.36*	*2.16*	*2.38*	*1.68, 1.01, 0.59*
	DFT, no VDW	*2.65*	*2.37*	*2.17*	*2.39*	*1.76, 0.79, 0.78*
2*-Cl-*sym*[a]	*DFT, no VDW*	*2.67*	*2.36*	*2.16*	*2.40*	*1.19, 1.17, 1.10*
3h		2.88(8)	2.41(3)	2.15(8)	2.42(1)	1.05, 0.84, 0.78
3*	*DFT*	*2.61*	*2.48*	*2.16*	*2.36*	*1.98, 0.68, 0.63*
	DFT, no VDW	*2.64*	*2.49*	*2.17*	*2.41*	*1.83, 0.90, 0.88*
3*-Br-*sym*[a]	*DFT, no VDW*	*2.66*	*2.47*	*2.16*	*2.42*	*1.23, 1.22, 1.17*
4i		2.91(3)	2.58(3)	2.19(1)	2.41(1)	1.22, 1.05, 1.05
4*	*DFT*	*2.57*	*2.54*	*2.15*	*2.38*	*2.07, 0.66, 0.62*
	DFT, no VDW	*2.57*	*2.52*	*2.20*	*2.45*	*0.77, 0.77, 0.73*
Ref. 3	R = NMe_2, X = Br	2.79(3)	2.43(2)	2.23(2)	2.27(1)	1.19, 1.05, 0.73
	R = OMe, X = Br	2.66(1)	2.40(2)	2.20(1)	2.36(1)	1.03, 0.86, 0.75

[a] Optimised minimum for symmetrical halide bridges (all halides at similar distances below Cu_3 plane).

of the NMR parameters for a structure with all non-hydrogen atoms kept in the positions found in the best crystal structure (**3a**) gave an even better agreement with experiment. The ^{1}H NMR shifts for the ring positions confirmed the assigned axial and equatorial positions. Single point calculations for **2a** and **2*** with the B3LYP functional gave NMR shifts even closer to the experiment at the cost of much longer computation times. Calculated structural and NMR data are listed alongside the experimental values for comparison in Table 1 and in the ESI.† In all cases, HOMO and HOMO–1 are close in energy and mainly copper-centered orbitals (Fig. 9). The HOMO energy decreases from the chloride to the iodide complexes (**2a** (Cl): –3.48, **2b** (Br): –3.54; **2*** (Cl): –3.61, **3*** (Br): –3.75 and **4*** (I): –3.90 eV) and is much lower for thioether complexes relative to pyridyl complexes. Thus, pyridyl-substituted chloride complexes should be easiest, and thioether-substituted iodide complexes hardest, to oxidise as observed for their air-sensitivity. For the thioether complexes **2*** and **3***, the LUMO was located at the Cu_3X_3 ring with a significant contribution in the centre of the Cu_3 triangle (Fig. 10). The position of the LUMO indicates that a nucleophile may attack at the centre of the copper triangle as proposed for the initial attack of O_2 in multi-copper oxidases.[1] The pyridyl complexes **2a** and **3a** have unoccupied orbitals of similar shape and energy but the LUMOs are among two sets of three orbitals of π* symmetry centered in the pyridine rings (Fig. 11). This leads to a much smaller HOMO–LUMO gap and explains the yellow colour of pyridyl complexes *versus* the colourless thioether complexes.

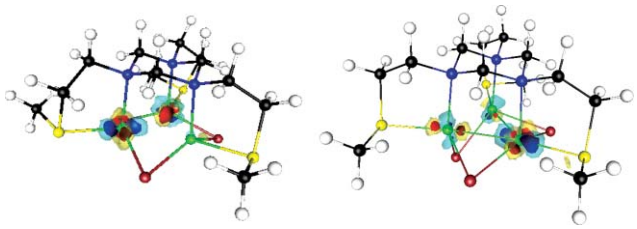


Fig. 9 Contour plots[19] of the HOMO of **2*** (–3.63 eV) (left) and HOMO–1 of **2*** (–3.67 eV) (right).

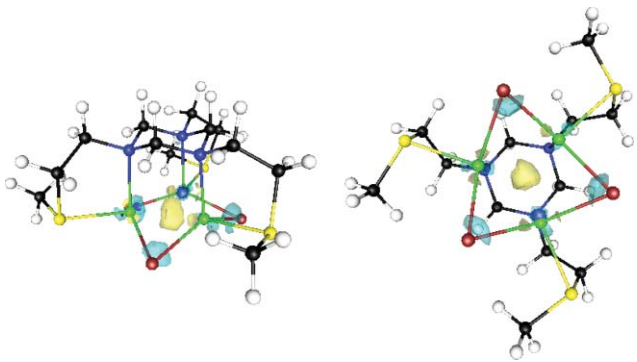


Fig. 10 Contour plots[19] of the LUMO of **2*** (–1.27 eV) (views from the side and from below).

The copper–copper interaction as indicated by the optimised distances and Mayer bond orders[7] (**2a**/**3a** 0.21, **2***/**3*** 0.17) show little difference between chloride and bromide complexes but a decrease from pyridyl to thioether complexes and confirms the experimental trends. The Mulliken charge[8] on the copper atoms also drops significantly from pyridyl (Cl: +0.22, Br: +0.29) to thioether (Cl: +0.17, Br: +0.20) complexes. Calculation at the X-ray atom positions for **3a** and at the B3LYP level gives smaller bond orders (0.14 and 0.07) and slightly larger copper charges (0.28 and 0.34, respectively) without changes in the trends.

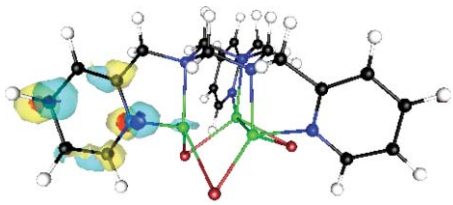


Fig. 11 Contour plot[19] of the LUMO of **2a** (–2.26 eV).

Experimental section

General methods and instrumentation

All manipulations were carried out using standard Schlenk line or dry-box techniques under an atmosphere of argon or of dinitrogen. Solvents were refluxed over the appropriate drying agent, distilled and stored in Teflon valve flasks in the dry-box. NMR samples were prepared under dinitrogen in the dry-box. ^{1}H and ^{13}C NMR spectra were recorded on Bruker Avance 300 MHz, 400 MHz or 500 MHz spectrometers at 298 K and assignments were confirmed by COSY, HSQC, HMBC or NOESY (ax. or eq. ring CH_2) spectra. Residual protio solvent was used as reference for ^{1}H ($CDCl_3$, 7.26 ppm; D_2O, 4.85 ppm) and ^{13}C spectra ($CDCl_3$, 77.16 ppm) or the solvent signal for non-deuterated NMR spectra (neat solvent peak referenced *vs.* TMS stated). Values are quoted in ppm. Coupling constants are quoted in Hz. C–H coupling constants are stated where they were obtained by non-decoupled ^{13}C or HMBC spectra. The concentration of (mostly saturated) solutions in the NMR tube was obtained by integration relative to the solvent signal in non-deuterated NMR spectra and estimated by integration against the residual $CHCl_3$ in $CDCl_3$ (0.1% H) and listed with the NMR solvent. High-resolution electrospray mass spectra were obtained on a Bruker TOF instrument. Isotope patterns match the assignments and calculated exact *m*/*z* values are given for the most intense ion. Elemental analyses were carried out by Mr Alan Carver (University of Bath) on an Exeter Analytical Instruments CE-440 Elemental Analyser.

Starting materials

The triazacyclohexanes **1** were prepared analogous to pyridylmethyl-triazacyclohexane **1a**[9] from the corresponding amine and paraformaldehyde or formalin solution. The previously described oily **1a** crystallised after a year and could be washed with hexane and isolated as a solid. Its structure was confirmed by X-ray analysis.

2-(4-*tert*-Butyl)pyridylmethylamine. 2-Cyano-4-*tert*-butylpyridine (prepared according to Shuman *et al.*[10]) (14.74 g, 92 mmol) was dissolved in 500 mL of THF and added to 92 mL of 2 M BH_3·THF in THF (184 mmol). The mixture was heated to reflux overnight and worked up to yield 30% of the amine.

^{1}H NMR ($CDCl_3$): 8.37 d (1H, J = 5.3 Hz, 6-py), 7.17 d (1H, J = 1.9 Hz, 3-py), 7.06 dd (1H, J = 5.3 and 1.9 Hz, 5-py), 3.87 s (2H, py-CH_2), 1.97 br (2H, NH_2), 1.22 s (9H, ^{t}Bu). ^{13}C-{^{1}H} NMR ($CDCl_3$): 161.4 and 160.4 (2- and 4-py), 148.8 (6-py), 118.7 and 117.9 (3- and 5-py), 47.8 (py-CH_2), 34.4 (C), 30.3 (CH_3).

Tris(2-(4-*tert*-butyl)pyridylmethyl)triazacyclohexane (1b). 2-(4-*tert*-Butyl)pyridylmethylamine (1.30 g, 7.91 mmol) was dissolved in toluene (20 mL). Parafomaldehyde (237 mg, 7.91 mmol) was added and the mixture was stirred overnight. Then the solvent was distilled off and the residual yellow oil dried *in vacuo* to give 1.20 g yield (86%).

^{1}H NMR ($CDCl_3$): 8.33 dd (3H, J = 5.3 and 0.7 Hz, 6-py), 7.37 d (3H, J = 1.9 Hz, 3-py), 7.03 dd (3H, J = 5.3 and 1.9 Hz, 5-py), 3.83 s (6H, py-CH_2), 3.54 br (6H, ring CH_2), 1.19 s (27H, ^{t}Bu). ^{13}C-{^{1}H} NMR ($CDCl_3$): 160.4 (2-py), 158.5 (4-py), 149.0 (6-py), 119.3 (3-py), 119.0 (5-py), 74.1 (CH_2, ring), 58.9 (py-CH_2), 34.6 (C), 30.5 (CH_3).

2-(3-Phenylpropylthio)ethylamine. Sodium hydroxide (1.2 g, 30 mmol) was dissolved in MeOH (50 mL) followed by the addition of mercaptoethylamine hydrochloride (1.71 g, 15 mmol). After 30 min, 1-bromo-3-phenylpropane (3 g, 15 mmol) was run into the solution. The reaction mixture was vigorously stirred under nitrogen overnight. The solution was filtered and the solvent removed under vacuum. The remaining product was dissolved in ether, filtered and the solvent evaporated affording a yellow oil (79% yield).

^{1}H NMR ($CDCl_3$ with some CD_3OD): 7.3 m and 7.15 (5H, Ph), 2.9 t (2H, J = 6.01, CH_2–NH_2), 2.85 t (2H, J = 7.72, S–CH_2), 2.6 t (2H, J = 6.05, CH_2–S), 2.5 t (2H, J = 7.72, Ph–CH_2), 1.9 m (2H, J = 7.54, Ph–CH_2–CH_2). ^{13}C-{^{1}H} NMR ($CDCl_3$ with some CD_3OD): 141.33, 128.41, 128.03, 125.93 (i, *m*, *o*, *p*-Ph), 40.37 (*C*H_2–N), 35.20 (S–*C*H_2), 34.69 (Ph*C*H_2CH_2CH_2–S), 31.15 (PhCH_2*C*H_2CH_2–S), 30.96 (PhCH_2CH_2*C*H_2–S).

Tris(2-(3-phenylpropylthio)ethyl)triazacyclohexane (1c). 2-(3-Phenylpropylthio)ethylamine (700 mg, 3.57 mmol) was dissolved in toluene and one equivalent of paraformaldehyde (111 mg, 3.57 mmol) was added. The reaction ran overnight and the solvent was removed by distillation. The remaining oil was dried under reduced pressure, redissolved in ether, filtered and the solvent removed under vacuum yielding 85% of yellow oil.

^{1}H NMR ($CDCl_3$): 7.2 and 7.1 (15H, Ph), 3.3 br (6H, ring CH_2), 2.65 t (6H, S–CH_2), 2.55 m (12H, CH_2–S and CH_2–N), 2.45 t (6H, J = 7.54, Ph–CH_2), 1.85 m (6H, Ph–CH_2–CH_2). ^{13}C-{^{1}H} NMR ($CDCl_3$): 141.58, 128.58, 128.30, 126.04 (i, *m*, *o*, *p*-Ph), 74.14 (ring CH_2), 52.75 (*C*H_2–N), 35.19 (S–*C*H_2), 31.75 (Ph*C*H_2CH_2CH_2–S), 31.32 (PhCH_2*C*H_2CH_2–S), 30.36 (PhCH_2CH_2*C*H_2–S) ppm.

2-(2-Ethylbutylthio)ethylamine. To a solution of NaOH (614 mg, 15.3 mmol) in 30 mL of methanol, 2-mercaptoethylamine hydrochloride (0.81 g, 7.14 mmol) was added. The solution was stirred under nitrogen, 1-bromo-2-ethylbutane (1 mL, 1.179 g, 7.14 mmol) added and left stirring overnight. Filtration and solvent removal *in vacuo* afforded a colourless oil that was dissolved in diethyl ether, filtered, and dried under vacuum. A colourless oil was obtained in a 61% yield.

^{1}H NMR ($CDCl_3$): 2.79 t (2H, J = 6.3, CH_2–NH_2), 2.51 t (2H, J = 6.3, S–CH_2), 2.40 d (2H, J = 5, CH_2–S), 1.30–1.35 (5H, CH_3–CH_2 and C*H*), 1.27 s (2H, NH_2), 0.86 t (6H, J = 7.0 Hz, CH_3). ^{13}C-{^{1}H} NMR ($CDCl_3$): 41.57 (*C*H_2–NH_2), 41.30 (*C*H), 37.03 (S–*C*H_2), 36.34 (*C*H_2–S), 25.33 (CH_3–*C*H_2), 11.20 (*C*H_3).

Tris(2-(2-ethylbutylthio)ethyl)triazacyclohexane (1d). 2-(2-Ethylbutylthio)ethylamine (700 mg, 4.34 mmol) was dissolved in toluene and reacted with p-formaldehyde (130 mg, 4.34 mmol) for one hour. The solvent was distilled off *in vacuo* affording a colourless oil in 68% yield.

^{1}H NMR ($CDCl_3$): 3.41 br (6H, ring CH_2), 2.66 m (6H, CH_2–NH_2, J = 5.9), 2.58 m (6H, S–CH_2), 2.48 d (6H, J = 5, CH_2–S), 1.35–1.42 m (15H, CH_3–CH_2 and C*H*), 0.8 t (18H, J = 6.9, CH_3). ^{13}C-{^{1}H} NMR ($CDCl_3$): 74.26 (ring *C*H_2), 52.93 (*C*H_2–N), 41.01 (*C*H), 36.69 (S–*C*H_2), 31.16 (*C*H_2–S), 25.18 (CH_3–*C*H_2), 10.97 (*C*H_3).

2-(4-Heptylthio)ethylamine. Prepared analogously to the precursor of **1d** from 2-mercaptoethylamine hydrochloride (4 g, 35.2 mmol), KOH (4 g, 70 mmol) and 4-bromoheptane (6.5 mL, 35 mmol) as a colourless oil in 75% yield.

^{1}H NMR ($CDCl_3$): 2.85 t (2H, J = 6.4, CH_2–NH_2), 2.59 t (2H, J = 6.4, S–CH_2), 2.58 m (1H, C*H*), 1.43–1.55 m (10H, CH–CH_2CH_2–CH_3 and NH_2), 0.91 t (6H, J = 7.2, CH_3). ^{13}C-{^{1}H} NMR ($CDCl_3$): 45.3 (*C*H), 41.6 (*C*H_2–NH_2), 37.2 (CH_2*C*H_2CH), 34.6 (*C*H_2–S), 19.9 (CH_3–*C*H_2), 13.9 (*C*H_3).

^{1}H NMR ($CDCl_3$): 3.4 br (6H, ring CH_2), 2.65 m (6H, CH_2–N), 2.58 m (9H, C*H*–S–CH_2), 1.4–1.55 m (24H, CH_3–CH_2CH_2), 0.90t (18H, J = 7.1, CH_3) ppm. ^{13}C-{^{1}H} NMR ($CDCl_3$): 74.27 (ring *C*H_2), 53.19 (*C*H), 45.75 (*C*H_2–N), 37.30 (*C*H_2–S), 28.66 (CH_2*C*H_2CH), 20.10 (CH_3–*C*H_2), 14.18 (*C*H_3) ppm.

^{1}H NMR (7.0 w% in DCM): 3.33 br (6H, ring CH_2), 2.58 m (6H, CH_2–N), 2.56 m (9H, S–CH_2 and C*H*), 1.4–1.5 m (24H, CH_3–CH_2C_{H2}), 0.88 t (18H, J = 7.1, CH_3) ppm. ^{13}C-{^{1}H} NMR ($CDCl_3$): 74.0 (ring *C*H_2), 52.8 (*C*H_2–N), 45.6(*C*H), 37.1 (CH_2*C*H_2CH), 28.4 (*C*H_2S), 20.0 (CH_3–*C*H_2), 13.9 (*C*H_3) ppm.

Tris(2-(4-heptylthio)ethyl)triazacyclohexane (1e). Prepared analogously to **1d** from the amine (1.58 g, 9 mmol) and paraformaldehyde (271 mg, 9 mmol) in toluene as oil in 87% yield.

2-(1-Heptylthio)ethylamine. Prepared analogously to the precursor of **1d** from 2-mercaptoethylamine hydrochloride (4 g, 35.2 mmol), NaOH (2.82 g, 70.4 mmol) and 1-bromoheptane (6.5 mL, 35 mmol) as a yellow oil in 81% yield.

^{1}H NMR ($CDCl_3$): 2.8 t (2H, J = 6.40, CH_2–N), 2.5 t (2H, J = 6.40, S–CH_2), 2.4 t (2H, J = 7.35, CH_2–S), 1.85 s (2H, NH_2), 1.5 q (2H, J = 7.35, CH_2–CH_2–S), 1.2–1.3 (8H, set of signals for CH_2–CH_2–CH_2–CH_2), 0.9 t (3H, J = 7.16 CH_3). ^{13}C-{^{1}H} NMR ($CDCl_3$): 41.02 (*C*H_2–NH_2), 36.15 (*C*H_2–S), 32.14 (*C*H_2), 31.83 (*C*H_2), 29.78 (*C*H_2), 29.19 (*C*H_2), 28.83 (*C*H_2), 22.58 (*C*H_2), 14.02 (*C*H_3).

Tris(2-(1-heptylthio)ethyl)triazacyclohexane (1f). Prepared analogously to **1d** from the amine (6.3 g, 36 mmol) and paraformaldehyde (1.08 g, 36 mmol) in toluene (50 mL). The residue was taken up with Et_2O, decanted from insoluble material and isolated by solvent removal *in vacuo* as an oil in 65% yield.

^{1}H NMR ($CDCl_3$): 3.38 br (6H, ring CH_2), 3.03 m (6H, CH_2–N), 2.58 m (6H, S–CH_2), 2.48 t (6H, J = 7.54, CH_2–S), 1.53 q (6H, J = 7.54, CH_2–CH_2S), 1.25–1.45 (18H, set of signals for CH_3–CH_2–CH_2–CH_2), 0.83 t (9H, J = 7.35, CH_3). ^{13}C-{^{1}H} NMR ($CDCl_3$):

74.26 (ring CH_2), 52.89 (CH_2–N), 32.55 (CH_2–S), 31.88 (CH_2), 30.50 (CH_2), 29.90 (CH_2), 29.06 (CH_2), 29.02 (CH_2), 22.75 (CH_2), 14.21 (CH_3).

2-(2,4,6-Trimethylbenzylthio)ethylamine. Prepared analogously to the precursor of **1d** from 2-mercaptoethylamine hydrochloride (3.37 g, 29.6 mmol), NaOH (2.37 g, 59.5 mmol) and 2,4,6-trimethylbenzylchloride (α^2-chloroisodurene) (5 g, 29.6 mmol) as a yellow oil in 70% yield.

^{1}H NMR ($CDCl_3$): 6.85 s (2H, Ph), 3.8 s (2H, Ph–CH_2–S), 2.95t (2H, $J = 6$, CH_2–N), 2.7 t (2H, $J = 6$, CH_2–S), 2.4 s (6H, 2,6-CH_3), 2.25 s (3H, 4-CH_3), 1.3 br (2H, NH_2). ^{13}C-{^{1}H} NMR ($CDCl_3$): 136.91 (*o*-Ph), 136.68 and 131.16 (*p*- and *i*-Ph), 129.17 (*m*-Ph), 47.72 (CH_2–NH_2), 41.36 (S–CH_2), 37.33 (CH_2–S), 21.03 (4-CH_3), 19.74 (2,6-CH_3).

Tris(2-(2,4,6-trimethylbenzylthio)ethyl)triazacyclohexane (1g). Prepared analogously to **1d** from the amine (2.9 g, 13.9 mmol) and paraformaldehyde (0.416 g, 13.9 mmol) in toluene (30 mL) as a yellow oil in 77% yield.

^{1}H NMR ($CDCl_3$): 6.8 s (6H, Ph), 3.75 s (6H, Ph–CH_2–S), 3.35 br (6H, ring CH_2), 2.65 m (12H, CH_2–N and CH_2–S), 2.35 s (18H, 2,6-CH_3), 2.2 s (9H, 4-CH_3). ^{13}C-{^{1}H} NMR ($CDCl_3$): 136.97 (*o*-Ph), 136.63 and 131.26 (*p*- and *i*-Ph), 129.15 (*m*-Ph), 74.22 (ring CH_2), 52.95 (CH_2–N), 31.32 and 31.16 (CH_2–S–CH_2), 21.05 (CH_3), 19.82 (2,6–CH_3).

2-(2-Methylbenzylthio)ethylamine. Prepared analogously to the precursor of **1d** from 2-mercaptoethylamine hydrochloride (3.07 g, 27.0 mmol), NaOH (1.62 g, 54.0 mmol) and 2-methylbenzylchloride (5 g, 27.0 mmol) as a yellow oil in 69% yield.

^{1}H NMR ($CDCl_3$): 7.2 m (4H, Ph), 3.85 s (2H, Ph–CH_2–S), 2.9 t (2H, $J = 6.78$, CH_2–N), 2.6 t (2H, $J = 6.78$, S–CH_2), 2.4 s (3H, CH_3), 1.4 br (2H, NH_2). ^{13}C-{^{1}H} NMR ($CDCl_3$): 136.71 and 136.03 (C, Ph), 130.77, 129.67, 127.41 and 125.91 (CH, Ph), 41.06 (CH_2–NH_2), 35.98 (S–CH_2), 34.09 (CH_2–S), 19.20 (CH_3) ppm.

Tris(2-(2-methylbenzylthio)ethyl)triazacyclohexane (1h). Prepared analogously to **1d** from the amine (700 mg, 3.86 mmol) and paraformaldehyde (0.116 g, 3.86 mmol) in toluene (20 mL) as a yellow oil in 87% yield.

^{1}H NMR ($CDCl_3$): 7.1–7.2 m (12H, Ph), 3.75 s (6H, Ph–CH_2–S), 3.3 br (6H, ring CH_2), 2.60 m (6H, CH_2–N), 2.55 m (6H, S–CH_2), 2.4 s (9H, CH_3). ^{13}C-{^{1}H} NMR ($CDCl_3$): 136.83 and 135.91 (C, Ph), 130.84, 129.76, 127.47 and 125.94 (CH, Ph), 74.13 (ring CH_2), 52.58 (CH_2–N), 34.76 (S–CH_2), 29.95 (CH_2–S), 19.34 (CH_3).

2-(2-Fluorobenzylthio)ethylamine. Prepared analogously to the precursor of **1d** from 2-mercaptoethylamine hydrochloride (3.92 g, 34.6 mmol), NaOH (2.76 g, 69.2 mmol) and 2-fluorobenzylchloride (4.12 mL, 34.6 mmol) as a yellow oil in 91% yield.

^{1}H NMR ($CDCl_3$): 7.35 t (1H, $J = 7.5$, 3-Ph), 7.25 dd (1H, $J = 5.7$, 5-Ph), 7.15 t (1H, $J = 7.4$, 4-Ph), 7.05 (1H, $J = 8.5$, 6-Ph), 3.75 s (2H, Ph–CH_2–S), 2.85 br (2H, CH_2–N), 2.6 t (2H, $J = 6.2$, S–CH_2), 1.8 br (2H, NH_2). ^{13}C-{^{1}H} NMR ($CDCl_3$): 160.8 d ($J = 246$, 1-Ph), 130.9 d ($J = 3.9$, 3-Ph), 129.1 d ($J = 8.1$, 5-Ph), 125.7 d ($J = 14.8$, 2-Ph), 124.2 d ($J = 3.6$, 4-Ph), 115.4 d ($J = 21.9$, 6-Ph), 40.7 (CH_2–N), 35.7 (CH_2–S), 28.6 d ($J = 3.0$, Ph–CH_2) ppm.^{19}F NMR ($CDCl_3$): –118.3 ppm.

^{1}H NMR ($CDCl_3$, 7.26 ppm): 7.30 t (1H, $J = 7.3$, 3-Ph), 7.17 m (1H, 5-Ph), 7.05 t (1H, $J = 6.7$, 4-Ph), 6.98 t (1H, $J = 10$, 6-Ph), 3.69 s (2H, Ph–CH_2–S), 2.80 m (2H, CH_2–N), 2.51 m (2H, S–CH_2), 1.26 s (2H, NH_2). ^{13}C-{^{1}H} NMR ($CDCl_3$, 77.16 ppm): 160.7 d ($J_{CF} = 246$, 1-Ph), 130.9 d ($J_{CF} = 3.5$, J_{CH}(d) = 159, 3-Ph), 128.7 d ($J_{CF} = 9$, J_{CH}(dd) = 162 and 9, 5-Ph), 125.7 d (J_{CF} and J_{CH}(dddd) all about 5, 2-Ph), 124.2 d ($J_{CF} = 3.5$, J_{CH}(dd) = 162 and 8, 4-Ph), 115.4 d ($J_{CF} = 22$, J_{CH}(dd) = 162 and 9, 6-Ph), 40.8 (J_{CH}(tt) = 136 and 3, CH_2–N), 35.8 ($J_{CH} = 138$, CH_2–S), 28.6 d ($J_{CF} = 2.4$, J_{CH}(td) = 141 and 3, PhCH_2).

Tris(2-(2-fluorobenzylthio)ethyl)triazacyclohexane (1i). Prepared analogously to **1f** from the amine (5.85 g, 31.9 mmol) and paraformaldehyde (0.948 g, 31.6 mmol) in toluene (50 mL) as a yellowish oil in 87% yield.

^{1}H NMR ($CDCl_3$): 7.1–7.6 (12H, multiple signals for Ph), 3.85 s (6H, Ph–CH_2), 3.4 br (6H, ring CH_2), 2.7 m (6H, CH_2–N), 2.6 m (6H, S–CH_2). ^{13}C-{^{1}H} NMR ($CDCl_3$): 162 d ($J = 249$, C–F), 131.63 d ($J = 4.1$, 6-C), 130.1 d ($J = 8.4$, 4-C), 126.6 d ($J = 15.3$, 1-C), 124.94 d ($J = 3.6$, 5-*C*H), 115.5 d ($J = 21.35$, 3-*C*H), 74.05 (ring CH_2), 42.01 (CH_2–N), 36.05 (CH_2–S), 26.82 (Ph–CH_2) ppm.^{19}F NMR ($CDCl_3$): –118.0.

^{1}H NMR ($CDCl_3$, 7.26 ppm): 7.33 td (3H, $J = 7.5$ and 1.5, 3-Ph), 7.22 m (3H, 5-Ph), 7.09 td (3H, $J = 7.5$ and 1.0, 4-Ph), 7.02 ddd (3H, $J = 9.3$, 8.5 and 1.5, 6-Ph), 3.75 s (6H, FPh–CH_2), 3.33 br (6H, ring CH_2), 2.63 m (6H, N–CH_2), 2.54 m (6H, S–CH_2). ^{13}C-{^{1}H} NMR ($CDCl_3$, 77.16 ppm): 161.0 d ($J_{CF} = 247$, 1-Ph), 131.1 d ($J_{CF} = 3.5$, J_{CH}(d) = 159, 3-Ph), 128.9 d ($J_{CF} = 9$, J_{CH}(dd) = 162 and 9, 5-Ph), 125.9 d (J_{CF} and J_{CH}(dddd) all about 5, 2-Ph), 124.3 d ($J_{CF} = 3.5$, J_{CH}(dd) = 162 and 8, 4-Ph), 115.6 d ($J_{CF} = 22$, J_{CH}(ddd) = 162, 8 and 2, 6-Ph), 74.0 (J_{CH}(tt) = 143 and 4, ring CH_2), 52.4 (J_{CH}(t) = 133, CH_2–N), 29.9 (J_{CH}(tt) = 139 and 4, CH_2–S), 28.9 d ($J_{CF} = 3$, J_{CH}(td) = 141 and 3, PhCH_2).

(Triazacyclohexane)tris(copper halide) complexes

CuCl, CuBr and CuI were purchased from Aldrich and used as received. In some cases indicated, CuBr was recrystallised as colourless CuBr(MeCN). No significant improvement of the cluster synthesis was found using this purer starting material.

2a. **1a** (333 mg, 0.92 mmol) and CuCl (274.4 mg, 2.77 mmol) were suspended in 100 mL of MeCN. The CuCl slowly dissolved. While stirring the mixture overnight, a yellow solid precipitated. The solid was filtered off and dried *in vacuo* to yield 230 mg. Removal of the solvent from the solution yielded another 273 mg of yellow product (total yield 83%). The product was slightly soluble in MeCN and DCM but not in THF. Crystals suitable for X-ray crystallography were grown from an MeCN solution.

Anal. found (calcd for $C_{21}H_{24}N_6Cl_3Cu_3$): C, 37.8 (38.36); H, 3.69 (3.68); N, 13.4 (12.78)%; recrystallised material contained one equivalent of MeCN: found (calcd for $C_{23}H_{27}N_7Cl_3Cu_3$): C, 39.45 (39.55); H, 3.89 (3.90); N, 14.05 (14.04)%.

^{1}H NMR (CD_3CN, 1.94 ppm): 8.54 d (3H, $J = 4.4$ Hz, 6-py), 7.80 td (3H, $J = 7.8$, 1.6 Hz, 4-py), 7.36 m (6H, 3- and 5-py), 3.97 s (6H, py-CH_2), 3.65 br (3H, eq. ring CH_2), 3.32 br (3H, ax. ring CH_2). ^{13}C-{^{1}H} NMR (CD_3CN, 1.32 ppm): 156.4 (2-py), 150.4

(6-py), 138.8 (4-py), 125.8, 125.0 (5- and 3-py), 74.5 (CH_2, ring), 58.3 (py-CH_2).

^{1}H NMR (CH_3CN, 1.93 ppm, 1.9 mM): 8.53 d (3H, J = 5.0, 6-py), 7.78 t (3H, J = 7.8, 4-py), 7.36 d (3H, J = 7.8, 3-py), 7.33 t (3H, J = 6.5, 5-py), 3.94 s (6H, py-CH_2), 3.58 br (3H, eq. ring CH_2), 3.29 br (3H, ax. ring CH_2). ^{13}C-{^{1}H} NMR (CH_3CN, 1.28 ppm): 156.3 (2-py), 150.0 (6-py), 138.5 (4-py), 125.4 (5-py), 124.6 (3-py), 73.9 (CH_2, ring), 58.0 (py-CH_2).

3a. CuBr (108 mg, 0.753 mmol) was dissolved in 5 mL of MeCN. This produced a slightly greenish solution with some insoluble solids. The solution was allowed to settle and the clear solution was decanted onto **1a** (66.8 mg, 0.185 mmol). A yellow solid was formed immediately. The mixture was shaken for 5 min, allowed to settle, the solution decanted and the residue washed with further 4 mL of MeCN, two portions of 4 mL Et_2O and dried *in vacuo* giving 122 mg of **3a** (83%). A saturated solution in MeCN was about 1–2 mM by NMR.

EI-HRMS: m/z found (calcd for $C_{21}H_{24}N_6Br_2Cu_3$ [M – Br]$^+$), 710.8311 (710.8275). Anal. found (calcd for **3a**·MeCN, $C_{23}H_{27}N_7Br_3Cu_3$): C, 33.1 (33.21); H, 3.22 (3.27); N, 11.7 (11.79)%.

^{1}H NMR (MeCN, 1.93 ppm, 2.2 mM): 8.57 d (3H, J = 4.2, 6-py), 7.76 t (3H, J = 7.8, 4-py), 7.32 m (6H, 3- and 5-py), 3.83 s (6H, pyCH_2), 3.71 br (3H, eq. ring CH_2), 3.16 br (3H, ax. ring CH_2).

^{1}H NMR (MeCN, 1.93 ppm, 1.0 mM): 8.65 d (3H, J = 4.2, 6-py), 7.81 t (3H, J = 7.8, 4-py), 7.40 t (3H, J = 6, 3-py), 7.32 d (3H, J = 7, 5-py), 3.86 d (3H, J = 8, eq. ring CH_2), 3.77 s (6H, pyCH_2), 3.05 br (3H, ax. ring CH_2) ppm. ^{13}C-{HMBCGPND} NMR (MeCN, 1.28 ppm): 155.5 (2-py), 150.0 (6-py), 138.3 (4-py), 124.9 (3-py and 5-py), 74.6 (ring CH_2), 58.0 (pyCH_2).

^{1}H NMR (MeCN–DCM (60 : 40 w%), 1.93 ppm, 2.0 mM): 8.59 d (3H, J = 4.7, 6-py), 7.75 dt (3H, J = 1.3/7.8, 4-py), 7.34 t (3H, J = 6.4, 5-py), 7.29 d (3H, J = 7.2, 3-py), 3.82 s (6H, pyCH_2), 3.77 br (3H, eq. ring CH_2), 3.12 br (3H, ax. ring CH_2). ^{13}C-{HMBCGPND} NMR (MeCN, 1.28 ppm): 154.4 (2-py), 149.7 (6-py), 137.8 (4-py), 124.2 and 124.4 (3-py and 5-py), 74.6 (ring CH_2), 57.5 (pyCH_2).

^{1}H NMR (CH_2Cl_2, 5.30 ppm, 0.9 mM): 8.75 d (3H, J = 4.3, 6-py), 7.69 t (3H, J = 7.7, 4-py), 7.34 t (3H, J = 6.1, 3-py), 7.12 d (3H, J = 7.4, 5-py), 3.96 d (3H, J = 8.0, eq. ring CH_2), 3.66 s (6H, pyCH_2), 2.84 d (3H, J = 7, ax. ring CH_2) ppm.

^{1}H NMR ($PhNO_2$, *para*-H 7.68 ppm, 4.5 mM): 8.93 d (3H, J = 4, 6-py), (other pyridyl signal hidden by solvent), 4.25 br (3H, eq. ring CH_2), 3.98 s (6H, pyCH_2), 3.27 br (3H, ax. ring CH_2). ^{13}C-{^{1}H} NMR ($PhNO_2$, p-CH 135.32 ppm): 154.3 (2-py), 150.7 (6-py), 138.0 (4-py), (3-py and 5-py obscured by solvent), 75.9 (ring CH_2), 58.2 (pyCH_2).

3b. **1b** (1.20 g, 2.26 mmol) was dissolved in MeCN (60 mL) and CuBr (972 mg, 6.78 mmol) added. The mixture was stirred overnight and then allowed to settle. The clear yellow solution was decanted, layered with THF and then hexane and left standing in a glovebox. After several months, large yellow crystals formed. A saturated solution in fluorobenzene at 298 K is 0.6 mM.

EI-HRMS (fluorobenzene): m/z found (calcd for $C_{33}H_{48}N_6Br_3Cu_3$ [M]$^+$), 957.9277 (957.9337). Anal. found (calcd for $C_{33}H_{48}N_6Br_3Cu_3$): C, 41.0 (41.32); H, 5.01 (5.04); N, 8.44 (8.76)%.

^{1}H NMR (CD_3NO_2, 4.33 ppm): 8.585 d (3H, J = 5.44, 6-py), 7.463 d (3H, J = 5.09, 5-py), 7.391 s (3H, 3-py), 3.970 d (3H, J = 8.3, eq. ring CH_2), 3.798 s (6H, pyCH_2), 3.088 d (3H, J = 8.3, ax. ring CH_2), 1.323 d (27H, J = 1.57, ^{t}Bu). ^{13}C-{^{1}H} NMR (CD_3NO_2, 62.8 ppm): 163.7 (2-py), 154.9 (4-py), 150.5 (6-py), 122.6, 121.7 (3- and 5-py), 76.8 (ring CH_2), 58.8 (pyCH_2), 36.0 (C), 30.6 (CH_3).

^{1}H NMR ($PhNO_2$, p: 7.68 ppm, 5.0 mM): 8.86 d (3H, J = 5, 6-py) other py signals obscured by solvent, 4.31 d (3H, J = 8, eq. ring CH_2), 3.92 s (6H, pyCH_2), 3.29 d (3H, J = 8, ax. ring CH_2), 1.25 s (27H, ^{t}Bu).

^{1}H NMR (PhF, 0.6 mM): 8.77 br (3H, 6-py), (3,5-py covered by solvent), 4.05 br (3H, eq. ring CH_2), 3.40 s (6H, pyCH_2), 2.73 br (3H, ax. ring CH_2), 1.09 s (27H, ^{t}Bu).

2c. A saturated solution of NaCl (300 mg, 5.2 mmol) in water was prepared and degassed by bubbling nitrogen through it. In another flask, **3c** (300 mg, 0.285 mmol) was dissolved in dichloromethane and added into the saturated sodium chloride solution. Silver nitrate (145 mg, 0.855 mmol) was added to the mixture. The two phase mixture was stirred for 2 h. The organic phase (grey) was collected and the solvent evaporated leaving a white-grey solid in 62% yield.

ESI-HRMS: m/z found 880.0573 (880.0505 calcd for $C_{36}H_{51}Cl_2Cu_3N_3S_3$ [M – Cl]$^+$).

^{1}H NMR ($CDCl_3$, 0.9 mM): 7.10–7.25 (15H, sets of signals for Ph), 4.07 br (3H, eq. ring CH_2), 2.95 br (3H, ax. ring CH_2), 2.45–2.80 (24H, set of signals for CH_2–S, S–CH_2 and CH_2–N), 1.95 br (6H, Ph–CH_2–CH_2). ^{13}C-{^{1}H} NMR ($CDCl_3$): 140.02, 129.69, 127.54 and 125.5 (Ph), 72.98 (ring CH_2), 53.10 (CH_2–N), 35.22 (S–CH_2), 32.09 (Ph–CH_2), 31.67 ($CH_2CH_2CH_2$–S), 30.72 (CH_2–S).

3c. **1c** (140 mg, 0.228 mmol) was dissolved in dry acetonitrile (25 mL) and added to CuBr (98.2 mg, 685 mmol). The reaction ran overnight affording a green solution over a colourless precipitate. The solution was decanted and the colourless solid was washed with diethyl ether and dried *in vacuo* yielding 76% of the cluster.

ESI-HRMS: m/z 966.9420 found (966.9421 calcd for $C_{36}H_{50}Br_2Cu_3N_3S_3$ [M – Br]$^+$). Anal. found (calcd for $C_{36}H_{50}Br_3Cu_3N_3S_3$): C, 41.2 (41.09); H, 4.84 (4.88); N, 3.87 (3.99)%. Mp 180 °C.

^{1}H NMR ($CDCl_3$, 0.5 mM): 7.15–7.2 (15H, sets of signals for Ph), 4.23 d (3H, J = 7.6, eq. ring CH_2), 2.6–2.8 m (27H, Ph–CH_2, CH_2–S–CH_2CH_2–N, ax. ring CH_2), 1.98 m (6H, Ph–CH_2–CH_2), 2.5 t (6H, Ph–CH_2). ^{13}C-{^{1}H} NMR ($CDCl_3$): 138.31, 128.92, 128.67 and 125.5 (Ph), 74.49 (ring CH_2), 53.10 (CH_2–N), 35.22 (S–CH_2), 32.09 (Ph–CH_2), 31.66 ($CH_2CH_2CH_2$–S), 30.71 (CH_2–S).

^{1}H NMR ($CDCl_3$–CD_3NO_2, 4.33 ppm, 5 mM): 7.1–7.25 (15H, sets of signals for Ph), 4.2 d (3H, J = 8.1, eq. ring CH_2), 2.6–2.8 m (27H, Ph–CH_2, CH_2–S–CH_2CH_2–N, ax. ring CH_2), 2.0 m (6H, Ph–CH_2–CH_2).

4c. **3c** (200 mg, 0.19 mmol) was dissolved in dichloromethane. A saturated aqueous solution of NaI (200 mg, 1.34 mmol) was added over this solution. Both solutions were stirred for 1 h. The colourless organic phase was collected and the solvent evaporated under vacuum. A white solid was obtained in 71% yield.

ESI-HRMS: m/z 1063.9151 found (1063.9217 calcd for $C_{36}H_{51}Cu_3I_2N_3S_3$ [M – I]$^+$). Anal. found (calcd for

$C_{36}H_{51}I_3Cu_3N_3S_3$): C, 36.3 (36.23); H, 4.34 (4.31); N, 3.50 (3.52)%.

^{1}H NMR ($CDCl_3$, 4 mM): 7.10–7.25 (15H, sets of signals for Ph), 3.99 d (3H, $J = 8.0$, eq. ring CH_2), 3.23 d (3H, $J = 8.0$, ax. ring CH_2), 2.64 (18H, CH_2–S and S–CH_2CH_2N), 2.48 t (6H, $J = 7.2$, Ph–CH_2), 1.82 m (6H, Ph–CH$_2$–CH_2). ^{13}C-{^{1}H} NMR ($CDCl_3$): 141.48, 128.65, 128.63 and 126.20 (Ph), 75.49 (ring CH_2), 52.79 (CH_2–N), 35.04 (S–CH_2), 33.66 (Ph–CH_2), 31.9 ($CH_2CH_2CH_2$–S), 30.25 (CH_2–S).

3d. **1d** (200 mg, 0.394 mmol) was dissolved in acetonitrile (20 mL) and CuBr (MeCN) (0.169 mg, 1.18 mmol) was added. After stirring overnight the solvent was removed *in vacuo* and the colourless solid washed with hexane and dried *in vacuo* yielding 70% of **3d**.

Anal. found (calcd for $C_{27}H_{57}Br_3Cu_3N_3S_3$): C, 35.3 (34.12); H, 6.23 (6.05); N, 4.58 (4.42)%.

^{1}H NMR ($CDCl_3$, 7 mM): two broad peaks corresponding to ring CH_2 4.0 and 3.3, 2.75 m (12H, S–CH_2–CH_2–N), 2.56 d (6H, $J = 5.9$, CH_2–S), 1.47 m (3H, CH), 1.41 m (12H, CH$_3$–CH_2), 0.87 t (18H, $J = 7.3$, CH_3). ^{13}C-{^{1}H} NMR ($CDCl_3$): 70.69 (ring CH_2), 52.68 (CH_2–N), 40.39 (CH), 37.70 (S–CH_2), 31.32 (CH_2–S), 25.07 (CH$_3$–CH_2), 11.02 (CH_3).

2e. Direct method: **1e** (100 mg, 0.178 mmol) was dissolved in dry acetonitrile (20 mL) and degassed. The solution was added to CuCl (53 mg, 0.534 mmol) and the solution was stirred overnight. The solution was reduced under vacuum and the precipitate isolated. Crystallisation by slow evaporation of a solution in $CHCl_3$–$MeNO_2$ resulted in a small amount of crystals.

Anal. found (calcd for **2e** with 1.5 $CHCl_3$, $C_{31.5}H_{64.5}Cl_{7.5}Cu_3N_3S_3$): C, 36.5 (36.45); H, 6.33 (6.26); N, 4.05 (4.05)%.

Method *via* **3e**: **3e** (300 mg, 0.302 mmol) was converted to **2e** analogously to **2c** with saturated NaCl and $AgNO_3$ (153.69 mg, 0.904 mmol) in 58% yield.

ESI-HRMS: *m/z* 820.1474 found (820.1444 calcd for $C_{30}H_{63}Cl_2Cu_3N_3S_3$ [M – Cl]$^+$).

^{1}H NMR (DCM, 5.31 ppm, 33 mM): 4.10 br (3H, eq. ring CH_2), 2.93 q (3H, $J = 6.0$, CH), 2.74 m (6H, S–CH_2), 2.61 m (6H, N–CH_2), 2.59 br (3H, ax. ring CH_2), 1.60 m (12H, CH_2–CH), 1.40 m (12H, CH$_3$–CH_2), 0.90 t (18H, $J = 7.3$, CH_3). ^{13}C-{^{1}H} NMR (DCM, 53.73 ppm): 76.42 (J_{CH}(t) = 142, ring CH_2), 53.09 (J_{CH}(t) = 136, CH_2–N), 46.09 (J_{CH}(d) = 137, CH), 34.58 (J_{CH}(t) = 124, CH_2CH_2CH), 29.00 (J_{CH}(t) = 140, CH_2–S), 19.02 (J_{CH}(t) = 123, CH$_3$–CH_2), 13.92 (J_{CH}(qt) = 125 and 7.3, CH_3).

^{1}H NMR (PhF, 0.5 mM): 4.11 br (3H, eq. ring CH_2), 2.96 m (3H, CH), 2.61 m (6H, S–CH_2), 2.40 m (6H, N–CH_2), 2.59 br (3H, ax. ring CH_2), 1.63 m (12H, CH_2–CH), 1.40 m (12H, CH$_3$–CH_2), 0.85 t (18H, CH_3). ^{13}C-{^{1}H} NMR (PhF): 77.0 (ring CH_2), 54.0 (CH_2–N), 47.4 (CH), 35.4 (CH_2CH_2CH), 29.3 (CH_2–S), 19.7 (CH$_3$–CH_2), 14.4 (CH_3).

3e. **1e** (0.60 g, 1.0 mmol) was dissolved in acetonitrile (15 mL) and CuBr (0.46 g, 3.2 mmol) was added. After stirring overnight the solution was decanted, the solvent removed *in vacuo* yielding 68% of colourless solid **3e**.

ESI-HRMS: *m/z* 908.0416 found (908.0433 calcd for $C_{30}H_{63}Br_2Cu_3N_3S_3$ [M – Br]$^+$). Anal. found (calcd for $C_{30}H_{63}Br_3Cu_3N_3S_3$): C, 36.2 (36.31); H, 6.31 (6.40); N, 4.23 (4.23)%. Mp 163 °C.

^{1}H NMR ($CDCl_3$, 2 mM): 4.28 d (3H, $J = 7.7$, eq. ring CH_2), 3.0 q (3H, $J = 6$, CH), 2.80 m (6H, CH_2–N), 2.65 m (6H, CH_2–S), 2.61 d (3H, $J = 7$, ax. ring CH_2), 1.65 m, 1.60 m, 1.45 m and 1.40 m (6H each, CH$_3$–CH_2CH_2–CH), 0.91 t (18H, $J = 7.3$, CH_3). ^{13}C-{^{1}H} NMR ($CDCl_3$): 73.2 (ring CH_2), 53.76 (CH_2–N, J_{CH}(t) = 138), 46.76 (CH, J_{CH}(d) = 142), 34.78 (CH_2CH_2CH, J_{CH}(t) = 127), 28.90 (CH_2–S, J_{CH}(t) = 137), 19.29 (CH$_3$–CH_2, J_{CH}(t) = 125), 14.45 (CH_3, J_{CH}(q) = 117) ppm.

4e. **3e** (0.20 g, 0.2 mmol) was converted with aq. NaI to **4e** analogous to **4f** in 69% yield.

ESI-HRMS: *m/z* 1004.0271 found (1004.0271 calcd for $C_{30}H_{63}I_2Cu_3N_3S_3$ [M – I]$^+$). Anal. found (calcd for $C_{30}H_{63}I_3Cu_3N_3S_3$): C, 32.0 (31.79); H, 5.58 (5.60); N, 3.68 (3.71)%.

^{1}H NMR ($CDCl_3$): 4.22 d (3H, $J = 6.4$, eq. ring CH_2), 3.05 d (3H, $J = 6$, ax. ring CH_2), 2.95 q (3H, $J = 5$, CH), 2.80 br (12H, CH_2–N and S–CH_2), 1.65 m (12H, CH$_3$–CH_2CH_2), 1.45 m (12H, CH$_3$–CH_2CH$_2$), 0.92 t (18H, $J = 7.2$, CH_3). ^{13}C-{^{1}H} NMR ($CDCl_3$): 76.6 (ring CH_2), 55.60 (CH_2–N), 46.64 (CH), 34.59 (CH_2CH_2CH), 28.31 (CH_2–S), 19.33 (CH$_3$–CH_2), 14.53 (CH_3).

^{1}H NMR (CH_2Cl_2, 5.31 ppm, 97 mM): 4.18 d (3H, $J = 7.5$, eq. ring CH_2), 2.95 br (3H, ax. ring CH_2), 2.91 q (3H, $J = 5.3$, CH), 2.78 m (6H, S–CH_2), 2.71 m (6H, CH_2–N), 1.62 m and 1.58 m (6H each, CH$_3$–CH_2CH_2), 1.41 m and 1.39 m (6H each, CH$_3$–CH_2CH$_2$), 0.90 t (18H, $J = 7.3$, CH_3). ^{13}C-{^{1}H} NMR (CH_2Cl_2, 53.73 ppm): 76.77 (ring CH_2, J_{CH}(dd) = 141 and 153), 53.69 (CH_2–N, J_{CH}(dd) = 138), 46.23 (CH, J_{CH}(d) = 140), 34.27 (CH_2CH_2CH, J_{CH}(t) = 125), 27.90 (CH_2–S, J_{CH}(t) = 140), 19.08 (CH$_3$–CH_2, J_{CH}(t) = 125), 14.07 (CH_3, J_{CH}(t) = 125).

2f. **3f** (300 mg, 0.302 mmol) was converted to **2f** analogous to **2c** with saturated NaCl and $AgNO_3$ (153.69 mg, 0.906 mmol) in 60% yield.

ESI-HRMS: *m/z* 722.2471 found (722.2459 calcd for $C_{30}H_{63}Cl_2Cu_3N_3S_3$ [M – Cl]$^+$).

^{1}H NMR (1,2-dichloroethane, 3.73 ppm, 50 mM): 4.07 d (3H, $J = 8$, ax. ring CH_2), 2.71 br (6H, CH_2–N), 2.63 d (3H, $J = 8$, eq. ring CH_2), 2.57 br (6H, S–CH_2), 2.53 t (6H, $J = 7.3$, CH_2–S), 1.58 m (6H, CH_2–CH$_2$–S), 1.36 m and 1.2–1.3 (24H, sets of signals for CH_2–CH_2–CH_2–CH_2), 0.86 t (9H, $J = 7.5$, CH_3). ^{13}C-{^{1}H} NMR ($CDCl_3$): 76.21 (ring CH_2), 51.51 (CH_2–N), 32.37 (CH_2), 31.10 (CH_2), 29.31 (CH_2–S), 28.30 (CH_2), 28.18 (CH_2), 27.74 (CH_2), 22.02 (CH_2), 13.33 (CH_3).

3f. **1f** (2 g, 3.5 mmol) was dissolved in dry acetonitrile (35 mL) and CuBr (1.53 g, 10.7 mmol) was added. The cluster was soluble in acetonitrile. The solvent was removed *in vacuo* and the white solid was washed with hexane. After drying under vacuum, 2.5 g of a colourless solid (71% yield) was obtained.

ESI-HRMS: *m/z* 908.0416 found (908.0433 calcd for $C_{30}H_{63}Br_2Cu_3N_3S_3$ [M – Br]$^+$). Anal. found (calcd for $C_{37}H_{54}Br_3Cu_3N_3S_3$): C, 36.15 (36.31); H, 6.13 (6.40); N, 4.1 (4.23)%. Mp 155 °C.

^{1}H NMR ($CDCl_3$, 3 mM): 4.19 d (3H, $J = 7$, ax. ring CH_2), 3.12 d (3H, $J = 7$, eq. ring CH_2), 2.83 m (12H, S–CH_2 and CH_2–N), 2.63 t (6H, $J = 6.5$, CH_2–S), 1.65 m (6H, CH_2–CH$_2$–S), 1.2–1.5 (24H, set of signals for CH_2–CH_2–CH_2–CH_2), 0.9 t (9H, $J = 7.3$,

CH_3). ^{13}C-{^{1}H} NMR ($CDCl_3$): 74.45 (ring CH_2), 53.08 (CH_2–N), 33.09 (CH_2–S), 32.44 (CH_2), 32.11 (CH_2), 30.71 (CH_2), 30.23 (CH_2), 29.92 (CH_2), 29.23 (CH_2), 14.45 (CH_3).

^{1}H NMR (*o*-dichlorobenzene, 7.19 ppm, 21 mM): 4.17 d (3H, $J = 7.5$, eq. ring CH_2), 2.71 br (6H, CH_2–N), 2.58 d (3H, $J = 7.5$, ax. ring CH_2), 2.54 br (6H, CH_2–S), 2.53 t (6H, $J = 7.5$, SCH_2), 1.53 q (6H, $J = 7.3$, CH_2–CH_2–S), 1.1–1.2 (24H, CH_3–CH_2CH_2–CH), 0.83 t (9H, $J = 7.3$, CH_3).

4f. **3f** (200 mg, 0.2 mmol) was dissolved in dichloromethane. A saturated aqueous solution of NaI (200 mg, 1.3 mmol) was added and the mixture stirred for 1 h. The colourless organic phase was collected and the solvent evaporated under vacuum. A white solid was obtained in 65% yield.

ESI-HRMS: *m/z* 1004.0271 found (1004.0156 calcd for $C_{30}H_{63}I_2Cu_3N_3S_3$ $[M - I]^+$). Anal. found (calcd for $C_{30}H_{63}I_3Cu_3N_3S_3$): C, 33.3 (31.79); H, 5.82 (5.60); N, 3.87 (3.71)%.

^{1}H NMR ($CDCl_3$, 40 mM): 4.1 d (3H, $J = 7$, eq. ring CH_2), 3.5 d (3H, $J = 7$, ax. ring CH_2), 2.90 m and 2.85 m (12H, S–CH_2 and CH_2–N), 2.5 t (6H, $J = 7.5$, CH_2–S), 1.6 q (6H, $J = 7.1$, CH_2CH_2S), 1.2–1.4 m (24H, set of signals for CH_2–CH_2–CH_2–CH_2), 0.90 t (9H, $J = 6.9$, CH_3). ^{13}C-{^{1}H} NMR ($CDCl_3$): 74.65 (ring CH_2), 52.75 (CH_2–N), 34.05 (CH_2–S), 31.87 (CH_2), 29.61 (CH_2), 29.10 (CH_2), 28.94 (CH_2), 28.57 (CH_2), 22.74 (CH_2), 14.25 (CH_3).

3g. **1g** (175 mg, 0.263 mmol) was dissolved in acetonitrile (25 mL) and stirred while CuBr (113 mg, 0.79 mmol) was added into the solution. The reaction mixture was stirred overnight. The solution was decanted and the solvent pumped off, affording a white solid in 69% yield.

ESI-HRMS: *m/z* 1009.9936 found (1009.9969 calcd for $C_{39}H_{57}Br_2Cu_3N_3S_3$ $[M - Br]^+$). Anal. found (calcd for $C_{39}H_{57}Br_3Cu_3N_3S_3$): C, 40.0 (42.80); H, 4.77 (5.25); N, 3.61 (3.84)%. Mp 190 °C.

^{1}H NMR (*o*-dichlorobenzene, 7.0 mM): 6.63 s (6H, Ph), 4.24 d (3H, $J = 7.5$, eq. ring CH_2), 3.83 s (6H, Ph–CH_2–S), 2.70 m (6H, CH_2–N), 2.53 m (9H, CH_2–S and ax. ring CH_2), 2.31 s (18H, 2,6-CH_3), 2.13 s (9H, 4-CH_3). ^{13}C-{^{1}H} NMR (*o*-dichlorobenzene): 136.8 (*o*-Ph), 136.6 and 130.9 (*i* and *p*-Ph), 129.36 (*m*-Ph), 77.02 (ring CH_2), 53.70 (CH_2–N), 32.59 (S–CH_2), 31.19 (CH_2–S), 20.96 (CH_3), 20.55 (CH_3).

3h. **1h** (212 mg, 0.36 mmol) was dissolved in acetonitrile (15 mL) and stirred while three equivalents of CuBr (127 mg, 1.09 mmol) were added into the solution. The reaction mixture was stirred overnight. The solution was decanted and the solvent pumped off, affording a white solid that was washed with hexane and dried *in vacuo*. Yield 54%.

ESI-HRMS: *m/z* 925.9021 found (995.9030 calcd for $C_{33}H_{45}Br_2Cu_3N_3S_3$ $[M - Br]^+$). Anal. found (calcd for $C_{33}H_{45}Br_3Cu_3N_3S_3$): C, 39.12 (39.23); H, 4.77 (4.49); N, 4.15 (4.16)%.

^{1}H NMR (*o*-dichlorobenzene, 0.6 mM): 4.26 d (3H, $J = 7.8$, eq. ring CH_2), 3.75 s (6H, Ph–CH_2–S), 2.52 m (6H, CH_2–N), 2.45 m (6H, S–CH_2), 2.37 d (3H, $J = 7.8$, ax. ring CH_2), 2.18 s (9H, CH_3) (aromatic signals obscured by solvent). ^{13}C-{^{1}H} NMR (*o*-dichlorobenzene): 136.80, 132.24, 130.93, 130.74, 127.21 and 127.84 (Ph), 75.72 (ring CH_2), 53.45 (CH_2–N), 35.67 (S–CH_2), 32.02 (CH_2–S), 21.0 (CH_3).

2i. Direct method: **1i** (2 g, 3.375 mmol) was dissolved in MeCN and 3 equivalents of CuCl (1 g, 10.125 mmol) was added. A white precipitate was formed instantaneously. The white product was filtered, washed with hexanes and dried under vacuum affording a 85% yield of the cluster.

Method *via* halide exchange: a saturated solution of NaCl (300 mg, 1.76 mmol) in water was prepared and degassed by bubbling nitrogen through it. In another flask, **3i** (300 mg, 0.258 mmol) was dissolved in dichloromethane and added to the saturated sodium chloride solution. Silver nitrate (131 mg, 0.774 mmol) was added to the mixture. The two phase mixture was stirred for 2 h. The organic phase (grey) was collected and the solvent evaporated, leaving a white-grey solid in 54% yield.

ESI-HRMS: *m/z* 849.9251 found (849.9283 calcd for $C_{30}H_{36}Cl_2Cu_3F_3N_3S_3$ $[M - Cl]^+$). Anal. found (calcd for $C_{30}H_{36}Cl_3Cu_3F_3N_3S_3$): C, 40.5 (40.54); H, 4.03 (4.08); N, 5.00 (4.73)%.

^{1}H NMR ($CDCl_3$, 6 mM): 7.4, 7.2, 7.1, 7.0 (12H, set of signals for Ph), 4.3 br (3H, eq. ring CH_2), 3.95 br (6H, Ph–CH_2), 3.3 br (3H, ax. ring CH_2), 2.9 br (12H, S–CH_2–CH_2–N). ^{19}F NMR ($CDCl_3$): –117.2.

^{1}H NMR (DCM, 5.31 ppm, 10 mM): 7.45 t (3H, $J = 7.40$, 3-Ph), 7.25 q (3H, $J = 6.6$, 5-Ph), 7.13 t (3H, $J = 7.4$, 4-Ph), 7.03 t (3H, $J = 9.2$, 6-Ph), 4.18 d (3H, $J = 7.9$, eq. ring CH_2), 3.87 s (6H, FPh–CH_2), 2.70 m (6H, S–CH_2), 2.66 m (6H, N–CH_2), 2.63 (3H, ax. ring CH_2). ^{13}C-{^{1}H} NMR (DCM, 53.73 ppm): 160.8 d ($J_{CF} = 246$, 1-Ph), 131.6 d ($J_{CF} = 3.5$, 3-Ph), 129.2 d ($J_{CF} = 8.2$, $J_{CH} = 163$, 5-Ph), 124.5 d ($J_{CF} = 3.5$, $J_{CH} = 163$, 4-Ph), 123.8 d ($J_{CF} = 15$, 2-Ph), 115.2 d ($J_{CF} = 22$, $J_{CH} = 169$, 6-Ph), 76.7 ($J_{CH} = 150$, ring CH_2), 51.7 ($J_{CH} = 124$, CH_2–N), 29.6 ($J_{CH} = 130$, CH_2–S), 29.5 d ($J_{CF} = 2.4$, $J_{CH} = 143$, PhCH_2).

3i. **1i** (4 g, 6.75 mmol) was dissolved in dry acetonitrile (35 mL) and a solution of CuBr (2.9 g, 20.27 mmol) was added. A white solid precipitated instantaneously. This solid was filtered and washed several times with hexane. The solution was decanted and placed in the fridge. A crystalline solid precipitated. Both solids were dried under vacuum to give a combined yield of 94%.

ESI-HRMS: *m/z* 796.0228 found (795.9793 calcd for $[M - Br]^+$). Anal. Found (calcd for $C_{30}H_{36}Br_3Cu_3F_3N_3S_3$): C, 36.0 (35.25); H, 3.66 (3.55); N, 4.70 (4.11)% (calcd for **3j**·MeCN, $C_{32}H_{39}Br_3Cu_3F_3N_4S_3$: C, 36.15; H, 3.70; N, 5.27%).

^{1}H NMR ($CDCl_3$, 13 mM): 6.95–7.40 (12H, 4 sets of signals for Ph), 4.25 br (3H, eq. ring CH_2), 3.95 s (6H, Ph–CH_2), 3.75 br (3H, ax. ring CH_2), 3.0 m (12H, S–CH_2–CH_2–N). ^{19}F NMR ($CDCl_3$): –117.3.

^{1}H NMR ($CHCl_3$, 7.26 ppm, 8 mM): 7.38 t (3H, $J = 7$, 3-Ph), 7.18 q (3H, $J = 6$, 5-Ph), 7.07 t (3H, $J = 7.5$, 4-Ph), 6.99 t (3H, $J = 9.3$, 6-Ph), 4.21 d (3H, $J = 7.8$, eq. ring CH_2), 3.81 s (6H, FPh–CH_2), 3.36 d (3H, $J = 7.8$, ax. ring CH_2), 2.91 m (6H, N–CH_2), 2.72 m (6H, S–CH_2). ^{13}C-{^{1}H} NMR ($CHCl_3$, 77.36 ppm): 161.0 d ($J_{CF} = 247$, 1-Ph), 131.8 d ($J_{CF} = 3.9$, 3-Ph), 129.4 d ($J_{CF} = 7.3$, 5-Ph), 124.6 d ($J_{CF} = 3.8$, 4-Ph), 124.1 d ($J_{CF} = 15.0$, 2-Ph), 115.5 d ($J_{CF} = 21.5$, 6-Ph), 76.9 (ring CH_2), 52.1 (CH_2–N), 30.1 (PhCH_2), 29.6 (CH_2–S). (+ signals for 1 equiv. MeCN and 4 equiv. H_2O.)

^{1}H NMR (DCM, 5.31 ppm, 17 mM): 7.41 td (3H, $J = 7.6$ and 1.6, 3-Ph), 7.24 q (3H, $J = 7.9$, 5-Ph), 7.11 td (3H, $J = 7.5$ and

1.0, 4-Ph), 7.03 t (3H, $J = 9.2$, 6-Ph), 4.22 d (3H, $J = 8.2$, eq. ring CH_2), 3.83 s (6H, FPh–CH_2), 2.75 d (3H, $J = 8.0$, ax. ring CH_2), 2.68 m (6H, N–CH_2), 2.68 m (6H, S–CH_2). ^{13}C-{^{1}H} NMR (DCM, 53.73 ppm): 160.8 d ($J_{CF} = 246$, 1-Ph), 131.5 d ($J_{CF} = 3.7$, 3-Ph), 129.2 d ($J_{CF} = 8.1$, 5-Ph), 124.5 d ($J_{CF} = 3.5$, 4-Ph), 123.8 d ($J_{CF} = 15$, 2-Ph), 115.3 d ($J_{CF} = 22$, 6-Ph), 77.1 (ring CH_2), 52.0 (CH_2–N), 29.7 d ($J_{CF} = 2.5$, PhCH_2), 29.1 (CH_2–S). (+ signals for 1 equiv. MeCN.)

4i. Direct method: **1i** (4 g, 6.75 mmol) was dissolved in MeCN and 3 equivalents of CuI (2.9 g, 20.27 mmol) were added. A white precipitate was formed instantaneously. The white product was filtered, washed with hexanes and dried under vacuum affording a 94% yield of the cluster.

Method *via* halide exchange: **3i** (200 mg, 0.19 mmol) was dissolved in dichloromethane. A saturated aqueous solution of NaI (300 mg, 2 mmol) was added over this solution. Both solutions were stirred for 1 h. The colourless organic phase was collected and the solvent evaporated under vacuum. A white solid was obtained in 76% yield.

ESI-HRMS: m/z 1043.8915 found (1043.8783 calcd for $C_{30}H_{36}Cu_3F_3I_2N_3S_3$ [M – I]$^+$). Anal. found (calcd for $C_{30}H_{36}Cu_3F_3I_3N_3S_3$): C, 31.20 (30.98); H, 3.56 (3.12); N, 3.54 (3.61)%.

^{1}H NMR ($CDCl_3$, 8 mM): 7.37 t (3H, $J = 7$, 3-Ph), 7.23 m (3H, 5-Ph), 7.10 t (3H, $J = 7$, 4-Ph), 7.01 t (3H, $J = 9$, 6-Ph), 4.3 d (3H, $J = 8$, eq. ring CH_2), 3.8 s (6H, Ph–CH_2), 3.3 d (3H, $J = 8$, ax. ring CH_2), 2.9 m (6H, CH_2–N), 2.7 m (6H, CH_2–S). ^{19}F NMR ($CDCl_3$): –117.7.

^{1}H NMR (DCM, 5.31 ppm, 4.4 mM): 7.40 t (3H, $J = 7.6$, 3-Ph), 7.26 q (3H, $J = 7.9$, 5-Ph), 7.13 t (3H, $J = 7.5$, 4-Ph), 7.04 t (3H, $J = 9.2$, 6-Ph), 4.29 d (3H, $J = 7.9$, eq. ring CH_2), 3.81 s (6H, FPh–CH_2), 2.66 m (6H, N–CH_2), 2.70 d (3H, $J = 8.6$, ax. ring CH_2), 2.66 m (6H, S–CH_2). ^{13}C-{^{1}H} NMR (DCM, 53.73 ppm): 160.8 d ($J_{CF} = 246$, 1-Ph), 131.4 d ($J_{CF} = 3.5$, 3-Ph), 129.2 d ($J_{CF} = 8.1$, 5-Ph), 124.6 d ($J_{CF} = 3.1$, 4-Ph), 123.9 d ($J_{CF} = 15$, 2-Ph), 115.2 d ($J_{CF} = 22$, 6-Ph), 77.6 (ring CH_2), 51.7 (CH_2–N), 30.7 (CH_2–S), 28.1 d ($J_{CF} = 5$, PhCH_2).

Computational details

All calculations reported in this paper have been obtained with the ORCA electronic structure program version 2.6.35.[6] A Wachters basis set[11] was used for copper and contracted triple-ζ quality basis sets with a polarisation for all other atoms (TZVP[12]). Ahlrich's auxiliary basis sets TZV/J[13] for all atoms were used for the RI method. The ORCA implementation of zero-order relativistic correction (ZORA) and of a COSMO solvent model with infinite ε was used for all calculations.

DFT calculations were performed with the BP86 and B3LYP functionals.[14] Geometry optimisation was done with the former using the RI method as implemented in ORCA. Maximum integration grid 7 was used for the heavier atoms Cu, Br and I. The use of Grimme's van der Waals corrections[15] gave shorter bond distances without substantial improvements relative to the experimental structures. The much slower B3LYP functional was used in some cases in single point calculations of the NMR shifts for comparison. NMR shifts were calculated using the IGLO method as implemented in ORCA relative to TMS calculated with the same method as reference. In the case of **2a**, the structures were optimised for both the *sym* and *asym* conformer. The energy difference at the RI-BP86 level was small (1.76 kJ mol^{-1}) without a significant difference in the NMR parameters or the bond lengths to copper . The values given are those for the slightly more stable *asym* form. Bond lengths were found to differ up to 0.1 Å (Cu–Cu up to 0.3 Å) compared to the crystal structures. Only hydrogens were optimised with all other atoms at the fixed coordinates of the best crystal structure (**3b**) to estimate the effect of different bond lengths on the electronic structure and calculated NMR parameters.

Crystal data and refinement details for 1a, 2a, 3a-A, 3a-B, 3b, 2e, 3h and 4i. Intensity data for all structures were collected at 150 K on a Nonius Kappa CCD diffractometer equipped with an Oxford cryostream, using graphite monochromated Mo Kα radiation ($\lambda =$ 0.71073 Å). Data were processed using the Nonius Software.[16] For **3a-B**, **3b**, **2e**, **3h** and **4i**, a symmetry-related (multi-scan) absorption correction was applied. Crystal parameters and details on data collection, solution and refinement for the complexes are provided in Table 2. Structure solution, followed by full-matrix least-squares refinement was performed using the WINGX-1.70 suite of programs throughout.[17]

2a and **3a-B** crystallise with two molecules of acetonitrile in the asymmetrical unit. One solvent molecule shows disorder with 50% occupation for both parts. **3a-A** contains solvent-accessible voids which could be filled with two solvent molecules of acetonitrile. However, these were so severely disordered that the PLATON programme SQUEEZE[18] was employed to take this model into the refinement process. Data collection of **2a** and **3h** resulted in weak data at high theta angles due to poor crystal quality despite numerous attempts on different crystals from several crystal batches. Refinement for **2a** still gave reasonable structural parameters but **3h** gave high R_{int} and R values with some unreasonable bond lengths. Hence, for **3h**, the phenyl rings of the ligands were idealised and bond lengths of C21–C22, C1–N3 and C3–N3 restrained. The asymmetrical unit of **4i** contains one solvent molecule of CH_2Cl_2.

Conclusions

Well defined triangular tricopper complexes supported by pyridyl- and thioether-functionalised triazacyclohexanes have been synthesised and characterised. Their much improved solubility and stability allows investigations in solution and gives access to the exploration of their chemistry. The cluster complexes are robust enough to allow exchange of the halide bridges in aqueous media. Future studies will explore the introduction of non-halide bridges by this method to make these triangular clusters more similar to the (hydr)oxo bridges typical of natural enzymes.

The tricopper complexes were well characterised by NMR spectroscopy. In particular the characteristic equatorial and axial ring hydrogen signals of the triazacyclohexanes were very sensitive to changes in the N-substituents, halide bridges and even the solvent, and showed, at least in some cases, a surprising exchange on the NMR time scale. Relatively low-level DFT calculations were able to reproduce the structures and NMR spectra reasonably well to aid the assignments and indicate an empty orbital in the centre of the copper triangle that could be involved in reactions with nucleophiles.

Table 2 Crystal and structure refinement data for **1a**, **2a**, **3a-A**, **3a-B**, **3b**, **2e**, **3h** and **4i**

Compound	**1a**	**2a**	**3a-A**	**3a-B**	**3b**	**2e**	**3h**	**4i**
Formula	$C_{21}H_{24}N_6$	$C_{23}H_{27}Cl_3Cu_3N_7$	$C_{21}H_{24}Br_3Cu_3N_6$	$C_{23}H_{27}Br_3Cu_3N_7$	$C_{33}H_{48}Br_3Cu_3N_6$	$C_{30}H_{63}Cl_3Cu_3N_3S_3$	$C_{33}H_{45}Br_3Cu_3N_3S_3$	$C_{31}H_{38}C_{12}Cu_3F_3I_3N_3S_3$
M_w	360.46	698.49	790.81	831.87	959.12	858.98	1010.25	1248.04
Crystal system	Triclinic	Triclinic	Triclinic	Triclinic	Triclinic	Monoclinic	Monoclinic	Monoclinic
Space group	*P*-1	*P*-1	*P*-1	*P*-1	*P*-1	$P2_1/n$	$P2_1/a$	$P2_1/n$
a/Å	10.0590(3)	11.3310(8)	7.3337(3)	11.50940(10)	7.42200(10)	22.3040(3)	19.5700(8)	12.78690(10)
b/Å	10.0802(3)	16.0940(9)	10.5558(5)	16.16180(10)	12.21700(10)	7.12300(10)	8.1390(3)	12.88420(10)
c/Å	10.5680(4)	16.8830(13)	18.1198(8)	17.23840(10)	20.9620(2)	25.6510(5)	23.9110(12)	24.9879(3)
α/°	88.1730(10)	62.264(3)	74.658(2)	62.5160(10)	82.5910(10)	90	90	90
β/°	82.2380(10)	84.221(2)	81.920(2)	83.9880(10)	84.0060(10)	102.4270(10)	103.246(2)	98.3490(10)
γ/°	61.5410(10)	79.050(3)	86.404(2)	79.1640(10)	79.9630(10)	90	90	90
U/Å^3	932.79(5)	2675.2(3)	1338.81(10)	2793.35(3)	1849.46(3)	3979.73(11)	3707.2(3)	4073.10(7)
D/g cm^{-3}	1.283	1.734	1.962	1.978	1.722	1.434	1.810	2.035
Z	2	4	2	4	2	4	4	4
Abs. coeff./mm^{-1}	0.080	2.690	6.859	6.581	4.982	1.971	5.136	4.152
Theta range for data collection/°	2.96 to 27.46	3.97 to 24.07	3.18 to 27.5	3.66 to 30.06	3.41 to 30.08	3.01 to 25.00	3.89 to 24.08	3.58 to 30.07
Reflections collected/ unique/ R_{int}	12625/4238/ 0.0387	10962/6886/ 0.0585	18540/6127/ 0.0943	70160/16330/ 0.0520	35778/10804/ 0.0635	38731/6925/ 0.0664	27748/5791/ 0.2015	68317/11880/0.1269
Data/restraints/ parameter	4238/0/244	6886/0/675	6127/0/299	16330/0/677	10804/0/415	6925/0/379	5791/3/338	11880/0/433
Largest diff. peak and hole/e Å^{-3}	0.180/–0.226	0.518/–0.599	0.717/–0.885	0.758/–0.998	0.904/–1.556	0.858/–0.657	2.929/–1.402	1.846/–2.078
Final $R^{a,b}$ indices [$I > 2\sigma(I)$]	0.0418, 0.1016	0.0524, 0.0939	0.0488, 0.0911	0.0342, 0.0788	0.0403, 0.0995	0.0506, 0.1159	0.1991, 0.4477	0.0546, 0.1333
$R^{a,b}$ indices (all data)	0.0568, 0.1101	0.0923, 0.1098	0.1059, 0.1065	0.0464, 0.0847	0.0506, 0.1058	0.0723, 0.1284	0.2383, 0.4677	0.0937, 0.1491

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

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References

1 E. I. Solomon, A. J. Augustine and J. Yoon, *Dalton Trans.*, 2008, 3921–3932 and references therein.
2 R. D. Köhn, Z. Pan, M. F. Mahon and G. Kociok-Köhn, *Chem. Commun.*, 2003, 1272–1273; R. D. Köhn, Z. Pan, M. Haufe and G. Kociok-Köhn, *Dalton Trans.*, 2005, 2793–2797.
3 G. Kickelbick, D. Rutzinger and T. Gallauner, *Monatsh. Chem.*, 2002, **133**, 1157–1164.
4 *e.g.* R. D. Köhn, P. Kampe and G. Kociok-Köhn, *Eur. J. Inorg. Chem.*, 2005, 3217–3223.
5 R. D. Köhn, G. Seifert, Z. Pan, M. F. Mahon and G. Kociok-Köhn, *Angew. Chem., Int. Ed.*, 2003, **42**, 793 and references therein.
6 F. Neese, *ORCA, an Ab Initio, Density Functional and Semiempirical Electronic Structure Program Package, Version 2.6, revision 35*, Max-Planck Institute for Bioinorganic Chemistry, Mülheim an der Ruhr, Germany, 2008.
7 A. J. Bridgeman, G. Cavigliasso, L. R. Ireland and J. Rothery, *J. Chem. Soc., Dalton Trans.*, 2001, 2095–2108 and references therein.
8 R. S. Mulliken, *J. Chem. Phys.*, 1955, **23**, 1833–1840.
9 R. D. Köhn, Z. Pan, M. F. Mahon and G. Kociok-Köhn, *J. Chem. Soc., Dalton Trans.*, 2003, 2269–2275.
10 R. T. Shuman, P. L. Ornstein, J. W. Paschal and P. D. Gesellchen, *J. Org. Chem.*, 1990, **55**, 738–741.
11 A. J. H. Wachters, *J. Chem. Phys.*, 1970, **52**, 1033; A. J. H. Wachters, *IBM Tech. Rept. RJ584*, 1969; F exponents; C. W. Bauschlicher, Jr, S. R. Langhoff and L. A. Barnes, *J. Chem. Phys.*, 1989, **91**, 2399.
12 A. Schaefer, H. Horn and R. Ahlrichs, *J. Chem. Phys.*, 1992, **97**, 2571; R. Ahlrichs and K. May, *Phys. Chem. Chem. Phys.*, 2000, **2**, 943; A. Schäfer, C. Huber and R. Ahlrichs, *J. Chem. Phys.*, 1994, **100**, 5829.
13 K. Eichkorn, O. Treutler, H. Ohm, M. Haser and R. Ahlrichs, *Chem. Phys. Lett.*, 1995, **240**, 283; K. Eichkorn, F. Weigend, O. Treutler and R. Ahlrichs, *Theor. Chem. Acc.*, 1997, **97**, 119.
14 A. D. Becke, *Phys. Rev. A*, 1988, **38**, 3098; J. P. Perdew, *Phys, Rev. B*, 1986, **33**, 8822; A. D. Becke, *J. Chem. Phys.*, 1993, **98**, 5648; C. Lee, W. Yang and R. G. Parr, *Phys. Rev. B*, 1988, **37**, 785.
15 S. Grimme, *J. Comput. Chem.*, 2006, **27**, 1787–1799 and references therein.
16 Z. Otwinowski and W. Minor, in *Methods in Enzymology, Volume 276: Macromolecular Crystallography, part A*, ed. C. W. Carter, Jr. and R. M. Sweet, Academic Press, 1997, pp. 307–326.
17 L. J. Farrugia, *J. Appl. Crystallogr.*, 1999, **32**, 837–838.
18 Sluis and A. L. Spek, *Acta Crystallogr., Sect. A*, 1990, **46**, 194–201.
19 Orbital contour plots were generated using gOpenMol version 3.00 (Leif Laaksonen *et al.*). The software is available free of charge at: http://www.csc.fi/english/pages/g0penMol (accessed 2008). Positive levels are shown in yellow (small) and red (large), negative levels in blue (light small and dark large.).

