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The synthesis and structure of a neutral tetranuclear zinc(II) complex $[Zn_4(L)_4]$ $[LH_2$ = *N*,*N*-bis(2-mercaptoethyl)benzylamine]

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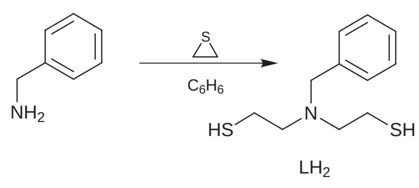
The reaction of benzylamine with ethylene sulfide yields the monoamine–dithiol *N*,*N*-bis(2-mercaptoethyl)benzylamine, LH_2. Reaction of Na_2L with $Zn(BF_4)_2$ affords the neutral tetranuclear complex $[Zn_4L_4]$, which shows an unusual Zn_4S_4 metallacyclic structure.

There are a number of metalloenzymes that incorporate Zn(II) thiolates in their prosthetic group. These include alcohol dehydrogenases,[1,2] metallothioneins,[3] and zinc fingers.[4] The study of thiolate complexes of Zn(II) as models for these enzymes, particularly of LADH (liver alcohol dehydrogenase),[2] has therefore become an active area of investigation.[5–7] Complexes of thiolates with Zn(II) show interesting co-ordination chemistry because of their tendency to form oligomers and clusters[8,9] comprising cages or aggregates of $[ZnS_4]$ units formed *via* S-bridging between metal centres. Other structures including binuclear[9,10] and tetrameric[11] species have been reported. Monomeric compounds featuring Zn(II) co-ordinated to an NS_2-donor set have also been reported as models for the active centre of LADH.[6,12,13] These are rare examples of non-polymeric neutral Zn(II) complexes of the type $Zn(SR)_2$ containing tetrahedrally co-ordinated Zn(II) ions bridged by RS^-. As part of a study of thiolate-bridged complexes of biological significance,[7,14] we report herein a novel, neutral tetranuclear Zn(II) system with bridging thiolates.

The sodium salt of the ligand *N*,*N*-bis(2-mercaptoethyl)-benzylamine (LH_2)[15,16] (Scheme 1) reacts with $Zn(BF_4)_2$ in a 1 : 1 molar ratio in THF to give a white solid after removal of the solvent.† Colourless crystals suitable for crystallographic studies were grown by diffusion of Et_2O vapour into a solution of the complex in $CHCl_3$. Elemental analysis, IR spectroscopy and FAB mass spectrometry confirm the product to have the stoichiometry $[Zn_4L_4]$ and this was confirmed by X-ray diffraction studies on a single crystal of the diethyl ether hemi-solvate.‡



Scheme 1

The complex contains four crystallographically independent Zn(II) centres (Fig. 1), each co-ordinated by an equivalent $[NS_3]$ donor set comprising a tertiary amine from one ligand [Zn–N 2.109(3)–2.161(4) Å], one thiolate donor from the same ligand co-ordinated terminally [Zn–$S_{terminal}$ 2.261(4) Å] and a second thiolate bridging two Zn(II) ions in two different [ZnL] units [Zn–$S_{bridging}$ 2.313(2)–2.3572(14) Å]. Therefore, an overall Zn_4S_4 metallacycle is formed within the structure. Most of the previously reported structures of Zn(II) with mixed amine–thiolate ligands involve the N-donors as part of a heteroaromatic ring (pyrazoles, imidazoles and pyridines).[5,6,12,13,17] In this case we observe a rare example[9,11,12] of aliphatic amine group functionality at Zn(II). Lippard and co-workers have reported[11] a tetranuclear Zn(II) complex with the ligand *N*,*N*′-dimethyl-*N*,*N*′-bis(2-mercaptoethyl)ethylenediamine (L^1H_2) (see below) to give $[Zn_4Cl_4(L^1)_2]$, while Darensbourg and co-workers have prepared[9] a neutral binuclear Zn(II) complex $[Zn_2(L^2)_2]$ [L^2H_2 = *N*,*N*′-bis(2-mercaptoethyl)-1,5-diazacyclooctane] (see below). The bond distances in both of these structures[9,11] are similar to those in $[Zn_4(L)_4]$ with Zn–N bond lengths of 2.079(11), 2.103(11) Å, Zn–$S_{bridging}$ 2.284(4)–2.356(4) Å,[11] and Zn–N 2.231(2)–2.255(2) Å, Zn–$S_{terminal}$ 2.327(1) Å, Zn–$S_{bridging}$ 2.394(1)–2.494(1) Å, respectively.[9]

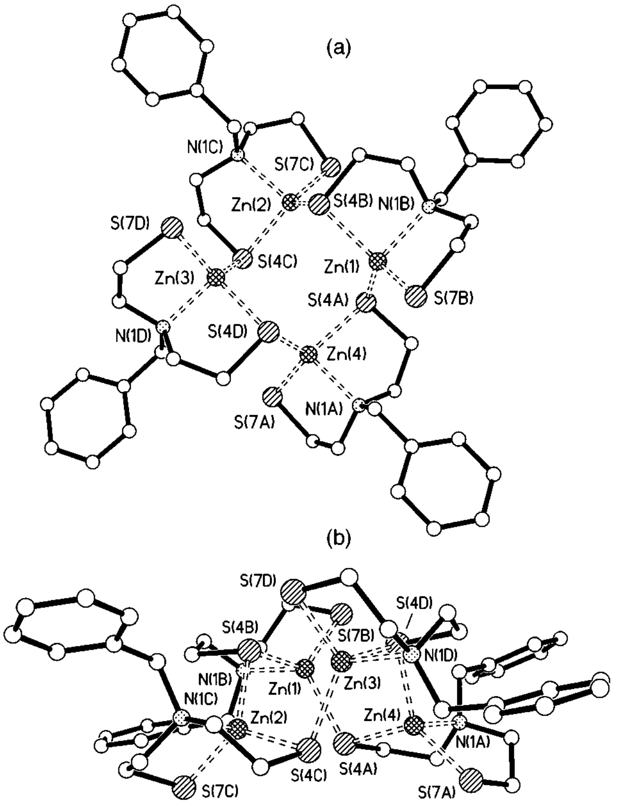
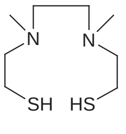
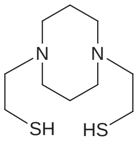


Fig. 1 Complementary views of the structure of $[Zn_4(L)_4]\cdot0.5Et_2O$ with numbering scheme adopted. Hydrogen atoms and solvent molecule are omitted for clarity. (a) View approximately along *a* axis; (b) view approximately along *c* axis.



L^1H_2



L^2H_2

Interestingly, tetrahedral co-ordination at Zn(II) in [Zn$_4$(L)$_4$] is highly distorted with rather acute N–Zn–S$_{\text{terminal}}$ and N–Zn–S$_{\text{bridging}}$ angles, N1B–Zn1–S7B 91.27(10), N1C–Zn2–S7C 92.62(11), N1D–Zn3–S7D 91.97(11), N1A–Zn4–S7A 91.70(11), N1B–Zn1–S4B 88.86(11), N1C–Zn2–S4C 91.17(11), N1D–Zn3–S4D 90.35(10), N1A–Zn4–S4A 88.69(10)°, and expanded S$_{\text{bridging}}$–Zn–S$_{\text{terminal}}$ angles, S7B–Zn1–S4B 125.93(6), S4C–Zn2–S7C 125.03(6), S4D–Zn3–S7D 122.29(5), S4A–Zn4–S7A 129.79(5)°. This distortion is probably due to the steric factors inherent in the formation of the tetranuclear complex and within individual [ZnL] units. The aromatic rings orientate themselves *exo* to the central Zn$_4$S$_8$ core and are arranged alternately up and down (Fig. 1b) due to the inversion of successive ligand units around the metallocyclic [Zn$_4$S$_4$] centre. This also reduces the steric interactions between the aromatic rings. There is no evidence of π–π stacking either within or between molecules. FAB and electrospray mass spectrometry confirm the integrity of the complex, at least in part, in solution with molecular ions observed for the monomer, dimer, trimer and tetramer.[18]

Current work is aimed at further developing thiolate chemistry at Zn(II) and related biologically relevant metal ions.

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Notes and references

† Synthesis of LH$_2$ and Na$_2$L. Benzylamine (5 g, 0.0467 mol) in benzene (5 cm^3) was placed in a Schlenk tube flushed with N$_2$. Ethylene sulfide (5.9 g, 0.098 mol) in benzene (5 cm^3) was added dropwise and the resulting solution stirred at 65 °C. After 48 h analysis by ^{1}H and ^{13}C NMR spectroscopy confirmed that a mixture of starting material and mono-substituted product was present. A further two equivalents of ethylene sulfide (5.9 g, 0.098 mol) were added and the solution left stirring under N$_2$ at 65 °C. After a further 48 h, analysis by NMR spectroscopy revealed that the reaction had gone to completion. The bulk solution was filtered and the excess solvent removed *in vacuo* to yield a foul-smelling yellow oil. The oil was redissolved in CH$_2$Cl$_2$, the solution filtered through a plug of silica to remove polymeric impurities, and the excess solvent removed *in vacuo* to yield a clear oil (5.32 g, 0.023 mol, 52%) which was stored under N$_2$. IR spectroscopy $\nu_{\max}$/cm^{-1} (neat) 3059w, 3025w, 2962m, 2935m, 2803m, 2552w, 1600w, 1493m, 1369w, 1293w, 1260m, 1109m, 1028, 734, 698m (Found: C, 57.35; H, 7.71; N, 5.81. C$_{11}$H$_{17}$NS$_2$ requires C, 58.15; H, 7.49; N, 5.81%). δ_H (CDCl$_3$) 1.68 (2H, s, CH$_2$S*H*), 2.64 (4H, m, NCH$_2$C*H*$_2$SH), 2.70 (4H, m, NC*H*$_2$CH$_2$SH), 3.64 (2H, s, PhC*H*$_2$N) and 7.34 (5H, m, H of Ph). δ_C (CDCl$_3$) 22.87 (CH$_2$SH), 57.13 (NCH$_2$CH$_2$SH), 58.63 (PhCH$_2$N), 127.28, 128.42 and 128.92 (CH of Ph) and 138.91 (*ipso* C). *m*/*z* (EI) 225 (M$^+$). **CAUTION**: The ligand has been found to cause severe allergic reactions and contact with skin should be avoided.

Na$_2$L was prepared in quantitative yield by reaction of NaH (0.127 g, 5.29 mmol) with LH$_2$ (0.4 g, 1.76 mmol) in THF.

Preparation of [Zn$_4$L$_4$]. Reaction of Na$_2$L with Zn(BF$_4$)$_2$ (1 : 1 molar ratio) in THF gave a white solid after removal of the solvent. The solid was dissolved in CHCl$_3$ and the solution filtered to remove sodium salts. The solution was reduced in volume and the complex crystallised by addition of Et$_2$O (Found: C, 44.25; H, 5.61; N, 4.44. Calc. for C$_{46}$H$_{65}$N$_4$S$_8$O$_{0.5}$Zn$_4$: C, 44.04; H, 5.42; N, 4.67%). IR (KBr)/cm^{-1}: 3025w, 2921w, 2849w, 1629s, 1494s, 1452s, 1310m, 1095m, 1003m, 825m, 721w, 668w. *m*/*z* (+ve FAB) 1156 (^{64}Zn$_4$L$_4$)$^+$, 868 (^{64}Zn$_3$L$_3$ + 1)$^+$, 579 (^{64}Zn$_2$L$_2$ + 1)$^+$ with correct isotopic distribution. *m*/*z* (+ve ES) 1161 (M$^+$), 874 and 581.

‡ Crystal data: C$_{44}$H$_{60}$N$_4$S$_8$Zn$_4$·0.5C$_4$H$_{10}$O, M = 1199.98, triclinic, space group $P\bar{1}$, a = 13.926(3), b = 14.593(3), c = 14.631(5) Å, α = 88.90(2), β = 88.70(2), γ = 62.674(14)°, U = 2640.7(12) Å^3, T = 220 K, Z = 2, D_c = 1.509 g cm^{-3}, λ(Cu-Kα) = 1.54184 Å, μ = 5.297 mm^{-1}. 9255 unique data measured and used in all calculations. A molecule of Et$_2$O was found to be half-occupied and disordered over two sites. Final $wR(F^2)$ was 0.104, R_1 = 0.0448. CCDC reference number 186/1354. See http://www.rsc.org/suppdata/dt/1999/1041 for crystallographic files in .cif format.

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