

# The synthesis and structure of a neutral tetranuclear zinc(II) complex $[\text{Zn}_4(\text{L})_4]$ [ $\text{LH}_2 = N,N$ -bis(2-mercaptoethyl)benzylamine]

Douglas J. E. Spencer,<sup>a</sup> Alexander J. Blake,<sup>a</sup> Simon Parsons<sup>b</sup> and Martin Schröder<sup>\*a</sup>

<sup>a</sup> School of Chemistry, The University of Nottingham, Nottingham, UK NG7 2RD

<sup>b</sup> Department of Chemistry, The University of Edinburgh, West Mains Road, Edinburgh, UK EH9 3JJ

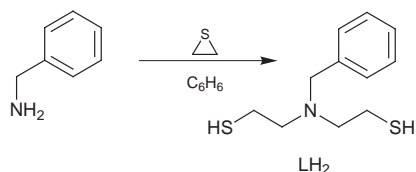
Received 2nd November 1998, Revised manuscript received 16th February 1999,

Accepted 16th February 1999

The reaction of benzylamine with ethylene sulfide yields the monoamine–dithiol  $N,N$ -bis(2-mercaptoethyl)benzylamine,  $\text{LH}_2$ . Reaction of  $\text{Na}_2\text{L}$  with  $\text{Zn}(\text{BF}_4)_2$  affords the neutral tetranuclear complex  $[\text{Zn}_4\text{L}_4]$ , which shows an unusual  $\text{Zn}_4\text{S}_4$  metallacyclic structure.

There are a number of metalloenzymes that incorporate  $\text{Zn}(\text{II})$  thiolates in their prosthetic group. These include alcohol dehydrogenases,<sup>1,2</sup> metallothioneins,<sup>3</sup> and zinc fingers.<sup>4</sup> The study of thiolate complexes of  $\text{Zn}(\text{II})$  as models for these enzymes, particularly of LADH (liver alcohol dehydrogenase),<sup>2</sup> has therefore become an active area of investigation.<sup>5–7</sup> Complexes of thiolates with  $\text{Zn}(\text{II})$  show interesting co-ordination chemistry because of their tendency to form oligomers and clusters<sup>8,9</sup> comprising cages or aggregates of  $[\text{ZnS}_4]$  units formed *via* S-bridging between metal centres. Other structures including binuclear<sup>9,10</sup> and tetrameric<sup>11</sup> species have been reported. Monomeric compounds featuring  $\text{Zn}(\text{II})$  co-ordinated to an  $\text{NS}_2$ -donor set have also been reported as models for the active centre of LADH.<sup>6,12,13</sup> These are rare examples of non-polymeric neutral  $\text{Zn}(\text{II})$  complexes of the type  $\text{Zn}(\text{SR})_2$  containing tetrahedrally co-ordinated  $\text{Zn}(\text{II})$  ions bridged by  $\text{RS}^-$ . As part of a study of thiolate-bridged complexes of biological significance,<sup>7,14</sup> we report herein a novel, neutral tetranuclear  $\text{Zn}(\text{II})$  system with bridging thiolates.

The sodium salt of the ligand  $N,N$ -bis(2-mercaptoethyl)-benzylamine ( $\text{LH}_2$ )<sup>15,16</sup> (Scheme 1) reacts with  $\text{Zn}(\text{BF}_4)_2$  in a



Scheme 1

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  $\text{Et}_2\text{O}$  vapour into a solution of the complex in  $\text{CHCl}_3$ . Elemental analysis, IR spectroscopy and FAB mass spectrometry confirm the product to have the stoichiometry  $[\text{Zn}_4\text{L}_4]$  and this was confirmed by X-ray diffraction studies on a single crystal of the diethyl ether hemi-solvate.‡

The complex contains four crystallographically independent  $\text{Zn}(\text{II})$  centres (Fig. 1), each co-ordinated by an equivalent  $[\text{NS}_2]$  donor set comprising a tertiary amine from one ligand [ $\text{Zn}-\text{N}$  2.109(3)–2.161(4) Å], one thiolate donor from the same ligand co-ordinated terminally [ $\text{Zn}-\text{S}_{\text{terminal}}$  2.261(4) Å] and a second thiolate bridging two  $\text{Zn}(\text{II})$  ions in two different  $[\text{ZnL}]$  units [ $\text{Zn}-\text{S}_{\text{bridging}}$  2.313(2)–2.357(14) Å]. Therefore, an overall  $\text{Zn}_4\text{S}_4$  metallacycle is formed within the structure. Most of the previously reported structures of  $\text{Zn}(\text{II})$  with mixed amine–thiolate ligands involve the N-donors as part of a heteroaromatic ring (pyrazoles, imidazoles and pyridines).<sup>5,6,12,13,17</sup> In this

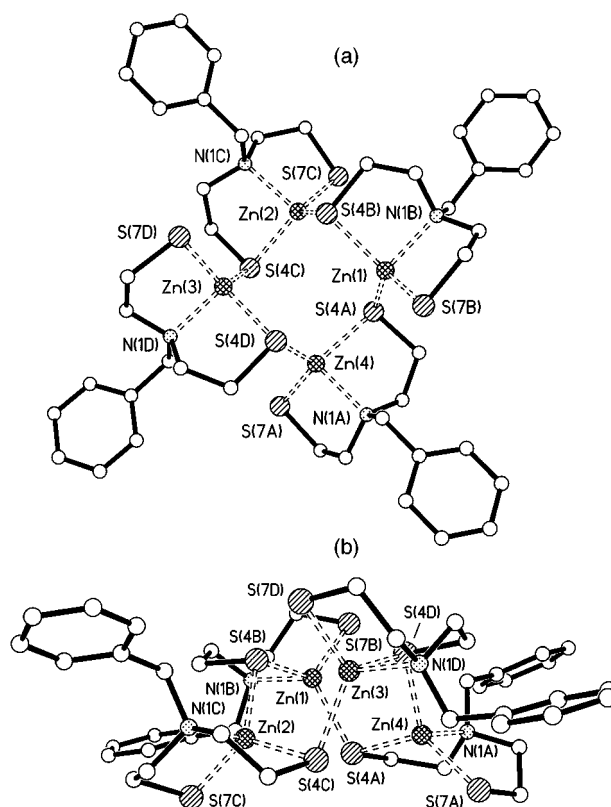
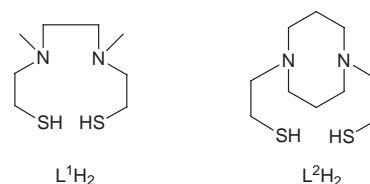


Fig. 1 Complementary views of the structure of  $[\text{Zn}_4(\text{L})_4] \cdot 0.5\text{Et}_2\text{O}$  with numbering scheme adopted. Hydrogen atoms and solvent molecule are omitted for clarity. (a) View approximately along  $a$  axis; (b) view approximately along  $c$  axis.

case we observe a rare example<sup>9,11,12</sup> of aliphatic amine group functionality at  $\text{Zn}(\text{II})$ . Lippard and co-workers have reported<sup>11</sup> a tetranuclear  $\text{Zn}(\text{II})$  complex with the ligand  $N,N'$ -dimethyl- $N,N'$ -bis(2-mercaptoethyl)ethylenediamine ( $\text{L}^1\text{H}_2$ ) (see below) to give  $[\text{Zn}_4\text{Cl}_4(\text{L}^1)_2]$ , while Darensbourg and co-workers have prepared<sup>9</sup> a neutral binuclear  $\text{Zn}(\text{II})$  complex  $[\text{Zn}_2(\text{L}^2)_2]$  [ $\text{L}^2\text{H}_2 = N,N'$ -bis(2-mercaptoethyl)-1,5-diazacyclooctane] (see below). The bond distances in both of these structures<sup>9,11</sup> are similar to those in  $[\text{Zn}_4(\text{L})_4]$  with  $\text{Zn}-\text{N}$  bond lengths of 2.079(11), 2.103(11) Å,  $\text{Zn}-\text{S}_{\text{bridging}}$  2.284(4)–2.356(4) Å,<sup>11</sup> and  $\text{Zn}-\text{N}$  2.231(2)–2.255(2) Å,  $\text{Zn}-\text{S}_{\text{terminal}}$  2.327(1) Å,  $\text{Zn}-\text{S}_{\text{bridging}}$  2.394(1)–2.494(1) Å, respectively.<sup>9</sup>



Interestingly, tetrahedral co-ordination at Zn(II) in  $[\text{Zn}_4(\text{L})_4]$  is highly distorted with rather acute N–Zn–S<sub>terminal</sub> and N–Zn–S<sub>bridging</sub> 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<sub>bridging</sub>–Zn–S<sub>terminal</sub> 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  $[\text{ZnL}]$  units. The aromatic rings orientate themselves *exo* to the central  $\text{Zn}_4\text{S}_8$  core and are arranged alternately up and down (Fig. 1b) due to the inversion of successive ligand units around the metallo-cyclic  $[\text{Zn}_4\text{S}_4]$  centre. This also reduces the steric interactions between the aromatic rings. There is no evidence of  $\pi$ – $\pi$  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.<sup>18</sup>

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

## Acknowledgements

We thank the EPSRC for support and the EPSRC Centre for mass spectrometry at the University of Swansea.

## Notes and references

† Synthesis of  $\text{LH}_2$  and  $\text{Na}_2\text{L}$ . Benzylamine (5 g, 0.0467 mol) in benzene (5 cm<sup>3</sup>) was placed in a Schlenk tube flushed with  $\text{N}_2$ . Ethylene sulfide (5.9 g, 0.098 mol) in benzene (5 cm<sup>3</sup>) was added dropwise and the resulting solution stirred at 65 °C. After 48 h analysis by <sup>1</sup>H and <sup>13</sup>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  $\text{N}_2$  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  $\text{CH}_2\text{Cl}_2$ , 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  $\text{N}_2$ . IR spectroscopy  $\nu_{\text{max}}/\text{cm}^{-1}$  (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).  $\text{C}_{11}\text{H}_{17}\text{NS}_2$  requires C, 58.15; H, 7.49; N, 5.81%.  $\delta_{\text{H}}$  ( $\text{CDCl}_3$ ) 1.68 (2H, s,  $\text{CH}_2\text{SH}$ ), 2.64 (4H, m,  $\text{NCH}_2\text{CH}_2\text{SH}$ ), 2.70 (4H, m,  $\text{NCH}_2\text{CH}_2\text{SH}$ ), 3.64 (2H, s,  $\text{PhCH}_2\text{N}$ ) and 7.34 (5H, m, H of Ph).  $\delta_{\text{C}}$  ( $\text{CDCl}_3$ ) 22.87 ( $\text{CH}_2\text{SH}$ ), 57.13 ( $\text{NCH}_2\text{CH}_2\text{SH}$ ), 58.63 ( $\text{PhCH}_2\text{N}$ ), 127.28, 128.42 and 128.92 (CH of Ph) and 138.91 (*ipso* C). *m/z* (EI) 225 ( $\text{M}^+$ ). **CAUTION:** The ligand has been found to cause severe allergic reactions and contact with skin should be avoided.

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

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

+ 1)<sup>+</sup>, 579 ( $^{64}\text{Zn}_2\text{L}_2 + 1$ )<sup>+</sup> with correct isotopic distribution. *m/z* (+ve ES) 1161 ( $\text{M}^+$ ), 874 and 581.

‡ Crystal data:  $\text{C}_{44}\text{H}_{60}\text{N}_4\text{S}_8\text{Zn}_4 \cdot 0.5\text{C}_4\text{H}_{10}\text{O}$ ,  $M = 1199.98$ , triclinic, space group  $P\bar{1}$ ,  $a = 13.926(3)$ ,  $b = 14.593(3)$ ,  $c = 14.631(5)$  Å,  $\alpha = 88.90(2)$ ,  $\beta = 88.70(2)$ ,  $\gamma = 62.674(14)^\circ$ ,  $U = 2640.7(12)$  Å<sup>3</sup>,  $T = 220$  K,  $Z = 2$ ,  $D_c = 1.509$  g cm<sup>-3</sup>,  $\lambda(\text{Cu-K}\alpha) = 1.54184$  Å,  $\mu = 5.297$  mm<sup>-1</sup>. 9255 unique data measured and used in all calculations. A molecule of  $\text{Et}_2\text{O}$  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.

- H. Eklund and C.-I. Bränden, in *Zinc Enzymes*, ed. T. G. Spiro, Wiley, New York, 1983, p. 124.
- Y. Pocker, in *Metal Ions In Biological Systems*, ed. H. Sigel and A. Sigel, Dekker, New York, 1989, vol. 25, p. 335; H. Eklund and C.-I. Bränden, in *Active Sites of Enzymes*, ed. F. A. Jornak and A. McPherson, *Biological Macromolecules and Assemblies*, Wiley, New York, 1987, vol. 3, ch. 2.
- J. H. R. Kägi, S. R. Himmelhoch, P. D. Whanger, J. L. Bethune and B. L. Vallee, *J. Biol. Chem.*, 1973, **39**, 127.
- W. Kaim and B. Schwederski, *Bioinorganic Chemistry: Inorganic Elements In the Chemistry of Life*, Wiley, New York, 1991, ch. 12.
- B. Kaptein, L. Wang-Griffin, G. Barf and R. M. Kellogg, *J. Chem. Soc., Chem. Commun.*, 1987, 1457; B. Kaptein, G. Barf, R. M. Kellogg and F. Van Bolhuis, *J. Org. Chem.*, 1990, **55**, 1890; R. M. Kellogg and R. P. Hof, *J. Chem. Soc., Perkin Trans. 1*, 1996, 1651 and refs. therein.
- C. Kimblin, T. Hascall and G. Parkin, *Inorg. Chem.*, 1997, **36**, 5680 and refs. therein.
- A. J. Blake, A. Marin-Becerra, N. D. J. Branscombe, W.-S. Li, S. Parsons, L. Ruiz-Ramirez and M. Schröder, *Chem. Commun.*, 1996, 2573.
- K. S. Hagen, D. W. Stephan and R. H. Holm, *Inorg. Chem.*, 1982, **21**, 3928; A. Choy, D. Craig, I. Dance and M. Scudder, *J. Chem. Soc., Chem. Commun.*, 1982, 1246; I. Dance, *J. Chem. Soc., Chem. Commun.*, 1980, 818; I. Dance, *J. Am. Chem. Soc.*, 1980, **102**, 3445; J. L. Hencher, M. A. Kahn, F. F. Said and D. G. Tuck, *Polyhedron*, 1985, **4**, 1263; R. H. Holm and M. J. O'Connor, *Prog. Inorg. Chem.*, 1971, **14**, 241; F. F. Sai and D. G. Tuck, *Inorg. Chim. Acta*, 1982, **59**, 1.
- T. Tuntulani, J. H. Reibenspies, P. J. Farmer and M. Y. Darensbourg, *Inorg. Chem.*, 1992, **31**, 3497.
- D. C. Goodman, T. Tuntulani, P. J. Farmer, M. Y. Darensbourg and J. H. Reibenspies, *Angew. Chem., Int. Ed. Engl.*, 1993, **32**, 116; C. A. Grapperhaus, T. Tuntulani, J. H. Reibenspies and M. Y. Darensbourg, *Inorg. Chem.*, 1998, **37**, 4052.
- W. J. Hu, D. Barton and S. J. Lippard, *J. Am. Chem. Soc.*, 1973, **95**, 467.
- S. C. Shoner, K. J. Humphreys, D. Barnhart and J. A. Kovacs, *Inorg. Chem.*, 1995, **34**, 5933.
- D. T. Corwin, Jr. and S. A. Koch, *Inorg. Chem.*, 1988, **27**, 493.
- A. J. Atkins, A. J. Blake and M. Schröder, *J. Chem. Soc., Chem. Commun.*, 1993, 1662; A. J. Atkins, A. J. Blake, D. Black, A. Marin-Becerra, S. Parsons, L. Ruiz-Ramirez and M. Schröder, *Chem. Commun.*, 1996, 457.
- G. J. Colpas, M. Kumar, R. O. Day and M. J. Maroney, *Inorg. Chem.*, 1990, **29**, 4779.
- S. A. Mirza, M. A. Pressler, M. Kumar, R. O. Day and M. J. Maroney, *Inorg. Chem.*, 1993, **32**, 977.
- L. F. Lindoy and D. H. Busch, *J. Chem. Soc., Chem. Commun.*, 1972, 683.
- C. K. Meng and J. B. Fenn, *Org. Mass Spectrom.*, 1991, **26**, 542.

Communication 9/01251F