Hydrolysis of Esters and Amides by the Metallo Nucleophile $Tp^{Cum,Me}Zn-OH$

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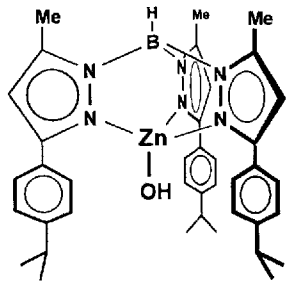
The molecular zinc hydroxide complex $Tp^{Cum,Me}Zn-OH$ [**1**, $Tp^{Cum,Me}$ = tris(3-cumenyl-5-methylpyrazolyl)hydroborate] is a powerful nucleophile. It effects stoichiometric hydrolysis of activated esters RCO−OX and amides RCO−NHX in nonaqueous media. The cleavage products are $Tp^{Cum,Me}Zn-OCOR$ and HOX or H_2NX, resp. Two of them ($Tp^{Cum,Me}Zn-OCO-CH_2-CH_2OH$ resulting from propiolactone and $Tp^{Cum,Me}Zn-OCO-CF_3$ resulting from trifluoroacetamide) were characterized by crystal structure determinations.

Metal ion catalysis is a standard procedure in hydrolytic reactions of organic compounds, and the conventional method of activation is the attachment of the metal ion as an electrophile to a carbonyl function[1]. It is less known that the metal ions are not only able to activate the substrates of hydrolytic reactions but also the reagent water by converting its OH constituent into the powerful metallo nucleophile M−OH. This latter mode of action is used for the cleavage by hydrolytic metallo enzymes which are almost exclusively zinc enzymes[2]. Convincing evidence for this was accumulated in recent years by investigations of the acid/base and nucleophile/electrophile properties of zinc-bound water in these enzymes[3].

In order to carry out mechanistic or model studies with metallo nucleophiles of the M−OH type one would like to work with isolable complexes containing the metal-bound hydroxide ligand. Relatively few of these are known in zinc chemistry, in contrast to the rich chemistry of basic zinc salts[4] or hydroxide-bridged oligonuclear zinc complexes[5]. Outside our own work only two such complexes containing tetrahedral zinc were fully characterized, Kimura's $[LZnOH]^+$ with L = [12]aneN$_3$[6] and Parkin's $[LZnOH]^+$ with L = tris(4-*tert*-butyl-2-isopropylimidazolyl)phosphane[7]. The first of these[6] and Wooley's $[(cyclam)ZnOH]^+$ complex[8] were found to be moderately efficient catalysts for CO_2 hydration and hydrolysis of activated esters. Kimura's complex[6] and Kitajima's LZnOH with L = tris(3,5-diisopropylpyrazolyl)hyroborate[9] were also found to cleave activated phosphate esters. To our knowledge hydrolysis of amides or peptides with L_3ZnOH complexes has not been reported so far.

We have been contributing to this in the field of (pyrazolylborate)zinc complexes, in competition with Parkin's[10] and the late Kitajima's[9] groups. The complexes LZnOH with L = $Tp^{tBu,Me}$[11] and $Tp^{Cum,Me}$ (**1**)[12] were fully characterized. The former has allowed the construction of a complete stoichiometric carbonic anhydrase model[11], the latter has turned out to be a stronger nucleophile and to be able to incorporate labile substrates in its highly encapsulating hydrophobic pocket around the zinc ion[12,13]. We therefore treated it with a series of substrates amenable to nucleophilic attack or nucleophilic cleavage. In this paper, of which a preliminary communication has appeared[14], we report on the results of the reactions with esters and amides.



$Tp^{Cum,Me}Zn-OH$ = **1**

Ester Cleavages

Esters are significantly more sensitive to metal-activated hydrolysis than amides[15], and peptide-cleaving metallo enzymes are often powerful esterases as well[16]. We therefore expected the strong nucleophile **1** to be able to cleave esters. This was borne out by the reactions with activated esters, albeit not with simple ones like ethyl acetate. As a rule and here as well, hydrolytic reactions of **1** are stoichiometric rather than catalytic which is attributed to the insolubility of **1** in protic solvents and the hydrolytic stability of the zinc-bound cleavage products. The latter, in turn, ensures the identification of the reaction course by fixing at least one of the leaving groups.

The three esters used bear their activation in the form of the efficient leaving groups *p*-nitrophenolate (**a**), trifluoroacetate 8**b**) or of the β-lactone ring tension (**c**). Their reactions with **1** in benzene or dichloromethane were complete

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in about half an hour at room temperature. The reaction products **2a–c** have the acid function of the esters coordinated to zinc as a monodentate carboxylate. In the case of *p*-nitrophenyl acetate the liberated *p*-nitrophenol reacts with **1** itself yielding the *p*-nitrophenolate complex **3**. In the case of propiolactone the liberated alcoholic function stays in the complex as part of the carboxylate ligand. Only with methyl trifluoroacetate the cleavage product methanol is really set free.

$$\underset{\mathbf{1}}{Tp^{Cum,Me}Zn\text{-}OH} + RO\text{-}C(O)R' \rightarrow ROH + \underset{\mathbf{2}}{Tp^{Cum,Me}Zn\text{-}OC(O)R'}$$

$$\mathbf{1} + O_2N\text{-}C_6H_4O\text{-}C(O)Me \rightarrow O_2N\text{-}C_6H_4OH + \mathbf{2a}\ (R' = Me)$$

$$\mathbf{1} + MeO\text{-}C(O)CF_3 \rightarrow MeOH + \mathbf{2b}\ (R' = CF_3)$$

$$\mathbf{1} + \text{propiolactone} \rightarrow \mathbf{2c}\ (R' = CH_2CH_2OH)$$

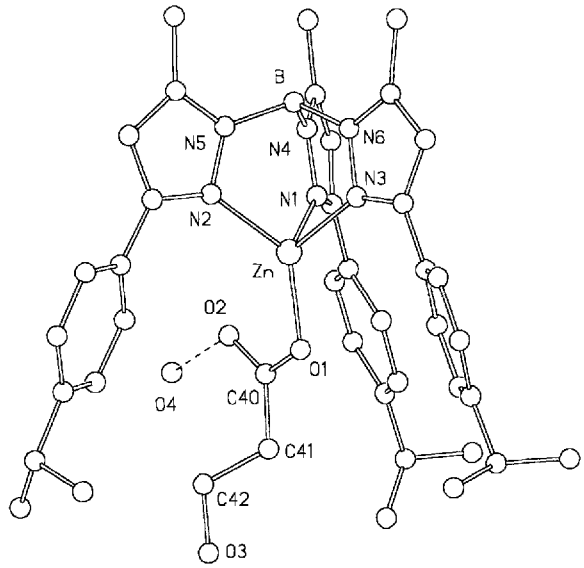
$$Tp^{Cum,Me}Zn\text{-}OH + O_2N\text{-}C_6H_4OH \rightarrow \underset{\mathbf{3}}{Tp^{Cum,Me}Zn\text{-}OC_6H_4\text{-}NO_2} + H_2O$$

The constitutions of products **2a–c** and **3** could be deduced from their spectra (see Experimental), specifically from the ^{1}H-NMR data of the $Tp^{Cum,Me}$ ligand which differ only slightly from those of **1**, the full set of ^{1}H-NMR resonances for the carboxylate or phenolate coligands, and the strong ν(CO) bands in the IR spectra which, in comparison with reference compounds[17,18], characterize the carboxylate coligands as monodentate.

Complex **2c** was subjected to a structure determination which revealed that the compound had crystallized as a hydrate. Figure 1 gives a view of the molecule which emphasizes the attachment of the additional water molecule to the noncoordinating carboxylate CO group and the noninvolvement of the OH group of the coligand in complexation.

A detailed inspection revealed that the carboxylate ligand is on the borderline of monodentate coordination: The Zn–O2 distance is rather short and compares with the Zn···O distance of semibidentate nitrate in $Tp^{Ph}Zn\text{–}ONO_2$[18], and the Zn–O1 distance is about 0.1 Å longer than in TpZn-carboxylate complexes with clearly monodentate coordination[17,19,20]. Correspondingly, the O–Zn–N angles are quite uneven, as are the N–Zn–N angles and the Zn–N bond lengths, indicating a trend toward trigonal-bipyramidal coordination with N3 and O2 on the apical positions. Otherwise, there are no unusual features in the Tp or hydroxypropionate ligands. The fact that the water molecule is attached by hydrogen bonding close to the center of the molecule indicates that the hydrophobic pocket enclosed by the *p*-cumenyl substituents can be opened for hydrophilic interactions.

Figure 1. Molecular structure of **2c**. Pertinent bond lengths: Zn–O1 1.929(4), Zn–O2 2.580(5), Zn–N1 2.031(4), Zn–N2 2.035(4), Zn–N3 2.090(5), C40–O1 1.277(8), C40–O2 1.255(7), O2–O4 2.71(1) Å. Bond angles: N1–Zn–N2 99.0(2), N1–Zn–N3 90.4(2), N2–Zn–N3 91.2(2), O1–Zn–N1 122.2(2), O1–Zn–N2 129.2(2), O1–Zn–N3 114.7(2), Zn–O1–C40 105.7(4)°



Amide Cleavages

In contrast to ester hydrolysis, peptide hydrolysis is of extreme importance in biology, featuring zinc enzymes like carboxypeptidase as the most prominent catalysts[2,16]. But model studies of peptide cleavage with metal-containing catalysts have less frequently been performed than those of ester cleavage[16,21] which is due to the fact that peptide hydrolysis is more difficult. Thus, we found that only the most highly activated amides are cleaved by complex **1**. As such we used trifluoroacetamide and propiolactame. Due to their strong activation their reactions proceed even somewhat more rapidly than the ester reactions. In the case of trifluoroacetamide the reaction product **2b** is identical with that of methyl trifluoroacetate cleavage. With propiolactame the whole substrate stays in the product complex **2d** again, whose aminopropionate ligand is analogous to the hydroxypropionate ligand in **2c**.

$$\underset{\mathbf{1}}{Tp^{Cum,Me}Zn\text{-}OH} + RNH\text{-}C(O)R' \rightarrow RNH_2 + \underset{\mathbf{2}}{Tp^{Cum,Me}Zn\text{-}OC(O)R'}$$

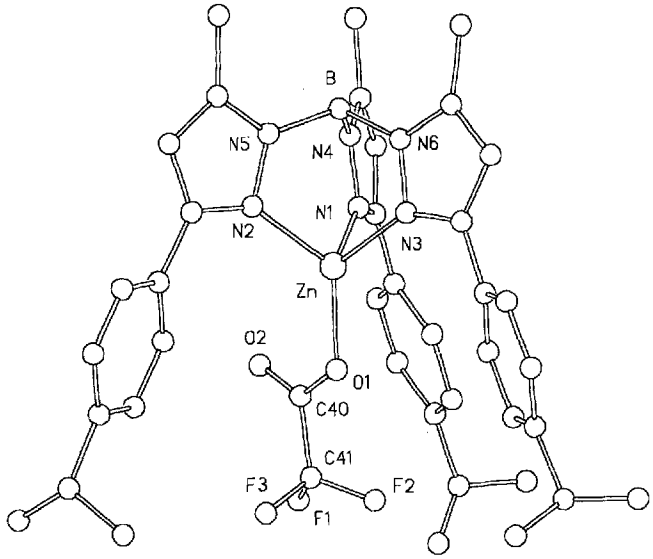
$$\mathbf{1} + H_2N\text{-}C(O)CF_3 \rightarrow NH_3 + \mathbf{2b}\ (R' = CF_3)$$

$$\mathbf{1} + \text{propiolactame} \rightarrow \mathbf{2d}\ (R' = CH_2CH_2NH_2)$$

The highly similar spectra of **2c** and **2d** ensure the constitutional assignment of **2d**. This time the other reaction product, **2b**, was confirmed by a structure determination. Figure 2 shows its molecular shape with a clearly monodentate carboxylate ligand.

Besides the difference in the Zn–O bond lengths the most important indication that the trifluoroacetate is coordinated in a monodentate manner is the difference in the C–O bond lengths for the coordinating and non-coordinating oxygen atoms. The other noticeable molecular features of **2b** (relatively long Zn–N3 and Zn–O1 bond lengths and uneven distribution of O–Zn–N and N–Zn–N angles) resemble those of **2c** and thus cannot reflect the denticity of the carboxylate ligand alone. The wide N1–Zn–N2 angle corresponds with the orientation of the carboxylate group

Figure 2. Molecular structure of **2b**. Pertinent bond lengths: Zn–O1 1.929(2), Zn···O2 2.950(3), Zn–N1 2.026(2), Zn–N2 2.021(3), Zn–N3 2.045(2), C40–O1 1.274(4), C40–O2 1.201(4) Å. Bond angles: O1–Zn–N1 118.05(11), O1–Zn–N2 126.90(11), O1–Zn–N3 120.51(11), N1–Zn–N2 99.39(12), N1–Zn–N3 91.30(12), N2–Zn–N3 92.73(12), Zn–O1–C40 114.5(2)°



in both complexes, and in **2b** the long Zn–O1 bond seems to be a consequence of the electron-withdrawing properties of the trifluoroacetate, i.e. the more ionic nature of the Zn–O bond.

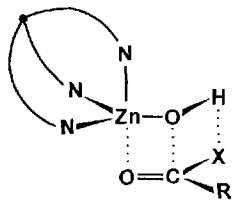
The solid-state structures of **2b** and **c** seem to be without disorder. In other cases, specifically **2d** and **3**, the threefold symmetry of the pyrazolylborate ligand dominates the packing in the crystals giving rise to a disorder of the coligands and making a satisfactory solution of the structures impossible. This finding and the visual impression from Figures 1 and 2 support the conclusion that even voluminous coligands are really hidden in the hydrophobic pocket created by the $Tp^{Cum,Me}$ ligands.

Conclusions

The reactions described in this paper are stoichiometric equivalents of metal-assisted catalytic processes. Their products give support to the mechanistic ideas put forth for the metal-assisted cleavage of esters and peptides[2,3,15,16] which involve Zn–OH and Zn–OC(O)R intermediates. The high stability of the zinc-carboxylate complexes **2** and the hydrophobicity of the reagents prevent a catalytic turnover.

The high nucleophilicity of **1** has made amide cleavage by a $M-OH_2$ or M–OH complex possible for the first time. The increase in nucleophilicity in going from $Tp^{tBu,Me}Zn$–OH to $Tp^{Cum,Me}Zn$–OH cannot be related to the electron-releasing power of the substituents (*tert*-butyl > cumenyl) of the pyrazolylborate. Instead, it must be assumed that the higher degree of encapsulation by $Tp^{Cum,Me}$, i.e. a more hydrophobic environment of the Zn–OH unit, accounts for the observed effects.

Mechanistically, the cleavage reactions can be envisaged by the fictitious reaction intermediate **A**. It displays the nucleophilic attack of the zinc-bound OH on the carbonyl carbon atom while at the same time allowing the zinc ion to activate the carbonyl oxygen electrophilically and placing the OH hydrogen atom in close contact with the oxygen or nitrogen atom of the leaving group (X = OR or NHR). In a stepwise or synchronous process the three dotted lines can be converted into bonds while the O–H, C–X, and C=O double bonds are broken. The resulting bidentate carboxylate complex would then need only a slight rearrangement to adopt the orientation observed in the molecular structures of **2b** and **c**.



A

In terms of esterase and peptidase action complex **1** is an enzyme model reduced to its central features: a zinc ion coordinated by a nucleophilic water constituent and a ligand L providing three heteroaromatic nitrogen donors. We have yet to learn how the activity of the complex (i.e. reaction specificity or catalytic performance) can be tuned by the geometrical (i.e. encapsulating) or polar (i.e. hydrophilic) properties of our substituted pyrazolylborate ligands.

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Experimental

The general working and measuring methods were as described before[22], the synthesis of **1** is described in ref.[12]. All reagents were obtained commercially.

Ester Cleavages. – p-Nitrophenyl Acetate: A solution of 200 mg (0.29 mmol) of **1** and 27 mg (0.15 mmol) of *p*-nitrophenyl acetate in 10 ml of benzene was stirred for 2 h. After removal of the solvent in vacuo, the residue was taken up in 15 ml of dichloromethane/methanol (1:2). Cooling of the solution to 4 °C yielded 103 mg (88%) of **3** as yellowish crystals, m.p. 241 °C. After filtration and cooling of the mother liquor to −20 °C 89 mg (84%) of **2a** precipitated as colorless crystals, m.p. 214 °C.

2a: IR (KBr, cm^{-1}): $\tilde{\nu}$ = 2549 m (BH), 1632 s (CO). – ^1H NMR ($CDCl_3$): δ = 1.26 [d, *J* = 6.9 Hz, 18H, Me(*i*Pr)], 1.49 [s, 3H, Me (acetate)], 2.52 [s, 9H, Me (pz)], 2.91 [sept., *J* = 6.9 Hz, 3H, H (*i*Pr)], 6.17 [s, 3H, H (pz)], 7.21 [d, *J* = 8.2 Hz, 6H, Ph(3,5)], 7.56 [d, *J* = 8.2 Hz, 6H, Ph(2,6)]. – $C_{41}H_{49}BN_6O_2Zn$ (734.1): calcd. C 67.09, H 6.73, N 11.45; found C 67.17, H 6.59, N 11.49.

3: IR (KBr, cm $^{-1}$): $\tilde{\nu}$ = 2552 m (BH), 1584 s (N=O), 1307 s (N=O). – ^1H NMR ($CDCl_3$): δ = 1.08 [d, *J* = 6.9 Hz, 18H, Me (*i*Pr)], 2.56 [s, 9H, Me (pz)], 2.72 [sept., *J* = 6.9 Hz, 3H, H (*i*Pr)], 5.75 (d, *J* = 8.7 Hz, 2H, Ph), 6.24 [s, 3H, H (pz)], 7.01 [d, *J* = 8.2 Hz, 6H, Ph(3,5)], 7.42 (d, *J* = 8.7 Hz, 2H, Ph), 7.53 [d, *J* = 8.2 Hz, 6H, Ph(2,6)]. – $C_{45}H_{50}BN_7O_3Zn$ (813.1): calcd. C 66.47, H 6.20, N 12.06; found C 65.75, H 6.24, N 12.03.

Methyl Trifluoroacetate: A solution of 200 mg (0.29 mmol) of **1** and 37 mg (29 µl, 0.29 mmol) of methyl trifluoroacetate in 10 ml of dichloromethane was stirred for 30 min. After removal of all volatile components in vacuo the residue was taken up in 30 ml of dichloromethane/methanol (1:2). Slow evaporation of the solution at room temp. yielded 212 mg (93%) of **2b** as colorless crystals, m.p. 219°C. – IR (KBr, cm^{-1}): $\tilde{\nu}$ = 2554 m (BH), 1711 s (CO). – ^1H NMR ($CDCl_3$, δ): 1.24 [d, J = 6.9 Hz, 18H, Me (*i*Pr)], 2.54 [s, 9H, Me (pz)], 2.90 [sept., J = 6.9 Hz, 3H, H (*i*Pr)], 6.20 [s, 3H, H (pz)], 7.22 [d, J = 8.2 Hz, 6H, Ph(3,5)], 7.47 [d, J = 8.2 Hz, 6H, Ph(2,6)]. – ^{19}F NMR ($CDCl_3$ vs. $CFCl_3$): δ = −75.3. – $C_{14}H_{46}BF_3N_6O_2Zn$ (788.0): calcd. C 62.49, H 5.88, N 10.67; found C 62.46, H 5.79, N 10.59.

Propiolactone: A solution of 200 mg (0.29 mmol) of **1** and 21 mg (20 µl, 0.29 mmol) of propiolactone (90%) in 10 ml of benzene was stirred for 30 min. The solvent was removed in vacuo and the residue washed with 3 ml of methanol. Recrystallization from dichloromethane/96% ethanol (1:2) yielded 155 mg (68%) of **2c** · H_2O as colorless crystals, m.p. 183°C. – IR (KBr, cm^{-1}): $\tilde{\nu}$ = 3415 s, br (OH), 2546 m (BH), 1739 s (CO). – ^1H NMR ($CDCl_3$): δ = 1.25 [d, J = 6.9 Hz, 18H, Me (*i*Pr)], 1.87 (t, J = 5.1 Hz, 2H, C−CH_2), 2.53 [s, 9H, Me (pz)], 2.92 [sept., J = 6.9 Hz, 3H, H (*i*Pr)], 3.27 (m, 1H, OH), 3.40 (m, 2H, OCH_2), 6.18 [s, 3H, H (pz)], 7.22 [d, J = 8.2 Hz, 6H, Ph(3,5)], 7.50 [d, J = 8.2 Hz, 6H, Ph(2,6)]. – $C_{42}H_{51}BN_6O_3Zn$ · H_2O (764.1 + 18.0): calcd. C 64.50, H 6.83, N 11.30; found C 64.02, H 6.46, N 10.75.

Amide Cleavages. – Trifluoroacetamide: A solution of 200 mg (0.29 mmol) of **1** and 33 mg (0.29 mmol) of trifluoroacetamide in 10 ml of dichloromethane was stirred for 30 min. After removal of the solvent in vacuo, the residue was taken up in a minimum amount of dichloromethane/methanol (1:2). Slow evaporation of the solution at room temp. yielded 215 mg (94%) of **2b** as colorless crystals.

Propiolactame: A solution of 200 mg (0.29 mmol) of **1** and 21 mg (0.30 mmol) of propiolactame in 10 ml of dichloromethane was stirred for 20 min. The solvent was removed in vacuo. Recrystallization of the residue from 2,2-dimethoxypropane yielded 211 mg (90%) of **2d** · 0.5 $Me_2C(OMe)_2$ as colorless crystals, m.p. 164°C. – IR (KBr, cm^{-1}): $\tilde{\nu}$ = 3269 w (NH), 2545 m (BH), 1697 s (CO). – ^1H NMR ($CDCl_3$): δ = 1.16 [d, J = 6.9 Hz, 18H, Me (*i*Pr)], 1.66 (t, J = 4.1 Hz, 2H, C−CH_2), 2.21 (t, J = 4.1 Hz, 2H, NCH_2), 2.44 [s, 9H, Me (pz)], 2.83 [sept., J = 6.9 Hz, 3H, H (*i*Pr)], 6.10 [s, 3H, H (pz)], 7.16 [d, J = 8.2 Hz, 6H, Ph(3,5)], 7.48 [d, J = 8.2 Hz, 6H, Ph(2,6)]. – $C_{42}H_{52}BN_7O_2Zn$ · 0.5 $C_5H_{12}O_2$ (763.1 + 52.0): calcd. C 65.56, H 7.17, N 12.03; found C 66.37, H 6.91, N 12.03.

Structure Determinations[23]: Crystals of **2b** and **c** were obtained from the recrystallizations as described above. Diffraction data were recorded with a Nonius CAD4 diffractometer by using Mo-K_α radiation and the ω/2Θ technique. They were used without an absorption correction for the structure solutions by direct methods. In the anisotropic refinement the H atoms were included with fixed C−H and N−H distances of 0.96 Å and isotropic temperature factors fixed at 1.2 times (1.5 times in methyl groups) that of their attached atoms. All calculations were performed with the SHELX program system[24].

2b: Crystal size 0.7 × 0.4 × 0.3 mm, monoclinic, space group $P2_1/n$, Z = 4, a = 9.196(2), b = 20.775(4), c = 21.375(4) Å, β = 99.01(3)°, V = 4.033(1) nm^3, d_{calcd} = 1.30, d_{obs} = 1.23 gcm^{-3}, μ = 0.67 mm^{-1}, Θ range 2.5 to 26.0°, h range −11 to 0, k range 0 to 25, l range −26 to 26, refl. measd. 8413, indep. refl. obsd. [$I > 2\sigma(I)$] 5445, 487 parameters, R (obs. refl.) = 0.046, $wR2$ (all refl.) = 0.218, res. el. densities +0.6 and −0.5 e/Å^3.

2c: Crystal size 0.6 × 0.3 × 0.3 mm, monoclinic, space group $P2_1/n$, Z = 4, a = 8.923(1), b = 22.302(2), c = 20.561(1) Å, β = 94.26(1)°, V = 4.080(1) nm^3, d_{calcd} = 1.27, d_{obs} = 1.22 gcm^{-3}, μ = 0.65 mm^{-1}, Θ range 3.0 to 26.3°, h range 0 to 11, k range −27 to 27, l range −25 to 25, refl. measd. 17348, indep. refl. obsd. [$I > 2\sigma(I)$] 4000, 487 parameters, R (obs. refl.) = 0.058, $wR2$ (all refl.) = 0.230, residual electron densities: +0.6 and −0.7 e/Å^3.

[1] A. E. Martell, *Pure Appl. Chem.* **1968**, *17*, 129–178.
[2] W. Kaim, B. Schwerderski, *Bioanorganische Chemie*, 2nd ed., B. G. Teubner, Stuttgart, **1995**.
[3] J. E. Coleman in *Zinc Enzymes* (Eds.: I. Bertini, C. Luchinat, W. Maret, M. Zeppezauer), Birkhäuser, Boston, **1986**, pp. 49–58.
[4] A. F. Wells, *Structural Inorganic Chemistry*, Clarendon Press, Oxford, **1975**, pp. 410, 529, 913.
[5] R. Alsfasser, H. Vahrenkamp, *Chem. Ber.* **1993**, *126*, 695–701, and references cited therein.
[6] E. Kimura, *Prog. Inorg. Chem.* **1994**, *41*, 443–491.
[7] C. Kimblin, W. E. Allan, G. Parkin, *J. Chem. Soc., Chem. Commun.* **1995**, 1813–1815.
[8] P. Wooley, *J. Chem. Soc., Perkin Trans. 2*, **1977**, 318–324; J. Chin, X. Zhou, *J. Am. Chem. Soc.* **1984**, *106*, 3687–3688; S. H. Gellmann, R. Petter, R. Breslow, *ibid.* **1986**, *108*, 2388–2394.
[9] S. Hikichi, M. Tanaka, Y. Moro-oka, N. Kitajima, *J. Chem. Soc., Chem. Commun.* **1992**, 814–815.
[10] A. Looney, R. Han, K. McNeill, G. Parkin, *J. Am. Chem. Soc.* **1993**, *115*, 4690–4697.
[11] R. Alsfasser, M. Ruf, S. Trofimenko, H. Vahrenkamp, *Chem. Ber.* **1993**, *126*, 703–710.
[12] M. Ruf, H. Vahrenkamp, *Inorg. Chem.*, in press.
[13] M. Ruf, K. Weis, H. Vahrenkamp, *J. Am. Chem. Soc.*, in press.
[14] M. Ruf, K. Weis, H. Vahrenkamp, *J. Chem. Soc., Chem. Commun.* **1994**, 135–136.
[15] J. Chin, *Acc. Chem. Res.* **1991**, *24*, 145–152.
[16] T. H. Fife in *Perspectives on Bioinorganic Chemistry* (Eds.: R. W. Hay, J. R. Dilworth, K. B. Nolan), Jai Press, London, **1991**, pp. 43–93; R. S. Brown, J. Huguet, N. J. Curtis in *Zinc and its Role in Biology and Nutrition* (Ed.: H. Sigel), Marcel Dekker, New York, **1983**, pp. 55–100.
[17] R. Han, I. B. Gorell, A. Looney, G. Parkin, *J. Chem. Soc., Chem. Commun.* **1991**, 717–719.
[18] R. Alsfasser, A. K. Powell, S. Trofimenko, H. Vahrenkamp, *Chem. Ber.* **1993**, *126*, 685–694.
[19] D. J. Darensbourg, M. W. Holtcamp, B. Khandelwal, K. K. Klausmeyer, J. H. Reibenspies, *Inorg. Chem.* **1995**, *34*, 2389–2398.
[20] U. Hartmann, H. Vahrenkamp, *Chem. Ber.* **1994**, *127*, 2381–2385.
[21] cf. R. W. Hay, A. K. Basak, M. P. Pujari, A. Perotti, *J. Chem. Soc., Dalton Trans.* **1989**, 197–201.
[22] M. Förster, R. Burth, A. K. Powell, T. Eiche, H. Vahrenkamp, *Chem. Ber.* **1993**, *126*, 2643–2648.
[23] Further details of the structure determinations are available on request from the Fachinformationszentrum Karlsruhe, D-76344 Eggenstein-Leopoldshafen, on quoting the depository numbers CSD-405183 (for **2b**) and CSD-405186 (for **2c**), the names of the authors, and the journal citation.
[24] G. M. Sheldrick, *SHELXL* and *SHELXS*, Universität Göttingen, **1986** and **1993**.

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