Inorg. Chem. **2005**, *44*, 3321–3329

Zinc Complex Chemistry of N,N,O Ligands Providing a Hydrophobic Cavity

Florian Gross and Heinrich Vahrenkamp*

Institut für Anorganische und Analytische Chemie der Universität Freiburg, Albertstrasse 21, D-79104 Freiburg, Germany

Received January 12, 2005

Three new highly substituted bis(2-picolyl)(2-hydroxybenzyl)amine ligands were synthesized, and their biomimetic zinc complex chemistry was explored. They have *tert*-butyl substituents at the 3-and 5-positions of their phenyl rings, and they bear one phenyl group (H**L**^{2}), two methyl groups (H**L**^{3}), or two phenyl groups (H**L**^{4}) at the 6-positions of their pyridyl rings. Their reactions with hydrated zinc perchlorate yield three distinctively different complex types. **L**^{2} forms a trigonal-bipyramidal aqua complex, and **L**^{3}, a square-pyramidal aqua complex. The substituents on **L**^{4} leave no room for a water ligand, and the resulting zinc complex is trigonal-monopyramidal with a vacant coordination site. The water ligands on the **L**^{2}Zn and **L**^{3}Zn units can be replaced by anionic halide, thiocyanate, *p*-nitrophenolate, benzoate, and organophosphate as well as uncharged pyridine ligands. The **L**^{4}Zn unit forms labile halide, *p*-nitrophenolate, and pyridine complexes. Triethylamine converts the aqua complexes to the labile hydroxides **L**^{2}Zn–OH and **L**^{3}Zn–OH, and in polar media [**L**^{3}Zn–OH$_2$]$^+$ seems to be in equilibrium with **L**^{3}Zn–OH. The hydroxides, but not the water complexes, effect the hydrolytic cleavage of tris(*p*-nitrophenyl) phosphate to bis(*p*-nitrophenyl) phosphate. The kinetic investigation of the cleavage reactions has shown them to be second-order reactions, thereby supporting the proposed four-center mechanism.

Introduction

The N,N,O donor motif provided by histidine and glutamate or aspartate is a very common one in hydrolytic zinc enzymes,[1,2] including their most prominent representative, carboxypeptidase.[3] Accordingly, many polydentate ligands containing N and O donors have been prepared in attempts to model the zinc chemistry associated with them. Early attempts in this field[4] were not very successful because neither the coordination number of zinc could be kept low nor a hydrophobic encapsulation of the metal could be provided, which are essential prerequisites for the formation of the Zn−OH nucleophile and for catalytic activity of the complexes.

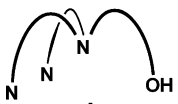
In recent years zinc enzyme modeling has evolved rather quickly to a higher level of sophistication.[5] This holds particularly for the area of tripodal ligands with N,N,O donor sets. Using ligand construction around central carbon or boron anchors, the groups of Parkin,[6,7] Carrano,[8,9] and Burzlaff[10,11] have provided tridentate ligands for tetrahedral zinc model complexes. Using weakly coordinating nitrogen atoms as the centers of ligand construction, the groups of Fenton[12−15] and Ichikawa[16] synthesized various tripodal ligands which form trigonal-bipyramidal zinc complexes with pseutotetrahedral coordination geometries. Although convincing structural enzyme models and in some cases catalytic hydrolytic activity could be achieved with these complexes,[5] the key model species in the form of a (N,N,O)Zn−OH complex or a truly tetrahedral (N,N,O)Zn·OH$_2$ complex have eluded researchers until now.

* Author to whom correspondence should be addressed. E-mail: vahrenka@uni-freiburg.de.

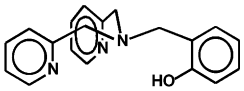
(1) *Zinc Enzymes*; Spiro, T. G., Ed.; Wiley: New York, 1983.
(2) *Metal Ions in Biological Systems, Vol. 15: Zinc and its Role in Biology and Nutrition*; Sigel, H., Ed.; Marcel Dekker: New York, 1983.
(3) Christianson, D. W.; Lipscomb, W. N. *Acc. Chem. Res.* **1989**, *22*, 62.
(4) Brown, R. S.; Huguet, J.; Curtis, N. J. In ref 2, pp 55−99.
(5) Parkin, G. *Chem. Rev.* **2004**, *104*, 699.
(6) Dowling, C.; Parkin, G. *Polyhedron* **1996**, *15*, 2463.
(7) Ghosh, P.; Parkin, G. *J. Chem. Soc., Dalton Trans.* **1998**, 2281.
(8) Higgs, T. C.; Spartalian, K.; O'Connor, C. J.; Matzanke, B. F.; Carrano, C. J. *Inorg. Chem.* **1998**, *37*, 2263.
(9) Hammes, B. S.; Carrano, C. J. *Inorg. Chem.* **1999**, *38*, 4593.
(10) Beck, A.; Weibert, B.; Burzlaff, N. *Eur. J. Inorg. Chem.* **2001**, 521.
(11) Hegelmann, I.; Beck, A.; Eichhorn, C.; Weibert, B.; Burzlaff, N. *Eur. J. Inorg. Chem.* **2003**, 339.
(12) Adams, H.; Bailey, N. A.; Campbell, I. K.; Fenton, D. E.; He, Q.-Y. *J. Chem. Soc., Dalton Trans.* **1996**, 2233.
(13) Adams, H.; Bailey, N. A.; Rodriguez de Barbarin, C. O.; Fenton, D. E.; He, Q.-Y. *J. Chem. Soc., Dalton Trans.* **1995**, 2323.
(14) Adams, H.; Bailey, N. A.; Fenton, D. E.; He, Q.-Y. *J. Chem. Soc., Dalton Trans.* **1996**, 2857.
(15) Rodriguez de Barbarin, C. O.; Bailey, N. A.; Fenton, D. E.; He, Q.-Y. *J. Chem. Soc., Dalton Trans.* **1997**, 161.
(16) Ogawa, K.; Nakata, K.; Ichikowa, K. *Chem. Lett.* **1998**, 797.

10.1021/ic050042u CCC: $30.25
Published on Web 04/05/2005

For our investigations in this field we have used ligand construction around central nitrogen atoms to obtain tripods of general type **A**. Our initial attempts with the ligands dipicolylglycine[17] and dipicolyl-β-alanine[18] also suffered from limited control of the coordination number of zinc due to aggregation or coligand association. The situation improved when we turned to the phenolate-containing ligands derived from **B**.[18] Particularly the bis(*tert*-butyl)-substituted system **L**[1] allowed us the isolation of a zinc−aqua complex, proof of its conversion to a zinc−hydroxide complex, and the use of the latter for the hydrolytic cleavage of tris(*p*-nitrophenyl) phosphate with second-order kinetics.[19]

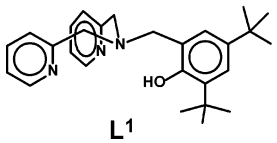


A

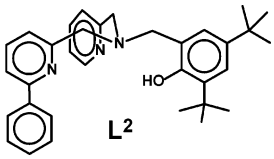


B

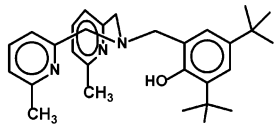
We have now extended this work by attaching further substituents at the ligands of type **B**, with the purpose of improving the encapsulation of zinc in the ligand pocket. Methyl and phenyl groups were placed at the 6-postions of the pyridyl rings, yielding ligands **L**[2], **L**[3], and **L**[4]. This paper reports the consequences of this in terms of structures and reactivities of the zinc complexes derived from the new ligands.



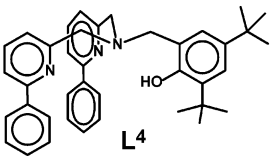
L[1]



L[2]



L[3]



L[4]

Results and Discussion

Ligand Syntheses. The preparation of H**L**[2], H**L**[3], and H**L**[4] followed the scheme developed by us for the reference compound H**L**[1].[19] First the substituted dipicolylamines were synthesized by condensation between the corresponding pyridine-2-aldehyde and the corresponding 2-(aminomethyl)-pyridine and subsequent reduction with sodium borohydride. Then the dipicolylamines were combined with 2,4-di-*tert*-butyl-6-(chloromethyl)phenol. H**L**[2], H**L**[3], and H**L**[4], which are colorless solids, had to be purified by chromatography. They are characterized by intense ν(pyridine) vibration bands at 1591, 1593, and 1588 cm^{-1}, respectively. Their methylene groups give rise to singlet ^{1}H NMR resonances in the range 3.75−4.00 ppm.

Complexation of Zinc Perchlorate. All three protonated ligands H**L** were treated with $Zn(ClO_4)2\cdot 6H_2O$ and an equimolar amount of KOH in methanol/dichloromethane mixtures. Crystallization rendered complexes **1**−**3** in yields of 50−75%. All three show the ligand attachment by the typical high-energy shift of the ν(pyridine) vibration bands to 1607, 1609, and 1608 cm^{-1}, respectively, and the presence of anionic perchlorate by its intense ν(ClO) vibration band near 1100 cm^{-1}. A typical feature in the ^{1}H NMR spectra is the splitting of the pyridylmethylene resonances into doublets with geminal coupling upon complexation of the H**L** ligands, as observed before[19] and for all Zn**L** complexes here. Complexes **1** and **2** showed a ^{1}H NMR signal for zinc-bound water in the 2.9 ppm range. This signal was missing in the ^{1}H NMR spectrum of **3**, which instead showed a signal for noncoordinated water at 1.53 ppm. This was the basis for the given formulations of **1**−**3**, which were subsequently confirmed by the structure determinations.

Table 1. Bond Lengths (Å) and Angles (deg) in the Hydrated **L**·Zn Perchlorates

	L[1]Zn(OH$_2$)$^+$ [19]	**L**[2]Zn(OH$_2$)$^+$ (**1**)	**L**[3]Zn(OH$_2$)$^+$ (**2**)	**L**[4]Zn$^+$ (**3**)
Zn−O(OH$_2$)	2.059(6)	2.025(7)	2.011(2)	
Zn−O1	1.945(6)	1.892(7)	2.025(2)	1.877(2)
Zn−N1	2.099(7)	2.180(8)	2.204(3)	2.034(2)
Zn−N2	2.061(7)	2.114(8)	2.064(3)	2.031(2)
Zn−N3	2.178(7)	2.162(7)	2.145(3)	2.076(2)
N3−Zn−O(OH$_2$)	165.0(3)	169.4(1)	145.2(1)	
N3−Zn−O1	94.7(2)	90.9(2)	89.4(1)	100.0(1)
N3−Zn−N1	78.8(3)	75.9(3)	76.6(1)	85.3(1)
N3−Zn−N2	79.4(3)	80.6(3)	85.0(1)	82.4(1)
N2−Zn−O1	112.1(2)	120.5(2)	155.1(1)	131.5(1)
N1−Zn−O1	114.6(2)	115.5(3)	98.5(1)	114.3(1)
N1−Zn−N2	129.6(3)	118.9(2)	100.6(1)	114.2(1)

$$[\mathbf{L}^2\mathrm{Zn(OH_2)}]\mathrm{ClO_4} \quad [\mathbf{L}^3\mathrm{Zn(OH_2)}]\mathrm{ClO_4} \quad [\mathbf{L}^4\mathrm{Zn}]\mathrm{ClO_4}$$
$$\mathbf{1} \qquad\qquad \mathbf{2} \qquad\qquad \mathbf{3}$$

The structures of all four **L**·Zn perchlorate compounds are closely related, including the nonhydrated complex **3**; see Table 1. Yet there are significant differences among details. One of them concerns the coordination geometry: while **1** is close to ideally trigonal-bipyramidal (84% TBP according to the Holmes method[20]), **2** is almost perfectly square-pyramidal (73% SP[20]). The situation in **L**[1]Zn(OH$_2$)$^{+}$[19] closely resembles that in **L**[2]Zn(OH$_2$)$^+$. In a comparison of complexes **1** and **3**, it becomes evident that the latter can be described as trigonal-monopyramidal; i.e., it is characterized by a vacant coordination site. The bond lengths show a considerable spread among the four complexes: both the 0.15 Å variation of the Zn−O(phenolate) bond lengths and the fact that the typical elongation of the axial bonds does not occur in **1** and **3** are remarkable. Part of this may be related to the fact that hydrogen-bonding interactions exist between the perchlorate ions and the oxygen donors of **1** and **2**.

The structures of the complex cations of **1**−**3** are displayed in Figures 1−3. It is evident that the zinc ions (and in case of **1** the aqua ligand as well) are encapsulated between the *tert*-butyl and phenyl substituents of ligands **L**[2] and **L**[4]. This is not the case for ligand **L**[3], whose methyl substituents are much less space-filling. The consequences of this for the aqua ligands in **1** and **2** are comparable. While in **1** there is

(17) Abufarag, A.; Vahrenkamp, H. *Inorg. Chem.* **1995**, *34*, 2207.
(18) Trösch, A.; Vahrenkamp, H. *Eur. J. Inorg. Chem.* **1998**, 827.
(19) Trösch, A.; Vahrenkamp, H. *Inorg. Chem.* **2001**, *40*, 2305.
(20) Holmes, R. R. *Acc. Chem. Res.* **1979**, *12*, 257.

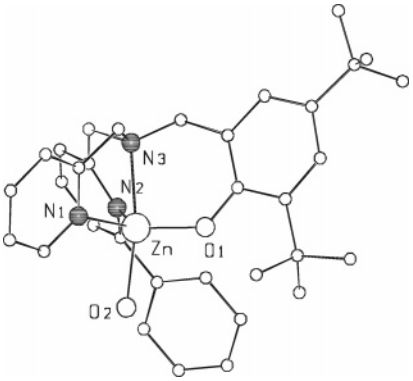


Figure 1. Structure of the complex cation of **1**.

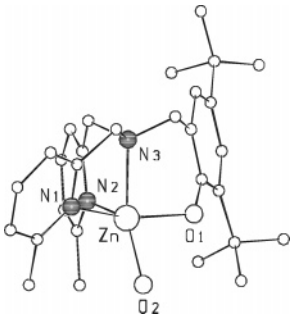


Figure 2. Structure of the complex cation of **2**.

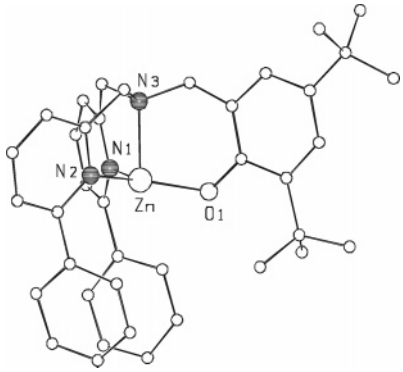


Figure 3. Structure of the complex cation of **3**.

an open site for access to the zinc-bound water, due to the missing substituent on the second pyridine ring, in **2** the *tert*-butyl group, the two methyl groups, and the zinc-bound water lie roughly in one plane, thereby making the aqua ligand accessible from the open side of this plane.

In complex **3** the sterical demands of the phenyl substituents obviously are so large that the situation becomes unfavorable for the binding of a water molecule at the zinc ion. As a result, the coordination geometry is truly trigonal-monopyramidal, and the zinc ion is actually placed outside the plane defined by its three equatorial donors by 0.02 Å. Due to the lower coordination number, all zinc-ligand bond lengths are shorter than their counterparts in the other three complexes of Table 1. The two phenyl substituents are positioned face-to-face, approximating a stacking interaction with distances of 3.41 Å between their *para*-carbons and 4.28 Å between their *ipso*-carbons. Both have one hydrogen within contact range of the zinc ion (2.65 and 3.06 Å), but both these hydrogens are displaced considerably from the trigonal axis of the coordination polyhedron, such that agostic interactions can be ruled out. It is noteworthy that there is a water molecule in the environment of the complex, but it is located on the far side of the tripodal ligand and hydrogen-bonded to the perchlorate anion.

Trigonal-monopyramidal coordination is not unprecedented in zinc chemistry. Borovik reported the structures of two (tris(carbamoylmethyl)aminato)zinc complexes.[21,22] In addition a copper complex of tris(6-phenylpicolyl)amine has this coordination.[23] In both cases small rodlike coligands such as NO or CH_3CN could be incorporated in the ligand cavity, demonstrating that despite the limited access the metal center may be available for catalytic activity.

Attachment of Anionic Ligands. The water ligand in its hydrophobic environment could be expected to be a good leaving group. This was easily verified for complexes **1** and **2**. Reactions with the corresponding potassium salts yielded **4a**−**c** as well as **5a**,**b**. Likewise *p*-nitrophenolate, *p*-nitrobenzoate, and bis(*p*-nitrophenyl) phosphate were attached in complexes **4d**−**f** as well as **5d**−**f**. Complexes **a**−**c** can be called simple models for the inhibition of zinc enzymes by simple anions. Complexes **d**−**f** were prepared as reference compounds for the hydrolytic cleavage reactions described below.

$$\underset{\mathbf{4a-f}}{\mathbf{L}^2\mathrm{Zn-X}} \qquad \underset{\mathbf{5a,b,d-f}}{\mathbf{L}^3\mathrm{Zn-X}}$$

(**a**) X = Cl, (**b**) X = I, (**c**) X = SCN,
(**d**) X = *p*-nitrophenolate, (**e**) X = *p*-nitrobenzoate,
(**f**) X = bis(*p*-nitrophenyl) phosphate

Complexes **4** and **5** are uncharged molecular species with five-coordinate zinc. Their IR and ^{1}H NMR spectra confirm (by comparison with **1** and **2**) the tripodal attachment of $\mathbf{L}^2$ or $\mathbf{L}^3$. For **d**−**f** they show the bands for the aromatic coligands. It is to be assumed that, like in complexes **1**−**3**, the coordination geometries in complexes **4** and **5** represent various stages of the transition between trigonal-bipyramidal and square-pyramidal. For **4d**, the structure of which was determined (see Supporting Information), it is about halfway. The two independent molecules of **4d** in the asymmetric unit show geometries which according to the Holmes method[20] calculate as 60% and 66% square-pyramidal.

Anionic coligands could also be attached to complex **3**. Reactions with the corresponding salts and quick precipitation yielded the products **6a**−**c**:

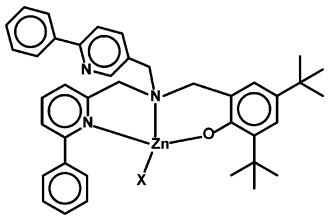
$$\underset{\mathbf{6a-c}}{\mathbf{L}^4\mathrm{ZnX}}$$

(**a**) X = Br, (**b**) X = I, (**c**) X = *p*-nitrophenolate

While the compositions of **6a**−**c** are evident from their spectra and elemental analyses, their structures could not be

(21) Hammes, B. S.; Ramos-Maldonado, D.; Yap, G. P. A.; Liable-Sands, L.; Rheingold, A. L.; Young, V. G.; Borovik, A. S. *Inorg. Chem.* **1997**, *36*, 3210.
(22) Ray, M.; Hammes, B. S.; Yap, G. P. A.; Rheingold, A. L.; Borovik, A. S. *Inorg. Chem.* **1998**, *37*, 1527.
(23) Chuang, C.-L.; Lim, K.; Chen, Q.; Zubieta, J.; Canary, J. W. *Inorg. Chem.* **1995**, *34*, 2562.

determined. After precipitation the compounds dissolve only in very polar solvents in which they slowly decompose and from which they cannot be recovered in a pure or crystalline form. This may indicate that **6a**−**c** are salts [$\mathbf{L}^4$Zn]X with the same $\mathbf{L}^4$Zn cation as **3**. However, the solid-state IR spectra of the complexes show vibration bands for both coordinated pyridine rings around 1605 cm^{-1} and uncoordinated pyridine rings around 1590 cm^{-1}. Likewise the ^{1}H NMR spectra of **6a**,**b** contain singlet signals for the picolyl methylene groups in addition to the doublets, while that of **6c** is dominated by decomposition products. As discussed above, the doublet signals indicate zinc coordination of the pyridine rings, while the singlets are observed for the uncoordinated ligands **L**. The intensity ratio of the singlets and doublets, however, is not 1:1. This may again indicate decomposition of the complexes with release of the free ligands. Yet alternatively it may point to another structure (possibly of an equilibrium constituent) in which the zinc ion is only four-coordinate due to the noncoordination of one of the pyridyl rings, depicted as



Attachment of Pyridine Donors. The water ligands in complexes **1** and **2** were also replaced easily by pyridine ligands, and likewise could pyridine ligands be added to complex **3**. Pyridine and 2-acetylpyridine were used, the latter with the purpose of finding out whether the formation of a favorable five-membered chelate ring and of a octahedrally coordinated zinc ion would induce coordination of the carbonyl oxygen, a very weak donor which was found by us both to coordinate[24−27] and not to coordinate[25,28] to zinc. Combination of the reagents in methanol or dichloromethane yielded complexes **7**−**9**.

$[\mathbf{L}^2\mathrm{Zn}\cdot\mathrm{Py}']\mathrm{ClO}_4$ **7a**,**b** $[\mathbf{L}^3\mathrm{Zn}\cdot\mathrm{Py}']\mathrm{ClO}_4$ **8a** $[\mathbf{L}^4\mathrm{Zn}\cdot\mathrm{Py}']\mathrm{ClO}_4$ **9a**,**b**

(**a**) Py′ = pyridine, (**b**) Py′ = 2-acetylpyridine

These complexes are stable in the solid state and in solution. This includes **9a**,**b**, in contrast to the lability of the $\mathbf{L}^4$-derived complexes **6**. **7**−**9** indicate the zinc coordination of all pyridine donors present by vibration bands at or above 1600 cm^{-1}. The IR data are inconclusive with respect to a coordination of the carbonyl function in **7b** and **9b**. The corresponding vibration bands (1690 and 1675 cm^{-1}) are lower than that of free 2-acetylpyridine at 1700 cm^{-1}, as expected when the carbonyl oxygen is attached to a metal. Yet the lowering of the wavenumbers is not in the 30−45 cm^{-1} range observed for confirmed cases of N,O-chelating 2-acetylpyridine.[27]

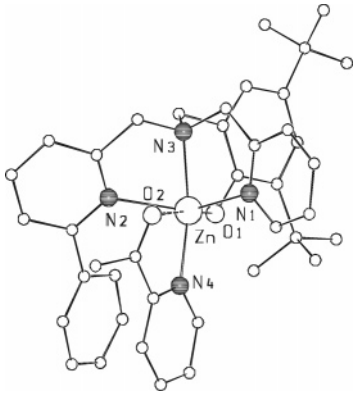


Figure 4. Structure of the complex cation of **7b**. Relevant bond lengths (Å) and angles (deg): Zn−O1 1.927(6), Zn−N1 2.142(7), Zn−N2 2.217(6), Zn−N3 2.113(7), Zn−N4 2.093(7); O1−Zn−N1 105.5(2), O1−Zn−N2 107.7(2), O1−Zn−N3 96.1(2), O1−Zn−N4 105.4(3), O1−Zn−O2 175.0(3), N1−Zn−N2 140.9(3), N3−Zn−N4 158.3(3).

The attachment of the pyridine donors was confirmed by structure determinations of **7a**,**b**. The zinc coordination in **7a** (see Supporting Information) is halfway between trigonal-bipyramidal and square-pyramidal (55% TBP according to the Holmes method[20]) with a Zn−N(pyridine) bond length of 2.10 Å. The structure of **7b** is displayed in Figure 4. The five donor atoms around zinc define a square-pyramidal coordination to a good approximation (80% SP according to the Holmes method[20]) with O1 at the apex. However, the interaction between zinc and the carbonyl oxygen (Zn···O2 = 2.56 Å) cannot be ignored, giving the zinc ion a seriously distorted octahedral coordination. This Zn···O2 interaction is nevertheless a rather weak one when compared to similar ones in zinc acetyl- and benzoylpyridine complexes,[24,26,29] where Zn−O bond distances around 2.1 Å were observed.

One reason for the orientation of the zinc-bound pyridine ligand in **7a**,**b** is π-stacking with the phenyl substituent of the tripod ligand $\mathbf{L}^2$, with distances of 3.4−3.8 Å between opposing carbon atoms. This also explains the location of the acetyl group (which is in the plane of the pyridine ring) without invoking attractive interactions between zinc and oxygen. π-Stacking may also be the reason the pyridine adducts **9a**,**b** are more stable than their counterparts **6a**−**c** with anionic coligands. While the steric stress due to the two phenyl substituents on $\mathbf{L}^4$ may labilize the Zn−anion interactions in **6a**−**c**, the presence of π-stacking beetween the pyridine ligand and both phenyl groups in **9a**,**b** may outweigh this labilization.

Hydrolytic Activity. We had already found that the aqua complex of $\mathbf{L}^1$ can be deprotonated to form the labile hydroxide complex.[19] The latter in turn was found to be the active species in the hydrolytic cleavage of tris(*p*-nitrophenyl) phosphate (TNP). One reason for the synthesis of $\mathbf{L}^2$, $\mathbf{L}^3$, and $\mathbf{L}^4$ was the hope that these ligands, due to the better

(24) Müller, B.; Vahrenkamp, H. *Eur. J. Inorg. Chem.* **1999**, 137.
(25) Müller, B.; Schneider, A.; Tesmer, M.; Vahrenkamp, H. *Inorg. Chem.* **1999**, *38*, 1900.
(26) Sudbrake, C.; Vahrenkamp, H. *Inorg. Chim. Acta* **2001**, *318*, 23.
(27) Schneider, A.; Vahrenkamp, H. *Z. Anorg. Allg. Chem.* **2003**, *629*, 2122.
(28) Tesmer, M.; Shu, M.; Vahrenkamp, H. *Inorg. Chem.* **2001**, *40*, 4022.
(29) Sheldrick, G. M.; Stotter, D. A. *J. Chem. Soc., Dalton Trans.* **1975**, 666−668.

encapsulation of a zinc-bound water molecule, would facilitate its deprotonation and stabilize the resulting **L**·Zn−OH complexes. The accessibility of the water complexes **1** and **2** allowed us to test this for $\mathbf{L}^2$ and $\mathbf{L}^3$.

Treatment of **1** or **2** with equimolar amounts of triethylamine in chloroform or acetonitrile resulted in small, but significant, shifts of the ^{1}H NMR resonances (see Experimental Section), allowing the conclusion that deprotonation with formation of **10** and **11** has occurred. But this conclusion could not be supported by a characteristic sharp ν(OH) vibration band in the IR spectra near 3600 cm^{-1}, nor were **10** or **11** isolable by precipitation. Attempts to separate the hydroxide complexes from the triethylammonium perchlorate byproduct yielded cloudy precipitates presumed to contain $Zn(OH)_2$ and solutions in which the ^{1}H NMR signals of the uncoordinated ligands **L** were observed. Thus, as observed for $\mathbf{L}^1$Zn−OH before,[19] complexes **10** and **11** evade isolation by decomposition, and their presumed identity rests solely on their reactivity.

$\mathbf{L}^2$Zn−OH **10** $\qquad$ $\mathbf{L}^3$Zn−OH **11**

The reactivity studies, however, revealed a distinction between **1** and **2**, the precursors of **10** and **11**. When **1** was treated with TNP in CD_3CN, no interconversion could be detected by ^{1}H or ^{31}P NMR. Equimolar mixtures of **2** and TNP, in contrast, were interconverted to new compounds within a few hours. The initial ^{31}P NMR signal of TNP at −18.7 ppm vanished and was replaced by the signal of bis(p-nitrophenyl) phosphoric acid at −10.2 ppm. Addition of triethylamine to the resulting colorless solution effected an immediate color change to yellow. This color change did not occur when bis(p-nitrophenyl) phosphoric acid alone was treated with triethylamine. We interpret these observations by the presence of **11** as an equilibrium species in solutions of **2**. As observed for all our (tripod)Zn−OH complexes,[5,19] **11** then is the nucleophilic agent cleaving TNP and producing bis(*p*-nitrophenyl) phosphate and *p*-nitrophenol. The former is protonated by residual water in the solution, which also regenerates complex **2**. The latter is colorless and turns yellow when deprotonated by triethylamine. The conclusion that **2** is more acidic than **1** is in agreement with their substitution patterns, the two methyl substituents in **11** offering a better stabilization of the resulting hydroxide complex by hydrophobic encapsulation than the single phenyl substituent in **10**.

The hydroxide complexes **10** and **11**, generated in situ, proved their nucleophilic strengh by the cleavage of TNP. Stoichiometric mixtures of **1** or **2**, triethylamine, and TNP in acetonitrile underwent quantitative conversions with formation of the bis(*p*-nitrophenyl) phosphate complexes **4f** and **5f** (see above), which were indentified by their ^{31}P NMR resonances at −12.6 and −11.5 ppm. The byproduct of these hydrolyses is *p*-nitrophenol. In the presence of excess triethylamine, this becomes *p*-nitrophenolate with its characteristic yellow color and its UV band maximum at 402 nm. When both **1** or **2** and triethylamine are present in excess, the liberated *p*-nitrophenolate is also fixed by complexation with formation of **4d** and **5d** (see above), which are also yellow with UV band maxima at 392 and 380 nm. Performing the hydrolyses in this way did not lead to free bis(p-nitrophenyl) phosphoric acid, as evident by the absence of its ^{31}P NMR resonance at −10.2 ppm.

These quantitative interconversions enabled a kinetic study which was performed with the purpose of comparing the hydrolytic strength of complexes **10** and **11** with that of other Zn−OH_2 or Zn−OH complexes investigated by other groups[14,30−33] and ourselves.[19,34−36] Pseudo-first-order kinetic data were obtained by treating TNP with large excesses of **10** or **11** in acetonitrile. As observed above, under these conditions both cleavage products *p*-nitrophenolate and bis(*p*-nitrophenyl) phosphate become zinc-bound in complexes **4d**/**4f** and **5d**/**5f**, respectively. Control experiments also confirmed that *p*-nitrophenolate fixation to **4d** and **5d** is much faster than the formation of the phosphate complexes **4f** and **5f**. The latter, however, according to the four-center mechanism established for such hydrolytic cleavages,[36] are the primary cleavage products resulting without liberation of anionic bis(*p*-nitrophenyl) phosphate. This was favorable for obtaining the kinetic data which were gathered by recording the intensities of the UV−vis absorption bands of **4d** and **5d**, the only colored species in the reaction mixtures. The rate of formation of **4d** and **5d** is thus identical with the rate of disappearance of TNP, and the pseudo-first-order rate constants are obtained using the equation

$$\ln[1 - (I_t/I_\infty)] = -k_{obs}t$$

The values of k_{obs} for both cleavage reactions were obtained for five different concentrations each of **10** and **11** in the presence of 0.025 mM of TMP. The resulting plots are given in the Supporting Information. They define clean second-order reactions. The least-squares lines show a small, but not insignificant, intercept of the ordinate, indicating that hydrolysis reactions occur also in the absence of **10** or **11**, presumably by traces of water. The dominating reactions, the TNP cleavages by the **L**Zn−OH complexes, are characterized by the second-order rate constants k_2 of 0.34 M^{-1} s^{-1} for **10** and 0.67 M^{-1} s^{-1} for **11**.

These two k_2 values indicate that **10** and **11** are indeed strong nucleophiles for TNP hydrolysis, taking into account that both substrate and nucleophile as well as the solvent of the reactions were nonpolar. Alkaline hydrolysis of nitrophenyl phosphates in solvent mixtures containing water was found to be faster but only around 1 order of magnitude.[30,31,37] When zinc complexes of other polydentate ligands were used, whose hydrolytically active constituent is assumed to be a

(30) Gellmann, S. H.; Petter, R.; Breslow, R. *J. Am. Chem. Soc.* **1986**, *108*, 2388.
(31) Koike, T., Kimura, E. *J. Am. Chem. Soc.* **1991**, *113*, 8935.
(32) Ito, T.; Fujii, Y.; Tada, T.; Yoshikawa, Y.; Hisada, H. *Bull. Chem. Soc. Jpn.* **1996**, *69*, 1265.
(33) Jurek, P.; Martell, A. E. *Inorg. Chim. Acta* **1999**, *287*, 47.
(34) Weis, K.; Rombach, M.; Ruf, M.; Vahrenkamp, H. *Eur. J. Inorg. Chem.* **1998**, 263.
(35) Weis, K.; Vahrenkamp, H. *Eur. J. Inorg. Chem.* **1998**, 271.
(36) Rombach, M.; Maurer, C.; Weis, K.; Keller, E.; Vahrenkamp, H. *Chem.—Eur. J.* **1999**, *5*, 1013.
(37) Cox, J. R.; Ramsay, O. B. *Chem. Rev.* **1964**, *64*, 317.

(ligand)Zn−OH species, the reaction rates for the hydrolyses in water/organic solvent mixtures were found to be 5−8 times faster than here, and it was observed that solvent polarity has a strong influence on the reaction rate.[14,30−32] Our own investigations on the cleavage of TNP by the pyrazolylborate complex $Tp^{Ph,Me}$Zn−OH in chloroform yielded a k_2 value of 1.55 M^{-1} s^{-1}.[36] The fact that this cleavage is 3−5 times faster than that by **10** or **11** can be explained by the fact that the TpZn−OH complexes exist as such at neutral pH in contrast to the **L**Zn−OH complexes applied here which in the absence of an additional base are **L**Zn$(OH_2)^+$.

The closest relative of $\mathbf{L}^2$Zn−OH (**10**) and $\mathbf{L}^3$Zn−OH (**11**) is $\mathbf{L}^1$Zn−OH, which has yielded a k_2 value for TNP hydrolylsis in chloroform of 0.27 M^{-1} s^{-1}.[19] Considering that such reactions in acetonitrile are 3−5 times faster than in chloroform,[36] the "corrected" k_2 value for $\mathbf{L}^1$Zn−OH should be around 1.0 M^{-1} s^{-1}. We then have an influence of **L** on the rate of the TNP hydrolysis by **L**Zn−OH in the order $\mathbf{L}^1 > \mathbf{L}^3 > \mathbf{L}^2$. This sequence reflects both steric and hydrophobic effects. The accessibility of the Zn−OH center decreases in the order $\mathbf{L}^1 > \mathbf{L}^2 > \mathbf{L}^3$, while the hydrophobic encapsulation increases the nucleophilicity of the zinc-bound hydroxide in the reverse order, i.e., $\mathbf{L}^1 < \mathbf{L}^2 < \mathbf{L}^3$. The combination of both effects makes $\mathbf{L}^2$Zn−OH the slowest reagent and leads to comparable reactivities of $\mathbf{L}^1$Zn−OH and $\mathbf{L}^3$Zn−OH.

Conclusions

This work has brought the zinc complex chemistry of the tetradentate tripodal N,N,O-ligands **L** to a stage that is comparble with that for the 3-substituted tris(pyrazolyl)-borates. While in the complexes of the unsubstituted ligand the zinc ion is exposed to the environment, the step-by-step attachment of organic substituents around it in ligands $\mathbf{L}^1$−$\mathbf{L}^4$ results in a progressive encapsulation. In the extreme case of $\mathbf{L}^4$ the encapsulation has become so severe that complexes $\mathbf{L}^4$Zn−X bind the coligands X only weakly, and the most stable species is the cation $[\mathbf{L}^4Zn]^+$ with a vacant coordination site.

The main purpose of the enhanced encapsulation, the protection and activation of a zinc-bound water molecule, was achieved. There seems to be an increasing ease of deprotonation of the $[\mathbf{L}Zn-OH_2]^+$ complexes in going from $\mathbf{L}^1$ to $\mathbf{L}^3$. Although we still failed to determine the corresponding pK_a values or to isolate one of the resulting **L**Zn−OH complexes, there is evidence that $\mathbf{L}^3$Zn−OH exists in equilibrium with its parent complex $[\mathbf{L}^3Zn-OH_2]^+$.

The results of this work again underline the observation that the zinc−hydroxide complexes are the active species in the hydrolytic cleavage of biologically relevant substrates. As shown here for the hydrolysis of tris(*p*-nitrophenyl) phosphate, the ease of formation of the **L**Zn−OH species corresponds with the ease of substrate cleavage, and as the kinetic data have shown, the hydrolytic activity can rise despite reduced access to the **L**Zn−OH center due to steric hindrance.

Experimental Section

General Information. The general working and measuring techniques were as described previously.[38] Starting materials were obtained commercially; 2,4-di-*tert*-butyl-6-(chloromethyl)phenol,[39] 6-phenylpyridine-2-aldehyde,[40] 6-phenyl-2-(aminomethyl)pyridine,[22] and 6-methyl-2-(aminomethyl)pyridine[21,41] were prepared according to the published procedures.

The ^{1}H NMR data for ligands $\mathbf{L}^2$, $\mathbf{L}^3$, and $\mathbf{L}^4$ are virtually identical for all their complexes. Therefore, full spectra are reported only for two cases each (**1**/**4a**, **2**/**5a**, **3**/**6a**), and for the other complexes only the ^{1}H NMR data for the coligands are given. A frequent problem with the elemental analyses of this kind of complexes is that the carbon values are outside the accepted range. When this was the case here, at least one additional analysis value (N or S) was determined.

Ligands HL. H$\mathbf{L}^2$. A solution of 6-phenylpyridine-2-aldehyde (1.33 g, 7.26 mmol) in ethanol (35 mL) was cooled with ice. A solution of 2-(aminomethyl)pyridine (743 μL, 785 mg, 7.26 mmol) in ethanol (35 mL) was added dropwise with stirring. The mixture was stirred 30 min at 0 °C and then 2 h at room temperature. Then it was cooled to 0 °C again and NaBH4 (549 mg, 14.5 mmol) was added in small portions. After the mixture was stirred overnight at room temperature, 20 mL of 5 M hydrochloric acid were slowly added and the mixture stirred for 1 h at room temperature. Then 2 M sodum hydroxide was added until the solution was strongly alkaline. This mixture was extracted three times with 25 mL of dichloromethane each. The organic phase was dried over sodium sulfate, filtered, and evaporated to dryness. The raw (6-phenyl-2-pyridylmethyl)(2-pyridylmethyl)amine was disolved in dioxane (40 mL) and treated with triethylamine (3.57 mL, 2.57 g, 25.4 mmol). After the solution was cooled to 0 °C, a solution of 2,4-di-*tert*-butyl-6-(chloromethyl)phenol (1.85 g, 7.26 mmol) in dioxane (40 mL) was added dropwise with stirring, upon which a colorless precipitate formed. After the mixture was stirred for 15 h at room temperature and filtration, the solvent was evaporated in vacuo. The resulting yellow oil was chromatographed over a 2 × 10 cm silica gel column with cyclohexane/ethyl acetate/triethylamine (3:1:1). H$\mathbf{L}^2$ was eluted with a R_f value of 0.59. Removal of the solvent in vacuo left behind 2.37 g (66%) of H$\mathbf{L}^2$ as a colorless solid, mp 90 °C. IR (KBr; cm^{-1}): 1591 (s) (C═N). ^{1}H NMR ($CDCl_3$): δ 1.24 (s, 9H, t-Bu), 1.43 (s, 9H, t-Bu), 3.86 (s, 2H, CH_2-phenol), 3.89 (s, 2H, CH_2-py), 3.93 (s, 2H, CH_2-py), 6.85−7.68 (m, 11H, Ar), 8.08 [dd, J = 8.0/1.5 Hz, 2H, Ph(2,6)], 8.50 (d, J = 5.0 Hz, 1H, H_α), 10.76 (s, 1H, OH). ^{13}C NMR ($CDCl_3$): δ 30.0 [Me(t-Bu)], 32.1 [Me(t-Bu)], 34.5 [C(t-Bu)], 35.4 [C(t-Bu)], 59.0 (CH_2), 59.7 (CH_2), 60.2 (CH_2), 121.9, 122.3, 122.7, 123.6, 124.4, 124.7 (phenol), 127.6, 129.1, 129.3 (phenyl), 136.2, 137.2, 137.6, 139.7, 140.9, 148.9, 154.3, 157.5, 157.9, 156.2 (pyridyl).

Anal. Calcd for $C_{33}H_{39}N_3O$ (M_r = 493.69): C, 80.25; H, 7.96; N, 8.51. Found: C, 79.97; H, 8.05; N, 8.34.

H$\mathbf{L}^3$. This was synthesized like H$\mathbf{L}^2$ from 6-methylpyridine-2-aldehyde (1.43 g, 11.8 mmol), 6-methyl-2-(aminomethyl)pyridine (1.44 g, 11.8 mmol), $NaBH_4$ (1.32 g, 35.0 mmol), triethylamine (5.79 mL, 4.17 g, 41.2 mmol), and 2,4-di-*tert*-butyl-6-(chloromethyl)phenol (3.00 g, 11.8 mmol). Chromatography (R_f = 0.39) yielded 4.2 g (81%) of H$\mathbf{L}^3$ as a colorless solid, mp 84 °C. IR (KBr; cm^{-1}): 1593 (vs) (C═N). ^{1}H NMR ($CDCl_3$): δ 1.26 (s, 9H,

(38) Förster, M.; Burth, R.; Powell, A. K.; Eiche, T.; Vahrenkamp, H. *Chem. Ber.* **1993**, *126*, 2643.
(39) Abufarag, A.; Vahrenkamp, H. *Inorg. Chem.* **1995**, *34*, 3279.
(40) Parks, J. E.; Wagner, B. E.; Holm, R. H. *Inorg. Chem.* **1971**, *10*, 2472.
(41) Fuentes, O.; Paudler, W. W. *J. Org. Chem.* **1975**, *40*, 1210.

t-Bu), 1.46 (s, 9H, t-Bu), 2.56 (s, 6H, CH_3), 3.76 (s, 2H, CH_2-phenol), 3.84 (s, 4H, CH_2-py), 6.88 (d, $J = 2.3$ Hz, 1H, H_α), 6.96−7.20 (m, 5H, Ar), 7.49 (t, $J = 7.7$ Hz, 2H, H_γ), 10.65 (s, 1H, OH). ^{13}C NMR ($CDCl_3$): δ 24.5 [Me(py)], 30.0 [Me(t-Bu)], 32.1 [Me-(t-Bu)], 34.5 [C(t-Bu)], 35.4 [C(t-Bu)], 58.3 (CH_2), 59.9 (CH_2), 120.6, 122.0, 122.4, 123.4, 125.2 (phenol), 135.9, 137.3, 140.5, 154.3, 158.1, 158.2 (pyridyl).

Anal. Calcd for $C_{29}H_{39}N_3O$ ($M_r = 445.65$): C, 78.16; H, 8.82; N, 9.43. Found: C, 77.94; H, 8.89; N, 9.25.

HL^4. This was synthesized like H**L**^{2} from 6-phenylpyridine-2-aldehyde (3.06 g, 16.4 mmol), 6-phenyl-2-(aminomethyl)pyridine (3.02 g, 16.4 mmol), $NaBH_4$ (1.86 g, 49.1 mmol), triethylamine (8.05 mL, 5.80 g, 57.3 mmol), and 2,4-di-*tert*-butyl-6-(chloromethyl)phenol (4.17 g, 16.4 mmol). Chromatography (4:1 cyclohexane/triethylamine 4:1; $R_f = 0.53$) yielded 8.12 g (87%) of H**L**^{4} as a colorless solid, mp 64 °C. IR (KBr; cm^{-1}): 1588 (s) (C═N). ^{1}H NMR ($CDCl_3$): δ 1.27 (s, 9H, t-Bu), 1.47 (s, 9H, t-Bu), 3.96 (s, 2H, CH_2-phenol), 4.01 (s, 4H, CH_2-py), 6.89 (d, $J = 2.3$ Hz, 1H, H_α), 7.21 (d, $J = 2.3$ Hz, 1H, H_γ), 7.26−7.69 (m, 12H, Ar), 8.10 [dd, $J = 7.9/1.6$ Hz, 2H, Ph(2,6)], 11.00 (s, 1H, OH). ^{13}C NMR ($CDCl_3$): δ 29.6 [Me(t-Bu)], 31.6 [Me(t-Bu)], 34.1 [C(t-Bu)], 34.9 [C(t-Bu)], 58.5 (CH_2), 59.3 (CH_2), 119.0, 121.3, 122.2, 123.3, 124.2 (phenol), 127.1, 128.7, 128.9 (phenyl), 137.2, 139.2, 154.1, 157.0 (pyridyl).

Anal. Calcd for $C_{39}H_{43}N_3O$ ($M_r = 569.79$): C, 82.21; H, 7.61; N, 7.37. Found: C, 81.71; H, 7.74; N, 7.23.

Zinc Perchlorate Reactions. **Complex 1.** A solution of Zn-$(ClO_4)_2\cdot 6H_2O$ (1.39 g, 3.72 mmol) in methanol (30 mL) was dropped slowly with stirring into a solution of H**L**^{2} (1.84 g, 3.72 mmol) in dichloromethane (50 mL). After the solution was stirred for 10 min, a solution of KOH (209 mg, 3.72 mmol) in methanol (15 mL) was added, upon which a colorless precipitate formed. After it was stirred for 3 h, the mixture was filtered and the filtrate evaporated to dryness. The residue was recrystallized from hot methanol (10 mL) after cooling to 0 °C. A yield of 153 g (62%) of **1** resulted as colorless crystals, mp 155 °C. IR (KBr; cm^{-1}): 3396 (m, br) (H_2O), 1607 (s) (C═N), 1104 (vs) (ClO_4). ^{1}H NMR ($CDCl_3$): δ 1.22 (s, 9H, t-Bu), 1.40 (s, 9H, t-Bu), 2.94 (s, 2H, H_2O), 3.35−4.55 (m, 6H, CH_2), 6.82 (d, $J = 2.5$ Hz, 1H, H_α), 7.04 (d, $J = 7.8$. Hz, 1H, H_δ), 7.09 (d, $J = 2.5$ Hz, 1H, H_γ), 7.21 (m, 1H, H_β), 7.39 (d, $J = 7.8$ Hz, 1H, H_δ), 7.64 (m, 5H, Ar), 8.01 (t, $J = 7.8$ Hz, 1H, H_γ), 8.21 (m, 2H, Ar), 8.41 (d, $J = 4.5$ Hz, 1H, H_α).

Anal. Calcd for $C_{33}H_{40}ClN_3O_6Zn$ ($M_r = 675.54$): C, 58.67; H, 5.97; N, 6.22. Found: C, 58.13; H, 6.25; N, 6.08.

Complex 2. This was synthesized like **1** from $Zn(ClO_4)_2\cdot 6H_2O$ (1.61 g, 4.32 mmol), H**L**^{3} (1.92 g, 4.32 mmol), and KOH (242 mg, 4.32 mmol). The raw product was dissolved in acetone (5 mL), and diethyl ether was added dropwise until a fluffy precipitate formed. This was filtered off and discarded. Further addition of diethyl ether to the filtrate led to the slow formation of a colorless powder. After the mixture was stirred overnight, the powder was filtered off and dried in vacuo, leaving behind 1.32 g (74%) of **2** as a colorless powder, mp 188 °C. IR (KBr; cm^{-1}): 3474 (m, br) (H_2O), 1609 (s) (C═N), 1108 (vs) (ClO_4). ^{1}H NMR ($CDCl_3$ with one drop of DMSO-d_6): δ 1.09 (s, 9H, t-Bu), 1.19 (s, 9H, t-Bu), 2.66 (s, 6H, CH_3), 2.85 (s, br, 4H, H_2O), 3.84 (s, 2H, CH_2-phenol), 4.06 (d, $J = 16.1$ Hz, 2H, CH_2-py), 4.18 (d, $J = 16.1$ Hz, 2H, CH_2-py), 6.73 (s, br, 1H, H_α), 6.85 (d, $J = 2.8$ Hz, 1H, H_γ), 6.94−7.12 (m, 4H, Ar), 7.55 (t, $J = 7.5$ Hz, 2H, H_γ).

Anal. Calcd for $C_{29}H_{40}ClN_3O_6Zn\cdot H_2O$ ($M_r = 627.40 + 18.02$): C, 53.96; H, 6.56; N, 6.51. Found: C, 54.23; H, 6.47; N, 6.52.

Complex 3. This was synthesized like **1** from $Zn(ClO_4)_2\cdot 6H_2O$ (248 mg, 0.67 mmol), H**L**^{4} (380 mg, 0.67 mmol), and KOH (37.4 mg, 0.67 mmol). After removal of the $KClO_4$ precipitate by filtration, the filtrate was evaporated to 5 mL, upon which a colorless powder precipitated. This was filtered off, washed with a small amount of ice-cold methanol, dissolved in dichloromethane (10 mL), and treated with *n*-heptane until the first traces of precipitation showed up. Slow evaporation of the solvent from the open flask resulted in the precipitation of 245 mg (49%) of **3** as colorless crystals, mp 280 °C (dec). IR (KBr; cm^{-1}): 1608 (s) (C═N), 1096 (vs) (ClO_4). ^{1}H NMR ($CDCl_3$): δ 1.30 (s, 9H, t-Bu), 1.52 (s, 2H, H_2O), 1.58 (s, 9H, t-Bu), 4.14 (s, 2H, CH_2-phenol), 4.50 (d, $J = 17.3$ Hz, 2H, CH_2-py), 4.73 (d, $J = 17.3$ Hz, 2H, CH_2-py), 7.00 (d, $J = 2.5$ Hz, 1H, H_α), 7.22−7.68 (m, 15H, Ar), 8.01 (t, $J = 7.8$ Hz, 2H, H_γ).

Anal. Calcd for $C_{39}H_{42}ClN_3O_5Zn\cdot H_2O$ ($M_r = 733.62 + 18.02$): C, 62.32; H, 5.90; N, 5.59. Found: C, 62.22; H, 5.89; N, 5.52.

Attachment of Anionic Ligands. **Complex 4a.** A solution of **1** (37.0 mg, 0.056 mmol) in methanol (10 mL) was added with stirring to a solution of KCl (4.64 mg, 0.062 mmol) in methanol (10 mL). After the mixture was stirred for 16 h, the fine precipitate of $KClO_4$ was filtered off and the filtrate evaporated to dryness. The colorless residue was dissolved in dichloromethane (2 mL), and *n*-heptane (5 mL) was added. Slow evaporation in the open flask resulted in the precipitation of 18 mg (54%) of **4a** as colorless crystals, mp 150 °C (dec). IR (KBr; cm^{-1}): 1604 (s) (C═N). ^{1}H NMR ($CDCl_3$): δ 1.20 (s, 9H, t-Bu), 1.43 (s, 9H, t-Bu), 3.17−4.51 (m, 6H, CH_2), 5.29 (s, 2H, CH_2Cl_2), 6.76 (d, $J = 2.6$ Hz, 1H, H_α), 6.87 (d, $J = 7.8$ Hz, 1H, H_δ), 7.02 (d, $J = 2.6$ Hz, 1H, H_γ), 7.11 (m, 1H, H_β), 7.25 (d, $J = 7.8$ Hz, 1H, H_δ), 7.54 (m, 4H, Ar), 7.65 (d, $J = 7.8$ Hz, 1H, H_β), 7.88 (t, $J = 7.8$ Hz, 1H, H_γ), 8.28 (m, 2H, Ar), 8.77 (d, $J = 5.3$ Hz, 1H, H_α).

Anal. Calcd for $C_{33}H_{38}ClN_3OZn\cdot CH_2Cl_2$ ($M_r = 593.53 + 84.93$): C, 60.19; H, 5.94; N, 6.19. Found: C, 59.84; H, 6.07; N, 6.06.

Complex 4b. This was synthesized like **4a** from **1** (35.0 mg, 0.060 mmol) and KI (10.0 mg, 0.060 mmol). Yield: 25 mg (65%) of **4b** as colorless needles. Mp: 146 °C. IR (KBr; cm^{-1}): 1603 (s) (C═N).

Anal. Calcd for $C_{33}H_{38}IN_3OZn\cdot CH_2Cl_2$ ($M_r = 684.98 + 84.93$): C, 53.04; H, 5.24; N, 5.46. Found: C, 52.62; H, 5.43; N, 5.41.

Complex 4c. This was synthesized like **4a** from **1** (200 mg, 0.296 mmol) and KSCN (28.8 mg, 0.296 mmol). Yield: 115 mg (63%) of **4c** as a colorless powder. Mp: 210 °C. IR (KBr; cm^{-1}): 1605 (s) (C═N).

Anal. Calcd for $C_{34}H_{38}N_4OSZn$ ($M_r = 616.16$): C, 66.28; H, 6.22; N, 9.09; S, 5.20. Found: C, 65.56; H, 6.29; N, 9.00; S, 5.17.

Complex 4d. A solution of *p*-nitrophenol (30.9 mg, 0.222 mmol) and KOH (12.6 mg, 0.222 mmol) in methanol (20 mL) was added slowly with stirring to a solution of **1** (150 mg, 0.222 mmol) in dichloromethane (30 mL). After 5 h of stirring, the solution was filtered and the filtrate evaporated to dryness. The residue was dissolved in dichloromethane (5 mL), and methanol (5 mL) was added. Evaporation in an open flask yielded 89 mg (58%) of **4d** as yellow crystals, mp 260 °C (dec). IR (KBr; cm^{-1}): 1603 (s) (C═N), 1292 (vs) NO_2). ^{1}H NMR ($CDCl_3$): δ 6.49 [d, $J = 9.3$ Hz, 2H, Ph(2,6)], 7.05−7.91 [m, 14H, therein Ph(3,5)].

Anal. Calcd for $C_{39}H_{42}N_4O_4Zn$ ($M_r = 696.18$): C, 67.29; H, 6.08; N, 8.05. Found: C, 67.13; H, 6.10; N, 8.02.

Complex 4e. This was synthesized like **4d** from *p*-nitrobenzoic acid (24.7 mg, 0.148 mmol), triethylamine (20.8 μL, 15.0 mg, 0.148 mmol), and **1** (100 mg, 0.148 mmol). Recrystallization from ethanol at −20 °C yielded 78 mg (68%) of **4e** as a yellow solid, mp 225

°C (dec). IR (KBr; cm^{-1}): 1625 (m) (C═N), 1594 (m, COO), 1343 (vs, NO_2). ^1H NMR ($CDCl_3$): δ 7.49 [m, 7H, therein Ph(2,6)], 8.00 [d, J = 8.5 Hz, 2H, Ph(3,5)].

Anal. Calcd for $C_{40}H_{42}N_4O_5Zn \cdot 2H_2O$ (M_r = 724.19 + 36.03): C, 63.20; H, 6.10; N, 7.37. Found: C, 63.25; H, 6.18; N, 6.99.

Complex 4f. This was synthesized like **4d** from bis(p-nitrophenyl) phosphoric acid hydrate (109 mg, 0.323 mmol), KOH (18.1 mg, 0.323 mmol), and **1** (218 mg, 0.323 mmol). Recrystallization from dichloromethane/*n*-heptane by evaporation yielded 138 mg (48%) of **4f** as light yellow crystals, mp 200 °C (dec). IR (KBr; cm^{-1}): 1608 (s) (C═N), 1345 (vs) (NO_2), 1111 (vs) (PO_2). ^1H NMR ($CDCl_3$): δ 6.89−8.01 [m, 18H, therein Ph(2,6) and Ph (3,5)]. ^{31}P NMR: δ ∠13.44 in $CDCl_3$, −12.61 in CD_3CN.

Anal. Calcd for $C_{45}H_{46}N_5O_9PZn$ (M_r = 897.25): C, 60.24; H, 5.17; N, 7.81. Found: C, 60.01; H, 5.39; N, 7.81.

Complex 5a. This was synthesized like **4a** from **2** (200 g, 0.319 mmol) and KCl (26.0 mg, 0.35 mmol). Yield: 130 mg (75%) of **5a** as a colorless powder. Mp: 250 °C (dec). IR (KBr; cm^{-1}): 1604 (s) (C═N). ^1H NMR ($CDCl_3$): δ 1.13 (s, 9H, t-Bu), 1.37 (s, 9H, t-Bu), 2.87 (s, 6H, CH_3), 3.52 (s, 2H, CH_2-phenol), 4.06 (d, J = 15.1 Hz, 2H, CH_2-py), 4.36 (d, J = 15.1 Hz, 2H, CH_2-py), 6.55 (d, J = 2.8 Hz, 1H, H_α), 6.68−7.06 (m, 5H, Ar), 7.50 (t, J = 7.5 Hz, 2H, H_γ).

Anal. Calcd for $C_{29}H_{38}ClN_3OZn$ (M_r = 545.48): C, 63.86; H, 7.02; N, 7.70. Found: C, 63.65; H, 7.16; N, 7.65.

Complex 5b. This was synthesized like **4a** from **2** (200 mng, 0.319 mmol) and KI (80.0 mg, 0.482 mmol). Yield: 95 mg (47%) of **5b** as a colorless powder. Mp: 215 °C (dec). IR (KBr; cm^{-1}): 1605 (vs) (C═N).

Anal. Calcd for $C_{29}H_{38}IN_3OZn$ (M_r = 636.93): C, 54.49; H, 6.01; N, 6.60. Found: C, 54.60; H, 6.09; N, 6.47.

Complex 5d. This was synthesized like **4d** from *p*-nitrophenol (44.4 mg, 0.319 mmol), KOH (17.9 mg, 0.319 mmol), and **2** (200 mg, 0.319 mmol). The residue after evaporation to dryness was suspended in diethyl ether (5 mL), stirred for 3 h, filtered, and evaporated to dryness, leaving behind 80 mg (39%) of **5d** as a yellow powder, mp 160 °C (dec). IR (KBr; cm^{-1}): 1605 (s) (C═N), 1301 (vs) (NO_2). ^1H NMR ($CDCl_3$): δ 6.54 [d, J = 9.2 Hz, 2H, Ph(2,6)], 7.94 [d, J = 9.2 Hz, 2H, Ph(3,5)].

Anal. Calcd for $C_{35}H_{42}N_4O_4Zn \cdot H_2O$ (M_r = 648.13 + 18.02): C, 63.11; H, 6.66; N, 8.41. Found: C, 63.74; H, 6.66; N, 8.45.

Complex 5e. This was synthesized like **4d** from *p*-nitrobenzoic acid (53.3 mg, 0.319 mmol), KOH (17.9 mg, 0.319 mmol), and **2** (200 mg, 0.319 mmol). Crystallization by slow evaporation from dichloromethane/*n*-heptane yielded 78 mg (36%) of **5e** as yellow crystals, mp 150 °C (dec). IR (KBr; cm^{-1}): 1625 (s) (COO), 1604 (s) (C═N), 1341 (vs) (NO_2). ^1H NMR ($CDCl_3$): δ 7.59−8.15 (m, 4H).

Anal. Calcd for $C_{36}H_{42}N_4O_5Zn$ (M_r = 676.14): C, 63.95; H, 6.26; N, 8.29. Found: C, 64.57; H, 6.77; N, 7.94.

Complex 5f. This was synthesized like **4d** from bis(p-nitrophenyl) phosphoric acid hydrate (107 mg, 0.319 mmol), KOH (17.9 mg, 0.319 mmol), and **2** (200 mg, 0.319 mmol). Yield: 125 mg (42%) of **5f** as a yellowish powder. Mp: 190 °C (dec), which was not analytically pure but showed only one ^{31}P NMR signal. IR (KBr; cm^{-1}): 1605 (s) (C═N), 1344 (vs) (NO_2), 1115 (vs) (PO_2). ^1H NMR ($CDCl_3$): δ 6.75−7.95 [m, 18H, therein Ph(2,6) and Ph(3,5)]. ^{31}P NMR: δ ∠11.98 in $CDCl_3$, −11.52 in CDCN.

Complex 6a. To a solution of **3** (100 mg, 0.133 mmol) in methanol was added solid KBr (19.0 mg, 0.160 mmol). After a few minutes a precipitate formed which was filtered off, suspended in dichloromethane (10 mL), and filtered again. To the filtrate was slowly added *n*-heptane to precipitate the product. A yield of 49 mg (52%) of **6a** resulted as a colorless powder, mp 270 °C (dec). IR (KBr; cm^{-1}): 1602 (m) (pyridine coordinated), 1588 (m) (pyridine uncoordinated). ^1H NMR ($CDCl_3$): δ 1.25 (s, 9H, t-Bu), 1.54 (s, 9H, t-Bu), 3.89 (s, 2H, CH_2-phenol), 4.41 (d, J = 15.8 Hz, 2H, CH_2-py), 4.61 (d, J = 15.6 Hz, 2H, CH_2-py), 6.71 (d, J = 2.5 Hz, 1H, H_α), 7.27 (m, 3H, Ar), 7.57 (m, 6H, Ar), 7.73 (d, J = 7.7 Hz, 2H, H_β), 7.88 (d, J = 7.7 Hz, 2H, H_γ), 8.13 (m, 4H, Ar). In addition to these signals attributable to **6a** further signals with nonintegral intensity values are observed as described in the text.

Anal. Calcd for $C_{39}H_{42}BrN_3OZn$ (M_r = 714.07): C, 65.60; H, 5.93; N, 5.88. Found: C, 65.37; H, 6.01; N, 5.83.

Complex 6b. To a solution of **3** (135 mg, 0.179 mmol) in methanol (20 mL) was added a solution of NaI (35.0 mg, 0.233 mmol) in methanol (10 mL), upon which a precipitate formed. After the mixture was stirred overnight, the precipitate was filtered off, washed with a few milliliters of ice-cold methanol, and dried in vacuo. A yield of 100 mg (73%) of **6b** remained as a colorless powder, mp 285 °C (dec). IR (KBr; cm^{-1}): 1605 (m) (pyridine coordinated), 1590 (m) (pyridine uncoordinated). ^1H NMR: like that of **6a**.

Anal. Calcd for $C_{39}H_{42}IN_3OZn$ (M_r = 761.07): C, 61.55; H, 5.56; N, 5.52. Found: C, 61.69; H, 5.73; N, 5.48.

Complex 6c. This was synthesized like **4d** from *p*-nitrophenol (27.8 mg, 0.200 mmol), KOH (11.2 mg, 0.280 mmol), and **3** (150 mg, 0.200 mmol). After filtration, the filtrate was evaporated to 10 mL and cooled to −20 °C. A yield of 31 mg (20%) of **6c** precipitated as yellow crystals, mp 125 °C (dec). IR (KBr; cm^{-1}): 1585(s) (pyridine uncoordinated). ^1H NMR ($CDCl_3$): δ 6.55 [d, J = 8.9 Hz, 2H, Ph(2,6)], 7.0−8.0 [m, 14H, therein Ph(3,5)].

Anal. Calcd for $C_{39}H_{46}N_4O_4Zn$ (M_r = 772.27): C, 69.99; H, 6.00; N, 7.25. Found: C, 69.31; H, 6.16; N, 7.13.

Attachment of Pyridine Donors. **Complex 7a.** Pyridine (18.0 μL, 17.6 mg, 0.222 mmol) was added with vigorous stirring to a solution of **1** (150 mg, 0.222 mmol) in methanol (35 mL). After the solution was stirred overnight, the solvent was removed in vacuo. The residue was dissolved in dichloromethane (5 mL) to which was added *n*-heptane (5 mL). Slow evaporation from the open flask yielded 120 mg (74%) of **7a** as yellow crystals, mp 190 °C (dec). IR (KBr; cm^{-1}): 1606 (s) (C═N), 1100 (vs) (ClO_4). ^1H NMR ($CDCl_3$): δ 7.0−7.8 (m, 15H, therein pyridine-H_β and -H_γ), 8.36 (m, 2H, pyridine-H_α).

Anal. Calcd for $C_{38}H_{43}ClN_4O_5Zn \cdot 0.5CH_2Cl_2 \cdot 0.5H_2O$ (M_r = 736.62 + 9.01): C, 58.68; H, 5.76; N, 7.11. Found: C, 58.46; H, 5.86; N, 6.90.

Complex 7b. This was synthesized like **7a** from 2-acetylpyridine (35.9 mg, 0.296 mmol) and **1** (200 mg, 0.296 mmol). Yield: 122 mg (52%) of **7b** as dark yellow crystals. Mp: 140 °C (dec). IR (KBr; cm^{-1}): 1690 (s) (C═O), 1602 (s) (C═N), 1095 (vs) (ClO_4). ^1H NMR ($CDCl_3$): δ 2.54 (s, 3H, CH_3CO), 6.95−7.72 (m, 13H, therein 2py-H), 8.13 (m, 1H, H_β), 8.35 (d, J = 7.3 Hz, 1H, H_α).

Anal. Calcd for $C_{40}H_{45}ClN_4O_6Zn$ (M_r = 778.66): C, 61.70; H, 5.82; N, 7.20. Found: C, 61.47; H, 6.04; N, 7.12.

Complex 8a. This was synthesized like **7a** from pyridine (25.8 μL, 25.2 mg, 0.319 mmol) and **2** (200 mg, 0.319 mmol). Yield: 36 mg (16%) of **8a** as a yellow powder. Mp: 175 °C (dec). IR (KBr; cm^{-1}): 1608 (s) (C═N), 1097 (vs) (ClO_4). ^1H NMR ($CDCl_3$): δ 7.45 (m, 2H, H_β), 7.82 (m, 1H, H_γ), 8.79 (m, 2H, H_α).

Anal. Calcd for $C_{34}H_{43}ClN_4O_5Zn$ (M_r = 688.58): C, 59.31; H, 6.29; N, 8.14. Found: C, 58.76; H, 6.44; N, 7.96.

Complex 9a. This was synthesized like **7a** from pyridine (9.2 μL, 8.9 mg, 0.11 mmol) and **3** (85 mg, 0.11 mmol). Yield: 48 mg (54%) of **9a** as yellow crystals. Mp: 250 °C (dec). IR (KBr; cm^{-1}):

Table 2. Crystallographic Data

	1	2	3	4d	7a	7b
formula	$C_{33}H_{40}ClN_3O_6Zn\cdot CH_2Cl_2$	$C_{29}H_{40}ClN_3O_6Zn$	$C_{39}H_{42}ClN_3O_5Zn\cdot H_2O$	$C_{39}H_{42}N_4O_4Zn\cdot CH_3OH\cdot 0.5CH_2Cl_2\cdot 0.5H_2O$	$C_{38}H_{43}ClN_4O_5Zn\cdot 0.5CH_2Cl_2\cdot 0.5H_2O$	$C_{40}H_{45}ClN_4O_6Zn\cdot 2CH_2Cl_2$
M_r	760.6	627.4	751.6	779.7	788.1	948.5
space group	$P\bar{1}$	$P\bar{1}$	$P2_1/c$	$P\bar{1}$	$C2/c$	$P2_1/n$
Z	2	2	4	4	8	4
a (Å)	11.848(5)	10.030(2)	21.658(4)	11.08(2)	21.204(4)	13.355(6)
b (Å)	12.462(5)	12.151(2)	10.257(2)	15.48(3)	18.506(3)	11.687(6)
c (Å)	14.445(6)	13.196(2)	17.680(3)	24.18(3)	19.580(4)	29.348(14)
α (deg)	96.51(1)	85.685(3)	90	83.08(3)	90	90
β (deg)	108.21(1)	81.476(3)	112.659(4)	83.92(3)	95.286(7)	94.385(9)
γ (deg)	111.18(1)	73.702(3)	90	79.88(4)	90	90
V (Å^3)	1826(1)	1525.6(5)	3624.5(11)	4036(12)	7651(2)	4567(4)
d(calcd) (g cm^{-3})	1.38	1.37	1.37	1.27	1.37	1.38
μ(Mo Kα) (mm^{-1})	0.94	0.94	0.80	0.72	0.83	0.88
R1 (obsd reflcns)	0.052	0.050	0.048	0.069	0.060	0.098
wR2 (all reflcns)	0.125	0.150	0.153	0.217	0.189	0.333

1610 (m) (C═N), 1096 (vs) (ClO_4). ^{1}H NMR ($CDCl_3$): δ 6.70−7.80 (m, 21H, therein H_β and H_γ), 7.87 (t, J = 7.8 Hz, 2H, H_α).

Anal. Calcd for $C_{44}H_{47}ClN_4O_5Zn$ (M_r = 812.72): C, 65.03; H, 5.83; N, 6.89. Found: C, 64.11; H, 5.73; N, 6.72.

Complex 9b. This was synthesized like **7a** from 2-acetylpyridine (29.8 μl, 32.2 mg, 0.266 mmol) and **3** (200 mg, 0.266 mmol). Crystallization from dichloromethane/cyclohexane by slow evaporation yielded 152 mg (61%) of **9b** as orange crystals, mp 215 °C. IR (KBr; cm^{-1}): 1675 (s) (C═O), 1599 (s) (C═N), 1091(vs) (ClO_4). ^{1}H NMR (CD_3CN, 320 K): δ 2.45 (s, 3H, CH_3CO), 6.90−8.60 (m, 22H, therein H_α, H_β, H_γ).

Anal. Calcd for $C_{46}H_{49}ClN_4O_6Zn\cdot CH_2Cl_2$ (M_r = 854.76 + 84.93): C, 60.07; H, 5.47; N, 5.96. Found: C, 59.79; H, 5.48; N, 5.94.

In Situ Preparation of the Hydroxide Complexes. Complex 10. 1 (10.0 mg, 0.015 mmol) and triethylamine (2.11 μL, 1.52 mg, 0.015 mmol) were added to 500 μL of CD_3CN, shaken, and used as such for the hydrolytic reactions.

^{1}H NMR (CD_3CN, all signals broad): δ 1.03 [t, J = 7.0 Hz, 9H, CH_3 (NEt_3)], 1.18 (s, 9H, t-Bu), 1.36 (s, 9H, t-Bu), 2.61 [q, J = 7.0 Hz, 6H, CH_2 (NEt_3)], 3.50 (s, 2H, CH_2-phenol), 4.08 (s, 4H, CH_2-py), 6.5−8.5 (m, 14H, Ar).

Complex 11. **2** (10.0 mg, 0.016 mmol) and triethylamine (2.22 μL, 1.60 mg, 0.016 mmol) were added to 500 μL of CD_3CN, shaken, and used as such for the hydrolytic reactions.

^{1}H NMR (CD_3CN, all signals broad): δ 1.18 (s, 9H, t-Bu), 1.22 [t, J = 7.3 Hz, 9H, CH_3 (NEt_3)], 1.31 (s, 9H, t-Bu), 2.67 [s, 6H, CH_3 (py)], 3.02 [q, J = 7.3 Hz, 6H, CH_2 (NEt_3)], 3.65 [s, 2H, CH_2-phenol], 4.18 [s, 4H, CH_2-py], 6.78 (s, 1H, H_α), 6.96 (s, 1H, H_γ), 7.03−7.40 (m, 4H, py), 7.72 (t, J = 7.6 Hz, 2H, H_γ).

Hydrolysis of Tris(*p*-nitrophenyl) Phosphate (TNP). With 10. A CD_3CN solution of **10** (see above) was treated with the equimolar amount of TNP (6.7 mg, 0.015 mmol) in a NMR tube and the reaction followed by ^{31}P NMR. Within 2 h the resonance of TNP at −18.7 disappeared and was replaced by the resonance of **4f** at −12.6 ppm.

With 11. Using **11** and TNP (7.1 mg, 0.016 mmol) the resonance of TNP was replaced by that of **5f** at −11.5 ppm.

Kinetic Study. General Methods. Measurements were performed on a JASCO V-570 UV−vis spectrometer by continually recording the 392 nm absorption of **4d** (the 380 nm absorption of **5d**). The measuring chamber and the solutions were thermostated to 25 °C for 30 min prior to the measurements and during the kinetic runs. Stock solutions of **1** (203 mg, 0.300 mmol, in 10.0 mL of CH_3CN), **2** (194 mg, 0.300 mmol, in 10.0 mL of CH_3CN), NEt_3 (84.3 μL, 60.7 mg, 0.300 mmol, in 20 mL of CH_3CN), and TNP (5.78 mg, 0.013 mmol, in 25 mL of CH_3CN) were prepared shortly before the experiments. The solutions of **1** (or **2**) and NEt_3 were mixed in the quartz cuvettes and supplemented to a total volume of 2.85 mL with CH_3CN. Immediately prior to the measurements 150 μL of the TNP solution was added. Thus, the concentration of TNP was 0.025 mM for all measurements.

TNP Cleavage with 10. Reagents were mixed such that there was a 60-, 120-, 180-, 240-, and 300-fold excesses of **10**. Absorption intensities were taken for at least $5t_{1/2}$, and their final values were taken as I_∞. The measurements could be reproduced by a first-order rate law with a correlation coefficient greater than 0.999. For the computations the measurements up to $2t_{1/2}$ were included. The reproducibility of the I values was within 10%.

TNP Cleavage with 11. The same procedure as for **10** was used, again with 60-, 120-, 180-, 240-, and 300-fold excesses of **11**. Correlation coefficients throughout were greater than 0.999.

Structure Determinations. Crystals of **1**−**3** and **7a**,**b** were obtained by layering CH_2Cl_2 solutions with *n*-heptane, and those of **4d**, by slow evaporation of a CH_2Cl_2/MeOH solution. Diffraction data were recorded with a Bruker AXS Smart CCD diffractometer at −50 °C with Mo Kα radiation and subjected to empirical absorption corrections.[42] The structures were solved with direct meethods and refined anisotropically.[42] Hydrogen atoms were included with fixed distances and isotropic temperatures factors 1.5 times those of their attached atoms. Parameters were refined against F^2. Drawings were produced with SCHAKAL.[43] Crystallographic data are listed in Table 2.

Acknowledgment. This work was supported by the Fonds der Chemischen Industrie. We are indebted to Profs. C. Röhr and B. Kersting for their help with crystallographic problems and Drs. H. Brombacher and C. Perez Olmo for measurements.

Supporting Information Available: Fully labeled ORTEP plots for all six structure determinations, two plots of the rate constants for the TNP cleavages, and six crystallographic files, in CIF format. This material is available free of charge via the Internet at http://pubs.acs.org.

IC050042U

(42) Sheldrick, G. M. *Bruker AXS, SHELXTL Program Package*, version 5.1; Universität Göttingen: Göttingen, Germany, 1998.
(43) Keller, E. *Schakal for Windows*; Universität Freiburg: Freiburg, Germany, 2001.