A Sterically Hindered N,N,O Tripod Ligand and Its Zinc Complex Chemistry

Alexander Trösch and Heinrich Vahrenkamp*

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

Received November 1, 2000

The new ligand bis(2-picolyl)(2-hydroxy-3,5-di-*tert*-butylbenzyl)amine (H**L**) was prepared from bis(2-picolyl)-amine and 2,4-di-*tert*-butyl-6-(chloromethyl)phenol. It acts as a tetradentate N,N,O tripod ligand ensuring 5-fold coordination in all its zinc complexes **L**·Zn−X. The central complex of the series was [**L**·Zn(OH_2)]ClO_4 (**1**) obtained from zinc perchlorate. Together with the more labile complex **L**·Zn−C_2H_5 (**2**), obtained from diethyl zinc, it was used as a starting material for ligand substitutions. In the presence of bases, **1** was converted to **L**·Zn−OH (**3**), [**L**·Zn(py)]ClO_4 (**4**), and [(**L**·Zn)$_3$(μ_3-CO_3)]ClO_4 (**5**). Metathetical reactions produced the neutral complexes **L**·Zn−X with X = Br (**6**), OAc (**7**), OC_6H_5 (**8**), SC_6H_5 (**9**), OP(O)(OPh)$_2$ (**10**), *p*-nitrophenolate (**11**), 1-methyluracilate (**12**), *o*-formylphenolate (**13**), and *o*-hydroxymethylphenolate (**14**). Structure determinations of **1**, **5**, **7**, **10**, **11**, **13,** and **14** confirmed the strictly monodentate attachment of all units X in **L**·Zn−X. The hydrolytic cleavage of tris(*p*-nitrophenyl) phosphate by **1** was investigated preparatively and kinetically. **L**·Zn−OH was found to be the hydrolytically active nucleophile. The second-order rate constant for the cleavage reaction was found to be slightly lower than the values for related systems, reflecting the steric hindrance in the *tert*-butyl-substituted ligand **L**.

The zinc model complex chemistry with respect to catalytic or bioinorganic systems has reached a considerable level of sophistication today. Encapsulating ligands have become the ligands of choice for mimicking the donor environment of the metal and to restrain the number of available "active" coordination sites to one or two. Among these the tripodal ligands are the most popular ones. The majority of research groups active in a preparative zinc model complex chemistry have put efforts in the design or use of tripodal ligands, as evidenced by recent publications.[1−18] We have contributed to this mostly with pyrazolylborate ligands[19] but also with tripods possessing central carbon,[20] nitrogen,[21] phosphorus, or arsenic atoms[22] and cyclohexane rings.[23]

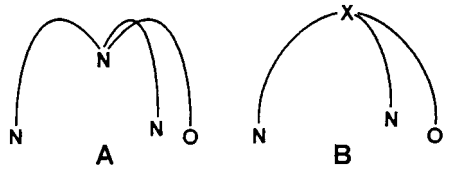
While the well-established tripod ligands possess three identical arms (more correctly feet), sophistication has been achieved by making them unsymmetrical or heteroleptic. Induced by Nature's predominating mixed N/S or N/O donor sets (provided by cysteinate, histidine, tyrosinate, glutamate, and aspartate), mixed N/S or N/O tripod ligands have become popular. Recent examples of N_2S or NS_2 tripods with central carbon,[24] boron,[5,25,26] or nitrogen atoms[18] underline this, including examples from our research group.[27]

This paper deals with tripods containing a N_2O donor set. The motivation for their design and use comes from the fact that important hydrolytic enzymes such as carboxypeptidase A,[28] thermolysine,[29] alkaline phosphatase,[30] L-fuculose 1-phosphate

(1) Kimblin, C.; Bridgewater, B. M.; Churchill, D. G.; Parkin, G. *J. Chem. Soc., Chem. Commun.* **1999**, 2301.
(2) Adams, H.; Bailey, N. A.; Fenton, D. E.; He, Q.-Y. *J. Chem. Soc., Dalton Trans.* **1997**, 1533.
(3) Hammes, B. S.; Carrano, C. J. *Inorg. Chem*. **1999**, *38*, 4593.
(4) Cronin, L.; Greener, B.; Foxon, S. P.; Heath, S. L.; Walton, P. H. *Inorg. Chem*. **1997**, *36*, 2594.
(5) Chiou, S.-J.; Innocent J.; Riordan, C. G. *Inorg. Chem.* **2000**, *39*, 4347.
(6) Mann, K. L. V.; Jeffery, J. C.; McCleverty, J. A.; Ward, M. D. *J. Chem. Soc., Dalton Trans.* **1998**, 3029.
(7) Kläui, W.; Berghahn, M.; Rheinwald, G.; Lang, H. *Angew. Chem.* **2000**, *112*, 2590; *Angew. Chem., Int. Ed. Engl.* **2000**, *39*, 2464.
(8) Reglinski, J.; Garner, M.; Cassidy, I. D.; Slavin, P. A.; Spicer, M. D.; Armstrong, D. R. *J. Chem. Soc., Dalton Trans.* **1999**, 2119.
(9) Darensbourg, D. J.; Holtcamp, M. W.; Longridge, E. M.; Khandelwal, B.; Klausmeyer, K. K.; Reibenspies, J. H. *J. Am. Chem. Soc.* **1995**, *117*, 318.
(10) Weber, M.; Kuppert, D.; Hegetschweiler, K.; Gramlich, V. *Inorg. Chem.* **1999**, *38*, 859.
(11) Murthy, N. N.; Karlin, K. D. *J. Chem. Soc., Chem. Commun.* **1993**, 1236.
(12) Hihichi, S.; Tanaka, M.; Moro-oka, Y.; Kitajima, N. *J. Chem. Soc., Chem. Commun.* **1992**, 814.
(13) Le Cloux, D. D.; Tolman, W. B. *J. Am. Chem. Soc*. **1993**, *115*, 1153.
(14) Itho, T.; Fujii, Y.; Tada, T.; Yoshikawa, Y.; Hisada, H. *Bull. Chem. Soc. Jpn.* **1996**, *69*, 1265.
(15) Meyer, F.; Rutsch, P. *J. Chem. Soc., Chem. Commun.* **1998**, 1037.
(16) Xu, X.-D.; Lajmi, A. R.; Canary, J. W. *J. Chem. Soc., Chem. Commun.* **1998**, 2701.
(17) Ray, M.; Hammes, B. S.; Yap, G. P. A.; Rheingold, A. L.; Borovik, A. S. *Inorg. Chem.* **1998**, *37*, 1527.
(18) Berreau, L. M.; Allred, R. A.; Makowska-Grzyska, M. M.; Arif, A. M. *J. Chem. Soc., Chem. Commun.* **2000**, 1423.
(19) Vahrenkamp, H. *Acc. Chem. Res.* **1999**, *32*, 589.
(20) Brandt, W.; Wirbser, J.; Powell, A. K.; Vahrenkamp, H. *Z. Naturforsch.* **1991**, *46b*, 440. Titze, C.; Hermann, J.; Vahrenkamp, H. *Chem. Ber.* **1995**, *128*, 1095.
(21) Gregorzik, R.; Hartmann, U.; Vahrenkamp, H. *Chem. Ber*. **1994**, *127*, 2117. Hartmann, U.; Gregorzik, R.; Vahrenkamp, H. *Chem. Ber*. **1994**, *127*, 2123. Burth, R.; Vahrenkamp, H. *Z. Anorg. Allg. Chem.* **1998**, *624*, 381.
(22) Gregorzik, R.; Wirbser, J.; Vahrenkamp, H. *Chem. Ber*. **1992**, *125*, 1575.
(23) Brand, U.; Vahrenkamp, H. *Inorg. Chim. Acta* **1992**, *198*−*200*, 663.
(24) Hammes, B. S.; Carrano, C. J. *J. Chem. Soc., Chem. Commun.* **2000**, 1635.
(25) Kimblin, C.; Hascall, T.; Parkin, G. *Inorg. Chem.* **1997**, *36*, 5680.
(26) Chiou, S.-J.; Ge, P.-H.; Riordan, C. G.; Liable-Sands, L. M.; Rheingold, A. L. *J. Chem. Soc., Chem. Commun.* **1999**, 159.
(27) Burth, R.; Stange, A.; Schäfer, M.; Vahrenkamp, H. *Eur. J. Inorg. Chem*. **1998**, 1759. Alsfasser, R.; Vahrenkamp, H. *Inorg. Chim. Acta* **1993**, *209*, 19.
(28) Rees, D. C.; Lewis, M.; Lipscomb, W. N. *J. Mol. Biol.* **1983**, *168*, 367.
(29) Holmes, M. A.; Matthews, B. W. *J. Mol. Biol.* **1982**, *160*, 623.

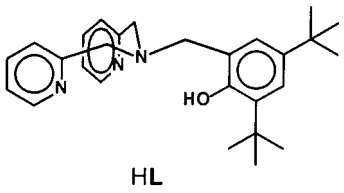
10.1021/ic001204j CCC: $20.00
Published on Web 04/11/2001

aldolase,[31] or the peptidase astacin[32] contain the catalytically active zinc ion in a N_xO_y donor environment. Major contributions to the ligand design and zinc complex chemistry of N,N,O tripods based on a central N atom (type **A**) were made by Fenton.[33,34] But also Carrano,[35] Parkin,[36] and others[37,38] published new ways of obtaining and applying such tripods, including those with a central noncoordinating atom X (type **B**).



We made our entry into the field of N,N,O tripods with the reaction chemistry of dipicoylglycinate complexes of zinc[39] and a report on the first chiral N,N,O tripod,[40] followed by some studies of the zinc complex chemistry of dipicolylalanate and dipicolyl-2-oxybenzylate.[41] Like our competitors[3,14,33] we could accumulate some evidence that the reactive species in water-containing solutions of these complexes is the monoaqua cation $[(\text{ligand})Zn(OH_2)]^+$. Yet so far neither of us had been able to prepare or isolate this elusive species ot its even more interesting deprotonated form (ligand)Zn−OH.

We therefore resorted to a technique that had been so successful for us in (pyrazolylborato)zinc chemistry,[19] the introduction of voluminous substituents on the ligand **L,** which favor lower coordination numbers of zinc and induce a hydrophobic environment of the metal. Both effects should enhance the stability of a **L**·$Zn(OH_2)$ or **L**·Zn−OH complex. This paper reports the synthesis of the so designed ligand bis-(2-picolyl)(2-hydroxy-3,5-di-*tert*-butylbenzyl)amine (H**L**) and the reaction chemistry of its zinc aqua complex $[\mathbf{L}\cdot Zn(H_2O)]^+$. The latter is the first zinc monoaqua complex of a N,N,O tripod. It has allowed to prove that the hydrolytically active species in its reactions is actually the hydroxide **L**·Zn−OH.



HL

Results and Discussion

Ligand HL. The ligand synthesis was straightforward, combining H**L** from the easily available components bis(2-picolyl)amine[42] and 2,4-di-*tert*-butyl-6-(chloromethyl)phenol.[40] Chromatographic purification yielded 70% H**L** as a yellowish solid which is soluble in organic solvents but insoluble in water. H**L** is easily identified by its NMR spectrum and its characteristic pyridine IR band at 1591 cm^{-1}.

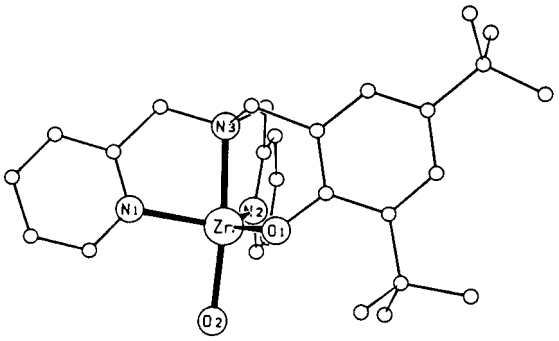


Figure 1. Molecular structure of **1.** (One cationic complex is shown; in one of them the water ligand is hydrogen-bonded to two water molecules, and in the other it is bonded to one water and one THF molecule). Important bond lengths (Å) and angles (deg) for both independent cations: Zn−O1 1.945(6)/1.924(6), Zn−N1 2.099(7)/2.073(8), Zn−N2 2.061(7)/2.059(8), Zn−N3 2.178(7)/2.219(7), Zn−O2 2.059(6)/2.079(7); O2−Zn−O1 99.8(3)/94.0(3), O2−Zn−N1 91.8-(3)/95.4(3), O2−Zn−N2 98.3(3)/97.6(3), O2−Zn−N3 165.0(3)/173.2(3).

Starting Complexes. It had been shown that the simplest way of generating a Zn−OH_2 or Zn−OH function in the pocket of an encapsulating tripodal ligand is the reaction between the ligand and the hydrated zinc salt of a noncoordinating anion. This had worked for us for the tris(pyrazolyl)borate−Zn−OH and tris(benzimidazolylmethyl)amine−Zn−OH_2 complexes[19,21] but failed for others and ourselves when applied to ligands analogous to H**L**.[3,14,33,34,39−41] It worked now for H**L** due to the presence of the *tert*-butyl substituents. Complex **1** resulted from H**L**, KOH, and $Zn(ClO_4)_2\cdot 6H_2O$ in methanol. Its characteristic spectroscopic features are a proton resonance for the aqua ligand at 3.34 ppm in $CDCl_3$ and the typically shifted pyridine IR band at 1610 cm^{-1}.

$$[\mathbf{L}\cdot Zn(OH_2)]ClO_4 \quad \mathbf{L}\cdot Zn-C_2H_5$$
$$\mathbf{1} \qquad\qquad \mathbf{2}$$

While **1** served the purpose of functionalization by replacement of the aqua ligand in polar media (see below), another starting complex for derivatizations by proteolytic cleavage in nonpolar media was found in **2**. As experienced for a similar system before,[40] **2** was obtained from H**L** and diethylzinc in hydrocarbon solvents. Its lability and its high solubility in nonpolar media prevented its purification, but it was easily identified by its proton resonances for the Zn−C_2H_5 unit. For derivatizations **2** was prepared and used in situ.

Proof for the existence and structure of **1** was obtained by a X-ray analysis; see Figure 1. **1** crystallizes with two formula units/asymmetric unit which differ in the hydrogen-bonding patterns of the ligated water molecules but not in the gross molecular features. The coordination geometry is roughly trigonal-bipyramidal with a typical distortion toward a pseudotetrahedral ligation (long Zn−N bonds to the apical nitrogen atom and O(axial)−Zn−O,N(equatorial) angles above 90°.

There are some trigonal-bipyramidal Zn−OH_2 complexes

(30) Kim, E. E.; Wyckof, H. W. *J. Mol. Biol.* **1991**, *218*, 449.
(31) Dreyer, M. K.; Schulz, G. E. *J. Mol. Biol.* **1993**, *231*, 549.
(32) Bode, W.; Goumis-Rüth, F.; Huber, R.; Zwilling, R.; Stöcker, W. *Nature* **1992**, *358*, 164.
(33) Adams, H.; Bailey, N. A.; Fenton, D. E.; He, Q.-Y. *J. Chem. Soc., Dalton Trans.* **1996**, 2857.
(34) Rodriguez de Barbarin, C. O.; Bailey, N. A.; Fenton, D. E.; He, Q.-Y. *J. Chem. Soc., Dalton Trans.* **1997**, 161.
(35) Higgs, T. C.; Spartalian, K.; O'Connor, C. J.; Matzanke, B. F.; Carrano, C. J. *Inorg. Chem.* **1998**, *37*, 2263.
(36) Ghosh, P.; Parkin, G. *J. Chem. Soc., Dalton Trans.* **1998**, 2281.
(37) Otero, A.; Fernandez-Baeza, J.; Tejeda, J.; Antiñolo, A.; Carillo-Hermosilla, F.; Diez-Barra, E.; Lara-Sanchez, A.; Fernandez-Lopez, M. *J. Chem. Soc., Dalton Trans.* **2000**, 2367.
(38) Mao, Z.-W.; Yu, K.-B.; Chen, D.; Han, S.-Y.; Sui, Y.-X.; Tang, W.-X. *Inorg. Chem.* **1993**, *32*, 3104.
(39) Abufarag, A.; Vahrenkamp, H. *Inorg. Chem.* **1995**, *34*, 2207.
(40) Abufarag, A.; Vahrenkamp, H. *Inorg. Chem.* **1995**, *34*, 3279.
(41) Trösch, A.; Vahrenkamp, H. *Eur. J. Inorg. Chem.* **1998**, 827.
(42) Romary, J. K.; Zachariasen, R. D.; Bargar, J. D.; Schiesser, H. *J. Chem. Soc.* **1968**, 2884.

with N_3O ligands in the literature,[43,44] but their N_3O ligands differ too much from **L** to allow useful comparisons of molecular details. The geometry of **1**, including the Zn−O(H_2O) distance, compares well, however, with that of the tris(benzimidazolylmethyl)amine−Zn−OH_2 complex.[45] Compared to all other **L**·Zn−OX complexes described below, the axial Zn−O bond in **1** is long, possibly reflecting the cationic nature of **1**. An important comparison is that of **1** with the zinc environment in the peptidase astacin, containing a Zn−OH_2 unit ligated in a trigonal-bipyramidal fashion by a tyrosine oxygen and three histidine nitrogens.[32] The similarity in terms of bond lengths and angles is satisfying, with the exception that the phenol-derived ligand in the enzyme is in an axial position (Zn−O = 2.6 Å) and the water ligand in the enzyme is equatorial (Zn−O = 2.1 Å).

Reactions with Bases. While complexes of the type **L**·Zn−OH_2 are analogues of the resting state of hydrolytic zinc enzymes, complexes **L**·Zn−OH are models of the active enzymes. We have shown this extensively for the pyrazolylborate−Zn−OH complexes,[19] but it was also shown indirectly for the zinc complex chemistry of ligands analogous to **L**. We therefore hoped to identify or isolate the deprotonated state of **1**, the neutral comple **3**.

L·Zn−OH
3

Ligand H**L** and its complex **1** are not suitable for potentiometric titrations in aqueous solution due to solubility problems. **1** was therefore treated with various bases in organic or organo−aqueous solutions. Complex **3** could not be isolated from such reactions, but spectra and reactivity support its existence. We propose that **3** is formed from equimolar amounts of **1** and triethylamine in chloroform. The impure solid obtained has a NMR spectrum that differs from that of **1**, specifically by the absence of the H_2O resonance. The assumption that **3** is an enzyme model, i.e., its Zn−OH function is a hydrolytically active nucleophile, is borne out by its phosphate ester cleavage described below which does not take place with nondeprotonated **1**.

Treatment of **1** with a stoichiometric amount of pyridine in methanol resulted in the replacement of the water ligand by the pyridine donor. The resulting complex **4** was identified by its spectra, the most notable features of which are the absence of water signals in the IR as well as in the NMR.

$[\mathbf{L}\cdot Zn(py)]ClO_4$ **4** $[(\mathbf{L}\cdot Zn)_3(\mu_3\text{-}CO_3)]ClO_4$ **5**

When a methanolic solution of **1** was treated with 1 equiv of NaOH and left to stand in an open vessel, it absorbed CO_2 from the atmosphere, resulting in the crystallization of the trinuclear carbonato complex **5**. **5** is another member of this group of complexes having three zinc units with polydentate ligands attached to the three carbonate oxygen atoms.[11,14,46,47] Again the formation of **5** is evidence for the existence of **3**, in analogy to the observation by Karlin[11] that an isolated dinuclear Zn−OH complex binds CO_2 to form a carbonato complex analogous to **5**.

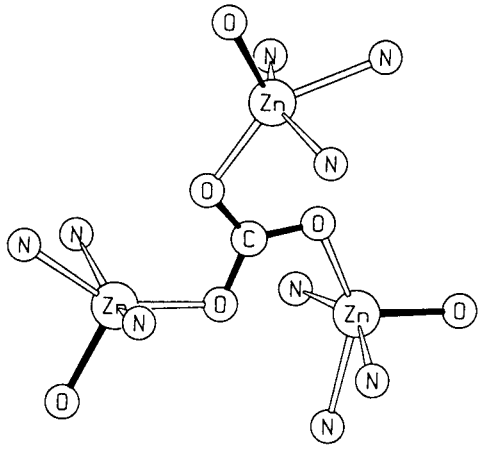


Figure 2. Coordination of the three zinc ions in **5**. Important bond lengths (Å) and angles (deg): C−O(carbonate) 1.288(9), 1.281(9), 1.305(8); Zn−O(carbonate) 2.000(5), 2.003(5), 1.985(5); Zn−O(phenolate) 1.967(5), 1.951(5), 1.957(5); Zn−N(amine) 2.163(6), 2.169(6), 2.153(6); Zn−N(pyridine) 2.118(7)/2.144(6), 2.140(6)/2.138(6), 2.162(6)/2.157(7); N(pyridine)−Zn−N(pyridine) 150.0(3), 150.6(2), 150.2(3); N(amine)−Zn−O(carbonate) 144.1(2), 144.0(2), 147.5(2); Zn−O−C(carbonate) 107.3(4), 105.9(4), 107.7(4).

The structure of **5** (complete figure in the Supporting Information; for a schematic drawing, see Figure 2) displays the tris-monodentate attachment of the carbonate ligand to the three **L**·Zn units. Unlike in all other complexes in this paper the coordination of the three zinc ions is square-pyramidal, which is also unique in comparison to the other reported trinuclear zinc carbonato complexes.[11,14,46,47] For each **L**·Zn unit the phenolate oxygen atom occupies the apical position. As a consequence, all Zn−N bonds have about the same length, while the Zn−O(carbonate) bonds are slightly longer than the Zn−O(phenolate) bonds. Figure 3 is meant to display the coordination pattern. Otherwise there are no unusual features of **5** in comparison to the other complexes of this paper or the other (μ_3-carbonato)zinc complexes. The crystals of **5** contain three water molecules/formula unit of **5** which, however, are not located in the vicinity of the zinc ions.

Metathetical Reactions. The replacement of the water molecule in **1** and the proteolytic removal of the ethyl group from **2** were applied to introduce other ligands at the **L**·Zn moiety which are either standard ligands in zinc coordination chemistry or bear some relevance to the bioinorganic chemistry of zinc. Bromide, acetate, phenolate, and thiophenolate were chosen for the first group of these. Bromide and acetate could be introduced as **6** and **7** by treating **1** with their sodium salts. Alternatively and more conveniently, **6** was prepared from deprotonated H**L** and $ZnBr_2$. Phenolate and thiophenolate could be introduced as **8** and **9** by reacting **2** with phenol and thiophenol.

L·Zn−Br **6** **L**·Zn−$OC(O)CH_3$ **7**

L·Zn−OC_6H_5 **8** **L**·Zn−SC_6H_5 **9**

Complexes **6**−**9** are molecular species with a good solubility in nonpolar organic solvents, thereby indicating their mononuclear nature. Their similarity is underlined by their spectro-

(43) Kratochvil, B.; Ondracek, J.; Novotny, J. *Acta Crystallogr. C* **1991**, *47*, 2207.
(44) Kimura, E.; Koike, T.; Toriumi, K. *Inorg. Chem.* **1988**, *27*, 3687.
(45) Brandsch, T.; Schell, F. A.; Weis, K.; Ruf, M.; Müller, B.; Vahrenkamp, H. *Chem. Ber.* **1997**, *130*, 283.
(46) Bazzicalupi, C.; Benini, A.; Bianchi, A.; Corana, F.; Fusi, V.; Giorgi, C.; Paoli, P.; Paoletti, P.; Valtancoli, B.; Zanchini, C. *Inorg. Chem.* **1996**, *35*, 5540.
(47) Schrodt, A.; Neubrand, A.; van Eldik, R. *Inorg. Chem.* **1997**, *36*, 4579.

scopic features. The coligands X in these species **L**·Zn−X are monodentate. Only the acetate ligand in **7** has the alternative to be bidentate. Therefore, **7** was chosen for a structure determinataion which is documented in the Supporting Information. It confirmed the strictly monodentate acetate attachment (Zn−O−C = 138°). Thus the four simple complexes **6**−**9** can be assigned a structure like **1** with the coligand X on an apical position of a distorted trigonal-bipyramidal $ZnON_3X$ ligand set.

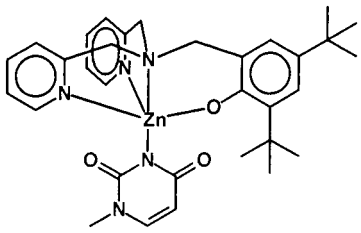
The second group of coligands chosen contained diphenyl phosphate and *p*-nitrophenolate which are substrate and product analogues of zinc enzyme catalyzed phosphate ester hydrolyses. At the same time they were meant to provide a structural background for the mechanistic investigation of the phosphate ester cleavage by **3** described below. Complexes **10** and **11** were obtained from **1** by addition of base and the reagent (diphenylphosphoric acid or *p*-nitrophenol). Both reaction courses (deprotonation of **1** before addition of the reagent or deprotonation of the reagent before addition to **1**) are feasible. Alternatively, **10** and **11** are accessible from the ethyl complex **2** and the reagent.

$$\underset{\mathbf{10}}{\mathbf{L}\cdot Zn-OP(O)(OPh)_2} \qquad \underset{\mathbf{11}}{\mathbf{L}\cdot Zn-OC_6H_4\text{-}p\text{-}NO_2}$$

Solubility and spectroscopic properties confirm the mononuclear and molecular nature of **10** and **11**. One significant spectroscopic feature of **11** is the position of the UV absorption band due to the *p*-nitrophenyl group (λ_{max} = 385 nm) which allows one to distinguish **11** from free *p*-nitrophenolate (λ_{max} = 400 nm), which is important for the mechanistic investigation described below. Both **10** and **11** were subjected to crystal structure determinations which are documented in the Supporting Information. They confirmed the distorted trigonal-bipyramidal ZnN_3O_2 coordination with axial angles of 167° in **10** and 160° in **11** and with Zn−O(substrate) bond lengths of 1.99 Å in **10** and 1.98 Å in **11**. The other molecular details of **10** and **11** correspond closely to those reported by us[39−41] for similar phosphate complexes and by Fenton[48] and us[40] for related phenolate complexes, and the ligand arrangements in **11** and **13**/**14** (see below) are also very similar.

The third group of coligands contained those which are potentially bidentate and relevant in the context of nonhydrolytic zinc enzymes. We had observed that nucleobases, which are synthesized and metabolized inter alia by zinc enzymes, are bound to zinc preferably via their deprotonated NH functions and can use their additional donor functions for chelation.[49,50] We tested this here for 1-methyluracil as the simplest analogue of uridine and the uridine nucleotides. Its reaction with **2** yielded the uracilate **12**. The spectroscopic data for **12** support the formulation given without coordination of the C=O functions to zinc. The main indicator is the ν(CO) absorption in the IR at 1644 cm^{-1} which exactly corresponds to that of the pyrazolylborate complex $Tp^{Cum,Me}$Zn−1-methyluracilate which we have structurally characterized.[51]

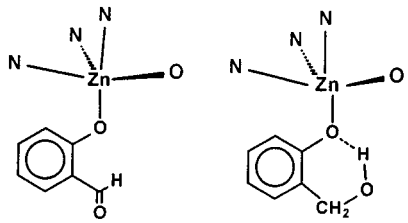
o-Formylphenolate (the anion of salicylic aldehyde) and *o*-hydroxymethylphenolate were applied with the clear expectation that they might act as bidentate ligands. Their formyl and hydroxymethyl groups represent the oxidized and reduced forms of the substrates (aldehyde/alcohol) which are interconverted



12

by the zinc-containing alcoholdehydrogenase enzymes. We had observed before[52,53] that the enzyme−substrate interactions of these enzymes can be modeled by zinc complexes in which the aldehydic and alcoholic functions are attached to zinc in a chelating fashion. As the second donor of the chelating alcohol or aldehyde ligands we had used pyridine nitrogen[52] or phenolate oxygen,[53] and even in the pocket within encapsulating pyrazolylborate ligands could the increase of the coordination number of zinc be realized. With this in mind, complexes **L**·Zn−OC_6H_4-*o*-CHO **(13)** and **L**·Zn−O−C_6H_4-*o*-CH_2OH **(14)** were synthesized from **1** and the potassium salts of *o*-formylphenol and *o*-(hydroxymethyl)phenol.

The relevant spectroscopic data for **13** and **14** [ν(CO-aldehyde) and δ(CHO) as well as $\delta(CH_2OH)$] do not differ significantly from those of the free substrates and hence speak against a zinc coordination by the CHO or CH_2OH groups. Structure determinations confirmed this conclusion. Both **13** and **14** (details in the Supporting Information) have a zinc coordination which is virtually identical to that of **11** and related complexes.[40,48] The aldehyde donor in **13** is turned away from the zinc ion. The alcoholic function in **14** is bent inward but not enough to have a bonding interaction with zinc (Zn···O = 4.27 Å). Instead it is connected to the phenolate oxygen by a hydrogen bond (O···O = 2.66 Å), as displayed below. The major conclusion from these findings is that the steric situation of ligand **L** is such that it unambiguously enforces 5-fold coordination in its zinc complexes.



13 **14**

Phosphate Ester Cleavage. The abundance of zinc-containing phosphatases and the biological importance of phophate transfer have induced numerous mechanistic studies of zinc complex mediated phosphate ester cleavages.[14,33,54−56] We have contributed to this with preparative and detailed kinetic investigations involving (pyrazolylborato)zinc complexes.[57−59] Our

(48) Rodriguez de Barbarin, C. O.; Bailey, N. A.; Fenton, D. E.; He, Q.-Y. *Inorg. Chim. Acta* **1994**, *219*, 205.
(49) Ruf, M.; Weis, K.; Vahrenkamp, H. *Inorg. Chem.* **1997**, *36*, 2130.
(50) Koppenhöfer, A.; Hartmann, U.; Vahrenkamp, H. *Chem. Ber.* **1995**, *128*, 779.
(51) Badura, D.; Vahrenkamp, H. Unpublished results.
(52) Müller, B.; Schneider, A.; Tesmer, M.; Vahrenkamp, H. *Inorg. Chem.* **1999**, *38*, 1900.
(53) Walz, R.; Ruf, M.; Vahrenkamp, H. *Eur. J. Inorg. Chem.* **2001**, 139.
(54) Gellmann, S. H.; Petter, R.; Breslow, R. *J. Am. Chem. Soc.* **1986**, *108*, 2388.
(55) Koike, T.; Kimura, E. *J. Am. Chem. Soc.* **1991**, *113*, 8935.
(56) Jurek, P.; Martell, A. E. *Inorg. Chim. Acta* **1999**, *287*, 47.
(57) Weis, K.; Rombach, M.; Ruf, M.; Vahrenkamp, H. *Eur. J. Inorg. Chem.* **1998**, 263.
(58) Weis, K.; Vahrenkamp, H. *Eur. J. Inorg. Chem.* **1998**, 271.
(59) Rombach, M.; Maurer, C.; Weis, K.; Keller, E.; Vahrenkamp, H. *Chem. Eur. J.* **1999**, *5*, 1013.

preparative work proved that the Zn−OH unit is the hydrolytically active nucleophile. In our kinetic work we observed for the first time the strongly negative activation entropies indicative of the four-center association of the Zn−OH and P═O functions in the rate-determining step. The availability of the Zn−OH complex **3** in this work provided a chance to verify the previous conclusions for the **L**·Zn complexes. Work by Fenton had already provided indirect evidence for the involvement of a Zn−OH complex with a tripodal ligand similar to **L**.[33]

As usual for these studies, tris(*p*-nitrophenyl) phosphate (TNP) was chosen for the cleavage reactions which we performed in chloroform because several of the uncharged molecular species involved are insoluble in water. We observed that the aqua complex **1** does not react with TNP but the hydroxo complex **3** does, thereby underlining the essentiality of the Zn−OH function. The reaction of 2 equiv of **3** with 1 equiv of TNP produces a mixture of the phosphate complex L·Zn−OPO-$(OC_6H_4$-*p*-$NO_2)_2$ (**15**) and the nitrophenolate complex **11**. The individual components of this mixture were prepared from **3** and bis(*p*-nitrophenyl) phosphate (**15**) or *p*-nitrophenol (**11**; see above), respectively. **15** could not be obtained in a pure form but was easily identified by its ^{31}P NMR signal at −15.4 ppm. The individual preparations from **3** showed that the formation of **15** is about 2 orders of magnitude slower than the formation of **11**. The nucleophilic strength of **3** is not high enough to effect hydrolytic cleavage of bis(*p*-nitrophenyl) phosphate.

All these observations were favorable for the kinetic study under pseudo-first-order conditions, i.e., with a large excess of **3** for the cleavage of TNP. It can be assumed that the cleavage initially produces **15** and free *p*-nitrophenol. The latter is then converted by a fast reaction with excessive **3** into **11**. The concentration of **11** can be monitored by UV spectroscopy using its unobscured absorption band at 385 nm. It is a measure of the concentration of TNP, and from the UV extinctions I the pseudo-first-order rate constant can be derived using the equation

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

The values of k_{obs} were determined this way for six different concentrations of **3** in the presence of 0.1 mM TMP. The resulting plot is given in the Supporting Information. The linearity of the plot points to a clean second-order reaction, as expected. The slope yields a second-order rate constant k'' of 0.27 s^{-1} M^{-1}. The least-squares line does not pass through the origin. This means that hydrolysis occurs also in the absence of **3**, e.g. by traces of water in the reaction system. As mentioned above, the aqua complex **1** is not hydrolytically active. The intercept of the ordinate is small enough to ensure that complex **3** is the essential hydrolytically active species.

Of the previous investigations of phosphate ester hydrolysis with zinc complexes few were done in solvents other than water. As these reations are generally much faster in water, our rate constant can only be compared with those obtained in similar solvents. We found k'' values between 0.45 and 1.55 s^{-1} M^{-1} for TNP cleavage by pyrazolylborate−Zn−OH complexes.[59] Fenton found k'' values between 0.90 and 2.21 s^{-1} M^{-1} for the cleavage by Zn−OH complexes of ligands similar to **L**.[33] The k'' value of 0.27 s^{-1} M^{-1} observed here for **L**·Zn−OH has the same order of magnitude but is considerably smaller than the others. We invoke steric hindrance by **L** to explain this. Just like **L** prevents all its stable zinc complexes from being octahedral, it should make it more difficult than the other ligands to bring in the phosphate substrate and form the four-center Zn−OH/P═O aggregate which is a reaction intermediate or the transition state of the cleavage reaction.

Conclusions

The chemistry of the new ligand **L** has fulfilled the expectations put into it. It is easy to synthesize, it makes stable zinc complexes of great variety, the complexes **L**·Zn-X are easy to handle due to their molecular nature, they are strictly and reliably five-coordinate, and the functionality of the Zn−X unit can be exploited in the intact **L**·Zn environment. All these properties provide the **L**·Zn moiety with the same advantages for five-coordinate zinc that the pyrazolylborate−Zn moiety has for four-coordinate zinc.

The ZnN_3O coordination pattern provided by **L** corresponds to the ligation of zinc in several hydrolytic enzymes. In addition to this structural analogy there exists the functional analogy in the form of the stable complex $[\mathbf{L}\cdot Zn(OH_2)]^+$ (**1**). **1** is the first isolated monoaquazinc complex for the class of tripodal ligands such as **L**. Its relevance could be demonstrated by the preparation and use of the complex **L**·Zn−OH (**3**), resulting from deporotonation of **1**. **3** is a general base, being able to deprotonate species HX which then form complexes **L**·Zn−X. It is also strong enough a base to bind CO_2 from the air forming the trinuclear carbonato complex $[(\mathbf{L}\cdot Zn)_3(\mu_3\text{-}CO_3)]^+$ (**5**).

The functional analogy of **1** or **3** with the hydrolytic zinc enzymes could be verified by phosphate ester cleavage. The kinetic data of this reaction show that, although the bulky ligand **L** limits access to the hydrolytically active Zn−OH center, the reactivity of the complex is only slightly lower than that of related systems. Complexes $[\mathbf{L}\cdot Zn(OH_2)]^+$ and **L**·Zn(OH) thereby suggest themselves for further biomimetic studies concerning the hydrolysis of phosphates, esters, peptides, and CO_2.

Experimental Section

General Information. The general working techniques were as described previously.[60] Reactions involving $ZnEt_2$ were performed in dehydrated solvents and in a nitrogen atmosphere. Starting materials were obtained commercially. Bis(picolyl)amine[42] and 2,4-di-*tert*-butyl-6-(chloromethyl)phenol[40] were prepared according to the published procedures. The term hexanes is used for petroleum ether boiling between 60 and 70 °C. In those cases where several preparations yielded the same complex only the best procedure is described.

Ligand HL. A solution of bis(picolyl)amine (4.00 g, 20.1 mmol) and triethylamine (7.26 g, 71.8 mmol) in dioxane (30 mL) was treated with a solution of 2,4-di-*tert*-butyl-6-(chloromethyl)phenol (5.12 g, 20.1 mmol) in dioxane (20 mL). After stirring of the mixture for 1 day, the triethylammonium chloride was filtered off and the filtrate evaporated to dryness. Chromatography with ethanol/ethyl acetate (7:3) over a 6 × 30 cm silica gel column using UV detection allowed us to separate the product H**L** with a R_f value of 0.78. A 5.89 g (70%) amount of H**L** remained as a yellowish solid, mp 96 °C. IR (KBr): 3210 (m, br) (OH), 1591 (s) (C═N). ^{1}H NMR ($CDCl_3$): 1.19 [s, 9H, *t*-Bu], 1.38 [s, 9H, *t*-Bu], 3.73 [s, 2H, CH_2−phenol], 3.80 [s, 4H, CH_2−py], 6.80−7.60 [m, 8H, aromatic], 8.48 [d, J = 4.9 Hz, 2H, H_α], 10.58 [s, 1H, OH].

Anal. Calcd for $C_{27}H_{35}N_3O$ (M_r = 417.6): C, 77.66; H, 8.45; N, 10.06. Found: C, 77.12; H, 8.49; N, 9.44.

Complex 1. A solution of H**L** (300 mg, 0.72 mmol) and KOH (40 mg, 0.72 mmol) in methanol (20 mL) was treated with a solution of $Zn(ClO_4)_2\cdot 6H_2O$ (268 mg, 0.72 mmol) in methanol (10 mL). After stirring of the mixture for 30 min, the $KClO_4$ precipitate was filtered off and the filtrate evaporated to dryness. Crystallization from benzene yielded 259 mg (60%) of **1** as colorless crystals, mp 250 °C. IR (KBr): 3434 (m, br) (OH), 1610 (s) (C═N), 1105 (vs) (ClO_4). ^{1}H NMR ($CDCl_3$): 1.22 [s, 9H, *t*-Bu], 1.30 [s, 9H, t-Bu], 3.34 [s, 2H, H_2O], 3.82 [s, 2H, CH_2−phenol], 3.97 [d, J = 16.3 Hz, 2H, CH_2−py], 4.12

(60) Förster, M.; Burth, R.; Powell, A. K.; Eiche, T.; Vahrenkamp, H. *Chem. Ber.* **1993**, *126*, 2643.

[d, J = 16.3 Hz, 2H, CH_2−py], 6.81 [d, J = 2.6 Hz, 1H, H_c], 7.10 [d, J = 2.6 Hz, 1H, H_a], 7.32−7.90 [m, 6H, aromatic], 8.95 [d, J = 4.5 Hz, 2H, H_α].

Anal. Calcd for $C_{27}H_{36}ClN_3O_6Zn$ (M_r = 599.4): C, 54.10; H, 6.05; N, 7.01. Found: C, 54.29; H, 6.11; N, 6.32.

Complex 2. A solution of $ZnEt_2$ (1 M, 0.72 mmol, 0.72 mL) in *n*-hexane was added to a solution of H**L** (300 mg, 0.72 mmol) in toluene/*n*-hexane (5:1) and stirred for 1 h. Filtration and removal of the solvent from the filtrate left behind 316 mg (86%) of impure **2** as a yellowish solid which decomposes within hours. ^{1}H NMR (C_6D_6): 0.76 [q, J = 8.2 Hz, 2H, Zn−CH_2], 1.37 [s, 9H, *t*-Bu], 1.71 [t, J = 8.2 Hz, 3H, ethyl-CH_3], 1.85 [s, 9H, *t*-Bu], 3.45 [s, 2H, CH_2−phenol], 3.74 [d, J = 15.0 Hz, 2H, CH_2−py], 4.04 [d, J = 15.0 Hz, 2H, CH_2−py], 6.40−7.40 [m, 8H, aromatic], 8.19 [d, J = 4.6 Hz, 2H, H_α].

Complex 3. A mixture of **1** (100 mg, 0.17 mmol) and triethylamine (17 mg, 0.17 mmol) in chloroform (5 mL) was stirred for 10 min. Removal of the solvent in vacuo left behind a mixture of triethylammonium perchlorate and **3** as a colorless solid. ^{1}H NMR ($CDCl_3$): 1.10 [t, J = 7.2 Hz, 9H, CH_3-ethyl], 1.26 [s, 9H, *t*-Bu], 1.35 [s, 9H, *t*-Bu], 2.66 [q, J = 7.2 Hz, 6H, N−CH_2], 3.83 [s, 2H, CH_2−phenol], 4.12 [d, J = 16.6 Hz, 2H, CH_2−py], 4.23 [d, J = 16.6 Hz, 2H, CH_2−py], 6.87 [d, J = 2.4 Hz, 1H, H_c], 7.17−7.83 [m, 7H, aromatic], 8.85 [d, J = 4.8 Hz, 2H, H_α].

Complex 4. A solution of pyridine (40 mg, 0.50 mmol) in methanol (5 mL) was added to a solution of **1** (300 mg, 0.50 mmol) in methanol (15 mL). After the solution was stirred for 1 h, the solvent was removed in vacuo and the residue crystallized from ethanol, yielding 116 mg (35%) of **4** as a colorless solid, mp 196 °C. IR (KBr): 1608 (s) (C═N), 1098 (vs) (ClO_4). ^{1}H NMR ($CDCl_3$): 1.15 [s, 9H, *t*-Bu], 1.30 [s, 9H, *t*-Bu], 3.74 [s, 2H, CH_2−phenol], 4.12 [d, J = 16.0 Hz, 2H, CH_2−py], 4.40 [d, J = 16.0 Hz, 2H, CH_2−py], 6.78 [d, J = 2.4 Hz, 1H, H_c], 7.03 [d, J = 2.4 Hz, 1H, H_a], 7.19−8.02 [m, 11H, aromatic], 9.15 [d, J = 4.6 Hz, 2H, H_α].

Anal. Calcd for $C_{32}H_{39}ClN_4O_5Zn$ (M_r = 660.5): C, 58.19; H, 5.95; N, 8.48; Zn, 9.90. Found: C, 60.21; H, 6.23; N, 8.18; Zn, 9.47.

Complex 5. A solution of **1** (500 mg, 0.83 mmol) in methanol (20 mL) was treated with a solution of NaOH (33 mg, 0.83 mmol) in methanol (10 mL), stirred for 1 h, and left standing in an open beaker for 2 days. A 763 mg (57%) amount of **5** precipitated as colorless crystals, mp 195 °C, which were filtered off and washed with hexanes. IR (KBr): 1708 (w) (C═O_{as}), 1605 (s) (C═N), 1262 (s) (C═O_{sym}), 1101 (vs) (ClO_4). ^{1}H NMR ($CDCl_3$): 1.32 [s, 9H, *t*-Bu], 1.55 [s, 9H, *t*-Bu], 3.74 [s, 2H, CH_2−phenol], 3.99 [s, 4H, CH_2−py], 6.76 [d, J = 2.5 Hz, 1H, H_c], 7.04 [d, J = 2.5 Hz, 1H, H_a], 7.13−7.80 [m, 6H, aromatic], 9.26 [d, J = 5.2 Hz, 2H, H_α].

Anal. Calcd for $C_{82}H_{102}ClN_9O_{10}Zn_3 \cdot 3H_2O$ (M_r = 1605.4 + 54.0): C, 58.71; H, 6.61; N, 7.52. Found: C, 58.50; H, 6.30; N, 6.96.

Complex 6. A solution of $ZnBr_2$ (162 mg, 0.72 mmol) in methanol (10 mL) was added to a solution of H**L** (300 mg, 0.72 mmol) and NaOH (29 mg, 0.72 mmol) in methanol (20 mL). After the solution was stirred for 2 h, diethyl ether (50 mL) was added, precipitating **6**. Recrystallization from methanol yielded 289 mg (64%) of **6** as colorelss crystals, mp 268 °C. IR (KBr): 1607 (s) (C═N). ^{1}H NMR ($CDCl_3$): 1.16 [s, 9H, *t*-Bu], 1.35 [s, 9H, *t*-Bu], 3.39 [s, 6H, methanol], 3.69 [s, 2H, CH_2−phenol], 3.80 [d, J = 15.9 Hz, 2H, CH_2−py], 4.04 [d, J = 15.9 Hz, 2H, CH_2−py], 6.71 [d, J = 2.5 Hz, 1H, H_c], 7.04 [d, J = 2.5 Hz, 1H, H_a], 7.16−7.79 [m, 6H, aromatic], 9.48 [d, J = 5.0 Hz, 2H, H_α].

Anal. Calcd for $C_{27}H_{34}BrN_3OZn \cdot 2CH_3OH$ (M_r = 561.9 + 64.1): C, 55.65; H, 6.76; N, 6.71. Found: C, 55.43; H, 6.74; N, 6.72.

Complex 7. A solution of glacial acetic acid (40 mg, 0.67 mmol) and NaOH (27 mg, 0.67 mmol) in methanol (15 mL) was added to a solution of **1** (400 mg, 0.67 mmol) in methanol (20 mL) and stirred for 1 h. The solvent was removed in vacuo and the residue taken up in 5 mL of dichloromethane. Layering with hexanes yielded, within 3 days, 180 mg (43%) of **7** as colorless crystals, mp 221 °C. IR (KBr): 1609 (vs) (C═O and C═N). ^{1}H NMR ($CDCl_3$): 1.08 [s, 9H, *t*-Bu], 1.28 [s, 9H, *t*-Bu], 2.02 [s, 3H, acetate], 3.58 [s, 2H, CH_2−phenol], 4.06 [s, 4H, CH_2−py], 5.32 [s, 2H, CH_2Cl_2], 6.62 [d, J = 2.6 Hz, 1H, H_c], 6.83 [d, J = 2.6 Hz, 1H, H_a], 7.00−7.66 [m, 6H, aromatic], 8.72 [d, J = 5.0 Hz, 2H, H_α].

Anal. Calcd for $C_{29}H_{37}N_3O_3Zn \cdot CH_2Cl_2$ (M_r = 541.0 + 84.9): C, 57.57; H, 6.28; N, 6.71. Found: C, 57.24; H, 6.13; N, 6.95.

Complex 8. To a solution of H**L** (300 mg, 0.72 mmol) in toluene (10 mL) were added 0.72 mmol (0.72 mL of a 1 M solution in *n*-hexane) of diethylzinc and a solution of phenol (68 mg, 0.72 mmol) in toluene (5 mL). After the mixture was stirring for a few minutes, the product precipitated. Recrystallization from methanol yielded 341 mg (78%) of **8** as a colorless solid, mp 225 °C. IR (KBr): 1606 (s) (C═N). ^{1}H NMR ($CDCl_3$): 1.23 [s, 9H, *t*-Bu], 1.36 [s, 9H, *t*-Bu], 3.39 [s, 3H, methanol], 3.80 [s, 2H, CH_2−phenol], 3.88 [d, J = 15.8 Hz, 2H, CH_2−py], 4.11 [d, J = 15.8 Hz, 2H, CH_2−py], 6.81 [m, 1H, phenolate], 7.12 [d, J = 2.6 Hz, 1H, H_c], 7.18 [d, J = 2.6 Hz, 1H, H_a], 7.20−7.78 [m, 10H, aromatic], 9.06 [d, J = 5.0 Hz, 2H, H_α].

Anal. Calcd for $C_{33}H_{39}N_3O_2Zn \cdot CH_3OH$ (M_r = 575.1 + 32.0): C, 67.26; H, 7.14; N, 6.92. Found: C, 67.72; H, 6.90; N, 6.70.

Complex 9. This was made as was **8** from H**L** (300 mg, 0.72 mmol), with 0.72 mmol of diethylzinc and thiophenol (79 mg, 0.72 mmol). Yield: 294 mg (69%) of **9** as a colorless solid, mp 179 °C. IR (KBr): 1604 (s) (C═N). ^{1}H NMR ($CDCl_3$): 1.13 [s, 9H, *t*-Bu], 1.29 [s, 9H, *t*-Bu], 3.65 [s, 2H, CH_2−phenol], 3.90 [d, J = 15.7 Hz, 2H, CH_2−py], 4.06 [d, J = 15.7 Hz, 2H, CH_2−py], 6.68−7.70 [m, 13H, aromatic], 8.97 [d, J = 4.9 Hz, 2H, H_α].

Anal. Calcd for $C_{33}H_{39}N_3OSZn$ (M_r = 591.2): C, 67.05; H, 6.65; N, 7.11. Found: C, 66.56; H, 6.70; N, 6.86.

Complex 10. A solution of diphenyl phosphate (168 mg, 0.67 mmol) and NaOH (27 mg, 0.67 mmol) in methanol (15 mL) was added to a solution of **1** (400 mg, 0.67 mmol) in methanol (20 mL). After the solution was stirred for 1 h, the solvent was removed in vacuo and the residue crystallized from acetone, yielding 159 mg (30%) of **10** as colorless crystals, mp 217 °C. IR (KBr): 1607 (s) (C═N), 1281 (s), 1211 (s) (P═O). ^{1}H NMR ($CDCl_3$): 1.22 [s, 9H, *t*-Bu], 1.43 [s, 9H, *t*-Bu], 2.09 [s, 6H, acetone], 3.74 [s, 2H, CH_2−phenol], 3.81 [d, J = 16.0 Hz, 2H, CH_2−py], 4.08 [d, J = 16.0 Hz, 2H, CH_2−py], 6.77 [d, J = 2.4 Hz, 1H, H_c], 7.04−7.82 [m, 17H, aromatic], 9.08 [d, J = 5.2 Hz, 2H, H_α].

Anal. Calcd for $C_{39}H_{44}N_3O_5PZn \cdot (CH_3)_2CO$ (M_r = 731.2 + 58.0): C, 63.92; H, 6.39; N, 5.32. Found: C, 64.51; H, 6.18; N, 5.33.

Complex 11. A solution of *p*-nitrophenol (93 mg, 0.68 mmol) in chloroform (5 mL) was added to a solution of **1** (400 mg, 0.67 mmol) and triethylamine (68 mg, 0.67 mmol) in chloroform (15 mL). After the soution was stirred for 5 min, the solvent was removed in vacuo and the residue crystallized from acetone, yielding 224 mg (54%) of **11** as yellow crystals, mp 238 °C. IR (KBr): 1609 (s) (C═N), 1287 (vs) (N═O). ^{1}H NMR ($CDCl_3$): 1.17 [s, 9H, *t*-Bu], 1.27 [s, 9H, *t*-Bu], 3.76 [s, 2H, CH_2−phenol], 3.83 [d, J = 16.0 Hz, 2H, CH_2−py], 4.07 [d, J = 16.0 Hz, 2H, CH_2−py], 6.74 [d, J = 2.5 Hz, 1H, H_c], 7.08 [d, J = 2.5 Hz, 1H, H_a], 7.19−8.09 [m, 10H, aromatic], 8.83 [d, J = 5.0 Hz, 2H, H_α].

Anal. Calcd for $C_{33}H_{38}N_4O_4Zn$ (M_r = 620.1): C, 63.92; H, 6.18; N, 9.04. Found: C, 63.70; H, 6.23; N, 8.87.

Complex 12. To a solution of H**L** (300 mg, 0.72 mmol) in acetonitrile (10 mL) were added 0.72 mmol of diethylzinc (0.72 mL of a 1 M solution in *n*-hexane). After 5 min of stirring and subsequent heating to 50 °C, a solution of 1-methyluracil (91 mg, 0.72 mmol) in acetonitrile (10 mL) was added. After being stirred for 1 h at 50 °C, the mixture was allowed to cool to room temperature upon which the product was precipitated. Recrystallization from methanol/water (6:1) yielded 142 mg (31%) of **12** as a colorless solid, mp 120 °C. IR (KBr): 1644 (vs) (C═O), 1605 (s) (C═N). ^{1}H NMR (DMSO-d_6): 1.09 [s, 9H, *t*-Bu], 1.30 [s, 9H, *t*-Bu], 3.16 [s, 3H, CH_3–N], 3.47 [s, 2H, CH_2−phenol], 4.22 [d, J = 15.5 Hz, 2H, CH_2−py], 4.38 [d, J = 15.5 Hz, 2H, CH_2−py], 5.30 [d, J = 7.4 Hz, 1H, uracil], 6.64 [d, J = 2.5 Hz, 1H, H_c], 6.66 [d, J = 2.5 Hz, 1H, H_a], 7.27−7.83 [m, 7H, aromatic + uracil], 8.32 [d, J = 4.7 Hz, 2H, H_α].

Anal. Calcd for $C_{32}H_{39}N_5O_3Zn \cdot 1.5H_2O$ (M_r = 607.1 + 27.0): C, 60.61; H, 6.68; N, 11.04. Found: C, 60.75; H, 6.48; N, 11.04.

Complex 13. A solution of potassium 2-formylphenolate (89 mg, 0.67 mmol) in methanol (15 mL) was added to a solution of **1** (400 mg, 0.67 mmol) in methanol (20 mL). After the mixture was stirred for 1 h, the $KClO_4$ precipitate was filtered off and the filtrate evaporated to dryness. The residue was taken up in 5 mL of THF and layered

with hexanes. After 3 days, 199 mg (44%) of **13** had separated as yellowish crystals, mp 128 °C. IR (KBr): 1635 (s) (C═O), 1606 (vs) (C═N). ^{1}H NMR ($CDCl_3$): 1.13 [s, 9H, *t*-Bu], 1.25 [s, 9H, *t*-Bu], 1.85 [broad, 4H, THF], 3.75 [broad, 4H, THF], 3.78 [s, 2H, CH_2−phenol], 3.93 [d, J = 15.6 Hz, 2H, CH_2−py], 4.08 [d, J = 15.6 Hz, 2H, CH_2−py], 6.68 [d, J = 2.4 Hz, 1H, H_c], 6.93 [d, J = 2.4 Hz, 1H, H_a], 7.09−7.69 [m, 10H, aromatic], 8.78 [d, J = 4.0 Hz, 2H, H_α], 10.01 [s, 1H, CHO].

Anal. Calcd for $C_{34}H_{39}N_3O_3Zn{\cdot}C_4H_8O$ (M_r = 603.1 + 72.1): C, 67.60; H, 7.02; N, 6.22; Zn, 9.68. Found: C, 66.42; H, 7.05; N, 6.04; Zn 9.43.

Complex 14. Like **13** from **1** (400 mg, 0.67 mmol) and potassium 2-(hydroxymethyl)phenolate (109 mg, 0.67 mmol). The residue after filtration was picked up in 5 mL of acetone and exposed to an atmosphere of diethyl ether. After 4 days, 302 mg (68%) of **14** had separated as yellowish crystals, mp 207 °C. IR (KBr): 1605 (s) (C═N). ^{1}H NMR ($CDCl_3$): 1.23 [s, 9H, *t*-Bu], 1.38 [s, 9H, *t*-Bu], 2.09 [s, 6H, acetone], 3.82 [s, 2H, CH_2−phenol], 3.91 [d, J = 16.0 Hz, 2H, CH_2−py], 4.14 [d, J = 16.0 Hz, 2H, CH_2−py], 4.86 [s, 2H, CH_2OH], 6.56−7.79 [m, 12H, aromatic], 8.93 [d, J = 5.2 Hz, 2H, H_α].

Anal. Calcd for $C_{34}H_{41}N_3O_3Zn{\cdot}(CH_3)_2CO$ (M_r = 605.1 + 58.1): C, 67.01; H, 7.14; N, 6.34. Found: C, 67.09; H, 7.12; N, 6.24.

Reaction of 3 with TNP. A solution of 0.17 mmol of **3** in 15 mL of chloroform was prepared as described above. Tris(*p*-nitrophenyl) phosphate (39 mg, 0.085 mmol) was added with stirring and the resulting solution monitored by ^{31}P NMR and UV. After 2 h the ^{31}P NMR resonance of TNP (−20.0 ppm) had completely disappeared and been replaced by the resonance of **15** (−15.4 ppm). The solution had turned yellow, and the UV spectrum confirmed the formation of **11** by the unperturbed absorption band at 385 nm. When an equimolar amount of bis(*p*-nitrophenyl) phosphate (58 mg, 0.17 mmol) was added to the solution of **3**, the UV spectrum showed no sign of the formation of *p*-nitrophenol or **11**, and the NMR spectrum showed the quantitative formation of **15**.

Kinetic Data. Measurements were performed on a JASCO V-570 UV spectrometer by continually recording the 385 nm absorption of **11**. Chloroform (UV quality) was used as a solvent. Samples of TNP were taken from a 2.00 mM stock solution. Stock solutions of **3** (0.100 M) were prepared prior to use as described above from **1** and triethylamine. The measuring chamber and the solutions were thermostated to 25.0 °C for 30 min prior to the measurements and during the kinetic runs. Reagents were mixed in the quartz cuvettes. The concentration of TNP was 0.100 mM for all measurements; that of **3** was adjusted to 5.00, 10.00, 15.00, 20.00, and 25.00 mM, corresponding to a 50-, 100-, 150-, 200-, and 250-fold excess.

The absorption intensities were recorded for $5t_{1/2}$. The I value at this time was taken as I_∞. Reaction times for 90% conversion were 2−8 h. Up to a conversion of 75% the reactions were cleanly of first order with a correlation coefficient greater than 0.997. For the computations the measurements up to $2t_{1/2}$ were included. The reproducibility of the I values was within 10%. Each data point in Figure 8 represents the average of three measurements.

Structure Determinations. Crystals of **5**, **10**, **11**, **13,** and **14** were obtained directly from the preparations, those of **1** and **9** by layering THF solutions with hexanes. They were immersed in fluorinated polyether oil for the measurements on a Nonius CAD4 diffractometer with graphite-monochromatized Mo Kα radiation (λ = 0.7107 Å) at 180 K (room temperature for **13** and **14**). No absorption corrections were applied. The structures were solved with direct methods and refined anisotropically with the SHELX program suite.[61] Hydrogen atoms were included with fixed distances and isotropic temperature factors 1.5 times those of their attached atoms. Parameters were refined against F^2. Complexes **1**, **5**, and **7** show a rotational disorder of one of their *tert*-butyl groups; complex **10** has one of its phosphate phenyl groups disordered over two positions. Drawings were produced with SCHAKAL.[62] The crystallographic data are listed in the Supporting Information.

Acknowledgment. This work was supported by the Deutsche Forschungsgemeinschaft and the Fonds der Chemischen Industrie. We are indebted to Drs. W. Deck, M. Tesmer, and M. Rombach for assistance during the measurements and their interpretation.

Supporting Information Available: A table with all crystallographic details, fully labeled ORTEP plots for all seven structure determinations, a plot of the rate constants of the phosphate cleavage, and seven crystallographic files, in CIF format. This information is available free of charge via the Internet at http://pubs.acs.org.

IC001204J

(61) Sheldrick, G. M. *SHELXS-86 and SHELXL-93*; Universität Göttingen: Göttingen, Germany, 1986 and 1993.
(62) Keller, E. *SCHAKAL for Windows*; Universität Freiburg: Freiburg, Germany, 1999.