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Article

Hydrolysis of Bis(*p*-nitrophenyl)phosphate by Tetravalent Metal Complexes with Kläui's Oxygen Tripodal Ligand

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The treatment of $HfCl_4$ with NaL_{OEt} ($L_{OEt}^- = [(\eta^5-C_5H_5)Co\{P(O)(OEt)_2\}_3]^-$) in nitric acid afforded $L_{OEt}Hf(NO_3)_3$ (**1**). Hydrolysis of **1** in acetone/water (4:1, v/v) yielded the hydroxy-bridged dimer $[(L_{OEt})_2Hf_2(H_2O)_4(\mu\text{-}OH)_2][NO_3]_4$ (**2**). The treatment of $(NH_4)_2[Ce(NO_3)_6]$ with 2 equiv of NaL_{OEt} in water afforded $(L_{OEt})_2Ce(NO_3)_2$ (**3**), whereas that with 1 equiv of NaL_{OEt} in CH_2Cl_2 gave $L_{OEt}Ce(NO_3)_3$ (**4**). While **4** is stable in organic solvents such as acetone, it was converted completely to **3** in acetone/water. The treatment of **3** with bis(*p*-nitrophenyl)phosphate (BNPP) afforded $(L_{OEt})_2Ce[\eta^1\text{-}OPO(OR)_2]_2$ (**5**; R = *p*-NO_2C_6H_4), whereas the reaction of **4** with $NaPO_2(OR)_2$ yielded dinuclear $[L_{OEt}Ce(NO_3)_2\{\mu\text{-}O_2P(OR)_2\}]_2$ [R = *p*-NO_2C_6H_4 (**6**), Ph (**7**)]. The addition of **3** in acetone to an aqueous solution of NaH_2PO_4 yielded the cerium(IV) dihydrogen phosphate complex $(L_{OEt})_2Ce(PO_4H_2)_2$ (**8**). Complexes **1**−**5** and **7** have been characterized by X-ray crystallography. The hydrolysis of BNPP with $L_{OEt}M(NO_3)_3$ (M = Zr, Hf, Ce) in acetone/water has been studied by ^1H NMR spectroscopy. At 25 °C, with [Ce] = 20[BNPP], in an acetone-d_6/*N*-(2-hydroxyethyl)piperazine-*N'*-2-ethanesulfonic acid (4:1, v/v) buffer solution (50 mM) (4:1, v/v), the hydrolysis of BNPP with **4** was found to exhibit first-order kinetics with a rate constant of $(1.1 \pm 0.1) \times 10^{-3} s^{-1}$.

Introduction

The aqueous chemistry of metal ions[1] is of significance because of its relevance to the mechanisms of metal-catalyzed organic reactions in water and the important roles of metal ions in biological systems. We are particularly interested in the hydrolytic chemistry of tetravalent metal ions such as Zr^{4+}, Hf^{4+}, Ce^{4+}, and Th^{4+}, which are highly active in the hydrolysis of the phosphodiester linkage.[2] Of note are the Ce^{4+} ion and its complexes, which have been used as artificial nucleases for the cleavage of phosphate esters and DNA.[3−5]

The Ce^{4+}-based hydrolysis suffers from the drawback of ease of formation of an insoluble hydroxide gel in aqueous solutions at around pH 7. In the presence of stabilizing ligands such as ethylenediaminetetraacetic acid (EDTA), aqueous solutions containing Ce^{4+} are homogeneous and can cleave DNA selectively under neutral conditions.[5−7]

Although the exact mechanism of the Ce^{IV}-mediated cleavage of phosphodiesters is not fully understood, it is believed that the coordination and activation of phosphate diesters by Ce^{IV} and nucleophilic attack by Ce-bound hydroxide play important roles.[7,8] The superior hydrolytic activity of Ce^{4+} compared with other lanthanide ions has been attributed to (a) the high electron-withdrawing ability of Ce^{IV} and (b) the formation of hybrid orbitals between the Ce 4f and O 2p orbitals.[2b,9] Recently, Komiyama and co-workers reported the isolation of cerium(IV) dipicolinate complexes, which are active in DNA hydrolysis.[10] X-ray

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Chart 1
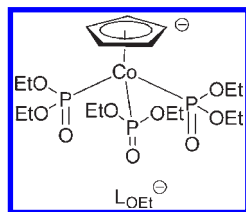
crystallography revealed that the Ce atoms in these complexes contain a number of labile coordinated water molecules that are presumably essential for their hydrolytic activity. To our knowledge, Ce^{IV} complexes containing phosphate diester ligands have not been isolated, although the structure of a dinuclear Ce^{III} complex with a bridged dimethylphosphate ligand has been reported.[2a]

We have a long-standing interest in metal complexes with Kläui's tripodal ligand $[(\eta^5\text{-}C_5H_5)Co\{P(O)(OEt)_2\}_3]^-$ (Chart 1, denoted as L_{OEt}^- hereafter), which can serve as models of metal aqua ions and metal oxides.[11] In a previous paper, we reported that the interaction of zirconyl nitrate with NaL_{OEt} in nitric acid led to formation of the tetranuclear cluster $[(L_{OEt})_4Zr_4(\mu_3\text{-}O)_2(\mu\text{-}OH)_4(H_2O)_2]^{4+}$. In acetone/water, $Zr^{IV}L_{OEt}$ complexes such as $L_{OEt}Zr(NO_3)_3$ can hydrolyze bis-(p-nitrophenyl)phosphate (BNPP) to give p-nitrophenol and a zirconium(IV) phosphate cluster, $[L_{OEt}Zr(\mu_3\text{-}PO_4)]_4$.[12] As an extension of this study, we examine the hydrolytic chemistry of analogous Hf^{IV} and Ce^{IV} complexes. In this paper, we describe the synthesis and solid-state structures of Hf^{IV}- and $Ce^{IV}L_{OEt}$ complexes and their activity in BNPP hydrolysis. In addition, the syntheses and structures of $Ce^{IV}L_{OEt}$ complexes containing phosphate diester and phosphate ligands that may serve as models for intermediate(s) for the Ce^{IV}-catalyzed hydrolysis of phosphate diesters will be reported.

Experimental Section

General Considerations. NMR spectra were recorded on a Bruker AV 400 spectrometer operating at 400 and 162.0 MHz for ^1H and ^{31}P, respectively. Chemical shifts (δ, ppm) were reported with reference to $SiMe_4$ (^1H) and H_3PO_4 (^{31}P). IR spectra were recorded on a Perkin-Elmer 16 PC Fourier transform infrared spectrophotometer. Electrospray ionization mass spectrometry was recorded on a Finningan MAT TSQ-7000 spectrometer. Elemental analyses were performed by Medac Ltd., Surrey, U.K.

The complexes $L_{OEt}Zr(NO_3)_3$ and $[(L_{OEt})_4Zr_4(\mu_3\text{-}O)_2(\mu\text{-}OH)_2(H_2O)_4][NO_3]_4$ were prepared as described elsewhere.[12] The ligand NaL_{OEt} was synthesized according to a literature method.[13] $NaO_2P(OR)_2$ (R = p-$NO_2C_6H_4$, Ph) complexes were prepared by the treatment of $(RO)_2P(O)(OH)$ with 1 equiv of sodium hydride in tetrahydrofuran (THF). The resulting solid was washed with Et_2O and dried in vacuo.

Preparation of $L_{OEt}Hf(NO_3)_3$ (1). To a solution of $HfCl_4$ (195 mg, 0.61 mmol) in 70% nitric acid (4 mL) was added NaL_{OEt} (280 mg, 0.48 mmol) in acetone (1 mL) dropwise, and the reaction mixture was stirred at room temperature for 30 min. The yellow precipitate was collected, washed with water (3 × 1 mL), redissolved in CH_2Cl_2, and dried over anhydrous $MgSO_4$. Evaporation of the solvent afforded an analytically pure yellow crystalline solid. Yield:

240 mg (56%). ^1H NMR ($CDCl_3$): δ 1.29 (t, J = 7.0 Hz, 18H, CH_3), 4.12 (m, 12H, OCH_2), 5.15 (s, 5H, C_5H_5). $^{31}P\{^1H\}$ NMR ($CDCl_3$): δ 121.8 (s). IR (KBr, cm^{-1}): 1292, 1385, 1542, 1565 [$\nu(NO_3)$]. MS (FAB): m/z 839 ($M^+ - NO_3 + 1$). Anal. Calcd for $C_{17}H_{35}CoHfO_{18}N_3P_3$: C, 22.69; H, 3.92; N, 4.67. Found: C, 22.58; H, 3.89; N, 5.00.

Preparation of $[(L_{OEt})_2Hf_2(H_2O)_4(\mu\text{-}OH)_2][NO_3]_4$ (2). A solution of **1** (90 mg, 0.10 mmol) in acetone/H_2O (4:1, v/v) was left to stand in air overnight. Slow evaporation of the solvent afforded yellow crystals that were suitable for X-ray diffraction. Yield: 81 mg (91%). ^1H NMR ($CDCl_3$): δ 1.27 (t, J = 7.0 Hz, 36H, CH_3), 1.90 (s, 8H, H_2O), 4.13 (m, 24H, CH_2), 5.09 (s, 10H, C_5H_5), 9.01 (s, 2H, OH). $^{31}P\{^1H\}$ NMR ($CDCl_3$): δ 121.1 (s). Anal. Calcd for $C_{34}H_{80}Co_2Hf_2O_{36}P_6N_4$: C, 22.92; H, 4.53; N, 3.15. Found: C, 23.04; H, 4.30; N, 3.36.

Preparation of $(L_{OEt})_2Ce(NO_3)_2$ (3). To a solution of NaL_{OEt} (198 mg, 0.35 mmol) in water (10 mL) was added $(NH_4)_2[Ce(NO_3)_6]$ (97.2 mg, 0.18 mmol) in water (5 mL) dropwise over 5 min. The orange precipitate was collected, washed with water, and dried in vacuo. X-ray-quality crystals were obtained by the slow evaporation of a saturated CH_2Cl_2/hexane solution. Yield: 220 mg (93%). ^1H NMR ($CDCl_3$): δ 1.30 (t, J = 7.0 Hz, 36H, CH_3), 4.08−4.12 (m, 24H, CH_2), 5.12 (s, 10H, C_5H_5). $^{31}P\{^1H\}$ NMR ($CDCl_3$): δ 121.1 (s). IR (KBr, cm^{-1}): 1292 [$\nu(NO_3)$]. MS (FAB): m/z 1272 ($M^+ - NO_3$), 1210 ($M^+ - 2NO_3$). Anal. Calcd for $C_{34}H_{70}CeCo_2N_2O_{24}P_6$: C, 30.60; H, 5.29; N, 2.10. Found: C, 30.21; H, 5.42; N, 2.18.

Preparation of $L_{OEt}Ce(NO_3)_3$ (4). A mixture of NaL_{OEt} (232 mg, 0.42 mmol) and $(NH_4)_2[Ce(NO_3)_6]$ (220 mg, 0.41 mmol) in CH_2Cl_2 (45 mL) was stirred under nitrogen overnight. The solvent was removed in vacuo, and the residue was washed with hexanes (3 × 4 mL). Recrystallization from THF/hexanes afforded dark-brown crystals that were suitable for X-ray crystallography. Yield: 252 mg (70%). ^1H NMR ($CDCl_3$): δ 1.31 (t, J = 7.0 Hz, 18H, CH_3), 4.10−4.17 (m, 12H, CH_2), 5.17 (s, 5H, C_5H_5). $^{31}P\{^1H\}$ NMR ($CDCl_3$): δ 123.4 (s). IR (KBr, cm^{-1}): 1259, 1385, 1521, 1542 [$\nu(NO_3)$]. Anal. Calcd for $C_{17}H_{35}CeCoO_{18}N_3P_3$: C, 23.70; H, 4.10; N, 4.88. Found: C, 23.65; H, 4.12; N, 4.64.

Preparation of $(L_{OEt})_2Ce[\eta^1\text{-}OP(O)(OR)_2]_2$ (5; R = p-NO_2-C_6H_4). To a solution of **3** (40 mg, 0.030 mmol) in water (10 mL) was added 2 equiv of BNPP (0.06 mmol) in water (5 mL), and the mixture was stirred at room temperature for 10 min. The reddish-brown precipitate was collected, washed with H_2O (2 × 2 mL), redissolved in CH_2Cl_2, and dried over anhydrous Na_2SO_4. Recrystallization from CH_2Cl_2/hexanes afforded red crystals that were suitable for X-ray diffraction. Yield: 52 mg (91%). ^1H NMR ($CDCl_3$): δ 1.17 (t, J = 7.0 Hz, 36H, CH_3), 4.18 (m, 24H, CH_2), 5.03 (s, 10H, C_5H_5), 7.44 (d, J = 4.5 Hz, 4H, phenyl protons), 8.05 (d, J = 4.5 Hz, 4H, phenyl protons). $^{31}P\{^1H\}$ NMR ($CDCl_3$): δ −20.1 (s, BNPP), 119.3 (s, L_{OEt}). Despite two attempts, we have not been able to obtain good analytical data for the compound. The carbon content of the sample was found to be lower than the calculated value. However, this compound has been well characterized spectroscopically and by X-ray diffraction.

Preparation of $[L_{OEt}Ce(NO_3)_2\{\mu\text{-}O_2P(OR)_2\}]_2$ [R = p-NO_2-C_6H_4 (6), C_6H_5 (7)]. A mixture of **4** (86 mg, 0.10 mmol) and $NaPO_2(OR)_2$ (0.10 mmol) in CH_2Cl_2 (30 mL) was stirred overnight and filtered. The solvent was removed in vacuo, and the residue was washed with hexanes (3 × 4 mL). Recrystallization from CH_2Cl_2/hexane (for **6**) and Et_2O (for **7**) gave brown crystals.

For **6**. Yield: 96 mg (85%). ^1H NMR ($CDCl_3$): δ 1.18 (m, 36H, CH_3), 3.99 (m, 24H, CH_2), 5.06 (s, 10H, C_5H_5), 7.42 (d, 8H, phenyl protons), 8.14 (d, 8H, phenyl protons). $^{31}P\{^1H\}$ NMR ($CDCl_3$): δ 122.1 (s, L_{OEt}^-), −29.4 (s, BNPP). IR (KBr, cm^{-1}): 1222, 1347, 1494, 1593, and 1614 [$\nu(NO_3)$]. Despite two attempts, we have not been able to obtain good analytical data for the compound. The carbon content was found to be lower than

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Table 1. Crystallographic Data and Experimental Details for Complexes **1−5** and **7**

	1	**2**	**3**	**4**	**5**	**7**
formula	$C_{17}H_{35}CoHfN_3$-$O_{18}P_3$	$C_{34}H_{84}Co_2$-$Hf_2N_4O_{38}P_6$	$C_{34}H_{70}CeCo_2$-$N_2O_{24}P_6$	$C_{21}H_{43}CeCoN_3$-$O_{19}P_3$	$C_{58}H_{86}CeCo_2$-$N_4O_{35}P_8$	$C_{58}H_{90}Ce_2Co_2$-$N_4O_{38}P_8$
fw	899.81	1817.71	1334.72	933.54	1905.05	2097.20
T, K	173(2)	100(2)	173(2)	100(2)	253(2)	173(2)
cryst syst	monoclinic	monoclinic	monoclinic	orthorhombic	monoclinic	monoclinic
space group	$P2_1/c$	$P2_1/n$	$C2/c$	$P2_12_12_1$	$P2_1/n$	$P2_1/n$
a, Å	17.44590(10)	10.8073(11)	20.351(4)	13.4996(8)	12.5077(5)	13.8865(2)
b, Å	10.83490(10)	19.274(2)	10.8702(18)	13.5632(8)	29.5374(12)	24.9546(3)
c, Å	16.73140(10)	15.8459(16)	26.204(4)	19.4555(12)	21.9626(9)	24.3263(4)
α, deg	90	90	90	90	90	90
β, deg	93.0850(10)	99.2430(10)	110.673(2)	90	95.0510(10)	99.742(2)
γ, deg	90	90	90	90	90	90
V, Å^3	3158.06(4)	3257.9(6)	5423.4(16)	3562.3(4)	8082.5(6)	8308.3(2)
Z	4	2	4	4	4	4
ρ_{calcd}, g cm^{-3}	1.893	1.853	1.635	1.741	1.566	1.677
μ, mm^{-1}	12.233	3.919	1.684	1.941	1.204	13.613
$F(000)$	1784	1816	2728	1888	3896	4240
no. of reflns	43 454	24 485	26 583	19 610	43 902	28 516
no. of indep reflns	5659	6359	5210	6184	15 827	13 856
R_{int}	0.0474	0.0655	0.027	0.0413	0.0540	0.1216
GOF ^{a}	1.028	1.020	1.037	0.965	1.075	1.015
R1, wR2 [$I > 2\sigma(I)$]	0.0205, 0.0492	0.0360, 0.0631	0.0272, 0.0678	0.0246, 0.0464	0.0566, 0.1226	0.0747, 0.1533
R1, wR2 (all data)	0.0231, 0.0499	0.0534, 0.0677	0.0307, 0.0693	0.0293, 0.0475	0.0927, 0.1324	0.1378, 0.1807

^{a} GOF $= [(\sum w|F_o| - |F_c|)^2/(N_{obs} - N_{param})]^{1/2}$.

the calculated value. However, this compound has been well characterized spectroscopically. In addition, the structure of the diphenylphosphate analogue **7** has been established by X-ray diffraction.

For **7**. Yield: 68 mg (65%). ^{1}H NMR (CDCl$_3$). δ 1.10 (36H, CH$_3$), 4.00 (24H, OCH$_2$), 4.99 (10H, C$_5$H$_5$), 7.04 (4H, phenyl protons), 7.20 (16H, phenyl protons) (all broad resonances). ^{31}P-$\{^1$H$\}$ NMR (CDCl$_3$): δ 120.9 (L$_{OEt}^-$), −28.9 [P(O)$_2$Ph$_2$]. IR (KBr, cm^{-1}): 1235, 1290, 1494, 1521 [ν(NO$_3$)]. Anal. Calcd for $C_{29}H_{45}CeCoO_{19}N_2P_4$: C, 33.22; H, 4.33; N, 2.67. Found: C, 33.15; H, 4.29; N, 2.56.

Preparation of (L$_{OEt}$)$_2$Ce(PO$_4$H$_2$)$_2$ (8). To a solution of NaH$_2$PO$_4$·2H$_2$O (18 mg, 0.12 mmol) in water (1 mL) was added **3** (40 mg, 0.030 mmol) in acetone (0.20 mL). An orange precipitate formed immediately, and the suspension mixture was stirred for 10 min and filtered. The orange solid was dissolved in CH$_2$Cl$_2$/hexane (6:1, v/v) and dried over anhydrous Na$_2$SO$_4$. Evaporation of the filtrate afforded an orange-yellow solid, which was recrystallized from CH$_2$Cl$_2$/hexane to give orange crystals. Yield: 35 mg (85%). ^{1}H NMR (CDCl$_3$): δ 1.26 (t, J = 7.0 Hz, 36H, CH$_3$), 4.13 (m, 24H, OCH$_2$), 5.04 (s, 10H, C$_5$H$_5$). ^{31}P$\{^1$H$\}$ NMR (CDCl$_3$): δ −5.3 (s, PO$_4$H$_2$), 117.2 (s, L$_{OEt}$). Anal. Calcd for $C_{34}H_{74}CeCo_2O_{26}P_8$: C, 29.07; H, 5.31. Found: C, 28.67; H, 5.18.

Hydrolysis of BNPP with L$_{OEt}$M(NO$_3$)$_3$ (M = Zr, Hf). To a solution of L$_{OEt}$M(NO$_3$)$_3$ (M = Zr, H; 6 μmol) in acetone-d_6 (0.48 mL) was added BNPP (0.3 μl, 0.12 mL of a 2.5 mM solution in water). The progress of the reaction was followed by monitoring the integration of the p-nitrophenol resonance at δ 7.01 (d, J_{HH} = 4.6 Hz) in the ^{1}H NMR spectrum.

Kinetics of the Hydrolysis of BNPP with 4. A buffered BNPP solution was prepared by adding BNPP (8.5 mg, 0.025 mmol), NaClO$_4$ (306 mg, 2.5 mmol), and 2.5 mL of a N-(2-hydroxyethyl)piperazine-N'-2-ethanesulfonic acid (HEPES) buffer (1 M, pH 7.0) to 7.5 mL of water. To a solution of **4** (6 μmol) in acetone-d_6 (0.48 mL) was added 0.12 mL of the above buffered BNPP solution (containing ca. 0.3 μmol of BNPP). The concentration of HEPES in the resulting the mixture is approximately 50 mM. The mixture was shaken to ensure homogeneity and quickly transferred to a 5-mm NMR tube. The ^{1}H NMR spectrum of the reaction mixture was recorded at 3.5-min intervals. The rate of hydrolysis was determined by monitoring the integration of the p-nitrophenol resonance at

δ 7.01 for at least 3 half-lives. The rate constant (k_{obs}) was obtained by fitting the first 3 half-lives of the reaction according to a first-order kinetics equation. The formation of PO$_4^{3-}$ in the reaction was confirmed by ion chromatography (after treatment of the final mixture with EDTA to remove Ce^{IV}).

X-ray Crystallography. Crystallographic data and experimental details for complexes **1−5** and **7** are summarized in Table 1. Intensity data were collected on a Bruker SMART APEX 1000 CCD diffractometer using graphite-monochromated Mo Kα radiation (λ = 0.710 73 Å). The collected frames were processed with the software *SAINT*.[14] Structures were solved by direct methods and refined by full-matrix least squares on F^2 using the *SHELXTL* software package.[15] The atomic positions of non-hydrogen atoms were refined with anisotropic parameters. In complex **3**, the carbon atoms C18 and C22 of an ethoxy group were found to be disordered. Each of these carbon atoms were split into two sites with occupancies of 0.6 and 0.4. In complex **5**, the ethoxy groups of ligand L$_{OEt}^-$ were found to be seriously disordered.
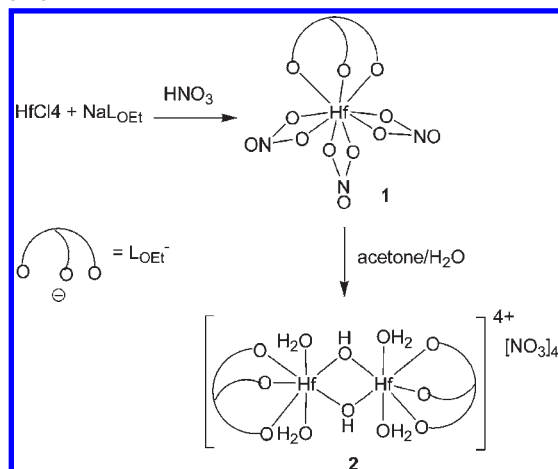
Results and Discussion

Hf^{IV} Complexes. The syntheses of Hf^{IV}L$_{OEt}$ complexes are summarized in Scheme 1. The treatment of HfCl$_4$ in 70% nitric acid with 1 equiv of NaL$_{OEt}$ in acetone afforded the tri(nitrate) complex **1**. The use of concentrated nitric acid is essential for the isolation of **1** in pure form. The reaction of HfCl$_4$ with NaL$_{OEt}$ in less concentrated nitric acid (< 1 M) gave a mixture of **1** and uncharacterized species. The IR spectrum of **1** showed the N−O bands at 1542 and 1565 cm^{-1}, which are typical for κ^2-nitrate ligands. Complex **1** exhibited one set of ^{1}H NMR signals for the ethyl groups of the L$_{OEt}^-$ ligands and a sharp singlet in the ^{31}P$\{^1$H$\}$ NMR spectrum, indicative of the high symmetry of the molecule. Although **1** is stable in CH$_2$Cl$_2$ and CHCl$_3$ solutions, it hydrolyzes easily in aqueous media. Dissolution of **1** in
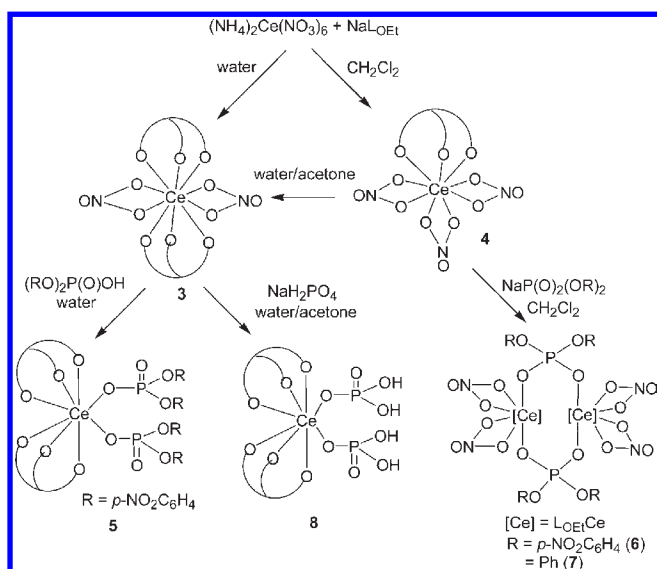
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Scheme 1

Scheme 2

Figure 1. Molecular structure of **1**. Hydrogen atoms are omitted for clarity. The thermal ellipsoids are drawn at a 30% probability level. Selected bond length (Å) and angle (deg): Hf1−O(L$_{OEt}$) 2.0809-(15)−2.0913(16), Hf1−O11 2.3641(18), Hf1−O12 2.2637(17), Hf1−O14 2.3620(18), Hf1−O15 2.2615(17), Hf1−O17 2.2759(16), Hf1−O18 2.3599(17); O(L$_{OEt}$)−Hf1−O(L$_{OEt}$) 83.16(6)−84.11(6), O11−Hf1−O12 55.11(6), O14−Hf1−O15 54.88(6), O17−Hf1−O18 55.29(6).
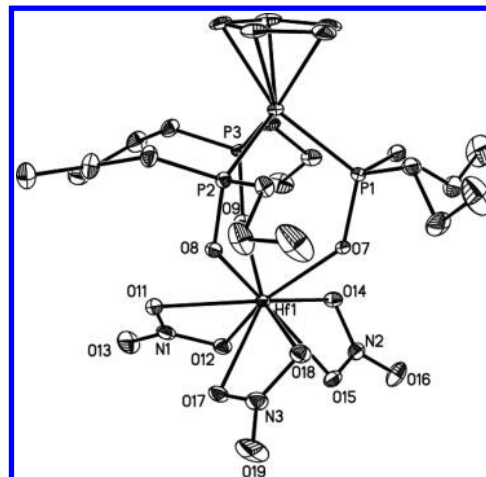
acetone/water (4:1, v/v), followed by the slow evaporation in air, afforded yellow crystals identified as the hydroxy-bridged dimer **2**. It may be noted that the hydrolysis of the Zr analogue L$_{OEt}$Zr(NO$_3$)$_3$ in water afforded tetranuclear [(L$_{OEt}$)$_4$Zr$_4$(H$_2$O)$_2$(μ_3-O)$_2$(μ-OH)$_4$]-[NO$_3$]$_4$, while depending upon experimental conditions, L$_{OEt}$Zr(OTf)$_3$ hydrolyzes to dinuclear [(L$_{OEt}$)$_2$Zr$_2$(H$_2$O)$_4$-(μ-OH)$_2$][OTf]$_4$ or trinuclear [(L$_{OEt}$)$_3$Zr$_3$(H$_2$O)$_3$(μ_3-O)-(μ-OH)$_3$][OTf]$_4$.[16]

Cerium(IV) Nitrate Complexes. The syntheses of Ce^{IV}L$_{OEt}$ complexes are summarized in Scheme 2. As reported previously, the treatment of (NH$_4$)$_2$[Ce(NO$_3$)$_6$] with NaL$_{OEt}$ in water led to isolation of the bis(tripod) compound **3**. Mono(tripod) compounds were not formed even when excess (NH$_4$)$_2$[Ce(NO$_3$)$_6$] (2 equiv) was employed. In this work, we found that the reaction of (NH$_4$)$_2$[Ce(NO$_3$)$_6$] with 1 equiv of NaL$_{OEt}$ in CH$_2$Cl$_2$ afforded half-sandwich **4** as the sole isolated product. Although complex **4** is stable in a CH$_2$Cl$_2$ solution, it converted rapidly to **3** in aqueous media. Dissolution of **4**

in acetone/water (4:1, v/v), followed by the slow evaporation in air, led to the isolation of **3** almost quantitatively (>98% with respect to L$_{OEt}$$^-$). The remaining Ce^{IV} byproduct, presumably a L$_{OEt}$-free species, has not been characterized. The facile conversion of **4** to **3** in aqueous media is presumably due to the high affinity of electron-deficient Ce^{IV} for the π-donating oxygen ligand L$_{OEt}$$^-$.

Cesium(IV) Phosphate Diester and Phosphate Complexes. Efforts have been made to synthesize Ce^{IV} complexes with phosphate diester and phosphate ligands that may serve as models of intermediates of the Ce^{IV}-mediated hydrolysis of phosphate diesters. The treatment of **3** with BNPP in water resulted in precipitation of the bis(phosphate diester) complex **5**. The ^{31}P{^{1}H} NMR spectrum of **5** displayed a singlet at δ −20.1 due to the deprotonated η^1-phosphate diester ligand, which is more upfield than that of free BNPP (δ −13.4 in D$_2$O). The treatment of **4** with Na[PO$_2$(OR)$_2$] (R = p-NO$_2$C$_6$H$_4$) in CH$_2$Cl$_2$ afforded dinuclear **6** containing bridged phosphate diester ligands. An analogous complex with diphenylphosphate, **7**, has been prepared from **4** and NaP(O)$_2$(OPh)$_2$. The ^{31}P NMR resonance for the diphenylphosphate ligands in **7** was found at δ −28.9, which is more upfield than that for the free diphenylphosphate (δ −9.0 in D$_2$O).

The addition of **3** in acetone to an aqueous solution of NaH$_2$PO$_4$ led to formation of the dihydrogen phosphate complex **8**. A preliminary X-ray diffraction study showed that **8** is an eight-coordinated Ce complex containing two cisoid η^1-H$_2$PO$_4$$^-$ ligands (see the Supporting Information). The ^{31}P NMR resonance for the dihydrogen phosphate ligand in **8** was observed at δ −5.3. The mono(tripod) compound **4** was also found to react with NaH$_2$PO$_4$, as evidenced by ^{31}P NMR spectroscopy. Unfortunately, we were not able to isolate any half-sandwich L$_{OEt}$ cesium(IV) phosphate complex(es) from the reaction mixture.

Crystal Structures. Figures 1 and 2 show the molecular structures of **1** and **4**, respectively, which are isostructural with L$_{OEt}$Zr(NO$_3$)$_3$. Both **1** and **4** are nine-coordinated,

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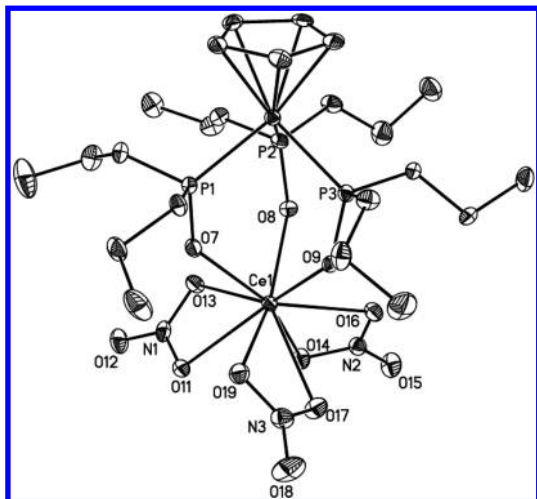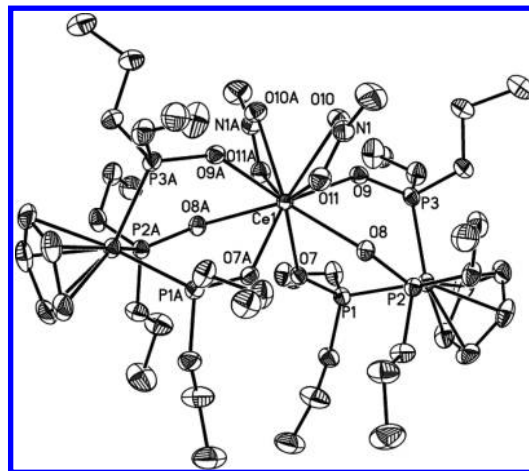
Figure 2. Molecular structure of **4**. Hydrogen atoms are omitted for clarity. The thermal ellipsoids are drawn at a 30% probability level. Selected bond length (Å) and angle (deg): Ce1−O(L_{OEt}) 2.220(2)−2.232(2), Ce1−O11 2.461(3), Ce1−O13 2.468(2), Ce1−O14 2.462(2), Ce1−O16 2.473(3), Ce1−O17 2.476(3), Ce1−O19 2.471(2); O(L_{OEt})−Ce1−O(L_{OEt}) 79.26(9)−80.52(8), O11−Ce1−O13 51.84(8), O14−Ce1−O16 51.68(8), O19−Ce1−O17 51.36(8).
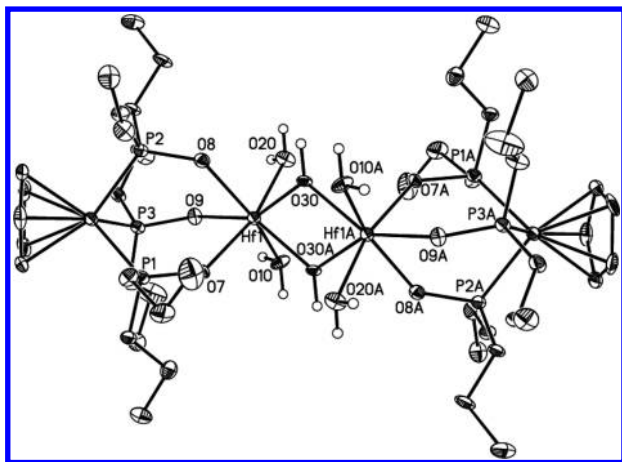
Figure 3. Molecular structure of **2**. Hydrogen atoms of the L_{OEt}^- ligands are omitted for clarity. The thermal ellipsoids are drawn at a 50% probability level. Selected bond length (Å) and angle (deg): Hf1−O(L_{OEt}) 2.056(3)−2.137(3), Hf1−O30 2.092(3), Hf1−O30A 2.104(3), Hf1−O10 2.189(3), Hf1−O20 2.153(3), Hf1−Hf1A 3.492(1); O(L_{OEt})−Hf1−O(L_{OEt}) 79.94(11)−83.97(12), Hf1−O30−Hf1A 112.63(14), O20−Hf1−O10 78.73(12). Symmetry operator: A = −x + 1, −y + 1, −z + 1.

with the nitrate ligands binding to the metal center in a bidentate-O,O' fashion. The Hf−O(L_{OEt}) [2.0809(15)−2.0913(16) Å] and Hf−O(nitrate) [2.2615(17)−2.3641(18) Å] distances in **1** are comparable to those in L_{OEt}-Zr(NO$_3$)$_3$ [2.088(2)−2.095(2) and 2.275(2)−2.365(2) Å, respectively].[12] As expected, the corresponding bond distances in **4** [2.220(2)−2.232(2) and 2.461(3)−2.476(3), respectively] are longer than those in **1** because of the bigger ionic radius of Ce^{4+} compared with Hf^{4+}.

Figure 3 shows the structure of the cation [(L$_{OEt}$)$_2$Hf$_2$-(H$_2$O)$_4$(μ-OH)$_2$]$^{4+}$ in **2**, which is isostructural with that in [(L$_{OEt}$)$_2$Zr$_2$(H$_2$O)$_4$(μ-OH)$_2$][OTf]$_4$.[16] The complex cation consists of two symmetry-related {L$_{OEt}$Hf(H$_2$O)$_2$(μ-OH)}$^{2+}$ moieties related by an inversion center. The Hf−O(L_{OEt}) distances of 2.056(3)−2.137(3) Å are slightly longer than

Figure 4. Molecular structure of **3**. Hydrogen atoms are omitted for clarity. The thermal ellipsoids are drawn at a 30% probability level. Selected bond length (Å) and angle (deg): Ce1−O(L_{OEt}) 2.326(2)−2.350(2), Ce1−O10 2.496(2), Ce1−O11 2.748(2); O(L_{OEt})−Ce1−O(L_{OEt}) 72.77(6)−75.92(6), O10−Ce1−O11 47.72(6).

those in **1**. The Hf−OH distance [2.104(3) Å] is shorter than the Hf−OH$_2$ distances [2.153(3) and 2.189(3) Å] and compares well with those in [HfCl$_2$(μ-OH)(κ^3-bdmpza)]$_2$ [bdmpza = bis(3,5-dimethylpyrazol-1-yl)acetae; 2.084(3)−2.106(3) Å].[17]

Figure 4 shows the molecular structure of **3**. The complex is formally 10-coordinated, with the Ce atom located at the inversion center. The Ce−O(L_{OEt}) [2.326(2)−2.350(2) Å] and Ce−O(nitrate) [2.496(2) and 2.748(2) Å] distances are longer than those in **4** presumably because of the steric effect of the oxygen tripodal ligands. Unlike **4**, the bidentate nitrate ligands in **3** bind to the Ce center in a more unsymmetrical fashion with Ce−ONO$_2$ distances of 2.496(2) and 2.748(2) Å.

Figures 5 and 6 show the structures of **5** and **7**, respectively. To our knowledge, **5** and **7** are the first cerium(IV) phosphate diester complexes characterized by X-ray crystallography. In **5**, the two phosphate diester ligands bind to the Ce atom in a unidentate fashion. Unlike **1**, the two phosphate diesters in **5** are adjacent to each other. The Ce−O(phosphate diester) distances [2.370(3) and 2.373(3) Å] are slightly longer than the Ce−O(L_{OEt}) distances [2.289(3)−2.358(3) Å]. The terminal P−O distances [1.444(4) and 1.439(4) Å] of the phosphate diester ligands are shorter than the P−O(Ce) distances [1.487(3) and 1.489(3) Å], consistent with the formulation of the P=O double bond. **7** consists of two {L$_{OEt}$Ce(κ_2-NO$_3$)$_2$}$^+$ fragments that are bridged by two μ-O,O'-diphenylphosphate ligands. Dinuclear phosphate diester complexes of d-block metals, e.g., Cu[18] and Ni,[19] are well documented. The Ce−O(phosphate diester) distances [2.261(7)−2.346(7) Å] in **7** are shorter than those in **5**.

Hydrolysis of BNPP with Zr^{IV} and Hf^{IV} Complexes. As reported previously, reaction of L$_{OEt}$Zr(NO$_3$)$_3$ with

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(18) Kato, M.; Tanase, T.; Mikuriya, M. *Inorg. Chem.* **2006**, *45*, 2925.
(19) (a) Goldberg, D. P.; Watton, S. P.; Masschelein, A.; Wimmer, L.; Lippard, S. J. *J. Am. Chem. Soc.* **1993**, *115*, 5346. (b) Pothiraja, R.; Shanmugan, S.; Walawalkar, M. G.; Nethaji, M.; Butcher, R. J.; Murugavel, R. *Eur. J. Inorg. Chem.* **2008**, 1834.
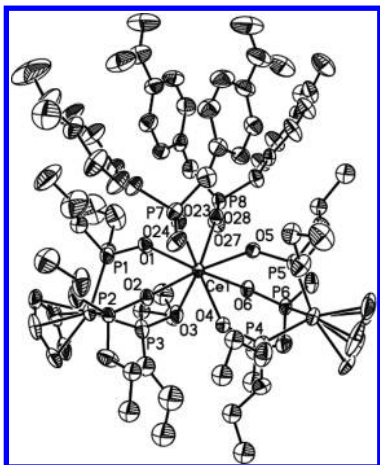
Figure 5. Molecular structure of **5**. Hydrogen atoms and cocrystallized water molecules are omitted for clarity. The thermal ellipsoids are drawn at a 30% probability level. Selected bond length (Å) and angle (deg): Ce1$-$O-(L$_{OEt}$) 2.289(3)$-$2.358(3), Ce1$-$O23 2.370(3), Ce1$-$O27 2.373(3), P7$-$O23 1.489(3), P7$-$O24 1.439(4), P7$-$O25 1.622(4), P7$-$O26 1.610(4), P8$-$O27 1.487(3), P8$-$O28 1.444(4), P8$-$O29 1.612(4), P8$-$O30 1.618(3); O(L$_{OEt}$)$-$Ce1$-$O(L$_{OEt}$) 73.34(12)$-$75.75(12), O23$-$Ce1$-$O27 79.38(12), O23$-$P7$-$O24 121.8(2), O25$-$P7$-$O26 101.0(2), O27$-$P8$-$O28 122.4(2), O29$-$P8$-$O30 100.9(2).
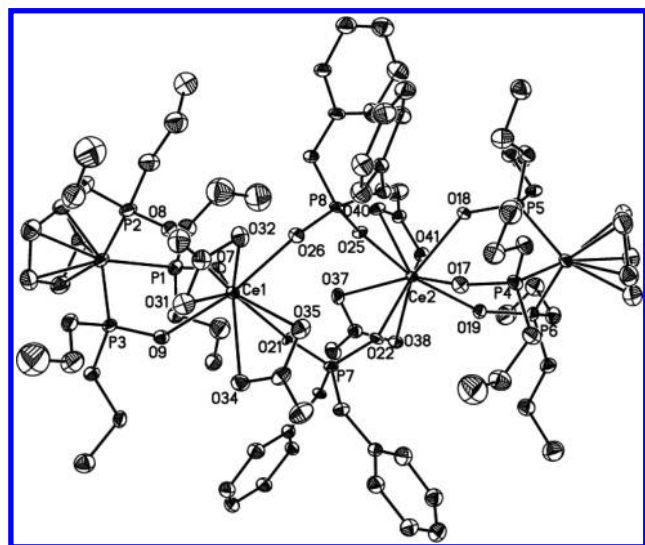
Figure 6. Molecular structure of **7**. Hydrogen atoms are omitted for clarity. The thermal ellipsoids are drawn at a 30% probability level. Selected bond length (Å) and angle (deg): Ce1$-$O(L$_{OEt}$) 2.264(7)$-$2.345(8), Ce2$-$O(L$_{OEt}$) 2.282(8)$-$2.351(7), Ce1$-$O21 2.364(7), Ce1$-$O26 2.261(7), Ce2$-$O22 2.332(7), Ce2$-$O25 2.285(7), P7$-$O21 1.470(7), P7$-$O22 1.493(7), P7$-$O23 1.576(7), P7$-$O24 1.592(8), P8$-$O25 1.475(7), P8$-$O26 1.494(8), P8$-$O27 1.578(8), P8$-$O28 1.587(8); O(L$_{OEt}$)$-$Ce1$-$O-(L$_{OEt}$) 73.5(3)$-$78.8(3), O21$-$P7$-$O22 118.0(4), O25$-$P8$-$O26 117.2(4).

BNPP in aqueous media such as acetone/water yielded *p*-nitrophenol and the cubane cluster [L$_{OEt}$Zr(PO$_4$)]$_4$.[12] (L$_{OEt}$)$_2$M(NO$_3$)$_2$ (M = Zr, Hf) cannot hydrolyze BNPP presumably because the metal center in these complexes is more sterically crowded and less electrophilic. The hydrolysis of BNPP with L$_{OEt}$Zr(NO$_3$)$_3$ has been investigated by ^{1}H NMR spectroscopy. Upon the addition of excess L$_{OEt}$Zr(NO$_3$)$_3$ (10 mM) to BNPP (0.5 mM) in acetone-d_6/water (4:1, v/v), the doublets at δ 7.33 and 8.33 due to BNPP dropped in intensity and concomitantly new signals at δ 7.01 and 8.15 attributable to *p*-nitrophenol

appeared. The hydrolysis was found to be complete in ca. 2 h, when the resonances at δ 7.33 and 8.33 almost disappeared and broad signals at δ 123 and $-$24 due to [L$_{OEt}$Zr-(μ_3-PO$_4$)]$_4$ were observed in the ^{31}P{^{1}H} NMR spectrum. Apart from the resonances for L$_{OEt}$Zr(NO$_3$)$_3$ and [L$_{OEt}$-Zr(μ_3-PO$_4$)]$_4$, no other ^{31}P NMR signals were found during the reaction, indicating that either no intermediate(s) was involved or the concentration of the intermediate(s) was too low to be detected by NMR spectroscopy.

The hydrolysis of BNPP with a 20-fold excess of L$_{OEt}$-Zr(NO$_3$)$_3$ in acetone-d_6/water (4:1, v/v) has been followed by monitoring the integration of the *p*-nitrophenol signal at δ 7.01 [I(7.01)]. The plot of I(7.01) versus time was found to exhibit sigmoidal behavior. A similar plot was found for [(L$_{OEt}$)$_4$Zr$_4$(μ_3-O)$_2$(μ-OH)$_4$(H$_2$O)$_2$][4+] under the same conditions (see Figure S3 in the Supporting Information). Previously, we have demonstrated that L$_{OEt}$Zr(NO$_3$)$_3$ can be converted to [(L$_{OEt}$)$_4$Zr$_4$(μ_3-O)$_2$(μ-OH)$_4$(H$_2$O)$_2$][4+] readily in aqueous media.[1] Therefore, it seems reasonable to assume that the L$_{OEt}$Zr-mediated hydrolysis of BNPP in acetone/water involves a tetrameric or other oligomeric Zr active species. The hydrolysis of BNPP with **1** was also found to exhibit sigmoidal behavior with a longer induction period (Figure S3 in the Supporting Information). The hydrolytic activity of the hydroxyl-bridged Hf dimer **2** was not studied because of its low solubility in acetone/water. Neither L$_{OEt}$Ti(OTf)$_3$ nor (L$_{OEt}$)$_2$Ti$_2$(μ-O)$_2$(μ-SO$_4$)[17] is capable of hydrolysis of BNPP in acetone/water.

Hydrolysis of BNPP by Ce[IV] complexes. As expected, the bis(tripod) compound **3** cannot hydrolyze BNPP in aqueous media. The reaction of **3** with BNPP in water led to precipitation of the bis(phosphate diester) complex (see the section above), which does not undergo hydrolysis with bases such as Et$_3$N, NaOH, and *n*-Bu$_4$NOH. The treatment of **4** with BNPP in acetone/water (4:1, v/v) led to the formation of **3**, as evidenced by NMR spectroscopy. When the reaction mixture was left to stand in air for a long period of time (3$-$4 days), pale-yellow fine crystals identified as Ce(PO$_4$)(PO$_4$H)$_{0.5}$(H$_2$O)$_2$ formed, indicating that in an aqueous acetone solution **4** could hydrolyze BNPP, albeit rather slowly. A preliminary X-ray diffraction study (see the Supporting Information) revealed that Ce(PO$_4$)(PO$_4$H)$_{0.5}$(H$_2$O)$_2$ has a three-dimensional framework structure similar to that of reported Ce(H$_2$O)(PO$_4$)$_{1.5}$(H$_3$O)$_{0.5}$(H$_2$O)$_{0.5}$.[20]

Previous studies demonstrated that the Ce[IV]-mediated hydrolysis of phosphate diesters is pH-dependent. Moss and co-workers reported that the hydrolysis of BNPP with Ce[IV] ions in aqueous micellar solutions is very sensitive to the pH and the highest rate enhancement was found at pH 7.[3a] Thus, the hydrolysis of BNPP with **4** in an acetone/HEPES buffer (pH 7) solution was studied. The treatment of BNPP with excess **4** (20-fold) in an acetone/HEPES buffer (4:1, v/v) resulted in the immediate formation of *p*-nitrophenol, as evidenced by ^{1}H NMR spectroscopy. The formation of phosphate in the reaction was confirmed by ion chromatography (after treatment of the final reaction mixture with EDTA to remove Ce^{4+}).

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At 25 °C in an acetone-d_6/HEPES buffer (4:1, v/v) with [Ce] = 20[BNPP], the hydrolysis of BNPP by **4** was found to follow pseudo-first-order kinetics with a rate constant of $(1.1 \pm 0.1) \times 10^{-3}$ s^{-1}. It is interesting to note that, unlike the Ce analogue, the hydrolysis of BNPP by $L_{OEt}Zr(NO_3)_3$ was found to be decelerated rather than accelerated by the addition of a HEPES buffer. In the absence of BNPP, **4** in an acetone/HEPES buffer was converted rapidly to **3** along with a byproduct, presumably a L_{OEt}-free Ce^{IV} species. Because **3** alone cannot hydrolyze BNPP in an acetone/HEPES buffer, it is reasonable to assume that the active species for the Ce^{IV}-mediated hydrolysis is a L_{OEt}-free Ce^{IV} complex. Support for this suggestion also comes from the formation of L_{OEt}-free Ce(PO$_4$)(PO$_4$H)$_{0.5}$(H$_2$O)$_2$ from the reaction of **4** with BNPP in acetone/water.

Concluding Remarks

In an attempt to model tetravalent Zr, Hf, and Ce ions in aqueous solutions, $L_{OEt}M(NO_3)_3$ (M = Zr, Hf, Ce) containing Kläui's oxygen tripodal ligand were synthesized and characterized. These complexes exhibit different reactivities in aqueous media. $L_{OEt}Zr(NO_3)_3$ is converted to tetranuclear $[(L_{OEt})_4Zr_4$-(μ-O)$_2$(μ-OH)$_4$(H$_2$O)$_2$]$^{4+}$ or other oligomeric species depending upon the experimental conditions,[12,16] whereas **1** hydrolyzes to a hydroxyl-bridged dimer. **4** undergoes ligand exchange in acetone/water to give **3**. The difference in reactivity between the Ce^{IV} complex and the Zr^{IV} and Hf^{IV} analogues can be attributed to the larger size of Ce^{4+} and higher affinity of electron-deficient Ce^{4+} for the oxygen tripod ligand. The hydrolysis of BNPP by $L_{OEt}M(NO_3)_3$ in acetone/water has been investigated. Unlike the Zr and Hf analogues, **4** can only hydrolyze BNPP in the presence of a HEPES buffer. We have isolated and structurally characterized the first Ce^{IV} complexes with terminal and bridged phosphate diester and hydrogen phosphate ligands. The L_{OEt} cesium(IV) phosphate diester complexes **5**−**7** are stable with respect to hydrolysis in aqueous media, suggesting that they are not involved in the Ce^{IV}-mediated hydrolysis of phosphate diesters. It seems likely that the active species for the Ce-based hydrolysis of BNPP is a L_{OEt}-free Ce^{IV} species derived from the ligand-exchange reaction of **4** in acetone/water.

Supporting Information Available: X-ray crystallographic data in CIF format for complexes **1**−**5** and **7**, crystal data and structures for **8** and Ce(PO$_4$)(PO$_4$H)$_{0.5}$(H$_2$O)$_2$, and plots of I(7.01) versus time for the hydrolysis of BNPP with $L_{OEt}M$-(NO$_3$)$_3$ (M = Zr, Hf, Ce). This material is available free of charge via the Internet at http://pubs.acs.org.