Supplementary Information

Cyclophosphates as Ligands for Cobalt(III) in Water

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General procedures. Aqueous solutions were prepared using reagent grade deionized water ($\rho \geq 18$ MΩ cm; Ricca Chemical Company, USA). Organic solvents were reagent grade or better, and were not dried prior to use. Commercially available reagents, including $Na_3P_3O_9$ (Sigma) and $Na_5P_3O_{10}$ (Fluka), were used as received. The starting materials $[Co(TACN)(H_2O)_3](CF_3SO_3)_3 \bullet H_2O$ (TACN = 1,4,7-triazacyclononane; complex **1**) [1] and $Na_4P_4O_{12} \bullet 4H_2O$ [2] were prepared according to literature procedures. Cold room procedures used for the purification of complex **4** (see below) were carried out in the laboratory of Prof. J. Stubbe (Massachusetts Institute of Technology).

Analysis. NMR spectra were recorded at the Department of Chemistry Instrumentation Facility (DCIF) of the Massachusetts Institute of Technology (MIT), by using a Bruker Avance-400 spectrometer equipped with a SpectroSpin superconducting magnet and a QNP probe (^1H, ^{13}C, ^{31}P, ^{19}F), or a Bruker Avance-400 spectrometer equipped with a Magnex Scientific superconducting magnet and a BBO probe (^1H, ^{13}C, ^{31}P, ^{59}Co). All NMR measurements were done at 22°C unless noted otherwise. For aqueous solutions, ^1H and ^{13}C NMR chemical shifts are reported in ppm relative to the sodium salt of 2,2-dimethyl-2-silapentane-5-sulfonate (DSS). The chemical shifts of these nuclei are referenced to dioxane as an internal standard. For methanol solutions (only for the dilithiated salt of complex **2**), ^1H and ^{13}C NMR chemical shifts are reported in ppm relative to tetramethylsilane (TMS) and are referenced to the solvent peaks. ^{31}P NMR chemical shifts are reported in ppm relative to H_3PO_4 and referenced to an external

[1] F. Galsbøl, C. H. Petersen, K. Simonsen, *Acta Chem. Scand.*, 1996, **50**, 567-570.
[2] S. Greenfield, M. Clift, *Analytical Chemistry of the Condensed Phosphates*; Pergamon Press: Oxford, 1975, p. 190.

solution of 85% aqueous phosphoric acid. ^{59}Co NMR chemical shifts are reported in ppm relative to $K_3[Co(CN)_6]$ and referenced to an external saturated aqueous solution of $K_3[Co(CN)_6]$. Abbreviations used in the description of NMR data are as follows: br, broad; s, singlet; d, doublet; t, triplet; m, multiplet. NMR data processing, including NMR simulations, was carried out with the MestReNova software package, v. 6.0.2, developed and distributed by Mestrelab Research, Santiago de Compostela, Spain. Infrared spectroscopy was carried out at the DCIF by using a Perkin-Elmer Model 2000 FT-IR spectrophotometer. Abbreviations used in the description of IR data are as follows: br, broad; s, strong; m, medium; w, weak. UV-Vis spectroscopy was performed in the laboratory of Prof. D. G. Nocera (MIT) by using a Varian Cary 5000 UV-Vis-NIR spectrophotometer. All UV-Vis spectra were recorded at room temperature. High resolution electrospray ionization mass spectrometry (ESI-MS) was carried out at the DCIF by using a Bruker Daltonics APEXIV 4.7 Tesla Fourier Transform Ion Cyclotron Resonance Mass Spectrometer (FT-ICR-MS). Qualitative elemental analysis via energy-dispersive X-ray (EDX) spectroscopy was performed at the MIT Center for Materials Science and Engineering (CMSE), by using a JEOL JSM-5910 scanning electron microscope. Quantitative elemental analysis was performed by Midwest Microlab, LLC, Indianapolis, Indiana.

Literature and crystallographic data searches. General literature searches for starting materials, procedures and previously reported cyclophosphato complexes were carried out using SciFinder (web-based version).[3] Crystal structures from the Cambridge Structural Database (CSD; version 5.31, November 2009)[4,5] were retrieved using ConQuest 1.12.[6] Crystal structures from the Inorganic Crystal Structure Database (ICSD) were retrieved using its web-based interface (version 1.2.0, April 2010).[7]

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[3] *SciFinder*, Chemical Abstracts Service: Columbus, OH; https://scifinder.cas.org.
[4] *Cambridge Structural Database* (CSD; version 5.31), Cambridge Crystallographic Data Centre, 12 Union Road, Cambridge, England, 2009.
[5] F. H. Allen, *Acta Cryst.*, 2002, **B58**, 380-388.
[6] I. J. Bruno, J. C. Cole, P. R. Edgington, M. Kessler, C. F. Macrae, P. McCabe, J. Pearson, R. Taylor, *Acta Cryst.*, 2002, **B58**, 389-397.
[7] *Inorganic Crystal Structure Database* (ICSD), Fachinformationszentrum (FIZ) Karlsruhe, Eggenstein-Leopoldshafen, Germany; http://icsd.fiz-karlsruhe.de.

X-ray crystallography. Low-temperature diffraction data for the salt $[Co(TACN)(D_2O)_3](P_3O_9)\bullet 3D_2O$ were collected on a Siemens Platform three-circle diffractometer coupled to a Bruker-AXS Smart Apex CCD detector with graphite-monochromated Mo Kα radiation (λ = 0.71073 Å). Low-temperature diffraction data for complex **3** were collected on a Bruker D8 three-circle diffractometer coupled to a Bruker-AXS Smart Apex CCD detector with graphite-monochromated Cu Kα radiation (λ = 1.54178 Å). In both cases φ-and ω-scans were performed. The structures were solved by direct methods using SHELXS [8] and refined against F^2 on all data by full-matrix least squares with SHELXL-97 [9] following established refinement strategies.[10] All non-hydrogen atoms were refined anisotropically. Hydrogen atoms bound to carbon were included into the models at geometrically calculated positions and refined using a riding model. Coordinates for hydrogen atoms bound to oxygen or nitrogen were located in the difference Fourier synthesis and subsequently refined semi-freely with the help of distance restraints. The isotropic displacement parameters of all hydrogen atoms were fixed to 1.2 times the *U* value of the atoms they are linked to. Crystals of $[Co(TACN)(D_2O)_3](P_3O_9)\bullet 3D_2O$ were grown from a D_2O solution and it is likely that all of the O- and N-bound hydrogen atoms in the structure are in fact deuterium atoms. However, these atoms were treated as hydrogen atoms for the structure determination. Details of the data quality and a summary of the residual values of the refinements are listed in Table 1.

Reaction of complex 1 with $Na_3P_3O_9$ in water at room temperature. Formation of the salt $[Co(TACN)(H_2O)_3](P_3O_9)\bullet 3H_2O$. To a solution of 45 mg (0.064 mmol) of complex **1** in 2.5 ml of H_2O was added a solution of 20 mg (0.066 mmol) of $Na_3P_3O_9$ in 3 ml of H_2O. The resulting pink solution was stirred at room temperature for 5 min, and then allowed to stand at room temperature, in a closed glass vial. Red prismatic crystals appeared in the sample within several hrs. After 2 days the liquid phase was decanted

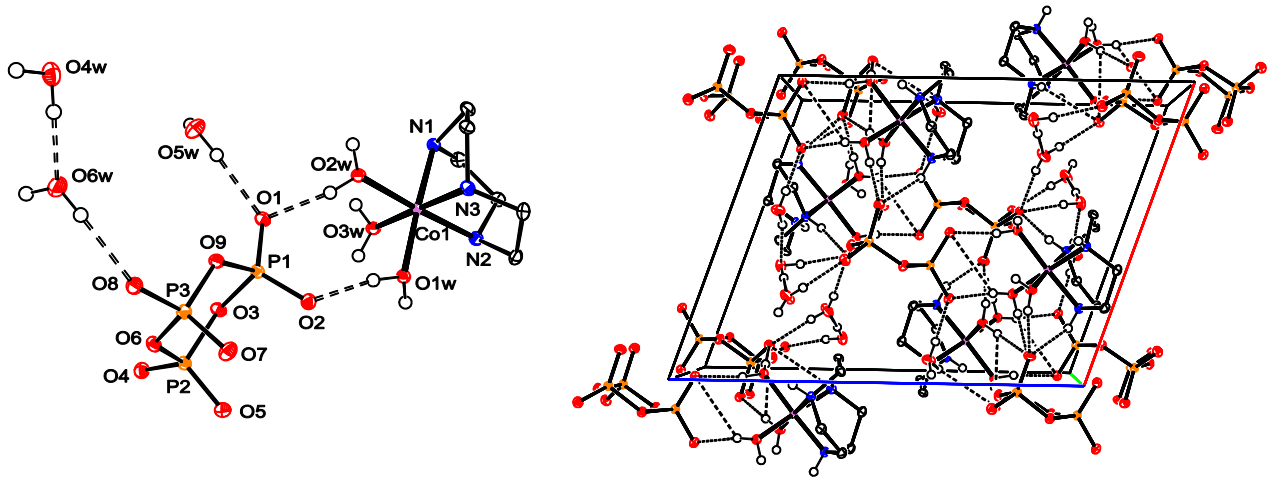
[8] G. M. Sheldrick, *Acta Cryst.*, 1990, **A46**, 467-473.
[9] G. M. Sheldrick, *Acta Cryst.*, 2008, **A64**, 112-122.
[10] P. Müller, *Crystallogr. Rev.*, 2009, **15**, 57-83.

and the crystals were washed with 2 × 2 ml of H_2O, 2.5 ml of ethanol and 3 ml of diethyl ether, and dried under vacuum. This afforded 21 mg (0.040 mmol; 59% yield) of the product. This product was found to be sparingly soluble in water.

IR (KBr, cm^{-1}): 3631 (m), 3532 (s), 3430 (s), 3215 (s), 3146 (s), 3114 (s), 2945 (br s), 2881 (s), 2610 (m), 1636 (m), 1495 (m), 1459 (m), 1421 (m), 1380 (m), 1345 (m), 1284 (s), 1267 (s), 1262 (s), 1246 (s), 1231 (s), 1227 (s), 1223 (s), 1219 (s), 1161 (s), 1138 (s), 1119 (s), 1095 (s), 1083 (s), 1059 (s), 991 (s), 971 (s), 907 (m), 858 (w), 811 (w), 766 (s), 695 (m), 668 (w), 642 (m), 635 (m), 602 (m), 569 (m), 535 (s), 506 (s), 472 (m), 454 (m).

Elemental analysis: found: C 13.68%, H 4.97%, N 7.83%; calcd. for $C_6H_{27}CoN_3O_{15}P_3$ (including 6 H_2O molecules): C 13.52%, H 5.10%, N 7.88%.

Crystals of $[Co(TACN)(D_2O)_3](P_3O_9)\bullet 3D_2O$ suitable for X-ray diffraction were grown as red prisms from a D_2O solution at room temperature. See Table 1 for the crystallographic data and Figure S1 for an ORTEP drawing of the crystal structure.



(a) (b)

Figure S1. ORTEP drawings (50% probability level) of the salt $[Co(TACN)(D_2O)_3](P_3O_9)\bullet 3D_2O$: (a) asymmetric unit (all hydrogen atoms on TACN were omitted for clarity); (b) unit cell, viewed along the *b* axis (carbon-bound hydrogen atoms on TACN were omitted for clarity). In both drawings hydrogen bonds are marked with dashed lines.

Table 1. Crystallographic data for $[Co(TACN)(D_2O)_3](P_3O_9)\bullet 3D_2O$,* and complex **3**.		
	$[Co(TACN)(D_2O)_3](P_3O_9)\bullet 3D_2O$	Complex **3**
Formula	$C_6H_{27}CoN_3O_{15}P_3$	$C_6H_{23}CoLiN_3O_{16}P_4$
FW, g mol^{-1}	533.15	583.02
Space group	$P2_1/n$	$P2_1/n$
Crystal system	monoclinic	monoclinic
a, Å	12.0751(10)	7.7646(2)
b, Å	10.6607(8)	32.3379(9)
c, Å	15.4913(12)	8.6387(3)
α, °	90.0	90.0
β, °	109.078(1)	114.3960(10)
γ, °	90.0	90.0
Cell volume, Å^3	1884.6(3)	1975.42(10)
Z	4	4
D (calc), Mg m^{-3}	1.879*	1.960
μ, mm^{-1}	1.246	10.704
Temperature, K	100(2)	100(2)
Wavelength, Å	0.71073 (Mo Kα)	1.54178 (Cu Kα)
F(000)	1104	1192
Crystal size, mm	0.32 × 0.16 × 0.06	0.25 × 0.20 × 0.03
θ range for data collection, °	1.87 to 27.43	5.79 to 67.73
Index ranges	$-15\le h\le 15$, $-13\le k\le 13$, $-20\le l\le 20$	$-9\le h\le 9$, $-38\le k\le 38$, $-9\le l\le 10$
Reflections collected	41610	37835
Independent reflections	4294	3494
Completeness to max. θ, %	99.8	97.4
Absorption correction	Semi-empirical from equivalents	Semi-empirical from equivalents
Max. / min. transmission	0.9290 / 0.6912	0.7395 / 0.1750
Refinement method	Full-matrix least-squares on F^2	Full-matrix least-squares on F^2
Restraints / parameters	30 / 298	17 / 313
Goodness-of-fit on F^2	1.050	1.105
R_{int}, %	5.83	3.60
R_1 ($I > 2\sigma(I)$), %	3.04	2.60
wR_2 ($I > 2\sigma(I)$), %	7.00	6.66
R_1 (all data), %	4.13	2.65
wR_2 (all data), %	7.61	6.69
Largest diff. peak / hole, eÅ^{-3}	0.517 / -0.355	0.317 / -0.442

* All D atoms were treated as H for the purpose of structural determination.

Reaction of complex 1 with $Na_3P_3O_9$ in water at 80°C. Formation of complex 2 by hydrolytic cleavage of cyclotriphosphate. Complex **2** was obtained by facile hydrolysis of cyclotriphosphate in water at 80°C, and was isolated in pure form as either the free acid (diprotonated triphosphato ligand) or dilithium salt (completely deprotonated triphosphato ligand), as described below. This complex was also obtained directly from the linear triphosphate, $Na_5P_3O_{10}$ (see below), showing that reaction of complex **1** with either $P_3O_9^{-3}$ or $P_3O_{10}^{-5}$ in water leads to the same product. It should be noted that complex **2** has been reported previously,[11] but only limited preparative and characterization data is available in the original manuscript. Herein we present detailed information regarding both synthesis and characterization of this complex:

*(a) Isolation of complex **2** in the free acid form (**2•H_2**):* 150 mg (0.212 mmol) of complex **1** were dissolved in 6.5 ml of H_2O and the solution was loaded into a 25-ml round-bottom flask. The flask was then fitted with a condenser and placed in an oil bath at 80°C, with stirring. To the hot stirring solution was then added a solution of 65 mg (0.212 mmol) of $Na_3P_3O_9$ in 2.0 ml of H_2O. The addition of this solution was carried out via syringe in a dropwise fashion, at 2 ml min^{-1}, and the resulting reaction mixture was stirred at 80°C for 30 min, during which its color changed from red to magenta. The solution was then cooled rapidly to 0°C (ice bath) to avoid further reaction, and was subsequently warmed to room temperature prior to the chromatographic purification step.[12] The solution was then loaded onto a 1 cm × 30 cm column of Dowex 1×4 (200 mesh) ion-exchange resin in the Cl^- form (after it had been washed with 0.1 M HCl, followed by pure H_2O immediately before use). The sample was eluted with aqueous HCl, using a linear concentration gradient of 0.5 mol L^{-2}, beginning at 0 M (pure H_2O), with an elution rate of 1.4 ml min^{-1}. The reaction mixture afforded only one significant slow-moving band of magenta color (a single fast-moving band was attributed to residual $[Co(TACN)(H_2O)_3]^{+3}$). This band, containing the desired product, began eluting out of

[11] G. P. Haight, T. W. Hambley, P. Hendry, G. A. Lawrance, A. M. Sargeson, *J. Chem. Soc., Chem. Commun.*, 1985, 488-491.

[12] The ^{31}P NMR spectrum of the reaction mixture at this stage indicated a pH level of about 2.5, based on the chemical shifts of the NMR signals of complex **2** (see below for the effect of pH on NMR chemical shifts). This pH level is consistent with hydrolytic cleavage of the cyclophosphate P-O bonds to form the acidic P-OH groups of complex **2**.

the column after about 105 ml. The afforded solution was collected in several fractions, which were subsequently examined by ^{31}P NMR spectroscopy to determine the presence of the desired product, as well as undesirable impurities. The fractions containing the pure product were combined to give a total of 24 ml, which were then mixed with 240 ml of acetone to yield a turbid mixture. This mixture was centrifuged in order to separate the solid product from the liquid phase, which was then decanted. The solids were then washed with 4 × 15 ml of acetone, followed by 2 × 15 ml of diethyl ether, and dried under vacuum. This afforded 57 mg (0.129 mmol; 61% yield) of the product as a pink powder. The solubility of this product in water was found to be relatively low, at less than 14 mM or 6 mg ml^{-1}.

^{31}P{^{1}H} NMR (162 MHz, D_2O, 6 mM): 2.15 (d, $^{2}J_{PP}$ = 16.6 Hz, 2P), -8.49 (t, $^{2}J_{PP}$ = 16.6 Hz, 1P). See Figure S2 for the experimental ^{31}P NMR spectrum. ^{1}H NMR (400 MHz, D_2O, 6 mM): 7.13 (s, 3H, N*H*), 3.23 (m, 6H, NC*H*$_2$), 2.69 (m, 6H, NC*H*$_2$). ^{13}C{^{1}H} NMR (101 MHz, D_2O, 6 mM): 53.11 (s, N*C*H$_2$), 53.04 (s, N*C*H$_2$), 52.99 (s, N*C*H$_2$).

IR (KBr, cm^{-1}): 3434 (br w), 3232 (w), 3151 (m), 3130 (m), 3015 (w), 2944 (w), 2884 (w), 2824 (w), 1645 (br w), 1489 (w), 1452 (w), 1377 (w), 1349 (w), 1337 (w), 1274 (s), 1262 (s), 1227 (m), 1136 (s), 1120 (s), 1093 (s), 1059 (s), 1025 (s), 1000 (s), 989 (s), 973 (s), 884 (s), 810 (w), 763 (w), 728 (m), 641 (w), 628 (w), 607 (w), 576 (m), 536 (m), 498 (w), 485 (m), 470 (m), 449 (w).

ESI-MS (CH_3OH/H_2O): M$^-$, m/e 441.9367; calcd. for $C_6H_{16}CoN_3O_{10}P_3$ (complex - H$^+$): 441.9381. UV-Vis (0.1 M HNO_3): 375 nm (ε = 46 M^{-1} cm^{-1}), 536 nm (ε = 121 M^{-1} cm^{-1}). Elemental analysis: found: C 16.20%, H 3.92%, N 9.34%, P 20.94%; calcd. for $C_6H_{17}CoN_3O_{10}P_3$ (anhydrous complex): C 16.26%, H 3.87%, N 9.48%, P 20.97%.

*(b) Isolation of complex **2** as a dilithium salt (**2•Li$_2$**):* the preparation of the dilithium salt of complex **2** follows the same procedure as the free acid, except for the ion-exchange chromatography. Thus, a reaction mixture obtained for 150 mg (0.212 mmol) of complex **1** and 65 mg (0.212 mmol) of $Na_3P_3O_9$ in a total of 8.5 ml of H_2O was loaded onto a 1 cm × 27 cm column of Dowex 1×4 (200 mesh) ion-exchange resin in the Cl$^-$ form (after it had been washed with 1 M LiCl, followed by pure H_2O immediately before use). The sample was eluted with aqueous LiCl, using a linear concentration gradient of 1 mol L^{-2},

beginning at 0 M (pure H_2O), with an elution rate of 0.9 ml min^{-1}. The reaction mixture afforded several slow-moving bands of pink or magenta color (a single fast-moving band was attributed to residual $[Co(TACN)(H_2O)_3]^{+3}$). The desired product eluted as the second slow-moving band, and began eluting out of the column after about 175 ml. The afforded solution was collected in several fractions, which were subsequently examined by ^{31}P NMR spectroscopy to determine the presence of the desired product, as well as undesirable impurities. The fractions containing the pure product were combined to give a total of 35 ml, which were then mixed with 350 ml of acetone to yield a turbid mixture. The resulting mixture was then centrifuged to afford a purple, viscous oily residue and a clear colorless supernatant. The latter was decanted and the residue was dissolved in 2 ml of H_2O and added to 15 ml of acetone, with stirring. The liquid phase was then decanted and the resulting solid residue was crushed to powder, washed with 15 ml of acetone and dried under vacuum. This afforded 79 mg (0.155 mmol; 73% yield) of the product as a magenta powder. This compound was found to be soluble in both water and methanol, in contrast to complexes **2•H$_2$**, **3** and **4**, which are only soluble in water. $^{31}P\{^1H\}$ NMR (162 MHz, D_2O, 52 mM): 4.74 (d, $^2J_{PP}$ = 16.2 Hz, 2P), -5.38 (t, $^2J_{PP}$ = 16.2 Hz, 1P). ^1H NMR (400 MHz, D_2O, 52 mM): 7.17 (s, 2H, N*H*), 6.42 (s, 1H, N*H*), 3.35-3.15 (m, 6H, NC*H*$_2$), 2.75-2.60 (m, 6H, NC*H*$_2$). $^{13}C\{^1H\}$ NMR (101 MHz, D_2O, 52 mM): 52.88 (m, N*C*H$_2$), 52.78 (s, N*C*H$_2$), 52.68 (m, N*C*H$_2$), 52.65 (s, N*C*H$_2$), 52.58 (s, N*C*H$_2$).[13] ^{59}Co NMR (95 MHz, D_2O, 52 mM): 9925 (br s; $\nu_{½} \approx 2650$ Hz). $^{31}P\{^1H\}$ NMR (162 MHz, CD_3OD, 17 mM): 5.70 (d, $^2J_{PP}$ = 17.3 Hz, 2P), -6.21 (t, $^2J_{PP}$ = 17.3 Hz, 1P). ^1H NMR (400 MHz, CD_3OD, 17 mM): 3.31-3.16 (m, 6H, NC*H*$_2$), 2.66-2.51 (m, 6H, NC*H*$_2$).[14] $^{13}C\{^1H\}$ NMR (101 MHz, CD_3OD, 17 mM): 50.95 (s, N*C*H$_2$), 50.72 (s, N*C*H$_2$), 50.68 (s, N*C*H$_2$). ^{59}Co NMR (95 MHz, CD_3OD, 17 mM): 9912 (br s; $\nu_{½} \approx 4130$ Hz).

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[13] The ^{13}C NMR spectrum of complex **2•Li$_2$** in D_2O exhibits more signals than would be expected on the basis of its known structure and symmetry (effectively C_s in solution), as reported by Haight et al. (see ref. 11) and is evident from the other NMR spectra (^{31}P and ^1H) presented here. The reason for this apparent discrepancy is unclear, but it does not originate from impurities in the sample, as is evident from NMR and elemental analysis data. Moreover, all NMR spectra in CD_3OD, including ^{13}C, are in full agreement with the expected structure and symmetry of **2•Li$_2$**.

[14] No ^1H NMR signals for the NH protons of the TACN ligand were observed due to facile H/D exchange with the solvent.

IR (KBr, cm^{-1}): 3397 (br s), 3171 (s), 3112 (s), 3009 (m), 2984 (m), 2950 (m), 2880 (m), 1669 (br w), 1491 (w), 1475 (w), 1448 (w), 1429 (w), 1377 (w), 1363 (w), 1347 (w), 1284 (w), 1258 (m), 1228 (s), 1211 (s), 1197 (s), 1167 (s), 1164 (s), 1126 (s), 1102 (s), 1093 (s), 1087 (s), 1062 (s), 1058 (m), 1044 (m), 1026 (m), 1007 (m), 993 (s), 976 (s), 962 (m), 909 (s), 881 (w), 857 (w), 813 (w), 809 (w), 761 (m), 728 (m), 645 (m), 628 (m), 622 (m), 597 (m), 579 (s), 530 (s), 500 (m), 488 (m), 481 (m), 448 (m). ESI-MS (CH_3OH/H_2O): M^-, m/e 441.9379; calcd. for $C_6H_{16}CoN_3O_{10}P_3$ (complex - $2Li^+$ + H^+): 441.9381; M^-, m/e 447.9471; calcd. for $C_6H_{15}CoLiN_3O_{10}P_3$ (complex - Li^+): 447.9462. UV-Vis (0.01 M NaOH): 380 nm (ε = 45 M^{-1} cm^{-1}), 541 nm (ε = 122 M^{-1} cm^{-1}). Elemental analysis: found: found: C 14.03%, H 4.24%, N 8.14%, P 18.54%; calcd. for $C_6H_{21}CoLi_2N_3O_{13}P_3$ (including 3 H_2O molecules): C 14.16%, H 4.16%, N 8.26%, P 18.26%.

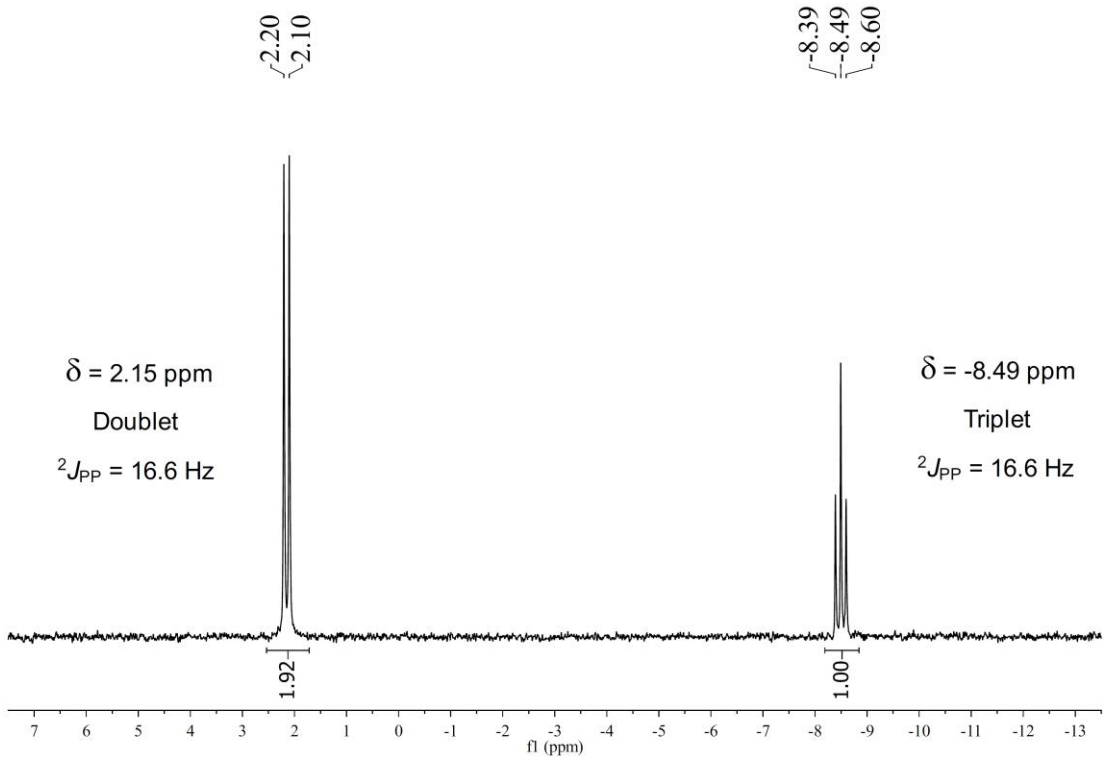

Figure S2. $^{31}P\{^1H\}$ NMR spectrum of complex **2** (free acid form) in D_2O (6 mM).

Reaction of complex 1 with $Na_5P_3O_{10}$ in water at 80°C. Formation of complex 2 by coordination of the linear triphosphate. For comparative purposes, complex **2** was also prepared directly from the linear triphosphate, $Na_5P_3O_{10}$. As described above, this demonstrates that $P_3O_9^{-3}$ and $P_3O_{10}^{-5}$ lead to the same product upon reaction with complex **1** in water. The complex obtained from $Na_5P_3O_{10}$ was isolated as either the free acid or dilithium salt, as described below:

*(a) Isolation of complex **2** in the free acid form (**2•H_2**):* A solution of 150 mg (0.212 mmol) of complex **1** in 1.0 ml of H_2O was loaded into a 20-ml glass vial and then mixed with a solution of 79 mg (0.214 mmol) of $Na_5P_3O_{10}$ in 1.0 ml of H_2O. The vial was capped and the solution was stirred at room temperature for 5 min, then heated to 80°C in an oil bath and stirred at this temperature for 15 min, during which its color changed from red to magenta. The solution was then cooled rapidly to 0°C (ice bath) to avoid further reaction, and was subsequently warmed to room temperature prior to the chromatographic purification step. The solution was then loaded onto a 1 cm × 30 cm column of Dowex 1×4 (200 mesh) ion-exchange resin in the Cl^- form (after it had been washed with 0.1 M HCl, followed by pure H_2O immediately before use). The sample was eluted with aqueous HCl, using a linear concentration gradient of 0.5 mol L^{-2}, beginning at 0 M (pure H_2O), with an elution rate of 1.3 ml min^{-1}. The reaction mixture afforded only one significant slow-moving band of magenta color (a single fast-moving band was attributed to residual $[Co(TACN)(H_2O)_3]^{+3}$). This band, containing the desired product, began eluting out of the column after about 105 ml. The afforded solution was collected in several fractions, which were subsequently examined by ^{31}P NMR spectroscopy to determine the presence of the desired product, as well as undesirable impurities. The fractions containing the pure product were combined to give a total of 24.5 ml, which were then mixed with 250 ml of acetone to yield a turbid mixture. This mixture was centrifuged in order to separate the solid product from the liquid phase, which was then decanted. The solids were then washed with 4 × 15 ml of acetone, followed by 2 × 15 ml of diethyl ether, and dried under vacuum. This afforded 49 mg (0.111 mmol; 52% yield) of the product as a pink powder. The product exhibits the same properties as complex **2•H_2** which was prepared from $Na_3P_3O_9$ (see above).

*(b) Isolation of complex **2** as a dilithium salt (**2•Li$_2$**):* A solution of 200 mg (0.283 mmol) of complex **1** in 1.5 ml of H_2O was loaded into a 20-ml glass vial and then mixed with a solution of 105 mg (0.285 mmol) of $Na_5P_3O_{10}$ in 1.5 ml of H_2O. The vial was capped and the solution was stirred at room temperature for 5 min, then heated to 80°C in an oil bath and stirred at this temperature for 15 min, during which its color changed from red to magenta. The solution was then cooled rapidly to 0°C (ice bath) to avoid further reaction, and was subsequently warmed to room temperature prior to the chromatographic purification step. The solution was then loaded onto a 1 cm × 50 cm column of Dowex 1×4 (200 mesh) ion-exchange resin in the Cl^- form (after it had been washed with 1 M LiCl, followed by pure H_2O immediately before use). The sample was eluted with aqueous LiCl, using a linear concentration gradient of 1 mol L^{-2}, beginning at 0 M (pure H_2O), with an elution rate of 0.5 ml min^{-1}. The reaction mixture afforded several slow-moving bands of pink or magenta color (a single fast-moving band was attributed to residual $[Co(TACN)(H_2O)_3]^{+3}$). The desired product eluted as the second slow-moving band, and began eluting out of the column after about 220 ml. The afforded solution was collected in several fractions, which were subsequently examined by ^{31}P NMR spectroscopy to determine the presence of the desired product, as well as undesirable impurities. The fractions containing the pure product were combined to give a total of 30 ml, which were then mixed with 300 ml of acetone to yield a turbid mixture. The resulting mixture was then centrifuged to afford a purple, viscous oily residue and a clear colorless supernatant. The latter was decanted and the residue was dissolved in 2 ml of H_2O and added to 15 ml of acetone, with stirring. The colorless supernatant was then decanted and the resulting oily residue was dried under vacuum, crushed to powder and dried again. This afforded 84 mg (0.165 mmol; 58% yield) of the product as a magenta powder. The product exhibits the same properties as complex **2•Li$_2$** which was prepared from $Na_3P_3O_9$ (see above).

Reaction of complex 1 with $Na_3P_3O_9$ in buffer solutions at room temperature. *In situ* formation of complex 2 at pH = 5.5-7.0. A solution containing 30 mM of complex **1** at pH = 5.5 was prepared by dissolving 21.2 mg (0.030 mmol) of complex **1** in 1.0 ml of a 1.0 M solution of the buffer 4-morpholineethanesulfonic acid (MES; pH adjusted with NaOH). A solution containing 30 mM of $Na_3P_3O_9$ at pH = 5.5 was similarly prepared by dissolving 9.3 mg (0.030 mmol) of the cyclophosphate salt in 1.0 ml of the buffer. 0.3 ml of the cobalt precursor solution was then mixed with 0.3 ml of the cyclophosphate solution and the resulting solution (containing 15 mM of each reactant in 1.0 M of buffer) was loaded into an NMR tube and allowed to stand at room temperature. ^{31}P NMR spectra of this solution were then recorded periodically over a few days. The same procedure was carried out for 30 mM solutions of complex **1** and $Na_3P_3O_9$ at pH = 7.0, by using a 1.0 M solution of the buffer 1,4-piperazinediethanesulfonic acid (PIPES; pH adjusted with NaOH). Control experiments were conducted by dissolving 13.9 mg (0.045 mmol) of $Na_3P_3O_9$ in 3.0 ml of each buffer (MES or PIPES) to afford 15mM of the cyclophosphate, and monitoring the ^{31}P NMR spectra of the afforded solutions as a function of time at room temperature.

It should be noted that the above buffers, known as Good-type[15] or "non-coordinating" buffers, were used as alternatives to common buffers, such as phosphate or acetate, which may strongly interfere with cyclophosphate coordination to the Co(III) center.

The ^{31}P NMR spectra of the above solutions revealed that in both buffer solutions complex **2** is the predominant reaction product at room temperature, throughout the monitoring period. As expected, the reaction was much slower than at 80°C, affording a molar ratio of **2**:$Na_3P_3O_9$ = 1.5 at pH = 5.5 (MES) within 48 hrs, and a molar ratio of **2**:$Na_3P_3O_9$ = 0.5 at pH = 7.0 within the same period. During this time, no complexes of $P_3O_9^{-3}$ were detected in any significant amount. Other phosphate-containing species were observed in solution, but they totaled less than 35% of complex **2** itself (in phosphorus-atom terms) and all appear to be hydrolytic decomposition products. The control experiments revealed that no detectable hydrolysis of $Na_3P_3O_9$ occurred in the buffer solutions in the absence of complex **1**.

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[15] N. E. Good, G. D. Winget, W. Winter, T. N. Connolly, S. Izawa, R. M. M. Singh, *Biochemistry*, 1966, **5**, 467-477.

Potentiometric titration of complex 2 and attempted determination of its pK_a values.

Potentiometric titrations of complex **2** were performed using a ROSS Ultra gel-filled pH/ATC triode with a built-in temperature probe (Thermo Scientific), and an Orion Symphony pH meter. The electrode was calibrated, immediately prior to use, against standard buffer solutions at pH = 4, 7 and 10. Aqueous solutions were prepared using deionized water of reagent grade ($\rho \geq 18$ MΩ cm; Ricca Chemical Company), which were degassed by alternating vacuum and nitrogen purge cycles. All titrations were carried out at 22 ± 1 °C, with continuous stirring of the titrand solution. The titrand solutions contained 0.1 M $NaNO_3$ (99.999%; Alfa Aesar) as the electrolyte in order to maintain constant ionic strength. During each titration, 6.0 ml of a 4 mM solution of complex **2•H₂** (containing 0.1 M $NaNO_3$) were titrated with 0.1 M NaOH, which was standardized with potassium hydrogen phthalate (KHP) immediately prior to use. The total amount of added titrant did not exceed 0.6 ml (10% of initial titrand volume) in order to avoid significant changes in ionic strength. The titration was carried out manually, with the titrant solution being dispensed in microliter quantities using micropipettes. After each incremental addition of titrant the solution was allowed to stir for a few seconds until the pH reading stabilized. A titration curve was thus generated, a typical example of which is displayed in Figure S3. The titration of complex **2•H₂** was repeated for a total of three times.

Attempts were made to fit the titration data using the program HYPERQUAD2006 v3.1.48,[16] in order to extract the pK_a values of complex **2**. However, no satisfactory fit could be generated for the experimental data, possibly due to the lack of features associated with the first deprotonation event (low pH). Repeating the titration at significantly higher concentrations of complex **2** was not feasible due to its limited solubility at low pH. Nonetheless, visual curve fitting of the titration data indicated that for complex **2**, $pK_{a2} < 3.8$. Moreover, the initial pH value of each titration, i.e., pH ≈ 2.5 for 4 mM of complex **2**, indicates a much lower pK_a value for the first deprotonation event. The above conclusions are supported by the observed behavior of the ^{31}P NMR spectrum of complex **2** as a function of pH, as detailed below.

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[16] P. Gans, A. Sabatini, A. Vacca, *Talanta*, 1996, **43**, 1739-1753.

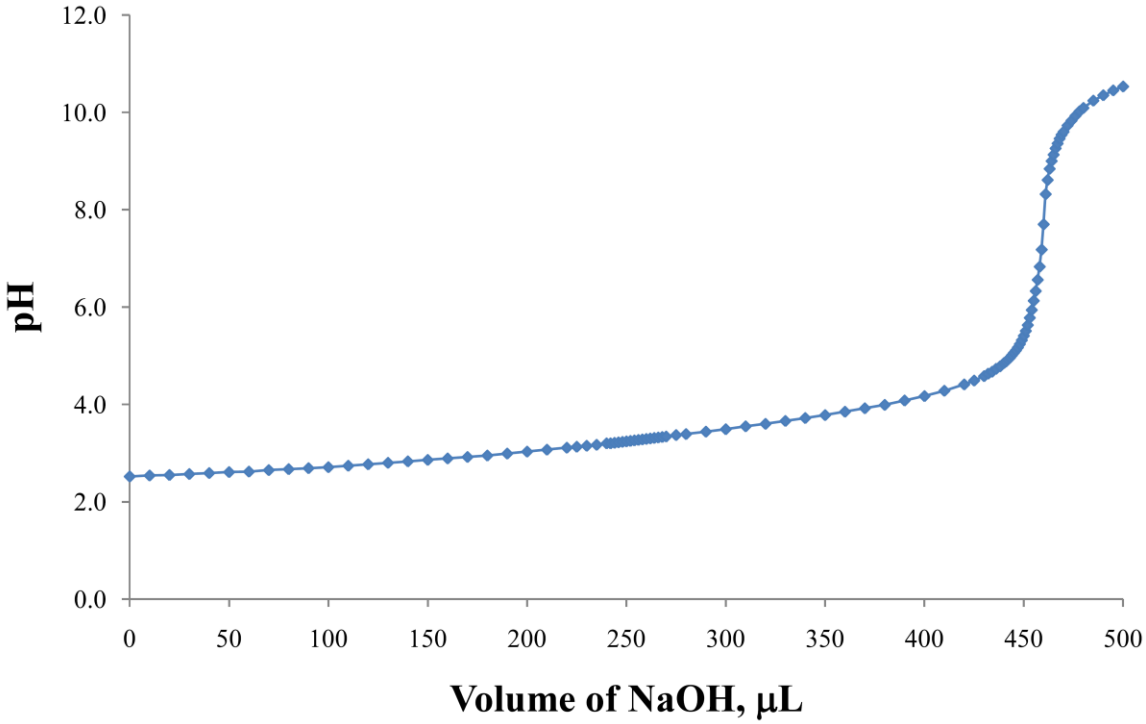


Figure S3. Titration curve for complex **2•H$_2$** in 0.1M $NaNO_3$, using NaOH as titrant (V_0 = 6 ml; [**2•H$_2$**]$_0$ = 4 mM; [NaOH] = 0.1022 M). A distinct equivalent point occurs at V(NaOH) = 460 µl and pH = 7.7, and corresponds to two proton equivalents.

Examination of the effect of pH on the ^{31}P NMR chemical shifts of complex 2.[17] 2 mg (0.005 mmol) of complex **2•H$_2$** were dissolved in 15 ml of 1 M HNO_3 (prepared with degassed, reagent grade H_2O). The pH level of the resulting solution was then adjusted by addition of microliter amounts of NaOH solutions of various concentrations (5, 1 and 0.1 M). Addition of the NaOH solutions was carried out with micropipettes and pH was measured with a ROSS Ultra gel-filled pH/ATC triode connected to an Orion Symphony pH meter. The total volume of NaOH added to the solution did not exceed 3% of the initial volume in order to avoid significant changes in ionic strength. At each desirable

[17] For previous accounts of the effect of pH on ^{31}P NMR chemical shifts of phosphate derivatives, see, for example: (a) H. Lachmann, K. D. Schnackerz, Org. Magn. Resonance, 1984, **22**, 101-105; (b) R. N. Bose, N. Goswami, S. Moghaddas, *Inorg. Chem.*, 1990, **29**, 3461-3467; (c) P.-M. L. Robitaille, P. A. Robitaille, G. G. Brown, Jr., G. G. Brown, *J. Magn. Reson.*, 1992, **92**, 73-84; (d) N. Yoza, N. Ueda, S. Nakashima, *Fresenius J. Anal. Chem.*, 1994, **348**, 633-638.

pH level a 1-ml aliquot was removed from the solution and its ^{31}P NMR spectrum was recorded at 22 ± 1 °C. A sealed glass capillary containing an aqueous solution of TMPO ($\delta(^{31}P)$ = 53.80 ppm) was inserted into the NMR tube as an internal standard.[18] The examined aliquot was not returned to the original solution and addition of base was carried out to the remaining parent solution. In this manner, ten ^{31}P NMR spectra were recorded for the range pH = 1-11. A plot of the ^{31}P NMR chemical shifts as a function of pH for the NMR signals associated with complex **2** is shown in Figure S4. It can be seen that the chemical shifts of these NMR signals move downfield by about 3.5 ppm with increasing pH. Moreover, the change in chemical shifts occurs in a linear fashion up to pH ≈ 5, at which point no significant change is observed upon increasing the pH level. This behavior is consistent with the conclusion drawn from the potentiometric titration, whereby pK_a < 3.8, such that complex **2** is essentially fully deprotonated at pH > 5. Furthermore, a linear fit of the data for pH < 5 gives the following relations between the ^{31}P NMR chemical shift (δ, in ppm) and pH: (a) for the end phosphate groups of the triphosphate ligand: $\delta = 1.0247(pH) + 0.0465$; (b) for the middle phosphate group: $\delta = 0.9815(pH) - 10.4126$. These equations can be used to estimate pH from the ^{31}P NMR signals of complex **2**. It should be noted that equation (a) is deemed to be more accurate, since it is based on the end phosphate groups which undergo protonation, while the middle phosphate group is not expected to be protonated to a significant extent and its ^{31}P NMR signals are only indirectly influenced by protonation of the end groups.

[18] Trimethylphosphine oxide (TMPO) in H_2O exhibits a ^{31}P NMR resonance at 53.80 ppm (singlet), which is far-removed from all other signals observed for the reaction mixtures obtained in the present work. Furthermore, TMPO is soluble and highly stable in water, permitting its use in aqueous media. Therefore, TMPO was chosen as an internal NMR standard for the present study.

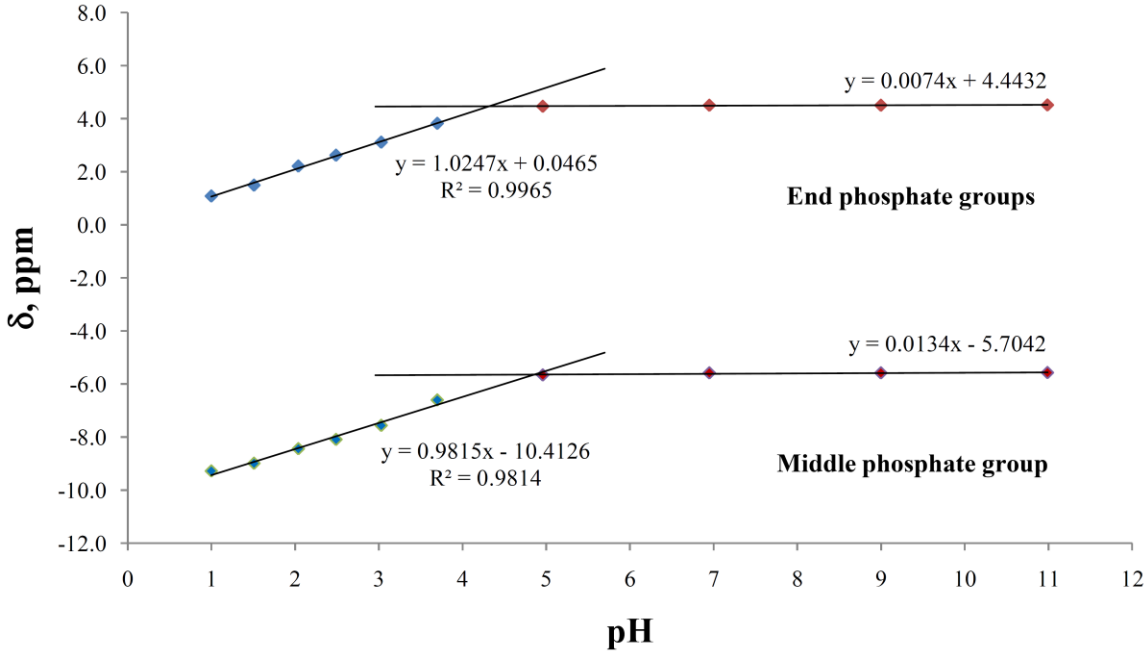


Figure S4. Chemical shifts (δ) as a function of pH for the ^{31}P NMR signals associated with complex **2** (22°C). The initial solution contained 0.3 mM of the complex and 0.1 M HNO_3, and pH was adjusted with NaOH.

Reaction of complex 1 with $Na_4P_4O_{12}$ in water at room temperature. Formation of the salt $[Co(TACN)(H_2O)_3]_4(P_4O_{12})_3 \cdot 7H_2O$. To a solution of 72 mg (0.102 mmol) of complex **1** in 0.5 ml of H_2O was added a solution of 50 mg (0.104 mmol) of $Na_4P_4O_{12} \cdot 4H_2O$ in 0.5 ml of H_2O. The resulting clear red solution was then stirred at room temperature for 22 hrs, during which a highly turbid pink suspension was obtained. This suspension was centrifuged in order to separate the solid product from the pink liquid phase, which was decanted. The product was washed with 0.5 ml of H_2O, followed by 5 ml of methanol and 5 ml of diethyl ether, and then dried under vacuum. This afforded 30 mg (0.015 mmol; 57% yield) of a pink powder. This powder has low solubility in water, on the order of 1 mg ml^{-1}.

$^{31}P\{^1H\}$ NMR (162 MHz, D_2O): -23.50 (br s). ^1H NMR (400 MHz, D_2O): 3.31 (m, 6H, NCH_2), 2.84 (m, 6H, NCH_2).[14] These NMR signals are consistent with solvated $P_4O_{12}^{-4}$ and $[Co(TACN)(H_2O)_3]^{+3}$ fragments, which are not mutually coordinated. No triflate

ions were observed by solution ^{19}F NMR spectroscopy, and no sodium was observed by EDX spectroscopy of the solid material.

IR (KBr, cm^{-1}): 3469 (s), 3427 (m), 3257 (s), 3194 (s), 3095 (s), 2976 (br s), 1635 (br w), 1493 (w), 1464 (w), 1454 (w), 1418 (w), 1378 (w), 1346 (w), 1341 (w), 1291 (s), 1285 (s), 1262 (s), 1244 (s), 1219 (s), 1166 (m), 1157 (w), 1136 (m), 1121 (s), 1111 (s), 1102 (s), 1077 (m), 1063 (m), 1052 (m), 987 (s), 911 (m), 881 (m), 873 (m), 856 (w), 813 (m), 744 (m), 722 (m), 699 (m), 669 (w), 642 (w), 625 (w), 574 (m), 566 (m), 533 (s), 521 (s), 507 (s), 475 (w).

Elemental analysis: found: C 14.26%, H 4.81%, N 7.94%, P 18.10%; calcd. for $C_{24}H_{98}Co_4N_{12}O_{55}P_{12}$ (including 12 coordinated and 7 non-coordinated H_2O molecules): C 14.11%, H 4.84%, N 8.23%, P 18.20%. The elemental analysis data provide an element ratio of C:N:P = 2.03:0.97:1.00, which is consistent with the proposed formulation of the product as a combination of 4 units of $[Co(TACN)(H_2O)_3]^{+3}$ and 3 units of $P_4O_{12}^{-4}$ (expected ratio of C:N:P = 2:1:1).

Synthesis and isolation of complex 3. 432 mg (0.611 mmol) of complex **1** were dissolved in 15 ml of H_2O and the resulting solution was loaded into a 25-ml round-bottom flask. The flask was then fitted with a condenser and placed in an oil bath at 80°C, with stirring. A solution of 301 mg (0.627 mmol) of $Na_4P_4O_{12}•4H_2O$ in 5 ml of H_2O was then added dropwise via syringe, at 2 ml min^{-1}, to the hot stirring solution. The resulting magenta solution was stirred at 80°C for an additional 10 min, and then cooled rapidly to 0°C (ice bath) to prevent decomposition of the product. The solution was then loaded onto a 1 cm × 50 cm column of Dowex 1×4 (200 mesh) ion-exchange resin in the Cl^- form (after it had been washed with 1 M LiCl, followed by pure H_2O immediately before use). The sample was eluted with aqueous LiCl, using a linear concentration gradient of 1 mol L^{-2}, beginning at 0.1 M, with an elution rate of 0.6 ml min^{-1}. The reaction mixture afforded several slow-moving bands of pink or magenta color (a single fast-moving band was attributed to residual $[Co(TACN)(H_2O)_3]^{+3}$). The desired product eluted as the second slow-moving band, and began eluting out of the column after about 160 ml. The afforded solution was collected in several fractions, which were

subsequently examined by ^{31}P NMR spectroscopy to determine the presence of the desired product, as well as undesirable impurities. The fractions containing the pure product were combined to give a total of about 30 ml. Isolation of the product from this solution was carried out by two alternative methods, as follows:

(a) *Precipitation:* to the 30 ml of eluted solution were added 300 ml of acetone and the resulting turbid mixture was centrifuged in order to separate the solid product from the liquid phase. The supernatant was then decanted and the product was redissolved in 2 ml of H_2O. The resulting solution was then added to 15 ml of acetone, with stirring, to reprecipitate the product. The liquid phase was decanted and the product was washed with 2 × 15 ml of acetone, followed by 2 × 15 ml of diethyl ether. The product was then dried under vacuum to afford 149 mg (0.272 mmol; 45% yield) of a flocculent pink powder. The product obtained by this procedure contains two molecules of water per complex, as indicated by elemental analysis.
^{31}P{^{1}H} NMR (162 MHz, D_2O, 17 mM): -11.80 (t, $^{2}J_{PP}$ = 20.5 Hz, 1P), -14.70 (dd, $^{2}J_{PP}$ = 26.8 Hz, $^{2}J_{PP}$ = 20.5 Hz, 2P), -26.81 (t, $^{2}J_{PP}$ = 26.8 Hz, 1P). See Figure S5 for the experimental ^{31}P NMR spectrum. Connectivity of the phosphorus nuclei was corroborated by ^{31}P COSY. ^{1}H NMR (400 MHz, D_2O, 17 mM): 3.30 (m, 2H, NC*H*$_2$), 3.19 (m, 4H, NC*H*$_2$), 2.74 (m, 2H, NC*H*$_2$), 2.67 (m, 4H, NC*H*$_2$).[14] ^{13}C{^{1}H} NMR (101 MHz, D_2O, 17 mM): 53.21 (s, N*C*H$_2$), 53.13 (s, N*C*H$_2$), 53.09 (s, N*C*H$_2$). ^{59}Co NMR (95 MHz, D_2O, 17 mM): 9877 (br s; $\nu_{½} \approx 1600$ Hz). ESI-MS (CH_3OH/H_2O): M^-, m/e 503.8940; calcd. for $C_6H_{15}CoN_3O_{12}P_4$: 503.8938. UV-Vis (H_2O): 375 nm (ε = 37 M^{-1} cm^{-1}), 532 nm (ε = 98 M^{-1} cm^{-1}). UV-Vis spectra were also recorded in 0.1 M PIPES-NaOH buffer (pH = 7.0) and 1.0 M HOTf, and were found to be essentially identical to the spectrum recorded in H_2O. Elemental analysis: found: C 13.29%, H 3.47%, N 7.51%, P 22.37%; calcd. for $C_6H_{19}CoLiN_3O_{14}P_4$ (including 2 H_2O molecules): C 13.17%, H 3.50%, N 7.68%, P 22.65%.
Crystals of complex **3** suitable for X-ray diffraction were grown at room temperature from an aqueous solution overlaid with acetonitrile. See Table 1 for the crystallographic data and Figure S6 for an ORTEP drawing of the crystal structure. The crystals grown

from THF/water as described in the preparative procedure were found to have identical unit cell dimensions as those grown from acetonitrile/water.

(b) *Crystallization:* to the 30 ml of eluted solution were added 240 ml of THF and the resulting turbid mixture was stored at 3°C for 17 days (the mixture changed into a clear solution upon cooling). During this time the product precipitated as pink, needle-like crystals, which were subsequently separated from the supernatant by decantation. The crystals were washed with 4 × 5 ml of THF, followed by 4 × 5 ml of diethyl ether, and then dried under vacuum. This afforded 125 mg (0.214 mmol; 34% yield) of the product as a crystalline magenta powder. The product obtained by this procedure contains four molecules of water per complex, as indicated by elemental analysis and X-ray crystallography.

IR (KBr, cm^{-1}): 3421 (s), 3293 (m), 3230 (m), 3104 (s), 2882 (m), 1624 (w), 1494 (w), 1486 (w), 1456 (m), 1444 (m), 1374 (w), 1352 (m), 1314 (s), 1276 (s), 1269 (s), 1232 (m), 1164 (s), 1116 (s), 1062 (s), 1041 (s), 1026 (m), 990 (s), 967 (s), 909 (w), 877 (w), 863 (w), 855 (w), 812 (w), 786 (w), 735 (m), 723 (s), 709 (m), 647 (w), 635 (w), 619 (w), 590 (m), 569 (s), 556 (s), 523 (m), 499 (m), 494 (m), 414 (m).

Elemental analysis: found: C 12.53%, H 3.79%, N 7.00%, P 21.57%; calcd. for $C_6H_{23}CoLiN_3O_{16}P_4$ (including 4 H_2O molecules): C 12.36%, H 3.98%, N 7.21%, P 21.25%.

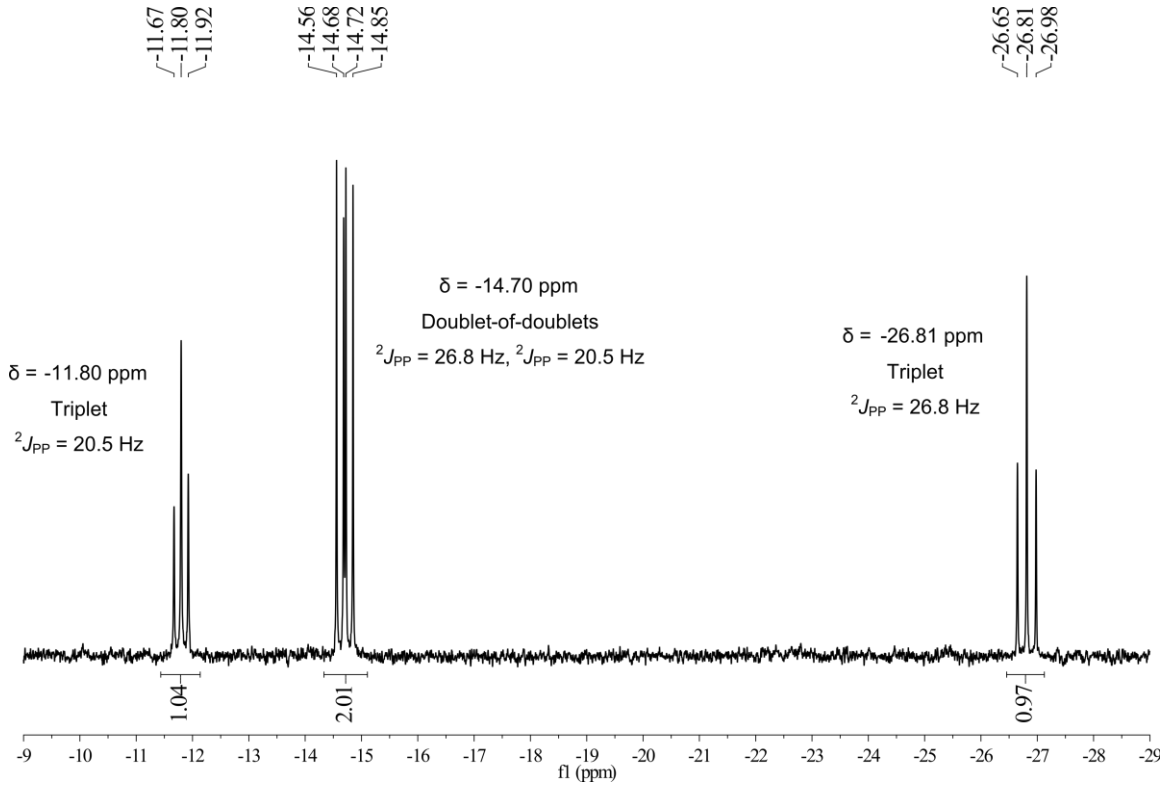
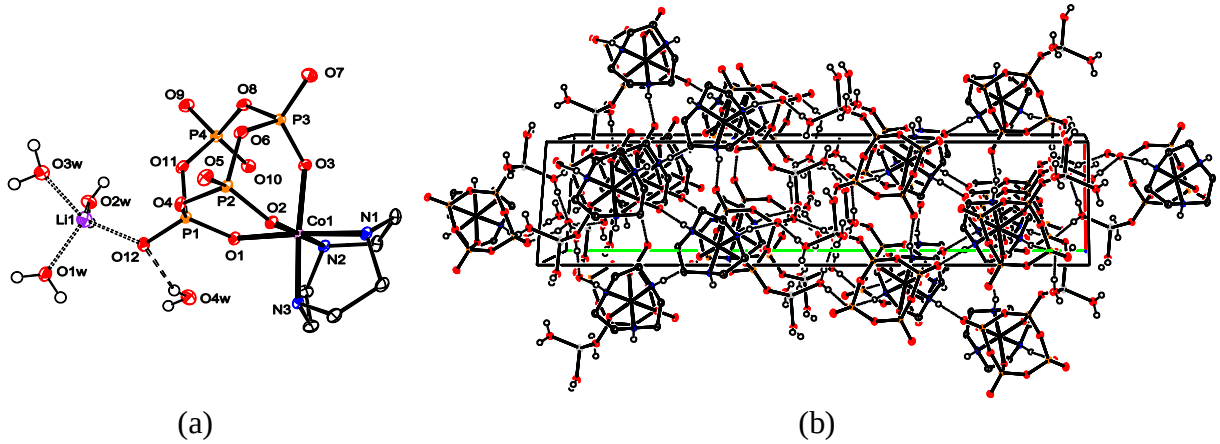


Figure S5. $^{31}P\{^1H\}$ NMR spectrum of complex **3** in D_2O (17 mM).



(a) (b)

Figure S6. ORTEP drawings (50% probability level) of complex **3**: (a) asymmetric unit (all hydrogen atoms on TACN were omitted for clarity); (b) unit cell, viewed along the *c* axis (carbon-bound hydrogen atoms on TACN were omitted for clarity). In drawing (a) dotted lines indicate Li-O dative bonds, and in both drawings hydrogen bonds are marked with dashed lines.

Effect of heating on complex 3 in water. Cyclophosphate hydrolysis at 80°C and formation of complex 2. 5 mg (0.009 mmol) of complex **3** (produced by the precipitation route) were dissolved in 2.0 ml of H_2O and the resulting solution was loaded into a 5-ml glass vial. The vial was capped and placed in an oil bath at 80°C. The solution was then allowed to stand at this temperature, without stirring, and was periodically examined by ^{31}P NMR spectroscopy (at room temperature) over a period of several hrs (see Figure S7). The ^{31}P NMR spectra of the solution revealed the gradual appearance of complex **2**, alongside other products of the hydrolytic decomposition of complex **3**. It was found that a yield of approximately 65% of complex **2** was obtained within 12 hrs at 80°C and remained essentially constant for at least 3 additional hrs.[19] The yield of complex **2** was estimated on the basis of ^{31}P NMR signal integration, by using a known amount of trimethylphosphine oxide (TMPO) which was added to the NMR sample as an internal standard[18] immediately prior to the measurement itself.
A few words are in order regarding the yield determination procedure. Reliable NMR signal integration requires a delay time of $5T_1$ (T_1 = spin-lattice relaxation time) between scans, but this can result in prohibitively long NMR experiments (several hours) for the phosphate species involved in the present work, since T_1 for oligophosphates (linear or cyclic) ranges from a few to tens of seconds.[20] Therefore, a procedure was adopted by which a short delay time of 2 seconds was employed, in order to allow for a large number of scans within a reasonable period of time, and the effects of spin saturation on the signal integrals were offset by use of a correction factor. This correction factor was determined in the following manner: aqueous solutions containing known concentrations of both TMPO and the analyte (e.g., complex **2**) were prepared, their ^{31}P NMR spectra were recorded, and the signal integrals were determined. The correction factor (*f*) was then calculated using the following equation:

$$f = \frac{[\text{analyte}]/[\text{TMPO}]}{(I_{\text{analyte}}/n) / I_{\text{TMPO}}}$$

[19] The ^{31}P NMR spectrum of the reaction mixture indicated a pH level of about 2.6, based on the chemical shifts of the NMR signals of complex **2** (see above for the effect of pH on NMR chemical shifts). This pH level is consistent with hydrolytic cleavage of the cyclophosphate P-O bonds to form the acidic P-OH groups of complex **2**.
[20] T. Glonek, P. J. Wang, J. R. Van Wazer, *J. Am. Chem. Soc.*, 1976, **98**, 7968-7973.

where [analyte] and [TMPO] are the molar concentrations; $I_{analyte}$ and I_{TMPO} are the signal integrals (determined for the sum of all signals per species); and n is the number of phosphorus atoms in the analyte species (for TMPO n = 1). For complex **2** the correction factor was f = 1.1.

The obtained correction factor was then used to estimate the concentration of the analyte in a reaction mixture on the basis of the known concentration of added TMPO and the integral ratio, as follows: [analyte] = f • [TMPO] • $\{(I_{analyte} / n) / I_{TMPO}\}$

The reaction yield was then calculated by dividing the estimated analyte concentration by the theoretical concentration expected for quantitative yield.

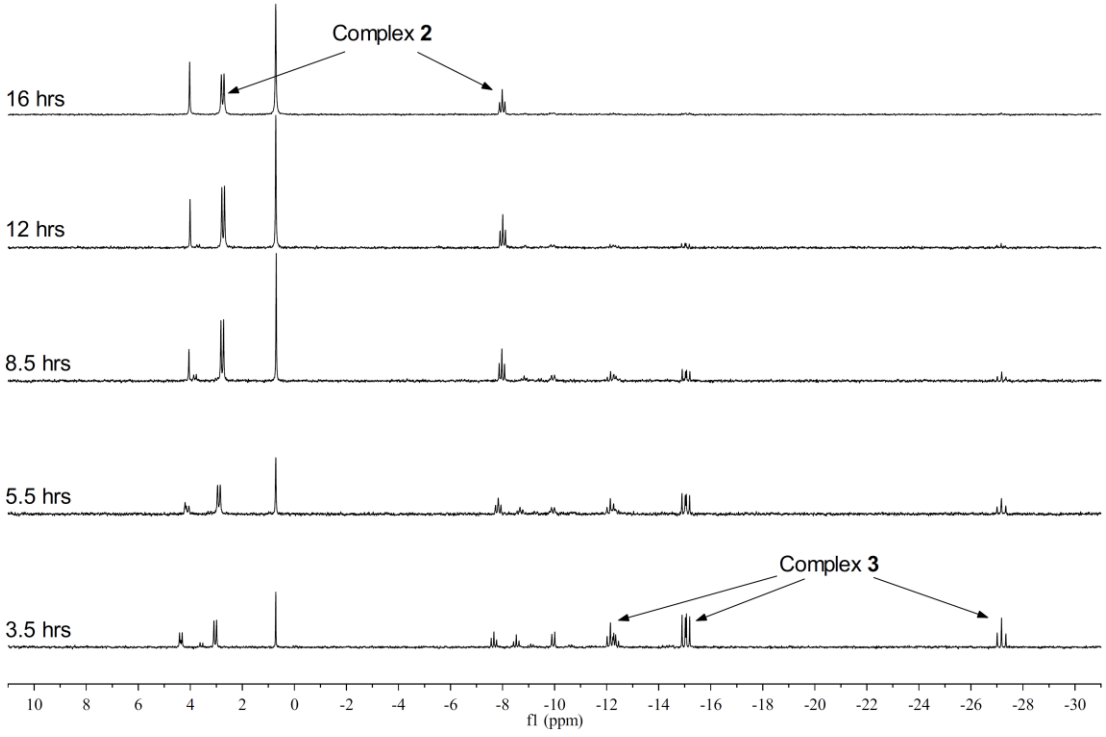


Figure S7. $^{31}P\{^{1}H\}$ NMR spectra showing the gradual hydrolysis of the cyclophosphate ligand upon heating an aqueous solution of complex **3** at 80°C (spectra were recorded at room temperature).

Hydrolysis of complex 3 and $Na_4P_4O_{12}$ in nitric acid. A comparative ^{31}P NMR kinetic study. 7-10 mg (0.012-0.017 mmol) of complex **3** (produced by the crystallization route) were dissolved in 0.6 ml of 1.0 M HNO_3 to afford 20-30 mM solutions of the complex. Each solution was then loaded into an NMR tube, together with a sealed glass capillary containing 0.5 M aqueous TMPO as an internal ^{31}P NMR standard.[18] The NMR tube was then sealed with a plastic cap and placed in an NMR spectrometer which had been pre-heated to 40 ± 1 °C. The ^{31}P NMR spectra of the solution were recorded at this temperature as a function of time, at intervals of 10-12.5 min. For each sample, spectra were collected over more than two reaction half-lives (≥300 min total). Kinetic data analysis was based on ^{31}P NMR signal integration, with the integral for the TMPO signal being used as a reference point and set at I = 1. The signal for complex **3** at -15 ppm was used for the determination of complex concentration, on the basis of its initial concentration and the integral value at the beginning of the kinetic experiment. The calculated concentrations of complex **3** were found to follow a pseudo-first-order rate law, i.e., $\ln([\text{complex } \mathbf{3}]/[\text{complex } \mathbf{3}]_0) = -k_{obs}\, t$. The apparent rate constant, k_{obs}, was obtained from a linear regression of $\ln([\text{complex } \mathbf{3}]/[\text{complex } \mathbf{3}]_0)$ as a function of time (see Figure S8). Three independently obtained k_{obs} values were used to determine the average k_{obs} for the acid hydrolysis of complex **3**, as follows: $k_{obs} = (7.89 \pm 0.05) \times 10^{-5}\ s^{-1}$. The half-life corresponding to this rate constant is $t_{½} = 146.4 \pm 0.9$ min.

The above procedure was also employed for the examination of the hydrolysis of $Na_4P_4O_{12}$ in nitric acid. Thus, 20-30 mM solutions of the cyclophosphate salt were prepared by dissolving 10-14 mg (0.021-0.029 mmol) of $Na_4P_4O_{12}•4H_2O$ in 0.6 ml of 1.0 M HNO_3. Kinetic experiments were then conducted at 40 ± 1 °C as described above for complex **3**, showing that hydrolysis of $Na_4P_4O_{12}$ also follows a pseudo-first-order rate law, as expected.[21] Since the hydrolysis of $Na_4P_4O_{12}$ was found to be somewhat slower than that of complex **3**, ^{31}P NMR spectra of the former were collected over more than 340 min (two reaction half-lives). Data analysis was carried out as described above (See

[21] G. Kura, *Polyhedron*, 1987, **6**, 531-533.

Figure S9), yielding the following average rate constant: $k_{obs} = (6.6 \pm 0.1) \times 10^{-5}$ s^{-1}. The half-life corresponding to this rate constant is $t_{½} = 174 \pm 3$ min.

The pseudo-first-order rate constants for the acid-promoted hydrolysis of complex **3** and $Na_4P_4O_{12}$ are remarkably similar, indicating similar hydrolytic stabilities of the cyclophosphate moiety in both species. This, in turn, demonstrates that coordination of $P_4O_{12}^{-4}$ to the Co(III) center does not significantly activate the cyclophosphate towards hydrolysis, as might otherwise be expected.

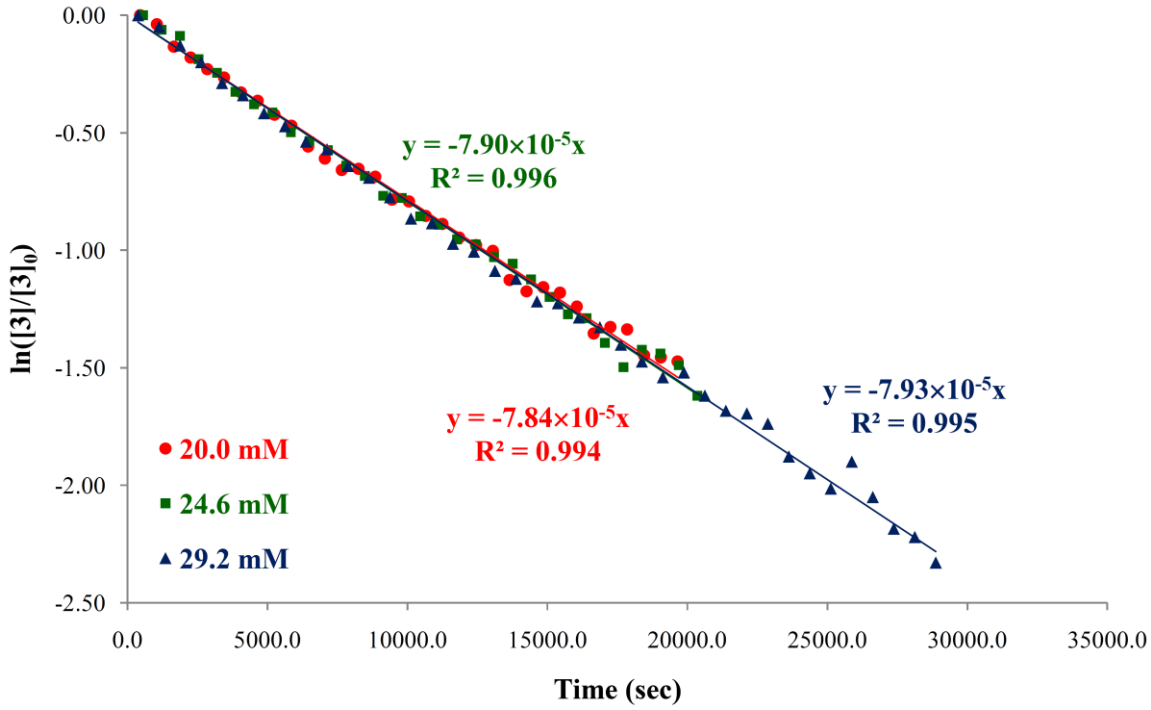


Figure S8. ^{31}P NMR kinetic study of the hydrolysis of complex **3** in 0.1 M HNO_3 at 40°C. The plot shows ln([**3**]/[**3**]$_0$) as a function of time.

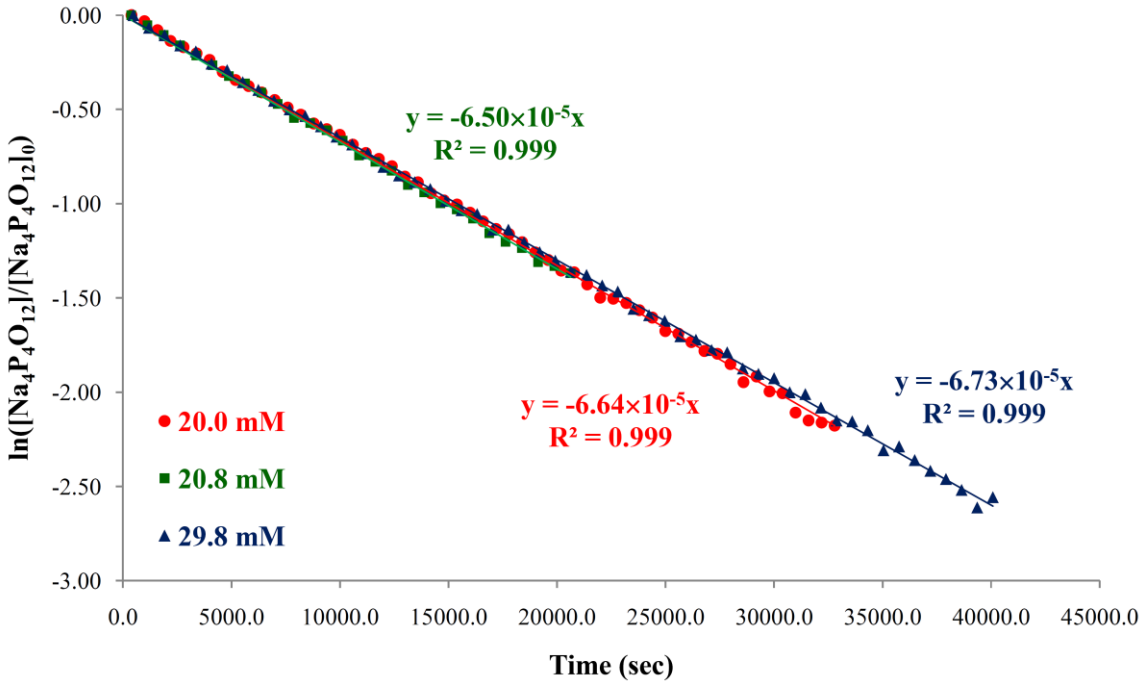


Figure S9. ^{31}P NMR kinetic study of the hydrolysis of $Na_4P_4O_{12}$ in 0.1 M HNO_3 at 40°C. The plot shows $\ln([Na_4P_4O_{12}]/[Na_4P_4O_{12}]_0)$ as a function of time.

Treatment of complex 3 with excess LiOH at room temperature. 5 mg (0.009 mmol) of complex **3** (produced by the precipitation route) were dissolved in 0.6 ml of H_2O and the solution was treated with 30 µl of 1.0 M LiOH. The resulting solution was allowed to stand at room temperature for 10 min and then 30 µl of 1.0 M HNO_3 were added. To the neutralized solution was then added a known amount of TMPO (as an internal NMR standard[18]) and the ^{31}P NMR spectrum of the reaction mixture was recorded. This spectrum featured a prominent singlet at -23.5 ppm, corresponding to non-coordinate $P_4O_{12}^{-4}$, as well as numerous minor signals attributed to other phosphate species. On the basis of NMR signal integrals the yield of $P_4O_{12}^{-4}$ was estimated at 80%, using the procedure outlined above (correction factor f = 1.2; see *Effect of heating on complex **3** in water*).

Regeneration of complex 3 after treatment with excess LiOH. 5 mg (0.009 mmol) of complex **3** (produced by the precipitation route) were dissolved in 0.6 ml of H_2O and the solution was treated with 30 μl of 1.0 M LiOH. The resulting solution was allowed to stand at room temperature for 10 min and then 30 μl of 1.0 M HNO_3 were added. The neutralized solution was then heated to 80°C and stirred at this temperature for 30 min. To the resulting solution was then added a known amount of TMPO (as an internal NMR standard[18]) and its ^{31}P NMR spectrum was recorded. This spectrum revealed the regeneration of complex **3** in about 50% yield (using the abovementioned yield estimation procedure with correction factor f = 1.1; see *Effect of heating on complex **3** in water*). The spectrum also featured numerous signals which are consistent with products of cyclophosphate hydrolysis (e.g., orthophosphate and complex **2**).

Synthesis and isolation of complex 4. 50 mg (0.092 mmol) of complex **3** (produced by the precipitation route) were dissolved in 3 ml of H_2O and the resulting solution was loaded into a 5-ml glass vial and cooled to 0°C (ice bath). To the cold, stirring solution were then added 250 μl of 1.0 M LiOH in 25 μl portions over 5 min. The resulting purple solution was then stirred at 0°C for an additional 5 min, after which 250 μl of 1.0 M HNO_3 were added. Addition of the acid resulted in an immediate color change from purple to pink. The desired product was then isolated from the reaction mixture by ion-exchange chromatography, which was carried out in a cold room at 4°C in order to hinder the reversion of the product to complex **3**. The solution was loaded onto a 0.7 cm × 20 cm column of Dowex 1×4 (200 mesh) ion-exchange resin in the Cl^- form (after it had been washed with 1 M LiCl, followed by pure H_2O immediately before use). The sample was eluted with aqueous LiCl, using a linear concentration gradient of 1 mol L^{-2}, beginning at 0.1 M, with an elution rate of 0.8 ml min^{-1}. The desired product eluted as the first slow-moving band, and began eluting out of the column after 20 ml. The afforded solution was collected in several fractions, which were subsequently examined by ^{31}P NMR spectroscopy to determine the presence of the desired product, as well as undesirable impurities. In order to avoid the reversion of the product to complex **3** the collected fractions were stored at 0°C before and after the NMR examination, which was

itself carried out at 5°C. The fractions containing the pure product were combined to give a total of 20 ml, which were then mixed with 200 ml of acetone at room temperature to yield a turbid mixture. This mixture was centrifuged in order to separate the solid product from the liquid phase, which was then decanted. The solids were then redissolved in 2 ml of H_2O and quickly reprecipitated by addition of 20 ml of acetone. The resulting solids were then isolated by centrifugation, washed with 2 × 15 ml of acetone, 2 × 15 ml of diethyl ether, and dried under vacuum. This afforded 22 mg (0.037 mmol; 42% yield) of the product as a pink powder.

$^{31}P\{^1H\}$ NMR (162 MHz, D_2O, 5°C, 32 mM): -14.51 (m, $^2J_{AA'}$ = 23 Hz, $^2J_{AX} = {}^2J_{A'X'}$ = 25 Hz, 2P; downfield part of AA'XX' system), -24.89 (m, $^2J_{XX'} = {}^2J_{AX} = {}^2J_{A'X'}$ = 25 Hz, 2P; upfield part of AA'XX' system). See Figure S10 for the experimental ^{31}P NMR spectrum. Connectivity of the phosphorus nuclei was corroborated by ^{31}P COSY. ^1H NMR (400 MHz, D_2O, 5°C, 32 mM): 3.27 (m, 4H, NCH_2), 3.21 (m, 2H, NCH_2), 2.74 (m, 6H, NCH_2).[14] $^{13}C\{^1H\}$ NMR (101 MHz, D_2O, 5°C, 32 mM): 53.45 (s, NCH$_2$), 53.22 (s, NCH$_2$), 53.17 (s, NCH$_2$). ^{59}Co NMR (95 MHz, D_2O, 5°C, 32 mM): 9805 (br s; $\nu_{½} \approx$ 3600 Hz).

$^{31}P\{^1H\}$ NMR (162 MHz, D_2O, 32 mM): -14.41 (m, $^2J_{AA'}$ = 23 Hz, $^2J_{AX} = {}^2J_{A'X'}$ = 25 Hz, 2P; downfield part of AA'XX' system), -24.82 (m, $^2J_{XX'} = {}^2J_{AX} = {}^2J_{A'X'}$ = 25 Hz, 2P; upfield part of AA'XX' system). ^1H NMR (400 MHz, D_2O, 32 mM): 3.28 (m, 4H, NCH_2), 3.21 (m, 2H, NCH_2), 2.73 (m, 6H, NCH_2).[14]

IR (KBr, cm^{-1}): 3417 (br s), 3301 (m), 3207 (s), 3135 (s), 2950 (m), 2886 (m), 1653 (br w), 1491 (w), 1457 (w), 1384 (w), 1351 (w), 1289 (s), 1256 (s), 1158 (s), 1112 (s), 1066 (s), 1008 (s), 991 (s), 910 (w), 896 (w), 857 (w), 811 (w), 792 (w), 727 (m), 679 (w), 646 (w), 634 (w), 599 (w), 553 (m), 520 (m), 486 (m).

ESI-MS (CH_3OH/H_2O): only complex **3** and its fragmentation products were observed, in line with the thermal instability of complex **4** with respect to conversion to **3**. UV-Vis (H_2O): 372 nm (ε = 35 M^{-1} cm^{-1}), 532 nm (ε = 67 M^{-1} cm^{-1}). UV-Vis spectra were also recorded in 0.1 M PIPES-NaOH buffer (pH = 7.0) and 1.0 M HOTf, and were found to be essentially identical to the spectrum recorded in H_2O. Elemental analysis: found: C 12.76%, H 4.05%, N 7.10%, P 21.65%; calcd. for $C_6H_{23}CoLiN_3O_{16}P_4$ (including 4 H_2O molecules): C 12.36%, H 3.98%, N 7.21%, P 21.25%.

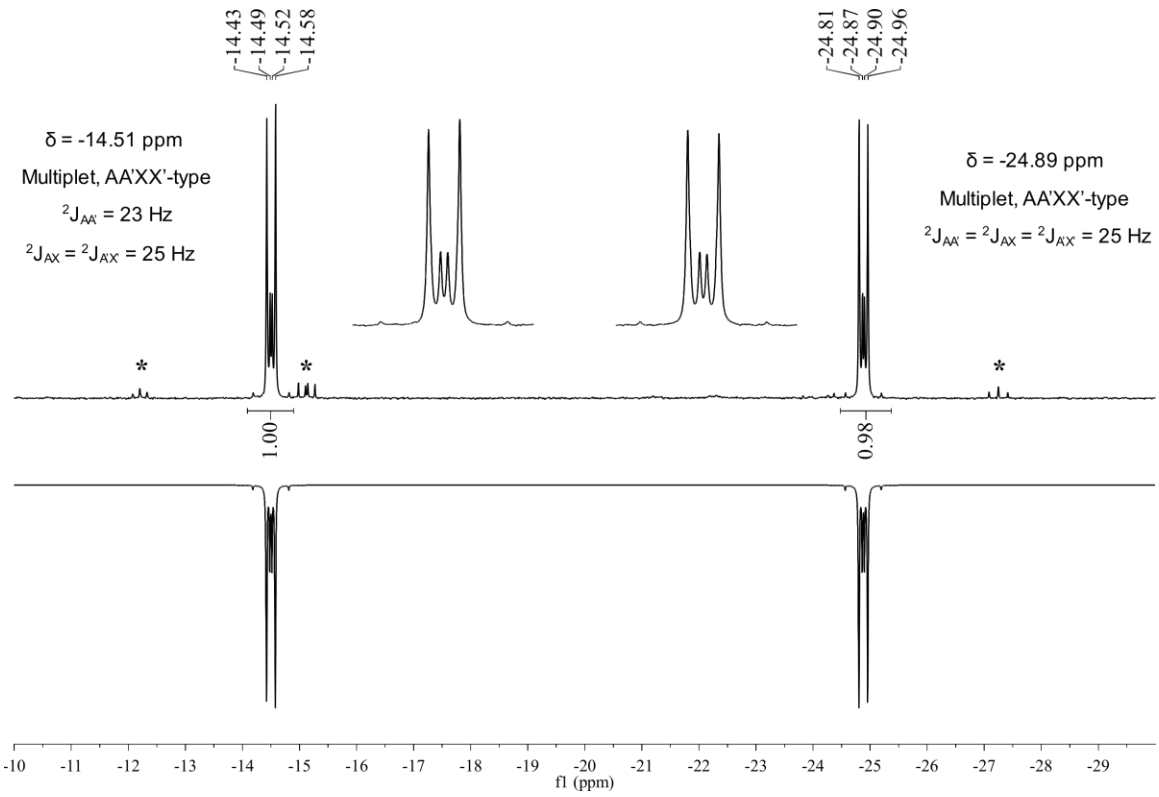


Figure S10. $^{31}P\{^1H\}$ NMR spectrum of complex **4** in D_2O (5°C, 32 mM). A simulated spectrum is shown below (inverted). Signals attributed to a small amount of complex **3** are marked with asterisks (*).

Determination of the self-diffusion coefficients of complexes 3 and 4 by ^{1}H diffusion-ordered NMR spectroscopy (DOSY). As part of the structural characterization of complex **4**, it was necessary to determine whether it is a monomer or dimer, since its NMR spectra (particularly ^{31}P) are consistent with both structural alternatives and crystallographic data is not available. The molecular size of complex **4** can be estimated from its diffusion coefficient by utilizing the Stokes-Einstein equation:[22] $D = k_BT/6\pi\eta r$, where k_B = Boltzmann constant; T = temperature; η = solvent viscosity; r = hydrodynamic radius of the molecule. Since complexes **3** and **4** are structurally related and carry the same charge, and since the molecular structure of **3** is fully characterized,

[22] (a) W. S. Price, *Concepts Magn. Res.*, 1997, **9**, 299-336; (b) W. S. Price, *Concepts Magn. Res.*, 1998, **10**, 197-237.

comparison of the diffusion coefficients of the two complexes will indicate whether **4** is monomeric ($D_3 \approx D_2$) or dimeric ($D_3 \approx 0.5D_2$). Measurement of the self-diffusion coefficients of the two complexes in D_2O was carried out by ^1H diffusion-ordered NMR spectroscopy (DOSY).[22,23]

DOSY experiments were carried out at 20 ± 1 °C on a Bruker Avance-400 spectrometer equipped with a BBO probe, using 9 mM solutions of complexes **3** and **4** in D_2O. The standard Bruker pulse program *stegp1s* was used, with gradient duration δ = 3.3 ms and diffusion time Δ = 100 ms. The intensity (I) of an appropriate ^1H resonance for either complex **3** (2.71 ppm) or **4** (2.68 ppm) was recorded as a function of magnetic field gradient strength (g). The diffusion coefficient, D, is related to I by the following equation:[22] $I/I_0 = \exp[-D\gamma^2 g^2 \delta^2(\Delta - \delta/3)]$, where I_0 = signal intensity in the absence of field gradient, γ = gyromagnetic ratio, and Δ and δ are as mentioned above. A plot of $\ln(I/I_0)$ as a function of g^2 gives a linear graph with a slope $-D\gamma^2\delta^2(\Delta - \delta/3)$, from which D can be extracted. Examples of typical plots of $\ln(I/I_0)$ as a function of g^2 for complexes **3** and **4** in D_2O are presented in Figures S11 and S12. An average self-diffusion coefficient for each complex was calculated on the basis of three independent measurements. The obtained diffusion coefficients are as follows: $D_3 = (3.8 \pm 0.1) \times 10^{-10}$ m^2 s^{-1}; $D_4 = (3.73 \pm 0.04) \times 10^{-10}$ m^2 s^{-1}. These values are identical within the experimental error and it may therefore be concluded that complex **4** exhibits a monomeric structure in aqueous solution.

[23] K. F. Morris, C.S. Johnson, Jr., *J. Am. Chem. Soc.*, 1992, **114**, 3139-3141.

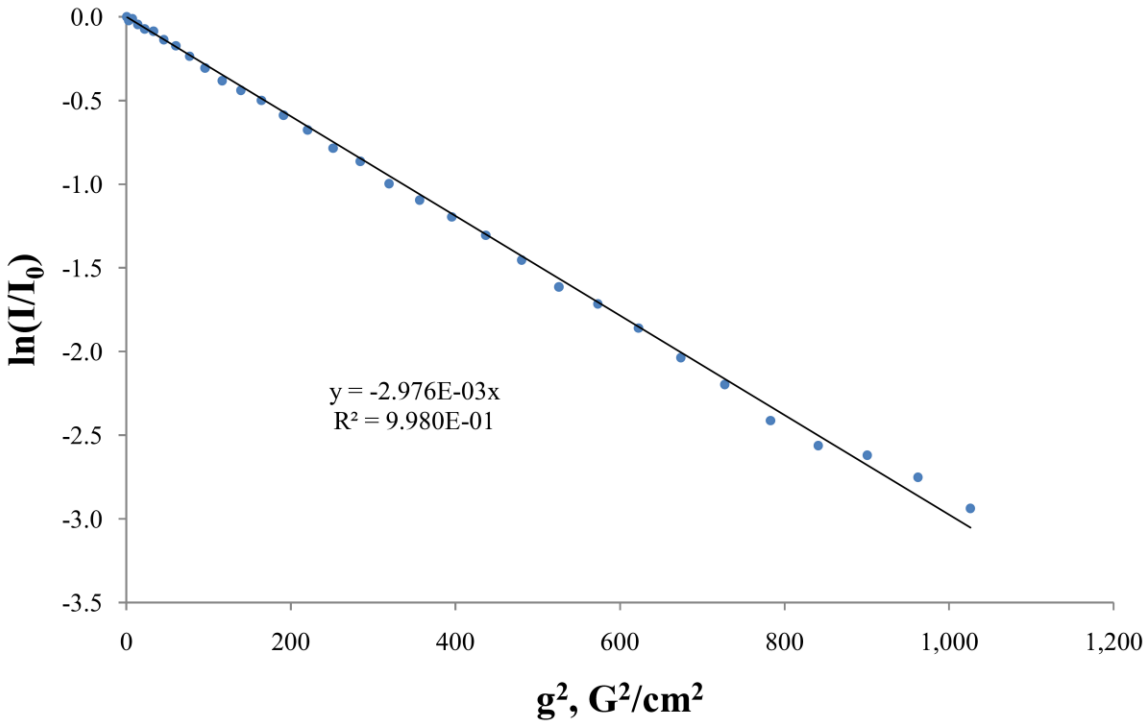


Figure S11. Typical ^{1}H DOSY data for complex **3** in D_2O at 20°C. The plot shows $\ln(I/I_0)$ as a function of g^2 for complex **3**.

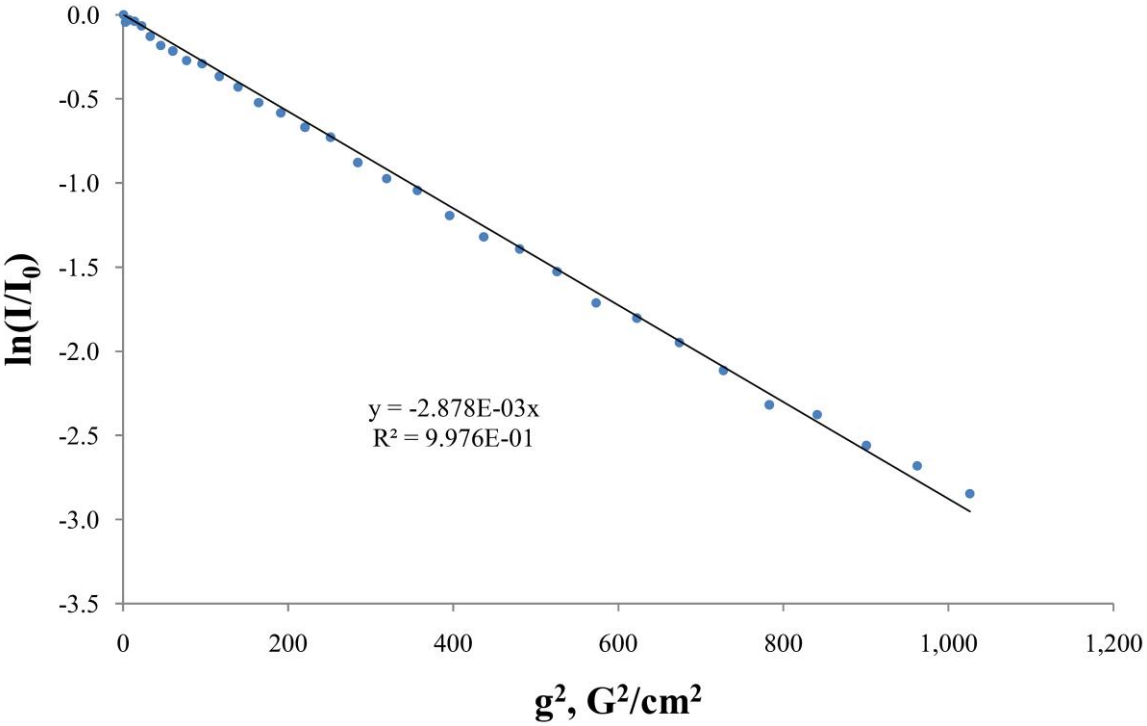


Figure S12. Typical ^{1}H DOSY data for complex **4** in D_2O at 20°C. The plot shows $\ln(I/I_0)$ as a function of g^2 for complex **4**.

Reversible interconversion of complexes 3 and 4 in water. 4.2 mg (0.007 mmol) of complex **3** (produced by the crystallization route) were dissolved in 0.7 ml of D_2O. The solution was then allowed to stand at room temperature and was monitored occasionally by ^{31}P NMR spectroscopy. The ^{31}P NMR spectra of this solution are shown in Figure S13 as a function of time. These spectra demonstrate the gradual appearance of complex **4** when pure complex **3** is dissolved in water. A similar procedure was carried out with a pure sample of complex **4**, and its ^{31}P NMR spectra are shown in Figure S14 as a function of time. These spectra show that complex **4** gradually reverts to complex **3** in water. In both cases the system reaches a state of equilibrium within a few days, yielding a constant molar ratio of **3**:**4** ≈ 10:1.

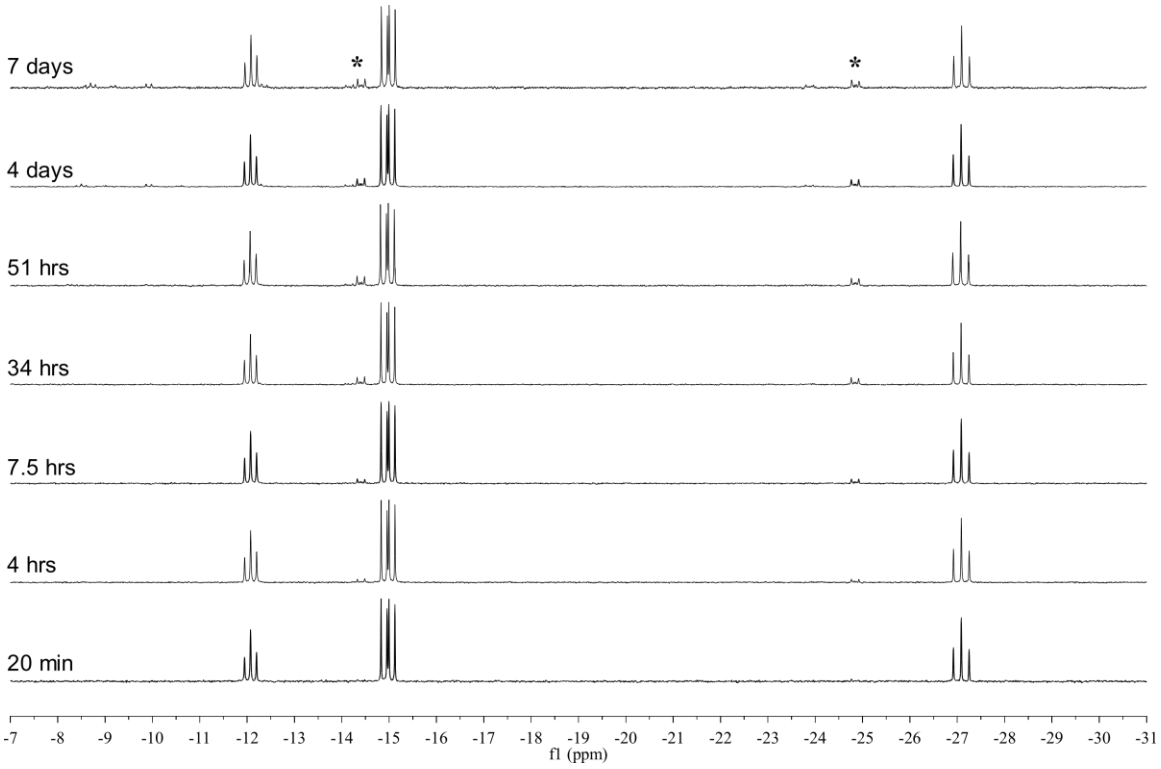


Figure S13. $^{31}P\{^1H\}$ NMR spectra of complex **3** in D_2O as a function of time at 22°C, showing the gradual appearance of complex **4**. The latter is marked with asterisks (*).

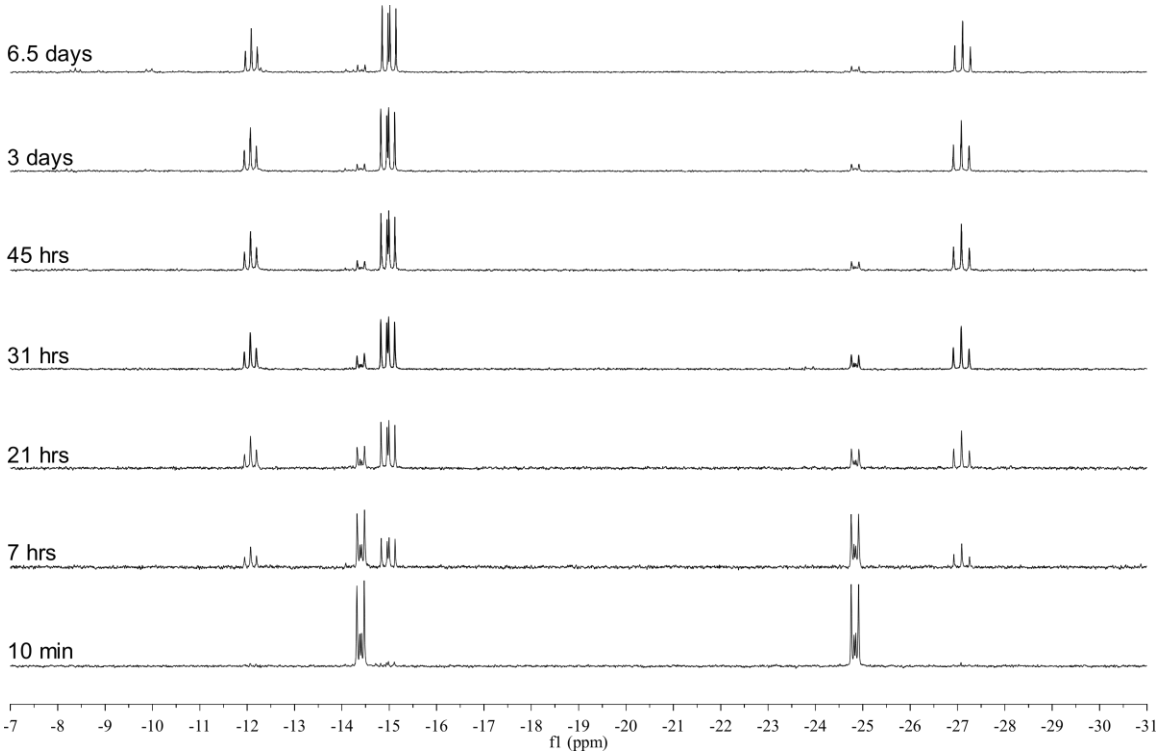


Figure S14. $^{31}P\{^{1}H\}$ NMR spectra of complex **4** as a function of time at 22°C, showing its gradual reversion to complex **3**.

Examination of the effect of pH on the ^{31}P NMR chemical shifts of complexes 3 and 4. 2 mg (0.003 mmol) of either complex **3** or **4** were dissolved in 10 ml of 1 M HNO_3 (prepared with degassed, reagent grade H_2O). The pH level of the resulting solution was then adjusted by addition of microliter amounts of NaOH solutions of various concentrations (5, 1 and 0.1 M). Addition of the NaOH solutions was carried out with micropipettes and pH was measured with a ROSS Ultra gel-filled pH/ATC triode connected to an Orion Symphony pH meter. The total volume of NaOH added to the solution did not exceed 2% of the initial volume in order to avoid significant changes in ionic strength. At each desirable pH level a 1-ml aliquot was removed from the solution and its ^{31}P NMR spectrum was recorded. A sealed glass capillary containing an aqueous solution of TMPO ($\delta(^{31}P)$ = 53.80 ppm) was inserted into the NMR tube as an internal standard.[18] The examined aliquot was not returned to the original solution and addition of base was carried out to the remaining parent solution. In this manner, four ^{31}P NMR spectra were recorded for complex **4** in the range pH = 1-7 (higher pH levels result in

significant decomposition), and five ^{31}P NMR spectra were recorded for complex **3** in the range pH = 1-9 (higher pH levels result in significant decomposition). Plots of the ^{31}P NMR chemical shifts as a function of pH are shown in Figures S15 and S16. As can be seen in these plots, no significant changes in chemical shift were observed for the NMR signals of either complex **3** or **4**. This indicates that the $P_4O_{12}^{-4}$ ligand is a very weak base in both complexes ($pK_a < 1$).

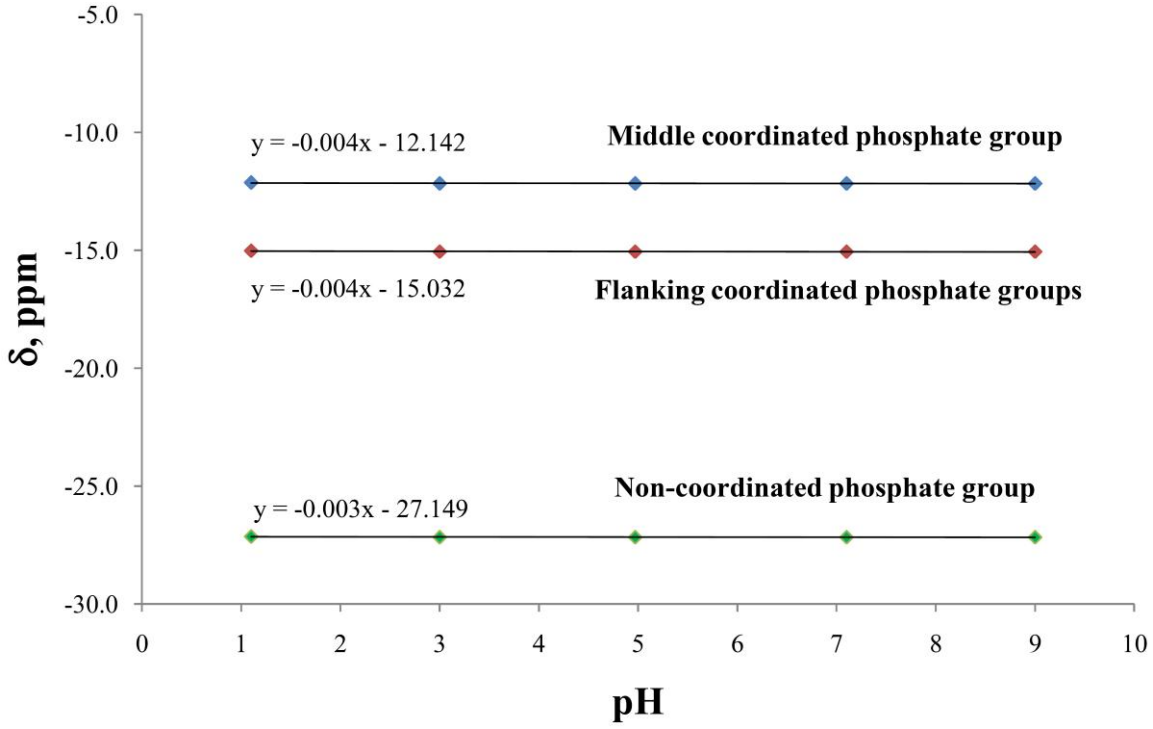


Figure S15. Chemical shifts (δ) as a function of pH for the ^{31}P NMR signals associated with complex **3** (22°C). The initial solution contained 0.3 mM of the complex and 0.1 M HNO_3, and pH was adjusted with NaOH.

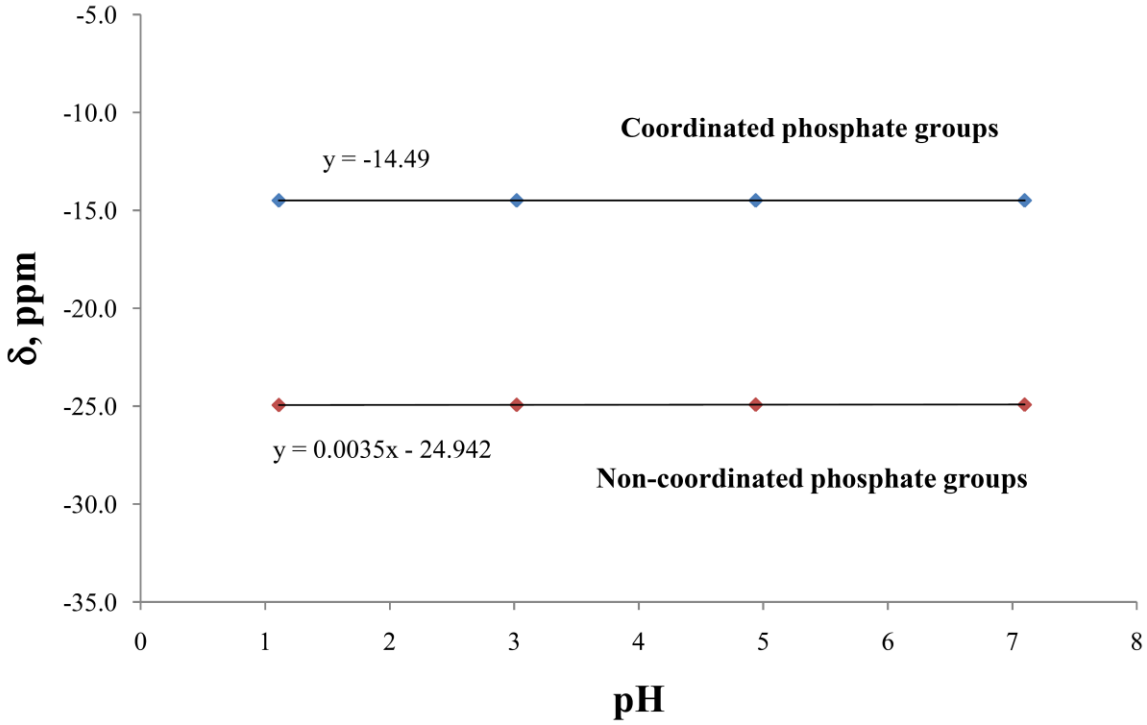


Figure S16. Chemical shifts (δ) as a function of pH for the ^{31}P NMR signals associated with complex **4** (22°C). The initial solution contained 0.3 mM of the complex and 0.1 M HNO_3, and pH was adjusted with NaOH.