# Multinuclear NMR Study of the Complexation of Lanthanide(III) Cations with Sodium Triphosphate: Induced Shifts and Relaxation Rate Enhancements

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Abstract: The complexation of lanthanide cations with <sup>17</sup>O-labeled triphosphate was studied with the use of multinuclear NMR shift and relaxation rate measurements. Depending upon the choice of the lanthanide cation, separate signals for the 1:2 lanthanide-triphosphate complex and the free triphosphate ligand, or averaged spectra, were obtained. The longitudinal relaxation was always in the fast exchange region. From the analyses of the shift and relaxation data it is concluded that the lanthanide ion is coordinated with two triphosphate ligands and one water in the first coordination sphere, while seven alkali counterions are present in the second coordination sphere. Triphosphate is coordinated to the lanthanide ion via two oxygens of one PO<sub>3</sub> group, one oxygen of the other PO<sub>3</sub> group, and one oxygen of the PO<sub>2</sub> moiety. In the exchange of triphosphate between the free and the complexed states, both associative and dissociative mechanisms play a role.

Sodium triphosphate (STP) is one of the most effective detergent builders.<sup>1</sup> Its main purpose is the sequestering of Ca(II) and Mg(II) cations. In addition, lanthanide(III) triphosphates have been demonstrated to be versatile aqueous NMR shift reagents for cations with application in, for example, the study of the transport processes of alkali metal ions through biological membranes.<sup>2</sup> Complexes of Mg(II) and Ca(II) with esters of triphosphoric acid, such as adenosine triphosphate (ATP), play

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an important role in many biological processes and have been studied by several authors.3-9

Up to now, however, the evidence as to the structure of ATP complexes with divalent cations is not conclusive:  $\alpha,\beta,\gamma$ -tridentate,<sup>3,4</sup>  $\beta$ , $\gamma$ -bidentate,<sup>6,7</sup>  $\beta$ -monodentate,<sup>8</sup> as well as a mixture of  $\alpha,\beta$ -,  $\alpha,\gamma$ - and  $\beta,\gamma$ -bidentate coordination<sup>5</sup> have been proposed. Williams et al.<sup>9</sup> have studied the geometry of Ln(III) complexes of ATP in detail. It was concluded that the Ln(III) ion binds predominantly to the  $\beta$ - and  $\gamma$ -phosphate moiety. The complexes of TP and Ca(II), Mg(II), or Ln(III) ions, however, have been studied to a lesser extent. On the basis of the experiments published, no definitive conclusions about their structures could be derived.2,3,10-12

The worldwide concern about the eutrophication of surface water by phosphates has initiated a search toward new builders

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for detergent formulations. In this field, we have studied with the use of multinuclear NMR several (hydr)oxycarboxylates in the presence of Ln(III) cations, as model cations for Ca(II).<sup>7</sup> The use of Ln(III) cations as NMR probes for Ca(II) can be justified by the often-observed structural similarity between the Ca(II) and the Ln(III) complexes of a particular ligand.<sup>9,13</sup> It has been shown that both the lanthanide-induced shifts (LnIS) and the lanthanide-induced relaxation rate enhancements (LnIRE) of the various nuclei can be translated into valuable structural information about the ligand.13

We now report on a study of the complexation of Ln(III) by triphosphate (TP) with the use of <sup>17</sup>O and <sup>31</sup>P NMR. To get an impression about the position of monovalent counterions near the negatively charged Ln(III)-triphosphate complex, also <sup>23</sup>Na and <sup>6</sup>Li NMR techniques were applied. The TP ligand has only a few different nuclei, which probably all will be at a relatively short distance from the lanthanide cation. Generally, for this situation Dy(III)-induced <sup>17</sup>O shifts<sup>14</sup> and Gd(III)-induced relaxation rate enhancements<sup>15</sup> are most suitable to obtain structural information. The close proximity of the ligand nuclei to the Ln(III) ions in addition to the high association constants of the Ln(III)-triphosphate complexes,<sup>16</sup> however, gave rise to slow ligand-exchange phenomena in the NMR spectra. Therefore, some extensions of the previously developed techniques<sup>13</sup> were required. The problems encountered are expected to be characteristic for the study of the complexation of potential organic phosphate substitutes, which should have an association constant higher than the (hydr)oxycarboxylates studied so far by us.<sup>13</sup>

#### Methods and Materials

NMR Measurements. All NMR spectra were recorded with a Nicolet NT-200 WB spectrometer. Measurements were performed with samples containing 0.35 M  $Na_5P_3O_{10}$  6H<sub>2</sub>O in D<sub>2</sub>O in the presence of various amounts of LnCl<sub>3</sub>·6H<sub>2</sub>O. The <sup>17</sup>O NMR spectra were recorded of 2.2% <sup>17</sup>O-enriched compounds using 1K datapoints, 20-kHz spectral width, and a repetition rate of 25 ms. Usually, about 10<sup>4</sup> transients were needed to obtain a good signal-to-noise ratio. The data were processed using zero filling to 4K datapoints, followed by double exponential weighing. A baseline correction was applied to the transformed spectra. <sup>17</sup>O chemical shifts were measured with respect to  $D_2O$  as external standard, <sup>31</sup>P and  $^{23}Na$  chemical shifts with respect to the  $P_{\alpha,\gamma},$  and the  $^{23}Na$  signal of

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Table I. Observed <sup>17</sup>O-Bound Shifts (ppm) in Ln(TP)<sub>2</sub>(D<sub>2</sub>O)<sub>x</sub> at 73 °C

				_
Ln	$\Delta(\mathrm{PO}_3)^a$	$\Delta(\mathrm{PO}_2)^b$	$\Delta(D_2O)^c$	
La	9	8 - 38	-110	
Ce	69	67 - 100	95	
Pr	160	159 - 219	205	
Nd	201	193 - 264	490	
Sm	-15	-16 - 5	20	
Eu	d	d	-710	
Dy	d	d	-2870	
Yb	d	d	190	

<sup>a</sup> PO<sub>3</sub>: nonbridging oxygens at  $P_{\alpha}$  and  $P_{\gamma}$ . <sup>b</sup> PO<sub>2</sub>: nonbridging oxygens at  $P_{\beta}$ . Upper and lower limits are given as the PO<sub>2</sub> signal is hidden under the large PO<sub>3</sub> signal. <sup>c</sup>Calculated as  $(55.3/0.35) \times$  slope of LnIS(D<sub>2</sub>O) vs.  $\rho$ . <sup>d</sup> Not observed owing to slow exchange.

Na<sub>5</sub>P<sub>3</sub>O<sub>10</sub>·6H<sub>2</sub>O in D<sub>2</sub>O as external standard, respectively, and <sup>6</sup>Li chemical shifts with respect to 5 M LiCl in D<sub>2</sub>O as external standard. Downfield induced shifts are denoted as positive.

Relaxation rates were measured after bubbling nitrogen gas through the sample for 10 min. The longitudinal relaxation rates were determined using a  $[(90^{\circ}_{x}180^{\circ}_{y}90^{\circ}_{x})-\tau-(12^{\circ})-acq]$  inversion recovery pulse sequence. The  $1/T_1$  values were calculated using a three-parameter fit of the experimental data.<sup>17</sup> The  $1/T_2$  values were calculated from the linewidths at half-height by way of the relation  $1/T_2 = \pi \Delta \nu_{1/2}$ . Materials. Water (20% <sup>17</sup>O-enriched) was obtained from Rohstoff-

Einfuhr Düsseldorf, and the LnCl<sub>3</sub>·6H<sub>2</sub>O salts were from Alfa Products. STP (purity >99%) was obtained by repetitive precipitation from 33% aqueous ethanol<sup>18</sup> of commercial STP (Alfa Products), which contained about 15% diphosphate.

<sup>17</sup>O-Enriched Pentasodium Triphosphate.<sup>18,19</sup> Water (5% <sup>17</sup>O-enriched, 13.9 mL, 0.772 mol) was added cautiously to PCl<sub>5</sub> (22.8 g, 0.110 mol) at 0 °C in the course of 30 min. The mixture was then kept under vacuo at 40 °C to remove HCl, yielding 16.4 g of a mixture of H<sub>3</sub>PO<sub>4</sub> and  $H_2O$ . This mixture was brought to pH 5.3 with a concentrated NaOH solution and heated at 550 °C for 5 h in a porcelain dish. After the reaction mixture was cooled, an equal amount of pure nonlabeled STP was added and the resulting mixture was purified as described above to give 11.3 g 2.2% <sup>17</sup>O-enriched pentasodium triphosphate (as the hexahydrate) (23.7 mmol, yield 11%): <sup>31</sup>P NMR (80.99 MHz, D<sub>2</sub>O, 25 °C)  $\delta$  0.0 (d, J = 18.8 Hz), -14.44 (t, J = 18.8 Hz); <sup>17</sup>O NMR (27.13 MHz,  $D_2O$ , 94 °C)  $\delta$  124 (broad m), 107.8 (d, J = 80 Hz), 100.2 (partially overlapping with the signal at  $\delta$  107.8).

### **Results and Discussion**

Ln(III)-Induced <sup>17</sup>O Shifts. Previously, we have observed that Dy(III) gives rise to an induced shift per bound oxygen, which is rather independent of the nature of the oxygen.<sup>14</sup> Therefore Dy(III)-induced <sup>17</sup>O shifts are useful to determine the coordinating oxygens of a ligand. Unfortunately, upon addition of DyCl<sub>3</sub> to a solution of STP in D<sub>2</sub>O at 73 °C, no shift of the TP <sup>17</sup>O signals was observed. The intensities of the <sup>17</sup>O signals, however, were reduced proportionally to the amount of Dy(III) added. Apparently, the TP ligand exchange is slow on the NMR time scale. The signals of the Dy(III) complex could not be observed, probably as the result of extensive line broadening. The decrease of the intensity of the <sup>17</sup>O signals of the free ligand as a function of the molar ratio of added Dy(III)/total TP ( $\rho$ ) confirmed the formation of a 1:2 Dy(III)-TP complex.<sup>16</sup> The behavior of the water-<sup>17</sup>O signal showed that the  $D_2O$  ligand exchange is fast with respect to the NMR time scale.

In order to obtain information on the coordination of TP, we attempted to use another Dy(III) shift reagent, NaDy(edta). This should give rise to a mixed ligand complex, [Dy(edta)(TP)]<sup>6-</sup>, with a lower stability constant than  $Dy(TP)_2^{7-20}$  This might result in a shorter residence time of the TP ligand in the complex. Although a faster exchange of the TP ligand was indeed observed, line broadening still did not allow any conclusions on the TP coordination. Therefore, we screened some of the other Ln(III) cations as shift reagent for <sup>17</sup>O. It appeared that the lighter

Table II. F and G Values of  $Ln(TP)_2(D_2O)_x$  Calculated<sup>a</sup> from <sup>17</sup>O-Bound Shifts at 73 °C

signal	PO <sub>3</sub>	PO <sub>2</sub>	D <sub>2</sub> O
F	$-39.7 \pm 0.3$	$-43 \pm 12$	$-74 \pm 7$
G	$-3.1 \pm 0.1$	$-5 \pm 4$	$+8 \pm 2$
no. of Ln(III)	4 <sup>b</sup>	4 <sup>b</sup>	8

<sup>a</sup> Using the data of Table I. <sup>b</sup> La, Ce, Pr, and Nd.

Ln(III) cations (La(III), Ce(III), Pr(III), Nd(III), and Sm(III)) gave rise to fast TP ligand exchange with respect to the NMR time scale. This may be ascribed to both the generally observed higher ligand exchange rate in complexes of the lighter Ln(III) cations,<sup>21,22</sup> and the smaller shifts induced by these cations (vide infra). The bound shifts of the  $Ln(TP)_2(D_2O)_x$  complexes, derived from the slopes of the straight lines in plots of the LnIS vs.  $\rho$ , are summarized in Table I.

The experimental bound shifts can be corrected for any contributions caused by conformational changes, inductive effects, and direct field effects by substracting the bound shifts of the corresponding diamagnetic La(III) or Lu(III) complexes. The resulting paramagnetic shift ( $\Delta$ ) is a combination of contact (through-bonds) shift and pseudocontact (through-space) shift, and can be expressed by the equation:

$$\Delta = \Delta_{\rm c} + \Delta_{\rm p} = F \langle S_z \rangle + G C^{\rm D} \tag{1}$$

Here the first term of the right-hand side represents the contact shift as the product of a ligand-dependent parameter F and a Ln(III)-dependent parameter  $\langle S_z \rangle$ , and the second term represents the pseudocontact shift as the product of a Ln(III)-dependent parameter  $C^{D}$  and a term G dependent upon the geometry of the ligand:

$$G = K_1 \frac{(3 \cos^2 \theta - 1)}{r^3} + K_2 \frac{(\sin^2 \theta \cos 2 \phi)}{r^3}$$
(2)

Here r,  $\theta$ , and  $\phi$  are the spherical coordinates of the observed nucleus with respect to Ln(III) at the origin and with the principal magnetic axis of the system as z axis.  $K_1$  and  $K_2$  are dependent upon crystal-field parameters and temperature.<sup>23-26</sup> Rapid random reorientations of the ligand may cause vanishing of the pseudocontact shift.

Previously we observed that Dy(III)-induced <sup>17</sup>O shifts of various relative weakly complexing ligands are predominantly of contact origin.<sup>14</sup> The induced shifts per bound oxygen were all in a rather small range. For TP, because of the required fast exchange, we had to rely on Ln(III) ions other than Dy(III). Since the assumptions made in the studies with Dy(III) might not be valid here, a separation of contact and pseudocontact shift was performed. The data of Table I were fit to eq 1 with Reilley's nonlinear regression procedure,<sup>27</sup> using literature values of  $\langle S_z \rangle^{28}$ and  $C^{D,29}$  The resulting F and G values are given in Table II.

From the F values in  $Ln(H_2O)_{9}^{3+}$ , given by Reilley,<sup>27</sup> it can be calculated that the contribution to F per bound oxygen is -70 $\pm 11.^{30}$  The F value of the PO<sub>3</sub> group is an average of six oxygens, of which the contributions of the noncoordinating oxygens to the contact shift presumably can be neglected.<sup>31</sup> Therefore, the

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Figure 1. Examples of <sup>31</sup>P NMR spectra of Ln(TP)<sub>2</sub> complexes, illustrating fast and slow exchange on the <sup>31</sup>P NMR time scale (25 °C;  $\rho = 0.25$ ): (a) Ce(III) fast exchange:  $\delta 9.7$  (P<sub>a,\gamma</sub>), -3.7 (P<sub>b</sub>). (b) Eu(III) fast exchange for P<sub>b</sub>,  $\delta - 13.9$ ; slow exchange for P<sub>a,\gamma</sub>,  $\delta 0.0$  (free ligand), -48.3 (complex). (c) Yb(III) slow exchange:  $\delta 0.0$  (P<sub>a,\gamma</sub>, free ligand), -14.4 (P<sub>b</sub>, free ligand), -52.6 (P<sub>b</sub>, complex), -58.6 (P<sub>a,\gamma</sub>, complex).

Table III. Observed  ${}^{31}P$ -Bound Shifts (ppm) in Ln(TP)<sub>2</sub>(D<sub>2</sub>O) at 25 °C

Ln	$\Delta P(\alpha, \gamma)$	exchange <sup>a</sup>	$\Delta P(\beta)$	exchange <sup>a</sup>
La	-0.7	fast	+1.9	fast
Ce	+19.5	fast	+21.4	fast
Pr	+26.1	slow	+12.8	fast
Nd	+21.0	slow	+1.9	fast
$\mathrm{Sm}^{b}$	+3.2	intermediate	+9.1	intermediate
Eu	-48.3	slow	+0.9	fast
$Gd^c$			-52.2	intermediate
Tb	+125.8	slow	+394.2	slow
Dy	+142.6	slow	+252.6	slow
Ho	+40.9	slow	+122.7	slow
Er	-134.8	slow	-118.2	slow
Tm	-194.1	slow	-213.2	slow
Yb	-58.6	slow	-38.2	slow
Lu	-0.6	fast	+2.6	slow

<sup>a</sup>Slow: separate signals for free and complexed TP observed; fast: averaged signals observed. <sup>b</sup>Calculated from experiments at 80 °C (fast exchange). <sup>c</sup>Calculated from experiments at 90 °C (fast exchange).

number of bound oxygens of the two PO<sub>3</sub> groups in TP is  $(6 \times -39.7/-70) = 3.4 \pm 0.5$ .

Analogously, the number of coordinated PO<sub>2</sub> oxygens and D<sub>2</sub>O ligands can be calculated to be  $1.2 \pm 0.5$  and  $1.1 \pm 0.2$ , respectively. Assuming a coordination number of 9 for the Ln(III) ion, it can be concluded that the stoichiometry of the Ln(III)-TP complex is Ln(TP)<sub>2</sub>(D<sub>2</sub>O), with one of the PO<sub>2</sub> oxygens and three of the PO<sub>3</sub> oxygens of each TP ligand coordinated.

As the signal of the P-O-P oxygens was very broad, accurate LnIS values for these nuclei could not be determined. It was clear, however, that the LnIS did not exceed 10 ppm. This supports the assumption that the contact shift in noncoordinated oxygens can be neglected.

Ln(III)-Induced <sup>31</sup>P Shifts. The shape of the observed <sup>31</sup>P NMR spectra of the Ln(III)-doped samples appeared to be dependent upon the Ln(III) ion (as a consequence of the ionic radius and the induced shift), the concentration, and the temperature; both fast and slow exchange with respect to the <sup>31</sup>P NMR time scale were observed (see Figure 1).

In contrast to  ${}^{17}O$  NMR, here in the cases with slow ligand exchange the signals for the complexed ligand could be observed. Once more, integrals in the slow exchange spectra confirmed the

Table IV. F and G Values of  $Ln(TP)_2(D_2O)$  Calculated<sup>a</sup> from <sup>31</sup>P Bound Shifts at 25 °C.

signal	$P_{\alpha,\gamma}$	P <sub>β</sub>	
F	$-3.7 \pm 0.3$	$-1.4 \pm 0.5$	
G	$-2.6 \pm 0.1$	$-3.1 \pm 0.2$	
no. of Ln(III)	13	13	
			-

<sup>a</sup> Using the data of Table III, excluding Tb for  $P_{\beta}$ , because of its negative influence on the goodness of fit.

Table V. Values of  $1/T_{1,exp}$ ,  $1/T_{2,exp}$ , and Residence Times at 25 °C.

		$1/T_{1,exp}$ (s <sup>-1</sup> )		$1/T_{2,exp}$		T
Ln(III)	ρ	Ρ <sub>α,γ</sub>	P <sub>β</sub>	$P_{\alpha,\gamma}$	P <sub>β</sub>	$(10^{-3} s)$
	0	0.150	0.217			
La	0.309	0.37	0.56			
Nd	0.373	12.20	10.83			
Eu	0.108	0.71	0.75	1525		0.66
Gd	0.0009	7.81	7.94			>0.23
Tm	0.131	43.67	56.82	824	838	1.2
Yb	0.119	5.38	7.46	550	518	1.9

<sup>a</sup>Calculated from  $1/T_{2,exp} = 1/T_{2,compl} + 1/\tau_{compl}$  with  $1/T_{2,compl} = 1/T_{1,compl}$ .

1:2 stoichiometry of the Ln–TP complex, as should be expected considering the high association constants<sup>16</sup> and low  $\rho$  values used ( $\rho < 0.3$ ). The bound shifts were evaluated from plots of the LnIS vs.  $\rho$  in the case of fast exchange or directly from the shift difference between free and complexed species in the case of slow exchange (Table III).

A separation between contact and pseudocontact shifts as described above afforded the F and G values given in Table IV. It may be noted that no break in F and G values was observed between the lighter (La-Gd) and heavier (Tb-Lu) lanthanides.

The contact shifts appear to be very small in comparison with those observed for  ${}^{17}O$  (see Table II). Since the sign of these shifts is the same, a spin delocalization pathway, possibly in combination with a spin polarization pathway, is involved in the electron spin transmission through the TP ligand.

The Ln(III) coordination derived from <sup>17</sup>O NMR implies equal Ln(III)-P distances. The magnitudes of the G values of the two different P nuclei are about the same. Inspection of molecular models shows that this can be explained by a position of the (pseudo) magnetic axis which is about perpendicular to the plane through the Ln(III) ion and the P atoms, when it is assumed that in eq 2 the second term on the right-hand side can be neglected as a result of axial symmetry or averaging due to ligand reorientations.<sup>32,33</sup>

Ln(III)-Induced Relaxation Rate Enhancements. Ln(III)-induced longitudinal  $(1/T_1)$  and transversal  $(1/T_2)$  relaxation rate enhancements may afford information on both the residence time of the entities involved in the complexation and the distances between the nuclei under consideration and the Ln(III) ion.

<sup>31</sup>P LnIRE values were determined for a selection of Ln(III) ions (see Table V). In those cases where separate signals were observed for free and complexed ligand (see Table III), the LnIRE values for both signals appeared to be identical. The magnetization recovery curve after the inverting nonselective 180° pulse was always single exponential within the experimental accuracy. Application of a selective (soft) 180° pulse<sup>34-37</sup> on either the signals for the free ligand or those for the complex gave analogous results: the magnetization transfer between free and complexed nuclei is fast on the experimental time scale. It can be concluded that the relaxation is in the fast exchange region as defined by

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**Table VI.** Ln(III)-P Distances (Å) as Calculated from  $1/T_{1 \text{ compl}}$ 

Ln	$Ln-P_{\alpha,\gamma}$	Ln-P <sub>β</sub>	
Nd	$3.44 \pm 0.05$	$3.52 \pm 0.05$	
Eu	$3.06 \pm 0.08$	$3.13 \pm 0.08$	
Tm	$3.59 \pm 0.08$	3.43 ± 0.05	
Yb	$3.57 \pm 0.05$	$3.38 \pm 0.05$	

McLaughlin and Leigh.<sup>38,39</sup> This phenomenon does not often occur when separate signals are observed for the exchanging entities. According to McLaughlin and Leigh, and taking into account the high association constants of the 1:2 complexes, in the fast exchange region the following approximation is valid<sup>39</sup> for both the free ligand and the complex:

$$1/T_{1,exp} = 2\rho/T_{1,compl} + (1 - 2\rho)/T_{1,fl}$$
(3)

Here  $1/T_{1,exp}$  is the experimental longitudinal relaxation rate,  $1/T_{1,\text{compl}}$  is the relaxation rate of the Ln(TP)<sub>2</sub> complex, and  $1/T_{1,\text{fl}}$  is the relaxation rate of the free ligand.<sup>40</sup>

In the fast exchance region (with separate signals for complex and free ligand), the transversal relaxation rates of TP in the free and the complexed state can be evaluated with eq 4 and 5, respectively:39

free ligand: 
$$1/T_{2,exp} = 1/T_{2,fl} + 1/\tau_{fl}$$
 (4)

complex: 
$$1/T_{2,exp} = 1/T_{2,compl} + 1/\tau_{compl}$$
 (5)

Here  $\tau_{\rm fl}$  and  $\tau_{\rm compl}$  are the residence times of the TP ligand in the free and the complexed state, respectively. From eq 3 and 5, and assuming that  $1/T_{2,compl} = 1/T_{1,compl}^{42}$  the values of  $\tau_{compl}$  for the Eu(III), Tm(III), and Yb(III) complexes were calculated (see Table V). The magnitudes of  $\tau_{compl}$  obtained were in good agreement with the rough estimate of  $\tau_{compl}$  for Lu(TP)<sub>2</sub> from coalescence ( $\tau_{compl} = 3 \times 10^{-3}$  s). The magnitudes of  $\tau_{compl}$  also agree with the generally observed trend of increasing lifetimes upon decreasing Ln(III) ionic radius.<sup>21,22</sup> Therefore, the  $\tau_{compl}$ values show that the condition for the use of the fast exchange approximation for  $1/T_1$  (eq 3) is fulfilled.<sup>39</sup>

Gd(III) is often the Ln(III) ion of choice in relaxation rate enhancement studies because of its isotropic g tensor. Moreover, the enhancements induced by Gd(III) are much larger than those by the other Ln(III) ions, because of its much larger electron relaxation time.<sup>43</sup> Therefore, the measurements with Gd(III) were performed at low  $\rho$  values ( $\rho < 10^{-3}$ ). Under this condition eq 6 can be used to obtain  $1/T_{1,compl}^{38}$ 

$$1/T_{1,exp} = 2\rho/(T_{1,compl} + \tau_{compl}) + 1/T_{1,fl}$$
(6)

The values of  $1/T_{1,exp}$  for the Gd(III) system are of the same order of magnitude as the  $1/\tau_{\rm compl}$  values obtained so far. Although in this case an accurate value of  $T_{1,compl}$  cannot be evaluated from these relaxation rates from  $1/T_{1,exp}$  and eq 6, it can be concluded that  $\tau_{compl} > 0.23 \times 10^{-3}$  s.

The  $1/T_{1,compl}$  values for the other paramagnetic Ln(III) ions were corrected for any diamagnetic contributions by using the  $1/T_{1,\text{compl}}$  value of La(TP)<sub>2</sub> to give  $1/T'_{1,\text{compl}}$ . The ratio of  $1/T'_{1,\text{compl}}$  $T'_{1,\text{compl}}$  for  $P_{\alpha,\gamma}$  and  $P_{\beta}$  appears to be rather independent of the Ln(III) ion used, showing that the interaction with the Ln(III) ion gives rise to isotropic relaxation behavior.<sup>42</sup> Assuming that the contact contribution to the LnIRE is negligible,<sup>42</sup>  $1/T'_{1,compl}$ can be related to the distances between the Ln(III) ion and the



Figure 2. Relation between  $1/\tau_{compl}$  and  $\rho$  in the Yb(III)-TP system.

P nucleus under consideration with the reduced Solomon-Bloembergen equation:42,43

$$1/T'_{1,\text{compl}} = 4/3(\mu_0/4\pi)^2(\mu^2\gamma^2\beta^2T_{1e}/r^6)$$
(7)

Here  $\mu_0/4\pi$  is the magnetic permeability under vacuum,  $\mu$  is the magnetic moment,  $\gamma$  is the magnetogyric ratio,  $\beta$  is the Bohr magneton, and  $T_{1e}$  is the electron spin relaxation time. The latter parameter is shown to be rather independent of the ligation of the Ln(III) cation.<sup>44-46</sup> Using the  $T_{1e}$  values for the Ln(III)-aquo cations given by Alsaadi et al.,<sup>44</sup> from  $1/T'_{1,compl}$  and eq 7, the Ln(III)-P distances were calculated (Table VI). The distances obtained point to a structure of  $Ln(TP)_2(D_2O)$  in which the two  $PO_3$  groups and the  $PO_2$  moiety are coordinated with the Ln(III) cation. Any substantial contribution of structures in which only two of the phosphate moieties of TP are coordinated can be excluded. The structural picture thus obtained is analogous to that proposed for the Ln-ATP complex by Williams et al.9

Triphosphate Ligand Exchange Mechanism. The TP exchange mechanism has been studied in some detail for the Yb(III)-TP system. Several equilibria (eq 8-11) have been considered. In these equilibria  $D_2O$  and the monovalent counterions are not taken into account.

$$Yb^{3+} + TP^{5-} \underbrace{\frac{k_1}{k_{1-}}} Yb(TP)^{2-}$$
(8)

$$Yb(TP)^{2^{-}} + TP^{5^{-}} \frac{k_2}{k_{2^{-}}} Yb(TP)_2^{7^{-}}$$
 (9)

$$Yb(TP)_{2}^{7-} + TP^{5-} \frac{k_{3}}{k_{3-}} Yb(TP)_{3}^{12-}$$
 (10)

$$Yb(TP)_{2}^{7-} + Yb(TP)^{2-} \xrightarrow{k_{4}} (TP)Yb(TP)Yb(TP)^{9-} (11)$$

In eq 10 a 1:3 Yb-TP complex is involved. Since the coordination number of Yb(III) usually does not exceed 9 or 10, the coordination of TP in this complex will differ from that in  $Yb(TP)_2^{7-}$ .

Equilibrium 11 is a self-association mechanism, in which a binuclear complex is involved. Self-association is a commonly observed phenomenon in Ln complexation.<sup>13</sup> Equations 12 and

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<sup>(40)</sup> From measurements of  $1/T_1$  of the <sup>1</sup>H nuclei in the internal standard *teri*-butyl alcohol, the contribution to the relaxation of intermolecular inter-actions was shown to be negligible.<sup>41</sup>

<sup>(41)</sup> J. A. Peters, H. van Bekkum, and W. M. M. J. Bovee, Tetrahedron, 38, 331 (1982).

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<sup>(44)</sup> B. M. Alsaadi, F. J. C. Rossotti, and R. J. P. Williams, J. Chem. Soc., Dalton Trans., 2147 (1980). (45) B. M. Alsaadi, F. J. C. Rossotti, and R. J. P. Williams, J. Chem. Soc.,

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13 for the residence times  $\tau_{\rm fl}$  and  $\tau_{\rm compl}$  can be derived from eq 8-11.

$$1/\tau_{\rm fl} = k_1 [\rm Yb^{3+}] + k_2 [\rm Yb(TP)^{2-}] + k_3 [\rm Yb(TP)_2^{7-}]$$
(12)

$$1/\tau_{\rm compl} = k_{2-} + k_3[\rm TP^{5-}] + k_4[\rm Yb(\rm TP)^{2-}]$$
(13)

From eq 12 it follows that  $1/\tau_{\rm fl}$ , and concurrently the line width of the free ligand signals, should increase upon increase of  $\rho$ . This was indeed observed. The line width of the complex signals, on the other hand, appeared to decrease upon increase of  $\rho$  (see Figure 2). Since  $k_3$ [TP<sup>5-</sup>] is the only term in eq 13 that decreases at higher  $\rho$  values, equilibrium 10 will play an important role in the exchange mechanism.

Fitting of the experimental  $1/\tau_{compl}$  values to eq 13 with neglect of  $k_4[Yb(TP)^{2-}]$  gives  $k_2 = 120 \text{ s}^{-1}$  and  $k_3 = 780 \text{ }1 \cdot \text{mol}^{-1} \cdot \text{s}^{-1}$ . Inclusion of  $k_4[Yb(TP)^{2-}]$  into the fitting procedure gives only a slight improvement of the fit, which was rather insensitive for the value of  $k_4$ . Anyhow, it is clear that both associative (eq 10 and/or 11) and dissociative (eq 9) mechanisms are operative in the TP ligand exchange.

Monovalent Counterions. As stated before, the highly charged Ln-TP complexes have a strong affinity for cations. This has led to the application of these systems as shift reagents for monovalent cations.<sup>2</sup> Up to the maximum  $\rho$  values used in the present study ( $\rho \leq 0.25$ ), a linear relation between the LnIS and  $\rho$  was observed for <sup>23</sup>Na. A bound <sup>23</sup>Na shift of 61.3 ppm in the Na<sub>7</sub>Tm- $(TP)_2(D_2O)$  complex, which is expected to be almost completely dipolar in origin, was calculated from extrapolation of the TmIS to  $\rho = 0.5$ . This rather high value compared with the bound <sup>31</sup>P shifts (see Table III) suggests that the Na(I) counterions in the  $Na_7Tm(TP)_2(D_2O)$  complex prefer distinct positions. If this would not be the case, Na(I) would experience all possible pseudocontact shifts equally, resulting in an average shift of about zero.<sup>47</sup> Using our previous assumptions about the position of the magnetic axis and the applicability of the (pseudo)axial form of eq 2, the sign of the induced shift implies that the Na(I) cations have a preference for sites with  $-54.7^{\circ} < \theta < +54.7^{\circ}$ , in the proximity of the negatively charged oxygens coordinated to the Ln(III) ion.

In order to obtain an estimate of the distance between Na(I)and Tm(III), an attempt was made to measure the TmIRE of <sup>23</sup>Na. Unfortunately, the relaxation rate in a 0.35 M aqueous solution of STP was already too high to allow any TmIRE measurement. Therefore, an equivalent amount of LiCl (up to 1.75 M) was added and <sup>6</sup>Li NMR was applied for the relaxation rate measurements. The <sup>6</sup>Li nucleus has a quadrupolar moment which is smaller by a factor of  $\sim 100$  than that for <sup>23</sup>Na. Consequently, smaller relaxation rates for the undoped samples are to be expected. The addition of LiCl resulted in 37% reduction of the TmIS for <sup>23</sup>Na. The TmIS for <sup>6</sup>Li was about equal to the reduction of the TmIS for <sup>23</sup>Na, and, therefore, it may be concluded that 37% of Na(I) coordinated to  $Tm(TP)_2^{7-}$  is replaced by Li(I). From the observed TmIRE for <sup>6</sup>Li at  $\rho = 0.25$ ,<sup>48</sup> the longitudinal relaxation rate in the complex  $M_7 Tm(TP)_2$  (M = Li and Na) was calculated to be  $1.25 \text{ s}^{-1}$ . From this, with the use of eq 3 and 7, a mean Tm-Li distance of 5.8 Å was calculated. This suggests that the seven monovalent cations are in the second coordination sphere of the Tm(III)-(TP) system. If the number of monovalent cations in the second coordination sphere were lower, the calculation would result in a smaller Tm-Li distance, which seems less likely.



Figure 3. Structure of the  $Ln(TP)_2^{7-}$  system.

It may be noted that a structure analogous to the binuclear complex  $NaLn(TP)_2^{6-}$  suggested by Chu et al.,<sup>2</sup> in which the monovalent cation is very close to Ln(III), would give rise to a much larger TmIRE than was observed.

#### Conclusions

The <sup>31</sup>P NMR data reveal that the 1:2 Ln–TP complexes are isostructural. Both <sup>31</sup>P and <sup>17</sup>O NMR shows that the two PO<sub>3</sub> groups and the PO<sub>2</sub> moiety of TP are all coordinated to the Ln(III) cation. The Ln(III)-induced <sup>17</sup>O shifts indicate that the PO<sub>2</sub> and one of the PO<sub>3</sub> groups are coordinated in a monodentate fashion, while the other PO<sub>3</sub> group is coordinated in a bidentate fashion. The experimental data demonstrate that the two PO<sub>3</sub> groups show a rapid interconversion as to their coordination. One D<sub>2</sub>O ligand is also present in the first coordination sphere leading to a coordination number of 9 for Ln(III). The <sup>23</sup>Na and <sup>6</sup>Li NMR data indicate that the negative charge of the Ln(TP)<sub>2</sub><sup>7–</sup> complex is neutralized by seven monovalent cations in the second coordination sphere of the Ln(III) cation. These cations show some preference for positions in the proximity of Ln-coordinated oxygen atoms that carry the negative charge. The resulting structure of the Ln(TP)<sub>2</sub><sup>7–</sup> system is depicted in Figure 3.

The present study demonstrates that slow exchange phenomena sometimes may hamper the use of LnIS measurements on  $^{17}O$  and of LnIRE measurements. Since the exchange rate usually is dependent upon the Ln(III) cation, these problems can be overcome by a proper choice of the shift reagent and/or by the study of mixed ligand systems.

Further work on triphosphate monoesters of organic hydroxy compounds is in progress.

Acknowledgment. Thanks are due to The Netherlands Foundation for Advancement of Pure Research (ZWO) for financial support, to Dr. A. H. E. F. Ebaid for preliminary experiments, and to Drs. W. M. M. J. Bovée and M. van Duin for helpful discussions.

**Registry** No. La(TP)<sub>2</sub>(H<sub>2</sub>O), 93453-51-1; Ce(TP)<sub>2</sub>(H<sub>2</sub>O), 93453-52-2; Pr(TP)<sub>2</sub>(H<sub>2</sub>O), 93453-53-3; Nd(TP)<sub>2</sub>(H<sub>2</sub>O), 93453-54-4; Sm(TP)<sub>2</sub>(H<sub>3</sub>-O), 93453-55-5; Eu(TP)<sub>2</sub>(H<sub>2</sub>O), 93453-56-6; Gd(TP)<sub>2</sub>(H<sub>2</sub>O), 93453-57-7; Tb(TP)<sub>2</sub>(H<sub>2</sub>O), 93453-58-8; Dy(TP)<sub>2</sub>(H<sub>2</sub>O), 93453-59-9; Ho(T-P)<sub>2</sub>(H<sub>2</sub>O), 93453-60-2; Er(TP)<sub>2</sub>(H<sub>2</sub>O), 93453-61-3; Tm(TP)<sub>2</sub>(H<sub>2</sub>O), 93453-62-4; Yb(TP)<sub>2</sub>(H<sub>2</sub>O), 93453-63-5; Lu(TP)<sub>2</sub>(H<sub>2</sub>O), 93453-64-6; <sup>17</sup>O, 13968-48-4.

<sup>(47)</sup> Cf. C. C. Bryden, C. N. Reilley, and J. F. Desreux, Anal. Chem., 53, 1418 (1981).

<sup>(48)</sup> The  $1/T_1$  values for <sup>6</sup>Li measured were: 5 M LiCl, 0.0011 s<sup>-1</sup>; 0.35 M STP, 1.75 M LiCl + Tm(III) at  $\rho = 0.25, 0.83 \text{ s}^{-1}; 0.35 \text{ M STP}, 1.75 \text{ M}$  LiCl + La(III) at  $\rho = 0.15, 0.019 \text{ s}^{-1}$ .