Complexation Properties of Ethylenediaminetetramethylenephosphonic Acid (EDTMP) with Al^{III} and $V^{IV}O$

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Keywords: Aluminum / Aminophosphonates / Bioinorganic chemistry / Speciation / Vanadium

The complexation properties (including stoichiometries and stability constants of the complexes formed) of ethylenediaminetetramethylenephosphonic acid with Al^{III} and $V^{IV}O$ were studied in aqueous solution at an ionic strength of 0.2 M KCl, at 25 °C by means of pH potentiometry. For Al^{III} both mononuclear ($AlLH_n$) and dinuclear (Al_2LH_n) species were found in solution, whereas for $V^{IV}O$ only mononuclear complexes were detected. For each metal ion, a solid complex was isolated at acidic pH and was characterized stoichiometrically. ^1H and ^{31}P NMR (for Al^{III}), UV/Vis and EPR (for $V^{IV}O$) spectra were used to confirm the potentiometric results and to suggest the most probable binding mode of the complexes formed in solution.

Introduction

Al^{III} is a toxic metal ion for living organisms. In many cases, the biological mechanism of its toxicity is well documented and includes enzyme inhibition, nucleotide destruction and mineral formation.[1] These effects are the results of a complicated chain of reactions involving the relatively unexplored chemical interactions of the metal ion with the relevant biomolecules.

Vanadium is a trace element and is beneficial for living organisms. Its most important oxidation states are +4 and +5, and some vanadium compounds have promising insulin-mimetic properties both in vitro and in vivo.[2,3] As for aluminium, the molecular action of vanadium is still not well known.

The complexation properties of ethylenediaminetetramethylenephosphonic acid (EDTMP, Figure 1) with metal ions allow its use as a valuable model for an understanding of their interactions with more complicated biomolecules containing the same amino and phosphonate moieties. EDTMP complexes with a number of metal ions have been studied;[4−13] almost exclusively divalent metal ions were considered: Mg^{II}, Ca^{II}, Sr^{II}, Ba^{II}, Mn^{II}, Fe^{II}, Co^{II}, Ni^{II}, Zn^{II}, Cd^{II}, Cu^{II} and Pb^{II}. In a few cases, trivalent cations were also studied (e.g. Sm^{III} and Ho^{III} by Jarvis et al.[11]) because of the use of EDTMP−lanthanide complexes as therapeutic radiopharmaceuticals. Fe^{III}−EDTMP complexes have been investigated by Westerback et al.,[7] Motekaitis et al.[9] and Oakes et al.,[14] but only in a qualitative way, with no reports of any definite data. In a recent paper, Popov et al.[15] reported a critical evaluation of the proton- and metal-complexation stability constants to be found in the literature up to 2000 for various aminophosphonic acids.

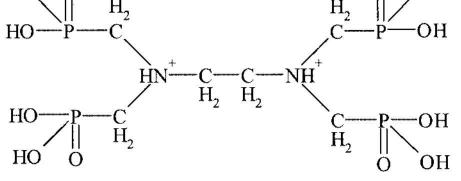

Figure 1. EDTMP in its fully protonated form ($H_{10}L^{2+}$)

In the present paper, Al^{III}−EDTMP and $V^{IV}O$−EDTMP interactions were examined by means of pH-potentiometric titrations and independent spectroscopic techniques.

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DOI: 10.1002/ejic.200300693

Results and Discussion

Acidity Constants of EDTMP

In principle EDTMP is a decaprotic acid (see Figure 1). Ichikawa et al. proposed the following deprotonation sequence for the fully protonated cation $H_{10}L^{2+}$: seven phosphonic protons, the first ammonium proton, the eighth phosphonic proton and the second ammonium proton.[16] Table 1 summarizes the pK_a values obtained from our potentiometric titrations. The pK_a for the species H_nL refer to the equilibrium $H_nL^{n-8} \rightleftarrows H_{n-1}L^{n-9} + H^+$. Under the experimental conditions used in our study, six of the possible ten proton dissociations could be detected. The first three pK_a values could not be measured in water because they are too low, while the last pK_a could not be measured because it is too high.[15]

Table 1. Acidity constants (pK_a ± 3 standard deviations) for EDTMP at 25 °C and $I = 0.2$ M KCl

Species	pK_a
H_7L^-	(1.16 ± 0.12)
H_6L^{2-}	2.80 ± 0.05
H_5L^{3-}	5.00 ± 0.03
H_4L^{4-}	6.24 ± 0.02
H_3L^{5-}	7.72 ± 0.02
H_2L^{6-}	9.64 ± 0.02
No. of points:	345
Fitting parameter:[a]	7.38×10^{-3}

[a] Goodness of the fit between the experimental and the calculated titration curves expressed in mL of the titrant.

Our results are in reasonable agreement with most of the data obtained in previous studies, as listed in Table 2. The only important difference was that in all the previous papers a pK_a value for HL^{7-} was also given, even if sometimes with very high uncertainty. The recent IUPAC critical compilation[15] suggests a provisional value for this protonation process, pK(HL) = 13.8 (see Table 2). We attempted to refine our data in light of these results, but it was not possible to obtain a reliable value for this very high pK_a. To achieve this, the ligand should be applied in a high concentration at pC = pK_w − pK_a + 0.5.[20] However, in this case the ionic strength could not be kept constant in the sample during the titration, and thus the pK_a value could be determined only with a rather high uncertainty. It is likely that an insufficient ligand concentration was the reason for our previous reporting of a pK_a value of 12.04.[17] Accordingly, we disregarded this last proton-dissociation process and considered HL^{7-} as the complex-forming species in the formation equilibrium $p\text{M} + q\text{HL} + r\text{H} \rightleftarrows \text{M}_p\text{L}_q\text{H}_{r+q}$. In this way, more accurate formation constants could be obtained, although their numerical values differed by the value of the last pK_a from those calculated in the usual way for the equilibrium $p\ \text{M} + q\ \text{L} + r\ \text{H} \rightleftarrows \text{M}_p\text{L}_q\text{H}_r$.

Al^{III} Complexes

The stability constants for the Al^{III}−EDTMP complexes, determined by potentiometric titration, are listed in Table 3.

Table 3. Stability constants (log β ± 3 standard deviations) for the Al^{III}−EDTMP complexes at 25 °C and $I = 0.2$ M KCl [the constants are calculated for the equilibrium: $p\ \text{M} + q\ \text{HL} + r\ \text{H} \rightleftarrows \text{M}_p\text{L}_q\text{H}_{r+q}$ (see text)]

Species	p	q	r	log β
$[Al_2LH_3]^+$	2	1	2	36.01 ± 0.08
$[Al_2LH_2]$	2	1	1	32.61 ± 0.09
$[Al_2LH]^-$	2	1	0	28.85 ± 0.07
$[AlLH]^{4-}$	1	1	0	17.21 ± 0.04
$[AlL]^{5-}$	1	1	−1	10.95 ± 0.03
$[AlLH_{-1}]^{6-}$	1	1	−2	0.40 ± 0.08
No. of points:				731
Fitting parameter:[a]				1.11×10^{-2}

[a] Goodness of the fit between the experimental and the calculated titration curves expressed in mL of the titrant.

A typical distribution diagram of the various metal−ligand species as a function of pH is shown in Fig-

Table 2. Acidity constants (pK_a) of EDTMP reported in the literature (if not specified, data are at 25 °C)

Conditions	H_8L	H_7L^-	H_6L^{2-}	H_5L^{3-}	H_4L^{4-}	H_3L^{5-}	H_2L^{6-}	HL^{7-}	Ref.
KCl (0.2 M)	−	(1.16)	2.80	5.00	6.24	7.72	9.64	−	this work
KCl (0.2 M)	−	1.34	2.75	5.00	6.28	7.80	9.70	12.04	[17]
KNO_3 (0.1 M)	2.43	2.73	3.80	5.63	7.39	9.27	10.48	10.60	[4]
KNO_3 (0.1 M)	−	(1.37)	3.15	5.26	6.57	8.13	10.01	(13.14)	[9]
KNO_3 (0.1 M)	−	1.33	3.02	5.17	6.42	7.94	9.78	12.99	[10]
KNO_3 (0.1 M)	−	−	2.96	5.12	6.40	7.87	9.85	13.0	[16]
K^+ (0.1 M)	−	1.3	3.00	5.12	6.40	7.90	9.82	13.8[a]	[15]
(I = 0.1 M)	1.46	2.72	5.05	6.18	6.63	7.43	9.22	10.95	[7]
KNO_3 (3 M)	−	1.24	2.98	4.86	6.05	7.60	9.36	12.36	[9]
KNO_3 (3 M)	−	1.24	2.82	4.77	5.88	7.42	9.02	12.01	[10]
NaCl (0.15 M, 37 °C)	−	1.24	2.83	5.08	6.31	7.63	9.47	10.67	[11]
NaCl (3 M)	−	2.03	3.79	5.32	6.65	8.22	10.51	14.0	[18]
−	−	−	3.00	5.23	6.54	8.08	10.18	12.10	[19]

[a] I = 3.5 M (Me_4N^+).

ure 2. The accepted speciation model includes both mononuclear and dinuclear complexes, which predominated in the different pH ranges. In the pH range 11−7, only mononuclear species exist in solution: $[Al(OH)_4]^-$, $[AlLH_{-1}]^{6-}$, $[AlL]^{5-}$ and $[AlLH]^{4-}$. The most important Al^{III} complex is $[AlL]^{5-}$. It was initially expected that, at pH values lower than 6.5, other mononuclear species are formed. However, the best speciation model obtained with the assumption of mononuclear species only — $[AlLH_5]$, $[AlLH_4]^-$, $[AlLH_3]^{2-}$, $[AlLH_2]^{3-}$, $[AlLH]^{4-}$, $[AlL]^{5-}$ and $[AlLH_{-1}]^{6-}$ — had to be rejected because the fitting parameter was more than 70% poorer than the one reported in Table 3, obtained with the assumption of parallel-formed dinuclear complexes. The species detected at a pH below 6.5 are probably the dinuclear complexes $[Al_2LH]^-$, $[Al_2LH_2]$ and $[Al_2LH_3]^+$, although other oligonuclear complexes cannot be excluded. Although usually only mononuclear metal−EDTMP complexes have been detected so far,[4−13] it is noteworthy that dinuclear species have been recently reported for the Fe^{III}−EDTMP system.[16] The high affinity of Al^{III} towards phosphonic acid groups and the electrostatic repulsion between the negatively charged phosphonate arms of the ligand may explain the formation of some dinuclear complexes.[15]

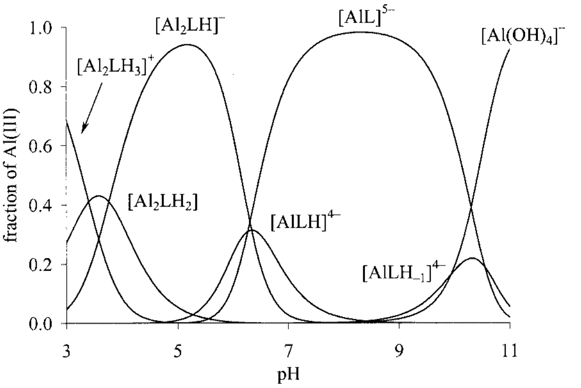

Figure 2. Distribution diagram (mol fraction of Al^{III} as a function of pH) for the Al^{III}−EDTMP system; $c_{Al^{III}} = c_{EDTMP} = 0.001$ M

It is known that Al^{III} readily forms dihydroxo-bridged dinuclear species. Accordingly, it would be reasonable to assume the formation of a complex $[Al_2L_2]^{10-}$ {or more precisely $[Al_2(HL)_2(OH)_2]^{10-}$} in which one of the amino groups is in a protonated form and two OH^- groups link the Al(HL) units together. However, when this species was assumed instead of the mononuclear complex $[AlL]^{5-}$ the fit was poorer by about 30%; when both species were included in the speciation model and were refined simultaneously, the dinuclear species was always rejected by the computer program. Furthermore, the ^1H and ^{31}P NMR results (at the pH value where $[AlL]^{5-}$ forms, vide infra) do not seem to support formation of the dinuclear species, either.

As mentioned in the Exp. Sect., the back-titrations (from the basic to the acidic pH range) had to be stopped at pH ≈ 3 because a solid compound precipitated (the species distribution diagram shown in Figure 2 is limited to this pH value). The elemental and ICP analyses of this solid compound gave the stoichiometry $Al_{1.00}C_{5.86}N_{2.04}$, which is in close agreement with the theoretic AlC_6N_2 stoichiometry of a 1:1 aluminium/ligand compound. The only neutral 1:1 species is $[AlLH_5]$. Therefore, this should be the stoichiometry of the compound that precipitates. The hydrogen content (vide infra) is in agreement with this formula, assuming between four and five coordinated water molecules, which are necessary to fill the hexacoordination sphere of the metal ion. The 1:1 stoichiometry of the solid suggests that mononuclear species actually exist in solution at acidic pH values, together with dinuclear species, which are formed, however, in negligible concentrations. In particular, $[AlLH_5]$ could not be detected during the potentiometric titrations due to its low solubility, which was found experimentally to be below 5×10^{-4} M. In the solid state Al^{III} forms poorly soluble, often layered, chain-polyphosphates[21] which may occur also in acidic solutions at higher Al^{III} concentrations.[15] The dinuclear species $[Al_2LH_x]$ (x = 1, 2, 3) assumed in this paper may be the precursors of these polyphosphates. The solid complex precipitated and characterised by the composition $[AlLH_5]$ is probably a mononuclear species, which exists at such low Al^{III} concentrations, although an oligonuclear structure cannot be fully excluded, either.

The ^1H and ^{31}P NMR spectra of the ligand alone are shown in Figure 3. Due to its symmetry, the free ligand has only two proton signals (a singlet and a doublet, assigned to the NCH_2 and PCH_2 moieties, respectively) and only one phosphorus signal. Signals of a small amount of P-containing impurities can be observed in the NMR spectra (see Exp. Sect.). It has been reported in the literature that the chemical shifts of these signals vary with the pH in a quite irregular manner[6,16] due to the parallel deprotonations and because these may be accompanied by the formation or disruption of intramolecular hydrogen bonding. Our measurements verified this reported pH dependence (data not shown here).

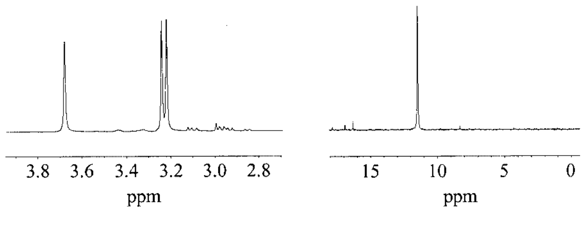

Figure 3. ^1H (left) and proton-decoupled ^{31}P (right) NMR spectra of an aqueous EDTMP solution at pH = 8.38; $c_{EDTMP} = 0.0249$ M

Selected ^1H and ^{31}P NMR spectra of solutions containing both Al^{III} and the ligand in a 0.8:1 ratio are shown in Figure 4. The speciation curves at this higher concentration are shown in Figure 5. At pH = 12.1 only the signals of the free ligand (denoted "lig.") are present, in agreement with the potentiometric data, which confirms negligible metal−ligand complexation at this pH value. Although complex formation between Al^{III} and phosphonates is very strong [displacement of the last dissociable proton of the ligand ($pK_a \approx 13.8$) and coordination of this donor group starts at $pH \approx 6$], the affinity of Al^{III} to form the tetrahydroxo species $[Al(OH)_4]^-$ is even higher, and at $pH > 12$ the ligand is completely displaced by OH^- ions. At lower pH values (10.8, 8.3 and 6.3) new signals of the Al^{III}−EDTMP complexes appear in the spectra. For example, at pH = 8.3 two phosphorus signals (denoted "P" and "Q") and six groups of proton signals (denoted "A", …, "F") can be seen. The couplings in the ^1H NMR spectrum at pH = 8.3 were assessed by means of a COSY spectrum (Figure 1 in the Supporting Information; see footnote on the first page of this article): "A" couples with "E", "B" with "F" and "C" with "D". There are also weak couplings between "A" and "B" and between "B" and "C". Accordingly, signals "A" and "E" can be assigned to the methylene protons of the NCH_2CH_2N moiety: they are the simplest signals because they are those of the only protons which cannot couple with ^{31}P. Only the homonuclear coupling splits the signal, resulting in a "doublet-like structure" (AB quadruplet). The rest of the signals of different multiplicity should belong to the methylene protons of the four $CH_2PO_3^{2-}$ arms. Other assignments are less obvious and therefore have not been made. However, the spectra obtained are in agreement with the proposed structure of the complex $[AlL]^{5-}$, shown in Figure 6, which, according to the potentiometric data, is the most important aluminium species in the pH range 10.5−6.5. In this species, the fully deprotonated ligand chelates the metal ion in a hexadentate fashion. A similar hexadentate coordination mode was assumed for the carboxylate analogue EDTA in its $[AlL]^-$ complex.[22,24] This structure is rather rigid, accounting for the narrow peaks in the NMR spectra obtained, and has a C_2 symmetry axis so that the phosphorus atoms and the protons are equivalent in a pairwise manner. The $CH_2PO_3^{2-}$ arms bound to the same N atom are not equivalent; for this reason two ^{31}P signals of equal intensity are observed. A slight distortion of the structure may account for some asymmetry observed, especially in the ^1H NMR spectrum. The other assumption that only one N is involved in the coordination (the ligand is in the HL form) and an OH^- ion saturates the coordination sphere of each metal ion in a dinuclear dihydroxo-bridged species $[Al_2(HL)_2(OH)_2]^{10-}$ (vide supra) is not compatible with the relatively simple ^{31}P and complicated ^1H NMR spectra. In the case of a rigid dimer, at least three different P resonances should occur in the spectra: (i) the P atoms of the two $CH_2PO_3^{2-}$ arms at the coordinating side of the molecule, (ii) the coordinated P of the partially bound side of the molecule, and (iii) the P of the non-coordinating $CH_2PO_3^{2-}$ arm of this side. On the other hand, in the case of a flexible dimer the methylene protons in the N-attached phosphonate arms should become equivalent resulting in the appearance of a high-intensity doublet in the ^1H NMR spectra, which is not observed, instead rather complicated spectra are obtained (see Figure 4). It is noteworthy that identical structures for ML-type EDTMP complexes with other trivalent metal ions, such as Fe^{III}, Sm^{III} and Ho^{III}, were suggested by Westerback et al.[7] and by Motekaitis et al.,[10] and partly confirmed by Jarvis et al.[11]

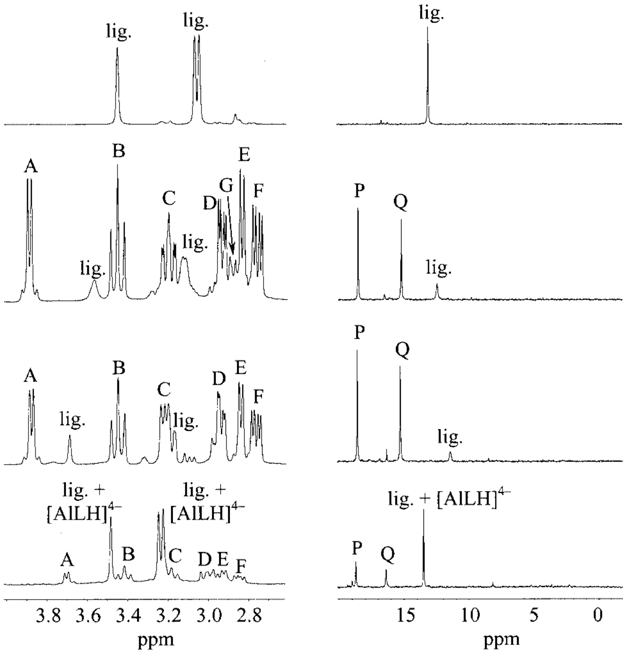

Figure 4. ^1H (left) and proton-decoupled ^{31}P (right) NMR spectra of solutions containing 0.020 M Al^{III} and 0.0252 M EDTMP; pH = 12.06, 10.81, 8.31 and 6.34 (from top to bottom)

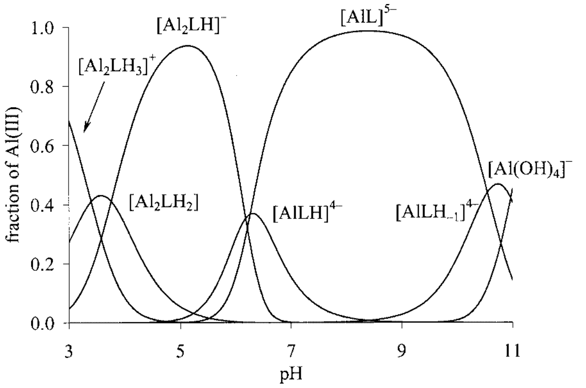

Figure 5. Distribution diagram (mol fraction of Al^{III} as a function of pH) for the Al^{III}−EDTMP system; $c_{Al^{III}} = 0.020$ M, $c_{EDTMP} = 0.025$ M

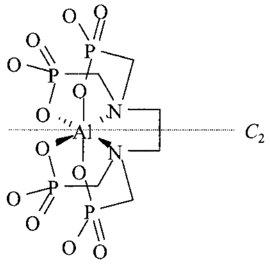

Figure 6. Proposed structure of $[AlL]^{5-}$; the symmetry axis is shown

The spectra at pH = 10.81, where the species $[AlL]^{5-}$ and $[AlLH_{-1}]^{6-}$ should coexist in solution, are very similar to those at pH = 8.31: the phosphorus signals are only slightly shifted, whereas in the ^{1}H NMR spectrum only a change in the shape of signals "C" and the appearance of a new signal, "G", can be observed. These suggest that $[AlLH_{-1}]^{6-}$ should have a similar structure to that of $[AlL]^{5-}$, apart from the fact that at least one coordinating site of the metal atom is no longer coordinated by the ligand, but by an OH^- ligand; in addition, it is suggested that the coordinated ligand arms rapidly exchange with the free ligand arm, so that the general symmetry of the complex is maintained and only a small shift of the signals can be observed. This binding mode is in accordance with the rather low value of the deprotonation constant of the species $[AlL]^{5-}$ ($pK_{AlL} = 10.55$).

In contrast, in the spectra at pH = 6.34, where the species $[AlL]^{5-}$ and $[AlLH]^{4-}$ coexist, the sharp signals of $[AlL]^{5-}$ tend to vanish without apparently being replaced by other well-separated metal−ligand peaks. To explain this finding, we may assume that EDTMP no longer chelates to the metal atom in a hexadentate way in $[AlLH]^{4-}$, as one of the amino groups is now protonated. Al^{III} coordinates mostly to the phosphonate functions, and the intramolecular exchange rate of the coordinated or free phosphonate moieties is high, as was found in previous studies for other Al^{III}−phosphonato complexes.[23,24] Due to this fast internal motion in the complex, no different ^{31}P or ^{1}H signals of the free and Al^{III}-bound phosphonate arms are observed, but the signals are merged and slightly shifted with pH. An amino group as the first protonated function has been reported for the Al^{III} complexes of other hexadentate aminophosphonates and aminocarboxylates.[22,24]

The pK_a calculated from the data in Table 3 for the deprotonation of $[AlLH]^{4-}$ to produce $[AlL]^{5-}$ is 6.26, significantly lower than the pK_a of the free ligand with the same number of protons, HL ($pK_a \approx 13$; see Table 2). This considerable decrease in the pK_a of the HL^{7-} proton due to the coordination of Al^{III} indicates the high stability of the hexadentate coordinated complex $[AlL]^{5-}$.

As seen in Figures 2 and 5, dinuclear complexes are formed at pH < 6. The NMR spectra of the equimolar Al^{III}−EDTMP solutions at acidic pH (not shown) are dominated by the signals of the free ligand, due to the low extent of formation of the dinuclear complexes under these conditions. In order to observe the signals of the Al^{III}-bound ligands, samples with an excess of metal ion were prepared and measured by NMR spectroscopy. These spectra are shown in Figure 7. At pH = 6.1, four new signals (denoted "R", "S", "T" and "U") could be observed at δ = 2−5 ppm in the ^{31}P NMR spectrum. The ^{1}H NMR spectrum is also significantly different from those obtained at higher pH values. The peaks are not well resolved, and only four signals (denoted "I", "J", "K" and "L") can be clearly distinguished in the chemical shift range δ = 3.6−4.1 ppm. From the integration values, it is evident that each of the signals "I", "J", "K" and "L" is due to a single proton of the Al^{III}-bound ligand. A new proton signal is observed at δ ≈ 10 ppm, which may belong to the amino or phosphonic protons. This low-field signal could not be detected in any of the other spectra, either in the absence or in the presence of Al^{III}. According to the speciation data (see Figure 5), the species $[Al_2LH]^-$ is the dominating complex at pH = 6.1. The NMR spectra suggest that $[Al_2LH]^-$ should be a rigid compound, and the four P and the two Al atoms must be chemically inequivalent. In Figure 8, a hypothetical structure is shown for $[Al_2LH]^-$. In this species two phosphonate arms behave as bridging moieties. Only one of the two amino-N atoms is coordinated, and the other may be involved in hydrogen bonding to a water molecule in the coordination sphere of the Al^{III} atom. This binding mode explains the appearance of the extra peak at δ ≈ 10 ppm, which belongs to the N-bound proton. Surprisingly, this amino (or phosphonic) proton does not undergo fast exchange with the bulk water protons on the NMR timescale. The slow kinetics of these processes is also suggested by the fairly long pH-equilibration time observed during the potentiometric titrations (see Exp. Sect.). Another possible explanation of this NMR feature is that besides the dinuclear complex, other oligonuclear complexes are formed at the higher concentrations used for the NMR measurements.

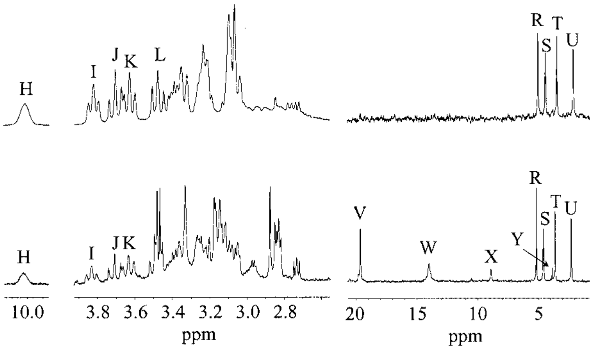

Figure 7. Top: ^{1}H (left) and proton-decoupled ^{31}P (right) NMR spectra of a solution containing 0.0471 M Al^{III} and 0.0251 M EDTMP at pH = 6.1; bottom: ^{1}H (left) and proton-decoupled ^{31}P (right) NMR spectra of a solution containing 0.0415 M Al^{III} and 0.0225 M EDTMP at pH = 3.9

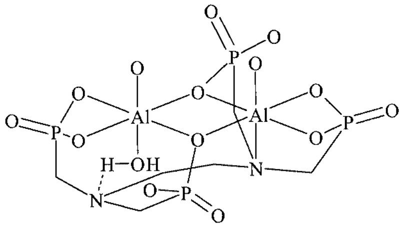

Figure 8. Proposed binding modes for $[Al_2LH]^-$

The NMR spectra measured at pH = 3.9 for the sample with an excess of Al^{III} are in agreement with the potentiometric data, predicting the presence of protonated dinuclear species $[Al_2LH]^-$ and $[Al_2LH_2]$. In the ^{31}P NMR spectrum (Figure 7), four new phosphorus signals appear ("V", "W", "X" and "Y") in addition to those ("R", "S", "T" and "U") belonging to the species $[Al_2LH]^-$. The assignation of these new signals is rather ambiguous, and they may belong to various binding isomers and/or to distinct species of different stoichiometry or protonation state. In the ^{1}H NMR spectrum the pattern is more complicated, but new signals can again be seen in the range $\delta = 3.7-2.8$ ppm, together with those also detected at pH = 6.1. These new signals are attributed to the neutral complex [Al_2LH_2], which is probably not a single dinuclear species but a mixture of various (neutral) oligonuclear complexes (substituted by the single species [Al_2LH_2] in the potentiometric speciation calculation). This may explain the rather complicated ^{1}H and ^{31}P NMR features of the Al^{III}−ligand system observed at this pH value (see Figure 7). Again, the proton signal at $\delta \approx 10$ ppm is observed, although with lower intensity than before. This allows us to assign this signal exclusively to the complex [Al_2LH]$^-$. Both [Al_2LH]$^-$ and [Al_2LH_2] (or other oligonuclear species) are asymmetric molecules (Figure 8), in accordance with their NMR behaviour.

$V^{IV}O$ Complexes

The stability constants for the $V^{IV}O$−EDTMP complexes, determined by potentiometric titration, are listed in Table 4.

Table 4. Stability constants (log β ± 3 standard deviations) for the $V^{IV}O$−EDTMP complexes at 25 °C and $I = 0.2$ M KCl (the constants are calculated for the equilibrium: $p\,M + q\,HL + r\,H \rightleftarrows M_pL_qH_{r+q}$)

Species	p	q	r	log β
[$VOLH_4$]$^{2-}$	1	1	3	29.72 ± 0.08
[$VOLH_3$]$^{3-}$	1	1	2	26.70 ± 0.07
[$VOLH_2$]$^{4-}$	1	1	1	22.85 ± 0.07
[$VOLH$]$^{5-}$	1	1	0	16.29 ± 0.06
[VOL]$^{6-}$	1	1	−1	8.63 ± 0.06
[$VOLH_{-1}$]$^{7-}$	1	1	−2	−2.07 ± 0.09
No of points:				305
Fitting parameter:[a]				-1.03×10^{-2}

[a] Goodness of the fit between the experimental and the calculated titration curves expressed in mL of the titrant.

A typical speciation diagram of the complexes as a function of pH is shown in Figure 9. The speciation model accepted for the $V^{IV}O$−EDTMP system includes only mononuclear complexes. A slight improvement in the fitting was obtained when alternative speciation was considered for the experimental data: the fitting parameter was about 5% lower when the species [$(VO)_2L_2H_{-2}$]$^{14-}$ was assumed instead of [$VOLH_{-1}$]$^{7-}$ in the speciation model. However, we chose the model reported in Table 4 in view of the EPR results (vide infra).

The EPR and UV/Vis spectroscopic data for the $V^{IV}O$−EDTMP system at different pH values, together with the most probable equatorial donor atom arrangements around the metal ion, are reported in Table 5. No EPR parameters for species formed in the acidic pH range could be determined because of the low intensity of the spectra (due to precipitation).

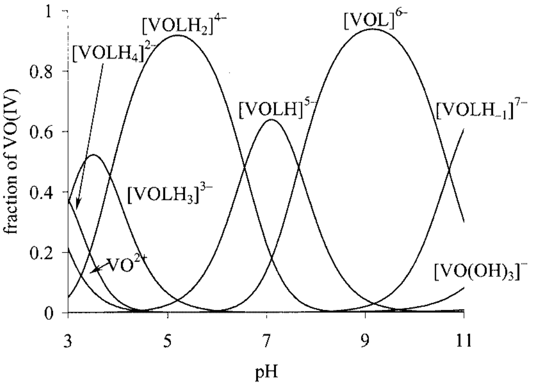

Figure 9. Distribution diagram (mol fraction of $V^{IV}O$ as a function of pH) for the $V^{IV}O$−EDTMP system; $c_{V^{IV}O} = c_{EDTMP} = 0.001$ M

As regards the EPR spectra, at pH = 12 a single species with $g_{\|} = 1.942$ and $A_{\|} = 166.4 \times 10^{-4}$ cm^{-1} is observed. Since these parameters are different than those of [$VO(OH)_3$]$^-$ ($g_{\|} = 1.957$ and $A_{\|} = 161.4 \times 10^{-4}$ cm^{-1}), this peak is attributed to [$VOLH_{-1}$]$^{7-}$. When this $A_{\|}$ value is compared with the estimated values obtained from the Chasteen additivity rule[25] it may correspond to either a species with two N [$A_{\|}^{est}$(N, N, PO_3^{2-}, PO_3^{2-}) = 165.2 or $A_{\|}^{est}$(N, N, PO_3^{2-}, OH^-) = 161.4] or with one N [$A_{\|}^{est}$(N, PO_3^{2-}, PO_3^{2-}, PO_3^{2-}) = 167.6 or $A_{\|}^{est}$(N, PO_3^{2-}, PO_3^{2-}, OH^-) = 163.8] in the equatorial plane. The metal ion must also be coordinated to an OH^- moiety, probably in the axial position, so this species should be [$VOL(OH)$]$^{7-}$, with a binding mode (N, N, PO_3^{2-}, PO_3^{2-})$_{eq}$(OH^-)$_{ax}$. The alternative dihydroxo-bridged, and thus EPR-silent, dimeric species [$(VO)_2L_2H_{-2}$]$^{14-}$ assumed from the pH-metric measurements in place of the mononuclear species [$VOLH_{-1}$]$^{7-}$ (vide supra) was rejected as no decrease in intensity of the EPR signal was observed in the formation pH range (pH > 10) of this species. At pH ≈ 9, where the potentiometric data indicates the predominant formation of [VOL]$^{6-}$, a single EPR signal could be detected, with parameters $g_{\|} = 1.936$ and $A_{\|} = 172.1 \times 10^{-4}$ cm^{-1}. The corresponding species is likely to have only one amino group in the equatorial plane of the metal centre (the other N may occupy the axial position or may be in the protonated non-coordinating form), because the half-field splitting constant is closer to the estimated value ($A_{\|}^{est} = 167.6 \times 10^{-4}$ cm^{-1}), and very similar to the half-field splitting constants of the analogous complexes of other aminooligophosphonic acids with the same binding mode.[26] The potentiometric data suggest that three species should coexist in the pH range 8.4−5.7: [VOL]$^{6-}$, [$VOLH$]$^{5-}$ and [$VOLH_2$]$^{4-}$. The EPR and potentiometric results correspond to one another. Namely, the stepwise protonation of species [$VOLH_{-1}$]$^{7-}$ → [VOL]$^{6-}$ → [$VOLH$]$^{5-}$ → [$VOLH_2$]$^{4-}$ should involve the axial OH^- group, one of the amino groups and one PO_3^{2-} group. These reactions may proceed in a parallel, overlapping way. What seems to be certain, though, is that only one N atom is in the equatorial plane. Under these conditions, [VOL]$^{6-}$, [$VOLH$]$^{5-}$ and [$VOLH_2$]$^{4-}$ have practically the

Table 5. Spectral (EPR and UV/Vis) data and the most probable binding set of the $V^{IV}O-EDTMP$ complexes

Complex	$g_{\parallel}$	$10^4 \times A_{\parallel}$ (^{51}V) [cm^{-1}]	Equatorial donor set	λ_{max} [nm]
$VOLH_4^{2-}$	–	–	(PO_3^{2-}, 2 × HPO_3^-)	–
$VOLH_3^{3-}$	–	–	(2 × PO_3^{2-}, HPO_3^-)	–
$VOLH_2^{4-}$	1.936	172.1	(N, 2 × PO_3^{2-}, HPO_3^-)	860, 636
$VOLH^{5-}$	1.936	172.1	(N, 3 × PO_3^{2-})	864, 632
VOL^{6-}	1.936	172.1	(N, 3 × PO_3^{2-})	874, 642
$VOLH_{-1}^{7-}$	1.942	166.4	(2 × N, 2 × PO_3^{2-})[a]	878, 636

[a] See text.

same coordination geometry and donor sets in the equatorial plane, and therefore give the same EPR signals (see Table 5). At more acidic pH values the second nitrogen atom is also protonated and the EPR signals display the typical features of the exclusive coordination of phosphonate functions, as expected.

The main feature of the UV/Vis spectra is a blue-shift of the band at ca. 870 nm upon passing from $[VOLH_{-1}]^{7-}$ to $[VOLH_2]^{4-}$. This band may be attributed to the $d_{xy} \rightarrow d_{xz}$, d_{yz} transition.[27] Since the d_{xz} and d_{yz} orbitals are involved in π-bonds with the oxo ligand, the shift of the band indicates a stronger V=O ligand strength. This may be attributed to the structural and electronic rearrangements following the loss of the second nitrogen coordination and the stepwise protonations of the phosphonic arms.

As for Al^{III}, a solid compound was formed in the $V^{IV}O-EDTMP$ system at pH ≈ 3, and the pH-metric back-titrations had to be stopped at this point. The elemental and ICP analyses of the solid complex **2** gave the stoichiometry $(VO)_{1.80}C_{6.00}N_{2.14}$, (the average for the two solids isolated), which is between the theoretical 1:1 vanadium/ligand stoichiometry $[VOLH_6]$ and the 2:1 vanadium/ligand stoichiometry $[(VO)_2LH_4]$ (both are neutral). Therefore, it is reasonable to suggest that both these compounds may precipitate. The 2:1 stoichiometry of the solid appears a little surprising because no dinuclear species could be detected in solution. It may be supposed that $[(VO)_2LH_4]$ is an ionic compound formed by $[VO]^{2+}$ interacting with $[VOLH_4]^{2-}$.[28] However, the non-simple stoichiometry may more strongly suggest a chain-like oligomeric structure for the solid compound through simultaneous metal ion coordination to the (PO_3^{2-}, PO_3H^-) donor sets at both ends of the molecule, resulting in a similar stoichiometry $(VO)_n$-$[(VOLH_4)_n]$ (see Figure 10). The negatively charged chain oligomers $[VOLH_4]_n^{2n-}$ may be partially neutralized by H^+ instead of $[VO]^{2+}$, leading to an $H_{2n}[(VOLH_4)_n]$ stoichiometry. The empty apical coordination sites of the $V^{IV}O$ centres and the free coordination sites of the terminal $V^{IV}O$ ions may be occupied by water molecules. Accordingly, the water content is not strictly defined; it may be around three or four, or even more. These facts are probably responsible for the moderate agreement between the found and calculated elemental analysis data (see Exp. Sect.). The NIR spectrum of the solid compound as compared with that of the ligand alone displays broad, poorly resolved signals, with little information about the binding mode of the complex. The intensity decrease in the ν[P(O)−H] stretching frequency range indicates at least partial deprotonation of the phosphonic groups, which is in accordance with the coordination of $V^{IV}O$ to these functions. The vibration occurring at $\tilde{\nu}$ = 980 cm^{-1} confirms the presence of $V^{IV}O$ in the solid compound.

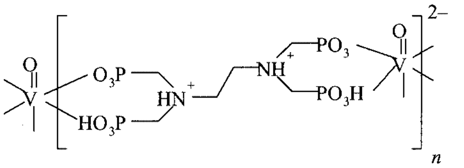

Figure 10. Schematic structure of the oligonuclear solid $V^{IV}O$ complex **2**

Conclusion

Potentiometric titrations of the $Al^{III}-EDTMP$ and $V^{IV}O-EDTMP$ systems revealed for both metal ions that even in equimolar solution the complexes formed are sufficiently stable to avoid the precipitation of $Al(OH)_3$ or $VO(OH)_2$ and the oxidation of $V^{IV}O$, respectively, in the neutral and basic pH range. In the predominant ML species formed in this pH range, the ligand seems to be coordinated to the metal ions through all six donors. In the more basic pH range, at pH > 10, mixed hydroxo species result, while in the acidic pH range partially protonated complexes are formed.

Besides these mononuclear 1:1 species, dinuclear complexes (and probably polynuclear species at higher concentrations) are also formed through the simultaneous coordination of metal ions at both ends of the ligand molecule. The solubilities of these complexes are different, due to the different charges of the metal ions. This may result in precipitation of the neutral complex $VO_n[VOLH_4]_n$ in the $V^{IV}O-EDTMP$ system and the mononuclear species $[AlLH_5]$ in the $Al^{III}-EDTMP$ system in the acidic pH range.

Experimental Section

Reagents: The ligand EDTMP was kindly provided by Monsanto,[29] and was used as received. The purity of the ligand was checked by potentiometry. The solid EDTMP sample was assessed to be 94.5% pure, the impurity being mainly neutral compounds and water.[30] The P-containing impurities were less than 2%, obtained from peak integration of the NMR spectrum. A stock solution of Al^{3+} was prepared from $AlCl_3{\cdot}6H_2O$ (Fluka); the metal-ion concentration was determined gravimetrically from its oxinate. The stock solution of VO^{2+} was prepared as described previously[31] and standardized for metal-ion concentration by cerimetric titration. To prevent hydrolysis, both metal-ion stock solutions contained ca. 0.1 M HCl. All other chemicals were Fluka (KHphthalate) or Reanal (HCl, KOH and KCl) products.

pH-Metric Measurements: The potentiometric titrations on 25-mL or 50-mL samples were performed in aqueous solution at 25 ± 0.1 °C under argon. The titrations were recorded with an Orion pH-meter equipped with a Metrohm 6.0234.100 combined glass electrode and a Metrohm Dosimat automatic burette. The electrode system was calibrated for hydrogen-ion concentration according to Irving et al.[32] The value obtained for pK_w was 13.764 ± 0.005. EDTMP was standardized by KOH titration in the concentration range from 0.002 to 0.004 M. The data were processed with the computer program SUPERQUAD,[33] which allowed determination of the exact concentrations of the ligand solutions, and calculation of the protonation constants. Precipitation was observed when either Al^{III} or $V^{IV}O$ was added to acidic solutions containing the ligand, in agreement with previous findings on Fe^{III}−EDTMP complexes.[9,14] Accordingly, for determination of the metal−ligand complex-formation constants, back-titrations had to be performed: the starting solutions containing the ligand, the metal ion and excess KOH were titrated with an HCl solution of known concentration. Back-titrations were started at $pH \approx 11$ and stopped when precipitation was observed (at pH = 2.5−3.5, depending on the composition of the samples). The volume of the titrant to reach the final pH value varied between 1.4 and 3.8 mL. Stable pH values were always reached within 1 min after addition of the titrant, except for the Al^{III} systems in the pH ranges 3.5−4 and 5.5−6, where the equilibration time was 5−6 min. Samples at different metal ion/ligand ratios were measured pH-potentiometrically. The composition of the samples varied between M/L ratios of 1:1 and 1:4, with Al^{III} concentrations ranging from 0.00080 M to 0.0036 M, and $V^{IV}O$ concentrations from 0.00052 M to 0.0020 M. Duplicate titrations were performed for both systems. For Al^{III}, titrations with excess metal ion were also planned in the pH range between 3 and 6. However, the precipitation of a solid compound (which seemed to be $AlLH_5$) could not be avoided, regardless of the procedure adopted for the addition of the metal-ion and the ligand solutions. Its dissolution at slightly acidic pH values is very slow (several hours), so that no accurate potentiometric titrations could be carried out under these conditions. The stability constants were calculated with the computer program PSEQUAD.[34] The following formation constants of the hydroxo complexes of Al^{III} and $V^{IV}O$ were taken from the literature, corrected to an ionic strength of 0.2 M by use of the Davies equation, and used during the data evaluation: $\log \beta(AlH_{-1}) = -5.41$, $\log \beta(AlH_{-2}) = -11.03$, $\log \beta(Al_3H_{-4}) = -13.09$, $\log \beta(Al_{13}H_{-32}) = -108.19$,[35] and $\log \beta(AlH_{-4}) = -23.44$;[36] $\log \beta[(VO)H_{-1}] = -5.94$, $\log \beta[(VO)_2H_{-2}] = -6.95$;[37] $\log \beta[(VO)H_{-3}] = -18.0$ and $\log \beta[(VO)_2H_{-5}] = -22.5$.[38]

NMR Experiments: ^1H and ^{31}P NMR spectra (the latter with ^1H decoupling) were recorded with a Bruker DMX 500 spectrometer at 298 K on solutions containing the ligand alone (0.025 M) and on solutions containing both the ligand and Al^{III}. Two metal/ligand ratios were explored: 0.8:1 and 1.9:1. Solutions were prepared in a 90:10 (v/v) mixture of H_2O and D_2O (Janssen, 98% D). The pH values were measured with a Metrohm glass electrode, previously calibrated in three buffer aqueous solutions (Sigma, pH = 4, 7 and 10, at 25 °C). The slight difference in composition of the solvents of the calibration and the sample solutions was ignored. A standard water pre-saturation technique was used to eliminate the intense water signal during the relaxation delay (2−3 s). The pH was adjusted by the addition of concentrated KOH and/or HCl solutions. In the samples containing an excess of metal ion, a small amount of solid was present (vide supra). NMR spectra were recorded on the supernatant.

EPR Experiments: Anisotropic X-band EPR spectra (9.15 GHz) were recorded at 120−140 K on aqueous solutions with a Varian E-9 spectrometer. As usual, a few drops of DMSO were added to the samples to ensure good glass formation in frozen solutions. Solutions containing 8×10^{-3} M EDTMP and 4×10^{-3} M $V^{IV}O$ at different pH values were analysed. The EPR spectra may be of further help in elucidating the binding modes of the complexes formed. For the $V^{IV}O$ systems, Chasteen[25] has introduced an additivity rule to estimate the hyperfine coupling constants $A_{\|}^{est}$ ($A_{\|}^{est} = \Sigma A_{\|i}$), based on the contributions $A_{\|i}$ of each of the four equatorial donor groups, its estimated uncertainty being $\pm 3 \times 10^{-4}$ cm^{-1}. The parameters $A_{\|i}$ of the individual coordinating groups were presented by Chasteen[25] and more recently by Smith et al.[39]

UV/Vis Experiments: Spectra were recorded with a Hewlett-Packard 8452 diode-array spectrometer. Solutions containing 2.4×10^{-2} M EDTMP and 2.4×10^{-2} M $V^{IV}O$ at different pH values were analysed in the wavelength range 300−900 nm.

Solid-State Preparation and Analysis

$Al(LH_5){\cdot}4H_2O$ (1): 10 mL of a 0.0316 M aqueous solution of the free acid H_6L (0.32 mmol) and 10 mL of 0.0320 M $AlCl_3$ (0.32 mmol) were mixed. The pH of the resulting solution was ca. 2. The sample was centrifuged and the supernatant was discarded. The white solid material was treated with 2 mL of 0.02 M HCl solution, stirred in an ultrasonic bath for about 30 min and left to stand overnight at room temperature. The same treatment was repeated three times, on the last occasion with the addition of 2 mL of water instead of HCl. Finally, the solid sample was lyophilized overnight and submitted to elemental analysis. The metal content was measured by ICP-AES. Yield: 130 mg (76%). $C_6H_{17}AlN_2O_{12}P_4{\cdot}4H_2O$ (532): calcd. C 13.53, H 4.70, Al 5.08, N 5.26; found C 13.33, H 4.70, Al 5.01, N 5.40.

$(VO)_x(LH_4)_y{\cdot}zH_2O$ (2): The complex was prepared in the same way as the Al^{III} complex, but the aqueous solution of the ligand EDTMP was mixed with 10 mL of a 0.0320 M $VOCl_2$ solution (0.32 mM). The solid obtained was a light-blue powder. Yield: 135 mg (78%). The best agreement with the experimental elemental analysis data was obtained with $x = 1.8$, $y = 1$ and $z = 4$. $C_6H_{16}N_2O_{12}P_4(VO)_{1.8}{\cdot}4H_2O$ (541): calcd. C 11.78, H 4.09, N 4.58, V 15.02; found C 12.13, H 4.16, N 4.98, V 15.2. This indicates that the solid is probably not a compound with well-defined stoichiometry, but a mixture of the mononuclear metal complex $[VOLH_6]$ and various oligonuclear $VO(L-VO)_n$-type species with an average stoichiometric ratio of VO/L = 1.8 (see Results and Discussion).

Acknowledgments

The work was supported by the bilateral cooperation scheme of the Hungarian Academy of Sciences and CNR of Italy (MTA I108) and by the National Scientific Research Fund (OTKA T31896 and

T37385). The authors thank Dr. D. Sanna (University of Sassari, Italy) for the preliminary EPR measurements, and Dr. G. Galbács and Mrs I. Varga for the elemental analyses of the compounds.

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Received October 1, 2003
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