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Holo- and Hemidirected Lead(II) in the Polymeric $[Pb_4(\mu\text{-3,4-TDTA})_2(H_2O)_2]\cdot 4H_2O$ Complex. *N,N,N′,N′*-Tetraacetate Ligands Derived from *o*-Phenylenediamines as Sequestering Agents for Lead(II)

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The coordinating ability of the ligands 3,4-toluenediamine-*N,N,N′,N′*-tetraacetate (3,4-TDTA), *o*-phenylenediamine-*N,N,N′,N′*-tetraacetate (*o*-PhDTA), and 4-chloro-1,2-phenylenediamine-*N,N,N′,N′*-tetraacetate (4-Cl-*o*-PhDTA) (H_4L acids) toward lead(II) is studied by potentiometry (25 °C, $I = 0.5$ mol dm^{-3} in $NaClO_4$), UV–vis spectrophotometry, and ^{207}Pb NMR spectrometry. The stability constants of the complex species formed were determined. X-ray diffraction structural analysis of the complex $[Pb_4(\mu\text{-3,4-TDTA})_4(H_2O)_2]\cdot 4H_2O$ **(1)** revealed that **1** has a 2-D structure. The layers are built up by the polymerization of centrosymmetric $[Pb_4L_2(H_2O)_2]$ tetranuclear units. The neutral layers have the aromatic rings of the ligands pointing to the periphery, whereas the metallic ions are located in the central part of the layers. In compound **1**, two types of six-coordinate lead(II) environments are produced. The Pb(1) is coordinated to two nitrogen atoms and four carboxylate oxygens from the ligand, whereas Pb(2) has an O_6 trigonally distorted octahedral surrounding. The lead(II) ion is surrounded by five carboxylate oxygens and a water molecule. The carboxylate oxygens belong to four different ligands that are also joined to four other Pb(1) ions. The selective uptake of lead(II) was analyzed by means of chemical speciation diagrams as well as the so-called conditional or effective formation constants K_{Pb}^{eff}. The results indicate that, in competition with other ligands that are strong complexing agents for lead(II), our ligands are better sequestering agents in acidic media.

Introduction

Lead is one of the seven basic metals that gave names to the seven days of the week (Saturday, from the Saturn planet).[1] Owing to its easy extraction from its ores upon heating, lead in the metallic form was already known by the old civilizations, and its toxic effects were indicated by Greeks, Romans, and Arabs. Due to the intensive use of leaden vessels (food was cooked, wine stored, and water piped) in the Roman Empire, the Romans suffered from lead toxicity, contributing to the empire's decline.[2−6]

Lead may enter the environment at any stage of mining, melting, and refining, in manufacturing processes, and during the use of lead-containing products. Atmospheric lead and lead in food are the two major routes of exposure for the

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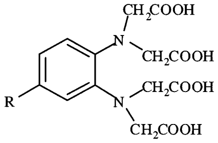
general population.[7,8] The only oxidation state important in biological systems is Pb(II).[9] The permitted free Pb(II) concentrations in body fluids are very low; therefore, any significant quantities of total Pb(II) must be complexed in some way.[6] Pb(II) binds preferentially to sulfydryl groups, acting as a soft acid, but also binds to phosphate groups in nucleic acids, acting as a hard acid, proteins, and cell membranes.[6,10−14] Lead accumulates in bone, where it replaces calcium, a typical hard acid, and the skeleton contains approximately 95% of the body burden of lead.[6,8,14] The toxicity of lead is aggravated by calcium deficiency.[5,6,15,16] Lead is harmful mainly through its neurotoxicological effects.[7,8] Pb(II) inhibits the synthesis of hemoglobin, causing anemia.[16−18] Lead interferes with the metabolism and action of essential metals such as Ca, Fe, and Zn.[5−8,19−22]

According to its electronic configuration, $[Xe]4f^{14}5d^{10}6s^2$, and size, Pb(II) exhibits the inert pair effect and variable coordination numbers and geometries. Its adaptive coordination sphere can explain its ability to interact in biological sites normally harboring smaller metal ions such as Ca(II) and Zn(II).[6,19−22] At these variable coordination numbers and coordination geometries the role of the lone pair of electrons has a great influence. Recently Simoni-Livny et al. have discussed the possible stereochemical activity of the lone pair in divalent lead compounds.[17] They classify lead complex coordination as *holodirected*, in which the bonds to ligand atoms are distributed throughout the surface of an encompassing globe, or *hemidirected*, in which the bonds to ligand atoms are directed throughout only part of an encompassing globe, leaving a void in the distribution of the bonds of the ligand. Pb(II) compounds are hemidirected for low coordination numbers (2−5) and holodirected for high coordination numbers (9−10), but for the intermediate coordination numbers (6−8), examples of either type of stereochemistry are found.[17]

To design sequestering agents capable of removing Pb(II) selectively from biological systems, it is important to consider the factors that affect the stereoactivity of the lone pair of electrons.[17,23] Lead(II) poisoning has been treated by the infusion of $[Ca(EDTA)]^{2-}$ solutions.[7] Moreover, chelates have been shown to enhance phytoextraction of Pb from contaminated soils, and EDTA has been used for these purposes.[24] However, we have found that the ligands 3,4-toluenediamine-*N*,*N*,*N*′,*N*′-tetraacetate (3,4-TDTA), *o*-phenylenediamine-*N*,*N*,*N*′,*N*′-tetraacetate (*o*-PhDTA), and 4-chloro-1,2-phenylenediamine-*N*,*N*,*N*′,*N*′-tetraacetate (4-Cl-*o*-PhDTA) (Chart 1) are good sequestering agents[25−28] for toxic Be(II),[25] essential Fe(III),[26] and toxic Cd(II).[27] In this context we present herein a study of these ligands with the toxic Pb(II) in the perspective of (i) their influence on the lone pair of electrons, leading to a holodirected or hemidirected geometry, and (ii) their ability as sequestering agents of Pb(II) over a wide pH range.

Chart 1



o-PhDTA: R = H
3,4-TDTA: R = CH_3
4-Cl-*o*-PhDTA : R = Cl

Experimental Section

Starting Materials. 3,4-TDTA, *o*-PhDTA, and 4-Cl-*o*-PhDTA were synthesized and their protonation constants determined as previously reported.[29,30] The solutions of $Pb(ClO_4)_2$ and $NaClO_4$ were prepared by dissolving the respective salts (Merck, analytical grade) in doubly distilled water. A carbonate-free sodium hydroxide solution was prepared from an ampoule of Titrisol (Merck) and standardized against potassium hydrogen phthalate. A solution of $HClO_4$ (0.5 mol dm^{-3}) was prepared by dissolving concentrated $HClO_4$ (70%, Merck) in doubly distilled water and standardized against the previously mentioned NaOH solution. Other chemicals were obtained from commercial sources and used without further purification.

Emf Measurements. The automatic titrations and the H^+ free ion concentration measurements were performed at 25 °C and $I = 0.5$ mol dm^{-3} in $NaClO_4$ as previously described.[26,27] The equilib-

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rium was considered to be reached when the variation in emf was less than 0.1 mV in 10 min. The treatment of emf (H^+) data was carried out by means of the HYPERQUAD[31a] and LETAGROP[32] programs. The stability constants of the complexes formed were determined by processing the emf obtained at the concentrations and pH ranges listed in Table S1 of the Supporting Information.

Multiwavelength Spectrophotometric Measurements. Spectrophotometric measurements were performed using a Shimadzu UV-2101PC spectrophotometer in the 220−350 nm range at the same conditions as those of the potentiometric measurements (T = 25 °C, $I = 0.5$ mol dm^{-3} in $NaClO_4$), by adding an aqueous solution of $Pb(ClO_4)_2$ (0.050 mol dm^{-3}) to an aqueous solution of the *o*-PhDTA ligand (initial concentration $C_L = 1.15\ 10^{-4}$ mol dm^{-3}). The concentration of Pb(II) was varied within the range from 0 to 3.42×10^{-4} mol dm^{-3}. A total of 28 measurements at M/L ratios ranging from 0 to 3/1 were performed. A solution of NaOH (0.1000 mol dm^{-3}) was used to keep the pH at 5.00(2). The data were analyzed by means of LETAGROP SPEFO.[33]

^{207}Pb NMR Measurements. ^{207}Pb NMR natural abundance spectra were recorded utilizing a Bruker AMX 500 instrument at the RIAIDT NMR service of the University of Santiago de Compostela in 10 mm o.d. Wilmad tubes, using a 10 mm VSP Bruker probe. pH adjustments were made with a Crison micro pH 2000 pHmeter. Experiments were carried out for the system 4-Cl-*o*-PhDTA/Pb(II) at a concentration of $Pb(ClO_4)_2$ of 1×10^{-2} mol dm^{-3} prepared from a stock solution of a mixture of $Pb(ClO_4)_2$ (5×10^{-2} mol dm^{-3}) and $NaClO_4$ (5×10^{-1} mol dm^{-3}); dilutions were made by adding the corresponding volume of the $NaClO_4$ solution and 5 mL of D_2O for internal lock, at the metal/ligand ratios 1/2, 1/1, and 1/0.5, and studied in the pH range 2−7. The experiments were performed by adding to 25 mL of the acceptor the weighted stoichiometric amounts of the ligand in the solid state. The required pH values were obtained, at 25 °C, by adding drops of a very concentrated solution of NaOH or $HClO_4$. When the reading stabilized, 3 mL of the solution was taken, transferred to a tube, immediately recorded at 298 K, and accumulated in a 995 ppm window, until peaks with a good signal/noise ratio were obtained. Between 1K and 60K scans were necessary. Chemical shifts are reported in parts per million from neat tetramethyllead using a saturated solution of $Pb(Ph)_4$ in $CDCl_3$ (−178 ppm) as external reference. The low solubility of the other ligands prevents similar experiments from being carried out.

Safety note: $Pb(Ph)_4$ is a very toxic reagent and must be handled with care in a well-ventilated hood!

Synthesis of the Complex $[Pb_4(\mu\text{-}3,4\text{-TDTA})_2(H_2O)_2]\cdot 4H_2O$ (1). $Pb(NO_3)_2$ (0.85 g, 2.6 mmol) dissolved in 10 mL of water was reacted with an aqueous solution (50 mL) of the monopotassium salt of the 3,4-TDTA acid (0.5 g, 1.27 mmol). The solution was stirred at room temperature for 30 min. A white precipitate was obtained (0.68 g, yield 64%), which was filtered, washed with water, and then dried with ethanol and diethyl ether. Colorless single crystals of **1** suitable for X-ray crystallography were grown by recrystallizing the white powder from hot water. Anal. Calcd for $C_{30}H_{40}N_4O_{22}Pb_4$: C, 22.0; H, 2.5; N, 3.4. Found: C, 21.82; H, 2.38; N, 3.35.

Table 1. Crystal Data and Structural Refinement Parameters $[Pb_4(\mu\text{-}3,4\text{-TDTA})_2(H_2O)_2]\cdot 4H_2O$

empirical formula	$C_{15}H_{20}N_2O_{11}Pb_2$	Z	2
fw	816.73	D_{calcd}/g·cm^{-3}	2.741
cryst syst	triclinic	μ(Mo Kα)/mm^{-1}	17.011
space group	$P\bar{1}$	temp/K	100(2)
radiation (λ/Å)	Mo Kα, graphite-monochromated (0.71073)	θ range/deg	1.65−29.99
a/Å	8.911(3)	no. of data collected	12301
b/Å	9.601(2)	no. of unique data [$I > 2\sigma(I)$]	5781
c/Å	13.052(2)	R1[a]	0.0319
α/deg	74.41(1)	wR2[a]	0.0803
β/deg	75.26(2)	GOF[b]	1.052
γ/deg	69.61(2)	no. of params refined	272
V/Å^3	992.1(4)		

[a] $R1 = \sum||F_o| - |F_c||/\sum|F_o|$, $wR2 = \{\sum[w(F_o^2 - F_c^2)^2]/\sum w(F_o^2)^2\}^{1/2}$. $w = 1/[\sigma^2(F_o)^2 + (0.0344P)^2 + 1.8955P]$; $P = (F_o^2 + 2F_c^2)/3$. [b] Goodness of fit.

X-ray Structure Analysis. The details of the structure analysis carried out on the lead compound are listed in Table 1. No absorption correction was performed. The structure was solved by direct methods (SHELX-86)[34] and refined with SHELX-97.[35] Refinement was made on F^2 for all reflections. The weighted R factor wR2 and goodness of fit S are based on F^2, and the conventional R factor R1 is based on F, with F set to zero for negative F^2. The threshold expression of $F^2 > 2\sigma(F^2)$ is used only for calculating R factors, etc., and is not relevant to the choice of reflections for refinement. R factors based on F^2 are statistically about twice as large as those based on F, and R factors based on all data are even larger. Reflections were weighted according to the formula $w = 1/[\sigma^2(F_o)^2+(0.0344P)^2 + 1.8955P]$, where $P = (F_o^2 + 2F_c^2)/3$. No extinction correction was applied. The positions of the hydrogen atoms were computed and refined with an overall isotropic temperature factor. The hydrogen atoms of the water molecules were not taken into account.

Results and Discussion

Crystal Structure of $[Pb_4(\mu\text{-}3,4\text{-TDTA})_2(H_2O)_2]\cdot 4H_2O$. The structure of compound **1** is built up by the infinite stacking of bidimensional networks (see Figure 1). The layers are made by the polymerization of centrosymmetric $[Pb_4L_2(H_2O)_2]$ tetranuclear units (see Figure 2). The neutral layers have the aromatic rings of the ligands pointing to the periphery, whereas the lead(II) ions are located in the central part of the structure.

In compound **1**, two types of six-coordinate lead(II) environments are produced (see Figure 2). The chelated Pb(1) is coordinated to two nitrogen atoms and four carboxylate oxygens from a 3,4-TDTA ligand. The Pb(1)−N bonds in **1** (see Table 2) are more similar in length [2.520(4) and 2.562(4) Å] to each other than those observed for the $[Pb(EDTA)]^{2-}$ complex (2.518 and 2.604 Å).[36] The Pb(1)−O bonds fall in the range of previously reported Pb−O interactions for the $[Pb(EDTA)]^{2-}$ complex [from 2.494 to 2.735

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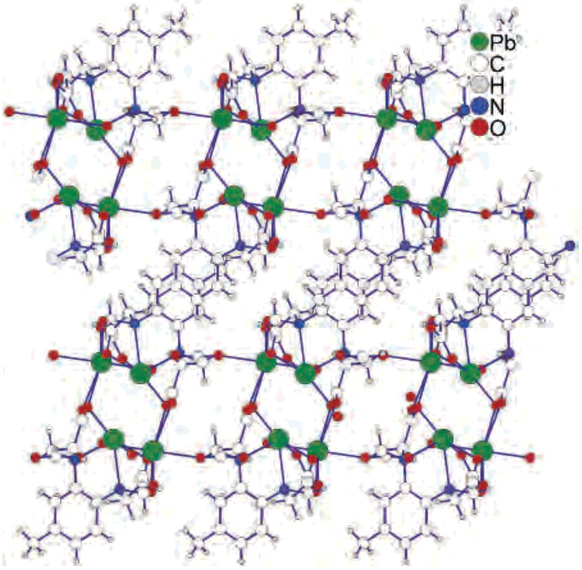

Figure 1. Structural diagram of the stacking of the bidimensional layers in the solid-state complex $[Pb_4(\mu\text{-}3,4\text{-TDTA})_2(H_2O)_2]\cdot 4H_2O$.

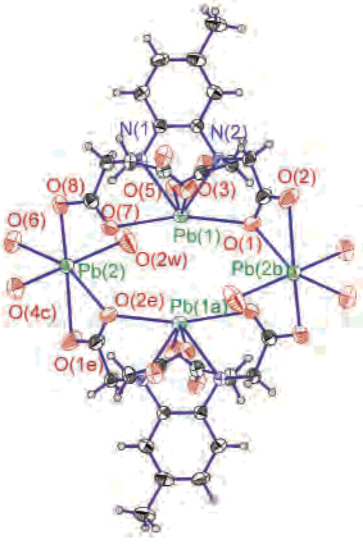

Figure 2. View of the tetrameric unit $[Pb_4(\mu\text{-}3,4\text{-TDTA})_2(H_2O)_2]\cdot 4H_2O$ with labeling scheme. Symmetry codes: (a) $-x$, $1 - y$, $1 - z$; (b) $-x$, $3 - y$, $1 - z$; (c) $-1 + x$, $1 + y$, z; (d) x, $1 + y$, z; (e) $-x$, $2 - y$, $1 - z$.

Å].[36] Pb(1) has a hemidirected geometry (the ligand is not distributed through the entire sphere surrounding the lead atom), and there is a clearly identifiable gap in the lead coordination sphere, suggesting that Pb(1) contains a stereochemically active lone pair of electrons. The three-dimensional environment of the lone pair of electrons in the crystal structure is of significant interest in the design of ligands as sequestering agents. In compound **1** opposite the Pb(1) we find another symmetrically related Pb(1a) (symmetry code a, $-x$, $1 - y$, $1 - z$) at a distance of 3.96(4) Å. Thus, we will have two pairs of electrons filling the space between the two hemidirected Pb(II) ions.

Pb(2) has an O_6 trigonally distorted octahedral surrounding, the lead(II) ion being surrounded by five carboxylate oxygens and a water molecule with distances ranging from 2.461(4) to 2.764(6) Å, the angles deviating considerably from the ideal ones. In addition to those six oxygens surrounding the Pb(2), there is another one at a longer distance [Pb(2)···O(7) = 2.919(8) Å]. The carboxylate oxygens belong to four different ligands that are also joined to four other Pb(1) ions. O(1) acts as a μ-oxo bridge between Pb(1) and Pb(2b) (symmetry code b, $-x$, $3 - y$, $1 - z$). For Pb(2) there is not a clear gap in the coordination sphere of the ion, so a holodirected geometry is observed. In the holodirected geometry the lone pair can be stereochemically active or inactive. The mean Pb−O distance with a holodirected homoleptic stereochemistry is 2.53(15) Å.[17] Here we observe three shorter adjacent distances [2.461(4), 2.488(4), and 2.509(6) Å] and three adjacent long Pb−O bonds [2.654(6), 2.764(6), and 2.733(4) Å). In agreement with Brown[37] and others,[38] such a specific pattern of differences in bond lengths in holodirected homoleptic complexes can be attributed to repulsions involving the stereochemically active lone pair of electrons. Then also in this Pb(2) ion the lone pair can be considered as stereochemically active.

Table 2. Selected Distances (Å) and Angles (deg) for $[Pb_4(\mu\text{-}3,4\text{-TDTA})_2(H_2O)_2]\cdot 4H_2O^a$

	Distances		
Pb(1)−N(1)	2.520(4)	Pb(2)−O(1e)	2.733(4)
Pb(1)−N(2)	2.562(4)	Pb(2)−O(2e)	2.764(6)
Pb(1)−O(1)	2.638(4)	Pb(2)−O(4c)	2.461(14)
Pb(1)−O(3)	2.498(4)	Pb(2)−O(6)	2.488(11)
Pb(1)−O(5)	2.502(5)	Pb(2)−O(8)	2.509(19)
Pb(1)−O(7)	2.633(4)	Pb(2)−O(2w)	2.654(6)
Pb(1)···O(4)	4.44(6)	Pb(2)···O(7)	2.919(8)
Pb(1)···Pb(1a)	3.96(4)	Pb(2)···Pb(2b)	9.13(4)
	Angles		
N(2)−Pb(1)−N(1)	70.76(1)	N(1)−Pb(1)−O(5)	75.52(1)
N(2)−Pb(1)−O(3)	75.32(1)	O(3)−Pb(1)−O(1)	104.81(1)
N(2)−Pb(1)−O(1)	129.80(1)	O(3)−Pb(1)−O(7)	85.78(1)
N(2)−Pb(1)−O(7)	64.32(1)	O(3)−Pb(1)−O(5)	132.86(1)
N(2)−Pb(1)−O(5)	67.06(1)	O(1)−Pb(1)−O(7)	163.76(1)
N(1)−Pb(1)−O(3)	65.77(1)	O(1)−Pb(1)−O(5)	80.29(1)
N(1)−Pb(1)−O(1)	64.63(1)	O(7)−Pb(1)−O(5)	101.72(1)
N(1)−Pb(1)−O(7)	131.58(1)		
O(2w)−Pb(2)−O(6)	106.74(1)	O(6)−Pb(2)−O(1e)	158.08(1)
O(2w)−Pb(2)−O(8)	86.90(1)	O(6)−Pb(2)−O(2e)	112.61(1)
O(2w)−Pb(2)−O(4c)	173.38(1)	O(8)−Pb(2)−O(4c)	89.73(1)
O(2w)−Pb(2)−O(1e)	90.14(1)	O(8)−Pb(2)−O(1e)	115.56(1)
O(2w)−Pb(2)−O(2e)	106.45(1)	O(8)−Pb(2)−O(2e)	156.99(1)
O(6)−Pb(2)−O(8)	80.00(1)	O(4c)−Pb(2)−O(1e)	86.18(1)
O(6)−Pb(2)−O(4c)	78.22(1)	O(4c)−Pb(2)−O(2e)	74.98(1)

[a] Symmetry codes: (a) $-x$,$1 - y$, $1 - z$; (b) $-x$, $3 - y$, $1 - z$; (c) $-1 + x$, $1 + y$, z; (d) x, $1 + y$, z; (e) $-x$, $2 - y$, $1 - z$.

Complex Formation of 3,4-TDTA, *o*-PhDTA, and 4-Cl-*o*-PhDTA with Pb(II) in Solution. Potentiometric Studies. Taking into account the following general equilibrium in eq 1,

$$pH^+ + qPb^{2+} + rL^{4-} \rightleftarrows [H_pPb_qL_r]^{(p+2q-4r)}\ \beta_{pqr} \qquad (1)$$

the model and the log β_{pqr} that best fit the experimental data are shown in Table 3 and compared with the literature values for EDTA[39] and *o*-PhDTA.[40a] The experimental data have been processed by means of HYPERQUAD,[31a] and a very

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Table 3. log β_{pqr} for the Complexes Formed by Pb(II) with the Ligands 4-Cl-*o*-PhDTA, *o*-PhDTA, and 3,4-TDTA at 25 °C and $I = 0.5$ mol dm^{-3} in $NaClO_4$[a]

pqr	4-Cl-o-PhDTA	o-PhDTA	3,4-TDTA	o-PhDTA[40a]	EDTA[39]
111	15.44(2)	16.20(4)	16.42(5)	16.28	20.8
011	13.14(2)	13.89(4)	14.00(5)	13.89(4)	18.04
−111	2.68(3)	3.08(4)	4.6(1)		
212	25.28(4)	26.64(4)	27.36(5)		
112	20.77(4)	22.58(4)	22.74(5)		
012	15.52(3)	16.52(4)			
221	18.80(3)	20.78(7)	19.65(5)		
021	14.85(3)	16.06(9)	15.77(6)		
−121		9.37(6)			
$\sigma(E)$	0.54	1.17	0.85		
Δ(pH)	1.79.9	2.09.7	2.08.5		
n/N	312/5	405/6	551/9		

[a] $\sigma(E)$ = standard deviation of the refinement, Δ(pH) = pH range studied, n = number of experimental data processed, and N = number of potentiometric titrations.

high concordance between the experimental and the calculated data has been obtained. The experimental and the simulated (by means of Hyss)[31b] potentiometric curves are shown in the Supporting Information (20 curves), confirming the accuracy of the fitting. The following order of complexation is mainly found: EDTA > 3,4-TDTA > *o*-PhDTA > 4-Cl-*o*-PhDTA. The ligands 3,4-TDTA, *o*-PhDTA, and 4-Cl-*o*-PhDTA show a drastic decrease in the basicity of the two nitrogen atoms, compared with EDTA, as expected from the electron-withdrawing effect, and the planarity imposed by the benzene ring. These ligands are strong complexing agents and form very stable complexes with many metals.[28] This causes the general equilibrium in eq 2

$$Pb^{2+} + H_4L \rightleftarrows [PbL]^{2-} + 4H^+ \qquad (2)$$

to be almost completely displaced to the right side, and the degree of complex formation is not sensitive to the hydrogen ion concentration. Under such conditions it is not possible to obtain the values of the stability constants from potentiometric pH measurements, and other methods must be developed.[41] The problem is that the ligand has such a high affinity for the metal that there is no competition between the metal and the hydrogen ion for the ligand. A way to increase the competition for the ligand of the H^+ ions is to decrease the pH, but below pH 2 we are out of the working range of the electrodes. We have developed a method to increase the competition of the hydrogen ions without decreasing the pH but decreasing the metal ion concentration to 10^{-4} mol dm^{-3}. Thus, at pH 2 the H^+ ions are 100 times more concentrated than the metal ions, and equilibrium 2 is reestablished. These conditions allow determination of the stability constants for the Pb(II)/3,4-TDTA and Pb(II)/*o*-PhDTA systems that could not be obtained at the usual concentrations. This procedure can be very useful in the study of strong complexing agents since it is very simple and is based on the most used and successful technique employed for metal complex equilibrium measurements. For the Pb(II)/4-Cl-*o*-PhDTA system direct potentiometry at millimolar concentrations gave a good result.

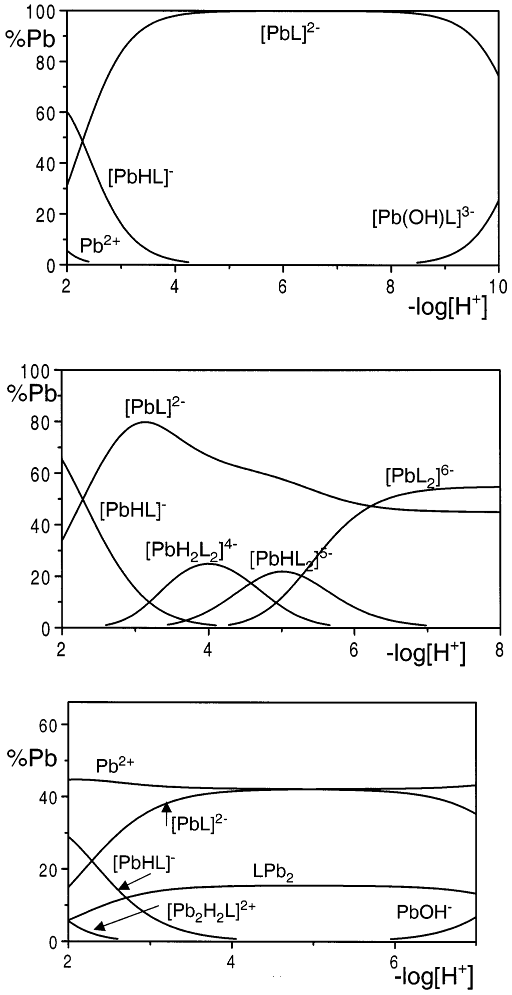

Figure 3. Species distribution diagram as a function of pH for the Pb(II)/4-Cl-*o*-PhDTA system. ($[Pb^{2+}]_{tot} = 1 \times 10^{-2}$ mol dm^{-3}) at the metal/ligand ratios **(**a, top**)** 1/1, **(**b, middle**)** 1/2, and **(**c, bottom**)** 1/0.5

These ligands have previously been studied with other metals[27,28] (*o*-PhDTA[40a] also with Pb(II)), and mainly monomeric ($[MH_2L]$, $[MHL]$, $[ML]$, and $[M(OH)L]$) complexes were found. In this study in addition to the expected $[PbHL]^-$ and $[PbL]^{2-}$ species, the ligand-rich species $[PbL_2]^{6-}$, $[PbHL_2]^{5-}$, and $[PbH_2L_2]^{4-}$ and the metal-rich species $[Pb_2L]$ and $[Pb_2H_2L]^{2+}$ have been found in solution by potentiometric studies, obtaining a model very similar to that found for Cd(II).[27] As can be seen in the species distribution diagrams (Figure 3) the main species are the monomeric ones. However, due to the large size of lead ion and its ability to have a variable coordination number, more than one ligand molecule can be bound to the metal, forming ligand-rich species. These ligand-rich species do not reach a very high concentration, but if they are ignored, there is not a convergence of the experimental data and those predicted by the model.

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The equilibrium of the formation of the $[PbL]^{2-}$ complexes in eq 3 has a much higher value of the stability constant [log K = 13.14(2), 13.89(4), and 14.00(5)

$$Pb^{2+} + L^{4-} \rightleftarrows [PbL]^{2-} \quad (3)$$

for 4-Cl-*o*-PhDTA, *o*-PhDTA, and 3,4-TDTA, respectively] than that of the formation of the ligand-rich complexes in eq 4 [log K = 2.38(5) and 2.63(8) for 4-Cl-*o*-PhDTA and *o*-PhDTA, respectively; not formed for 3,4-TDTA]. This may indicate that the second ligand is only bound to the metal via carboxylato groups as was observed for Cd(II) complexes.[27]

$$[PbL]^{2-} + L^{4-} \rightleftarrows [PbL_2]^{6-} \quad (4)$$

Another feature of these ligands is that the carboxylato groups already bound to a metal ion, forming the $[ML]^{2-}$ species, are able to join another metal, generating the $[M_2L]$ species. These species were first observed for Cd(II)[27] and now are also observed for Pb(II). The values of the stability constants of the formation of those species (eq 5) are log K = 1.71(5), 2.2(1), and 1.8(1) for 4-Cl-*o*-PhDTA, *o*-PhDTA, and 3,4-TDTA, respectively. The constants have a very low value, and these species will be present at high M/L ratios.

$$Pb^{2+} + [PbL]^{2-} \rightleftarrows [Pb_2L] \quad (5)$$

Species Distribution Diagrams. The species distribution diagrams as a function of pH were calculated from the values of the ionization constants of the ligands, the log β_{pqr} of the complexes, and the formation constants of hydrolytic species of lead(II),[42] using the program HYSS.[31b] Figure 3 shows the species distribution diagram for the Pb(II)/4-Cl-*o*-PhDTA system at the concentrations used in the NMR studies. At the M/L = 10/10 ratio (Figure 3a) only monomeric species are observed. The complex formation is sensitive to the change in the pH, since the concentration of free lead(II) varies with increasing pH. Under these conditions, the direct determination of the stability constants from potentiometries at normal concentrations is possible. On increasing the ligand concentration (Figure 3b), the ligand-rich species become appreciable, and above pH 6.5 the $[PbL_2]^{2-}$ species reaches higher in concentration than $[PbL]^{2-}$. On the other hand, the hydrolytic species are minimized. At the M/L = 1/0.5 (Figure 3c) ratio, the metal-rich species are in appreciable concentration, coexisting with the more concentrated monomeric ones. Free Pb(II) is present in all the pH range studied and hydrolyzes above pH 6.

NMR Studies. ^{207}Pb NMR spectroscopy can provide useful insights into lead coordination chemistry. ^{207}Pb isotopes are particularly good candidates for nuclear magnetic resonance (NMR) because they have a nuclear spin that can be exploited for NMR spectroscopy (I = 1/2), an excellent receptivity (11.7 times greater than that of ^{13}C), a high natural abundance (22.6%), and a large chemical shift range (over 16000 ppm).[43,44] Here we report ^{207}Pb NMR data for the system Pb(II)/4-Cl-*o*-PhDTA at the M/L ratios 1/2, 1/1, and 1/0.5. The spectra are shown in Figure 4.

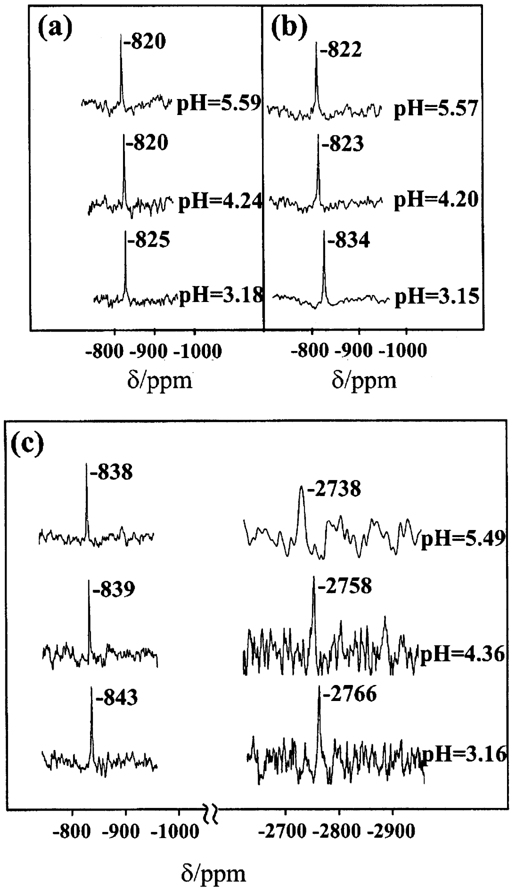

Figure 4. ^{207}Pb NMR spectra for the Pb(II)/4-Cl-*o*-PhDTA system ($[Pb^{2+}]_{tot} = 1 \times 10^{-2}$ mol dm^{-3}) at the metal/ligand ratios **(**a, top**)** 1/2, **(**b, middle**)** 1/1, and (c, bottom**)** 1/0.5.

In Figure 4a,b, corresponding to the spectra with an excess of ligand (M/L = 1/2), and with an equimolecular metal/ligand ratio (M/L = 1/1), only one signal is observed in all the pH range studied ($\delta_{M/L=1/2} = -820$ to -825 ppm, and $\delta_{M/L=1/1} = -822$ to -834 ppm). In the species diagram at the M/L = 1/2 ratio (Figure 3b) we have the monomeric $[PbHL]^{-}$ and $[PbL]^{2-}$ species and the ligand-rich $[PbH_2L_2]^{4-}$, $[PbHL_2]^{5-}$, and $[PbL_2]^{6-}$ species. When the complexes undergo rapid exchange in solution (on the NMR time scale), the chemical shifts of the individual species are not observed; on the other hand, we have a single averaged chemical shift for similar species. All these species have very similar coordination environments around Pb(II) and therefore similar or equal chemical shifts. In the ligand-rich species one of the ligands is bound to the metal ion in a fashion similar to that found in the monomeric complexes. The Pb(II) is bound to two nitrogen atoms and four carboxylato oxygens from one ligand molecule; the second ligand

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molecule is coordinated to the Pb(II) only by the carboxylato oxygens, displacing the coordinated water molecules or carboxylato groups from the ligand already bound to the Pb(II). Under these conditions we will have very similar environments for Pb(II) in the monomeric and ligand-rich complexes and, therefore, similar chemical shifts as observed in the spectra.

At the 1/1 M/L ratio (Figure 4b), the chemical shift decreases to −834 ppm at pH 3.15, by the formation of the protonated $[PbHL]^-$ complex (see the species distribution diagram, Figure 3a). In the $[PbHL]^-$ complex, the Pb(II) is less shielded than in the $[PbL]^{2-}$ complex, and the binding of the H^+ to the ligand will decrease its electron density available for donation and for shielding the Pb(II), in a way similar to that observed in Cd(II)/4-Cl-*o*-PhDTA complexes.[27] The values of the chemical shifts are in good agreement with those reported for the Pb(II) complexes of the amido derivatives of the ethylenediaminetetraacetic acid (EDTA)[45] ($\delta = 2189$ and 2441), keeping in mind that the lead resonance of a 1.0 mol dm^{-3} aqueous solution of $Pb(NO_3)_2$ appears −2961 upfield from neat $Pb(CH_3)_4$.[46] The crystal structure of the lead(II) ethylenediaminetetraacetamide complex, reported in ref 45, presents a Pb(II) environment very similar to that observed for Pb(1) in compound **1** (Figure 2), a six-coordinated hemidirected lead(II) being surrounded by two nitrogen and four oxygen atoms in both complexes.

In Figure 4c the ^{207}Pb NMR spectra for the metal/ligand = 1/0.5 ratio are shown. At *high field* a shift of $\delta = -843$ to −838 ppm is observed, similar to that shown in Figure 4a,b, corresponding to the monomeric complexes (see the species distribution diagram, Figure 3c). In these species we consider that Pb(II) is bound to two phenylenediamine nitrogen atoms, to one or various water molecules, and to carboxylato oxygens, filling its coordination sphere. In addition to those high-field resonances, other signals in the range −2766 to −2738 ppm are observed. These chemical shifts must correspond to the free Pb(II) ion [$\delta = -2867$ ppm for a 0.01 M $Pb(ClO_4)_2$ aqueous solution at pH 3.13] and to the second Pb(II) in the $[Pb_2L]$ species. The latter Pb(II), in the metal-rich species, must be bound to water molecules and carboxylato oxygens that may have been detached from the $[PbL]^{2-}$ complex.[40] Typically, substitution of nitrogen by oxygen within the lead(II) coordination sphere tends to increase the *deshielding* and shifts the ^{207}Pb resonances *downfield.*[43] Here again due to the rapid exchange we observe just one resonance for two similarly surrounded Pb(II) ions. The NMR spectra can be explained by the occurrence of metal-rich species in which one of the metal ions is surrounded by water molecules and carboxylato oxygens. If we did not have metal-rich species, we could not explain the occurrence of these downfield resonances.

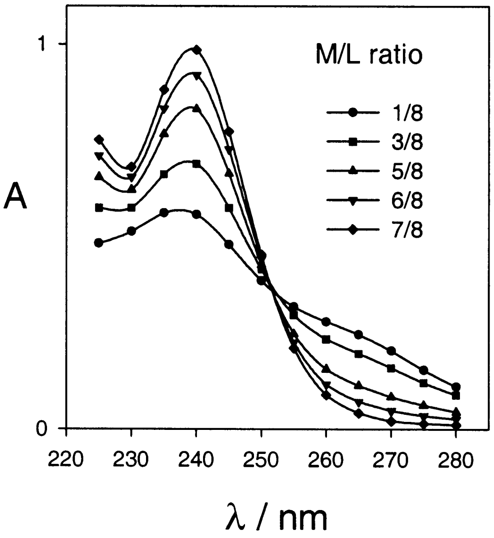

Figure 5. Selected curves showing the change in the spectra of *o*-PhDTA on addition of lead(II) perchlorate at pH 5.00(2). The M/L ratio is indicated in the inset legend. The experimental data are shown as symbols, and the solid lines correspond to the data calculated by means of LETAGROP SPEFO.[33]

Spectrophotometric Studies. The spectrophotometric measurements were performed at pH 5.00(2) to minimize the number of species in an attempt to minimize the number of variables to be determined by the program. Taking into account the species distribution diagrams for the Pb(II)/*o*-PhDTA system, at pH 5, depending on the M/L ratio, we expect the $[PbHL_2]^{5-}$, $[PbL_2]^{6-}$, and $[PbL]^{2-}$ species. However, under these experimental conditions we were not able to calculate the values of the constants from spectrophotometric data. Nevertheless, fixing the pH and the constants obtained by potentiometry, by means of LETAGROP SPEFO,[33] we have been able to simulate the spectrophotometric spectra that match very well the absorbance data as shown in Figure 5.

Effective Stability Constants. Competitive Sequestering of Pb(II). The ability of these ligands to remove Pb(II) from a system can be studied by means of the effective binding constants, which take into account the competition of hydrogen ions and other metal ions that may be present and also the competition of other ligands such as OH^-.[31b] The effective formation constants $K_{ML}{}^{eff}$ are related to the conventional stability constants by eq 6,

$$\log K_{PbL}{}^{eff} = \log K_{PbL} + \log \alpha_{PbL} - \log \alpha_{Pb(OH)} - \log \alpha_L \qquad (6)$$

where $\alpha_{PbL} = 1 + [H^+]K^H{}_{PbHL} + ... + K^{OH}{}_{PbOHL}/[H^+] + 2[Pb^{2+}]K^{Pb}{}_{Pb2L} + ...$, $\alpha_{Pb(OH)} = 1 + \beta_{-11}/[H^+] + \beta_{-21}/[H^+]^2 + \beta_{-12}[Pb^{2+}]/[H^+]$, and $\alpha_L = 1 + \sum\beta_i{}^H[H^+]^i$. α_{PbL} takes into account the formation of protonated and/or ligand- or metal-rich species, $\alpha_{Pb(OH)}$ the decrease in Pb(II) available due to the removal of Pb(II) by the formation of the hydrolytic species, and α_L the decrease of L due to the protonation of the ligand, the main factor being the latter in acidic media. log $K^{eff}{}_{PbL}$ is a function of the pH for each ligand and is plotted in Figure 6 for the complexation of Pb(II) by the ligands 3,4-TDTA, *o*-PhDTA, 4-Cl-*o*-PhDTA, dimercaptosuccinate (DMSA), diethylenetriaminepentaacetate (DTPA), and EDTA. DMSA, EDTA, and DTPA have been used as antidotes for lead(II).[47] It is found that the ligands 4-Cl-*o*-

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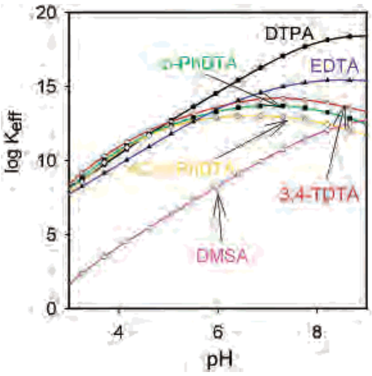

Figure 6. Effective stability constants as a function of pH for Pb(II) with the ligands 3,4-TDTA, *o*-PhDTA, 4-Cl-*o*-PhDTA, DTPA, DMSA, and EDTA. DMSA, EDTA, and DTPA have been used as antidotes for lead(II).[52]

PhDTA, *o*-PhDTA, and in particular 3,4-TDTA are better sequestering agents than EDTA in acidic media. The lower basicity of the nitrogen atoms derived from aromatic diamines facilitates the chelation of the Pb(II) in those conditions.[17] The effectiveness of 3,4-TDTA is better than that of EDTA at pH < 6.4. DTPA is the most effective at pH > 5.2.

Lead(II) Speciation in Human Blood Serum in the Presence of *o*-PhDTA. The metal speciation in human blood serum has recently been studied by P. Letkeman by means of computer modeling.[48] From that work and others[49,50] we have taken the individual concentrations of the main components in blood serum and the stability constants of the complexes formed by citric acid (Ct), glutathione (Gs), cysteine (Cy),[49] and chloride[50] with lead(II). In addition, the stability constant of the complex of lead(II) with human transferrin (hTF) has been estimated by the method proposed by H. Sun et al.,[51] giving a value of log $K_{\mathrm{Pb(hTF)}} = 9.6$. These authors find a correlation of the first metal binding constant of human transferrin for divalent and trivalent metal ions with that for hydroxide binding, the intercept of this correlation being ca. −3.4. With those data (by means of HYSS[31b]) we have calculated the binding of lead(II) at physiologic pH (7.4) with all those complexing agents. At a concentration of 1 μM in lead(II) 4.9% of the metal is bound to the cysteine and 94.1% to the hTF. In the presence of 1 μM *o*-PhDTA, the transferrin is displaced, 2.6% of the lead(II) being bound to the hTF and 97.4% to the *o*-PhDTA. At a concentration of *o*-PhDTA of 10 μM, 99.1% of the lead(II) is bound to the *o*-PhDTA.

Conclusions

The ligands 3,4-TDTA, *o*-PhDTA, and 4-Cl-*o*-PhDTA form very stable complexes with Pb(II). The processing of data resulting from experiments at low Pb(II) concentration allowed the determination of the model and the calculation of the stability constants of the systems. This approach can be used to study other systems in which strong complexes are formed. There is an agreement among the potentiometric, spectrophotometric, and ^{207}Pb NMR studies. These ligands are not those of the highest effective constant in all the pH range studied, but the constants are high enough for these ligands to be considered as good complexing agents in a wide pH range. In addition, the 3,4-TDTA builds a very interesting 2-D structure with Pb(II), in which two nonequivalent environments are observed for the Pb(II), one of them exhibiting a hemidirected geometry, the other being holodirected. Compound **1** constitutes a very good example of the influence of the nature of the donor atom and the geometric restrictions of the ligand in the stereochemistry of Pb(II).

Abbreviations

3,4-Toluenediamine-*N*,*N*,*N*′,*N*′-tetraacetate (3,4-TDTA), *o*-phenylenediamine-*N*,*N*,*N*′,*N*′-tetraacetate (*o*-PhDTA), 4-chloro-1,2-phenylenediamine-*N*,*N*,*N*′,*N*′-tetraacetate (4-Cl-*o*-PhDTA), ethylenediamine-*N*,*N*,*N*′,*N*′-tetraacetate (EDTA), cytric acid (Ct), glutathione (Gs), cysteine (Cy), human transferrin (hTF), dimercaptosuccinate (DMSA), diethylenetriaminepentaacetate (DTPA).

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Supporting Information Available: Experimental conditions for the potentiometric experiments (Table S1), experimental and calculated potentiometric curves (20), and position and thermal parameters of non-hydrogen atoms and full bond distances and angles for **1** in CIF format. This material is available free of charge via the Internet at http://pubs.acs.org.

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