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Comparison of Two Tetrapodal N,O Ligands: Impact of the Softness of the Heterocyclic N-Donors Pyridine and Pyrazine on the Selectivity for Am(III) over Eu(III)

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To quantify the impact of the N-donor softness on the coordination of f elements in aqueous solution, and in particular on the selectivity for Am(III) over Eu(III), we have designed the two tetrapodal hexadentate ligands N,N-bis(2-pyridylmethyl)ethylenediamine-N′,N′-diacetic acid (L^{py}) and N,N-bis(2-pyrazylmethyl)ethylenediamine-N′,N′-diacetic acid (L^{pz}). These ligands bear two hard acetate groups to provide stability to the An(III) and Ln(III) complexes and two N-heterocyclic soft groups to provide Am(III) versus Eu(III) selectivity. They only differ in their N-donor moieties, pyridine or pyrazine. The proton NMR and potentiometric analyses performed on the lanthanide complexes of the two ligands indicate that a unique metallic complex, LnL, is formed and that LnL^{py+} and LnL^{pz+} have the same structure in water. Furthermore, the hydration numbers of the europium and terbium ions in these complexes, measured by luminescence decay, have the same value ($q = 3$), indicating that the two ligands act as hexadentate donors in both systems. As expected, the softer pyrazine-based ligand gives less stable complexes than the pyridine-based ligand with the hard Ln(III) cations. The fragment $N(CH_2pz)_2$ containing two pyrazine functions has a very low contribution to the stability of the lanthanide complexes, even though the pyrazine groups are coordinated to the cation in water. The stabilities of the americium(III) complexes were determined by potentiometry and are greater than those found for the isoelectronic europium complexes. The selectivity for Am(III) over Eu(III) increases from 60 to 500 when the pyridine-containing fragment $N(CH_2py)_2$ is substituted by the pyrazine-containing fragment $N(CH_2pz)_2$, which demonstrates that the selectivity for Am(III) over Eu(III) is significantly enhanced when the softness of the N-heterocycle increases from pyridine to pyrazine. These new hydrophilic ligands present attractive selectivities for Am(III) over Eu(III) that could make them good candidates for the selective back extraction of Am(III) from organic solutions containing 4f and 5f elements.

Introduction

The separation of trivalent actinides (An(III)) from trivalent lanthanides (Ln(III)) is a key step in partitioning and transmutation strategy, which is one of the scenarios being seriously considered for the future management of nuclear waste. It aims to separate long-lived α-emitting minor actinides from spent nuclear fuel and to transmute them by nuclear fission into shorter-lived isotopes. Indeed, the transmutation of the minor actinides will only be possible after separation from the abundant fission products, lanthanides, having large neutron capture cross-sections.[1−3]

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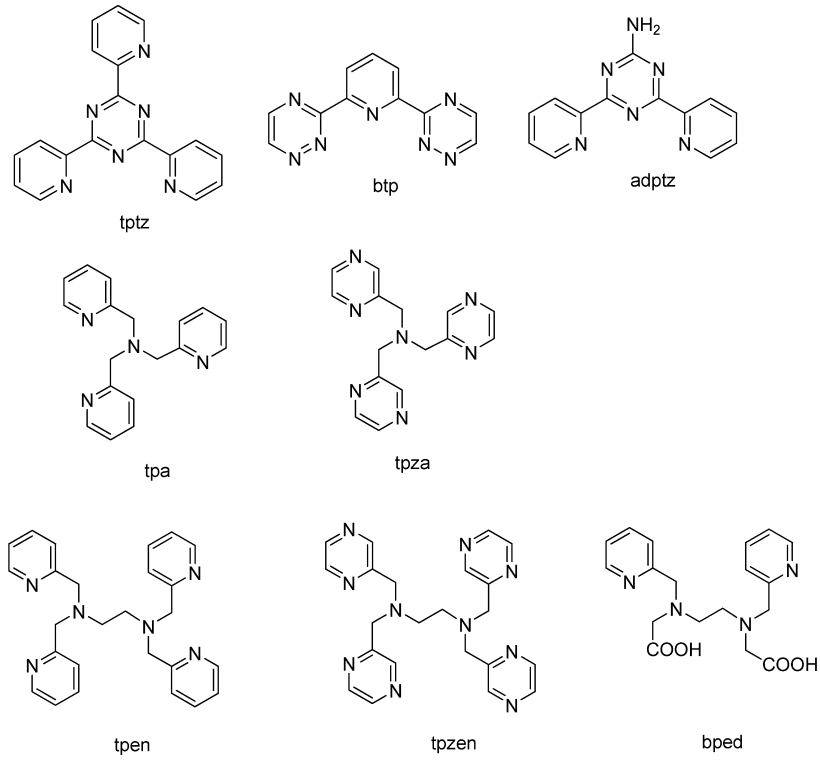
Chart 1



This separation is one of the most challenging issues, owing to the very similar physicochemical properties of An(III) and Ln(III). Indeed, lanthanides and transplutonium actinides both exist predominantly in their trivalent oxidation states in solution. They are hard acids in the Pearson classification (HSAB for Hard and Soft Acids and Bases)[4] with close ionic radii. Their interactions with inorganic and organic ligands are therefore predominantly determined by electrostatic and steric factors. Even if both An(III) and Ln(III) are considered to be hard acids in HSAB theory, the higher spatial expansion of 5f actinide orbitals with respect to the 4f lanthanide orbitals opens possibilities to discriminate them through their relative hardness. Therefore, it was pointed out by Musikas in the 1980s that extractant molecules containing nitrogen or sulfur functionalities which are softer than oxygen donors offered great potential to achieve the wanted discrimination.[5] Interestingly, sulfur-based soft-donor extractants like bisalkyldithiophosphinic acids have been developed by Zhu and have given excellent separation factors (SFs); for instance, $SF_{Am/Eu}$ is as high as 5900 for Cyanex 301.[6]

Soft nitrogen-containing molecules have also been developed by many research groups and have good separation properties that are even less selective than sulfur donors. The pioneering work of Musikas demonstrated that the aromatic nitrogen donor ligand tptz was able to selectively extract americium(III).[5] Since then, many molecules containing aromatic nitrogen as donor atoms have been developed and tested for their separation properties: for instance, tridentate polyaromatic ligands like btp,[7−11] tetradentate tripodal amines bearing simple aromatic N-donors like pyridine (tpa) or pyrazine (tpza),[12,13] and hexadentate tetrapodal ligands like tpen[14−16] and tpzen (see Chart 1).[17] Extraction studies have demonstrated their ability to bind Am(III) more strongly than Ln(III).

The main objective of most fundamental studies was to demonstrate that the discrimination of An(III) from Ln(III) by N-donor ligands originated from a greater degree of covalency in the M−N bond for Am(III). The separation factors estimated from extraction experiments increase with the softness of the extracting molecules. For instance, $SF_{Am/Eu}$ increases from 2 to

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10 when the pyridine groups are replaced by the softer pyrazine groups in the tripodal architectures of tpa and tpza.[12] However, in the extraction experiments, many parameters have to be taken into account, and it is therefore difficult to simply attribute the observed selectivity to a difference in the cation's bonding. Hence, to study the nature of the metal−nitrogen bond, U(III) has been used as a model of the radioactive α-emitting trivalent minor actinides Am(III) and Cm(III). Comparative studies of Ln(III) and U(III) complexes, which associated X-ray structures with calculations, demonstrated that the deviation of the U−N bond lengths from a purely ionic bonding model was consistent with the presence of a stronger π-backbonding interaction between the U(III) ion and the nitrogen ligand.[18−21] The complexation of Ce(III) and U(III) with simple N-heterocyclic ligands, which are the basic units of the polydentate extractant molecules, showed that the selectivity of the azine molecule in favor of U(III) increases with its π-accepting ability.[22] However, recent theoretical as well as experimental investigations have evidenced significant differences between U(III) and heavier actinide complexes,[23−26] pointing out the need to achieve experimental characterization of minor actinide complexes.

A greater degree of covalency in the bonds between an actinide ion and a ligand compared to the equivalent lanthanide complex should be reflected in the thermodynamic data of the complexation reactions. The thermodynamic analyses of the complexation of f elements with polyaminocarboxylates indicate only slight differences in the affinities or enthalpies between Am(III) and Eu(III), and therefore in the Eu−N and Am−N bond strengths.[27−29] On the contrary, significant differences in the stability constants and the enthalpies of complexation of Am(III) and Ln(III) have been evidenced for ligands containing only soft donor atoms, namely tpen[30] and adptz.[31] To our knowledge, no systematic thermodynamic studies have been reported on the stability of An(III) versus Ln(III) complexes as a function of the softness of the N-donor ligand.

The objective of this work was to demonstrate that the selectivity of N-heterocycles for Am(III) over the isoelectronic lanthanide Eu(III) is correlated with the softness of the N donor. We focused on the two N-heterocycles pyridine and pyrazine because they significantly differ in their soft character. Indeed, the softness S[32] is defined as $1/\eta$, η being the absolute hardness, which is related to the ionization potential (IP) and the electron affinity (EA) of the species according to eq 1.[33]

$$\eta = \frac{\mathrm{IP} - \mathrm{EA}}{2} \quad (1)$$

Whereas the IPs of the two N-heterocycles are very similar,[34] the experimental or calculated EAs are systematically higher for pyrazine than for pyridine, leading to a softer character of the former N donor.[35−38] To compare the selectivity of these two heterocycles for Am(III) over Ln(III), we have designed two ligands, whose complexation properties can be accurately studied in water and which only differ in their N-donor moieties, pyridine or pyrazine. Ligands containing only pyrazine groups like tpza[12] or tpzen[17] have very low affinities for lanthanides, preventing the study of their complexation properties in water, which is a highly competing medium, as An(III) and Ln(III) are very hydrophilic. Therefore, we chose to synthesize ligands bearing both hard and soft donors to obtain stable complexes in aqueous solution. The data presented in this paper, namely the comparison of the stability constants of Ln(III) and Am(III) complexes of these two ligands, which have the same structures, demonstrate that the selectivity for Am(III) over Eu(III) is significantly enhanced when the softness of the N-heterocycle increases from pyridine to pyrazine. Furthermore, these new hydrophilic ligands presenting attractive selectivities for Am(III) over Eu(III) could be good candidates for the selective back extraction of Am(III) from organic solutions containing 4f and 5f elements.

Experimental Section

General Details. Solvents and starting materials were purchased from Aldrich, Acros, Fluka, and Alfa Aesar and used without further purification. Lanthanide salts were purchased from Aldrich and deuterium oxide (99.9 atom% D) from Euriso-Top. All water solutions were prepared from ultrapure laboratory-grade water that had been filtered and purified by reverse osmosis using a Millipore MilliQ reverse-osmosis cartridge system (resistivity, 18 MΩ cm). Thin-layer chromatography was performed on either silica gel 60 F_{254} (Merck), aluminum oxide 60 F_{254} neutral (Merck), or RP-18 F_{254S} (Merck). Flash chromatography was performed on either silica gel 60 (40−63 μm, Merck), aluminum oxide 90 active neutral (+ 4.9% water wt, 63−200 μm, Merck), or silica gel 60 RP18 (40−63 μm, Merck). ^{1}H NMR and ^{13}C NMR spectra were recorded on either

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a Unity or a Mercury Varian 400 spectrometer. Chemical shifts are reported in ppm with the solvent as the internal reference. Mass spectra were acquired with a Finigan LCQ-ion trap equipped with an electrospray source. Elemental analyses were performed by the Service Central d'Analyze (Solaize, France).

2-Chloromethylpyrazine was obtained from commercially available 2-methylpyrazine according to a previously described procedure.[18]

Synthesis of L^{py} (N,N-Bis(2-pyridylmethyl)ethylenediamine-N′,N′-diacetic Acid). N,N-Bis(2-pyridylmethyl)-N′-acetylethylenediamine. To a stirred solution of N-acetylethylenediamine (90%, 1.57 mL, 14.76 mmol) in dry acetonitrile (100 mL) were successively added 2-(chloromethyl)pyridine hydrochloride (5.81 g, 35.42 mmol), potassium carbonate (9.79 g, 70.84 mmol), and potassium iodide (5.88 g, 35.42 mmol) under an argon atmosphere. After being stirred for 2 h at room temperature, the suspension was refluxed overnight, cooled, and filtered through a pad of celite. Then, the filtrate was evaporated, and the resulting red oil (4.82 g) was purified by chromatography on aluminum oxide (200 mL, 95:5 ethyl acetate/methanol) to afford N,N-bis(2-pyridylmethyl)-N′-acetylethylenediamine (2.80 g, 9.85 mmol) as a brown powder. Yield: 67%. ^{1}H NMR (400 MHz, $CDCl_3$, 298 K): δ 8.56 (d, J = 4.5 Hz, 2H, H^6), 7.63 (td, J = 2.0 and 7.8 Hz, 2H, H^4), 7.33 (d, J = 7.8 Hz, 2H, H^3), 7.17 (dd, J = 4.5 and 7.8 Hz, 2H, H^5), 3.88 (s, 4H, H^2), 3.35 (q, J = 5.5 Hz, 2H, H^7), 2.74 (t, J = 5.5 Hz, 2H, H^1), 2.02 (s, 3H, C(O)CH_3). ES-MS: (m/z) 285 (MH^+).

N,N-Bis(2-pyridylmethyl)ethylenediamine. A degassed 1 M HCl solution (140 mL) was added to N,N-bis(2-pyridylmethyl)-N′-acetylethylenediamine (1.40 g, 4.92 mmol), and the resulting mixture was refluxed for 20 h under an argon atmosphere. After the solution cooled at room temperature, a saturated $NaHCO_3$ aqueous solution (220 mL) was slowly added, and the resulting solution was evaporated. To remove the inorganic salts, the solid residue was partially dissolved in chloroform and filtrated, and the filtrate was evaporated. The resulting crude product, N,N-bis(2-pyridylmethyl)ethylenediamine (1.25 g), was used without purification. ^{1}H NMR (400 MHz, $CDCl_3$, 298 K): δ 8.53 (dd, J = 5.0 and 0.8 Hz, 2H, H^6), 7.64 (td, J = 7.8 and 2.0 Hz, 2H, H^4), 7.48 (d, J = 7.8 Hz, 2H, H^3), 7.14 (ddd, J = 5.0, 7.8 and 0.8 Hz, 2H, H^5), 3.84 (s, 4H, H^2), 2.79 (t, J = 5.9 Hz, 2H, H^1/H^7), 2.66 (t, J = 5.9 Hz, 2H, H^1/H^7). ES-MS: (m/z) 243 (MH^+).

N,N-Bis(2-pyridylmethyl)-N′,N′-bis(ethylacetate)ethylenediamine. To a solution of crude N,N-bis(2-pyridylmethyl)ethylenediamine (4.92 mmol) in dry acetonitrile (110 mL) under an argon atmosphere were added ethylchloroacetate (1.32 mL, 12.34 mmol) and potassium carbonate (1.70 g, 12.34 mmol). After being stirred for 2 h at room temperature, the suspension was refluxed overnight, cooled at room temperature, filtered, and evaporated. The resulting oil (2.25 g) was purified by chromatography on aluminum oxide (200 mL, dichloromethane/ethanol, gradient from 100:0 to 98:2) to afford N,N-bis(2-pyridylmethyl)-N′,N′-bis(ethylacetate)ethylenediamine (1.57 g, 3.79 mmol) as a yellow oil. Yield: 77%. ^{1}H NMR (400 MHz, $CDCl_3$, 298 K): δ 8.51 (d, J = 5.0 Hz, 2H, H^6), 7.64 (td, J = 7.8 and 1.6 Hz, 2H, H^4), 7.52 (d, J = 7.8 Hz, 2H, H^3), 7.13 (dd, J = 5.0 and 7.8 Hz, 2H, H^5), 4.12 (q, J = 7.0 Hz, 4H, COOCH_2CH$_3$), 3.84 (s, 4H, H^2), 3.51 (s, 4H, H^8), 2.94 (t, J = 7.0 Hz, 2H, H^1/H^7), 2.72 (t, J = 7.0 Hz, 2H, H^1/H^7), 1.22 (t, J = 7.0 Hz, 6H, COOCH$_2$CH_3). ES-MS: (m/z) 415 (MH^+).

$L^{2py}H_2$ (N,N-Bis(2-pyridylmethyl)ethylenediamine-N′,N′-diacetic acid)·3HCl. A degassed 2 M HCl solution (250 mL) was added to N,N-bis(2-pyridylmethyl)-N′,N′-bis(ethylacetate)ethylenediamine (1.22 g, 2.95 mmol), and the resulting mixture was refluxed for 16 h under an argon atmosphere, cooled at room temperature, and evaporated. The residue was washed with anhydrous ethanol (3 × 20 mL) and dried under a vacuum to afford $L^{2py}H_2$·3HCl (1.17 g, 2.36 mmol) as a white solid. Yield: 80%. ^{1}H NMR (400 MHz, D_2O, 298 K): δ 8.58 (d, J = 7.8 Hz, 2H, H^6), 8.12 (t, J = 7.8 Hz, 2H, H^4), 7.72 (d, J = 7.8 Hz, 2H, H^3), 7.62 (t, J = 7.8 Hz, 2H, H^5), 4.07 (s, 4H, H^2), 3.66 (s, 4H, H^8), 3.52 (t, J = 5.4 Hz, 2H, H^7), 3.15 (t, J = 5.4 Hz, 2H, H^1). ^{13}C NMR (100 MHz, D_2O, 298 K): δ 172.56 (C9), 156.98 (C10), 147.59 (C6), 144.89 (C4), 128.49 (C3), 127.25 (C5), 60.23 (C2), 59.10 (C8), 54.78 (C7), 51.13 (C1). ES-MS: (m/z) 359 (MH^+). Elem anal. calcd (%) for $C_{18}H_{22}N_4O_4$·3HCl·1.5H_2O: C, 43.69; H, 5.70; N, 11.32; Cl, 21.50. Found: C, 43.70; H, 5.70; N, 11.47; Cl, 21.82.

Monocrystals suitable for X-ray diffraction were obtained by slow evaporation of the neutral form $L^{py}H_2$ in propan-2-ol.

Synthesis of $L^{pz}H_2$ (N,N-Bis(2-pyrazylmethyl)ethylenediamine-N′,N′-diacetic Acid). N,N-Bis(2-pyrazylmethyl)-N′-acetylethylenediamine. To a stirred solution of 2-(chloromethyl)pyrazine (3.65 g, 28.41 mmol) in dry acetonitrile (75 mL) were successively added N-acetylethylenediamine (90%, 1.26 mL, 11.84 mmol), potassium carbonate (3.93 g, 28.41 mmol), and potassium iodide (4.72 g, 28.41 mmol) under an argon atmosphere. After being stirred for 2 h at room temperature, the suspension was refluxed overnight and then filtered through a pad of celite. After evaporation of the solvent, the residue was partitioned between dichloromethane (150 mL) and a saturated $NaHCO_3$ aqueous solution (100 mL). After decantation, the aqueous layer was extracted with dichloromethane (6 × 50 mL). The combined organic layers were dried over Na_2SO_4, filtered, and concentrated. The resulting brown oil (4.03 g) was purified by chromatography on aluminum oxide (200 mL, 95:5 ethyl acetate/methanol) to afford N,N-bis(2-pyrazylmethyl)-N′-acetylethylenediamine (2.63 g, 9.18 mmol) as an orange powder. Yield: 78%. ^{1}H NMR (400 MHz, $CDCl_3$, 298 K): δ 8.60 (d, J = 1.5 Hz, 2H, H^6), 8.52 (dd, J = 1.5 and 2.6 Hz, 2H, H^3), 8.47 (d, J = 2.4 Hz, 2H, H^5), 6.85 (large s, 1H, NH), 3.94 (s, 4H, H^2), 3.39 (q, J = 5.5 Hz, 2H, H^7), 2.80 (t, J = 5.5 Hz, 2H, H^1), 2.00 (s, 3H, C(O)CH_3). ES-MS: (m/z) 287.1 (MH^+).

N,N-Bis(2-pyrazylmethyl)ethylenediamine. A degassed 1 M HCl solution (260 mL) was added to N,N-bis(2-pyridylmethyl)-N′-acetylethylenediamine (2.57 g, 8.98 mmol). The resulting mixture was refluxed for 20 h under an argon atmosphere and then cooled at room temperature. The resulting solution was extracted with dichloromethane (300 mL and then 8 × 50 mL). Then, a saturated $NaHCO_3$ aqueous solution (450 mL) was added to the aqueous layer until a pH of 8 was reached, and the resulting aqueous solution was extracted with dichloromethane (4 × 350 mL). The aqueous layer was evaporated, and the solid residue was partially dissolved in ethanol (110 mL) and chloroform (150 mL) and filtrated. Then, the filtrate was evaporated. The resulting crude product, N,N-bis(2-pyrazylmethyl)ethylenediamine (3.18 g), was used without purification. ^{1}H NMR (400 MHz, $CDCl_3$, 298 K): δ 8.71 (d, J = 1.6 Hz, 2H, H^6), 8.51 (dd, J = 1.6 and 2.3 Hz, 2H, H^3), 8.45 (d, J = 2.7 Hz, 2H, H^5), 3.92 (s, 4H, H^2), 2.84 (t, J = 5.9 Hz, 2H, H^1/H^7), 2.71 (t, J = 5.9 Hz, 2H, H^1/H^7). ES-MS: (m/z) 245.4 (MH^+).

N,N-Bis(2-pyrazylmethyl)-N′,N′-bis(ethylacetate)ethylenediamine. To a solution of crude N,N-bis(2-pyrazylmethyl)ethylenediamine (8.98 mmol) in dry acetonitrile (150 mL) under argon atmosphere were added ethylchloroacetate (2.32 mL, 21.57 mmol) and potassium carbonate (2.98 g, 21.57 mmol). After being stirred for 1 h at room temperature, the suspension was refluxed overnight and then cooled at room temperature, filtered, and evaporated. The resulting oil was purified by chromatography on aluminum oxide (200 mL, dichloromethane/ethanol, gradient from 100:0 to 95:5) to afford N,N-bis(2-pyrazylmethyl)-N′,N′-bis(ethylacetate)ethyl-

enediamine (1.38 g, 3.31 mmol) as a yellow oil. Yield: 37%. ^{1}H NMR (400 MHz, $CDCl_3$, 298 K): δ 8.74 (d, $J = 1.6$ Hz, 2H, H^6), 8.48 (dd, $J = 1.6$ and 2.4 Hz, 2H, H^3), 8.44 (d, $J = 2.4$ Hz, 2H, H^5), 4.13 (q, $J = 7.2$ Hz, 4H, $COOCH_2CH_3$), 3.93 (s, 4H, H^2), 3.53 (s, 4H, H^8), 2.98 (t, $J = 7.0$ Hz, 2H, H^7), 2.77 (t, $J = 7.0$ Hz, 2H, H^1), 1.24 (t, $J = 7.2$ Hz, 6H, $COOCH_2CH_3$,). ES-MS: (m/z) 417.3 (MH^+).

L^{pz}HK (N,N-Bis(2-pyrazylmethyl)ethylenediamine-N′,N′-diacetic Acid). A degassed 1 M KOH solution (5.6 mL, 5.60 mmol) was added to a stirred solution of N,N-bis(2-pyrazylmethyl)-N′,N′-bis(ethylacetate)ethylenediamine (0.962 g, 2.31 mmol) in H_2O/EtOH (3/1, 26 mL) solution, and the resulting mixture was stirred for 16 h under an argon atmosphere at room temperature. Then, the resulting solution was evaporated, and the pH was adjusted to 6.3 with a 1 M HCl aqueous solution. After evaporation, the resulting crude product was purified by chromatography on RP18 reverse-phase silica gel (100 mL, water/methanol, gradient from 100:0 to 98:2) to afford L^{2pz} (0.737 g, 1.66 mmol) as an orange oil. Yield: 72%. ^{1}H NMR (400 MHz, D_2O, 298 K): δ 8.61 (d, $J = 1.2$ Hz, 2H, H^6), 8.55 (dd, $J = 1.3$ and 2.6 Hz, 2H, H^3), 8.47 (d, $J = 2.7$ Hz, 2H, H^5), 4.02 (s, 4H, H^2), 3.75 (s, 4H, H^8), 3.58 (t, $J = 5.6$ Hz, 2H, H^7), 3.18 (t, $J = 5.6$ Hz, 2H, H^1). ^{13}C NMR (100 MHz, D_2O, 298 K): δ 170.08 (C9), 153.46 (C10), 144.99 (C6), 143.92 (C3), 143.00 (C5), 57.17 (C2), 56.13 (C8), 51.66 (C7), 48.49 (C1). ES-MS: (m/z) 359 ($M - H)^-$, 361 ($M + H)^+$. Elem anal. calcd (%) for $C_{16}H_{19}N_6O_4K \cdot 2.5H_2O$: C, 43.33; H, 5.45; N, 18.95. Found: C, 43.46; H, 5.18; N, 19.11.

Monocrystals suitable for X-ray diffraction were obtained by slow evaporation of the neutral form L^{pz}H$_2$ in propan-2-ol.

X-Ray Crystallography. The crystals were analyzed using a Bruker SMART CCD area detector three-circle diffractometer (Mo Kα radiation, graphite monochromator, $\lambda = 0.71073$Å). The cell parameters were obtained with intensities detected on three batches of 15 frames with an exposure time of 10 s for L^{py}H$_2$ and 180 s for L^{pz}H$_2$. The crystal-detector distance was 5 cm. For three settings of φ, narrow data frames were collected at 0.3° increments in ω. A quadrant of data was collected with a 30 s exposure time for L^{py}H$_2$. A hemisphere of data was collected with a 180 s exposure time for L^{pz}H$_2$. At the end of data collection, the first 50 frames were recollected to establish that crystal decay had not taken place during the collection. Unique intensities with $I > 10\sigma(I)$ detected on all frames using the Bruker program were used to refine the values of the cell parameters. The substantial redundancy in data allows empirical absorption corrections to be applied using multiple measurements of equivalent reflection with the SADABS Bruker program.[39] Space groups were determined from systematic absences, and they were confirmed by the successful solution of the structure (see Table 1). Complete information on crystal data and data collection parameters is given in the Supporting Information.

The structures were solved by direct methods using the SHELXTL 6.14 package,[40] and for all structures, all atoms, including hydrogen atoms, were found by difference Fourier syntheses. All non-hydrogen atoms were anisotropically refined on F^2. Hydrogen atoms were refined isotropically.

Potentiometry. All titrant solutions were prepared using water purified by passing it through a Millipore Milli-Q reverse-osmosis cartridge system (resistivity 18 MΩ cm). Carbonate-free 0.1 mol L^{-1} KOH and 0.1 mol L^{-1} HNO_3 were prepared from Fisher Chemicals concentrates. Potentiometric titrations were performed in 0.1 mol L^{-1} aqueous KNO_3 under an argon atmosphere; the temperature was controlled to ±0.1 °C with a circulating water bath. The p[H] (p[H] = −log[H$^+$], concentration in molarity) was measured in each titration with a combined pH glass electrode (Metrohm) filled with 3 mol L^{-1} KCl, and the titrant addition was automated by use of a 751 GPD titrino (Metrohm). The electrode was calibrated at hydrogen ion concentrations by the titration of HNO_3 with KOH in 0.1 mol L^{-1} KNO_3.[41] A plot of meter reading versus p[H] allows the determination of the electrode standard potential ($E°$) and the slope factor (f).

The ligand's concentration was determined by potentiometric titrations and was in accordance with the elemental analysis of the molecules. Lanthanide salt solutions were prepared by dissolving the appropriate amount of lanthanide nitrate in water. The exact metal ion concentration was determined by colorimetric titration using standardized EDTA solutions (Fisher Chemicals) and xylenol orange as an indicator. The americium stock solution was prepared by the dissolution of AmO_2 (100% ^{241}Am) in HNO_3 followed by Am(III) purification using a Dowex-50 cation-exchange resin.[31] Am(III) in 0.1 M HNO_3 was sorbed on the resin, washed several times with 0.1 M HNO_3, and eluted with 5 M HNO_3. Americium hydroxide was then precipitated, washed, and redissolved in dilute HNO_3. The americium concentration in this stock solution (0.028 M) was measured by UV−visible spectrophotometry and γ-spectrometry (energy 59.5 keV).

Continuous potentiometric titrations with 0.1 mol L^{-1} KOH were conducted in 20 mL of aqueous solutions containing 10^{-3} mol L^{-1} of the ligand and 0, 0.5, 1, and 2 equiv of the desired metallic cation. Back titrations with 0.1 mol L^{-1} HNO_3 were systematically performed after each experiment to check whether equilibration had been achieved. In a typical experiment, 100 points were measured with a 2 min delay between the measurements for the free ligand and a 5 min delay for metallic complexes. The titrations with ^{241}Am were performed in a dedicated glovebox.

Experimental data were refined using the computer program Hyperquad 2000.[42,43] All equilibrium apparent constants are expressed as concentration ratios and not activities. The ionic product of water at 25 °C and 0.1 mol L^{-1} ionic strength is pK_w =

Table 1. Crystallographic Data for the Structures of L^{py}H$_2$ and L^{pz}H$_2$

	L^{py}H$_2$ propan-2-ol	L^{pz}H$_2$ H$_2$O
formula	$C_{19.5}H_{26}N_4O_{4.5}$	$C_{16}H_{22}N_6O_5$
fw	388.44	378.40
T, K	298(2)	298(2)
cryst syst	orthorhombic	monoclinic
space group	*Iba*2	*P*2(1)/*c*
a, Å	26.188(5)	19.42(4)
b, Å	10.947(2)	7.104(15)
c, Å	14.206(3)	13.77(3)
α, deg	90	90
β, deg	90	108.45(3)
γ, deg	90	90
V (Å^3), Z	4072.5(14), 8	1803(7), 4
D_{calcd}, gcm^{-3}	1.267	1.394
μ (Mo Kα), mm^{-1}	0.091	0.106
R_1, wR_2[a] [$I > 2\sigma(I)$]	0.0723, 0.1590	0.0413, 0.0958

[a] Structure was refined on F_o^2 using all data: $wR_2 = [\sum[w(F_o^2 - F_c^2)^2]/\sum w(F_o^2)^2]^{1/2}$, where $w^{-1} = \sum(F_o^2) + (aP)^2 + bP$ and $P = [\max(F_o^2, 0) + 2F_c^2]/3$.

(39) *SMART*; *SAINT*; Siemens Analytical X-Ray Instruments Inc.: Madison, WI, 1995.
(40) Sheldrick, G. M. *SHELXTL-Plus*, version 5.1; Siemens Analytical X-ray Instruments Inc.: Madison, WI, 1998.
(41) Martell, A. E.; Motekaitis, R. J. *Determination and Use of Stability Constants*; VCH: New York, 1992.
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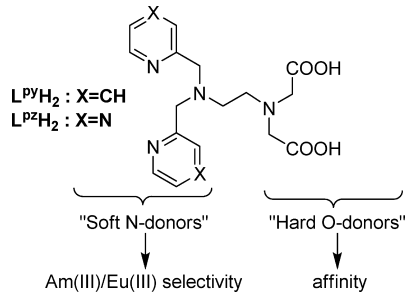
(43) Alderighi, L.; Gans, P.; Ienco, A.; Peters, D.; Sabatini, A.; Vacca, A. *Coord. Chem. Rev.* **1999**, *184*, 311–318.

Scheme 1. Design of the Two Ligands L^{py} and L^{pz}



13.78.[44] The initial concentrations of the ligand, metal, and proton were fixed, as well as the ligand's pK_a values for the metallic complex stability constant determination. All values and errors (one standard deviation) reported represent the average of at least three independent experiments.

NMR Spectroscopy. NMR spectra were recorded either on a UNITY or a MERCURY 400 Varian spectrometer. Samples for NMR spectroscopy were prepared by mixing appropriate volumes of stock solutions of the ligand (~0.005 mol L^{-1}) and the lanthanide chloride salt in deuterium oxide. The ligand's concentrations were determined by potentiometric titration, and the metal concentrations by EDTA titrations using xylenol orange as an indicator. The pD's of the samples were adjusted to the desired value by adding stock solutions of DCl or NaOD in D_2O. The pD's were measured according to $pD = pH_{read} + 0.41$.[45]

The spectra of the americium complexes were recorded on an INOVA 400 Varian spectrometer. The americium stock solution prepared in light water for potentiometric experiments was used to obtain the NMR samples. In that case, the proton NMR spectra were recorded using water presaturation solvent suppression.

Luminescence. Terbium and europium luminescence lifetimes were measured on a Perkin-Elmer LS50B spectrofluorimeter by recording the decay of the emission intensity at 545 nm for Tb and 616 nm for Eu (excitation at 274 nm). The decays of luminescence intensities followed systematically monoexponential laws and were analyzed as single-exponential decays. The instrument settings were as follows: a gate time of 1 ms, a flash count of 1, excitation and emission slit widths of 10 nm, and a varied delay time. The complexes were prepared in situ by mixing 0.9 equiv of the metal solution with 1 equiv of the ligand. The concentrations used were 1 mM for europium complexes and 0.5 mM for terbium complexes either in H_2O or D_2O. The pH (or pD) was then adjusted to 6.5−7 with a NaOH (or NaOD) solution. Reported lifetimes, τ, are the average of three separate measurements calculated by monitoring the emission intensity after at least 20 different delay times covering two or more lifetimes.

Results

Design and Synthesis of the N,O Ligands. In order to quantify the impact of N-donor softness on the coordination of f elements in aqueous solution, and in particular on the selectivity for Am(III) over Eu(III), we have designed the two tetrapodal hexadentate ligands L^{py} and L^{pz} (see Scheme 1). These ligands bear (i) two hard acetate groups to provide stability to the An(III) and Ln(III) complexes and (ii) two N-heterocyclic soft groups to provide Am(III) versus Eu(III) selectivity. These functions are introduced on an ethylene diamine bridge. L^{py} has a similar structure to the ligand bped developed by Orvig and co-workers to evaluate the effect of replacing an acetate group with a 2-pyridylmethyl group in EDTA,[46,47] except that the ethylene diamine bridge is non-symmetrically functionalized in L^{py}. The two ligands L^{py} and L^{pz} have similar chemical structures and differ only in the nature of the N-heterocycles.

The synthetic procedure for the ligand L^{py} is summarized in Scheme 2. First, condensation of 2-chloromethylpyridine with commercially available N-acetylethylenediamine in the presence of potassium carbonate and potassium iodide gave the corresponding N,N-bis(2-pyridylmethyl)-N′-acetylethylenediamine in 67% yield. After deprotection of the N-acetyl group by acid hydrolysis, subsequent reaction with ethyl chloroacetate in the presence of potassium carbonate gave the N,N-bis(2-pyridylmethyl)-N′,N′-bis(ethylacetate)ethylenediamine in 77% yield. Cleavage of the ethyl ester groups under acidic conditions using an aqueous HCl solution afforded the desired ligand L^{py} as the corresponding trihydrochloride salt. Simple filtration and subsequent washing with ethanol led to analytically pure $L^{py}H_2 \cdot 3HCl$ in 80% yield.

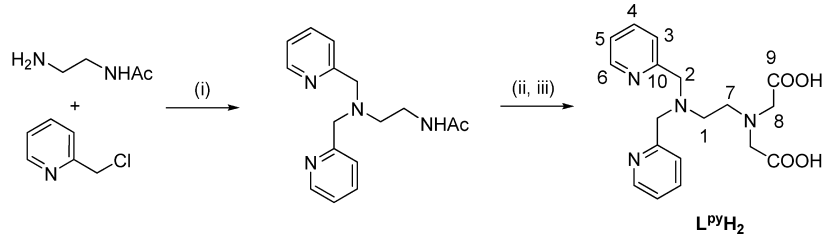
The synthetic procedure for the ligand L^{py} is summarized in Scheme 3. The analogous synthetic pathway using 2-chloromethylpyrazine, prepared from commercially available 2-methylpyrazine according to the previously published procedure,[18] afforded L^{pz} in five steps with a total yield of approximately 10%. The attempted cleavage of the ethyl ester groups under acidic conditions using a HCl solution gives a mixture of products probably due to the decomposition of the methylpyrazine units. The desired L^{pz} was obtained as the potassium salt by saponification using a KOH solution and purified by RP18 reverse-phase chromatography. The ligands L^{py} and L^{pz} were fully characterized by NMR, ESMS, and elemental analysis.

Crystal Structures of the Free Ligands. Crystals of the neutral diprotonated ligands were obtained by slow evaporation of a propan-2-ol solution of the ligands $L^{py}H_2$ and $L^{pz}H_2$. ORTEP diagrams of the two molecular structures are shown in Figure 1. The two ligands adopt zwitterionic forms in which the tertiary amine connected to the acetate groups is protonated, and one carboxylate function is also protonated. The orientations of the two acetate arms are similar in the two structures. The methylpyridine arms and the diethylene bridge adopt a helical conformation around the aliphatic nitrogen atom in the $L^{py}H_2$ structure, whereas the methylpyrazine arms and the diethylene bridge in $L^{pz}H_2$ adopt a pincerlike conformation.

The proton NMR spectra of the two ligands in D_2O indicate the presence of C_{2v}-symmetric species in which the two pyridine or pyrazine arms are equivalent, as well as the two acetate arms.

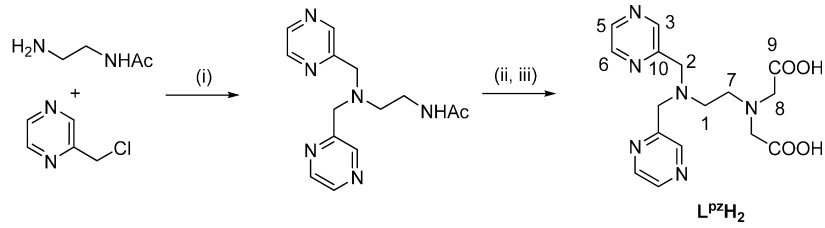
(44) Smith, R. M.; Martell, A. E.; Motekaitis, R. J. NIST Critically Selected Stability Constants of Metal Complexes Database, *NIST Standard Reference Database 46*; NIST: Gaithersburg, MD, 2001.
(45) Glasoe, P. K.; Long, F. A. *J. Phys. Chem.* **1960**, *64*, 188–190.
(46) Caravan, P.; Rettig, S. J.; Orvig, C. *Inorg. Chem.* **1997**, *36*, 1306–1315.
(47) Caravan, P.; Mehrkhodavandi, P.; Orvig, C. *Inorg. Chem.* **1997**, *36*, 1316–1321.

Scheme 2. Synthesis of the Ligand $L^{py}H_2$[a]



[a] Reagents and conditions: (i) K_2CO_3, KI, CH_3CN, reflux, 67%. (ii) a. HCl (1 M) quantitative; b. $ClCH_2COOEt$, K_2CO_3, CH_3CN, reflux, 77%. (iii) HCl (2 M), H_2O, 80%.

Scheme 3. Synthesis of the Ligand $L^{pz}H_2$[a]



[a] Reagents and conditions: (i) K_2CO_3, KI, CH_3CN, reflux, 78%. (ii) a. HCl (1 M) quantitative; b. $ClCH_2COOEt$, K_2CO_3, CH_3CN, reflux, 37%. (iii) KOH, $EtOH/H_2O$, 72%.

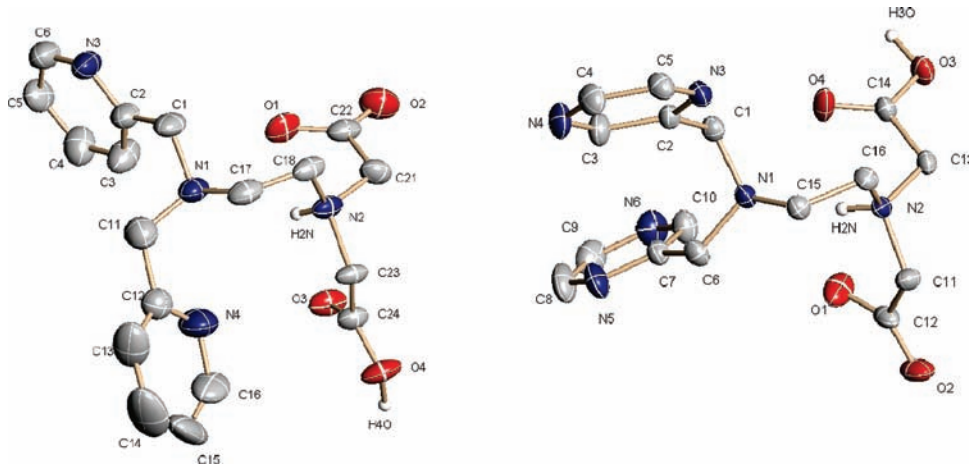


Figure 1. ORTEP diagrams of the diprotonated ligands $L^{py}H_2$ (left) and $L^{pz}H_2$ (right) with thermal ellipsoids at 30% probability.

Table 2. Protonation Constants of the Ligands L^{py} and L^{pz} from Potentiometric Measurements in Water and 0.1 M KNO_3 at 298 K

			L^{py}		L^{pz}	
	l	h	log β_{lh}	pK_a	log β_{lh}	pK_a
LH^-	1	1	9.60(6)	9.60(6)	9.35(8)	9.35(8)
LH_2	1	2	15.06(2)	5.46(8)	11.89(4)	2.5(1)
LH_3^+	1	3	18.43(3)	3.4(1)		

Protonation of the Ligands. All potentiometric studies have been performed in KNO_3 0.1 M at 298 K. The protonation constants of L^{py} and L^{pz} could be obtained from the titrations of the free ligands with KOH and HNO_3 and are listed in Table 2. The titration of $L^{py}H_2 \cdot 3HCl$ is indicative of three acidic sites. Variable-pH ^1H NMR spectroscopy allows assignment of the deprotonation scheme (see the Supporting Information, Figure S1). The first protonation (pK_{a1} = 9.60) occurs at the aliphatic nitrogen atom adjacent to the two acetate functions, like in EDTA. Indeed, at high pH, protons H_7 and H_8 experience the greatest chemical shift variations, 0.6 and 0.3 ppm, respectively. The other two protonations (pK_{a2} = 5.46 and pK_{a3} = 3.37) can be assigned either to the two nitrogen atoms of the pyridyl groups or to one aliphatic and one pyridyl nitrogen atom. From pH 6 to 3, the aromatic protons of the pyridines are significantly downfield-shifted, especially H_4 (0.6 ppm), as well as the aliphatic protons H_2 (0.5 ppm). As H_1 experiences only a little shift (0.2 ppm), we can assign the two lower pK_a values to the protonation of pyridines. The second aliphatic nitrogen atom of L^{py} does not protonate for pH > 2.5. The same protonation scheme was assigned for the ligand bped, which has similar pK_a values.[46]

The titration of $L^{pz}H_2$ is indicative of only two acidic sites. Variable-pH ^1H NMR spectroscopy (see the Supporting Information, Figure S2) indicates no significant change in the pyrazine proton chemical shifts between pH 2.5 and 12. At high pH, protons H_7 and H_8 experience great chemical shift variations, 0.7 and 0.5 ppm, respectively, demonstrating that the first protonation also occurs at the aliphatic nitrogen atom adjacent to the two acetate functions. This first pK_a is

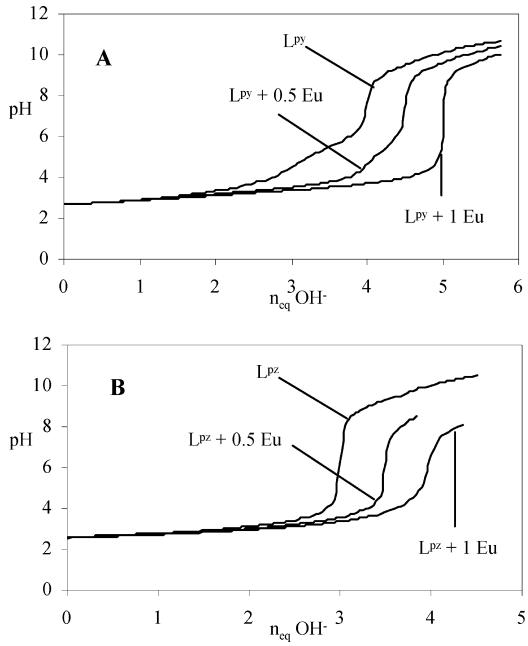


Figure 2. Alkalimetric titrations of solutions containing 10^{-3} M $L^{py}H_2 \cdot 3HCl$ (A) or $L^{pz}H_2 \cdot 2HCl$ (B) with 0, 0.5, and 1 equiv of $Eu(NO_3)_3$ in water and 0.1 M KNO_3 at 298 K.

Table 3. Stability Constants of the Complexes ML^{py+} and ML^{pz+} from Potentiometric Measurements in Water and 0.1 M KNO_3 at 298 K

	EDTA[a]	L^{py}	L^{pz}
log β_{110} La	15.5	9.86(6)	8.30(7)
log β_{110} Nd	16.6	11.46(1)	8.90(2)
log β_{110} Eu	17.3	11.62(4)	9.37(9)
log β_{110} Dy	18.3	11.89(2)	9.6(1)
log β_{110} Lu	19.9	13.05(6)	9.77(1)
log β_{110} Am	18.1	13.4(2)	12.1(1)
K_{sel}(Am/Eu)[b]	6	60	500

[a] From ref 41. [b] $K_{sel}(Am/Eu) = \beta_{110}(Am)/\beta_{110}(Eu)$.

slightly decreased in comparison to L^{py}, probably because of the larger electron-withdrawing effect of the methylpyrazyl groups in respect to methylpyridyl groups. Below pH 3.5, protons H_2 and H_1 are significantly downfield-shifted, 0.4 and 0.5 ppm, respectively, showing that the second protonation occurs at the other aliphatic nitrogen atom, adjacent to the methylpyrazinyl groups. This low pK_a value for a tertiary amine is explained by the strong electron-withdrawing effect of the methylpyrazyl groups.

As expected, the ligand L^{py} is much more basic than L^{pz} because the pyridine groups are more basic than the pyrazine groups: the pK_a of 2-methylpyridine is 5.96, whereas the pK_a of 2-methylpyrazine is only 1.65.[44]

Potentiometric Studies of the Lanthanide Complexes. The lanthanide complexes of the two ligands have been studied by potentiometric titrations for five representative cations of the 4f series, namely La(III), Nd(III), Eu(III), Dy(III), and Lu(III). Typical titration curves are shown for the europium cation in Figure 2 for L^{py} and L^{pz}. For every cation, these data could be fitted according to the formation of a unique metallic species, namely LnL^+, for pH values inferior to 7. The corresponding stability constants are given in Table 3. Above pH 7, the curves are characteristic of the formation of hydroxo complexes. Nevertheless, it was not possible to obtain reliable thermodynamic constants of the hydrolysis

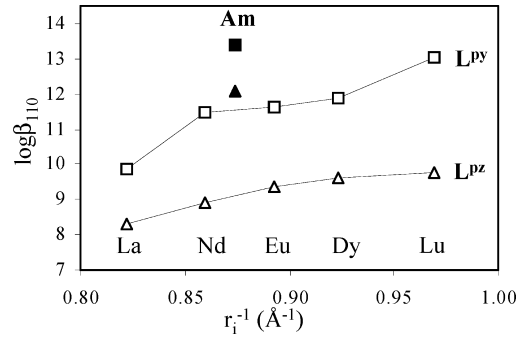


Figure 3. Evolution of the stability constants, log β_{110}, of ML^{py+} and ML^{pz+} as an inverse function of the cation ionic radii.

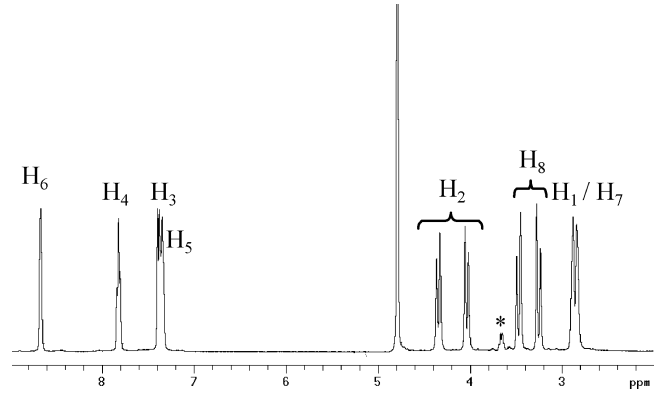


Figure 4. 400 MHz proton NMR spectrum of LaL^{py+} in D_2O (pD = 7.0) at 298 K.

reactions because a hysteresis exists between the direct titration with KOH and the back-titration with HNO_3 in this high-pH region.

The evolution of the stability constants as an inverse function of the cation ionic radii, related to the hardness of the ion, is represented in Figure 3 for the two ligands. As expected, both series of complexes show an increase of the complex stability from lanthanum to lutetium, according to the well-known electrostatic trend. The larger increase observed for L^{py} in comparison to L^{pz} can be attributed to the harder character of the pyridine in comparison to the pyrazine cycles that amplifies electrostatic effects across the lanthanide series.

^{1}H NMR Studies of Lanthanide Complexes. Diamagnetic Cations La^{3+} and Lu^{3+}. The proton NMR spectra of the diamagnetic complexes show the presence of only one set of signals, indicating the presence of one isomer having C_2 symmetry. The spectra of LaL^{py+} and LaL^{pz+} are presented in Figures 4 and 5, respectively. They were assigned with classical 2D NMR experiments. The aromatic protons are slightly shifted in respect to the free ligands. The splitting of H_2 and H_8 into AB patterns indicates that the aliphatic nitrogen atoms are coordinated to the lanthanide cation on the NMR time scale.[48] Whereas the AB patterns are well-resolved for protons H_8 for all complexes, Figure 5 shows that H_2 protons give a large AB system at 298 K in the complex LaL^{pz+}. This system becomes well-resolved when the temperature reaches 278 K. This behavior indicates that the coordination of the fragment containing the two pyrazine

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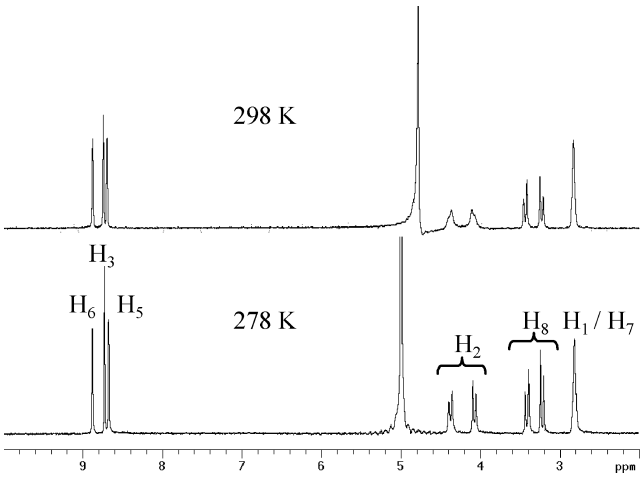

Figure 5. 400 MHz proton NMR spectra of LaL^{pz+} in D_2O (pD = 6.5) at 298 and 278 K.

groups is more labile than the coordination of the fragment containing the two pyridine groups.

As the ionic radius decreases from lanthanum to lutetium, the chemical shift separation between H_{2A} and H_{2B}, which are close to the aromatic rings, decreases from 0.30 to 0.05 ppm for both ligands. However, the chemical shift separation between H_{8A} and H_{8B}, which are close to the carboxylate groups, increases from 0.21 to 0.55 ppm for L^{py} and from 0.20 to 0.39 ppm for L^{pz}.

The formation of only one complex was confirmed by the spectra obtained either in excess of the ligand or in excess of the cation. Indeed, the same set of signals was obtained for the complex, in slow exchange with the ligand in default of the cation. Above pH 7, the proton signals of the complexes become larger, which is consistent with the formation of hydroxo complexes.

Paramagnetic Complexes. The spectrum of EuL^{py+} shows only a few broad resonances at 298 K, in agreement with the presence of slow exchange processes, the coalescence temperatures (T_C) of many protons being close to 298 K. When the temperature is increased to 363 K, these processes become faster, and the proton NMR spectra show only one set of nine sharper signals, which have been assigned using 2D NMR experiments (see the Supporting Information, Figure S3). This behavior can be attributed to exchanges between several conformations in the complex EuL^{py+}, as already described for a hexadentate tetrapodal N-donor ligand.[18] At high temperatures, namely, 363 K, an average C_2-symmetric conformation is detected. The same behavior was observed for the complexes TmL^{py+} and EuL^{pz+}.

Only the average conformation is observed for the diamagnetic lanthanum and lutetium complexes. Indeed, the chemical shift differences ($\Delta\nu$) between the exchanging protons of the different conformations are smaller than for paramagnetic species, and therefore the rate constant, k_C, at T_C, approximated by the relation, $k_C = \pi\Delta\nu/\sqrt{2}$, is also expected to be smaller. Then, the coalescence temperature is expected to be lower for the diamagnetic complexes, which explains why spectra with sharp resonances corresponding to an average conformation are detected for the lanthanum and lutetium complexes at 298 K.

Table 4. Luminescence Lifetimes and Calculated Hydration Numbers (q)

	τ_{H_2O} (ms)	τ_{D_2O} (ms)	q^a
EuL^{py+}	0.28(1)	1.35(1)	3.1(2)
EuL^{pz+}	0.29(1)	2.03(1)	3.2(2)
TbL^{py+}	1.02(3)	2.77(2)	2.8(2)
TbL^{pz+}	0.89(3)	2.24(2)	3.1(2)

[a] The hydration numbers, q, were calculated using the equation of Parker and co-workers:[49] $q = A_{Ln}(1/\tau_{H_2O} - 1/\tau_{D_2O} - \alpha_{Ln})$, with $A_{Tb} = 5$ ms, $A_{Eu} = 1.2$ ms, $\alpha_{Tb} = 0.06$ ms^{-1}, and $\alpha_{Eu} = 0.25$ ms^{-1}.

Hydration Numbers of the Lanthanide Complexes. Due to the different quenching efficiencies of the O−H and O−D oscillators, the measurements of Eu(III) or Tb(III) luminescence lifetimes of the excited state of the complex (τ) in H_2O and D_2O allow an estimation of the number of coordinated water molecules (q) present in solution. The empirical equations of Parker and co-workers,[49] which are corrected versions of the equations of Horrocks and Sudnick[50,51] accounting for closely diffusing OH oscillators, can then be used. The calculated number of coordinated water molecules is 3 within the experimental errors (see Table 4). We can therefore conclude that the hydration numbers are the same for the lanthanide complexes with the pyridine-based ligand L^{py} and the pyrazine-based ligand L^{pz}.

As expected, the collected data show that the environments of the trivalent lanthanide cations in the complexes of L^{py} and L^{pz} are very similar. L^{py} and L^{pz} act as hexadentate ligands with two aliphatic nitrogen atoms, two aromatic nitrogen atoms of either pyridine or pyrazine moieties, and two oxygens of carboxylates as coordinating groups. Three water molecules complete the Ln(III) coordination sphere in each case. The only difference between these two systems is the replacement of pyridines with pyrazines, which allows an appropriate comparison of these two types of aromatic N donors.

Americium (III) Complexes. Proton NMR and potentiometry experiments were performed with Am(III) in order to get the complexation properties of this minor actinide with the two ligands L^{py} and L^{pz}. Potentiometric titrations show very similar behavior to what was obtained with lanthanides. As Am(III) is more acidic than Ln(III), the titrations were stopped just after the end point around pH 6−7. The back-titrations were carefully recorded to ensure that the ligand was not subjected to radiolysis due to the radioactive α-emitting americium cation, for the duration of the entire experiment. The titration curves could be fitted with a unique complex corresponding to a 1:1 stoichiometry, AmL^+. The affinity constant values are reported in Table 3. Interestingly, the stability constants found with Am(III) are significantly higher than those previously obtained with Ln(III).

Very few NMR experiments on samples containing americium have been published.[52] Am(III) has a $5f^6$ configuration leading to a $^7F_0$ ground-state term (Russel-Saunders term) as Eu(III). This fundamental state is diamagnetic

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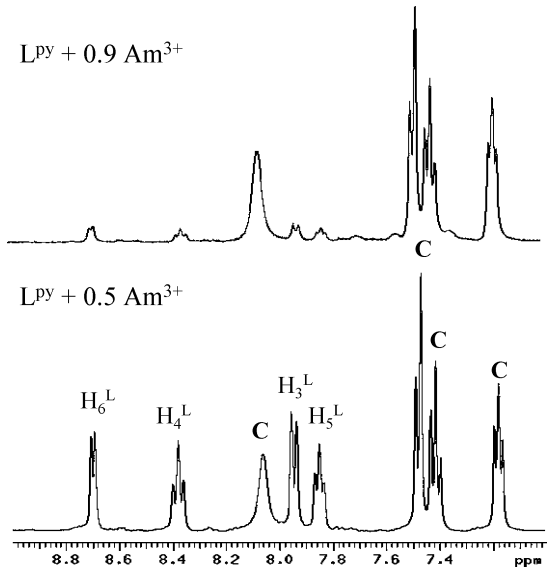

Figure 6. Aromatic region of the 400 MHz proton NMR spectra of L^{py} with 0.5 and 0.9 equiv of Am^{3+} in H_2O/D_2O (10/90 v/v; pD = 6), at 298 K. The C indicates the proton resonances of the Am^{3+}complex.

(spin−orbit coupling, $J = 0$), and therefore the paramagnetism of Am(III) is only due to the contribution of the paramagnetic excited states of lowest energies. It has been shown that the magnetic behaviors of isoelectronic lanthanide and actinide ions are similar, but differences exist, notably between Am(III) and Eu(III). Indeed, the effective magnetic moment of Am(III) is significantly lower than that of Eu(III).[53−55] Therefore, the paramagnetic contributions to the proton chemical shifts and the relaxation times in the NMR spectra are expected to be weaker for Am(III) than Eu(III). In this study, the proton NMR spectra of the ligands were recorded with various amounts of Am(III) at pH 6 and at room temperature. The spectra in the aliphatic region show only a few large NMR resonances, as in the case of Eu(III) complexes, whereas in the aromatic region, one set of proton resonances clearly appears in the presence of Am(III). The aromatic region of the spectra recorded for the AmL^{py+} complex is presented in Figure 6. The four (L^{py}) or three (L^{pz}) aromatic protons experience rather small paramagnetic chemical shifts of only a few tenths of a part per million, and half-widths of only a few hertz, as expected from the magnetic properties of Am(III) discussed above. These data confirm the formation of only one Am(III) C_2-symmetric complex with each ligand.

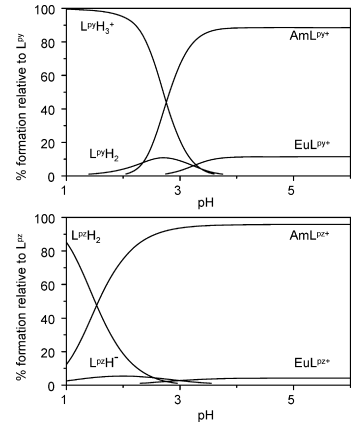

Figure 7. Speciation diagrams of solutions containing 1 mM of the ligand, Eu(III), and Am(III). The stability constants tabulated in Tables 2 and 3 were used to generate these diagrams.

Discussion

The two ligands L^{py} and L^{pz} have been designed to study their f-element complexes in water and to compare the complexation properties of the two aromatic N-donor groups, pyridine and pyrazine, for Am(III) versus Eu(III). Thanks to the presence of two acetate functions in their EDTA-like structure, the affinity of L^{py} and L^{pz} for lanthanide ions is strong enough to be measured accurately in water. The proton NMR and potentiometric analyses performed on the lanthanide complexes of the two ligands indicate that a unique metallic complex, LnL, is formed and that LnL^{py+} and LnL^{pz+} have the same structure in water. Furthermore, the hydration numbers of the europium and terbium ions in these complexes, measured by luminescence decay, have the same value ($q \approx 3$), which is very close to the value found for $Ln(edta)^-$ complexes. Indeed, depending on the empirical equations used, the hydration number of the lanthanide ion in $Ln(edta)^-$ complexes was found to be between 2.6 and 3.0 for Eu and between 2.8 and 2.9 for Tb.[49,50,56] This indicates that L^{py} and L^{pz} act as hexadentate ligands like the parent molecule EDTA. The neutral pyridine donor has already been demonstrated to be an effective ligating group for the lanthanides in tripodal or tetrapodal ligands' architectures, in the highly competing solvent water.[12,47,57] We demonstrate here that the weak N-donor pyrazine, introduced in EDTA-like structures, also coordinates Ln(III) in water. The structures of LnL^{py+} and LnL^{pz+} being similar in solution, the evolution of the stability constants from L^{py} to L^{pz} is directly correlated to the replacement of two pyridine groups by two pyrazine groups.

L^{py} and the ligand bped developed by Orvig et al. differ only by the respective positions of the two pyridine and the two acetate groups.[46,47] In addition, the lanthanide complex stability constants are very close for L^{py} and bped and range from 10 to 13 log units from La(III) to Lu(III). The increase of the stability constants across the 4f series is common and of the same order of magnitude as EDTA ($\log \beta_{Lu} - \log \beta_{La} \approx 3$, 30%). Indeed, as lanthanides are hard cations, they give mainly electrostatic

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interactions which increase with the hardness of the cation, and therefore when the ionic radius of the lanthanide ion diminishes from lanthanum to lutetium. The electrostatic trend is less marked for the second ligand L^{pz} ($\log \beta_{Lu} - \log \beta_{La} \approx 1.5$, 18%), which can be attributed to the softer character of the pyrazine-based ligand, which produces smaller electrostatic interactions and therefore a smoother electrostatic evolution of the stability constants across the 4f series.

As expected, the softer pyrazine-based ligand gives less-stable complexes than the pyridine-based ligand with the hard Ln(III) or Am(III) cations. Indeed, 2-methylpyrazine is a much weaker base than 2-methylpyridine, as exemplified by the values of their pK_a, 5.96 (py) and 1.65 (pz).[44] To compare the contributions of the fragments $N-(CH_2-X)_2$ to the complex stabilities in the EDTA-like chelate structures, we can consider that each $N-(CH_2-COO^-)_2$ in EDTA contributes equally to the stability of the Eu(III) complex, for 17.3/2 = 8.65 log units. The contribution of the fragments $N(CH_2X)_2$ can then be deduced from the log β_{110} found for the EuL^{py+} and EuL^{pz+} complexes. So the fragments $N-(CH_2-py)_2$ and $N-(CH_2-pz)_2$ contribute for 3.0 and 0.7 log units, respectively. It appears clearly that the fragment containing two pyrazine groups has a very low contribution to the stability of the lanthanide complexes, even though we have demonstrated by luminescence lifetime measurements that the pyrazine groups are coordinated to the cation in water. In addition, the coordination of pyrazine functions to lanthanide ions was also evidenced in the solid state or in acetonitrile solutions in the tripodal or tetrapodal N-donor ligands tpza and tpzen.[12,17]

As commonly observed with polyaminocarboxylates, the stabilities of the Am(III) complexes are slightly greater than those of the isoelectronic Eu(III) complexes. To evaluate the effect of the softness of the ligand on the selectivity for Am(III) over Eu(III), it is interesting to compare the three hexadentate ligands, EDTA, L^{py}, and L^{pz}, which have similar architectures with increasing soft character. Whereas the stability constants with the hard trivalent f cations decrease as the softness of the ligand increases, the selectivity for Am(III) over Eu(III) enhances: $K_{sel}(Am/Eu) = \beta_{Am}/\beta_{Eu} = 10^{0.8} = 6$ (EDTA), $10^{1.8} = 60$ (L^{py}), and $10^{2.7} = 500$ (L^{pz}). Interestingly, the ligand tpen bearing four pyridine groups has a selectivity constant $K_{sel}(Am/Sm) = 100$,[30] a higher value than L^{py}. This indicates that a greater number of soft donors coordinated to the f cation (here pyridines) induces a higher thermodynamic selectivity. Nevertheless, the selectivity obtained with tpen remains significantly lower than that measured with L^{pz}, which bears only two soft N-donor pyrazines.

These results clearly demonstrate that, for a series of ligands with similar chemical architectures, the selectivity for Am(III) over Ln(III) is correlated with the softness of the molecules and in particular of the N-donor groups coordinated to the cation. The selectivity for Am(III) over Eu(III) increases by a factor 8 when the pyridine-containing fragment $N(CH_2py)_2$ in L^{py} is substituted with the pyrazine-containing fragment $N(CH_2pz)_2$ in L^{pz}. The two ligands L^{py} and L^{pz} present attractive selectivities for Am(III) over Eu(III) that could be exploited to separate these two families of cations. In particular, the ligand L^{pz} combines many advantages that could make it a good candidate for the selective back extraction of Am(III) from organic solutions containing 4f and 5f elements: (i) It has good selectivity for Am(III) over Ln(III). (ii) Despite its soft character due to the presence of the two pyrazine groups, it has significant affinity for f ions in water due to the two acetate groups. (iii) Finally, because of its low basicity, it has still efficient conditional stability constants at pH 2−3. It can be seen on the speciation diagrams given in Figure 7 that, in an equimolar Am/Eu solution, L^{pz} is able to selectively complex Am(III) versus Eu(III) at low pH (95/5 at pH 2).

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Supporting Information Available: Proton NMR pH titrations of the two ligands. Temperature-dependent proton NMR spectra of EuL^{py+}. This material is available free of charge via the Internet at http://pubs.acs.org.

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