Hydrophobic tartaric acid monoamides as complexing and tensioactive agents

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A simple method for the preparation of monoamide derivatives of tartaric acid is proposed. The direct synthesis of the products HOOC–CHOH–CHOH–CONHR, where R is an alkyl chain with 3, 8, 10 or 14 carbons, from tartaric acid and the corresponding amines is described. The tensioactive properties of the C_8 molecule have been evaluated; this compound forms micelles in water and the critical micellar concentration has been measured. The complexing ability of these molecules toward the trivalent lanthanide cation Pr(III) has been checked with the C_3 compound. The formation of a neutral complex and the hydrophobic character of these molecules make them good candidates for liquid–liquid extraction in order to extract and separate lanthanide(III) ions.

Tartaric and gluconic acids belong to the category of polyhydroxylated carboxylic acids, the complexing properties of which are well known.[1] In a preliminary work[2] we have shown that gluconic acid presents good complexing ability towards lanthanide(III) cations with selectivity along the series. The use of hydrophobic analogues of this molecule as extracting agents can be envisaged. Preparing hydrophobic derivatives of gluconic acid without losing the complexing properties of this molecule is not easy. This is why we set out to synthesize hydrophobic complexing compounds from tartaric acid by branching a long chain onto one of the two carboxylic functions. The complexing part (*i.e.*, the carboxylic and the two OH functions), which looks like that of gluconic acid, is in this way kept. The choice of tartaric acid was also made because of the symmetry of the molecule. Regardless of which side of the molecule is modified by reaction on one carboxylic acid function, the final products are the same. In order to make this molecule more hydrophobic, the esterification of one carboxylic function by an alcohol with a large number of carbon atoms is a possibility, but esters are sensitive to hydrolysis. Another solution consists of preparing monoamide derivatives.

In this paper we report a simple and efficient method to synthesize the fatty monoamides HOOC–CHOH–CHOH–CONHR, where R is a C_3, C_8, C_{10} or C_{14} alkyl chain, by the direct reaction of tartaric acid with the corresponding amines without a coupling agent. The compound with a propyl chain was prepared in order to study the complexing properties of these amides towards the trivalent lanthanide cation Pr(III) in aqueous solutions, as this compound is largely soluble in water, in contrast to the other molecules with longer chains. One of our aims was to verify the ability of this molecule to form a neutral complex with the lanthanide(III) cations and to see if the complexation strength is comparable to that of gluconic acid (see above). Additionally the tensioactive properties of the C_8 compound have been evaluated as well as its ability to form micelles in water (the other molecules are not soluble enough for such a study). Finally, we checked the potential of these compounds for liquid–liquid extraction of the praseodymium(III) ion with the C_8 compound. The study of the complexation and extraction of trivalent lanthanides is justified by the search for ligands that show selectivity for cations along the lanthanide series.

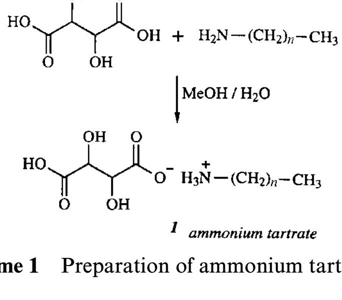
Results and discussion

Synthesis of the monoamides (tartramides)

The usual method for the preparation of monoamides from dicarboxylic acids is to utilize the intramolecular anhydride as in the case of the synthesis of monoesters.[3] The application of this approach to tartaric acid is however limited: protection of the hydroxyl groups is necessary to the stability of the anhydride.[4–13] Another route is *via* the use of sulfinylamines.[14] In these multistep methods the obtention of the intermediates is not always easy.

In this work we use a more direct and simple method for the formation of amides. The first step involves a simple addition of the fatty amine to the tartaric acid (Scheme 1). The quantity of solvent is a major factor shifting the equilibrium and favouring the formation of the salt. L-(+)-Tartaric acid is dissolved in a minimum of water (4×10^{-3} mol per mL of water) and 1 equiv. of the amine suspended or dissolved in methanol (6×10^{-3} mol per mL of methanol) is added slowly. Heating is necessary to homogenize the mixture in the case of the long-chain compounds. The monosalts are obtained, after filtration or evaporation, almost quantitatively as white crystalline solids, which were characterized by IR and NMR (^{1}H and ^{13}C) spectroscopies and microanalyses.

The second step is the pyrolysis of the salts. These compounds are dissolved in toluene or in heptane and the mixture is heated under azeotropic reflux, leading to the formation of the desired amide (tartramide) **2** and cyclic imide (tartrimide) **3** (Scheme 2) or exclusively **3** for prolonged heating conditions. The proportions of these two compounds depend on the length of the chain and on the time of heating (Table 1).



1 *ammonium tartrate*

Scheme 1 Preparation of ammonium tartrates.

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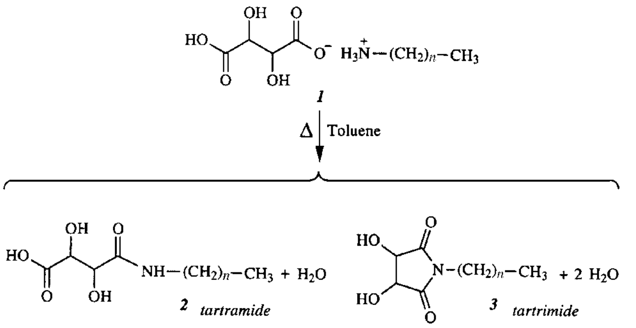


Scheme 2 Pyrolysis of ammonium tartrates.

However, in the case of C_3 or C_8 tails, tartrimides **3** react with 1 equiv. of sodium hydroxide to afford the monoamide-monocarboxylate in good yields (Table 2 and Scheme 3).

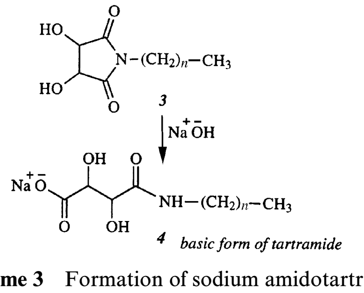
Complexing properties in aqueous solution

The complexing properties of the monoamides synthesized have been studied for the propyl chain (C3T) bearing ligand, which is soluble in water and cannot form micelles because of the shortness of the C_3 alkyl chain. The study was initially performed by potentiometry, which involves titrating the ligand alone and then in the presence of a cation with soda. The titration curves allow the nature of the complexes formed in solution to be determined and their formation constants evaluated (see experimental section). The cation chosen for this study was Pr(III); this cation presents relatively simple UV–visible spectra and does not induce large signal broadening in the NMR spectra.

The results of the simulation of the titration curves show the existence of the following three complexes: ML, MLH_{-1} and MLH_{-2} (the acidic form of the ligand is noted LH). Another species is evidenced in basic solutions: MLH_{-3} or $M_2L_2H_{-5}$. Therefore, from the calculations, there are two systems of complexes compatible with the potentiometric results. Systems 1 and 2 differ only in the species formed in basic media. The corresponding formation constants are summarized in Table 3. The values of log β are very similar for the species present in both systems.

Table 1 Proportions of compounds **1**, **2** and **3** obtained from the pyrolysis of propylammonium tartrate

Time of heating/h	**1**(%)	**2**(%)	**3**(%)
6	50	23	27
14	10	13	77
24	<1	<1	99
48	0	0	100



Scheme 3 Formation of sodium amidotartrate.

Table 2 Synthesis yields of the final products for different values of *n*

n	3	8	10	14
Final product	**4a**	**4b**	**2a**	**2b**
Designation	C3T	C8T	C10T	C14T
Yield(%)	95	95	40	80

Table 3 Logarithm of the formation constants (log β_{pqr}) of the complexes for the system Pr(III)–C3T, obtained from potentiometric measurements[a]

	System 1	System 2
ML	2.76 ± 0.02	2.72 ± 0.02
MLH_{-1}	-3.66 ± 0.02	-3.69 ± 0.02
MLH_{-2}	-10.71 ± 0.01	-10.75 ± 0.01
MLH_{-3}	-22.34 ± 0.03	—
$M_2L_2H_{-5}$	—	-29.98 ± 0.04

[a] The acidity constant of the ligand is 3.02 ± 0.01.

ML corresponds probably to a complex in which the carboxylate group is coordinated to the cation, this species appearing at pH 2. The β_{110} value found in this work ($\beta_{110} = 560$) is of the same order of magnitude as that found by Powell *et al.*[15] for 2,3-dihydroxy-2-methylpropanoate ($\beta_{110} = 887$) or 2,3-dihydroxy-2-methylbutanoate ($\beta_{110} = 903$). These authors also propose the formation of complexes ML_2 and ML_3, which have not been observed in this study. For the species MLH_{-1} and MLH_{-2}, deprotonated hydroxyl functions are also probably bound to the cation, leading to the formation of five-membered rings. For the binuclear species $M_2L_2H_{-5}$, it could be considered that two MLH_{-2} entities are linked by a hydroxo bridge. MLH_{-3} would be formed from the complex MLH_{-2} in which a water molecule of the coordination sphere would be deprotonated.

The distribution diagrams for the two systems are shown in Fig. 1. It can be seen that the complexation of the cation Pr^{3+} starts at low pH values, the species ML being predominant up to pH ~6. At pH 9, the main species is MLH_{-2}.

It should also be noted that the species MLH_{-2} is neutral; thus it can be envisaged that the molecules synthesized in this work could be used for liquid–liquid extraction of trivalent lanthanides. The value of log β corresponding to the formation of this complex is very close to that observed in the case of gluconic acid[2] (log $\beta_{11\text{-}2} = -10.1$).

The potentiometric study was completed by spectroscopic studies in order to confirm the above proposed structures and to ascertain which type of complex (MLH_{-3} or $M_2L_2H_{-5}$) is actually formed in basic solutions.

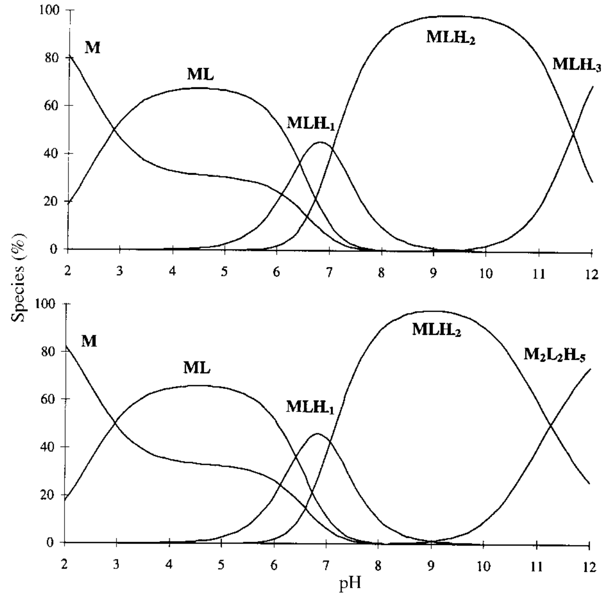


Fig. 1 Distribution diagrams for Pr(III)–C3T (0.005 mol L^{-1}) drawn from the results reported in Table 3 for a metal-to-ligand ratio equal to 1 : 3. Top: System 1; bottom: System 2.

First, a UV–visible spectrophotometry study was performed. The cation Pr^{3+} presents absorption bands in the visible domain. We were more particularly interested by the transitions $^3P_2$, $^3P_1$ and $^3P_0$. Although the shifts of the bands due to complexation are weak—as is often the case with lanthanide ions[16]—new bands are nevertheless observed when the pH is varied [Fig. 2(*a*)]. The spectra obtained are consistent with the formation of the four different complexes obtained from the potentiometric experiments. Each band can be split into four peaks [Fig. 2(*b*)] from a calculation taking into account the concentrations of the species given by the pH-metric results (see experimental).

Circular dichroism (CD) experiments were also carried out in the wavelength range of 430–500 nm, corresponding to the ^3P transitions of the Pr(III) ion. CD effects are observed as a consequence of the proximity of chiral centres (carbons in the α and β positions relative to the carboxylate and/or deprotonated alcohol functions). Spectra for 4 different pH values are presented in Fig. 3. For pH 5, a very small effect is observed, confirming that coordination takes place on the carboxylate group and that the chiral sites are not involved in coordination to the metal ion. At pH 6, parallel to the formation of MLH_{-1}, a CD spectrum arises due to the coordination of the deprotonated α-OH group. At pH 8, when the MLH_{-2} species is predominent, the CD spectrum is modified (for example, the signal at 470 nm becomes positive); this can be explained by the intervention in the coordination sphere of the second deprotonated hydroxyl function. There are some changes in the intensities of the peaks in the spectrum at pH 10.4, proving the existence of another complex ($M_2L_2H_{-5}$ or MLH_{-3}) in which the same coordination sites as in the above-mentioned species are involved.

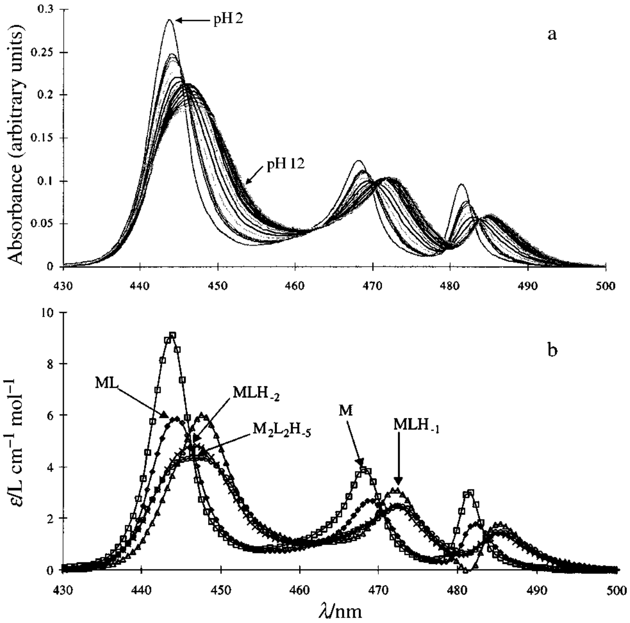


Fig. 2 Visible spectrophotometric spectra of the system Pr(III)–C3T in a 1 : 2.5 ratio ([Pr(III)] = 0.03 mol L^{-1}) in the wavelength range 430—500 nm: (*a*) Evolution of the spectra from pH 2 to pH 12. (*b*) Calculated ε values for the five species present in solution, as a function of λ.

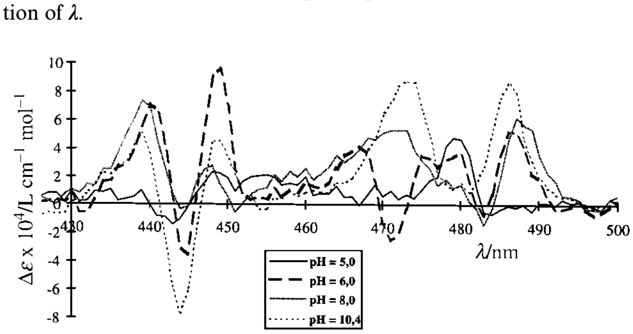


Fig. 3 Circular dichroism spectra of Pr(III)–C3T (1 : 2) solutions ([Pr(III)] = 0.05 mol L^{-1}) for different pH values: (——) 5.0, (– – –) 6.0, (——) 8.0 and (····) 10.4.

CD spectra recorded for ligand-to-metal ratios equal to 1 : 1 and 1 : 2 are similar; this means that 1 : 2 complexes are not formed and the potentiometric results are confirmed.

The ^{13}C NMR study of the system Pr^{3+}–C3T shows that, at low pH, the carboxylate group is bound to the cation since the corresponding signal is shifted and broadened because of the interaction between this group and the paramagnetic cation. For a M : L ratio of 1 : 20, the carboxylate signal is shifted more than 5 ppm whereas that of the CO group of the amide function is essentially stationary. The chemical shifts of the signals corresponding to carbons bearing OH groups are increased by ~2 ppm. The signals of the propyl chain are not affected. Around pH ~7, where the species MLH_{-1} is predominant, the signal of the carboxylate group is considerably broadened, as well as the signals of the carbons in the α and β positions relative to this group. This observation is consistent with a situation in which the alcoholate groups are bound to the cation.

It is seen in the ^1H NMR spectra that, at pH ~4 at which the ML species predominates, the hydrogens of the CHOH groups are shifted to low field. The most shifted signal (Fig. 4) probably corresponds to the hydrogen close to the carboxylic

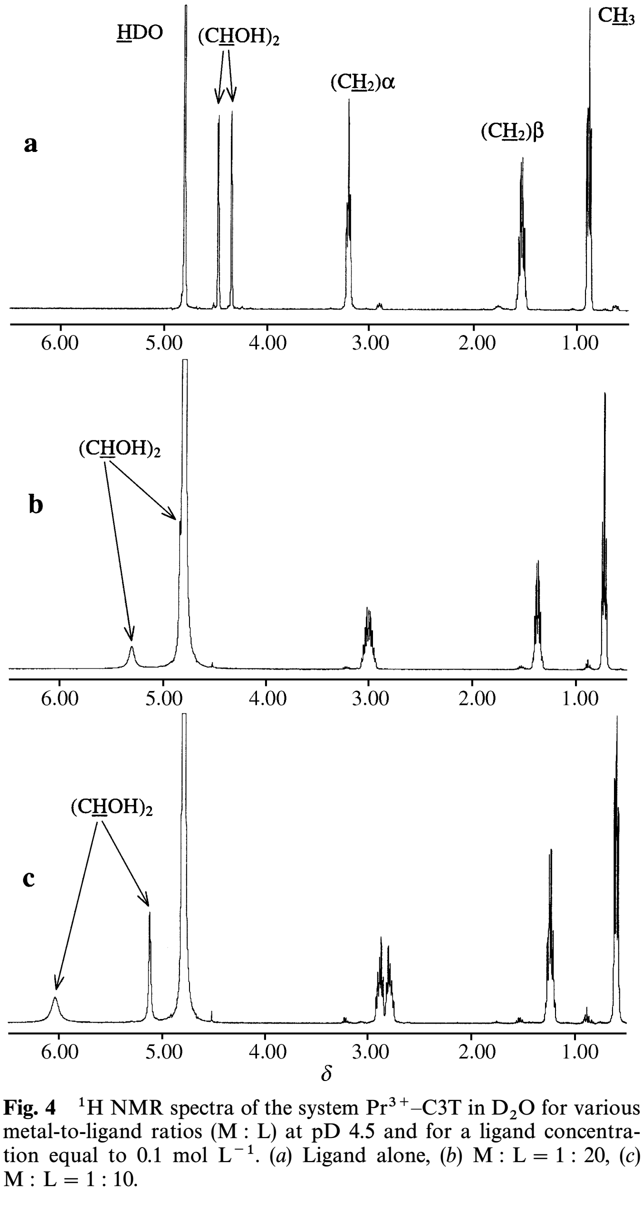


Fig. 4 ^1H NMR spectra of the system Pr^{3+}–C3T in D_2O for various metal-to-ligand ratios (M : L) at pD 4.5 and for a ligand concentration equal to 0.1 mol L^{-1}. (*a*) Ligand alone, (*b*) M : L = 1 : 20, (*c*) M : L = 1 : 10.

function. These significant shifts could indicate complexation by the non-deprotonated α-hydroxyl group, which would lead to the formation of MLH_{-1} consecutively to the deprotonation of the function when pH is increased. At pH 7 the signals of the hydrogen atoms in the α and β positions relative to the carboxylate group are much broadened (but little shifted). They are more broadened than at pH 4 for identical ligand-to-metal ratios. This could indicate that, in the species MLH_{-1}, an alcohol function is ionized due to its coordination to the cation Pr^{3+}.

At basic pH values, the ^1H and ^{13}C NMR signals are narrow. Even for low ligand-to-metal ratios, signals are not shifted relative to the free ligand and are very little broadened. The integrals of the ligand signals correspond to the amount of free ligand present and it can be concluded that a certain amount of the ligand is missing. This indicates that the signals corresponding to the bound ligand are probably very broad and/or shifted and are not detected. This also indicates that the exchange between free and bound molecules is slow. This situation is observed for the paramagnetic cation Pr^{3+} as well as for the diamagnetic cation Lu^{3+}. As the signals of the ligand bound to the diamagnetic cation Lu(III) cannot be greatly shifted, this means that the signal corresponding to the bound molecules is very broad and is not detected in our NMR experiments. This observation could mean that polymeric species of the type $(M_2L_2H_{-5})_n$ or $(MLH_{-3})_n$ are formed at high pH values. In these species, MLH_{-2} entities would be linked together by hydroxo bridges, for instance. The weak mobility of these chains would explain the existence of very broad signals that are not detected in the NMR experiments. It can be noted that the potentiometric measurements cannot discriminate between mono or polymeric species since, in each case, the quantity of soda used for producing these species is the same. In summary, the NMR results are consistent with the potentiometric ones but they do not allow us to determine the exact stoichiometry of the species formed in basic media.

Surfactant properties

Compounds with an alkyl chain of 10 or 14 carbon atoms are not very soluble at 25 °C in water but the surface tension of the saturated solution (*i.e.* $\gamma_{\mathrm{C10}}^{\mathrm{saturated}} = 34.7$ mN m^{-1}) is lowered compared to that of water, indicating that these molecules have some tensioactive character. No Krafft temperature was observed up to 60 °C.

The C8T compound is soluble enough at 25 °C in water at pH 10 (at this pH value, the compound is fully ionized and the solubility is about 0.11 mol L^{-1}) that the surface tension of the solution varies significantly within this concentration range. The variation is linear with the logarithm of the concentration up to a certain value, beyond which it is constant (Fig. 5). This clearly indicates that C8T forms micelles in water with a critical micellar concentration (CMC) equal to 5.4×10^{-2} mol L^{-1}. Although the presence of a polar part more hydrophilic than in the linear carboxylates (owing to the OH groups in the α and β positions relative to the carboxylate), the CMC of C8T is situated between that of sodium decanoate (CMC = 9.55×10^{-2} mol L^{-1}) and that of sodium dodecanoate (CMC = 2.30×10^{-2} mol L^{-1})[17] as if the OH groups and the amide function do not contribute much to the hydrophilicity of the molecule. By applying the Gibbs equation the area per polar head can be evaluated as 48 Å^2.

Liquid–liquid extraction of the Pr(III) ion

As mentioned above, a neutral species MLH_{-2} is formed above pH ∼7 and it can be envisaged that the praseodymium(III) ion could be extracted in this form into an organic phase. Preliminary studies of liquid–liquid extraction of Pr(III) aqueous solutions (∼10^{-3} mol L^{-1}) by C8T dissolved in CH_2Cl_2 were performed. The concentration of Pr(III) in the aqueous phase was followed by UV–visible spectrophotometry. The pH of the aqueous solution was maintained constant (pH ∼7.2) by addition of a tris(hydroxymethyl)aminomethane buffer solution. The quantity of the extractant was 10 times that of the metal and the ratio of the organic phase volume to that of the aqueous phase was 2 : 1. Under these conditions extraction of the Pr(III) ion occurs but the complex formed is not soluble enough in the organic phase and a precipitate appears at the interface between the two phases. The complex MLH_{-2} is insufficiently hydrophobic because the coordination sphere of the cation is probably completed by water molecules, in addition to the ligand.

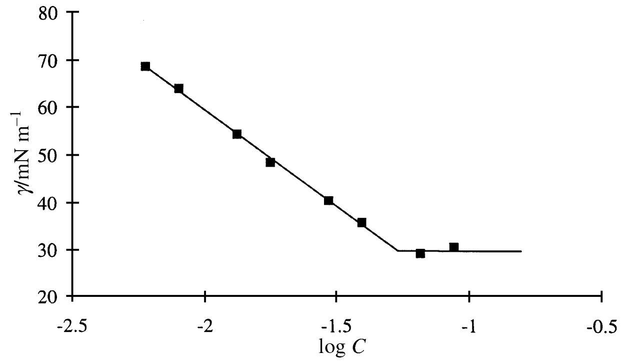


Fig. 5 Surface tension γ of aqueous solutions of the monoamide C8T as a function of the logarithm of the surfactant concentration at pH 10 and 25 °C.

If tributylphosphate (TBP) is added to the organic phase (two moles of TBP per mole of cation), total extraction of the ligand (in the limit of the detection of the visible absorption bands) is performed without precipitation. The TBP molecules probably enter into the coordination sphere of the Pr(III) cation (replacing water molecules), leading to the formation of a hydrophobic species soluble in the organic phase. It must be noted that, under the same conditions but using only TBP as extractant, the lanthanide(III) cation is not extracted. These preliminary results prove the ability of the monoamide ligands in extracting lanthanide(III) ions.

Conclusion

Monoamide derivatives of tartaric acid have been synthesized. It has been shown that these molecules have complexing properties towards trivalent lanthanide cations, forming, among four different complexes, a neutral complex. Preliminary extraction experiments were performed, showing that these compounds can be envisaged as extracting agents. Additional work is in progress in order to study these properties more thoroughly. Only the C8T compound has been used for the extraction study but the other molecules with longer alkyl chains should also be investigated. The choice of the diluent in the liquid–liquid extraction experiments is crucial because compounds with a longer tail than an octyl chain are not soluble in dichloromethane, the solvent used in this work. The tensioactive properties of these molecules are also very interesting and the extraction of cations by ultrafiltration of complexing micelles could be envisaged.

Experimental

All reagents and solvents were reagent grade and were used without purification. NMR spectra (^1H and ^{13}C) were recorded on Bruker AC 250 or AM 400 spectrometers; the chemical shifts are reported in ppm downfield from tetramethylsilane (TMS). The IR spectra were recorded on a Perkin–Elmer

1600 FTIR spectrometer. The progress of the reaction and the purity of the products were evaluated on silica gel thin layer chromatographic (TLC) plates (Merck, Kieselgel 60 F_{254}). Melting points were determined by an Electrothermal electronic apparatus and were not corrected. Elemental analyses were performed by the Centre National de la Recherche Scientifique (CNRS) at Vernaison (France); they are in agreement with the corresponding structures and illustrative results are reported for some compounds.

Typical procedure for the preparation of the salts 1 derived from tartaric acid

In a round-bottom flask, 32 mmol (5 g) of (*R*,*R*)-tartaric acid [L-(+)-tartaric acid] were dissolved in a minimum of water (10 mL). To this well-stirred solution was added dropwise 1 equiv. of fatty amine dissolved in a small amount of methanol (8 mL). For the compounds with a tail of three or eight carbons, the solution was evaporated under reduced pressure and the residual product washed with diethyl ether (3 × 25 mL) and dried. For the compounds with a longer tail the resulting precipitate was filtered and washed with diethylether (3 × 25 mL).

Characterisation of the products

The products are obtained as white crystalline powders. The chemical shifts of the α and β methylene groups (^{1}H NMR) of the fatty chain are characteristic of an ammonium structure and the chemical shift of the C=O signal at 177.9 ppm (^{13}C NMR) is representative of a carboxylate moiety.

(*R-R*)-Propylammonium tartrate. Mp = 150 °C. ^{1}H NMR ($\mathrm{CD_3OD}$): 1.00 (t, 3H, $^3J = 7.5$ Hz, $\mathrm{C}\mathit{H}_3\mathrm{CH_2CH_2NH_3^+}$); 1.75 (m, 2H, $\mathrm{CH_3C}\mathit{H}_2\mathrm{CH_2NH_3^+}$); 2.90 (t, 2H, $^3J = 7.5$ Hz, $\mathrm{CH_3CH_2C}\mathit{H}_2\mathrm{NH_3^+}$); 4.45 (s, 2H, $\mathrm{-C}\mathit{H}\mathrm{OH}$).

(*R-R*)-Octylammonium tartrate. Mp = 100 °C. ^{1}H NMR ($\mathrm{CD_3OD}$): 0.85 [t, 3H, $^3J = 10$ Hz, $\mathrm{C}\mathit{H}_3\mathrm{(CH_2)_5CH_2CH_2NH_3^+}$]; 1.40 [m, 10H, $\mathrm{CH_3(C}\mathit{H}_2\mathrm{)_5CH_2CH_2NH_3^+}$]; 1.75 [m, 2H, $\mathrm{CH_3(CH_2)_5C}\mathit{H}_2\mathrm{CH_2NH_3^+}$]; 2.95 [t, 2H, $^3J = 12$ Hz, $\mathrm{CH_3(CH_2)_3CH_2C}\mathit{H}_2\mathrm{NH_3^+}$]; 4.45 (s, 2H, $\mathrm{-C}\mathit{H}\mathrm{OH}$). Elem. anal. ($\mathrm{C_{12}H_{25}O_6N}$) % calcd. (found): C 51.60 (51.66); H 9.02 (9.07); N 5.01 (5.07).

(*R-R*)-Decylammonium tartrate. Mp = 122 °C. ^{1}H NMR ($\mathrm{CD_3OD}$): 0.90 [t, 3H, $^3J = 10$ Hz, $\mathrm{C}\mathit{H}_3\mathrm{(CH_2)_7CH_2CH_2NH_3^+}$]; 1.40 [m, 14H, $\mathrm{CH_3(C}\mathit{H}_2\mathrm{)_7CH_2CH_2NH_3^+}$]; 1.70 [m, 2H, $\mathrm{(CH_3(CH_2)_7C}\mathit{H}_2\mathrm{CH_2NH_3^+}$]; 2.95 [t, 2H, $^3J = 12$ Hz, $\mathrm{CH_3(CH_2)_7CH_2C}\mathit{H}_2\mathrm{NH_3^+}$]; 4.45 (s, 2H, $\mathrm{-C}\mathit{H}\mathrm{OH}$). Elem. anal. ($\mathrm{C_{14}H_{29}O_6N}$) % calcd. (found): C 54.70 (55.29); H 9.51 (9.68); N 4.56 (4.12).

(*R-R*)-Tetradecylammonium tartrate. Mp = 117 °C. ^{1}H NMR ($\mathrm{CD_3SOCD_3}$–TFA): 0.85 [t, 3H, $^3J = 7.5$ Hz, $\mathrm{C}\mathit{H}_3\mathrm{(CH_2)_{11}CH_2CH_2NH_3^+}$]; 1.25 [m, 22H, $\mathrm{CH_3(C}\mathit{H}_2\mathrm{)_{11}C}\mathit{H}_2\mathrm{C}\mathit{H}_2\mathrm{NH_3^+}$]; 1.50 [m, 2H, $\mathrm{CH_3(CH_2)_{11}C}\mathit{H}_2\mathrm{CH_2NH_3^+}$]; 2.75 [m, 2H, $\mathrm{CH_3(CH_2)_{11}CH_2C}\mathit{H}_2\mathrm{NH_3^+}$]; 4.35 (s, 2H, $\mathrm{-C}\mathit{H}\mathrm{OH}$).

Common characteristics. IR: $\nu_{(\mathrm{NH_3^+})}$ and $\nu_{(\mathrm{OH})}$ 3000–3600 cm^{-1} (br); $\nu_{(\mathrm{COO^-})}$ and $\nu_{(\mathrm{COOH})}$ 1710–1715 cm^{-1} (br). ^{13}C NMR ($\mathrm{CD_3OD}$ or $\mathrm{CD_3SOCD_3}$–TFA): 15.0 [$\mathit{C}\mathrm{H_3(CH_2)}_n\mathrm{CH_2CH_2NH_3^+}$]; 24.5–31.4 [$\mathrm{CH_3(}\mathit{C}\mathrm{H_2)}_n\mathrm{CH_2CH_2NH_3^+}$]; 33.8 [$\mathrm{CH_3(CH_2)}_n\mathit{C}\mathrm{H_2CH_2NH_3^+}$]; 41.5 [$\mathrm{CH_3(CH_2)}_n\mathrm{CH_2}\mathit{C}\mathrm{H_2NH_3^+}$]; 75.0 ($\mathit{C}\mathrm{HOH}$); 177.9 ($\mathit{C}$=O).

Typical procedure for the preparation of the sodium alkylamidotartrate 4

In a round-bottom flask equipped with a Dean Stark apparatus, 30 mmol of the corresponding salt were placed in suspension of 50 mL of anhydrous toluene and allowed to stand at reflux with stirring until complete consumption of the salt (48–72 h). After cooling to room temperature, the solution was filtered to remove toluene. For the C_3 and C_8 products the residual oil (mixture of compounds **2** and **3** or exclusively **3**) was then treated with NaOH (0.1 mol L^{-1}) in water (30 mL). Sodium hydroxide was added to obtain pH 7. The solvent was then evaporated under reduced pressure at 50 °C. For the other compounds, the oil (a mixture of compounds **2** and **3**) was washed with diethyl ether to remove product **3**.

Characterisation of the products

Common characteristics. IR: $\nu_{(\mathrm{NH})}$ and $\nu_{(\mathrm{OH})}$ 3200–3500 cm^{-1} (br); $\nu_{(\mathrm{COOH})}$ 1740 cm^{-1}; $\nu_{(\mathrm{COO^-})}$ 1620 cm^{-1}; $\nu_{(\mathrm{CONH})}$ 1650 cm^{-1}.

Sodium (*R-R*)-propylamidotartrate 4a. Mp = 215 °C (decomp.). $[\alpha]_D^{23} = +72.0°$ ($\mathrm{CH_3OH}$, *c* = 1). ^{1}H NMR ($\mathrm{D_2O}$): 0.81 (t, 3H, $^3J = 7.25$ Hz, $\mathrm{-CONH-CH_2CH_2C}\mathit{H}_3$); 1.45 (m, 2H, $\mathrm{-CONH-CH_2C}\mathit{H}_2\mathrm{CH_3}$); 3.13 (t, 3H, $^3J = 6.75$ Hz, $\mathrm{-CONH-C}\mathit{H}_2\mathrm{CH_2CH_3}$); 4.26 (d, 1H, $^3J = 2$ Hz, $\mathrm{-C}\mathit{H}\mathrm{OH}$); 4.39 (d, 1H, $^3J = 2$ Hz, $\mathrm{-C}\mathit{H}\mathrm{OH}$). ^{13}C NMR ($\mathrm{D_2O}$): 13.2 ($\mathrm{-CONH-CH_2CH_2}\mathit{C}\mathrm{H_3}$); 23.1 ($\mathrm{-CONH-CH_2}\mathit{C}\mathrm{H_2CH_3}$); 43.4 ($\mathrm{-CONH-}\mathit{C}\mathrm{H_2CH_2CH_3}$); 77.0 ($\mathrm{-}\mathit{C}\mathrm{HOH}$); 178.9 ($\mathit{C}$=O). Elem. anal. ($\mathrm{C_7H_{12}O_5NNa}$) % calcd. (found): C 39.45 (39.32); H 5.67 (5.69); N 6.57(6.61); Na 10.77 (10.81).

Sodium (*R-R*)-octylamidotartrate 4b. Mp = 204 °C (decomp.). $[\alpha]_D^{23} = +47.9°$ ($\mathrm{CH_3OH}$, *c* = 1). ^{1}H NMR ($\mathrm{CD_3COCD_3}$): 0.83 [t, 3H, $^3J = 7$ Hz, $\mathrm{-CONH-CH_2CH_2(CH_2)_5C}\mathit{H}_3$]; 1.22–1.32 [m, 10H, $\mathrm{-CONH-CH_2CH_2(C}\mathit{H}_2\mathrm{)_5CH_3}$]; 1.51 [m, 2H, $\mathrm{-CONH-CH_2C}\mathit{H}_2\mathrm{(CH_2)_5CH_3}$]; 3.23 [t, 2H, $^3J = 7$ Hz, $\mathrm{-CONH-C}\mathit{H}_2\mathrm{CH_2(CH_2)_5CH_3}$]; 4.43 (d, 1H, $^3J = 2$ Hz, $\mathrm{-C^2}\mathit{H}\mathrm{OH}$); 4.55 (d, 1H, $^3J = 2$ Hz, $\mathrm{-C^3}\mathit{H}\mathrm{OH}$). ^{13}C NMR ($\mathrm{D_2O}$): 13.2 [$\mathrm{-CONH-CH_2CH_2(CH_2)_5}\mathit{C}\mathrm{H_3}$]; 23.0–29.3 [$\mathrm{-CONH-CH_2CH_2(}\mathit{C}\mathrm{H_2)_5CH_3}$]; 32.0 [$\mathrm{-CONH-CH_2}\mathit{C}\mathrm{H_2(CH_2)_5CH_3}$]; 39.2 [$\mathrm{-CONH-}\mathit{C}\mathrm{H_2CH_2(CH_2)_5CH_3}$]; 77.0 ($\mathrm{-}\mathit{C}\mathrm{HOH}$); 178.9 ($\mathit{C}$=O).

(*R-R*)-Alkylamidotartaric acid (*C10T* and *C14T*) 2a and 2b. Mp = 110 °C (*C10T*); 156 °C (*C14T*). $[\alpha]_D^{23} = +46.9°$ ($\mathrm{CH_3OH}$, *c* = 1) (*C14T*). ^{1}H NMR ($\mathrm{CD_3OD}$): 0.94 [t, 3H, $^3J = 7$ Hz, $\mathrm{-CONH-CH_2CH_2(CH_2)}_n\mathrm{C}\mathit{H}_3$]; 1.30–1.40 [m, 2*n*H, $\mathrm{-CONH-CH_2CH_2(C}\mathit{H}_2\mathrm{)}_n\mathrm{CH_3}$]; 1.57 [m, 2H, $\mathrm{-CONH-CH_2C}\mathit{H}_2\mathrm{(CH_2)}_n\mathrm{CH_3}$]; 3.28 [t, 2H, $^3J = 7$ Hz, $\mathrm{-CONH-C}\mathit{H}_2\mathrm{CH_2(CH_2)}_n\mathrm{CH_3}$]; 4.46 (d, 1H, $^3J = 2$ Hz, $\mathrm{-C^2}\mathit{H}\mathrm{OH}$); 4.55 (d, 1H, $^3J = 2$ Hz, $\mathrm{-C^3}\mathit{H}\mathrm{OH}$). ^{13}C NMR ($\mathrm{CD_3OD}$): 13.4 [$\mathrm{-CONH-CH_2CH_2(CH_2)}_n\mathit{C}\mathrm{H_3}$]; 22.7–29.5 [$\mathrm{-CONH-CH_2CH_2(}\mathit{C}\mathrm{H_2)}_n\mathrm{CH_3}$]; 32.0 [$\mathrm{-CONH-CH_2}\mathit{C}\mathrm{H_2(CH_2)}_n\mathrm{CH_3}$]; 39.2 [$\mathrm{-CONH-}\mathit{C}\mathrm{H_2CH_2(CH_2)}_n\mathrm{CH_3}$]; 72.1 and 73.3 ($\mathrm{-}\mathit{C}\mathrm{HOH}$); 173.1 and 174.4 ($\mathit{C}$=O). Elem. anal. % calcd. (found) (*C14T*): C 61.90 (62.58); H 10.09 (10.21); N 4.03 (4.05).

The melting point of the C_8 compound in its acidic form has been measured (mp = 151 °C) and corresponds to the values published in the literature.[12,18]

pH-Metric measurements

The protonation and coordination equilibria were investigated by potentiometric titrations in aqueous solution at a constant ionic strength (0.1 mol L^{-1} $\mathrm{NaClO_4}$ and $T = 298 \pm 0.1$ K) under argon atmosphere using an automatic titration apparatus including a Dosimat 665 (Metrohm) autoburette, an Orion-710A precision digital pH-meter and an Orion 9103SC type combined glass electrode. The species formed in the systems were characterized by the following general equilibrium process:

$$pM + qL + rH \rightleftharpoons M_pL_qH_r \quad (\beta_{pqr})$$

$$\beta_{pqr} = \frac{[M_pL_qH_r]}{[M]^p[L]^q[H]^r}$$

[where M denotes the lanthanide(III) cation and L the non-protonated ligand molecule]. Charges are omitted for simplicity, but can be easily calculated taking into account that the fully protonated ligands are denoted LH. A detailed description of the experimental procedure and data evaluation (from the PSEQUAD computer program[19]) was reported earlier.[20]

The protonation and the complex formation constants were determined from 4 and 8 independent titrations (~100 data points per titration), respectively. The metal-to-ligand ratios varied between 1 : 1 and 1 : 6, using lanthanide(III) concentrations ranging from 1×10^{-3} to 5×10^{-3} mol L^{-1}. pH-Metric data between pH 2 and 11.3 were used for the evaluation.

For the analysis of the titration curves, the formation of the hydroxo complex MOH^{2+} (MH_{-1}) was taken into consideration, with a formation constant value (log $\beta_{10\text{-}1}$) equal to -8.82.[21]

The acidity constant for the compound C3T was found to equal 3.02.

UV–Visible spectrophotometry and circular dichroism experiments

The visible absorption and CD spectra were recorded on a Varian Cary 3E UV/Vis spectrophotometer and on a Jobin–Yvon DCG circular dichroism spectrophotometer, respectively.

The concentration in Pr(III) for visible absorption spectrophotometry was 3×10^{-2} mol L^{-1} initially. pH was varied by addition of soda or perchloric acid. The different spectra were normalized by considering the band of the nitrate anions, the intensity of which depends only on the concentration of these ions (and not on pH). The ligand-to-metal ratio was 2 : 1.

Knowing the concentrations of the five possible species present in solution (M_{aquo}, ML, MLH_{-1}, MLH_{-2}, $M_2L_2H_{-5}$) from the potentiometric results and using the Beer–Lambert equation, we could compute the ε values of each complex as a function of the wavelength taking into account five spectra recorded at five different pH values:

$$D_i(\lambda) = \sum_j \varepsilon_j(\lambda) \cdot C_{ji} \cdot l$$

where j denotes one of the five complexes ($j = 1$ to 5) and $i = 1$ to 5 for the five different pH values.

CD spectra were recorded on solutions of Pr(III) with a concentration equal to 5×10^{-2} mol L^{-1}. The ligand-to-metal ratio was 1 : 1 or 2 : 1.

NMR spectroscopy and surface tension measurements

^{13}C and ^1H NMR spectra for the complexation studies were recorded on a Bruker DRX 400 apparatus at 100.6 and 400 MHz, respectively. ^1H chemical shifts in aqueous solutions were measured relative to DSS (sodium 2,2-dimethyl-2-silapentan-5-sulfonate). The chemical shift of the DSS signal is the same as that of TMS.

The surface tension was measured at 25 °C using the Wilhelmy plate method (Krüss digital tensiometer K10T).

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