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Article

Understanding the Recovery of Rare-Earth Elements by Ammonium Salts

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Abstract: While the recovery of rare earth elements (REEs) from aqueous solution by ionic liquids (ILs) has been well documented, the metal compounds that are formed in the organic phase remain poorly characterized. Using spectroscopic, analytical, and computational techniques, we provide detailed chemical analysis of the compounds formed in the organic phase during the solvent extraction of REEs by [(n-octyl)3NMe][NO3] (IL). These experiments show that REE recovery using IL is a rapid process and that IL is highly durable. Karl-Fischer measurements signify that the mode of action is unlikely to be micellar, while ions of the general formula REE(NO3)4(IL)2− are seen by negative ion electrospray ionization mass spectrometry. Additionally, variable temperature 139La nuclear magnetic resonance spectroscopy suggests the presence of multiple, low symmetry nitrato species. Classical molecular dynamics simulations show aggregation of multiple ILs around a microhydrated La3+ cation with four nitrates completing the inner coordination sphere. This increased understanding is now being exploited to develop stronger and more selective, functionalized ILs for REE recovery.

Keywords: ionic liquids; extraction; rare-earths; mass-spectrometry; computational modelling

1. Introduction

Ionic liquids (ILs) are particularly desirable as reagents and solvents due to their ability to be tailored through the modification of their cation and anion components, and their perception as having “green credentials” due to their negligible vapor pressure, high thermal stability, and non-flammability [1]. They are often immiscible with aqueous phases, and this feature, combined with their other properties, has been exploited in the separation and recovery of metals such as the rare earth elements (REEs) by solvent extraction [2–8]. The use of ILs in solvent extraction processes can minimize extractant loss, reduce environmental contamination, and limit the use of volatile organics as diluents [3,9]. This contrasts with the purification of REEs in China by traditional solvent extraction techniques, which have been found to produce 20 million tons of wastewater contaminated with, in some cases, an excess of 50 g/L of organic compounds [10]. ILs are therefore not only research curiosities, but also have strategic industrial importance.

The transport of REEs from aqueous (acidic) solutions into an immiscible IL phase has been extensively studied for a variety of hydrophobic ILs, and some, but not always complementary, insight into the mechanisms of extraction has been gained [2]. The transport of Nd or Eu in a biphasic aqueous/C4mim*Tf2N− IL system (C4mim = N-methyl-N-butylimidazolium; NTf2− = bis(triflimide) anion \[\text{N(SO}_2\text{CF}_3\text{)}_2\]) by the acetylacetonate 2-thenoyltrifluoroacetone (tta) has been shown by Extended X-ray Absorption Fine Structure (EXAFS) spectroscopy, molecular dynamics (MD) simulations, and fluorescence lifetime measurements to proceed through the formation of
the ion pair [C₄mim][Ln(tta)(Tf₂N)] [11]. Further studies have shown that the water molecules in the hydrate [Eu(tta)₂(OH₂)₃] are substituted by the Tf₂N⁻ anion, with the [Ln(tta)(Tf₂N)]⁻ anion identified in the ESI-MS of the IL phase [12]. ILSs of hydrophobic ammonium (R₃N⁺, where R is an alkyl chain) and phosphonium (R₄P⁺) cations with a variety of coordinating anions have been studied; anions of the phosphorus acids tend to favor recovery of the heavy REEs, whereas the use of more simple anions such as nitrate or Tf₂N⁻ favors light REE recovery. For example, the alkyl ammonium chloride Aliquat® 336 (A336, MeR₃NCl, where R = 2:1 C₈-C₁₀ alkyl chains of various isomers [13]) when used in combination with the anion of the dialkylphosphoric acid, D2EHPA, ((RO)₂P=O(OH), R = 1′BuCH₂(CH₃)CHCH₂) or the phosphinic acid Cyanex® 272 (R₂P(O)(OH), R = 1′BuCH₂(CH₃)CHCH₂) produces bifunctional ionic liquid extractants (Bif-ILs) which recover Nd and Pr from aqueous acidic chloride [14]; slope analyses suggest a 3:1 Bif-IL:Ln stoichiometry in the transported species, possibly LnCl₃(Bif-IL)₃. Similar A336/dialkylphosphinate or diglycolamate Bif-ILs recovered europium from acidic nitrate solutions and slope analysis suggested a 3:1 Bif-IL:Ln stoichiometry consistent with Eu(NO₃)₃(Bif-IL)₃ [15]. In contrast, combinations of A336 and the trialkylphosphateon, DEHEHP, ((RO)₂P=O, R = 2-ethylhexyl) have been found to recover REEs from acidic nitrate under high nitrate salt conditions, in this case by the formation of either Ln(NO₃)₃(DEHEHP)₃ or the ion pairs [A336]ₙ⁻₁[Ln(NO₃)₅] as suggested by slope analysis and infrared (IR) spectroscopy [3]. Furthermore, a Bif-IL comprising PR₃R⁺ cations (R = hexyl, R' = tetradecyl) and Cyanex® 272 anions extracts the heavy REEs preferentially, but in this case slope analysis and release of acid on REE transport suggests the formation of Ln(O₂P(PR₃R)₂) complexes through a cation-exchange mechanism [16].

While [A336]Cl does not extract REEs from aqueous solution, it is well known that [A336]NO₃ is effective for light REE recovery, particularly under high aqueous nitrate concentrations (through salting-out [17]) [18,19]. This effect has been exploited in REE separation using [A336]NO₃ and EDTA (ethylenediamine tetraacetic acid) to partition the light and heavy REEs in the IL and the aqueous phase, respectively [20]. Initial interpretations of the mechanism of transport by [A336]NO₃ suggest the formation of ion pairs [A336]₀⁻₃[Ln(NO₃)₃] or alternatively IL adducts of neutral Ln complexes, i.e., Ln(NO₃)₃([A336]NO₃)₃. Further studies have proposed, through slope analysis, the formation of simple lanthanide nitrate anions [A336]Ln(NO₃)₃ or those with more complex speciation [A336]Ln(NO₃)₄(atenORM) [21]. The discrete ion pairs [A336][Ln(NO₃)₃] and [A336][Ln(NO₃)₄] may also be observed, as suggested by Nuclear Magnetic Resonance (NMR) [22,23], IR [24], and UV-vis spectroscopic analysis [22], and X-ray crystallography (see, for example, [25–27]). The relevant hexakis(nitrato) lanthanide ion Nd(NO₃)₆³⁻ has been characterized by EXAFS in dry [C₄mim][Tf₂N] and shows high stability constants by optical spectroscopy [25], whereas in wet [C₄mim][Tf₂N] ElectroSpray Ionization Mass Spectrometry (ESI-MS) analysis suggests the formation of Eu(NO₃)₅⁻ ions [29]. ILS comprising [PR₃R⁺] cations (R = hexyl, R’ = tetradecyl) and nitrate anions have also been exploited in the separation of REEs from Co and Ni by solvent extraction, with slope analysis suggesting the formation of the ion pairs [PR₃R⁺]₂Sm(NO₃)₅ and [PR₃R⁺]₂La(NO₃)₆ in the IL phase [30].

While it is clear that hydrophobic ILs and Bif-ILs are effective in the extraction and separation of REEs, with or without added organic diluent, the species formed in the hydrophobic phase are diverse and poorly characterized, which impacts the chemical understanding of the separation process. The formation of ion pairs of various stoichiometries is prevalent, yet seemingly counterintuitive, as we have shown computationally that nitrate anions are more likely to be bound in the outer-sphere of a hydrated Ln³⁺ cation, e.g., [Ln(OH₂)₆][NO₃]₃ [31]; this is supported by the lack of extraction of Ln nitrates by common anion exchangers that have been exploited extensively for the recovery of halometalates of transition metals [32–34]. Herein, we review the recovery of REEs by the simple analogue of [A336]NO₃, [l⁶octyl]NMeNO₃ (IL) under high NaNO₃ conditions and provide characterization of the extracted species by ¹³⁹La NMR spectroscopy, ESI-MS, and computational modelling in order to understand better the mode of action of these reagents.
2. Materials and Methods

2.1. Materials

Unless otherwise stated, all solvents and reagents were purchased from Sigma-Aldrich (Gillingham, UK), Fisher scientific UK (Loughborough, UK), Alfa Aesar (Heysham, UK), Acros Organics (Geel, Belgium), or VWR international (Lutterworth, UK) and used without further purification. Deionised water was produced using a Milli-Q purification system (Sigma-Aldrich, Gillingham, UK).

2.2. Characterisation and Computational Techniques

NMR spectra were recorded at 298K on a Bruker AVA400, AVA500 or AVA600 spectrometer (Coventry, UK) operating at 399.90, 500.12, or 599.95 MHz, respectively, for $^1$H, and 100.55, 125.76, or 150.83 MHz, respectively, for $^{13}$C. ESI-MS measurements were recorded in negative-ion mode using the standard Bruker ESI sprayer operated in “infusion” mode coupled to a Bruker SolariX Fourier transform ion cyclotron resonance mass spectrometer (Bruker Daltronics, Coventry, UK). Direct infusion spectra were a sum of 10 acquisitions. All mass spectra were analyzed using DataAnalysis software version 4.1 SR1 build 359 (Bruker Daltronics, Coventry, UK) and ions were assigned manually. A Perkin Elmer Optima 8300 Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES) (Beaconsfield, UK) was used to determine metal concentration (in 1-methoxy-2-propanol). Samples were taken up by a peristaltic pump at a rate of 1.0 mL·min$^{-1}$ into a Gem Tip cross flow nebulizer and glass cyclonic spray chamber. Conditions for plasma, auxiliary, and nebulizer argon gas flows were 18, 1.5, and 0.5 L·min$^{-1}$ with 1500 W RF forward power, respectively. ICP-OES external calibration standards were obtained from VWR International or Sigma-Aldrich. Karl-Fischer titrations were carried out using a Mettler-Toledo Coulometric KF Titrator C30S with DM 143-SC probe (Leicester, UK), and pH measurements were obtained using a Mettler Toledo Excellence Titrator T5 with a DGi115-SC probe (Leicester, UK). Nitrate anion concentrations were determined using an ICS-110 RFIC ion chromatography system with AS22 diluent. Infrared spectrum were acquired using a Nicolet Avatar 360 FT-IR spectrometer (Fisher Scientific, Loughborough, UK).

Classical molecular dynamics (MD) simulations were employed using the Optimized Potentials for Liquid Simulations—All Atoms (OPLS-AA) force field within the Large Scale Atomic/Molecular Parallel Simulations (LAMMPS) software package from Sandia National laboratories, Albuquerque, NM, USA [35]. An initial model, comprising three ILs, three $\text{NO}_3^-$, three $\text{H}_2\text{O}$, and one $\text{La}^{3+}$ randomly distributed in a cubic simulation cell of length 60 Å was constructed using Packmol [36]. The generated xyz file was then converted into a LAMMPS data file using the Visual Molecular Dynamics (VMD) Topo tools [37]. The optimized geometries for the ammonium cation (octyl)$_3\text{NMe}^+$, $\text{NO}_3^-$, toluene, and water were obtained using the Gaussian 09 program (Gaussian Inc., Wallingford, UK) and with the B3LYP/6-31G** level of theory applied to all atoms present [38]. Structures were considered optimized when the forces and atomic displacements fell to within the program default convergence criteria. The integration time step of the MD simulations was set to 0.5 fs, and time increments accrued using the standard Velocity-Verlet algorithm. In total, system dynamics were accrued for a minimum of 10,200 ps. This included 500 ps equilibration time under canonical (constant Number of atoms, Volume, and Temperature, NVT) ensemble conditions followed by a production run of 9700 ps under isothermal-isobaric conditions (constant number of atoms, pressure, and temperature, NPT). NVT and NPT conditions were themostated at room temperature and pressure using the Nosé–Hoover thermostat-barostat system [39,40].

2.3. Synthesis of Triocetyltrimethylammonium Nitrate (IL)

Following a standard preparation [41], iodomethane (4.44 g, 31 mmol) was added dropwise to a stirred solution of trioctylamine (8.85 g, 25 mmol) in THF (100 mL), and the mixture was stirred at
were obtained at 1.00 M IL (0.01–1.00 M) is found to transport La, Nd, and Dy (0.01 M) from aqueous NaNO₃ (1 h, room temperature). The organic phase was separated and concentrated under vacuum to yield a viscous orange oil (100%). ¹H NMR (500 MHz, CDCl₃): δH 3.41–3.35 (m, 6H, NCH₂), 3.24 (s, 3H, NCH₃), 1.74–1.64 (m, 6H, CH₂), 1.43–1.23 (m, 30H, CH₂), 0.89 (t, J = 6.8 Hz, 9H, CH₂CH₃). ¹³C{¹H} NMR (126 MHz, CDCl₃): δC 61.70, 48.83, 31.62, 29.10, 29.01, 26.30, 22.57, 22.43, 14.04.

2.4. General REE Recovery Procedure

An aqueous solution of the hydrated REE nitrate Ln(OH₂)₃(NO₃)₃ (La, Nd, or Dy, 0.01 M unless otherwise stated) (2 mL) was contacted with a toluene organic phase containing tri-n-octylmethyl ammonium nitrate IL (0.10 M unless otherwise stated) (2 mL) and stirred (12 h, 1000 rpm, 25 °C). The phases were then separated physically and diluted (80×) with 1-methoxy-2-propanol for ICP-OES analysis. La, Nd, and Dy were chosen as light, intermediate, and heavy REEs.

3. Results and Discussion

3.1. Solvent Extraction of La, Nd, and Dy by IL

A series of REE recovery experiments were carried out in which the concentrations of the IL, NaNO₃ salt, and HNO₃, and extraction time were varied (see Table S1 for data in terms of distribution coefficients). Additionally, the ability to back-extract the metal from the organic phase into a fresh aqueous phase, in conjunction with recyclability of IL was studied. The IL in toluene solution (0.01–1.00 M) is found to transport La, Nd, and Dy (0.01 M) from aqueous NaNO₃ (7 M) into the organic phase in the order La > Nd > Dy (Figure 1). This trend was observed in all further studies, is similar to that seen previously for this class of extractants, and contrasts the typical commercial reagents for REE recovery, including naphthenic acid and the dialkylphosphoric acid D2EHPA that display the reverse preference [42–46]. Maximum recoveries of La (100%), Nd (98%), and Dy (92%) were obtained at 1.00 M IL with an expected gradual decrease in percentage recovery observed as the concentration of IL (M) decreased [14,15].

![Figure 1](image.png)

Figure 1. (Left): the recovery of La, Nd, and Dy (0.01 M) from an NaNO₃ (7 M) aqueous solution varying IL concentration (0.01–1.0 M) in toluene (recorded in triplicate). (Right): The recovery of La, Nd, and Dy (0.01 M) using IL (0.10 M) in toluene varying NaNO₃ concentration (1–7 M). Interpolation used to aid the eye only.

When IL concentration was constant (0.1 M) and NaNO₃ salt varied (1–7 M), the REE transportation into the organic phase increased substantially as NaNO₃ salt concentration increased (Figure 1), in line with previous work [3,4]. For La, Nd, and Dy minimal recovery (<5%) was obtained at 1 M NaNO₃, whereas at 7 M NaNO₃, 99% La, 85% Nd, and 52% Dy were recovered. Slope analysis
(Figure S1) provided a relationship of 1:3 between La or Nd and NaN\textsubscript{3}, in accordance with previous work [3], while a relationship of 1:1.5 was observed between La or Nd and IL.

A substantial reduction in the transport of La, Nd, and Dy (0.01 M) from the aqueous phase with IL (0.10 M) is seen as the concentration of HNO\textsubscript{3} is increased (0.005–1.00 M) (Figure 2), with a pronounced decrease seen starting at 0.1 M HNO\textsubscript{3} and minimal recovery (<5%) of all REEs at 1.0 M HNO\textsubscript{3}. The mixed chain/isomer analogue of IL, [A336]NO\textsubscript{3} is known to transport HNO\textsubscript{3} from the aqueous phase [21], so it is likely that competition between REE recovery and acid extraction occurs at higher concentrations of HNO\textsubscript{3} (see below).

![Figure 2](image-url)

**Figure 2.** The extraction of La, Nd and Dy (0.01 M) in using IL (0.1 M) with varying HNO\textsubscript{3} (0.005–1.0 M) at constant NO\textsubscript{3}\textsuperscript{−} concentration (7 M). Interpolation used to aid the eye only.

Using the optimized conditions of 0.01 M IL and 7 M NaN\textsubscript{3}, it was found that the transport of La from the aqueous to the organic phase by IL is rapid (Figure 3), as seen in similar studies [3,47,48]; after only 60 s the concentration of La in the organic phase is maximized.

![Figure 3](image-url)

**Figure 3.** (Left): The recovery of La (0.01 M) in NaNO\textsubscript{3} (7 M) using IL (0.1 M) with varying time (seconds). (Right): The recycling of IL (0.1 M) to load La (0.01 M) from aqueous NaNO\textsubscript{3} (7 M) following multiple load/strip cycles. Water was used to strip La (100%). Interpolation used to aid the eye only.

The back-extraction of the REEs from the IL organic phase into a fresh aqueous solution was studied and shows that complete back-extraction is achieved using water (Figure S2) [3,47], in contrast to pH swing reagents such as D2EHPA that typically require acidic strip conditions [42,43,49,50]. Some selectivity in the back-extraction process is achieved through the addition of NaN\textsubscript{3} to the aqueous phase. While Dy, the heavier REE, is readily back-extracted (>95%) by aqueous NaN\textsubscript{3} (<5 M), the transport of La, the lighter REE into the aqueous phase is hindered under these conditions,
with <20% stripped. Additionally, IL is durable and readily reusable, with only a minimal performance decrease (5%) seen following six load and strip cycles (Figure 3), with the loss observed likely due to entrainment [47].

3.2. Evaluation of the Mechanism of Ln Recovery by IL

3.2.1. Karl-Fischer Analysis of Water Content

Some metal recovery processes, in particular those involving solvating reagents, operate by a reverse micelle mechanism. Here, the metal ion is solvated (and hydrated) by a water pool, which is stabilized in the organic phase by spontaneous assembly of the hydrophobic extractant molecules to form micellar aggregates [51–56]. A feature of reverse-micelle mechanisms is therefore the transport of water into the organic phase, with increasing amounts associated with increasing metal extraction. The water content of the organic phase containing IL (0.01–1.00 M) was measured by Karl-Fischer titration following various aqueous phase contacts (Figure 4). These included extraction of La, Nd, and Dy (0.01 M) from NaNO₃ (7 M), contact with aqueous NaNO₃ (7 M), and contact with pure water. It is seen that IL is naturally hydrophilic, solubilizing a proportional amount of water in relation to its concentration. FT-IR studies have shown that ILs of ammonium cations readily extract water, indicated by the presence of a strong broad stretch at ~3450 cm⁻¹ following contact with water [3,4,47,57]. The water content seen for the metal-loaded IL phase is comparable, albeit slightly lower than that seen for the water-only contact, indicating that rare-earth extraction is not dependent on the extraction of water and that a reverse-micelle mechanism of extraction is unlikely. Interestingly, when the concentration of IL is constant but the concentration REE is varied, a decrease in extracted water is observed, and may be due to the IL preferentially interacting with the REE and displacing water into the aqueous phase.

![Graph 1: Water Content vs. IL Concentration](image1)

**Figure 4.** (Left): the water content (ppm) of IL (0.01–1.00 M) organic phases determined by Karl-Fischer titration. (Right): the water content (ppm) of organic phase IL (0.25 M) with varying Nd (0.01–0.5 M) was also determined by Karl-Fischer titration. Interpolation used to aid the eye only.

3.2.2. Nitric Acid and Nitrate Transport by IL

The IL (0.10 M) in toluene was contacted with aqueous phases of varying HNO₃ concentration (0.01–1.00 M) containing NaNO₃ (0 and 5 M) (5 min). The organic phase was then contacted with water (5 min) and the pH of the aqueous phase measured. As the HNO₃ concentration of the initial
aqueous phase increases, the pH of the final aqueous phase decreases, indicative of an increasing amount of HNO$_3$ being extracted by IL (Figure 5). The pH of the aqueous strip phase when the initial acidic solution was in 5 M NaNO$_3$ is lower in each instance when compared with the absence of NaNO$_3$, consistent with a salting-out effect. The amount of NO$_3^-$ anions in the final aqueous strip from 5 M NaNO$_3$ was determined by Na analysis using ICP-OES (Figure 5) and ion-chromatography (IC) (Figure 5) and shows that when NaNO$_3$ is present, the additional NO$_3^-$ extracted is derived predominately from the extraction of HNO$_3$; Na is not transported as the quantity of Na cations is independent of HNO$_3$ concentration. The IC data indicate that the concentration of NO$_3^-$ anions in the final aqueous phase increases as HNO$_3$ increases. Collectively, these data show that the transport of NO$_3^-$ anions into the organic phase by IL is due to co-extraction of H$^+$ rather than Na$^+$. 

Figure 5. (Top left): The pH of aqueous solutions following contact of IL (0.1 M) in toluene loaded with HNO$_3$ (0.01–2.00 M) from NaNO$_3$ (0 and 5 M); (Top right): The extraction of Na with IL (0.1 M) from 5 M NaNO$_3$ and HNO$_3$ (0.01–2.00 M) solution; (Bottom): Determination of the concentration of NO$_3^-$ extracted by IL using ion-chromatography. Interpolation used to aid the eye only.

3.2.3. Characterization by Mass Spectrometry and La NMR Spectroscopy

Negative-ion ESI-MS of the IL organic phases (0.1 M) loaded with La, Nd, and Dy (0.05 M) were recorded and show ions that comprise the metal cation, ammonium cations and NO$_3^-$ anions of the general formula Ln(NO$_3$)$_4$(IL)$_m^-$ (where $n$ is 0–3). The most prominent ion observed is for $n$ = 2 at $m/z$ 1252, i.e., Nd(NO$_3$)$_4$(IL)$_2^-$ that is also consistent with a formula of [(octyl)$_3$NMe$_2$][Ln(NO$_3$)$_5$] for the compound in the organic phase. Each ion seen experimentally displays isotopic patterns that agree with those calculated (Figure 6, Figure S3) and a repeating unit of 430.42 mass units is seen in each spectrum correlating to loss of IL.
Figure 6. (Top): Negative-ion mode ESI-MS of the IL organic phase (0.1 M IL) post-contact with an Nd aqueous phase diluted with methanol showing ions of Nd(NO₃)₃(IL)ₙ⁻ with m/z 391.8611 (n = 0, calc. 391.8596), 822.2779 (n = 1, calc. 822.2755), 1252.6933 (n = 2, calc. 1252.6890), and 1683.10823 (n = 3, calc. 1683.1024). (Bottom): Experimental negative-ion ESI-MS for n = 2 (red) compared with that calculated (black).

No ions that would suggest the presence of water in the organic phase are seen in the ESI-MS which corroborates the Karl-Fischer data above, although the dissociation of water from the supramolecular complex during ionization could occur [29]. To further probe the chemical environment of the species extracted into the hydrophobic phase, the ¹³⁹La NMR spectrum of the IL organic phase (0.05 M) after La extraction (0.05 M) was recorded and shows a single, broad resonance at −60 ppm when compared against LaCl₃ dissolved in water, i.e., [La(H₂O)₆][Cl]₃ (Figure 7). This chemical shift is consistent with the coordination of NO₃⁻ anions to La along with its dehydration [58], and the breadth of signal suggests that multiple, low symmetry nitrato complexes are present, as seen in the ESI-MS above; a variable temperature ¹³⁹La NMR study shows no significant change between +65 and +5 °C (Figure S4), mitigating against a dynamic process occurring.

Figure 7. ¹³⁹La NMR spectra of the La standard, LaCl₃ (0.01 M, 0.0 ppm) in D₂O (red) and the IL organic phase (0.05 M) after contact with a 0.05 M aqueous La solution extraction IL (blue).
3.2.4. Structural Analysis by Computational Modelling

To understand further the interactions between IL and La compounds in the organic phase, a toluene solvent box of 60 Å³ volume containing three ILs, three NO₃⁻ anions, three H₂O, and one La³⁺ cation was studied by classical MD techniques; these combinations are derived from the experimental information provided above (see Figure S5 for more details). Aggregation of all components in the solvent box is seen after 750 ps to form a partially hydrated La³⁺ cation with four NO₃⁻ anions within 5.1 Å of the La center, three H₂O molecules within 6.0 Å, and three nitrogen atoms from the encapsulating ammonium cations within 11 Å (Figure 8); all six NO₃⁻ are incorporated into the aggregate within 11 Å from the La³⁺ cation. It is clear that the formation of complexes in the organic phase is dynamic and that the nitrate anions and water molecules compete for interaction with the La³⁺ cation. This outcome is consistent with our previous studies on the ease of formation of La nitrato complexes in the aqueous phase, the breadth of resonance seen in the ¹³⁹La NMR spectrum, and that nitrate coordination is inferred by the presence of two peaks at 1435 and 1328 cm⁻¹ in the IR spectrum of an IL organic phase loaded with La (Figure S6). Microhydration [59,60] of the La³⁺ cation, nitrate anions, and the ammonium cation may be important, as this may provide extra thermodynamic stability through hydrogen bonding, but quantum mechanical calculations are required to probe this further.

![Figure 8. Three ‘snapshot’ images taken at 225 ps apart ((left) to (right)) from the classical MD simulations showing aggregation of water, nitrate, and ammonium cations around an La center within a 60 Å³ box of toluene. For clarity, the toluene box is omitted, and H atoms are colored white, oxygen atoms red, nitrogen atoms blue, carbon atoms grey, and the La atom green.](image)

The effectiveness of the encapsulation of the La cation and the attendant NO₃⁻ anions and water molecules by the lipophilic IL was probed by calculating the porosity of the aggregate using a Monte Carlo code. Here the La core (consisting of the La³⁺ cation, three water molecules, and six nitrate anions) is defined as the target, towards which a probe sphere is fired 10,000 times from random positions on the surface of a large sphere that encapsulates the aggregate; the number of probe spheres that successfully hit the core region (rather than be intercepted by the atoms on IL) is then recorded to give a percentage core exposure. In this way, the ability of IL to shield the La core can be quantified. From a random sample of 25 classical MD frames, the La core exposure was found to be 37 ± 3%; in contrast, targeting the La³⁺ cation exclusively reveals an exposure of 6.0 ± 1.3%. The simulations thus suggest that three ILs can be comfortably accommodated around a microhydrated La³⁺ cation.

4. Conclusions

This work has reinforced the efficacy of the [(t-octyl)₃NMe][NO₃] ionic liquid IL as a useful reagent for the recovery of REEs from mildly acidic, high nitrate salt, aqueous solutions. Extraction is fast and efficient, relatively selective for light REEs, and back-extraction may show additional selectivity if aqueous NaNO₃ is used. It can be concluded from the mode of action studies that the interactions between IL and REE nitrates are not (reverse) micellar; instead, ESI-MS, NMR, and computational
studies suggest that multiple NO$_3^-$ anions are coordinated in the inner-sphere of a partially hydrated REE to form a series of anions REE(NO$_3$)$_n$(H$_2$O)$_x$$^{-}$ that are stabilized by electrostatic association with lipophilic NR$_4^+$ cations. Classical MD simulations for La suggest that the most prevalent species is [(n-octyl)$_3$NMe$_3$][La(NO$_3$)$_6$(H$_2$O)$_3$] that incorporates a small number of water molecules in the hydrophobic phase through microhydration. We have shown previously that La(NO$_3$)$_4$ is unlikely to form in the aqueous phase [31], so it remains unclear in what form the REE is transported across the interface and whether complete dehydration of the metal occurs to facilitate transport across the phases. We are currently exploiting this mechanistic understanding to devise new, functionalized IL systems (Bif-ILs [2]) to engender stronger REE recovery from acidic feed streams and to be able to provide effective REE separation.

Supplementary Materials: The following are available online at http://www.mdpi.com/2075-4701/8/6/465/s1. Figure S1: Slope analysis; Figure S2: Back extraction (striping) studies of La, Nd and Dy; Figure S3: La and Dy negative ion ESI-MS; Figure S4: Variable temperature $^{139}$La NMR spectra; Figure S5: Computational outputs; Figure S6: Infrared spectra; Table S1: Distribution coefficients.

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