Dynamic lanthanides exchange between quadruple-stranded cages: effect of ionic radius differences on kinetics and thermodynamics

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Abstract

Seven different $[Ln_2L_4]^{2-}$ (Ln = La, Nd, Eu, Tb, Er, Tm and Lu) lanthanide-based quadruple-stranded helicates are here reported and transmetalation among pre-assembled cages was studied. Combining two homonuclear helicates $[Ln^A_2L_4]^{2-}$ and $[Ln^B_2L_4]^{2-}$ leads to the formation of a mixture of homo- and heteronuclear systems due to ion exchange. This dynamic behaviour was studied by electrospray ionization mass spectrometry (ESI-MS) both qualitatively and quantitatively allowing to gain information on the thermodynamics as well as on the kinetics of the process. The rate of the Ln ion exchange is strongly dependent on the difference in lanthanide effective ionic radius (Δ EIR). Upon increasing Δ EIR, the kinetic constants grow exponentially: from the minimum to the maximum value of Δ EIR, the kinetic constants of the forward and backward reactions increase by three orders of magnitude. On the contrary, the equilibrium constant is the same for all the $[Ln^A_2L_4]^{2-}/[Ln^B_2L_4]^{2-}$ couples, showing that the transmetalation is mainly entropy-driven towards a statistical mixture and not affected by Δ EIR.

Introduction

Among metallo-supramolecular systems, lanthanide (Ln) based architectures are attracting increasing attention due to their remarkable optical and magnetic properties. However, with Ln³⁺ ions the design and control of the final supramolecule is very challenging. This is a direct consequence of the inner nature of the 4f orbitals: ligand-field effects are small, and the coordination chemistry of these ions is similar across the entire series with coordination number and geometry very variable and basically dependent on the steric properties of the ligand. There is, however, a steady variation of the effective ionic radius (EIR) across the series, the so called "lanthanide contraction". Although the radii difference (Δ EIR) is quite small (*ca*. 0.20 Å between La³⁺ and Lu³⁺ and *ca*. 0.02 Å between two consecutive lanthanides), it can have important chemical consequences on the nature and features of supramolecular complexes. For instance, Δ EIR coupled to the use of multicompartmental ligands have been used to control the self-assembly of heterobimetallic helicates,^{1,2} while Δ EIR effect was shown to lead to lanthanide-selective self-

assembly through multivalency and cooperativity.^{3,4} Furthermore, Δ EIR effects proved to strongly affect the formation of the more stable thermodynamic product and the final metallo-supramolecular structure^{5–11} as well as the rate of conversion between different aggregates.¹¹ More subtle effects have been also reported such as variation of the twist angles in pseudo-helical Ln tripodal complexes¹² and fine-tuning of the helicity and of the helical winding in oligo(salamo)-based metal LZn₃Ln helicates.¹³

In the past decades, advances in the coordination chemistry of multinuclear compounds have been exploited to drive the self-assembly of many new discrete supramolecular motifs. Due to the nature of the metal-ligand interactions, many of these systems have a dynamic character with reversible association and dissociation able to generate complex mixtures. Unveil such dynamic behaviours, it is a priority to fully understand, control and design their functional properties. Mass spectrometry (MS) is a powerful tool to study such supramolecules^{14–16} both for determining the ensembles' structure in terms of composition, shape, and size, as well as their dynamic behaviour and formation pathways.^{17–25} However, only a relatively small number of studies report MS quantitative studies for metallo-supramolecular complexes.^{17–19,23–27} Among the dynamic processes displayed by supramolecular complexes, post-synthetic ion exchange is particular important since it provides new pathways to synthetize heterometallic systems or species that cannot be achieved by direct metal-ligand coordination.^{20,21,24–32} Despite the importance of this synthetic strategy, little rigorous work has been reported on the kinetics³² and the thermodynamics^{28,29} of the ion exchange process for supramolecular complexes.



Figure 1. (a) Self-assembly of seven $[Ln_2L_4]^{2-}$ cages (Ln = La, Nd, Eu, Tb, Er, Tm and Lu). (b) Dynamic Ln^{3+} ion exchange equilibrium between two pre-assembled cages and (c) exponential trend of the kinetic constants depending on the Ln Δ EIR.

Recently, we reported two $[Ln_2L_4]^{2-}$ quadruple-stranded helicates (Ln = La, Eu and Gd) that show dynamic and adaptive helicity reorganization due to a guest-to-host chirality transfer.³⁷ These helicates are self-assembled starting from achiral bis- β -diketone ligands. Oligo- β -diketones are versatile ligands for the preparation of metallo-supramolecular architectures^{38,39} ranging from metallocycles, cages and MOFs,^{40–44} to helicates^{37,45–47} and even to interlocked structures.^{48–50} Herein, by using a close related bis- β -diketone ligand, we present a larger series of seven $[Ln_2L_4]^{2-}$ quadruple-stranded helicates (Ln = La, Nd, Eu, Tb, Er, Tm and Lu), Figure 1, that once assembled undergo transmetalation. The thermodynamics and kinetics of the dynamic ion exchange has been studied and the role of the Ln^{3+} Δ EIR evaluated. The process has been qualitatively and quantitatively characterized by time-dependent electrospray ionization mass spectrometry (ESI-MS). Mixing a series of two homonuclear $[Ln^{A}_{2}L_{4}]^{2-}$ and $[Ln^{B}_{2}L_{4}]^{2-}$ with increasing Ln^{3+} Δ EIR always leads to the formation of a statistical mixture of homo- and heteronuclear helicates due to the Ln exchange. All the studied systems have an equilibrium constant close to K = 4. The Ln^{3+} Δ EIR, hence, does not affect the thermodynamics of the process that is mainly governed by statistical factors and entropy-driven. On the other hand, we demonstrate that the rate of the dynamic ion exchange is Ln radii-dependent, Figure 1b. The kinetic constants of the forward and backward reactions revealed an exponential trend depending on the Ln^{3+} Δ EIR of the two homonuclear pre-assembled cages, Figure 1c. This fundamental study hints new tools and guidelines to study dynamic processes in metallo-supramolecular ensembles, and for the precise preparation and control of lanthanide-based mixed coordination-driven systems.

Results and discussions

[Ln₂L₄]²⁻ cages synthesis and characterization



Figure 2. ESI-MS spectra of the seven $[Ln_2L_4]^{2-}$ cages (Ln = La, Nd, Eu, Tb, Er, Tm and Lu). Insets: experimental (black) and simulated (red) isotopic patterns.

The bis- β -diketone ligand was synthesized using a two-steps protocol: i) Ulmann coupling followed by ii) a Claisen condensation, and characterized as described in the Supporting Information, SI (NMR Figures S1-S4 and single crystal XRD Figure S6). The lantern-like cages with general formula $[Ln_2L_4]^{2-}$ were prepared by adding an ethanol solution of the deprotonated ligand to an ethanol solution of a Ln^{3+} salt. Seven different Ln^{3+} ions have been used to self-assemble $[Ln_2L_4]^{2-}$ cages where Ln = La, Nd, Eu, Tb, Er, Tm and Lu. A metal:ligand molar ratio of 1:2.5 leads to the pure compound in good yield (Table S1). All the cages show very clean ESI-MS spectra with only one signal ascribed to the $[Ln_2L_4]^{2-}$ double negative charged species. The experimental isotopic pattern of each species well

agreed with the calculated one, Figure 2. The systems have been also characterized by ¹H-NMR and Figure 3a shows the ligand (H₂L, L²⁻) and $[La_2L_4]^{2-}$ cage spectra. Upon deprotonation, all the ligand signals undergo upfield shifting. The strongest effect is observed for the proton H1, in α position of the β -diketonate moiety, shifting from *ca*. 7.1 to *ca*. 5.9 ppm while the tert-butyl protons (H4) are barely perturbated. After La³⁺ coordination, the cage shows only a single set of signals with a total of four resonances in agreement with the ligand *C*₂ symmetry and the mean *C*₄ symmetry of the quadruple-stranded [La₂L₄]²⁻ architecture. H1, the H atom closer to the metal center, is downfield shifted to *ca*. 6.2 ppm. Diffusion-ordered NMR spectroscopy (DOSY) was performed to provide dimensional information. Two distinct bands were observed and ascribed to the cage and to the DCHA⁺ cation. The calculated hydrodynamic diameter for [La₂L₄]²⁻ is 23.5 Å. Supporting information reports also the NMR for the Eu and Lu systems (Figures S5) while the Nd, Tb, Er and Tm analogues spectra showed very poor resolution due these metals high magnetic moments.



Figure 3. (a) ¹H-NMR spectra (25 °C, 300 MHz, DMF-d₇) of ligand H₂L, deprotonated ligand L^{2–} and the cage $[La_2L_4]^{2-}$. DOSY of $[La_2L_4]^{2-}$. * = DMF. (b) Crystal structure of the Eu helicate (*M* and *P* form), H atoms and external NEt₄⁺ ions omitted for clarity. Color code: C, grey; O, red; N, blue; F, green; Eu, orange.

For the Eu cage it was possible to obtain single crystals suitable for XRD from mother liquors (ethanol) slow evaporation. Structure determination ultimately confirmed the cage assembly and the formation of helicate systems (Figure 3b). Both the right-handed (P, $\Delta\Delta$) and left-handed (M, $\Lambda\Lambda$) helicates are present in 1:1 ratio as enantiomers pair in the asymmetric unit (Figures S7 and S8) similarly to what previously observed for a similar quadruple stranded helicate.³⁷ Each helicates host a tetraethylammonium (NEt₄⁺) counterion in their cavity. The Eu–O distances are in the range 2.486-2.639 Å and the Eu…Eu distances are 12.054 Å and 12.199 Å for P and M helicate, respectively. H…H distances from tert-butyl groups of opposite ligands are close to 23 Å. This value well-agrees with

the hydrodynamic diameter calculated from DOSY experiment (23.5 Å) for the lanthanum cage. Conversely to previous findings,³⁷ the Eu ions do not display an octa-coordination mode since they are nona-coordinated. The Eu ions are tetrakis-chelated by four β -diketonato groups and the nineth site is occupied by a water molecule in the case of the *M* helicate and by an ethanol molecule for the *P* helicate. The nona-coordination can be a consequence of the crystallization environment in the presence of good coordinating solvents such as ethanol and water. ESI-MS analysis did not show any adduct with water or ethanol. DFT studies were performed both on an octa- and nona-coordinated La cage. The comparison of the X-ray nona-coordinated Eu helicate and the DFT-optimized octa-coordinated La helicate shows that ligands arrangement in the two systems are very similar as highlighted by the overlay of the two structures (Figure S10). Moreover, the solvent molecules binding energy has been also determined: -7.4 and -8.5 kcal/mol for water and ethanol, respectively (see SI for details, Table S3). This suggests that these molecules can be easily lost as for instance during the electro-spray ionization.

Qualitative and quantitative ESI-MS of the Ln ion dynamic exchange

Time dependent ESI-MS analysis was used to study both qualitatively and quantitatively possible dynamic processes between two pre-assembled cages $[Ln^{A}_{2}L_{4}]^{2-}$ and $[Ln^{B}_{2}L_{4}]^{2-}$. Preliminary experiments were performed by mixing two equimolar solutions of the $[Eu_{2}L_{4}]^{2-}$ and $[Tb_{2}L_{4}]^{2-}$ cages in 1:1 ratio in a sealed vial at 50 °C, and monitoring their ESI-MS spectra at increasing time, Figure 4a.



Figure 4. Time-dependent ESI-MS spectra of an equimolar solution of $[Ln^{A}_{2}L_{4}]^{2-}$ and $[Ln^{B}_{2}L_{4}]^{2-}$. Dynamic Ln ion exchange between the couples a) $[Eu_{2}L_{4}]^{2-}/[Tb_{2}L_{4}]^{2-}$, b) $[Eu_{2}L_{4}]^{2-}/[Tm_{2}L_{4}]^{2-}$, c) $[Nd_{2}L_{4}]^{2-}/[Er_{2}L_{4}]^{2-}$ and d) $[La_{2}L_{4}]^{2-}/[Lu_{2}L_{4}]^{2-}$. Supporting information reports more spectra and simulated isotopic patterns (Figures S13, S14, S18, S19, S23, S24, S28, S29).

At time zero, only the patterns ascribed to the two homometallic cages are present. After 60 minutes, the isotopic pattern of the heterometallic cage $[EuTbL_4]^{2-}$ appears, as confirmed by comparison with the calculated one (Figure S14), showing that the two homometallic cages undergo ion exchange forming a mixture of heteronuclear and homonuclear systems. The intensity of the Lnmixed cage increases over time to the detriment of the homometallic ones. In order to apply ESI-MS to monitor the concentration of the different species at different times, we hypothesized that the $[Ln_2L_4]^{2-}$ species have comparable ionization efficiencies. To confirm this hypothesis, the ESI-MS spectrum of a solution containing equimolar amounts of the two homometallic cages $[Eu_2L_4]^{2-}$ and $[Tb_2L_4]^{2-}$ was repetitively measured just after mixing. If the hypothesis is correct, the two cages must yield MS spectra that indicate equal relative amount. Relative amount was deduced according to equation 1. Then, equation 2 can be easily used to derive the molarity of the species (see SI for details).

$$\mathscr{K}[Ln^{A}Ln^{B}L_{4}] = \frac{A[Ln^{A}Ln^{B}L_{4}]}{\sum A[Ln^{A}Ln^{B}L_{4}]} \cdot 100 \tag{1}$$

$$|Ln^{A}Ln^{B}L_{4}| = \frac{\%[Ln^{A}Ln^{B}L_{4}] \cdot (|Ln_{2}^{A}L_{4}|_{0} + |Ln_{2}^{B}L_{4}|_{0})}{100}$$
(2)

Where $%[Ln^A Ln^B L_4]$ is the relative amount of the cage, and $A[Ln^A Ln^B L_4]$ the integrated area of the species isotopic pattern, and $|Ln^A Ln^B L_4|$ is the molarity of homonuclear cage if $Ln^A = Ln^B$, and heteronuclear cage if $Ln^A \neq Ln^B$. $|Ln^A _2 L_4|_0$ and $|Ln^B _2 L_4|_0$ are the initial molar concentration of the homometallic species. Application of equation 1 always gave values of about 50 % for the relative amount of $[Eu_2 L_4]^{2-}$ and $[Tb_2 L_4]^{2-}$ cages (Table S4), as expected for an equimolar mixture of the two cages, confirming that they have similar ionization efficiencies.

ESI-MS spectra of Figure 4a and Figure S13 were used to derive the relative amount and concentration of the different cages during the ion exchange. At equilibrium, a statistical mixture of homometallic (25%) and heterometallic (50%) cages is obtained Figure 5a and Table S5. Then, the same approach has been applied to study the ion exchange with other [Ln^A₂L₄]²⁻/[Ln^B₂L₄]²⁻ couples, namely: $[Eu_2L_4]^2 / [Tm_2L_4]^2$, $[Nd_2L_4]^2 / [Er_2L_4]^2$ and $[La_2L_4]^2 / [Lu_2L_4]^2$. Homonuclear cages bearing different Ln³⁺ ions have been chosen in order to have Ln³⁺ ions spread across the lanthanide series providing a range of effective ionic radii (EIR) and ionic radii difference (Δ EIR), as detailed in Table 1. The use of ESI-MS allows to investigate also $[Ln^{A}_{2}L_{4}]^{2-}/[Ln^{B}_{2}L_{4}]^{2-}$ couples that cannot be analyzed by NMR due to poor resolution. The only important constraint in the choice of $[Ln^{A}_{2}L_{4}]^{2-}/[Ln^{B}_{2}L_{4}]^{2-}$ couple is that there must be no significant overlaps between the isotopic patterns of the homonuclear and heteronuclear cages. The same protocol used for the couple [Eu₂L₄]²⁻/[Tb₂L₄]²⁻ was applied. First, the two homonuclear cages were tested to verify they possess the same ionization efficiencies (Table S4, Figure S11) in order to draw quantitative information from ESI-MS. Second, time-dependent analyses were performed to follow the dynamic ion exchange (Figure 5, Tables S6-S8). Figure 5 clearly shows that all the $[Ln^{A}_{2}L_{4}]^{2-}/[Ln^{B}_{2}L_{4}]^{2-}$ couples give a statistic mixture of homonuclear and heteronuclear cages, but the times to reach it are different.



Figure 5. Concentration over time during the Ln ion exchange reaction as derived by time dependent ESI-MS of equimolar $[Ln^{A}_{2}L_{4}]^{2-}/[Ln^{B}_{2}L_{4}]^{2-}$ mixtures. Kinetic profiles (solid red, blue and black lines) according to equation 4 for the homometallic cages and equation 5 for the heterometallic cages. Fitting details in Figures S15-S17, S20-S22, S25-S27, S30-S32.

Table 1. Ln^{3+} ions EIR and Δ EIR for the couples $[Ln^{A}_{2}L_{4}]^{2-}/[Ln^{B}_{2}L_{4}]^{2-}$ and K, k_{f} , k_{b} and t_{eq} for the Ln ion exchange reactions.

	La ³⁺	Nd ³	+	Eu ³⁺	Tb ³⁺	Er ³⁺ Tm ³⁺		Lu ³⁺	
Ln ³⁺ EIR ^a (Å)	1.18	1.12	2	1.07	1.04	1.00	0.99		0.97
[Ln ^A 2L4] ²⁻ /[Ln ^B 2L4] ²⁻		ΔEIR (Å)	K		<i>k_f</i> (M ⁻¹ s ⁻¹)	<i>k</i> _b (M ^{−1} s ^{−1})		t _{eq} (min)	
[Eu ₂ L ₄] ²⁻ /[Tb ₂ L ₄] ²⁻		0.03	4.05 ± 0	.26	5.49 ± 0.07	1.37 ± 0.02		700.2 ± 9.3	
[Eu ₂ L ₄] ²⁻ /[Tm ₂ L ₄] ²⁻		0.08	3.98 ± 0	.29	12.78 ± 0.46	3.20 ± 0.11		300.9 ± 10.8	
$[Nd_2L_4]^{2-}/[Er_2L_4]^{2-}$		0.12	4.00 ± 0	.40	42.77 ± 1.46	10.69 ± 0.36		89.8 ± 3.1	
$[La_2L_4]^{2-}/[Lu_2L_4]^{2-}$		0.21	4.02 ± 0	.35 21	140.31 ± 166.50	535.08 ± 41.63		1.8 ± 0.1	

^a For octa-coordinated Ln³⁺ ions⁵¹

Thermodynamics and kinetics analysis of the Ln ion dynamic exchange

Starting from two homometallic cages with a 1:1 ratio, two homometallic and one heterometallic cages with a ratio 1:1:2 are obtained (equation 3). On the basis of a statistical analysis,⁵² we can anticipate that the equilibrium constant will be K = 4. Indeed, at equilibrium, the experimental

concentrations are all very closed to the following values: $|Ln^{A}_{2}L_{4}| = |Ln^{B}_{2}L_{4}| = 5 \cdot 10^{-6}$ M and $|Ln^{A}Ln^{B}L_{4}| = 1 \cdot 10^{-5}$ M. All the Ln ion exchange reactions, hence, have the same equilibrium constant (Table 1). This suggests that the ion exchange process is essentially entropy-driven and hence governed by statistical factors. If the enthalpic contribution is negligible, we can infer that the different homometallic and heterometallic cages have similar stabilities across the lanthanide series.

$$[Ln^{A}_{2}L_{4}]^{2-} + [Ln^{B}_{2}L_{4}]^{2-} \stackrel{k_{f}}{\rightleftharpoons} 2 [Ln^{A}Ln^{B}L_{4}]^{2-}$$
(3)
$$k_{b}$$

On the contrary, the kinetics of the Ln ion exchange reaction are very different. Figure 5 highlights that by increasing the ionic radii difference (Δ EIR) between the involved Ln³⁺ ions, the time to reach the statistic mixture decreases. Some previous works^{17–19} treated the kinetics of dynamic ligand exchange between pre-assembled metallo-supramolecular architectures as first- or second-order direct reactions without considering the reversible nature of the equilibrium. This simplification can be adopted only under specific conditions (see below), otherwise it can lead to misleading results (see SI, Figure S12). As a matter of fact, the dynamic exchange reaction (ion or ligand) is a reversible reaction and its kinetics must be treated as a pair of forward and backward reactions (kinetic constants k_f and k_b , respectively). These two reactions occur simultaneously and are related to the equilibrium constant by $K = k_f/k_b$. Only if $k_f \gg k_b$ (high value for K), the reverse reaction can be neglected, and the kinetics analysis simplifies to a rate law for a direct reaction. However, this is not the case, K = 4 and k_b will be one quarter of k_f : the backward reaction cannot be neglected. The kinetics of the dynamic Ln ion exchange has been treated as two opposing second-order reactions (see SI for the detailed treatment). This leads to equations 4 and 5 that give the concentrations of the homometallic and heterometallic species over time, respectively.

$$|Ln_2^A L_4| = |Ln_2^B L_4| = \frac{a_0}{2} (1 + e^{-k_f t 2a_0})$$
(4)

$$|Ln^{A}Ln^{B}L_{4}| = a_{0}(1 - e^{-k_{f}t2a_{0}})$$
(5)

Where a_0 is the initial concentration of the homometallic cages, k_f the kinetic constant of the forward reaction, and t the time. Moreover, the performed kinetic analysis allows to estimate t_{eq} , the time to reach the equilibrium *i.e.* the statistical mixture, equation 6 (see SI for details).

$$t_{eq} = \frac{1}{2a_0k_f} ln \frac{1}{\alpha} \tag{6}$$

Where α is an arbitrary small number (see SI for details). For calculations of t_{eq} we assumed $\alpha = 0.01$, that corresponds to a homometallic cage concentration that is 1% higher than the equilibrium concentration.

Fitting of experimental data with equations 4 and 5, Figure 5, allowed to determine k_f and then k_b for the different Ln ion dynamic exchange reactions. Table 1 summarizes the obtained results as the average of the values for the two homometallic cages and the heterometallic one (Table S9). The more the Δ EIR between the two Ln³⁺ ions increases, the more k_f (and k_b) increases and consequently t_{eq} decreases. For instance, k_f is 5.49 ± 0.07 M⁻¹s⁻¹ (t_{eq} 700.2 ± 9.2 min) for the couple (Eu₂L₄)²⁻/(Tb₂L₄)²⁻ with the minimum Δ EIR = 0.03 Å. For the exchange reaction (Eu₂L₄)²⁻/(Tm₂L₄)²⁻, Δ EIR = 0.08 Å, k_f is 12.78 ± 0.46 M⁻¹s⁻¹ (t_{eq} 300.9 ± 10.8 min) and for (Nd₂L₄)²⁻/(Er₂L₄)²⁻, Δ EIR = 0.12 Å, k_f is 42.77 ± 1.46 M⁻¹s⁻¹ (t_{eq} 89.8 ± 3.1 min). The couple (La₂L₄)²⁻/(Lu₂L₄)²⁻ with the highest Δ EIR =

0.21 Å evidences a dramatic increase of k_f (2140.31 ± 166.50 M⁻¹s⁻¹) with a t_{eq} of only 1.8 ± 0.1 minutes.



Figure 6. a) Exponential trends of k_f and k_b , and b) of t_{eq} for the Ln ion exchange kinetics depending on Ln Δ EIR. Inset: magnification of the 0.02-0.14 Å region. Fitting details in Figure S33.

Plotting k_f and k_b versus Δ EIR, Figure 6a, reveals an exponential dependence of the kinetic constant's values related to the Ln³⁺ ionic radii difference of the two homonuclear cages participating in the ion exchange. An exponential relationship was also found plotting t_{eq} versus Δ EIR, Figure 6b. These trends allow to gain information also on the rate of Ln ion exchange for $[Ln^A_2L_4]^{2-}/[Ln^B_2L_4]^{2-}$ couples that were not investigated in this study by simply knowing the Δ EIR difference between Ln^A and Ln^B.

Conclusions

In summary, a series of quadruple-stranded dinuclear helicates (Ln₂L₄)²⁻ was prepared using a bis- β -diketone ligand and seven different Ln³⁺ ions (Ln = La, Nd, Eu, Tb, Er, Tm and Lu) and fully characterized by NMR, ESI-MS, DFT and single crystal XRD. The dynamic behavior of these systems was studied qualitatively and quantitatively by ESI-MS, providing information on how fast the ion exchange process between two pre-assembled homonuclear cages is completed leading to a static mixture of homonuclear and heteronuclear cages. The thermodynamics of the transmetalation reaction it is not affected by the Ln^{3+} ionic radii difference (ΔEIR) of the two homonuclear preassembled cages participating in the ion exchange. This suggest that the process is mainly entropydriven and that both the homometallic and heterometallic cages have similar stabilities across the Ln series. On the contrary, the rate of Ln ion exchange is strongly affected by the ΔEIR. Both the forward and the backward kinetic constants (k_f and k_b) as well as the equilibration time (t_{eq}) have an exponential trend related to the Ln³⁺ ΔEIR. We envisage that this fundamental study will advance the supramolecular chemistry of Ln coordination-driven cages in terms of synthesis, properties, and applications in particular for Ln-mixed systems where the control of the composition is paramount for the final functional properties as for instance magnetism and luminescence. In fact, a precise knowledge of the ion exchange kinetics will allow the preparation of Ln-mixed systems with a precise control over their composition in term of homonuclear and heteronuclear systems by simply tailoring the mixing time of different pre-assembled cages.

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Author contributions

M.R.^a conceived and led the project. M.R.^b, A.C. and L.B. performed the synthesis and NMR characterization. R.S., M.R.^a, L.B. and M.R.^b performed ESI-MS and analyzed the ESI-MS data. M.R.^a and S.C. performed the kinetic analysis. J.T. and M.R.^a collected the X-ray data, M.R.^a solved and refined the structures. S.C. performed the DFT calculations. L.A., J.T. and G.H.C put forward many constructive suggestions. M.R.^a drafted the manuscript. All authors contributed to the writing of the manuscript.

References

- 1 N. André, R. Scopelliti, G. Hopfgartner, C. Piguet and J.-C. G. Bünzli, *Chem. Commun.*, 2002, 214–215.
- 2 N. André, T. B. Jensen, R. Scopelliti, D. Imbert, M. Elhabiri, G. Hopfgartner, C. Piguet and J. C. G. Bünzli, *Inorg. Chem.*, 2004, **43**, 515–529.
- 3 A. M. Johnson, M. C. Young, X. Zhang, R. R. Julian and R. J. Hooley, *J. Am. Chem. Soc.*, 2013, **135**, 17723–17726.
- 4 X.-Z. Li, L.-P. Zhou, L.-L. Yan, Y.-M. Dong, Z.-L. Bai, X.-Q. Sun, J. Diwu, S. Wang, J.-C. Bünzli and Q.-F. Sun, *Nat. Commun.*, 2018, **9**, 547.
- 5 Y. Wu, S. Morton, X. Kong, G. S. Nichol and Z. Zheng, *Dalt. Trans.*, 2011, **40**, 1041–1046.
- 6 S. Zebret, C. Besnard, G. Bernardinelli and J. Hamacek, *Eur. J. Inorg. Chem.*, 2012, **2012**, 2409–2417.
- 7 K. P. Carter, K. E. Thomas, S. J. A. Pope, R. J. Holmberg, R. J. Butcher, M. Murugesu and C. L. Cahill, *Inorg. Chem.*, 2016, **55**, 6902–6915.
- 8 A. Vuillamy, S. Zebret, C. Besnard, V. Placide, S. Petoud and J. Hamacek, *Inorg. Chem.*, 2017, **56**, 2742–2749.
- 9 H.-Y. Wong, W. T. K. Chan and G.-L. Law, *Inorg. Chem.*, 2018, **57**, 6893–6902.
- 10 C. Chen and A. Zhang, *New J. Chem.*, 2021, **45**, 20155–20163.
- 11 K. H. Yim, C. T. Yeung, M. R. Probert, W. T. K. Chan, L. E. Mackenzie, R. Pal, W. T. Wong and G. L. Law, *Commun. Chem.*, , DOI:10.1038/S42004-021-00553-8.
- 12 S. Mizukami, H. Houjou, M. Kanesato and K. Hiratani, *Chem. A Eur. J.*, 2003, **9**, 1521–1528.

- 13 S. Sairenji, S. Akine and T. Nabeshima, *Dalt. Trans.*, 2016, **45**, 14902–14906.
- 14 H. Wang, C. Guo and X. Li, CCS Chem., 2021, 3161–3184.
- 15 Z. Qi, T. Heinrich, S. Moorthy and C. A. Schalley, *Chem. Soc. Rev.*, 2014, 44, 515–531.
- 16 E. Kalenius, M. Groessl and K. Rissanen, *Nat. Rev. Chem.*, 2019, **3**, 4–14.
- 17 Y.-R. Zheng and P. J. Stang, J. Am. Chem. Soc., 2009, **131**, 3487–3489.
- 18 S. Sato, Y. Ishido and M. Fujita, J. Am. Chem. Soc., 2009, **131**, 6064–6065.
- 19 L. Wang, B. Song, S. Khalife, Y. Li, L.-J. Ming, S. Bai, Y. Xu, H. Yu, M. Wang, H. Wang and X. Li, J. Am. Chem. Soc, 2020, **142**, 1811–1821.
- M. Rancan, J. Tessarolo, P. L. Zanonato, R. Seraglia, S. Quici and L. Armelao, *Dalt. Trans.*, 2013, 42, 7534–7538.
- B. Akhuli, L. Cera, B. Jana, S. Saha, C. A. Schalley and P. Ghosh, *Inorg. Chem.*, 2015, 54, 4231–4242.
- 22 B. Jana, L. Cera, B. Akhuli, S. Naskar, C. A. Schalley and P. Ghosh, *Inorg. Chem.*, 2017, **56**, 12505–12513.
- 23 E. O. Bobylev, D. A. Poole, B. de Bruin and J. N. H. Reek, *Chem. Sci.*, 2021, **12**, 7696–7705.
- 24 E. O. Bobylev, B. de Bruin and J. N. H. Reek, *Inorg. Chem.*, 2021, **60**, 12498–12505.
- E. O. Bobylev, D. A. Poole, B. de Bruin and J. N. H. Reek, *Chem. A Eur. J.*, 2021, 27, 12667–12674.
- 26 F. J. Rizzuto, M. Kieffer and J. R. Nitschke, *Chem. Sci.*, 2018, **9**, 1925–1930.
- 27 C. Bravin, A. Guidetti, G. Licini and C. Zonta, *Chem. Sci.*, 2019, **10**, 3523–3528.
- 28 S. Akine, T. Taniguchi, T. Saiki and T. Nabeshima, J. Am. Chem. Soc., 2005, **127**, 540–541.
- 29 S. Akine, T. Taniguchi and T. Nabeshima, J. Am. Chem. Soc., 2006, **128**, 15765–15774.
- 30 Y.-B. Dong, P. Wang, J.-P. Ma, X.-X. Zhao, H.-Y. Wang, B. Tang and R.-Q. Huang, *J. Am. Chem. Soc.*, 2007, **129**, 4872–4873.
- 31 M. E. Carnes, M. S. Collins and D. W. Johnson, *Chem. Soc. Rev.*, 2014, **43**, 1825–1834.
- 32 D. Zare, Y. an Suffren, H. Nozary, A. Hauser, C. Piguet, D. Zare, D. Nozary, P. rof DrC Piguet, D. Suffren and D. Hauser, *Angew. Chemie Int. Ed.*, 2017, **56**, 14612–14617.
- 33 J. R. Shakirova, E. V. Grachova, V. V. Gurzhiy, S. K. Thangaraj, J. Jänis, A. S. Melnikov, A. J. Karttunen, S. P. Tunik and I. O. Koshevoy, *Angew. Chemie Int. Ed.*, 2018, **57**, 14154–14158.
- 34 H. Ube, K. Endo, H. Sato and M. Shionoya, J. Am. Chem. Soc., 2019, **141**, 10384–10389.
- 35 X. Hu, J. Chai, C. Zhang, J. Lang, S. P. Kelley, S. Feng, B. Liu, D. A. Atwood and J. L. Atwood, *J. Am. Chem. Soc.*, 2019, **141**, 9151–9154.
- X. Z. Li, L. P. Zhou, S. J. Hu, L. X. Cai, X. Q. Guo, Z. Wang and Q. F. Sun, *Chem. Commun.*, 2020, 56, 4416–4419.
- 37 M. Rancan, J. Tessarolo, A. Carlotto, S. Carlotto, M. Rando, L. Barchi, E. Bolognesi, R. Seraglia,

G. Bottaro, M. Casarin, G. H. Clever and L. Armelao, Cell Reports Phys. Sci., 2022, 3, 100692.

- 38 J. K. Clegg, F. Li and L. F. Lindoy, *Coord. Chem. Rev.*, 2022, 455, 214355.
- R. W. Saalfrank, H. Maid and A. Scheurer, *Angew. Chemie Int. Ed.*, 2008, **47**, 8794–8824.
- 40 J. K. Clegg, K. Gloe, M. J. Hayter, O. Kataeva, L. F. Lindoy, B. Moubaraki, J. C. McMurtrie, K. S. Murray and D. Schilter, *Dalt. Trans.*, 2006, 3977–3984.
- 41 J. K. Clegg, S. S. Iremonger, M. J. Hayter, P. D. Southon, R. B. Macquart, M. B. Duriska, P. Jensen, P. Turner, K. A. Jolliffe, C. J. Kepert, G. V. Meehan and L. F. Lindoy, *Angew. Chemie Int. Ed.*, 2010, **49**, 1075–1078.
- 42 M. Rancan, A. Dolmella, R. Seraglia, S. Orlandi, S. Quici and L. Armelao, *Chem. Commun.*, 2012, **48**, 3115–3117.
- 43 J. K. Clegg, F. Li, K. A. Jolliffe, L. F. Lindoy, G. V. Meehan, S. Parsons, P. A. Tasker and F. J. White, *Dalt. Trans.*, 2013, **42**, 14315–14323.
- 44 M. Rancan, J. Tessarolo, M. Casarin, P. L. Zanonato, S. Quici and L. Armelao, *Inorg. Chem.*, 2014, **53**, 7276–7287.
- 45 G. Han, Y. Zhou, Y. Yao, Z. Cheng, T. Gao, H. Li and P. Yan, *Dalt. Trans.*, 2020, **49**, 3312–3320.
- 46 Y. B. Tan, Y. Okayasu, S. Katao, Y. Nishikawa, F. Asanoma, M. Yamada, J. Yuasa and T. Kawai, *J. Am. Chem. Soc.*, 2020, **142**, 17653–17661.
- 47 N. Suko, H. Itamoto, Y. Okayasu, N. Okura and J. Yuasa, *Chem. Sci.*, 2021, **12**, 8746–8754.
- H. Ju, J. K. Clegg, K.-M. Park, L. F. Lindoy and S. S. Lee, J. Am. Chem. Soc., 2015, 137, 9535– 9538.
- 49 G. Truccolo, Z. Tessari, J. Tessarolo, S. Quici, L. Armelao and M. Rancan, *Dalt. Trans.*, 2018, **47**, 12079–12084.
- 50 M. Rancan, G. Truccolo, A. Carlotto, S. Quici and L. Armelao, *Inorganics*, 2019, **7**, 137.
- 51 W. M. Haynes, D. R. Lide and T. J. Bruno, Eds., *CRC Handbook of Chemistry and Physics*, CRC Press, 97th edn., 2016.
- 52 G. Ercolani, C. Piguet, M. Borkovec and J. Hamacek, *J. Phys. Chem. B*, 2007, **111**, 12195–12203.