Upconverting photons at the molecular scale with lanthanide complexes

Loïc J. Charbonnière, Aline M. Nonat, Richard C. Knighton and Léna Godec

In this perspective, we summarise the major milestones to date in the field of molecular upconversion (UC) with lanthanide based coordination complexes. This begins from the leap firstly from solid-state to nanoparticulate regimes, and further down the scale to the molecular domain. We explain the mechanistic intricacies of each differing way of generating upconverted photons, critiquing them and outlining our views on the benefits and limitations of each process, also offering our perspective and opinion on where these new molecular UC edifices will take us. This nascent area is already rapidly expanding and improving, having increased in luminance efficiency by more than four orders of magnitude in the last decade: we conclude that the future is bright for molecular UC.

1 Introduction

Upconversion (UC) is the process by which two or more photons are accumulated by a compound and restored as a photon of higher energy, with exclusion of the phenomenon associated to simple thermal population of the excited states. A full classification of the different mechanisms leading to UC and their relative efficiencies was given by Auzel in his seminal review of 2004. This anti-Stokes process allows to convert near infrared (NIR) light into UV-Vis light and finds applications in various fields. In microscopy, the UC light drastically removes artifact associated to auto-fluorescence of the biological samples and of light scattering in the setups, affording an excellent signal to noise ratio, which can also be of interest to biological sensing and analysis. Bringing NIR photons in the visible domain is also a promising way to improve the efficiency of solar cells, which are up to now poorly efficient in the NIR domain, but have their best performances in the visible. Alternatively, UC has proved
to be of interest for numerous other applications such as anti-counterfeiting inks, photodynamic therapy, diagnosis, ... However, whatever the application and for reasons that will be described in details in this perspective article, UC is still restricted to the use of bulk solids for materials and nanoparticles for biological applications. Considering issues such as reproducibility, stability and toxicity of nanoparticles, there is a large interest in designing chemically controlled molecular upconverting devices, that could be covalently bonded to (bio) molecules of interest, with improved chemical stability.

Historically, the observation of the phenomenon was rendered possible in the 1960’s by the development of high energy luminescence sources, but essentially on solids doped with d- or f-elements and lately on UC nanoparticles (UCNPs), a field which has exploded since then, with thousands of publications on the synthesis of UCNPs and their applications. It is only in 1996 that UC could be observed for the first time at the molecular level for ErCl₃ salts dissolved in POCl₃/SnCl₄ liquid medium, with a green emission band observed at 550 nm upon laser excitation at 800 nm.

At this stage of the discussion, it is important to note that UC was also reported as soon as 1962 for solutions containing purely organic luminescent compounds in cold (72 K) ethanol. The process was termed photosensitized triplet–triplet annihilation (TTA) and has been the subject of numerous research articles which can be found in different authoritative reviews. Although TTA is a topic of great interest for UC, with potential applications such as in solar energy conversion, the phenomenon is not purely molecular as it requires energy transfers between freely diffusing donors and acceptors in concentrated solution, with exceptions of very recent examples of supramolecular adducts. Hence, TTA will not be covered in this perspective article which is focused on lanthanide (Ln) based molecular UC devices.

The basic pre-requisites for the observation of UC are: firstly, the necessity to successively climb different energy levels, necessitating compounds with ladder like energy levels; and secondly long lived intermediate excited states enabling the ascent to the higher energy levels. This occurs by absorption of the next quantum of energy before it decays back to the ground state, either by simple luminescence or by non-radiative pathways. It is therefore unsurprising to find Ln elements as top players in the field of UC, whatever the physical state of the sample (solid, nanoparticulate, or molecules) as they possess both these characteristics. As evidenced in Fig. 1, the electronic configuration of Ln(III) cations ([Xe]4fⁿ with n = 0 to 14) is at the origin of a large number of electronic transitions, spanning the UV to near-infrared (NIR) domain, a perfect example of ladder like energy level diagram. Additionally, the Laporte forbidden character of electric dipole f–f electronic transitions provides them with very long radiative lifetimes, sometimes reaching the millisecond (ms) regime, that are two to six orders of magnitude larger than those of d-element coordination complexes or organic molecules respectively.

Unfortunately, a corollary of the forbidden character of the f–f electronic transition is that the corresponding absorption coefficients are very weak (a few units of M⁻¹ cm⁻¹), requiring high intensity excitation sources to populate the excited states. The radiative lifetime (Fig. 1b) is defined as the lifetime of a luminescent species in total absence of non-radiative contributions, that is for a 100% luminescence quantum yield. Unfortunately, luminescent compounds, including Ln compounds, are rarely perfect luminescent probes and an important part of the energy is lost by non-radiative pathways, among which is energy dissipation through the vibrations of the environment. In solids, these vibrations are called phonons and are defined as quasi-particles having the energy of a vibration of the lattice. In solution, the corresponding vibrations are those of the environment, the ligand for complexes and the solvent molecules for solvated ions. Part of the energy of the excited states can then be transferred to these vibrations or, more precisely, to their overtones. Despite some known deviations from the theory, it is generally assumed that the rate of the non-radiative processes, knr, is determined by the energy gap...
Excited state absorption (ESA) based molecular UC

Excited-state absorption (ESA) is the simplest and least demanding mechanism for molecular UC in terms of molecular design. Many lanthanide-based molecular species, ranging from mononuclear complexes to extended supramolecular edifices, have been shown to exhibit UC properties via this mechanism. In the ESA mechanism, the lanthanide complex is excited to a higher energy state via a first low-energy photon, bringing the ground state to an intermediate excited state, followed by the absorption of a second photon by the excited state to reach the doubly excited state, which finally emits light (Fig. 2). In this mechanism, the primary requirement arises from the lanthanide itself, which should possess multiple energy levels with a ladder-like pattern due to the complex interactions between the electrons.
These energy levels are conventionally described by the spectroscopic terms in the form \((S^L J_L)\) where \(S\), \(L\), and \(J\) stand for the usual quantum numbers: \(S\) is the spin quantum number defining the number of unpaired electrons; \(L\) is the total orbital momentum resulting from the electrostatic interaction within the orbital and \(J = L + S\) is the total angular momentum as a result of the spin–orbit coupling.36

As shown in Fig. 1, Er(III) is one of the lanthanide ions displaying transitions in both the near-infrared and visible regions. This characteristic is crucial in achieving ESA UC from NIR to visible light. In addition, Er(III) has a particularly strong absorption cross-section at 980 nm, which is a commonly used excitation wavelength for UC studies and application, establishing erbium as a prototypical species for ESA and for UC in general.35

There are two important electronic transitions for Er(III) in view of ESA UC. The first absorption band at ca. 10 000 cm\(^{-1}\) (around 1000 nm), corresponds to the transition from the \(^4I_{15/2}\) ground state to the \(^4I_{11/2}\) excited state (in red, Fig. 2b). Further excitation at the same energy allows to reach the higher \(^4F_{7/2}\) excited state (in blue, Fig. 2b). The second important transition is at ca. 12 500 cm\(^{-1}\) and is responsible for the ascendance from the ground state to the \(^4I_{9/2}\) excited state. From there, decays to the \(^4I_{11/2}\) or \(^4I_{13/2}\) excited states, followed by absorption of the second photon allowing the climbing to higher excited states emitting in the green region at ca. 550 nm (in green, Fig. 2b).

In that context, basic ErCl\(_3\) salts dissolved in low phonon liquids composed of a mixture of POCl\(_3\) and SnCl\(_4\) were shown to display ESA UC upon excitation at 800 nm with a modest 500 mW excitation power.36 The clever use of low phonon liquids is unfortunately not compatible with Er(III) based coordination complexes composed of organic ligands which might react chemically with reactive species such as POCl\(_3\). For coordination compounds, it is then mandatory to use benign solvents, generally displaying high energy vibrations such as O–H, N–H or C–H oscillators, with the concomitant deleterious effect on the lifetime and quantum efficiencies of the excited states (vide supra). A way to bypass this inconvenience is then to use high intensity excitation sources. But even in this case, the studies of Reinhard and Güdel on Er(III) tris-dipicolinate DPA (DPA = 2,6-pyridine-dicarboxylate, Fig. 3) complexes in water failed to show any UC.37 Similar experiments were also conducted with isostructural Tm(III) and Yb(III) complexes, yielding the same outcome.

Nevertheless, UC was achieved with the same molecules ([Er(DPA)]\(^{3+}\) and [Er(EDTA)]\(^{3-}\), Fig. 3) three years later by Xiao and co-workers in D\(_2\)O.38 By combining two highly focused high intensity (ca. 100 kW, \(P > 10^7\) W cm\(^{-2}\)) lasers, corresponding to the two electronic transitions from the ground state to the first excited state and from the latter to the second excited state, and by reducing the losses by non-radiative deactivation using a deuterated solvent, visible UC emission from Er(III) was finally observed. With a similar two-laser setup with high pump power, the energy ladder of Nd(III) and Tm(III) could also be climbed and ESA UC emission was observed in the UV (386 nm) and visible (480 nm), respectively. However, very weak UC signals were observed for the solutions in H\(_2\)O.

The intensity of the UC signal arising from an ESA mechanism depends on various factors such as the lanthanide ion of interest and its absorption cross-section (or extinction coefficient in solution studies), the experimental conditions (photon energy of the matrix, solvent, temperature), the concentration of the lanthanide ions in the sample, the excitation wavelength and the laser power. Generally, the efficiency of UC expressed by its UC quantum yield \(\Phi_{\text{UC}}\) (eqn (1)), typically falls within the range of \(10^{-10}\) to \(10^{-7}\) in solution.

\[
\Phi_{\text{UC}} = \frac{\sum P_{\text{emitted}}}{\sum P_{\text{absorbed}}} \tag{1}
\]

For more details, these parameters have been recently reviewed by Yao and co-workers.32 As demonstrated in the study by Xiao and co-workers discussed above,38 vibrational quenching is the principal enemy of ESA-based UC systems but it is also a parameter that can be limited by a careful design of the ligands. Several strategies have been investigated over the last ten years in the quest of limiting high-energy oscillators from the ligand and solvent molecules.

The simplest one is basically to use deuterated solvents as the impact of deuteration was recognized to improve the luminescence properties of Ln ions.39 Introducing X–D in place of X–H bonds (where X = O, N or C atoms) increases the reduced mass of the bond within the frame of an harmonic oscillation, thereby decreasing the energy of the corresponding oscillation, while requiring more of these oscillators to quench the luminescence.\(^{31}\) For coordination compounds, the impact of deuteration of the solvent is essentially on the second coordination sphere. Thus, a logical step forward is the deuteration of the ligands themselves, which now requires far more synthetic work.36,40,41 Some authors even went a step further by fluorinating the ligands, which appears particularly efficient for Yb complexes.42 In order to repel solvent molecules as far as possible from the Ln atoms, another strategy consists in using bulky aromatic substituents, possibly fluorinated ones.43

In our very first study on UC, we measured ESA on a mononuclear [ErL(H\(_2\)O)] complex in D\(_2\)O (Fig. 4a) and demonstrated that the signal was substantially increased while replacing the inner sphere water molecule by a fluoride ion.44 Furthermore,
the signal was further enhanced when the structure was rigidified through the formation of a supramolecular dimer [F·C(ErL)2]7−, stabilized by π–π interactions between the aromatic indazolyl moieties and augmented by a network of hydrogen bonds.45 The UC efficiency, as reflected by the emission intensity at 541 nm upon excitation at 980 nm (Fig. 4b), was very well correlated with the concentration of the dimeric species in solution. For a [NaF]/[ErL(H2O)] ratio of 0.5 (corresponding to approximately 90% dimer formation), UC emission increased by a factor of 7.7. Under these conditions, the UC process was confirmed by a slope of two in the log I/log P plot (Fig. 4c).

Subsequently, Piguet and his group designed a series of nonadentate triple–helicate complexes with polyaromatic tridentate ligands derived from terpyridine and bis(benzimidazole)pyridine (Fig. 3).46,47 The absence of metal-bound solvent molecules is favorable for long-lived excited states (τEr,obs = 2–6 μs) and efficient UC properties, with a noticeable advantage for bis(benzimidazole)pyridine derivatives. Replacing terpyridine by benzimidazole substituents nonetheless enhances the UC intensity by extending the Er3+ excite state lifetime (from τEr,obs = 1.88 μs for [Er(Et-tpy)]3+ to τEr,obs = 5.56 μs for [Er(Et-bzimpy)]3+), but it also significantly raises the Er3+ molar absorption at 980 nm (increasing from 0.7 M−1 cm−1 for [Er(Et-tpy)]3+ to 26 M−1 cm−1 for [Er(Et-bzimpy)]3+). Within this series, quantum yield values up to 1.7 × 10−9 at P = 25 W cm−2 have been measured in CH3CN at room temperature upon NIR excitation of the 4I15/2 → 4I13/2 absorption band of Er3+ at 801 nm. Although these values reflect a clear trend in adjusting the UC capabilities through structural modifications of the ligands.47

As observed in the pioneering work of by Xiao and co-workers on Tm3+ and Nd3+ complexes with DPA and EDTA (Fig. 2), these two metal ions are also capable of ESA UC.48 So far, molecular ESA UC emission with these two ions has been limited to simple complexes or, simple solvates (such as [Tm(CF3SO3)3] in DMSO-d6), as reported by Sorensen, Beeby, and Faulkner, necessitating the use of high-power NIR lasers.49 It can be anticipated that UC with Nd3+ and Tm3+ is less efficient compared to Er3+ due to the shorter excited state lifetimes exhibited by Nd3+ and Tm3+, which are unfavorable for UC. As examples, τEr ([Er3+2Nd(NO3)3]) = 0.42 ms;26 τEr (Er(NO3)3) = 0.66 ms;26 τEr (Er(NO3)3) = 0.27 ms;34 τEr (Er(NO3)3) = 0.75 ms;49 τEr (G3+) = 0.29 ms.49 In addition, Nd3+ exhibits absorption cross-sections that are usually lower than that of Er3+ and Tm3+.60

UC is a valuable process, particularly in bioimaging, where the conversion of low-energy near-infrared light to visible light is advantageous for deep-tissue imaging.46 Despite its potential, it is important to highlight that the efficiency of UC via ESA may currently be insufficient, leading to a preference for other mechanisms. As a consequence, several research groups have turned towards mixed heterometallic coordination complexes or assemblies with the idea of taking advantage of the long-lived excited state and/or increased molar absorption coefficients of donors such as Cr3+ or Yb3+ and to favor UC emission processes other than ESA, such as energy transfer up-conversion (ETU) which will be detailed in the following section. Also, when ETU takes place, it is important to note that ESA UC is still present. This was indeed the case for the 3:2 sandwich-type complexes with naphthalysalenophen ligands developed by A. de Bettencourt-Dias et al.52 and for the [CrErCr(bpb-bzimpy)]3+ triple-stranded helicates synthesized by Piguet et al.31 In this very particular example were the experimental UC quantum yields was determined to be ηUC,tot = 1.7(2) × 10−9 (λexc = 801 nm and P = 25 W cm−2), state-of-the-art photophysical and theoretical studies have shown that ESA remains significantly more efficient than ETU, with a theoretical contribution of ESA exceeding 98.8%, while the theoretical contribution of ETU is limited to a maximum of 1.2%.
In addition, in the context of exploratory research, there remain unexplored possibilities for enhancing ESA efficiency. These possibilities involve exploring the use of pulse-shaping or laser pumping techniques to enhance ESA by optimizing the absorption of excited states, as well as further exploiting the temperature-dependent ligand field effect to encourage hyperfine transitions, with the goal of increasing their absorption coefficient.

3 Energy transfer upconversion (ETU) based molecular UC

The energy transfer UC (ETU) mechanism (Fig. 5) is distinguishable by its core principle: unlike ESA, it requires two ions in a neighboring environment.\(^1\) In this process, the first ion, termed the sensitizer (S), is excited from the ground state to a higher excited level by absorption of a photon. Energy is then transferred to the second ion, termed the activator (A), which is itself in an excited state, enabling it to reach a doubly excited state, from which light is emitted.

This breakthrough finds its roots in the pioneering work of Auzel reported in 1966, who introduced the concept of ETU to address the limitations associated with the direct excitation of parity-forbidden intra-f transitions within trivalent lanthanide cations.\(^5^8\,5^9\) This concept revolutionized the landscape by proposing the use of sensitizers possessing heightened absorption cross sections, initiating sequential energy transfer processes that lead to the multistep excitation of the activator. Thus, the ETU mechanism offers an efficient pathway to circumvent the limitations posed by activators with short-lived intermediate excited states, by using sensitizers with long-lived excited states.

Harnessing this mechanism, lanthanide-doped solids or nanoparticulate materials have emerged as promising platforms. In particular, the unique long-lived excited state of ytterbium ions, exploited as a relay in ETU, has enabled the effective UC of ions including erbium, thulium, and praseodymium.\(^1\)

Building upon this fundamental understanding of the ETU mechanism, we now investigate its intricate dynamics at the molecular scale. Through an analysis of established molecular examples, a comprehensive perspective on how ETU operates at the molecular level is attained, providing indispensable insights to optimize this phenomenon for diverse applications.

![Illustration of the ETU mechanism.](image)

Fig. 6 (a) Heterotritopic ligand L1 used in the preparation of the heterotrinitruclear [Cr\(_2\)Er(L1)]\(_{5+}\) complex displaying NIR to visible ETU UC.\(^2^9\) (b) NIR dye containing tridentate ligand L2 displaying ligand to Er ETU UC.\(^7^2\) with (c) single-crystal X-ray structure (ion colors: Cr = brown, Er = teal).

At the heart of molecular-scale ETU studies lies the trinuclear complex [Cr\(_{2}\)ErCr(L1)]\(_{3}^+\) (Fig. 6a), developed by Piguet and coworkers, where chromium (Cr) acts as the sensitizer (S) and erbium (Er) as the activator (A), being the first isolated molecular system to exhibit near-infrared to visible UC.\(^2^9\) Several factors, especially the high concentration of sensitizers, contribute to detectable molecular UC in frozen acetonitrile solution at 77 K. The quadratic dependence of upconverted emission on incident intensity and the crucial role of Cr → Er energy transfer processes supported the presence of the ETU pathway in these supramolecular complexes. The system’s main limitation lies in its relatively low efficiency in energy transfer, potentially attributed to a significant Cr–Er intermetallic distance which averages 8.8 Å.\(^5^1\) The significance of the number of sensitizers becomes apparent when comparing with a comparable dinuclear complex with a singular sensitizer (Cr\(^{3+}\)) per erbium activator, forming a SA pair.\(^2^9\,3^1\,6^0\) The resulting upconverted emission from NIR to green displayed a noticeable reduction in intensity by more than one order of magnitude compared to CrErCr.

These examples were followed by the first evidence of molecular photon UC achieved by ETU through an organic antenna-sensitized erbium complex in organic solution at room temperature.\(^6^1\) Efficiency gains were achieved through the utilization of the IR-806 dye with a large infrared absorption band, contributing to the notable improvement in the UC process compared to f-f transitions. Continuing from the progress achieved through organic dye antennas, another notable advancement emerged, involving a NIR dye antenna linked to a tridentate binding unit, effectively capturing NIR photons and transferring them efficiently thanks to the spatial proximity. The resulting complex, [L\(_2\)Er(hfac)]\(_3\) (hfac = hexafluoroacetetyl acetonate) (Fig. 6b), exhibited a remarkable UC brightness in nondeuterated acetonitrile at room temperature.\(^6^2\)

Employing a co-doping strategy with Yb\(^{3+}\) ions has emerged as a powerful tool to improve the NIR absorption lanthanide ions used for UC. In particular, the focus shifts to the well-
explored Er\(^{3+}\)-Yb\(^{3+}\) pair, a prominent and extensively investigated duo in the field of UC in solids.\(^1\)

Thus, Zeng et al. developed heteronuclear lanthanide complexes strategically composed of Yb/Er pairs, harnessing the ability of Yb\(^{3+}\) to trigger notable Er\(^{3+}\) UC emission through an ETU mechanism in CH\(_2\)Cl\(_2\) solution.\(^3\) Remarkably, this strategic assembly of complexes, carefully balanced the sensitizer-to-activator (S/A) ratio and incorporating fluoride for reduced vibrational quenching, yielded an UC quantum efficiency that surpassed previous examples by a factor of 20.

The abundance of Yb\(^{3+}\) significantly enhanced the probability of Yb \(\rightarrow\) Er energy transfer, emphasizing the critical role of the Yb/Er ratio in augmenting UC efficiency.\(^4\) This phenomenon has been particularly noticeable in the nanosized [Er\(_2\)Yb\(_{13}\)] complex. In light of their comparable chemical characteristics, the substitution of one lanthanide with another in these molecular entities is a viable option. This reveals the first example of Ho\(^{3+}\) complex exhibiting UC at the molecular scale in deuterated methanol solution with a [Gd\(_8\)Ho\(_2\)Yb\(_{10}\)] cluster.\(^5\)

The quest for efficient UC luminescence in molecular systems by ETU mechanism steers towards careful ligand selection, aiming to combine multiple lanthanides into cohesively nuclear assemblies. In this context, molecular lanthanide clusters,\(^6\) also called molecular cluster aggregates (MCA)\(^7\)\(^-\)\(^9\) offer distinct advantages. Their spherical topology confers structural rigidity, ensuring a stable framework. The high nuclearity and the possibility to interchange lanthanides within these molecular structures provide a versatile platform for tailoring properties and transitions. Moreover, these structures exhibit stability in various solvents, and their structural rigidity helps dampen molecular vibrations, leading to notably high UC quantum yields. These combined features position clusters as promising candidates for efficient and customizable UC applications.

The main difficulty to develop efficient ETU based complexes of Ln rely on the choice of the activator. Apart from the rare case of Ho, most of these systems are based on Er, where Tm or Pr should also be envisaged. But all of these potential activators possess NIR electronic transitions (Fig. 1), which are subject to the possibility to interchange lanthanides within these molecular entities is a viable option. This reveals the first example of Ho\(^{3+}\) complex exhibiting UC at the molecular scale in deuterated methanol solution with a [Gd\(_8\)Ho\(_2\)Yb\(_{10}\)] cluster.\(^5\)

The quest for efficient UC luminescence in molecular systems by ETU mechanism steers towards careful ligand selection, aiming to combine multiple lanthanides into cohesively nuclear assemblies. In this context, molecular lanthanide clusters,\(^6\) also called molecular cluster aggregates (MCA)\(^7\)\(^-\)\(^9\) offer distinct advantages. Their spherical topology confers structural rigidity, ensuring a stable framework. The high nuclearity and the possibility to interchange lanthanides within these molecular structures provide a versatile platform for tailoring properties and transitions. Moreover, these structures exhibit stability in various solvents, and their structural rigidity helps dampen molecular vibrations, leading to notably high UC quantum yields. These combined features position clusters as promising candidates for efficient and customizable UC applications.

The main difficulty to develop efficient ETU based complexes of Ln rely on the choice of the activator. Apart from the rare case of Ho, most of these systems are based on Er, where Tm or Pr should also be envisaged. But all of these potential activators possess NIR electronic transitions (Fig. 1), which are subject to the possibility to interchange lanthanides within these molecular entities is a viable option. This reveals the first example of Ho\(^{3+}\) complex exhibiting UC at the molecular scale in deuterated methanol solution with a [Gd\(_8\)Ho\(_2\)Yb\(_{10}\)] cluster.\(^5\)

The quest for efficient UC luminescence in molecular systems by ETU mechanism steers towards careful ligand selection, aiming to combine multiple lanthanides into cohesively nuclear assemblies. In this context, molecular lanthanide clusters,\(^6\) also called molecular cluster aggregates (MCA)\(^7\)\(^-\)\(^9\) offer distinct advantages. Their spherical topology confers structural rigidity, ensuring a stable framework. The high nuclearity and the possibility to interchange lanthanides within these molecular structures provide a versatile platform for tailoring properties and transitions. Moreover, these structures exhibit stability in various solvents, and their structural rigidity helps dampen molecular vibrations, leading to notably high UC quantum yields. These combined features position clusters as promising candidates for efficient and customizable UC applications.

The main difficulty to develop efficient ETU based complexes of Ln rely on the choice of the activator. Apart from the rare case of Ho, most of these systems are based on Er, where Tm or Pr should also be envisaged. But all of these potential activators possess NIR electronic transitions (Fig. 1), which are subject to the possibility to interchange lanthanides within these molecular entities is a viable option. This reveals the first example of Ho\(^{3+}\) complex exhibiting UC at the molecular scale in deuterated methanol solution with a [Gd\(_8\)Ho\(_2\)Yb\(_{10}\)] cluster.\(^5\)

The quest for efficient UC luminescence in molecular systems by ETU mechanism steers towards careful ligand selection, aiming to combine multiple lanthanides into cohesively nuclear assemblies. In this context, molecular lanthanide clusters,\(^6\) also called molecular cluster aggregates (MCA)\(^7\)\(^-\)\(^9\) offer distinct advantages. Their spherical topology confers structural rigidity, ensuring a stable framework. The high nuclearity and the possibility to interchange lanthanides within these molecular structures provide a versatile platform for tailoring properties and transitions. Moreover, these structures exhibit stability in various solvents, and their structural rigidity helps dampen molecular vibrations, leading to notably high UC quantum yields. These combined features position clusters as promising candidates for efficient and customizable UC applications.

The main difficulty to develop efficient ETU based complexes of Ln rely on the choice of the activator. Apart from the rare case of Ho, most of these systems are based on Er, where Tm or Pr should also be envisaged. But all of these potential activators possess NIR electronic transitions (Fig. 1), which are subject to the possibility to interchange lanthanides within these molecular entities is a viable option. This reveals the first example of Ho\(^{3+}\) complex exhibiting UC at the molecular scale in deuterated methanol solution with a [Gd\(_8\)Ho\(_2\)Yb\(_{10}\)] cluster.\(^5\)
of Yb ($^7F_{7/2} \leftrightarrow ^2F_{7/2}$, $\lambda_{ex} = 980$ nm) gave rise to the characteristic emission of Tb ($^7D_4 \rightarrow ^7F_j$ with $J = 6$ to 3, $\lambda_{em} = 475$–630 nm).

Subsequent work in the group built on this, using a trinuclear pyridylyphosphate triazacyclonane (TACN) scaffold. In this case, UC was visible in D$_2$O, but also importantly in H$_2$O. This case highlights the combined importance of both quantum yield and lifetime – and will be an important factor in the design of future upconverting molecular edifices. The TACN complex displays a comparable excited-state lifetime in H$_2$O ($2.8 \mu$s vs. $3.3 \mu$s for YbL$_{D0}$), but exhibits quantum yield of 0.75% (cf. 0.2% for YbL$_D$). These results are encouraging for future iterations but clearly one prospective challenge is enabling high stability of all metal ions – not just the sensiti-
ers. We envisage supramolecular multitopic ligands to satisfy this criterion.

While UC systems operative in aqueous solvents are highly desirable, they also represent the biggest challenge due to the appreciable quenching effect of outer-sphere OH and, to a lesser extent, OD oscillators. This is currently impinged by the fact that the molecular ligand toolbox for strong Ln chelators in water rarely includes bridging modalities for multimetallic assemblies. Indeed, we have already stated that short intranuclear Ln–Ln distances are crucial for the energy-transfer step (vide supra). In the area of CP UC, molecular clusters have again been promising UC candidates. While these systems are not amenable to aqueous environments, they are miniaturized congeners of the well-known Ln-nanoparticle based emitters, displaying short Ln–Ln distances of ca. 3.5 Å. The first example reported was that of an Ln$_{50}$ (Ln = Tb/Yb) cluster$^{46}$ the central Ln$_9$ core being isosstructural with hexagonal doped NaYF$_4$ UC nanoparticles. In this case the ligands were present as bridging deuteroxide ($\mu_4$-OD or $\mu_3$-OD), rather than fluoride in nanoparticles, which represents the primary mechanism of excited-state deactivation. Studies revealed that, contrary to the mechanistic interpretation, sensitizer to activator ratios approaching parity gave the most efficient UC platforms ($\Phi_{UC} = 2.8 \times 10^{-6}$ for Tb$_3$Yb$_5$ in Cd$_3$OD).$^{47}$ The commercial availability of these ligands and ease of synthesis has allowed rapid diversification of the acceptor. Murugesu and co-workers have worked extensively on an Ln$_{50}$ cluster compound and have reported a mixed Yb/Tb/Eu system (Fig. 8a) by doping a Gd host cluster matrix.$^{58}$ Excitation of the Yb ions at $\lambda_{ex} = 980$ nm gives rise to both Tb

![Image](14x290 to 26x354)

Fig. 8  Single-crystal X-ray structure of (a) [Gd$_7$Tb$_2$Eu$_{11}$] cluster,$^{48}$ (b) Yb$_3$Eu$_2$ metal–organic cage (ion colors: Eu = purple, Tb = green, Gd = teal, Yb = red).$^{74}$

Indeed, an example of Yb/Eu UC has recently been reported using a Ln$_8$ metal–organic cage containing a mixture of Eu and Yb ions.$^{79}$ By employing a statistical mixture of Yb and Eu, in analogy to the strategy used for cluster-based materials, cooperative photosensitization of Eu emission was observed in the solid-state upon irradiation of the Yb absorption band at 980 nm, with a QY of ca. 2 $\times$ 10$^{-5}$. The Ln–Ln distances were approximately 14.3 Å, demonstrating the ability for UC over significantly longer distances than previously thought (Fig. 8b).

Thus far, all systems have employed lanthanide sensiti-
ers and activators. One advantage of the molecular approach – diverging from nanoparticle-based systems – is the potential for changing the identity of the accepting chromophore. Indeed, the case of cooperative photosensitization is enigmatic in that the activator does not require intermediate energy levels to ascend the energy ladder (viz. Tb). This was exploited elegantly by Heinze, Resch-Genger, and Seitz through co-crystallisation of a mixture of a tricationium chromium complex, mer-[Cr$_{10}$B$_{13}$](dppd)$_{11}$ (dppd = N,N'-di-methyl-N,N'-dipyrindine-2,6-diamine) and a trianionic ytterbium complex, [Yb(DPA)$_3$]$^{3-}$ (Fig. 9a).$^{75}$

Upon excitation into the Yb manifold at 980 nm, concomitant energy transfer occurred, populating first the $^4$f$_2$ state, followed by intersystem crossing (ISC) to the $^2E^o$T$_1$ excited state of the Cr ion, resulting in emission at 775 nm arising from the $^2E^o$T$_1$ $\rightarrow$ $^4$A$_{2g}$ transition. As with other systems use of deuterium was key to observing the phenomenon, the included CH$_2$OH/CD$_3$OD solvates providing a significant quenching pathway. This work highlights the potential advantages of transition-metal acceptors; the additional excited state ISC relaxation mechanism permits both NIR-excitation and NIR-emission.

In a similar approach, we reported a related example which exhibits solution-state UC in a tetrametallic RuYb$_5$ assembly (Fig. 9b).$^{76}$ Through combination of [Ru(bpm)$_3$][Bar$_3$]$_2$ (bpm = 2,2-bipyridimidine, Bar$^{3+}$ = tetrakis[3,5-bis(trifluoromethyl)]
phenylborate), and \([\text{Yb(ttf}a)_2(\text{OH})_2] \) (ttfa = 2-thenoyltrifluoroacetone) in anhydrous acetonitrile we were able to form an assembled RuYb3 array. Irradiation of the peripheral Yb ions (\(\lambda_{\text{ex}} = 980 \text{ nm}\)) produced CP which sensitized the \(^{9}\text{MLCT}\) state of \([\text{Ru(bpm)}]^2+\), and ISC led to the emission from the \(^{9}\text{MLCT}\) state at 636 nm. Importantly the rate of \(k_{\text{UC}}\) was found to be 25 times higher than for Yb–Tb CP systems, demonstrating the advantage of using a spin-allowed absorption of d-metals vs. spin-forbidden Ln transitions. The quantum yield was determined to be \(2.1 \times 10^{-8}\) which compares favorably with Ln only systems, particularly given that these results were obtained in non-deuterated media. A unique case of CP UC was reported by Pérez-Preto, González-Béjar and co-workers using a fluorescein analogue. The authors mixed Yb(OTf)3 and Eosin Y to produce a material with the general constitution \([\text{Eosin Y}][\text{Yb}^x]\) (x = integer).\(^{77}\) This compound exhibits UC via sensitization of the Eosin YS1 state by the Yb** state after NIR excitation (\(\lambda_{\text{ex}} = 980 \text{ nm}\)). Emission from the S1 \(\rightarrow\) S0 transition is observed at 600 nm, with an impressive calculated quantum yield of \(7.2 \times 10^{-5}\). Both this example and the case using ruthenium demonstrates that the use of spin-allowed absorption can have a strong effect on the overall quantum yield by enhancing the efficiency of the energy-transfer step, and this area should be a strong focus of UC research in the future.

4.2 Cooperative luminescence

Cooperative luminescence (CL) is related to CP in that both use two Yb ions as energy relays for UC. While the two differ is that in CP two Yb sensitzers transfer their energy to a single acceptor ion, while in CL there is no central visible-emitting acceptor. Rather – conversely to all other mechanisms considered here – CL can be considered a second order process whereby a Yb*Yb* state recombines to emit from a doubly Yb** excited state (Fig. 10a). The phenomenon of CL had, until recently, only been reported in solid-state materials.\(^{78,79}\) The absence of reports of CL in nanoparticles owe to the fact that such materials display a high propensity for energy migration and as such either exhibit conventional Yb-based NIR downshifting photoluminescence or non-radiative decay of the Yb excited state before CL can occur. In this regard, molecular level systems have proved invaluable due to their lower nuclearity and hence reduced susceptibility for quenching via successive energy migration steps.\(^{80}\) Despite this, such molecular CL systems are still relatively rare. The first such molecular example was reported in a powdered sample of a monometallic \([\text{Yb(N}_2\text{N}_2\text{)}(\text{ttfa})_2]\) complex in 2019.\(^{80}\) Cooperative luminescence occurred through an intermolecular process between neighbor Yb complex in the solid-state, and exhibited emission at \(\lambda_{\text{em}} = 490 \text{ nm}\) upon excitation at 950 nm. In terms of discrete single-molecule UC in solution we first noticed an anomalous signal present in CP UC in molecular hetero-nonanuclear Yb/Tb clusters.\(^{80}\) This signal was not present in the downshifted photoluminescent spectra indicating the presence of an alternative UC process. Irradiation (\(\lambda_{\text{ex}} = 980 \text{ nm}\)) of the homonuclear \([\text{Yb}_2(\text{acac})_6(\text{OD})_{10}][\text{OD}]\) complex (Fig. 10b) in a CD3OD solution gave rise to a highly symmetrical structureless emission band at 503 nm. Importantly, the log/log plot of integrated emission intensity vs. incident laser power gave a slope of 1.8, confirming the two-photon process. The lifetime of the CL emission (8 \(\mu\)s) is approximately half that of the Yb-centred lifetime (15 \(\mu\)s), in good agreement with theory.\(^{79}\) Although this occurs within a Yb9 cluster, in theory this requires only two proximate Yb ions. Unequivocal proof of this bimetallic mechanism was demonstrated in through simplification into the mechanistically simplest components, molecular Yb2 dimers. This was observed in an homo-dimetallic ytterbium cryptate (Fig. 11a) and a 2,2’-bipyridine bridged complex.\(^{81}\) The CL UC signal was significantly more intense for the cryptate complex owing to the much shorter intermetallic distance (3.445 Å vs. 6.639 Å). Importantly the quantum efficiency of the CL phenomenon (4.7 \(\times\) \(10^{-8}\) in (CD3)2SO) far exceeded that of the higher nuclearity Yb9 cluster (cf. 3 \(\times\) \(10^{-9}\) in CD3OD), informing that CL does not show an improvement with increasing nuclearity, the additional absorption cross-section of high Yb concentrations notwithstanding. Time-resolved measurements and kinetic modelling reveals a rate-determining \(k_{\text{UC}}\) step to the (YbYb)** state. Interestingly the CL emission band profile at ca. 500 nm was shown to directly relate to the corresponding downshifted Yb photoluminescence profile due to the Stark-split sublevels of the \(^2\text{F}_{5/2} \rightarrow \ ^2\text{F}_{7/2}\) transition between 980–1050 nm (Fig. 11b), indicating the emission profile has some ‘memory’ of the excited state of each individual Yb* state from which it is derived.

One can conclude that the observation of molecular scale CL holds many possibilities for future research; circumventing the...
need for heterometallic CP systems, which can be hard to prepare, while not suffering from the main limitation of homometallic ETU phosphors based upon Er: significant quenching due to the presence of very low energy states (>1500 nm). We hope that these first few examples will serve as inspiration to more diverse and efficient systems.

5 Future outlook

Since the very first examples of molecular UC with Ln complexes in solution to now, the UC quantum yield and the brightness of these objects have been boosted by more than four orders of magnitude, allowing for their easy observation with traditional spectroscopic setups. However, there is still room in this recent topic for improvements, either for the efficiency of the devices, or for their implementation into applied systems. Within the frame of the ESA mechanism, the Achilles heel stands in the very weak absorption of the Ln elements and further progress might arise from the design of new compounds of very low symmetry, to improve the Ln based transition probabilities. Alternatively, another way to improve UC is also to reduce non-radiative relaxation pathways. If large efforts have been devoted to the use of per-deuterated compounds, organic solvents may open the door to the replacement of hydroxide anions by the isoelectronic fluoride anions in Ln based architectures.

In contrast, the use of molecular UC devices for photovoltaic applications might be regarded as a very unlikely outlook. The narrow and weak absorption bands of Ln atoms are here the bottlenecks limiting the photon collection in the NIR domain. The alternative would then be the development of Ln based complexes with broad band NIR absorption of associated ligands. Considering the efficiency spectra of common solar cells based on silicon or CIGS thin films, this absorption should be below 10,000 cm\(^{-1}\). Then, the UC photons must match the efficiency window of the cell, that is an emission above 10,000 cm\(^{-1}\), which, for the piling of two photons, fix the energy of the intermediate Ln excited state above 5000 cm\(^{-1}\). If one could potentially consider Ln elements such as Er (with its \(^{4}I_{13/2} \rightarrow ^{4}I_{15/2}\) transition at 1550 nm, \(i.e.\) 6450 cm\(^{-1}\)) or Tm (\(^{3}F_{4} \rightarrow ^{3}H_{6}\) transition at ca. 1900 nm, \(i.e.\) 5200 cm\(^{-1}\)) for such UC process, the low energy of these NIR transitions and their propensity to be quenched by the vibrations of the medium, are hardly compatible with a high quantum efficiency and an interesting UC process at the molecular scale.

Concerning applications, the holy grail would clearly be to reach efficient molecular UC in water for biolabeling and biosensing applications. The plethora of examples obtained with UC nanoparticles would be available with molecular precision and reproducibility, while removing the potential toxicity and stability aspects associated to nanoparticles (providing the molecular devices are themselves stable complexes in biological media). Examples of molecular UC in water are still rare, but have merit and can pave the way to improved performances. In that respect, a combination of ligand-based photosensitization with a convenient composition of Ln atoms in heteropolymeric assemblies based on ETU or CL UC should be a convenient way to tackle this issue.

Author contributions

L. J. C. conceptualized, wrote and supervised the manuscript and A. M. N., R. C. K. and L. G. wrote and edited the perspective.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

The French National Research Agency is gratefully acknowledged for financial support (ANR LUCAS ANR-19-CE29-0014-01 and POPUP project ANR-22-CE29-0005-01).

Notes and references

65 D. A. Galico, R. Ramdani and M. Murugesu, Nanoscale, 2022, 14, 9675.
69 D. A. Gálico, C. M. S. Calado and M. Murugesu, Chem. Sci., 2023, 14, 5827.