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Significant developments in rare-earth-containing polyoxometalate chemistry: synthetic strategies, structural diversities and correlative properties

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Owing to their unique and abundant structures and potential multi-fold applications in various fields such as luminescence, magnetism, catalysis, etc., rare-earth-containing polyoxometalates (RECPs) play an important role in the development of polyoxometalate chemistry. In this article, the major progress in RECPs made in the past decade involving synthetic strategies, structural characteristics and some significant properties related to optics, catalysis and magnetism is highlighted and discussed. The final section is committed to looking forward to some future perspectives in this field and providing some personal insights or viewpoints for the ongoing trends in the future.

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1. Introduction

Polyoxometalates (POMs) are discrete anionic clusters that can be condensed by oxo-bridged early transition metal atoms in their high oxidation states (usually Mo^{VI}, W^{VI}, V^V, Nb^V or Ta^V).¹ These metal atoms are coordinated by six oxygen ligands giving rise to {MO₆} octahedral geometries and the resulting {MO₆} units are further joined together by corner- or edge- (rarely face-) sharing oxygen atoms (formally O²⁻ or occasionally HO⁻ ions).² With regard to polyoxoanions (POAs), several classical types have been reported: Keggin, Wells–Dawson, Lindqvist, Anderson–Evans, Weakley,

Silverton, Strandberg, *etc.*³ After Pope and Müller published a review article that comprehensively elucidated the fascinating structural characteristics and important potential of POMs in several disciplines in 1991,⁴ a myriad of unexpected POM structures have constantly emerged. Then a special thematic issue on POMs organized by Hill in 1998 not only rapidly accelerated the discovery of peculiar POM species, but also provoked the emergence of some new research areas in POM chemistry.⁵ Due to their flexible and diversiform structures, POM-based materials exhibit many versatile performances in various areas such as catalysis, medicine, materials science, nanotechnology, molecular magnetism and photochemistry.⁶ Hitherto, the synthesis and preparative chemistry of POMs still remain a great driving force in exploring and discovering novel POM-based materials despite the discovery of the first POM (NH₄)₃PMo₁₂O₄₀ by Berzelius as early as 189 years ago

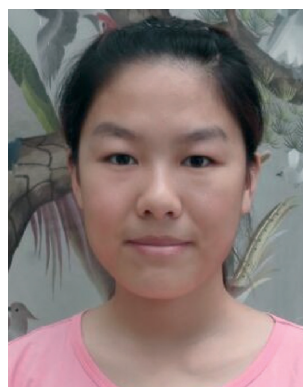
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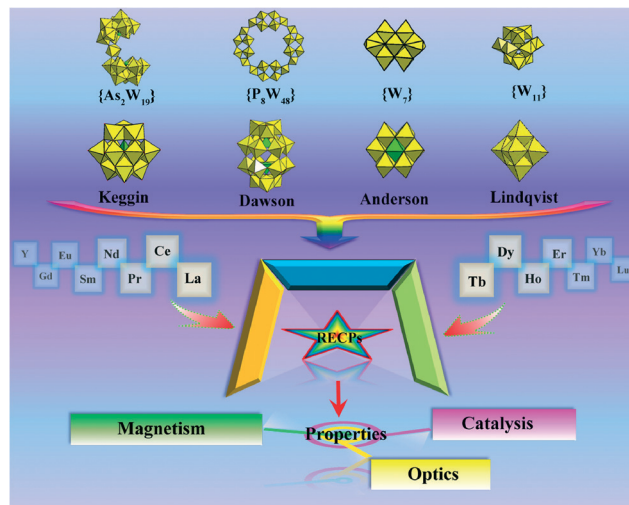


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and even the first structural determination of the phosphotungstic acid $\text{H}_3[\text{PW}_{12}\text{O}_{40}]\cdot 29\text{H}_2\text{O}$, which was accomplished in 1936 by Keggin by virtue of a powder X-ray diffraction study.⁷

Based on their nucleophilic oxygen-enriched surfaces, POM units can act as excellent inorganic multidentate candidates for integrating transition metal (TM), rare-earth (RE) or both into their structures.⁸ Thereby, a vast array of novel TM, RE or TM-RE-containing POMs have been prepared gradually. For example, the first RE-containing POM (RECP) $(\text{NH}_4)_2[\text{H}_6\text{CeMo}_{12}\text{O}_{42}]\cdot n\text{H}_2\text{O}$ was discovered by Barbieri in 1914.⁹ Then in 1971, Peacock and Weakley successfully separated a family of 1:2 series RECPs $[\text{RE}(\text{W}_5\text{O}_{18})_2]^{9-}$, $[\text{RE}(\text{SiW}_{11}\text{O}_{39})_2]^{13-}$ and $[\alpha_2\text{-RE}(\text{P}_2\text{W}_{17}\text{O}_{61})_2]^{17-}$, which are a milestone in the history of RECP chemistry.¹⁰ Historically, the first TM substituted POM (TMSP) was communicated by Simmons at the 1962 (Stockholm) International Conference on Coordination Chemistry (ICCC) and its structure (it is an 11-tungstosilicate wherein one W atom of the Keggin structure was replaced by a Co^{2+} ion) was confirmed by St. Moritz at the 1966 ICCC.¹¹ Moreover, the composition, size, shape, solubility, redox potential, magnetic and catalytic properties of TMSPs are relatively easy to be fine-tuned by elaborate selection of types and oxidation states of TM ions.¹² Therefore, the development of TMSPs is much faster than that of RECPs. However, RECPs can exhibit special luminescent, Lewis acid catalytic or magnetic functionalities by taking advantage of the electronic and structural features of RE ions (Scheme 1):¹³ (i) depending on the special electronic properties of lanthanide (Ln) cations (the shielding of the 4f orbitals by the filled $5s^25p^6$ subshells), Ln-containing compounds often have good fluorescence activity and long lifetime, which makes them promising be used in optical fields such as light-emitting diodes, plasma displays, sensory probes, medicinal analyses, drug delivery monitoring and cell



Scheme 1 Schematic representation of the assembly processes of RECPs. Several typical POAs and three significant properties are highlighted.

imaging;¹⁴ (ii) the high coordination numbers and flexible coordination geometries of RE ions endow them with the ability to leave some residual coordination sites that can act as effective Lewis acids for the activation of substrates.^{13e} It has been proved that the introduction of some RE ions (Lewis acidic cations) into POM skeletons can form recoverable catalysts with high chemoselectivities.^{13c} On the other hand, oxyphilic RE ions can easily combine with oxygenic ligands (such as POM fragments herein) that are guided by the Hard and Soft Acids and Bases (HSAB) theory;¹⁵ (iii) on account of the presence of a large number of unpaired 4f electrons, RE ions are widely utilized to manufacture molecule-based magnetic materials.¹⁶ Hence, RECPs have always been a sparkling and important subclass in the large



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family of POMs. Moreover, the emergence of some novel high-nuclearity RECPs in the past decade has also aroused worldwide increasing attention to high-nuclearity RECP chemistry.¹⁷

In this highlight article, we will begin to give intensive accounts on some typical RECPs obtained in the past decade according to the number of RE cations and the structure types of POAs per molecular unit (Fig. 1). The synthetic strategies, structural characteristics and some important properties will be simultaneously involved in this highlight article. We hope that this highlight article will be able to provide some useful highlights for designing and synthesizing novel RECPs with neoteric structures and wonderful properties in the future.

2. Results and discussion

2.1 Mononuclear RECPs

2.1.1 Mononuclear Keggin-type RECPs (MKRECPs). It is generally known that the removal of a {M=O} group can make the Keggin-type $[XM_{12}O_{40}]^{m-}$ skeleton transform to a $[XM_{11}O_{39}]^{m-}$ fragment with a larger “bite angle” defect site, which can bind a metal ion to the defect site. Meanwhile, the high coordination RE ion inserted into the vacant site of the monovacant $[XM_{11}O_{39}]^{m-}$ moiety can provide several (usually

2–4) additional available coordination sites which are further used as linkers to combine one or more lacunary POM units together. Since Peacock and Weakley first isolated the sandwich-type $[RE(SiW_{11}O_{39})_2]^{13-}$ POAs, a large number of mononuclear RECPs have been unremittingly reported. For a long period, Peacock–Weakley-type MKRECPs (1:2-type) with discrete structures have dominated the mainstream status in the realm of MKRECPs.^{12,18} Until 2001, Pope *et al.* communicated for the first time two 1-D zigzag chains based on 1:1-type $[RE(\alpha-SiW_{11}O_{39})(H_2O)_3]^{5-}$ (RE = Ce^{III}, La^{III}) MKRECP units.¹⁹ After that, several kinds of special MKRECPs with extended structures have been obtained.²⁰ By virtue of the nature of different RE cations, Mialane and coworkers not only synthesized a 1-D zigzag chain-like MKRECP $[Eu(\alpha-SiW_{11}O_{39})(H_2O)_2]^{5-}$ but also isolated a 1-D linear MKRECP $[Yb(\alpha-SiW_{11}O_{39})(H_2O)_2]^{5-}$.^{20a} Inspired by the previous innovative work, Niu's group addressed a novel 1-D chain MKRECP built by $[\alpha-SiW_{11}O_{39}Pr(H_2O)_4]^{5-}$ units *via* $[NaPr_2(H_2O)_{12}]^{7+}$ bridges.^{20b} With further exploration, they reported a novel 1-D zigzag chain architecture based on $[\alpha-GeW_{11}O_{39}Y(H_2O)_2]^{5-}$ in 2006 (Fig. 2a and b),^{20d} which is different from Pope's work. Besides, in the past decade, some other discrete MKRECPs have also been synthesized.²¹ The more {M=O} groups removed from the Keggin POA, the higher the negative charge of the resulting vacant POA, which renders the vacant POA more nucleophilic and endows it with higher

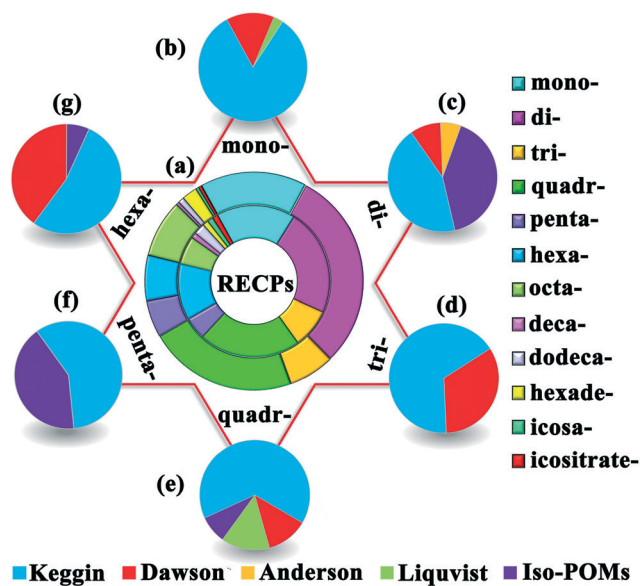


Fig. 1 (a) The inner ring represents the number of reported papers (sum: 83), while the outer ring represents the number of as-synthesized RECPs (sum: 221) between 2005 and 2015. (b) The percentages of different structural types in mononuclear RECPs: MKRECPs: 82.8%, MDRECPs: 14.3%, MLRECPs: 2.9%. (c) The percentages of different structural types in dinuclear RECPs: DKRECPs: 43.9%, DDRECPs: 9.1%, DARECPs: 6.1%. (d) The percentages of different structural types in trinuclear RECPs: TKRECPs: 66.7%, TDRECPs: 33.3%. (e) The percentages of different structural types in quadronuclear RECPs: QKRECPs: 65.3%, QDRECPs: 12.2%, QLRECPs: 12.2%. (f) The percentages of different structural types in pentanuclear RECPs: PKRECPs: 58.3%. (g) The percentages of different structural types in hexanuclear RECPs: HKRECPs: 53.3%, HDRECPs: 40%.

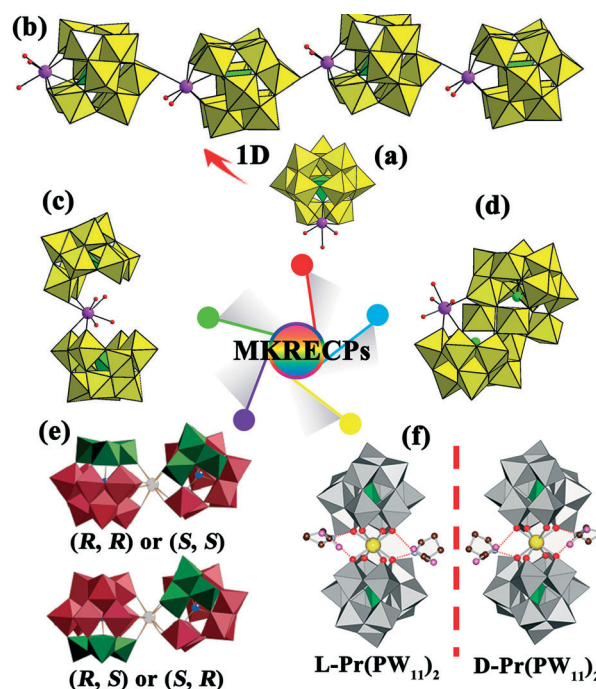


Fig. 2 (a) The $[\alpha-GeW_{11}O_{39}Y(H_2O)_2]^{5-}$ building block. (b) The 1-D chain formed by $[\alpha-GeW_{11}O_{39}Y(H_2O)_2]^{5-}$ units. (c) View of $\{(RE(H_2O)_4)(\gamma-SiW_{10}O_{36})_2\}^{13-}$. (d) View of $[RE(H_2O)_4Sb_2W_{21}O_{72}(OH)]^{10-}$. (e) Two possible isomers of the structural unit of $[Ln(\beta_2-SiW_{11}O_{39})_2]^{13-}$ (copied from ref. 25). (f) View of enantiopure $K_{1.3}Na_{3.2}H_{6.5}[L-Pr(PW_{11}O_{39})_2] \cdot 8.3$ L-proline·21.5H₂O and $K_{1.3}Na_{3.2}H_{6.5}[D-Pr(PW_{11}O_{39})_2] \cdot 8.3$ D-proline·17H₂O (copied from ref. 26). (WO₆: yellow, XO₄: bright green, RE: light purple, O: red).

reactivity to bind with RE ions.² In 2013, by reaction of the divacant precursor $\text{TBA}_4\text{H}_4[\gamma\text{-SiW}_{10}\text{O}_{36}]$ with $[\text{RE}(\text{acac})_3]$ (RE = Dy^{III}, Gd^{III}, La^{III}; acac = acetylacetonate) in a mixed acetone-water solvent system, Mizuno *et al.* synthesized a new type of sandwich-type MKRECP with vacant sites $[\{\text{RE}(\text{H}_2\text{O})_4\}(\gamma\text{-SiW}_{10}\text{O}_{36})_2]^{13-}$ (Fig. 2c), in which the vacant sites are surrounded by coordinating W–O and Ln–O oxygen atoms.²² In the same year, Kortz's group prepared the mono-RE derivatives of the Krebs-type 22-tungsto-2-antimonate RECPs $[\text{RE}(\text{H}_2\text{O})_4\text{Sb}_2\text{W}_{21}\text{O}_{72}(\text{OH})]^{10-}$ (RE = Yb^{III}, Lu^{III}) (Fig. 2d) by reaction of RE ions with $[\text{Sb}_2\text{W}_{22}\text{O}_{74}(\text{OH})_2]^{12-}$ in aqueous acidic (pH 5) medium.²³ It is rather intriguing that $[\text{RE}(\text{H}_2\text{O})_4\text{Sb}_2\text{W}_{21}\text{O}_{72}(\text{OH})]^{10-}$ contains two $[\text{B-}\alpha\text{-SbW}_9\text{O}_{33}]^{9-}$ fragments joined by two tungsten ions, leading to the formation of the lacunary $[\text{Sb}_2\text{W}_{20}\text{O}_{70}]^{14-}$ unit, which is then coordinated to a RE ion and a tungsten atom, giving rise to an architecture with an idealized C_s symmetry (Fig. 2d). On the other hand, recently, the exploration and preparation of chiral MKRECPs has become an emerging field in POM chemistry because of the flexible rotation of the $[\text{XM}_{11}\text{O}_{39}]^{m-}$ moiety and intriguing 4f–4f transitions of RE ions; thus, chiral $[\text{RE}(\text{XW}_{11}\text{O}_{39})_2]^{n-}$ POAs have attracted increasing interest due to their potential applications in asymmetric catalysts, chiral recognition and biological fields.^{13e,24} Kortz *et al.* used the reaction of RE ions with the chiral monovacant Keggin-type $[\beta_2\text{-SiW}_{11}\text{O}_{39}]^{8-}$ precursor in a 1 : 2 molar ratio in KCl medium at pH 5 and separated a series of chiral MKRECPs $[\text{RE}(\beta_2\text{-SiW}_{11}\text{O}_{39})_2]^{13-}$ (RE = La^{III}, Ce^{III}, Sm^{III}, Eu^{III}, Gd^{III}, Tb^{III}, Yb^{III}, Lu^{III}) (Fig. 2e), which represent the first RECPs based on chiral $[\beta_2\text{-SiW}_{11}\text{O}_{39}]^{8-}$ fragments.²⁵ The results indicate that large RE ions seem to be favorable to an (R,R) or (S,S) configuration of the Keggin units with an increasing amount of (R,S) or (S,R) configuration found in the solid state as the RE ion size decreases.²⁵ Different from Kortz's method, Naruke and collaborators utilized chiral amino acids (L- and D-proline) as chirality transfer agents to prepare the chiral phosphotungstate-based MKRECPs $\text{K}_{1.3}\text{Na}_{3.2}\text{H}_{6.5}[\text{L-Pr}(\text{PW}_{11}\text{O}_{39})_2] \cdot 8.3\text{L-proline} \cdot 21.5\text{H}_2\text{O}$ and $\text{K}_{1.3}\text{Na}_{3.2}\text{H}_{6.5}[\text{D-Pr}(\text{PW}_{11}\text{O}_{39})_2] \cdot 8.3\text{D-proline} \cdot 17\text{H}_2\text{O}$ (Fig. 2f) and also investigated their optical activities by circular dichroism (CD) spectroscopy.²⁶ Similarly, we also obtained the acentric phosphotungstate $\text{KNa}_3[\text{HPro}]_2[\text{Sm}(\alpha\text{-PW}_{11}\text{O}_{39})_2] \cdot \text{Pro} \cdot 18\text{H}_2\text{O}$ (Pro = D-proline) by means of the chirality transfer strategy and preliminarily studied its ferroelectric properties.^{21c}

2.1.2 Mononuclear Dawson-type RECPs (MDRECPs). In comparison with the abundant MKRECPs, sporadic MDRECPs were also made. In 2005, Pope *et al.* isolated two λ -shaped MDRECPs with a syn C_2 conformation $[\text{Ce}(\text{XH}_4\text{W}_{17}\text{O}_{61})_2]^{19-}$ (X = P^V, As^V) by reaction of the $[\text{H}_4\text{XW}_{18}\text{O}_{62}]^{7-}$ POA and the Ce³⁺ cation.²⁷ This λ -shaped MDRECP anion is constructed from two monovacant Dawson-like polyoxotungstate fragments $[\text{XH}_4\text{W}_{17}\text{O}_{61}]^{11-}$ anchoring a Ce³⁺ cation (Fig. 3a), in which the “empty” $\{\text{O}_4\}$ tetrahedra are in the remote positions of the Ce³⁺ cation.²⁷ In 2014, our group also reported a λ -shaped Dawson-like Ce^{IV}-hybridized selenotungstate with a syn C_2 conformation

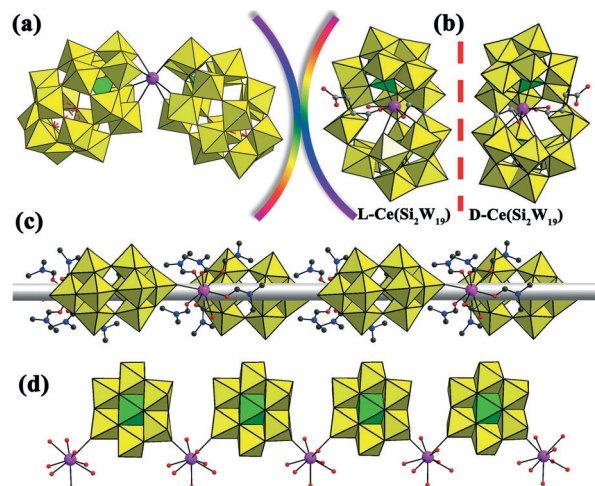


Fig. 3 (a) The structure of $[\text{Ce}(\text{X}(\text{H}_4)\text{W}_{17}\text{O}_{61})_2]^{19-}$. (b) Views of two enantiomerically pure polytungstates $\text{Na}_2[(\text{CH}_3)_2\text{NH}_2]_3\{\text{Na}[\text{Ce}^{\text{III}}(\text{H}_2\text{O})(\text{CH}_3\text{CH}_2\text{OH})(\text{L-tartH}_3)(\text{H}_2\text{Si}_2\text{W}_{19}\text{O}_{66})]\} \cdot 3.5\text{H}_2\text{O}$ [L-Ce(Si₂W₁₉)] and $[(\text{CH}_3)_2\text{NH}_2]_7\{\text{Na}[\text{Ce}^{\text{III}}(\text{H}_2\text{O})(\text{CH}_3\text{CH}_2\text{OH})(\text{D-tartH}_3)(\text{Si}_2\text{W}_{19}\text{O}_{66})]\} \cdot 2.5\text{H}_2\text{O}$ [D-Ce(Si₂W₁₉)]. (c) The 1-D helical chain of $[\text{Ce}(\text{H}_2\text{O})(\text{DMF})_6(\text{W}_{10}\text{O}_{32})] \cdot \text{DMF} \cdot \text{CH}_3\text{CH}_2\text{OH}$. (d) View of the 1-D zigzag chain of $[\text{La}(\text{H}_2\text{O})_7\text{Al}(\text{OH})_6\text{Mo}_6\text{O}_{18}]_n \cdot 4n\text{H}_2\text{O}$. (WO₆ and MoO₆: yellow, XO₄: bright green, RE: light purple, O: red, C: gray, N: blue).

$[\text{Ce}(\text{SeW}_{17}\text{O}_{59})_2]^{20-}$.²⁸ Notably, the main difference between $[\text{Ce}(\text{XH}_4\text{W}_{17}\text{O}_{61})_2]^{19-}$ and $[\text{Ce}(\text{SeW}_{17}\text{O}_{59})_2]^{20-}$ lies in the fact that the tetrahedral geometry of the As^V (P^V) atoms in the former and the trigonal pyramid geometry of the Se^{IV} atom in the latter lead to the distinction of the number of oxygen atoms in Dawson-like $[\text{XH}_4\text{W}_{17}\text{O}_{61}]^{11-}$ and $[\text{SeW}_{17}\text{O}_{59}]^{12-}$ fragments. In 2014, Xu *et al.* obtained two enantiomerically pure polyoxotungstates $\text{Na}_2[(\text{CH}_3)_2\text{NH}_2]_3\{\text{Na}[\text{Ce}^{\text{III}}(\text{H}_2\text{O})(\text{CH}_3\text{CH}_2\text{OH})(\text{L-tartH}_3)(\text{H}_2\text{Si}_2\text{W}_{19}\text{O}_{66})]\} \cdot 3.5\text{H}_2\text{O}$ and $[(\text{CH}_3)_2\text{NH}_2]_7\{\text{Na}[\text{Ce}^{\text{III}}(\text{H}_2\text{O})(\text{CH}_3\text{CH}_2\text{OH})(\text{D-tartH}_3)(\text{Si}_2\text{W}_{19}\text{O}_{66})]\} \cdot 2.5\text{H}_2\text{O}$ (tartH₄ = tartaric acid) by reaction of the trivalent Keggin $[\alpha\text{-SiW}_9\text{O}_{34}]^{10-}$ and L-(+)-cerium tartrate or D-(−)-cerium tartrate (Fig. 3b).²⁹ More interestingly, chiral tartrate ligands are directly combined with the unprecedented vacant $[\text{Si}_2\text{W}_{19}\text{O}_{66}]^{10-}$ segments. Moreover, Z-scan results illustrate that the two enantiomerically pure polyoxotungstates are the first chiral POMs that show two-photon absorption properties typical of the third-order nonlinear optical response.

2.1.3 Mononuclear Anderson-type RECPs (MARECPs). Due to the low surface charges of Anderson POAs, reports on MARECPs in the past decade are very rare. However, in 2002, Das and co-workers reported a 1-D zigzag chain-like MARECP $[\text{La}(\text{H}_2\text{O})_7\text{Al}(\text{OH})_6\text{Mo}_6\text{O}_{18}]_n \cdot 4n\text{H}_2\text{O}$ based on Anderson-type $[\text{Al}(\text{OH})_6\text{Mo}_6\text{O}_{18}]^{3-}$ units and RE connectors (Fig. 3d).³⁰ Another series of 1-D chain-like MARECPs $[\text{RE}(\text{H}_2\text{O})_7\text{Cr}(\text{OH})_6\text{Mo}_6\text{O}_{18}]_n \cdot 4n\text{H}_2\text{O}$ (RE = La^{III}, Gd^{III}) and $[\text{RE}(\text{H}_2\text{O})_7\text{Al}(\text{OH})_6\text{Mo}_6\text{O}_{18}]_n \cdot 4n\text{H}_2\text{O}$ (RE = Gd^{III}, Eu^{III}) were obtained by their group in 2014.³¹ This work fills a vacancy of the Anderson-type species in the field of mononuclear RECPs.

2.1.4 Mononuclear Lindqvist-type RECPs (MLRECPs). In the classical Lindqvist POM family, the typical decatungstate $[\text{W}_{10}\text{O}_{32}]^{4-}$ isopolyanion can be considered as two

monovacant Lindqvist $[W_5O_{14}]^{2-}$ units linked by four corner-sharing oxygen atoms. To date, relevant reports on MLRECPs are very rare. Luo *et al.* utilized the assembly of decatungstate $[W_{10}O_{32}]^{4-}$ units and $[Ce(H_2O)(DMF)_6]^{4+}$ cations and successfully separated a novel 1-D MLRECP $[Ce(H_2O)(DMF)_6(W_{10}O_{32})] \cdot DMF \cdot CH_3CH_2OH$ (DMF = dimethyl formamide),³² in which each $[Ce(H_2O)(DMF)_6]^{4+}$ is covalently bonded to two $[W_{10}O_{32}]^{4-}$ units *via* corner-sharing oxygen atoms, generating an infinite 1-D helical chain (Fig. 3c).

2.2 Dinuclear RECPs

2.2.1 Dinuclear Keggin-type RECPs (DKRECPs). Same as MKRECPs in the family of mononuclear RECPs, DKRECPs also hold the dominant position in the realm of dinuclear RECPs. In terms of purely inorganic DKRECPs, the reported structures are kaleidoscopic. For instance, in 2009, Niu's group separated novel phosphotungstate-based DKRECPs $[\{(\alpha-PW_{11}O_{39}H)RE(H_2O)_3\}_2]^{6-}$ (RE = Nd^{III}, Gd^{III}) (Fig. 4a), where two mono-RE substituted Keggin $[\alpha-PW_{11}O_{39}RE(H_2O)_3]^{4-}$ subunits are bridged by two RE–O–W linkers to form the first 2:2-type monovacant Keggin phosphotungstate dimers.³³ Through a stepwise incorporation strategy of two different RE cations into the vacant sites of POMs, Mizuno *et al.* separated a series of heterodinuclear DKRECPs $\{[RE(\mu_2-OH)_2RE'](\gamma-SiW_{10}O_{36})_2]\}^{10-}$ (RE = Gd^{III}, Dy^{III}; RE' = Eu^{III}, Yb^{III}, Lu^{III}) (Fig. 4b).²² As expected, all the DyRE' species exhibit the single-molecule magnet (SMM) behavior; furthermore, their

energy barriers for magnetization reversal ($\Delta E/k_B$) could be manipulated by modulating the coordination geometry and anisotropy of the Dy³⁺ ion by tuning the adjacent RE' ion in the heterodinuclear $[Dy(\mu_2-OH)_2RE']^{4+}$ moieties. The energy barriers increase in the order DyLu ($\Delta E/k_B = 48$ K) < DyYb (53 K) < DyDy (66 K) < DyEu (73 K) with increasing ionic radii of the RE' ions.²²

Meanwhile, remarkable progress in organic–inorganic hybrid DKRECPs has been made and some novel structures of this subset should be highlighted here. Niu and coworkers not only communicated a class of novel $(\eta^2, \mu-1, 1)$ -acetato-bridging phosphotungstate-based DKRECP hybrids with discrete structures $[\{(\alpha-PW_{11}O_{39})RE(H_2O)(\eta^2, \mu-1, 1)-CH_3COO\}_2]^{10-}$ (RE = Sm^{III}, Eu^{III}, Gd^{III}, Tb^{III}, Ho^{III}, Er^{III}) (Fig. 4c),³³ but also successfully obtained another two types of oxalate-bridging DKRECPs constructed by lacunary Keggin phosphotungstate-supported RE derivatives $[\{(\alpha-PW_{11}O_{39})RE(H_2O)\}_2(C_2O_4)]^{10-}$ (RE = Y^{III}, Dy^{III}, Ho^{III}, Er^{III}) (Fig. 4d) and $\{(\alpha-x-PW_{10}O_{38})Tm_2(C_2O_4)(H_2O)_2\}^{3-}$ (Fig. 4e).³⁴ It should be noted that $[\{(\alpha-PW_{11}O_{39})RE(H_2O)\}_2(C_2O_4)]^{10-}$ show discrete structures including two mono-RE substituted Keggin $[RE(\alpha-PW_{11}O_{39})]_2^{14-}$ subunits bridged by an oxalate ligand while $\{(\alpha-x-PW_{10}O_{38})Tm_2(C_2O_4)(H_2O)_2\}^{3-}$ displays a 1-D chain motif formed by the unusual divacant di-Tm-containing $[\alpha-x-PW_{10}O_{38}]^{11-}$ subunits connected by oxalate linkers (Fig. 4f). Moreover, these interesting 1-D chains are aligned in two different spatial orientations (Fig. 4f). This construction fashion was observed for the first time in POM chemistry. In 2014, Hussain *et al.* reported a

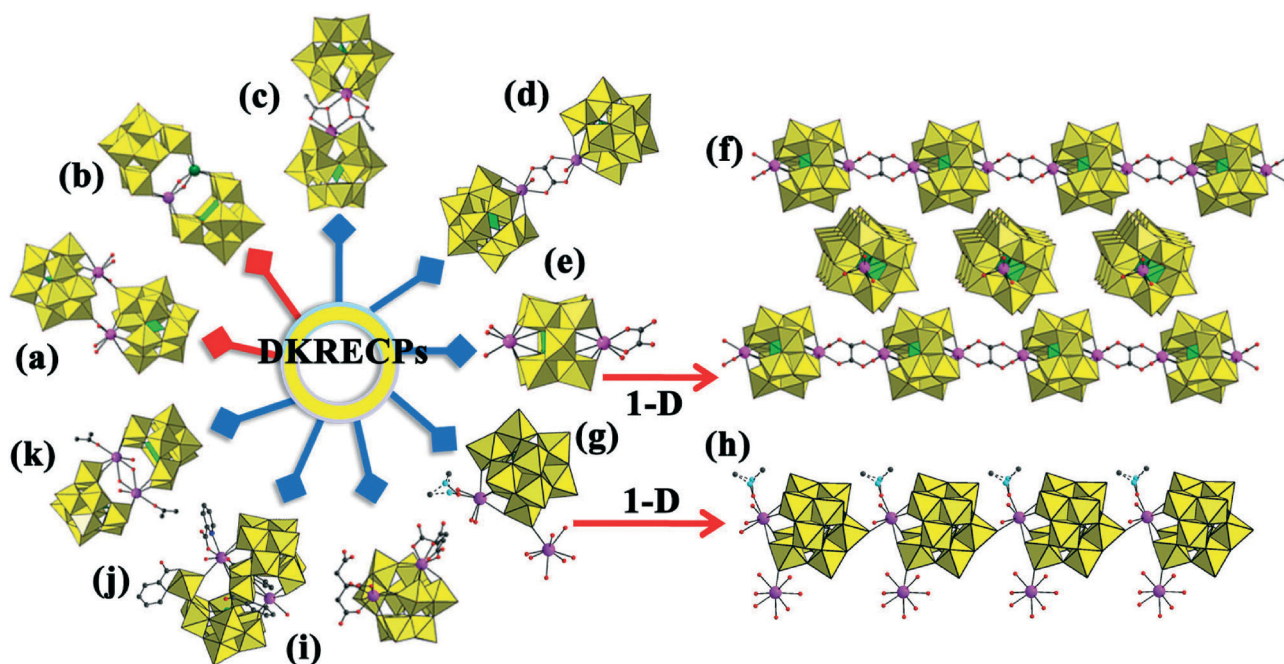


Fig. 4 (a) View of $[\{(\alpha-PW_{11}O_{39}H)RE(H_2O)_3\}_2]^{6-}$. (b) View of the heterodinuclear $\{[RE(\mu_2-OH)_2RE'](\gamma-SiW_{10}O_{36})_2]\}^{10-}$. (c) View of $[\{(\alpha-PW_{11}O_{39})RE(H_2O)(\eta^2, \mu-1, 1)-CH_3COO\}_2]^{10-}$. (d) View of the oxalate-bridging $[\{(\alpha-PW_{11}O_{39})RE(H_2O)\}_2(C_2O_4)]^{10-}$. (e) View of the structural unit of $\{(\alpha-x-PW_{10}O_{38})Tm_2(C_2O_4)(H_2O)_2\}^{3-}$. (f) The interesting 1-D chain alignment of $\{(\alpha-x-PW_{10}O_{38})Tm_2(C_2O_4)(H_2O)_2\}^{3-}$. (g) View of the structural unit of $\{Sm(H_2O)_7[Sm(H_2O)_2(DMSO)(\alpha-SiW_{11}O_{39})]\}^{2-}$. (h) The 1-D architecture of $\{Sm(H_2O)_7[Sm(H_2O)_2(DMSO)(\alpha-SiW_{11}O_{39})]\}^{2-}$. (i) View of $[Tb_2(pic)(H_2O)_2(B-\beta-AsW_8O_{30})_2(WO_2(pic)_3)]^{10-}$. (j) View of $\{[RE(H_2O)_2(acetone)]_2(\gamma-SiW_{10}O_{36})_2\}^{10-}$. (k) View of $[Dy_2(Hcit)_2(AsW_{10}O_{38})]^{11-}$. (WO₆: yellow, XO₄: bright green, RE: light purple and green, O: red, S: turquoise, C: gray, N: blue).

series of ($\eta^2, \mu-1, 1$)-acetato-bridging silicotungstate-based DKRECP hybrids $\{[\text{RE}(\alpha\text{-SiW}_{11}\text{O}_{39})(\text{H}_2\text{O})_2(\mu\text{-CH}_3\text{COO})_2]\}^{12-}$ (RE = Eu^{III}, Gd^{III}, Tb^{III}, Dy^{III}, Ho^{III}, Er^{III}, Tm^{III}) by the reaction of Na₁₀[$\alpha\text{-SiW}_9\text{O}_{34}$] $\cdot 16\text{H}_2\text{O}$ with RE(NO₃)₃ $\cdot n\text{H}_2\text{O}$ in a KAc-HAc buffer at pH 4.5,^{21b} which are almost isostructural to the phosphotungstate-based DKRECP hybrids made by Niu *et al.*³³ Aside from the above discussed oxalate-bridging 1-D chain architecture, Niu *et al.* also discovered another novel 1-D organic-inorganic hybrid DKRECP $\{\text{Sm}(\text{H}_2\text{O})_7[\text{Sm}(\text{H}_2\text{O})_2(\text{DMSO})(\alpha\text{-SiW}_{11}\text{O}_{39})]\}^{2-}$ with mixed $[\text{Sm}(\text{H}_2\text{O})_7]^{3+}$ and $[\text{Sm}(\text{H}_2\text{O})_2(\text{DMSO})]^{3+}$ pendants on both sides of the 1-D chain (DMSO = dimethyl sulfoxide) (Fig. 4g and h).³⁵ In addition, Xu *et al.* reported a citrate-decorated Keggin-type di-Dy^{III}-containing tungstoarsenate $[\text{Dy}_2(\text{Hcit})_2(\text{AsW}_{10}\text{O}_{38})]^{11-}$ (H₄cit = citric acid) with the two non-adjacent substituted sites occupied (Fig. 4i).³⁶ Notably, the citric acid ligand is first introduced to the RE-POM system and this compound is the first DKRECP with two non-adjacent substituted sites. It is well known that aromatic carboxylic acids are excellent multifunctional ligands in the construction of TMSP hybrids; therefore, they should also be introduced to the system of RECPs.³⁷ Thus, by reaction of picH (pic = 2-picolate), $[\text{As}_2\text{W}_{19}\text{O}_{67}(\text{H}_2\text{O})]^{14-}$ precursor and Tb(OAc)₃ in ratios of 4:1:2 at acidic conditions (pH 3.6–3.9), Boskovic *et al.* separated a di-Tb^{III}-containing tungstoarsenate with pic ligands $[\text{Tb}_2(\text{pic})(\text{H}_2\text{O})_2(\text{B-}\beta\text{-AsW}_8\text{O}_{30})_2(\text{WO}_2(\text{pic}))_3]^{10-}$ (Fig. 4j), in which two tetra-vacant Keggin $[\text{B-}\beta\text{-AsW}_8\text{O}_{30}]^{9-}$ units oriented at 180° with respect to each other are connected by three $\{\text{WO}_2(\text{pic})\}$ moieties and two Tb³⁺ centers.³⁸ Among the multitude of applications of POMs, Lewis acid catalysts are very rare in comparison with Brønsted acid and oxidation catalysts in most situations.^{13d,39} Nevertheless, by virtue of the high coordination numbers and flexible coordination geometries, RE cations can not only leave residual coordination sites but also further act as effective Lewis acids for activation of substrates.^{13c,e,40} On the basis of this feature, Mizuno and collaborators designed and synthesized a series of efficient POM-based Lewis acid DKRECP catalysts $\{[\text{RE}(\text{H}_2\text{O})_2(\text{acetone})_2]\{\gamma\text{-SiW}_{10}\text{O}_{36}\}_2\}^{10-}$ (RE = Y^{III}, Nd^{III}, Eu^{III}, Gd^{III}, Tb^{III}, Dy^{III}) by reactions of TBA₄H₄[$\gamma\text{-SiW}_{10}\text{O}_{36}$] with RE(acac)₃ in 2012 (Fig. 4k),⁴¹ in which two silicotungstate units are pillared by two RE cations. In these DKRECP catalysts, nucleophilic oxygen-enriched surfaces of negatively charged POMs and incorporated RE cations can respectively function as Lewis bases and Lewis acids. The experimental results of cyanosilylation of carbonyl compounds with trimethylsilyl cyanide indicate that DKRECPs with larger RE cations manifest higher catalytic activities for cyanosilylation due to the higher activation ability of C=O bonds (higher Lewis acidity) and sterically less hindered Lewis acid sites. Amongst these DKRECP catalysts checked, $[\{\text{Nd}(\text{H}_2\text{O})_2(\text{acetone})\}_2\{\gamma\text{-SiW}_{10}\text{O}_{36}\}_2]^{10-}$ shows remarkable catalytic performance for cyanosilylation of various ketones and aldehydes while producing the corresponding cyanohydrin trimethylsilyl ethers in high yields.⁴¹

2.2.2 Dinuclear Dawson-type RECPs (DDRECPs). Compared with DKRECPs, the research developments of

DDRECPs are slow and few examples have been reported during the past decade. In 2006, Hasenknopf *et al.* separated a centrosymmetric DDRECP $[\{\alpha_1\text{-La}(\text{H}_2\text{O})_4\text{P}_2\text{W}_{17}\text{O}_{61}\}_2]^{14-}$ in aqueous solution (Fig. 5a).⁴² Such a phenomenon where a RECP is composed of two monovacant Dawson phosphotungstate subunits with an α_1 configuration is very uncommon in the field of POMs. Meanwhile, by controlling the ratio of Nd³⁺/ $[\alpha_2\text{-P}_2\text{W}_{17}\text{O}_{61}]^{10-}$, Wang *et al.* obtained the first 2-D extended structure based on $[\text{Nd}_2(\text{H}_2\text{O})_9(\alpha_2\text{-P}_2\text{W}_{17}\text{O}_{61})]^{4-}$ DDRECP units (Fig. 5b) connected *via* trivalent Nd³⁺ ions under hydrothermal conditions (Fig. 5b–d).⁴³ In this compound, the Nd³⁺ ions located in the vacant sites of the $[\alpha_2\text{-P}_2\text{W}_{17}\text{O}_{61}]^{10-}$ fragments firstly connect adjacent $[\alpha_2\text{-P}_2\text{W}_{17}\text{O}_{61}]^{10-}$ fragments to form a 1-D chain $[\text{Nd}(\text{H}_2\text{O})_2(\alpha_2\text{-P}_2\text{W}_{17}\text{O}_{61})]_n^{7n-}$ (Fig. 5c), and then these 1-D $[\text{Nd}(\text{H}_2\text{O})_2(\alpha_2\text{-P}_2\text{W}_{17}\text{O}_{61})]_n^{7n-}$ chains are further combined with adjacent chains to create a 2-D extended layer by means of all Nd³⁺ ions (Fig. 5d). It should be pointed out that the most evident difference between $[\{\alpha_1\text{-La}(\text{H}_2\text{O})_4\text{P}_2\text{W}_{17}\text{O}_{61}\}_2]^{14-}$ and $[\{\text{Nd}(\text{H}_2\text{O})_9(\alpha_2\text{-P}_2\text{W}_{17}\text{O}_{61})\}_2]^{4-}$ is that the former comprises monovacant $[\alpha_1\text{-P}_2\text{W}_{17}\text{O}_{61}]^{10-}$ fragments whereas the latter consists of monovacant $[\alpha_2\text{-P}_2\text{W}_{17}\text{O}_{61}]^{10-}$ fragments. As we know, the coronary $[\text{P}_8\text{W}_{48}\text{O}_{184}]^{40-}$ POA is one important derivative of Dawson POMs and can be viewed as a combination of four hexavacant Dawson $[\text{P}_2\text{W}_{12}\text{O}_{48}]^{14-}$ entities connected *via* eight W–O–W linkers. By reaction of the coronary precursor $[\text{P}_8\text{W}_{48}\text{O}_{184}]^{40-}$ and early RE cations, Pope *et al.* obtained novel 3-D frameworks constructed from $[\text{KCP}_8\text{W}_{48}\text{O}_{184}(\text{H}_4\text{W}_4\text{O}_{12})_2\text{RE}_2(\text{H}_2\text{O})_{10}]^{25-}$ (RE = La^{III}, Ce^{III}, Pr^{III}, Nd^{III}) DDRECP units (Fig. 5e and f),⁴⁴ which opens the way for studying the RE chemistry of the $[\text{P}_8\text{W}_{48}\text{O}_{184}]^{40-}$ anion.

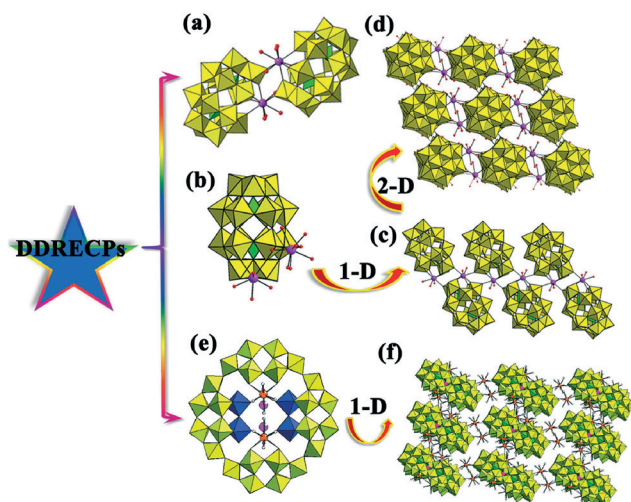


Fig. 5 (a) The centrosymmetric structure of $[\{\alpha_1\text{-La}(\text{H}_2\text{O})_4\text{P}_2\text{W}_{17}\text{O}_{61}\}_2]^{14-}$. (b) View of the structural unit of $[\text{Nd}_2(\text{H}_2\text{O})_9(\alpha_2\text{-P}_2\text{W}_{17}\text{O}_{61})]^{4-}$. (c) The 1-D chain motif of $[\text{Nd}(\text{H}_2\text{O})_2(\alpha_2\text{-P}_2\text{W}_{17}\text{O}_{61})]_n^{7n-}$. (d) The 2-D extended layer of $[\text{Nd}_2(\text{H}_2\text{O})_9(\alpha_2\text{-P}_2\text{W}_{17}\text{O}_{61})]^{4-}$. (e) View of the structural unit of $[\text{KCP}_8\text{W}_{48}\text{O}_{184}(\text{H}_4\text{W}_4\text{O}_{12})_2\text{RE}_2(\text{H}_2\text{O})_{10}]^{25-}$ (copied from ref. 42). (f) The 3-D framework of $[\text{KCP}_8\text{W}_{48}\text{O}_{184}(\text{H}_4\text{W}_4\text{O}_{12})_2\text{RE}_2(\text{H}_2\text{O})_{10}]^{25-}$ (copied from ref. 42). (WO₆: yellow and blue, XO₄: bright green, RE: light purple, O: red).

2.2.3 Dinuclear Anderson-type RECPs (DARECPs). During the course of probing dinuclear RECPs, the research on DARECPs remains largely unexplored because of the low surface charge of Anderson POAs. In 2004, Krebs *et al.* obtained a family of 1-D infinite chain-like polyoxomolybdates based on DARECP building blocks $\{[\text{La}(\text{H}_2\text{O})_6]_2(\text{TeMo}_6\text{O}_{24})\}_n \cdot 6n\text{H}_2\text{O}$, $\{[\text{Ce}(\text{H}_2\text{O})_7]_2(\text{TeMo}_6\text{O}_{24})\}_n \cdot 7n\text{H}_2\text{O}$, $\{[\text{Pr}(\text{H}_2\text{O})_7]_2(\text{TeMo}_6\text{O}_{24})\}_n \cdot 8n\text{H}_2\text{O}$ and $\{[\text{Nd}(\text{H}_2\text{O})_7]_2(\text{TeMo}_6\text{O}_{24})\}_n \cdot 8n\text{H}_2\text{O}$ by reaction of telluric acid, potassium molybdate and rare earth salts in a pH 5.5 aqueous solution; however, their 1-D chain construction modes are somewhat different. In the construction of 1-D chains, the $[\text{TeMo}_6\text{O}_{24}]^{6-}$ POA acts as a hexadentate ligand for La^{3+} ions and as a tetradentate ligand for Ce^{3+} , Pr^{3+} and Nd^{3+} ions.^{45a} As an extension of their work, in 2005, they found two di-RE bisupporting DARECPs $[(\text{RE}(\text{H}_2\text{O})_6)_2(\text{TeMo}_6\text{O}_{24})] \cdot 10\text{H}_2\text{O}$ ($\text{RE} = \text{Ho}^{\text{III}}$, Yb^{III}).^{45b} Their results show that the lanthanide contraction has a remarkable influence on the structural construction modes. In 2006, two unusual 2-D extended network DARECPs $[(\text{C}_6\text{H}_5\text{NO}_2)_2\text{RE}(\text{H}_2\text{O})_4]_2[\text{IMo}_6\text{O}_{24}][\text{NO}_3] \cdot 4\text{H}_2\text{O}$ ($\text{RE} = \text{La}^{\text{III}}$, Ce^{III} , $\text{C}_6\text{H}_5\text{NO}_2 =$ pyridine-4-carboxylic acid) (Fig. 6a) were synthesized by Wang's group.⁴⁶ Interestingly, this 2-D extended network is constituted by RE coordination polymer chains linked together by $[\text{IMo}_6\text{O}_{24}]^{5-}$ POAs (Fig. 6b) and is a representative of the first example of 2-D inorganic-organic hybrid polyoxomolybdates based on A-type Anderson POAs.

2.2.4 Other dinuclear RECPs. Apart from the abovementioned dinuclear RECPs, several interesting isopolymetalates stabilized by dinuclear RE cations have also been discovered in the past decade. In the field of isopolymolybdates, Evans' group reported a class of novel dinuclear RECPs based on octamolybdate units: highly hydrated $[\text{Dy}_2(\text{H}_2\text{O})_{12}][\text{Mo}_8\text{O}_{27}] \cdot 8\text{H}_2\text{O}$ and its partially dehydrated product $[\text{Dy}_2(\text{H}_2\text{O})_6][\text{Mo}_8\text{O}_{27}]$, and highly hydrated $[\text{Nd}_2(\text{H}_2\text{O})_{12}][\text{Mo}_8\text{O}_{27}] \cdot 6\text{H}_2\text{O}$ and its partially dehydrated product $[\text{Nd}_2(\text{H}_2\text{O})_6][\text{Mo}_8\text{O}_{27}] \cdot 3\text{H}_2\text{O}$,⁴⁷ and they found that the partial dehydration of both highly hydrated RE octamolybdates topotactically condenses the isolated $\text{RE}_2\text{Mo}_8\text{O}_{27}$ chains into 3-D framework structures, leading to the formation of channels along the $[\text{Mo}_8\text{O}_{27}]^{6-}$ chain direction in the obtained products. In the domain of isopolytungstates, many building blocks have been separated such as $[\text{W}_6\text{O}_{19}]^{2-}$, $[\text{H}_4\text{W}_{11}\text{O}_{38}]^{6-}$, $[\text{H}_2\text{W}_{12}\text{O}_{40}]^{6-}$, $[\text{H}_2\text{W}_{12}\text{O}_{42}]^{10-}$, $[\text{H}_4\text{W}_{22}\text{O}_{74}]^{12-}$, and

$[\text{H}_{12}\text{W}_{36}\text{O}_{120}]^{12-}$.⁴⁸ In 2006, Jiang *et al.* synthesized a class of rare 3-D frameworks built by dinuclear RECPs $\{[\text{RE}(\text{H}_2\text{O})_5]_2(\text{H}_2\text{M}_{12}\text{O}_{42})\}^{4-}$ ($\text{RE} = \text{La}^{\text{III}}$, Sm^{III} , Eu^{III} , Gd^{III} , Tb^{III} , Dy^{III} , Ho^{III} , Er^{III} , Yb^{III} , Lu^{III} ; $\text{M} = \text{W}$ or W/Mo), which are assembled from the arrangement of paradodecatungstate $[\text{H}_2\text{M}_{12}\text{O}_{42}]^{10-}$ POAs and $[\text{RE}(\text{H}_2\text{O})_5]^{3+}$ linkers.⁴⁹ In 2008, Cao and collaborators isolated a novel dinuclear cerium(III)-containing pentadecatungstate $[\text{H}_6\text{Ce}_2(\text{H}_2\text{O})\text{Cl}(\text{W}_5\text{O}_{18})_3]^{7-}$ with an approximate C_3 symmetry by reaction of $\text{Na}_2\text{WO}_4 \cdot 2\text{H}_2\text{O}$ and $\text{Ce}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$ in aqueous acidic medium (optimal pH = 5.0) (Fig. 7a).⁵⁰ The most remarkable structural characteristic of this compound is that three $[\text{W}_5\text{O}_{18}]^{6-}$ units are connected with each other to give rise to a 15-membered ring connected by corner-sharing WO_6 octahedra and this asymmetrical 15-membered ring was stabilized by two Ce^{3+} ions, in which the Cl^- ion plays the role of a terminal ligand for one of the Ce^{3+} ions. Thereafter, Kortz *et al.* synthesized a V-shaped $[\text{RE}_2(\text{H}_2\text{O})_{10}\text{W}_{28}\text{O}_{92}(\text{OH})_2]^{14-}$ POA ($\text{RE} = \text{Sm}^{\text{III}}$, Eu^{III}) by reaction of RE and WO_4^{2-} ions in aqueous acidic medium (pH = 3.2) (Fig. 7b),⁵¹ in which the $\{\text{W}_{28}\}$ cluster is made up of two

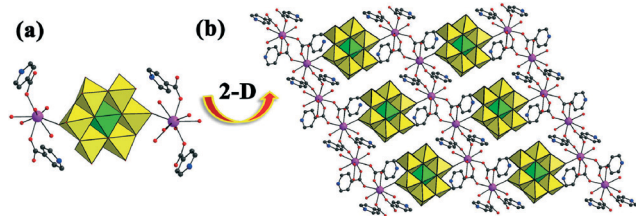


Fig. 6 (a) View of the structural unit of $[(\text{C}_6\text{H}_5\text{NO}_2)_2\text{RE}(\text{H}_2\text{O})_4]_2[\text{IMo}_6\text{O}_{24}][\text{NO}_3] \cdot 4\text{H}_2\text{O}$. (b) The 2-D extended network of $[(\text{C}_6\text{H}_5\text{NO}_2)_2\text{RE}(\text{H}_2\text{O})_4]_2[\text{IMo}_6\text{O}_{24}][\text{NO}_3] \cdot 4\text{H}_2\text{O}$. (WO_6 : yellow, XO_4 : bright green, RE: light purple, O: red, C: gray, N: blue).

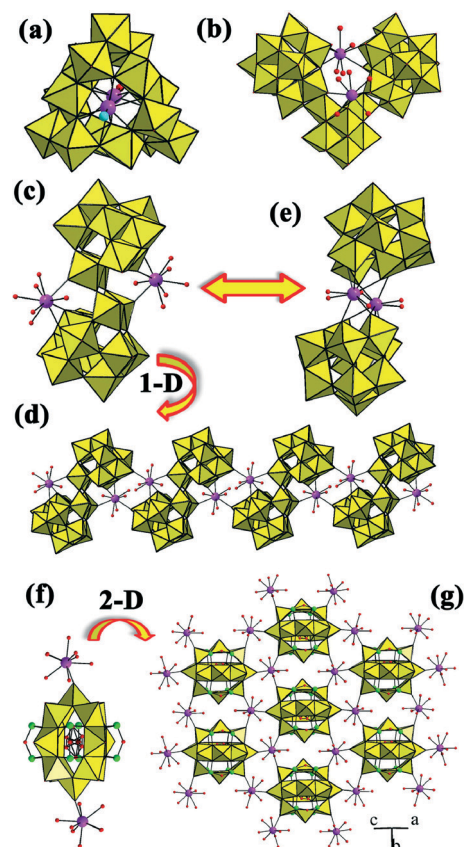


Fig. 7 (a) View of $[\text{H}_6\text{Ce}_2(\text{H}_2\text{O})\text{Cl}(\text{W}_5\text{O}_{18})_3]^{7-}$. (b) View of $[\text{RE}_2(\text{H}_2\text{O})_{10}\text{W}_{28}\text{O}_{92}(\text{OH})_2]^{14-}$. (c) View of the structural unit of $[\text{RE}_2(\text{H}_2\text{O})_{10}\text{W}_{28}\text{O}_{92}(\text{OH})_2]^{14-}$. (d) The 1-D chain fashion of $[\text{RE}_2(\text{H}_2\text{O})_{10}\text{W}_{28}\text{O}_{92}(\text{OH})_2]^{14-}$. (e) View of $[\text{Ce}_2(\text{H}_2\text{O})_6\text{W}_{22}\text{O}_{72}(\text{OH})_4]^{10-}$. (f) View of the structural unit of $[(\text{RE}(\text{H}_2\text{O})_6)_2\text{As}_8\text{V}_{14}\text{O}_{42}(\text{SO}_3)] \cdot 8\text{H}_2\text{O}$. (g) The 2-D extended structure of $[(\text{RE}(\text{H}_2\text{O})_6)_2\text{As}_8\text{V}_{14}\text{O}_{42}(\text{SO}_3)] \cdot 8\text{H}_2\text{O}$. (WO_6 and VO_5 : yellow, RE: light purple, As: green, O: red, Cl: turquoise, S: dark red).

undecatungstate $\{W_{11}\}$ subunits and a hexatungstate $\{W_6\}$ subunit and one RE ion bridges two $\{W_{11}\}$ subunits together by four μ -oxo bridges while the other RE ion simultaneously coordinates to two $\{W_{11}\}$ subunits and a $\{W_6\}$ subunit by three μ -oxo bridges. In the same year, they also reported a family of S-shaped dinuclear RE-containing isopolytungstates $[RE_2(H_2O)_{10}W_{22}O_{72}(OH)_2]^{8-}$ (RE = La^{III}, Ce^{III}, Tb^{III}, Dy^{III}, Ho^{III}, Er^{III}, Tm^{III}, Yb^{III}, Lu^{III}) (Fig. 7c) and these S-shaped dinuclear RE-containing 22-isopolytungstates can be polymerized to 1-D chain structures by the bridging role of RE ions (Fig. 7d).⁵² Subsequently, Su's group also separated a novel S-shaped dicerium(III) 22-isopolytungstate $[Ce_2(H_2O)_6W_{22}O_{72}(OH)_4]^{10-}$ by reaction of $Na_2WO_4 \cdot 2H_2O$, Na_2SO_3 and $Ce(NO_3)_3 \cdot 6H_2O$ (pH = 5.5), which is constructed from two discrete $\{W_{11}\}$ subunits linked through two nine-coordinate Ce^{3+} ions (Fig. 7e).⁵³ The obvious distinction between the abovementioned two S-shaped dinuclear RE-containing 22-isopolytungstates is as follows: two $[HW_{11}O_{38}]^{7-}$ subunits are directly connected with each other by sharing two oxygen atoms in $[RE_2(H_2O)_{10}W_{22}O_{72}(OH)_2]^{8-}$, whereas two $[H_2W_{11}O_{38}]^{8-}$ subunits are bridged together by two Ce^{3+} linkers in $[Ce_2(H_2O)_6W_{22}O_{72}(OH)_4]^{10-}$. In addition, utilizing the linking propensity of the sulfite encapsulated polyoxovanadate precursor $[As_8V_{14}O_{42}(SO_3)]^{6-}$ with RE cations, Das and co-workers obtained a group of novel RE-containing polyoxovanadates $[\{RE(H_2O)_6\}_2As_8V_{14}O_{42}(SO_3)] \cdot 8H_2O$ (RE = La^{III}, Sm^{III}, Ce^{III}) with 2-D extended structures.⁵⁴ In the structural unit, fourteen distorted $\{VO_5\}$ square pyramids combine with each other in an edge-sharing mode to form a $\{V_{14}\}$ cluster with a disordered SO_3^{2-} unit in the centre, and then four handle-like $\{As_2O_5\}$ units graft to the equatorial position of the $\{V_{14}\}$ cluster to construct the basic skeleton of the $[As_8V_{14}O_{42}(SO_3)]^{6-}$ cluster anion (Fig. 7f). Finally, two $[RE(H_2O)_6]^{3+}$ ions are symmetrically attached to the cluster anion by a terminal oxygen from the cluster anion. In the 2-D extended structure, each $[As_8V_{14}O_{42}(SO_3)]^{6-}$ cluster anion is surrounded by six $[RE(H_2O)_6]^{3+}$ ions, whereas each $[RE(H_2O)_6]^{3+}$ ion connects with three $[As_8V_{14}O_{42}(SO_3)]^{6-}$ cluster anions (Fig. 7g).

2.3 Trinuclear RECPs

2.3.1 Trinuclear Keggin-type RECPs (TKRECPs). Because of the existence of the lone pair electrons located on the top of trigonal pyramids of As^{III}, Sb^{III} and Bi^{III} heteroatoms, the stereochemistry effect of the lone pair electrons may play a role in the structural formation of POMs. Thus, As^{III}, Sb^{III} and Bi^{III} containing RECPs always exhibit unique spatial structures. Specifically speaking, the stereo-directing lone pair electrons of these heteroatoms greatly influence the further condensation of the POAs such as preventing the formation of plenary structures. Nevertheless, these lone pair electrons are beneficial to the formation of more open architectures through introducing bridging electrophiles.^{17a,55} In the past decade, many interesting trinuclear RECPs have emerged by continuous attempts of chemists. Using adaptable precursors and bench-top reaction conditions in acidic

(pH < 2) aqueous media, the 1-D chain tungstoarsenate $[Nd_3As_4W_{41}O_{141}OH(H_2O)_{10}]^{16-}$ was synthesized by Boskovic *et al.* in 2010.⁵⁶ The $[Nd_3As_4W_{41}O_{141}OH(H_2O)_{10}]^{16-}$ POA consists of three $[B-\alpha-As^{III}W_9O_{33}]^{9-}$ fragments and one $[B-\beta-As^{III}W_8O_{29}(OH)]^{8-}$ fragment (Fig. 8a), in which the $[B-\beta-As^{III}W_8O_{29}(OH)]^{8-}$ fragment was firstly observed. There are three crystallographically unique square antiprismatic Nd^{3+} ions in the $[Nd_3As_4W_{41}O_{141}OH(H_2O)_{10}]^{16-}$ POA; moreover, the Nd^{3+} ion acts as a template for the assembly of POA and two Nd^{3+} ions serve as linkers to construct the 1-D chain (Fig. 8b). Then, Xu *et al.* reported a carbonate and trinuclear dysprosium sandwiched tungstoarsenate $K_8H_3[Dy_3(H_2O)_3(CO_3)(A-\alpha-AsW_9O_{34})(A-\beta-AsW_9O_{34})] \cdot 22H_2O$ in 2012,³⁶ in which three Dy^{3+} ions create an equatorial belt formed by two isomeric trivalent Keggin fragments $[A-\alpha-AsW_9O_{34}]^{9-}$ and $[A-\beta-AsW_9O_{34}]^{9-}$, and CO_3^{2-} is encapsulated in the triangle plane (Fig. 8c), giving rise to a stable dysprosium carbonate-containing sandwich-type POM. During the exploration of novel tungstoarsenate-based TKRECPs, tungstoantimonate-based TKRECPs have also attracted increasing interest due to some similar reaction behaviors of Sb^{III} and As^{III} elements. In 2011, Kortz's group successfully synthesized a special trinuclear Y^{III}-containing tungstoantimonate $\{ [Y(\alpha-SbW_9O_{31}(OH)_2)(CH_3COO)(H_2O)]_3(WO_4) \}^{17-}$ by a simple one-pot reaction of Y^{3+} ions with $[\alpha-SbW_9O_{33}]^{9-}$ and WO_4^{2-} ions in a 3:3:1 molar ratio in a LiOAc/AcOH buffer at pH 5.3 (Fig. 8d).⁵⁷ In this POA, a tetrahedral WO_4^{2-} capping unit is surrounded by three $[\alpha-SbW_9O_{33}]^{9-}$ units linked by three Y^{3+} ions. Although As^{III}, Sb^{III} and Bi^{III} heteroatoms all own lone pair electrons, the ionic radius of Bi^{III} (1.17 Å) is bigger than those of As^{III} (0.72 Å) and Sb^{III} (0.90 Å), which shows that there is a significant difference between these atoms in inducing the

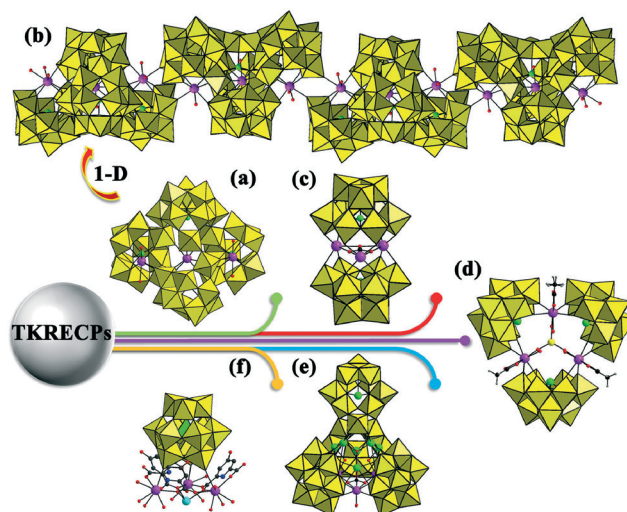


Fig. 8 (a) View of the structural unit of $[Nd_3As_4W_{41}O_{141}OH(H_2O)_{10}]^{16-}$. (b) The 1-D chain of $[Nd_3As_4W_{41}O_{141}OH(H_2O)_{10}]^{16-}$. (c) View of $[Dy_3(H_2O)_3(CO_3)(A-\alpha-AsW_9O_{34})(A-\beta-AsW_9O_{34})]^{11-}$. (d) View of $[Y(\alpha-SbW_9O_{31}(OH)_2)(CH_3COO)(H_2O)]_3(WO_4)^{17-}$. (e) View of $[(BiW_9O_{33})_4-(WO_3)(Bi_6(\mu_3-O)_4(\mu_2-OH)_3)(RE_3(H_2O)_6CO_3)]^{22-}$. (f) View of $\{Na(H_2O)_3[RE-(HCAM)(H_2O)_3]_3\}[SiW_{12}O_{40}] \cdot nH_2O$. (WO₆: yellow, blue and orange, X: bright green, RE: light purple, O: red, C: gray, N: blue, Na: turquoise).

structural diversity of RECPs. In addition, with the appearance of underlying applications in catalytic activity, ferroelectric, piezoelectric and non-linear dielectric susceptibility, tungstobismuthates are regarded as one of the potential solid functional materials.⁵⁸ In 2012, Xu and coworkers isolated three unprecedented giant TKRECPs $[(\text{BiW}_9\text{O}_{33})_4(\text{WO}_3)\{\text{Bi}_6(\mu_3\text{-O})_4(\mu_2\text{-OH})_3\}(\text{RE}_3(\text{H}_2\text{O})_6\text{CO}_3)]^{22-}$ (RE = Pr^{III}, Nd^{III}, La^{III}) by reacting $\text{Na}_{12}[\text{Bi}_2\text{W}_{22}\text{O}_{74}(\text{OH})_2]\cdot 44\text{H}_2\text{O}$ and $\text{Na}_9[\text{BiW}_9\text{O}_{33}]\cdot 16\text{H}_2\text{O}$ with LnCl_3 in the presence of Na_2CO_3 in aqueous solution (pH ~ 7.0) (Fig. 8e).⁵⁹ The formation of the framework of the $[(\text{BiW}_9\text{O}_{33})_4(\text{WO}_3)\{\text{Bi}_6(\mu_3\text{-O})_4(\mu_2\text{-OH})_3\}(\text{RE}_3(\text{H}_2\text{O})_6\text{CO}_3)]^{22-}$ POA can be explained as follows: the $[\{\text{Pr}_3(\text{H}_2\text{O})_6\text{CO}_3\}]^{7+}$ cation first connects three trivalent $[\alpha\text{-B-BiW}_9\text{O}_{33}]^{9-}$ fragments together forming a trigonal alignment, and then is connected to the fourth $[\alpha\text{-B-BiW}_9\text{O}_{33}]^{9-}$ fragment through a $[\{\text{Bi}_6(\mu_3\text{-O})_4(\mu_2\text{-OH})_3\}]^{7+}$ cation and an additional six-coordinate tungsten atom. This POA represents the largest RE-containing polyoxotungstobismuthate. Furthermore, a suitable ligand selection is the key factor to obtain the desired structural features and properties. By making use of H₃CAM (2,6-dicarboxy-4-hydroxypyridine), Mirzaei *et al.* synthesized a series of novel inorganic-organic hybrids $\{\text{Na}(\text{H}_2\text{O})_3[\text{RE}(\text{HCAM})(\text{H}_2\text{O})_3]_3[\text{SiW}_{12}\text{O}_{40}]\cdot n\text{H}_2\text{O}$ (RE = La^{III}, Ce^{III}, Eu^{III}), in which the polynuclear cation $\{\text{Na}(\text{H}_2\text{O})_3[\text{RE}(\text{HCAM})(\text{H}_2\text{O})_3]_3\}^{4+}$ coordinates to the $[\text{SiW}_{12}\text{O}_{40}]^{4-}$ POA (Fig. 8f).⁶⁰ Moreover, unprecedented anion- π interactions in inorganic-organic Keggin-type POM frameworks were described and analyzed for the first time.⁶⁰

2.3.2 Trinuclear Dawson-type RECPs (TDRECPs). In addition to the above discussed neoteric TKRECPs, several interesting TDRECPs with infinite extended architectures were discovered. In 2006, Wang's group separated the first 1-D chain TDRECP built by monovacant Dawson anions and trinuclear cations $[\text{Nd}_3(\text{H}_2\text{O})_{17}(\alpha_2\text{-P}_2\text{W}_{17}\text{O}_{61})]^-$ (Fig. 9a and b).⁴³ In 2011, four open Wells-Dawson silicotungstates with similar 2-D extended structures $\text{Na}_2\text{Cs}_3\text{H}_2\text{Tb}[\text{Tb}_2(\text{H}_2\text{O})_7\text{Si}_2\text{W}_{18}\text{O}_{66}]\cdot 17\text{H}_2\text{O}$, $\text{Na}_4\text{Cs}_3\text{DyH}[\text{Dy}_2(\text{H}_2\text{O})_{6.5}(\text{C}_2\text{H}_4\text{O}_2)_{0.5}\text{Si}_2\text{W}_{18}\text{O}_{66}]\text{Cl}$

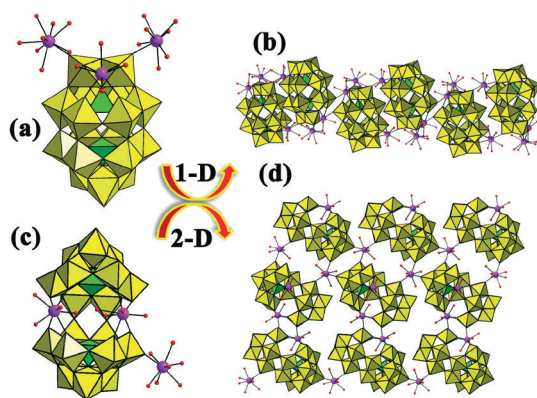


Fig. 9 (a) View of $[\text{Nd}_3(\text{H}_2\text{O})_{17}(\alpha_2\text{-P}_2\text{W}_{17}\text{O}_{61})]^-$. (b) The 1-D chain of $[\text{Nd}_3(\text{H}_2\text{O})_{17}(\alpha_2\text{-P}_2\text{W}_{17}\text{O}_{61})]^-$. (c) View of $\text{Na}_4\text{Cs}_3\text{Ho}[\text{Ho}_2(\text{H}_2\text{O})_7\text{Si}_2\text{W}_{18}\text{O}_{66}]\cdot 18\text{H}_2\text{O}$. (d) The 2-D extended architecture of $\text{Na}_4\text{Cs}_3\text{Ho}[\text{Ho}_2(\text{H}_2\text{O})_7\text{Si}_2\text{W}_{18}\text{O}_{66}]\cdot 18\text{H}_2\text{O}$. (WO_6 : yellow, XO_4 : bright green, RE: light purple, O: red).

$\cdot 17\text{H}_2\text{O}$, $\text{Na}_4\text{Cs}_3\text{Ho}[\text{Ho}_2(\text{H}_2\text{O})_7\text{Si}_2\text{W}_{18}\text{O}_{66}]\cdot 18\text{H}_2\text{O}$ (Fig. 9c and d) and $\text{Na}_{2.5}\text{Cs}_{3.5}\text{GdH}_2[\text{Gd}_2(\text{H}_2\text{O})_7\text{Si}_2\text{W}_{18}\text{O}_{66}](\text{C}_2\text{H}_3\text{O}_2)\cdot 16\text{H}_2\text{O}$ were isolated by Patzke *et al.* from the one-step reaction of $\text{Na}_{10}\text{-}[\text{SiW}_9\text{O}_{34}]\cdot n\text{H}_2\text{O}$ with $\text{RE}(\text{NO}_3)_3\cdot n\text{H}_2\text{O}$ in a sodium acetate buffer, which are the first open Wells-Dawson RE encapsulated silicotungstates containing $[\alpha\text{-Si}_2\text{W}_{18}\text{O}_{66}]^{16-}$ POAs.⁶¹

2.4 Quadronuclear RECPs

2.4.1 Quadronuclear Keggin-type RECPs (QKRECPs). In the preparation of QKRECPs, the divacant $[\text{As}_2\text{W}_{19}\text{O}_{67}(\text{H}_2\text{O})]^{14-}$ precursor has aroused considerable interest and stimulated the production of a class of novel $\{\text{AsW}_9\text{O}_{33}\}$ -based QKRECPs because of the following reasons: (i) the stereo-directing influence of the lone pair on the As^{III} atom allows the formation of lacunary Keggin fragments and endows it with distinctive reactivity compared with those defect POM moieties anchoring tetrahedral heteroatom groups;² (ii) the $\{\text{WO}(\text{H}_2\text{O})\}$ linker between two $[\text{B-}\alpha\text{-AsW}_9\text{O}_{33}]^{9-}$ fragments could serve as a starting point for rotation and dissociation, which may facilitate the generation of various building blocks in solution at different pH values;³⁷ (iii) this precursor is easier to be prepared in good yield. In the following discussion, the statements will be expounded according to the number of $\{\text{AsW}_9\text{O}_{33}\}$ subunits per compound. Utilizing the preformed precursor and through disassembly and reassembly processes, Boskovic *et al.* obtained a novel QKRECP $[\text{Dy}_4\text{As}_2\text{W}_{22}\text{O}_{76}(\text{H}_2\text{O})_{19}(\text{C}_2\text{H}_5\text{NO}_2)_2]^{2-}$ ($\text{C}_2\text{H}_5\text{NO}_2 = \text{glycine}$) involving two glycine ligands (Fig. 10a).⁵⁶ This skeleton of the $[\text{Dy}_4\text{As}_2\text{W}_{22}\text{O}_{76}(\text{H}_2\text{O})_{19}(\text{C}_2\text{H}_5\text{NO}_2)_2]^{2-}$ POA is assembled from two $[\text{B-}\alpha\text{-AsW}_9\text{O}_{33}]^{9-}$ fragments connected *via* two unprecedented $\{\text{W}_2\text{O}_5(\text{glycine})\}$ groups accompanying each glycine ligand coordinating to two W^{VI} centers in a bidentate fashion. Moreover, in this compound, the Dy³⁺ cations act as linkers to form the novel 1-D chain architecture (Fig. 10b). Very recently, Niu *et al.* obtained six tartrate-bridging tetra-RE substituted QKRECP dimers $[\text{RE}_2(\text{C}_4\text{H}_4\text{O}_6)(\text{C}_4\text{H}_2\text{O}_6)\text{-}(\text{AsW}_9\text{O}_{33})_2]^{18-}$ (RE = Ho^{III}, Er^{III}, Tm^{III}, Yb^{III}, Lu^{III}, Y^{III}) (Fig. 10c),⁶² which consist of two $[\text{B-}\alpha\text{-AsW}_9\text{O}_{33}]^{9-}$ fragments in a staggered fashion, sandwiching a unique cage-like RE-organic cluster formed by four RE cations and four tartaric acid segments. Three more kinds of novel QKRECPs containing four $[\text{AsW}_9\text{O}_{33}]^{9-}$ fragments have been synthesized by the precursor $[\text{As}_2\text{W}_{19}\text{O}_{67}(\text{H}_2\text{O})]^{14-}$ in the past decade. For example, in 2011, Boskovic and collaborators synthesized and characterized a new family of QKRECPs with gly ligands $[\text{RE}_4\text{As}_5\text{W}_{40}\text{O}_{144}(\text{H}_2\text{O})_{10}(\text{gly})_2]^{21-}$ (RE = Gd^{III}, Tb^{III}, Dy^{III}, Ho^{III}, Y^{III}), in which two $[\text{As}_2\text{W}_{19}\text{O}_{68}]^{16-}$ subunits are bridged together by four RE cations and two tungsten centers (Fig. 10d).⁶³ In the formation of this series of compounds, the $[\text{As}_2\text{W}_{19}\text{O}_{67}(\text{H}_2\text{O})]^{14-}$ POA experiences a structural rearrangement so as to accommodate the inclusion of RE ions, with transformation into the $[\text{As}_2\text{W}_{19}\text{O}_{68}]^{16-}$ subunits. This process occurs *via* loss of the terminal aqua ligand from the $\{\text{WO}_5(\text{H}_2\text{O})\}$ linker, with the subsequent change in the respective orientation of two trivalent $[\text{B-}\alpha\text{-AsW}_9\text{O}_{33}]^{9-}$

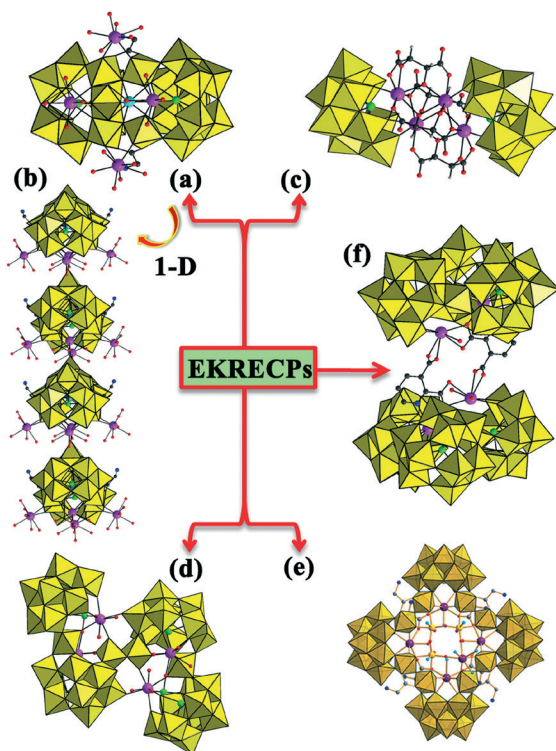


Fig. 10 (a) View of the structural unit of $[\text{Dy}_4\text{As}_2\text{W}_{22}\text{O}_{76}(\text{H}_2\text{O})_{19}(\text{C}_2\text{H}_5\text{NO}_2)_2]^{2-}$. (b) The 1-D chain of $[\text{Dy}_4\text{As}_2\text{W}_{22}\text{O}_{76}(\text{H}_2\text{O})_{19}(\text{C}_2\text{H}_5\text{NO}_2)_2]^{2-}$. (c) View of $[\text{RE}_2(\text{C}_4\text{H}_4\text{O}_6)(\text{C}_4\text{H}_2\text{O}_6)(\text{AsW}_9\text{O}_{33})_2]^{18-}$. (d) View of $[\text{RE}_4\text{As}_5\text{W}_{40}\text{O}_{144}(\text{H}_2\text{O})_{10}(\text{gly})_2]^{21-}$. (e) View of $[\text{As}^{\text{III}}_4(\text{Y}^{\text{III}}\text{W}^{\text{III}}_3)\text{W}^{\text{VI}}_{44}\text{Y}^{\text{III}}_4\text{O}_{159}(\text{Gly})_8(\text{H}_2\text{O})_{14}]^{9-}$ (copied from ref. 61). (f) View of $[\text{As}_6\text{W}_{58}\text{O}_{206}\text{Ce}_4(\text{pydc})_2(\text{H}_2\text{O})_6]^{38-}$. (WO_6 : yellow, blue and orange, RE: light purple, Na: turquoise, O: red, C: gray, N: blue).

fragments. Alternating current magnetic susceptibility data have indicated the onset of slow magnetic relaxation for $[\text{Dy}_4\text{As}_5\text{W}_{40}\text{O}_{144}(\text{H}_2\text{O})_{10}(\text{gly})_2]^{21-}$ with the energy barrier for magnetization reversal determined to be 3.9(1) K. Furthermore, its X-band EPR spectrum further shows the presence of a non-negligible fourth order transverse component of the anisotropy, which is responsible for the small effective energy barrier observed for $[\text{Dy}_4\text{As}_5\text{W}_{40}\text{O}_{144}(\text{H}_2\text{O})_{10}(\text{gly})_2]^{21-}$. To date, it represents the first POM-supported polynuclear lanthanoid-based SMM.⁶³ In 2014, Boskovic's group first afforded a novel QKRECP $[\text{As}_4(\text{YW}_3)\text{W}_{44}\text{Y}_4\text{O}_{159}(\text{Gly})_8(\text{H}_2\text{O})_{14}]^{9-}$ (Fig. 10e) by incorporation of glycine (Gly) ligands into an yttrium-tungstoarsenate structural backbone and then utilized the site-selective incorporation of Mo and replacement of glycine with enantiopure L- or D-norleucine (L- or D-Nle) to give rise to two enantiomeric compounds $\{[\text{As}^{\text{III}}_4(\text{Mo}^{\text{VI}}_2\text{Mo}^{\text{VI}}_2)\text{W}^{\text{VI}}_{44}\text{Y}^{\text{III}}_4\text{O}_{160}(\text{L-Nle})_9(\text{H}_2\text{O})_{11}]^{18-}$ and $\{[\text{As}^{\text{III}}_4(\text{Mo}^{\text{VI}}_2\text{W}^{\text{VI}}_2)\text{W}^{\text{VI}}_{44}\text{Y}^{\text{III}}_4\text{O}_{160}(\text{D-Nle})_9(\text{H}_2\text{O})_{11}]^{18-}$.⁶⁴ They all consist of four $[\text{B-}\alpha\text{-AsW}_9\text{O}_{33}]^{9-}$ fragments bridged by a cyclic $\{\text{Y}_4\text{W}_8\text{L}_8\}$ (L = zwitterionic Gly, L-Nle, D-Nle) unit. Nevertheless, by means of intensive structural, spectroscopic, electrochemical, magnetochemical and theoretical investigation, the site-selective metal substitution and photoreduction capability of the tetranuclear $\{\text{M}_4\text{O}_4\}$ core of these hybrid POAs were

also elucidated.⁶⁴ In 2014, Niu *et al.* synthesized a unique large Ce-containing POM-carboxylate hybrid $[\text{As}_6\text{W}_{58}\text{O}_{206}\text{Ce}_4(\text{pydc})_2(\text{H}_2\text{O})_6]^{38-}$ (H_2pydc = pyridine-2,3-dicarboxylic acid) containing six $[\text{B-}\alpha\text{-AsW}_9\text{O}_{33}]^{9-}$ subsets by the bridging role of two pydc ligands (Fig. 10f).⁶⁵ It shouldn't be neglected that the trivacant precursor $[\text{B-}\alpha\text{-AsW}_9\text{O}_{33}]^{9-}$ can also construct some novel QKRECPs due to the excellent coordination ability of the vacant sites. Thereby, Wang *et al.* successfully synthesized three large Ce-containing tungstoarsenate aggregates $[\{\text{Ce}_2\text{O}(\text{H}_2\text{O})_5\}\{\text{WO}(\text{H}_2\text{O})\}\{\text{AsW}_9\text{O}_{33}\}_2]^{16-}$, $[\text{Ce}_4\text{As}_4\text{W}_{41}\text{O}_{149}]^{24-}$ and $[\text{Ce}_4\text{As}_4\text{W}_{44}\text{O}_{151}(\text{ala})_4(\text{OH})_2(\text{H}_2\text{O})_{10}]^{12-}$ (ala = L- α -alanine) by the precursor $[\text{B-}\alpha\text{-AsW}_9\text{O}_{33}]^{9-}$ using *via* a step-by-step assembly process.^{66a} The tetrameric POA $[\{\text{Ce}_2\text{O}(\text{H}_2\text{O})_5\}\{\text{WO}(\text{H}_2\text{O})\}\{\text{AsW}_9\text{O}_{33}\}_2]^{16-}$ is constructed from two sandwich-type $[\{\text{Ce}_2\text{O}(\text{H}_2\text{O})_5\}\{\text{WO}(\text{H}_2\text{O})\}\{\text{AsW}_9\text{O}_{33}\}_2]^{8-}$ moieties bridged by two Ce^{4+} ions (Fig. 11a). In the POA $[\text{Ce}_4\text{As}_4\text{W}_{41}\text{O}_{149}]^{24-}$, the four Ce^{4+} ions function as linkers to link four $[\text{B-}\alpha\text{-AsW}_9\text{O}_{33}]^{9-}$ units, generating a new type of cryptand cluster (Fig. 11b). In contrast to the classical cryptate POA $[\text{As}_4\text{W}_{40}\text{O}_{140}]^{28-}$,^{66b,c} for $[\text{Ce}_4\text{As}_4\text{W}_{41}\text{O}_{149}]^{24-}$ it can be considered that the positions of four W linkers are replaced by four Ce^{4+} centers. The unusual alanine-decorated cryptand-type POA $[\text{Ce}_4\text{As}_4\text{W}_{44}\text{O}_{151}(\text{ala})_4(\text{OH})_2(\text{H}_2\text{O})_{10}]^{12-}$ is assembled from four $[\text{B-}\alpha\text{-AsW}_9\text{O}_{33}]^{9-}$ subunits connected by two $\{\text{WO}_2\}$, two $\{\text{W}_2\text{O}_5(\text{ala})\}$, two $\{\text{Ce}_2(\text{H}_2\text{O})_5(\text{ala})\}$ and a linear $\{\text{W}_2\text{O}_5(\text{OH})_2\}$ group (Fig. 11c), in which four organic α -alanine ligands are coordinated directly on the surface of the aggregate. Apart from $\{\text{AsW}_9\text{O}_{33}\}$ -based QKRECPs, other QKRECPs were also discovered. For instance, two QKRECPs $[\text{RE}_4(\alpha(1,4)\text{-GeW}_{10}\text{O}_{38})_2(\text{H}_2\text{O})_6]^{12-}$ (RE = Dy^{III} , Er^{III}) containing two $[\alpha(1,4)\text{-GeW}_{10}\text{O}_{38}]^{12-}$ subunits were obtained by Xu *et al.* based on the $[\gamma\text{-GeW}_{10}\text{O}_{36}]^{8-}$ precursor, which represent the first RECPs with two dilacunary Keggin-type POA units sandwiching four RE ions (Fig. 12a).⁶⁷ Different from Xu's method, Reinoso *et al.* utilized GeO_2 , Na_2WO_4 and RE cations in a NaOAc buffer to obtain a series of QKRECPs $[\text{RE}_4(\text{H}_2\text{O})_6(\beta\text{-GeW}_{10}\text{O}_{38})_2]^{12-}$ (RE = Gd^{III} , Tb^{III} , Dy^{III} , Ho^{III} , Er^{III} , Tm^{III} , Yb^{III} , Lu^{III}).⁶⁸ In addition, Niu and coworkers reported an interesting double-parallel chain germanotungstate based on QKRECP subunits $\{[\text{Sm}_2(\text{GeW}_{11}\text{O}_{39})(\text{DMSO})_3(\text{H}_2\text{O})_6]_2\}^{4-}$ (Fig. 12b),^{20d} in which the two parallel chains $\{[\text{Sm}(\text{GeW}_{11}\text{O}_{39})(\text{DMSO})(\text{H}_2\text{O})_5]^{-}\}_n$ are joined together through $[\text{Sm}(\text{DMSO})_2(\text{H}_2\text{O})_4]^{3+}$ moieties (Fig. 12c). Further, Liu *et al.* reported a tri-Nb^V substituted germanotungstate-based QKRECP $[(\text{GeW}_9\text{Nb}_3\text{O}_{40})_4\text{Eu}_4(\text{H}_2\text{O})_{22}]^{16-}$ (Fig. 12d),⁶⁹ which is

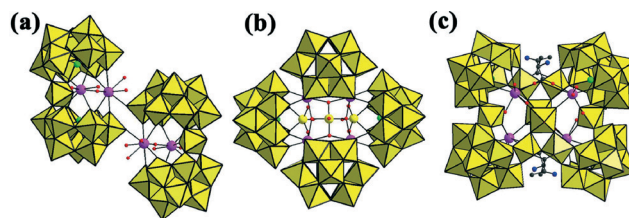


Fig. 11 (a) View of $[\{\text{Ce}_2\text{O}(\text{H}_2\text{O})_5\}\{\text{WO}(\text{H}_2\text{O})\}\{\text{AsW}_9\text{O}_{33}\}_2]^{16-}$. (b) View of $[\text{Ce}_4\text{As}_4\text{W}_{41}\text{O}_{149}]^{24-}$. (c) View of $[\text{Ce}_4\text{As}_4\text{W}_{44}\text{O}_{151}(\text{ala})_4(\text{OH})_2(\text{H}_2\text{O})_{10}]^{12-}$. (WO_6 : yellow, XO_4 : bright green, RE: light purple, O: red, C: gray, N: blue).

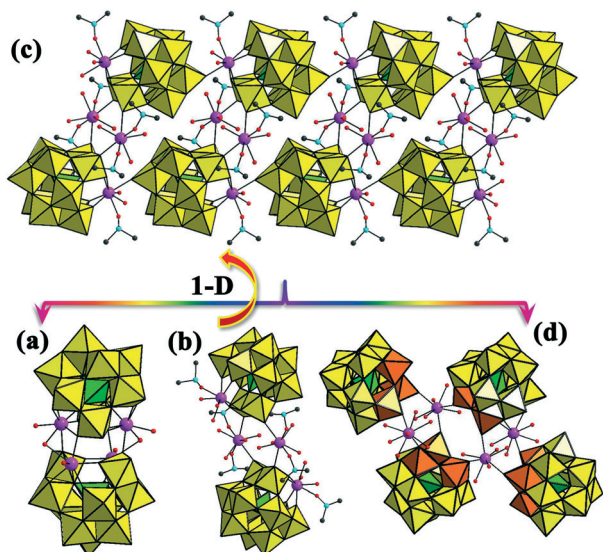


Fig. 12 (a) View of $[\text{RE}_4(\alpha(1,4)\text{-GeW}_{10}\text{O}_{38})_2(\text{H}_2\text{O})_6]^{12-}$. (b) View of the structural unit of $\{[\text{Sm}_2(\text{GeW}_{11}\text{O}_{39})(\text{DMSO})_3(\text{H}_2\text{O})_6]_2\}^{4-}$. (c) View of the 1-D chain of $\{[\text{Sm}_2(\text{GeW}_{11}\text{O}_{39})(\text{DMSO})_3(\text{H}_2\text{O})_6]_2\}^{4-}$. (d) View of $[(\text{GeW}_9\text{Nb}_3\text{O}_{40})_4\text{Eu}_4(\text{H}_2\text{O})_{22}]^{16-}$. (WO_6 : yellow, NbO_6 : orange, XO_4 : bright green, RE: light purple, O: red, S: turquoise, C: gray, N: blue).

made up of four tri-Nb^V substituted Keggin $[\text{GeW}_9\text{Nb}_3\text{O}_{40}]^{7-}$ segments bonded by four Eu^{3+} cations. In addition, Wang *et al.* communicated a tungstoantimonate-based QKRECP $\{[\text{Y}(\text{H}_2\text{O})_7]_4\text{Sb}_2\text{W}_{22}\text{O}_{76}\}^{2-}$, in which the Krebs-type $[\text{Sb}_2\text{W}_{22}\text{O}_{76}]^{14-}$ subunit was supported by four Y^{3+} ions.⁷⁰

2.4.2 Quadronuclear Dawson-type RECPs (QDRECPs). Through the one-step reaction of $\text{Na}_{10}[\text{SiW}_9\text{O}_{34}]_3 \cdot n\text{H}_2\text{O}$ with $\text{Gd}(\text{NO}_3)_3 \cdot n\text{H}_2\text{O}$ in a sodium acetate buffer, Patzke *et al.* synthesized a novel QDRECP $\{\text{Gd}_2(\text{H}_2\text{O})_{13}[\text{Gd}_2(\text{H}_2\text{O})_7\text{Si}_2\text{W}_{18}\text{O}_{66}]\}^{4-}$ (Fig. 13a),⁶¹ in which two Gd^{3+} cations are located in the peripheral pocket of the $[\alpha\text{-Si}_2\text{W}_{18}\text{O}_{66}]^{16-}$ anion, whereas two Gd^{3+} cations are bound to the terminal oxygen atoms of both sides. More intriguingly, adjacent $[\text{Gd}_2(\text{H}_2\text{O})_7\text{Si}_2\text{W}_{18}\text{O}_{66}]^{10-}$ moieties are combined together through the Gd^{3+} cations

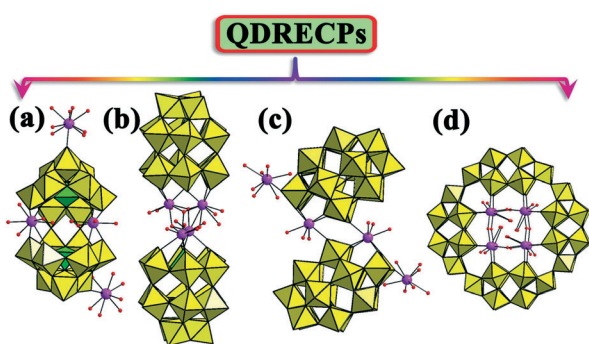


Fig. 13 (a) View of $\{\text{Gd}_2(\text{H}_2\text{O})_{13}[\text{Gd}_2(\text{H}_2\text{O})_7\text{Si}_2\text{W}_{18}\text{O}_{66}]\}^{4-}$. (b) View of $\{[\text{Y}_4(\mu_3\text{-OH})_4(\text{H}_2\text{O})_8](\alpha\text{-P}_2\text{W}_{15}\text{O}_{56})_2\}^{16-}$. (c) View of $\{[\text{Nd}(\text{H}_2\text{O})_7]_2[\text{Nd}(\text{H}_2\text{O})_3(\alpha_2\text{-P}_2\text{W}_{17}\text{O}_{61})_2]\}^{8-}$. (d) View of $\{[\text{RE}_2(\mu\text{-OH})_4(\text{H}_2\text{O})_{12}]_2(\text{H}_{24}\text{P}_8\text{W}_{48}\text{O}_{184})\}^{12-}$. (WO_6 : yellow, XO_4 : bright green, RE: light purple, O: red).

located on both sides forming the 3-D framework, which represents the first 3D inorganic coordination polymer based on Ln-substituted Wells–Dawson POMs. In 2005, Hill *et al.* separated a novel sandwich-type QDRECP $\{[\text{Y}_4(\mu_3\text{-OH})_4(\text{H}_2\text{O})_8](\alpha\text{-P}_2\text{W}_{15}\text{O}_{56})_2\}^{16-}$ consisting of a $\{\text{Y}_4(\text{OH})_4\}$ cubane cluster encapsulated by two trivalent Dawson $[\alpha\text{-P}_2\text{W}_{15}\text{O}_{56}]^{12-}$ subunits (Fig. 13b).⁷¹ In the same year, a fascinating bisupporting DDRECP $\{[\text{Nd}(\text{H}_2\text{O})_8]_2[\text{Nd}(\text{H}_2\text{O})_3(\alpha_2\text{-P}_2\text{W}_{17}\text{O}_{61})_2]\}^{8-}$ (Fig. 13c) was found by Wang *et al.*, which is assembled from a dimeric $[\{\text{Nd}(\text{H}_2\text{O})_3(\alpha_2\text{-P}_2\text{W}_{17}\text{O}_{61})_2\}]^{14-}$ anion and two $[\text{Nd}(\text{H}_2\text{O})_7]^{3+}$ cations.⁴³ The dimeric $[\{\text{Nd}(\text{H}_2\text{O})_3(\alpha_2\text{-P}_2\text{W}_{17}\text{O}_{61})_2\}]^{14-}$ anion is made up of two $[\text{P}_2\text{W}_{17}\text{O}_{61}\text{Nd}(\text{H}_2\text{O})_3]^{7-}$ subunits connected *via* two common terminal oxygen atoms. In 2013, Yang *et al.* reported the $\{\text{P}_8\text{W}_{48}\}$ including QDRECPs $\{[\text{RE}_2(\mu\text{-OH})_4(\text{H}_2\text{O})_{12}]_2(\text{H}_{24}\text{P}_8\text{W}_{48}\text{O}_{184})\}^{12-}$ $[\text{RE} = \text{Sm}^{\text{III}}, \text{Tb}^{\text{III}}]$ (Fig. 13d),⁷² in which each Sm^{3+} ion in the cavity is positionally disordered and has a site occupancy of 0.5.

2.4.3 Quadronuclear Lindqvist-type RECPs (QLRECPs). In 2014, our group made a groundbreaking work in the development of QLRECPs and successfully obtained two types of unique oxalate-connective QLRECPs $[\text{RE}_2(\text{C}_2\text{O}_4)(\text{H}_2\text{O})_4(\text{OH})\text{W}_4\text{O}_{16}]^{10-}$ (Fig. 14a) and $[\text{RE}(\text{C}_2\text{O}_4)\text{W}_5\text{O}_{18}]_4^{20-}$ ($\text{RE} = \text{Eu}^{\text{III}}, \text{Ho}^{\text{III}}, \text{Er}^{\text{III}}, \text{Tb}^{\text{III}}$) (Fig. 14b).⁷³ It should be pointed out that $[\text{RE}_2(\text{C}_2\text{O}_4)(\text{H}_2\text{O})_4(\text{OH})\text{W}_4\text{O}_{16}]^{10-}$ were obtained when only Na^+ ions are present in the reaction, whereas $[\text{RE}(\text{C}_2\text{O}_4)\text{W}_5\text{O}_{18}]_4^{20-}$ were formed when Na^+ and K^+ ions are used in the reaction. $[\text{RE}_2(\text{C}_2\text{O}_4)(\text{H}_2\text{O})_4(\text{OH})\text{W}_4\text{O}_{16}]^{10-}$ represent the first rectangular double-oxalate-bridging tetra-Ln cluster encapsulated divacant Lindqvist isopolyoxotungstate hybrids and $[\text{RE}(\text{C}_2\text{O}_4)\text{W}_5\text{O}_{18}]_4^{20-}$ represent the first square double-oxalate-bridging tetra-Ln cluster anchored isopolyoxotungstate hybrids. This work provides the remarkable feasibility of constructing unprecedented gigantic hybrid poly(isopolyoxotungstate) species with special properties. Moreover, the solid-state luminescent and decay behavior of $[\text{RE}_2(\text{C}_2\text{O}_4)(\text{H}_2\text{O})_4(\text{OH})\text{W}_4\text{O}_{16}]^{10-}$ and $[\text{RE}(\text{C}_2\text{O}_4)\text{W}_5\text{O}_{18}]_4^{20-}$

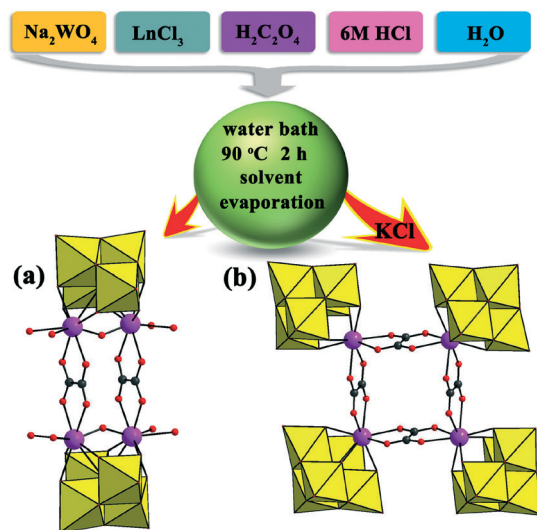


Fig. 14 (a) View of $[\text{RE}_2(\text{C}_2\text{O}_4)(\text{H}_2\text{O})_4(\text{OH})\text{W}_4\text{O}_{16}]^{10-}$. (b) View of $[\text{RE}(\text{C}_2\text{O}_4)\text{W}_5\text{O}_{18}]_4^{20-}$. (WO_6 : yellow, RE: light purple, O: red, C: gray).

(RE = Eu^{III}, Tb^{III}) have been profoundly probed.⁷³ Further, Niu and coworkers reported the first class of novel tetranuclear RE-containing peroxopolyoxotungstates [RE₄(WO₄)(H₂O)₁₆{W₇O₂₂(O₂)₂}]₄¹⁴⁻ (RE = La^{III}, Pr^{III}) with a WO₄²⁻ template core (Fig. 15a).⁷⁴ The central WO₄²⁻ core and four tetradentate building blocks {W₇O₂₂(O₂)₂} are bridged together by four {REO₉} linkers with a distorted tricapped trigonal prism coordination geometry; moreover, the central WO₄²⁻ core exhibits an interesting tetrahedral geometry. Seven W atoms are regularly arranged in a bent 2–3–2 pattern to complete the skeleton of {W₇O₂₂(O₂)₂}, in which two W atoms in the opposite sides of the {W₃} hinge exhibit a distorted pentagonal bipyramidal coordination environment and the remaining W atoms adopt the common WO₆ octahedral geometry (Fig. 15b). In 2014, Su's group explored a versatile one-pot strategy to obtain two tetra-Ce^{III} containing polyoxotungstate nanoclusters [Ce₄(H₂O)₁₂W₄₄O₁₄₄(OH)₁₂]²⁴⁻ (Fig. 15c) (pH = 4.5) and [Ce₂(H₂O)₉W₃₆O₁₁₀(OH)₁₂]²⁰⁻ (Fig. 15e) (pH = 1.5), which represent the largest RE-containing isopolyoxotungstates to date.⁵³ The former is a tetrameric POA based on four novel {CeW₁₁} building blocks linked by four Ce³⁺ bridges, in which the {W₁₁} fragment (Fig. 15d) is derived from the α-Keggin [H₂W₁₂O₄₀]⁶⁻ by removal of a {WO₆} octahedron. The latter is a dimeric POA containing two identical {Ce₂W₃₆} subunits related by an inversion center. In the {Ce₂W₃₆} subunit, one Ce³⁺ cation is trapped at the bottom of the central cavity in the {W₃₆} entity and the other Ce³⁺ cation attaches to the flank of the {W₃₆} entity. The two {W₃₆} entities are combined by two “attached” Ce³⁺ cations and stabilized by two “trapped” Ce³⁺ cations. The {W₃₆} entity is constructed from three {W₁₁} fragments (Fig. 15f) linked by three {WO₆} octahedra. It is worth mentioning that the {W₁₁} fragment (Fig. 15f) in the latter is completely distinct from the {W₁₁} fragment (Fig. 15d) in the former.

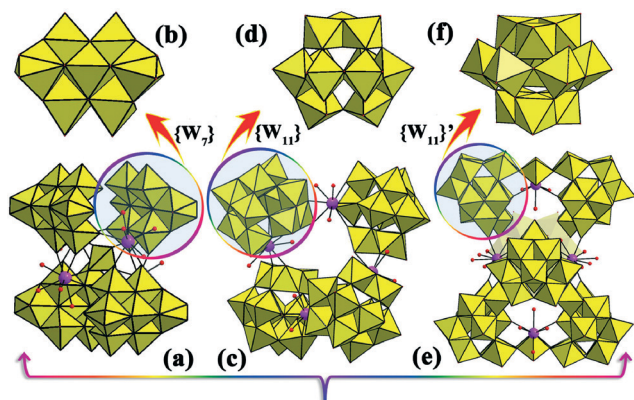


Fig. 15 (a) View of [RE₄(H₂O)₁₆(MoO₄)(Mo₇O₂₂(O₂)₂)₄]¹⁴⁻. (b) The {W₇O₂₂(O₂)₂} fragment in [RE₄(H₂O)₁₆(MoO₄)(Mo₇O₂₂(O₂)₂)₄]¹⁴⁻. (c) View of [Ce₄(H₂O)₁₂W₄₄O₁₄₄(OH)₁₂]²⁴⁻. (d) The {W₁₁} fragment in [Ce₄(H₂O)₁₂W₄₄O₁₄₄(OH)₁₂]²⁴⁻. (e) View of [Ce₂(H₂O)₉W₃₆O₁₁₀(OH)₁₂]²⁰⁻. (f) The {W₁₁} fragment in [Ce₂(H₂O)₉W₃₆O₁₁₀(OH)₁₂]²⁰⁻. To show the structures more clearly, some polyhedra are omitted. (WO₆: yellow, orange, RE: light purple, O: red).

2.5 Pentanuclear Keggin-type RECPs (PKRECPs)

In the past ten years, only a few PKRECPs were reported. In 2006, Krebs *et al.* separated a unique PKRECP [Ho₅(H₂O)₁₆(OH)₂As₆W₆₄O₂₂₀]²⁵⁻ (Fig. 16a) consisting of six trivalent Keggin [B-α-AsW₉O₃₃]⁹⁻ subunits joined by a bridging [Ho₅W₁₀(H₂O)₁₆(OH)₂O₂₂]²⁹⁻ group, which exhibits an neoteric arrangement fashion of six trilaunary Keggin [B-α-AsW₉O₃₃]⁹⁻ subunits.⁷⁵ In 2010–2012, An and coworkers discovered several 3-D extended inorganic frameworks based on PKRECP units [REK(H₂O)₁₂][RE(H₂O)₆]₂[(H₂O)₄REBW₁₁O₃₉H]₂·20H₂O (RE = Ce^{III}, Nd^{III}) (Fig. 16b), {RE[(H₂O)₆RE]₂[(H₂O)₄RESiW₁₁O₃₉]₂}⁻ (RE = La^{III}, Ce^{III}) and {[(H₂O)₆Nd]₂[(H₂O)₇Nd][RE(H₂O)₁₂][RE(H₂O)₆]₂[(H₂O)₄REBW₁₁O₃₉H]₂·20H₂O} is made up of RE-substituted double Keggin-type POAs [RE(H₂O)₄RE(BW₁₁O₃₉H)₂]¹⁰⁻ linked by Ln cations to generate a 3-D open framework with 1-D channels (Fig. 16c), {RE[(H₂O)₆RE]₂[(H₂O)₄RESiW₁₁O₃₉]₂}⁻ demonstrates a similar 3-D open framework with 1-D channels to [RE(H₂O)₁₂][RE(H₂O)₆]₂[(H₂O)₄REBW₁₁O₃₉H]₂·20H₂O, and {[(H₂O)₆Nd]₂[(H₂O)₇Nd] [(H₂O)₄NdSiW₁₁O₃₉][RE(H₂O)₁₂][RE(H₂O)₆]₂[(H₂O)₄REBW₁₁O₃₉H]₂·20H₂O} reveals another type of 3-D open framework constructed from two kinds of building blocks [RE(H₂O)₄RE(BW₁₁O₃₉H)₂]¹⁰⁻ and [RE(H₂O)₃RE(SiW₁₁O₃₉)]₂¹⁰⁻ that are concatenated together by Nd³⁺ cations. In 2012, a neoteric W/Nb mixed-addendum quadrangular PKRECP [Cs(GeW₉Nb₃O₄₀)₄(SO₄)Eu₅(H₂O)₃₆]¹⁴⁻ (Fig. 16d) was isolated by Liu's group, which is composed of two telephone-receiver-like {(GeW₉Nb₃O₄₀)₂Eu₂} (Fig. 16e) building units linked by two Eu³⁺ cations *via* O–Eu–O

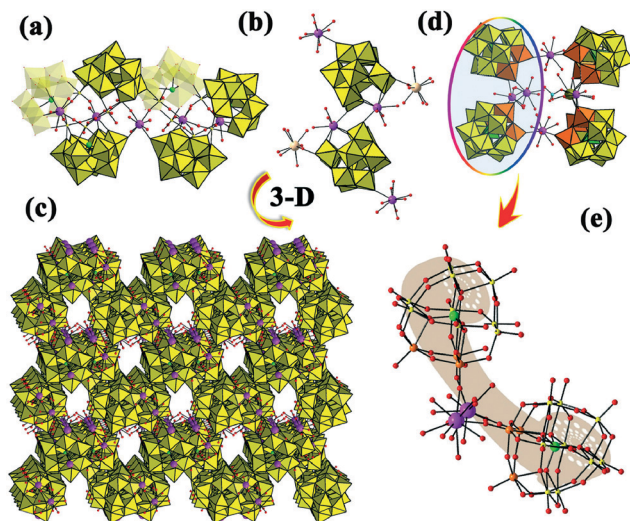


Fig. 16 (a) View of [Ho₅(H₂O)₁₆(OH)₂As₆W₆₄O₂₂₀]²⁵⁻. (b) View of [REK(H₂O)₁₂][RE(H₂O)₆]₂[(H₂O)₄REBW₁₁O₃₉H]₂·20H₂O. (c) The 3-D extended framework of [REK(H₂O)₁₂][RE(H₂O)₆]₂[(H₂O)₄REBW₁₁O₃₉H]₂·20H₂O showing 1-D channels. (d) View of [Cs(GeW₉Nb₃O₄₀)₄(SO₄)Eu₅(H₂O)₃₆]¹⁴⁻. (e) The telephone receiver-like building unit in [Cs(GeW₉Nb₃O₄₀)₄(SO₄)Eu₅(H₂O)₃₆]¹⁴⁻. To show the structures more clearly, some polyhedra are omitted. (WO₆: yellow, NbO₆: orange, XO₄: bright green, RE: light purple, O: red, Cs: dark yellow, S: turquoise).

bridges. It should be pointed out that one of the Eu^{3+} cations in the telephone-receiver-like building unit is substituted by an eleven-coordinate Cs^+ cation and a sulfate ion bridges the Cs^+ ion and an adjacent Eu^{3+} ion leading to the decrease of the symmetry of the quadrangle from D_{2h} to C_s .⁶⁹ In addition, Niu *et al.* prepared a novel 1-D chain-like $\{\text{La}_6\}$ containing peroxoisopolyoxomolybdate $[\text{H}_4\text{La}_5(\text{H}_2\text{O})_{21}(\text{MoO}_4)\{\text{Mo}_7\text{O}_{22}(\text{O}_2)_2\}_4]^{7-}$ (Fig. 17b), in which adjacent tetra- La^{III} including peroxopolyoxomolybdate $[\text{La}_4(\text{MoO}_4)(\text{H}_2\text{O})_{16}\{\text{Mo}_7\text{O}_{22}(\text{O}_2)_2\}_4]^{14-}$ (Fig. 17a) units are connected by additional La^{3+} cations to create the 1-D structure.⁷⁷

2.6 Hexanuclear RECPs

In 2008, Boskovic and collaborators communicated a $\{\text{Gd}_6\}$ incorporated hexanuclear Keggin RECP (HKRECP) with additional acetate ligands $[\text{Gd}_6\text{As}_6\text{W}_{65}\text{O}_{229}(\text{OH})_4(\text{H}_2\text{O})_{12}(\text{OAc})_2]^{38-}$ (Fig. 18a) that comprises four $[\text{B}-\alpha\text{-AsW}_9\text{O}_{33}]^{9-}$ and two $[\text{B}-\beta\text{-AsW}_9\text{O}_{33}]^{9-}$ trivalent Keggin subunits that are connected together through a corner-sharing with an edge-sharing $\{\text{W}_3\text{O}_{13}\}$ group, two edge-sharing $\{\text{W}_2\text{O}_{10}\}$ groups and four $\{\text{WO}_6\}$ octahedra,^{17a} which represents the highest nuclearity POM-encapsulated Gd^{III} complex. Its variable temperature magnetic susceptibility investigation reveals spin-only magnetism with a near perfect Curie-type temperature dependence of the susceptibility.^{17a} Furthermore, some extended architectures including HKRECP building units were also discovered. For instance, Li *et al.* obtained a series of 1-D chain-like QKRECPs $[\text{RE}_6(\text{H}_2\text{O})_x\{\text{As}_4\text{W}_{44}(\text{OH})_2(\text{proline})_2\text{O}_{151}\}]^{10-}$ (Fig. 18b) ($\text{RE} = \text{Tb}^{\text{III}}, \text{Dy}^{\text{III}}, x = 22$; $\text{RE} = \text{Nd}^{\text{III}}, x = 26$) in 2013,⁷⁸ in which adjacent $[\text{RE}_6(\text{H}_2\text{O})_x\{\text{As}_4\text{W}_{44}(\text{OH})_2(\text{proline})_2\text{O}_{151}\}]^{10-}$ clusters are linked together by double eight-coordinate RE cations producing the 1-D chain motif (Fig. 18c). It is worth mentioning that the $[\text{RE}_6(\text{H}_2\text{O})_x\{\text{As}_4\text{W}_{44}(\text{OH})_2(\text{proline})_2\text{O}_{151}\}]^{10-}$ cluster consists of four $[\text{B}-\alpha\text{-AsW}_9\text{O}_{33}]^{9-}$ fragments, two $\{\text{WO}_2\}$ fragments, two unfamiliar $\{\text{W}_2\text{O}_5(\text{proline})\}$ moieties, one $\{\text{W}_2\text{O}_5(\text{OH})_2\}$ dimer and four hydrated $\{\text{RE}(\text{H}_2\text{O})_n\}$ ($n = 2$ or 3) ions. Niu and coworkers also reported a type of novel 3-D extended architecture with hybrid

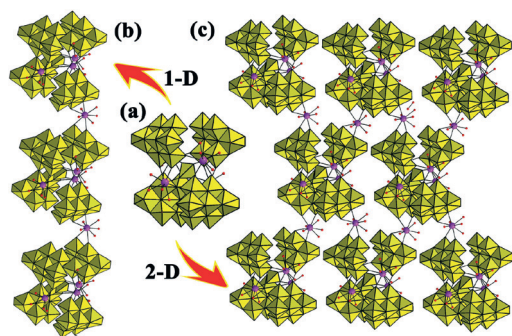


Fig. 17 (a) View of the tetra-Ln including peroxopolyoxomolybdate $[\text{RE}_4(\text{MoO}_4)(\text{H}_2\text{O})_{16}\{\text{Mo}_7\text{O}_{22}(\text{O}_2)_2\}_4]^{14-}$. (b) The 1-D chain-like structure of $[\text{H}_4\text{La}_5(\text{H}_2\text{O})_{21}(\text{MoO}_4)\{\text{Mo}_7\text{O}_{22}(\text{O}_2)_2\}_4]^{7-}$. (c) The 2-D extended architecture $[\text{H}_3\text{RE}_6(\text{H}_2\text{O})_{26}(\text{MoO}_4)\{\text{Mo}_7\text{O}_{22}(\text{O}_2)_2\}_4]^{7-}$. (WO_6 : yellow, bright green, RE: light purple, O: red).

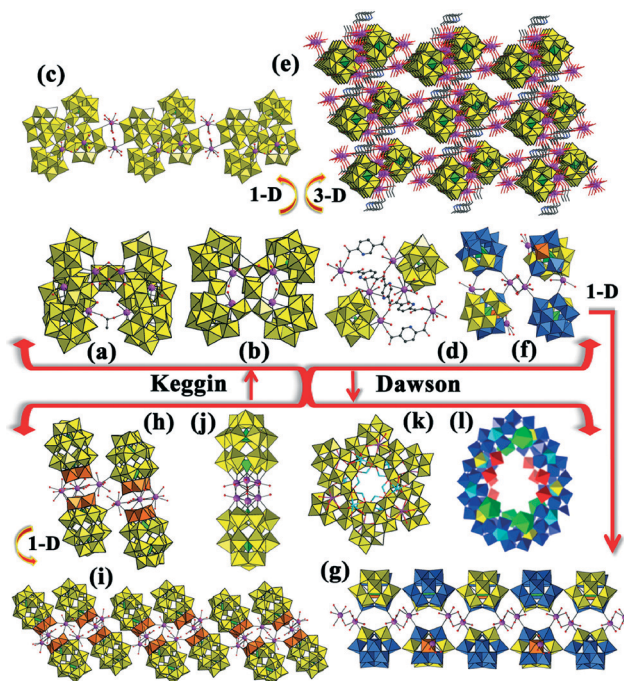


Fig. 18 (a) View of $[\text{Gd}_6\text{As}_6\text{W}_{65}\text{O}_{229}(\text{OH})_4(\text{H}_2\text{O})_{12}(\text{OAc})_2]^{38-}$. (b) View of the structural unit of $[\text{RE}_6(\text{H}_2\text{O})_x\{\text{As}_4\text{W}_{44}(\text{OH})_2(\text{proline})_2\text{O}_{151}\}]^{10-}$. (c) The 1-D chain of $[\text{RE}_6(\text{H}_2\text{O})_x\{\text{As}_4\text{W}_{44}(\text{OH})_2(\text{proline})_2\text{O}_{151}\}]^{10-}$. (d) View of the hybrid HKRECP unit of $[\text{RE}(\text{HL})(\text{L})(\text{H}_2\text{O})_6\{\text{RE}(\text{H}_2\text{L})_{0.5}(\alpha\text{-PW}_{11}\text{O}_{39}\text{H})\text{RE}(\text{H}_2\text{O})_4\}_2]$. (e) The 3-D extended architecture of $[\text{RE}(\text{HL})(\text{L})(\text{H}_2\text{O})_6\{\text{RE}(\text{H}_2\text{L})_{0.5}(\alpha\text{-PW}_{11}\text{O}_{39}\text{H})\text{RE}(\text{H}_2\text{O})_4\}_2]$. (f) View of $[(\text{GeW}_9\text{Nb}_3\text{O}_{40})_4\text{Eu}_{5.5}(\text{H}_2\text{O})_{26}]^{11.5-}$. (g) The 1-D chain architecture of $[(\text{GeW}_9\text{Nb}_3\text{O}_{40})_4\text{Eu}_{5.5}(\text{H}_2\text{O})_{26}]^{11.5-}$. (h) View of $[\text{RE}_6(\text{H}_2\text{O})_{38}(\text{P}_2\text{W}_{15}\text{Nb}_3\text{O}_{62})_4]^{18-}$. (i) The 1-D chain motif of $[\text{RE}_6(\text{H}_2\text{O})_{38}(\text{P}_2\text{W}_{15}\text{Nb}_3\text{O}_{62})_4]^{18-}$. (j) View of $[(\text{Yb}_6(\mu_6\text{-O})(\mu_3\text{-OH})_6(\text{H}_2\text{O})_6)(\alpha\text{-P}_2\text{W}_{15}\text{O}_{56})_2]^{14-}$. (k) View of $\{\text{Na}_{12}[(\alpha\text{-2-P}_2\text{W}_{17}\text{O}_{61}\text{H}_2)\text{La}(\text{H}_2\text{O})_4]_6\}^{6-}$. (l) View of the giant molybdenum blue wheel RECP $[\text{Mo}_{80}\text{V}^{\text{I}}\text{Mo}_{20}\text{V}^{\text{V}}(\text{Ce}_6)^{\text{III}}\text{O}_{306}\text{H}_{10}(\text{H}_2\text{O})_{70}]^{4-}$ (copied from ref. 17c). (WO_6 : yellow, NbO_6 : orange, W/NbO_6 : blue, XO_4 : bright green, RE: light purple, O: red, C: gray, N: blue, K: turquoise).

HKRECP units $[\text{RE}(\text{HL})(\text{L})(\text{H}_2\text{O})_6\{\text{RE}(\text{H}_2\text{L})_{0.5}(\alpha\text{-PW}_{11}\text{O}_{39}\text{H})\text{RE}(\text{H}_2\text{O})_4\}_2]$ ($\text{RE} = \text{La}^{\text{III}}, \text{Ce}^{\text{III}}, \text{H}_2\text{L} = 2,5\text{-pyridinedicarboxylic acid}$) (Fig. 18d and e) and examined their photocatalytic properties for degradation of Rhodamine-B (RhB) upon 500 W Hg lamp irradiation.⁷⁹ Liu's group reported a 1-D Nb/W mixed-addendum HKRECP $[(\text{GeW}_9\text{Nb}_3\text{O}_{40})_4\text{Eu}_{5.5}(\text{H}_2\text{O})_{26}]^{11.5-}$ (Fig. 18f and g) assembled from telephone receiver-like $\{(\text{GeW}_9\text{Nb}_3\text{O}_{40})_2\text{Eu}_2\}$ building units by sharing water ligands from adjacent Eu^{3+} cations,⁶⁹ and two isostructural hexanuclear Dawson-type RECPs (HDRECPs) with the formula unit of $[\text{RE}_6(\text{H}_2\text{O})_{38}(\text{P}_2\text{W}_{15}\text{Nb}_3\text{O}_{62})_4]^{18-}$ ($\text{RE} = \text{Eu}^{\text{III}}, \text{Ce}^{\text{III}}$) (Fig. 18h) and their 1-D chain alignment is constructed from sandwich-type tri- Nb^{V} substituted Dawson $[\text{RE}_3(\text{P}_2\text{W}_{15}\text{Nb}_3\text{O}_{62})_2]^{9-}$ fragments linked by alternative RE-O-W bridges (Fig. 18i).⁸⁰ Reviewing the history, in 2005 Hill *et al.* synthesized a sandwich POM-supported hydroxo/oxo cluster $[(\text{Yb}_6(\mu_6\text{-O})(\mu_3\text{-OH})_6(\text{H}_2\text{O})_6)(\alpha\text{-P}_2\text{W}_{15}\text{O}_{56})_2]^{14-}$ anchoring a trigonal antiprismatic hexa- Yb^{III} cluster around a $\mu_6\text{-oxo}$ atom, which was obtained from the carbonate-assisted hydrolysis of Yb^{3+} cations in the presence of the trivalent Dawson

$[\alpha\text{-P}_2\text{W}_{15}\text{O}_{56}]^{12-}$ precursor (Fig. 18j).⁷¹ Its magnetization measurements reveal the existence of intermolecular dipolar exchange interactions below 15 K.⁷¹ In 2013, Niu *et al.* reported an unprecedented HDRECP hexamer $\{\text{Na}_{12}[(\alpha_2\text{-P}_2\text{W}_{17}\text{O}_{61}\text{H}_2)\text{La}(\text{H}_2\text{O})_4]_6\}^{6-}$ (Fig. 18k) established by two trimeric $[(\alpha_2\text{-P}_2\text{W}_{17}\text{O}_{61}\text{H}_4)\text{La}(\text{H}_2\text{O})_4]_3^{9-}$ subunits linked by twelve Na^+ cations.⁸¹ Moreover, Cronin *et al.* prepared a giant $\{\text{Ce}_6\}$ molybdenum blue wheel RECP $\{\text{Mo}_{80}^{\text{VI}}\text{Mo}_{20}^{\text{V}}\text{Ce}_6^{\text{III}}\text{O}_{306}\text{H}_{10}(\text{H}_2\text{O})_{70}\}^{4-}$ (Fig. 18l) by the building block rearrangement of the tetradecameric $\{\text{Mo}_{154}\}$ archetype and the control of the architecture's curvature in solution from the addition of the Ce^{3+} cation. The wheel RECP includes 10 $\{\text{Mo}_8\}$, 4 $\{\text{Mo}_2\}$, 10 $\{\text{Mo}_1\}$, 2 $\{\text{Mo}^*\}_1$, 4 $\{\text{Ce}(\text{H}_2\text{O})_5\}$ and 2 $\{\text{Ce}(\text{H}_2\text{O})_6\}$ groups.^{17c} Furthermore, 2-D extended architectures $[\text{H}_3\text{RE}_6(\text{H}_2\text{O})_{26}(\text{MoO}_4)\{\text{Mo}_7\text{O}_{22}(\text{O}_2)_2\}_4]^{7-}$ (RE = Ce^{III} , Pr^{III} , Sm^{III} , Eu^{III} , Nd^{III}) (Fig. 17c) constructed from hexa-RE containing polyoxomolybdate units were also reported.⁷⁷

2.7 Octanuclear RECPs

Historically, the first octa- Gd^{III} bridging polytungstoarsenate nanocluster $[\text{Gd}_8\text{As}_{12}\text{W}_{124}\text{O}_{432}(\text{H}_2\text{O})_{22}]^{60-}$ (Fig. 19a) was reported by Hussain *et al.* in 2009 by a one-pot reaction starting from a 1 : 2 ratio of the divacant POM $\text{K}_{14}[\text{As}_2\text{W}_{19}\text{O}_{67}(\text{H}_2\text{O})]$ and $\text{Gd}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$ in a $\text{NaOAc}/\text{CH}_3\text{COOH}$ buffer at pH 4.7.⁸² This nanocluster is formed by two equivalent $[\text{Gd}_4\text{As}_6\text{W}_{62}\text{O}_{216}(\text{H}_2\text{O})_{11}]^{30-}$ (Fig. 19b) units related by an inversion center and the $[\text{Gd}_4\text{As}_6\text{W}_{62}\text{O}_{216}(\text{H}_2\text{O})_{11}]^{30-}$ unit can be visualized as a fusion of two equally charged trimeric units

$[\text{Gd}_2\text{As}_3\text{W}_{31}\text{O}_{108}(\text{H}_2\text{O})_6]^{15-}$ connected *via* W–O–W and Gd–O–W linkers. Another octanuclear RE-containing polytungstoarsenate hybrid $[\text{Tb}_8(\text{pic})_6(\text{H}_2\text{O})_{22}(\text{B-}\beta\text{-AsW}_8\text{O}_{30})_4(\text{WO})_2(\text{pic})_6]^{12-}$ (Fig. 19c) was also reported by Boskovic and collaborators through the reaction of the preformed precursor $[\text{As}_2\text{W}_{19}\text{O}_{67}(\text{H}_2\text{O})]^{14-}$.³⁸ Its photophysical measurements demonstrate the importance of the smaller Tb–O–W angles provided by edge- rather than corner-sharing in limiting the quenching of the organic-ligand-sensitized terbium luminescence by the POM ligands.³⁸ In 2013, by precise control of the one-pot reaction, the first Ce^{III} -stabilized RECP with Se^{IV} or Te^{IV} heteroatoms $[\{(\text{XO}_3)\text{W}_{10}\text{O}_{34}\}_8\{\text{Ce}_8(\text{H}_2\text{O})_{20}\}(\text{WO}_2)_4(\text{W}_4\text{O}_{12})]^{48-}$ (X = Se^{IV} or Te^{IV}) (Fig. 19d) was successfully separated by Wang *et al.*, which is an octameric aggregate constructed from eight $\{(\text{XO}_3)\text{W}_{10}\text{Ce}\}$ units, four $\{\text{WO}_6\}$ octahedra and a $\{\text{W}_4\}$ unit.^{17b} Alternatively, this octameric aggregate can be visualized as a fusion of two half-units of $[\{(\text{XO}_3)\text{W}_{10}\text{O}_{34}\}_4\{\text{Ce}_4(\text{H}_2\text{O})_{10}\}(\text{WO}_2)_2(\text{W}_2\text{O}_6)]^{24-}$ (Fig. 19e). Moreover, their electrochemical activities and solution behavior were investigated.^{17b} In 2014, Reinoso *et al.* reported a family of octanuclear RECP tetramers $[\{\text{RE}_4(\text{H}_2\text{O})_5(\text{GeW}_{10}\text{O}_{38})_2\}_2]^{24-}$ (RE = Ho^{III} , Er^{III} , Tm^{III} , Yb^{III} , Lu^{III}) (Fig. 19f and g), which can be assembled by the chiral $[\text{RE}_4(\text{H}_2\text{O})_6(\beta\text{-GeW}_{10}\text{O}_{38})_2]^{12-}$ dimers when the Cs^+ cation is present.⁶⁸ More interestingly, two types of tetramers ($\beta\beta\text{-}[\{\text{RE}_4(\text{H}_2\text{O})_5(\text{GeW}_{10}\text{O}_{38})_2\}_2]^{24-}$ and $\alpha\beta\text{-}[\{\text{RE}_4(\text{H}_2\text{O})_5(\text{GeW}_{10}\text{O}_{38})_2\}_2]^{24-}$) coexist in the solid state. Moreover, electronic spray ion (ESI) mass spectrometry and ^{183}W NMR spectroscopy reveal that $[\{\text{RE}_4(\text{H}_2\text{O})_5(\text{GeW}_{10}\text{O}_{38})_2\}_2]^{24-}$ tetramers can disassemble into $[\text{RE}_4(\text{H}_2\text{O})_6(\beta\text{-GeW}_{10}\text{O}_{38})_2]^{12-}$ dimers upon dissolution.⁶⁸ In the same year, Hussain *et al.* isolated a series of tetra-RE substituted tetrameric tungstophosphates $[(\text{RE}_2\text{PW}_{10}\text{O}_{38})_4(\text{W}_3\text{O}_8)(\text{OH})_4(\text{H}_2\text{O})_2]^{26-}$ [RE = Y^{III} , Sm^{III} , Eu^{III} , Gd^{III} , Tb^{III} , Dy^{III} , Ho^{III} , Er^{III} , Tm^{III} , Yb^{III}] (Fig. 19h) by reaction of the divacant $[\text{P}_2\text{W}_{19}\text{O}_{69}(\text{H}_2\text{O})]^{14-}$ poly-anion with $\text{Ln}(\text{NO}_3)_3 \cdot n\text{H}_2\text{O}$ salts in potassium chloride solution.⁸³ The backbone of $[(\text{RE}_2\text{PW}_{10}\text{O}_{38})_4(\text{W}_3\text{O}_8)(\text{OH})_4(\text{H}_2\text{O})_2]^{26-}$ is built by four $[\text{A-}\alpha\text{-PW}_9\text{O}_{34}]^{9-}$ fragments, eight RE cations and seven additional tungsten atoms in a $[\text{RE}_8\text{W}_7\text{O}_{30}]^{6+}$ group and can be also viewed as two packman-shaped asymmetric entities (Fig. 19i) that are symmetry-related by a C_2 axis through the central tungsten atom.

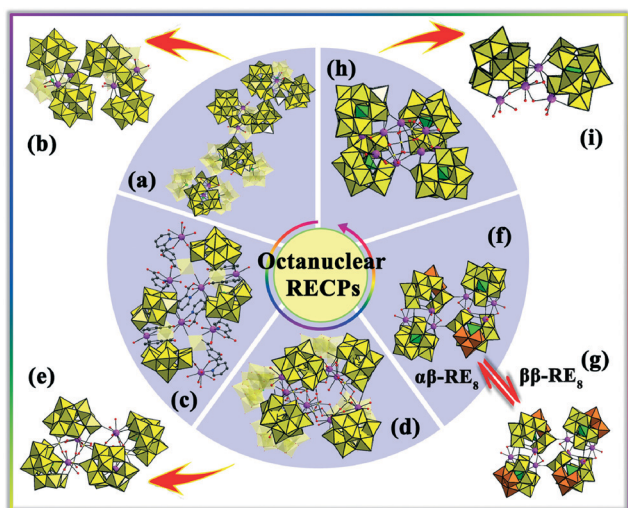


Fig. 19 (a) View of $[\text{Gd}_8\text{As}_{12}\text{W}_{124}\text{O}_{432}(\text{H}_2\text{O})_{22}]^{60-}$. (b) View of $[\text{Gd}_4\text{As}_6\text{W}_{62}\text{O}_{216}(\text{H}_2\text{O})_{11}]^{30-}$. (c) View of $[\text{Tb}_8(\text{pic})_6(\text{H}_2\text{O})_{22}(\text{B-}\beta\text{-AsW}_8\text{O}_{30})_4(\text{WO})_2(\text{pic})_6]^{12-}$. (d) View of $[\{(\text{XO}_3)\text{W}_{10}\text{O}_{34}\}_8\{\text{Ce}_8(\text{H}_2\text{O})_{20}\}(\text{WO}_2)_4(\text{W}_4\text{O}_{12})]^{48-}$. (e) The half-unit of $[\{(\text{XO}_3)\text{W}_{10}\text{O}_{34}\}_4\{\text{Ce}_4(\text{H}_2\text{O})_{10}\}(\text{WO}_2)_2(\text{W}_2\text{O}_6)]^{24-}$. (f) View of $\alpha\beta\text{-}[\{\text{RE}_4(\text{H}_2\text{O})_5(\text{GeW}_{10}\text{O}_{38})_2\}_2]^{24-}$ ($\alpha\beta\text{-RE}_8$). (g) View of $\beta\beta\text{-}[\{\text{RE}_4(\text{H}_2\text{O})_5(\text{GeW}_{10}\text{O}_{38})_2\}_2]^{24-}$ ($\beta\beta\text{-RE}_8$). (h) The octanuclear RECPs $[(\text{RE}_2\text{PW}_{10}\text{O}_{38})_4(\text{W}_3\text{O}_8)(\text{OH})_4(\text{H}_2\text{O})_2]^{26-}$. (i) The packman-shaped asymmetric entity of $[(\text{RE}_2\text{PW}_{10}\text{O}_{38})_4(\text{W}_3\text{O}_8)(\text{OH})_4(\text{H}_2\text{O})_2]^{26-}$. To show the structures more clearly, some polyhedra are omitted. (WO_6 : yellow and orange, XO_4 : bright green, RE: light purple, O: red, C: gray, N: blue).

2.8 Decanuclear RECPs

In 2009, Boskovic's group performed one-pot reactions of the trivalent precursor $\text{Na}_9[\text{B-}\alpha\text{-AsW}_9\text{O}_{33}]$ and $\text{YbCl}_3 \cdot 6\text{H}_2\text{O}$ in a 1 : 3 mole ratio in a NaAc-HAc buffer at pH 4.7 and obtained a decanuclear RECP $[\text{Yb}_{10}\text{As}_{10}\text{W}_{88}\text{O}_{308}(\text{OH})_8(\text{H}_2\text{O})_{28}(\text{OAc})_4]^{40-}$.^{17a} The giant decanuclear RECP cluster is composed of eight $[\text{B-}\alpha\text{-AsW}_9\text{O}_{33}]^{9-}$ subunits, two pyramidal AsO_3 groups, twelve WO_6 octahedra, two edge-shared and acetate-bridged W_2O_{10} groups and ten Yb^{3+} cations (Fig. 20a).^{17a} Its structural novelty partly arises from the incorporation of additional bridging acetate ligands that can bridge both Yb and W centers. The variable temperature magnetic susceptibility study indicates that the intramolecular magnetic exchange interactions

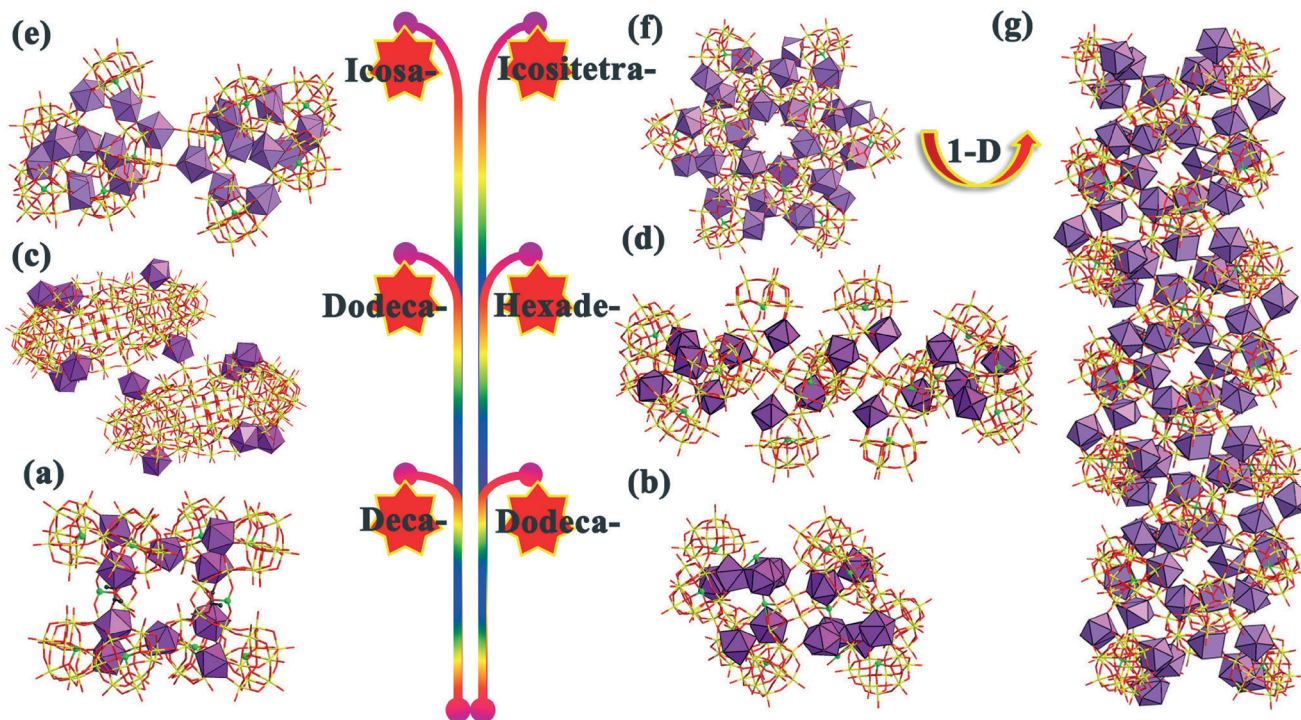


Fig. 20 (a) The decanuclear RECP $[\text{Yb}_{10}\text{As}_{10}\text{W}_{88}\text{O}_{308}(\text{OH})_8(\text{H}_2\text{O})_{28}(\text{OAc})_4]^{40-}$. (b) The dodecanuclear RECP $\{[(\text{SeO}_3)_4\text{W}_{10}\text{O}_{34}]_8\{\text{Ce}_8(\text{H}_2\text{O})_{20}\}(\text{WO}_2)_4\{(\text{W}_4\text{O}_6)\text{Ce}_4(\text{H}_2\text{O})_{14}(\text{SeO}_3)_4(\text{NO}_3)_2\}\}^{34-}$. (c) The dodecanuclear RECP $\{\text{Mo}_{80}^{\text{VI}}\text{Mo}_{20}^{\text{V}}\text{Ce}_6^{\text{III}}\text{O}_{306}\text{H}_{10}(\text{H}_2\text{O})_{70}\}_2^{8-}$. (d) The hexadecanuclear RECP $[\text{RE}_{16}\text{As}_{16}\text{W}_{164}\text{O}_{576}(\text{OH})_8(\text{H}_2\text{O})_{42}]^{80-}$. (e) The icosanuclear RECP $[\text{Ce}_{20}\text{Ge}_{10}\text{W}_{100}\text{O}_{376}(\text{OH})_4(\text{H}_2\text{O})_{30}]^{56-}$. (f) The icositetranuclear RECP $[\text{K}\langle\text{K}_7\text{Ce}_{24}\text{Ge}_{12}\text{W}_{120}\text{O}_{456}(\text{OH})_{12}(\text{H}_2\text{O})_{64}\rangle]^{52-}$. (g) The 1-D alignment of $[\text{K}\langle\text{K}_7\text{Ce}_{24}\text{Ge}_{12}\text{W}_{120}\text{O}_{456}(\text{OH})_{12}(\text{H}_2\text{O})_{64}\rangle]^{52-}$. (REO_x: light purple).

within Yb^{3+} cations *via* the Yb–O–W–O–Yb pathways are negligible.^{17a}

2.9 Dodecanuclear RECPs

In the past decade, only two dodeca-Ce^{III} containing POMs appeared. In 2013, Wang *et al.* separated an unprecedented dodeca-Ce^{III} substituted selenotungstate aggregate $\{[(\text{SeO}_3)_4\text{W}_{10}\text{O}_{34}]_8\{\text{Ce}_8(\text{H}_2\text{O})_{20}\}(\text{WO}_2)_4\{(\text{W}_4\text{O}_6)\text{Ce}_4(\text{H}_2\text{O})_{14}(\text{SeO}_3)_4(\text{NO}_3)_2\}\}^{34-}$ (Fig. 20b) by the one-pot reaction of $\text{Na}_2\text{WO}_4 \cdot 2\text{H}_2\text{O}$, Na_2SeO_3 and $\text{Ce}(\text{NO}_3)_3 \cdot 6\text{H}_2\text{O}$.^{17b} This polyoxoanionic skeleton consists of eight Keggin-type $\{(\text{SeO}_3)_4\text{W}_{10}\text{Ce}\}$ derivative segments, four $\{\text{WO}_6\}$ octahedra, a folded-planar-like $\{\text{W}_4\}$ group and two $\{\text{Ce}_2(\text{NO}_3)(\text{SeO}_3)_2\}$ segments. Moreover, four Ce^{3+} cations in $\{\text{Ce}_2(\text{NO}_3)(\text{SeO}_3)_2\}$ segments are well connected with the folded-planar-like $\{\text{W}_4\}$ group by SeO_3^{2-} and NO_3^- linkers. The transmission electron microscopy (TEM) study indicates that its single POAs assemble into intact uniform-sized inorganic hollow spheres in dilute water/acetone solution. In 2014, Cronin *et al.* reported a gigantic Ce₁₂-doped decameric molybdenum blue wheel RECP $\{\text{Mo}_{80}^{\text{VI}}\text{Mo}_{20}^{\text{V}}\text{Ce}_6^{\text{III}}\text{O}_{306}\text{H}_{10}(\text{H}_2\text{O})_{71}\}_2^{8-}$ (simplified as $\{\text{Mo}_{200}\text{Ce}_{12}\}$) (Fig. 20c), which comprises two interconnected $\{\text{Mo}_{80}^{\text{VI}}\text{Mo}_{20}^{\text{V}}\text{Ce}_6^{\text{III}}\text{O}_{306}\text{H}_{10}(\text{H}_2\text{O})_{70}\}_2^{4-}$ $\{\text{Mo}_{100}\text{Ce}_6\}$ clusters through two Ce^{3+} cations.^{17c} Intriguingly, the dimeric cluster $\{\text{Mo}_{200}\text{Ce}_{12}\}$ can be transformed directly to monomeric species $\{\text{Mo}_{100}\text{Ce}_6\}$ upon addition of a potassium salt.^{17c} This

controllable strategy to synthesize gigantic POMs incorporating “active sites” in their anionic scaffolds allows them to be used as “molecular synthons” for higher-order assembly.

2.10 Hexadecanuclear RECPs

Based on a self-assembly process of the precursor $[\text{As}_2\text{W}_{19}\text{O}_{67}(\text{H}_2\text{O})]^{14-}$ and oxophilic RE cations, a neoteric class of hexadecanuclear RE substituted arsenotungstates $[\text{RE}_{16}\text{As}_{16}\text{W}_{164}\text{O}_{576}(\text{OH})_8(\text{H}_2\text{O})_{42}]^{80-}$ (RE = Eu^{III}, Gd^{III}, Tb^{III}, Dy^{III}, Ho^{III}) were isolated in alkali salt solutions (Fig. 20d).^{17d} This POA can be seen as a combination of two identical $[\text{RE}_8\text{As}_8\text{W}_{82}\text{O}_{288}(\text{OH})_4(\text{H}_2\text{O})_{21}]^{40-}$ asymmetric subunits related by an inversion centre. Different from the reported $[\text{Ce}_{16}\text{As}_{12}(\text{H}_2\text{O})_{36}\text{W}_{148}\text{O}_{524}]^{76-}$ POA,⁸⁴ two kinds of building blocks type-1- $[(\text{AsW}_9\text{O}_{33})(\text{WO}_2)(\text{OH})_2]^{16-}$ and type-2- $[(\text{AsW}_9\text{O}_{33})_2\text{W}_3\text{O}_5(\text{OH})_5]^{15-}$ coexist in the skeleton of $[\text{RE}_8\text{As}_8\text{W}_{82}\text{O}_{288}(\text{OH})_4(\text{H}_2\text{O})_{21}]^{40-}$ with an arrangement mode of type-1-type-2-type1-type2.

2.11 Icosanuclear RECPs

In 2007, Kortz's group obtained the 20-cerium(III)-containing 100-tungsto-10-germanate RECP $[\text{Ce}_{20}\text{Ge}_{10}\text{W}_{100}\text{O}_{376}(\text{OH})_4(\text{H}_2\text{O})_{30}]^{56-}$ by the conventional reaction of the trivalent precursor $\text{Na}_{10}[\alpha\text{-GeW}_9\text{O}_{34}]$ and $\text{CeCl}_3 \cdot 7\text{H}_2\text{O}$ in a 1:1 ratio in water (pH = 5.0) (Fig. 20e).^{17e} This POA can be described as a dimeric entity composed of two half units of

[Ce₁₀Ge₅W₅₀O₁₈₈(OH)₂(H₂O)₁₅]²⁸⁻ bridged by two Ce–O(W) bonds. Each half unit contains five unprecedented dilacunar Keggin {β(4,11)-GeW₁₀O₃₈} subunits connected asymmetrically by ten Ce³⁺ ions, leading to an asymmetric assembly with a C₁ symmetry. Notably, this work demonstrates that large RE cations are excellent linkers for integrating lacunar POM building blocks together to construct specific and giant assemblies.

2.12 Icositetranuclear RECPs

Inspired by the isolation of icosanuclear RECPs based on trivacant [α-GeW₉O₃₄]¹⁰⁻ building blocks, Reinoso and collaborators performed a simple one-pot reaction of Na₂WO₄·2H₂O, GeO₂, and Ce(NO₃)₃·6H₂O and isolated the first giant crown-shaped ring icositetranuclear RECP [KCK₇Ce₂₄Ge₁₂W₁₂₀O₄₅₆(OH)₁₂(H₂O)₆₄]⁵²⁻ (Fig. 20f),^{17f} which can be regarded as the product of the K⁺-directed self-assembly of twelve di-Ce^{III} substituted Keggin [Ce₂GeW₁₀O₃₈]⁶⁻ subunits. This crown-shaped POA not only comprises a unique Ce₆O₄₂ central ring showing Ce^{III}–Ce^{III} antiferromagnetic interactions in which a K⁺ ion is captured by internal H₂O molecules, but also demonstrates a central cavity available for ion encapsulation in an inorganic analogue of the crown ether. In addition, adjacent [KCK₇Ce₂₄Ge₁₂W₁₂₀O₄₅₆(OH)₁₂(H₂O)₆₄]⁵²⁻ units can be combined together by Ce–O–W bridges to propagate the 1-D alignment (Fig. 20g).

3. Applications

It is well known that the orbitally degenerate ground states of almost all the RE ions, apart from Gd^{III} and Eu^{II} ions with the f⁷ electron configuration, are split by spin–orbit coupling and the crystal field effect. However, due to the internal nature of 4f orbitals of RE ions, the contribution of spin–orbit coupling is larger than that of the crystal-field effect to some extent, which not only greatly influences the magnetic properties of RE ions, but also provides a significant reason why RE-containing compounds hold an important position in the magnetism field.^{85,86} In the past decade, magnetic investigations on RECPs have been also performed by some researchers. The related summary is listed in Table 1,^{7a,17b,d,f,19,21b,22,33,36,49,59–63,68,73,76,79} and several selected examples are discussed below.

In 2013, Mizuno *et al.* synthesized a class of heterodinuclear RECPs TBA₈H₄[{Ln(μ₂-OH)₂Ln'}(γ-SiW₁₀O₃₆)₂] (Ln = Dy³⁺; Ln' = Eu³⁺, Yb³⁺, Lu³⁺) (Fig. 4b) by the stepwise incorporation of two types of Ln cations into the vacant sites of lacunar [γ-SiW₁₀O₃₆]⁸⁻ fragments and investigated their magnetic properties.²² Alternating-current (ac) measurements under zero external field indicate that TBA₈H₄[{Dy(μ₂-OH)₂Eu}(γ-SiW₁₀O₃₆)₂] (DyEu) and TBA₈H₄[{Dy(μ₂-OH)₂Lu}(γ-SiW₁₀O₃₆)₂] (DyLu) exhibit temperature- and frequency-dependent χ'_m and χ''_m signals, explicitly revealing the SMM behavior. However, weak ac signals for TBA₈H₄[{Dy(μ₂-OH)₂Yb}(γ-SiW₁₀O₃₆)₂] (DyYb) were seen under zero external

field, which may be derived from the strong quantum tunneling of magnetization that was caused by the adjacent Yb³⁺ ion. Thus, in order to inhibit the quantum tunneling of magnetization, the ac magnetic susceptibilities of DyYb were measured under an external field of 1800 Oe; at this time, the temperature- and frequency-dependent χ'_m and χ''_m signals were observed. Furthermore, their relaxation times (τ) were obtained by the frequency dependence of the χ''_m signals. Using Arrhenius' law (τ = τ₀exp(ΔE/k_BT)) to fit the plots of ln τ versus 1/T, energy barriers for magnetization reversal (ΔE/k_B) of 1.8 × 10⁻⁷ s for DyEu, 8.2 × 10⁻⁷ s for DyYb, and 1.9 × 10⁻⁶ s for DyLu were afforded. The energy barriers increase in the order DyLu < DyYb < DyEu with an increase in the ionic radii of Ln' ions, which suggests that their energy barriers for magnetization reversal can be tuned by adjusting the coordination geometry and anisotropy of the Dy³⁺ ion and by tuning the adjacent Ln³⁺ ion in the heterodinuclear [Dy(μ₂-OH)₂Ln']⁴⁺ cores.

In 2011, Patzke *et al.* measured the variable-temperature magnetic susceptibility of [Gd₁₆As₁₆W₁₆₄O₅₇₆(OH)₈(H₂O)₄₂]⁸⁰⁻ from 5 K to 300 K in an applied magnetic field of 2000 Oe with respect to the presence of sixteen Gd³⁺ centers (Fig. 21).^{17d} As it is a paramagnetic system without orbital contribution, the curve of magnetic susceptibility can be fitted by using the following equation:

$$\chi = [N\beta^2 g^2 S(S + 1)/3kT] + \chi_{\text{dia}}$$

Here, *g* is defined as 2.0, the resulting χ_{dia} value is 0.0034 emu mol⁻¹ (χ_{dia} denotes the diamagnetic correction) and the resulting spin value *S* was 3.468. The χ_{dia} value is in good agreement with the value of diamagnetic susceptibility calculated from Pascal's constants. The spin value corresponds to the spin of non-interacting Gd³⁺ ions (*S* = 7/2) and is consistent with the large Gd–Gd distances from 5.9 to 6.3 Å because of the indirect linking through O–W–O bridges.

On the other hand, RE-doped materials are of great interest for a wide range of potential applications in light-emitting diodes, tunable lasers, sensory probes, fluorescent tubes, plasma displays, *etc.*^{87–90} These unique application functionalities can be ascribed to the narrow emission and high color purity generated from the RE ions.⁹¹ Additionally, RE ions are often subjected to weak light absorption owing to the forbidden f–f transitions, entailing the direct excitation of RE ions to be very inefficient if high-power laser excitation isn't used. This difficulty can be surmounted by luminescence sensitization or the antenna effect.^{91a,92} Thus, the photoluminescence properties of some RECPs have been also investigated at room temperature (Table 1).^{21,39,44,51,59,61,68,69,73,77,78,80} For example, Zhao and co-workers probed the solid-state photoluminescence behavior of Na₁₀[Tb₂(C₂O₄)(H₂O)₄](OH)W₄O₁₆·30H₂O at room temperature.⁷³ The emission spectrum upon excitation at 369 nm exhibits four groups of bands at 490, 495 nm; 543, 545 nm; 584, 588 nm; and 621 nm, which can be assigned to the ⁵D₄ → ⁷F₆, ⁵D₄ → ⁷F₅, ⁵D₄ → ⁷F₄, and ⁵D₄ → ⁷F₃ transitions of

Table 1 Summary of applications of some RECPs

Formula	RE	Properties	Ref.
$\text{Na}_{15.69}\text{Cs}_{15.31}\text{H}_9[\text{Yb}_{10}\text{As}_{10}\text{W}_{88}\text{O}_{308}(\text{OH})_8(\text{H}_2\text{O})_{28}(\text{OAc})_4]\cdot 84\text{H}_2\text{O}$	Yb^{3+}	The decrease in $\chi_m T$ with decreasing temperature is due to the thermal depopulation of higher multiplet states	17a
$\text{K}_{32}\text{Na}_{16}[\{(\text{SeO}_3)\text{W}_{10}\text{O}_{34}\}_8\{\text{Ce}_8(\text{H}_2\text{O})_{20}\}(\text{WO}_2)_4(\text{W}_4\text{O}_{12})]\cdot 81\text{H}_2\text{O}$	Ce^{3+}	The dominant antiferromagnetic interactions	17b
$\text{Na}_{55}\text{K}_{14}\text{Cs}_{11}[\text{Gd}_{16}\text{As}_{16}\text{W}_{164}\text{O}_{576}(\text{OH})_8(\text{H}_2\text{O})_{42}]\cdot n\text{H}_2\text{O}$ ($n \approx 220$)	Gd^{3+}	The single ion behavior	17d
$\text{Na}_{40}\text{K}_6[\text{Ni}(\text{H}_2\text{O})_6]_3[\text{K}-\text{K}-\text{Ce}_2\text{Ge}_{12}\text{W}_{120}\text{O}_{456}(\text{OH})_{12}(\text{H}_2\text{O})_{64}]\cdot n\text{H}_2\text{O}$ ($n \approx 178$)	Ce^{3+}	The antiferromagnetic interactions	17f
$[\text{Sm}(\text{H}_2\text{O})_6]_{0.25}[\text{Sm}(\text{H}_2\text{O})_5]_{0.25}\text{H}_{0.5}\{\text{Sm}(\text{H}_2\text{O})_7[\text{Sm}(\text{H}_2\text{O})_2(\text{DMSO})(\alpha\text{-SiW}_{11}\text{O}_{39})]\}_2\cdot 4.5\text{H}_2\text{O}$	Sm^{3+}	The coexistence of strong spin-orbit coupling interactions and very weak ferromagnetic responses	20e
$\text{TBA}_8\text{H}_4\{\{\text{RE}(\mu_2\text{-OH})_2\text{RE}'\}(\gamma\text{-SiW}_{10}\text{O}_{36})_2\}$	$\text{RE} = \text{Dy}^{3+},$ $\text{RE}' = \text{Eu}^{3+},$ $\text{Yb}^{3+}, \text{Lu}^{3+}$	The single molecule magnet behavior	22
$[(\text{CH}_3)_4\text{N}]_6\{(\alpha\text{-PW}_{11}\text{O}_{39}\text{H})\text{Nd}(\text{H}_2\text{O})_3\}_2\}_3 \cdot 8\text{H}_2\text{O}[(\text{CH}_3)_4\text{N}]_{10}\{(\alpha\text{-PW}_{11}\text{O}_{39})\text{Sm}(\text{H}_2\text{O})(\eta^7, \mu\text{-}1, 1)\text{-CH}_3\text{COO}\}_2\}_3 \cdot 6\text{H}_2\text{O}$	$\text{Nd}^{3+}, \text{Sm}^{3+}$	The coexistence of the spin-orbit coupling interactions and weak antiferromagnetic exchange interactions	33
$[\text{C}(\text{NH}_2)_3]_{11}[\text{Dy}_2(\text{Hcit})_2(\text{AsW}_{10}\text{O}_{38})]\cdot 9\text{H}_2\text{O}$	Dy^{3+}	The weak antiferromagnetic coupling interactions and the thermal depopulation of the Dy^{3+} excited states	36
$\text{Na}_{22}[(\text{BiW}_9\text{O}_{33})_4(\text{WO}_3)\{\text{Bi}_6(\mu_3\text{-O})_4(\mu_2\text{-OH})_3\}(\text{Pr}_3(\text{H}_2\text{O})_6\text{CO}_3)]\cdot 95\text{H}_2\text{O}$	Pr^{3+}	The progressive depopulation of excited Stark sublevels of the Pr^{3+} ions at low temperature and the weak antiferromagnetic interactions	59
$\text{K}_{13}\text{H}_4\text{Li}[\text{Ho}_2(\text{C}_4\text{H}_4\text{O}_6)(\text{C}_4\text{H}_2\text{O}_6)(\text{AsW}_9\text{O}_{33})_2]\cdot 28\text{H}_2\text{O}$	Ho^{3+}	The progressive depopulation of excited Stark sublevels of the Ho^{3+} ions at low temperature and the weak antiferromagnetic interactions	62
$(\text{HDABCO})_8\text{H}_5\text{Li}_8[\text{Tb}_4\text{As}_5\text{W}_{40}\text{O}_{144}(\text{H}_2\text{O})_{10}(\text{gly})_2]_3\cdot 25\text{H}_2\text{O}$	Tb^{3+}	The single molecule magnet behavior	63
$\text{Na}_{12}[\text{Dy}_4(\text{H}_2\text{O})_6(\beta\text{-GeW}_{10}\text{O}_{38})_2] \approx 44\text{H}_2\text{O}$	Dy^{3+}	The single molecule magnet behavior	68
$\text{Na}_{10}[\text{Eu}_2(\text{C}_2\text{O}_4)(\text{H}_2\text{O})_4(\text{OH})\text{W}_4\text{O}_{16}]_2\cdot 30\text{H}_2\text{O}$	Eu^{3+}	The decline in $\chi_m T$ upon cooling prevalingly originates from the progressive depopulation of the excited state of Eu^{3+} cations	73
$\text{K}_4\text{Na}_{16}[\text{Ho}(\text{C}_2\text{O}_4)\text{W}_5\text{O}_{18}]_4\cdot 60\text{H}_2\text{O}$	Ho^{3+}	The antiferromagnetic coupling interactions within Ho^{III} centers and thermal depopulation of the Stark sublevels of the Ho^{3+} cation	73
$[\text{CeK}(\text{H}_2\text{O})_{12}][\text{Ce}(\text{H}_2\text{O})_6]_2[(\text{H}_2\text{O})_4\text{CeBW}_{11}\text{O}_{39}\text{H}]_2\cdot 20\text{H}_2\text{O}$	Ce^{3+}	The decline in $\chi_m T$ upon cooling is due to the depopulation of the higher Stark levels of the Ce^{3+} ions	76a
$\text{KCe}[(\text{H}_2\text{O})_6\text{Ce}]_2[(\text{H}_2\text{O})_4\text{CeSiW}_{11}\text{O}_{39}]_2\cdot 40\text{H}_2\text{O}$	Ce^{3+}	The decline in $\chi_m T$ upon cooling is due to the depopulation of the higher Stark levels of the Ce^{3+} ions	76b
$[\text{Ce}(\text{HL})(\text{L})(\text{H}_2\text{O})_6\{\text{Ce}(\text{H}_2\text{L})_{0.5}(\alpha\text{-PW}_{11}\text{O}_{39}\text{H})\text{Ce}(\text{H}_2\text{O})_4\}]_2\cdot 12\text{H}_2\text{O}$ ($\text{H}_2\text{L} = 2,5\text{-pyridine dicarboxylic acid}$)	Ce^{3+}	The antiferromagnetism coupling interactions	79
$\text{K}_{11}[\text{Eu}(\text{PW}_{11}\text{O}_{39})_2]\cdot x\text{H}_2\text{O}$	Eu^{3+}	Red photoluminescence Excitation peak: 460 nm Emission peaks: $^5\text{D}_0 \rightarrow ^7\text{F}_0$ (582 nm), $^5\text{D}_0 \rightarrow ^7\text{F}_1$ (596 nm), $^5\text{D}_0 \rightarrow ^7\text{F}_2$ (616 nm), $^5\text{D}_0 \rightarrow ^7\text{F}_3$ (652 nm) and $^5\text{D}_0 \rightarrow ^7\text{F}_4$ (704 nm)	21a
$\text{Na}_4\text{K}_8\{[\text{Tb}(\alpha\text{-SiW}_{11}\text{O}_{39})(\text{H}_2\text{O})]_2(\mu\text{-CH}_3\text{COO})_2\}\cdot 22\text{H}_2\text{O}$	Tb^{3+}	Green photoluminescence Excitation peak: 330 nm Emission peaks: $^5\text{D}_4 \rightarrow ^7\text{F}_5$ (546 nm), $^5\text{D}_4 \rightarrow ^7\text{F}_4$ (584 nm) and $^5\text{D}_4 \rightarrow ^7\text{F}_3$ (623 nm)	21b
$\text{KNa}_3[\text{HPro}]_7[\text{Sm}(\alpha\text{-PW}_{11}\text{O}_{39})_2]\cdot \text{Pro}\cdot 18\text{H}_2\text{O}$	Sm^{3+}	Excitation peak: 410 nm Emission peaks: $^4\text{G}_{5/2} \rightarrow ^6\text{H}_{5/2}$ (555 nm), $^4\text{G}_{5/2} \rightarrow ^6\text{H}_{7/2}$ (595 nm) and $^4\text{G}_{5/2} \rightarrow ^6\text{H}_{9/2}$ (620 nm)	21c
$\text{K}_4\text{Li}_4\text{H}_4[\text{Tb}_8(\text{pic})_6(\text{H}_2\text{O})_{22}(\text{B}\text{-}\beta\text{-AsW}_8\text{O}_{30})_4(\text{WO}_2)(\text{pic})_6]\cdot 58\text{H}_2\text{O}$	Tb^{3+}	Green photoluminescence Excitation peak: 275 nm Emission peaks: $^5\text{D}_4 \rightarrow ^7\text{F}_6$ (492 nm), $^5\text{D}_4 \rightarrow ^7\text{F}_5$ (544 nm), $^5\text{D}_4 \rightarrow ^7\text{F}_4$ (583 nm) and $^5\text{D}_4 \rightarrow ^7\text{F}_3$ (623 nm)	39
$(\text{H}_2\text{bpy})_2[\text{Eu}_2(\text{H}_2\text{O})_9(\alpha_2\text{-P}_2\text{W}_{17}\text{O}_{61})]\cdot 5\text{H}_2\text{O}$	Eu^{3+}	Excitation peak: 398 nm Emission peaks: $^5\text{D}_0 \rightarrow ^7\text{F}_0$ (578 nm), $^5\text{D}_0 \rightarrow ^7\text{F}_1$ (591 nm), $^5\text{D}_0 \rightarrow ^7\text{F}_2$ (648 nm) and $^5\text{D}_0 \rightarrow ^7\text{F}_3$ (696 nm)	44
$[\text{Na}_2(\text{H}_2\text{O})_2\text{K}_5(\text{H}_2\text{O})_6][\text{H}_6\text{Ce}_2(\text{H}_2\text{O})\text{ClW}_{15}\text{O}_{54}]\cdot 6\text{H}_2\text{O}$	Ce^{3+}	Blue photoluminescence Excitation peak: 264 nm Emission peaks: $5d \rightarrow ^2\text{F}_{5/2}$ (488 nm)	51
$\text{Na}_{22}[(\text{BiW}_9\text{O}_{33})_4(\text{WO}_3)\{\text{Bi}_6(\mu_3\text{-O})_4(\mu_2\text{-OH})_3\}(\text{Pr}_3(\text{H}_2\text{O})_6\text{CO}_3)]\cdot 95\text{H}_2\text{O}$	Pr^{3+}	Excitation peak: 230 nm Emission peaks: $^1\text{S}_0 \rightarrow ^1\text{I}_6$ (411 nm), $^3\text{H}_4 \rightarrow ^1\text{D}_2$ (464 nm), f-f transitions of $^3\text{P}_0 \rightarrow ^3\text{H}_4$ (480 nm, 492 nm)	59
$\text{Na}_4\text{Cs}_3\text{DyH}[\text{Dy}_2(\text{H}_2\text{O})_{6.5}(\text{C}_2\text{H}_4\text{O}_2)_{0.5}\text{Si}_2\text{W}_{18}\text{O}_{66}]\text{Cl}_3\cdot 17\text{H}_2\text{O}$	Dy^{3+}	Excitation peak: 357 nm Emission peaks: $^4\text{F}_{9/2} \rightarrow ^6\text{H}_{15/2}$ (479 nm) and $^4\text{F}_{9/2} \rightarrow ^6\text{H}_{13/2}$ (574 nm)	61
$\text{Na}_{12}[\text{Dy}_4(\text{H}_2\text{O})_6(\beta\text{-GeW}_{10}\text{O}_{38})_2] \approx 44\text{H}_2\text{O}$	Dy^{3+}	Yellow photoluminescence Excitation peak: 325 nm Emission peaks: $^4\text{F}_{9/2} \rightarrow ^6\text{H}_{15/2}$ (485 nm), $^4\text{F}_{9/2} \rightarrow ^6\text{H}_{13/2}$ (573 nm) and $^4\text{F}_{9/2} \rightarrow ^6\text{H}_{11/2}$ (663 nm).	68

Table 1 (continued)

Formula	RE	Properties	Ref.
Cs ₃ K ₄ [(Ge ₂ W ₁₈ Nb ₆ O ₇₈)Eu(H ₂ O) ₄] ₂ ·23H ₂ O	Eu ³⁺	Excitation peak: 394 nm Emission peaks: ⁵ D ₀ → ⁷ F ₀ (579 nm), ⁵ D ₀ → ⁷ F ₁ (592 nm), ⁵ D ₀ → ⁷ F ₂ (614 nm), ⁵ D ₀ → ⁷ F ₃ (651 nm) and ⁵ D ₀ → ⁷ F ₄ (699 nm); solution photoluminescence behavior; selective luminescence response to malonic acid	69
Na ₁₀ [Tb ₂ (C ₂ O ₄)(H ₂ O) ₄ (OH)W ₄ O ₁₆] ₂ ·30H ₂ O	Tb ³⁺	Excitation peak: 369 nm Emission peaks: ⁵ D ₄ → ⁷ F ₆ (490 nm, 495 nm), ⁵ D ₄ → ⁷ F ₅ (543 nm, 545 nm), ⁵ D ₄ → ⁷ F ₄ (584 nm, 588 nm) and ⁵ D ₄ → ⁷ F ₃ (621 nm)	73
Na ₂ (NH ₄) ₃ [H ₃ Sm ₆ (H ₂ O) ₂₆ (MoO ₄) ₂ {Mo ₇ O ₂₂ (O ₂) ₂ }] ₄ ·24H ₂ O	Sm ³⁺	Excitation peak: 435 nm Emission peaks: ⁴ G _{5/2} → ⁶ H _{5/2} (551 nm), ⁴ G _{5/2} → ⁶ H _{7/2} (570 nm), and ⁴ G _{5/2} → ⁶ H _{9/2} (653 nm)	77
Na ₁₀ [Tb ₆ (H ₂ O) ₂₂ {As ₄ W ₄₄ (OH) ₂ (proline) ₂ O ₁₅₁ }] ₂ ·22H ₂ O	Tb ³⁺	Green photoluminescence Excitation peak: 348 nm Emission peaks: ⁵ D ₄ → ⁷ F ₆ (490 nm), ⁵ D ₄ → ⁷ F ₅ (544 nm), ⁵ D ₄ → ⁷ F ₄ (586 nm) and ⁵ D ₄ → ⁷ F ₃ (621 nm)	78
K ₆ Na ₄ H ₈ [Eu ₆ (H ₂ O) ₃₈ (P ₂ W ₁₅ Nb ₃ O ₆₂) ₄] ₂ ·45H ₂ O	Eu ³⁺	Excitation peak: 394 nm Emission peaks: ⁵ D ₀ → ⁷ F ₀ (579 nm), ⁵ D ₀ → ⁷ F ₁ (591 nm), ⁵ D ₀ → ⁷ F ₂ (613 nm), ⁵ D ₀ → ⁷ F ₃ (653 nm) and ⁵ D ₀ → ⁷ F ₄ (699 nm)	80
KNa ₃ [HPro] ₇ [Sm(α-PW ₁₁ O ₃₉) ₂] ₂ ·Pro·18H ₂ O	Sm ³⁺	The ferroelectric behavior	21c
Na ₂ [(CH ₃) ₂ NH ₂] ₃ [NaC[Ce ^{III} (H ₂ O)(CH ₃ CH ₂ OH)(l-tartH ₃)(H ₂ Si ₂ W ₁₉ O ₆₆)] ₂ ·3.5H ₂ O	Ce ³⁺	Two-photon absorption properties typical of the third-order nonlinear optical response	29
[(CH ₃) ₂ NH ₂] ₇ [NaC[Ce ^{III} (H ₂ O)(CH ₃ CH ₂ OH)(l-tartH ₃)(Si ₂ W ₁₉ O ₆₆)] ₂ ·2.5H ₂ O			
TBA ₆ H ₄ [RE(H ₂ O) ₂ ·n(acetone)] ₂ {γ-SiW ₁₀ O ₃₆ }] ₂ ·2H ₂ O	Gd ³⁺	The Lewis acid-base catalysis for cyanosilylation	42
Na ₄ Cs ₃ Ho[Ho ₂ (H ₂ O) ₇ Si ₂ W ₁₈ O ₆₆] ₃ ·18H ₂ O	Ho ³⁺	The photochromic behavior	61
[La(HL)(L)(H ₂ O) ₆ {La(H ₂ L) _{0.5} (α-PW ₁₁ O ₃₉ H)La(H ₂ O) ₄ }] ₂ ·8H ₂ O (H ₂ L = 2,5-pyridinedicarboxylic acid)	La ³⁺	The photocatalytic degradation of the Rhodamine-B	79
K ₆ Na ₄ H ₈ [Ce ₆ (H ₂ O) ₃₈ (P ₂ W ₁₅ Nb ₃ O ₆₂) ₄] ₂ ·56H ₂ O	Ce ³⁺	The good electrocatalytic activity towards the reduction of nitrite	80

Tb³⁺ cations, respectively (Fig. 22a). By monitoring Tb³⁺ ⁵D₄ → ⁷F₅ emission at 543 nm, it can be seen that the excitation spectrum displays a broadband between 250 and 350 nm that originated from the absorption of the [W₄O₁₆]⁸⁻ segment, indicating that the luminescence emission partly comes from the contribution of the POM-centered ligand-to-metal charge-transfer (LMCT) process. This phenomenon somewhat differs from the observation in [Tb₈(pic)₆(H₂O)₂₂(B-β-AsW₈O₃₀)₄(WO₂(pic))₆]¹²⁻,³⁸ and the result reported by Yamase.^{13a} Moreover, its decay behavior conforms to a biexponential function as $I = A_1 \exp(-t/\tau_1) + A_2 \exp(-t/\tau_2)$, affording lifetimes of $\tau_1 = 0.43$ ms and $\tau_2 = 1.25$ ms (Fig. 22b). This behavior is analogous to

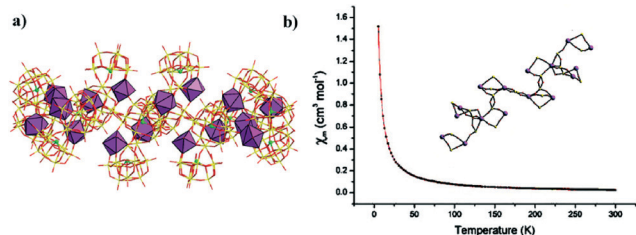


Fig. 21 (a) The structure of hexadecanuclear RECP [Gd₁₆As₁₆W₁₆₄O₅₇₆(OH)₈(H₂O)₄₂]⁸⁰⁻. (b) Temperature dependence of magnetic susceptibility recorded between 5 K and 300 K (inset: ball-and-stick representation of the connection mode of Gd³⁺ centers) (copied from ref. 17d).

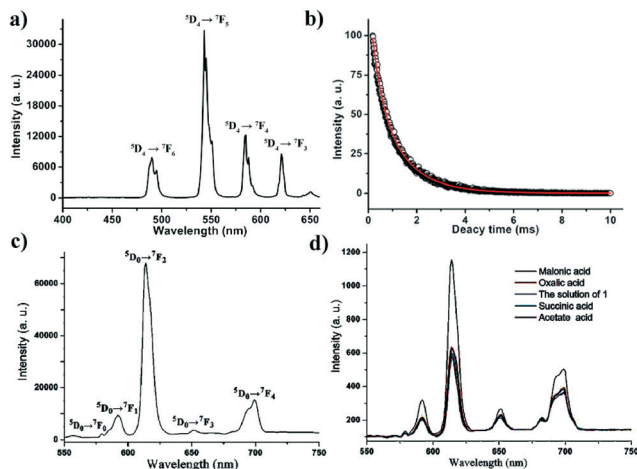


Fig. 22 (a) The emission spectrum ($\lambda_{\text{ex}} = 369$ nm) of Na₁₀[Tb₂(C₂O₄)(H₂O)₄(OH)W₄O₁₆]₂·30H₂O (copied from ref. 73 with some changes). (b) The luminescence decay curve of Na₁₀[Tb₂(C₂O₄)(H₂O)₄(OH)W₄O₁₆]₂·30H₂O (copied from ref. 69 with some changes). (c) The emission spectrum ($\lambda_{\text{ex}} = 394$ nm) of solid-state Cs₃K₄[(Ge₂W₁₈Nb₆O₇₈)Eu(H₂O)₄]₂·23H₂O (copied from ref. 69 with some changes). (d) The luminescence spectra of Cs₃K₄[(Ge₂W₁₈Nb₆O₇₈)Eu(H₂O)₄]₂·23H₂O (1.0×10^{-3} mol L⁻¹, in 0.5 mol L⁻¹ HCl solution) upon addition of acetate acid, oxalic acid, malonic acid and succinic acid (1.0 equal, $\lambda_{\text{ex}} = 394$ nm) (copied from ref. 69 with some changes).

those of hydrated Tb^{III} complexes,^{38,93} which also coincides with the case where each Tb³⁺ cation is coordinated by two water ligands based on the single-crystal structural analysis of Na₁₀[Tb₂(C₂O₄)(H₂O)₄(OH)W₄O₁₆]₂·30H₂O. Liu's group investigated the solid-state photoluminescence behavior of Cs₃K₄[(Ge₂W₁₈Nb₆O₇₈)Eu(H₂O)₄]₂·23H₂O at room temperature.⁶⁹ Five characteristic emission bands located at 579, 592, 614, 651 and 699 nm are seen and correspond to the ⁵D₀ → ⁷F₀, ⁵D₀ → ⁷F₁, ⁵D₀ → ⁷F₂, ⁵D₀ → ⁷F₃ and ⁵D₀ → ⁷F₄ transitions of Eu³⁺ ions, respectively (Fig. 22c). In general, the ⁵D₀ → ⁷F₀ transition is symmetry-forbidden in a field of symmetry. But the ⁵D₀ → ⁷F₀ transition is seen here, revealing that the site symmetry of the Eu³⁺ ions is low in Cs₃K₄[(Ge₂W₁₈Nb₆O₇₈)Eu(H₂O)₄]₂·23H₂O. Furthermore, the $I(^5D_0 \rightarrow ^7F_2)/I(^5D_0 \rightarrow ^7F_1)$ ratio is 7.25, which also supports this point. Moreover, its solution photoluminescence behavior was also probed and the solution emission spectrum manifests the same features as the solid-state emission spectrum, suggesting the uniform coordination environments of Eu³⁺ ions in the solid and solution states. Luminescence response experiments to various carboxylic acids such as acetate, oxalic, malonic and succinic acids have been performed. The results illustrate that the emission intensity significantly rises upon the addition of malonic acid while the introduction of the other three carboxylic acids does not lead to obvious changes in the emission spectra (Fig. 22d). This luminescence response may be interpreted by the substitution of coordinated water molecules by the polarizable C–O donors of the malonic acid in the solution state.^{69,94}

Apart from the abovementioned magnetic and luminescence properties of RECPs, other application explorations such as Lewis acid–base catalysis, photocatalysis, electrocatalysis, photochromism, ferroelectric properties, *etc.* have been also involved in this field (Table 1).^{21c,42,61,79,80} These properties are not discussed here.

4. Summary and outlook

In the past decade, a large number of inorganic or organic–inorganic hybrid RECPs with diverse structures and interesting properties have been prepared and probed due to the driving force originating from their intriguing applications ranging from catalysis to magnetism. These systematic and profound research studies on RECPs not only gradually highlight and underline an important place of the RECP branch in the frontier area of POM chemistry, but also can provide great valuable guidance to the ongoing and continuous developments in exploring and discovering novel functional RECPs. Obviously, during the course of preparing RECPs, the conventional solution approach is the most useful and efficient method; however, the hydrothermal technique is rarely employed. In the conventional solution system, initial reactants, pH value, reaction time, temperature and the selection of solvent are often considered as the important reaction parameters in controlling the possibility of reaction and affecting the formation and crystal growth of the product

phases. In addition to these various parameters, the judicious option of synthetic strategies is a crucial factor. Hitherto, some effective synthetic strategies such as the one-pot reaction strategy of simple starting materials, the adaptive POM precursors as the starting building blocks, the mixed solvent method, the buffer solution control with the appropriate pH range, the alkali metal-directed self-assembly, and the reaction-inducing strategy of the lone electron pair stereochemical effect of some heteroatoms have been constantly and intensively utilized and attempted in the preparation of RECPs. These synthetic strategies have been involved in the abovementioned discussion. Above all, this review primarily concentrates on the elaborate statements about novel structures from mononuclear RECPs to icositetranuclear RECPs. We put emphasis on illuminating the structural characteristics, linking or assembly modes of different compositions and structural types of different building blocks in some representative examples. Certainly, some interesting or important properties are also concerned at the same time.

The area of POMs is currently entering a new phase whereby it is possible to design and control both the structures and functionalities of the systems.⁹⁵ On the basis of the previous results and our critical comprehension, several personal insights or viewpoints are presented here to help researchers that are engaged in this domain to understand the frontiers of RECP science and grasp the future development direction of neoteric RECPs. Meanwhile, we hope to motivate others to step into this area bringing in new ideas and perspectives.

(i) From the viewpoint of synthetic chemistry, in view of the fact that the hydrothermal reaction is seldom used to prepare RECPs, as a result, the extension of the synthetic approach from the conventional solution system to the hydrothermal reaction system will favor the discovery of novel RECP hybrids accompanying the introduction of some functional components and can also result in the formation of unseen non-equilibrium POM fragments and unexpected functionalities that are not accessible from near equilibrium environments under conventional solution conditions.

(ii) As a hotspot research field of inorganic chemistry, chiral POM-based materials have attracted extensive interest while relevant reports about chiral RECPs are sparse, which suggests that introducing appropriate chiral ligands (including inorganic and organic) to the RECP system to produce chiral RECPs will be an emerging area that bears potential applications in asymmetric catalysis, nonlinear optics, gas separation and molecular recognition.

(iii) The exploration and discovery of much higher nuclearity RE incorporated POM aggregates or nanoclusters remains a great and severe challenge albeit the fact that an icositetranuclear RECP has been isolated because the encapsulation of much more RE cations to the POM matrixes can enhance and tune the magnetic, luminescence or bifunctional catalytic performances of high-nuclearity RECPs.

(iv) To date, the majority of reported RECPs are purely inorganic, which inevitably entails the synthesis and study of

organic–inorganic hybrid RECPs to become a new research topic, whereby, multi-functional organic ligands (*e.g.* polycarboxylic ligands, amino acids, *etc.*) will be incorporated in the reaction system to construct organic–inorganic hybrid RECP clusters or high-dimensional frameworks. In addition, the antenna effect of functional organic ligands can in some degree overcome or improve the low absorptivity of RE cations in the ultraviolet-visible region, sensitize the emission of RE cations, and thus enhance the luminous efficiency of RE cations.

Abbreviations

POM	Polyoxometalate
POA	Polyoxoanion
RE	Rare earth
TM	Transition metal
Ln	Lanthanide
TMSP	Transition metal substituted polyoxometalate
RECP	Rare-earth containing polyoxometalate
HSAB	Hard and Soft Acids and Bases theory
MKRECP	Mononuclear Keggin-type RECP
MDRECP	Mononuclear Dawson-type RECP
MLRECP	Mononuclear Lindqvist-type RECP
DKRECP	Dinuclear Keggin-type RECP
DDRECP	Dinuclear Dawson-type RECP
DARECP	Dinuclear Anderson-type RECP
TKRECP	Trinuclear Keggin-type RECP
TDLECP	Trinuclear Dawson-type RECP
QKRECP	Quadronuclear Keggin-type RECP
QDRECP	Quadronuclear Dawson-type RECP
QLRECP	Quadronuclear Lindqvist-type RECP
PKRECP	Pentanuclear Keggin-type RECP
PDRECP	Pentanuclear Dawson-type RECP
HKRECP	Hexanuclear Keggin-type RECP
HDRECP	Hexanuclear Dawson-type RECP
CD	Circular dichroism
SMM	Single molecule magnet
pro	Proline
tartH ₄	Tartaric acid
ala	L- α -Alanine
DMF	N,N-Dimethylformamide
TBA	Tetra- <i>n</i> -butylammonium
DMSO	Dimethyl sulfoxide
Hpic	4-Picolinic acid
C ₆ H ₅ NO ₂	Pyridine-4-carboxylic acid
HAc	Acetic acid
acac	Acetylacetonato
H ₄ cit	Citric acid
H ₃ CAM	2,6-Dicarboxy-4-hydroxypyridine
gly	Glycine
Nle	Norleucine
H ₂ pydc	Pyridine-2,3-dicarboxylic acid
TEM	Transmission electron microscopy

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