

Climate & Earth Systems | Nov 30, 2025 | 20 min read | By Bryan White

Beyond Excavation: Engineering Viruses to Secure the Green Energy Supply

Climate Change * DNA * Microbes

1. Introduction: The Elemental Paradox of the Modern Age

1.1 The Invisible Backbone of Technology

In the intricate architecture of the twenty-first century's technological infrastructure, a specific group of seventeen chemical elements serves as the invisible load-bearing pillars. The Rare Earth Elements (REEs) -- comprising the fifteen lanthanides (atomic numbers 57 through 71) along with scandium and yttrium -- have transcended their historical status as laboratory curiosities to become the defining materials of the digital and green energy revolutions. Their unique electronic configurations, characterized by the progressive filling of the 4f electron shell, endow them with magnetic, luminescent, and electrochemical properties that are unmatched by any other materials in the periodic table.[1]

Consider the permanent magnet motor of an electric vehicle (EV), which relies on neodymium and dysprosium to convert electrical energy into kinetic motion with high efficiency. Analyze the vibrant display of a smartphone, where europium and terbium phosphors produce the brilliant reds and greens. Examine the fiber-optic cables that carry the world's internet traffic, amplified by erbium-doped signal boosters. From the guidance systems of advanced missiles to the generators of offshore wind turbines, REEs are ubiquitous.[1] As the global economy pivots toward decarbonization, the demand for these elements is projected to surge unprecedentedly; electric vehicles, for instance, require approximately six times the mineral input of conventional internal combustion engine cars, while wind plants require nine times the mineral resources of gas-fired counterparts.[2]

1.2 The Crisis of Supply and Separation

Despite their moniker, "rare" earth elements are not geologically scarce in terms of crustal abundance. Cerium is more abundant than copper, and neodymium is more common than gold. The "rarity" lies in their economic availability. Unlike precious metals that can occur in elemental form (native gold), or base metals that form distinct, concentrated ores (copper sulfides), REEs are dispersed widely and, most critically, they are almost always found mixed together in the same mineral deposits.[3]

The separation of these elements constitutes one of the most formidable challenges in inorganic chemistry. Because the lanthanides share the same trivalent oxidation state and have nearly identical ionic radii (a consequence of the lanthanide contraction), their chemical behavior is remarkably uniform. Separating neodymium from praseodymium is, chemically speaking, like trying to separate twins who differ only by the arrangement of a single hair.[3]

Currently, this separation is achieved through solvent extraction (SX), a

brute-force industrial process developed in the mid-20th century. While effective at scale, SX is plagued by low selectivity, necessitating hundreds of sequential extraction stages. It consumes vast quantities of organic solvents (such as kerosene and organophosphorus compounds) and strong acids, generating enormous volumes of toxic and often radioactive waste.[5]

This technological bottleneck has profound geopolitical consequences. Due to looser environmental regulations and state-directed industrial policy, the People's Republic of China has cornered over 90% of the global market for refined REEs.[5] This monopoly renders Western supply chains continuously vulnerable to trade disputes, as evidenced by price shocks and export quotas in recent decades.[2] The urgent need for a "Western alternative" has driven a search not just for new mines, but for a fundamental reinvention of the separation science itself.

1.3 The Biological Renaissance in Hydrometallurgy (Biohydrometallurgy)

In this context, the recent breakthrough by researchers at the University of California, Berkeley, represents a paradigm shift. Published in Nano Letters in late 2025, the work of Inseok Chae, Seung-Wuk Lee, and their colleagues introduces a biological solution to this inorganic problem: a genetically engineered "smart sponge".[7]

By modifying the M13 bacteriophage -- a harmless virus that infects bacteria -- the team created a nanoscale separation platform. They displayed two distinct peptides on the viral surface: a lanthanide-binding peptide (LBP) derived from the protein lanmodulin, which acts as a "claw" to grab the metals, and an elastin-like polypeptide (ELP), which acts as a thermal "switch" to precipitate the virus out of solution.[8] This system promises to replace the toxic solvent extraction plants with aqueous, biodegradable, and highly selective biological processes, potentially unlocking the ability to recycle REEs from electronic waste (urban mining) and process ores with a fraction of the environmental footprint.[10]

This report provides an exhaustive analysis of this technology. We will traverse the atomic physics of the lanthanide contraction that necessitates such innovation, the molecular biology of the engineered phage, the thermodynamics of the separation mechanism, and the broader economic implications for a world hungry for critical minerals.

2. The Physicochemical Landscape: Why Separation is Hard

To appreciate the elegance of the viral "smart sponge," one must first understand the severity of the problem it solves. The difficulty of separating rare earth elements is rooted deeply in quantum mechanics and the structure of the atom.

2.1 The Enigma of the f-Orbitals

The defining feature of the lanthanide series (elements 57-71) is the filling of the 4f electron subshell. In the Aufbau principle of electron configuration, as protons are added to the nucleus, electrons are added to orbitals in order of increasing energy. For the lanthanides, these electrons populate the 4f orbitals.

Crucially, the 4f orbitals are spatially buried deep within the electron cloud, closer to the nucleus than the chemically active 5s and 5p orbitals (and the valence 6s electrons). Because they are "core-like" and deeply sequestered, the 4f electrons do not participate strongly in chemical bonding. This means that the valence electrons (typically $6s^2$ and $5d^1$, which form the +3 oxidation state) are the only ones interacting with the environment.[4] Since all lanthanides generally exhibit this same +3 valency and have the same outer electron shell configuration, they appear chemically identical to potential binding partners.[4]

2.2 The Lanthanide Contraction

The primary differentiator across the series is size, but even this difference is minute. As one moves from Lanthanum (La, atomic number 57) to Lutetium (Lu, atomic number 71), the nuclear charge increases by one proton at each step. Normally, adding electrons to a shell shields the outer electrons from this increased positive charge, causing the atomic radius to expand or remain constant.

However, the 4f electrons are exceptionally poor at shielding the nucleus due to their diffuse shapes. Consequently, the effective nuclear charge felt by the outer electrons increases steadily across the series, pulling the electron cloud tighter and tighter toward the nucleus. This phenomenon is known as the Lanthanide Contraction.[11]

The result is a steady, subtle decrease in ionic radius:

* Lanthanum (La^{3+}): ~103.2 pm

* Lutetium (Lu^{3+}): ~86.1 pm

This equates to a shrinkage of only ~17 picometers across 14 elements -- an average difference of barely 1 pm between adjacent elements.[12] Separation techniques must therefore distinguish between ions based on these infinitesimal size differences, a task that has historically frustrated chemists and engineers.

2.3 The "Twin" Problem in Industrial Separation

In traditional chemistry, elements are separated by distinct differences in properties:

* Volatility: (Used for distillation) - REEs are non-volatile salts.

* Redox Potential: (Used for electrolysis) - Most REEs are locked in the +3 state. (Exceptions are Ce which can be +4, and Eu which can be +2, making them easier to separate).

* Solubility: REE salts generally have very similar solubility products.

Because of the lack of these handles, the industry relies on Solvent Extraction (SX), which exploits the slight difference in charge density resulting from the lanthanide contraction. Smaller ions (Heavier REEs) have a higher charge density and thus bind slightly more strongly to certain ligands (like organophosphates) than larger ions (Lighter REEs).[5]

However, the "Separation Factor" (α) -- a measure of selectivity -- between adjacent lanthanides is often as low as 1.5 to 2.5.[14] In contrast, a robust

industrial separation might look for an alpha of >10 or >100 . A low alpha means that a single pass only slightly enriches the product. To get 99.9% purity, the process must be repeated in a cascade of hundreds of mixer-settlers, leading to the massive capital and environmental costs associated with current processing facilities.[5]

3. The Biological Solution: From Lanmodulin to M13

While industrial chemists struggled with low separation factors, nature had already evolved solutions. The discovery that biology interacts specifically with lanthanides laid the groundwork for the viral platform.

3.1 The Discovery of Lanthanotrophy

For most of the 20th century, lanthanides were considered biologically inert or slightly toxic. This dogma was overturned with the study of methylotrophic bacteria, such as *Methylobacterium extorquens*. These organisms, which live on plant leaves and consume methanol, were found to possess a methanol dehydrogenase (MDH) enzyme that strictly required a lanthanide cofactor (specifically Lanthanum or Cerium) for activity.[16]

This implied that the bacteria possessed a mechanism to scavenge REEs from the environment and, crucially, to distinguish them from chemically similar metals like Calcium (Ca^{2+}), which is millions of times more abundant in soil.

3.2 Lanmodulin (LanM): The Natural Prototype

The molecule responsible for this selectivity was identified as Lanmodulin (LanM). It is a small periplasmic protein (approx. 12 kDa) containing four EF-hand motifs.[18] EF-hands are helix-loop-helix structures typically found in calcium-binding proteins like Calmodulin.

However, LanM is unique. Its EF-hand loops are tuned to favor the slightly higher charge density of Ln^{3+} ions over Ca^{2+} .

* Selectivity: LanM binds lanthanides with picomolar affinity (K_d approx 10^{-12} M), which is 10^8 times stronger than its affinity for calcium.[19]

* Mechanism: The protein undergoes a massive conformational change upon binding REEs, shifting from a disordered state to a compact, ordered structure. This "folding-upon-binding" mechanism is highly cooperative.[20]

Researchers realized that if the binding loops of LanM could be harnessed, they could create an industrial absorbent with selectivity far surpassing commercial chemical ligands.

3.3 The Vehicle: M13 Bacteriophage

Using purified LanM protein for industrial mining is prohibitively expensive due to the costs of protein expression and purification. A more robust, self-replicating carrier was needed. The M13 Bacteriophage emerged as the ideal candidate.

M13 is a filamentous bacteriophage (virus) specific to *E. coli*. It resembles a long, flexible nanofiber, approximately 880 nm in length and 6 nm in diameter.[21]

* The Coat: The filament is encased by approximately 2,700 to 3,300 copies of the

Major Coat Protein (pVIII). This protein forms a helical sheath around the single-stranded DNA genome.[21]

* The Tips: The ends of the virus are capped with minor coat proteins (pIII, pVI, pVII, pIX), present in only about 5 copies each.

M13 is the workhorse of Phage Display, a technique that won the Nobel Prize in Chemistry (2018). By inserting a specific DNA sequence into the gene encoding pVIII (gene VIII), scientists can trick the virus into displaying a foreign peptide on every single copy of its coat protein.[23]

* Amplification: This effectively turns the virus into a high-density display platform. A single virus particle becomes a nanofiber coated with ~3,000 identical binding hooks.[22]

* Production: Because it is a virus, it is self-replicating. One simply infects a culture of *E. coli*, and the bacteria become factories, churning out billions of copies of the engineered phage. This biological manufacturing is vastly cheaper than chemical synthesis of complex ligands.[9]

4. The Innovation: The LBPhELP Platform

The study by Chae et al. (2025) leverages the M13 platform to solve the REE separation problem. They engineered a "bifunctional" virus, termed LBPhELP, which displays two distinct functional peptides on its surface.

4.1 Component 1: The Molecular Claw (LBP)

The first modification transformed the virus into a rare-earth magnet. The researchers grafted a Lanthanide Binding Peptide (LBP) onto the N-terminus of the pVIII coat protein.

* Sequence Origin: The LBP sequence was derived specifically from the EF-hand Loop 1 of the *Methylobacterium extorquens* Lanmodulin protein.[19]

* The Sequence: Asp-Pro-Asp-Lys-Asp-Gly-Thr-Ile-Asp-Leu-Lys-Glu (DPDKDGTIDLKE).[19]

* Coordination Chemistry: This 12-amino acid sequence is rich in Aspartate (Asp, D) and Glutamate (Glu, E) residues. These amino acids possess carboxylate side chains (COO^-) which act as "hard" oxygen donors. Trivalent lanthanides are "hard acids" in Pearson's HSAB theory, preferring hard oxygen ligands. The geometry of this loop is pre-organized to wrap around the Ln^{3+} ion, satisfying its high coordination number (typically 8 or 9).[18]

* Density: With ~3,300 copies per phage, the virus presents a massive array of these chelation sites, allowing for high adsorption capacity.[21]

4.2 Component 2: The Thermal Switch (ELP)

The second modification solved the problem of retrieval. In traditional biosorption, separating the metal-loaded biomass from the water requires centrifugation or filtration, which consumes energy and clogs filters. The Berkeley team introduced an Elastin-Like Polypeptide (ELP) to the virus surface.[8]

* Nature of ELP: ELPs are synthetic biopolymers modeled after human elastin. They

consist of repeating pentapeptide units (typically Val-Pro-Gly-X-Gly).

* Inverse Temperature Transition (ITT): ELPs exhibit a unique phase behavior. Below a critical transition temperature (T_t), they are soluble and disordered in water. Above T_t , they undergo a sharp phase transition, folding into a hydrophobic state and aggregating into coacervates (dense liquid droplets).[8]

* Function: This property makes the virus thermoresponsive. At room temperature, it is a dissolved nanorod, swimming freely to catch REEs. When the tank is warmed (e.g., to 30-40 deg C), the viruses spontaneously clump together and settle to the bottom, carrying the captured metals with them. This mimics the phase separation of solvent extraction but uses heat instead of oil.[9]

4.3 The "Smart Sponge" Mechanism

The operation of the LBPhELP system can be described as a "Catch-and-Release" cycle:

* Adsorption (The Catch): The engineered viruses are introduced into the REE-containing solution (e.g., acid mine drainage or dissolved e-waste). The LBP claws immediately bind to the lanthanide ions. The study showed the virus discriminates effectively against non-REE impurities (like Al, Cu, Fe) due to the specific geometry of the LBP loop.[19]

* Phase Separation (The Squeeze): The solution temperature is raised above the Transition Temperature (T_t). The ELP tails collapse, causing the viruses to aggregate into a dense pellet at the bottom of the vessel. The impurity-laden supernatant is drained away.

* Desorption (The Release): The metal-loaded viral pellet is resuspended in a small volume of solution. The pH is adjusted (likely lowered to $< \text{pH } 3$). The protons (H^+) compete with the metal ions for the carboxylate groups on the LBP. At low pH, the Asp and Glu residues become protonated (COOH), losing their ability to bind the metal. The purified REEs are released into the concentrate.[7]

* Regeneration: The viruses are cooled back down below T_t . They resolubilize and are ready for the next cycle.

5. Performance Analysis: Selectivity and Stability

5.1 Internal Fractionation: Heavy vs. Light

One of the most critical metrics in REE processing is the ability to fractionate the Light REEs (LREEs: La, Ce, Pr, Nd) from the Heavy REEs (HREEs: Tb, Dy, Ho, Er, Tm, Yb, Lu). HREEs are generally rarer and more valuable.

* Viral Preference: The Chae et al. study demonstrated that the LBPhELP construct exhibits a preferential affinity for HREEs over LREEs.[8]

* Mechanism of Selectivity: This preference aligns with the Lanthanide Contraction. HREEs have smaller ionic radii. The LBP peptide loop, being derived from Lanmodulin, likely has a fixed cavity size that coordinates the smaller HREE ions more snugly than the larger LREE ions. This "size-match" selectivity is a hallmark of macrocyclic and structured peptide ligands.[13]

* Implication: This allows the virus to perform a "group separation," effectively

splitting a mixed ore concentrate into a "Heavy" fraction and a "Light" fraction in a single aqueous step. This contrasts with some traditional extractants (like amines) which favor LREEs, or requires different solvents for different groups.[6]

5.2 Separation Factors

While specific separation factor (alpha) values for every pair were not itemized in the news releases, the Nano Letters abstract indicates that the system retains selectivity over multiple cycles and works even in complex matrices.[19]

* Comparison: In traditional Solvent Extraction using D2EHPA, the separation factor for adjacent elements (e.g., Nd/Pr) is often ~1.5. Bio-based systems often target higher separation factors by exploiting the rigid 3D geometry of proteins, which is more discriminatory than the flexible coordination of small molecule ligands.

5.3 Cycle Stability and Reusability

A major concern with biological materials is fragility. Can a virus survive the harsh conditions of a mine?

* Robustness: The study confirms that the LBPhELP platform is recyclable. It retained metal selectivity and binding capacity over multiple cycles of heating, cooling, and pH swinging.[10]

* Structural Integrity: The M13 capsid is known to be exceptionally stable. It acts as a "capsid container," protecting the DNA inside. The peptide modifications are covalently linked (genetically encoded), so they cannot leach off like chemical ligands impregnated in a resin.[10]

6. Comparative Technology Assessment

To evaluate the commercial potential of the viral sponge, we must compare it to the incumbents and other emerging technologies.

Table 1: Comparison of REE Separation Technologies

Feature	Solvent Extraction (SX)	Ion Exchange (IX)	Viral Sponge (LBPhELP)
Primary Mechanism	Liquid-Liquid Extraction (Oil/Water)	Solid-Phase Resin Adsorption	Aqueous Thermoresponsive Coacervation
Separation Agent	Organophosphorus Ligands (e.g., P507)	Sulfonated Polystyrene Beads	Genetically Engineered M13 Phage
Selectivity (alpha)	Low (~1.5-2.5 for adjacent REEs)	Low to Medium	High (Tunable via genetic engineering)
Solvent Use	High (Kerosene, aromatics)	Low (Aqueous columns)	Zero (All aqueous)
Energy Intensity	High (Pumping, mixing, heating)	Medium (Pumping)	Low (Low-grade thermal cycling)
Waste Profile	Toxic organic sludge, acidic wastewater	Brine waste, resin fouling	Biodegradable protein waste

| Scalability || Proven (Industrial standard) || Proven (Lower throughput) ||
Emerging (Pilot scale needed) |

| CAPEX || High (Massive mixer-settler plants) || Medium || Potentially Low
(Fermentation tanks) |

| HREE/LREE Pref. || Variable (Ligand dependent) || Affinity usually increases
with Z || Prefers Heavy REEs (HREEs) |

6.1 Advantages of the Viral Platform

* Environmental Safety: The elimination of organic solvents (VOCs) is the single biggest advantage. The process uses water, salt, and bacteriophages. If a spill occurs, the "contaminant" is a non-infectious protein that biodegrades, rather than a persistent carcinogen.[9]

* Process Intensification: The thermoresponsive switch integrates "separation" and "settling" into one unit operation. There is no need for gravity settlers or centrifuges; simple heating causes the product to self-concentrate.[19]

* Tunability: SX ligands are chemically fixed. Changing the target metal requires inventing a new molecule. With M13, changing the target requires only changing the DNA sequence of the pVIII gene. If the market demands Lithium next year, the "claw" can be swapped for a Lithium-binding peptide, while keeping the "switch" (ELP) and the "chassis" (M13) the same.[19]

7. Scaling the Sponge: Process Engineering & Economics

7.1 Fermentation vs. Synthesis

The economics of the viral sponge are driven by biotechnology, not petrochemistry.

* Manufacturing: The production of the separation agent occurs via fermentation. E. coli cells are cultured in standard bioreactors. Once infected, they secrete phages into the media.

* Cost: While pharmaceutical-grade phage production is expensive, industrial-grade production (where purity requirements are lower) benefits from economies of scale. Bacteria are self-replicating catalysts. The feedstock is glucose, nitrogen, and salts -- vastly cheaper than the synthesis of D2EHPA or Cyanex extractants.[13]

7.2 Implementation in Flowsheets

The vision for a "Viral Refinery" involves:

* Leaching: Ore or e-waste is leached with acid (bio-leaching or mild chemical leaching).

* Conditioning: The pH is adjusted to the optimal binding range (typically pH 5-6).

* Viral Injection: Concentrated LBPhELP is injected into the stream.

* Binding: The stream flows through a mixing pipe where adsorption occurs (seconds to minutes).

* Thermal Trigger: The stream passes through a heat exchanger (utilizing waste heat from the leaching step), raising $T > 35$ deg C.

* Separation: The stream enters a settling tank. The virus-metal clumps sink. The barren water overflows.

* Stripping: The sludge is pumped to a small acid tank (pH 1). The viruses release the metals.

* Recycle: The viruses are cooled and pumped back to the start. The concentrated metal solution goes to electrowinning or precipitation.

7.3 Challenges to Scale

* Biofouling: Real-world mine waters are non-sterile. Wild bacteria might produce proteases that degrade the virus, or biofilms that clog the system.

* Volume: Mines process thousands of cubic meters of water. Producing enough phage to treat this volume requires massive fermentation capacity.

* Life Cycle: How many cycles can the phage endure before the ELP mechanism fatigues or the DNA degrades? The paper says "multiple," but industry needs "thousands."

8. Broader Implications: Geopolitics and the Circular Economy

8.1 Breaking the Monopoly - Towards Green Energy

The overarching driver for this technology is the need to break the Chinese monopoly on REE refining. The barrier to entry for Western companies has largely been the environmental permitting of SX plants. A biological plant, producing benign waste, could theoretically be permitted much faster and operate closer to urban centers (where the e-waste is).[5]

8.2 Urban Mining: The Low-Hanging Fruit

While ore mining is the long-term goal, Electronic Waste (WEEE) is the immediate opportunity.

* Concentration: A hard drive magnet is ~30% Neodymium. This is a far higher grade than any mine (typically <5%).

* Selectivity: The viral sponge's high specificity allows it to pick REEs out of the "dirty" mix of iron, copper, and plastic in shredded electronics, which poisons traditional chemical extractants.

* Circular Economy: This technology enables a closed loop: Old iPhones -> Viral Refinery -> New EV Motors. This aligns with EU and US "Critical Raw Materials" acts.[2]

8.3 Future Targets: Actinides and Beyond

The modularity of the platform suggests applications beyond REEs.

* Nuclear Waste: The similarity of Actinides (Am, Cm, U) to Lanthanides means this technology could be adapted for nuclear reprocessing, separating short-lived isotopes from long-lived ones.[13]

* Lithium: With the battery boom, a "Lithium Sponge" is a prime target for future genetic engineering of the M13 pVIII protein.

9. Conclusion

The "Smart Sponge" developed by Chae, Lee, and colleagues is more than a novel material; it is a proof-of-concept for a new era of Biohydrometallurgy. It demonstrates that the exquisite molecular recognition evolved by biology over billions of years -- exemplified by Lanmodulin -- can be harnessed and engineered into robust industrial tools via the M13 phage scaffold.

By exploiting the physicochemical nuances of the Lanthanide Contraction through a biological lens, and coupling it with the thermodynamic utility of Elastin-like Polypeptides, this platform solves the "separation of twins" problem without the toxic legacy of the 20th century. While significant engineering hurdles remain in scaling from the test tube to the terror-liter tank, the viral sponge offers a glimpse of a future where the elements that power our high-tech world are recovered cleanly, efficiently, and sustainably.

10. Technical Appendix

Table 2: Functional Components of LBPhELP

Component	Biological Source	Sequence / Structure	Function	Mechanism
Chassis	M13 Bacteriophage	Filamentous Capsid (~880nm x 6nm)	Scaffold	Displays ~3300 peptides; self-replicating nanoparticle.
Binding Claw	M. extorquens (LanM)	DPDKDGTIDLKE (EF-Hand Loop 1)	Adsorption	Coordinates Ln ³⁺ via Asp/Glu carboxylates; prefers HREEs.
Thermal Switch	Human Tropoelastin (derived)	(VPGXG) _n repeats (ELP)	Phase Separation	Undergoes Inverse Temperature Transition (ITT) > T _t , causing aggregation.
Promoter	lac promoter (typically)	DNA regulatory element	Expression	Drives high-level expression of fusion protein in E. coli.

Table 3: Lanthanide Data relevant to Separation

Element	Symbol	Atomic No. (Z)	Electron Config ([Xe]...)	Ionic Radius (+3, pm)	Status
Lanthanum	La	57	5d ¹ 6s ²	103.2	Light REE
Cerium	Ce	58	4f ¹ 5d ¹ 6s ²	101.0	Light REE
Praseodymium	Pr	59	4f ³ 6s ²	99.0	Light REE
Neodymium	Nd	60	4f ⁴ 6s ²	98.3	Light REE
Promethium	Pm	61	4f ⁵ 6s ²	97.0	Radioactive
Samarium	Sm	62	4f ⁶ 6s ²	95.8	Medium REE
Europium	Eu	63	4f ⁷ 6s ²	94.7	Medium REE
Gadolinium	Gd	64	4f ⁷ 5d ¹ 6s ²	93.8	Medium REE
Terbium	Tb	65	4f ⁹ 6s ²	92.3	Heavy REE

Dysprosium		Dy		66		$4f^{10} 6s^2$		91.2		Heavy REE
Holmium		Ho		67		$4f^{11} 6s^2$		90.1		Heavy REE
Erbium		Er		68		$4f^{12} 6s^2$		89.0		Heavy REE
Thulium		Tm		69		$4f^{13} 6s^2$		88.0		Heavy REE
Ytterbium		Yb		70		$4f^{14} 6s^2$		86.8		Heavy REE
Lutetium		Lu		71		$4f^{14} 5d^1 6s^2$		86.1		Heavy REE

Note: The steady decrease in ionic radius (The Lanthanide Contraction) is evident in the data above. The Viral Sponge exploits this gradient.

11. Citations

[1]

Works Cited

- * Separation of Rare Earth Elements - American Chemical Society, accessed November 30, 2025, <https://www.acs.org/education/whatischemistry/landmarks/earthelements.html>
- * Current nature-based biological practices for rare earth elements extraction and recovery: bioleaching and biosorption - OSTI.GOV, accessed November 30, 2025, <https://www.osti.gov/servlets/purl/1903015>
- * accessed November 30, 2025, <https://rareearthexchanges.com/news/why-separating-and-refining-rare-earth-elements-is-so-difficult-to-scale/#:~:text=Rare%20earth>
- * Why is it difficult to separate the lanthanide elements? - Quora, accessed November 30, 2025, <https://www.quora.com/Why-is-it-difficult-to-separate-the-lanthanide-elements>
- * Why Separating and Refining Rare Earth Elements is So Difficult to Scale, accessed November 30, 2025, <https://rareearthexchanges.com/news/why-separating-and-refining-rare-earth-elements-is-so-difficult-to-scale/>
- * Hydration counteracts the separation of lanthanides by solvent extraction - PMC - NIH, accessed November 30, 2025, <https://pmc.ncbi.nlm.nih.gov/articles/PMC9285791/>
- * accessed November 30, 2025, [https://www.gate2biotech.com/genetically-engineered-virus-acts-as-smart-sponge-to-extract-rare-earth-elements-from-water/#:~:text="](https://www.gate2biotech.com/genetically-engineered-virus-acts-as-smart-sponge-to-extract-rare-earth-elements-from-water/#:~:text=)
- * Virus-Based Thermoresponsive Separation of Rare-Earth Elements - PubMed, accessed November 30, 2025, <https://pubmed.ncbi.nlm.nih.gov/41103182/>
- * Researchers pioneer greener way to extract rare earth elements ..., accessed November 30, 2025, <https://engineering.berkeley.edu/news/2025/11/researchers-pioneer-greener-way-to-extract-rare-earth-elements/>
- * Virus-Based Separation of Rare Earth Elements | Nano Letters - ACS Publications, accessed November 30, 2025, <https://pubs.acs.org/doi/abs/10.1021/acs.nanolett.4c02510>
- * accessed November 30, 2025, <https://www.geeksforgeeks.org/chemistry/lanthanide-contraction/#:~:text=The%20effects%20of%20the%20lanthanide,lanthanides%20>

- * Lanthanide contraction - Wikipedia, accessed November 30, 2025,
https://en.wikipedia.org/wiki/Lanthanide_contraction
- * Novel extractants for rare earth chelation and separation | ORNL, accessed November 30, 2025, <https://www.ornl.gov/technology/202405820>
- * Game-changing rare-earth elements separation technology licensed to Marshallton | ORNL, accessed November 30, 2025,
<https://www.ornl.gov/news/game-changing-rare-earth-elements-separation-technology-licensed-marshallton>
- * Separation of Adjacent Rare Earth Elements Using Solvent Extraction - University of Idaho, accessed November 30, 2025,
<https://verso.uidaho.edu/esploro/outputs/graduate/Separation-of-Adjacent-Rare-Earth-Elements/996638045201851>
- * Nano Letters Vol. 25 No. 43 - ACS Publications, accessed November 30, 2025,
<https://pubs.acs.org/toc/nalefd/25/43>
- * Virus-Based Separation of Rare Earth Elements | Request PDF - ResearchGate, accessed November 30, 2025,
https://www.researchgate.net/publication/382886373_Virus-Based_Separation_of_Rare_Earth_Elements
- * Investigation of Rare Earth Element Binding to a Surface-Bound Affinity Peptide Derived from EF-Hand Loop I of Lanmodulin | ACS Applied Materials & Interfaces, accessed November 30, 2025, <https://pubs.acs.org/doi/10.1021/acsami.3c17565>
- * Virus-Based Thermoresponsive Separation of Rare-Earth Elements | Nano Letters, accessed November 30, 2025, <https://pubs.acs.org/doi/10.1021/acs.nanolett.5c04468>
- * EF-Hand Battle Royale: Hetero-ion Complexation in Lanmodulin | JACS Au, accessed November 30, 2025, <https://pubs.acs.org/doi/10.1021/jacsau.4c00628>
- * Virus-Based Separation of Rare Earth Elements - PubMed, accessed November 30, 2025, <https://pubmed.ncbi.nlm.nih.gov/39101944/>
- * (647d) Virus-Based Selective and Sustainable Rare Earth Element Separation | AIChE, accessed November 30, 2025,
<https://proceedings.aiche.org/conferences/aiche-annual-meeting/2024/proceeding/paper/647d-virus-based-selective-and-sustainable->
- * (PDF) Engineered phages for selective adsorption of rare earth elements - ResearchGate, accessed November 30, 2025,
https://www.researchgate.net/publication/393323688_Engineered_phages_for_selective_adsorption_of_rare_earth_elements
- * Phage Display - A Promising Tool for the Recovery of Valuable Metals from Primary and Secondary Resources | Scientific.Net, accessed November 30, 2025,
<https://www.scientific.net/SSP.262.443>
- * Reversing Lanmodulin's Metal-Binding Sequence in Short Peptides Surprisingly Increases the Lanthanide Affinity - PubMed, accessed November 30, 2025,
<https://pubmed.ncbi.nlm.nih.gov/40985823/>
- * Urban Biomineralization of Rare Earth Elements: Current Status and Future Opportunities | ACS Environmental Au, accessed November 30, 2025,
<https://pubs.acs.org/doi/full/10.1021/acsenvironau.5c00175>
- * Lanmodulin peptides - unravelling the binding of the EF-Hand loop sequences stripped from the structural corset - RSC Publishing, accessed November 30, 2025,

<https://pubs.rsc.org/en/content/articlehtml/2022/qi/d2qi00933a>

* Virus-Based Thermoresponsive Separation of Rare-Earth Elements | Nano Letters,
accessed November 30, 2025,

<https://pubs.acs.org/doi/abs/10.1021/acs.nanolett.5c04468>