Triadic Framework Technology for 10 Rarest Elements on Earth

Overview and History

The story of the rarest elements on Earth is a narrative woven from both natural history and the ingenuity of modern science. As researchers have peered deeper into matter's fundamental structure, the effort to identify and create the rarest elements has become an enterprise at the frontier of chemistry, physics, and engineering. The rarest chemical elements are defined by their negligible abundance in the Earth's crust, rapid radioactive decay, or artificial synthesis in nuclear reactors and accelerators. Most of these elements exist only fleetingly, with half-lives measured in seconds to years, and some can only be found as decay products of more stable isotopes[2][3].

From uranium (atomic number 92), the so-called "transuranium" elements-neptunium, plutonium, americium, curium, berkelium, californium, and beyond-were first synthesized in the 20th century as atomic physics matured[5]. Their discovery rests on the work of pioneering scientists: neptunium was first isolated by Edwin McMillan and Philip Abelson in 1940, curium by Glenn Seaborg and his team in 1944, and the elusive end-members such as astatine and francium were revealed through both natural decay chains and deliberate laboratory synthesis. Due to their scarcity and instability, these elements have historically been absent from the practical world and are chiefly of interest for research, specialized industrial processes, or as stepping stones to even heavier synthetic nuclei[7][8].

The following table summarizes the ten rarest elements in Earth's environment, taking into consideration their natural abundance, isotopic stability, and current accessibility via laboratory techniques:

Element	Properties & Natural Occurrence	Refining/Synthesizing Methods	Potential Improvements via TFT/Quantum/AI
Neptunium	Actinide, radioactive, only trace natural abundance	Byproduct in nuclear reactors; solvent extraction from spent fuel	Quantum resonance-aided separation
Curium	Synthetic, alpha emitter, not found in nature	Neutron irradiation of plutonium; chemical separation	AI-optimized irradiation/separation; TFT refining
Americium	Synthetic, alpha and gamma emitter, minute amounts at best	Production from neutron capture on plutonium	Copilot-driven waste minimization, resonance control

Californium	Synthetic, neutron emitter, only via high flux reactors	Neutron bombardment of berkelium/curium, reactor separation	Quantum resonance optimization; TFT chelation
Promethium	Lanthanide, radioactive, trace fission product	Recovered from spent nuclear fuel, also via neodymium irradiation	TFT tracking of isotopic partitioning
Protactinium	Actinide, rare, occurs in ppb levels in uranium ores	Extraction from uranium ores, refined via ion-exchange	AI calibration of separations; quantum elution
Francium	Alkali, extremely unstable, barely measurable in nature	Lab synthesis from actinium decay and particle accelerators	Quantum/time-resolved Copilot-aided monitoring
Berkelium	Synthetic, actinide, only via neutron bombardment	Produced by irradiation of americium/curium targets in reactors	TFT-enabled decay chain modeling
Astatine	Halogen, <1 gram in Earth's crust at any time	Bombardment of bismuth targets with alpha particles	Quantum-state modeling, TFT synthesis planning
Einsteinium	Synthetic, actinide, produced in microgram amounts	Neutron capture of californium in reactors; complex separation	Quantum and Copilot-based decay management

---

While rare earth elements in the strict IUPAC definition refer to lanthanides plus scandium and yttrium, this chapter focuses on the "true rarest" in a physical and practical sense: those elements that are only available via nuclear decay chains or the most advanced forms of particle accelerator and reactor technology. Most, such as einsteinium and francium, are so short-lived and unstable that their direct study presents extraordinary technical challenges.
The history of these elements echoes advances in instrumentation and method: from the cyclotron-era discoveries (U.C. Berkeley, 1940s-1950s) to modern reactor synthesis and sophisticated separation chemistry, each element's identity was confirmed through creative experiment and, frequently, rivalry among competing laboratories[9][6][12][13]. Modern rare element science is inextricably tied to both state and private investment, such as the U.S. Department of Energy's efforts at Oak Ridge National Laboratory and partnerships with institutes like Virginia Tech and Stanford for advanced refining and AI-driven research[15].

Scientific Efforts and Unfinished Tests

Scientific progress on the rarest elements often straddles the line between the possible and the theoretical. For each, the journey from predicted existence to confirmed creation has been shaped by the limitations of experiment and the imagination of researchers.

Neptunium's initial recovery involved careful irradiation of uranium in reactors; only traces arise in natural uranium ores as decay byproduct, making its identification a matter of separating extremely minute quantities amid other actinides[17]. Recovery methods at sites such as Hanford have relied on solvent extraction cycles where neptunium is co-extracted with uranium and plutonium before final purification via ion-exchange chromatography, but efforts for scaled or purer separation remain a constant challenge.

Curium's story highlights the secrecy and urgency of the Manhattan Project, with multiple isotopes discovered clandestinely during World War II. Initial tests with curium focused on characterizing its chemical behavior-alpha emission, oxidation states, and structural assignment-and curium-244 has enabled analysis on Mars via alpha particle X-ray spectrometers, but attempts to industrialize or broadly apply curium have been stymied by high radioactivity and scarcity[10].

Americium synthesis and isolation have been gradually improved, most notably with the United Kingdom's breakthough in extracting industrial-scale americium-241 for radioisotope batteries and deep-space power applications. However, cross-laboratory variation in isolation efficiency and consistency remains a topic of unfinished work, with recent U.S. Department of Energy programs emphasizing reduced waste, increased yield, and safety[19].

Californium stands out for its unique ability to emit neutrons, sparking a broad array of scientific inquiry, from new element synthesis to neutron radiography. Despite its wide utility in starting nuclear reactors or identifying trace ore minerals, only a few grams are made worldwide annually-about 25mg per year produced at Oak Ridge-and efforts continue to improve the scaling, purity, and safety of californium-252 sources. Novel techniques for advanced resonance filtering of neutron flux, aimed at maximizing heavy isotope production, remain in experimental phases[20].

Promethium presented a puzzle for nearly half a century; evidence of its existence eluded confirmation until American chemists isolated and characterized it from reactor byproducts in the 1940s. Its lack of stable isotopes and the challenge of distinguishing it from chemically similar lanthanides have kept its scientific profile high but commercial presence limited[22][24].

Protactinium's history is marked by ever-improving separation from uranium and niobium alloys. Recent efforts have focused on refining extraction protocols for radiochronometry and nuclear forensics, with ongoing interlaboratory discrepancies and material loss in isolating ultra-trace quantities. Advanced anion-exchange and solvent-based protocols are under continuous development for better yield and reproducibility, yet the process is still not universally efficient, especially for complex reactor alloys[26].

Francium, the last element discovered first in nature rather than the lab, was confirmed by Marguerite Perey in 1939 via alpha decay from actinium. Every attempt to study francium in bulk remains foiled by its incredible instability and rapid decay. Only small numbers of atoms are produced in accelerators and isotope laboratories, where they almost instantly decay, constraining chemical and physical studies to indirect methods or sophisticated spectroscopy[12].

Berkelium's primary utility since its 1949 discovery has involved providing targets for the synthesis of even heavier transuranic elements. As only microgram-to-milligram quantities can be prepared and handled at any time, attempts to scale up production for extensive chemical characterization remain ongoing, with focus on reducing lanthanide contamination during synthesis[11].

Astatine trials center around maximizing yield in cyclotron irradiation of bismuth, minimizing target vaporization, and characterizing fleeting chemical species. Disagreement persists over the feasibility of collecting condensed astatine, while proposed medical applications in radiotherapy are hampered by its rapid decay and dehalogenation in physiological environments[2].

Einsteinium synthesis remains a byproduct of long, complex irradiation chains in reactors and thermonuclear explosions. Advanced separation chemistry and handling (e.g., cation-exchange resins, solvent extraction chromatography) have enabled microgram-scale characterization, but the self-radiation damage and short half-lives restrict usable sample windows and represent an ongoing technical barrier to deeper study[3][11].

In summary, each of these rarest elements sits at the intersection of theoretical expectation and experimental intractability. Scientific progress continues to push methods, but in nearly every case, unfinished tests and unresolved inefficiencies define the state of the art.

Current Refining and Synthesizing Methods

Extraction and refinement of the world's rarest elements requires a convergence of high-flux neutron sources, particle accelerators, complex chemical separation, and finely tuned safety regimes.

General Refinement Approaches

Refining rare and synthetic elements is hindered by low yields, high background contamination, and, for most actinides, copious co-production of toxic or radioactive byproducts. Several key industrial and academic methods are used:

1. **Solvent Extraction:** Widely applied for actinides, this uses differences in solubility and oxidation states (e.g., PUREX, UREX processes for nuclear fuel) to separate neptunium, americium, and curium from uranium, plutonium, and fission products. Drawbacks include high volumes of radioactive and chemical waste[27][24].
2. **Ion Exchange Chromatography:** Enables separation of f-block elements based on ionic size and charge; commonly deployed for berkelium, curium, and einsteinium, using specialized resins and pH gradients[26][24].
3. **Precipitation:** Often mixed with solvent extraction, this exploits differential solubility of actinide and rare earth compounds (e.g., oxalate or peroxide precipitation). This is critical for protactinium and lanthanide separation due to their similar chemistry[24].
4. **Electrochemical Methods:** For certain rare earths, fused salt electrolysis and reduction of rare earth oxides are used, but this method is less applicable to highly radioactive actinides.
5. **Metal-Organic Framework (MOF) Crystallization:** Recent breakthroughs have highlighted the potential of MOFs for highly selective extraction of actinides-especially promising for contaminants or radionuclides in complex matrices[24].

6. **High-Flux Reactors and Irradiation:** Synthesis of most elements beyond uranium involves bombarding lighter actinide targets (plutonium, americium, curium, berkelium) in facilities like Oak Ridge's HFIR or Russia's SM-2, followed by chemical separation and purification[20][3].

Example Element-Specific Methods

- **Neptunium**: Extracted from spent nuclear fuel using solvent extraction and ion-exchange protocols, with emphasis on keeping neptunium-VI stable in solution for selective partitioning[17].
- **Curium**: Obtained via neutron irradiation of plutonium or americium, followed by exhaustive multi-step separation protocols (including hydroxide precipitation, cation exchange, and batch solvent extraction)[11][10].
- **Americium**: Industrial production from plutonium-241 decay, with separation using oxidation/reduction chemistry, solvent extraction, and now pelletization technology for applications such as radioisotope thermoelectric generators[19].
- **Californium**: Produced by prolonged neutron bombardment of berkelium, curium, or americium; separation and purification requires precise irradiation schedules and cation/anion-exchange steps to maximize Cf-252 yield and minimize radioactive waste. Methods such as resonance neutron filtering are under development for efficiency gains[20].
- **Promethium**: Recovered primarily as a byproduct of uranium fission, purified via ion exchange and reduction of promethium fluoride with calcium; research focuses on isolation efficiency from competing lanthanides[22][23].
- **Protactinium**: Extracted from uranium ore leachates using complex multistep solvent extraction and ion chromatographic methods, with continued efforts to decrease sample size and maximize yield from niobium-rich industrial metals[26].
- **Francium**: Generated for research by bombarding thorium targets or isolating from decays from actinium-227, with laser trapping and spectroscopy as the only practical study methods due to its minuscule and transient yields[12].
- **Berkelium**: Neutron irradiation of curium/americium targets in high-flux reactors, using Cleanex batch extraction, sequential ion exchange, and high-temperature volatilization to minimize cofractionation of other actinides and lanthanides[11].
- **Astatine**: Synthesized by alpha particle bombardment of bismuth-209 targets, then recovered via dry heating or wet dissolution/extraction; efforts to maximize isotopic purity focus on preventing rapid self-destruction via radioactivity[2].
- **Einsteinium**: High-flux neutron irradiation of californium and other heavy actinide targets yields einsteinium isotopes, followed by intensive cation/anion exchange chromatography with radiological safety protocols. Output is typically only microgram to milligram quantities-just stable enough for radiochemical study[3][11].

Table: 10 Rarest Elements - Properties, Current Methods, and Potential Improvements

Element	Properties/History	Current Methods	Potential Improvements via TFT/Quantum/AI
Neptunium	Radioactive actinide	Reactor byproduct, solvent extraction	Quantum-aided separation, AI-driven model calibration
Curium	Synthetic, alpha emitter	Neutron irradiation, multi-step chemical separation	TFT path mapping for irradiation optimization
Americium	Synthetic, gamma/alpha emitter	Reactor production, solvent extraction, pelletization	Copilot-guided minimization of radiological dose, AI waste profiling
Californium	Synthetic, neutron emitter	Neutron irradiation, advanced resonance filtering	Quantum resonance/neutron flux predictive tuning
Promethium	Lanthanide, no stable isotope	Uranium fission byproduct, reduction/ extraction	TFT-directed partitioning and AI chelation design
Protactinium	Actinide, uranium ore trace	Ion-exchange from ores and alloys	Predictive Copilot optimization, quantum column tuning
Francium	Alkali, extremely unstable	Particle accelerators, actinium decay	Real-time quantum state tracking, Copilot decay management
Berkelium	Synthetic actinide	Neutron irradiation of Am/Cm, sequential extractions	TFT-enabled decay chain management, AI-assisted purification
Astatine	Halogen, <1g on Earth	Alpha bombardment of Bi, dry/wet separation	Quantum state modeling, AI-driven isotope enrichment
Einsteinium	Synthetic, alpha emitter	Reactor irradiation/separation	Predictive Copilot modeling of production/decay, AI separation planning

Future Improvements via Quantum Resonance and Triadic Framework Technology (TFT)

High-precision control at the atomic, electronic, and quantum level is becoming a necessity for advancing the science and engineering of the rarest elements. Two promising frontiers-Quantum Resonance approaches and Triadic Framework Technology-promise to unlock profound advances in element refinement, synthesis, and application.

Quantum Resonance

Quantum resonance refers to the exploitation of resonant energy states and transitions during synthesis or separation processes. Harnessing resonance conditions, such as energy matching in neutron capture and selective excitation of vibrational, rotational, or electronic states, can dramatically enhance yield and selectivity, potentially enabling the production of previously inaccessible isotopes or rapidly decaying elements[29][30].
For example, by tuning reactor and irradiation parameters to quantum resonance conditions, it may be possible to:

- **Enhance neutron capture cross-sections** for selected isotopes (improving yield and purity)
- **Suppress competing (parasitic) reactions** that deplete target isotopes
- **Selectively excite or manipulate specific isotopes** during chemical separation via laser resonance or electromagnetic fields

The translation of these quantum phenomena into practical protocols is an active area of simulation, theoretical modeling, and pilot experimentation across global research facilities.

Triadic Framework Technology (TFT)

TFT represents a tri-layered approach-merging deterministic semantic models, universal object referencing, and quantum-mechanical (Hamiltonian) dynamics-to material processing and element synthesis. TFT, as documented in current research, leverages:

1. **Semantic Addressability:** Assigning canonical semantic “addresses” (or digests) to atomic and electronic configuration states, enabling lossless, dynamic “navigation” of synthesis pathways and results.
2. **Partial Information Decomposition (PID):** Optimizing local goals or trajectories in atomic/catalytic processes by tracking information redundancy, uniqueness, and synergy, enabling modular, traceable process design.
3. **Hamiltonian Flow Modeling:** Describing atomic and electronic transitions as smooth, reversible Hamiltonian flows-thereby mapping the evolution of a material’s quantum states deterministically and predictably.

This triadic methodology opens the door to:

- **Real-time, interpretable feedback** during high-flux irradiation runs
- **In-silico, lossless simulation of rare-element syntheses**

- **Mathematically auditable process documentation**, ideal for regulatory, security, and patent tracking in strategic materials research
- **Dynamic, adaptive control of chemical separations**, reducing waste and maximizing yield

Application to rare element refining is seen as a critical step toward integrating quantum mechanical, information-theoretic, and practical process controls in a single, scalable system.

Synergy with Copilot-Assisted Calculations

AI co-pilots (or "Copilots") are rapidly transforming high-performance computation for materials discovery and process optimization. Copilot systems now assist with:

- **Automated workflow generation** for quantum chemistry simulations (e.g., DFT, band structure analysis)
- **Rapid literature and data mining**, integrating new findings into simulation pipelines
- **Real-time molecular visualization and analysis,** enabling advanced model validation and redesign
- **Code generation** to run/rerun quantum simulations based on a handful of keywords or schematic instructions

By combining Copilot platforms (like Azure Quantum Elements and its Retrieval-Augmented Generation (RAG) capabilities) with quantum resonance and TFT, researchers can:

- **Streamline the design and execution of rare element synthesis protocols**, from code to experiment
- **Model synthesis and separation pathways with unprecedented detail and reproducibility**
- **Rapidly iterate on isotopic enrichment strategies**, material compositions, and reactor parameters[32].

These AI-enhanced methods dramatically lower the barrier to entry for new researchers and accelerate the pace of experimental innovation, especially when cross-referenced with massive, curated scientific datasets.

Copilot-Assisted Calculations in Materials R&D

The informational complexity of rare element R&D has traditionally required interdisciplinary expertise-spanning chemistry, physics, materials science, and computer science. Copilot-assisted calculation platforms are being deployed to disrupt this paradigm by:

1. **Interfacing directly with quantum simulation environments.** Using Copilot, researchers convert natural-language queries or high-level hypotheses into simulation-ready code, such as DFT for electronic structure or Monte Carlo models for neutron flux optimization.
2. **Generating and optimizing entire workflow pipelines.** For instance, Copilot can recommend and script methods for evaluating actinide/lanthanide separation, tune

irradiation and decay models for target isotope enrichment, and perform on-the-fly error analysis for process adjustments.

3. **Visualizing multi-element materials and isotopic chains.** Copilot leverages vast chemical datasets, libraries of molecular/atomic structures, and advanced visualization engines to represent even fleetingly stable elements, assisting in identification and experimental planning.
4. **Integrating experimental data with predictive models.** By grounding outputs in hundreds of thousands of peer-reviewed articles and laboratory reports-retrieved and cited in real time-Copilot-guided modeling ensures that experimental protocols reflect the very latest research and are immediately comparable to published best practices.
5. **Modeling AI-driven process exploration.** As evidenced by recent AI-accelerated materials studies, Copilot systems can suggest novel separation agents, predict environmental impacts of refining techniques, and optimize quantum circuit designs for controlling synthesis sequences, reducing both time and cost toward discovery[30].

The result is an unprecedented level of convergence between abstract theory, computational simulation, and hands-on experiment-one that promises to unlock access to new rare elements, improved separation methods, and downstream applications in medicine, energy, and quantum computing.

Table: The 10 Rarest Elements-Properties, Current Methods, and Future Directions

Element	Atomic No.	Natural Occurrence / Properties	Current Methods of Refining /Synthesis	Potential Improvements via TFT, Quantum, Copilot
Neptunium	93	Trace natural (U decay), first transuranic, α emitter	Reactor byproduct, solvent extraction cycles	Quantum-enhanced extraction selectivity, AI process modeling
Curium	96	Not natural, strong α emitter, heats macroscopically	Neutron irradiation on Pu/Am, multi-stage purification	TFT-mapped irradiation, AI for safety/admin dose minimization
Americium	95	Synthetic, γ and α emitter, used in smoke detectors, batteries	Recovered from reactor waste, ion-exchange separation	Copilot-driven yield optimization, resonance-aided purification

Californium	98	Synthetic, neutron source, complex decay chain	Multi-year irradiation of heavy actinides	AI-controlled neutron field, quantum resonance production
Promethium	61	Natural trace in U ore, all isotopes radioactive, lanthanide	Recovery from spent fuel, Ne irradiation	TFT separation design, AI for cross-lanthanide selectivity
Protactinium	91	Trace in uranium ores, half-life ~32k yr, actinide	Ion-exchange and precipitation from U ores	Universal resin separation, Copilot-guided protocol refinement
Francium	87	Shortest-lived alkali, extremely rare and unstable	Lab synthesis via Ac/Th decay, accelerator reactions	Quantum state modeling, AI-assisted decay/spectroscopy design
Berkelium	97	Synthetic, actinide, target for superheavy element synthesis	Reactor irradiation of Am/Cm, cation/anion-exchange	TFT for decay trajectory, AI purification and waste tracking
Astatine	85	Rarest natural, halogen, isotopes t1⁄2 ~8 hr, med applications	Alpha bombardment of Bi (cyclotron), solvent/thermal	TFT-based process mapping, quantum resonance for yield max
Einsteinium	99	Synthetic, decay by α/β, produced in H-bomb/test reactors	Neutron capture of Cf, complex separation	Copilot-run process coordination, quantum state prediction

---

Conclusion: Toward a Quantum and AI-Driven Era in Rare Element Science

The pursuit of Earth’s rarest chemical elements is a journey of both scientific necessity and philosophical wonder. From the isolation of microgram-quantities of rare actinides to the dream of an “island of stability” for superheavy elements, our progress reflects the synergy of theory, experiment, and, increasingly, computation.
The integration of quantum resonance, Triadic Framework Technology, and Copilot-assisted calculations marks a paradigm shift: what was once defined by slow, incremental advances is

now accelerating as data and simulation meet laboratory ingenuity. Crucially, these tools together allow researchers to:

- **Model, predict, and validate atomic synthesis steps at quantum precision**
- **Iteratively optimize experimental protocols with real-time AI-powered feedback**
- **Navigate and document process pathways with auditable, lossless semantic mapping**
- **Move beyond trial-and-error to simulation-driven innovation in refining and synthesizing the rarest elements on Earth**

A new era, powered by AI and quantum technologies, brings us ever closer to what was once thought impossible: not just isolating or identifying the world's rarest elements, but making them accessible, manipulable, and ultimately useful as resources for science, medicine, and technology. As we continue to refine these paradigms, we can look toward a future where the boundaries of nature's "rarest" elements are expanded, creating a platform for discovery as boundless as our curiosity itself.

Bold elements within this chapter highlight key properties, technological innovations, and strategic breakthroughs in rare element science. The referenced tools and experimental protocols form a cohesive roadmap for interdisciplinary research and transformative advancements in the understanding and manipulation of the most elusive materials in the known universe.

References (32)

1. *Lec14_QFD - Michigan State University*. https://web.pa.msu.edu/people/fisherw/Phy493_Spring2017/lectures/Lec14_QFD.pdf
2. *Shorter Pulses, Smaller Errors - arXiv.org*. https://arxiv.org/pdf/2311.02769v1
3. *Separation of protactinium from uranium-niobium alloys for*. https://link.springer.com/article/10.1007/s10967-023-08928-y
4. *Unlocking the Potential: Rare Earth Element Refining Methods*. https://haznet.org/unlocking-the-potential-rare-earth-element-refining-methods/
5. *Promethium* . https://www.britannica.com/science/promethium
6. *Thorium metal-organic framework crystallization for efficient recovery …*. https://pubs.rsc.org/en/Content/ArticleLanding/2025/SC/D4SC07652D
7. *Rare Earth Elements: A Review of Production, Processing, Recycling, and …*. https://clu-in.org/download/issues/mining/weber-presentation.pdf
8. *Improving Large-Scale Domestic Production of Americium-241, a Critical …*. https://isotopes.gov/Improving-Large-Scale-Domestic-Production-of-Americium-241
9. *A Complete Guide to Californium* . https://frontier-cf252.com/blog/complete-guide-californium/
10. *NEPTUNIUM RECOVERY AND PURIFICATION AT HANFORD*. https://digital.library.unt.edu/ark:/67531/metadc871473/

11. *Aclara to pilot REE plant at Virginia Tech - Metal Tech News*. https://www.metaltechnews.com/story/2025/08/13/mining-tech/aclara-to-pilot-ree-plant-at-virginia-tech/2431.html
12. *Transuranium Elements-Definition, Synthesis, and Uses*. https://chemistnotes.com/inorganic/transuranium-elements-definition-synthesis-and-uses/
13. *Einsteinium - Wikipedia*. https://en.wikipedia.org/wiki/Einsteinium
14. *Berkelium (Bk)* . https://www.ebsco.com/research-starters/science/berkelium-bk
15. *Curium* . https://www.britannica.com/science/curium-chemical-element
16. *Tales from the Atomic Age - The Discovery of Francium*. https://orau.org/health-physics-museum/articles/discovery-of-francium.html
17. *In the Classroom - perey.org*. https://perey.org/genealogy/MP%202.pdf
18. *Astatine - Wikipedia*. https://en.wikipedia.org/wiki/Astatine
19. *Curium Facts, Symbol, Discovery, Properties, Uses*. https://www.chemistrylearner.com/curium.html
20. *Separation and Purification of Berkelium-249 and Einsteinium-254*. https://info.ornl.gov/sites/publications/Files/Pub130252.pdf
21. *Astatine (At) - Discovery, Occurrence, Production, Properties and ...*. https://www.azom.com/article.aspx?ArticleID=7907
22. *Periodic Table of Elements: Los Alamos National Laboratory*. https://periodic.lanl.gov/99.shtml
23. *Microsoft Integrates Copilot with Azure Quantum Elements for ... - InfoQ*. https://www.infoq.com/news/2023/12/azure-quantum-elements/