The New Alchemy

By Michael McClure

In 1927, Georges Lemaitre, a Belgian priest, proposed that the universe began with a cosmic explosion of gigantic proportion. He suggested that before the explosion, there was a time when all of the matter and energy of the universe were packed together into one fantastically dense and unstable mass that he called the *cosmic egg*. A few minutes after the violent blast, protons and neutrons joined to create simple atomic nuclei. Some time later, electrons began interacting with the nuclei and atoms of the simplest elements, hydrogen and helium, were formed. As the rapidly expanding universe cooled, great clumps of gas condensed, heated up, and exploded in a burst of light. The first stars were born.

The stars were the crucibles in which nuclei were fused to form heavier elements. A star's energy comes from the fusion of nuclei as mass is converted to energy, according to Einstein's famous equation $E = mc^2$. Carbon, oxygen, neon, and all of the elements up to and including iron are synthesized during the life cycle of a star. Elements beyond iron are made when massive stars end their lives as supernovae. The nuclear reactions that produce elements beyond iron require more energy than they produce, so these elements will not form under the conditions of a normal star. But the enormous energy available in an exploding supernova is sufficient to drive nuclei and other particles together. As nuclei are forced to absorb protons and neutrons, they can grow to form elements with masses greater than that of iron, and they can continue to grow, forming elements as heavy as uranium.

The early years: Who were the players?

Billions of years later after that initial, tremendous blast, scientists in the 19th and 20th centuries would organize all of the known elements into neat rows and columns based on properties and atomic composition—the Periodic Table. In those early years, discoveries came fast and furious. It was predicted that new discoveries might one day reveal elements with masses and atomic numbers beyond uranium. What were these discoveries? Who were the men and women that unlocked the secrets of atoms and created the first transuranium (i.e., "beyond uranium") elements? Who succeeded in doing what early alchemists failed at—transforming one element into another?

Before we dive into these discoveries, let's first take a look at the basics of radioactivity.

Radioactivity

Radioactivity refers to spontaneous nuclear reactions that occur in various forms. Atoms that decay by alpha emission, for example, eject a particle consisting of 2 protons and 2 neutrons, in other words, a helium 2+ ion. The decay product, or daughter, is an element with two fewer atomic number units. For example, the isotope uranium-238 decays into thorium-234 by alpha emission.

$$^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}He$$

Other modes of radioactive decay include beta decay, positron emission, and electron capture.

Radioactivity can be used as a tool for exploring the atomic nucleus. In 1919, the New Zealand-born physicist Ernest Rutherford observed the reaction between alpha particles and gaseous nitrogen atoms in a cloud chamber. The cloud chamber is a flask filled with supersaturated vapor, in this case, nitrogen gas. Alpha particles streaking through the vapor knocked electrons from nitrogen molecules, creating electrically charged ions. Vapor mol-

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ecules condensed around the ions, allowing Rutherford to see the alpha particle path as a trail of tiny droplets, like the contrails of a jet aircraft.

Rutherford recorded the short tracks of many alpha particles in his experiment. Occasionally, he observed condensation tracks that were longer than expected. Because longer tracks implied less massive particles, Rutherford suggested that perhaps alpha particles were knocking out protons from the nucleus of nitrogen atoms. Gaining two protons, then losing one proton would change the nitrogen nucleus into oxygen-17. Rutherford had just observed the first artificial transmutation of an element.

$$^{14}_{7}\mathrm{N} + ^{4}_{2}\mathrm{He} \rightarrow ^{17}_{8}\mathrm{O} + ^{1}_{1}\mathrm{H}$$

Transmutation is the transformation of one element into another through one or a series of nuclear reactions

An artificial isotope

Later on in 1934, Irene Curie-Joliot, the daughter of Marie and Pierre Curie, and her husband Fredrick Joliot performed an experiment similar to Rutherfords'. Instead of nitrogen, they used aluminum as the target. In addition to protons flying away from the collision event, they observed the emission of neutrons and some new form of radiation (called a positron emission). Surprisingly, when they stopped the experiment, neutron emission stopped, but the radiation continued. How could this be? Curie-Joliot and her husband discovered that the reaction created the artificial element phosphorus-30. This isotope does not occur in nature, and it decayed into silicon by this newly discovered form of radiation—positron emission. They had witnessed the first artificial transmutation of a stable element into a radioactive isotope, by emission of an artificial form of radiation. In 1935, the Curie-Joliot's shared a Nobel Prize for this work.

$$^{27}_{13}\mathrm{Al} + ^{4}_{2}\mathrm{He} \rightarrow ^{30}_{15}\mathrm{P} + ^{1}_{0}n$$

$$^{30}_{15}\mathrm{P} \rightarrow ^{30}_{14}\mathrm{Si} + ^{0}_{+1}\mathrm{e}$$

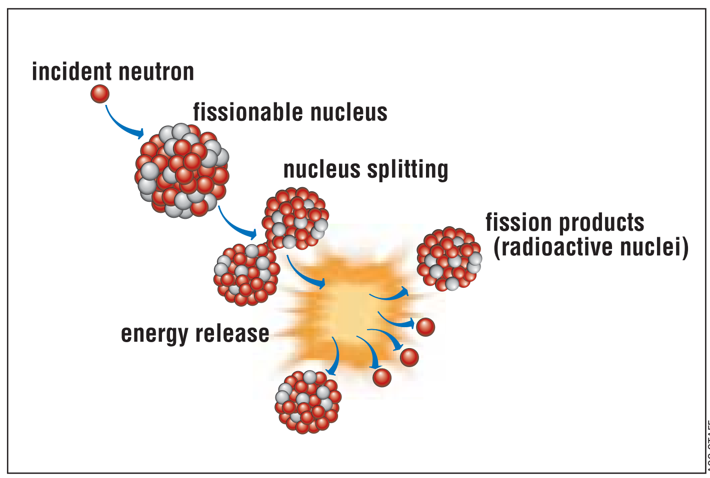
Transmutation is the transformation of one element into another through one or a series of nuclear reactions

Building new atoms and a stunning discovery

Early alchemists worked furiously trying to change one element into another, and they all came to the same conclusion: it's not easy. What they did not know is that positively charged protons inside the nucleus of every atom repel similarly charged particles. The characters of our story found that only positively charged particles with sufficient energy can overcome the strong repulsive forces and penetrate the nucleus. For this reason, Enrico Fermi, an Italian physicist, suggested that neutrons might make better nuclear missiles. Neutrons carry no electrical charge; they are neutral. Fermi and others believed that if a nucleus captured a neutron, it would try to correct for its neutron excess by beta decay, turning a neutron into a proton, thus creating an atom with an atomic number increased by one unit. Suppose uranium, the heaviest known naturally occurring element, could be forced to capture a neutron. This might make the uranium nucleus unstable and radioactive. If the unstable nucleus decayed by beta emission, a new element beyond uranium would be created.

Fermi and his collaborators bombarded uranium-238 (atomic number 92) atoms with slow neutrons. Other research groups were performing similar experiments. Initially, everyone claimed success in creating a new element with atomic number 93. But the mass of the product did not agree with the expected mass of element 93. Furthermore, its chemical properties seemed surprisingly like barium, an element much lighter than uranium. Lise Meitner, an Austrian physicist, was troubled by these findings. Looking closely at the results and making detailed calculations she came to the astonishing conclusion that uranium nuclei were splitting into smaller fragments! In seeking new elements beyond uranium, Fermi and others had stumbled upon the process of atomic fission. This discovery and the subsequent development of nuclear weapons and nuclear reactors impacted all of humanity.

Today, we know that Fermi's uranium sample contained trace amounts of uranium-235, a rare isotope that undergoes atomic fission when bombarded with neutrons. What Fermi and others did not realize was that element 93 had actually formed in the experiment, but was undetectable in the complex mixture.



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The process of nuclear fission.

A planetary element

The emission of alpha particles creates a recoil effect. This causes the product isotopes to fly away from each other and deposit some distance from where the decay event occurred. American physicist Edwin McMillan in the Radiation Laboratory at the University of California, Berkeley, wanted to know exactly how far the fission products would travel through matter. His experiment was simple. First, he stacked thin sheets of paper together to form a small book. On the top sheet he placed a sample of uranium salt. Next, he exposed the salt to a source of neutrons, which induced fission. As expected, the fission fragments traveled through the paper sheets stopping at various layers in the book. McMillan could determine the location of each fission product by separating the pages and measuring the radioactivity with a Geiger counter. But in addition to finding various fission products scattered among the pages, McMillan detected two separate beta activities in the topmost sheet. Two isotopes were not recoiling with the other fission fragments.

McMillan reasoned that perhaps not all isotopes of uranium undergo fission. Maybe uranium-238 was indeed capturing a neutron, as Fermi had suspected, and decaying into a new element. In 1940, Philip Abelson, another American physicist from the Carnegie Institution in Washington, went to Berkeley to help McMillan identify the mysterious beta activities. Soon they had successfully separated and identified the first transuranium element. They named the element neptunium (Np).

$$^{238}_{92}\mathrm{U} + ^{1}_{0}n \rightarrow ^{239}_{92}\mathrm{U}$$

$$^{239}_{92}\mathrm{U} \rightarrow ^{239}_{93}\mathrm{Np} + ^{0}_{+1}\mathrm{e}$$

Why name #93 neptunium? First take a guess, and then look to the end of the article for the answer.

The search went on …

McMillan suggested that the second short-lived beta decay product in the mixture might be an element with atomic number 94. The American scientists Glenn Seaborg, Arthur Wahl, and Joseph Kennedy were working on the World War II Manhattan Project with McMillan and decided to test his idea. First, they had to overcome two difficult problems. In McMillan's experiment, only small amounts

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Glenn Seaborg

of uranium-239 and neptunium were formed. And the long half-life of the unknown isotope made it difficult to measure its activity. Seaborg's group knew they would need to synthesize larger quantities of neptunium if they were to be successful in identifying the mysterious product. They solved these problems with the help of (American physicist) Ernest Lawrence's proton merry-go-round—the cyclotron. Lawrence's cyclotron could accelerate particles to enormous speeds, imparting enough energy to overcome the repulsive forces inside an atomic nucleus. Using the cyclotron, they produced large quantities of neptunium and then watched as the neptunium decayed into an element with atomic number 94. Seaborg's group was able to show that element 94 was radioactive, emitting alpha particles with a half-life of 90 years. After the tradition of naming elements for the planets, element 94 was named plutonium.

McMillan moved on to other projects, but

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between 1944 and 1974, Seaborg's group discovered nine additional transuranium elements. A few were synthesized in ever larger and more powerful cyclotrons, and some in nuclear reactors. Two new elements, einsteinium and fermium, were discovered in the nuclear fallout during thermonuclear weapons testing in the 1950s.

Revamping the periodic table

Where did the transuranium elements fit into the Periodic Table? Scientists soon learned that many transuranium elements had

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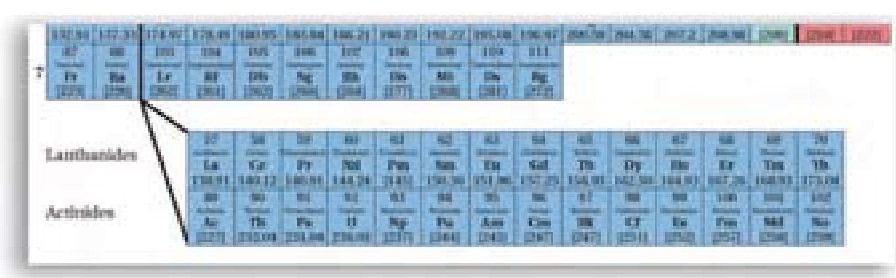
Seven-kilometer–long accelerator in French and Swiss country side near Geneva.

properties similar to the transition metals. In 1944, Seaborg proposed his Actinide hypothesis. He predicted that thorium, protactinium, uranium, and the first 11 transuranium elements would form a series of chemically similar elements following actinium (atomic number 89), similar to how the lanthanides follow lanthanum. Much research into the chemical properties of the transuranium elements has confirmed Seaborg's hypothesis.

The search continues …

Today, 111 elements are listed in the Periodic Table. There are 19 transuranium elements named after planets, countries of discovery, and scientists. And elements beyond atomic number 111 have been reported but remain unconfirmed and unnamed. Will there be an end to the discovery of transuranium elements? Will scientists reach the hypothesized "Island of Stability" where theory predicts elements with atomic numbers as high as 126 may be stable? No one knows the answers. But we do know the search will continue, and perhaps you might be involved. Larger accelerators will be built to smash atoms. New detectors will allow researchers to track and interpret the zoo of particles that form when atoms collide. And each new discovery will increase our understanding of the world around us, including you and me!



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