

# An Elementary Problem: Artificial Atoms, Nobel Prizes, and Your Smoke-Detector

*Delphine Farmer*

In 1941, Edwin McMillan and Glenn Seaborg discovered the atom that led us out of the Industrial Age and into the Atomic Age. Their discovery—a fissionable heavy isotope of plutonium—unleashed both massively destructive and fantastically profitable technologies. It led to the development of the atomic bomb, but also led to the generation of cheap and plentiful electricity. It resulted in cancer-causing nuclear radiation, but also in medical diagnostic technologies, and even the humble yet life-saving smoke detector. This story relates the discovery of one history-making atom, and the many others that followed.

Beginning in the late 1930's, there was a tremendous growth of interest in radiochemistry, spurred by the hope of finding or making new elements with unique and useful properties. Many

of the new elements (and earlier ones as well) were named for the places they were found or mined: gallium was identified in Gallia (Latin for France), germanium was found in Germany, yttrium was mined in Ytterby, Sweden. The search for new elements was also driven by patriotism and a healthy dose of competition. Not to be outdone, Seaborg, McMillan, and their colleagues at the University of California at Berkeley created berkelium, californium, and americium, pioneering the discovery of the artificial transuranium elements by the 1940s and winning Nobel Prizes for their work. Since then, the synthesis of new elements has continued, led by the scientists of UC Berkeley and the Ernest Orlando Lawrence Berkeley National Laboratory (LBL) in the USA, of Dubna in Russia, and of Darmstadt in Germany.

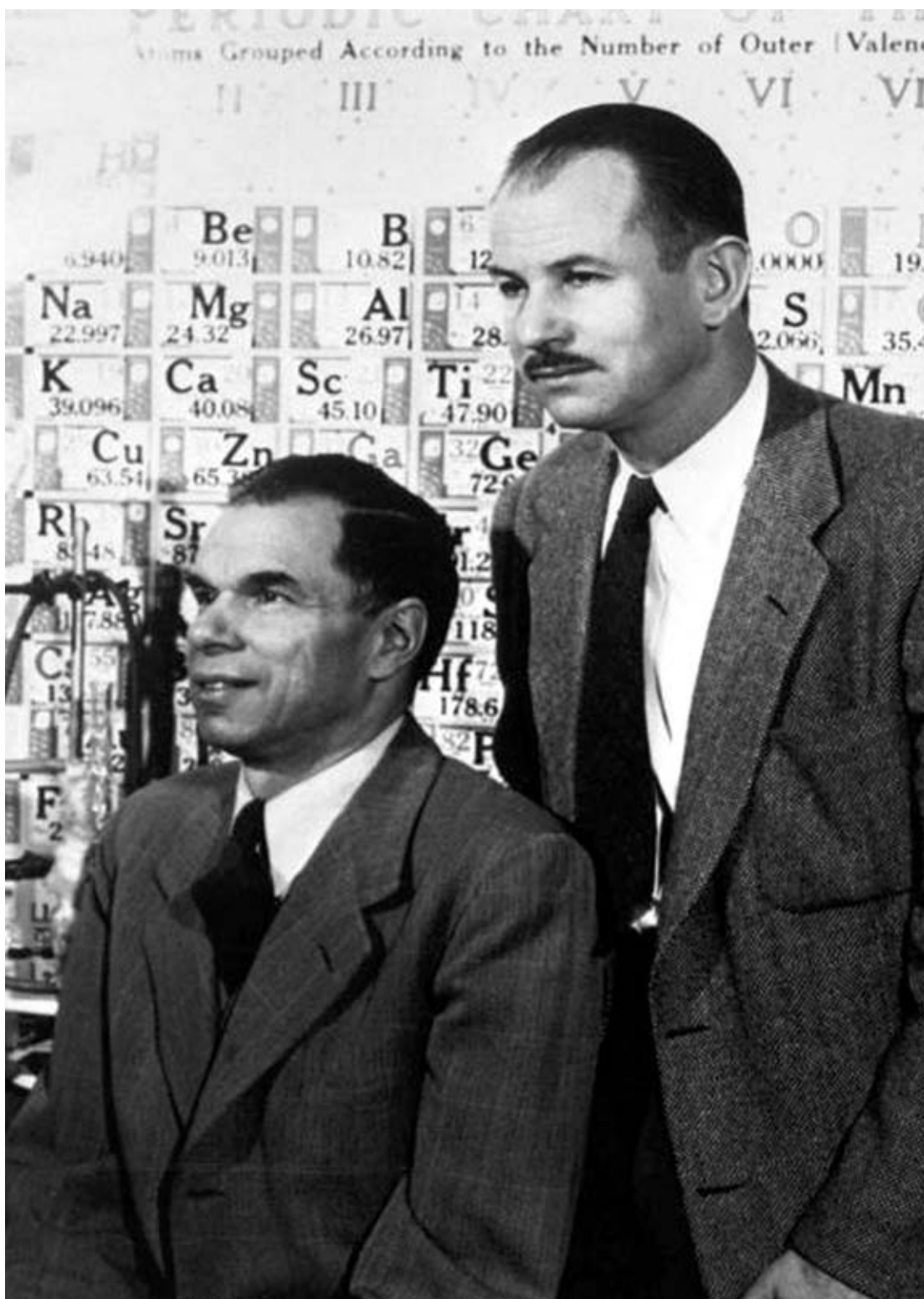
## Behold the Glory: Unstable Elements and the Periodic Table

When Russian chemist Dmitri Mendeleev conceived of the Periodic Table in 1872, he was interested in classifying the known elements on the basis of chemical properties and weight, but unwittingly managed to arrange the elements on the basis of electron configurations as well. Mendeleev's table has since been updated; at present, it features 112 elements, including the rare earth and artificial elements.

Each element of the periodic table has its own box, complete with two important quantities: atomic number and mass number. The atomic number is the number of protons in one atom of the element; atomic number determines the arrangements of the atom's electrons in space, which in turn determines the chemical properties of the atom. Elements in the same column of the table (called groups, or families) have a conserved number of electrons, each in a slightly different-shaped outer, or valence, shell. Elements in the same row, or period, of the Periodic Table have different numbers of electrons in similarly sized valence shells.

Most elements of the periodic table occur naturally. Each element exists in a number of unique forms, called isotopes. These forms have essentially identical structure, differing only in the number of neutrons contained by the atom. Certain isotopes are stable, while others—the radioisotopes—are not. Some elements, notably the artificial ones, have no known stable forms and are called "radioelements."

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Glenn Seaborg and Ed McMillan standing in front of the Periodic Table. The pair's work led to several additions to the Table, including plutonium and neptunium. Seaborg's name now appears alongside all the elements he helped discover. Element 106 is named seaborgium (LBNL Image Library).



Glenn Seaborg adjusts a Geiger counter during a search for plutonium. He looked a lot more excited when he finally found the first transuranium element (LBNL Image Library)

How did it all begin? In 1938, Otto Hahn and Fritz Strassman in Berlin developed a technique of fission by means of neutrons. By bombarding a nucleus with neutrons, these visionaries were able to make a nucleus so unstable that it flew apart with great energy. In 1939, news of this discovery reached UC Berkeley, prompting Edwin McMillan, a young physicist, to perform what he later described as “an experiment of a very simple kind.”

McMillan was interested in measuring the range of fission products as nuclei flew apart. To do this, he layered sheets of aluminium foil around a thin layer of uranium oxide. McMillan then shot accelerated deuterons (deuterium nuclei each composed of one neutron and one proton) at the uranium oxide, causing the products of radioactive fission to fly into the aluminium sheets. By analyzing the aluminium for radioactivity sheet by sheet, McMillan was able to determine where the fission products stopped, and thus their distance travelled.

This led to further experiments, in which McMillan obtained evidence of two processes following neutron bombardment of uranium: first, the absorption of a neutron to form a heavy uranium isotope ( $U^{239}$ ), and second, the resulting transformation to a new and heavier element. This new and heavier element—discovered by McMillan with the help of Berkeley chemist Philip H. Abelson—was, in fact, the first artificial element with more protons than uranium: the first transuranium element.

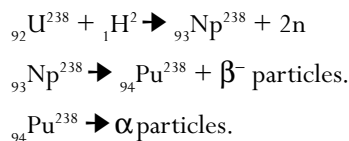
How did this transformation occur? Through the process of beta-decay, a neutron was converted to a proton, with the release of a beta-particle and excess energy from an antineutrino. This transformed the  $U^{239}$  into what McMillan first called element 93. This atom behaved in a very unexpected way. Periodic theory dictated that elements in a column of the periodic table would have similar properties, due to the similarity of their electron configurations. Thus McMillan and chemist Emilio Segrè thought that element 93 should behave like rhenium, another element in its column.

Instead, Segrè found the behavior to be more consistent with that of the rare earth elements. By performing some basic experiments, McMillan found a very simple explanation for the surprising results. The key was the oxidation state of the fission product. In a reduced state, with more electrons, the fission product behaved like a rare earth element. In an oxidized state, with fewer electrons, it did not. At this point, McMillan began examining the decay processes of the fission products, starting with a chemical isolation of the newly created element 93.

In 1940, Glenn Seaborg entered the game. Seaborg was a chemist, having received his doctorate in neutron research from UC Berkeley. Seaborg first observed alpha decay “growing into” isolated quantities of element 93. The simplest explanation for this alpha particle accumulation was contamination by uranium, which produces alpha-decay particles. But an analysis of alpha-decay particle path lengths and range soon ruled out that possibility. This suggested that a distinct alpha-producing element was being formed from element 93.

Then, one night in February 1941, Seaborg and his collaborators realized that something interesting was going on. Upon bombarding uranium with deuterons, he was getting McMillan’s element with 93 protons. Element 93 then underwent beta-decay to form a *new* element with 94 protons. Element 94 was relatively stable, but could undergo alpha-decay, producing the alpha particles originally observed:

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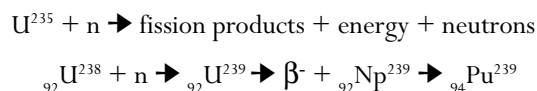


(The symbol  ${}_a\text{X}^b$  indicates an atom of an element with symbol X that has  $a$  protons and an atomic weight of  $b$ .  ${}_{92}\text{U}^{238}$ , for example means an atom of uranium, U, that has 92 protons and an atomic weight of 238, and thus 146 neutrons.)

Hence, while McMillan is credited with discovering element 93, Seaborg is credited with identifying element 94. By this time, the two new elements had not been completely characterized, but names were needed. McMillan suggested “neptunium” for element 93, as the element follows uranium in the same way that the planet Neptune follows Uranus. Following suit, Seaborg and his graduate student, Arthur Wahl, suggested “plutonium” for element 94. Of course, there is now some debate over whether or not Pluto is a planet, but it is unlikely that the name for element 94 will ever be changed.

Seaborg’s discovery that plutonium could be created by bombarding a sample of uranium with deuterons led directly to the artificial creation of several other transuranium elements, including americium (95), curium (96), berkelium (97), californium (98), einsteinium (99), fermium (100), mendelevium (101), nobelium (102) and seaborgium (106). Indeed, Seaborg and McMillan continued their search for new elements with a further examination of the recently discovered plutonium. In 1941, McMillan’s group made a heavier plutonium isotope with mass number 239, which had one more neutron than the previously discovered  ${}^{238}\text{Pu}$ .  ${}^{239}\text{Pu}$ , the heavier isotope, released vast amounts of energy in nuclear fission upon being bombarded with slow neutrons. Seaborg and his colleagues realized  ${}^{239}\text{Pu}$  could be used to generate energy, and thus immediately began working to manufacture pure  ${}^{239}\text{Pu}$  in large quantities.

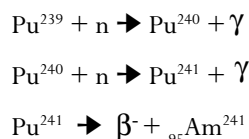
The problem of large-scale production was solved using chain-reacting units to take advantage of neutron-induced fission reactions of  $\text{U}^{235}$  in natural uranium. Enrico Fermi and his co-workers had demonstrated this technique in December 1942. Excess neutrons would be absorbed by  $\text{U}^{238}$ , which would then decay to form  ${}^{239}\text{Pu}$ :



At this point, Seaborg and his colleagues moved from UC Berkeley to the Metallurgical Laboratory at the University of Chicago to work

on the subsequent isolation of heavy plutonium. The group of young scientists, notably including Stanley G. Thompson, developed an isolation procedure for  ${}^{239}\text{Pu}$ .

In the late fall of 1944, Seaborg began bombarding plutonium with neutrons, leading to the formation of the next transuranium elements, starting with americium:



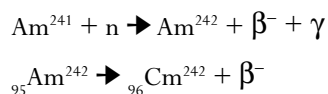
The new element americium (Am) had 95 protons, a 475-year half-life, and underwent alpha decay. Not only had Seaborg identified the element now used in most household smoke detectors, but he



Ed McMillan recreating his search for neptunium for a lab photographer. He wore a tie to school that day. (LBNL Image Library)

## feature

had also produced curium following bombardment of americium by neutrons:



In his 1951 Nobel acceptance speech, Seaborg commented that the chemical properties of these two new elements, americium and curium, were so consistent with expectation that they were almost boring. Based on their location on the periodic table, one would expect americium and curium to be very similar, both to each other and to all the rare earth elements. However, this expectation proved problematic when it was discovered that the two new elements were nearly impossible to isolate from each other and from the other rare earths. As actinides, the outermost, or valence, shell electron configuration was identical for both elements and their initial reactants. Thus the elements had similar chemical properties, such as solubility and reactivity with other chemicals, making standard separation on the basis of these properties difficult.



Fritz Strassmann (left), Lise Meitner, and Otto Hahn, 1956, in Mainz, Germany. Strassman and Hahn invented the technique of fission by neutron bombardment. The most recently named element, number 109, is the only one named for a woman. It's called meitnerium (LBNL Image Library).

### Behold the Glory: Unstable Elements and the Periodic Table *(cont.)*

By 1925, all the stable elements of the periodic table had been discovered. Two of the naturally occurring unstable elements had been discovered as well—uranium, the largest naturally occurring element, in 1789 and thorium in 1828. Soon afterward, Marie and Pierre Curie discovered another naturally occurring unstable element, radium, while investigating the process of radioactive decay. The idea of extending the periodic table by making new, but unstable, artificial elements led to the discovery of the previously missing elements technetium (Tc) and promethium (Pm). The study of artificial elements has also led to new technologies: nuclear energy, medical diagnostics, and even smoke detectors. To make a new element, a radiochemist must create a nucleus with more protons than those of previously discovered elements. However, for heavy elements this becomes difficult, as the addition of protons requires significantly more neutrons to maintain even slightly stable nuclei. The very existence of artificial elements has raised fundamental questions about our knowledge of atomic structure and the system of the periodic table. At the bottom of the periodic table, there are two rows each of fourteen artificial elements—the lanthanide and actinide series. The elements of these two series are often referred to as the rare earth elements, and were first discovered in the 1930s in Sweden. Interestingly, all the elements in the upper lanthanide row have similar properties—a pattern normally attributed to columns, not rows, of the periodic table.

This peculiarity can be explained by Niels Bohr's theory of the electron arrangement in an atom. In general, as atomic number increases among the elements, the additional electrons required to balance the additional protons are added to the outer shells. However, from lanthanum to lutetium, the additional electrons are placed in inner shells. Thus the outer shell configuration, which determines the element's chemical properties, remains the same, and the members of the lanthanide series retain similar properties and behavior. The discovery of the lanthanide series marked a turning point in the understanding of the system of the periodic table. The work of Seaborg and McMillan later showed that the actinide series behaves similarly.

The isolation of curium and americium gave the research group so many problems that the names “pandemonium” and “delirium” were proposed for the two elements. However, success was finally achieved when the elements were isolated and characterized. Element 95 was named americium after the Americas and by analogy to its homologue europium (63), named after the continent of Europe. Element 96 was named curium after pioneering radiochemists Pierre and Marie Curie.

Between 1940 and 1941, McMillan was obliged to give up his research in nuclear science to develop wartime radar and sonar equipment at the Massachusetts Institute of Technology. His studies at MIT led to the development of the synchrotron and the synchrocyclotron, two instruments that allow particles to be accelerated to extremely high energies. From 1942 to 1945, McMillan, like many of the era’s great physicists and chemists, was engaged in national defense research at the Manhattan District of Los Alamos. In 1946, McMillan returned to UC Berkeley as a professor of physics.

After World War II, Seaborg also returned to UC Berkeley, as a professor of chemistry. Once there, he continued to assist other Berkeley and LBL chemists in the discovery of berkelium in 1949 (named for the city in which the work was done, in the same way that its rare earth homologue, terbium, had been named after the Swedish town of Ytterby). The Berkeley group also discovered californium (98) in 1950, named in honor of both the university and the state.

In 1961, President John F. Kennedy appointed Seaborg as the Chairman of the Atomic Energy Commission—a position Seaborg continued to hold under the Johnson and Nixon administrations. Seaborg stepped down from the post in 1971 and returned to his research at LBL and UC Berkeley. He was an active researcher, educator, and civil servant until his death in February 1999.

Despite McMillan’s protestations that he was not a chemist, he and Glenn Seaborg received the 1951 Nobel Prize in Chemistry for their discoveries in the chemistry of the transuranium elements. UC Berkeley has since continued at the forefront of radiochemistry, investigating the synthesis and use of radionuclides and producing outstanding research in conjunction with LBL.

Given the great effort required to create, isolate, and characterize a new element, it seems only fitting that research teams should be able to name their discoveries themselves. While choosing a name for a new element is the prerogative of the origi-

## Occupational Hazards of a World Famous Scientist



Nobel Prize-winning scientist Glenn Seaborg was enjoying a swim in Berkeley’s University Club pool, when he was summoned directly from the clear chlorinated waters to receive a telephone call from President Johnson. At this time it was an exclusively male club and members frequently swam nude. “I didn’t have time to even grab a towel because I knew

whatever he wanted I’d have to react right away. He came up with some kind of proposal I knew wouldn’t be feasible, but if I didn’t talk him out of it right then I’d be in trouble... then, of course, I went back and continued my swim.”

Cartoon by Herb Stansbury (LBNL)

nal discovery team, official recognition must await independent confirmation of the discovery by the scientific community. The naming of elements has resulted in numerous arguments between the Germans, Russians, and Americans, as the discovery of ever-bigger elements became a matter of national pride at the height of the Cold War.

For example, element 104 was first identified in 1964 by Russian scientists in Dubna, who named it “kurchatoviu” (Ku), in honor of a Russian physicist. The Berkeley scientists who had been simultaneously working on the same element named it “rutherfordium” (Ru) in honor of Ernest Rutherford, a New Zealand-born physicist who made his discoveries in England and Canada. Although the Dubna group was the first to announce element 104, they had difficulty in distinguishing between different isotopes—a feat that was successfully accomplished by the Berkeley group in 1969. The two groups, of course, laid claims to different names, with the result that the International Union of Pure and Applied Physics has chosen a neutral and temporary name, “unnilquadium.”

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Birkett is quick to explain that worksheets and teaching notes aren't enough: "You can have the best [curriculum] materials in the world, but if the teacher doesn't know how to use them, it doesn't matter. Supporting the GSIs is crucial." To help GSIs in their own professional teaching development, Birkett teaches Physics 300, the Department's graduate pedagogy course. The course is required for first-time GSIs, and it allows GSIs to share observations and comments. These can be quite specific, since everyone teaches from the same worksheets and teaching notes. First-time 7A and 7B GSIs also receive extra pre-semester training to prepare them for going "into the trenches" (as Birkett likes to put it) with their students.

This is the moment when Birkett gets to ask his two favorite questions of his new GSIs: "How do you, a successful graduate student at Cal, learn material that is hard for you?" and "What do you want your students to do to help them learn physics for themselves?" His goal is to help students in his courses develop the same habits as successful graduate students at UC Berkeley. "No teacher can *make* a student learn anything. Indeed, I read a quote recently that 'the aim of teaching is to make student learning possible.' I think I agree," muses Birkett.

So perhaps the secret of the success of the DL format classes is that the format encourages students to do a better job of helping themselves learn. "In-class participation is really high," says Vale. "Some of the kids are real hams who are ecstatic to finally have a teacher who actually wants them to talk in class." Instructors also report surprisingly high attendance for Physics 7A and 7B. "[My students] kept coming to 7A discussion section throughout the term, whereas in the other classes they drifted away as the semester went on," says former GSI Robin Blume-Kahout.

Vale sums it all up dramatically: "My 8 a.m. section attendance is about 95%, compared with about 50% for my afternoon (old-format) 7A section... And within a few weeks, the whole class is merrily chatting away about—can you believe it—Physics!" ■

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## An Elementary Problem (cont. from previous page)

Element 105 has a similarly awkward history. While it was first announced by the Dubna scientists in 1970, the Berkeley group claimed to have identified it a year earlier. The Soviet group had not proposed a name, so the Berkeley group named it "hahnium" after Otto Hahn. However, in 1997, panel members of the International Union of Pure and Applied Physics suggested that element 105 be called "dubnium," in honor of the Joint Institute for Research in Dubna, Russia. Although the name "hahnium" is still used by some, the rules for naming new elements prevent it from ever being officially appropriated into the periodic table. In any case, as the the Russian and American groups raced to claim new elements, their analytical and synthetic techniques improved. Many of the techniques they developed are now widely used in the field of radiomedicine.

Even today, many of the elements named in periodic tables published in the United States are contested in international settings. However, the most recently named element, meitnerium (109), has avoided such controversy, as the crucial role of Lise Meitner in nuclear chemistry is recognized worldwide. Meitner is the only woman to occupy her own square on the periodic table; curium was named for the husband-and-wife team of Pierre and Marie Curie.

Those who have paid close attention to more recent versions of the periodic table may have noticed that element 106 has acquired a new name—seaborgium. In 1994, seaborgium was named after Glenn Seaborg, the first living person to have an element named in his honor. The element was made by a team of scientists at LBL and the Lawrence Livermore National Laboratory, led by Kenneth Hulet and Albert Ghiorso. Seaborgium has a half-life of less than half a minute, so it exists only in ephemeral laboratory-confined flashes. Yet Seaborg responded to his new namesake by enthusiastically proclaiming, "this is the greatest honor ever bestowed upon me—even better, I think, than winning the Nobel Prize."

While the search for ever-heavier artificial elements continues, the difficulty in synthesizing them increases: for every proton added, many more neutrons are required for stability. There is, however, hope for future artificial elements—theory predicts an "island of stability" for elements with 114 protons and 184 neutrons. But until that island is reached, chemists must be satisfied with 112 identified elements, and 109 of those elements named. But while the names may endure for generations to come, the newest elements tend to last only a few moments before decaying away towards stability. ■