

Transuranium Elements: Past, Present, and Future

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Beginning in 1940, we have seen the synthesis and identification, i.e., the discoveries, of 19 elements with atomic numbers greater than that of uranium (element 92): the transuranium elements. This has added 20% to our list of chemical elements. The study of these elements has added much of our understanding of nuclear and atomic structure, the periodic table, and nuclear reaction mechanisms.

Each of these elements has a number of known isotopes, all radioactive, the overall total being about 200. Predictions indicate that an additional 500 should have half-lives sufficiently long to allow identification (greater than 10^{-6} s). Synthetic in origin, they are produced in a variety of transmutation reactions by neutrons or charged particles, including heavy ions. [Neptunium (element 93) and plutonium (element 94) are, in addition, present in nature in very small concentrations.] There is a total of some 30 isotopes with half-lives long enough to be available in macroscopic (weighable) quantities.

Many of the transuranium elements are produced and isolated in large quantities through the use of neutrons furnished by nuclear fission reactors: plutonium in ton quantities; neptunium, americium (atomic number 95), and curium (atomic number 96) in kilogram quantities; berkelium (atomic number 97) in 100-mg quantities; californium (atomic number 98) in gram quantities; and einsteinium (atomic number 99) in milligram quantities. Transuranium isotopes have found many practical applications: as nuclear fuel for the large-scale generation of electricity; as compact, long-lived power sources for use in space exploration; as means for diagnosis and treatment in medicine; and as tools in numerous industrial processes, in agriculture, and in research in the arts and humanities.

In this illustrative Account I shall concentrate on four of these elements, chosen for their current interest or pivotal role. The story of plutonium is one of the most dramatic in the history of science, and today, plutonium is at the focus of an extraordinary dilemma. Mendelevium (element 101) has played a pivotal role in blazing the trail for the discovery of the heaviest elements on the basis of "one atom at a time" produc-

tion. Seaborgium (element 106) was recently named in my honor by the discoverers and may be the last element, at least for some time, for which it will be possible to determine many chemical properties. And element 110 represents recent evidence, after a lapse of 10 years, for the discovery of a chemical element.

Recent (1994) recommendations of the IUPAC Commission on the Nomenclature of Inorganic Chemistry for the renaming of elements 104–108 have met with widespread rejection. I am using here the names proposed by the acknowledged discoverers (elements 106–109) or, in the case of the disputed elements 104 and 105, the most logical names.

Plutonium (94)

Soon after the discovery of neptunium¹ (element 93) in the spring of 1940 at the University of California, Berkeley, by Edwin M. McMillan and Phillip H. Abelson, the search for the next transuranium element was underway. Plutonium was discovered in late 1940 and early 1941 by McMillan, Joseph W. Kennedy, Arthur C. Wahl, and me as a result of our bombarding uranium with deuterons in the Berkeley 60-in. cyclotron.^{2,3} This particular isotope was later shown to be ²³⁸94. Early in 1941 the isotope of major interest, ²³⁹94, was discovered by Kennedy, Emilio Segrè, Wahl, and me⁴ in uranium bombarded with neutrons produced in the Berkeley cyclotron. It was shown to be fissionable with slow neutrons. These experiments, conducted as a part of the research program of the investigators in an academic environment and without governmental financial support, led to the plutonium part of the Manhattan Project.

When the United States entered World War II immediately after Pearl Harbor in December 1941, plans were immediately implemented to develop methods for the manufacture of plutonium in sufficient quantity for use as the explosive ingredient in atomic bombs. I moved to Chicago to be responsible for the chemical process to be used for the extraction of plutonium after its production in chain reactors (known in those days as piles). After the operation of the pilot plant in Oak Ridge, TN, plutonium was produced in the production plant at Hanford, WA, leading to the atomic bomb tested on July 16, 1945, at Alamogordo, NM, and used at Nagasaki, Japan, on August 9, 1945, to bring an end to World War II.

The name plutonium (with the chemical symbol Pu)

[†] This work was supported by the U.S. Department of Energy under Contract DE-AC03-76SF00098.

(1) McMillan, E. M.; Abelson, P. H. *Phys. Rev.* **1940**, *57* (12), 1185–1186.

(2) Seaborg, G. T.; McMillan, E. M.; Kennedy, J. W.; Wahl, A. C. *Phys. Rev.* **1946**, *69* (7/8), 366–367.

(3) Seaborg, G. T.; Wahl, A. C.; Kennedy, J. W. *Phys. Rev.* **1946**, *69* (7/8), 367.

(4) Kennedy, J. W.; Seaborg, G. T.; Segrè, E.; Wahl, A. C. *Phys. Rev.* **1946**, *70* (7/8), 555–556.

Winner of the 1951 Nobel prize in chemistry (with E. M. McMillan) for his work on the chemistry of the transuranium elements, Glenn T. Seaborg is one of the discoverers of plutonium (element 94) and nine other transuranium elements and the founder of the actinide concept of heavy element electronic structure. His codiscoveries include many isotopes which have practical applications in research, medicine, and industry. Known also for his contributions to science education and community service, he has been awarded 50 honorary degrees. From 1961 to 1971, he served as chairman of the United States Atomic Energy Commission. Today, he is university professor of chemistry at the University of California, Berkeley, associate director at large of the Lawrence Berkeley Laboratory, and chairman of the Lawrence Hall of Science. He is actively involved with research on new isotopes and new elements at the upper end of the periodic table. On March 13, 1994, the discoverers of element 106 recommended that element 106 be named seaborgium, with the chemical symbol Sg, in his honor.



Figure 1. Room 307 Gilman Hall at the University of California, Berkeley. This photograph was taken on February 21, 1966, when the room was still much the same as it was at the time of the first chemical identification of plutonium.

was suggested for element 94 in a secret report⁵ written on March 21, 1942, but published after the war. The results were held secret in our reports to the government on a voluntary basis. Room 307 Gilman Hall (on the Berkeley campus) (Figure 1), where the critical step in the chemical identification of plutonium was conducted on February 23–24, 1941, has been declared a National Historic Landmark. Likewise, Room 405 Jones Laboratory (at the University of Chicago), where the first isolation of a weighable amount of plutonium took place on September 10, 1942, has also been declared a National Historic Landmark. My journals giving a day-by-day account of this entire period have recently been published in *The Plutonium Story*.⁶

The intervening years of the Cold War have seen the buildup of the stockpile of weapons plutonium by both the United States and the Soviet Union to the level of hundreds of tons. With the end of the Cold War, we are now faced with the dilemma of disposing of these huge quantities of plutonium. One option being considered is to dispose of them in waste form in such a manner that it would be difficult or impos-

sible to recover the plutonium. Another option is to incorporate the plutonium in a mixed-oxide fuel, a mixture of plutonium and uranium oxides, and use it to fuel commercial power reactors. This second option is the one that I believe is the more sensible. Russia is inclined to exploit the use of weapons plutonium as fuel in nuclear power reactors.

Some countries, notably Japan and France, foresee a broad use of civilian stocks of plutonium as fuel for breeder reactors or other types of advanced nuclear reactors. The quantity of such plutonium is even larger than that in military stocks and growing much faster, by some 60–70 metric tons (t) each year. Close to 100 t of civilian reactor-grade plutonium is now stored in separated form in various countries, and a much larger quantity, about 600 t, is present in the unprocessed spent fuel from civilian power reactors.

Another legacy of the Cold War program is the negative environmental impact of the concomitant pileup of nuclear materials at the various production and fabrication sites. The cleanup programs will require the expenditure of huge sums of money over the coming decades and the training of a cadre of scientists to give direction to this effort. Unfortunately, there is a severe shortage of scientists with the proper background. One organization that is gearing up to solve this problem is the Glenn T.

(5) Seaborg, G. T.; Wahl, A. C. *J. Am. Chem. Soc.* **1948**, *70*, 1128–1134.

(6) *The Plutonium Story: The Journal of Professor Glenn T. Seaborg 1939–1946*; Kathren, R. L., Gough, J. B., Benefiel, G. T., Eds.; Battelle Press: Columbus, OH, and Richland, WA, 1994.

1 H 1.008																	1 H 1.008	2 He 4.003		
3 Li 6.940	4 Be 9.02													5 B 10.82	6 C 12.010	7 N 14.008	8 O 16.000	9 F 19.00	10 Ne 20.183	
11 Na 22.997	12 Mg 24.32	13 Al 26.97													13 Al 26.97	14 Si 28.06	15 P 30.98	16 S 32.06	17 Cl 35.457	18 Ar 39.944
19 K 39.096	20 Ca 40.08	21 Sc 45.10	22 Ti 47.90	23 V 50.95	24 Cr 52.01	25 Mn 54.93	26 Fe 55.85	27 Co 58.94	28 Ni 58.69	29 Cu 63.57	30 Zn 65.38	31 Ga 69.72	32 Ge 72.60	33 As 74.91	34 Se 78.96	35 Br 79.916	36 Kr 83.7			
37 Rb 85.48	38 Sr 87.63	39 Y 88.92	40 Zr 91.22	41 Nb 92.91	42 Mo 95.95	43 Tc	44 Ru 101.7	45 Rh 102.91	46 Pd 106.7	47 Ag 107.880	48 Cd 112.41	49 In 114.76	50 Sn 118.70	51 Sb 121.76	52 Te 127.61	53 I 126.92	54 Xe 131.3			
55 Cs 132.91	56 Ba 137.36	57 La 138.92	58-71 SEE SERIES	72 Hf 178.6	73 Ta 180.88	74 W 183.92	75 Re 186.31	76 Os 190.2	77 Ir 193.1	78 Pt 195.23	79 Au 197.2	80 Hg 200.61	81 Tl 204.39	82 Pb 207.21	83 Bi 209.00	84 Po	85 At	86 Rn 222		
87 Fr	88 Ra	89 Ac SEE SERIES	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm											

LANTHANIDE SERIES	57 La 138.92	58 Ce 140.13	59 Pr 140.92	60 Nd 144.27	61 Pm	62 Sm 150.43	63 Eu 152.0	64 Gd 156.9	65 Tb 159.2	66 Dy 162.46	67 Ho 163.5	68 Er 167.2	69 Tm 169.4	70 Yb 173.04	71 Lu 174.99
ACTINIDE SERIES	89 Ac	90 Th 232.12	91 Pa 231	92 U 238.07	93 Np 237	94 Pu	95 Am	96 Cm							

Figure 2. Periodic table showing the heavy elements as members of an actinide series. The author formulated this arrangement in 1944, and it was first published in *Chemical & Engineering News* in December 1945. Source: Seaborg, G. T. *Chem. Eng. News*, Dec 10, 1945, 23 (23), 2190-2193. Published 1945 American Chemical Society.

Seaborg Institute for Transactinium Science (ITS), created and centered at the Lawrence Livermore Laboratory. One of the missions of the ITS is to help furnish a supply of scientists and engineers with the knowledge and expertise required to meet the changing needs of the United States in national security and energy policy, including environmental restoration and remediation, environmental studies, processing and waste minimization, and nuclear waste isolation. The ITS, as a part of the University of California, is able to draw on the university's resources, particularly its background in the science and technology of the heaviest elements, long a specialty of the UC-managed national laboratories: Lawrence Berkeley Laboratory, Lawrence Livermore National Laboratory, and Los Alamos National Laboratory. The ITS also has ready access to expertise at other national laboratories with programs in heavy element science as well as campuses in the University of California system and numerous universities and research institutes in the United States and abroad.

Mendelevium (101)

Mendelevium (element 101), the ninth transuranium element to be discovered, was first identified by Albert Ghiorso, Bernard G. Harvey, Gregory R. Choppin, Stanley G. Thompson, and me⁷ in early 1955 as a result of the bombardment of about 10⁹ atoms of the isotope ²⁵³Es (20-day half-life) with helium ions in the Berkeley 60-in. cyclotron. The isotope produced was ²⁵⁶Md, which decays with a short half-life (approximately 1 h) by electron capture to ²⁵⁶Fm, which in turn decays predominately by spontaneous fission with a half-life of 2.6 h. This first identification was notable

(7) Ghiorso, A.; Harvey, B. G.; Choppin, G. R.; Thompson, S. G.; Seaborg, G. T. *Phys. Rev.* 1955, 98, 1518-1519.

in that only a few atoms per experiment were produced. The definitive experiments were performed in a memorable all night session, February 18, 1955, with chemical identification by the ion exchange adsorption elution technique. A total of five spontaneous fission counts were observed in the element 101 portion, and a total of eight spontaneous fission events were also observed in the element 100 position. This element was the first to be discovered on a one-atom-at-a-time basis, and the techniques developed served as a prototype for the discovery of subsequent elements. The extreme sensitivity for detection depended on the fact that mendelevium's chemical properties could be accurately predicted as eka-thulium, and a high sensitivity for detection existed because of the spontaneous fission decay.

The chemical identification could be made on the basis of my actinide concept which I had proposed in a secret report⁸ in July 1944 at the Metallurgical Laboratory at the University of Chicago. In this concept, I placed the transuranium elements as homologues of the rare earth, i.e., the lanthanide, elements. My first version of this periodic table was published after the war in December 1945, in *Chemical & Engineering News* (Figure 2). This made it possible to predict that element 101 would be chemically analogous to the rare earth element thulium and, thus, could be chemically identified on a one-atom-at-a-time basis using the technique of elution from a cation ion-exchange resin in which element 101 would elute in the eka-thulium position. The elution curve for the 1955 discovery experiment is shown in Figure

(8) Seaborg, G. T. Metallurgical Laboratory Memorandum MUC-GTS-858, July 17, 1944; Metallurgical Project Report CK-1968, July 17, 1944; pp 55-57. Also reproduced in the following: *Modern Alchemy: The Selected Papers of Glenn T. Seaborg*; Seaborg, G. T., Ed.; World Scientific Publishing: Singapore, River Edge, NJ, London, and Hong Kong, 1994; pp 145-148.

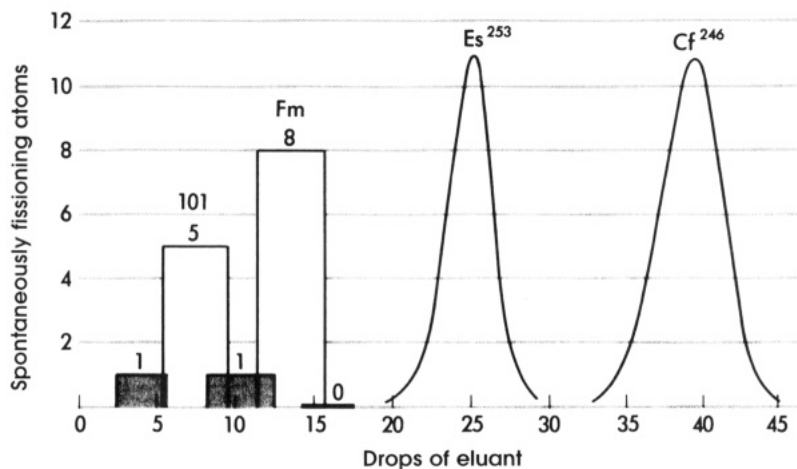


Figure 3. Original elution data corresponding to the discovery of mendelevium, February 18, 1955. The calibration curves for einsteinium-253 and californium-246 are for α -particle emissions. (Dowex-50 ion-exchange resin was used, and the eluting agent was ammonium α -hydroxyisobutyrate).

3. The elements elute in the reverse order of atomic number, leading to an element by element correspondence between the individual lanthanide and actinide elements.

The discoverers suggested the name mendelevium for element 101, in recognition of the pioneering role of the great Russian chemist, Dmitri I. Mendeleev, who devised the periodic table and predicted the chemical properties of undiscovered elements, a principle which served as the key to the discovery of so many transuranium elements.

In 1992, a nine-member group, the Transfermium Working Group (TWG), including seven members representing the International Union of Pure and Applied Physics (IUPAP) and only two members of the International Union of Pure and Applied Chemistry (IUPAC), issued a report, "Discovery of the Transfermium Elements",^{9,10} with suggestions for the allocation of credit for the discovery of the elements with atomic numbers greater than 100. In this report, credit for the discovery of mendelevium was mistakenly, I believe, not allocated to the 1955 Berkeley group. This chemical identification on a "one atom at a time" basis has always been regarded by the scientific community as a classic radiochemical experiment.

Seaborgium (106)

The element with the atomic number 106 was synthesized and identified 20 years ago (1974) but was not given a name until this year. The investigators¹¹ who have now been officially sanctioned as the discovery team were a group from the Lawrence Berkeley Laboratory (LBL)—Albert Ghiorso, J. Michael Nitschke, Jose R. Alonso, Carol T. Alonso, Matti Nurmi, and I—and from the Lawrence Livermore National Laboratory (LLNL)—E. Kenneth Hulet and Ronald W. Loughheed (Figure 4). The experiment was performed at LBL's Heavy Ion Linear Accelerator

(HILAC) by bombarding ^{249}Cf with ^{18}O to produce the isotope $^{263}106$. The new nuclei were shown to decay by the emission of α particles with a half-life of 0.9 s and a principal α energy 9.06 MeV to the previously known ^{259}Rf , which in turn was shown to decay to the known $^{104}_{102}\text{No}$. Thus the atomic number of the new nucleus was firmly established by a genetic relationship to its daughter and granddaughter.

At about the same time another claim¹² to the discovery of element 106 was made by a Russian group working at the Laboratory of Nuclear Reactions at the Joint Institute for Nuclear Reactions in Dubna, Russia: Georgiy N. Flerov, Yuri Ts. Oganessian, Yu. P. Tretyakov, A. S. Iljinov, A. G. Demin, A. A. Pleve, S. P. Tret'yakova, V. M. Plotko, M. P. Ivanov, N. A. Danilov, and Yu. S. Korotkin. They reported the observation of a spontaneous fission activity with a half-life of 4–10 ms, produced by bombarding $^{207}_{82}\text{Pb}$ with $^{54}_{24}\text{Cr}$, which they assigned to $^{259}106$ on the basis of reaction systematics.

Because of the competing claims, the two groups agreed not to propose a name for element 106 until it could be determined which group had priority for the discovery. In 1976, an international group of scientists proposed criteria¹³ for the discovery of new chemical elements and suggested that one of these should be that new elements not have a name proposed by the discoverers until the observation is confirmed.

In 1984, another group of investigators¹⁴ at the Dubna laboratory showed that the spontaneous fission activity attributed in 1974 to element 106 by the Flerov group was actually due primarily to the daughter of element 106 and not to element 106, thus effectively invalidating the Dubna claim to the discovery of element 106. In 1992, the Transfermium Working Group credited the discovery of element 106 to the Berkeley–Livermore group.

(9) Barber, R. C.; Greenwood, N. N.; Hryniewicz, A. Z.; Jeannin, Y. P.; Lefort, M.; Sakai, M.; Ulehla, I.; Wapstra, A. H.; Wilkinson, D. H. *Prog. Part. Nucl. Phys.* **1992**, *29*, 453–530.

(10) Barber, R. C.; Greenwood, N. N.; Hryniewicz, A. Z.; Jeannin, Y. P.; Lefort, M.; Sakai, M.; Ulehla, I.; Wapstra, A. H.; Wilkinson, D. H. *Pure Appl. Chem.* **1991**, *63*, 879; **1993**, *65*, 1757–1814.

(11) Ghiorso, A.; Nitschke, J. M.; Alonso, J. R.; Alonso, C. T.; Nurmi, M.; Seaborg, G. T.; Hulet, E. K.; Loughheed, R. W. *Phys. Rev. Lett.* **1974**, *33*, 1490–1493.

(12) Oganessian, Yu. Ts.; Tretyakov, Yu. P.; Iljinov, A. S.; Demin, A. G.; Pleve, A. A.; Tret'yakova, S. P.; Plotko, V. M.; Ivanov, M. P.; Danilov, N. A.; Korotkin, Yu. S.; Flerov, G. N. *JEPT Lett.* **1974**, *20*, 265–266.

(13) Harvey, B. G.; Herrmann, G.; Hoff, R. W.; Hoffman, D. C.; Hyde, E. K.; Katz, J. J.; Keller, O. L., Jr.; Lefort, M.; Seaborg, G. T. *Science* **1976**, *193*, 1271–1272.

(14) Demin, A. G.; Tret'yakova, S. P.; Utryonkov, V. K.; Shirokovsky, I. V. *Z. Phys.* **1984**, *A315*, 197–200.



Figure 4. The codiscoverers of element 106, seaborgium (Sg) at the Heavy Ion Linear Accelerator building of the Lawrence Berkeley Laboratory at the time of discovery in 1974. From left to right: Matti Nurmi, Jose R. Alonso, Albert Ghiorso, E. Kenneth Hulet, Carol T. Alonso, Ronald W. Lougheed, Glenn T. Seaborg, and J. Michael Nitschke.

In 1993, another LBL group of investigators,¹⁵ using the 88-in. cyclotron, repeated and confirmed the results obtained by Ghiorso *et al.* on the discovery of element 106 in 1974. Thus the way was cleared for the Ghiorso group to suggest a name for element 106.

The eight members of the Ghiorso group each suggested a name or names, with very disparate results. Some of the names suggested to be honored were the famous and extraordinarily versatile nuclear physicist Luis Alvarez; the eminent French nuclear scientist Frederic Joliot (a transfer of the Dubna suggestion for naming element 102); the scientific giant Sir Isaac Newton; the famous inventor Thomas Edison; the famous scholar and inventor Leonardo da Vinci; early explorers such as Christopher Columbus, Ferdinand Magellan, and the mythical Ulysses; the great American statesman George Washington; a Russian scientist such as Peter Kapitza or Andrei Sakharov; and the native land of a member of the discovery team, Finland.

(15) Gregorich, K. E.; Lane, M. R.; Mohar, M. F.; Lee, D. M.; Kacher, C. D.; Sylwester, E. R.; Hoffman, D. C. *Phys. Rev. Lett.* **1994**, *72*, 1423–1426.

Then Ghiorso took the initiative to suggest another approach. He met with (or contacted) the other six members of the discovery group (i.e., without my participation) and suggested that element 106 be named “seaborgium” (symbol Sg). He received unanimous agreement on this suggestion. Ghiorso then met with me and made this proposal for the naming of element 106. Caught completely by surprise, I asked for time to consider it. After discussing it with my wife Helen and a number of others, all of whom were enthusiastically in favor of this suggestion, I assented to this action.

It was decided to have the announcement made by Kenneth Hulet of the Lawrence Livermore National Laboratory at the meeting of the American Chemical Society (ACS) in San Diego to be held in March 1994. The occasion would be the opening session on Sunday, March 13, of the symposium in honor of Hulet in recognition of his receipt of the prestigious ACS Award for Nuclear Chemistry. This was done by Hulet in a dramatic session, well attended, that morning in San Diego.

The name seaborgium for element 106 has been

endorsed by the ACS Committee on Nomenclature and Board of Directors. The International Union of Pure and Applied Chemistry (IUPAC) is in the process of considering the names proposed by the discoverers for elements 104–109; its Commission on the Nomenclature of Inorganic Chemistry (CNIC) met in August 1994 and made some disparate recommendations which I shall not attempt to review here.

Recently, longer-lived isotopes (^{265}Sg and ^{266}Sg) have been synthesized and identified (with half-lives as long as tens of seconds).¹⁶ This should make it possible to study the chemical properties of seaborgium, which is a homologue of tungsten (atomic number 74). Thus we may look forward to obtaining evidence for such compounds as seaborgium bromide, seaborgium sulfate, calcium seaborgate, etc.

Element 110

It is now 10 years since the discovery of a transuranium element, hassium (element 108), in 1984, at the GSI laboratory in Germany. Recently, successful efforts have been made, and are presently underway, for the discovery of the next one, element 110.

The half-lives and yields of the transuranium elements decrease rather dramatically with increasing atomic number. The known isotopes of nielsbohrium (107), hassium (108), and meitnerium (109) have half-lives of only milliseconds and production rates that decrease to the level of one atom per weeks of bombardment. Thus the half-lives and yields of isotopes of element 110 are expected to be very small.

In August and September 1991, an experiment to synthesize element 110 by the $^{59}\text{Co} + ^{209}\text{Bi} \rightarrow ^{267}\text{110} + \text{n}$ reaction was performed at the Lawrence Berkeley Laboratory by a group under the leadership of Albert Ghiorso.¹⁷ One event with many of the expected characteristics of a successful synthesis of $^{267}\text{110}$ was observed. The basic idea of the experiment was to bombard ^{209}Bi with ^{59}Co ions, furnished by the Super-HILAC, at an energy near the barrier to observe the production of a very short-lived α particle emitter (predicted energy 11–12 MeV) that would be connected genetically to known nuclei of lower atomic number. (This is the method of establishing the atomic number of a new element through its genetic relationship with known descendants of decay, such as was used for the discovery of seaborgium, element 106, as described in the previous section.)

A new gas-filled magnetic separator and detector was especially constructed for this experiment. One unique event was observed in the entire 41-day interval, the element-110 candidate, with the observed magnetic rigidity, energy, and energy loss expected for element 110. This atom of element 110, presumed to

be $^{267}\text{110}$, decayed with the emission of an 11.6-MeV α particle, after 4 μs (reasonably consistent with predictions). Due to a failure of the electronics, the α decay of the daughter $^{263}\text{108}\text{Hs}$ to $^{259}\text{106}\text{Sg}$ could not be detected. Presumably the ^{259}Sg then underwent undetected electron capture decay to $^{259}\text{95Ha}$, which in turn decayed in 6.0 s to $^{255}\text{103}\text{Lr}$ by the emission of an α particle which escaped in the backward direction. Finally, the known 22-s. ^{255}Lr decayed in 19.7 s with the observed full energy of its known 8.3-MeV α particle.

Alternative scenarios, such as might be devised from transfer-product decays or random events, were found to be unlikely by orders of magnitude, and, on balance, the association of this event with the formation of element 110 appears to be the simplest and most probable explanation of the observation. Unfortunately, the SuperHILAC has been shut down so that it is impossible to repeat the experiment in the very near future.

In November 1994, an international group¹⁸ working at the GSI laboratory in Germany announced the synthesis and identification of an isotope of element 110, $^{269}\text{110}$ (half-life, 270 μs , 11.13-MeV α particles), produced in the reaction $^{208}\text{Pb} + ^{62}\text{Ni} \rightarrow ^{269}\text{110} + \text{n}$. The identification was made by the observation of four subsequent α particle decays.

Members of Russian–American collaboration led by Yuri A. Lazarev of Dubna and Ronald W. Loughheed of the Lawrence Livermore National Laboratory are currently attempting to synthesize element 110 by the reaction $^{244}\text{Pu} + ^{34}\text{S} \rightarrow ^{273}\text{110} + 5\text{n}$ in experiments at Dubna. It is hoped that a predicted deformed subshell at 162 neutrons will lead to longer half-lives and higher yields of such an isotope of element 110.

Reflections

There are almost unlimited possibilities for future research on transuranium elements, which already have extended by 20% the total of known chemical elements. When thinking in terms of the distant future, the tendency is to underestimate potential contributions.

Of central importance is a national policy discussion to retain and recover the potential stock of heavy transuranium nuclides now in storage basins at the Savannah River Plant in South Carolina. These are a priceless treasure and should not be discarded as irretrievable waste. This store, which includes some 7 kg of ^{243}Am and 2.5 kg of ^{244}Cm , can serve as starting material for the synthesis of increasing amounts of heavier transuranium nuclides for years to come.

As indicated earlier, estimates suggest that 500 transuranium nuclides would have half-lives sufficiently long to be detectable experimentally (longer than a microsecond). The synthesis and identification of another half-dozen or so elements seems likely; this would include the discovery of superheavy elements and the extension of the present peninsula of elements to connect with the “island of stability” which would be centered around element 114. Longer-lived isotopes than those now known will probably be found

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(18) Hofmann, S.; Ninov, V.; Hessberger, F. P.; Armbruster, P.; Folger, H.; Münzenberg, G.; Schött, H. J.; Popeko, A. G.; Yeremin, A. V.; Andreyev, A. N.; Saro, S.; Janik, R.; Leino, M. *Z. Phys. A* **1995**, *350* (4), 277–280.

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	57 La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	89 Ac	104 Rf	105 Ha	106 Sg	107 Ns	108 Hs	109 Mt	110	111	(112)	(113)	(114)	(115)	(116)	(117)	(118)
(119)	(120)	(121)	(154)	(155)	(156)	(157)	(158)	(159)	(160)	(161)	(162)	(163)	(164)	(165)	(166)	(167)	(168)

LANTHANIDES													
58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu

ACTINIDES													
90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

SUPER-ACTINIDES													
(122)	(123)	(124)	(125)	(126)									(153)

Figure 5. Periodic table of the elements projected out to element 168. This table includes undiscovered elements 122 through 153, which comprise the predicted and probably unattainable "superactinide" series.

in the transactinide region especially among the early transactinide elements. The recently discovered longer-lived isotopes of lawrencium (element 103) (²⁶¹Lr and ²⁶²Lr, with half-lives of 39 and 216 min, respectively) will make possible the detailed study of the chemical properties of this element.¹⁹ It should be possible to study the chemical properties of elements beyond hahnium (element 105) and certainly of element 106.

Figure 5 shows an imaginative periodic table extending all the way up to element 168. The completion of the actinide series, with the filling of the 5f electron subshell, occurs at element 103 (lawrencium). Elements 104 (rutherfordium) through undiscovered 112 are formed by filling the 6d electron subshell, which makes them homologues in chemical properties with the elements hafnium (Z = 72) through mercury (Z = 80). Elements 113 through 118 would result from filling of the 7p subshell and are expected to be similar to the elements thallium (Z = 81) through radon (Z = 86). The 8s subshell should fill at elements 119 and 120, thus making these an alkali and alkaline earth metal, respectively. Next should come the filling of the 5g and 6f subshells, 32 places in all, which I have termed the "superactinide" elements, followed by the filling of the 7d subshell (elements 154 through 162) and 8p subshell (elements 163 through 168).

(19) Loughheed, R. W.; Moody, K. J.; Dougan, R. J.; Wild, J. F.; Hulet, E. K.; Dupzyk, R. J.; Henderson, C. M.; Gannett, C. M.; Henderson, R. A.; Hoffman, D. C.; Lee, D. M.; Sümmerner, K.; Hahn, R. L. *FY87 Annual Report*; Lawrence Livermore National Laboratory, Nuclear Chemistry Division: Livermore, California, 1987; pp 4.2-4.5.

Although we can feel confident that this is the approximate form the periodic table should assume, we, unfortunately, will not be able to verify much of this experimentally because the half-lives of the nuclei are too short and there are no nuclear synthesis reactions available to reach such heavy elements. However, I believe it will be possible to add some six new known elements (perhaps slightly more) to our periodic table.

Much more research on the macroscopic properties of einsteinium (element 99) will be possible with the availability of ²⁵⁴Es (half-life of 276 days) in microgram amounts. It will surely be possible to study the macroscopic properties of fermium (element 100) and not out of the question that this will eventually be done for mendelevium (element 101). The art of one-atom-at-a-time chemistry will advance far beyond what can be imagined today to make it possible to study the chemistry of heavier and heavier elements. All of this will result in the delineation of relativistic effects on the chemical properties of these very heavy elements, which might thus be substantially different from those expected by simple extrapolation from their lighter homologues in the periodic table.

Such a research program will require, for success, the availability of apparatus and equipment of increasing complexity, versatility, and power. Central will be the need for higher neutron flux reactors, such as the planned Advanced Neutron Source at Oak Ridge, for sustained operation as a research tool and to produce large quantities of transplutonium nuclides

for use in the research and as target materials as a source of the presently known and expected nuclides. (Higher neutron fluxes will be especially valuable for the production of the heaviest nuclides, ^{254}Es and ^{257}Fm , springboards to the region beyond.) Higher intensity heavy ion accelerators must be built and the means of coping with the heat generated in the target by such intense beams must be developed in order to overcome limitations due to small nuclear reaction cross sections. Increases by orders of magnitude in heavy ion intensity should make possible nuclear synthesis reactions with secondary (radioactive) beams of neutron-excess projectiles, which might greatly

(20) Hofmann, S.; Ninov, V.; Hessberger, F. P.; Armbruster, P.; Folger, H.; Münzenberg, G.; Schött, H. J.; Popeko, A. G.; Yeremin, A. V.; Andreyev, A. N.; Saro, S.; Janik, R.; Leino, M. *Z. Phys. A* **1995** *350* (4), 281–282.

(21) Loughheed, R. W.; Lazarev, Yu.; et al. To be published in *Phys. Rev. Lett.*

increase the yields of sought-after new nuclides. Improved methods for handling safely and efficiently and making chemical measurements on increasing quantities of the highly radioactive transcurium nuclides must also be developed.

It is my dream that in the future—perhaps the distant future—additional laboratories or institutes will be created for exclusive research on the transuranium elements.

Postscript (February 1995)

An isotope of element 111 was discovered by the GSI group in December 1994,²⁰ extending to 19 the number of known transuranium elements. Also the Russian–American collaboration announced evidence for the discovery of $^{273}110$ in January 1995.²¹

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