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THE DISCOVERY OF THE TRANSURANIUM ELEMENTS: THEIR HISTORY AND A PRESENTATION OF THE DIFFERENT METHODS USED IN THEIR DISCOVERY

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Since 1940 ten transuranium elements have been discovered. Several books have been written which contain much information about these elements.[1,2,3] In this lecture it is possible to discuss only a very limited portion of the available subject matter. I shall, therefore, confine my remarks largely to the interesting history of these elements.

A suitable beginning for the story seems to be the discovery of a number of radioactive substances produced by the irradiation of uranium with neutrons. This discovery was made in 1934 by E. Fermi, E. Amaldi, O. D'Agostino, F. Rasetti, and E. Segrè.[4] This group was led to assign the radioactivities to transuranium elements. These radioactivities, however, led to the discovery of the fission process instead of transuranium elements. Early in 1939 Hahn and Strassmann described experiments which made it certain that they had observed radioactive isotopes of barium and other "light" elements as the result of the bombardment of uranium with neutrons.[5] Subsequent work showed that practically all of the radioactivities previously ascribed to transuranium elements were actually due to fission products.

Neptunium

The actual discovery of the first transuranium element resulted from experiments aimed at understanding the fission process. Several experimenters, including E. M. McMillan of the University of California, measured the energies of the two main fission fragments by observing the distances they traveled from each other as a result of their mutual recoil when the nucleus explodes. McMillan noted that there was another radioactive product of the reaction, with a half life of 2.3 days, which did not recoil, at least not sufficiently to escape from the thin layer of fissioning uranium. He suspected that this was

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a product formed by simple neutron capture rather than by fission. In the spring of 1940 McMillan and P. H. Abelson[6] deduced by chemical means that this product was an isotope of element 93, arising by beta decay from U^{239}. Element 93 was given the name neptunium (symbol Np), because it is the next element after uranium, just as the planet Neptune lies beyond Uranus.

McMillan's and Abelson's tracer investigations of the chemical properties of neptunium showed that it has a chemical resemblance to uranium, and not rhenium, as was previously postulated. This was the first definite recognized evidence that the 5f electron shell undergoes filling in this region. Thus the discovery of neptunium was extremely important, not only from the standpoint of opening the transuranium field but also provided the first clue to the eventual understanding of the electronic structures and the place in the periodic system of the heaviest elements.

The early investigation of neptunium, as of all the transuranium elements, was made by the tracer technique. In this method, an element having chemical properties similar to those of the element being studied is used to follow the behaviour of the radioactive element, which can be present in amounts as small as 10^{-10} grams, or even less. The element is detected in the various reactions by means of its radioactivity rather than by chemical analysis. In spite of the smallness of the quantities present, much can be deduced about the chemical properties of an element -- for example, the solubility of its compounds, its oxidation-reduction potentials, and its formation of complex ions -- by the careful use of such methods.

Plutonium

The search for element 94 began in 1940 with experiments by Seaborg, McMillan, Kennedy, and Wahl in which uranium oxide was bombarded with 16 Mev deuterons from the 60-inch cyclotron. Alpha radioactivity was found to grow into the chemically separated element 93 fraction, and this alpha activity was chemically separated from the neighboring elements, especially elements 90 to 93 inclusive. These experiments, which constitute the positive identification of element 94, showed that this element has at least two oxidation states, distinguishable by their precipitation chemistry, and that it requires stronger oxidizing agents to oxidize element 94 to the upper state than is the case for element 93. The particular isotope identified has been shown to be of mass number 238 and the reactions for its preparation are shown in the first slide (Fig. 1).

$$_{92}U^{238} + {}_{1}H^{2} \longrightarrow {}_{93}Np^{238} + 2n$$

$$_{93}Np^{238} \xrightarrow[2.1\text{ days}]{\beta^-} {}_{94}Pu^{238} \text{ (90 years, } \alpha\text{)}$$

Figure 1.

The chemical properties of elements 93 and 94 were studied by the tracer method at the University of California for the next year and a half. During this time the first transuranium elements were referred to simply as "element 93" and "element 94". In the spring of 1942, when the first detailed reports[7] concerning these elements were written, it became necessary to have chemical symbols for the two elements. Since McMillan had suggested the name "neptunium" (symbol Np) for element 93 after Neptune, the planet immediately beyond Uranus, which gives its name to uranium, it was therefore thought proper that element 94 should assume the name "plutonium" (symbol Pu) after the next planet Pluto.

The plutonium isotope of major importance is the one with mass number 239. The search for this isotope, as a decay product of Np^{239}, was also in progress at this time, and these experiments were being performed by the same group with the added collaboration of Dr. E. Segrè. The isotope Pu^{239} was identified and its possibilities as a nuclear energy source were established during the spring of 1941 using a sample prepared by the decay of cyclotron produced Np^{239} which had been purified using the few facts known about the chemistry of plutonium.[8]

Once the value of the isotope Pu^{239} was established, the paramount problem was that of producing it on a large scale and isolating it after production. The production problem was solved, as is well known, through the development of the chain reacting units, or piles, utilizing the neutron induced fission reaction on U^{235} in natural uranium, in which the extra neutrons beyond those needed to perpetuate the chain reaction are absorbed by U^{238} to form the desired isotope Pu^{239}.

The realization that plutonium, as Pu^{239}, could serve as a nuclear weapon and that it might be created in quantity in a nuclear chain reactor made it imperative to carry out chemical investigations of plutonium with microgram quantities. In August 1942, B. B. Cunningham and L. B. Werner succeeded in isolating about a microgram of Pu^{239} which had been prepared by cyclotron irradiations.[9] Thus plutonium was the first man-made element to be obtained in visible quantity.

Plutonium is the only synthetic element that has been produced and isolated in kilogram quantities. The large plant at Hanford, Washington, was constructed on the basis of investigations performed with about 2 mg of plutonium; the scale-up between ultramicrochemical experiments to the final Hanford plant corresponded to a factor of about 10^9, surely a scale-up of unique proportions.[3]

After the completion of the most essential part of the investigations concerned with the chemical processes involved in the production of plutonium at the wartime Metallurgical Laboratory, Seaborg and his co-workers undertook the problem of synthesizing and identifying the next transuranium elements.

Americium and Curium

There followed quite a period during which the attempts to synthesize and identify elements 95 and 96 were not fruitful. These unsuccessful experiments were based on the premise that these elements should be much like plutonium in that it should be possible to oxidize them to the (VI) oxidation state and utilize this in the chemical isolation procedures. It was not until the middle of the summer of 1944, when it was first recognized that these elements were part of an actinide transition series that any advance was made, and then progress came quickly.

As soon as it was realized that these elements could be oxidized above the (III) state only with extreme difficulty, if at all, the identification of an isotope of element 96 followed immediately. Thus the isotope Cm^{242} was identified[10] in the summer of 1944 as a result of the bombardment of Pu^{239} with 32 Mev helium ions in the Berkeley 60-inch cyclotron. The reaction involved was $Pu^{239}(\alpha,n)Cm^{242}$. The material was then shipped to the Metallurgical Laboratory for chemical identification.

The identification of element 95 followed soon thereafter.[11] This came in the very late fall of 1944 as a result of the bombardment of Pu^{239} with pile neutrons, the production reaction being as shown in the following slide (Fig. 2).

$$Pu^{239} + n \longrightarrow Pu^{240} + \gamma$$

$$Pu^{240} + n \longrightarrow Pu^{241} + \gamma$$

$${}_{94}Pu^{241} \text{ (13 years) } \xrightarrow{\beta^-} {}_{95}Am^{241} \text{ (458 years, } \alpha)$$

Figure 2.

There are some comments which should be made here concerning the rare-earthlike properties of these two elements. The hypothesis that they should have a stable (III) oxidation state and greatly resemble the rare earth elements in their chemical properties proved to be so true that for a time it appeared to be most unfortunate. The better part of a year was spent unsuccessfully in trying to separate chemically the two elements from each other and from the rare earth elements, and although there was confidence on the basis of their radioactive properties and the methods of production, that isotopes of elements 95 and 96 had been produced, the chemical proof remained to be demonstrated.

Americium was first isolated by Cunningham[12] in the form of a pure compound in the fall of 1945 at the wartime Metallurgical Laboratory. It is now prepared in gram amounts by the neutron bombardment of plutonium, and thus it has been possible to investigate its chemical properties extensively using macroscopic quantities.

Curium was first isolated in the form of a pure compound of Cm^{242} by L. B. Werner and I. Perlman[13] at the University of California during the fall of 1947. The isotope Cm^{242} is so highly radioactive, due to its short half-life, that chemical investigations with it in macroscopic concentrations are very difficult. Nevertheless, a large number of such investigations have been carried on and much has been learned about its chemical properties. At the present time most of the research with macroscopic quantities of curium is done with Cm^{244} which has a much lower specific activity.

Berkelium and Californium

After the return of a number of us to the University of California in late 1945 and early 1946, an investigation of the production and identification of further transuranium elements was begun. Many problems had to be solved, mostly in connection with the small amounts of material available for irradiation and intense radioactivity of this material. To help counterbalance the many difficulties were the advances which had been made in the possibility of predicting the radioactive properties of the expected isotopes and especially the exact predictions of the chemical properties made possible on the basis of the actinide concept. According to this view, the elution positions of the transcurium elements should be analogous to those of the transgadolinium elements in the ion exchange column separation method. This knowledge proved of inestimable benefit in planning the ultimately successful experiments. In the case of berkelium, however, there was some uncertainty as to whether its most stable oxidation state would be (III) or (IV). Two approaches to the problem of producing the isotopes were undertaken: namely, that of neutron irradiation of the chain reacting piles and that of charged particle bombardment in the 60-inch cyclotron.

The neutron irradiations did not yield positive results. The reason is now clear; the product of cross-sections, neutron flux, and time were simply not large enough. I shall, therefore, go on to describe the cyclotron irradiations by which it was finally possible in December, 1949 for a group which included Ghiorso, Seaborg, and the author, to identify an isotope of the element with atomic number 97 formed in the bombardment of Am^{241} with 35 Mev helium ions.[15] This was followed a short time later by the identification by Street, Ghiorso, Seaborg, and the author, of an isotope of element 98 prepared in the bombardment of Cm^{242} with 35 Mev helium ions.[16] The first identification experiment in the case of element 98 involved the production and separation of only a few thousand atoms. The reactions involved are summarized in the following slide (Fig. 3).

$$_{95}Am^{241} + {_2}He^4 \longrightarrow {_{97}}Bk^{243} + 2n$$

(4.6 hours, $K/\alpha \cong 10^3$)

$$_{96}Cm^{242} + {_2}He^4 \longrightarrow {_{98}}Cf^{245} + n$$

(45 minutes, α)

Figure 3

Berkelium was found to have oxidation states (III) and (IV) of stability quite similar to the corresponding states of cerium.[16] It should be mentioned that the successful handling in a safe manner of the large amounts of radioactivity in the target material was made possible through the use of the excellent protective equipment provided by Nelson Garden and the members of the Health Chemistry Group at our Laboratory.

The name "berkelium" (symbol Bk) was suggested for element 97 after the city where the work was done, in analogy with the naming of its chemical homologue terbium, which was named after the town of Ytterby in Sweden where the rare earth minerals were first found. The name "californium" (symbol Cf) was suggested for element 98 in honor of the University and State where the work was done, thus abandoning in this case the custom of naming an element in the same way as its chemical homologue.

Shortly after the discovery of berkelium it became possible to produce isotopes of californium using heavy ions.[17] These experiments, in which uranium is bombarded with carbon ions,[18] led to the production of californium isotopes according to the reactions given in the following slide (Fig. 4).

$$_{92}U^{238} + {}_{6}C^{12} \longrightarrow {}_{98}Cf^{245} + 5n$$
$$(45 \text{ minutes}, \alpha)$$

$$_{92}U^{238} + {}_{6}C^{12} \longrightarrow {}_{98}Cf^{246} + 4n$$
$$(36 \text{ hours}, \alpha)$$

Figure 4

The fact that the transuranium elements are members of a transition series similar to the rare earth, or lanthanide, series is useful in predicting the chemical properties of these elements before they are actually detected. This particular pattern of similarity, was the key to the discovery of elements 95 and 96 (americium and curium) and has been essential to the discovery of the transcurium elements. Since all the elements beyond actinium seem to belong to the actinide group (a name chosen by analogy with the lanthanide group), the elements thorium, protactinium, and uranium have been removed from the positions they occupied in the Periodic Table before 1939 and placed in this transition family; as we shall see, elements 104, 105, and 106 will presumably take over the positions previously held by thorium, protactinium, and uranium. Thus we have the interesting result that the newcomers have affected the face of the Periodic Table, and a change has been made after many years during which it seemed to have assumed its final form.

Last year B. B. Cunningham and the author succeeded in isolating berkelium (atomic number 97) and californium (atomic number 98) in macroscopic or weighable amounts for the first time. In April, 1958 we isolated 0.23 micrograms of berkelium (as Bk^{249}) which had been formed as a result of the irradiation of about 8 grams of Pu^{239} and its transmutation products with neutrons for approximately five years in the Materials Testing Reactor (MTR) at Arco, Idaho. The first macroscopic quantity of californium isolated was obtained in July 1958 and consisted of 0.06 micrograms of a mixture of the isotopes Cf^{249}, Cf^{250}, Cf^{251}, and Cf^{252} which had been prepared by the same method as the berkelium.

With these materials we measured the magnetic susceptibilities of the tripositive ions of berkelium and californium over the temperature range 77 to 298° K. The results obtained in both investigations agree very well with those expected for berkelium and californium and are consistent only with the filling of the "5f" electronic shell in the actinide elements.

The absorption spectra of the ions Bk^{+3} and Cf^{+3} in aqueous solution have been studied also. Visual observation failed to reveal absorption for either ion in the region from about 4600 to 7400 A, but a photographic method has shown that broad and quite faint absorption bands occur in californium around 7800 and 8300 A.

Einsteinium and Fermium

Another example of the unexpected in science is in the discovery of elements 99 and 100. The seventh and eighth transuranium elements were found in debris from the "Mike" thermonuclear explosion[19] which took place in the Pacific in November of 1952. Debris from the explosion was collected first on filter papers attached to drone airplanes which flew through the clouds and, later in more substantial quantity, gathered up as fallout materials from the surface of a neighboring atoll. This debris was brought to the United States for chemical investigation in a number of laboratories.

Initial investigation at the Argonne National Laboratory in Chicago and at the Los Alamos Scientific Laboratory of the University of California in New Mexico led to the unforeseen observation of heavy isotopes such as Pu^{244} and Pu^{246}. At that time, the heaviest known isotope of plutonium was Pu^{243}. Since this pointed to the capture of many successive neutrons by the U^{238} in the device and thus the presence of neutron-excess isotopes in greater abundance than expected, a group at the University of California Lawrence Radiation Laboratory undertook to look for isotopes of transcalifornium elements in this material. Ion-exchange experiments of the type based upon the analogy between the chemical behavior of actinide and lanthanide elements immediately demonstrated the existence of a new element. Later, in order to secure a larger amount of source material, it was necessary to work up many hundreds of pounds of coral from one of the atolls adjoining the explosion area. Without going into the details, it may be pointed out that subsequent experiments involving the groups at the three laboratories led to the positive identification of isotopes of elements 99 and 100. A twenty-day activity emitting alpha particles of 6.6 Mev energy was identified as an isotope of element 99, (E^{253}) and a 7.1 Mev alpha activity of 16 hour half life was identified as an isotope of element 100 (Fm^{255}). The successive instantaneous capture of many neutrons by U^{238} is illustrated in the next slide (Fig. 5). The heavy uranium isotopes decayed into the isotopes above them by the emission of negative beta particles. The original data are plotted in the usual method in slide 6 in which it can be seen by comparison with slide 7 that element 100 falls very approximately in the predicted eka-erbium position and element 99 falls in the eka-holmium position. The first identification of element 100 was made with about 200 atoms only. The most striking previous accomplishment in this category was the positive identification of element 98 with a total of about 5000 atoms.

The two elements were discovered by Ghiorso, the author and co-workers at the three laboratories. We suggested for element 99 the name einsteinium (symbol E) in the honor of the great physicist, Albert Einstein, and for element

100 the name fermium (symbol Fm) in honor of the father of the atomic age, Enrico Fermi.

Before declassification and the subsequent announcement of the original discovery experiments could be accomplished, isotopes of elements 99 and 100 were synthesized by a number of other methods. Chief among these was the method of successive neutron capture as the result of intense neutron irradiation in the high-flux Materials Testing Reactor (MTR) at the National Reactor Testing Station in Arco, Idaho.[20,21] A diagram which illustrates the multiplicity of nuclear reactions which take place in this method of production is shown in Slide 8 (Fig. 8). The differences between this method of production and that of the Mike thermonuclear explosion are of time required and of starting material. In a reactor it is necessary to bombard gram quantities of plutonium for two or three years; thus the short-lived intermediate isotopes of the various elements have an opportunity to decay. In the fusion-fission device larger amounts of uranium were subjected to an extremely high neutron flux for a period of microseconds; the subsequent beta-decay of the ultra-heavy isotopes of uranium led to the nuclides found in the debris.

Slide No. 9 (Fig. 9) gives an indication of the time required to prepare the nuclides Cm^{248}, Cf^{252}, and E^{254}. It can be seen that by starting with one kilogram of Pu^{239} it would require approximately five to ten years to produce about one milligram of Cf^{252} using a neutron flux of 3×10^{14} neutrons per square centimeter per second. In the United States we have a program in progress for the production of milligram amounts of berkelium and californium, and microgram amounts of einsteinium. Einsteinium is probably the only remaining transuranium element capable of being isolated in macroscopic amounts (as the 280-day isotope E^{254} or the 20-day isotope E^{253}) but not yet so isolated by traditional methods. Fermium and higher elements are not expected to have isotopes with sufficiently long half-lives to permit their isolation in macroscopic quantity, although new techniques permitting special measurements are possible.

Mendelevium

The synthesis of element 101 was planned and accomplished with only about 10^9 atoms of target einsteinium (E^{253}), too small an amount to be weighable. A recoil technique was used to achieve the primary separation of element 101 from the einsteinium in the target. The einsteinium was electroplated on a gold foil in an invisibly thin layer. The helium-ion beam was sent through the back of the foil so that the atoms of element 101, recoiling because of the momentum of the impinging helium ions, could be caught on a second thin gold foil. This second gold foil, containing recoil atoms, yet relatively free of the target einsteinium, was dissolved and the chemical separations were performed. Very sensitive methods were available for the detection of isotopes decaying by alpha-particle emission or by spontaneous fission. These methods were so efficient that as little as one or two atoms of element 101 per experiment were detected.

The experiments resulted in the observation of large pulses due to spontaneous fission. Chemical experiments showed that the spontaneous fission counts occurred in chemical fractions corresponding approximately to element 100 or 101. The spontaneous fission activity in both the element 101 and 100 fractions decayed with a half-life of about three hours. It was proved that the isotope of element 101 has the mass number 256 and decays by electron capture with a half-life of the order of an hour, to the isotope Fm^{256} which is responsible for the spontaneous fission decay.

The discoverers[22] consisting of A. Ghiorso, B. G. Harvey, G. R. Choppin, G. T. Seaborg, and the author gave the new element the name mendelevium in recognition of the pioneering role of Dmitri Mendeleev, who was the first to use the periodic system of the elements to predict the chemical properties of undiscovered elements. Subsequent experiments using large amounts of einsteinium in the target have led to the production of over one thousand atoms of mendelevium. Mendelevium is a typical tripositive actinide element and a true eka-thulium, as illustrated in Slide 10 (Fig. 10).

Element 102

The discovery of element 102 was announced in 1957 as the result of work done at the Nobel Institute for Physics in Stockholm by a team of scientists from Argonne National Laboratory, The Atomic Energy Research Establishment at Harwell, and the Nobel Institute.[23] An isotope of the element was reportedly produced by bombarding Cm^{244} with cyclotron-produced $C^{13\ (+4)}$ ions and which decayed with a half-life of about ten minutes by the emission of 8.5 Mev alpha particles. It has not been possible to confirm this discovery in experiments performed at the University of California Lawrence Radiation Laboratory. In April 1958, a group consisting of Ghiorso, T. Sikkeland, J. R. Walton, and Seaborg at the Lawrence Radiation Laboratory identified the isotope 102^{254} as a product of the bombardment of Cm^{246} with C^{12} ions accelerated in the new Heavy Ion Linear Accelerator there.[25] (The reaction is $Cm^{246}(C^{12},4n)102^{254}$). The element 102 isotope decays by alpha-particle emission with a half life of about 3 seconds. It was detected by the chemical identification of its known daughter Fm^{250}, the atom of the daughter element being separated from the parent element 102 by taking advantage of the recoil due to element 102 alpha-decay.

Flerov and his group in the USSR have produced an isotope, emitting 8.8 ± 0.5 Mev alpha particles, in the bombardment of Pu^{241} with high energy O^{16} ions accelerated in their cyclotron.[25] This product was separated from the target by the recoil technique and the energy of the alpha particles was measured by use of a photographic emulsion technique. No chemical identification was made. This alpha activity observed in the USSR is due to the isotope 102^{253}, according to experiments by Ghiorso and co-workers at Berkeley.

Future Developments

It presently appears possible that new transuranium elements can be prepared and identified. Studies of the known isotopes of the transuranium elements have permitted the prediction of the decay properties of new isotopes. For decay by both alpha-particle emission and spontaneous fission, the regularities have been found to be greatest for nuclei which contain an even number of neutrons and an even number of protons, thus making predictions of the properties for undiscovered isotopes of this type more certain. The rates of decay by alpha-particle emission and by spontaneous fission are slower for isotopes having an odd number of protons or an odd number of both protons and neutrons. Unfortunately for the prospect of producing even higher elements, the predictions suggest shorter half-lives as atomic number increases. By the time elements 104 and 105 are reached, we shall probably find that the longest-lived isotopes that can be made may not exist long enough for chemical identification. In the case of element 104, the predicted half-lives of the longest-lived isotopes are measured in seconds or minutes and for element 105 in seconds. It should be mentioned, however, that any of these nuclides can have a specially hindered decay, leading to longer half-lives than those predicted. It seems that the time has come when the basic criterion for the discovery of a new element, namely chemical identification and separation from all previously known elements, must be changed. Careful measurements of decay properties and production yields and mechanisms, and the clever use of recoil techniques, should eventually allow the extension of effective identification beyond the heaviest now known.

The prediction of the chemical properties of elements beyond mendelevium seems to be quite straightforward, and I shall give a very brief summary of their expected properties. Element 103 should complete the actinide series, and it is expected that elements 104, 105, 106, etc., will be fitted into the Periodic Table under hafnium, tantalum, tungsten, etc. The filling of the 6d electronic shell should be followed by the addition of electrons to the 7p shell, with the attainment of the rare gas structure by hypothetical element 118. Element 102 might be expected to have a stable trivalent oxidation state and a somewhat unstable bivalent state. The stability of the bivalent state may be reflected in the properties of the metallic state of the element, resulting in an unusually low density and a relatively high volatility. Element 103 might be expected to have only a trivalent oxidation state. Element 104 should be exclusively tetravalent in aqueous solution and should resemble its homologue hafnium.

I have not yet discussed the methods by which these new elements may be synthesized. The possibility of preparing transfermium elements by the process of multiple neutron capture as a result of intense neutron bombardment over long periods of time is almost precluded by the fact that some of the intermediate isotopes have half-lives so short as to prohibit their presence in such appreciable concentrations as are required. There is however, another type of nuclear reaction that offers promise for the production of elements higher in atomic number than those now known. This is the method of bombardment with heavy ions which was mentioned earlier in my talk. Reactions of this type have already been observed in many laboratories; isotopes of californium, einsteinium, and fermium have been produced by the bombardment of uranium with carbon ions, nitrogen ions, and oxygen ions respectively. These ions can be accelerated in conventional cyclotrons. A linear accelerator capable of producing substantial beams of all the heavy ions up to neon and, possibly, usable beams of ions as heavy as those of argon has been constructed at the University of California at Berkeley. A similar accelerator is in operation at Yale University. Soviet scientists have also shown a great interest in heavy ions and their application to the synthesis of transuranium elements and accelerators for heavy ions are under construction. Even with the use of heavy ions, however, the source of target materials will present serious problems. New, expensive, high-flux reactors, producing 10^{15} to 10^{16} neutrons per square centimeter per second are needed in order to prepare even milligram amounts of berkelium, californium, and einsteinium with a reasonable space of time.

This short lecture has, of necessity, omitted even reference to many of the important aspects of the transuranium element field. In particular, it has not been possible to capture the international flavor of the work which has gone on in recent years. The emphasis has been on the historical aspects, and the possibilities for future advances in this field. Much of interest could be told of the methods of production and of the many new long-lived isotopes which are becoming available in weighable amounts. The nuclear properties, which were barely mentioned, are of great interest. Over 80 isotopes of the transuranium elements are now known. The decay properties of these have been of great importance for the development of the Copenhagen school's unified model of the nucleus, and the induced and spontaneous fission properties of such isotopes are very important to the future development of a satisfactory understanding of the fission process. In the latter connection, I would like to emphasize the advantage of using isotopes such as Cf^{252} which decay by spontaneous fission and can be produced in relatively large amounts as sources for the investigations of the fission process. Significant break-throughs in our understanding of the fission process may result from experiments now in progress and there may be many important applications.

REFERENCES

1. G. T. Seaborg, J. J. Katz, (Editors), "The Actinide Elements", National Nuclear Energy Series, Div. IV, Vol. 14A (1954).
2. J. J. Katz and G. T. Seaborg, "The Chemistry of the Actinide Elements". Methuen and Co. Ltd., London; John Wiley and Sons, Inc., New York, 1957.
3. G. T. Seaborg, "The Transuranium Elements". Yale University Press, New Haven, 1958.
4. L. L. Quill, Chem. Rev. 23, 87 (1938).
5. O. Hahn and F. Strassman, Naturwiss., 27, 11, 89 (1939).
6. E. McMillan and P. Abelson, Phys. Rev. 57, 1189 (1940).
7. G. T. Seaborg, E. M. McMillan, J. W. Kennedy, and A. C. Wahl, Phys. Rev. 69, 366 (1946).
8. J. W. Kennedy, G. T. Seaborg, E. Segrè, and A. C. Wahl, Phys. Rev. 70, 555 (1946).
9. B. B. Cunningham and L. B. Werner, J. Am. Chem. Soc. 71, 1521 (1949).
10. G. T. Seaborg, R. A. James, and A. Ghiorso, Paper 22.2, p. 1554 of "The Transuranium Elements", National Nuclear Energy Series, Div. IV, 14B (1949).
11. G. T. Seaborg, R. A. James, and L. O. Morgan, Paper 22.1, p. 1525 of "The Transuranium Elements", National Nuclear Energy Series, Div. IV, 14B, (1949).
12. B. B. Cunningham, Paper 19.2, p. 1363 of "The Transuranium Elements", National Nuclear Energy Series, Div. IV 14B (1949).
13. L. B. Werner and I. Perlman, Paper 22.5, p. 1586 of "The Transuranium Elements", National Nuclear Energy Series, Div. IV 14B (1949).
14. S. G. Thompson, A. Ghiorso, and G. T. Seaborg, Phys. Rev. 80, 781 (1950).
15. S. G. Thompson, K. Street, Jr., A. Ghiorso, and G. T. Seaborg, Phys. Rev. 80, 790 (1950).
16. S. G. Thompson, B. B. Cunningham, and G. T. Seaborg, J. Am. Chem. Soc. 72, 2798 (1950).
17. J. F. Miller, J. G. Hamilton, T. M. Putnam, H. R. Haymond, and G. B. Rossi, Phys. Rev. 80, 486 (1950).
18. A. Ghiorso, S. G. Thompson, K. Street, Jr., and G. T. Seaborg, Phys. Rev. 81, 154 (1951).

19. A. Ghiorso, S. G. Thompson, G. H. Higgins, G. T. Seaborg, M. H. Studier, P. R. Fields, S. M. Fried, H. Diamond, J. F. Mech, G. L. Pyle, J. R. Huizenga, A. Hirsh, W. M. Manning, C. I. Browne, H. L. Smith, and R. W. Spence, Phys. Rev. 99, 1048 (1955).

20. S. G. Thompson, A. Ghiorso, B. G. Harvey, and G. R. Choppin, Phys. Rev. 93, 908 (1954).

21. B. G. Harvey, S. G. Thompson, A. Ghiorso, and G. R. Choppin, Phys. Rev. 93, 1129 (1954).

22. A. Ghiorso, B. G. Harvey, G. R. Choppin, S. G. Thompson, and G. T. Seaborg, Phys. Rev. 98, 1518 (1955).

23 P. R. Fields, A. M. Friedman, J. Milsted, H. Atterling, W. Forsling, L. W. Holm, B. Åström, Phys. Rev. 107, 1460 (1957).

24. A. Ghiorso, T. Sikkeland, J. R. Walton, and G. T. Seaborg, Phys. Rev. Letters 1, 18 (1958).

25. G. N. Flerov, to be published in the Proceedings of the Geneva Conference on the Peaceful Uses of Atomic Energy (1958).

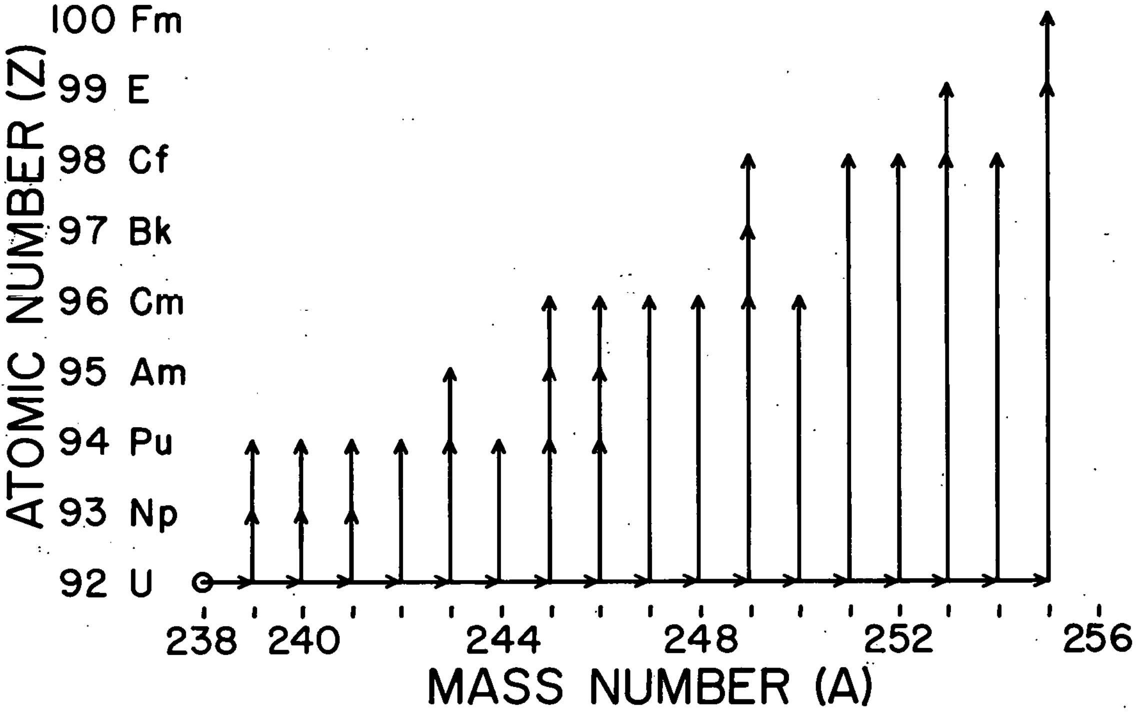

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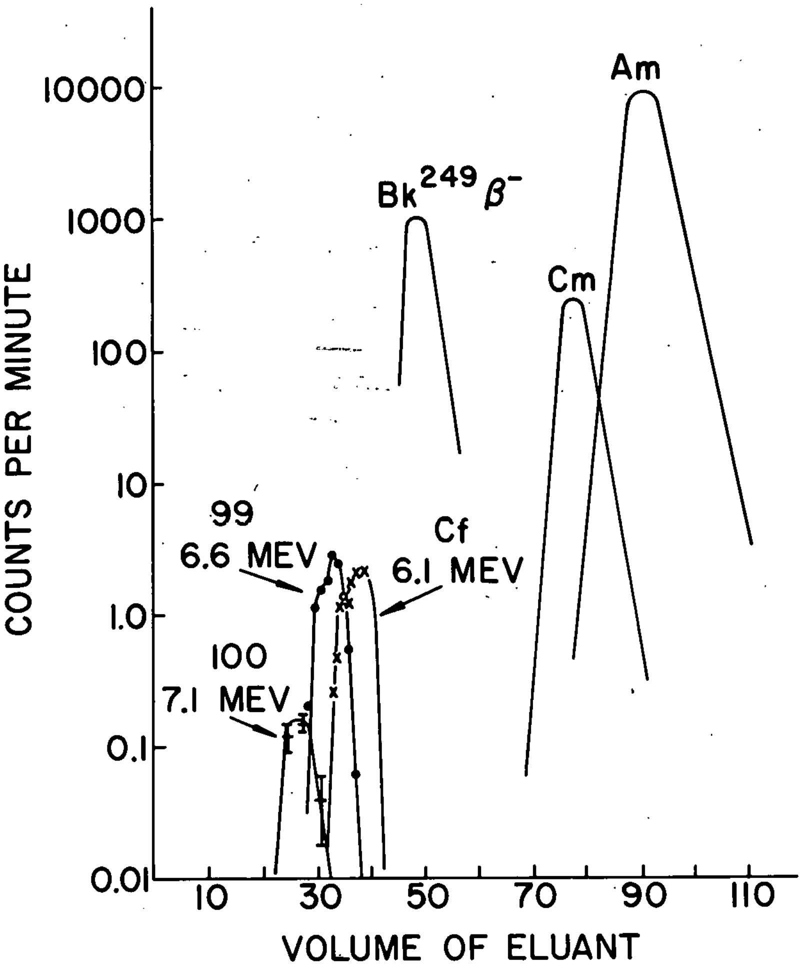
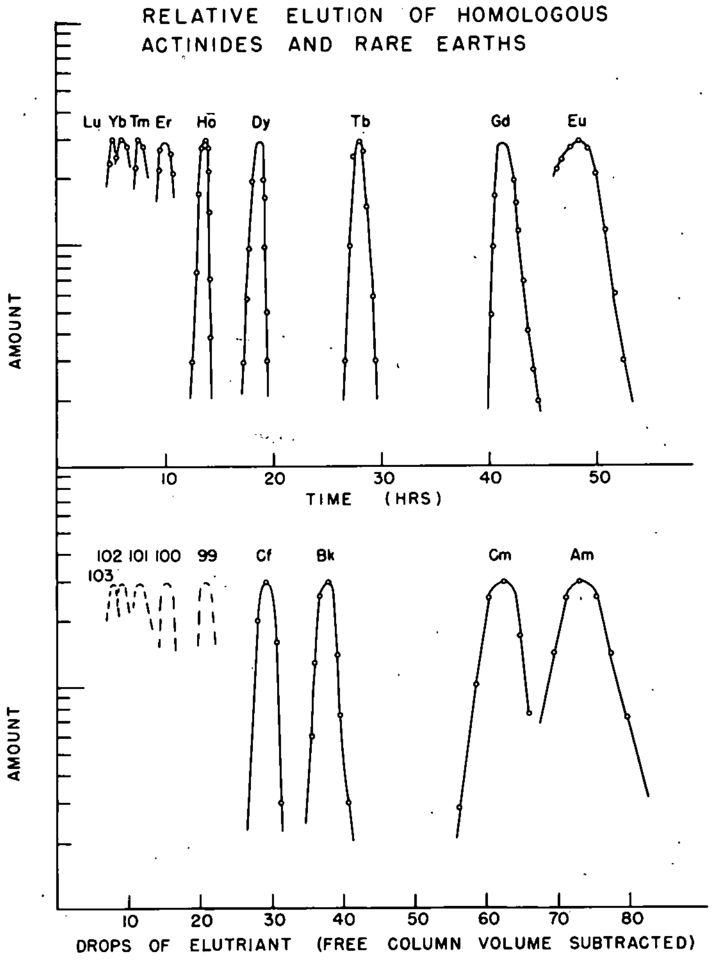
Fig. 5 Nuclear reactions for the production of elements 99 and 100 in the "Mike" thermonuclear explosion. The heavy uranium isotopes U^{239} to U^{255} were formed by the instantaneous addition of neutrons to U^{238}. Isotopes of higher atomic number resulted from the emission of negative beta particles from these uranium isotopes.



MU-15997

Fig. 6 Elution of elements 99 and 100 relative to other actinide elements. The cation-exchange resin Dowex-50 was used and the elution was performed at 87°C using ammonium citrate solution.



MU-5489

Fig. 7 Relative elution of homologous actinides and lanthanides in an experiment performed in 1950. The positions predicted for the then undiscovered elements 99 through 103 are shown by dotted lines. The cation-exchange resin Dowex-50 was used, and the elution was performed at 87°C with ammonium citrate buffered with citric acid in the case of the actinide elements. The data on the lanthanide elements were obtained using the same resin and eluant; the elution was carried out at 100°C.

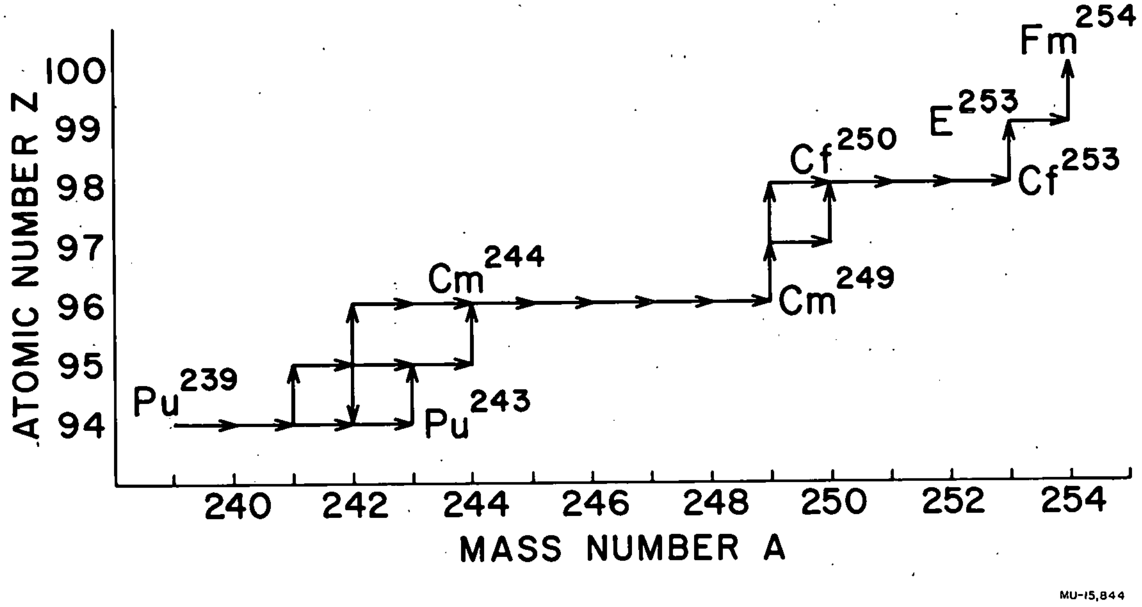
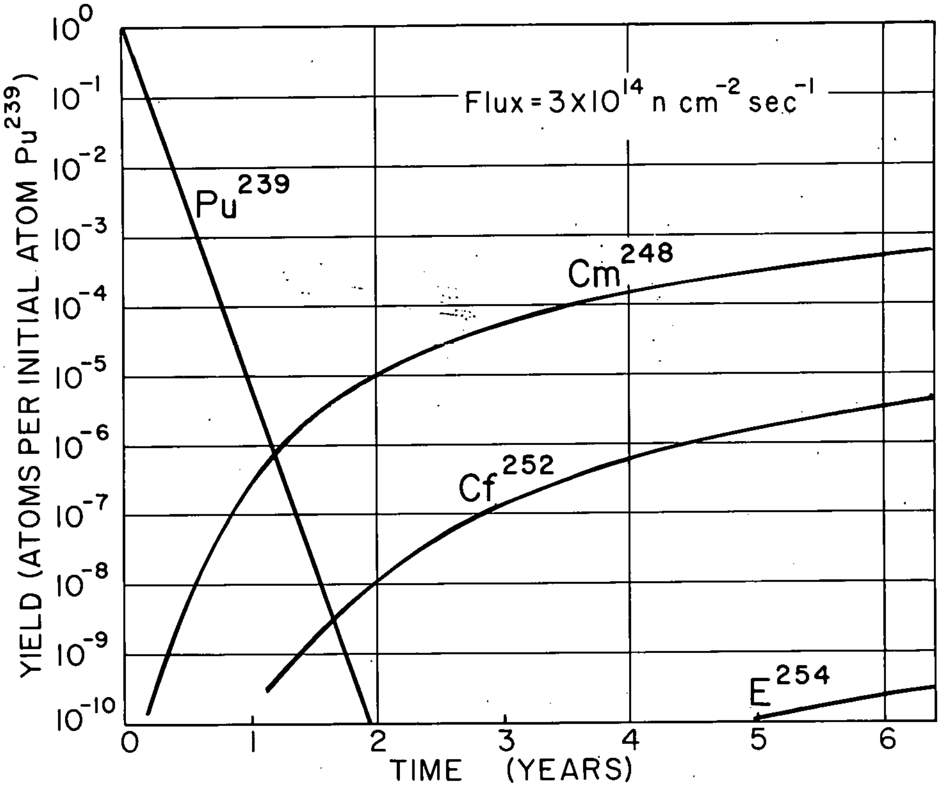


Fig. 8 Nuclear reactions for the production of heavy isotopes by intense neutron irradiation in the Materials Testing Reactor at Arco, Idaho.

644 020



MU-15787

Fig. 9 Production of heavy nuclides by the irradiation of Pu^{239} at a flux of 3×10^{14} neutrons per square centimeter per second.

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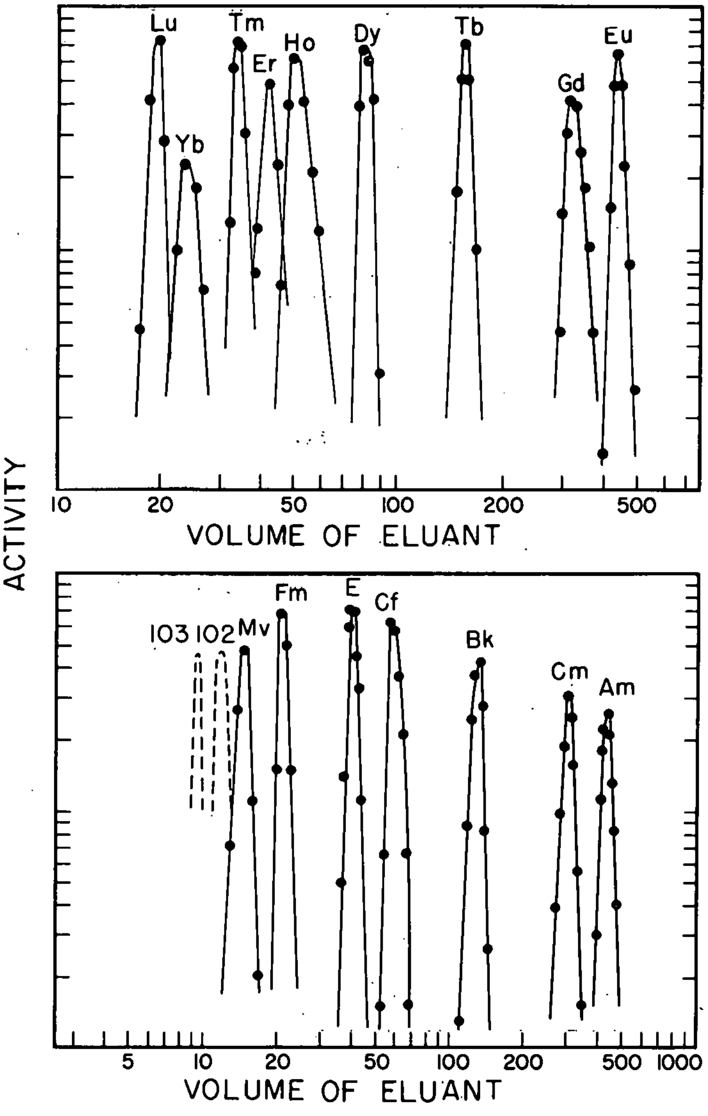

MU-15788

Fig. 10 Elution of tripositive lanthanide and actinide ions from Dowex-50 ion-exchange resin with ammonium α-hydroxy-isobutyrate. The predicted positions for elements 102 and 103 are indicated by dotted lines.