the man-made chemical elements beyond uranium

By ***Glenn T. Seaborg***

The following article is based on the Charles M. Schwab Memorial Lecture delivered on May 23 by Dr. Seaborg at a meeting of the American Iron and Steel Institute held in New York City. The author, who has been chairman of the United States Atomic Energy Commission since his appointment to that post by President Kennedy early last year, was previously professor of chemistry, associate director of the Lawrence Radiation Laboratory, and chancellor of the University of California at Berkeley.

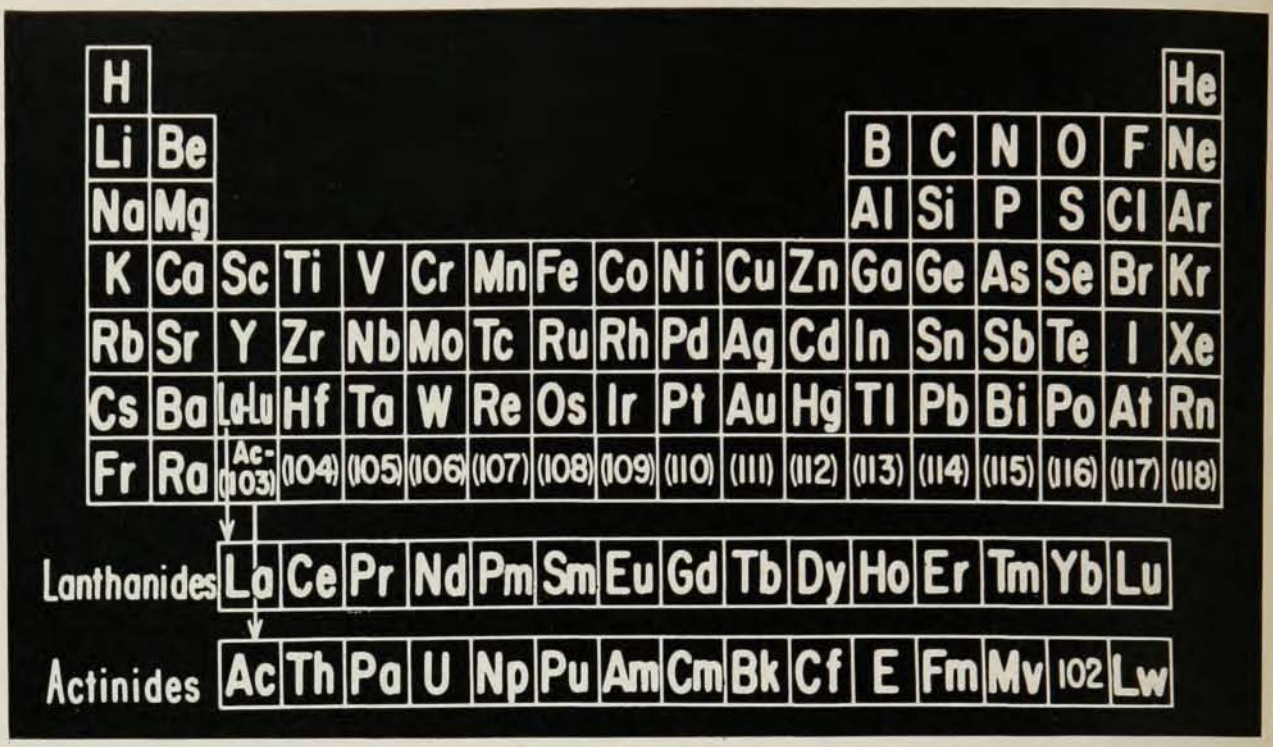
AN exciting branch of science, which started as recently as World War II and has a clearly discernible future of great promise, is that of the "transuranium elements". These are the man-made chemical elements with atomic numbers greater than that of the heaviest natural element, uranium, which has the atomic number 92.

The transuranium elements are, for all practical purposes, synthetic in origin and must be produced by transmutation, starting in the first instance with uranium. The key to the discovery of these essentially "synthetic" elements was their position in the Periodic Table.

Prior to the discovery of these transuranium elements, the relationship of the heaviest, naturally occurring elements—actinium, thorium, protactinium, and uranium—in the Periodic Table was not clearly understood. Recognition of the fact that the transuranium elements represented a whole new family of "actinide" elements analogous to the rare-earth series of elements, "lanthanides", permitted the discoverers to predict the chemical properties of the unknown transuranium elements and thereby enabled them to discover and separate them from all the other elements in the Periodic Table.

At the present time, eleven transuranium elements have been created and identified, with a total of nearly one hundred isotopes. All these new transuranium elements are unstable and therefore radioactive. The half-life of the various isotopes decreases in general with increasing atomic number—meaning that, as we create heavier and heavier elements, they exist for shorter and shorter periods, making their production, separation, and identification progressively more difficult.

It may still be possible to synthesize, separate, and identify a half-dozen or so more of the transuranium elements; but barring unknown experimental breakthroughs or unknown regions of stability in these heavier elements, the end should come somewhere in the region of element 110. The elements up to and in-



The Periodic Table of the Elements

cluding einsteinium, element 99, have isotopes sufficiently long-lived to be isolated in macroscopic (that is, weighable) quantities, but this does not seem to be true beyond einsteinium. Unfortunately for the prospect of studying ever-higher elements, the longest-lived isotopes that can be made beyond element 104 or 105 will probably not exist long enough for conventional chemical identification.

However, the prediction of the chemical properties of the yet undiscovered chemical elements is quite straightforward. Lawrencium, the element with the atomic number 103, completes 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., and have analogous chemical properties.

Let me briefly review some of the history of these discoveries. The efforts of men to change one element into another, or to create new elements, date back to the time of the alchemists. But the first serious scientific attempts to go beyond the heaviest of the known elements—uranium—and explore the transuranium region were those of Enrico Fermi, Emilio Segrè, and their co-workers in Rome, in 1934, shortly after the existence of the neutron had been discovered. This group bombarded uranium with slow neutrons in the hope that the uranium nucleus would capture a neutron. A number of radioactive products were found. In the immediately following years, many more such radioactive species were observed. However, chemical investigations led to the discovery that these were not transuranium elements, but, rather, products of the fission process. The discovery of fission by Otto Hahn and F. S. Strassman, in December 1938, which led to the "atomic age", was in a sense a dividend or by-product of man's quest for the transuranium elements.

AS fate would have it, the discovery of the first transuranium element—element No. 93, *neptunium*—was a by-product of studies of the fission process conducted by E. M. McMillan. McMillan, working at the University of California at Berkeley in the spring of 1940, was trying to measure the energies of the two main fragments from the neutron-induced fission of uranium. He placed a thin layer of a uranium compound (uranium oxide) on one piece of paper; and next to this he stacked very thin sheets of similar paper to stop and collect the fission fragments recoiling from uranium. The paper he used was ordinary cigarette paper, the kind that people who roll their own cigarettes use. In the course of his studies, he found that there was another unstable, radioactive product of the reaction—one which did not recoil sufficiently to escape from the thin layer of uranium undergoing fission. He suspected that this was a product formed by the capture of a neutron in the uranium. McMillan and P. H. Abelson, who joined him in this research, were able to show, on the basis of their chemical work, that this product was an isotope of the element with atomic number 93—neptunium-239, formed by neutron capture in uranium-238, followed by beta decay.

McMillan's and Abelson's investigation of neptunium showed that it resembles uranium—not rhenium, as predicted—in its chemical properties. Therefore, analogous to uranium, which was named after the planet Uranus,

element 93 was named neptunium, after the next planet, Neptune. This was the first definite evidence that an inner electron shell (the 5*f* electron shell) is filled in the transuranium region.

THE element with the atomic number 94, *plutonium*, was next to be discovered. By bombarding uranium with deuterons raised to a high energy in the 60-inch cyclotron at the University of California at Berkeley, E. M. McMillan, J. W. Kennedy, A. C. Wahl, and I, in late 1940, succeeded in preparing a new isotope of neptunium, neptunium-238, which decayed to plutonium-238.

The first bombardment of uranium oxide with the 16-MeV deuterons was performed on December 14, 1940. Alpha radioactivity was found to grow into the chemically separated element 93 fraction during the following weeks, and this alpha activity was chemically separated from the neighboring elements (especially elements 90 to 93, inclusive) in experiments performed during the next two months. These experiments constituted the positive identification of plutonium.

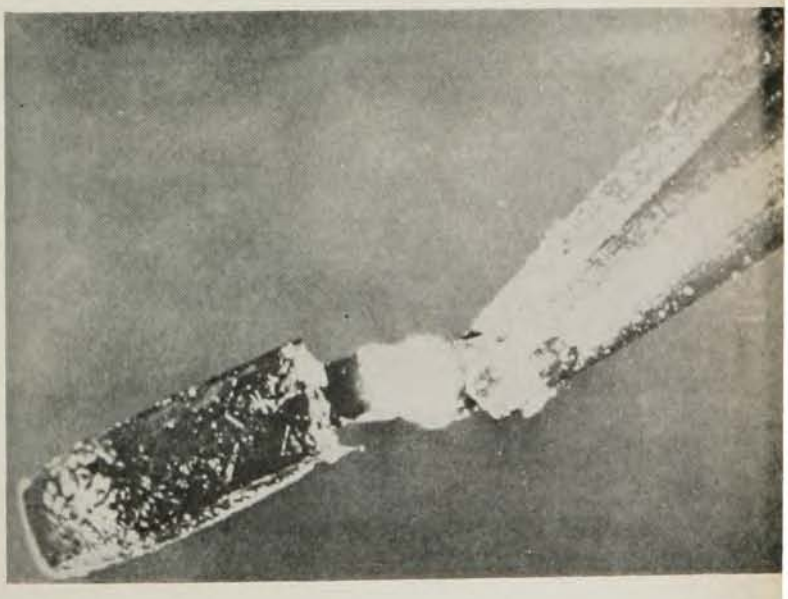
The chemical properties of elements 93 and 94 were studied by the so-called "tracer method" at the University of California for the next year and a half. This meant that invisible amounts of these elements were followed in chemical studies by their telltale radioactivity. These first two transuranium elements were referred to by the group simply as "element 93" and "element 94", or by code names, until the spring of 1942, at which time the first detailed reports on them were written. The early work, even in those days, was carried on under a self-imposed cover of secrecy. Throughout 1941, element 94 was referred to by the code name of "copper", which was all right until it was necessary to introduce the element copper into some of the experiments. This posed the problem of distinguishing between the two. For a while, plutonium was referred to as "copper" and the real copper was "honest-to-God copper". This seemed clumsier and clumsier as time went on, and element 94 was finally christened "plutonium", after the planet Pluto and analogous to uranium and neptunium.

The plutonium isotope of major importance is the one with mass number 239. The search for this isotope, as a decay product of neptunium-239, was being conducted by the same group, with the collaboration of E. Segrè, simultaneously with the experiments leading to the discovery of plutonium. The isotope plutonium-239 was identified, and its possibilities as a nuclear energy source established, during the spring of 1941.

Using neutrons produced by the 37-inch cyclotron at the University of California, the group first demonstrated, on March 28, 1941, with a sample containing 0.5 microgram of plutonium-239, that this isotope undergoes slow-neutron-induced fission with a cross section even larger than that of uranium-235. A fission cross section for plutonium-239 some 50 percent greater than that for uranium-235 was found, in remarkable agreement with the accurate values which were determined later.

The realization that plutonium-239 could serve as the explosive ingredient of a nuclear weapon, and that it might be created in quantity in a nuclear reactor, followed by chemical separation from uranium and the highly radioactive fission products, made it imperative to carry out chemical investigations of plutonium with weighable quantities, even though only microgram quantities could be produced using the cyclotron sources of neutrons available at that time. In August 1942, B. B. Cunningham and L. B. Werner, at the wartime Metallurgical Laboratory of the University of Chicago, succeeded in isolating about a microgram of plutonium-239—less than one ten-millionth of an ounce—which had been prepared by cyclotron irradiations. Thus, plutonium was the first man-made element to be obtained in visible quantity. The first weighing of this man-made element took place on September 10, 1942, and was performed by investigators Cunningham and Werner.

These so-called "ultramicrochemical" studies conducted by the research workers on plutonium were remarkable. It was possible to perform many significant studies with almost invisible amounts of material—work that was carried out under a microscope. If extremely small volumes are used, even microgram quantities of material can give relatively high concentrations in solu-



This magnified photograph of a compound of plutonium (2.77 micrograms of oxide) was first to be weighed by man (on September 10, 1942). The picture is enlarged approximately 14-fold. Plutonium oxide appears as crusty deposit (lower left) near end of platinum weighing boat held with forceps (upper right).

tion; and with the development of balances of the required sensitivity, micrograms were also sufficient for gravimetric analysis. Liquid volumes in the range of 10^{-1} to 10^{-5} cc were measured with an error of less than one percent by means of finely calibrated capillary tubing. Chemical glassware, such as test tubes and beakers, was constructed from capillary tubing and was handled with micromanipulators.

Plutonium is now produced in much larger quantities than any other synthetic element. The large, wartime chemical-separation plant at Hanford, Washington, was constructed on the basis of the investigations performed on the tracer and ultramicrochemical scale; the scale-up between ultramicrochemical experiments to the final Hanford plant corresponds to a factor of about one billion—surely, a scale-up of unique proportions.

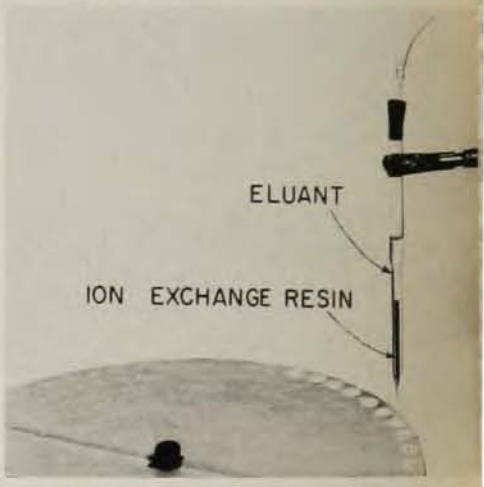
AFTER the completion, at the wartime Metallurgical Laboratory, of the most essential part of the investigations concerned with the chemical processes involved in the production and separation of plutonium, attention turned to the problem of synthesizing and identifying the next-heavier transuranium elements. As my collaborators in this endeavor, there were A. Ghiorso, R. A. James, and L. O. Morgan.

There followed a period during which the attempts to synthesize and identify elements 95 and 96 bore no fruit. The 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 a higher oxidation state and utilize this oxidation in the chemical-isolation procedures. It was not until the middle of the summer of 1944, upon the first recognition that these elements were part of an "actinide" transition series (i.e., were chemically very similar to the element actinium and to the long-known rare-earth elements) that any advance was made; and then progress came quickly. Incidentally, this element-by-element analogy in chemical properties between the actinide and lanthanide (rare-earth) elements has been the key to the chemical identification—and, hence, discovery—of the subsequent transuranium elements.

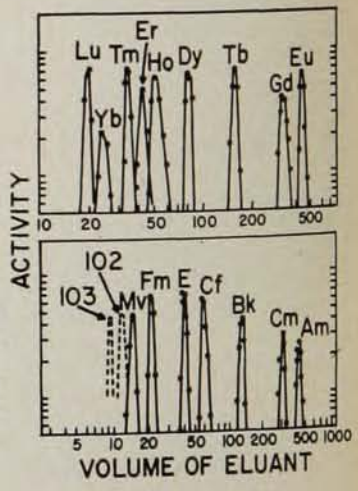
When it was recognized that these elements could be oxidized only with extreme difficulty, if at all, the identification of an isotope then thought to be due to element 95 or 96 followed immediately. Thus, the isotope of element 96—now known to be *curium-242*—was produced in the summer of 1944 as a result of the bombardment of plutonium-239 with 32-MeV helium ions in the cyclotron at Berkeley.

The identification of element 95, *americium*, in the form of the isotope americium-241 followed, during late 1944 and early 1945, as a result of the bombardment of plutonium-239 with neutrons in a nuclear reactor.

Some comments should be made concerning the rare-earth-like properties of these two elements. Our hypothesis that they should greatly resemble the rare-earth elements in their chemical properties proved to be so very true that, for a time, it appeared to be unfortunate. The better part of a year was spent in trying, without success, to separate chemically the two elements from each other and from the rare-earth elements; and although we felt entirely confident, 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 was still undemonstrated. The elements remained unnamed during this period of futile attempts at separation (although one of our group referred to them as "pandemonium" and "delirium", in recognition of our difficulties). The key to their final separation, and the technique which made feasible the separation and identification of these and subsequent transuranium elements, was the so-called ion-exchange technique. The elements were named americium, after the Americas, and curium, in honor of Pierre and Marie Curie, by analogy to the naming of their rare-earth counterparts, europium (after Europe) and gadolinium (after Finnish chemist Gadolin).



Experimental apparatus for ion-exchange separation used in the chemical separation and identification of actinide elements. Drops of eluant are collected on metal disks, and their radiations analyzed.



Example of experimental data obtained in ion-exchange method of chemical separations and identification of actinide elements based upon their analogous behavior to the lanthanide elements.

THE most important prerequisite to the process for making the transcurium elements was that sufficiently large amounts of americium and curium be manufactured to serve as starting materials. Because of the intense radioactivity of these starting substances, even in milligram or submilligram amounts, it was necessary to develop extremely efficient chemical separation methods in order to obtain the enormous separation factors needed for the isolation of the new elements from the starting material, so that it would be possible to detect the very small amounts of radioactivity due to the new transcurium elements. The dangerous radioactivity of the source material made it necessary to develop complicated methods for remote control operation to keep the health hazards at a minimum.

These production, separation, and protection problems were solved, and successful experiments were performed at the end of 1949 and the beginning of 1950. Americium for target material was prepared in milligram amounts by intense neutron bombardment of plutonium over a long period of time, and curium target materials were prepared in microgram amounts as the result of the intense neutron bombardment of some of this americium. Both of these neutron bombardments took place in a high-power reactor having a high neutron flux.

Element 97, *berkelium*, was discovered by S. G. Thompson, A. Ghiorso, and myself, in December 1949, as a result of the bombardment of the milligram amounts of americium-241 with 35-MeV helium ions accelerated in the 60-inch cyclotron of the University of California at Berkeley. The first isotope produced has the mass number 243 and decays with a half-life of 4.5 hours.

Element 98, *californium*, was first produced and similarly identified by Thompson, Ghiorso, K. Street, and myself in February 1950 at the University of California at Berkeley. The first isotope produced is now assigned the mass number 245 and decays with a half-life of 44 minutes. This isotope was produced by the bombardment of microgram amounts of curium-242 with 35-MeV helium ions accelerated in the 60-inch cyclotron. It is interesting to note that this identification of element 98 was accomplished with a total of only some 5000 atoms; someone remarked at the time that this number was substantially smaller than the number of students attending the university.

The naming of elements 97 and 98 presents an interesting story. Element 97 was called berkelium after the city of Berkeley, California, where it was discovered. Element 98 was named californium after the university and state where the work was done.

Upon learning about the naming of these elements, the "Talk of the Town" section of the *New Yorker* magazine had the following to say:

> New atoms are turning up with spectacular, if not downright alarming, frequency nowadays, and the University of California at Berkeley, whose scientists have discovered elements 97 and 98, has christened them berkelium and californium, respectively. While unarguably suited to their place of birth, these names strike us as indicating a surprising lack of public relations foresight on the part of the university, located, as it is, in a state where publicity has flourished to a degree matched perhaps only by evangelism. California's busy scientists will undoubtedly come up with another atom or two one of these days, and the university might well have anticipated that. Now it has lost forever the chance of immortalizing itself in the atomic tables with some such sequence as universitium (97), ofium (98), californium (99), berkelium (100).

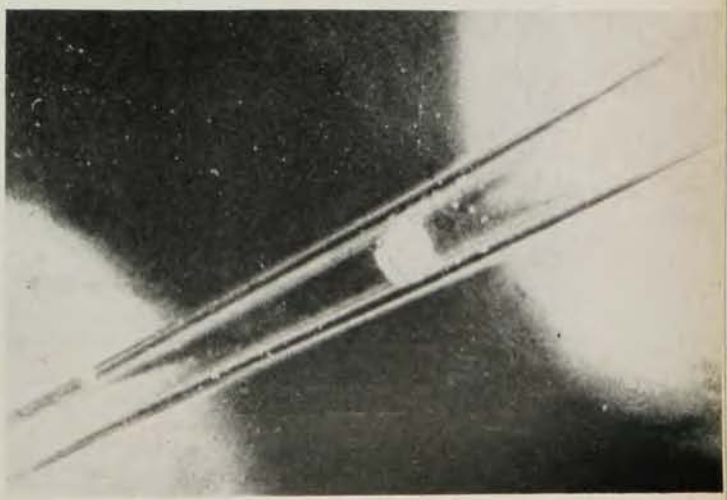
The discoverers sent the following reply:

> "Talk of the Town" has missed the point in their comments on naming of the elements 97 and 98. We may have shown lack of confidence but no lack of foresight in naming these elements "berkelium" and "californium". By using these names first, we have forestalled the appalling possibility that after naming 97 and 98 "universitium" and "ofium", some New Yorker might follow with the discovery of 99 and 100 and apply the names "newium" and "yorkium".

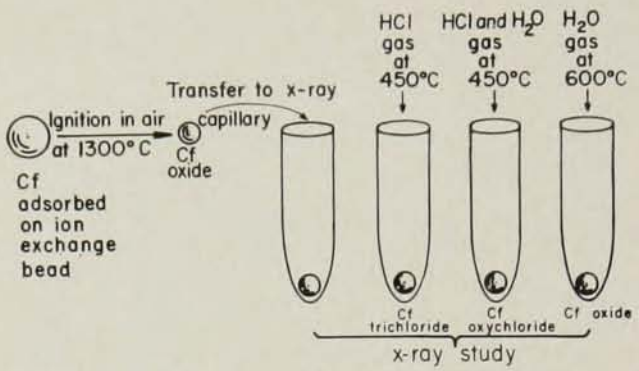
The answer from the *New Yorker* staff was brief:

> We are already at work in our office laboratories on "newium" and "yorkium". So far, we just have the names.

In 1958, S. G. Thompson and B. B. Cunningham at Berkeley succeeded in isolating, for the first time, macroscopic amounts of berkelium (as berkelium-249) and californium (as a mixture of californium-249 and -252), which were synthesized by the long-term irradiation of plutonium-239 and its transmutation products with neutrons. The first pure compound of californium was isolated in 1960, by B. B. Cunningham and J. C. Wallmann, using californium-249 obtained via the decay of previously separated berkelium-249. Three tenths of a microgram of californium oxychloride (CfOCl)



Photograph of first pure californium compound isolated in 1960 (0.3 μg of californium as the oxychloride, CfOCl), magnified about 35 times. The californium was in the form of the isotope californium-249.



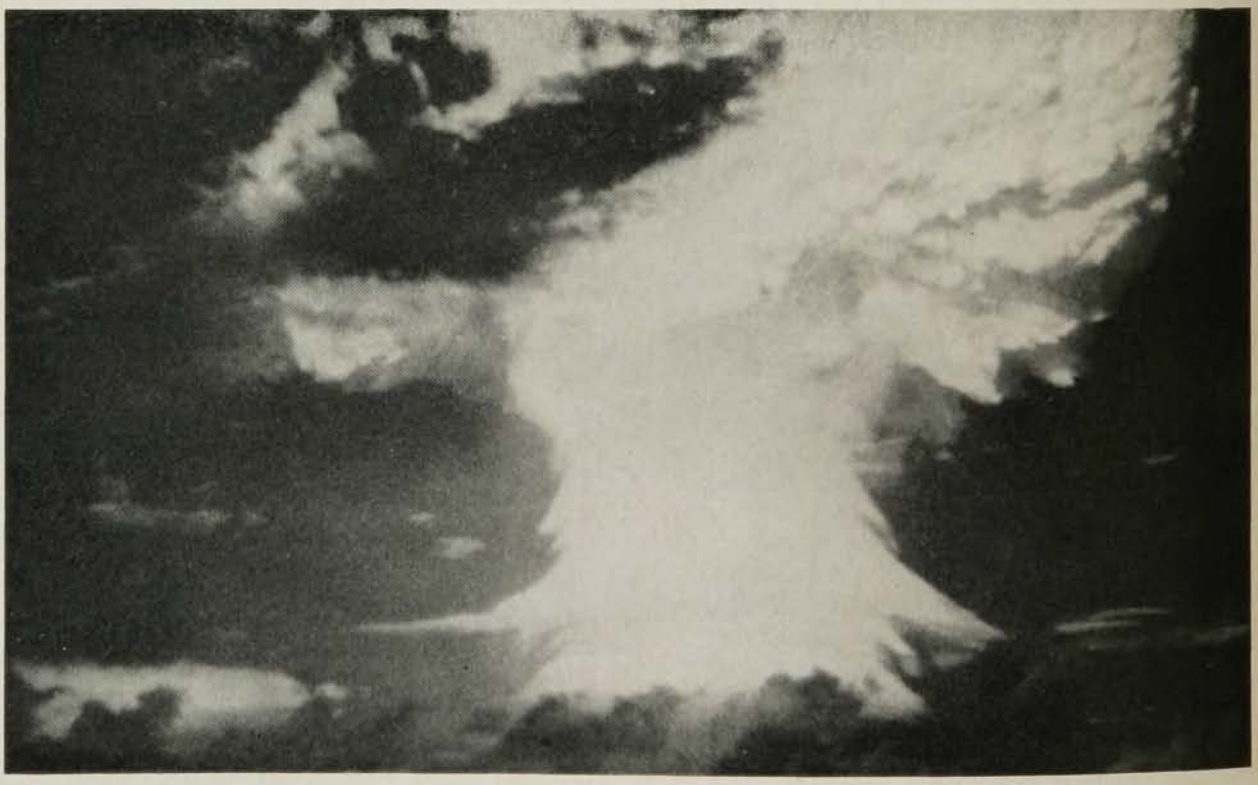
Submicrogram scale preparation of heavy element compounds for x-ray diffraction investigation

Experimental setup for preparation of heavy-element compounds—as, for example, those of californium—on the "submicrogram" scale for x-ray diffraction investigations.

was isolated. Later, the trichloride and oxide were also prepared. This experimental work was the first carried out on a "submicrogram" scale as a result of new techniques and represented an order-of-magnitude scale-down from the ultramicrochemical work done during the last war.

THE discovery of elements 99 and 100, *einsteinium* and *fermium*, represents an outstanding example of the unexpected in science. The seventh and eighth transuranium elements were discovered in debris from "Mike", the first, large thermonuclear or "hydrogen-bomb" explosion which took place in the Pacific in November 1952. Debris from the explosion was collected, first on filter papers attached to 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 of this debris 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 unexpected observation of heavy isotopes such as plutonium-244 and plutonium-246. At that time, the heaviest known isotope of plutonium was plutonium-243. Since this pointed to the capture of many successive neutrons by the uranium-238 in the device, and thus the presence of neutron-rich isotopes in greater abundance than expected, a group at the University of California Radiation Laboratory undertook to look for isotopes of transcalifornium elements in this material. Ion-exchange experiments of the type previously mentioned immediately demonstrated the existence of a new element. Later, in or-

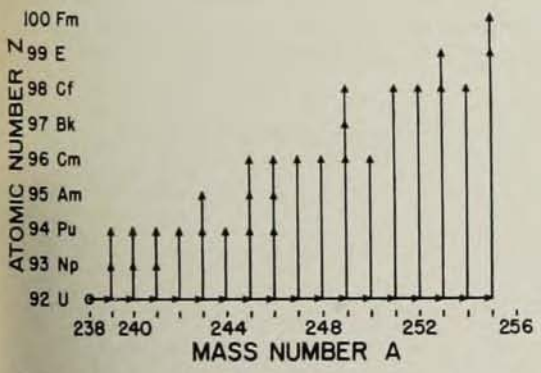


Einsteinium and fermium, elements 99 and 100, were initially discovered in the debris from the first large thermonuclear explosion, which took place in the Pacific in November 1952.

der 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. Eventually, such coral was worked up by the ton in a pilot-plant operation which went under the name of "Paydirt".

Without going into the details, it may be pointed out that the experiments by the research groups at the three laboratories led to the positive identification of isotopes of elements 99 and 100. A radioactive isotope with the mass number 253, which decays with a half-life of twenty days, was identified as an isotope of einsteinium—element 99—named in honor of Albert Einstein. A radioisotope with the mass number 255 and a half-life of about 20 hours was identified as an isotope of fermium, element 100, named in honor of Enrico Fermi.

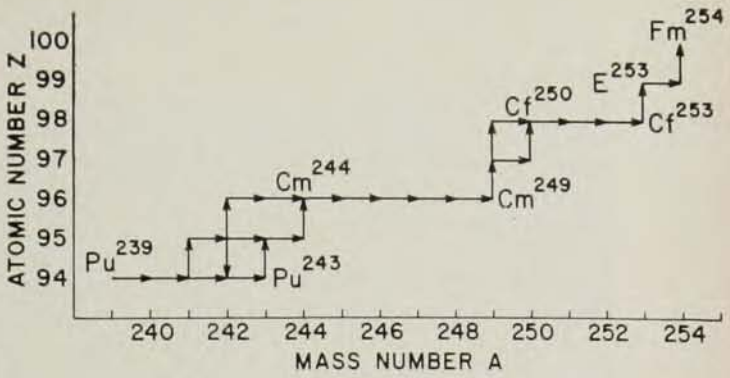
The successive instantaneous capture of many neutrons by uranium-238 had led to heavy uranium isotopes. The heavy uranium isotopes then decayed into the isotopes appearing beyond them in the Periodic Table, hence increasing the atomic number in successive steps. The first identification of element 100 was made with only about 200 atoms. The most striking



Nuclear reactions for the synthesis of einsteinium and fermium in the first thermonuclear explosion. The horizontal arrows represent the almost instantaneous capture of neutrons and the vertical arrows represent the subsequent beta decay.

previous accomplishment in this category was the positive identification of element 98 with a total of about 5000 atoms.

Before declassification and the subsequent announcement of the original discovery experiments could be accomplished, isotopes of elements 99 and 100 were produced by a number of other methods. Chief among these was that of successive neutron capture as the result of intense neutron irradiation in a nuclear reactor of high neutron density. The difference between this method of production and that of the "Mike" thermonuclear explosion is one of time as well as of starting material. In a reactor, it was necessary to bombard gram quantities of plutonium for several years; thus,



Nuclear reaction sequences for production of heavy nuclides by intense slow-neutron irradiation of Pu^{239}. Neutron-capture reactions (horizontal arrows) are interspersed with beta decays (vertical arrows).

the short-lived, intermediate isotopes of the various elements had an opportunity to decay. Unfortunately, this process cannot be used to prepare the elements beyond fermium (element No. 100), because some of the intermediate isotopes which must capture neutrons have half-lives so short as to preclude their presence in the appreciable concentrations that are necessary. In the thermonuclear device, larger amounts of uranium were subjected to an extremely high neutron irradiation for a period of a few millionths of a second; the subsequent decay of the ultraheavy isotopes of uranium formed the products of high atomic number found in the debris. In principle, this method could be used to prepare elements beyond fermium.

It was not until 1961 that sufficient einsteinium had been produced through intense neutron bombardment in reactors to permit separation of a macroscopic and weighable amount. B. B. Cunningham, J. C. Wallmann, L. Phillips, and R. C. Gatti, at Berkeley, were able to separate—working on the new, submicrogram scale—an extraordinarily small amount of einsteinium-253. A total amount of only a few hundredths of a microgram, a billionth of an ounce, was weighed on a special, magnetic-type balance.

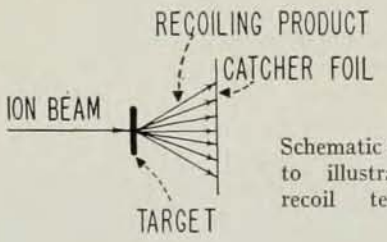
THE discovery of *mendelevium*, element 101, by A. Ghiorso, B. G. Harvey, G. R. Choppin, S. G. Thompson, and myself, was in many ways the most dramatic of them all. It was decided to make an attempt in a situation which would have been regarded by most sensible people as very premature. All of the previous discoveries of transuranium elements had been based on starting with weighable amounts of target materials; however, it was thought that techniques had advanced to a point where it might be possible to identify the element with the atomic number 101 in a target of unweighable amount.

The plan of attack involved the bombardment of the maximum available quantity of einsteinium, element 99, in the form of the isotope einsteinium-253, with helium

ions in the Berkeley 60-inch cyclotron. On gathering together all of the available einsteinium-253 which had been produced in nuclear reactors, we found that it amounted to about 10^9 atoms. In order to assay the possibilities, the number of atoms of element 101 which could reasonably be expected from the bombardment could be deduced from simple considerations. The calculation showed that we could expect to produce approximately one atom in each experiment!

Adding immeasurably to the complexity of the experiment was the absolute necessity for the chemical separation of the one atom of element 101 from the 10^9 atoms of einsteinium in the target and its ultimate, complete chemical identification by separation with the now familiar ion-exchange method. This separation and identification would presumably have to take place in a period of hours, or even one hour or less, because the expected half-life was of this order of magnitude.

The requirements indicated the desperate need for new techniques, together with some luck; and fortunately both were forthcoming. The new technique involved the separation of the element 101 by the recoil method from the einsteinium in the target. The einsteinium was placed on a gold foil in an invisibly thin



Schematic drawing to illustrate the recoil technique.

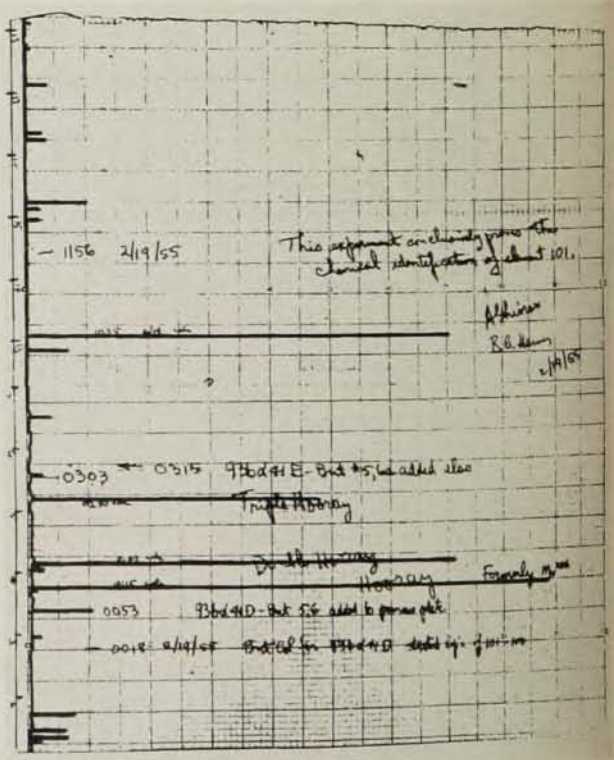
layer. The helium-ion beam produced in the cyclotron was sent through the back of the foil so that the atoms of element 101, recoiling due to the reaction with the impinging helium ions, could be caught on a second thin gold foil. This second gold foil which contained the recoiled atoms, and which was relatively free of the einsteinium target material, was dissolved, and the chemical operations performed began with this solution.

The earliest experiments were confined to looking for short-lived, alpha-particle-emitting isotopes of element 101. No alpha activity was observed that could be attributed to element 101, even when the time between the end of bombardment and the beginning of the alpha particle analyses had been reduced to five minutes.

However, the experiments were continued and, in one of the subsequent bombardments, a single large pulse caused by spontaneous fission was observed in the detection apparatus. With probably unjustified self-confidence, we thought that this might be a significant result. Although such an attitude might ordinarily have been considered foolish, it must be recalled that rapid decay by spontaneous fission was up until that time confined to only a few isotopes, none of which should have been introduced spuriously into the experiment or produced in the experiment. In addition, background counts due to this mode of decay should be essentially zero in proper equipment.

The major question, of course, was whether the experiment could be repeated. In a number of subsequent bombardments, spontaneous fission events were observed in some, while none was observed in others. This, of course, was to be expected, because of the statistical fluctuation inherent in the production of the order of one atom per experiment. Furthermore, more advanced chemical experiments seemed to indicate that the spontaneous fission counts, when they did appear, came in about the element 100 or 101 chemical fractions. At about this time, a huge fire bell was hung in the hall of the chemistry building, connected to the counting circuit in such a manner that a loud "clang" rang out on each occasion when one of these rare spontaneous fission events registered. However, this sport was put to a justifiable end when it came to the attention of the fire department.

The definitive experiments were performed in a memorable, all-night session. Three successive, three-hour bombardments were made, and, in turn, their transmutation products were completely and quickly separated by the ion-exchange method. A total of five spontaneous fission counts was observed in the element 101 chemical fraction, while a total of eight spontaneous fission counts was also observed in the fermium



Reproduction of original data sheet showing stylus tracing (and various annotations) from a spontaneous-fission recording system, corresponding to discovery of mendelevium, element 101 (February 19, 1955).

High Voltage Engineering Corporation . . .

"CHARGED PARTICLES"

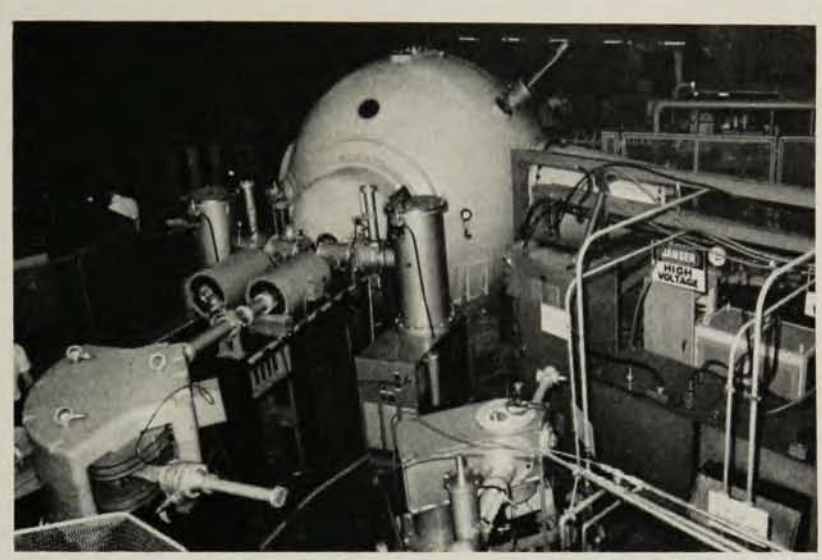
Nuclear-Structure Research

Initial work with the 12-Mev Tandem Van de Graaff has confirmed beyond expectations our early conviction that this accelerator system would greatly extend areas of useful research. A previously "dark" area, in fact the whole upper half of the periodic table, can now be investigated with precision. The range now beginning to be explored with extremely stable monoenergetic particle beams includes many isotope-rich elements and the important domain of fissionable materials. Current research indicates *the Tandem has increased the number of resolvable energy levels by an order of magnitude.* In constructing a theory of the nucleus, the precision we speak of is every bit as important as the extension in energy. Tandem ion beams permit discrimination between closely associated energy levels and reveal new subtleties in the fine structure of heavier elements.

The Tandem Van de Graaff's external ion source at ground potential is a boon to experimenters. There are at least seventeen stable nuclei up to oxygen that may be used as bombarding particles. With multiple stripping and two-stage acceleration, oxygen ions have been accelerated to 60 Mev.

A characteristic of truly new research tools is evident in the way the Tandem is shaping the direction and objectives of physics research programs. As a result, nine laboratories with machines installed and performing to specifications, and others awaiting Tandem delivery, are planning to undertake work that is new and challenging.

At High Voltage, a vigorous engineering and development program is extending the basic Tandem principle to higher energies and beam currents. Already in the process of construction are several "King-Size" Tandems (7.5 million-volt terminal potential) providing 15 Mev protons, and much higher energies with multiply-stripped heavy ions. The new "Emperor" Tandem design will generate 10 million-volts for two-stage acceleration of 20 Mev protons.



A formidable accelerator in its own right, this new company-sponsored Tandem development facility is designed specifically to investigate high current neutral, negative, and positive ion sources. It is an important empirical tool in the study of beam dynamics, pulsing techniques, and acceleration tube design.

The concept of heavy-ion acceleration opens up a new area to the experimenter. The acceleration of 200 Mev bromine ions, while retaining control in energy and homogeneity to a few kev, is feasible. The implications for nuclear structure research are quite profound. Certainly, new aspects of multiple coulomb excitation and nuclear-fission processes are among the realms that can be advantageously explored.

Three-stage Tandem acceleration extends the Proton energy capability of the Tandem principle to well over 30 Mev. The new Research Tandem at High Voltage is being pressed to develop ion sources with outputs that are orders of magnitude greater than currently available.

"Low-Energy" Physics

As we address ourselves to this subject, more elegantly called *nuclear-structure physics*, the reader may conclude we have an axe to grind, and we admit it. We believe a great deal of research remains to be done on light nuclei. There is, for example, time-consuming but rewarding precision nuclear spectroscopy to fill in gaps in existing energy level data, as well as new research related to the conservation of isotopic spin, excitation energies of low excited states and direct interaction mechanisms.

Because much nuclear-structure research can be accomplished with standard Van de Graaffs in the 1-6 Mev energy range, equipped with ion sources for hydrogen, helium or heavy elements, these machines represent ideal research instruments for the university physics laboratory of modest proportions. We are presently compiling information on exactly where machines of moderate cost and energy can make significant contributions in illuminating concepts of nuclear structure and would be happy to discuss this subject with you.

HIGH VOLTAGE ENGINEERING CORPORATION
BURLINGTON, MASSACHUSETTS, U.S.A.

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APPLIED RADIATION CORPORATION

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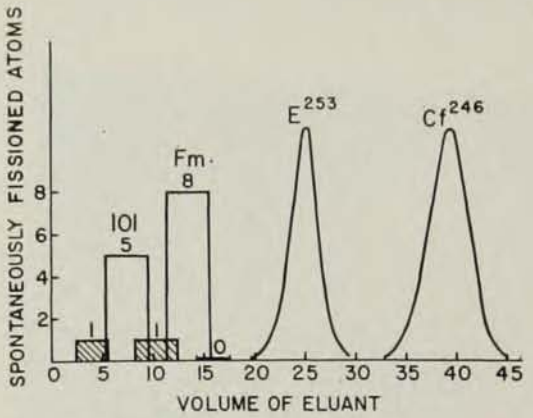
HIGH VOLTAGE ENGINEERING (EUROPA) N.V.



Original elution data corresponding to discovery of mendelevium (February 19, 1955). The curves for einsteinium-253 and californium-246 represent alpha radioactivity.

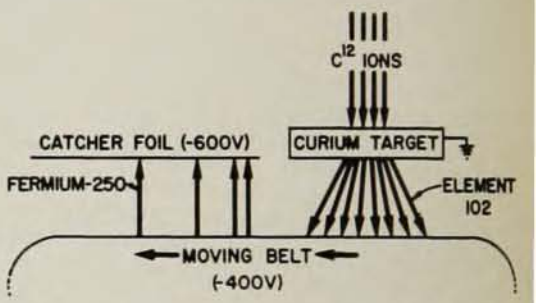
(element 100) chemical fraction; no such counts were observed in any other chemical fraction.

The spontaneous fission activity in both the element 101 and fermium (element 100) fractions decayed with a half-life of about three hours. This and other evidence led to the interpretation that the mendelevium, element 101, isotope has the mass number 256 and decays by electron capture—with a half-life of the order of one hour—to the isotope fermium-256, which is responsible for the spontaneous fission decay. Element 101 was named mendelevium in honor of the Russian scientist, Dmitri Mendeleev, who was the first to use the Periodic Table of the Elements to predict the chemical properties of undiscovered elements, a principle which has been the key to the discovery of so many of the transuranium elements.

IN 1957, a team of scientists from Argonne National Laboratory in the United States, the Atomic Energy Research Establishment in England, and the Nobel Institute for Physics in Sweden announced the discovery of an isotope of *element 102*, as a result of research performed at the Nobel Institute. The name "nobelium" for element 102 was suggested by this group. Unfortunately, neither experiments using the facilities at the University of California in Berkeley nor related experiments performed in the USSR have confirmed this Stockholm research.

In 1958, a group at the University of California—A. Ghiorso, B. G. Harvey, G. R. Choppin, S. G. Thompson, and I—reported the positive identification of the isotope of element 102 with the mass number 254 as a product of the bombardment of curium-246 with carbon-12 ions accelerated in the new, heavy-ion linear accelerator (HILAC) at Berkeley, specially constructed for experiments on the transuranium elements. The new element was detected by the chemical identification of its known daughter, fermium-250. Although the name "nobelium" for element 102 will undoubtedly have to be changed, these investigators have not yet made their suggestion for a new name.

The removal of the element 102 isotope from the target material and the separation of the daughter element from the parent element 102 were performed by the use of a new method in which two physical recoil separations were utilized. This experiment bears resemblance to that of the discovery of mendelevium, except that the half-life involved was even shorter, necessitating more sophisticated techniques. Here, again, the amount involved required identification of the new element, atom by atom. The target consisted of curium deposited on a thin nickel foil and was enclosed in a container filled with helium gas. The curium was bombarded with carbon-12 ions, and the transmuted atoms were knocked into the helium gas to absorb their recoil energy. With a sufficient electric field strength, it was found that practically all of these positively charged atoms could be attracted to a moving, negatively charged metallic belt placed directly beneath the target. The belt was then passed under a foil (the catcher



This schematic drawing shows the experimental arrangement used in the discovery of element 102.

foil), which was charged negatively relative to the belt. Approximately half of the element 102 atoms undergoing radioactive decay by alpha-particle emission would cause their daughter atoms to recoil from the surface of the belt to a catcher foil.

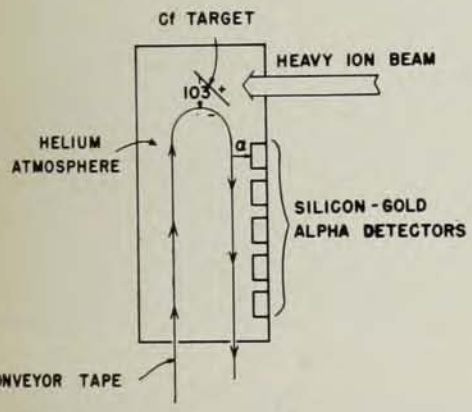
The catcher foil was cut transversely to the direction of the belt motion into five equal-length sections—after a time of bombardment suited to the half-life of the daughter atom to be examined—and each section was analyzed simultaneously in counters. All of the desired measurements could be made for identifying the daughter atoms caught on the catcher foils, and thus the half-life of the parent of the recoiling atoms could be determined. It was found that fermium-250 could be collected on the catcher foil in accordance with a parent half-life (i.e., half-life for element 102 with a mass number 254) of three seconds. Changing the belt speed was found to change the distribution of the fermium-250 on the catcher foil in a manner conforming to a three-second parent.

In later experiments, the recoil atoms of element 102 were caught on a belt which was quickly pulled inside an alpha-particle counter in order to measure directly

the energy of the alpha particles and the half-life of the isotope in question.

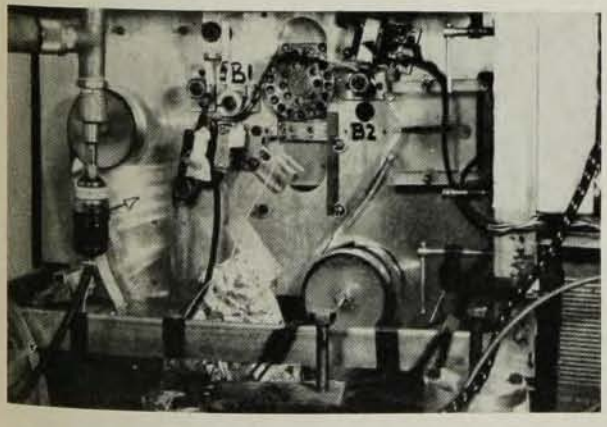
IN the spring of 1961, after almost three years of work which began shortly after the discovery of element 102, a group at the University of California, Berkeley (A. Ghiorso, T. Sikkeland, A. Larsh, and R. Latimer) found an isotope of element 103, *lawrencium*, named in honor of Ernest O. Lawrence.

The method used to produce and identify lawrencium was similar to that used in the later, direct-counting experiments performed in connection with the discovery of element 102. About three micrograms of a mixture of californium isotopes were bombarded with boron ions accelerated in the heavy-ion linear accelerator (HILAC). The atoms of lawrencium recoiled from the target into an atmosphere of helium, where they were electrostatically collected on a copper conveyor tape. This tape was then periodically pulled into place before radiation detectors to measure the emission rate and the energy of the alpha particles being emitted. By this means, it was possible to identify the lawrencium isotope, lawrencium-257, with a half-life of eight seconds. At present, because of the short half-life and the lack of a suitable daughter isotope, available in the case of element 102, it has not been possible to perform a chemical identification, and the discovery rests solely on nuclear evidence.



Schematic drawing above illustrates the experimental arrangement which made possible the discovery of an isotope of lawrencium, element 103.

The photograph below shows the apparatus used last year by the discoverers of lawrencium.



THE search is continuing for even heavier transuranium elements with atomic numbers beyond 103. These may be discovered by means of bombardments with heavy ions, as in the case of elements 102 and 103. This requires the use of isotopes of the heaviest available elements, especially californium and einsteinium, as target materials. Present supplies of californium are limited to microgram quantities, and in the case of einsteinium to submicrogram quantities.

A program recently initiated by the Atomic Energy Commission is aimed at the production, within some five years, of gram quantities of californium and milligram quantities of einsteinium. Some time ago, twelve kilograms of plutonium were inserted in a large production reactor. In several years this irradiation should produce relatively large quantities of plutonium-242, americium-243, and curium-244, which can be used as feed material for the production of californium and einsteinium in the new High Flux Isotope Reactor (HFIR) that the Atomic Energy Commission is building at the Oak Ridge National Laboratory.

As already mentioned, it is also possible to produce new transuranium isotopes—and perhaps even new elements—in thermonuclear explosions, owing to the very intense, although brief (order of a microsecond), neutron flux furnished by the explosion.

UP to this point, I have addressed myself, for the most part, to the exciting search for and discovery of the transuranium elements. The work was clearly basic research—a quest for further knowledge and understanding of the atomic and nuclear properties of the elements. However, as history would have it, this basic research work has developed into an outstanding example of the great and important effect that such discoveries can have on people everywhere. The most immediate effect that the discovery of a transuranium element had on the world was, of course, the use of plutonium in nuclear weapons.

Historically, after the fission reaction was discovered in uranium, effort was devoted to separating the fissionable uranium isotope, uranium-235, from the bulk of the uranium, uranium-238; that is, to the enrichment of uranium-235. During the crucial and urgent war years, an alternative method was vital for concentrating a fissionable isotope that might be used in atomic weapons. After the discovery of plutonium-239 and its fissionable properties, an intensive program of research and development engineering was sponsored to produce significant quantities of this new element for military uses.

Whereas the separation of uranium isotopes required exceedingly refined techniques, since chemically the two isotopes were nearly indistinguishable, the separation of plutonium from the uranium in which it was formed, and the huge quantities of radioactive fission products present with it, presented a more straightforward chemical problem. One could rely on the chemical properties of the new element to separate it from uranium and all the other elements present—if one knew the chemical properties of this new element. Fortunately, it was possible to determine the chemical properties of plutonium by means of the tracer and ultramicrochemical experiments. The engineering of large-scale separation plants based on this knowledge was of course successful.

The first large facility (constructed during World War II) for the production of plutonium was the Hanford Engineer Works at Hanford, Washington. Some years after World War II, a second plutonium production site, the Savannah River Plant, was constructed south of Aiken, South Carolina, on the Savannah River.

However, the uses of these transuranium elements are not limited to military applications. They also have very important peaceful applications. Plutonium-239 and -241, which are both fissionable by thermal neutrons, can also be used in power reactors. To date, no large reactors have been built to be fueled with plutonium; rather, natural uranium or enriched uranium has been used. However, most large reactors using either natural or slightly enriched uranium produce considerable quantities of plutonium, some of which is utilized in the nuclear reactor itself. The remainder is then available upon chemical separation of the fuel material. As more power reactors come into operation, more plutonium will be produced; and it will become more feasible to use this increasing supply of plutonium for fueling reactors. This will increasingly supplement ordinary fuels in meeting the large, growing need for additional electrical power in the future.

The really important role of plutonium in peaceful applications lies in the fact that a fissionable isotope can be produced from uranium-238, a nonfissionable isotope. In any analysis of the world's energy resources, it is evident that gas, oil, and coal are not inexhaustible, but eventually limited. Studies to date would indicate that the energy locked in available supplies of uranium is factors greater than that in these available fossil fuels. However, this relative excess of energy is calculated on the basis of our being able to utilize not only the several tenths of a percent of uranium-235 present, but the inherent energy in the abundant uranium-238 that can be converted into fissionable plutonium.

In the design and development of nuclear power reactors, there is a special effort given to the field known as "breeder reactors". In essence, these reactors produce more fissionable material than they use in the reaction. This is possible because a fissioning atom of plutonium-239, uranium-235, or uranium-233, yields in excess of two neutrons during the fission reaction. In a simplified view, one neutron is required to continue the chain of fission reactions. The remaining neutrons (now in excess of one) could theoretically be captured in uranium-238 or thorium-232 to produce new fissionable material (plutonium-239 or uranium-233) in excess of the amount consumed in the process.

In reality, of course, the situation is somewhat more complex. There are other parasitic materials present in the reactor which capture neutrons. All the fissionable isotopes themselves do not always undergo fission upon capturing neutrons, but a certain fraction of the neutrons, dependent upon the energy of the neutrons, is absorbed to produce heavier isotopes. Development of these theories and studies shows that use of the uranium-238/plutonium-239 breeding cycle is most profitable in a fast reactor—that is, a reactor which operates with a fast or high-energy neutron spectrum, rather than a thermal or low-energy one. On the other hand, the thorium-232/uranium-233 breeding cycle seems more feasible in a thermal-neutron reactor.

This is an area of reactor research and development in which great advances remain to be made. Over the next decade, this area in itself could make one of the exciting stories of mankind's technological development. Without these potential developments, the application of nuclear energy to the economic production of electrical power, which appears close at hand, will not have as significant an effect on our nation and on the world.

The application of the transuranium elements does not end with plutonium-239. One of the more exciting aspects gaining increased importance is the use of certain of these isotopes, particularly plutonium-238 and curium-242, as concentrated sources of power by themselves. Transuranium elements emit high-energy alpha particles. A few grams, then, of such an isotope, in an appropriately shielded container, can provide an intense source of heat, since the alpha particles can easily be stopped and their energy converted into heat. Using thermoelectric and thermionic devices, it is possible to convert this heat, without moving parts, into usable electricity.

This package power source is both small and light. Already, many uses have been made of it. The first nuclear energy used in space (June 29 and November 15, 1961) was in the form of radioisotope sources (utilizing plutonium-238) in the TRANSIT satellites. It is also possible to utilize curium-242 in other space studies —e.g., of the lunar surface. These package radioisotope electric generators can also be used in space to power some communication satellites and in terrestrial applications where there is need for a remote, unattended, small power source that is relatively impervious to conditions and hazards of its environment.

It is quite evident that even further applications will be found for these transuranium elements. Of even greater importance is the contribution which the study of their chemical and nuclear properties has made to the store of human knowledge. The time and effort devoted to the basic research involved in their discovery and investigation have been more than compensated for by the results.