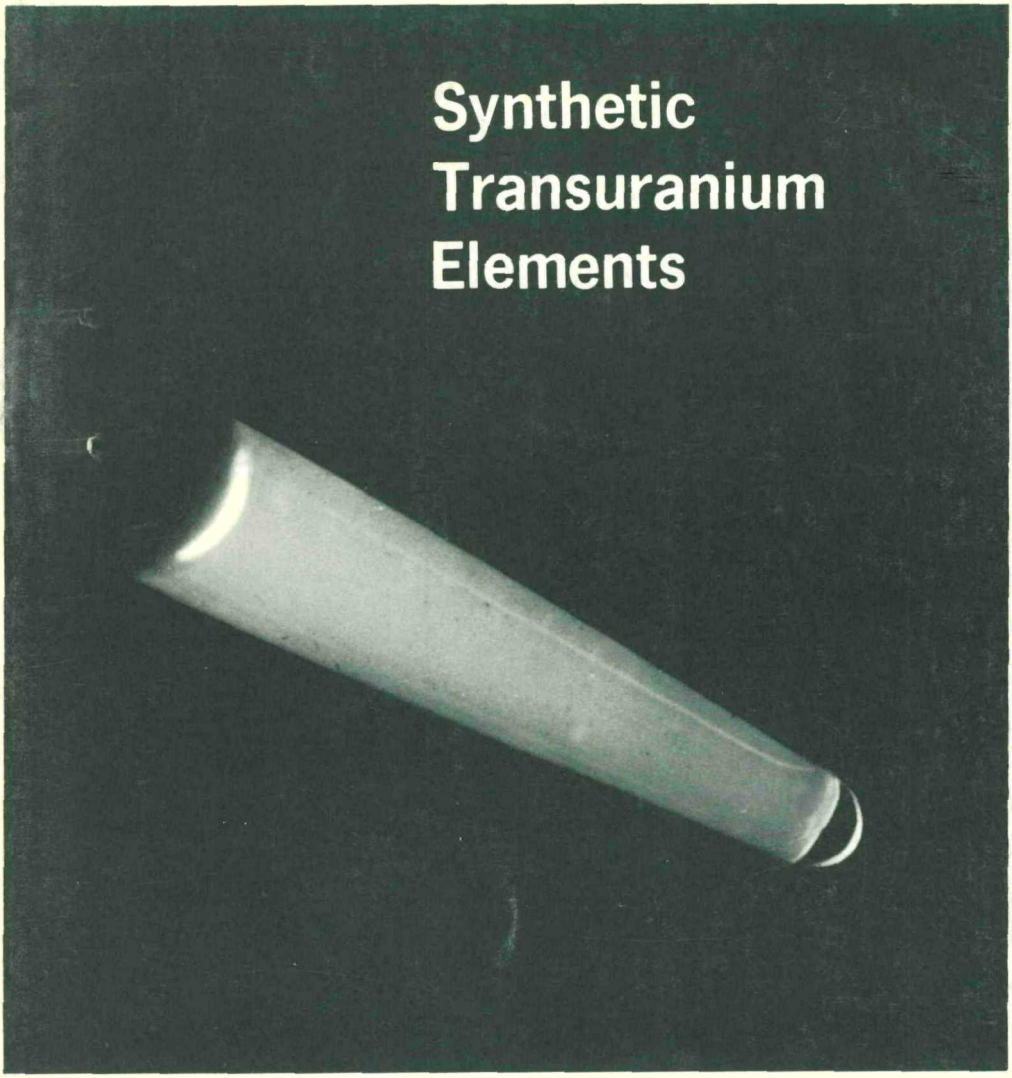
Synthetic Transuranium Elements



U.S. ATOMIC ENERGY COMMISSION / Division of Technical Information

Synthetic Transuranium Elements

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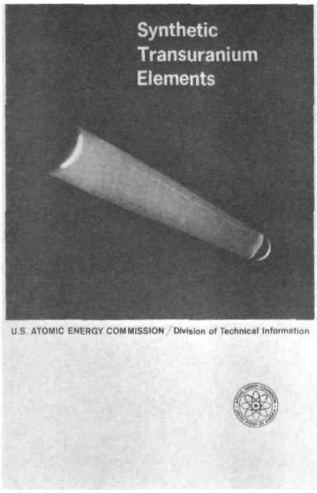
THE COVER

A solution of curium, element 96, photographed by its own light at the Lawrence Radiation Laboratory of the University of California, is shown on the cover. An isotope of curium-242 was produced in the summer of 1944. It was the first man-made element to be created purposely in a program of synthesis that started when scientific activity connected with production of plutonium for nuclear weapons had passed its peak. Curium was named for Pierre and Marie Curie. Its discoverers were Glenn T. Seaborg, Albert Ghiorso, and R. A. James.



THE AUTHOR

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He has published numerous scientific articles and review articles on the chemical and nuclear properties of the heavy elements including the synthetic transuranium elements. Together with Dr. Glenn T. Seaborg, present Chairman of the Atomic Energy Commission, and Prof. Isadore Perlman of the University of California, he has written a three-volume reference work covering all aspects of the nuclear properties of the heavy elements.

Synthetic Transuranium Elements

By EARL K. HYDE

NATURAL ELEMENTS AND THE DIFFICULTIES IN THEIR TRANSMUTATION

Origins of the Natural Elements

Chemical elements are often called the building blocks of nature. Everything in our physical world—the rocks and minerals of the earth's surface, the waters of rivers and seas, the gases of the atmosphere, the leaves of plants, and the flesh of animals—is constructed of a few dozen chemical elements. It is rather certain that the elements found in our solar system were produced in a series of nuclear fires burning inside ancient stars, the last one of which occurred not less than 10 billion years ago and probably considerably before that.

At the time of this last cosmic synthesis, many unstable forms of the elements were produced. These have been transmuted to the stable ones we are familiar with in everyday life by the spontaneous and continuous changes in the constitution of their nuclei which we call radioactivity. Of the first 82 elements in the periodic system, there are two which are missing in nature because they exist in no stable forms. These are elements 43 and 61, technetium and promethium. The elements above lead (element 82) have a pronounced nuclear instability because of the large number of protons in their nuclei; it is a lucky cosmic accident that any of these elements have survived since the last cosmic

event of element synthesis. The heavy elements uranium and thorium, elements 92 and 90, respectively, are unstable, but their rates of spontaneous radioactive change are so low that not all the original stock has been converted to lighter elements. In the course of their radioactive decay, uranium and thorium produce other radioactive elements, such as radium and polonium. None of the primordial stock of these elements remain, but, since they are continually replenished by the decay of uranium and thorium, we are able to find equilibrium amounts of them in natural ores such as pitchblende.

This booklet describes one of the great fundamental advances in modern scientific history—the extension of the list of known chemical elements by the manufacture in the laboratory of 11 new elements. The first synthesis of each of these elements was a thrilling accomplishment resulting from an extension of previous discoveries in chemistry and physics. Some of the milestones of previous epochs which were necessary antecedents are:

1869 *The Formulation of the Periodic System of the Elements*
1896 *The Discovery of Radioactivity*
1911 *The Hypothesis of the Nuclear Atom*
1929 *The Invention of the Cyclotron*
1932 *The Discovery of the Neutron*
1934 *The Discovery of Artificial Radioactivity*

These great discoveries led to an inspired series of experiments, starting about 1938, in which reactions of nuclear transmutation carried out with laboratory neutron sources, cyclotrons, and nuclear reactors allowed man for the first time to create chemical elements.* The laboratory processes were similar to those which formed our natural elements billions of years ago.

The Alchemists and Their Dream

From earliest times men have dreamed of the transmutation of one element into another, particularly of the trans-

*For more about these early discoveries and the nature of nuclear energy, see *Our Atomic World,* a companion booklet in this series

mutation of the base metals into the noble coinage metals, gold and silver. Enormous effort went into the chemical experiments of the medieval alchemists. We know now that their efforts were foredoomed to failure because there was no way their chemical treatments could affect the tiny nuclei of the atoms, wherein the identity of each element resides. Before we can discuss this further, we must review a few facts about the atom and its nucleus.

An Alchemist.

Some Nuclear Fundamentals

The atomic nucleus consists of neutrons and protons bound together by special forces of extreme strength and extremely short range. A proton is a heavy particle with unit positive electrical charge; it is identical with the nucleus of the simplest element, hydrogen. A neutron is an electrically neutral particle of nearly the same mass. The number of protons in the nucleus determines the chemical identity of the atom (i.e., its atomic number and, hence, its position in the Periodic Chart of the Elements).

To alter the composition of the atomic nucleus, it is necessary to change the number of neutrons and protons in it. This may occur spontaneously by the process known as radioactivity.

Beta Decay For example, it sometimes happens that the neutron-to-proton ratio is higher than the value most favored by the special forces acting between the constituents of the nucleus. In such a case the nucleus seeks to achieve greater stability by converting one of its neutrons into a proton by a radioactive process known as beta decay, expressed in this equation:

$$\text{neutron} \rightarrow \text{proton} + \text{electron} + \text{neutrino}$$

In order to maintain electrical neutrality, an electron (a light particle of unit negative charge), also called a beta particle, is created. This electron is ejected from the nu-

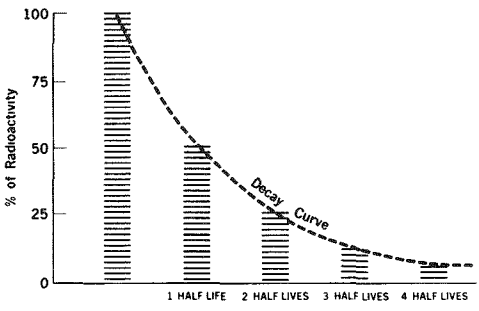
cleus with great kinetic energy. A weightless uncharged particle called the neutrino is also created and ejected.

Alpha Decay A second type of radioactive process is one known as alpha decay. In this process the nucleus spontaneously ejects a cluster of nuclear particles. This cluster is called an alpha particle and consists of two neutrons and two protons bound together. The loss of two protons (two units of charge) converts the nucleus of one element into one which is two places lower in atomic number. Consider the radioactive decay of radium by alpha decay:

$$^{226}_{88}\mathrm{Ra} \rightarrow {}^{222}_{86}\mathrm{Rn} + \alpha$$

This is a shorthand way of stating that a nucleus of radium (element 88) with 226 nuclear constituents has disintegrated to form a nucleus of radon (element 86) with 222 nuclear constituents and an alpha particle (cluster of two neutrons and two protons).

Half-Life The processes of beta decay and alpha decay are examples of a general class of spontaneous nuclear transformations known as radioactivity. The rates at which these processes occur vary enormously. One species may disintegrate completely in a fraction of a second. A collection of nuclei of another species (uranium-238, for example) may disintegrate only partially in billions of years. Each species (that is, each type of nucleus with a specific number of neutrons and protons) has a specific decay rate. (See typical decay pattern below.) Radioactive materials disintegrate at a rate proportional to the amount of material present at the time of disintegration. This gives rise to a logarithmic decay curve characterized by a "half-life," or the time required for half of the material to disintegrate. Every species of the synthetic elements we shall discuss in this booklet is



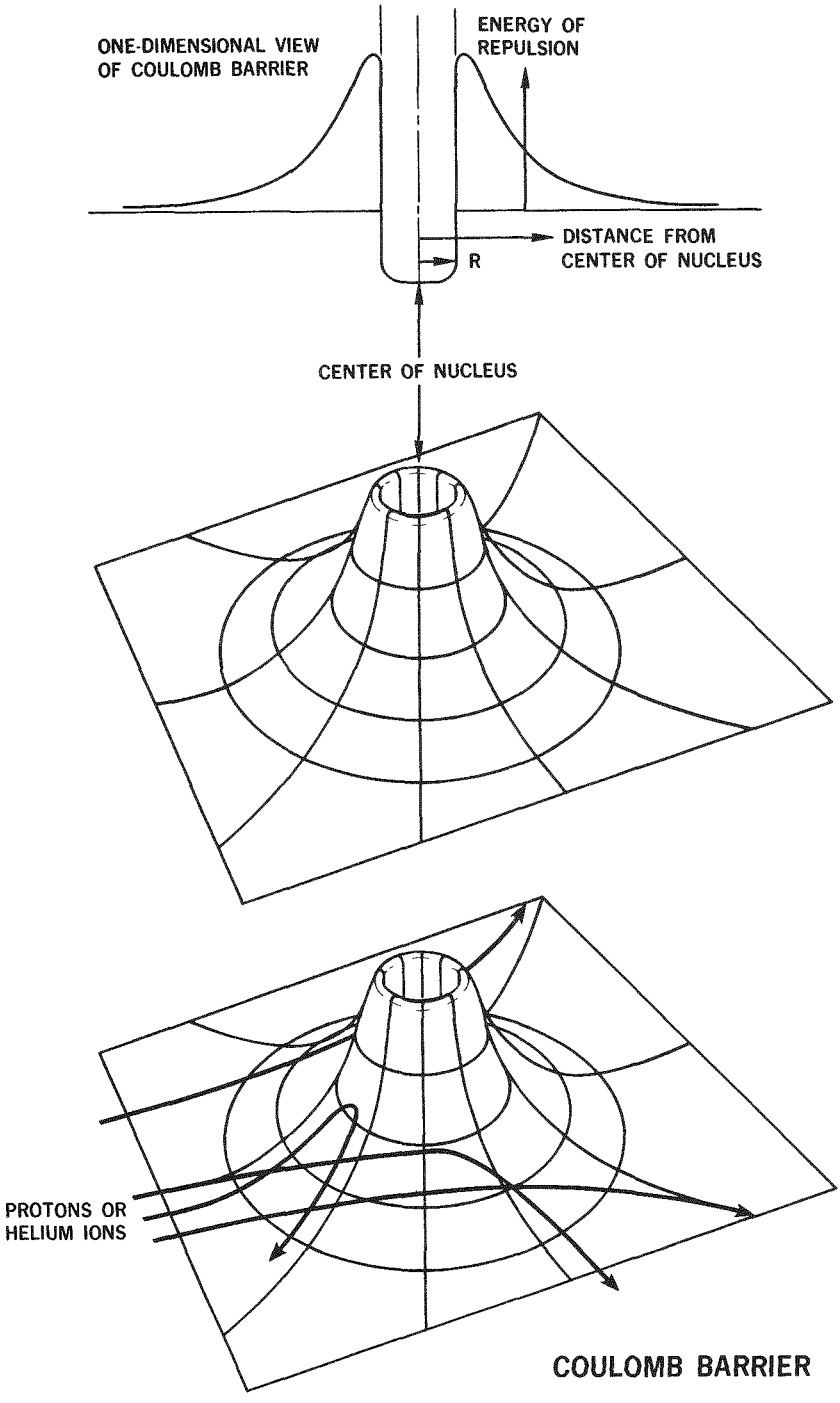
radioactive, and the half-life is one of the most important characteristic properties of each species.

Artificial Changes Aside from spontaneous changes, there are artificial changes in nuclear composition which may be caused by adding neutrons or protons to the nucleus. Experimental methods are known by which we may add a single neutron or proton or a group of neutrons and protons. The most commonly used clusters of nucleons* used in nuclear transmutation are the deuteron and the helium ion. The deuteron is a bound cluster of one neutron and one proton. The helium ion is a bound aggregate of two neutrons and two protons; it is identical to the alpha particle. More complex clusters also may be used. Some examples of importance are the boron-11 nucleus (a cluster of five protons and six neutrons) and the carbon-12 nucleus (a cluster of six protons and six neutrons).

The Enormous Energy Barrier to Alteration of the Nucleus

It is not an easy matter to transform one chemical element into another by adding protons to its nucleus. We may try to do this by directing a stream of protons, or of more complex nuclear projectiles, at a target composed of the element we wish to change. But protons are charged particles and hence repel each other. So the projectile protons (or more complex projectiles) must have sufficient kinetic energy to overcome the electrical repulsion of the protons in the nucleus. This barrier is described by Coulomb's law, which states that the repulsion of like particles varies as the product of their charges and inversely as the square of the distance between them. Because nuclei have extremely small dimensions, the inverse-square law requires that the Coulombic repulsion increase to an enormous value at the distance of approach required for contact between projectile and target. The uranium nucleus (for example) has a nuclear

*A nucleon is a constituent of the atomic nucleus; that is, a proton or a neutron. For definitions of other terms, see *Nuclear Terms, A Brief Glossary*, another booklet in this series.



COULOMB BARRIER

radius of about 10^{-12} centimeter (one millionth of one millionth of 1 centimeter). The Coulomb barrier is illustrated in the figure.

Let us consider the quantitative magnitude of the barrier. The physicists' unit for energy on the atomic scale is the electron volt. The Coulomb barrier is measured in millions of electron volts, usually expressed by the abbreviation, Mev. In the case of the uranium nucleus, the barrier to the approach of protons or deuterons is 12 Mev and to the approach of helium nuclei is 23 Mev. To make this magnitude more understandable, let us consider some energy values from our general experience.

A railroad locomotive traveling at 100 miles an hour has an enormous amount of kinetic energy; yet the energy of a single iron atom in the steel of the speeding locomotive is only 0.006 electron volt. A bullet traveling at a muzzle velocity of 3000 feet per second has a great deal of energy, but each atom of lead in the bullet has only 1 electron volt of energy. The most violent chemical explosions raise the energy of the explosion products to only a few electron volts. From these examples we see that the upper limit of energy required for events in the large-scale world is a million or more times less than that required to force

The Coulomb barrier which protects the atomic nucleus from nuclear transmutation. The top view shows the barrier along a line passing through the center of the nucleus. As a charged projectile like a proton or alpha particle (helium nucleus) approaches the nucleus, the potential energy of repulsion derived from Coulomb's law must be supplied by the kinetic energy of the particle. If the kinetic energy is enough to allow the projectile to approach the nuclear surface (the distance R in the figure), the short-range attractive nuclear forces suddenly reduce the potential energy. This energy becomes kinetic energy which is rapidly shared by all constituents of the nucleus or dissipated by emission of electromagnetic radiation (gamma radiation). This results in the trapping of the proton or alpha particle within the nucleus. The central figure illustrates the barrier in three dimensions. The lowest sketch shows the paths taken by protons or helium ions that approach the nucleus with insufficient energy to overcome the barrier. For uranium the radius, R, is 10^{-12} centimeter (one millionth of one millionth of 1 centimeter). The barrier height is 12 Mev for protons and 23 Mev for helium ions.

charged matter past the electrical defenses of the nucleus.

This is the fundamental fact that explains the importance to physics of the invention of such accelerating machines as the cyclotron. The purpose of such accelerators is to raise the kinetic energy of nuclear projectiles to an enormous value so they can penetrate the nuclei of target atoms and bring about nuclear reactions.*

The Neutron Simplifies Element Transformations

Sir James Chadwick discovered the neutron in 1932. It was soon learned that a copious source of neutrons was available from the reaction between light elements and the alpha rays emitted by polonium and radium. It was also found that neutrons are remarkably effective in causing nuclear transformations. Being electrically neutral, they are unaffected by the Coulomb barrier, and even at low velocity they can penetrate into the nuclear interior of atoms placed in their path. Once inside a nucleus they are acted upon by strong nuclear forces and bound into the nucleus. The immediate result of this absorption is simply to raise the nuclear mass by one unit without changing the proton number. But in most cases the changed neutron-to-proton ratio is not a stable one, and the neutron is transformed into a proton by the reaction known as beta decay, which we discussed earlier. The net result of neutron absorption and beta decay is to convert the original element to an element lying one place higher in the Periodic Chart of the Elements.

Reactions of this kind were intensively studied in the 1930s, and many dozens of new radioactive species of the known elements were produced and identified.

*For more information, see *Accelerators*, another booklet in this series.

DISCOVERY OF NEPTUNIUM AND PLUTONIUM

A False Start Leads to a Great Discovery

It was natural that scientists should investigate the effects of neutron irradiation of uranium, the heaviest known element, since, on the basis of past experience, it seemed likely that a new element of atomic number 93 would be formed. The prospect of the synthesis of an element not present in nature was exciting and intriguing. In the mid-1930s the great Italian physicist Enrico Fermi and his coworkers in Rome started a series of experiments with uranium. They expected uranium to capture a neutron and that this would produce a new uranium isotope by the reaction:

$$^{238}U + \text{neutron} \rightarrow {}^{239}U$$

Furthermore, they expected the new isotope to undergo radioactive decay to produce an isotope of element 93:

$$^{239}U \rightarrow {}^{239}93 + \text{electron} + \text{neutrino}$$

This sequence of events does indeed occur in uranium samples bombarded with slow neutrons, but the element 93 product was incorrectly identified in these experiments. The reason for this is that, in bombarding uranium with neutrons, Fermi and his group had unknowingly caused the rare isotope of uranium, ^{235}U, to undergo nuclear fission.

When ^{235}U undergoes fission it produces two radioactive elements of medium weight. In each fission event the splitting is slightly different. A group of fissioning uranium nuclei gives rise to many fission products, including many dozens of radioactive forms of many medium weight elements. This complex mixture of radioactive fission products obscured the radiations of the new element 93. Fermi and his co-workers did not know that fission had occurred, for no physicist at that time had dreamed that such a violent rearrangement of nuclear matter could occur. Naturally this led to considerable confusion. In the next few years several of the fission products were isolated by chemical analysis and incorrectly claimed to be new elements lying beyond uranium in the Periodic Chart. Elements as high as number 96 were reported. These interpretations were recognized as incorrect when the crucial 1938 experiments of the German chemists Otto Hahn and Fritz Strassmann revealed the reality of nuclear fission.

Thus it was that the first attempt to produce a synthetic transuranium element led to one of the most striking and important discoveries of all scientific history.

Renewed Search for Element 93

When fission was discovered in 1938, every nuclear physicist in the world hastened to perform some experiment that would reveal some new information about this astonishing phenomenon. At Berkeley, California, the physicist E. M. McMillan thought it might be useful to measure how far the energetic fragments of uranium fission would travel in matter. His experimental technique was quite interesting as it shows that all important experiments need not be performed with elaborate apparatus. He took ordinary cigarette papers, the kind that people use who prefer to roll their own, and stacked them up to form a little book. On the top sheet he put a thin layer of

Edwin M. McMillan shortly after he and Philip H. Abelson discovered element 93, neptunium, in 1940.

uranium oxide and then exposed the whole stack to neutrons produced in a cyclotron target. The fission fragments flew into the cigarette papers, stopping at various depths. Then he took the papers apart and measured the radioactivity in each one by means of a Geiger counter. So far so good. The results were about as expected. There was, however, an unexpected result that turned out to be of greater significance. The first piece of paper with the uranium layer on it also contained a radioactivity which did not travel with the rest and which did not emit the same radiations.

In trying to think why this should be, McMillan returned to the original thoughts of Fermi. If some of the neutrons did get absorbed in the uranium without causing fission, then some new heavy uranium isotope might be produced, and this might decay to form an isotope of element 93. This isotope would not fly out of the uranium oxide target.

At this point P. H. Abelson of the Carnegie Institution of Washington came to Berkeley and joined McMillan in an intensive study of the new radioactivity with the hope of identifying it as element 93. McMillan and Abelson were successful in this but only after doing some careful rethinking of the location of the heaviest elements in the Periodic Chart. This led them to the conclusion that their element 93 might resemble uranium in its chemical properties.

In naming their synthetic transuranium element, these researchers used an astronomical analogy. The element uranium had been named after the planet Uranus. The next planet beyond Uranus is Neptune so McMillan and Abelson chose the name neptunium (symbol Np) for the first element beyond uranium.

The isotope of neptunium which they discovered has a half-life of 2.2 days, and only tiny invisible amounts of it could be prepared.

Discovery of Plutonium

The work on neptunium made it seem highly likely that an additional element could be prepared, so they turned attention immediately to its synthesis. The first identification of an isotope of element 94 was made by G. T. Seaborg, E. M. McMillan, J. W. Kennedy, and A. C. Wahl early in 1941.

Uranium oxide samples were bombarded with deuterons of 16 Mev energy from the 60-inch cyclotron that had been constructed by E. O. Lawrence. Radiochemical separations, based on the earlier work of McMillan and Abelson, isolated a fraction containing pure element 93. In this fraction a new radioactive isotope with a 2-day half-life was observed. This was ^{238}Np, as shown in the nuclear reaction:

$$^{238}\text{U} + \text{deuteron} \rightarrow {}^{238}\text{Np} + 2 \text{ neutrons}$$

This isotope emits beta particles (negative electrons) to produce an isotope of element 94 with mass 238:

$$^{238}\text{Np} \xrightarrow[\text{Half-life} = 2\ 0 \text{ days}]{\beta^-} {}^{238}94$$

A new radioactive isotope emitting alpha particles was observed to form as the ^{238}Np decayed. This parent–daughter relationship established the identity of the alpha-emitting material as an isotope of element 94. The ratio of the alpha activity of the daughter to the beta activity of the parent established a value of 50 years for the half-life of ^{238}94. Chemical experiments showed that the new activity had radiochemical properties distinct from neptunium, uranium, thorium, or any other elements that might have been produced from the bombardment of uranium with deuterons.

Sometime later, the discoverers suggested the name plutonium (symbol Pu) for this element, since Pluto is the second planet beyond Uranus, just as plutonium is the second element beyond uranium.

Almost immediately after this identification of ^{238}Pu, the important isotope ^{239}Pu was identified by J. W. Kennedy, G. T. Seaborg, E. Segrè, and A. C. Wahl. Neptunium-239, the first isotope of element 93 to be discovered, undergoes radioactive decay by the process of beta emission, that is, by the conversion of a neutron into a proton plus an electron. It was recognized that this change must result in the production of element 94 of mass 239. At first, it proved impossible to observe the radiations of ^{239}Pu because of the small size of the available neptunium samples and because of the slow disintegration rate of ^{239}Pu. This problem was

solved by preparing a much larger sample of ^{239}Np by bombardment of uranium with an intense beam of neutrons produced at the Berkeley 60-inch cyclotron. Neptunium-239 was chemically isolated, and a new source of alpha activity was observed to form as ^{239}Np decayed. From the observed rate of alpha emission, the half-life of this isotope was estimated to be about 30,000 years. (This is close to the value of 24,400 years presently accepted for ^{239}Pu.)

It had been suggested that the isotope ^{239}Pu might resemble ^{235}U in exhibiting a high probability for nuclear fission when irradiated with slow neutrons. The discoverers of ^{239}Pu immediately measured this property and found the prediction to be true; ^{239}Pu had a probability for fission even greater than that of ^{235}U.

Production of Plutonium for Nuclear Weapons

This fact was immediately recognized as of possible importance in the release of nuclear energy for military purposes. This recognition led to the wartime Plutonium Project which had as its goal the production of kilogram quantities of plutonium and the development of a weapon in which enormous amounts of energy would be supplied by the fission of plutonium nuclei. The atomic bomb exploded over the Japanese city of Nagasaki in August 1945 was a plutonium weapon.

The large-scale production of plutonium required the development of processes absolutely unique to industrial practice. It was necessary to design large nuclear reactors* in which the nuclear fission of ^{235}U in tons of uranium fuel would furnish neutrons to maintain a nuclear chain reaction and cause the conversion of ^{238}U to ^{239}Pu by the reactions:

$$^{238}U + \text{neutron} \rightarrow {}^{239}U$$

$$^{239}U \xrightarrow{\beta \text{ decay}} {}^{239}Np$$

$$^{239}Np \xrightarrow{\beta \text{ decay}} {}^{239}Pu$$

*For information about reactors, see *Nuclear Reactors*, another booklet in this series.

It was necessary to devise chemical processes for the isolation and purification of the small concentrations of plutonium from ton quantities of irradiated uranium fuel. This process had to be one that could be operated by remote control from behind thick concrete shielding because of the truly enormous amounts of radioactivity emitted by the fission products.

Necessary Steps in the "Discovery" of a Synthetic Element

Before summarizing the discovery of additional elements, we need to emphasize the facts that determine the physical and chemical steps in the "discovery" of a synthetic element. These considerations governed the scientific methods applied to the synthesis and identification of elements 93 and 94 and of the nine elements of higher atomic number which will be discussed later:

1. One of the known elements must be transmuted to the new element This can be done only through nuclear reactions which change the number of protons in the atomic nucleus. The possible methods are
   (a) Neutron capture followed by beta decay
   (b) Direct addition of a proton.
   (c) Direct addition of a complex nuclear projectile that contains one or more protons; examples are deuterons helium-4 nuclei, carbon-12 nuclei, etc.
2. The amount of the new element available from the first experiment is so tiny that the element is invisible, unweighable, and completely undetectable by the ordinary techniques of analytical chemistry
3. The nucleus of the new element is always unstable and undergoes spontaneous radioactive disintegration with a characteristic rate (half-life) and a characteristic set of high-energy radiations.
4. This characteristic radiation assists in the establishment of the nuclear constitution of the new element It also is used as an indicator of the element's behavior during chemical treatment by the technique known as radiochemistry. A collection of new atoms has identical chemical properties These atoms travel together or are distributed in a characteristic pattern during any chemical separation step. Although the atoms cannot be located by ordinary chemical methods, those which spontaneously disintegrate reveal their presence by their penetrating radiations, which can easily be detected with suitable instruments The disintegrating atoms thus serve as tracers or indicators of

the location of the whole collection of atoms of the same element.

5. Radiochemical experiments must be performed to establish clearly that the new element has chemical properties different from those of any other element which conceivably could be produced in the nuclear reactions. Ideally it should be established that the new element has properties distinct from any other element in the periodic system. The only exception to this requirement is in the case of an element so unstable that the lifetime for radioactive disintegration is so short that there is no possibility to investigate chemical properties. In such cases the identification can be made solely on nuclear evidence.
6. The atomic number of the new element must be determined by physical or chemical evidence. In practice it is deduced from the method of production, from the parent–daughter relationship of the new element to known elements, and from its radiochemical properties.
7. Although not essential, it is desirable that the mass number of the new element be established by evidence related to its mode of production or its parent–daughter relationship through radioactive decay to a radioactive isotope of known mass number.

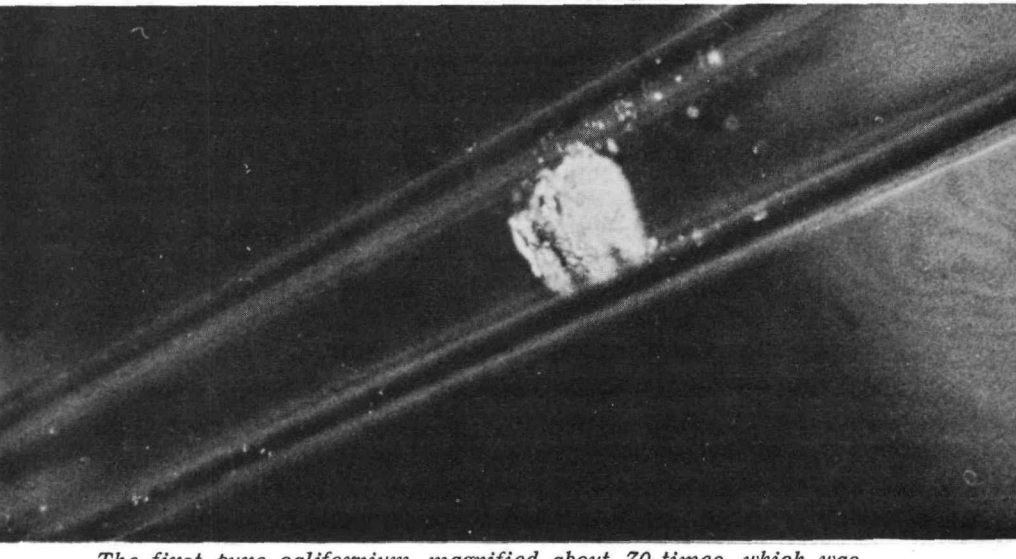
FURTHER DISCOVERIES

Summary of Eleven Transuranium Elements

Following the discovery of elements 93 and 94, nine more elements (americium, curium, berkelium, californium, einsteinium, fermium, mendelevium, nobelium, and lawrencium) were synthesized and identified. We do not have space to discuss each case in detail, so we must be content with the summary on page 22. Unfortunately, this brief and simple table by itself cannot convey any adequate impression of the difficulties faced by the original investigators who proved the equations, or of the brilliant planning and skill behind the experiments. The nuclear chemists had to make use of detailed theoretical knowledge and good scientific intuition in the fields of nuclear structure, radioactivity, and radiochemistry in order to predict the properties of the unknown element and in order to design properly an experiment for its discovery. Each series of experiments was, in its way, a tour-de-force of experimental techniques covering target preparation, accelerator operation, radiochemical separations, and the design and use of advanced detectors for the measurement of radiations. More detailed accounts may be found in the references cited at the end of this booklet.

Several of the synthetic elements were first prepared by the transmutation of a target made up of atoms of one of the transuranium elements of lower atomic number; for exam-

ple, element 95 was first made by neutron irradiation of plutonium. The rather large (microgram to milligram) quantities of the target element required in these experiments were synthesized in nuclear reactors, as discussed below, some years after the first synthesis of a few atoms of the element. This necessity to build upon the work of the past



The first pure californium, magnified about 70 times, which was isolated in 1960. The californium was in the form of the isotope ^{249}Cf. The crystals are lodged in a capillary tube.

explains why the synthetic elements were not all discovered at once, but in a regular sequence.

Element 95 was first prepared by a neutron capture plus beta-decay sequence. In this case a plutonium target absorbed two neutrons successively before undergoing beta decay.

Elements 96, 97, 98, and 101 were first prepared by bombardments of target elements with energetic helium ions (alpha-particles) in the Berkeley 60-inch cyclotron.

Elements 99 and 100 were synthesized in an unexpected and dramatic fashion when the U. S. Atomic Energy Commission made its first test of an explosive device releasing nuclear energy equivalent to the explosion of several million

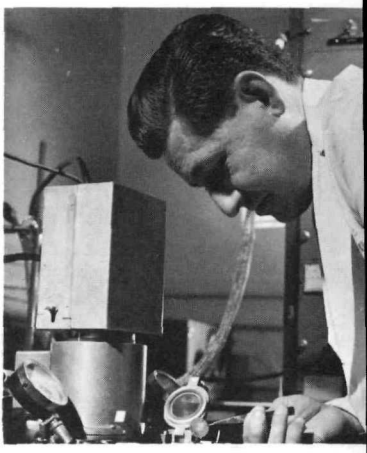
tons of high explosive. The "Mike" thermonuclear test at Eniwetok in November 1952 produced an enormous quantity of neutrons at the moment of detonation. Many of these neutrons were absorbed by uranium metal in the device. Because of the huge neutron flux, the uranium nuclei absorbed not just one but several neutrons in quick succession. Some uranium nuclei absorbed 15 or more neutrons, producing such superheavy nuclei as ^{253}U, ^{254}U, ^{255}U, etc. These nuclei had much too high a ratio of neutrons to protons for stability and therefore rapidly underwent beta decay to produce neptunium isotopes. These also were unstable and rapidly decayed to plutonium. Multiple beta decay continued by the following sequence as the nuclei sought to obtain a more favorable neutron–proton balance:

$$_{92}U \xrightarrow{\beta^-} {}_{93}Np \xrightarrow{\beta^-} {}_{94}Pu \xrightarrow{\beta^-} {}_{95}Am \xrightarrow{\beta^-} {}_{96}Cm \xrightarrow{\beta^-}$$
$$_{97}Bk \xrightarrow{\beta^-} {}_{98}Cf \xrightarrow{\beta^-} 99 \xrightarrow{\beta^-} 100$$

Part of the dust and debris from the explosion was collected and examined by nuclear chemists working at the Argonne National Laboratory, the Los Alamos Scientific Laboratory, and the Lawrence Radiation Laboratory. When many unknown heavy isotopes of plutonium, americium, and curium were found, a search was made for the possible presence of elements 99 or greater. This search resulted in the discovery of elements 99 and 100, later named einsteinium and fermium after the famous physicists.

Elements 102 and 103 were first synthesized by reactions of transmutation induced by rather unusual nuclear projectiles. The nuclei of the elements carbon and boron (containing six and five protons, respectively) were used instead of neutrons, deuterons, or helium ions. With such complex projectiles the atomic number of the target element can be raised by six or five units in one step. Special accelerators have been constructed for the acceleration of such complex nuclei to the required energy. Most attempts to produce new transuranium elements are being made with their assistance. (See figures on page 20 which describe the discovery of lawrencium.) The Coulomb barrier to the approach of carbon and boron nuclei, and similar projectiles,

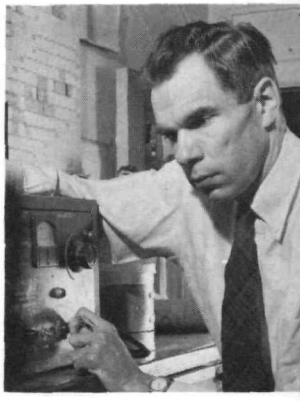
Stanley G. Thompson



Albert Ghiorso

is much greater than that operating on helium ions so these accelerators must raise the energies of these projectiles accordingly.

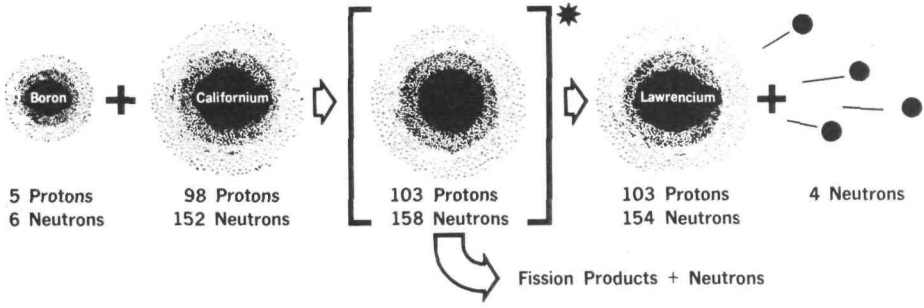
We close this section with a word about the scientists who performed these experiments. E. M. McMillan and G. T. Seaborg of the University of California shared the Nobel Prize in Chemistry in 1951 for their identification of elements 93 and 94. Dr. Seaborg also served as the inspiring and resourceful leader of the research teams which discovered additional elements. In all he contributed to the initial work on eight synthetic elements. His concept of the placement of these elements as an actinide series in the Periodic Chart of the Elements was a contribution of great importance.



Glenn T. Seaborg in 1940s.

S. G. Thompson and A. Ghiorso of the Lawrence Radiation Laboratory in Berkeley, California, must also be given great credit for their contributions to the discovery of several of these elements. They were co-discoverers of five and nine, respectively. Dr. Thompson must be given particular recognition for his key contributions to the work on berkelium and californium. Dr. Ghiorso has assumed leadership of the Berkeley group in the search for new elements since 1958.

LAWRENCIUM DISCOVERY AND HILAC ACCELERATOR



In the experiment leading to the discovery of lawrencium, 1 microgram of californium was bombarded with a stream of energetic boron nuclei. An unstable intermediate nucleus, designated here by a star, disintegrated by nuclear fission in the overwhelming majority of cases, but a few were deexcited by emission of neutrons to form lawrencium of mass 257.

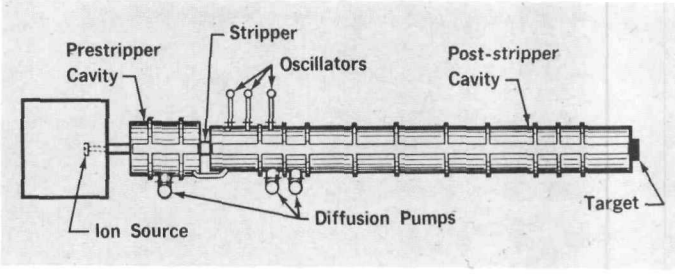
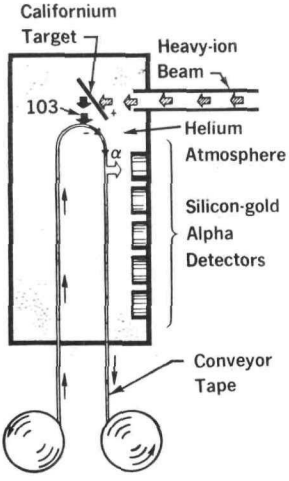
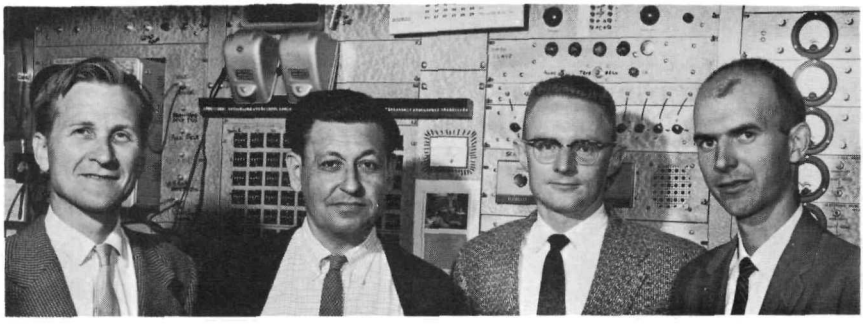


Diagram of the Heavy Ion Linear Accelerator (HILAC). Boron ions were accelerated in the prestripper cavity. When they reached the stripper section—a curtain of mercury vapor—further ionization occurred forming B^{+4} ions, which were then accelerated in the 90-foot poststripper cavity. They then struck the californium target.



The lawrencium atoms produced in the reaction were ejected from the target, slowed down in helium, and electrically attracted to a movable plastic tape. This tape transported the atoms to sensitive semiconductor detectors which could analyze the energy of the alpha particles emitted by ^{257}Lr.

The Discoverers



The scientific team responsible for the discovery of element 103, lawrencium. Left to right: Torbjorn Sikkeland, Albert Ghiorso, Almon E. Larsh, and Robert M. Latimer.

The Machine

The interior of a new type of particle accelerator used in the search for new elements. This linear accelerator is designed to accelerate heavy particles such as the ions of carbon, nitrogen, oxygen, or neon. These particles are fired through the center of the doughnut-shaped "drift tubes", which extend the length of the vacuum tank. The size of the tank (90 feet long × 10 feet in diameter) can be judged by the apparent size of the man standing at the far end. The Atomic Energy Commission has built one such accelerator at Yale University and one at the Lawrence Radiation Laboratory, Berkeley. The latter was used in the first synthesis of elements 102 and 103.

CHART OF THE TRANSURANIUM ELEMENTS*

Atomic number	Element	Symbol	Atomic weight†	First isotope identified	Discoverers and date of discovery	Source of first preparation	First isolation in weighable amount
93	Neptunium	Np	237	239	E. M. McMillan and P. H. Abelson, 1940	Irradiation of uranium with neutrons	1944 ^{237}Np (2.2×10^6 years), L. B. Magnusson and T. J. LaChapelle
94	Plutonium	Pu	242	238	G. T. Seaborg, E. M. McMillan, J. W. Kennedy, and A. C. Wahl, 1940–1941	Bombardment of uranium with deuterons	1942 ^{239}Pu (24,360 years), B. B. Cunningham and L. B Werner
95	Americium	Am	243	241	G. T. Seaborg, R. A. James, L. O. Morgan, and A. Ghiorso, 1944–1945	Irradiation of plutonium with neutrons	1945 ^{241}Am (458 years), B. B. Cunningham
96	Curium	Cm	248	242	G. T. Seaborg, R. A. James, and A. Ghiorso, 1944	Bombardment of plutonium with helium ions	1947 ^{242}Cm (162.5 days), L. B. Werner and I. Perlman
97	Berkelium	Bk	249	243	S. G. Thompson, A. Ghiorso, and G. T. Seaborg, 1949	Bombardment of americium with helium ions	1958 ^{249}Bk (314 days), S G. Thompson and B. B Cunningham
98	Californium	Cf	249	245	S. G. Thompson, K Street, Jr., A. Ghiorso, and G. T. Seaborg, 1950	Bombardment of curium with helium ions	1958 $^{249-252}$Cf, B. B Cunningham and S. G. Thompson

99	Einsteinium	Es	254	253	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. Hirsch, W. M. Manning, C. I Browne, H. L. Smith, and R. W. Spence, 1952	Irradiation of uranium with neutrons in first thermonuclear explosion	1961 ^{253}Es (20 days), B B. Cunningham, J. C Wallmann L. Phillips, and R. C Gatti
100	Fermium	Fm	253	255	(Same as einsteinium), 1953	In first thermonuclear explosion	
101	Mendelevium	Md	256	256	A. Ghiorso, B. G. Harvey, G. R. Choppin, S. G Thompson, and G. T. Seaborg, 1955	Bombardment of einsteinium with helium ions	
102	Nobelium	No	254	254	A. Ghiorso, T Sikkeland, J. R. Walton, and G T. Seaborg, 1958	Bombardment of curium with carbon ions	
103	Lawrencium	Lr	258	258	A. Ghiorso, T. Sikkeland, A. E. Larsh, and R. M. Latimer, 1961	Bombardment of californium with boron ions	
104	–	–	–	260	G. N. Flerov and co-workers, 1964	Bombardment of plutonium with neon ions‡	

*From Glenn T. Seaborg, *Man-made Transuranium Elements*, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1963.
†Mass number of longest-lived or more available isotope.
‡This work, representing the first report of the identification of an isotope of element 104, was done in the Soviet Union.

Further Synthesis of Transuranium Elements

Following the first identification of one isotopic form of a synthetic element, attempts are made to synthesize and identify as many isotopic species as possible. Since all nuclear species of these elements are radioactive, the experiments have as their purpose the determination of the nuclear decay properties. The extent of these "follow-up" experiments can be judged by the summary of data on more than 90 species presented in the table on page 38.

An inspection of this table reveals the steady decrease in the nuclear stability of these elements, a decrease which can be shown by listing the half-life of the most stable forms of each element in a separate table. See the table on page 41.

The discovery experiments have been followed up also by the development of methods for synthesis of the new elements in weighable amounts. Nuclear reactors have been used for this because high intensities of neutrons can be produced more easily and cheaply in reactors than high currents of charged particles can be produced in accelerators. In the case of plutonium the requirements of nuclear weapons programs have brought about the production of the thousands of kilograms by neutron irradiation of uranium. Neptunium and americium are produced as by-products in kilogram quantities. The other transplutonium elements can be made in lesser amounts in nuclear reactors, as will be discussed later.

IMPORTANCE OF TRANSURANIUM ELEMENTS

Chemistry

The synthetic elements represent a 10% extension of the roster of known elements. Their placement in the Periodic Chart of the Elements is a matter of great interest and importance. The periodic classification, familiar to all students of chemistry, groups the elements according to families with common properties. This grouping is based on the systematic way the electrons surrounding the atomic nucleus are placed in specific planet-like orbits with precisely quantized energy.* These orbits are occupied in a regular sequence, and the completion of certain sequences (referred to as the filling of a shell of electrons) produces particular stability. Elements at some points in the Periodic Chart have some of the outer shells or orbits occupied before all available inner shells are completely filled. When this happens there occurs further on in the table a group of elements, called transition elements, in which the unfilled inner shells are filled in with electrons, one by one. In these elements the outer electrons, which determine the majority of the chemical properties, are not disturbed; hence members of each group of transition elements have very similar chemical characteristics.

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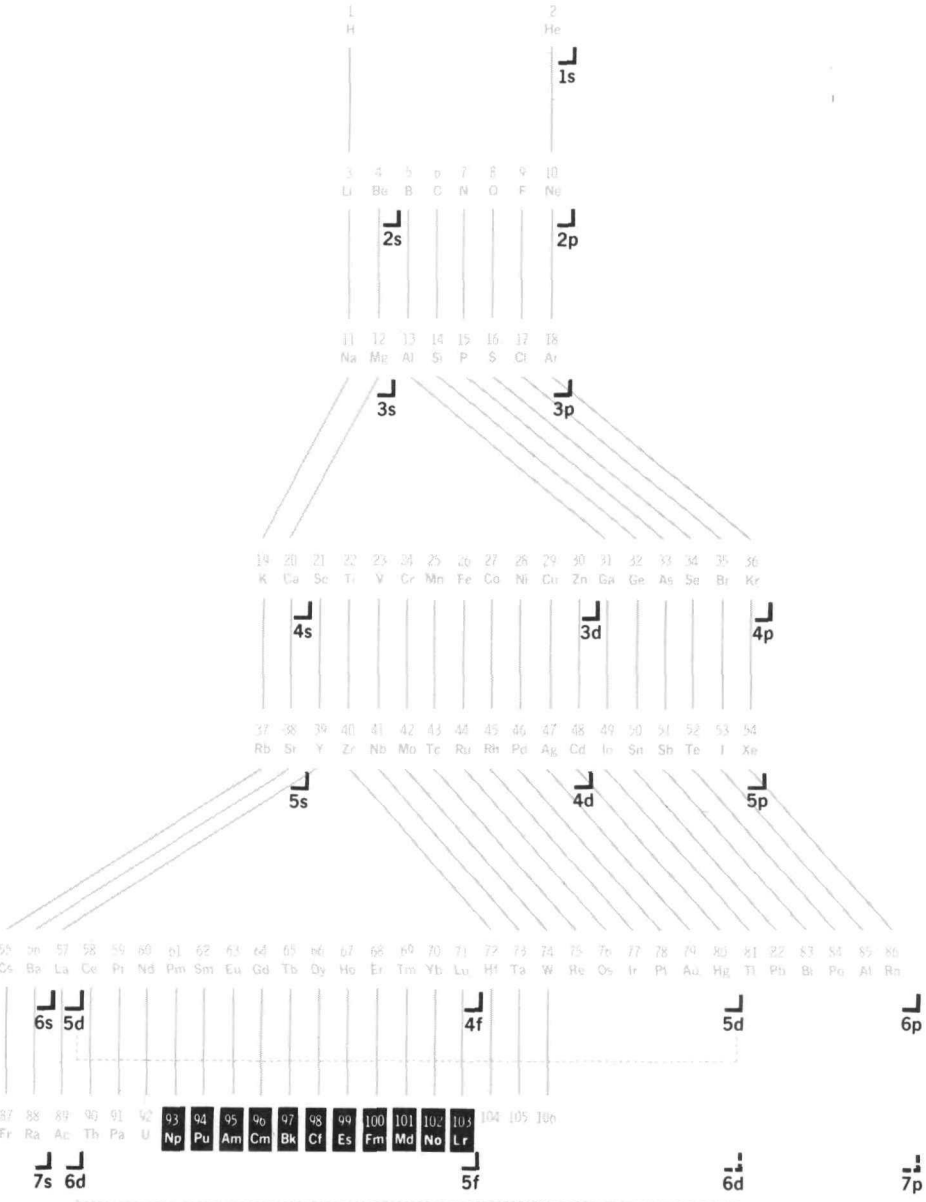
*This paragraph is phrased in the language of one of the simpler pictures of electronic structure. More sophisticated descriptions based on modern quantum mechanics would be written in different terms, but the basic idea of a shell structure would be the same.


1 H
2 He
1s
3 Li
4 Be
5 B
6 C
7 N
8 O
9 F
10 Ne
2s
2p
11 Na
12 Mg
13 Al
14 Si
15 P
16 S
17 Cl
18 Ar
3s
3p
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
4s
3d
4p
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
5s
4d
5p
55 Cs
56 Ba
57 La
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
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
6s
5d
4f
5d
6p
87 Fr
88 Ra
89 Ac
90 Th
91 Pa
92 U
93 Np
94 Pu
95 Am
96 Cm
97 Bk
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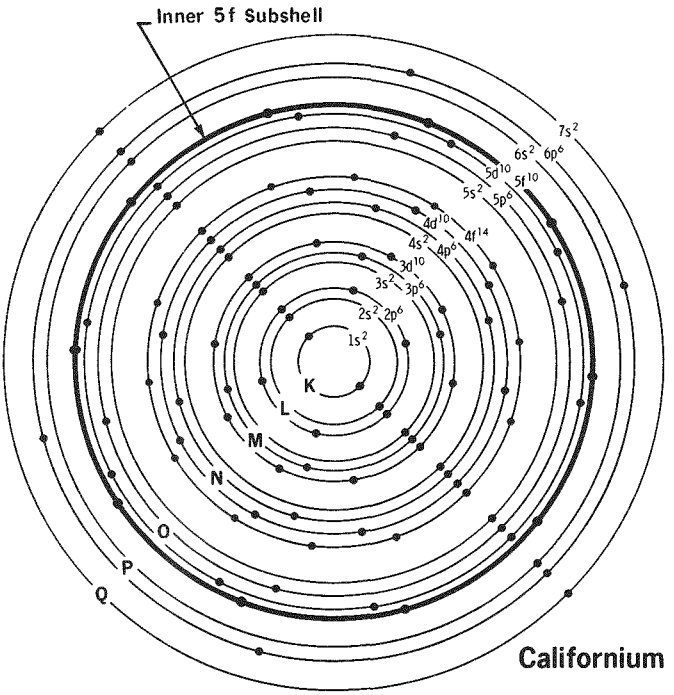
7s
6d
5f
6d
7p



AN ALTERNATE FORM OF THE PERIODIC TABLE

An alternate form of the Periodic Chart of the Elements. Elements of similar chemical properties are connected by the lines running from top to bottom. The atomic number of each element is given above the element symbol. The synthetic transuranium elements are shown in shaded squares in the last horizontal line. In each row there appear brackets with the labels 1s, 2s, 2p, and so on. Each of these brackets indicates the filling of an electronic subshell of electrons in the succession of the elements. The electron-shell structure of the element californium is given in the circular drawing at the top. This is a schematic drawing only and does not represent the actual shape or relative dimensions of the electronic orbits. The electron shells are labeled by two independent systems of nomenclature. The X-ray terminology uses the letters K, L, M, etc., while the spectrographic terminology uses 1s, 2s, 2p, etc. The mathematical laws governing the motions of the electrons specify that the maximum number of electrons in any s *subshell is 2, in any* p *subshell is 6, in any* d *subshell is 10, and in any* f *subshell is 14. The characteristic feature of the transuranium elements is that they belong to a series of elements (the actinide elements) in which the 5f subshell is being filled.*

The natural elements thorium, protactinium, and uranium, plus the eleven synthetic elements constitute a special group of transition elements which are given the family name of "actinide elements." In these, the 5*f* inner shell of electrons is gradually filled in while, throughout the group, there is no addition of electrons to the outermost shells.

This type of transition-element family had been encountered in the natural elements many years earlier in the case of the rare-earth group of elements. These are the 14 elements beginning with element 58, which have the family name of "lanthanide elements."*

In a widely used form of the Periodic Chart, shown on page 30, the 14 actinide elements and the 14 lanthanide elements are displayed separately since there is not room to show all members of a given family in the single position they occupy jointly in the third column on the main chart.

In many of their chemical and physical properties, the actinide and lanthanide elements are very similar. Much interesting chemical research has developed from a detailed intercomparison of the properties of both series of elements.

Element 103 should complete the actinide series of elements. Elements 104 through 118 should occupy places in the Periodic Chart similar to the elements 72 through 86 (hafnium through radon). That is, element 104 should resemble hafnium, element 105 tantalum, etc. It would be a fascinating study to discover whether this prediction is true. The nuclear stability of these elements will be low and perhaps the lifetimes of the most stable nuclei will be so short that a detailed study of the chemical properties of these elements will be out of the question. However, this can be settled only by additional work which may reveal that nature has some surprises for us in the synthetic elements of the future.

Physics

Detailed information on the nuclear radiations of about 90 species has been invaluable for the development and testing of theories of the structure of nuclei and of the qualities of

*See *Rare Earths, The Fraternal Fifteen,* a companion booklet in this series.

the forces at work in the nuclear interior. To cite but one interesting development, it is now clearly established that the nuclei of very heavy elements are not spherical, as was previously believed, but are of spheroidal (football) shape. This has many consequences for the nuclear energy states.

Heavy nuclei with their large content of positively charged protons are particularly susceptible to the radioactive decay mode known as alpha decay, that is, to the ejection of a bound aggregate of two neutrons and two protons. They are also the only group of nuclei which readily undergo nuclear fission. The heaviest of the synthetic elements fission spontaneously at an appreciable rate. This is a particularly pure form of nuclear fission, and one that is especially easy to investigate. Its study provides much information for a deeper understanding of the important phenomenon of nuclear fission. The isotope ^{252}Cf has been particularly important in this respect.

A knowledge of the transuranium elements and of the nuclear reactions by which they are made and transformed is of great importance to cosmologists, the theorists who seek to explain the origin, the energy-producing reactions, and the evolution of the stars. Knowledge of the heavy elements is essential in developing theories for the syntheses of elements in various types of stars, the peculiar features of the relative abundance of the elements and their isotopes in our solar system, the evolution of stars in which dense fluxes of neutrons are present, and other matters.

Defense and Industry

Up to now the biggest single use for the transuranium elements has been in nuclear weapons. Plutonium-239 and uranium-235 are the two materials from which weapons based on fission energy are made. Thousands of kilograms of plutonium have been produced by the Atomic Energy Commission in large reactors built at the Hanford Engineering Works in the state of Washington and at the Savannah River Plant in South Carolina.

Plutonium also is potentially very useful in reactors designed for the production of electrical power. Up to the present, ^{239}Pu has not been considered as useful as ^{235}U, but it has some innate advantages which ensure that it will play

PERIODIC CHART OF THE ELEMENTS

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	57-71 La* Series	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	89-103 Act† Series	(104)	(105)	(106)	(107)	(108)										

*Lanthanide Series	57 La	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
†Actinide Series	89 Ac	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

The transuranium elements (in shaded squares) are part of the actinide series of elements which as a group occupies a single square in the main figure. The rare-earth (lanthanide) series of elements, shown spread out in a horizontal row below the main diagram, also occupies a single square in the larger chart.

ALPHABETICAL LIST OF ELEMENTS AND SYMBOLS

Element	Symbol	Element	Symbol	Element	Symbol	Element	Symbol
Actinium	Ac	Erbium	Er	Mercury	Hg	Samarium	Sm
Aluminum	Al	Europium	Eu	Molybdenum	Mo	Scandium	Sc
Americium	Am	Fermium	Fm	Neodymium	Nd	Selenium	Se
Antimony	Sb	Fluorine	F	Neon	Ne	Silicon	Si
Argon	Ar	Francium	Fr	Neptunium	Np	Silver	Ag
Arsenic	As	Gadolinium	Gd	Nickel	Ni	Sodium	Na
Astatine	At	Gallium	Ga	Niobium	Nb	Strontium	Sr
Barium	Ba	Germanium	Ge	Nitrogen	N	Sulfur	S
Berkelium	Bk	Gold	Au	Nobelium	No	Tantalum	Ta
Beryllium	Be	Hafnium	Hf	Osmium	Os	Technetium	Tc
Bismuth	Bi	Helium	He	Oxygen	O	Tellurium	Te
Boron	B	Holmium	Ho	Palladium	Pd	Terbium	Tb
Bromine	Br	Hydrogen	H	Phosphorus	P	Thallium	Tl
Cadmium	Cd	Indium	In	Platinum	Pt	Thorium	Th
Calcium	Ca	Iodine	I	Plutonium	Pu	Thulium	Tm
Californium	Cf	Iridium	Ir	Polonium	Po	Tin	Sn
Carbon	C	Iron	Fe	Potassium	K	Titanium	Ti
Cerium	Ce	Krypton	Kr	Praseodymium	Pr	Tungsten	W
Cesium	Cs	Lanthanum	La	Promethium	Pm	(Wolfram)	
Chlorine	Cl	Lawrencium	Lr	Protactinium	Pa	Uranium	U
Chromium	Cr	Lead	Pb	Radium	Ra	Vanadium	V
Cobalt	Co	Lithium	Li	Radon	Rn	Xenon	Xe
Copper	Cu	Lutetium	Lu	Rhenium	Re	Ytterbium	Yb
Curium	Cm	Magnesium	Mg	Rhodium	Rh	Yttrium	Y
Dysprosium	Dy	Manganese	Mn	Rubidium	Rb	Zinc	Zn
Einsteinium	Es	Mendelevium	Md	Ruthenium	Ru	Zirconium	Zr

a more important role in the future. Uranium-235 makes up less than 1% of the total weight of natural uranium. The main isotope in natural uranium is ^{238}U, which does not undergo fission with slow neutrons. However, in reactors it is possible to convert ^{238}U to the fissionable ^{239}Pu. In "breeder" reactors, more ^{239}Pu is produced than ^{235}U is destroyed. Therefore, in principle, the total supply of fission energy can be greatly increased if ^{239}Pu is produced and burned for power production.

The transuranium elements have other uses. The heat released in the spontaneous radioactive emission of alpha particles can be converted to electricity in various devices. Such devices are very lightweight, compact, and reliable sources of modest amounts of electric power for periods of many years. The isotopes ^{238}Pu, ^{242}Cm, and ^{244}Cm can be used in power supplies in satellites and space vehicles, where they can replace much heavier and less reliable battery supplies. Curium-242, for example, has a specific heat generation rate of 120 watts per gram.*

Small portable sources of moderate fluxes of neutrons can be prepared from the synthetic elements. Alloys of americium and beryllium or of plutonium with beryllium are very useful. The neutrons result from the interaction of the alpha particles emitted by the heavy elements with the light element beryllium. The spontaneous fission of small samples of californium also supplies copious numbers of neutrons. Small portable sources of neutrons have important applications in research laboratories and in industry.

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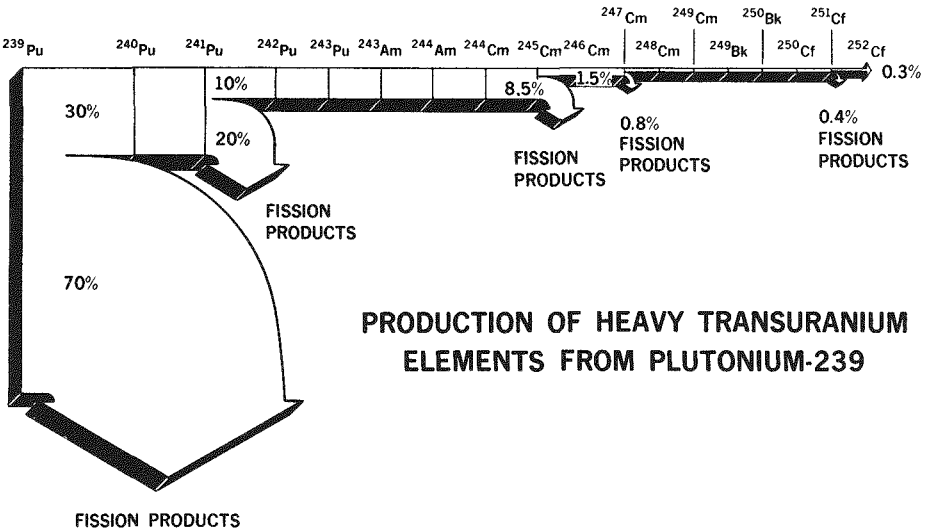
*For information on these devices see *Power from Radioisotopes*, another booklet in this series.

NATIONAL PROGRAM FOR TRANSPLUTONIUM ELEMENT PRODUCTION

The tiny amounts of these elements made by nuclear reactions induced by charged particles are quite insufficient for all that the research scientists would like to perform with them. The Atomic Energy Commission therefore has launched a major program for the production of larger amounts. The most suitable production method is the irradiation of large heavy element samples in reactors with large internal fluxes of neutrons. The most suitable starting material is plutonium since it is the heaviest element now available in kilogram or greater quantities. The production of the heaviest elements from ^{239}Pu is illustrated in the diagram on page 34.

In a high neutron flux ^{239}Pu captures successively several neutrons forming in turn ^{240}Pu, ^{241}Pu, ^{242}Pu, and ^{243}Pu. In the early steps of this capture chain, there is a high depletion of the plutonium by nuclear fission and only a small percent is ultimately converted to ^{243}Pu. When ^{243}Pu is produced, it undergoes beta decay to form ^{243}Am before it can capture another neutron. Americium-243 then captures a neutron to form ^{244}Am which is beta unstable and decays to form ^{244}Cm Curium in turn captures several neutrons until ^{249}Cm is produced; this is transformed by radioactive decay to the heavier element, berkelium. In this way the heavier elements are built up from the lighter.



PRODUCTION OF HEAVY TRANSURANIUM ELEMENTS FROM PLUTONIUM-239

This chart illustrates the major path of transuranium element production by successive neutron captures. In a nuclear reactor both fission and neutron capture take place in ^{239}Pu nuclei. About 70% fissions and is lost; the remainder is transmuted to ^{240}Pu. The ^{240}Pu nuclei then capture neutrons and become ^{241}Pu. The split between fission and capture is repeated at all the even–odd isotopes up the chain so that only 0.3% remains as transuranium elements when ^{252}Cf is reached. For each of the elements up the chain, an isotope is reached which decays by beta emission to become the element with the next higher atomic number. For plutonium this occurs at isotope 243, for americium at 244, for curium at 249, and for berkelium at 250.

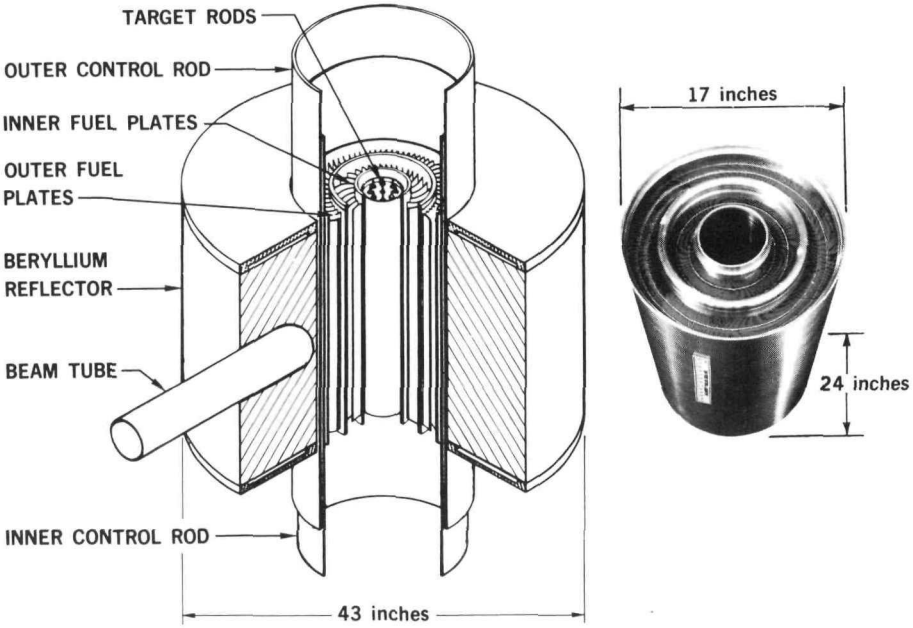
The loss because of fission competition is higher in the earlier steps so it is expedient to carry out the first part of this procedure as a separate step. To this end kilogram quantities of ^{239}Pu have been irradiated in a reactor at the Savannah River Plant to produce ^{242}Pu, ^{243}Am, and ^{244}Cm. These isotopes are separated from the accompanying fission products and refabricated to a form suitable for further irradiation.

The production rates for the higher elements are highly dependent upon the neutron intensity in the nuclear reactor. For example, a tenfold increase in the neutron flux can result in a millionfold increase in the production rate of cali-

fornium. Hence it is of critical importance to obtain the highest possible intensity of neutrons.

For this reason the Atomic Energy Commission has constructed at Oak Ridge National Laboratory a special reactor called the High Flux Isotope Reactor (HFIR). The useful flux in the interior of this advanced design reactor is 3 to 5 times 10^{15} (or, 3 or 5 followed by 15 zeros) neutrons per square centimeter per second. A sketch of the central core of this reactor is shown below.

The transmutation of the ^{242}Pu, ^{243}Am, or ^{244}Cm proceeds for several months. When the transmuted samples are with-



CENTRAL CORE OF THE HIGH FLUX ISOTOPE REACTOR

Central core of the High Flux Isotope Reactor designed for use in the production of transplutonium elements. Target rods, shown schematically at the center of the HFIR core drawing, are surrounded by concentric annular regions of fuel plates, control rods, and a beryllium reflector. The fuel plates, involute in shape, are arranged in two concentric rings. The control-rod arrangement allows symmetry to be maintained about the reactor midplane by withdrawing the rods in opposite directions. A photo of the fuel core is shown at right.

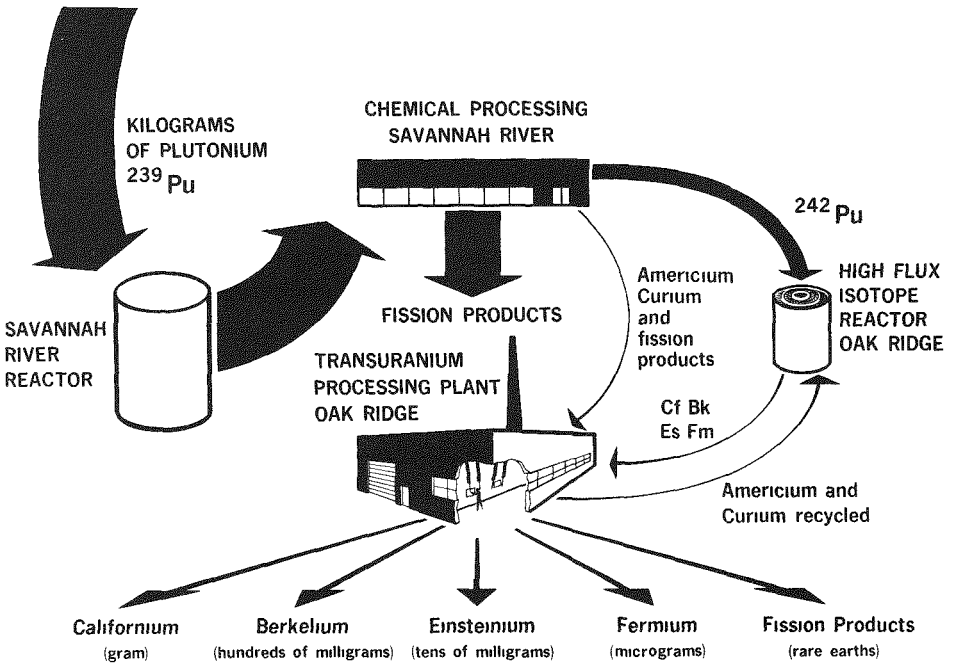
drawn from the High Flux Isotope Reactor, it is necessary to process them chemically to isolate and purify the curium, berkelium, californium, einsteinium, and fermium which have been produced. Because of the technical difficulties of this task, a special transuranium processing facility (designated TRU) has been built close to the reactor.

Most of the technical difficulties arise because of the enormous amounts of radioactivity, which have deleterious effects on the construction materials and chemicals used in the processing steps. These radiations are also highly dangerous to man. Hence all processing must be done by remotely controlled manipulators in massively shielded enclosed cells with carefully tested procedures. A large portion of the radioactivity originates with fission products removed in the initial processing steps. But the transplutonium elements are themselves highly radioactive. Serious processing problems arise because of their intense alpha activity. The alpha activity causes them to be deadly poisonous so that they must be handled by special techniques. The element californium poses an additional health hazard because of the neutrons emitted during the spontaneous fission of such isotopes as ^{252}Cf.

The transplutonium element facility is designed to produce almost 100 grams of ^{246}Cm and ^{248}Cm and fractions of grams of berkelium, californium, einsteinium, and fermium from batches of ^{242}Pu irradiated for 12 to 18 months. The chemical reprocessing also recovers untransmuted plutonium for reinsertion in the reactor. Some of the extracted curium isotopes are also reinserted in order to make gram quantities of californium, hundreds of milligrams of berkelium, tens of milligrams of einsteinium, and micrograms of fermium.

This production program ensures a steady supply of these elements to permit a vigorous program of expanded research and exploitation of their unique and useful properties.

SCHEME OF THE NATIONAL TRANSPLUTONIUM ELEMENT PRODUCTION PROGRAM



The plutonium is irradiated at the Atomic Energy Commission's Savannah River Plant The ^{242}Pu thus formed is isolated and shipped to Oak Ridge National Laboratory along with a mixture of americium–curium and rare-earth fission products The plutonium is made into targets for the High Flux Isotope Reactor (HFIR) without further treatment The americium–curium is separated from the rare earths in the Transuranium Processing Plant (TRU) and made into HFIR targets After exposure in the HFIR for about 18 months the targets are returned to TRU, where the transuranium elements are isolated and supplied to researchers The curium isotopes are returned to the HFIR for further irradiation to produce still more heavy transuranium elements

APPENDIX

Isotopic Forms of Transuranium Elements

Isotope	Half-life	Mode of radioactive disintegration*
Neptunium		
^{231}Np	~50 minutes	α
^{232}Np	~13 minutes	E.C.
^{233}Np	35 minutes	E.C.
^{234}Np	4.4 days	E.C.
^{235}Np	410 days	E.C.
^{236}Np	>5000 years	
^{236m}Np	22 hours	β^- (57%), E.C. (43%)
^{237}Np	2.2 million years	α
^{238}Np	2.10 days	β^-
^{239}Np	2.35 days	β^-
^{240}Np	60.3 minutes	β^-
^{240m}Np	7.3 minutes	β^-
^{241}Np	16 minutes	β^-
Plutonium		
^{232}Pu	36 minutes	E.C. (~90%), α (~10%)
^{233}Pu	20 minutes	E.C.
^{234}Pu	9 hours	E.C. (94%), α (6%)
^{235}Pu	26 minutes	E.C.
^{236}Pu	2.85 years	α
^{237}Pu	45.6 days	E.C.
^{238}Pu	86.4 years	α
^{239}Pu	24,360 years	α
^{240}Pu	6580 years	α
^{241}Pu	13.2 years	β^-
^{242}Pu	379,000 years	α

Isotope	Half-life	Mode of radioactive disintegration*
^{243}Pu	4.98 hours	β^-
^{244}Pu	76 million years	α
^{245}Pu	10.6 hours	β^-
^{246}Pu	10.85 days	β^-
Americium		
^{237}Am	1.3 hours	E.C.
^{238}Am	1.86 hours	E.C.
^{239}Am	12 hours	E.C.
^{240}Am	51 hours	E.C.
^{241}Am	458 years	α
^{242}Am	16.01 hours	β^- (84%), E.C. (16%)
^{242m}Am	152 years	γ emission
^{243}Am	7950 years	α
^{244}Am	26 minutes	β^-
^{244m}Am	10.1 hours	β^-
^{245}Am	1.98 hours	β^-
^{246}Am	25 minutes	β^-
Curium		
^{238}Cm	2.5 hours	E.C.
^{239}Cm	2.9 hours	E.C.
^{240}Cm	26.8 days	α
^{241}Cm	35 days	E.C. (99%), α (1%)
^{242}Cm	162.5 days	α
^{243}Cm	32 years	α
^{244}Cm	17.6 years	α
^{245}Cm	9320 years	α
^{246}Cm	5480 years	α
^{247}Cm	16.4 million years	α
^{248}Cm	470,000 years	α (90%), S.F. (10%)
^{249}Cm	64 minutes	β^-
^{250}Cm	20,000 years	S.F.
Berkelium		
^{243}Bk	4.5 hours	E.C.
^{244}Bk	4.4 hours	E.C.
^{245}Bk	4.98 days	E.C.
^{246}Bk	1.8 days	E.C.
^{247}Bk	1380 years	α
^{248}Bk	16 hours	β^- (70%), E.C. (30%)
^{248m}Bk	>9 years	E.C., α
^{249}Bk	314 days	β^-
^{250}Bk	3 hours	β^-
Californium		
^{244}Cf	25 minutes	α
^{245}Cf	44 minutes	E.C. (70%), α (30%)
^{246}Cf	36 hours	α
^{247}Cf	2.4 hours	E.C.

Isotope	Half-life	Mode of radioactive disintegration*
^{248}Cf	350 days	α
^{249}Cf	360 years	α
^{250}Cf	13.2 years	α
^{251}Cf	800 years	α
^{252}Cf	2.65 years	α (97%), S.F. (3%)
^{253}Cf	17.6 days	β^-
^{254}Cf	61 days	S.F.
Einsteinium		
^{245}Es	1.2 minutes	α (17%), E.C. (83%)
^{246}Es	7.3 minutes	E.C. (90%), α (10%)
^{247}Es	5.0 minutes	E.C. (93%), α (7%)
^{248}Es	25 minutes	E.C., α (0.3%)
^{249}Es	2 hours	E.C., α (0.1%)
^{250}Es	8 hours	E.C.
^{251}Es	1.5 days	E.C., α (~0.5%)
^{252}Es	~140 days	α
^{253}Es	20 days	α
^{254}Es	270 days	α (92%), β (8%)
^{254m}Es	38.5 hours	β
^{255}Es	38 days	β^-
^{256}Es	<1 hour	β^-
Fermium		
^{248}Fm	0.6 minute	α
^{249}Fm	150 seconds	α
^{250}Fm	~30 minutes	α
^{251}Fm	7 hours	E.C.
^{252}Fm	30 hours	α
^{253}Fm	3.0 days	E.C. (90%), α (10%)
^{254}Fm	3.24 hours	α
^{255}Fm	20 hours	α
^{256}Fm	160 minutes	S.F.
^{257}Fm	80 days	α
Mendelevium		
^{255}Md	~30 minutes	E.C. (90%), α (10%)
^{256}Md	1.5 hours	E.C. (97%), α (3%)
^{257}Md	3 hours	E.C. (92%), α (8%)
Nobelium		
^{251}No	0.8 second	α
^{252}No	2.3 seconds	α (33%), S.F. (67%)
^{253}No	105 seconds	α
^{254}No	55 seconds	α
^{255}No	185 seconds	α
^{256}No	2.9 seconds	α
^{257}No	23 seconds	α

Isotope	Half-life	Mode of radioactive disintegration*
Lawrencium		
^{256}Lr	~45 seconds	α
^{257}Lr	8 seconds	α

*Explanation of Symbols

α Alpha decay — E.C. Decay by nuclear capture of an orbital electron

β Beta decay — S.F. Spontaneous fission

m (after mass number) A second isotopic form with distinct radioactivity properties

Longest-lived Isotopic Forms of Transuranium Elements

Element	Isotope	Half-life	Amounts available from AEC programs
Neptunium	^{237}Np	2.1 million years	Kilograms
Plutonium	^{239}Pu	24,360 years	Multikilograms
	^{242}Pu	3.79×10^5 years	Kilograms
	^{244}Pu	76 million years	(No way to produce ^{244}Pu in large quantities)
Americium	^{241}Am	458 years	Kilograms
	^{243}Am	7950 years	Grams to kilograms*
Curium	^{242}Cm	162.5 days	Grams
	^{243}Cm	32 years	Mixtures of these isotopes will be made in quantities of hundreds of grams*
	^{244}Cm	18.1 years	
	^{245}Cm	9320 years	
	^{246}Cm	5480 years	
	^{247}Cm	16.4 million years	
	^{248}Cm	4.7×10^5 years	
Berkelium	^{247}Bk	1380 years	(No way to produce ^{247}Bk in large quantities)
	^{249}Bk	314 days	Hundreds of milligrams*
Californium	^{249}Cf	360 years	Mixtures of these isotopes will be made in gram quantities*
	^{250}Cf	13.2 years	
	^{251}Cf	800 years	
	^{252}Cf	2.65 years	

Element	Isotope	Half-life	Amounts available from AEC programs
Einsteinium	^{253}Es	20 days	These isotopes will be made in tens of milligrams*
	^{254}Es	270 days	
Fermium	^{252}Fm	30 hours	Tracer amounts
	^{253}Fm	3.0 days	
	^{255}Fm	20 hours	
	^{257}Fm	~100 days	
Mendelevium	^{256}Md	1.5 hours	Tracer amounts
Nobelium	$^{253-255}No$	1–3 minutes	Tracer amounts
Lawrencium	^{257}Lr	8 seconds	Tracer amounts

*These are projected production figures for the early 1970s.

The relation of the half-life to the difficulty of scientific research with these isotopes can be illustrated roughly by these examples. The 162-day ^{242}Cm is a dangerous poison to man. The high-energy radiations from samples of milligram size cause extensive damage to the structure of the compounds in which ^{242}Cm is incorporated and to surrounding material. This radiation damage seriously interferes with attempts to study the normal chemical properties of the element curium. Plutonium-239 (24,360 years) is a dangerous poison, but its chemical properties are only moderately affected by its radiations, even on a gram or higher scale. Isotopes of greater than one million years half-life (like the 2.1 million year ^{237}Np) can be handled with only moderate precautions almost as if they were stable.

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