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From the natural transmutations of uranium to its artificial fission

Nobel Lecture, December 13, 1946

The year 1946 marked a jubilee in the history of the chemical element, uranium. Fifty years earlier, in the spring of 1896, Henri Becquerel had discovered the remarkable radiation phenomena of this element, which were at that time grouped together under the name of radioactivity.

For more than 100 years, uranium, discovered by W. H. Klaproth in 1789, had had a quiet existence as a somewhat rare but not particularly interesting element. After its inclusion in the Periodic System by D. Mendeleev and Lothar Meyer, it was distinguished from all the other elements in one particular respect: it occupied the highest place in the table of the elements. As yet, however, that did not have any particular significance.

We know today that it is just this position of uranium at the highest place of the then known chemical elements which gives it the important properties by which it is distinguished from all other elements.

The echo of Becquerel's fundamental observations on the radioactivity of uranium in scientific circles was at first fairly weak. Two years later, however, they acquired an exceptional importance when the Curies succeeded in separating from uranium minerals two active substances, polonium and radium, of which the latter appeared to be several million times stronger than the same weight of uranium.

It was only a few years before the first surprising property of this "radiating" substance was explained. The radioactive elements decompose according to definite rules into other active elements with different chemical and physical properties, simultaneously emitting corpuscular particles, the α- and β-rays. The α-rays were characterized by Rutherford as positively charged helium nuclei, after it had been shown earlier that the β-rays consisted of negative elementary particles, the so-called electrons.

With the hypothesis, suggested by Rutherford and Soddy in 1902, of the disintegration of the atoms, the postulate of the indivisibility of chemical elements had to be abandoned.

Parallel with the investigation of the radioactive disintegration processes

of uranium, which produce radium, radium emanation, the so-called active deposits, and polonium, research was carried out on thorium, at that time the second highest element of the Periodic Table. From thorium were obtained, in an exactly similar manner, strongly active disintegration products: radiothorium, mesothorium, thorium X, etc. There was also a third series of disintegration products, the actinium series, which however also started from uranium.

By the systematic study of the penetration of α-particles through thin layers of material, Rutherford in 1911 was able to propose his model of the nuclei of chemical atoms. According to this view, the atoms of the elements consist of the positively charged nucleus, representing practically the whole mass of the atom, around which move, at a relatively great distance, electrons which neutralize the nuclear charge. The charge of the nucleus undoubtedly represents the position of the element in the Periodic System.

The radioactive disintegration reactions are thus nuclear changes which are not affected by the usual processes of physics or chemistry.

We are so certain of the unchangeability of these natural laws of radioactive breakdown, that from the speed of the changes we can construct a sort of "geological clock". Actually the final substance which is produced from uranium by way of these many active intermediate products is stable lead; from the quantity of the latter formed in the originally pure uranium mineral, it is possible to calculate the age of the mineral and therefore also of the geological deposit in which it has crystallized out. The same holds for thorium, which also produces as final product a kind of lead, although different from the "uranium lead".

Investigation proceeded further. Again the α-particles of radioactive substances formed the means for the solution of problems of nuclear physics. Following Rutherford's nuclear model, these particles were recognized as free helium nuclei. With their relatively large mass of 4 (compared with the small electron mass of about 1/1800) and their initial velocity of up to 15,000 km/set, they formed the bullets with which it might be possible to blast a way to the nuclei of the atoms, inaccessible to other means. And again it was the genius Rutherford who made the next discovery, which was to have extremely important results. In 1919 he was able to show that by bombardment of nitrogen with the energetic α-particles of radium C, an α–particle, that is a helium nucleus, was captured by the nitrogen nucleus, and a hydrogen nucleus - a proton - left the newly formed nucleus.

The process is represented by the equation:

$$\mathrm{^{14}_{7}N} + \mathrm{^{4}_{2}He} \rightarrow \mathrm{^{17}_{8}O} + \mathrm{^{1}_{1}H} + \text{energy}$$
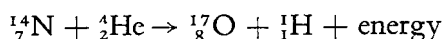
In this equation the lower indices represent the nuclear charges, the upper ones the nuclear masses (atomic weights). The remaining energy is given up in the form of kinetic energy to the released proton, which shows that the latter is derived from the nucleus.

Here for the first time was an artificial transmutation of atoms, actually a building-up of atoms, since an oxygen of mass 17 was produced from a nitrogen of mass 14.

In the following years a large number of reactions following the same pattern were discovered. On account of the positive charge of the α-particle this type of reaction did not succeed in bringing about nuclear transmutations of the heavy elements, since their high nuclear charge of positive sign repelled the α-particle sufficiently to prevent its penetration into the nucleus.

The year 1932 brought further important discoveries: the positron, heavy hydrogen, and - last but not least - the neutron. The discovery of the neutron was the result of detective work carried out in three countries. The initial impulse was given by Bothe and Becker in Germany, who were able to detect an exceptionally penetrating radiation, believed by them to consist of γ-rays, on exposing beryllium to α-particles. Then the Joliot-Curies in France proved that the "γ-rays" which appeared in the experiments of Bothe and Becker set free hydrogen nuclei (protons) with great energy from hydrogen-containing compounds, which is impossible for γ-rays. Finally Chadwick in England gave the final explanation of these results: in addition to γ-rays there occurred uncharged neutral atomic nuclei with a mass of 1, which he called neutrons. The course of the reaction is:

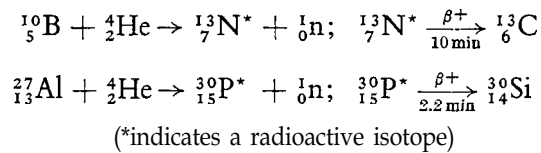$$\mathrm{^{9}_{4}Be} + \mathrm{^{4}_{2}He} \rightarrow \mathrm{^{12}_{6}C} + \mathrm{^{1}_{0}n} + \gamma$$
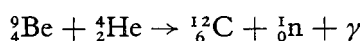
On the discovery of neutrons, the phenomenon of isotopy, known for a number of years, could readily be explained. The chemical elements are composed of protons and neutrons. The number of charged protons determines the chemical nature of the element: the sum of protons and neutrons determines the atomic weight. Thus a larger or smaller number of neutrons does not affect the chemical nature of the element, but merely produces isotopic kinds of atoms such as had been known for a long time in the different isotopes of lead, many mercury isotopes, two of chlorine, etc. Heavy hydrogen, discovered in 1932, is similarly an isotope of ordinary hydrogen. It has in its nucleus both a proton and a neutron, and thus has a mass of 2

instead of 1. The highest chemical element known at that time, uranium, is also not a simple element, but contains isotopes of which ^{238}U is the parent of the radium series and ^{235}U that of the protactinium and actinium series.

Soon was it seen that neutrons would form projectiles specially suited for the transmutation of atoms: they have no charge and are thus not repelled by the positive nuclei of the elements. While however the (α, p) decompositions of Rutherford - (α, p) is the abbreviated formula for a reaction in which an α-particle is taken up and a proton split off - nearly always produce stable kinds of atoms which occur naturally, in the (α, n) changes - the taking up of an α-particle and emission of a neutron - the Joliot-Curies had observed an entirely new phenomenon. In 1934 they found that, on irradiation of certain elements with α-particles, not only neutrons but also positrons, that is positive electrons, appeared, even after the irradiation with α-particles had ceased. The emission of positrons fell off in the same way as had already been observed in the decay of natural radioactive elements. Artificial active elements had been produced. The first elements with which this "artificial" activity on irradiation had been observed were boron and aluminium.

From boron was produced an active nitrogen; from aluminium an active phosphorus; and in their turn these were transformed into carbon and silicon respectively, with emission of positrons, according to the reactions

$$^{10}_{5}B + ^{4}_{2}He \rightarrow ^{13}_{7}N^* + ^{1}_{0}n; \quad ^{13}_{7}N^* \xrightarrow[10\,min]{\beta+} ^{13}_{6}C$$

$$^{27}_{13}Al + ^{4}_{2}He \rightarrow ^{30}_{15}P^* + ^{1}_{0}n; \quad ^{30}_{15}P^* \xrightarrow[2.2\,min]{\beta+} ^{30}_{14}Si$$

(*indicates a radioactive isotope)

A new and large field for further investigation was hereby opened. At the same time the experimental possibilities for carrying out nuclear physical investigations were fundamentally expanded.

While so far the particles from natural radioactive elements had been the sole means of producing artificial nuclear reactions, high-voltage installations - van de Graaff generators and the cyclotron - could now be used in addition. More and more intensive irradiations could be carried out, and more and more new reactions could be realized.

For the time being, however, radium-beryllium mixtures continued to be used, since they were very convenient, though perhaps not very intensive, sources of neutrons for further investigations, especially of the newly discovered artificial radioactivity. Such sources of neutrons were prepared by thor-

ough mixing of a well-dried, finely-powdered radium salt with the finest possible beryllium powder, and sealing the mixture into airtight glass or metal tubes. Uranium itself was only of importance because radium was obtained from it.

It was especially the Italian scientist Fermi who first realized the great importance of neutrons for the production of nuclear reactions: Fermi and his co-workers irradiated practically all of the elements of the Periodic System with neutrons, and made numerous artificial radioactive elements.

Generally, the course of the reaction was such that, especially when working with slow neutrons*, the neutrons were captured by the nucleus. Thereby in many cases an unstable isotope of the irradiated element was produced, passing into the next higher element with emission of β-rays. This latter was generally a stable atom occurring among the usual chemical elements, e.g.

$$^{127}_{53}I + ^{1}_{0}n \rightarrow ^{128}_{53}I^* + \gamma; \quad ^{128}_{53}I^* \xrightarrow[26\,\text{min}]{\beta} ^{128}_{54}Xe$$
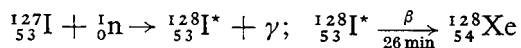
Fermi and his co-workers continued their tests through the whole of the Periodic System up to uranium. Here also they discovered many transmutations produced by neutrons, including some very rapid ones. They proceeded from the obvious assumption that initially there are produced artificial, active, short-living uranium isotopes; as these emit β-rays Fermi inferred the production of so-called "transuraniums", representatives of the element 93 which is not known naturally, and possibly even of the still higher element 94.

Fermi's proofs were not accepted everywhere. It was pointed out that for example in the case of the so-called 13-minute element - that detected with the greatest certainty - the possibility of its being an isotope of element 91, i.e. protactinium, could not be ruled out**.

At this point Lise Meitner and I decided to repeat Fermi's experiments in order to decide whether the 13-minute element was a protactinium isotope or not. This decision was taken the more readily since, by the discovery of protactinium (1917), we were familiar with its chemical properties. More-

* As Fermi first showed, such slow neutrons, of low energy, can be obtained from the primary high-energy neutrons by passing them through substances with a high content of hydrogen. The kinetic energy of the neutrons is then transferred to the hydrogen nuclei in elastic collisions.

** From another direction (Ida Noddack) the objection was raised that all the elements of the Periodic System must first be excluded before it was possible to draw the conclusion that an element 93 had been obtained. This objection was not taken seriously as it appeared to be in opposition to all physical views of nuclear physics.

over, a β-radiating isotope of element 91 was well known to us in the form of uranium Z, discovered by myself, which had the favourable half-life of 6.7 hours, and was available from uranium salts.

With the help of the "indicator method" we were able to prove without doubt that the 13-minute element of Fermi was neither a protactinium isotope, nor a uranium, actinium, or thorium. In accordance with the position of science at the time, Fermi's assertion should be correct, and the 13-minute element a representative of the element 93, that is a "transuranium".

We should point out here that other possibilities did not occur to anyone at that time. Since the discovery of the neutron and the application of artificial sources of radiation, a large number of most unusual nuclear reactions had been discovered; the products were always either isotopes of the irradiated substances, or their next, or at most next-but-one, neighbours in the Periodic System; the possibility of a breakdown of heavy atomic nuclei into various light ones was considered as completely excluded.

With the tests on Fermi's 13-minute element and the checking of other, rather less certain, results of Fermi, we found (later in co-operation with F. Strassmann) that the phenomena associated with the irradiation of the highest element of the Periodic System were much more complicated than had originally been supposed. Fermi and his co-workers had already, in their first communication, described two short-life β-radiating kinds of atoms (half-life 10 sec and 40 sec), which they naturally considered to be artificial isotopes of uranium produced from the original uranium by the capture of neutrons. Lise Meitner and I found, in addition, a substance with a half-life of 23 minutes, which we conclusively identified as an artificial radioactive uranium isotope. With Fermi's substances of short life, the isotopy with uranium can only be assumed, but not proved. The 23-minute element occurred without any other radiation conditions in a so-called "resonance process".

As the result of many years of work, we (Hahn, Meitner, and Strassmann) had finally obtained a great number of artificial active kinds of atoms, which all appeared to be formed directly or indirectly by β-radiation from the supposed short-living uranium isotopes, and which therefore must all represent so-called transuraniums - elements higher than uranium.

According to their chemical behaviour, these could be classified into various groups, and, since in many cases the gradual production from β-radiating parent substances could be directly observed, decay schemes were drawn up extending to elements 95 and 96. In so far as the work was repeated by others, the results were always confirmed.

Independently of the transuranium investigations of Hahn, Meitner, and Strassmann just mentioned, Curie and Savitch described in 1937 and 1938 a so-called 3.5-hour substance which they had obtained by irradiation of uranium with neutrons, and of which the chemical properties could not readily be determined. According to Curie and Savitch, the substance appeared to be a rare earth, but was not actinium; it had more resemblance to lanthanum, and could only be separated from the latter by "fractional crystallization". With some hesitation Curie and Savitch decided to include the substance in the transuranium series, but the possibilities put forward by them appeared difficult to understand and unsatisfactory.

As this 3.5-hour element had been included with the transuraniums, I, together with Strassmann, tried to obtain it. After careful experiments we arrived at remarkable results, which may be formulated approximately as follows: "In addition to the transuraniums described by Hahn, Meitner, and Strassmann, there are produced by two successive α-emissions three artificial, β-active radium isotopes with different half-life times, which in their turn change into artificial β-active actinium isotopes". The conclusion that radium isotopes had been produced was the only one possible since, according to the chemical properties, only barium and radium could be considered. Barium was, according to the physical viewpoint of the time, impossible, and thus only radium was left.

The separation of this active group was performed by means of a barium precipitate; not however in the form of barium sulphate, which with its large surface strongly adsorbs other elements, but, on the suggestion of Strassmann, as barium chloride, which crystallizes very well from concentrated hydrochloric acid and which precipitates uncontaminated by other substances.

At the same time the production of radium under these conditions of radiation was very remarkable: α-decompositions had never been observed with neutrons low in energy, and yet here, as with the transuraniums, a number of isotopes appeared simultaneously.

The experiments were continued in various directions. The preparations were, however, always very weak and the α-rays of the most stable of the new isotopes were so strongly absorbed that thicker layers could only be investigated with poor yields of radiation. An attempt was therefore made to separate the artificial "radium" as far as possible from the barium added as carrier, in order to obtain coatings permitting easier measurement. This was done by fractional crystallization using the method of Madame Curie,

a method with which we had been thoroughly familiar over a number of years. About 30 years previously I, together with Lise Meitner, had separated the radium isotope mesothorium from barium by fractional crystallization. More recently, with the assistance of a number of co-workers, the laws governing the formation of mixed crystals between radium and barium salts had been systematically investigated.

The attempts to separate our artificial "radium isotopes" from barium in this way were unsuccessful; no enrichment of the "radium" was obtained. It was natural to ascribe this lack of success to the exceptionally low intensity of our preparations. It was always a question of merely a few thousands of atoms, which could only be detected as individual particles by the Geiger-Müller counter. Such a small number of atoms could be carried away by the great excess of inactive barium without any increase or decrease being perceptible, even if the barium was precipitated in the form of barium chloride, which precipitates in a very pure form.

In order to check this, we repeated the same tests with a weak intensity of the natural radium isotopes mesothorium and thorium X. These substances were freed from every trace of their parent substance and decay products with the greatest care and, by systematic dilution, preparations were made which were only just detectable with the Geiger-Müller counter. Crystallizations were carried out with the chlorides, bromides and chromates, always with the corresponding barium salt as carrier.

The result was, as was to be expected for radium, that mesothorium and thorium X were concentrated in the first fractions of the salts named, and in fact in quantities such as we should expect from our previous experience. This proved that the few atoms of natural radium isotopes also behaved in exactly the same manner as strong preparations.

Finally we proceeded to direct "indicator tests". We mixed the pure natural radium isotopes with our artificial "radium" isotopes, also previously freed from their decay products, and fractionated the mixture in the same way as before. The result was that the natural radium isotopes could be separated from barium, but the artificial ones could not.

We checked the results in still another way. If the artificial alkaline earth isotopes were radium, then the decay products produced directly through β-emission should consist of actinium: from the element 88 should be produced the element 89. If on the other hand it was barium, then lanthanum should be formed: from element 56 the next higher element 57. With the aid of the pure actinium isotope mesothorium-2 we carried out an "indicator

test" by mixing mesothorium-2 with one of the known primary decay products of artificial radium isotopes, and then carrying out the chemical separation of actinium and lanthanum by the method of Madame Curie. During the fractionation of lanthanum oxalate with actinium, the latter accumulates in the final fractions. This actually occurred with the actinium isotope meso-thorium-2. The decay product of our so-called "radium isotope" however remained with the lanthanum. The artificial rare earth, which had been considered to be actinium, was really lanthanum. Thus it was established that the alkaline earth isotope, which we had believed to be radium, was in fact an artificial active barium; the lanthanum could have been produced only from barium and not from radium.

In order to make quite certain, we carried out a so-called "cycle" with barium. The most stable of the active isotopes, now identified as barium, was freed from active decay products and other impurities by recrystallization with inactive barium; one quarter of the total quantity was kept for comparison, and three quarters were subjected to the following cycle of barium precipitations: Ba-chloride → Ba-succinate → Ba-nitrate → Ba-carbonate → Ba-ferrimannite → Ba-chloride. After passing through this series of compounds, many of which crystallized beautifully, the resulting barium chloride and the recrystallized comparison preparation were measured alternately using the same counter, with equal weights and equal thicknesses of layers. The initial activity and the increase as the result of further formation of the active lanthanum were the same for both preparations, within the limits of error: the crystallization of so many and such different salts had produced no separation of the active barium from the carrier. It could only be concluded that the active product and the carrier were chemically identical, that is, barium.

In the first communication on these tests, which "were in opposition to all the phenomena observed up to the present in nuclear physics" (January 6th, 1939), the indicator tests mentioned had not been entirely completed, and we had therefore expressed ourselves cautiously. As a second partner in the new process we assumed an element with an atomic weight of about 100, as in that case the combined atomic weights would be that of uranium, "for example 138 + 101 (e.g. element 43) gives 239!"

After the completion of the measurements in hand, and of the "cycle", the possibility of error was still further excluded.

This completion of the tests and the above-mentioned "cycle" appeared in a second communication (February 10th, 1939). This also described the

splitting of the element thorium and its confirmation with the aid of indicator tests analogous to those described above. Here also reference was made to the detection of an inert gas and an alkali metal derived from it; the nature of the gas was recognized, and its separation from uranium accomplished by means of a current of air passed over the uranium during the irradiation. An active strontium and an active yttrium were identified in the uranium itself.

Immediately after the first publication on the production of barium from uranium, there appeared as a first communication an article by Lise Meitner and O. R. Frisch in which the possibility of a breakdown of heavy atomic nuclei into two lighter ones, with total charges equal to that of the original nucleus, was explained with the aid of Bohr's model of the original nucleus. Meimer and Frisch also estimated the exceptionally high energy output to be expected from this reaction, from the curve of the mass deficiencies of the elements in the Periodic Table. The great repulsive energy of the fragments produced by the splitting was first demonstrated experimentally by Frisch and shortly afterwards by F. Joliot. Meitner and Frisch soon proved that the active breakdown products, previously considered to be transuraniums, were in fact not transuraniums but fragments produced by splitting. They were able to accumulate these by "repulsion" outside the radiated uranium.

In quick succession there appeared a whole series of publications from European and American nuclear physics institutes, confirming and expanding the tests described.

Thus the process proceeds in such a way that the nucleus of the uranium with a charge of 92 is split into two nuclei of moderate size*. If one of these is barium, which has a nuclear charge of 56, there must be produced at the same time a krypton with a nuclear charge of 36. Together these nuclei add up to 92. Both have however, as may easily be seen from the masses of uranium and of the stable isotopes of barium and krypton which occur naturally, too great a mass, and thus an excess of neutrons. They should therefore pass over into stable elements with higher nuclear charges, with emission of β-rays; and in fact, as our later experiments showed, sometimes achieve stability by way of a great number of unstable intermediate decay products.

The highest stable krypton isotope has a mass of 86. In uranium fission there is produced, among other atoms, an unstable krypton with mass 88.

* The expression "nuclear fission" *(Kernspaltung; fission nucléaire)* is due to Meitner and Frisch.

Uranium 235 is responsible for the fission induced by thermal neutrons, as Bohr was the first to see; this fission forms by far the larger part. If there are no side reactions then the mass of the other fission product belonging to the krypton 88, that is of the barium, should be 236 - 88 = 148. As the highest stable barium isotope has a mass of 138, the first-mentioned product is not less than 10 units heavier. Strassmann and myself had already noted, in our second communication, the possibility that neutrons were set free in the fission process. That this was in fact the case was first established experimentally by F. Joliot.

The investigations continued at a rapid pace, both from the physical and the chemical side. Only a year after the first communication on the production of barium from uranium, there appeared in the *Reviews of Modern Physics* (U.S.A.) a bibliography on the splitting of heavy nuclei *(Nuclear Fission, by L. A. Turner)* in which nearly one hundred publications in this sphere were mentioned.

During the Second world War, the very confusing fission reactions were systematically investigated in the Kaiser Wilhelm Institute for Chemistry with a view to their chemical disentanglement, and numerous new reactions were discovered. Japanese investigators found that, when fast neutrons were used, the fission of uranium proceeded more symmetrically than with slow

Element	Natural isotopes	Isotopes occurring in the uranium fission
54 Xenon	124, 126, 128, 129, 130, 131, 132, 133, 134, 136	139 (unstable) together with
38 Strontium	84, 85, 87, 88	97 (unstable)
92		236
36 Krypton	78, 80, 82, 83, 84, 86	88 (unstable) together with
56 Barium	130, 132, 134, 135, 136, 137, 138	148 (unstable)
92		236

92 = nuclear charge of uranium = sum of the nuclear charges of the fragments
236 = mass number of uranium 235 plus 1 neutron

Table I. Atomic weights of some natural isotopes, and of artificial isotopes produced by nuclear fission, if the excess of neutrons is not released.

ones. At the beginning of 1945 we were able to make a table (Table 3) in which were collected, as direct or indirect products of uranium fission, 25 different elements, ranging from 35 (bromine) to 59 (praseodymium), in the form of about 100 active kinds of atoms. The active atoms, believed by us up to 1939 to be transuraniums, were all fission products and their active successors, and not elements with atomic number higher than uranium!

	Br	Kr	Rb	Sr	Y	Zr	Nb	Mo
	35	36	37	38	39	40	41	42
83	140^{min}→	113^{min} / stab.						
84	30^{min}→	stab.						
85	3^{min}→	4.6^{h}	stab.					
86	°	stab.						
87	50^{sec}→	75^{min}→	$6\cdot10^{10a}$→	stab.				
88		175^{min}→	18^{min}→	stab.				
89		2.5^{min}→	15^{min}→	55^{d}→	stab.			
90		?→	?→	5^{d}→	60^{h}→	stab.		
91		?→	?→	10^{h}→	50^{min} / 57 ^{d}→	stab.		
92		?→	80^{sec}→	2.7^{h}→	3.5^{h}→	stab.		
93						65^{d}→	55^{d} / stab.	
94		?→	?→	2^{min}→	20^{min}→	stab.		
95						17^{h}→	75^{min}	
96		?→	?→	7^{min}→	11.6^{h}→	stab.		
97		?→	?→	$\sim8^{h}$→	$\rangle100^{d}$→	26^{d}→	° →	stab.

Table 2. Fission products of uranium between elements 35 and 42.

From the nature of the problem, the physical work proceeded in a different direction. Especially important in this connection was the above-mentioned investigation of Joliot in which he proved experimentally, in the spring of 1939, that in the fission process, neutrons appeared in addition to the (always two) new elements.

Since by the action of neutrons on uranium, fresh neutrons are liberated, the latter, if they meet uranium atoms, produce further fissions, in their turn.

Table 3. Summary of the fission products of uranium known at the Kaiser Wilhelm
Institute for Chemistry by early 1945.
(s = seconds; m = minutes; h = hours; d = days; a = years)

If more than one fresh neutron is produced, and the process is so arranged that all the fresh neutrons strike uranium atoms, then we have a chain of continuously renewing fission reactions which, like an avalanche started by a snowball, can attain enormous dimensions. Thereby the practical application of atomic energy first came into the range of possibility. S. Flügge, then attached to the Kaiser Wilhelm Institute for Chemistry, was the first to refer to this.

About 10 years ago, Joliot concluded his Nobel Lecture with the following words : "If, turning to the past, we cast a glance at the progress achieved by Science at an ever-increasing pace, we are entitled to think that scientists, building up or shattering elements at will, will be able to bring about transmutations of an explosive type, true chemical chain reactions. If such transmutations do succeed in spreading in matter, the enormous liberation of usable energy can be imagined. But, unfortunately, if the contagion spreads to all the elements of our planet, the consequences of unloosing such a cataclysm can only be viewed with apprehension. Astronomers sometimes observe that a star of medium magnitude increases suddenly in size; a star invisible to the naked eye may become very brilliant and visible without any telescope - the appearance of a Nova. This sudden flaring up of the star is perhaps due to transmutations of an explosive character like those which our wandering imagination is perceiving now - a process that the investigators will no doubt attempt to realize while taking, we hope, the necessary precautions!"
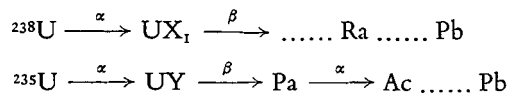
What was ten years ago only a figment of our "wandering imagination", has already become to some extent a threatening reality. The energy of nuclear physical reactions has been given into men's hands. Shall it be used for the assistance of free scientific thought, for social improvement and the betterment of the living conditions of mankind? Or will it be misused to destroy what mankind has built up in thousands of years? The answer must be given without hesitation, and undoubtedly the scientists of the world will strive towards the first alternative.

Postscript

In the preceding paragraphs we have given a general outline of how the investigation of the natural radioactivity of uranium led to the artificial splitting of that element. But this does not exhaust the possibilities of ura-

nium. Uranium consists mainly of two isotopes with atomic weights 235 and 238. The first is present in the mixture only to the extent of $\frac{1}{140}$ part; nevertheless the fission process described above, which is caused with special violence by "slow" neutrons, is to be ascribed chiefly to its rare isotope. It has already been mentioned above that Lise Meitner and the present writer were able to identify, after the irradiation of uranium with neutrons, a substance having a half-life of 23 minutes as undoubtedly a uranium isotope. (The short-lived isotopes, thought first by Fermi and later by ourselves to be artificial uranium isotopes, were actually fission products.) The 23-minute uranium was produced in a so-called resonance process by neutrons of a certain velocity. Since this substance emits β-rays, a representative of element 93, that is an actual transuranium, *must* be produced. Although we sought for it, we were unable to detect it in the very weak preparations which we had at the time. Later it was identified in the United States as a β-emitter with a half-life of 2.3 days. Thus it has an atomic weight of 239. Since this true transuranium 93 emits β-rays in turn, it must be concluded that an element 94, a further transuranium, is formed. This is a relatively long-living α-emitting substance (half-life 24,000 years). The American scientist Seaborg gave it the name plutonium, calling element 93 neptunium. A second isotope of element 93 also occurs, it is produced in another way from uranium 238, namely by a so-called (n, 2n) process with the aid of neutrons of great energy: one neutron, so to speak, in passing through the uranium nucleus knocks out another one. The result is a β-emitting uranium
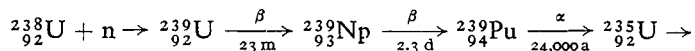

I. Natural

$$^{238}U \xrightarrow{\alpha} UX_I \xrightarrow{\beta} \ldots\ldots Ra \ldots\ldots Pb$$

$$^{235}U \xrightarrow{\alpha} UY \xrightarrow{\beta} Pa \xrightarrow{\alpha} Ac \ldots\ldots Pb$$

II. Artificial

(i) *Fission processes* with slow and fast neutrons, up to the present 25 elements in about 100 kinds of atoms.

(ii) *Capture of a neutron*:

$$^{238}_{92}U + n \rightarrow\ ^{239}_{92}U \xrightarrow[23\,m]{\beta}\ ^{239}_{93}Np \xrightarrow[2.3\,d]{\beta}\ ^{239}_{94}Pu \xrightarrow[24,000\,a]{\alpha}\ ^{235}_{92}U \rightarrow$$

(iii) *Loss of a neutron*:

$$^{238}_{92}U + n - 2n \rightarrow\ ^{237}_{92}U \xrightarrow[6.8\,d]{\beta}\ ^{237}_{93}Np \xrightarrow[2.25\cdot 10^6\,a]{\alpha}\ ^{233}_{91}Pa \rightarrow$$
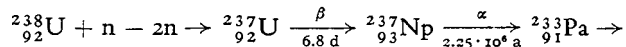

Table 4. Uranium transmutations.

isotope of mass 237, which thus transforms into a second neptunium isotope of which the half-life is some millions of years.

Thus the behaviour of uranium on irradiation with neutrons of different velocities, both fast and slow, is very complicated (see Table 4). In addition to the natural splitting process, which continues during the irradiation at a speed independent of all the other reactions, the following occur:

(1) Nuclear fission with formation of numerous artificial atoms of all elements between 30 and 64.

(2) Emission of surplus neutrons during this fission process, making a chain reaction possible.

(3) The resonance capture of a neutron with a definite energy by uranium 238, with formation of uranium 239, which in its turn is transformed into the elements neptunium and plutonium.

(4) The giving up of a surplus neutron by the ^{238}U with formation of a ^{237}U, which also forms a neptunium isotope.

As, in process (1), slow (thermal) neutrons mainly attack the rare isotope ^{235}U; process (3) is a kind of competitor of process (1), since in the resonance process (3) the neutrons are captured before they have reached thermal velocities. It is a matter of experimental technique to prevent this capture as much as possible, in order to facilitate the chain reaction. On the other hand, the extra neutrons produced in the fission of process (2) give rise to the resonance process, and thereby to the formation of plutonium. If this latter element is obtained in sufficient quantity by means of a slow controlled chain reaction carried out on a large scale (in a so-called "pile"), and is separated from uranium, then it can also act as carrier of a chain reaction. The same holds for pure ^{235}U after it has been separated from the isotope 238, since with ^{235}U the resonance process, which interrupts the chain reaction, does not occur.

Both uranium 235 and plutonium are made in the United States. The result was the bombing of Hiroshima and Nagasaki.