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ON THE WAY TO SUPER-ELEMENTS

MIR PUBLISHERS MOSCOW

SCIENTISTS
TO
SCHOOL-
CHILDREN

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На пути к сверхэлементам

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На английском языке

Contents

Enigmas of the Periodic Law

From time immemorial man has been asking himself what is the world about us composed of? Why is the environmental matter made up of so many diverse gases, liquids or solids? Can it be converted into other matter or can new hitherto unknown types be found? It was only about two centuries ago that the multitude of environmental matter became known to be the result of various combinations of a comparatively small number of chemical elements. At that time the properties of these elements seemed to be unrelated to each other. No one could say whether or not a new element would appear, and when one was actually discovered. The appearance of the new-born was often a complete surprise to the discoverer. Meanwhile the list of the elements grew with each new year, and by the second half of the 19th century there were about sixty elements identified.

The discovery of the periodic system by D. I. Mendeleev. At a some stage in its development every field of science passes through a period of reappraisal when all the knowledge acquired so far has to be systematized. Biology went through such a period in the late 18th century, whereas the physics of elementary particles is going through this period today. The list of chemical elements was ripe for reappraisal at the middle of the 19th century. The chemical properties of the elements were evaluated as to whether they were random, or whether they vary according to a difinite law. A system that would integrate all the known elements was a challenge for many scientists of that time. It was only in 1869 that the great Russian scientist D.I. Mendeleev discovered the famous Periodic Law, one of the most fundamental laws of the universe.

Today every schoolboy knows that the properties of elements vary periodically as their atomic weight increases. Therefore the elements may be arrayed into a table such that the properties of the elements in rows and in columns obey strict regulations.

When Mendeleev arranged the then known 63 elements into a table some of its cells remained unfilled. Using his periodic law he was able to predict the properties of some of the unknown elements naming them by their predecessors in the table using the prefix "eka". It was not long before these cells in the table were filled with names of the actual elements. Already by 1875 "eka-aluminium" was discovered and named gallium. In intervals of four and seven years "eka-boron" became known as scandium and "eka-silicium" as germanium. It was a great triumph for the periodic system. In the next half century the periodic system proved to be a reliable compass in the search for new elements in minerals. This search resulted in the discovery of 30 more chemical elements.

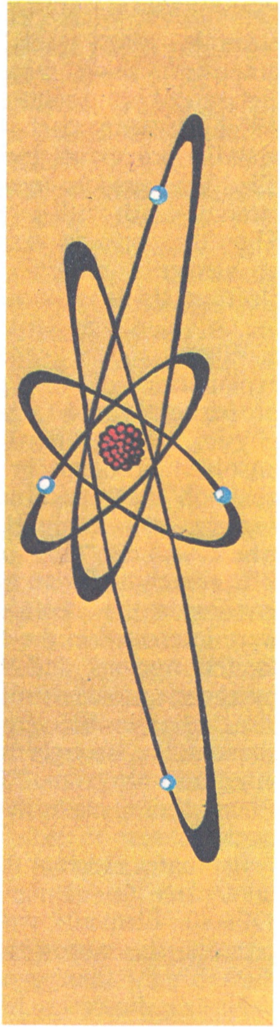
The atomic key. Unfortunately, neither Mendeleev nor other scientists of that time could interpret the underlying causes for the periodicity in the elements properties. In this respect, Mendeleev's discovery belonged to the future in that it held the seeds of great discoveries which lead to the vigorous development of physics and chemistry. Intuitively it was obvious that the key was hidden in the smallest particle of matter, the atom. Mendeleev wrote: "although it cannot be proved as yet it is easy to assume, that the atoms of elementary bodies are complicated species consisting of even smaller particles...

My periodic relationship between the properties and the atomic weight seems to confirm this expectation."

But these words had to wait 40 years to be confirmed. Lord Ernest Rutherford proved that the atom was a complicated system containing a positive charged nucleus at the centre and negative electrons orbiting around it. Niels Bohr gave a quantum interpretation to this planetary model of the atom. The theoretical foundation of modern physics was laid and the exploration of the strange and unusual world of the microscopic particles of matter began. Physics enjoyed a second youth. Quantum mechanics was established. New fields of research, atomic and nuclear physics evolved. The revolution in physics exerted a profound effect not only on the natural sciences but also in industry and peoples' way of looking at life. It is not an accident that the 20th century is often referred to as the atomic century.

The achievements of atomic physics shed light on many dark spots of the periodic system. First of all, it turned out that the place of an element in the periodic table was decided by the charge of its nucleus rather than its atomic weight. The number of an element in the table is numerically equal to the charge of its nucleus measured in units of electron charge. The most important achievement, however, was that the nature of the chemical properties of elements was explained. It has been determined that the electron orbits in an atom are not uniformly spaced, rather, they group into shells. Each shell is capable of accommodating a definite number of electrons: the first shell 2, the second 8, the third 18, the fourth 32. These numbers correspond exactly to the number of elements in the periods of the periodic table.

The chemical properties of elements are governed by



the number of electrons in the outermost shell. For example, alcali metals have one electron in their outermost shell, therefore they easily donate it to a chemical bond with other elements. The easiness with which elements part with their electrons defines their metallic properties. Inert gases whose outermost shell is filled and which terminate the periods of the table interact with other elements extremely unwillingly. Thus the periodic variation of the chemical properties of elements reflects the periodicity of filling their electron shells.

Where is the limit of the periodic table? The explanation of the periodic variation of chemical properties was a significant achievement of atomic physics. There remained, however, a number of unsolved problems in the periodic law. The principal question that concerned Mendeleev remained unclear, namely, how many elements were there in the total: where was the limit of the periodic table?

In searching for an answer to this problem researchers got inside the electron shell of the atom. Now they were interested in the behaviour of the electrons closest to the nucleus and therefore most strongly affected by the electrostatic attractive force. The larger the nuclear charge, the greater the mass number of the element, the stronger will be the attractive force for the innermost electrons. Eventually a situation would occur when these electrons would be captured by the nucleus.

Estimates indicate that this catastrophic situation will take place for elements with mass numbers of about 170-180. Elements with greater numbers cannot exist because the absorption of a negative electron will diminish the charge of the nucleus.

Nature, however, hid the solution to the boundary problem for the periodic table even deeper. The subsequent progress of physics showed that the instability of the electron shell does not decide the boundary of existence for elements. Rather, it is controlled by the instability of the nucleus itself, the source of the electric field which shapes the electron shells.

The development of physics in depth was continuing and the answer to the next fundamental question of the periodic law was given by nuclear physics which studied particles one ten-thousandth the size of the atom, which was believed to be indivisible not long ago. In the pages that follow we shall explain to you what advances have been made in this area in the last three decades.

The Stability Continent

A few words about nuclei. What new things have nuclear physicists learned about the Periodic System? It turned out that even a micro object such as the nucleus is composed of still smaller particles, neutrons and protons. These two particles have very much in common, so after they are referred to by the common name, nucleons. The major difference between these particles is that the proton has a positive charge equal in magnitude to the charge of an electron, whereas the neutron has no charge at all. The nuclear charge, Z, and hence the atomic number of the element in the periodic table, is equal to the number of protons in the nucleus. The mass number, A, defining the atomic weight of an element is the sum of the neutrons N and protons Z in the nucleus, $A = Z + N$.

The same cell of the periodic table may contain a few twin-atoms of one element, whose nuclei have equal number of protons but differ in the number of neutrons. Such nuclei are called isotopes. In order to identify isotopes symbolically the name of the atom is followed by the isotope mass number, as in uranium – 238, or the symbol of the atom is used with the mass number as a superscript and the nuclear charge as a subscript, as $^{238}_{92}U$.

The chemical properties of all isotopes of one element are the same because they are governed only by the nuclear charge, whereas their nuclear properties vary very widely. In particular it has been found that isotopes with even numbers of protons and even numbers of neutrons in the nucleus are very stable. Conversely, odd numbered nuclei are extremely unstable, especially those with an odd number of protons Z and an odd number of neutrons N. Odd isotopes readily take part in various nuclear reactions. Suffice it to say that the possibility of utilizing nuclear energy is connected with the so-called "Big three" uranium – 235, plutonium – 239, and uranium – 233. The mass number of an isotope defines its nuclear properties just as much as its atomic number does. Therefore the periodic table should show the number of protons Z and the number of neutrons N for an element, which together indicate the mass number of an isotope. As a result, the periodic table transforms into a map of isotopes (see p. 18–19).

How many isotopes can one element have? Many elements have a few stable isotopes, that is, such whose nuclei can remain stable without undergoing fission for an indefinite period. Rock minerals or a chemically pure sample of an element usually contain a mixture of long-lived isotopes. All stable isotopes have a characteristic ratio of neutrons to protons. For the light nuclei beginning the periodic table, the stable isotopes have an equal number of neutrons and protons. As the nuclear charge increases, this proportion varies, the stable heavy nuclei have 1.5 times more neutrons than protons.

The number of unstable isotopes is considerably larger. The "family" of a heavy element may contain several dozen "twins" whose neutron/proton ratio deviates to either side from the optimal. What will happen if we add a few neutrons to a stable nucleus? It will tend to get rid of the excess neutrons and to eventually convert to a stable isotope of another element.

Nuclear metamorphoses. The phenomenon of spontaneous conversion of atomic nuclei, when the nucleus of one element converts into the nucleus of another element without any influence from outside, is called radioactivity. This phenomenon was discovered by A.H. Becquerel in 1896. The discovery led to the important implication that the nucleus is not the simplest particle of matter, unchangeable and impenetrable by external forces. Indeed, already by 1919 E. Rutherford succeeded to break down the nucleus and convert one element into another – exactly what vainly alchemists tried to do for so many years. In 1934, Frederic and Iréne Joliot-Curie received the first artificial radioactive isotopes. This work was fundamental for the modern synthesis of new elements.

A few ways for the radioactive decay of nuclei were discovered. We illustrate them by taking a bismuth (Bi) nucleus as an example.

A nucleus oversaturated with neutrons will have one neutron become a proton while emitting an electron ${}_{-1}^{0}e$ and an antineutrino ${}_{0}^{0}\tilde{\nu}$. (The antineutrino is an elementary particle which has neither mass of rest nor charge.) As a result the nucleus is transformed into that of an adjacent element which has the same mass number but with a charge one unit higher. This type of radioactivity was termed β⁻decay, that is, electron decay. Symbolically this transformation is illustrated as

$$^{213}_{83}Bi \rightarrow ^{213}_{84}PO + ^{0}_{-1}e + ^{0}_{0}\tilde{v}$$

or

$$^{213}_{83}Bi \xrightarrow{\beta^-} ^{213}_{84}Po$$

Conversely in a nucleus with a deficit of neutrons transmutations take place that tend to decrease the charge of the nucleus. In this case there are far more possible ways for decaying. For example, a proton can convert into a neutron, whereby the nucleus emits a positron $^{0}_{+1}e$ (an antielectron, positively charged) and a neutrino $^{0}_{0}v$, which signifies the positron, or β^+-decay:

$$^{206}_{83}Bi \rightarrow ^{206}_{82}Pb + ^{0}_{+1}e + ^{0}_{0}v$$

or

$$^{206}_{83}Bi \xrightarrow{\beta^+} ^{206}_{82}Pb$$

Another possibility is for the proton to capture an electron from the closest electron orbit of the atom and become a neutron. This type of decay is known to proceed by electron capture

$$^{208}_{83}Bi + ^{0}_{-1}e \rightarrow ^{208}_{82}Pb + ^{0}_{0}v$$

or

$$^{208}_{83}Bi \xrightarrow{e.c.} ^{208}_{82}Pb$$

In both types of decay the nuclear charge decreases by one unit, whereas the atomic number does not alter.

Still another possibility is the so-called α-decay when the nucleus emits an alpha particle (the helium nuclide of mass 4 and charge 2) and decreases in mass by

4 units and in charge by 2 units:

$$^{211}_{83}Bi \rightarrow ^{207}_{81}Tl + ^{4}_{2}He$$

or

$$^{211}_{83}Bi \xrightarrow{\alpha} ^{207}_{81}Tl$$

The more neutron rich or deficient the nucleus and the farther it stands from its most stable isotope, the faster it converts into another nucleus and the shorter its lifetime. Whereas stable isotopes which constitute the material world around us can live forever, their neutron rich or deficient relatives have lifetimes of years, hours, seconds, and even thousandth fractions of a second depending on how far they differ from the longer-lived isotopes.

A map of isotopes. Let us plot a map of isotopes taking the number of protons Z and neutrons N in the nuclei as horizontal coordinates, and the lifetimes of the isotopes as the vertical coordinates in exactly the same manner as altitude is pictured by colour on geographical maps. Then the domain of feasible nuclei may be imagined as a continent crossed by the mountain ridge of stable isotopes flanked by vast open lands of radioactive neutron-deficient and neutron-rich nuclei. The Continent of Stability is surrounded by the Sea of Instability. The nuclei at the sea bottom are unstudiable because of their extremely short lifetimes.

The mountainous ridge occupies only a small part of the continent, only about 300 stable isotopes are known. After the discovery of artificial radioactivity by the Joliot-Curie couple, more than 1800 unstable isotopes of the known elements have been synthesized. According to estimates this amounts to only a third of the total number of all possible nuclei. To develop the wide reaches of the Stability Continent and reach the shore of the Instability Sea will require sizeable scientific efforts. Numerous enigmas and developments await research, but our way leads still farther through the Radioactivity Strait to the Heavy Nuclei Island.

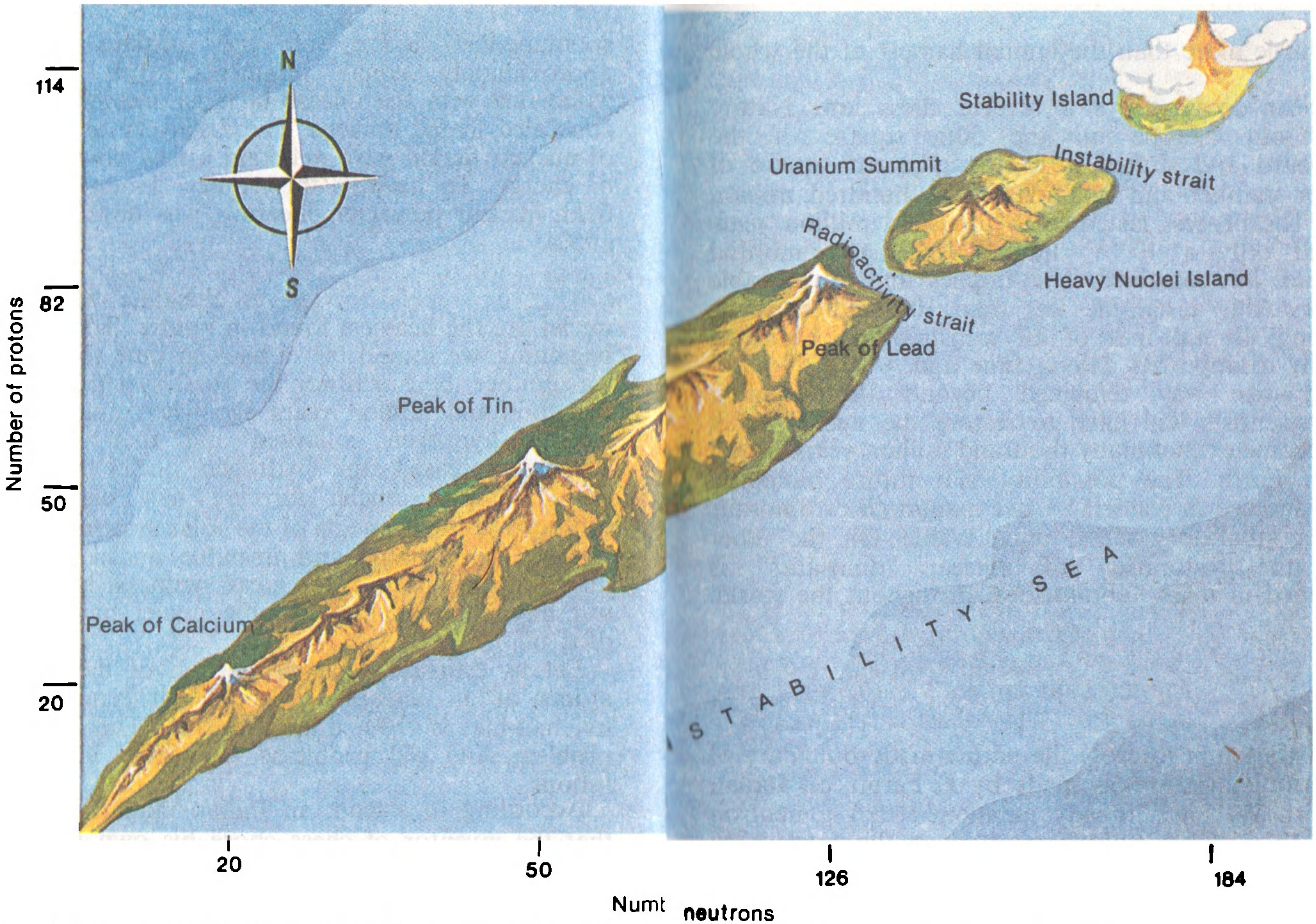
The last natural element. The two-peak summit at the south-west of the Heavy Nuclei Island is ($Z = 90$) and uranium ($Z = 92$). The uranium nucleus is the heaviest of all found in nature. This element was discovered in 1789. In 1874, Mendeleev placed it in the farthest cell of his table and for 70 years uranium remained the last element of the table. This positioning of element 92 naturally made it into an object of intense attention for scientists. Mendeleev wrote: "Being convinced that the study of uranium – beginning from its natural sources – will bring about many new discoveries, I recommend that all those searching for new fields of research commit themselves to uranium compounds".

Now we can only be amazed at the brilliant far-sightedness of Mendeleev. Indeed, studies in exactly this field led to the discovery of radioactivity, a most important phenomenon in nuclear physics. Soon after this discovery, in 1898 Marie and Pierre Curie isolated the first radioactive elements polonium and radium from pitchblende. In 40 years, O. Hahn and F. Strassman discovered the fission process in uranium nuclei by incident neutrons. Finally, in 1939, in the early days of the atomic era, one of the authors of this book along with K. A. Peterzhak was fortunate to prove that uranium nuclei can fission spontaneously without any stimulation from outside. This new and unusual type of radioactive decay exists in the domain of heavy nuclei. The thing is that the huge electrostatic repulsive forces operating between this large number of protons may not only cause induced but also spontaneous fission of the nucleus into two approximately equal fragments. The process is associated with the release of large amounts of energy concealed in the nucleus. The discovery of the process of nuclear fission gave mankind a new powerful source of energy. To harness this source a new engineering field, nuclear power engineering, was developed in the 1950s.

The chess problem. Let us elucidate why uranium nuclei are the heaviest found in nature. To start at the beginning, we should travel back in time to when there was neither the Earth nor the Solar system. More than five thousand million years ago when huge masses of galactic hydrogen collapsed and their temperature sharply increased, the hydrogen nuclei merged into more complex nuclei forming new elements. The synthesis of the elements of the solar system took place, yielding both stable and unstable nuclei. The stable nuclei formed during this great synthesis have lived to our day, whereas the unstable nuclei have gradually died off.

Let us estimate what proportion of the primordial atoms of an unstable isotope will remain alive if its half-life is 100 million years. This is an old problem, and old problems as a rule have old solutions.

According to legend, an Indian maharaja suggested that the inventor of chess chose his own reward. The sage asked for what seemed to be a little grain, namely, as much grain as would be apportioned to the 64th square of the chessboard given that the first square had two grains (2^1); the second four (2^2), the third eight (2^3), and the amount of grain was to double until the 64-th square. After a simple calculation it became clear that the amount of grain apportioned to the last square



The map of isotopes. The horizontal coordinates show the number of neutrons and protons in the nucleus. The figures indicate the magic numbers. Blue identifies the range of nuclei whose half-life is in the range between 10^{-10} s and 1 s, green shows the range between 1 s and 1 year, light-brown corresponds to the range from 1 year and 1000 millions of years. Dark brown identifies nuclei living longer than 1000 million years. White shows the magic summits. Unstudied terrae incognita lie beyond the map. The other islands of the Stability archipelago are to be found north-east from the first island. The Antinuclei Continent flanks the southwest outskirts of the Stability Continent. Far to the east lies the mainland of Stellar material, neutron drops was a little more than the annual harvest of the whole Earth.

Nuclear decay obeys a reverse chess law. Nature placed our isotope on the 50th square of the chessboard and shifted it to the adjacent square of a lesser number and half mass each hundred million years. The process lasted for 5 thousand million years so that only a 10^{-15} fraction of the primordial substance has remained. This implies that all unstable isotopes with a half-life less than 100 million years, including the isotopes of all transuranium elements, virtually disappeared a long time ago.

Only one way remained beyond the uranium peak – scientists will have to restore the nuclei which had become extinct many thousand million years before life on Earth. The possibility that future biologists would succeed in restoring a live mammoth or dinosaur in their laboratory seems unbelievable. On the other hand, the restoration of nuclear "dinosaurs" is performed in many laboratories throughout the world.

Neutron Synthesis

The first attempt to cross the nature-made boundary of the periodic system was made by E. Fermi, an Italian physicist. We have already mentioned that a neutron added to a stable isotope may cause the nucleus to undergo beta-decay resulting in the charge of the nucleus increasing by one unit. Fermi decided to use this fact in his experiments in the synthesis of element 93 by irradiating uranium with neutrons. Although these 1934 experiments failed to produce element 93, neutron bombardment is widely used in our days to yield many transuranium elements.

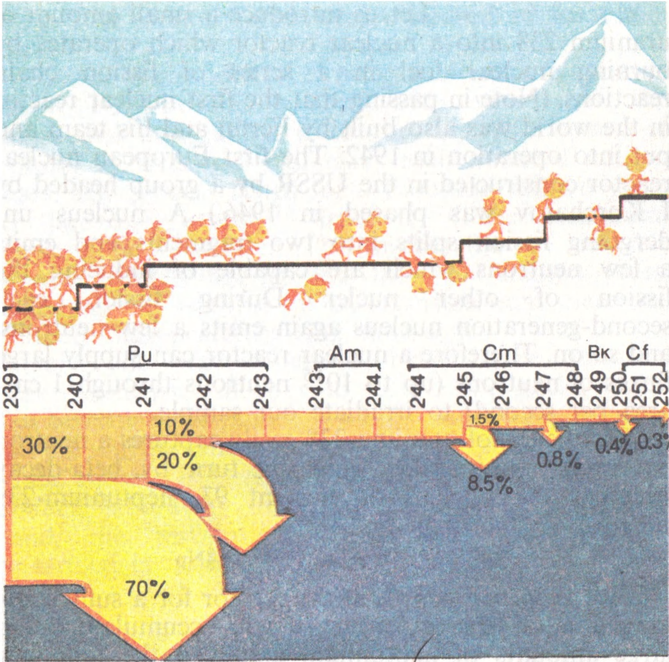
Reactor method. Let us introduce a small amount of uranium 238 into a nuclear reactor which operates by burning nuclear fuel in a series of fission chain reactions. (Note in passing that the first nuclear reactor in the world was also built by Fermi and his team and put into operation in 1942. The first European nuclear reactor constructed in the USSR by a group headed by I. Kurchatov was phased in 1946.) A nucleus undergoing fission splits into two fragments and emits a few neutrons which are capable of inducing the fission of other nuclei. During fission each second-generation nucleus again emits a few neutrons, and so on. Therefore a nuclear reactor can supply large fluxes of neutrons (up to 10^{15} neutrons through 1 cm^2 area per second) to irradiate our sample.

The nucleus of uranium-238 easily captures a neutron becoming uranium-239 which in turn by beta-decay becomes the nucleus of element 93, neptunium-239

$$^{1}_{0}n + ^{238}_{92}U \rightarrow ^{239}_{92}U \xrightarrow{\beta^-} ^{239}_{93}Np$$

If we keep our sample in the reactor for a sufficiently long time (a year or longer), it will accumulate rather large amounts of neptunium, and also the following elements that are formed in the reactor as a result of nuclear transmutations. For example, neptunium-239 may suffer beta decay and become element 93, plutonium-239. Then the nucleus of this element captures two neutrons to become plutonium-241 which yields the nucleus of element 95, americium, by beta decay, and so on. The figure on the adjacent page illustrates the further conversions of plutonium-239 into ever heavier elements.

After a long irradiation the uranium sample is removed from the reactor for chemists to isolate and identify all the synthesized elements. Because all these



The production of transuranium elements by the prolonged irradiation of plutonium-239 with neutrons in a nuclear reactor. The size of the arrows is indicative of the fraction of the initial nuclei split by fission and other types of decay. Only 0.3 per cent of the initial plutonium nuclei, element 94, are to go all the chain of transmutations to become the nuclei of element 98, californium-252

elements are very radioactive manipulating them requires special safety measures: working behind protective shields with mechanical manipulators.

Chemical factories for nuclear material processing are huge enterprises equipped by the most advanced technology and equipment.

It would seem that an easy life began for the nuclear researchers – relax at a “reactor incubator” and wait until a new nuclear “dinosaur” was hatched. Actually, however, the new elements succeeding californium ($Z = 98$) failed to appear in the reactor. What was the cause?

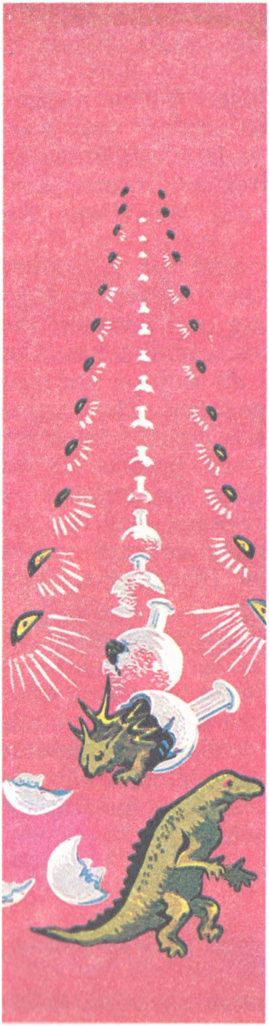
The heavier the element, the greater the difficulties we have to face. Let us return to the diagram on page 22. When one nucleus is converting into another, the amount of initial material decreases several times. The point is that not all the nuclei of an isotope undergo beta decay after capturing a neutron. The major portion of nuclei either transmutes or fissions by other processes which hamper the desired process to be effected in full measure. The higher the number of conversions which the original isotope suffers, the smaller the proportion of initial nuclei converting into the nuclei of the desired element. (Recall the chess problem.)

But all these are technical difficulties which could be overcome by constructing more powerful reactors. It turned out, however, that there were principal difficulties. Other types of decay scattered numerous pitfalls onto the path to new elements, leading the process away so that after a long series of transformations we may again arrive at the initial isotope. Such may be, for instance, the alpha decay of a nucleus

$$^{239}_{94}\text{Pu} \xrightarrow{n} {}^{240}_{94}\text{Pu} \xrightarrow{n} {}^{241}_{94}\text{Pu} \xrightarrow{\beta^-} {}^{241}_{95}\text{Am}$$

$$\xrightarrow{n} {}^{242}_{95}\text{Am} \xrightarrow{\beta^-} {}^{242}_{96}\text{Cm} \xrightarrow{\alpha} {}^{238}_{94}\text{Pu} \xrightarrow{n} {}^{239}_{94}\text{Pu}$$

If one link falls out of the conversion chain an insur-



mountable obstacle for the reactor method appears. This pitfall occurs when a nucleus lives only a short time in this chain or splits completely in an undesirable manner, like spontaneous fission.

Birth by explosion. A way out of the deadlock was found by chance. The unknown heavy isotopes of plutonium-244 and 246 were isolated from radioactive debris after the explosion of an American thermonuclear device in 1952, a piece of evidence of immence importance for scientists.

The thermonuclear fuel of deuterium-tritium mixture burns at extremely high temperatures, at a hundred million degrees, and within a tiny time interval of one millionth of a second. Within such a short time interval, the uranium envelope of the bomb received a flux of neutrons many times exceeding that in a nuclear reactor.

In such conditions a nucleus of uranium-238 immediately captures six to eight neutrons, after which uranium isotopes ${}^{244}_{92}U$ and ${}^{246}_{92}U$ undergo beta decay and produce neptunium nuclei ${}^{244}_{93}Np$ and ${}^{246}_{93}Np$. These nuclei are also β^-radioactive, and their decay leads to the formation of plutonium isotopes ${}^{244}_{94}Pu$ and ${}^{246}_{94}Pu$ found in the debris of the explosion.

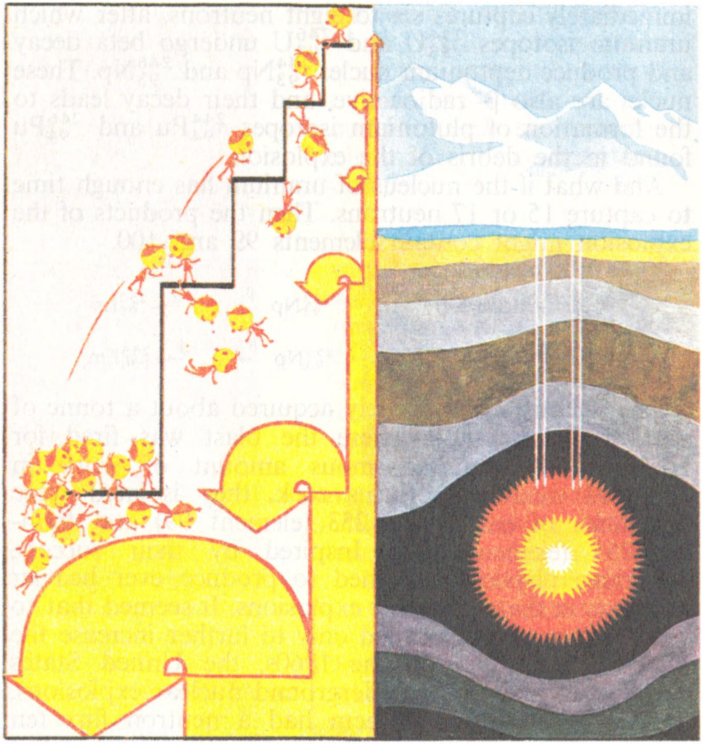
And what if the nucleus of uranium has enough time to capture 15 or 17 neutrons. Then the products of the explosion might contain elements 99 and 100.

$$ {}^{238}_{92}U + 15{}^{1}_{0}n \rightarrow {}^{253}_{92}U \xrightarrow{\beta^-} {}^{253}_{93}Np \xrightarrow{\beta^-} \ldots \xrightarrow{\beta^-} {}^{253}_{99}Es $$

$$ {}^{238}_{92}U + 17{}^{1}_{0}n \rightarrow {}^{255}_{92}U \xrightarrow{\beta^-} {}^{255}_{93}Np \xrightarrow{\beta^-} \ldots \xrightarrow{\beta^-} {}^{255}_{100}Fm $$

The scientists immediately acquired about a tonne of coral from the atoll where the blast was fired for analysis. After an enormous amount of work in chemical treatment of this rock, they isolated trace quantities of einsteinium-253 (element 99) and fermium-255 (element 100). Inspired by their success, American physicists planned to produce ever heavier elements in thermonuclear explosions. It seemed that to reach the goal they needed only to further increase the fluxes of neutrons. In the 1960s, the United States carried out a series of underground nuclear explosions. The most powerful of them had a neutron flux ten times as high as the flux in the first explosion. But thorough analysis of the products recovered from the cavity where nuclear flame raged failed to reveal any new elements with an atomic number higher than 100.

Why have thermonuclear explosions failed to give birth to an element from the second hundred? It is beyond doubt that a "leap" over a few tens of transmutation steps, which a nucleus makes when it captures a large number of neutrons in a negligible time, carries it over numerous obstacles barring the



The production of transuranium elements by pulse irradiation by neutrons in an underground nuclear explosion. Common to the reactor method, the proportion of the initial nuclei drastically decreases here in each new link of the transformation chain

transmutations of the nucleus in a reactor. A decrease in the total number of transmutations attenuates the fatal action of the chess law and increases the number of nuclei produced. Nevertheless, a "leap" should follow a long chain of beta decays. One of the first links in this chain leading to the formation of transfermium elements turns out to be broken. This link was cut by another powerful type of radioactive decay – spontaneous fission which reigns in the country of heavy nuclei.

Thus the hopes of scientists to reach the realm of heavier elements by advancing along the neutron-deficient shore of the Instability Sea (nuclear reactors) or by leaping from the uranium summit far into the Instability Sea and swimming up to the shore (thermonuclear explosions) failed to materialize. The possibilities of the neutron method for synthesis of new elements, first employed by Fermi, were exhausted at element 100, named fermium. This way may give birth to transfermium elements only in extraterrestrial conditions, similar to those which took place in the original synthesis of elements in the universe. For example, such processes may be encountered in the explosions of supernovae or deep in recently discovered unusual stars, pulsars, which are the remnants of such explosions.

Transuranium Elements

The eight elements that completed the first hundred of the periodic table were discovered by American scientists. Seven of them were identified by a group led by the greatest radiochemist G.I. Seaborg. Today the physical and chemical properties of certain transuranium elements are known even better than for some "aborigens" of the table. This fact is explained by the immence importance of the synthetic elements for current science and technology.

The atom at work. What has the synthesis of transuranium elements given to man? The scientific significance of these discoveries will be discussed later. It is a good thing to recover nuclear dinosaurs, record their behaviour and describe it in textbooks. But scientists did not stop at that. They succeeded in taming the dinosaur, making it work for people, and learning how to use its enormous nuclear power.

Modern nuclear reactors are fuelled by uranium-235. This isotope is hard to find in nature: uranium ore contains only 0.7%, the balance being ^{238}U which is not rated as fissile fuel. If mankind burns ^{235}U at the rate it currently does all the available uranium would be gone in one century. Obviously the fuel situation for nuclear reactors may become critical.

Here the valuable properties of plutonium-239 come to bear. This fissile element turned out to be an even better nuclear fuel than uranium-235. It only remained to devise such a means of converting fissionable nuclides of uranium-238 into fissile plutonium-239 that the reactor produced more novel fuel ($^{239}_{94}Pu$) than it burned igniting fuel ($^{235}_{92}U$). Such a process would enable nuclear fuel to be increased and stored for further use.

The basic type of reactors used is unsuitable for this purpose. These reactors are normally referred to as thermal reactors because they operate with thermal neutrons with an average speed of about 2000 m/s. On the average, a ^{235}U nucleus absorbing a thermal neutron produces a little more than two neutrons. One of them is needed to sustain the chain reaction. A proportion of neutrons is absorbed in the construction materials of the reactor while the remaining neutrons are available for production of plutonium-239 from uranium-238

$$^{1}_{0}n + ^{238}_{92}U \rightarrow ^{239}_{92}U \xrightarrow{\beta^-} ^{239}_{93}Np \xrightarrow{\beta^-} ^{239}_{94}Pu$$

For thermal reactors, the balance is less than unity. Therefore, when the initial uranium mix burns up it produces less plutonium than uranium-235 burned.

To solve the problem of the extended reproduction, or breeding, of nuclear fuel A. I. Leipunsky of the Ukrainian Academy of Sciences suggested using reactors with fast neutrons. The velocity of fast neutrons exceeds 10 km/s. Such reactors cannot operate on the natural mix of uranium isotopes, they should be charged with either enriched uranium-235, or plutonium-239. The advantage of these reactors, however, is that now 1.6 neutrons on the average are available for plutonium breeding.

If a fast reactor, also called a breeder reactor, is charged with uranium-238, then 1 kg of burnt nuclear fuel will produce in addition to a large amount of thermal energy, which can be transformed into electric power, 1.6 kg of plutonium-239. The principle of chain reaction can be extended in nuclear power stations so that each station will produce nuclear fuel for new stations, an increase in the number of power plants will bring about still further increase in the quantity of fuel produced, and so forth. The major implication is that plutonium, element 94, will be the principal material for future power engineering.

The field of applying the isotopes of plutonium and other synthetic elements is so extensively wide that to describe it we would need a few such books as this one. We confine ourselves to saying that artificial elements are employed now in space, deep under water, in remote places on the Earth, and in the man's chest to power the heart beats of the ill heart. These elements are the basis for powerful industries and power engineering in many countries. In a short period of time (only about 20 years) the production of synthetic elements has grown from thousandth fractions of a microgram to kilogram and even tonne quantities. The production is growing in response to ever wider use of man-made elements. Let us return to the principal theme of our narration. What scientific discoveries made while studying the properties of synthetic elements have enriched chemistry and physics, and improved our understanding of the periodic system?

What is the principle of the 7th period? All new elements were isolated and identified by chemical means. The researchers first evaluated the various chemical properties of a new element, and then compared them with the respective properties of the element's neighbours in the periodic table and with the properties of the lighter analogue, a member of the same group in the table. The evaluation as we can see is largely based on the periodic system.

At the time that uranium was the heaviest known element, chemists used to classify thorium, protactinium and uranium in group IV, V, and VI of the periodic system, respectively. However, the first transuranium elements already puzzled the chemists. Neptunium and plutonium according to their properties were similar to uranium rather than the elements of groups VII and VIII, rhenium, osmium and iridium. The interpretation of this fact was suggested by the periodic system itself. Similar to how the 6th period lanthanum is followed by 14 lanthanoid elements, the same column of the 7th period actinium should be followed by as numerous family of actinides. Indeed the subsequent transuranium elements turned out to be like their analogs in the group of lanthanides. After this refinement the periodic system was again able to reliably predict the chemical properties of elements yet to be discovered.

Nuclear instability and the boundary of the periodic table. The radioactive properties of transuranium elements also turned out to be very interesting. In nuclei with so great a number of nucleons, even the nuclear forces of attraction (the strongest of all forces known in nature) can hardly counteract the enormous repulsive forces between protons which tend to split the nucleus. Therefore the greater the atomic number of a nucleus, the shorter its half-life, the faster it disintegrates. For example, the nucleus of plutonium-244 lives about 100 million years, the nucleus of californium-250 lives already about 10 years, whereas the nucleus of fermium-252 lives only 20 hours.

The causes of such a catastrophic drop in the half-life of transuranium elements appeared to be alpha decay and spontaneous fission. The heavier the isotope, the greater the role played by the second cause, so that the stability of the elements of the second hundred is virtually completely decided by spontaneous fission.

It is an easy matter to extrapolate the tendency of reducing half-life into the area of nuclei of as yet unknown elements. We can readily see that the isotopes of elements 102 and 104 might live only minutes and microseconds, and the nuclei of element 110 and still heavier elements will have half-lives as negligible as 10^{-15} s. This is not enough time even to form an electron shell around the nucleus. Consequently, there is no point to speak of chemical elements.

It became clear that the question of where the boundary of the periodic system will be placed will be answered by nuclear physicists. It seemed that the boundary was within easy reach, but it was not easy to

Modern Periodic System

Period	Group																	
	Ia	IIa	IIIb	IVb	Vb	VIb	VIIb	VIIIb			Ib	IIb	IIIa	IVa	Va	VIa	VIIa	VIIIa
1	H 1																	He 2
2	Li 3	Be 4											B 5	C 6	N 7	O 8	F 9	Ne 10
3	Na 11	Mg 12											Al 13	Si 14	P 15	S 16	Cl 17	Ar 18
4	K 19	Ca 20	Sc 21	Ti 22	V 23	Cr 24	Mn 25	Fe 26	Co 27	Ni 28	Cu 29	Zn 30	Ga 31	Ge 32	As 33	Se 34	Br 35	Kr 36
5	Rb 37	Sr 38	Y 39	Zr 40	Nb 41	Mo 42	Tc 43	Ru 44	Rh 45	Pd 46	Ag 47	Cd 48	In 49	Sn 50	Sb 51	Te 52	I 53	Xe 54
6	Cs 55	Ba 56	57–71	Hf 72	Ta 73	W 74	Re 75	Os 76	Ir 77	Pt 78	Au 79	Hg 80	Tl 81	Pb 82	Bi 83	Po 84	At 85	Rn 86
7	Fr 87	Ra 88	89–103	Ku 104	Ns 105	106	107	108	109	110	111	112	113	114	115	116	117	118
8	119	120	121–															

Lanthanides	La 57	Ce 58	Pr 59	Nd 60	Pm 61	Sm 62	Eu 63	Gd 64	Tb 65	Dy 66	Ho 67	Er 68	Tm 69	Yb 70	Lu 71
Actinides	Ac 89	Th 90	Pa 91	U 92	Np 93	Pu 94	Am 95	Cm 96	Bk 97	Cf 98	Es 99	Fm 100	Md 101	Jl 102	Rf 103
Superactinides	121	122	123	124	125	126									

Modern Periodic System of Chemical Elements take these last steps. The neutron method – so helpful in the synthesis of all the transuranium elements – proved incapable of producing elements from the second hundred.

Heavy Ions

An idea on how to get around this next obstacle on the way to even heavier elements was not only in the air at the time but also was tested in experiments when creating certain transuranium elements. It is rather obvious that by making two medium nuclei merge into one compound nucleus we obtain an element with the charge equal to the sum of the charges of the component nuclei, that is, we are able to vault into the cell of the desired element of the periodic table.

Light artillery. The first steps in this direction were probing and uncertain. Powerful repulsive forces interact, however, between two similarly charged nuclei, therefore they can only merge provided that they are brought so close to each other that their surfaces touch. The state of contact corresponds to a very small internuclear distance, about 10^{-12} cm. Substitute this figure in the denominator of the Coulomb expression $F = kZ_1Z_2/r^2$ to see that a huge electrostatic repulsive force opposes the integration. Consequently, for a nucleus to overcome this force, or the Coulomb barrier as physicists call it, it should be accelerated so that its kinetic energy exceeded the potential energy of the electric repulsion.

In the 1940s and 50s physicists only possessed small power accelerating units capable of accelerating only the simplest nuclei, such as protons, ${}^{1}_{1}H$, deuterons ${}^{2}_{1}H$, and helium nuclei or alpha particles, ${}^{4}_{2}He$, to small

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energies. Therefore physicists often recur to the combined method of synthesis. They first prepared the nuclei of the heaviest known element in a reactor to make them a target which was then bombarded with deuterons or α-particles. As a result, they produced an element with an atomic number exceeding that of the nuclei in the target by one or two units. One needed no longer to wait for years until new elements could be accumulated in sufficient quantities in a reactor. This approach was employed to synthesize elements 94, 96, 97 and 98. Of course it cannot be used to obtain sizeable quantities of the new elements, but at first the amounts produced were enough to study the radioactive and chemical properties of the new elements.

Mendelevium. The last element synthesized by means of "light artillery" was element 101. Experimenters used all their skill and ingenuity to give birth to this nuclear child. The target was a thin, invisible to the naked eye, layer of nuclei of einsteinium-253 (in the total numbering only about one billion atoms) which was deposited on a thin (thinner than the human hair) gold foil. At the accelerator in Berkeley, California, this foil was bombarded with α-particles. The atoms of element 101 were produced through the following scheme

$$^{4}_{2}He + {}^{253}_{99}Es \rightarrow {}^{256}_{101}Md + {}^{1}_{0}n$$

An alpha particle running at a speed of 50 000 km/s knocked a nucleus of einsteinium out of the target, combined with it and the new nucleus then settled on the second foil of gold which was placed behind the first.

From this second foil chemists collected only 17 atoms of element 101. The negligible amount of this substance cannot be seen in the best resolving microscopes, nor could it be weighed in the most accurate balance. Yet the authors of the discovery – American scientists Seaborg, Ghiorso, Harvey, Choppin, and Thompson – managed to identify certain radioactive and chemical properties of the new element.

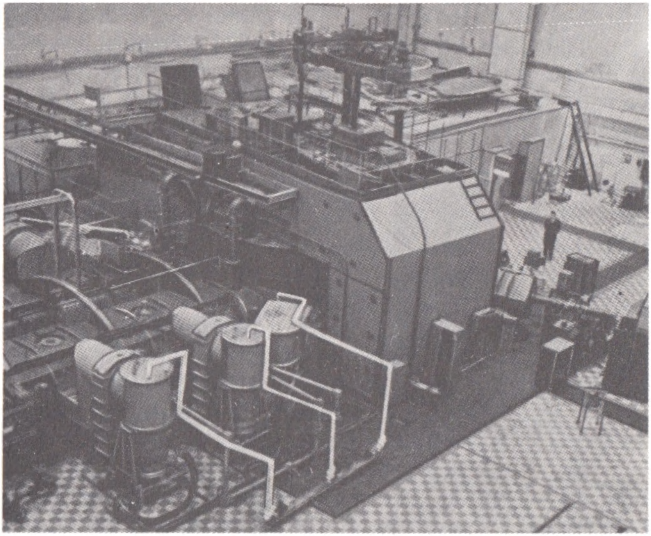
This element was called mendelevium after the great Russian chemist Dmitri Mendeleev. This discovery became a precious memorial to the brilliant creator of the periodic system which already more than a century serves as a reliable compass in search for and synthesis of new elements.

Mendelevium is outstanding not only in that it opens the second hundred of elements of the periodic system. Its synthesis is one of the culminating points in the transuranium epic because here the old methods that served faithfully in the synthesis of nine transuranium elements exhausted themselves completely. It became obvious that these small steps which added to the target-nucleus small nuclei of hydrogen or helium and thereby advancing it one or two squares of the periodic table, would not push the frontier very far. Ever heavier elements can be produced in reactors in increasingly smaller quantities, and to yield elements that have atomic numbers higher than 100 to make targets of them is altogether impossible.

New, powerful facilities capable of accelerating nuclei of various elements or, as physicists use to say, capable of producing beams of heavy ions were needed to perform long leaps to a desired cell of the periodic table. Scientists were to turn a new leaf in the absorbing book of creating new elements and to lay down the fundamentals of a promising new direction in nuclear physics – the physics of heavy ions. It took the physicists almost eleven years to get through the invisible barrier between element 101 and element 102.

The Czar-cannon of Dubna. Preparation for synthesizing transuranium elements by this new method, which employed accelerated nuclei of carbon, nitrogen, and neon in place of neutron fluxes, began almost simultaneously in the USA and in the USSR. In the Soviet Union it was initiated by the outstanding physicist I. V. Kurchatov. In order that the studies in this field be carried out at the highest possible level, a special cyclotron – then the most powerful accelerator of heavy ions – was con-

To be absorbed by the target-nucleus, the shell-particle should overcome the Coulomb barrier. The heavier the ion and the higher the mountain where the nuclear fortress is placed, the more powerful should be the accelerating cannon. This method of penetrating into a fortress is not new – in his time it was used by baron Münchhausen, the hero of the famous fantastic stories by R. Raspe



The 310-cm cyclotron of the Laboratory of Nuclear Reactions at the Joint Institute for Nuclear Research in Dubna

structed in 1961 at the International Research Centre of Socialist Countries in Dubna, near Moscow. For fifteen years this accelerator at the Laboratory of Nuclear Reactions of the Joint Institute for Nuclear Research in Dubna had been the record-holder in the principal performance characteristics. This cyclotron produced the most intense beams of heavy ions. The power of oxygen, neon, and argon ion beams exceeded a hundred times those achieved by the best American accelerators. The Dubna cyclotron was second to none also in the menu of the accelerated ions.

The cyclotron is a huge piece of equipment installed in a room comparable in dimensions with the hall of the Bolshoi Theater. The diameter of the pole pieces of the magnet is 310 cm and its weight is 2200 tonnes. All other units and details of the cyclotron are similar in size to the magnet's. Its multi-tonne winding carries a current of 2000 A. The power of an rf generator feeding the cyclotron is 500 kW. The electric potential difference between the dees, high frequency electrodes, is 260 kV.

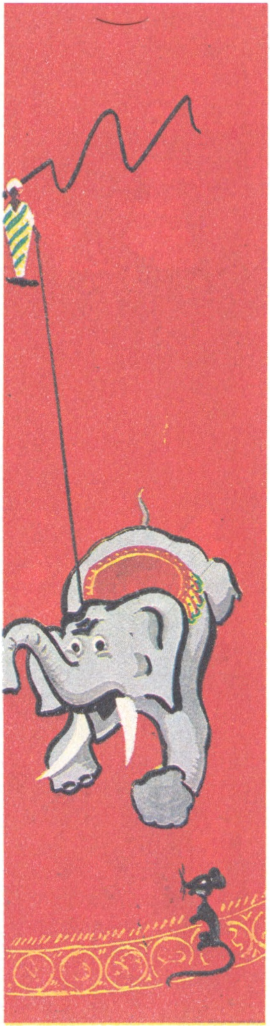
These unique characteristics can be traced to the specificity of the accelerated particles. The operation of a cyclotron is often compared with a circus arena around which runs a horse guided by an animal-trainer standing at the arena's centre. This analogy is also suitable for a heavy ion accelerator but with an elephant in place of the horse. Of course, the barrier around the arena (magnetic field) needed to keep the elephant within the arena should be much stronger than for a horse and the dimensions of the arena should be more impressive. For a thicker-skin elephant a stronger whip is required – a whiping up electric field. It is well known that elephants panic when there are mice at their feet. About the same relation can be observed for the heavy ions in the accelerator with the light ions of residual gas which is always present in the accelerator's chamber. Each encounter of these species causes the elephant to leave the arena. In order to eliminate such encounters the accelerator must be pumped out to a space vacuum.

We have already pointed out that the shell-nucleus may merge with the target-nucleus if its kinetic energy exceeds the magnitude of the Coulomb barrier, proportional to the nuclear charges. For example, the Coulomb barrier for the alpha particle is only one fifth of the barrier for neon ($Z = 10$). Consequently, the heavier the ion, the higher the energy to which it should be accelerated.

In a cyclotron, charged particles (ions) are accelerated by an electric field in the gap between the dees in multiple crossing where each time they gain a small amount of energy. The electric field is indifferent to neutral atoms of elements which we are going to accelerate. Therefore the atoms should be stripped of some electrons to be converted into charged ions. Ions heavier than helium are used to call heavy ions. It is important that the ions are multiple-charged, devoid of more than one or two electrons, because the more the charge of an ion the greater will be the energy gain it receives in the accelerating gap.

The heart of the accelerator is the heavy ions source placed in the centre of the cyclotron. Its prototype was already designed in the 1950s at the Institute of Atomic Energy in Moscow by a team of physicists headed by

Evocative comparison of accelerators of electrons and protons



L. A. Artsimovich. Since then the design of the source underwent multiple improvements although its major principles remained the same. A tube filled with neutral atoms has a powerful electric discharge burning between the electrodes. The electrons of the discharge collide with atoms and ionize them. To reach a multiple ionization large fluxes of electrons in the arc are required, the arc should develop great electric powers. In the Dubna source the limit is reached by releasing 50 kW of power in a pencil sized volume. A stronger plasma hurricane cannot be confined even by the most heat resistant of available materials.

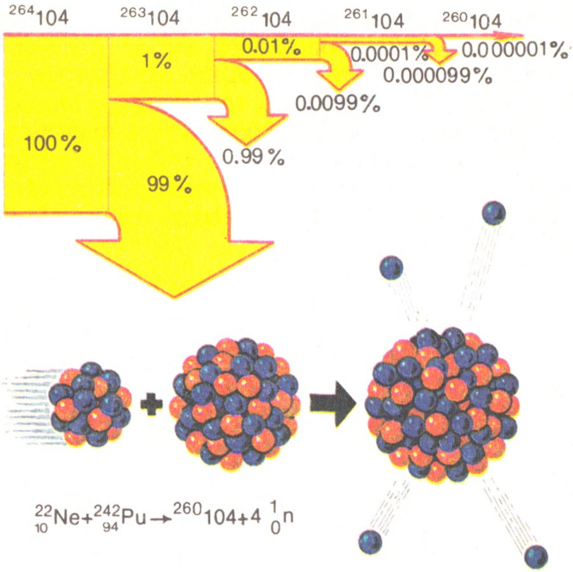
From this sophisticated device ions begin their path toward the target. This path is not very short – a few hundreds of meters. Even the most insignificant disturbance on this path may cause the loss of the ion.

This is an analogue of a heavy ion cyclotron

Collisions with the atoms of residual gas are especially dangerous. The only possible protection against these collisions is to trace the route of the ion through a deep vacuum. It is not an easy task to match all the units of a cyclotron so that powerful ion beams rush onto the target. The operation of the ion ejector, rf generator, vacuum pumps, magnet current regulators must all be compatible and accurately matched in spite of the giant size of the cyclotron.

A nucleus plus a nucleus. Physicists received a powerful tool for their experimentation. Next they learned how to use it most efficiently. What would happen when a nucleus dashing at an extremely high speed collides with a target nucleus? Scientists embarked on the study of one more mystery of nature. The process of a heavy ion colliding with a nucleus turned out to be far more intricate than all the previously studied nuclear reactions induced by a simple particle colliding with a nucleus. This phenomenon has exhibited so many various facets that its study is still going on. But one major thing excited the experimenters' expectations – heavy ions could be used for the synthesis of new element. A considerable proportion of all collisions led to the complete integration of the two nuclei. In the nuclear drop thus formed the number of protons equaled the sum of the atomic numbers of the shell and the target. Therefore it was fairly possible to take a long leap into a cell of an unknown element in the periodic table.

However, the path to the mysteries of nature is never all roses, especially when synthesizing new elements. The chess problem here again relentlessly collected its price. In merging the kinetic energy of the shell becomes the heat energy of the nuclear drop. It heats the drop so highly that it starts boiling. In common boiling the drop would cool down. Here the cooldown occurs in two ways:



The production of a new element by the capture of a heavy ion by a target-nucleus. The major proportion of the formed nuclei dies out because of fission. The arrows indicate the proportion of nuclei fissioned at each stage of emitting a neutron. Only a negligible fraction of the original number of nuclei survives in the competition with fission

either by "boiling off" neutrons, or by a process in which the surface of the drop deforms, begins oscillating, and finally the drop splits into two lighter fragments. Splitting is hundred times more probable than emitting a neutron. A new element will form provided that the hot nucleonic drop successively emits a few neutrons and remains unsplit. The heat energy turns out to be so great that to completely cool down the compound nucleus must "evaporate" as many as four or five neutrons. Introduce into the chess problem the condition that the number of grains diminishes hundred times when transferred to the next square and you realize that the formation of the nucleus of a new element is an extremely rare event – only one nucleus of the million being formed manages to survive in tough competition with the fission process.

Everything was ready for experimenting with synthesis, but the experimental difficulties were beyond comparison with anything encountered so far.

Kurchatovium

The way to the goal was open. However, to reach this goal experimenters had to demonstrate still higher skill and ingenuity than did the discoverers of the previous element, mendelevium. Among thousands of millions of radioactive fragment nuclei they had to identify the countable atoms of the furthest transuranium element, and to complete the search in a short time since the nuclei of the heavy element fission in fractions of a second. The search is compounded by the fact that the major nuclear reaction is parallelled by a few side reactions in which the shell-nucleus imparts to the target-nucleus only a part of its nucleons. The side reactions result in transuranium elements with lower atomic numbers. It is not an easy task to separate their nuclear radiation from the particles emitted by unknown atoms.

Physicists call this situation the background problem. To solve this problem one needs to identify a parameter of the sought atom which would sharply distinguish it from its background.

The importance of this fact will be obvious from the following example. Try to collect all the people on the globe in one place and find a person in the crowd with a birth-mark on the left cheek in a few seconds. This would be a formidable, if not insurmountable, problem, even for Sherlock Holmes. On the other hand, nothing could be simpler than to notice a single giraffe in the crowd.

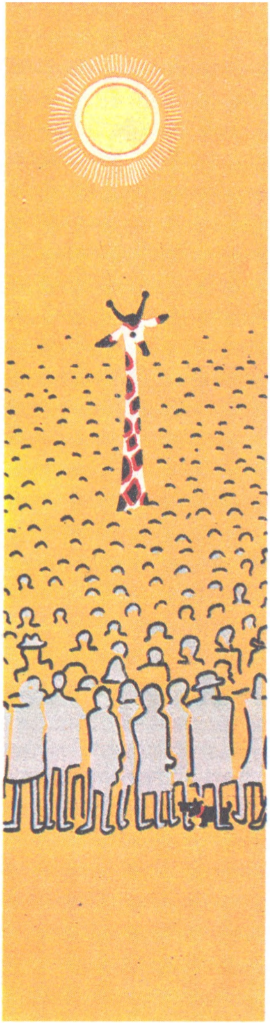
In such severe conditions (small number of nuclei and short half-life) the upper hand in the discovery of new elements was obtained from the chemical methods to the physical means. Scientists sought for new nuclei with unknown radioactive properties. Since the main types of decay for such heavy nuclei were alpha decay and spontaneous fission, all the experiments were targetted to measure the characteristics of there decays. This is where the record data of the Dubna "czar-cannon" had to say their word. Thanks to the unique performance parameters of their cyclotron the physical team of Dubna was the first to synthesize, over a decade, four new elements – 102, 103, 104, and 105. The history of the discovery of each of these elements is so absorbing that it merits a separate story. Each of the discoveries required the development of an original, sophisticated setup that embodied the original physical ideas. However there are other books on the subject and here we shall confine ourselves to a detailed discussion of the discovery of element 104. In many respects this element turned out to be the decisive point in the history of the synthesis of the transuranium elements.

Element 104 was produced in 1964 by the reaction:

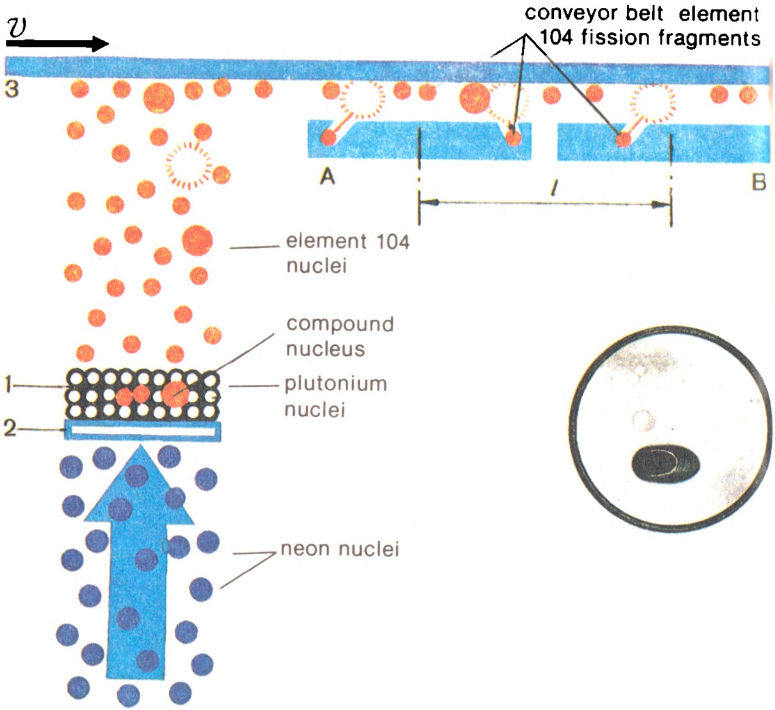
$$^{22}_{10}\mathrm{Ne} + {}^{242}_{94}\mathrm{Pu} \rightarrow {}^{260}104 + 4^{1}_{0}\mathrm{n}$$

This was the first transuranium element identified by recording the spontaneous fission of its nuclei. Spontaneous fission possesses a number of valuable advantages over alpha decay. The energy and mass of the fragment nuclei are much higher than those of the α-particles, therefore registration of the fragments is much more reliable. The background problem can be alleviated in this case much easier too, because the majority of the reaction by-products suffer alpha decay. That is why the recording of spontaneous fission is the dominant method of evaluation of the heavier elements.

The figure at p. 49 shows the idea of the experiment addressed the production and recording of the nuclei of element 104. The target is bombarded by a beam of fast neon nuclei. Having passed through the supporting aluminium foil, the neon beam penetrates into the layer of plutonium. Here the shell-nucleus and the target-nucleus merge into a compound nucleus. Only one in 10 thousand million of these compound nuclei becomes an atom of a new element, the other nuclei disintegrate into fragments. The momentum given by the neon nucleus brings the compound nucleus onto a moving nickel



Example of a correct solution of the background problem



The experimental arrangement to produce element 104. The insert shows the photograph of a track made in the glass by a fragment of the spontaneous fission of element 104

conveyor belt. Now the nuclei of new element move with the belt. A nucleus of element 104 will split, but not immediately – it takes some time until fission occurs. This time interval is enough for the conveyor to bring the atoms to the two arrays of detectors. The nuclei of the new element are splitting on the belt, therefore the far array of detectors will record a lesser number of new nuclei than the near array has done.

Assume that the near array of detectors has recorded 40 and the far array 20 fragments. Given the speed of the belt is v, and the distance between the detecting arrays is l, then the nuclei travel between the arrays the time $t = l/v$. If the far array detected half the number of fragments detected at the first array, it implies that half the nuclei has fissioned in time t, consequently t is the half-life. The distance l and speed v can be altered at will. Given these values and detector indications, the experimenters compute the half-life of a new element.

Very strict requirements are imposed on the detectors recording the radioactive decay. They should be sensitive only to the fission fragments and absolutely insensitive to other particles. Strange as it might seem, rather common materials such as glass, mica, and some others, possess such wonderful properties. Fission fragments entering, say, glass bore narrow channels in it. The diameter of the track of a fragment is equal to a chain of a few dozen atoms. These tiny tracks are impossible to detect even in the most powerful optical microscope. An electron microscope could discern them but it would take years to count the tracks. Here chemistry gave a helping hand. Glass dissolves in hydrofluoric acid. If a glass plate bombarded by fission fragments is immersed in a solution of hydrofluoric acid, the places where the fragments penetrated will dissolve faster and reveal small craters. Their size is hundred times greater than that produced initially by the fragments. Now the craters can be observed in a microscope with weak magnification. Other radioactive irradiations impart to the glass surface only insignificant defects and cannot be evaluated after etching.

And so after several years of strenuous efforts, in 1964 the physicists detected the traces of a long-expected

G. N. Flerov for the first time enters the name kurchatovium into the periodic table at a session of the Scientific Council of the Joint Institute for Nuclear Research in Dubna

isotope of element 104 with a mass of 260. One spontaneous fission of the new nucleus was recorded in 6 hours of operation of the most powerful cyclotron in the world.

To produce a new element is not the hardest work of all, however. It is far more difficult to prove that the new element has indeed been obtained. Dozens of control experiments, each of which is nowhere easier than the principal experiment, are run to repeat the result being obtained over and over again until a fully clarified and sufficiently dependable data is reached.

All the experiments took more than 1000 hours. On the total about 150 nuclei of element 104 were recorded. The half-life of isotope $^{260}104$ turned out to be only 0.1 s. Five years later the same reaction was used to produce another, but lighter isotope $^{259}104$ which occurs on the emission of five neutrons by a compound nucleus $^{264}104$. The half-life of this isotope was found to be 4.5 s.

Soviet physicists suggested element 104 to be named kurchatovium after Igor Kurchatov, an outstanding Soviet physicist and manager of large atomic projects*.

Superfast chemistry. Let us cast a glance at the periodic table. The last of actinides should be element 103. Indeed, up to element 101 the chemical properties of all transuranium elements were found to be very similar. Modern chemistry developed new materials and compounds of artificial elements which are widely used in nuclear technology and engineering. The materials and chemical compounds of each actinide, however, do not exhibit novel original, mechanical, optical, and electrical properties because of the chemical similarity of the elements. Qualitatively new chemical properties are to be expected from the elements of atomic numbers higher than 103, the first of which is kurchatovium. Therefore it was important for chemists to give answer to one of the key questions of modern chemistry asking whether or not kurchatovium is an homologue of hafnium.

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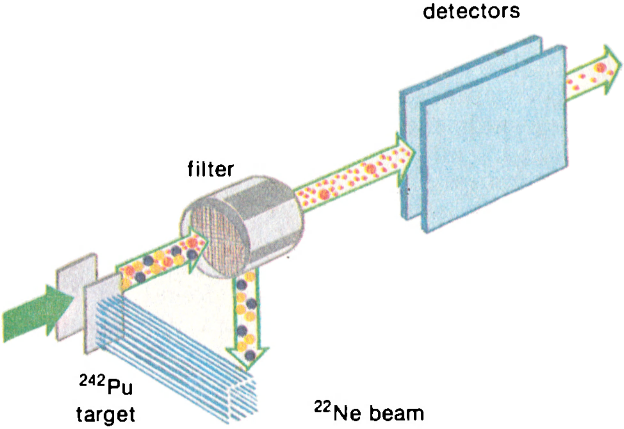
* There exist alternative claims from American physicists who suggested the following names for the elements: 102 nobelium (No), 103 lawrencium (Lr), 104 rutherfordium (Rf), and 105 hafnium (Ha).– *Translator's note.*



The idea of the experiment for studying the chemical properties of element 104. The green arrow indicates the gas stream consisting of a mix of hafnium chloride, $HfCl_4$. This stream decelerates the atoms of kurchatovium, chlorinates them and transports to the detectors. The yellow and blue dots represent actinides, the red dots represent kurchatovium atoms

How can a chemical experiment be carried out on element 104 – conduct a reaction, obtain a compound – if chemists have only a few atoms at their disposal and these atoms split in fractions of a second. The scientists were at a loss of suitable methods for solving such an intricate problem. Moreover, the basic concepts of chemistry were inapplicable to single atoms as was the case here. We must recall that the chemical properties of various substances used to be determined as the statistical properties of a large ensemble constituted by at least billions of billions of atoms.

A new and extremely fast method of determining the chemical properties of the countable atoms has been developed by a team of chemists at Dubna leaded by I. Zvara, a young scientist in those days and now Corresponding Member of the Czechoslovakian Academy of Sciences. On the way to the discovery, they had to reconsider the usual, century-old conceptual basis. Speaking about the chemist, one imagines a man operating with retorts, mixers, and test tubes. Actually, in the studies of the previous elements chemists dealt with solutions of compounds. A simple remixing of a solution takes at least a second. Therefore, performing a chemical experiment in fractions of a second was out of the question. The situation looks different for gaseous compounds. Gases mix rapidly, can be easily and rapidly transported via tubes, chemical reactions in gases proceed at a high rate, and the products may be separated in fractions of a second by filtering.

Chemists already knew for a long time that hafnium forms volatile compounds, say hafnium tetrachloride $HfCl_4$, while lanthanides fail to produce volatile compounds. Consequently, eka-hafnium should exhibit a higher tendency toward producing volatile compounds than all the known transuranium elements.

This trend is intimately connected with the chemical nature, that is, with the basic chemical properties of an element. Group III elements (lantanides and actinides) have their valent electrons placed in such a way that in a molecule of a compound with this element all atoms are aligned in one plane. Therefore when this substance condenses it builds up an ionic lattice and forms an involatile compound. Both hafnium and kurchatovium are elements of group IV and their molecules have nonplanar structure. In a molecule, a kurchatovium atom is as if immersed in an envelope of other atoms. Such molecules only weakly interact and such a compound will be volatile. Naturally, the higher the valency, the denser the atom of the new element is surrounded in a molecule. Consequently, the compounds of the succeeding new elements should also be volatile, therefore the new chemical method held great promise for future work.

In 1965 the researchers began experimenting with the setup operating on the new principles of gas radiochemistry. The experimental arrangement for the evaluation of the chemical properties of kurchatovium is illustrated in the figure. The recoil atoms, products of the nuclear reaction, once knocked out of the target, enter a stream of nitrogen to decelerate and then undergo chlorination. The gas stream will not only transfer the chlorides of the new element but also the chlorides of the actinides produced as a result of side nuclear reactions. Therefore the stream is channeled through a filter which easily retains all the nonvolatile actinide compounds. If kurchatovium belonged to the actinide series it would be detained by the filter. The study has indicated, however, that kurchatovium chlorides easily passed through the filter and were deposited exactly where $HfCl_4$ molecules were sedimented in the previous experimental runs.

Similar to physical experiments, the detection of kurchatovium is a very rare occasion. In a few hours of the accelerator busy operating only one decay may be detected. The setup operates as a chemical dredge which streams and filters out waste rock to separate rare precious grains.

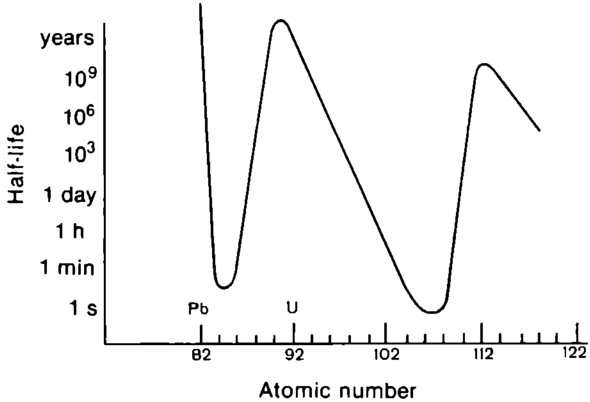
Later this setup was used to indicate that elements 102 and 103, discovered by physicists, belong to the actinide series, whereas element 105 is a homologue of tantalum. This was an outstanding success of the chemistry of individual short-lived atoms. Chemists not only confirmed the results of the previous physical experiments, but the experiments with elements 104 and 105 provided another proof of the validity of the periodic law. Now we may safely prognoze the chemical properties of the nearest, yet undiscovered elements.

What is the Superelement?

The sceptical reader may ask: "Of course, in principle it is important to study the properties of element 104. But who needs an element that fissions in a tenth of a second? Moreover, no one knows how it could be accumulated in sufficient quantities to study its properties in detail." It seemed at first that the studies of transuranium elements entered a calm but shallow course. Indeed, in the 1950s the discoveries of new elements increased like a vigorous stream – not a year without a new element. But now only four elements in almost twenty years.

Scientific problems, though, can be very enduring. The investigations seemed to have been performed on every possible aspect and there only remained a few steps to the finish, but all of a sudden new, unexpected depths appeared before the researchers.

The mystery of kurchatovium. One tenth of a second. Is it short or long? The question should not be put in this way, it should be augmented by a second question – compared with what? Well then, the experimental value of the half-life for kurchatovium-260 turned out to be tens of thousand times the theoretical value obtained under an assumption that on coming over to nuclei with 104 protons nothing new would occur and the lifetime of the nuclei decreases in just the same manner as it happened with the previous elements. The nuclei of kurchatovium turned out to be more stable than had been expected from the theoretical models that existed in the early 60s. Does this mean that beginning with element 104 the



The half-life of the most stable isotopes as a function of atomic number

catastrophic decline of half-life will decelerate as nuclei will increase in the number of protons? What will happen in the domain of still heavier elements?

Let us take a closer look at the periodic table. Thallium (element 81) and immediately following lead and bismuth possess isotopes with such a large half-life that it cannot be practically measured since the decay proceeds so slowly. But bismuth is followed by polonium, astatine, radon, francium... All nuclei from polonium to actinium decay into daughter nuclei in a very short time. Conversely the half-lives of the most stable isotopes of uranium and thorium–elements with higher atomic numbers–equal 4.5 and 14 thousand million years and are comparable in age with our planet. Neptunium, plutonium, americium, and curium are less radioactive than polonium or radium, although have considerably higher atomic numbers.

Thus the lifetime of the elements decreases nonregularly as the atomic number increases. The function experiences a decline beyond bismuth, then upgrade in the area of thorium to uranium, then a new drop behind uranium. The last decline continues up to element 102 and flattens out near kurchatovium. Does a new rise of half-life exist?

Magic nuclei. In early 1930 when nuclear physics was still in its infancy, a very strange regularity was noted: atomic nuclei containing a definite number of protons or neutrons (2, 8, 20, 50, 82, 126) differed from their neighbours by increased stability. In those days physicists did not understand the causes of such stability and jokingly nicknamed these figures magic numbers. Later, nuclei with magic numbers of protons and/or neutrons also received this name. It was only in 1948 that Maria Goeppert Mayer and Hans Jensen interpreted the existence of magic numbers. Similar to atomic electrons, nucleons form shells in nuclei. These shells are filled in succession as the number of particles in the nucleus increases. Similar to how in the periodic system the most stable are inert gases, the nuclei are most stable when their neutron and proton shells are completely filled. It is to these closed shells that the aforementioned magic numbers of protons and neutrons correspond. Hence, periodicity in properties is inherent not only in atoms but also in nuclei as well. A periodic system for nuclei, however, is by far a more complex venture – one needs to systematize the properties of a few thousand isotopes. There is no consistent periodic system of nuclei in existence so far, which would exactly describe and predict the properties of all isotopes as the periodic system of chemical elements does.

Coordinates of the Stability Island. Theoretical physicists faced a very formidable problem. They not only had to predict the values of the next magic nuclei, but also had to compute the properties of the magic nuclei. It was at the time when the nature of forces cementing the neutrons and protons in the nucleus was not clearly known. Even if everything was known about the nuclear forces, it would not have been easy to find a solution for a system consisting of a few hundreds of particles. An example may be the electron shells of heavy atoms. Although all the forces acting on the electrons are known, the equations defining their behaviour are so complicated that one has to confine oneself to an approximate solution which fails to give a detailed description of motion for these electrons. Only in recent years has the techniques of solution of the three-body problem been developed. But in our case the particles are hundred times more in number.

Theoreticians had to deviate from the rigirous solution of the problem to the way used a century ago by Mendeleev. In his days even the atomic structure was unknown. However, upon an attentive analysis of nonregular, at first sight, behaviour of all the then known elements he drew upon the common rules that show themselves in the periodic table. In the nuclear environment, analysis of the characteristics of the studied nuclei, especially transuranium nuclei, also proved to be helpful. It is well that the international efforts of physicists increased the number of isotopes produced in the transuranium range to more than one hundred. Scientists carefully examined how nuclear shells are filled and how this process reflects in diverse properties of nuclei. General regularities were detected. As a result, in 1966 V. M. Strutinsky, a Soviet theoretician, suggested a computational technique for the nuclear shell which fits rather well the periodic variations in the properties of known nuclei. It remained to expand the regularities found onto the realm of unknown nuclei. The computations ran by physicists of many countries in the following decade on the then most powerful computers defined the coordinates of the new Island of Stability and plotted its map. It was found that the next magic numbers were 114 for protons and 184 for neutrons. The isotopes placed close to the double-magic nucleus $^{298}_{114}X$, immediately below lead-208, should possess an increased stability and be long-livers. It is here that one can expect new rise of half-life for far elements.

The hypothetical elements with a number of protons close to 114 and a number of neutrons about 184 were called superelements, while the corresponding domain of atomic numbers was called the new domain of relative stability. Why relative? Because the supernuclei are generally unstable.

New types of decay which decide the lifetime of supernuclei are spontaneous fission and alpha decay. They divide the Stability Island into two regions. The north-western region is where alpha decay reins, while the south-eastern region belongs to spontaneous fission. Doubly magic nucleus $^{298}_{114}X$ possesses the highest stability with respect to spontaneous fission. But the half-life with respect to alpha decay decreases rapidly for all nuclei with an increase in the atomic number. The competition between the two decays for the spheres of influence leads to a situation where the longest-lived "subject" of the island is isotope $^{294}110$. Theoreticians predict it will have a half-life of one hundred and even one thousand million years.

The slopes of the island are almost sheer. If the number of neutrons or protons of the longest-lived nucleus $^{294}110$ is changed by 2 or 3 units, that is by only one per cent, the half-life will shorten ten million times. This effect is observed for the well known nuclei as well. For example, very high stability is found for the twice magic nucleus of lead, made up of 82 protons and 126 neutrons. But if the number of neutrons rise by one, the new isotope of lead having 127 neutrons will decay in only 3.3 hours. On the other hand, the nuclei of neighbouring lead-208 are so stable that no one has yet succeeded in detecting their decay. One has only to depart one step away from magic number 126 as the nucleus has lost its stability.

For all that, the area of the island is rather large. For the nuclei of half-life above 1 minute, the area of supernuclei will make a square between the proton parallels of 106 and 116 and the neutron meridians of 174 and 192.

What is to be done? Before we set out on a long and hard journey to the Stability Island it will be worth examining how accurate we know its whereabouts. All computations available without exclusion give one and the same result – the island of relative Stability does exist. This is a great achievement of theory, but so far it cannot give an absolutely exact answer to the question which of the supernuclei will be most stable and what will be its half-life? When we mentioned that a $^{294}110$ nucleus had a half-life of 100 million years we implied its most probable lifetime. Actually this period may be a factor of million higher or lower and the longest-lived may turn out to be one of elements from 108 to 126. This uncertainty can be easily interpreted. So long as no general theory of nuclear phenomena exists, each step away from the domain of known nuclei contains a possibility of error which increases away into terra incognita.

In such a situation the decisive word remained to be said by experimenters. As a knight in a Russian fairy-tail, they faced three possible routes. The left route led to the search of superelements in nature, i.e., in the galaxy, in the solar system and on the Earth. The direct route was the continuation of the old, traditional way of research – to synthesize ever more heavier elements in spite of increasing experimental difficulties. On the right was the leap over the "forbidden" zone of atomic numbers 102-107. The experimenters in Dubna decided to follow all the three paths.

A Shallow at the Stability Island

The way to the Stability Island demanded intense work. Both the leap over the domain of unstable nuclei and the sequential synthesis of elements have very much in common and will merge in perspective in a matter of time. They are united in one principal thing: to study the properties of a new element it should be created. This can be achieved by an accelerator of heavy ions, for as we have seen in the example of transfermium elements all the other means of artificial synthesis had totally exhausted their potentialities.

The leap to the Stability Island. The first to attempt a landing on the Stability Island were "paratroopers" which began their operation as soon as physicists came into possession of the landing craft – accelerators capable of producing ion beams of element 18, argon-40. Recall that the atomic number of the heaviest possible target is limited ($Z < 98$), therefore one can only move farther ahead by increasing the charge of the shell-nucleus.

In the mid-60s only physicists in Dubna and Berkeley, California, possessed accelerated ions of argon. However, after a few years the British, French, and West-German physicists joined the club. From the very beginning the studies on artificial synthesis of superelements became an international venture.

The first "landing" on the Stability Island was attempted in 1967 by American researchers who bombarded a target of curium-248 ($Z = 96$) with argon ions:

$$^{40}_{18}Ar + ^{248}_{96}Cm \rightarrow ^{288}114$$

No traces of supernuclei were found in this experiment. But the failure was not surprising. Any combined pair of a shell and a target will produce a neutron-deficient, that is unstable, supernucleus. This is because light stable nuclei have a lower ratio of the number of neutrons to the number of protons than heavy nuclei. When a nucleus of curium combines with a nucleus of argon it produces a compound nucleus of element 114 having only 174 neutrons. Observing that this nucleus is to boil off four neutrons, the resultant nucleus will be 14 neutrons below a magic number. Therefore the first landing occurred in the Sea of Instability, far west of the island and "sank" having failed to get ashore.

As a way out of the situation, American theoreticians V. Swietecki and J. R. Nix suggested that the landing "troops" should "overshoot" north-east of the island. The supernucleus produced would be unstable and after a series of alpha decays may reach the stability domain. Thus "troops" landing in the sea of Instability, will swim up to the Stability Island from north-east. Computations indicated that the most appropriate reaction for the synthesis of superelements would be by bombarding a thorium target ($Z = 90$) with germanium ions ($Z = 32$)

$$^{76}_{32}Ge + ^{232}_{90}Th \rightarrow ^{304}122 + 4^{1}_{0}n$$

$$\xrightarrow{\alpha} ^{300}120 \xrightarrow{\alpha} ^{296}118 \xrightarrow{\alpha} ^{292}116 \xrightarrow{\alpha} ^{288}114$$

However, a meticulous experimental check performed in Dubna in 1973 did not confirm the predictions of these theoreticians, the reaction failed to produce superelements. In spite of the negative result attempts in synthesizing supernuclei continued. The landing campaign lasted about a decade. Here are the coordinates of other landings

$^{65}_{29}Cu + ^{238}_{92}U \rightarrow {}^{303}121$ (Great Britain, West Germany)

$^{59}_{27}Co + ^{238}_{92}U \rightarrow {}^{297}119$ (Great Britain)

$^{60}_{28}Ni + ^{238}_{92}U \rightarrow {}^{298}120$ (Great Britain)

$^{76}_{32}Ge + ^{238}_{92}U \rightarrow {}^{314}124$ (Dubna, USSR)

$^{68}_{30}Zn + ^{243}_{95}Am \rightarrow {}^{311}125$ (Dubna, USSR)

$^{84}_{36}Kr + ^{232}_{90}Th \rightarrow {}^{316}126$ (France)

$^{84}_{36}Kr + ^{238}_{92}U \rightarrow {}^{322}128$ (France)

$^{84}_{36}Kr + ^{208}_{82}Pb \rightarrow {}^{292}118$ (France, West Germany)

None of these experiments revealed a trace of the elusive superelements. What happened with the expeditionary force?

As early as the 1960s, when the method of heavy ion bombardment came into wide use, it was established that the lighter the shell-particle bombarding target-nuclei, the more probable is the production of a new element. Indeed, a neutron is always completely absorbed by a target-nucleus, whereas in bombardment with heavy ions an ever greater part is played by the processes with only a part of the nucleons being captured by the target nucleus, the ever smaller proportion of collisions leading to coalescence of nuclei. It was concluded that colliding ions heavier than argon with a nucleus cannot produce a compound nucleus altogether.

It appeared that superelements are a thing in themselves. They do exist but cannot be obtained by either of the available means.

Creation through destruction. There was one more method of obtaining new nuclei. The fission of the compound nuclei being produced interfered with each synthesis of the transuranium elements. How about using this fission for our purpose? The neutron fluxes of fissioning uranium were known to produce the elements 43 (technetium) and 61 (promethium) in the reactor core that exist only in negligible quantities in nature. One kilogram of uranium-235 fission fragments is sided by about 7 grams of technetium.

In 1967 scientists at Dubna suggested that the nuclei of superelements should be sought among the fission fragments of giant nuclei produced by the bombardment of a uranium target with accelerated nuclei of uranium

$$^{238}_{92}U + ^{238}_{92}U \rightarrow ^{476}184 \rightarrow ^{166}_{70}Yb + ^{298}114 + 12^{1}_{0}n$$

In the early days of the first accelerators of heavy ions physicists could only dream about such experiments. Indeed, to accelerate these ions one needs to strip the uranium atom of about 20 electrons, but this task was beyond the capabilities of ion sources of that time.

In 1966, in an adjacent room of the Nuclear Reactions Laboratory the famous 310-cm cyclotron (U-300) got a smaller sister, a 200-cm unit (U-200). Physicists began to scratch their heads and ask could the multiple stage principle of rocket boosters used in space technology to enhance rocket power be exploited in cyclotrons? First the more powerful stage, U-300, will boost the ions and then the second stage, U-200, will continue the acceleration. Estimates indicated that the "range" of the tandem units would be considerably improved. This tandem-unit could produce ion beams of element 54, xenon-136.

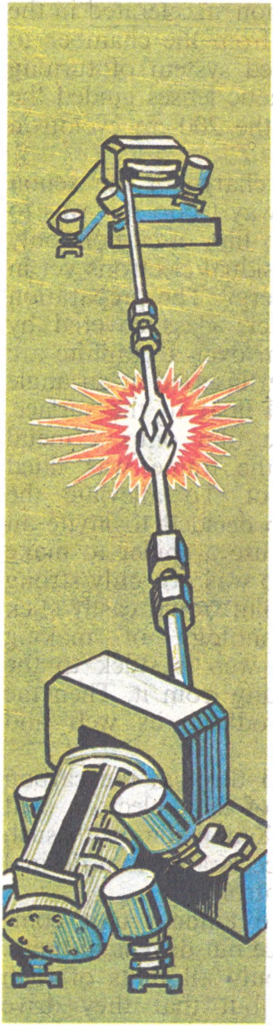
This very sophisticated technical program was conducted in 1971 by a large team headed by I.A.

Shelayev. Nine-charged ions of xenon, accelerated in the 300-cm cyclotron, were launched from the chamber to an ion guide where a sophisticated system of turning and correcting magnets and magnetic lenses guided the ions through a deep vacuum to the 200-cm cyclotron located 70 m from the first.

At the entrance to U-200 the charge of the xenon ions needed to be increased. One way to do this was to pass the beam through a very thin film of carbon, only 0.2 μm thick, to rob the ions of residual electrons yet in a way that the ions retain their energy. The preparation of such a film is a simple matter: glass covered by special grease is placed in vacuum over a graphite arc to deposite a layer of carbon, then inserted at an angle in water and the carbon film will float to the surface. However, all attempts to fix the film onto a metal rectangular frame failed – when the frame was lifted from the water the film fell out. To alleviate the problem a mechanic V. M. Plotko decided to invite an unusual assistant. He decided to use a spider to make a web as a reinforcement. The web was not only strong but also sticky material, and the film would easily stick to it, he decided. The technology of making a framework is rather simple: a web is stuck to the frame so that the spider would hang from it. Then the frame is rotated, the spider produces its web and a sticky net is ready.

When the ions of xenon passed through the carbon film they were robbed of a part of their electron coat and became thirty-charged ions. Xenon ions with such a large charge could be readily accelerated to a desired energy even by the 200-cm cyclotron.

The difficulties of aligning the tandem unit compounded the problem not just twice but dozens of times. Now it was required that not only all units of each cyclotron operated consistently, but that they drive



the whole system into synchronism. Even with the most precise adjustment, not all the ions could travel the long path to the target. The intensity of the xenon beam in the tandem system is decreased hundred times compared with that in the 300-cm unit. And still the first experiments with unique xenon beam may begin.

Nuclear dumb-bells. It was important to understand what happens when such massive particles as uranium and xenon collide. It was found that the two nuclei fail to merge into a spherical compound nucleus. Instead the nuclear drops stick together for only a short time forming a dumb-shell-like nuclear droplet revolving at high speed. Large centrifugal forces cause this unusual giant nucleus to split into two parts. Although the dumb-bell nucleus lives only a negligible time (about 10^{-21} s) it is enough for several dozen nucleons to migrate from one part into the other. The nuclei formed upon splitting are very hot and therefore boil off neutrons or fission in much the same manner as usual spherical compound nuclei do.

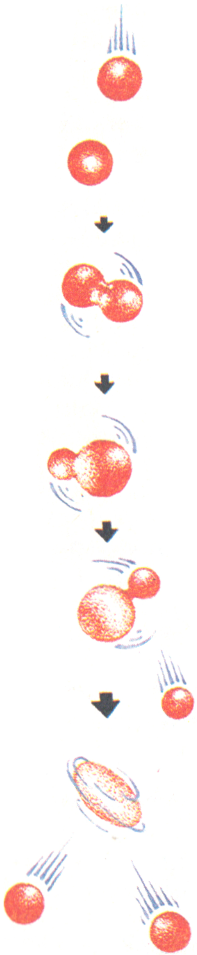
Experiments with xenon ions showed that the fission of dumb-bell nuclei can be employed to synthesize superelements. As a result of splitting giant nuclei hundreds of isotopes of diverse elements appear, including the heavy elements. If fusion may be compared with the shelling of the Stability Island by ordinary shells, each of which hits only one point, the method of fission may be compared with shrapnel bombardment when a shell bursts in the air into fragments covering a large area.

Already the first experiments had revealed the production of neutron rich nuclei of heavy transuranium elements which earlier had occurred only in thermonuclear explosions. An experimental finding was especially important for the synthesis of superelements: the heavier the ion colliding with the uranium nucleus, the heavier nuclei appear among the fission fragments. The bombardment of uranium with xenon could produce the following superelement

$$^{136}_{54}Xe + ^{238}_{92}U \rightarrow ^{374}146 \rightarrow ^{298}114 + ^{72}_{32}Ge + 4^{1}_{0}n$$

However, the intensity of the xenon beams accelerated in the tandem cyclotron was too small to identify and study superelements. It became clear that the synthesis of supernuclei by fission required new, more powerful accelerators capable of producing high intensity ion beams of all elements of the periodic system, including uranium. Feverish construction of these accelerators began in various laboratories throughout the world. In 1974, in Berkeley, at the University of California, the Super-HILAC went into operation; HILAC stands for a heavy-ion linear accelerator. In 1975 West-German physicists built the Unilac in Darmstadt. Construction works on the national heavy ion accelerators were under way in Caen, France, Darsbery in Great Britain, and Oak Ridge in the USA. At present the most intense beams of uranium ions are produced at the Unilac which is a tandem linear accelerator 113 m long. This accelerator enabled a record-sensitivity search for superelements in the fission products of dumb-bell nuclei.

For half a decade the attention of the West-German physicists was focused on the interaction of uranium nuclei. They collected and painstakingly analysed all the fission fragments of nuclear dumbbells. Most frequently the giant nucleus fissioned into two equal uranium nuclei. Light and heavy fragments were a less frequent occasion. The more asymmetric fragments are produced the more probable that such a fission will occur. Physicists succeeded in collecting all light fragments



The formation and fission of the dumb-bell nucleus including the nuclei of itterbium ($Z = 70$) that were conjugated with the nuclei of element 114. But the yield of heavy fragments of dumb-bell nuclei sharply decreased with an increase in their atomic number Z as compared with the yield of the conjugated light fragments. Much effort was expended to find negligible quantities of element 102, whereas the superelements vanished into thin air.

This surprising and disappointing result was interpreted later by a theory developed by V. Nörrenberg, a West-German theoretician. Almost all the kinetic energy of the uranium nucleus is spent to heat the fragment nuclei. This energy not only exceeds the energy of a light ion, say neon (recall the expression for the Coulomb barrier) by a factor of ten, but unfortunately almost all of it is concentrated in the heavy fragment. To make things worse, during partition of the dumb-bell the fragments retain their rapid spinning. Huge centrifugal forces tear the overheated, violently spinning (at a rate of 10^{20} rpm) fragment-nucleus into two fragments. Consequently, the heavy and even more so the superheavy, overheated rapidly spinning nuclei undergo fission rather than cool down by boiling off a few neutrons. Again fission succeeded in barring the way.

Sequential synthesis. This direction also was not without its own difficulties. Physicists were well aware that the investigation of nuclei with 106 and 107 protons would be an important step toward the superelements. The closer to the Stability Island the more distinct its contours become. However, we bumped into a new obstacle. If we bombarded, as before, ever heavier targets of plutonium ($Z = 94$), americium ($Z = 95$), curium ($Z = 96$) and berkelium ($Z = 97$) with neon ions ($Z = 10$), then the fraction of nuclei surviving the competition with fission would drastically decrease with the atomic number of the synthesized element. Therefore either the sensitivity of the experimental techniques should be materially improved or a new way should be found to the heavier elements.

In 1973, Yu. Oganesyan suggested ordinary lead to be used in place of heavy radioactive targets. The suggestion was not without good reason. We have already mentioned that magic nuclei possess improved stability because their nucleons are especially strongly bound. The most densely packed of all are the double magic nuclei of lead, having both the proton ($Z = 82$) and the neutron ($N = 126$) numbers magic. If an ion would be absorbed by a lead nucleus the excess energy of the ion will be spent into a loose packing of the compound nucleus so only a small residual amount of energy will go into heating. Such a reaction will produce "cold" compound nuclei. In contrast to "hot" nuclei, the "cold" cool down by "evaporating" 1 or 2 protons, rather than 4 or 5 as earlier.

Let us return to the chess problem. In our case, when a nucleus emits one neutron – and shifts by one square the number of nuclei surviving in the competition with fission decreases to one hundredth of the initial nuclei, and on a second square there remains 0.01 per cent of the initial nuclei, and so on, so that on a fourth square there will be only 0.000001 per cent of the initial number. In the magic method, a nucleus emits two or three neutrons less than in the ordinary method, which is equivalent to a ten thousand and million times gain in terms of the number of atoms of a new element being formed.

Because the start is at the 82nd square of the periodic table, the synthesis of elements of the second hundred by the magic method must use "long-range artillery" capable of accelerating ions heavier than argon ($Z = 18$). However, the failed landing expedition for superelements precluded the use of these ions. Therefore, at first it was decided to find the range for the new method by bombarding a lead target with titanium ions (Ti + Pb, 22 + 82 = 104). It was not by chance that the reaction was chosen to result in element 104. It was ten years since the discovery of the first isotope of kurchatovium, but the question about its unusual properties was still unanswered.

The expectations came true – the ranging revealed all the advantages of the magic method. The experiments succeeded in discovering three new isotopes of kurchatovium at one time. Although the number of accelerated ions of titanium was a factor of hundreds less than the ions of neon, the identification of the properties of each isotope required only a few dozen hours of the U-300 cyclotron's operation. Compare this figure with the duration of the first experiments in which element 104 was synthesized – over ten thousand hours.

Six years after the Dubna experiments with the magic method, similar experiments were launched on the Unilac accelerator in West Germany. To record the nuclei being produced the West-German physicists built a unique giant mass spectrometer (to be described later). This device was used to advantage to confirm the high efficiency of the new synthetic method and the properties of the kurchatovium isotopes discovered in Dubna.

Our old friend kurchatovium. Another finding of these experiments had no lesser significance – an answer to the mystery of kurchatovium was found. The investigation of the new isotopes proved that the unusual properties of the first isotope, kurchatovitum-260, were not a random deviation. Now the jump in the nuclear properties upon the transfer from atomic numbers 98, 100, and 102 to 104 was clearly evident.

After physicists in various laboratories throughout the world had evaluated the behaviour of dozens of isotopes of californium, fermium, and element 102, they noted that in addition to the major magic numbers, consistent with filled nuclear shells, "weaker" magic numbers existed that corresponded to filled subshells. The last investigated neutron subshell corresponds to 152 neutrons. All transuranium elements whose nuclei contain 152 neutrons exhibit improved stability. Therefore if we plot the half-life of nuclei controlled by spontaneous fission versus N we obtain a herringbone like curve with the apex at $N = 152$.

The last neutron subshell helped the theoreticians to more accurately predict the position of the Stability Island and the properties of supernuclei. But the same theory suggested that the isotopes of kurchatovium and still heavier nuclei might already lie within the island and feel the stabilizing effect of its principal magic number $N = 184$. The curve shows no bend – the periods of spontaneous fission gradually increase as more neutrons are added to the nucleus.

Elements 106 and 107. It was very important to take the following step. Will the next heavier nuclei exhibit the same change in properties of their nuclei as kurchatovium did? If a new regularity is discovered then the half-lives of the isotopes of elements 106 and 107 should not differ dramatically from the half-life of kurchatovium isotopes.

In the magic method the choice of the synthesis reaction is of principal importance. Not all pairs of ion + target can produce a "cool" compound nucleus sufficiently stable to give rise to nuclei of a new element. A meticulous theoretical analysis is needed which accounts for the individual likings of the interacting nuclei in order to arrive at a harmonious couple. The most direct way of producing the atoms of elements 106 and 107 appeared to be the bombardment of lead ($Z = 82$) and bismuth ($Z = 83$) with the ions of a very rare isotope of chromium of mass number 54. If instead of chromium-54 the target were bombarded by the most abundant isotope of chromium-52, then all other conditions being equal the number of atoms produced would have reduced hundred times.

In April 1974 in Dubna decay of the first atoms of element 106 produced by the reaction

$$^{54}_{24}Cr + ^{207}_{82}Pb \rightarrow ^{260}106 + ^{1}_{0}n$$

was detected. The half-life of the new isotope, decayed by spontaneous fission, was about 0.01 s. Two years later in Dubna, experiments were carried out concerning the synthesis of element 107. An isotope of the new element with mass number 261 originated in the reaction:

$$^{54}_{24}Cr + ^{209}_{83}Bi \rightarrow ^{261}107 + 2^{1}_{0}n$$

This isotope was found to live about 0.001 s and then, predominantly through alpha decay, undergo a transformation into isotope $^{257}105$. The spontaneous fission of nucleus $^{261}107$ is a very rare occasion, its half-life is 0.01 s. This is ten million times the half-life value that nucleus 107 would have had if it had not been for the increase in stability of heavy nuclei. In 1981, West-German physicists found that this reaction produced one more isotope 107 which occurred from the compound nucleus upon emitting one neutron.

Seamen know when they meet birds in the sea the ground is not far. The properties of the new isotopes of elements 104, 106 and 107 point out that the Island of Stability does exist. Figuratively speaking, physicists have already touched the sandbank of the Stability Island.

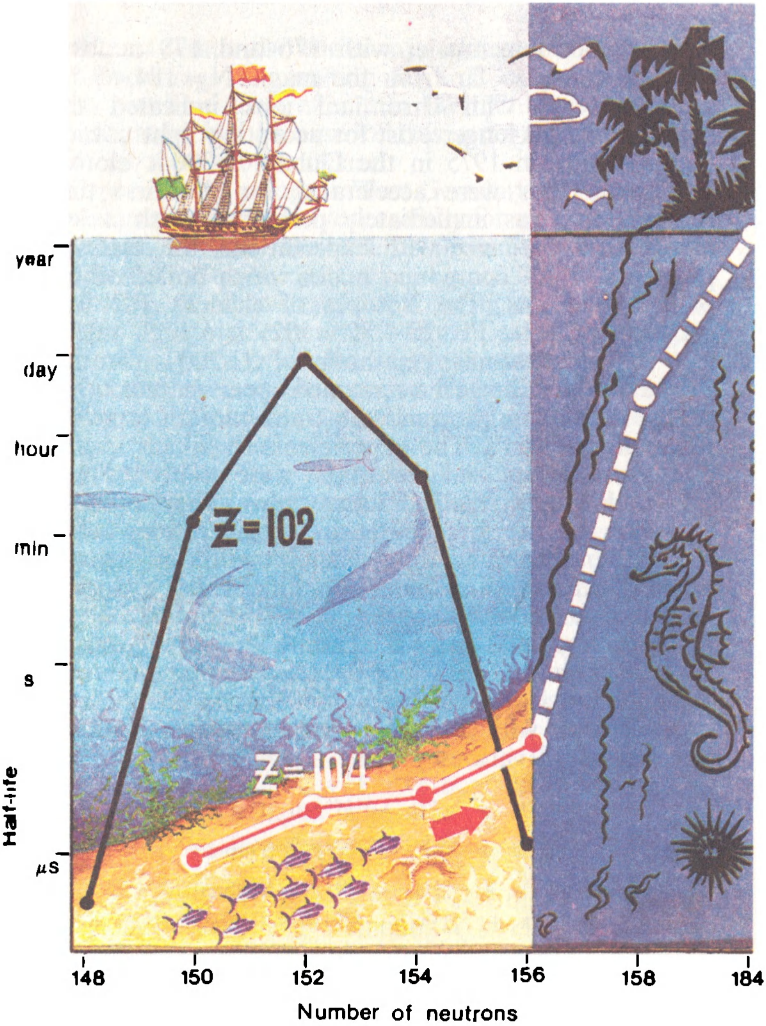
A leap with "cool" nuclei. The Dubna experiments with titanium and chromium ions were the preparation for a leap onto the Stability Island. These experiments refined and perfected the method for synthesizing superelements by merging two nuclei. They also revealed the crucial point of all the problems in artificial synthesis:

the necessity to produce "cool" nuclei. The failures with the "landing operations" and with the fission of dumb-bell nuclei can be traced primarily to the fact that those experiments produced "hot" supernuclei. And we already know that the higher the "temperature" of the nucleus the less likely it is to survive. In an exceedingly heated nuclear drop, the shell effects governing the enhanced stability of supernuclei "melt" and disappear causing immediate death of the just born superelements. However, the continuing experiments with titanium and chromium ions along the same lines could hardly lead to the Stability Island. A drawback of lead targets is that they combine with the accelerated nuclei of Ni ($Z = 28$), Zn ($Z = 30$) and Ge ($Z = 32$) to only produce exceedingly neutron-deficient supernuclei, that is, they find themselves in the Sea of Instability. Other combinations of ion-target couples had to be sought for which would produce a "cool" compound nuclei with a large number of neutrons.

Among 300 stable isotopes of various elements scientists found one extremely rare isotope of calcium-48 ($Z = 20$) which has only two atoms hidden among 10000 of its twin-sisters in the natural mix of calcium isotopes. All the whole world yield of calcium-48 collected after many years of operation of large separating facilities amounts to only a few dozen grams of this substance. The nucleus of this unique isotope is 8 neutrons heavier than the most abundant isotope of calcium-40. These additional neutrons come in handy when pushing the expedition to within close reach of the centre of the Stability Island by using exotic combinations with the heaviest transuranium targets being irradiated with the heaviest isotope of a light element. For example, the reactions

$$^{48}_{20}Ca + ^{244}_{94}Pu \rightarrow ^{290}114 + 2^{1}_{0}n$$

$$^{48}_{20}Ca + ^{248}_{96}Cm \rightarrow ^{294}116 + 2^{1}_{0}n$$



The shallow at the Stability Island evaluated by the increase of the spontaneous fission half-life of kurchatovium isotopes can produce supernuclei with 176 and 178 neutrons which are not so far from the magic $N = 184$.

Experiments with chromium ions indicated that prohibitions no longer exist for accepting light calcium ions. Already in 1975 in the Dubna U-300 cyclotron, calcium-48 ions were accelerated for the first time. A "ranging" was immediately performed with a lead target. In accordance with expectations, the reactions produced "cool" compound nuclei which boiled off one or two neutrons. The isotopes of element 102 were produced (Ca + Pb, $20 + 82 = 102$) at a high rate – a few thousand atoms per hour of U-300 operation.

The question, however, remained open whether or not "cool" nuclei would occur with transuranium targets in place of the lead's. The experiments in which ions of calcium, titanium and chromium were combined with lead and bismuth helped answer this. They provided a secure footing for theoretical considerations which showed that compounding calcium with the heaviest targets would produce "cool"supernuclei that evaporate only two neutrons.

A green light was on for the path to the Stability Island. By 1978 both in Dubna and Berkeley a large amount of experimental work had been done on the synthesis of superelements with calcium-48 ions. A new "expedition" was landed in various places:

$${}^{48}_{20}\mathrm{Ca} + {}^{232}_{90}\mathrm{Th} \rightarrow {}^{280}110 \quad \text{(Dubna)}$$

$${}^{48}_{20}\mathrm{Ca} + {}^{231}_{91}\mathrm{Pa} \rightarrow {}^{279}111 \quad \text{(Dubna)}$$

$${}^{48}_{20}\mathrm{Ca} + {}^{233}_{92}\mathrm{U} \rightarrow {}^{281}112 \quad \text{(Dubna)}$$

$${}^{48}_{20}\mathrm{Ca} + {}^{242}_{94}\mathrm{Pu} \rightarrow {}^{290}114 \quad \text{(Dubna)}$$

$${}^{48}_{20}\mathrm{Ca} + {}^{243}_{95}\mathrm{Am} \rightarrow {}^{291}115 \quad \text{(Dubna)}$$

$${}^{48}_{20}\mathrm{Ca} + {}^{246}_{96}\mathrm{Cm} \rightarrow {}^{294}116 \quad \text{(Dubna)}$$

$${}^{48}_{20}\mathrm{Ca} + {}^{248}_{96}\mathrm{Cm} \rightarrow {}^{296}116 \quad \text{(Dubna, Berkeley)}$$

But this attempt also ended in a failure. It, however, did not discourage the landing force. Conversely, it made them combine their efforts in the climb to the so far unreachable, but because of this even more attractive, peak of the Stability Island.

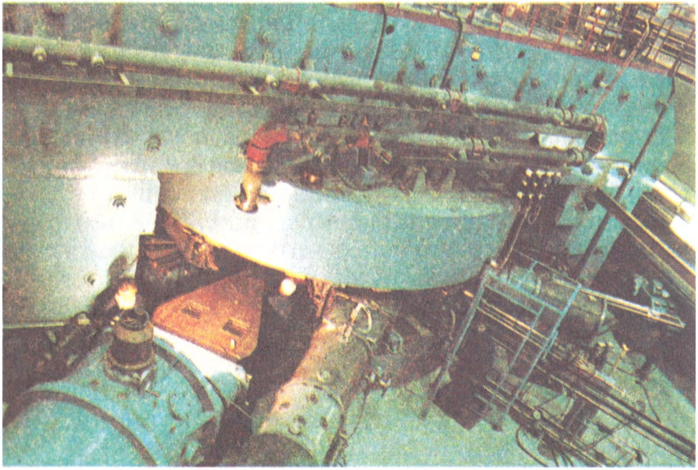
Experimental groups in West Germany and the United States prepared themselves carefully for a new attempt. It involved the best available facilities and methods of registration. The landing place was chosen at the most promising of all the evaluated combinations: ^{48}Ca + ^{248}Cm. The joint experiment terminated in 1983, again without any traces of the superelements.

Nature had one more surprise. Unfortunately this time, in contrast to the previous landing, the circle of questions closed. The method of synthesis was no longer under doubt, therefore there remained the sole question – what is the half-life of a supernuclei? The final answer to this question can only be found by experiment. So long as supernuclei are not synthesized, one may refine their properties theoretically, by evaluating the behaviour of the new isotopes of heavy elements 104-107. A group of Swedish theoreticians headed by S. G. Nielson undertook a large investigation that resulted in a new map of the Stability Island. The relief of the island changed considerably compared with the previous computations. The slopes became much steeper, and the island now looked more like a cliff with a vertical wall at the side of neutron-deficient supernuclei.

Such a relief makes the synthesis of superelements an extremely hard task because many supernuclei just occurred fall down right into the Sea of Instability. To notice individual nuclei managing to hold on to the steep slope the experimental techniques had to be improved in their sensitivity by hundreds of times. First of all this objective requires a new accelerator capable of providing very intense beams of heavy ions from elements of the first half of the periodic system.

A new cyclotron. There were progressively more talks in the Nuclear Reactions Laboratory in Dubna about how wise it would be to get a better accelerator with more intense beams... It is not an easy venture, though, to construct an accelerator which would exceed the performance data of the best analogous facilities existing in other laboratories.

In recent decades when physical setups grew in both sophistication and cost a certain style in their design has been established. Physicists take an active part in the design only at the initial stage. Then all the information is handed over to the designers and is distributed among numerous subdivisions – designers, mechanics, vacuum group, rf experts, electricians, construction engineers –



The new 400-cm cyclotron U-400

each of which solves its own problems. In time they embody what the physicists have invented, first in drawings then in metal, nuclear physics and technology were experiencing spurious development. And when the physicists at last come to possess the facility, there are new materials, novel engineering ideas, and, worst of all, similar facilities with better performance characteristics already constructed elsewhere. The team faces an unpleasant psychological challenge: to review the performance data of the facility and improve its design. However, any rearrangement causes a delay in the phasing in of the facility. And new experiments for which the setup was designed and built are delayed by many years.

Observing this, the team in Dubna, engaged in the development of a new, powerful cyclotron, adopted another track involving the whole collective, in creative process at each stage of the construction project. This approach was typical of construction projects concerning accelerators, reactors, and many other facilities developed under the leadership of Academician I. V. Kurchatov.

The decision on constructing the new U-400 accelerator was made in 1974. This event had been prepared by 20 years (!) of investigations conducted by the laboratory of accelerator physics and technology. The principal units of the future cyclotron had been manufactured and tested long before the major construction project began. The engineers had chosen principal, new solutions on the basis of the recent engineering achievements for such units as the ion source, ion beam exiting system, magnetic systems providing fields of precise configurations, and high vacuum systems. The project of U-400 developed in the laboratory focused all the achievements and experience acquired in the development, operation, and modernization of cyclotrons U-300, U-200 (half scaled prototype of U-400), and tandem unit. As a result, the U-400 cyclotron had the same weight electromagnet and drew the same current as U-300, but produced hundred times more intense accelerated beams. This cyclotron was a model for the development of such facilities in other socialist countries. In the near future, Polish scientists in co-operation with experts from Dubna, will construct the cyclotron U-200P in Warsaw.

The construction development of U-400 in Dubna was performed by the engineers and technicians of the Joint Institute for Nuclear Research. The Azovstal Metallurgical Works promptly manufactured 2000 tonnes of high quality sheet steel and Czechoslovak engineers designed and manufactured unique tools for assembling and finishing of the steel sheet stacks for the electromagnet's yoke. As a result, the first units of U-400 arrived for machining as soon as July, 1975. The erection of the accelerator was completed in August 1978 and on the eve of 1979 a beam of accelerated ions of argon was exited from the accelerator's chamber. Another benefit of the adopted approach to the project was that its construction cost reduced 3 fold.

The U-400 cyclotron was thought of as a specialized accelerator producing beams of ions of medium mass, from neon ($A = 20$) to silver ($A = 108$). At present U-400 particle beam intensity exceeds all the accelerators in the world taken together by several times. There are reasons to believe that in the years to come it will retain the honorable position of the most powerful accelerator of heavy ions. Thus the unit is capable of undertaking the most formidable problems of nuclear physics.

It is not surprising therefore that the very first experiments on the new facility were concerned with the sequential synthesis of new elements with $Z = 108$ and 109. All the years that U-400 was under construction, experiments in this direction were going on. The magic method was used to advantage in the Unilac accelerator in West Germany to produce a number of kurchatovium isotopes, and isotopes of elements 105 and 107. Finally, in 1982 there came news from Darmstadt that after ten days of continuous operation one alpha decay had been detected of element 109 produced in the reaction

$$^{56}_{26}Fe + ^{209}_{83}Bi \rightarrow ^{266}109 + ^{1}_{0}n$$

It was encouraging news, but one event, as a rule, is not enough to say anything definite about the properties of the new nucleus or about whether a new element occurred in the reaction. As experimenters usually say in these circumstances, the case calls for more statistical evidence, that is, for more events of element 109 decay.

The beam intensity of U-400 was so high that in several hours of operation the machine produced by the reaction studied earlier in U-300 as many as hundreds (!) of decays of elements 106 and 107. In 1984 in Dubna, three isotopes of element 108 were discovered simultaneously in the reactions

$$^{58}_{26}Fe + ^{208}_{82}Pb \rightarrow ^{265}108 + ^{1}_{0}n$$

$$^{58}_{26}Fe + ^{207}_{82}Pb \rightarrow ^{264}108 + ^{1}_{0}n$$

$$^{55}_{25}Mn + ^{209}_{83}Bi \rightarrow ^{263}108 + ^{1}_{0}n$$

At about the same time the decay of $^{265}108$ produced in the combination $^{58}Fe + ^{208}Pb$ was recorded in Darmstadt, too. And the experimental findings concerning element 109 turned out to be a complete surprise. The sensitivity of the Dubna experiments exceeded ten times the level achieved in Darmstadt, but the decay of element 109 in the reaction $^{58}Fe + ^{209}Bi$ was observed as occurring with far lesser probability than might have been expected from the Darmstadt findings. Again an obstacle arose in the way of sequential synthesis, which, frankly, never had been a child's play.

What is the nature of this obstacle and how can it be overcome?

An answer to these questions came from the experimental findings themselves. For the years of the development of the magic method, the Dubna and Darmstadt groups had obtained detailed information on how the elements from 100 to 109 form in a variety of ion-target combinations. Theoretical analysis of this information showed that as the mass of the ion bombarding a Pb or Bi target increases the factors which hamper the formation of cool compound nuclei increased in significance. Whereas it is sufficient to overcome the Coulomb barrier and bring the nuclei in contact to combine ions lighter than ^{40}Ar with heavy Pb, it is insufficient for more heavy ions. In order that the nuclei may combine into a compound drop, the ion should be given a bit more push, that is, it should be accelerated to an energy exceeding the Coulomb barrier. After merging, this additional energy of the push can go only toward heating the compound nucleus.

The energy of the push progressively grows from $^{40}_{18}Ar$ to $^{54}_{24}Cr$ ions, yet it remains below the energy which a loosely packed Pb nucleus, abandoning its magic status, spends for cooling. Although the yield of ever heavier elements produced after boiling off one or two neutrons from the compound nucleus diminishes in this series, their synthesis is still possible. But beginning with $^{58}_{26}Fe$ ions, the additional energy grows so fast that it is no longer possible to produce a compound nucleus by integrating heavier ions with lead or bismuth. As a result, in the synthesis of element 109 in the reaction Fe + Bi the adherents of the magic method bumped into an almost sheer wall due to this same additional push. Their hopes that one could succeed in producing element 110 in the reaction $^{64}_{28}Ni$ + $^{208}_{82}Pb$ or element 111 in the reaction $^{64}_{28}Ni$ + $^{209}_{83}Bi$ were dashed to the ground. And physicists dashed to feverishly look for a breach in the wall.

The amount of the additional energy may change drastically depending on the specific properties of interacting nuclei. This fact was suggested by the U-400 experiments in which one and the same $^{262}107$ nucleus occurred as the result of these various combinations:

$$^{54}_{24}Cr + ^{209}_{83}Bi \rightarrow ^{262}107 + ^{1}_{0}n$$

$$^{55}_{25}Mn + ^{208}_{82}Pb \rightarrow ^{262}107 + ^{1}_{0}n$$

$$^{58}_{26}Fe + ^{205}_{81}Tl \rightarrow ^{262}107 + ^{1}_{0}n$$

The yield of element 107 in the last reaction decreased by a factor of several decades. Therefore, to define the boundary of the magic method it was very important to carry out experiments on the synthesis of element 109 with different ion-target combinations. Moreover, when sufficient statistical material is collected on the decay of element 109, it will enable a more definitive proof for the new-born element observed by West-German physicists. Such experiments are currently under way in the U-400 cyclotron.

How can we penetrate into the domain of elements with $Z \geqslant 110$? It seems that the only way left is to return to the old method of synthesis but on a new basis. This return implies using heavy targets and the magic calcium-48 ion. The latter gives a certain advantage in terms of producing comparatively cool compound nuclei, while heavy targets enable the synthesis of elements 110-112 in the combinations $^{48}_{20}Ca$ + $^{232}_{90}Th$, $^{48}_{20}Ca$ + $^{231}_{91}Pa$, $^{48}_{20}Ca$ + $^{238}_{92}U$, and so on. Here the paths of the sequential synthesis and the "leap" merge already. Earlier Dubna experiments concerned with the synthesis of superelements showed that the yield of nuclei in these reactions should be very low, but the intensity of U-400 ion beams, it is hoped, is high enough to surmount this difficulty and obtain a sufficient number of atoms of elements 110-112.

The increase in beam intensity has revived the traditional method of synthesis. Isotopes of elements 107 and 108 may also be produced in the reactions

$$^{22}_{10}Ne + ^{249}_{97}Bk \rightarrow ^{267}107 + 4^{1}_{0}n$$

$$^{22}_{10}Ne + ^{249}_{98}Cf \rightarrow ^{267}108 + 4^{1}_{0}n$$

$$^{26}_{12}Mg + ^{245}_{95}Am \rightarrow ^{267}107 + 4^{1}_{0}n$$

$$^{26}_{12}Mg + ^{246}_{96}Cm \rightarrow ^{268}108 + 4^{1}_{0}n$$

In accord with the growth of the lifetime of neutron-rich nuclei discovered in the isotopes of elements 104-107, the half-life of the heavy isotopes of elements 107 and 108 and isotopes of elements 110-112 should range from fractions of a second to a few seconds. This fact hopefully will permit the study of the chemical properties of heavy elements with the express methods of the chemistry of individual atoms.

Thorough examination of a large number of isotopes with Z = 107-112 that lie on the shallow of the Stability Island will more accurately define the relief of the island and make possible the choice of a more appropriate landing place. Then it will again be possible to return to the synthesis of superelements via reactions combining calcium-48 ions with the heaviest targets. This direction in research took a time-out caused by the negative results of the previous attempts. Target material of curium (Z = 96), berkelium (Z = 97) and californium (Z = 98) is accumulating in the core of the superpowerful nuclear reactor in Dimitrovgrad. Meanwhile in Dubna engineers develop new devices capable of recording the decay of a supernucleus much faster than it could be done earlier. The intensity of the calcium-48 beams accelerated in

U-400 will improve the sensitivity of experiments hundreds of times.

Will the response time of the new detectors and the beam intensity of the new accelerator be sufficient to notice neutron-deficient supernuclei that have managed to hold on the steep slopes of the Stability Island? This question will be answered by future experiments. We hope, nevertheless, that the new powerful instrument will lead the scientists at Dubna to many new discoveries in various fields of physics as did the legendary U-300 machine.

The Ion Beam

Nature watchfully guards its secrets and all the more closely as more efforts are expended to disclose them. In nuclear physics these efforts mean new complicated and costly accelerators. It is often asked whether these costs will be offset, might it not be better to use these funds for the construction of a new factory which will manufacture many useful things. Of course the money side always should be taken into account, however one should not overlook the long-term prospects for society's development which materially depend on how the results of fundamental studies are applied in practice. The history of science has many, vivid examples of how the funds dedicated initially to purely academic problems find their way into applications of immence importance once these problems were solved.

It is not an easy matter to foretell all the consequences of the production of superelements and to answer the question of whether the Stability Island could turn into a treasure island. There are firm grounds to believe, however, that the discovery of superheavy nuclei will influence mankind at least as much as nuclear fission did. If the properties of supernuclei are predicted correctly then they may turn out to be far more powerful and compact sources of energy than uranium and plutonium. So far, of course, the uranium bird at hand looks much more attractive than two superelements in the bush.

Turning to beams of heavy ions, they found their way to many applications beyond the synthesis of new elements. Their applicational potential is now about at the same level at which laser beam technology was 15-20 years ago.

Compared with the laser beam, the effect of the ion beam on matter is substantially stronger and more effective. We have compared the heavy ion with an elephant. When the ion enters solid material it behaves as an elephant in a china shop. The result of such a visit may be catastrophic. In its path through the material the ion leaves mutilative tracks – it strips electron shells from the atoms it came across, knocks atoms out of their places in the crystal lattice or splits the nuclei of the atoms in fragments. Having expended all its energy, the ion resides at the end of the damage tunnel as a new inhabitant in the host material. Whereas a laser beam mainly heats the material, the beam of heavy ions produces several effects, primarily mechanical and thermal: being decelerated in the substance ions loose their energy and it evolves as heat. In addition, heavy ions penetrating the crystal lattice change the chemical composition of the solid.

Nuclear sieve. If accelerated heavy ions are so energetic as to make holes in thin materials why not use this effect in manufacturing ultrafine mesh filters – nuclear membranes? This idea has found wide application in the most unexpected fields of science, industry, medicine and even agriculture. Before going into a detailed discussion of this trade of heavy ions, it seems appropriate to recall the important role played in living nature by biological membranes; thin diaphragms with a large number of tiny holes. The biological cell is divided by membranes into multiple compartments each of which carries out its own activities. The transport of material and information between the compartments is also controlled by membranes. The total area of membranes in a human amounts to a few square kilometres. All of them are selective membranes which pass some molecules through and retain others.

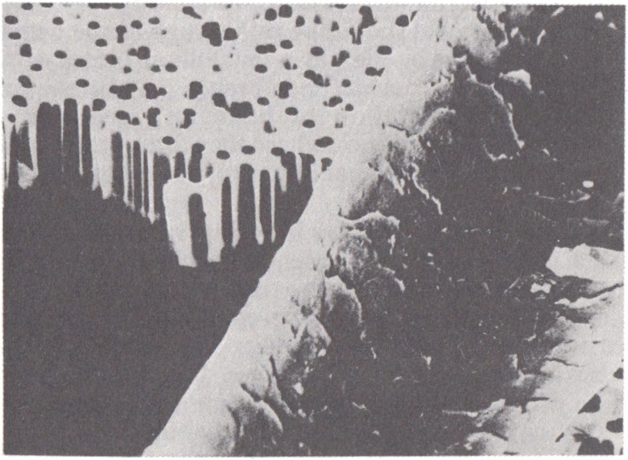
Here is a simple and well known example. Ocean and sea fish are insipid in spite spending all their lives in salty water. Membranes are capable of retaining their properties in fairly unusual conditions: bacteria have been found in hot springs that live at temperatures around 100°C. These are wonderful examples of nature that should be emulated.

One of the capacities of heavy ion accelerators is that they are able to produce thin porous films with characteristics very close to natural membranes. The underlying principle used in their manufacture is essentially the same as that utilized in the detectors recording the fragments of the spontaneous fission of new elements. The heavy ion performs the function of a microneedle, as fission fragments did in the detector glass. These films of lavsan, or fluoroplastic, and other polymers are irradiated by ions of various elements. Subsequent chemical treatment (etching) transforms the channels of radiation damage into through holes. The diameter and shape of these holes are conditioned by the type and energy of ions used, by the properties of the material being irradiated, and by etching conditions. By changing these parameters one can obtain "sieves" with strongly proportioned number of pores (up to one billion per square centimetre) of a defined size. At present in Dubna, membranes are manufactured with a pore diameter ranging from a thousandth fraction of a micrometre to a few micrometres. To imagine how small these holes are, note that the point of the thinnest needle can be no thinner than 1 μm, whereas bacteria detained by filters range in size from 0.2 to 8μm, viruses from 0.02 to 0.3 μm, and proteins from 0.004 to 0.015 μm. The unit operating with the U-300 cyclotron is able to readily produce hundreds of thousands of square metres of the unique film a year. The nuclear sieve is virtually an ideal filter. It differs from the best fibre microfilters in that its holes are round in shape and identical in size. An ordinary microfilter cannot completely filter out particles of a definite size because its mesh size covers a range of dimensions. The nuclear membrane is able to separate to a high degree of purity even those objects which are very close in size, say bacteria or viruses of different kind.

Although the filter seems to be a primitive device, its effects may be immense. The nuclear ieve is capable of retaining all particles exceeding the diameter of its pores. Hence, it may be used for fine purification of liquids and gases. The importance of this application is evident in the example of the modern electronic industry. In the manufacture of large integrated circuits accommodating ten thousands of devices on the area of a few square millimetres, the interference of the smallest extraneous body – a dust particle or a bacterium – renders the circuit useless and it has to be discarded. That is why the air in such shops and in working chambers and the fluids utilized in production – specifically the water for flushing the items – must be painstakingly purified from microparticles and microorganisms. Nuclear membranes have solved this problem favourably. Their use enables the yield of sound semiconductor items to be increased several times.

Nuclear membranes may be used in other industries and fields as well. In this time of sophisticated industries the problem of pollution control has come to a head. One example for its solution may be the application of nuclear membranes to protect operators' lungs from the detrimental impact of the polluted atmosphere. Effective respirators have been developed on the basis of nuclear membranes, which prevent dust from entering the lungs of people working in coal mines, cement manufacturing, and dusty chemical processes. Of course nuclear filters can be used as a protecting means as well as for providing special clean rooms that are devoid of all dust, microbes, and viruses. Such filters may also be used in ecological studies. Stacking a few membranes of different mesh size, one may screen the contaminants of air into fractions. In other words such nuclear sieve will analyse the type of impurities in probes from various environments.

In medicine nuclear filters are also badly needed. They are indispensable in vaccine purification. It is an easy matter to select a sieve which would separate large



Comparison of the hole size in a nuclear membrane with a human hair. (Courtesy Prof. R. Spor of Darmstadt, West Germany) impurities from a virus suspension, and a sieve which would concentrate the virus proper by detaining it while allowing small impurities like proteins to pass. Tested technological processes of purification and concentration using nuclear membranes for grippe, hydrophobia, and encephalitis viruses have made it possible to produce 10-20 times more effective vaccines against these illnesses.

Sterile medicinal materials preclude complications occurring in treatment of patients. A few methods of sterilization have been developed with nuclear membranes. First of all, the nuclear membrane is used as the most important component of apparatuses for controlling the sterility of medicines. Another technique is to employ expendable fittings which purify the drug immediately during injection. Fittings prepared from nuclear membranes are not only reliable but also rather cheap. This is an important factor in their mass manufacturing, and the yield should be rather high as the demand for such fittings is as high as a few billion pieces a year. Last but not least, nuclear membranes may be exploited for the cool sterilization of biological media in the manufacture of antibiotics, where they filter out microbes and viruses and considerably improve the quality of the drugs.

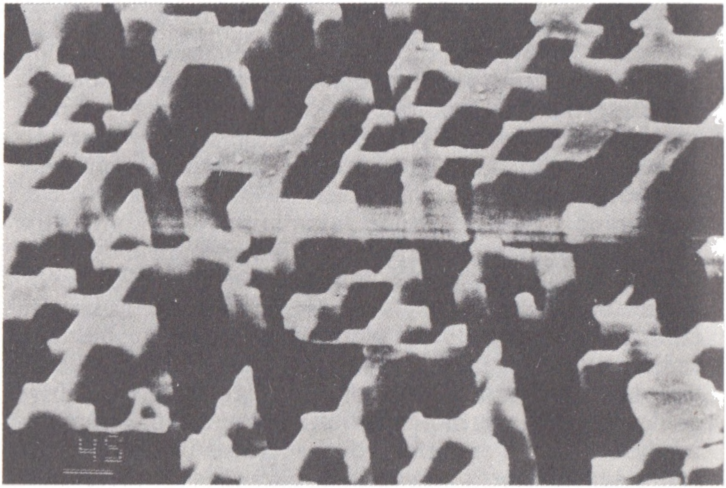
Whereas industry requires high flow-rate nuclear filters with a large number of pores, research works and fine medical analysis may call for membranes with a single hole. Such membranes may be employed to count and measure dimensions and mobility of such microscopic species as viruses, cells, and bacteria. A membrane having a hole with a size slightly smaller than the dimensions of the cell may be used to evaluate the ability of the cell to deform to squeeze through the narrow hole. This characteristic may be used to diagnose various diseases. For example, if the cardiovascular system is healthy, the red blood cells deform rather easily. A decline in the cells' deformability indicates that dangerous changes are present in the organism. Some other diseases may be diagnosed in a similar manner, for example, membranes easily separate from the blood the cells of cancer.

Another application may be found in laser technology. This field requires accurate apertures capable of cutting very thin light beams of an appropriate profile. Controlled etching of a single track in a glass plate produces an ideally round hole of the required submicrometer size. Such high precision apertures are able to improve the performance of optical, electron-optical, and ion-optical systems.

In various branches of science and technology ever wider use is made of cryogenic facilities operating at exceedingly low temperatures. To maintain such temperatures for longer time in terrestrial conditions or protect cosmonauts from cold in space, isolation is essential. Engineers normally use lamellar-vacuum thermal insulation which consists of a number of screens reflecting thermal radiation placed within an evacuated envelope. It has been learned that the nuclear sieve is capable of screening not only particulate matter and microorganisms, but also thermal waves. A nuclear membrane coated with aluminium is virtually nontransparent to radiation of a wavelength exceeding the size of the hole. For example, a screen with pores of 2 μm almost completely reflects the thermal radiation emitted by the body at ambient temperature because radiant energy at these temperatures is all transmitted at wavelengths below 5 μm. For closer and, consequently, colder layers of thermoinsulation the size of pores may be increased, as the thermal waves increase in length with lower temperatures. The use of packages of metallized nuclear membranes will considerably improve the thermal insulation of cryogenic devices and spacecraft.

Nuclear membranes is but one application of the method of nuclear tracks where the heavy ion plays the role of a "microdrill". The potentials of the ion instrument for transforming the structure of solids are much greater. In the following we consider the other applications of ion beams to intricate technological problems which have been extensively developed in recent years also in the Unilac accelerator in West Germany.

Ion tooling. Many properties of materials – wettability, cohesion, friction, electric strength, and optical properties – are decided by the structure of their surface. The method of nuclear tracks makes it possible to change the characteristics of the surface in a desired manner.



The surface of a superisolator after ion treatment. (Courtesy Prof. R. Spor)

Superfine finishing of materials by an ion "cutter" enables different technological problems to be solved.

Surface breakdown of isolators is a recurrent problem in high voltage electrical engineering. If such an isolator is submitted to irradiation by heavy ions and etched, the surface of the material becomes partitioned into a multitude of separate islands and the electric strength of the dielectric surface increases many times. The use of such "superisolators" appears to be especially promising in vacuum conditions where the surface is not contaminated by either dust or moisture.

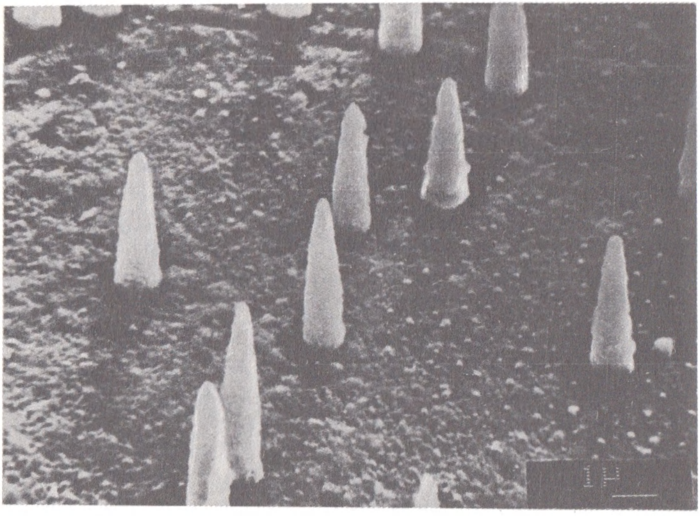
Another example of altering the properties of a material's surface is by controlling its reflectance. The reflection of light by a surface declines considerably if it is cut by an ion "cutter" so that it becomes covered by multiple microirregularities of size lower than the wavelength of light.

The surface texture may become rougher by treating it with an ion "cutter" to improve the cohesion of this material, used as a carrier, with a film of other material, say polymer, deposited on it. This effect may be applied for making permanent joints, where especially sizeable gain in the joint's strength is obtained when the surface of reinforcing material is covered by a multitude of crossing tracks.

The ion beam may be used as a precision tool in preparing special casting moulds. For example, a metal replica of the surface in which conic craters have been etched looks like a hedgehog covered by ten million extremely thin needles in each square centimetre. If a negative potential is applied to such a surface, the microneedles readily become electron emitters. Such cold cathodes are very economical and may replace ordinary thermoionic cathodes in common use.

The semiconductor industry already uses the method of implantation of heavy ions in semiconducting materials on a wide scale. A controlled ion beam is able to create a definite configuration of impurity of an element inside a semiconducting host material, while the depth of the implantation may be varied by controlling the energy of the beam. The resultant multilayered semiconductor structures may make up a large electronic circuit. This ionic architecture enables the following step to be made on the way to microminiaturization of electronic devices.

Ion implantation may be helpful in solving centuries-old technical problems. In medicine there exists the problem of biological compatibility of tissues, and industry faces the problem of physical incompatibility of various substances. No means can force iron and lead to



Electron microphotograph of the surface of a cold cathode prepared by the nuclear tracks method. (Courtesy Prof. R. Spor) form an alloy in the terrestrial environment. Intense beams of heavy ions, on the other hand, may suppress any incompatibility and drive into a host material additions of any desired elements to result in alloys of unheard-of strength, heat resistance, and chemical resistance.

The "cancer" of nuclear reactors. The capacity of heavy ions to exert strong mutilative effects on materials come handy in solving key problems of power engineering.

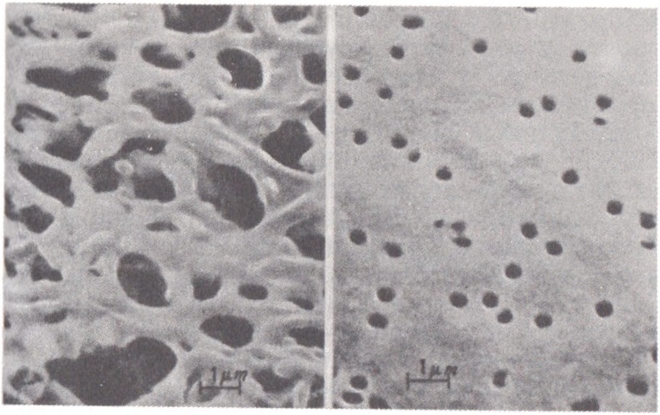
Because oil reserves and the resources of other fossil fuels are being progressively exhausted, the key role in the power engineering of the future will belong to nuclear power plants. The development of reactor engineering is hampered by the fact that materials of nuclear reactors gradually degrade as a result of permanent radiation with neutrons. Fast neutrons collide with the nuclei of construction materials and alter their structure. As a result, upon receiving a large radiation doze, the alloys are rendered brittle, lose their stability, and the construction materials loosen up and swell. The nuclear reactor gradually develops a killing process inside, comparable to cancer in a human. This "cancer" will be especially dangerous for future nuclear reactors – in future plants the fluxes of neutrons will exceed the current level by ten and hundred times.

Therefore scientists are continually searching for materials that will be immune to reactor cancer. The disease has a very complicated nature and depends on many conditions: composition of materials, their treatment, and operational temperature, to name a few. At present it seems impossible to predict the consequences of neutron radiation for different materials, therefore it remains only to model radiation damage. For an existing nuclear reactor to be utilized for this purpose would be prohibitively time consuming and difficult. The point is that in a powerful nuclear reactor, 10^{15} neutrons pass each second through an area of one square centimetre, while the damage of construction materials becomes evident only when the radiation doze exceeds the level of 10^{22} neutrons per sq. cm. Therefore tests of each specimen in a reactor would take years. The problem is compounded still more when it is concerned with the choice of optimal materials for thermonuclear plants which are expected to have not only more intense neutron fluxes, but also considerably higher neutron energy than nuclear reactors have.

Accelerated heavy ions have come to the fore as a promising new method for the simulation of radiation damage. Accelerated ions from the middle of the periodic system have turned out to be a hundred thousand and million times more efficient in solving this problem than fast neutrons. The application of these ions for this purpose implies that the process which took years in the most powerful nuclear reactors can be simulated only in a few dozen minutes with the U-400 cyclotron's beam that has an intensity of 10^{14} ions per second. The energy of these ions may be chosen at a level below the Coulomb barrier for the nuclei under study. Then the ions will not cause any nuclear conversions in the material, and unlike the reactor specimen this one will not be radioactive. The last circumstance markedly facilitates the post-radiation studies of material properties.

Heavy ion accelerators will play an important role in the selection of dependable and durable materials for nuclear and thermonuclear reactors to come.

People learned to use the wonderful properties of ion beams only recently. The most interesting directions may not be discovered yet. But it can already be stated that the use of heavy ions is able to cause revolutionary changes in technology and methods of nature research. Beams of heavy ions created for the synthesis and



A high quality cellulose filter (on the left) and a nuclear filter (right)

investigation of nuclei grow in importance in fields very far from physics. "Academic" discoveries always inflict a series of important practical applications.

Let us return to "pure" science and research which are concerned with the search for superelements in nature.

The Search for Long Livers

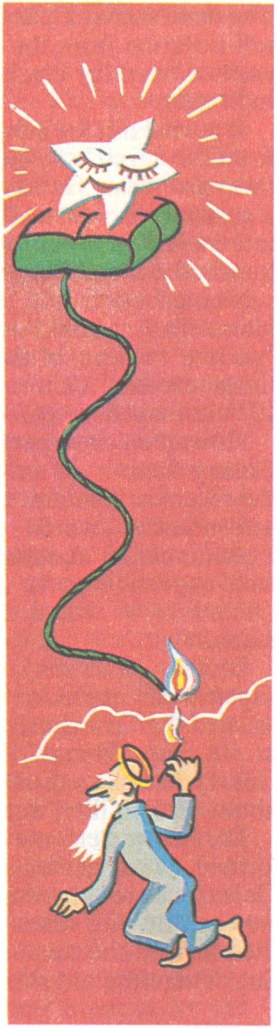
Theory does not exclude the possibility of a very high half-life for superelements, comparable even with the age of the Solar system. Accordingly, such elements may be found in their natural form in nature provided they were synthesized in a process which took place earlier in our universe.

The success of such a search is contingent on lucky coincidence involving many factors: the presence of an effective source of superelements, existence of at least one isotope with a long half-life, and, of course, a certain amount of good luck. Nevertheless, such experiments have principal significance. First, the evaluation of superelements in nature may turn out to be the only available means of getting long-lived supernuclei and therefore the only possibility for studying their physical and chemical properties. At any rate, so far it is the sole way to penetrate to the centre of the Stability Island. Second, should superelements be obtained artificially, it is now clear that the most powerful accelerators could yield at most a few superatoms a day. If at least one isotope of a superelement is found in the Earth's crust it will be available in weighable quantities. This would enable the domain of superelements to be expanded, similar to how this was done with uranium, having been the starting material for fifteen new artificial elements. Finally, the search for superelements in the Solar system and the Galaxy may improve our knowledge of the nature of those cosmic objects in which the synthesis of supernuclei took place.

Stellar "factories". In distant stellar worlds the synthesis of chemical elements of hydrogen is going on continuously. Astronomers were fortunate to find a few types of stellar "factories" which may produce superelements. The main "technological" process there is the same capture of neutrons with a succeeding chain of beta decays which synthesized elements 99 and 100 in a thermonuclear explosion. The difference is that in cosmic objects the conditions differ drastically from those in terrestrial explosions – the process lasts not for microseconds but for seconds, days and even years, and the neutron fluxes are more intense. The nuclei advance toward the Stability Island on the edge of the neutronrich coast of the continent (see the map of isotopes). Under such unusual conditions the limitations which bar our penetration into the domain of transfermium elements are lifted.

In what way does the production of the stellar "factories" leave them? Stars like people are born and die. The finite stage of the evolution of stars with mass exceeding the mass of the Sun by a factor of four is the explosion of a supernova, i.e. a new star. For a short period of a few hours or days the glare of a formerly ordinary star increases to such a brightness that in about a month the supernova shines as brightly as all the other galaxy.

As a result of this explosion of a supernova a large mass of matter, as much as a few Suns, bursts into interstellar space at a speed of 10000 km/s. Depending on the nature of the "aged" star it may have different fates. It may fly apart at explosion. At times the explosion leaves behind a "dying" neutron star or a "dead" star, one having undergone an ultimate gravitational compression – a black hole.



The dead star as if put on a cap of invisibility and fell into self isolation from the external observer – no radiation is emitted from the black hole and it can be evaluated only indirectly.

If it were not for interstellar medium, the matter ejected from the "aged" star along with superelements would fly away from our Galaxy. However in the Galaxy there is a gaseous disc about 10^{16} km thick made up of clouds of interstellar gas each of which having a mass of several hundred Suns and moving at a velocity of 10 km/s. The substance ejected in the explosion decelerates in the interstellar gas and is trapped there. Heavy elements "pollute" a mass of the interstellar gas which thousand times exceeds their own mass in a radius of about 10^{15} km from where the explosion took place.

How often do supernovae occur in the Galaxy? In our Galaxy there have only been three supernovae noted in the recent millenium, in 1054, 1572, and 1604. Although astronomers would be happy to observe such a phenomenon in close quarters, it would be better if the next explosion occur in some remote, galactic region. Otherwise it would have disastrous implications for mankind.

Be that as it may, from more safe observations of supernovae explosions in other galaxies it has been learned that in a galaxy like ours a supernova occurs once in 30 years. Hence, for the 10 billion years that our Galaxy has existed, 100 billion stars have given birth to about 300 million supernovae.

The heavy elements that we observe nowadays in stars formed at an earlier stage of the development of the Galaxy were thrown away in the explosions of supernovae into interstellar space, joined nebulae which then formed the stars of new generation, particularly the Sun. Therefore old stars born directly from the matter of the prestellar stage contain one hundredth as many heavy elements as young stars.

Superelements can occur in lower quantities also in processes taking place in neutron stars. The existence of such stars was theoretically predicted by L. D. Landau, an outstanding Soviet theoretical physicist, in 1932. Thirty five years later British astronomers discovered pulsars, powerful point sources of pulsed radio emission, operating with a period ranging from a tenth of a second to a few seconds, whose radiative energy is thousands and hundred thousands of times that of the Sun. Further studies have indicated that these space "radio beacons" are rapidly rotating, strongly magnetized neutron stars. The gravity of neutron stars compresses their substance so that the atomic envelopes of the atoms "flatten" and the density of the matter reaches the level of nuclear density. An unusual crystall lattice forms whose nodes are nuclei submersed in neutron and electron gases. The nuclei in this lattice are also exotic – they are made of hundreds and even thousands of nucleons. It has been learned that sometimes a pulsar may sharply change its period of emission. It might occur during a "starquake" when the outer shell of the neutron star is destroyed. In such situations, exotic nuclei and even batches of neutron material are ejected into interstellar medium. There the enormous gravity forces which stabilized such unusual nuclei are absent, therefore they emit "excess" neutrons, undergo fission and beta decay. Eventually superelements may result. In the search for places where superheavy elements may be born we have entered the continent of hypotheses. Astrophysics, an absorbing branch of modern physics, experienced a feverish development – ever new objects emerge that strike our imagination, ever new types of "stellar factories" are discovered. But it is time for us to follow the superelements away from their hypothetical sources to the Earth.

Galactic new-comers. A certain proportion of superelements that are thrown into interstellar medium travels in space, is gradually accelerated by electric and magnetic fields to light velocities and joins the galactic rays that permanently irradiate our Earth. Ashes from distant burnt stars may reach the Solar system, too. Current estimates indicate that the average age of cosmic rays is in all probability millions of years. Therefore, if the lifetime of a superelement is close to this value or exceeds it, the long-liver may be found in galactic ashes.

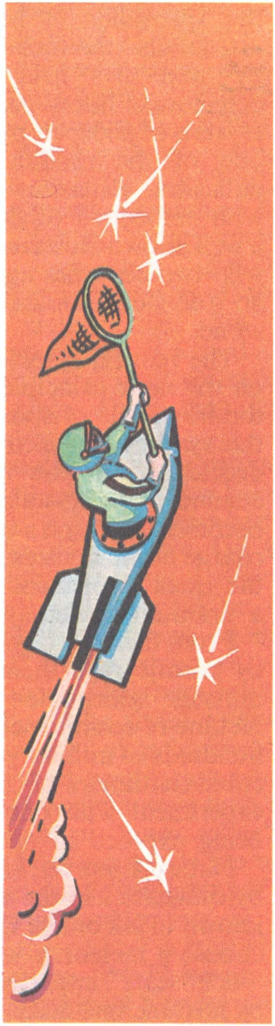
To verify this hypothesis experimentally P. Fowler and workers of Great Britain subjected large surfaces covered by photographic emulsion capable of recording the impact of atomic nuclei to irradiation by cosmic particles. The trouble is that cosmic nuclei fail to reach the Earth's surface being trapped in the upper layers of the atmosphere. Therefore the group had to send large photoplates of about 20 m^2 in area in a stratospheric balloon to an altitude of 40 km. The volume of the balloon was as high as 600 000 m^3.

The higher the charge of the nucleus, i.e. the atomic number of the element, the broader the track it is able to make in photoemulsion. Fowler and co-workers found comparatively "thin" tracks rather often. These were the tracks of element 26, iron. Occasionally they came across thick tracks. The study revealed that they belonged to nuclei of elements 80-90. Very broad tracks that could be due to transuranium elements were a rare occasion.

To evaluate supernuclei the time of exposure would have to be increased many times. One flight of a stratospheric balloon in the upper atmosphere lasts for a few dozen hours. Launchings of such sondes had been conducted for seven years (from 1967 to 1973) and only resulted in two tracks which might be due to superelements. However, even these tracks could not stand severe and recurrent check. After thorough analysis it became clear that these tracks in fact owed their existence to decelerated nuclei of lighter elements.

The scientists had to ask help from astronauts. In 1973 an experiment was carried out to detect cosmic supernuclei with a detector of 1.5 m^2 area on the Skylab orbital station. The flight time was eight months, many times the total exposure during the stratospheric-sonde experiments. Recently one more such experiment was performed on an American satellite. Overall, after 10 years of launching sondes, Skylab experiments, and satellites only 23 nuclei of thorium and uranium, and none of supernuclei were recorded from cosmic rays.

How should a sensitive experiment be carried out if even the latest achievements of space technology are helpless? A way out of the deadlock has been suggested by nature itself. Fortunately it took care of future investigators when it created certain celestial bodies of the Solar system. For example,



the specimens of Moon rock brought to Earth by astronauts – the rock is under continuous bombardment by space rays – held silica minerals which are natural detectors of heavy nuclei. Inclusions of such "detectors", crystals of feldspar, pyroxene, olivine, are encountered in one of the modifications of ferro-stone meteorites, pallasites. Pallasites are basically an iron-nickel alloy with embedded olivine grains. They were named after a well known Russian traveller and naturalist P. S. Pallas who two centuries ago found in the Krasnoyarsk region an iron-stone boulder which turned out to be a celestial stone.

The natural detectors contained in pallasites operate on the same principle as glass detectors which recorded the fragments of spontaneous fission in experiments on the synthesis of element 104. A heavy cosmic nucleus decelerated in the mineral leaves behind a damage channel in the crystal. After chemical etching this channel becomes visible on a common microscope. The larger the charge of the nucleus, the longer the track. For instance, the track of element 114 should be twice the track of a uranium nucleus.

From the early days of its birth a meteorite is irradiated by cosmic rays throughout its life and thereby accumulates information about cosmic supernuclei. The lifetime of cosmic meteorites may be as long as tens and hundreds of million years. Therefore examination of one cubic centimetre of celestial minerals is equivalent to an experiment with one or two tonnes of photoemulsion being exposed in outer space for a year.

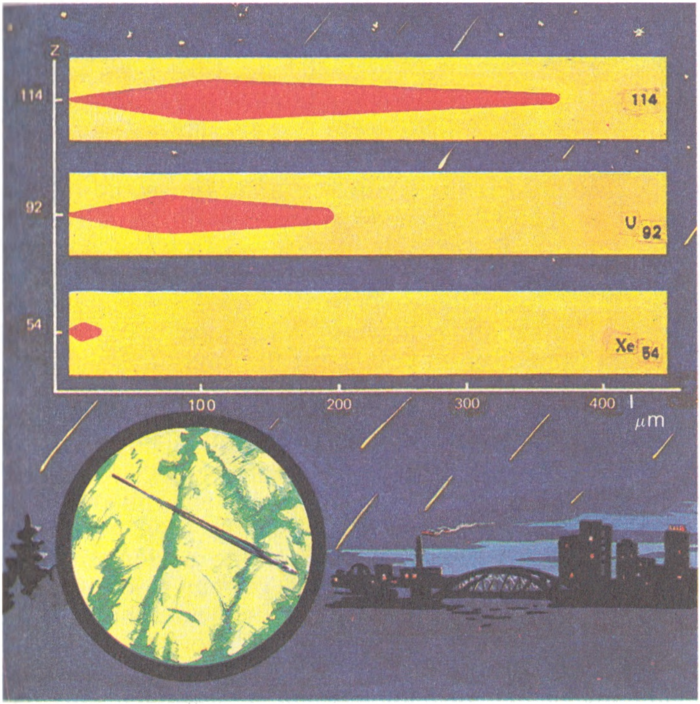
Nature, however, has a way to offset a gain in one area by difficulties in the next. For one thing, meteorites are known to fall on the Earth rather seldom. Next, one must choose a meteorite with the grains of desired minerals. Since "scars" imparted by cosmic rays are "healed over" by heating, one needs to select the grains from a portion of the meteorite which has not been burnt down as it entered the atmosphere. Then, only those grains are to be selected which lie 5 to 6 cm under the surface. Deeper crystals may not be reached by bombarding supernuclei because these are absorbed and fission in the meteorite crust. The crystals from a lower depth undergo multiple heating by solar radiation which also causes a "healing over" of the possible tracks. As a result, researchers find themselves in possession of only a few meteorites suitable for the purpose. Of many "applicants" for the participation in the search for supernuclei Dubna scientists selected meteorites named Eagle Station, Marjalahty, and Lipovsky Hutor age 45, 175, and 220 million years, respectively. Recall that meteorites are traditionally named after the place where they were found.

It was not easy to find in celestial crystals the tracks of galactic heavy nuclei and identify the element they belong to. To gain some experience in the field researchers had to carry out experiments with nuclei of Ti, Cr, Fe, Ge, Kr, and Xe accelerated in cyclotrons to a certain energy to build up the dependence of the length of track on the energy and charge of nuclei. This calibration enabled them to compute the lengths of tracks which various galactic nuclei could make in olivine. It has been learned that the track of element 110 should be about 1400 μm long. However, long tracks are concealed by shrouds of short tracks due to iron nuclei and its neighbours, which are million times more abundant in cosmic rays than the nuclei of elements heavier than platinum ($Z = 78$).

To circumvent this difficulty it has been decided to turn to good the unfortunate phenomenon of "healing over" of tracks that takes place on heating meteorites in the atmosphere. It emerged that if the crystal is heated to 430°C and held at this temperature for 32 hours the tracks due to iron disappear. The tracks of heavier nuclei shorten but remain. For example, 750-μm tracks of thorium and uranium decrease to 200-250 μm, and 1400-μm tracks of superelements to 350-400 μm. Moreover, such annealing of crystals reduced the losses of the tracks of heavy nuclei. A proportion of long tracks before annealing did not terminate in crystals of olivine size 1 mm across on the average. Upon annealing and shortening of tracks the length of most tracks can be measured.

A technique has been developed to evaluate tracks which lie in the core of the crystal. Multiple irradiation by a focused laser beam produces in the crystal a system of channels each of which is the origin of 3 to 5 radially fanning microcracks. Olivine, covered by a net of such artificial flaws, resists fragmentation in subsequent etching which reveals all the tracks that cross the cracks and channels. The efforts expended during the complicated and painstaking preparation for the principal experiments on the search for superelements paid off splendidly. An international group of scientists from France, India, Mongolia, the Soviet Union and Yugoslavia, headed by V. P. Perelygin studied over 2000 crystals of olivine, ranging in size from 2 to 8 mm, by viewing 60000 images under microscope. In a short period of time they evaluated more than one thousand tracks of thorium and uranium nuclei, that exceeded by a factor of tens the level of sensitivity attained during a decade of experimentation with sounding balloons and satellites. It is this record level of sensitivity that helped detect seven tracks hopefully made by a long-expected superelement.

Can any meteorite be abundant in tracks of "nuclear dinosaurs" similar to how the Goby desert was found to be the place of remains of the actual monsters? To answer this question, a greater amount of crystals from different meteorites needed to be investigated than the 2 cubic



Comparison of the tracks made in crystals by different nuclei. The bottom insert shows a track of superelement found in a meteorite

centimetres studied so far. The choice of meteorite for these studies was one of great consequence. Meteorites more than 150 million years old held greater promise for the search for supernuclei. At that time the Solar system passed through one of the spiral branches of the Galaxy.

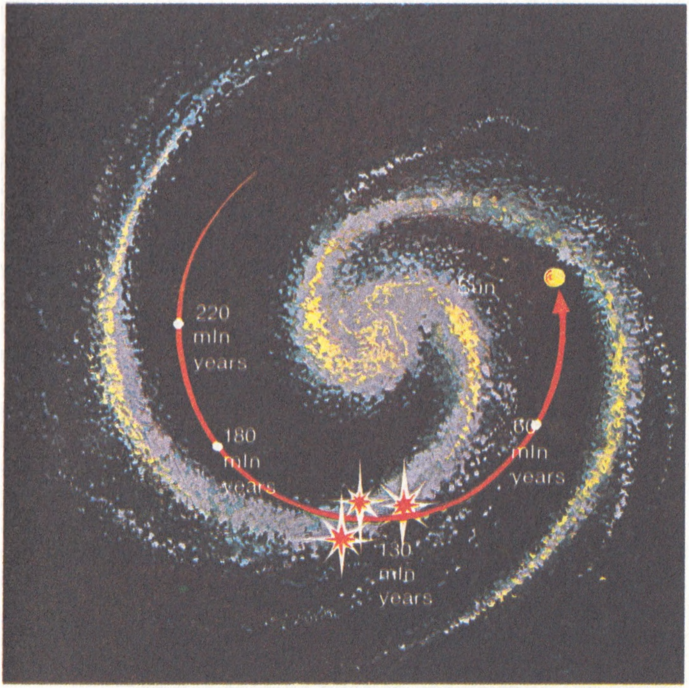
Explosions of supernovae that occurred at a distance of about 10^{15} km should have caused the direct irradiation of the Solar system by an intense flux of space rays. The minerals in the meteorites might have recorded unstable supernuclei of comparatively small half-life, about 100 years.

A meteorite is like a shot in a movie recording the image of the Galaxy made in ion rays during a certain time interval. By selecting meteorites of various age one may in principle edit a "movie" about the development of the Galaxy over the period of hundreds of millions of years. The shooting, however, was done by a moving camera from different points, yet the laws of this motion are well known.

Careful investigation of each shot may solve another problem. If a track terminates in a still "living" nuclear "dinosaur" then a beam of accelerated particles directed along the track might cause the spontaneous fission of the supernucleus which manifests itself in leaving a hammer-like track. Then since the age of the meteorites where living nuclear dinosaurs are still present is known, the half-life of the supernucleus can be determined.

Thus, in nuclear "paleontology" the potential was opened up not only for evaluating of tracks of galactic supernuclei but also for gaining new insight into the synthesis of elements at different stages in the development of the Galaxy.

Terrestrial long-livers. In the search for superelements in the substance of the Solar system scientists have to be more optimistic than in the similar search in the material of the Galaxy. The Galaxy is continuously producing superelements in "stellar factories" whereas the material of the Solar system may have received them only once, at the instant of original formation. This imposes more



The path of the Sun in the Galaxy. Figures mark the position of the Sun at various moments of time

severe limitations on the lifetime of the superelement.

According to modern views the formation of the solar system was preceded by a higher rate of element synthesis than in the previous period of the galactic history. The multiple explosions of supernovae and the interaction of the gas rejected by these explosions with the existent nebula might have initiated the formation of the Solar system. If an isotope of a superelement of more than 100 million years half-life got into the nebula at the time, it should be retained in the Solar system, specifically on Earth.

Let us estimate what proportion of a primordial element remained in a conditional "nugget" of mass 1 kg which 5 billion years ago was a pure isotope of element 110, assuming the half-life of this element be equal to 200 million years. Recall once again the chess problem and perform the same computation as we have made in earlier chapters but with the nugget lying this time on the 25th square of the chessboard. As the result of our computation we learn that only one tenth of a milligram could survive to our day.

The decay of superelements alone does not reduce their abundance in the terrestrial substance. The average content of uranium in the Earth's crust is about one ten thousandth per cent. To compare, any known process of nuclear synthesis may be able to produce superheavy elements in amounts by a factor of tens lower than uranium. Therefore it should be expected that the content of long-livers in the Solar substance will be exceedingly low, less than 10^{-13} g per gram of the substance. Sharp deviations from the average level of the concentrations of rare elements in various natural specimens raise scientists' hopes, however. For example, the abundance of gold in the Earth's crust is very low (only a millionth fraction of per cent), nevertheless large nuggets of pure gold are rather frequently found.

Consequently, one should seek for places with increased content of superelements. Again the periodic system shows the way. Recall that the discovery of element 104 in Dubna has confirmed that kurchatovium is an analogue of hafnium. After that the chemical properties of the superelements could be predicted rather accurately. So, element 108 should have chemical behaviour close to that of osmium, element 110 to that of platinum, and element 114 should be an analogue of lead.

It is highly probable that in the formation of the Earth's crust or meteorites, atoms of eka-platinum must have accompanied atoms of platinum, and atoms of eka-lead must have accompanied lead. The first thing that springs to mind is to examine ore and minerals containing osmium, platinum, gold and lead for the presence of superelements. It is enough to note the studies of the lead ore deposits in Dubna to form a notion of the scale of the search: Kola Peninsula, Western Ukraina, South-Eastern Republics of the USSR, Baikal area (USSR), Far East (USSR), Czechoslovakia, and Sweden.

In spite of all the expectations, however, the search in ores gave a negative result. This may be traced back to the fact that during the 4.5 thousand million years that the Solar system has existed the terrestrial rocks have been formed and reformed many times. On the other hand, the chemical behaviour of the superelements is not known well enough to predict the behaviour of their very small concentrations in the complicated geochemical process of ore formation. Instead of an expected increase in the concentration of a sample, a superelement may have been expelled beyond its boundaries. Therefore at the first stage it would be wise to concentrate the efforts on the search for superelements in specimens which escaped the complicated process of differentiation of the primordial planetary substance.

Again the attention of the superelement hunters was attracted to celestial stones. There exists an ancient type of stone meteorites, coal chondrites, which are basically the fragments of stone planetary material which has remained unaltered from the time the planets were born. The composition of the meteorites is very close to the original material of a nebula which gave birth to the Sun and the planets. Such a meteorite is a mixture of black coaly matter and chondres – globules of silica minerals (at times simply glass spherules) sized from fractions of a millimetre to a few millimetres across. The concentration of many volatile analogues of superelements such as mercury, thallium, lead, and bismuth in coaly chondrites is tens and hundreds of times that in ordinary stone meteorites. These favourable signs decided the choice in favour of coaly chondrites as the next class of objects to be studied. The Meteorite Committee of the Academy of Sciences of the USSR gave from its collection of meteorites a few samples of the meteorites Saratov, Efremovka, and others, and the American Museum of Natural History sent in 20 kg of the Allende meteorite to the Dubna researchers.

It is a difficult task to find on Earth specimens of rock with a composition close to that of the primordial planetary substance. The point is that, in the Earth's crust the separation or differentiation of elements has taken place owing to various natural processes, such as melting, weathering, effects of precipitation to name a few. In the Earth's mantle all elements are represented more uniformly, but it lies at large depths – 35 km deep on average under the continents – and so far samples from it are impossible to retrieve. Fortunately, some regions of the globe have deep faults in the Earth's crust (rifts) which can go down as far as the upper layers of the mantle. A rift is a 2-3 km wide stripe on the Earth's surface where the crust is absent and the cover is from loose alluvial soils. Abyssal waters penetrate through the fault to hot segments of the mantle and upon heating go up to the surface as hot springs or through specially drilled wells.

Heavy elements (osmium, mercury, lead and such) form strongly volatile compounds. The compounds of their superheavy homologs should be still more volatile. Therefore in an area where waters make contact with the mantle sublimation and dissolution of salts of heavy elements and superelements occurs. Geothermal waters are a ready chemical solution containing enormous amounts of salts (250 g per litre of solution). Analysis of its chemical composition showed that the waters are especially rich in thallium and lead. It is natural that in the outlets of geothermal waters on the surface, deposition of dissolved compounds takes place.

In the Soviet Union, such springs have been found on the Cheleken Peninsula which is on a deep fault protruding from the east coast of the Kaspian Sea to the south-eastern regions of Turkmenia. In 1971, 2000 cubic metres of water from a Cheleken well were passed through filters of ion-exchange resins adsorbing the compounds of heavy metals. Then 850 kg of this resin were sent to Dubna for further studies. A few years later an expedition

A geothermal water well in the desert of the Cheleken peninsula was organized to another rift zone, at the Baikal Lake. Again samples were collected from the mineral fractions isolated from water of the local geothermal springs.

Still another rift system is located in the central area of the Pacific Ocean. Here at the bottom, underwater volcanoes and geothermal springs are active which carry out into ocean water substances from deep layers of the Earth. It is impossible, however, to drill a well under many kilometers of water and erect a chemical facility there to filter the geothermal water. What could replace such an arrangement?

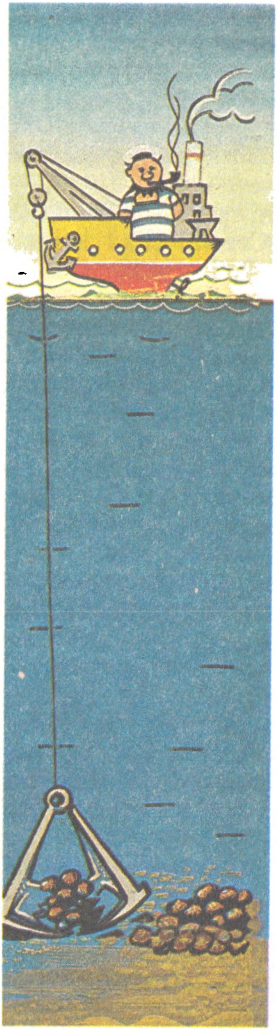
The ocean bottom is studded with spherical formations that look like potatoes dug from moist soil. These are concretions. Shark teeth or ground particles may act as seeds that are gradually overgrown with sediments. Because the central regions of the Pacific Ocean are remote from the areas where continent materials are brought into the water, the materials of which concretions are built up are rich in the substances carried from deep layers of the Earth through faults in the Earth's crust. Concretions grow at a rate of fractions of a millimetre over a period of a few millenia, their age averages are about million years old. These remarkable formations have been suggested for a superelement search by Academician A.N. Vinogradov.

Concretions are most valuable in that they are essentially small "dressing factories". During their long life concretions as if adsorbed from sea water compounds containing metal atoms. They are mainly made up of iron and manganese compounds, whence their name – ferromanganese concretions. But other elements, such as cobalt, copper, and gold are also found in them in tens of millions of times higher concentrations than in ocean water and in bottom rock. Naturally that superelements – analogues of these metals in the periodic table – should also accumulate in ocean "potatoes".

During its 48-th cruise, the research ship Vityaz of the Academy of Sciences of the USSR gathered about 7 tonnes of ferromanganese concretions from the bottom of the Pacific Ocean at the New Zealand Bank to send to Dubna for further analysis.

Unknown emitter. Scientists were going to study hundreds of samples recovered from space and from the Moon surface, from Arctic glaciers, Central Asian deserts, craters of volcanoes, and bottom of the Pacific Ocean. Possibly, in the tonnes of materials to be analyzed there were bluffed fractions of a microgram of superelements. Can such concentrations be revealed by the analytical techniques available? "Yes, they can, provided that techniques are improved in sensitivity a million times", physicists answered. Improving the performance data of an operating unit is a formidable problem in engineering. Hence, experimenters had to develop new, unique equipment to analyze the material composition at a record sensitivity level.

The principle of operation of these facilities is based on recording the spontaneous fission of supernuclei. This method first used in the evaluation of kurchatovium nuclei became fundamental in the search for superelements. First of all, theoreticians predict that the last link in the chain of radioactive transmutations of any supernucleus should be spontaneous fission. Then, nature has plenty of natural alpha emitters, whereas only one natural element, uranium, fissions spontaneously. The concentration of uranium in a specimen being studied can always be determined independently. Finally, the characteristics of the spontaneous fission of uranium must differ substantially from those of the fission of supernuclei. Therefore, the presence of superelements in a specimen should be signalled either by the excess of



spontaneous fission over the uranium background, or by the presence of unusual spontaneous fission.

The setup developed in Dubna by a group headed by G.M. Ter-Akopyan is built around the idea of simultaneous recording of a few neutrons emitted in spontaneous fission. In contrast to fission fragments, neutrons can freely penetrate through thick layers of material to be recorded by neutron detectors. Therefore the setup was able to analyze specimens up to 20 kg in weight.

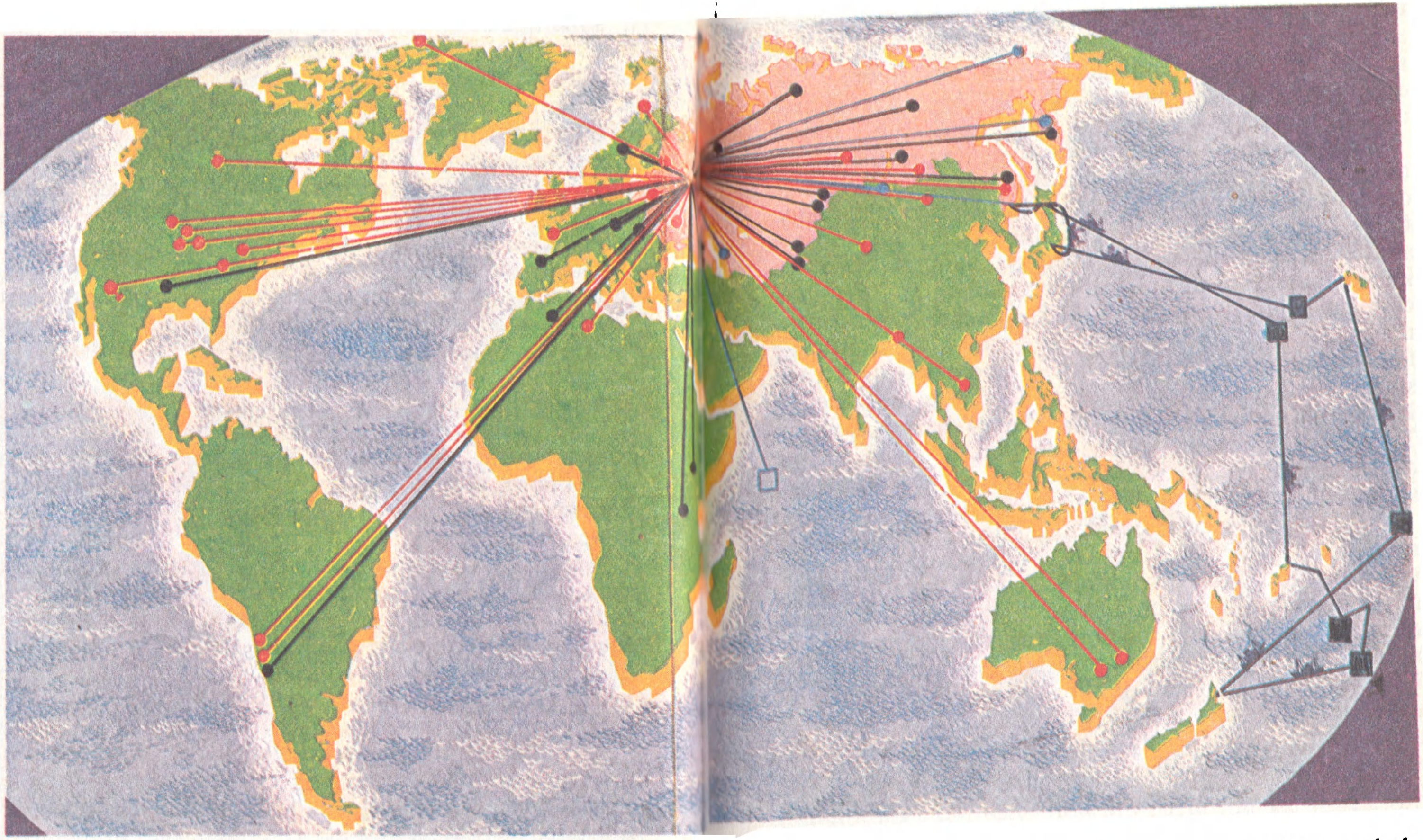
Large masses of the material enabled fantastic sensitivity to be reached in the setup – it can reveal one atom of a superelement even if it is concealed among 10^{15} atoms of other substances. This is 1000 times above the limit of sensitivity reached in other similar facilities. This sensitivity is so high that even cosmic rays passing through the atmosphere may interfere and impair it. A fast cosmic particle colliding with a heavy nucleus, say lead or bismuth, can split it into two fragments thereby simulating the spontaneous fission of a supernucleus. To avoid such an interference the measurements were carried out in a salt mine at a depth of 440 m where no cosmic particle can penetrate.

Scientists wait impatiently and hopefully for the results of the examination of the selected specimens. At times the researchers seemed to be very close to their objective, but then the recorded terrestrial "long-liver" or "cosmic stranger" turned out to be a "disguised terrestrial resident" uranium.

Finally in 1975, after four years of operation in the mine, there came a message from under the ground: "We've got it!" In samples of the Efremovka, Allende, and Saratov meteorites, an unknown, spontaneously fissioning emitter was detected. In analysing 10 kg of substance the setup recorded on average one decay in five days. This corresponded to an ultrasmall concentration – one atom of the unknown substance in 10^{14} known atoms. The count rate exceeded by several decades that of uranium should it be present in the meteorites.

If celestial stones exhibit the presence of a superelement then it should be present in terrestrial specimens as well. Indeed, soon the unknown emitter was detected in geothermal water from the Cheleken Peninsula. In the first 88-day analysis of 9 kg of ion-exchange resin, the setup recorded 42 decays. The concentration of the emitter in the resin was three times higher than in the meteorites.

In the years that passed since the discovery of the unknown emitter, researchers learned something about the "stranger" and managed to look behind its "mask". It appeared to possess a volatility close to that of polonium and lead compounds. This fact was established in an experiment with a few kilograms of material from the Allende meteorite that were heated to 1100°C in a hydrogen-oxygen flow, resulting in spontaneous fission



Locations on the globe where samples were collected for the search for superelements. The red dots are meteorites, black dots are ores, minerals, and igneous rock; blue dots are geothermal waters, black squares are ferromanganese concretions, and the broken curve shows the route of Vityaz activity developing along with other volatile substances from the meteorite. They had about the same properties that theory predicted for superelements. After a series of experiments, researchers became more confident in that in the meteorites and geothermal water they had observed the spontaneous fission of a previously unknown nucleus which belonged to the Stability Island.

The time came for experiments to determine the atomic number Z and the mass number A of this supernucleus. In order to be successful these experiments needed a million times higher concentration of the superelement in the studied specimens. So far chemists had succeeded to improve the concentration of the new emitter 1000 times over the original content in the specimens by sequential manipulations. All attempts at further concentrating failed because of the losses which increased with each stage of the treatment – there told the absence of knowledge on the chemical behaviour of the new element. Therefore at present much attention is given to the development of chemical methods of extraction of superelements from various substances.

Fine and sophisticated physical methods of identification of the terrestrial "long-liver" are being developed too. Much promise is held for the application of the mass spectrometer, a device to measure the masses of atomic nuclei. The ion source of this device ionizes atoms of the studied substance. These ions are accelerated by a voltage of a few tens of kilovolts and then formed by a system of slits into a weakly divergent beam of ions of about equal energy. In the major unit of the device, the analyser, this beam is separated into several beams of ions of different mass. The analyser not only sorts the ions by mass, but also focuses the beams so that the ions of the same mass but of slightly different energy or direction of travel arrive at the same place in the recording unit. In the simplest case the analyser may be a magnetic field, as illustrated in the figure. A photoplate (or photodetector) placed in the focal plane of the spectrometer will record the arriving beams of various isotopes as resolved lines.

The first mass spectrometer was built in 1910 by J. J. Thomson. Together with F. Aston, a student of his and an author of major discoveries in mass spectroscopy, he first found a few years later that many elements are blends of different isotopes. Since that time the design of this major instrument of nuclear physics has been continuously improved. The current sensitivity of these devices enables the impurity in a sample to be evaluated at a level of one part per billion (ppb). However, the ultrasmall concentrations of the superelements demand that this sensitivity be further improved by four or five orders of magnitude. To achieve this goal, a mass spectrometer is being developed in Dubna that concentrates all the best achievements in the field. It will operate on a laser source, developed by Yu. A. Bykovsky and co-workers, which will enable up to 10 billion ions per laser pulse to be ejected from the slit. The advantage of the laser source is its local heating of the sample, enabling analysis of substance from any given point on the specimen's surface. The accelerating potential will be increased to 100 kV, and the vacuum in the unit will be improved to cut down ion losses.

The complicated system of magnets will sort out the ions in mass three times. One analysis will take from a dozen minutes up to 2-3 hours. Upon the separation of the studied samples by mass, the lines corresponding to the mass numbers $A \approx 280\text{-}300$ may be identified either by spontaneous fission, or by fission caused by the irradiation of the recording unit with intense fluxes of neutrons or gamma quanta. Because the uranium line ($A = 238$) appears far from the line of the superelement, the uranium of the specimen will not interfere with the identification of the supernucleus.

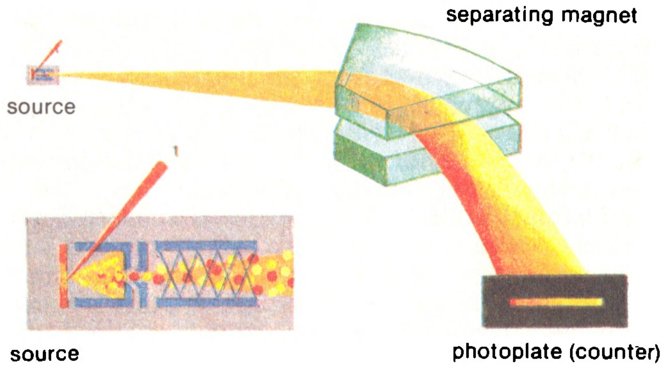
The measurement of the superelement's mass must be the last and decisive argument in favour of the existence of a long-lived supernucleus.

A walk over the Stability Island. The prospects of a detailed investigation of the Stability Island are decided by the possibility of isolating weighted quantities of superelements. If a "long-liver" does exist in the Earth's crust, it will be sooner or later extracted from the crust by some chemical or other isolation techniques yet to be developed.

To alleviate this problem one seeks such terrestrial specimens whose content of superelements is considerably higher than those of geothermal water and meteorites representing the average composition of the Solar system. To extend the boundaries of the search for superelements it would be worthwhile to design a planetary experiment with the aim of investigating the various combustion and treatment products of coals from different deposits which differ by their geological conditions and age. The samples to be collected should be subjected to analysis for superelements and should be examined for possible correlations of the presence of superelements with other elements being present. The knowledge of such correlations would give researchers a correct compass for rapid evaluation of "deposits" rich in superelements.

The more samples to be studied, the greater will be the number of "deposits" of superelements discovered, and the sooner the "guide" for the surveying of new depots of superelements will be established. This was obvious logic, but the facility in the salt mine could not analyse a large number of samples in short while. The interfering factors were the large separation of the mine from Dubna and difficult conditions of work deep underground.

At present a new setup was completed in Dubna. Al-



The principle of the mass-spectrometer; 1 – laser beam irradiates the sample to produce an ion beam

though its neutron detectors that record the fission of supernuclei are above the ground they are securely protected from cosmic rays. First, they are encrusted in concrete walls 8 m thick, weighing 2000 tonnes. These reduce the background caused by space radiation by an order of magnitude. The walls in the detector's room are lined by sheets of special plastic (scintillator), each 1.5 square metres in area. A cosmic particle passing through the scintillator excites its atoms and these emit quanta of light, photons. This light is collected by fibre light-guides and illuminates photoelectronic multipliers. The latter amplify the signal and convert it into an electric pulse directed to an electronic circuit to turn off the setup as soon as the cosmic guest is being felt. This electronic screen attenuates the space background by two more orders of magnitude. The detectors recording neutrons of superelement fission have also grown in sensitivity. In the near future a "neutron geologist" will start the search for superelement ores in many hundreds of specimens sent to

Dubna from museums, ore-dressing factories, and geological surveying parties.

The targets prepared from supernuclei will make it possible to approach step by step the Stability Island. When a target of only 10^{12} atoms of superelements is available, a number of new isotopes from the stability domain will be synthesized and studied.

One of the possibilities in this area is connected with neutron synthesis. Nuclear reactors realised the century-old dream of alchemists – within a few years of operation uranium can be converted into other elements, at least as valuable as gold. In a similar manner, after long-duration irradiation of a superelement in a reactor, it captures neutrons and becomes an isotope heavier by unit mass. Subsequent irradiation of the target will result in still heavier isotopes after absorbing 2, 3, 4 and more neutrons. Consequently, the reactor will carry us east from the summit of the Stability Island.

Other transportation means were also tested in the synthesis of transuranium elements. The absorption of an alpha particle with the target increasing the charge of a supernucleus by two units was already used for the synthesis of mendelevium. Similar to how it was used in the synthesis of elements of the second hundred, transfer to the integration of heavy ions with supernuclei will give us the possibility to advance farther north in the Stability Island. The use of the process of the incomplete merging of a heavy ion with the nucleus, failing to produce superelements in the U + U reaction, will enable us to travel over the island in all directions. Modern heavy ion accelerators are capable of producing highly intense beams for experiments with ultrasmall contents of superelements in the target.

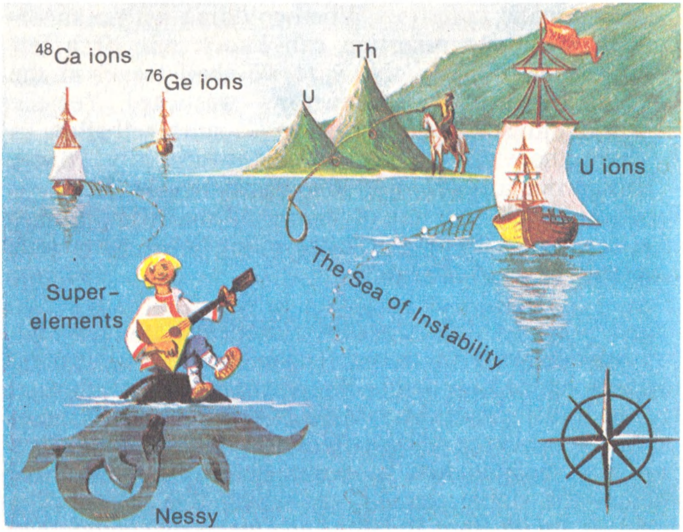
There is one more means of travel over the island. This is prolonged irradiation of a target in electron accelerators by intense beams of gamma quanta, a hard electromagnetic radiation. When colliding with a supernucleus, a gamma quantum can knock one or a few neutrons out of it. In this case we shall travel in the direction opposite to the reactor's – westward. Yet the process of knocking off protons by γ-quanta will allow us to study the southern region of the Stability Island.

Thus, a rich arsenal of reliable transportation is at our disposal and after landing on the island we will be able to have a look at its outskirts, travelling in all directions from the peak of Stability.

New horizons. Less than two decades after the search for superelements in nature began, new breath-taking horizons opened up before the seeker after new unusual nuclear transformations. Now they stand on the verge of the next stage in the development of stability studies. This stage is associated with a seemingly simple question of whether the stable elements of which the surrounding world is built – the Earth, Sun, galaxies – could last forever.

Answering a simple question connected with the universe is always very difficult. In this particular case, the answer called for penetrating further into the depth of matter where the structure of nucleons making up nuclei can be studied along with the interaction and interconversion of elementary particles. Note in passing that in reference to the nucleon the name elementary particle sounds obsolete because it is made up of still smaller objects named quarks and gluons. This is a sequel of the process begun a century ago by Mendeleev – from atoms to nuclei, from nuclei to elementary particles ...

Experience collected by science by the early 1970s indicated that there existed four types of fundamental interactions in nature (or four types of forces, which is the same): gravitational, electromagnetic, strong, and weak. They were called fundamental because all the other forces



The search in nature and the artificial synthesis of superelements – what is leading?

were their manifestations. For instance, the forces of friction, viscosity, and resilience are the manifestation of the electromagnetic interaction of the atoms making up the bodies. Electromagnetic and gravitational interactions were discovered earlier than the other interactions because the radius at which these forces are active is limitless and these forces manifest themselves in the macroworld. Short-range weak and strong interactions show up in the microworld, therefore they were discovered as late as in the 20th century. We have already mentioned that strong interaction is responsible for nuclear forces retaining protons and neutrons in the nucleus. As regards weak interaction, we have also encountered it in the earlier pages – it is responsible, for example, for beta decay of nuclei. Although electromagnetic interaction relates to far-range forces, it also plays a significant role in the microworld: as we saw earlier, it influences the stability of heavy nuclei and the integration of nuclei.

Science has always tended to learn the most general laws of nature by combining a multitude of seemingly independent manifestations to cut down the number of laws. The discovery of the periodic table in chemistry is a very good example of this point. It might be a pure coincidence, but just at that time (in 1864) Maxwell succeeded in the first integration of interactions in physics. He indicated that static electric and magnetic forces are basically the manifestations of a joint electromagnetic field. The next success had to wait for a century, although this time the problem was attempted by many outstanding men of science – Einstein devoted many years of his life to the development of a unified theory of gravity and electromagnetism.

In 1967 S. Feinberg and A. Salam came up with a theory capable of uniting weak and electromagnetic interactions. In the years to follow this theory was able to interpret many experimental findings, but its real triumph was the discovery of the elementary particles it had predicted, the so-called W- and Z-bosons in 1983 in the European Centre of Nuclear Research (CERN) in Geneve. Similar to how quanta of an electromagnetic field (gamma quanta) behave as carriers in the exchange process of two interacting electric charges, W- and Z-bosons are carriers of weak interaction. Thus, electroweak interaction, uniting weak and electromagnetic interactions, became fundamental to the current level of knowledge.

It is not surprising therefore that in the recent years, physicists in many countries concentrated their efforts on the development of a theory capable of uniting all the types of interaction dominant in the microworld: strong, electromagnetic, and weak. These efforts resulted in numerous versions of the theory, honorably referred to as the grand unification theory.

The decisive role in choosing the correct version of the great unification theory will be played by experimentation. The main sequel for the existence of a new fundamental interaction is the possibility of decay of the proton into other lighter elementary particles and the conversion of the neutron into its antiparticle – antineutron, $^{-1}_{0}\tilde{n}$ (so-called $n \leftrightarrow \tilde{n}$ oscillation). In other words, the nucleon, a basic building block of the universe, can be unstable. However, this decay of the nucleon proceeds terribly slowly. The estimated lifetime of a proton or neutron in a nucleus amounts to about 10^{30} years. This is 10^{20} times the age of the universe. That is why no one so far ever observed this decay. Nor is it a threat to our life – only a few protons decay in a human body during life.

How can the instability of the proton be evaluated? Can't the experimenter wait for 10^{30} years until the proton is decayed? There exists a simple way out here: one should simultaneously monitor 10^{30} rather than one proton, then in one year at least one of them will decay. This measurement time is already suitable. But hydrogen having a proton as its nucleus is rather inconvenient for such experimenting. The required number of protons is contained in about one tonne of the substance, and this amount of gaseous hydrogen occupies a volume of 10 000 cubic metres. It would be more appropriate to use a liquid or solid substance. In this case the volume that the detectors need to look through is smaller – one tonne of water occupies one cubic metre, while one tonne of lead only one tenth of a cubic metre. The task of detectors with such substances changes correspondingly: since these substances are made up of more complicated nuclei than the proton, the detectors should essentially seek the decay of neutrons and protons bound in the nucleus rather than free protons, that is to seek a new type of nuclear radioactivity.

At best experimenters may hope to observe a few radioactive decays in many tonnes of a substance. Therefore to reliably record the decay of a nucleus initiated by proton decay or an $n \leftrightarrow \tilde{n}$ oscillation experimenters should know as much as possible about the behaviour of such decay. Until the decay is found, they have to rely on the theoretical predictions of the properties of this new type of nuclear radioactivity.

Such a radioactive decay will be able to release an anomalously great amount of energy, equivalent to one (nucleon decay) or two ($n \leftrightarrow \tilde{n}$ oscillation) rest masses of a nucleon. This corresponds to five or ten times the energy released in the fission of uranium nucleus by a neutron – the basic energy of modern nuclear power engineering. So large a spontaneous release of energy within a nucleus will cause it to explode. The explosion will emit a large number of neutrons, protons, light nuclei (alpha particles) and various elementary particles which are not emitted in the known types of radioactivity. As a result, the parent nucleus will markedly loose weight and the daughter nucleus will retain three quarters to half the initial mass. A heavy nucleus will emit predominantly neutrons (as many as half a hundred). In some situations the decay will be accompanied by fission which differs from the spontaneous fission of heavy and superheavy nuclei by great numbers of neutrons.

One of the first experiments concerned with the search for the new radioactivity was carried out by one of the authors of this book (G. N. F.) a quarter of a century ago when the very thought about the instability of the proton seemed absurd, and such an experiment was viewed at best as Don Quixotic. The experiment was focused on the search for an unusual spontaneous fission of thorium-232 (the nucleus of $^{232}_{90}Th$ was known to be indivisible spontaneously unless its nucleons decay). At that time the limit of the nucleon lifetime was obtained to be about 10^{23} years.

The situation has changed drastically since that time. Nobody doubts now the worth and necessity of such investigations. In the recent years researchers of France, India, Japan, the USA, and the USSR have performed a number of experiments to detect new radioactivity. In some of them the mass of the substance monitored by the detectors reached several thousand tonnes. The new experiments lifted the limit of the nucleon's half-life tens of millions of times compared with the findings of the first experiments. It has been established that should the nucleon decay at all, then it would take more than $3 \cdot 10^{30}$ years for lifetime. In 1981 Indian physicists, and two years later Italian physicists reported a few mysterious decays, yet so far one cannot be absolutely certain that they were caused by nucleon instability.

The sensitive neutron method developed in Dubna turned out to be able to search for spontaneous fission of superelements and also nucleon instability. The advantage of neutrons is that they reach detectors wherever the decay has occurred in the setup. In addition the number of neutrons emitted by a heavy nucleus by far exceeds the number of other particles. At present engineers in Dubna are designing a setup to search for $n \leftrightarrow \tilde{n}$ oscillations by the neutron method. There is good reason to believe that this machine will enable researchers to penetrate into the range where the lifetime of the nucleon exceeds 10^{31} to 10^{32} years, and, with good luck, to find a new type of radioactivity.

Continents to be Discovered

One of us often meets with young people preparing to choose their way in life and science. Some of them ask me questions which you too might well ask "What drives a man like you, who has an honorable position and has made many discoveries, to keep persuing the development of new powerful accelerators, new scientific expeditions, and ideas for new research?" I know a simple answer that is helpful in answering questions like this. One should pause for a while to look at what he or she does from the side and decide how much remains to do compared with what has been already done. If only a little bit remains then one should probably look for some other work.

In our work only a small proportion has been done so far of what has to be done. Therefore, there should be no time for rest and self-complacency. The young branch of nuclear physics dealing with the synthesis of new elements develops rapidly. It faces challenging problems, many of which will have to be solved by yourself, the scientists of the future.

Eager to find the boundary of the periodic table, researchers have advanced far behind uranium, the last natural element. Sixteen elements have been synthesized in 40 years. The boundary always seemed to be round the corner – each next element exhibited ever shorter half-lives. But here lies the fascinating facet of science – each new step toward the unknown may bring about unexpected results or open up new horizons. The latter elements exhibited a slowdown in the lifetime decreases. This indicated the possibility that stable superelements exist. Similar to how birds encountered by the ships of Coloumb told the seamen that the ground was not far, the properties of the last elements 106-108 indicated that the Stability Island is not very far to go.

Real prospects of creating the second half of the periodic table of stable superheavy elements opened up. History saw many examples when the use of even one element caused tremendous changes in the life of the mankind. So it happened when man learned to make his tools from iron. The wonderful properties of germanium gave birth to the semiconductor industry. Uranium and plutonium gave man the possibility to use nuclear power. There is every reason to believe that superelements will be of no less use for mankind.

The wonderful properties of the superelements attract scientists irresistably to the Stability Island. It is an innate property of man to penetrate into areas where no one has been ever, and to learn something that no one else knows. The researcher studies a matter at superhigh and cryogenic temperatures, in superhigh magnetic fields, in deep vacuum, and at superhigh pressure believing that under extreme conditions he will discover something new.

Extreme conditions act on the substance in nuclei of superelements with the largest number of protons – there interact the largest electric repulsive forces between the protons. Therefore the investigation of supernuclei will be helpful in better understanding of the structure of the nucleus. Synthesis of new nuclei is an important step on the way to a unified nuclear theory, such that could – like the periodic table – interpret and predict the properties of all nuclei. This will make man the absolute master of the Stability Island and, consequently, will increase his power immeasurably.

In all probability the problem of the existence of the Stability Island – that of stable supernuclei near the doubly magic nucleus with 114 protons and 184 neutrons – will be solved in the near decade. What will remain for scientists of the 21st century?

Theory predicts that a few, rather than one, islands of Stability – a real archipelago – may exist in the ocean of

Instability. The next island of the highest "elevation" is to be found in the range of the twice magic nucleus with 164 protons and 308 neutrons. Nobody knows so far how to reach this island. It may happen that you will have to solve this problem.

What other treasures will you find in these fascinating travels? These might be nuclear "diamonds" – superdense nuclei, the existence of which was theoretically predicted by Academician A. B. Migdal. Similar to how carbon can be found in various modifications – loose graphite and hard diamond – the most dense nuclear substance of the universe can possess a stable state with still greater density. Today the technology exists to manufacture synthetic diamonds, yet no one is able to say so far what fantastically powerful facilities need to be constructed to compress nuclei and manufacture synthetic nuclear "diamonds". You are going to explore vast, little studied, new, nuclear continents. Man has made his first steps over the continent of antinuclei located in the north-east corner of the map of isotopes. Three isotopes of antihydrogen are already known, and in 1973 in Serpukhov one of the world's most powerful accelerators was used to discover nuclei of antihelium. Recently, researchers in CERN in Geneva have succeeded in producing antimatter – so far a few hundred nuclei of antihydrogen – and storing it in a magnetic torus of 24 m diameter for 85 hours. The production and investigation of antimatter is a formidable problem of the future.

A new mainland of Hypernuclei has been discovered at the meeting place of high energy physics and nuclear physics. These are unusual nuclei made up of not only neutrons and protons but also heavy elementary particles – hyperons. The latter deny a straightforward mapping of the Hypernuclei mainland on an ordinary map of isotopes: this time the two horizontal dimensions showing the number of protons and neutrons should be augmented by a third one defining the number of hyperons in nuclei. For the time being, only a few tens of isotopes of the lightest hypernuclei have been synthesized. We have just started our travel through the "hyperspace".

You are going to travel in a number of such terrae incognita. One of them is far at the east rand of the map of isotopes. After so much talk about supernuclei with the largest number of protons it would be natural to consider the maximal number of neutrons in the nucleus. The number of neutrons N in ordinary nuclei is not very far from the number of protons Z, and even supernuclei have the N/Z ratio of only 1.6.

An unexpected discovery for many of the physicists involved has been the finding in Dubna and at Berkeley of the stable helium-8 isotope among fission products of nuclear reactions. It indicated that the record-holding nuclei of the largest N/Z ratio were to be found in the opposite end of the Stability continent in the domain of the lightest nuclei. Compared with the ^4_2He isotope, the second abundant atom in the universe, the helium-8 isotope has three, rather than one, neutrons. In this day and age, experiments are under way in the U-400 cyclotron to search for the still heavier, helium-10 isotope of $N/Z = 4$.

The study of superheavy isotopes of the lightest nuclei, whose stability is decided by fine features of nuclear forces, is the first step on the way toward "macronuclei" of about one tonne weight and hundredth fractions of a millimetre size. The properties of such "macronuclei" have been discovered so far at the desk with pen and paper. These nuclei may be constituted only by neutrons and kept stable by great gravitational attractive forces between the neutrons. Such "neutron drops" are actually the drops of stellar matter. Hence, the neutron stars recently discovered by astronomers may well be representatives of a new class of nuclei containing tens and hundreds of times more neutrons than protons. Here the microworld merges with the macroworld!

Appendix

Additional Facts for Those Eager to Know More

Those of you eager to know more about the history of spontaneous fission discovery or wishing to learn in more detail the physics of accelerators we invite to read this appendix.

How spontaneous fission was discovered. In late 1930 s one of the authors (G. N. F.), a former undergraduate of professor I. V. Kurchatov, worked under his leadership in the Physico-Technical Institute (or Fiztekh for short) in Leningrad. The discovery of the fission of uranium nuclei by neutrons made in December 1938 by O. Hahn and F. Strassman excited scientists, so wonderful and promising it was. After this discovery the count for new discoveries in nuclear physics was kept in days. 1939 saw hundreds of reports concerned with this phenomenon.

The large amounts of energy released in each splitting were most attractive in nuclear fission. Immediately after publishing the first report in 1938, a number of researchers (Fermi, Hahn, and Strassman) concluded that fission could produce neutrons. Much depended on what was the average number of these neutrons. If more than two, then in principle one could realize a chain reaction and produce nuclear energy. Kurchatov suggested to L. I. Rusinov and G. N. Flerov that they conduct an experiment designed to measure this principal characteristic of the chain reaction.

Under severe competition we were feverishly active.

The experiment designed by Kurchatov was a complete success – each fission released about three neutrons on average. And here we learned first hand that the fate of scientific preeminence was decided by days at that time. We reported our findings at a neutron workshop in Fiztekh on April 10, 1939, and in May we learned that the preeminence belonged to the French: on April 7 F. Joliot-Curie and co-workers sent to *Nature* a letter where similar results were reported.

It became clear that once started the fission of uranium nuclei could continue by itself. Here physicists bumped into a contradictory situation. A chain reaction needs slow neutrons whereas the fission produced fast neutrons. We knew at the time how to slow down, or moderate, the neutrons. However slow neutrons were only able to split uranium-235, which was to be found in uranium ore in negligible amounts. Could this difficulty be avoided, and uranium-238 fissioned without moderating neutrons? Kurchatov suggested that natural uranium should be irradiated in an experiment by fast neutrons in order to induce a chain reaction.

This experiment was performed by K. A. Peterzhak, also a former Kurchatov undergraduate, who worked at the Radium Institute where Kurchatov headed the Physical Department, and myself. The experimental arrangement was very simple. The source of neutrons was a small ampoule with an emanation of radium – a radioactive gas, radon. A bit of berillium powder was added to it. Alpha particles emitted by radon collided with berillium nuclei and induced a nuclear reaction which produced neutrons emitted from the ampoule. In those days radon ampoules substituted the accelerator for much physical research – the only cyclotron in the world was in E. O. Lawrence laboratory in California.

Adjacent to the ampoule was a uranium ionization chamber, basically a flat capacitor. The plates of the

K. A. Peterzhak (on the right) and G. N. Flerov in the laboratory, 1939

chamber were charged by ions produced by fast fission fragments dashing through the gas. The fragments escaped under neutron bombardment from the uranium that covered the plates. Electric pulses from the plates were applied to an amplifier and then to recording equipment.

A specific feature of the experiment was to reach extreme sensitivity of the setup because natural uranium was known to fissure rather weakly. The more uranium charged into the chamber, the higher the effect. How can the loading of the chamber be increased? An idea was developed from a multifinned variable capacitor used for tuning radio sets. In analogy with this component we decided to fit the chamber with many alternating positive and negative plates. It is quite obvious that the more plates the more uranium in the chamber.

It is easy to tell, but actually we had to make all the equipment ourselves. The chamber called for the most attention. We bought uranium salt in photography shops – in those days it was used for treating photographic materials. Greenish-yellow crystals of uranil nitrate were baked in an oven. The oxide produced was ground in an agate mortar filled with alcohol to prevent radioactive dust from penetrating into our lungs. Then a glue (shellac) was dissolved in this black suspension.

What remained was to apply this material on the plates in a thin layer. But the gap between the plates was only 3 mm. Should a hair from a brush or a large crystal stick between the plates, a short circuit would occur! Here the former trade of Peterzhak came in handy – he had worked as a painter in a porcelain factory. The century-refined technology of applying designs to dishes proved extremely useful for applying uranium on the plates.

We assembled the setup, aligned the amplifier. Commonly the first run should be devoted to zero-effect measurement, that is to record the background without the neutron source operative. Yet we decided to check the real effect and moved the radon ampoule close to the chamber. The counter started clicking busily, recording the fission of uranium by neutrons.

We removed the ampoule and the clicking ceased. We were ready to assume that there was no zero effect when a click came, then again and again.... The chamber recorded six decays per hour without any source at all.

What was it? Spontaneous fission of uranium nuclei? Theory had predicted the existence of such a phenomenon and Niels Bohr had even derived the half-life of uranium by its spontaneous fission and obtained a huge value of 10^{22} years. W. Libby, an American physicist, attempted to detect the spontaneous fission of uranium but failed and established only the lower limit, eight orders of magnitude smaller than the value predicted by Bohr. Perhaps the lifetime of uranium determined by spontaneous fission had a value lying anywhere between 10^{14} and 10^{22} years? Our hopes, however, were raised by the fact that the sensitivity of our setup was much better than that of Libby's. Nevertheless, Kurchatov said: "Most probably this is due to some dirt. Have another thorough check".

We very rapidly excluded the effects of extraneous interference and pickups from the mains and tram in the nearby street. The latter was very simple to eliminate – we just switched to night work. To eliminate the effect of radioactive pollution of the laboratory in the Radium Institute, where radioactive experiments had already been performed for two decades, we moved to another place, Fiztekh. The chamber kept counting its six pulses per hour without fail!

In the situation it seemed safe to declare a discovery. "If the situation is as you have it, then you should put aside all the rest and concentrate on it. Verify it a year, two, a decade, take as long as you need. To observe a new phenomenon is the chance of a lifetime and then not for everybody", Kurchatov concluded and immediately designed a new series of control experiments.

In science one negative conclusion is at times more valuable than a dozen positive results. We could not exclude completely the other causes irrelevant to uranium fission. The effect, for example, might be traced to alpha decay of uranium. If a few α-particles were emitted simultaneously, then their compound impulse might be mistaken for a signal from a fission fragment. Or random charges might occur on the plates of the chamber.

Checking, rechecking and re-rechecking. They needed time. Weeks and months went and ever new articles concerned with uranium fission were published in physics journals. Holding our breath we leafed each fresh copy – afraid of finding a report on the discovery of spontaneous fission. Finally there remained only cosmic rays which when incident on the uranium plates might produce the familiar clicks. Where could we hide our setup from them?

At first we wished to put it into a submarine and dive to the bottom of the sea. However, the Baltic Sea is shallow near Leningrad and twenty meters of sea water is an insufficient shield from cosmic radiation. And we decided to descend into the Moscow underground. Our laboratory there was a small staff room in the underground station Dinamo. This station is at a depth sufficient for our experiment. The cosmic radiation there was only one twentieth of that on the surface. Half a year we worked at night, underground. We repeated all we had done at sea level. The effect was there!

Early in 1940, Ioffe, Director of Fiztekh, sent a cable about the discovery of spontaneous fission of uranium nuclei in the American Journal *Physical Review* where all fundamental studies on fission were published at that time.

A miraculous chance preserved our first domestic report on this work. The last page has this: "The fact that heavy nuclei undergo spontaneous fission has extremely important implications not only in physics but also in chemistry as it is able to answer the question about the boundary of the periodic system..."

The principle of the cyclotron. The idea of the first cyclic accelerator, a cyclotron, was devised by the American scientist Ernest O. Lawrence in 1930. Together with M. S. Livingston he constructed in 1932 the first ever cyclotron having a diameter of the magnet pole pieces of only 27.9 cm.

The charged particle, an ion, is accelerated in an electric field. It is a difficult engineering task to impart all the desired energy to the particle in one pass through the field. To this end one has to produce extremely strong electric fields with a potential difference as high as a few million volts. It is sufficient to just look at a high voltage transmission line to perceive that this way is bound to entail great technical difficulties. In the accelerator these high voltages would be applied at very small lengths such that the best available insulators would be helpless against breakdown.

The idea of Lawrence was to impart this energy to the particle in small multiple portions.

The ions to be accelerated emanate from the centre of the cyclotron where they are ejected by a source. The accelerator chamber evacuated to a high vacuum is placed in a magnetic field.

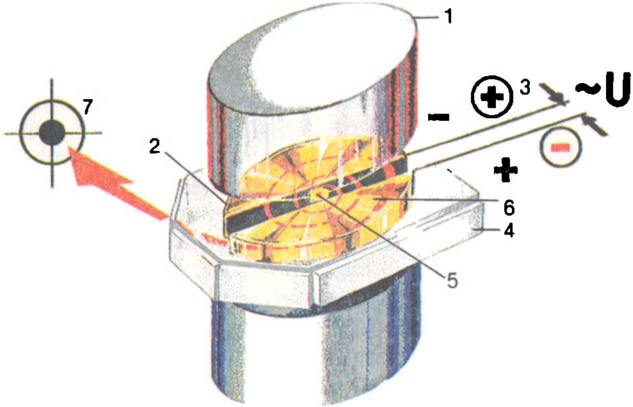
An ion of charge e moving at a velocity $\vec{v}$ in a magnetic field of magnetic flux density $\vec{B}$ is acted upon by the Lorentz force:

$$\vec{F} = e(\vec{v} \times \vec{B})$$

This force is applied perpendicular to both the direction of motion and the magnetic field. It continuously deflects the ion to the cyclotron's centre.

Without acceleration, the ion of mass m would move in the cyclotron in a circle of radius $r = mv/eB$, called the cyclotron radius. This radius increases progressively as the ion velocity increases on acceleration, so the particle moves in a spiral path.

The ion receives its acceleration from two metallic hollow semicylinders, called dees, which look like halves of a flat can cut by a perpendicular plane passing through the centre. The ions to be accelerated spiral inside the dees. The dees are slightly shifted apart and charged by opposite electric charges so that in the gap between them



Artist's rendition of the idea of the cyclotron
1 – magnet pole; *2* – dees; *3* – rf voltage; *4* – vacuum chamber; *5* – ion source; *6* – trajectories of ions, *7* – target

there is an electric field. Inside the dees an electric field is absent because, as will be recalled from electrostatics, a closed charged envelope has a zero field inside.

On the way from the positive dee to the negative, a positive ion is repelled by the former and attracted by the latter and, as a result, is accelerated in the gap. After a semicircle the ion again enters the accelerating gap. To supply it with another accelerating momentum the dees change their charges to the opposite by this moment.

It is important to note that the motion of the ion in the cyclotron is periodic with a frequency $\omega = eB/mc$. This frequency remains constant during acceleration as it depends only on the charge and mass of the ion and the magnetic flux density.

The dees are fed with an alternating electric current from a high frequency (rf) generator. If the frequency of the rf generator is equal to the cyclotron frequency ω the unit falls in synchronism and when the ion passes the gap it is always acted on by an accelerating electric field.

After multiple crossings through the gap the ion gradually picks up high energy. The ultimate energy (in cgs units) is conditioned by the radius of the cyclotron's magnet R:

$$E_{\text{lim}} = \frac{e^2 B^2}{2mc^2} R^2$$

where c is the velocity of light. This expression indicates that the heavier the ion the larger should be the size of magnet's pole pieces, and the greater the charge of the ion, the greater the energy it can be imparted in this cyclotron. That is why the ion source must strip as many electrons as possible from the electronic shell of the atom.

The successful operation of the U-300 cyclotron, that for fifteen years had remained second to none in its performance characteristics, and the development of the new record-holder U-400 have proved that the cyclotron was, is and, hopefully, will be the basic type of accelerator for heavy ions.

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G. N. Flerov, now a full member of the Academy of Sciences of the USSR, was born in 1913, graduated from the Leningrad Polytechnic Institute. He began his research work while still a student, in the laboratory headed by I. V. Kurchatov, the head of the Soviet atomic programme in the 1940-50s. The last two decades G. N. Flerov has been Director of the Laboratory of Nuclear Reactions at the Joint Institute for Nuclear Research in Dubna near Moscow. At this institute the research group he is leading has carried out a number of fundamental investigations into the physics of heavy ions and has discovered six new elements of the periodic table. Together with K. A. Peterzhak, a Soviet experimental physicist, Flerov discovered the spontaneous fission of nuclei in 1940. He received various awards and honors from the Soviet Government for his great scientific achievements, specifically, he holds the Lenin and State Prizes of the USSR.

A. S. Ilyinov, Dr Sc. (Physics) is a theoretical physicist at the Institute of Nuclear Research of the Academy of Sciences of the USSR. Born in 1944, he graduated from the physics department of the Polytechnic Institute, Tomsk, in 1968. His current research interests concern nuclear reactions. He is the author of about 70 technical publications and a co-author of the discovery of elements 106 and 107.