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150 years since the development of the Periodic System of Chemical Elements by D.I. Mendeleev

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The year 2019 has been declared by UNESCO as the year of the Periodic Table of Elements. 150 years ago, an outstanding Russian scientist D.I. Mendeleev systematized the chemical elements known at that time by chemical properties and created a table of elements. Since then, almost 60 chemical elements have been added to those known 150 years ago. Now the table has 118 chemical elements, most of which were synthesized artificially, in particular, on charged particle accelerators. Especially vigorous growth in the synthesis and research of new heavy transactinoid elements was observed during the last 20 years, when about 20 new heavy and super heavy elements were synthesized in various world research centers with powerful accelerator complexes. In the present article, the authors discuss the current situation in the synthesis of new elements with an atomic number greater than 110 and the prospects for further advancement in the region of super heavy elements.

Keywords: periodic system of chemical elements, heavy transactinoid elements, charged particle accelerator.

Introduction

On February 17 (March 1), 1869, Mendeleev submitted a manuscript “Experience in a system of elements based on their atomic weight and chemical similarity”—the first version of the Periodic Table of Elements. The final formulation of the Periodic Law, the fundamental law of nature, was presented to scientists in July 1871. A specific feature of the Periodic Law defining its place among other fundamental laws is that it is not expressed as a mathematical equation but has its graphic (tabular) expression in the form of the Periodic System of Elements

developed by Mendeleev. The discovery of the Periodic Table of Elements was not accidental; it was the result of enormous, long and painstaking work, which was done by Mendeleev himself and by many chemists from among his predecessors and contemporaries. "When I began to finalize my classification of elements, I wrote each element and its compound on a special card, and then, arranging them in the order of groups and series, I got the first visual table of the periodic law. But this was only the final chord, the result of all the previous work ...," said the scientist.

Mendeleev pointed out that his discovery was the culmination, which completed a twenty-year period of investigations of the relationships between the elements, deep pondering on their interrelations.

The manuscript of the article, containing the table entitled "Experience of a system of elements based on their atomic weight and chemical similarity" was completed and submitted for publishing with notes for typesetters and the date "February 17, 1869". The report on the discovery of Mendeleev was made by the editor of the Russian Chemical Society, Professor N.A. Menshutkin at the meeting of the company on February 22 (March 6), 1869. Mendeleev himself was not present at the meeting, because at that time, by the order of the Free Economic Society, he examined the cheese dairies of the Tver and Novgorod provinces.

In the first version of the system, the elements were arranged by the scientist in nineteen horizontal rows and six vertical columns. On February 17 (March 1), the discovery of the periodic law was not finished, it was just the beginning. Mendeleev continued its development for almost three years. In 1870, in the *Fundamentals of Chemistry*, Mendeleev published the second version of the system (The Natural System of Elements): horizontal columns of similar elements turned into eight vertically arranged groups; the six vertical columns of the first variant turned into periods beginning with an alkali metal and ending with a halogen. Each period was divided into two rows; elements of different rows included in the group formed subgroups.

Since the time of creation of the periodic table, dozens of new elements discovered in nature and artificially synthesized at accelerators were added to it. Especially great progress in this area has been made by physicists and chemists recently, who filled the last cells of the table up to the 118th element. A lot of monographs and articles have been written about the periodic table. In this article, we wanted to acquaint readers with the latest achievements in the artificial synthesis of heavy and superheavy elements [1-6]. Many elements heavier than uranium were synthesized in reactions of successive neutron capture by the nuclei of the uranium isotope ^{235}U in the long-term irradiation in powerful nuclear reactors. Long half-lives of the new nuclides made it possible to separate them from other reaction by-products by radiochemical methods, followed by measuring of their radioactive decay properties. These pioneering works of prof. G. Siborg and his colleagues, conducted in 1940-1953 at the Radiation National Laboratory (Berkeley, USA) led to the discovery of eight artificial elements with $Z=93-100$. The heaviest artificially synthesized isotope was ^{257}Fm ($T_{1/2} \approx 100$ days). Further advancement into the region of heavier nuclei was almost impossible due to the extremely short half-life of the next isotope – ^{258}Fm ($T_{1/2} = 0.3$ milliseconds).

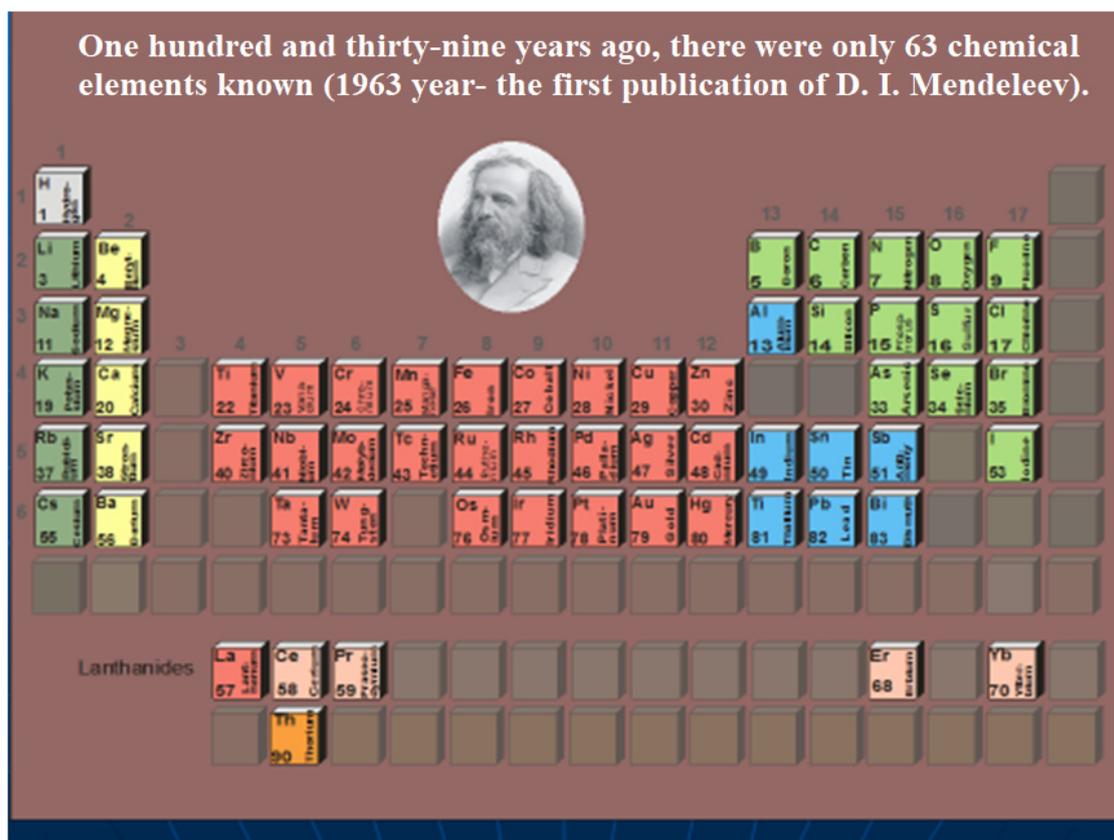


Figure 1. Only 63 chemical elements were known in 1880.

Attempts to circumvent this limitation in high-power pulsed neutron fluxes arising from a nuclear explosion did not produce the desired results: ^{257}Fm still remained the heaviest nucleus.

Elements heavier than Fm ($Z=100$) were synthesized in reactions with accelerated heavy ions, when a complex of protons and neutrons is introduced into the target nucleus. Physics of heavy ions has recently become one of the main directions of the science of the atomic nucleus. Heavy ions are ions of elements with $Z>2$ and $A>4$ (heavier than helium). The interaction of heavy ions with nuclei is characterized by a radical restructuring of nuclear systems containing hundreds of nucleons, which participate in such reactions. All this leads to a variety of reaction channels – the pathways along which changes in the interacting nuclei occur. In such reactions either a complete fusion of the ion with the nucleus or a transfer of a different number of nucleons (from one to several tens or a whole bunch of nuclear matter) from the ion to the nucleus or vice versa can occur. The resulting nuclear system can be unstable and decay in a very short time ($\approx 10^{-20}$ s), or it can reach thermal equilibrium and exist in such a state for a very large time on the nuclear scale.

The decay of this system can be associated both with the emission of individual nucleons, and with its decay into two approximately equal parts. Thus, the study of nuclear reactions with heavy ions makes it possible to obtain important data on the collective nuclear motion of large amplitude, which is characterized by an extremely large change in the nuclear form as well as by a strong and repeated redistribution of energy between different degrees of freedom of the system.

The first experiments with heavy ions showed that in collisions between two nuclei one can obtain composite nuclei with a very high temperature as high as several MeV, which is more than 10¹⁰ K. In a tangential collision, the spin of the nucleus can reach 50, 60, and even 80 h, and such a nucleus can be severely deformed with 3:1 axis ratio, and after all this, such a nucleus can still survive. After that, it became clear that heavy ions are an excellent tool to study nuclei with such extreme characteristics as high temperature, high angular momentum and strong deformation. And then, around the world, special heavy-ion accelerators were built, then national laboratories for investigations of heavy ions were created: in the USA, France, Germany, Italy, Japan. And then colliders for accelerating heavy ions were built: in Brookhaven (USA), at CERN, in Germany. In Dubna, a NIKIA heavy-ion collider is also being created. Thus, this direction – the physics of heavy ions began to develop rapidly and effectively in the World.

At present, very little is known about the motion of such a scale in the nuclei. In particular, there is little information on the dynamics of large-scale changes in the shape of the nucleus, and on the relationship between the collective motion of many nucleons of the nucleus and the motion of its individual particles. Nuclear reactions caused by light particles did not allow us to study these processes, and only the appearance of beams of accelerated heavy ions created conditions for their detailed study.

In collisions of heavy ions with nuclei, such an interesting and important property of nuclear matter as its viscosity is fully manifested. This property characterizes the intensity of energy exchange between collective degrees of freedom, which describe the geometric shape of the nucleus as a whole, and internal degrees of freedom, which determine the motion of individual nucleons with respect to a fixed shape. The data on the value of nuclear viscosity, its dependence on the excitation energy, and the nucleon composition of the nucleus are of fundamental importance for understanding the dynamics of the interaction of heavy ions with nuclei, in particular, for solving the problem of possibility of fusion of the heaviest nuclei and the value of the excitation energy of the resulting composite system.

The unique properties of heavy ions make it possible to obtain and study nuclei that are significantly different from those known in nucleon composition or in unusual states. A vast variety of nuclear reactions with heavy ions and a huge number of possible ion-target combinations open up favorable prospects for producing isotopes of known elements with a large excess or deficiency of neutrons lying on the boundary, or even beyond the nucleon stability boundary. Only in reactions with heavy ions can one obtain nuclei with an atomic number 20-30 units larger than the heaviest target nuclei. Therefore, such reactions are the only way to produce new transuranic elements. It is known that the stability of these elements rapidly decreases with increasing atomic number.

From the point of view of the classical concepts laid down by N. Bohr and J. Wheeler, a heavy nucleus with $Z > 110$ becomes absolutely unstable with respect to spontaneous fission (its lifetime should be only $\approx 10^{-20}$ s). However, the shell structure of the nuclei can significantly increase its stability. Studies of the properties of transuranic elements with $Z > 104$ have shown that their lifetimes with

respect to spontaneous fission decrease much more slowly than it follows from classical concepts. Theoretical calculations taking into account the shell structure of nuclei explain this result and predict the existence of a region of stable heavy nuclei near closed shells of 114 protons and 184 neutrons. Recent experiments conducted in Dubna showed that the island of stability of super heavy nuclei was reached [7, 8]. Thus, the physics of heavy ions studies nuclear matter in extreme states (exotic nuclei) and nuclear transformations occurring under extreme conditions. Heavy ions make it possible to obtain nuclei with a very high excitation energy (hot nuclei), with an extremely large angular momentum (madly rotating nuclei), highly deformed nuclei (super and hyper deformation, nuclei with an unusual shape configuration), nuclei with an anomalously high number of neutrons or protons (neutron-rich and proton-rich nuclei), super heavy nuclei with the number of protons $Z > 110$. Studying the properties of nuclear matter in extreme conditions provides important information about the properties of the microworld and thus allows us to simulate various processes occurring in the Universe. Reactions with heavy ions provide a unique opportunity to obtain nuclei near the boundaries of stability and penetrate into the region of chemical elements of the second hundred.

Nuclear reactions with heavy ions make it possible to study collective nuclear processes, characterized by extremely large changes in the nuclear form, and a strong redistribution of energy between different degrees of freedom of systems. At the same time, the use of heavy ions not only creates a solid foundation for the successful development of fundamental research in the physics of the atomic nucleus, but also opens up unique opportunities for solving many urgent applied problems in various fields of engineering, technology, biology, and medicine.

One of the examples is the radiation effect of accelerated heavy ions on a substance. High specific losses of ion energy during their passage through matter cause a strong destruction of materials with a very weak level of induced radioactivity. This opens up wide possibilities for using heavy ions to model radiation damage caused by fast neutrons in the structural materials of nuclear reactors, as well as in future thermonuclear installations. The number of such examples can be significantly increased - this is doping of semiconductor materials, production of nuclear filters, which can be attributed to nanotechnology, and production of radioactive isotopes for medicine. Currently, in a number of countries there are research centers where several dozen accelerators are already operating, on which intense ion beams with energies up to several thousand MeV/nucleon have been obtained. A wide range of studies, both fundamental and applied, are carried out on the beams of these ions. Summing up this information, it can be noted that heavy ion physics is primarily the physics of extreme nuclear states and the physics of nuclear transformations occurring under extreme conditions. This defines its originality and main merit. Before describing the processes that occur during the interaction of heavy ions with nuclei and the characteristics of the nuclei formed in these processes, it is appropriate to recall the basic concepts used in nuclear physics to describe the properties of nuclei. However, let us return to the synthesis of transfermium nuclei in reactions with heavy ions. This type of reaction is different from neutron capture reactions. When a neutron that does not have an electric charge is captured, the excitation energy

of the new nucleus is only (6-8) MeV. In contrast, when the target nuclei fuse even with light ions such as helium (${}^4\text{He}$) or carbon (${}^{12}\text{C}$), heavy nuclei will be heated up to an energy of $E_x = (20-40)$ MeV. With a further increase in the atomic number of the projectile nucleus, it will be necessary to supply more and more energy to overcome the electric forces of repulsion of positively charged nuclei (Coulomb reaction barrier). This circumstance leads to an increase in the excitation energy (heating) of the compound nucleus formed after fusion of two nuclei - the projectile and the target. Its cooling (transition to the ground state $E_x = 0$) will occur through the emission of neutrons and gamma rays.

However, a heated heavy nucleus can only emit a neutron in 1/100 of the cases. In most cases, it will be divided into two fragments, because nuclear energy is significantly higher than the height of its fission barrier. The probability of survival of a heated nucleus decreases sharply with increasing temperature (or E_x energy) due to an increase in the number of evaporated neutrons, with which fission strongly competes. In order to cool a nucleus heated to an energy of about 40 MeV, 4 or 5 neutrons must be evaporated. Each time, fission will compete with neutron emission, as a result of which the probability of survival will be only $(1/100)^{4-5} = 10^{-8} - 10^{-10}$. The situation is complicated by the fact that with increasing nucleus temperature the stabilizing effect of the shells decreases, therefore, the height of the fission barrier decreases and the fissility of the nucleus sharply increases. Both of these factors lead to an extremely low probability of formation of super heavy nuclides.

Advancement into the region of elements heavier than 106 became possible after the discovery of the "cold fusion" reactions in Dubna in 1974. In these reactions, the "magic" nuclei of stable isotopes ${}^{208}\text{Pb}$ ($Z=82, N=126$) or ${}^{209}\text{Bi}$ ($Z=83, N=126$), which are bombarded by ions heavier than argon, are used as target material. In the process of fusion, the high binding energy of nucleons in the "magic" target nucleus leads to energy absorption during the rearrangement of two interacting nuclei into a heavy nucleus of the total mass. This difference in the energies of the "packing" of nucleons in the interacting nuclei and in the final nucleus mainly compensates the energy needed to overcome the high Coulomb barrier of the reaction. As a result, the heavy nucleus has an excitation energy of only (12-20) MeV. To some extent, such a reaction is similar to the process of "backward fission". Indeed, if the fission of the uranium nucleus into two fragments occurs with the release of energy (it is used in nuclear power plants), then in the reverse reaction, when the fragments fuse, the formed uranium nucleus will be almost cold. Therefore, in the synthesis of elements in cold fusion reactions, it is sufficient for a heavy nucleus to emit only one or two neutrons in order to transfer to the ground state.

The cold fusion reactions of massive nuclei were successfully used to synthesize 6 new elements, from 107 to 112 at the GSI National Nuclear Physics Center in Darmstadt (Germany), as well as at the RIKEN National Center (Tokyo) for the synthesis of 110-113 elements. Both groups intend to move on to heavier elements using heavier projectiles. However, attempts to synthesize heavier elements in cold fusion reactions are associated with great difficulties. With an increase in the atomic charge of ions, the probability of their fusion with the nuclei of the ${}^{208}\text{Pb}$

or ^{209}Bi target decreases significantly due to an increase in the Coulomb repulsive forces proportional, as is known, to the product of nuclear charges. From the element 104, which can be obtained in the reaction $^{208}\text{Pb} + ^{50}\text{Ti}$ ($Z_1 \cdot Z_2 = 1804$) to the element 112 in the reaction $^{208}\text{Pb} + ^{50}\text{Ti}$ ($Z_1 \cdot Z_2 = 1804$), the probability of fusion decreases by more than 10^4 times.

In addition, the compound nuclei obtained in cold fusion reactions have a relatively small number of neutrons. In the case of the formation of the 112th element considered above, the final nucleus with $Z = 112$ has only 165 neutrons, while the stability increase is expected for the number of neutrons $N > 170$ (see Figure 2). Nuclei with a large excess of neutrons can, in principle, be obtained if artificial elements produced in nuclear reactors: plutonium ($Z = 94$), americium ($Z = 95$), curium ($Z = 96$), or californium ($Z = 98$) are used as targets, and as a projectile - a rare calcium isotope - ^{48}Ca . Super heavy elements up to the 118th can be synthesized. For the synthesis of elements with $Z > 118$, beams of even heavier ions are required. In the fusion of such heavy nuclei, quasi-fission processes play a significant role, significantly reducing the likelihood of a compound nucleus formation. Thus, the entire process of the formation of a "cold" (in the ground state) superheavy nucleus B , which is the final product of the "cooling" of the excited nucleus C , formed in the fusion reaction of two heavy nuclei $A_1 + A_2 \rightarrow B + n, p, \alpha, \gamma$, can be decomposed into three stages, shown schematically in Figure 3.

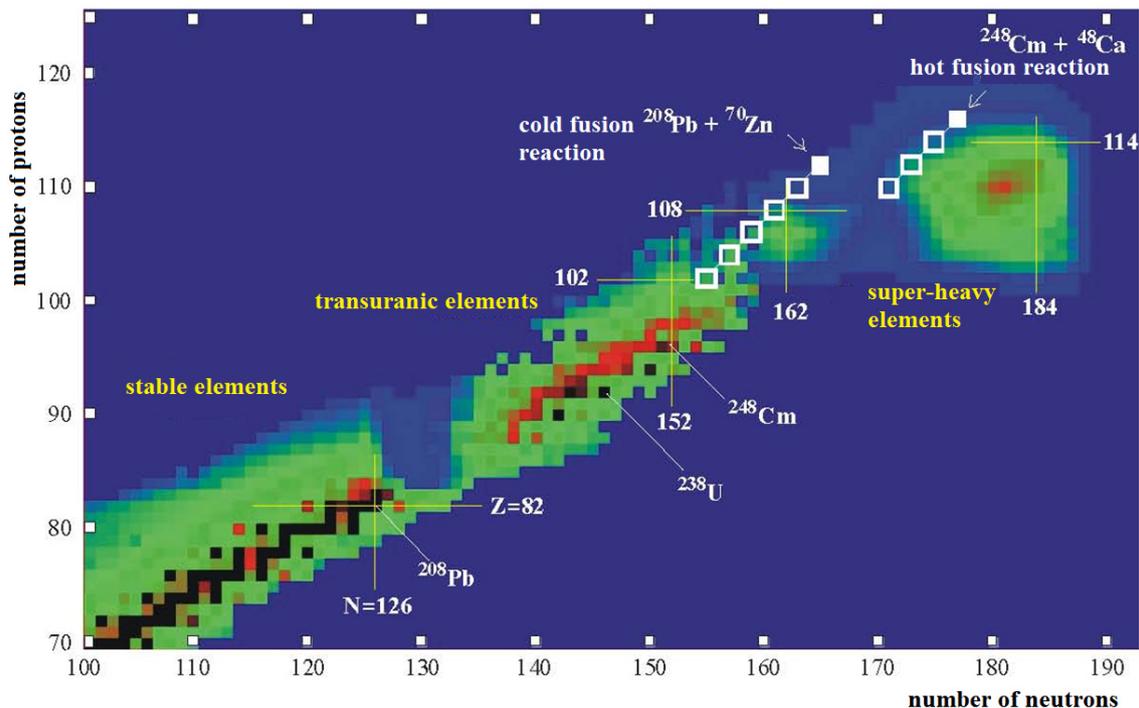


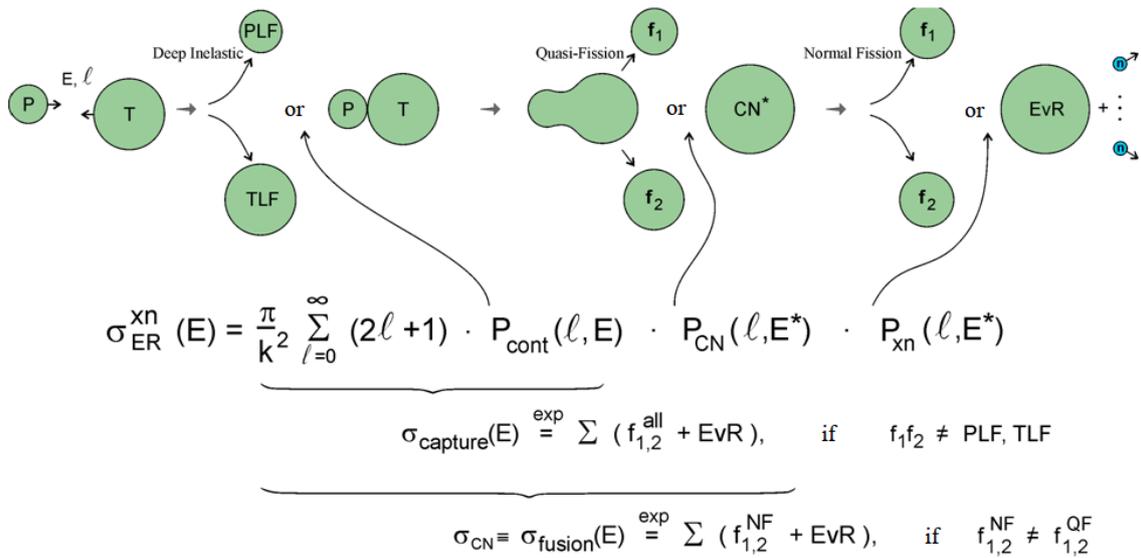
Figure 2. The map of heavy nuclides. The half-lives of the nuclei are represented in different colors (right scale). Black squares are isotopes of stable elements found in the earth's crust ($T_{1/2} \geq 109$ years). The dark blue color is the "sea of instability", where the nuclei live less than 10^{-6} seconds. The yellow lines correspond to closed shells indicating the magic numbers of protons and neutrons. The "islands of stability" following the "peninsula" of thorium, uranium and transuranium elements are predictions of the microscopic theory of the nucleus. Two nuclei with $Z = 112$ and 116, obtained in various nuclear reactions and their chain decay, show how close one can get to the "islands of stability" in the artificial synthesis of super heavy elements.

Super heavy elements can be synthesized up to the number 118. For the

synthesis of elements with $Z > 118$, beams of even heavier ions are required. In the fusion of such heavy nuclei, an important role is played by competing processes, for example, quasi-fission, which significantly reduces the likelihood of the formation of a compound nucleus. Thus, the entire process of the formation of a “cold” (in the ground state) super heavy nucleus B , which is the final product of the “cooling” of the excited nucleus C , formed in the fusion reaction of two heavy nuclei $A1 + A2 \rightarrow B + n, p, \alpha, \gamma$, can be decomposed into three stages, shown schematically in Figure 3.

At the first stage of the reaction, the colliding nuclei overcome the Coulomb barrier and come into close contact with the overlap of their surfaces. This process competes with elastic and quasi-elastic nuclear scattering (including reactions of low-nucleon transfers) with the formation of two fragments that are close in mass to the projectile and target. This competition is highly dependent on the energy of the colliding nuclei and on the impact parameter, i.e. the orbital momentum of the relative motion of the nuclei.

At the second stage of the reaction, the configuration of two contacting nuclei should be transformed into a configuration with respect to a spherically symmetric composite nucleus. During this evolution, a heavy nuclear system can decay into two fragments f_1 and f_2 without formation of a composite nucleus. This process is called quasi-fission.



P_{cont} : probability of passing through a multidimensional potential barrier $V_C^B(r, \beta_1, \beta_2, \varphi_1, \varphi_2) - ?$
 P_{CN} : spatial evolution of parameters of (?)
 P_{xn} : statistical decay of a low-excited nucleus ($\Gamma_n, \Gamma_f, E_n^{\text{sep}}, B_{\text{fis}} - ?$)

Figure 3. A scenario of formation of a superheavy nucleus in a fusion reaction.

If a compound nucleus is formed, then it has an angular momentum and an excitation energy E^* . The fission barriers of heavy nuclei are quite low, and the main decay channel of the excited states of these nuclei is fission. If, in competition with fission, the excited compound nucleus manages to emit several light particles and gamma rays, which will take away the excitation energy and the angular momentum of this nucleus, then the result is the so-called evaporation residue, i.e.

nucleus B , in the ground state. The cross section for formation of the evaporation residue of a super heavy nucleus is determined by the expression that includes the probability of the formation of a compound nucleus P_{CN} in competition with quasi-fission [5, 6]. Thus, two main factors make the cross sections for the formation of super heavy elements very small: low probability of formation of a compound nucleus in competition with the dominant quasi-fission process (P_{CN}) and low probability of survival of the excited compound nucleus (P_{EvR}^{xn}).

Estimation of cross sections for the formation of superheavy elements in the reactions of "hot" synthesis with a ^{48}Ca beam using heavy actinide targets showed that these reactions are optimal up to the atomic number 118. The nucleus of the ^{48}Ca atom contains 20 protons and 28 neutrons - both values correspond to closed shells. In the fusion reactions with ^{48}Ca nuclei, their "magic" structure will also work (this role in the cold fusion reactions was played by the magic nuclei of the target - ^{208}Pb) [9, 10], as a result of which the excitation energy of super heavy nuclei will be about (30-35) MeV. Their transition to the ground state will be accompanied by the emission of three neutrons and gamma rays. It can be expected that at this excitation energy, the effect of nuclear shells is still present in heated super heavy nuclei, which increases their survival. In this case, the asymmetry of the masses of interacting nuclei ($Z_1 \cdot Z_2 \leq 2000$) reduces their Coulomb repulsion and thus increases the probability of fusion. Despite these seemingly obvious advantages, all previous attempts to synthesize super heavy elements in reactions with ^{48}Ca ions made in various laboratories in 1977-1985 were not successful.

However, the development of experimental technology in recent years, and, above all, the production of intense ^{48}Ca ion beams at new generation accelerators, has made it possible to increase the sensitivity of the experiment by almost 1000 times. These achievements were used in a new attempt to synthesize super heavy elements.

In the fusion reactions of accelerated ^{48}Ca ions in Dubna at the turn of the 21st century 6 new elements were synthesized, starting from the 113th and ending with the 118th, obtained in the fusion reaction of ^{48}Ca ($Z=20$) with the heaviest ^{249}Cf target ($Z=98$). In November 2016, the discovery of new chemical elements with atomic numbers 113, 115, 117 and 118 in the D.I. Mendeleev Periodic Table was approved by the International Union of Pure and Applied Chemistry (IUPAC) and the International Union of Pure and Applied Physics (IUPAP).

For the element with atomic number 113, the authors of its discovery from RIKEN (Nishina Center for Accelerator-Based Science, Japan) proposed the name "nihonium" and the symbol Nh. Nihon is one of the variants of Japanese pronunciation of the word Japan and literally means "Land of the Rising Sun". All other elements, including the 114th (flerovium), as well as the elements with atomic numbers from 115 to 118 were discovered at G.N. Flerov Nuclear Reaction Laboratory in the JINR.

For the element with atomic number 115, the name "moscovium" and the symbol Mc were proposed, and for the element with atomic number 117 - "tennessine" and the symbol Ts. The names were given in honor of the place or geographical area and were jointly proposed by the authors of discoveries from the Joint Institute for Nuclear Research in Dubna (Russia), the Oak Ridge National Laboratory (USA),

Vanderbilt University (USA) and Lawrence Livermore National Laboratory (USA). The name "Muscovy" pays tribute to the city of Dubna, Moscow Region. The name "Tennessee" is given in recognition of the contributions of the Tennessee region, including the Oak Ridge National Laboratory, Vanderbilt University and the University of Tennessee at Knoxville in the study of super heavy elements.

For the element with atomic number 118, the collaborating teams of the authors of its discovery from JINR (Russia) and the Lawrence Livermore National Laboratory (USA) proposed the name "Oganesson" and the symbol Og. The proposal follows the tradition of honor and reflects the recognition of the innovative contribution of Professor Yuri Oganessyan to the study of transactinide elements.

His achievements inscribe the discovery of super heavy elements and significant progress in nuclear physics of super heavy elements, including experimental confirmation of the existence of the "island of stability" as it was formulated in the IUPAC decision.

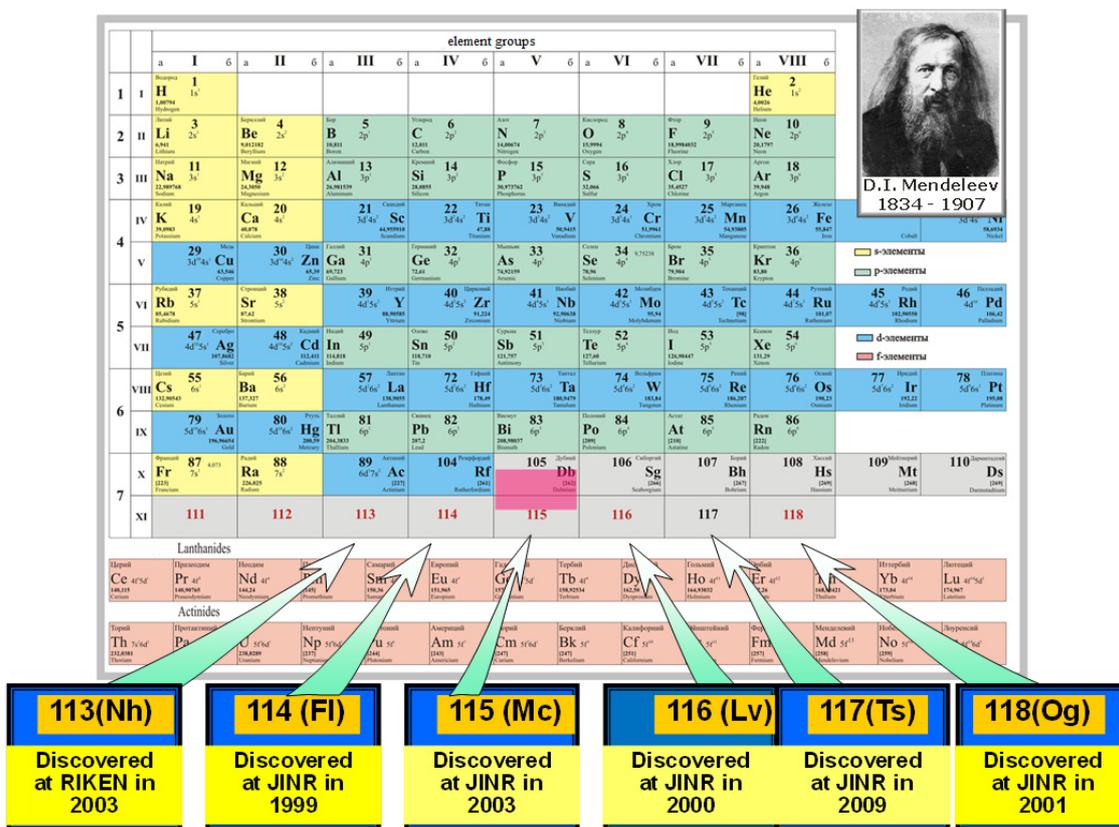


Figure 4. Modern Mendeleev table of chemical elements.

In the synthesis of Z-even nuclides – isotopes of 112, 114 and 116 elements – long decay chains are observed ending in spontaneous fission of nuclei with Z=104-110, the lifetime of which ranged from seconds to hours depending on the atomic number and neutron composition of the nucleus. To date, the data on the decay properties of 29 new nuclei with Z=104-118 have been obtained; they are presented on the nuclide map (Figure 4). The properties of the heaviest nuclei located in the trans actinoid region, their type of decay, energy and decay time are in good agreement with the predictions of modern theory [11-22]. The hypothesis of the existence of islands of stability of super heavy nuclei, significantly expanding

the world of elements, seems to have first found experimental evidence.

At present, the task is to study in more detail the nuclear and atomic structure of new elements, which is very problematic, primarily because of the small yield of the desired reaction products. In order to increase the number of atoms of super heavy elements, it is necessary to increase the intensity of the ion beam and the efficiency of physical methods. Modernization of heavy ion accelerators using all the latest achievements of accelerator technology will increase the ion beam intensity by about 5 times.

In 2019, the Laboratory of Nuclear Reactions launched a factory of super heavy elements, the basis of which is a high-intensity cyclotron of heavy ions. The solution of the second part requires a fundamental change in the setting of experiments; it can be found in the creation of a new experimental technique based on the properties of super heavy elements.

Figure 5 shows a nuclide map for heavy and super heavy elements. For the nuclei inside the ovals corresponding to various fusion reactions (shown in the Figure 5), the half-lives and energy of the emitted alpha particles (yellow squares) are given. The data are presented on a contour map dividing the region by the

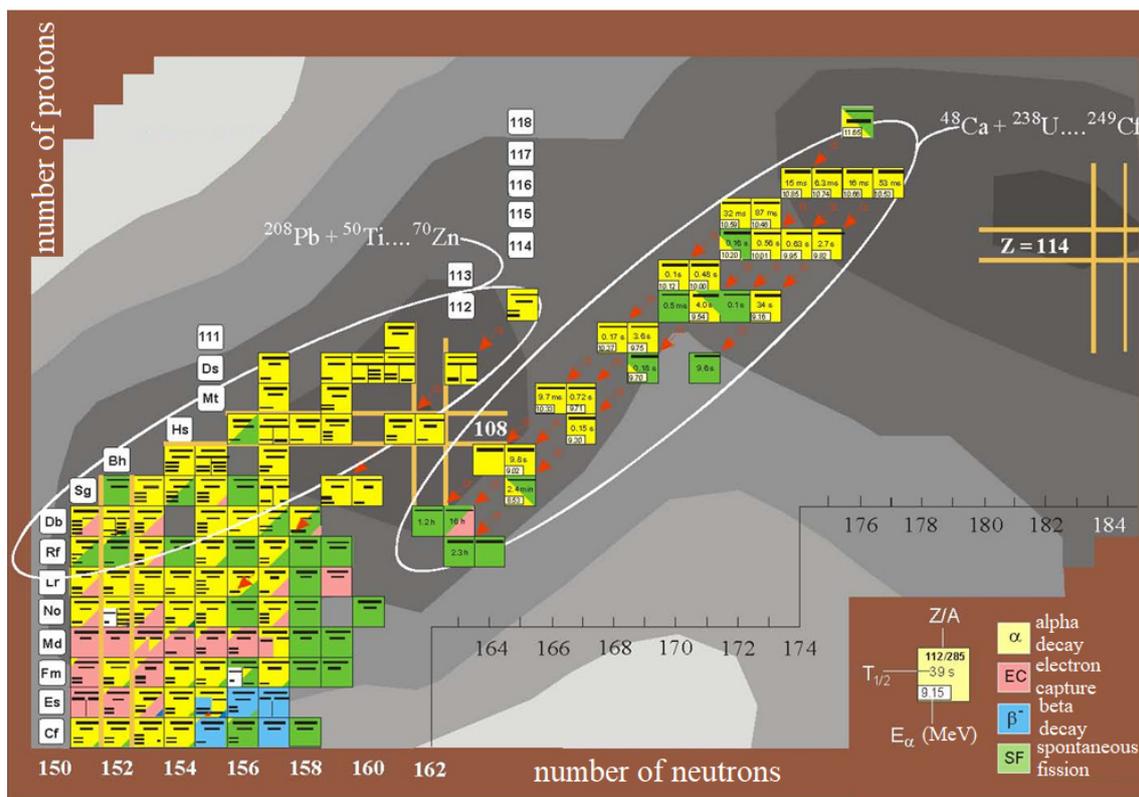


Figure 5. A map of nuclides of heavy and super heavy elements.

contribution of the nuclear shell effect to the binding energy of the nucleus. In the absence of the nuclear structure, the entire field would be white. The effect of shells increases with the darkening. Two neighboring zones differ by only 1 MeV. This, however, is sufficient to significantly increase the stability of nuclei with respect to spontaneous fission, as a result of which nuclides located near the "magic" numbers of protons and neutrons mainly experience alpha decay. On the other hand, in the isotopes of elements 110 and 112, an increase in the number of

neutrons by 8 atomic units leads to an increase in the alpha decay periods of nuclei by more than 105 times. Further advancement to the region $Z > 118$ is associated with the choice of an appropriate reaction. As mentioned above, the cross section for fusion reactions with actinide targets of ions heavier than ^{48}Ca dramatically decreases and does not give a chance to obtain new transuranic nuclei.

The heaviest target that can be used to produce super heavy nuclei in fusion reactions is californium ($Z=98$, $T_{1/2}(^{249}\text{Cf})=351$ years). If accelerated calcium ions ($Z=20$) are used as a projectile, it is possible to synthesize the element with atomic number 118. For the synthesis of elements with $Z > 118$, beams of even heavier ions are required. Therefore, in order to obtain super heavy elements with $Z > 118$, it is necessary to use projectiles heavier than ^{48}Ca . In this case, the likelihood of fusion decreases significantly. Figure 6 shows the predicted cross sections for the formation of elements 119 and 120 in the reactions $^{50}\text{Ti} + ^{249}\text{Bk}$, $^{50}\text{Ti} + ^{249}\text{Cf}$ and $^{54}\text{Cr} + ^{248}\text{Cm}$ and the upper boundaries of the experimental cross sections obtained at GSI (Darmstadt, Germany). To date (2019), these elements have not yet been synthesized, but the corresponding experiments continue in Dubna, at GSI and in the RIKEN laboratory (Japan). As already noted above, due

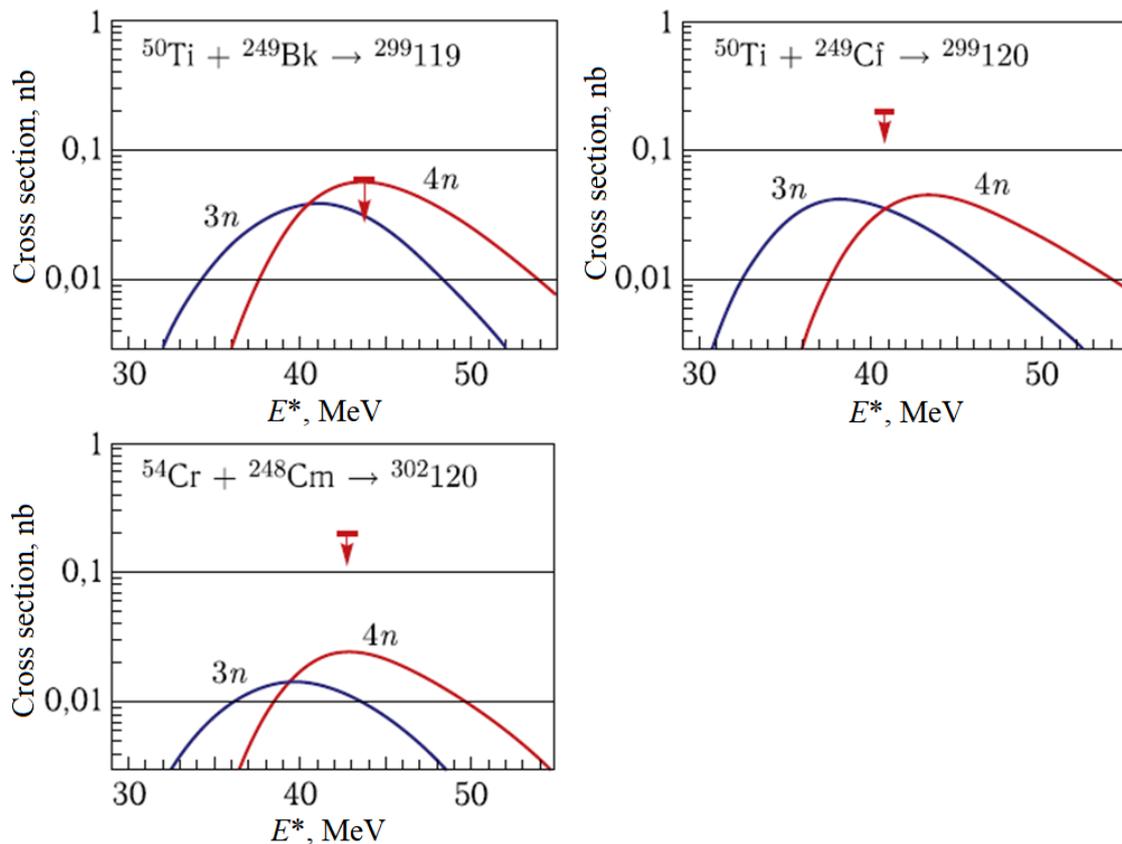


Figure 6. The predicted cross sections for the formation of superheavy elements 119 and 120 in the fusion reactions $^{50}\text{Ti} + ^{249}\text{Bk}$, $^{50}\text{Ti} + ^{249}\text{Cf}$ and $^{54}\text{Cr} + ^{248}\text{Cm}$. The arrows indicate the upper boundaries of the cross sections obtained in the experiments.

to the increasing inclination of the stability line to the neutron axis (an increase in the N/Z ratio with increasing A), in the fusion reactions of stable nucleon-rich proton-rich isotopes of heavy elements, located to the left of the stability line, are formed.

The use of beams of neutron-rich nuclei, such as ^{50}Ti , ^{54}Cr , ^{56}Fe , etc., may be almost the only method of synthesizing nuclei in the region of $40 < N < 70$ at the nucleon stability boundaries.

In the near future, it is planned to synthesize elements 119 and 120 in the fusion reactions $^{50}\text{Ti} + ^{249}\text{Bk}$, $^{50}\text{Ti} + ^{249}\text{Cf}$ and $^{54}\text{Cr} + ^{248}\text{Cm}$. Isotopes of these elements will also be located in the region of proton-rich nuclei, far from the island of stability. The existence of this island is indirectly proved by an increase by several orders of the lifetime of known isotopes of elements 112 and 113 as they approach the island of stability:

$$T_{1/2}(^{277}\text{112})=0.7\text{ms}, T_{1/2}(^{285}\text{112})=30\text{s},$$

$$T_{1/2}(^{278}\text{113})=0.24\text{ms}, T_{1/2}(^{286}\text{113})=13\text{s}.$$

Conclusion

Recently, the possibilities of deep inelastic transmission reactions with Kr, Xe, and U (U+U) beams for the synthesis of heavy and super heavy nuclei have been discussed. The U+U reaction at a uranium beam energy of 7.38 MeV/nucleon was studied. Mass distributions of reaction products (quasi-fission) were obtained, from which it follows that with a relatively high probability, products much heavier than uranium are formed. In addition, a structure in the mass distribution (bump in the mass region 208) is observed, which indicates the conservation of shell effects in such interactions. Therefore, this may be one of the methods of synthesizing nuclei near shell numbers, including super heavy nuclei with 182 neutrons. The possibilities of other reactions with heavy ions, accompanied by the release of high-energy light charged particles, are also discussed. Such particles with the energy near the kinematic limit for a two-body reaction can carry away all the excitation energy of the resulting system.

Currently, it has become possible to obtain and accelerate short-lived radioactive elements, including neutron-rich nuclei, which, in principle, could be used for the synthesis of neutron-enriched isotopes of super heavy elements located in the center of the "island of stability". All this can be investigated using beams of accelerated heavy ions, which, as already noted, are now practically the only tool for the synthesis and study of the properties of new exotic nuclei.

References

- [1] Yu.Ts. Oganessian, Lecture Notes in Physics (Springer Heidelberg) **33** (1975) 221.
- [2] S. Hofmann, G. Munzenberg Rev. Mod. Phys. **72** (2000) 733.
- [3] K. Morita et al., J. Phys. Soc. Jpn. **73** (2004) 2593.
- [4] K. Morita et al., J. Phys. Soc. Jpn. **81** (2012) 103201.
- [5] P. Möller et al., Z. Phys. **A359** (1997) 251.
- [6] P. Armbruster, Rep. Prog. Phys. **62** (1999) 465.
- [7] W.D. Myers, W.J. Swiatecki, Nucl. Phys. **81**(1) (1966).
- [8] A. Sobiczewski et al., Phys. Lett. **22** (1966) 500.

- [9] Y. Aritomo, Phys. Rev. C **80** (2009) 064604.
- [10] P. Möller et al., Atomic Data and Nuclear Data Tables **59** (1995) 185.
- [11] F.A. Ivanyuk et al., Phys. Rev. C **55** (1997) 1730.
- [12] H. Hofmann, Phys. Rep. **284** (1997) 137.
- [13] S. Yamaji et al., Nucl. Phys. A **612** (1997) 1.
- [14] Y. Aritomo, M. Ohta, Nucl. Phys. A **744** (2004) 3.
- [15] J. Maruhn, W. Greiner, Z. Phys. **251** (1972) 431.
- [16] K. Sato et al., Z. Phys. A **288** (1978) 383.
- [17] J. Blocki et al., Ann. Phys. **113** (1978) 330.
- [18] K.T.R. Davies et al., Phys. Rev. C **13** (1976) 2385.
- [19] Y. Aritomo et al., Phys. Rev. C **85** (2012) 044614.
- [20] F.A. Ivanyuk et al., Proceedings of Tours Symposium on Physics III. API Conference proceedings, New York (1998) 425.
- [21] M.D. Usang et al., Phys. Rev. C **94** (2016) 044602.
- [22] C. Ishizuka et al., Phys. Rev. C **96** (2017) 064616.