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Synthesis and study of properties of superheavy atoms. Factory of Superheavy Elements

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The state-of-the-art of studies dealing with the synthesis and properties of new superheavy elements is scrutinized. The experiments intended to identify and study the chemical properties of superheavy elements, as well as the facilities used for this purpose, are described. Special attention focuses on the theoretical assessment of the relativistic effects on the properties of these elements. The prospects of these investigations have been considered in the light of the creation of the world's first Factory of Superheavy Elements in Russia.
The bibliography includes 48 references.

Contents

I. Introduction 901
II. Synthesis of transuranium elements 903
III. Isotopes of superheavy elements 905
IV. Chemical identification and study of chemical properties of superheavy elements 908
V. Factory of Superheavy Elements 914

I. Introduction

The understanding of the boundaries of the material world is one of the fundamental problems of natural science. The discovery of the atomic planetary model by Rutherford (1911) and his excellent experiments demonstrating the existence of the nucleus in the atom and subsequent Bohr's description (1913) of the simplest system — the hydrogen atom — showed that this problem should be considered at the microscopic level of matter. However, the motion of particles and transformation of matter in the micro world, unlike the classical macro world, have the quantum-mechanical nature.

Analysis of the Dirac equation (1928) and subsequent development of quantum electrodynamics has shown that the Rutherford – Bohr model allows the existence of giant atoms with mass numbers up to 170. The abundance of elements heavier than uranium retained in the Earth's crust and even the content of all artificial transuranium elements is very low; this fact indicates that the limit of the existence of atoms (or chemical elements) is determined by the stability of the atomic nucleus. This circumstance brings the problem from the realm of atomic physics to the realm of nuclear physics and is inevitably associated with research into the structure of nuclear matter, which is far from being fully understood, and the nature of nuclear forces.

The first description of the nucleus as a charged liquid drop of huge density ($\sim 10^{15}$ g cm^{-3}) was made by Gamow,[1] who proposed the liquid drop model of the nucleus. Such a rather original approach, considering a microscopic nucleus of radius $\sim 1.25 \times A^{1/3} \times 10^{-13}$ cm (where A is the number of nucleons in the nucleus) as a macroscopic spherical drop, turned out to be very fruitful. Gamow demonstrated that calculations using this model reproduced well the nuclear masses and sizes available at that time. One of the outstanding results was that this model served as a basis for developed of the theory of nuclear α-decay — a phenomenon discovered long before by Becquerel (1896).

After Hahn and Strassmann[2] have observed neutron-induced uranium fission (1939), Bohr and Wheeler[3] developed in the same year the theory of nuclear fission based on the liquid-drop model of the nucleus. According to this theory, there is a potential barrier (fission barrier) that prevents the fission of a heavy nucleus into two fragments. For uranium, the fission barrier height (B_f) is ~ 6 MeV. Once a uranium nucleus has captured a neutron, its energy slightly exceeds the fission barrier height, so that within a

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very short time ($\sim 10^{-16}$ s), the uranium nucleus undergoes fission into two fragments. However, the authors have demonstrated that the uranium nucleus can undergo spontaneous fission by tunnelling through the fission barrier. A huge half-life — about 10^{22} years — was predicted for the spontaneous fission of uranium. The experimental half-life of 10^{16} years reported somewhat later by Flerov and Petrjak[4] was the first observation of the fourth type of radioactivity — spontaneous fission (SF), which was destined to play a key role in determining the boundaries of nuclear masses and of the existence of chemical elements.

According to the liquid drop model, in the region of transuranium elements ($Z > 92$), the fission barrier will rapidly decrease with increasing Z because of the increase in the Coulomb repulsion in the interior of their nuclei, which should lead to a significant increase in the probability of spontaneous fission and to an equally significant decrease in the stability of nuclei. When the fission barrier vanishes, the nucleus becomes totally unstable to spontaneous fission, and within $\sim 10^{-19}$ s the initially spherical nucleus takes a dumbbell shape at the breakup point. This is the stability limit of heavy nuclei. Correspondingly, heavier atoms or chemical elements are impossible. In the liquid drop model, this situation occurs for the second hundred elements ($Z \geqslant 100$).

The theoretical predictions were experimentally supported when nuclear reactors were started to be used for synthesis and then production of transuranium elements. From ^{238}U ($Z = 92$) to ^{256}Fm ($Z = 100$), the spontaneous fission half-life changed from 10^{16} years to 2.5 h (by almost a factor of 10^{20}). The half-lives of the isotopes of elements 102 and 104 with even numbers of protons (Z) and neutrons (N) produced in reactions with heavy ions decrease to seconds and thousandths of a second, respectively (by another $\sim 10^5$ times). Some hidrance of spontaneous fission that is observed for odd-odd isotopes does not change the conclusion that a further increase in Z beyond $Z > 104$ will rapidly lead to the boundary of the existence of Rutherford atoms since they will have no time to form during the short lifetimes of their nuclei ($T_{SF} \leqslant 10^{-14}$ s).

The experiments on the synthesis of element 104, located, in our opinion, very close to the boundary of the existence of elements, which were conducted at the Laboratory of Nuclear Reactions at the Joint Institute for Nuclear Research (FLNR JINR) (Dubna, Russia) in 1962, demonstrated that a reaction by-product — ^{242}Am ($Z = 95$) — undergoes spontaneous fission with two half-lives: with the previously known value $(T_{SF})_1 \geqslant 10^{14}$ years and with a new much shorter half-life $(T_{SF})_2 \approx 0.014$ s. Further experiments showed that a similar phenomenon is observed in 32 actinide isotopes with $Z = 92-97$. Even the uranium nucleus undergoes spontaneous fission with half-lives $(T_{SF})_1 = 10^{16}$ years and $(T_{SF})_2 \times 10^{-7}$ s; *i.e.*, the difference between these values is 30 orders of magnitude!

It has later been shown that such an effect is caused by fission of the nucleus from two states, the ground state and a strongly deformed (isomeric) one. The nucleus in the ground state is almost spherical. In the isomeric state, the nucleus is an ellipsoid with an axis ratio of 3 : 1. This situation is incompatible with the liquid drop model: a drop is not able to have two states. This means that nuclear matter in not amorphous; rather, it has the inner structure, which has an effect on nucleus deformation (nucleus fission).

It has already been known that nuclei with the 'magic' numbers of protons 2, 8, 20, 28, 50 and 82 and neutrons 2, 8, 20, 28, 50, 82 and 126 have considerably higher nucleon binding energies than the neighbouring nuclei. In the shell model of the nucleus, this effect is interpreted as a manifestation of the nuclear structure similar to the effect of closed electron shells in the atomic structures of noble gases in Group 18 of Mendeleev's Periodic Table. The naturally abundant doubly magical stable nuclei with closed proton and neutron shells — ^{4}He, ^{16}O, ^{40,48}Ca and ^{208}Pb — have a spherical shape and the highest nucleon binding energy. However, it was believed that this effect would rapidly decrease with increasing deformation of the nuclei. In fact, the nuclear structure does not disappear with increasing deformation; it alters and continues to play an essential role in the nuclear fission process.

Experimental studies of spontaneously fissioning isomers (shape isomerism) have contributed to the development of theory for elaborating models that describe the collective properties of the nucleus with taking into account its structure. In the first step, the effect of nuclear shells was considered as a correction in calculations of the potential energy of the nucleus [the macroscopic–microscopic (MM) nuclear model].[5,6] The MM-model calculations have explained many experimental facts that did not fit the classical liquid drop model, such as the two-humped fission barrier and shape isomerism of nuclei, the high fission barrier of the doubly magic ^{208}Pb nucleus, and the strong variations in the spontaneous fission probability with a minor change in the nuclear mass (sometimes, the difference is only by one proton or neutron).

The most impressive results have been obtained for very heavy nuclei. According to liquid drop model calculations, such nuclei have no fission barrier ($B_f = 0$) and cannot exist in macroscopic models since they are completely unstable to spontaneous fission ($T_{SF} \approx 10^{-19}$ s).

Systematic calculations of the energies of nuclei in the ground and deformed states have shown that not only the above spherical nuclei (spherical shells) but also deformed actinide nuclei can have a magic structure. In particular, the high stability of the known isotopes of thorium, uranium and long-lived transuranium elements is associated with the effect of deformed shells around $Z = 100$ and $N = 152$.

Macroscopic–microscopic calculations of the potential energy for the heavier, still unknown, nuclei have led to unexpected predictions. The next closed deformed shells with $Z = 108$ and $N = 162$ were found in a rather heavy nucleus with a mass of 270 with a roughly zero liquid-drop fission barrier. At the same time, it has been demonstrated that, due to the nuclear shell effect, a ~ 8 MeV single-humped fission barrier (higher than for ^{238}U) appears in this nucleus; the spontaneous fission half-life for it is $T_{SF} \approx 10^4 - 10^5$ s, which is 22 orders of magnitude higher than the value predicted by the liquid drop model.

An even stronger nuclear shell effect is predicted by MM theory[7–9] when moving towards superheavy nuclei. In the mass range around $A \sim 300$, there appears a strong effect of spherical nuclear shells with $Z = 114$ and $N = 184$ similar to the effect of the shells in doubly magic stable ^{208}Pb ($Z = 82$ and $N = 126$). The effect of the new spherical shells is responsible for the formation of a large region of very heavy (superheavy) nuclei located far from the region of the known nuclei, the 'island' of superheavy elements. Similar predictions appeared directly during the develop-

ment of microscopic nuclear theory. In none of the subsequent theoretical studies that have been carried out for the past 45 years, these predictions have been refuted neither by different approaches to MM model calculations, nor by pure microscopic models like the Hartree – Fock – Bogoliubov model or the relativistic mean field model.

All of the models predict the strong effect of the neutron shell $N = 184$. The effect of the proton shell is weaker and more 'spread' over Z. In the MM model, the magic proton number is $Z = 114$, whereas pure microscopic calculations predict the strongest effect of the proton shell for $Z = 120$, 122 and even 126 depending on the choice of parameters of the nucleon – nucleon interaction in the nucleus.

Regardless of these uncertainties, the calculations showed that the most stable superheavy nuclei in the centre of the island of superheavy elements could have huge half-lives of thousands, hundreds of thousands and even millions of years! As compared with the open nuclear fission channel with $B_f = 0$ ($T_{SF} \approx 10^{-19}$ s), the emergence of the fission barrier of structural origin inhibits spontaneous fission of the superheavy nucleus by a factor of $10^{30 \pm 5}$. Notwithstanding the difficulties in calculation of how the heavy nucleus passes over the fission barrier (tunnels through the potential barrier) and the resulting uncertainties in calculation of fission probabilities, the partial spontaneous fission half-lives of superheavy long-livers can be from 0.3 to 3×10^9 years.

Predictions of microscopic nuclear theory radically change our notion of the boundaries of the existence of nuclei (elements). In contrast with the liquid drop model predicting a rapid loss of stability of heavy nuclei as they occur deeper in the 'sea of instability', microscopic theory implies the emergence of islands of stability for superheavy nuclei caused by the effect of the new shells, which move away the limits of the existence of nuclei and significantly extend the boundaries of the chart of the nuclides and the table of chemical elements.

In this review, we have scrutinized and summarized the results of studies of superheavy elements carried out over the past decade in scientific centres in Russia and abroad,† as well as the results of experiments carried out by international teams of experts.

II. Synthesis of transuranium elements

Experimental verification of microscopic nuclear theory is difficult. It is evident that it is impossible to model the natural synthesis (nucleosynthesis) of such heavy nuclei in the lab. The reactions of synthesis of all transuranium elements through successive neutron capture, which are carried out in high-flux nuclear reactors, afford nuclei with masses $\leqslant 257$. Neutron capture chains alternating with β-decay in the course of long-term (~ 250 days) irradiation of the starting substance with an integral neutron flux up to 5.5×10^{22} n cm^{-2} lead, in the limit, to ^{257}Fm ($T_{1/2} \approx 100$ days). This is explained by the fact that the capture of a neutron by ^{257}Fm gives the short-lived spontaneously fissioning isotope ^{258}Fm ($T_{SF} = 3 \times 10^{-4}$ s). Attempts to overcome this threshold by using very intense pulsed neutron fluxes (nuclear explosions) have again led to nuclei with $A \leqslant 257$.

In another strategy, a complex of nucleons — ^{12}C, ^{18}O or ^{22}Ne — is introduced into the target nucleus. In reactions involving heavy ions, it is desirable to use rather heavy nuclei as a target, namely, long-lived and neutron-rich isotopes of uranium – curium. Nuclear fusion enabled the synthesis of isotopes of elements 102 – 106 with $N \leqslant 160$. Unfortunately, the compound nuclei (CNs) formed in these reactions were strongly heated; their excitation energy even at the Coulomb reaction barrier was 37 – 45 MeV. The transition of the nuclei to the ground state (cooling) can occur through emission of four or five neutrons. However, because of the strong competition with fission, only $10^{-6} - 10^{-8}$ of the primary nuclei can 'survive' in each step of neutron emission. Nevertheless, despite enormous losses, isotopes of the elements of the second hundred with $Z = 102 - 106$ were synthesized for the first time in this very kind of reactions.

II.1. Cold fusion reactions of massive nuclei

Advance into the range of $Z > 106$ has become possible after the discovery of so-called cold fusion reactions[10] realized through the fusion of magic target nuclei ^{208}Pb or ^{209}Bi with massive projectiles with $A \geqslant 40$. The compound nuclei formed in these reactions have an excitation energy of about 12 – 15 MeV. To lose this energy, the compound nucleus should emit only one neutron. The probability of the neutron emission is 1% – 2%, and in the other (98% – 99%) cases, the nucleus fissions into two fragments. However, this happens only once, which accounts for the high 'survivability' of the compound nucleus, and this is the key advantage of cold fusion reactions. In the past two decades, elements with $Z = 107 - 112$ have been synthesized at GSI *via* cold fusion reactions using massive ions ^{54}Cr, ^{58}Fe, ... , ^{70}Zn.[11] The next superheavy element with $Z = 113$ has been produced at RIKEN (Nishina Centre for Accelerator-Based Science, Japan) by the cold fusion reaction of ^{209}Bi and ^{70}Zn. The experiment has lasted for nine years; during this time interval, the decay events of only three atoms of element 113 have been detected.[12]

It is evident that the existence of elements with the nuclei containing 107 – 113 protons and 155 – 165 neutrons and undergoing α-decay with half-lives of milliseconds and even fractions of a millisecond is completely caused by the stabilizing effect of the deformed nuclear shells $Z = 108$ and $N = 161$.

Unfortunately, this method is inapplicable when moving to the region of spherical shells $Z = 114$ and $N = 184$, *i.e.*, to the theoretically predicted island of stability of superheavy elements. The prerequisite of cold fusion reactions is the use of magic nuclei ^{208}Pb or ^{209}Bi as the target. The synthesis of increasingly heavier nuclei is achieved by increasing the atomic number of the projectile. This leads to the increase in the Coulomb repulsion along the entire path of collective movement — from the moment of contact of the nuclei to the formation of the compound nucleus. As a result, the probability of the formation of the compound nucleus sharply decreases with increasing Z.

Another, presumably fundamental, limitation is a deficit of neutrons in the compound nucleus produced in the cold

† Foreign scientific centres mentioned in the review: GSI is Gesellschaft for Schwerionenforschung (Darmstadt, Germany); ORNL is Oak Ridge National Laboratory (Oak Ridge, TN, United States); LBNL is Lawrence Berkeley National Laboratory (Berkeley, CA, United States); LLNL is Lawrence Livermore National Laboratory (Livermore, CA, United States); PSI is Paul Scherrer Institute (Villingen, Switzerland).

fusion reaction. For example, the synthesis of element 114 *via* the fusion of ^{208}Pb and ^{76}Ge nuclei would lead to the formation of the nucleus with $Z_{CN} = 114$ and $N_{CN} = 170$, which differs from the shells $N = 162$ and $N = 184$ by 8 and 14 neutrons, respectively. At such a difference, the expected effect for both neutron shells is minimal; for the nucleus to occur in the range of the effect of the neutron shell $N = 184$, it is necessary to increase the number of neutrons in the nucleus. This is hardly achieved in a cold fusion reaction because of the definite ratio between the neutrons and protons in the colliding stable nuclei.

II.2. Hot fusion reactions of actinides with ^{48}Ca nuclei

Considering different methods of synthesis of neutron-rich nuclei with $Z \geqslant 112$, we have radically changed the method of synthesis of superheavy nuclei. Isotopes of artificial elements with $Z = 94-98$, produced through neutron capture reactions in high-flux nuclear reactors, were chosen as the target material, and the ions of the rare and expensive isotope ^{48}Ca (its natural abundance is 0.187%) were used as the projectile. The fusion reaction of ^{244}Pu and ^{48}Ca nuclei leads to the formation of the nucleus with $Z_{CN} = 114$ and $N_{CN} = 178$, which contains eight extra neutrons as compared with the product of the above cold fusion reaction ^{208}Pb + ^{76}Ge. As will be shown below, these eight extra neutrons have played a crucial role in the synthesis of superheavy elements.

It should be noted that, in the ^{244}Pu + ^{48}Ca reaction ($Z_1 \cdot Z_2 = 1880$), the Coulomb forces are ~40% weaker than in the ^{208}Pb + ^{76}Ge reaction ($Z_1 \cdot Z_2 = 2624$), which increases the probability of compound nucleus formation by 5–6 orders of magnitude. This is undoubtedly a great advantage. However, unlike the cold fusion reactions, the thermal energy of the compound nucleus in the reactions with ^{48}Ca ions is 35–40 MeV (hot fusion). This energy can be removed through emission of three or four neutrons. In each step of successive neutron emission, there is again a strong competition from the fission of the hot nucleus. This is an essential disadvantage of hot fusion reactions. The survivability of the compound nucleus will strongly depend on its fission barrier. In this context, it is necessary to pay attention to the following fact: since the height of the fission barrier of superheavy nuclei is determined in full by the effect of the nuclear shells (mainly by the shell $N = 184$), the increase in the fission barrier with approaching $N = 184$ should considerably enhance the 'survivability' and, as a consequence, increase the production cross sections of superheavy elements. The observation of this effect would be evidence that we set foot on the island of stability.

The transition from cold fusion reactions to An + ^{48}Ca reactions has considerably complicated the experiment. Instead of the stable lead or bismuth isotopes as the target material, there should be used neutron-rich isotopes of transuranium elements that were to be produced for 250–300 days in nuclear reactors with a neutron flux up to 2.5×10^{15} n cm^{-2} s^{-1}. Subsequent operations (removal of the irradiated sample, purification of transuranium elements from side products, radiochemical isolation of a given element and its isotopic enrichment by means of electromagnetic isotope separators) make the entire procedure of target manufacturing exclusively complicated. Even under such extreme conditions, the yield of the products to be used for manufacturing the target is only tenths and hundredths of a gram. This task has been successfully solved by the scientists of the Oak Ridge National Laboratory, State Scientific Centre 'Research Institute of Atomic Reactors' (Dimitrovgrad, Russia) and All-Russian Research Institute of Experimental Physics (Sarov, Russia).

The production of an intense beam of ^{48}Ca ions also involves solving a number of complex problems. Calcium is known to have no gaseous compounds. Thus, efficient gas diffusion methods used for high isotope enrichment of many elements (up to uranium) are inapplicable in this case, and the ^{48}Ca isotope is separated from natural calcium only by electromagnetic separation. The high cost of ^{48}Ca is directly dictated by the difficulty of its production. This task has been successfully accomplished by the experts of the Elektrokhimpribor plant (Lesnoy, Russia). Another challenge was how to produce an intense beam with minimum consumption of the ^{48}Ca isotope. Its solution required finding a compromise.

The first $^{48}Ca^{5+}$ beam with an intensity of ~0.3 pμA (1μA = 6.02×10^{12} ion s^{-1}) was produced in 1974 at the U300 heavy-ion cyclotron with an internal plasma source (Dubna); the working substance consumption was 20–30 mg h^{-1}. The experimental studies of the $^{206-208}$Pb + ^{48}Ca fusion reactions have demonstrated high yield of the ^{252}No ($Z = 102$) nucleus produced by evaporation of two to four neutrons from the compound nuclei $^{254-256}$No. However, taking into account the duration of the experiments (up to 6000 h per year) and the consumption of the ^{48}Ca isotope, we should state that the synthesis of superheavy elements with $Z \geqslant 112$ with the cross section ~6 orders of magnitude as low as the cross section of the formation of the ^{252}No nucleus is impracticable.

Further developments have been associated with a radical change in the scheme of acceleration of ^{48}Ca ions at the U-400 cyclotron at the Laboratory of Nuclear Research JINR. A new external source ECR-4M has been developed on the basis of the ECR-4 ion source (France). A low-energy beam of $^{48}Ca^{5+}$ ions (0.02 MeV nucleon^{-1}) from the external source was injected in the centre of the cyclotron chamber and accelerated to a high energy of 5.2 MeV nucleon^{-1}. After passing through a 0.15-μm carbon foil placed at the final cyclotron radius, the charge of calcium ions increased to 18+, the beam trajectory was changed, and the beam was extracted from the chamber and focused onto a distant target. In this scheme, the beam intensity on the target of 1.0–1.5 pμA has been achieved, the consumption of the substance (with allowance for its threefold regeneration) being about 0.5 mg h^{-1}. Up to the present moment, this result is the best ever; it corresponds to the conversion efficiency of neutral ^{48}Ca atoms into a beam of accelerated incident ions of ~0.5%. The accelerator was operated about 6000 h/year for 15 years (1999–2015).

For the detection of rare formation and decay events of superheavy nuclei, a fast-operation separator has been created that selects the evaporation products on the basis of the kinematics of the complete fusion reaction. Among all reaction products, these nuclei are the heaviest ones. They form as a result of complete momentum transfer from the accelerated ^{48}Ca ion to the compound nucleus of summed mass and leave the thin target in a narrow angular cone $\Delta\theta \pm 3^\circ$ with an average energy of ~30 MeV. Calculations and model experiments have demonstrated that ~50% of superheavy recoil nuclei and only 0.01%–0.02%

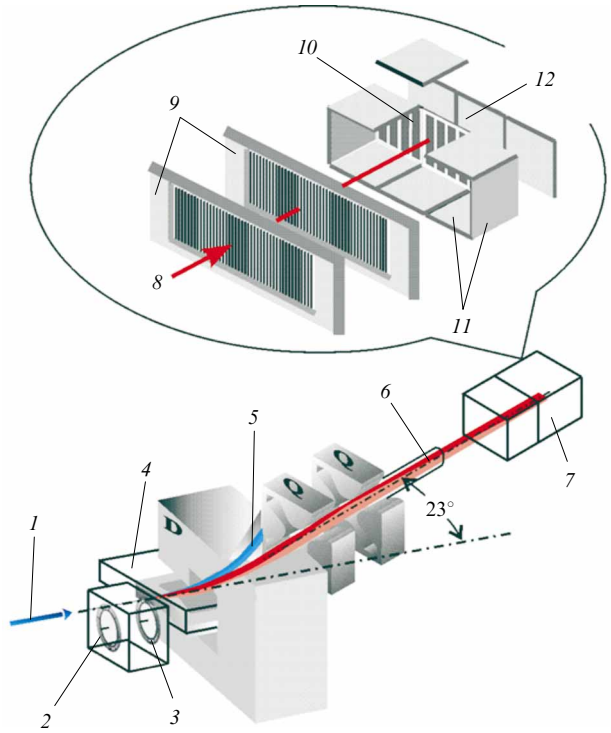


Figure 1. Scheme of experiments on the synthesis of superheavy elements employing gas-filled separator.[13]
(*1*) ^{48}Ca ion beam; (*2*) rotating entrance window; (*3*) rotating target; (*4*) gas-filled separator; (*5*) accelerated beam of ^{48}Ca ions; (*6*) recoils; (*7*) detector station; (*8*) recoil nuclei; (*9*) TOF detectors; (*10*) front position-sensitive strip detector; (*11*) side detectors; (*12*) 'veto' detectors.

of all incomplete nuclear fusion products fall within the angle range $0 \pm 3^\circ$ and the energy range ~ 10 MeV.

This principle is used at the Dubna gas-filled recoil separator (DGFRS) (Fig. 1). In this setup, the angle range is set by an aperture. The recoil nuclei are knocked out of the target into a low-pressure hydrogen medium (~ 1 mmHg) where they acquire different charges depending on their velocities, which makes them different in magnetic rigidity. Recoil atoms are selected based on energy in a magnetic field. The products with maximum magnetic rigidity are collected onto the focal plane of the separator located at a distance of 4 m from the target. A superheavy atom passes this distance in 1 μs.

A detector array is located in the focal plane. The recoil nuclei that have passed through the separator tuned to collect evaporation products, after passing through a time-of-flight spectrometer, are implanted into the front position-sensitive detector. The front detector generates signals of the implantation time of the recoil, its energy and position (coordinates) of its implantation on the detector surface. The decay products of the implanted nucleus (α-particles or fission fragments) emitted into the front hemisphere are detected directly by the front detector, while those that have escaped in the rear hemisphere are detected by side detectors surrounding the front detector. The detector assembly is a box with the open front wall. The signals of the decays can have different energies and be observed at different moments of time. However, their position on the front detector should coincide with the coordinates of the implanted nucleus. A similar system of measurements makes it possible to reveal the genetic relationships between the nucleus from the target and its decay products. From the radioactive properties of daughter, granddaughter, grand-granddaughter, *etc.* nuclei, the decay scenario and characteristics of the entire radioactive family are determined. The experimental results are directly compared with theoretical predictions.

At the beam intensity on the target of $(0.5-1.0) \times 10^{13}$ s^{-1}, the event counting rate of the front detector is no more than 50–100 s^{-1}. Under these conditions, it is possible to detect very rare (up to one event in a month) formation and decay events of a superheavy nucleus; the probability of a random coincidence of background signals mimicking a true decay event is negligible. For the detection of very long decay chains (up to 30 h), a special detection scheme is used where the ion beam is switched off immediately after the first parent nucleus has decayed into the daughter nucleus.

By 2000, the highest ever luminosity of 5×10^{30} s^{-1} cm^{-2} has been achieved at the ECR-4M–U400–DGFRS accelerator complex. As compared to all previous attempts to synthesize superheavy elements by reactions with ^{48}Ca, the experiment sensitivity has increased almost 500-fold.

III. Isotopes of superheavy elements

Highly enriched actinide isotopes (from uranium to californium) have been used as the target material in the experiments on synthesis and study of decay of superheavy elements. A rotating target is 120 mm in diameter and consists of 9-mm wide segments with a working layer of ~ 0.35 mg cm^{-2} deposited on titanium foil (1.5 μm thick); it contains ~ 10 mg of the working material. The heaviest isotope that can be accumulated in such an amount in the reactor is ^{251}Cf ($T_{1/2}$ = 898 years). It is worth noting that only 0.004 mg of the heavier nuclide ^{254}Es ($T_{1/2}$ = 276 days) was produced in the HFIR reactor (ORNL).

The result of these studies was the synthesis of six superheavy chemical elements with atomic numbers 113–118, which completed the seventh period of Mendelev's Periodic Table.[13,14] In these studies, more than 50 new neutron-rich isotopes of elements 104–118 have been synthesized for the first time and their decay properties have been determined. They considerably enlarged the chart of the nuclides and extended it to $Z = 118$ and $N = 177$ (Fig. 2). The results of synthesis of elements 112–118, obtained later in Dubna, were confirmed at GSI[15–17] and LBNL.[18] In 2012, the IUPAC Commission officially approved the name Flerovium (Fl) for element 114 (named after the Flerov Laboratory of Nuclear Reactions of JINR and its founder — the outstanding physicist Academician G.N.Flerov) and name Livermorium (Lv) for element 116 (named after the Lawrence Livermore National Laboratory, which has been actively involved in the research carried out in Dubna).[19] In December 2015, the IUPAC officially recognized the priority of the JINR–LLNL–ORNL collaborations in the discovery of new elements 115 and 117 and the priority of the JINR–LLNL team in the discovery of element 118.[20] The decay properties of new nuclides calculated[13] from the results of all experiments carried out to date (in Dubna, Darmstadt and Berkeley) are summarized in Table 1.

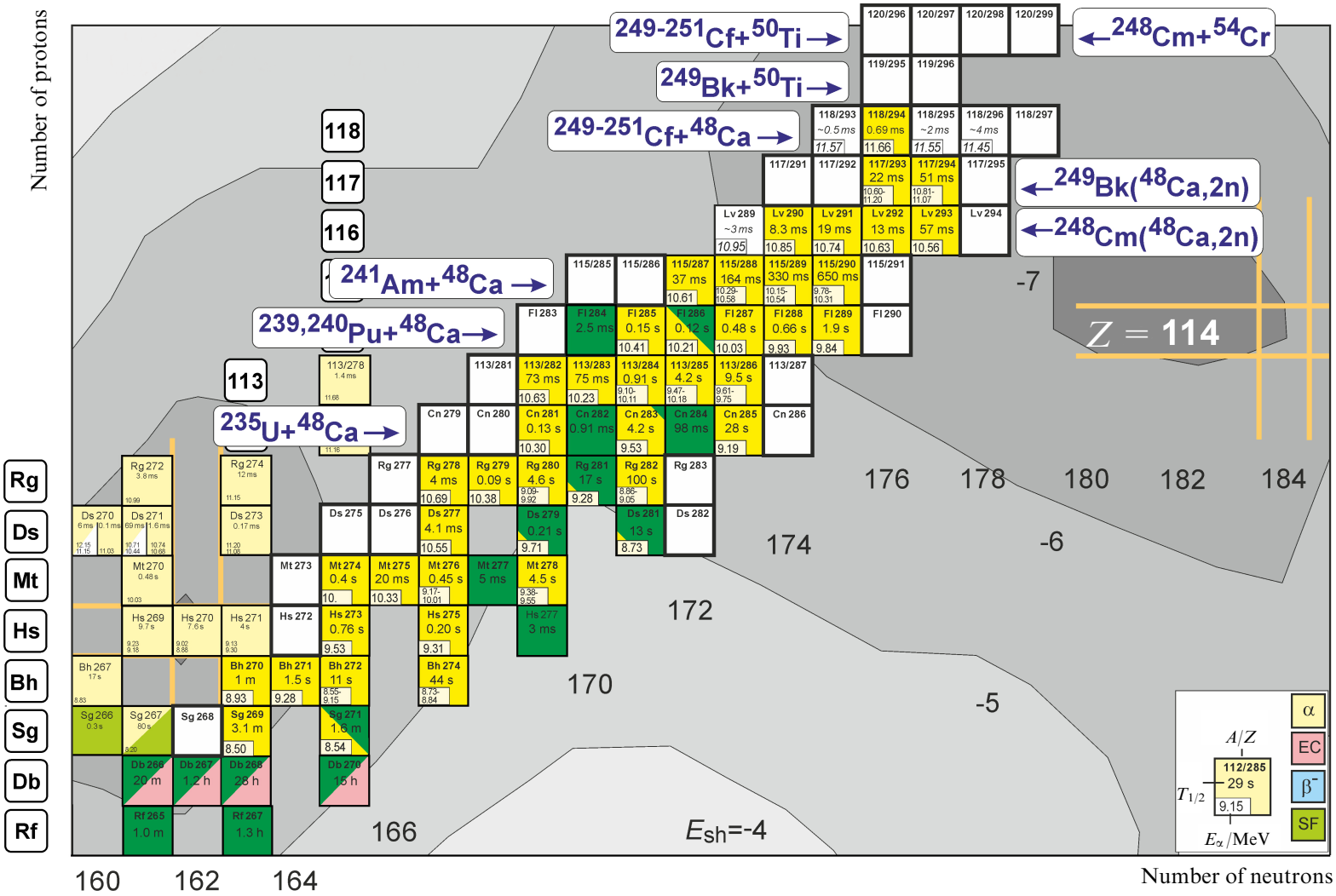


Figure 2. Chart of the nuclides.[13]

Table 1. Decay properties of superheavy nuclides.[13]

Z	N	A	Observed decay events [a]	Decay [b]	$T_{1/2}$ (see [c])	E_α/MeV	Q_α^{exp}/MeV
118	176	294	d : 4	α	$0.69^{+0.64}_{-0.22}$ ms	11.66 ± 0.06	11.82 ± 0.06
117	177	294	d : 3, t : 2	α	51^{+38}_{-16} ms	10.81 – 11.07	11.18 ± 0.04
	176	293	d : 15	α	22^{+8}_{-4} ms	10.60 – 11.20	11.32 ± 0.05
116	177	293	d : 4, s : 1	α	57^{+43}_{-17} ms	10.56 ± 0.02	10.71 ± 0.02
	176	292	d : 5, s : 4	α	13^{+7}_{-4} ms	10.63 ± 0.02	10.78 ± 0.02
	175	291	d : 3, s : 1	α	19^{+17}_{-6} ms	10.74 ± 0.07 10.50 ± 0.02	10.89 ± 0.07
	174	290	d : 11	α	$8.3^{+3.5}_{-1.9}$ ms	10.85 ± 0.07	11.00 ± 0.07
115	175	290	d : 4, t : 2	α	650^{+490}_{-200} ms	9.78 – 10.31	10.41 ± 0.04
	174	289	d : 16	α	330^{+120}_{-80} ms	10.15 – 10.54	10.49 ± 0.05
	173	288	d : 27, t : 19	α	164^{+30}_{-21} ms	10.29 – 10.58	10.63 ± 0.01
	172	287	d : 2, t : 1	α	37^{+44}_{-13} ms	10.61 ± 0.05	10.76 ± 0.05
114	175	289	d : 10, s : 1, t : 4, tc : 1	α	$1.9^{+0.7}_{-0.4}$ s	9.84 ± 0.02 9.48 ± 0.08	9.98 ± 0.02
	174	288	d : 17, s : 4, t : 11, ic : 2, tc : 1	α	$0.66^{+0.14}_{-0.10}$ s	9.93 ± 0.03	10.07 ± 0.03
	173	287	d : 16, s : 1, b : 1, ic : 1	α	$0.48^{+0.14}_{-0.09}$ s	10.03 ± 0.02	10.17 ± 0.02
	172	286	d : 25, b : 2	α : 60^{+10}_{-11}	$0.12^{+0.04}_{-0.02}$ s	10.21 ± 0.04	10.35 ± 0.04
	171	285	b : 1	α	$0.13^{+0.60}_{-0.06}$ s		
113	173	286	d : 4,t : 2	α	$9.5^{+6.3}_{-2.7}$ s	9.61 – 9.75	9.79 ± 0.05
	172	285	d : 17	α	$4.2^{+1.4}_{-0.8}$ s	9.47 – 10.18	10.01 ± 0.04
	171	284	d : 27, t : 20	α	$0.91^{+0.17}_{-0.13}$ s	9.10 – 10.11	10.12 ± 0.01
	170	283	d : 1, t : 1	α	75^{+136}_{-30} ms	10.23 ± 0.01	10.38 ± 0.01
	169	282	d : 2	α	73^{+134}_{-29} ms	10.63 ± 0.08	10.78 ± 0.08
112	173	285	d : 10, s : 1, t : 4, ic : 1, tc : 1	α	28^{+9}_{-6} s	9.19 ± 0.02	9.32 ± 0.02
	172	284	d : 19, s : 4, t : 11, ic : 2, tc : 1	SF	98^{+20}_{-14} ms		
	171	283	d : 22, s : 4, b : 1, ic : 6	α : ⩾93	$4.2^{+1.1}_{-0.7}$ s	9.53 ± 0.02 9.33 ± 0.06 8.94 ± 0.07	9.66 ± 0.02
	170	282	d : 12, b : 2	SF	$0.91^{+0.33}_{-0.19}$ ms		
	169	281	b : 1	α	$0.10^{+0.46}_{-0.05}$ s	10.31 ± 0.04	10.46 ± 0.04
111	171	282	d : 4,t : 2	α	100^{+70}_{-30} s	8.86 – 9.05	9.16 ± 0.03
	170	281	d : 20	SF : 88^{+7}_{-9}	17^{+6}_{-3} s	9.28 ± 0.05	9.41 ± 0.05
	169	280	d : 27, t : 18	α	$4.6^{+0.8}_{-0.7}$ s	9.09 – 9.92	9.91 ± 0.01
	168	279	d : 2, t : 1	α	90^{+170}_{-40} ms	10.38 ± 0.16	10.53 ± 0.16
	167	278	d : 2	α	$4.2^{+7.5}_{-1.7}$ ms	10.69 ± 0.08	10.85 ± 0.08
110	171	281	d : 10, s : 1, t : 4, ic : 1, tc : 1	SF : 93^{+5}_{-9}	$12.7^{+4.0}_{-2.5}$ s	8.73 ± 0.03	8.85 ± 0.03
	169	279	d : 26, s : 3, b : 1, ic : 6	SF : 89^{+4}_{-6}	$0.21^{+0.04}_{-0.04}$ s	9.71 ± 0.02	9.85 ± 0.02
	167	277	b : 1	α	$0.006^{+0.027}_{-0.003}$ s	10.57 ± 0.04	10.72 ± 0.04
109	169	278	d : 3, t : 2	α	$4.5^{+3.5}_{-1.3}$ s	9.38 – 9.55	9.58 ± 0.03
	168	277	d : 2	SF	5^{+9}_{-2} ms		
	167	276	d : 27, t : 16	α	$0.45^{+0.12}_{-0.09}$ s 6^{+5}_{-3} s	9.17 – 10.01	10.03 ± 0.01
	166	275	d : 2, t : 1	α	20^{+24}_{-7} ms	10.33 ± 0.01	10.48 ± 0.01
	165	274	d : 2	α	440^{+810}_{-170} ms	10.0 ± 1.1 9.76 ± 0.10	10.2 ± 1.1

Table 1 (continued).

Z	N	A	Observed decay events [a]	Decay [b]	$T_{1/2}$ (see [c])	E_α/MeV	Q_α^{exp}/MeV
108	169	277	t : 1	SF	3^{+15}_{-1} ms		
	167	275	d : 3, s : 1	α	$0.20^{+0.18}_{-0.06}$ s	9.31 ± 0.02	9.45 ± 0.02
	165	273	b : 1	α	$0.2^{+1.2}_{-0.1}$ s	9.59 ± 0.04	9.73 ± 0.04
107	167	274	d : 4, t : 2	α	44^{+34}_{-13} s	8.73–8.84	8.94 ± 0.03
	165	272	d : 27, t : 17	α	$10.9^{+2.0}_{-1.5}$ s	8.55–9.15	9.18 ± 0.01
	164	271	d : 1, t : 1	α	$1.5^{+2.8}_{-0.6}$ s	9.28 ± 0.07	9.42 ± 0.07
	163	270	d : 1	α	61^{+292}_{-28} s	8.93 ± 0.08	9.06 ± 0.08
106	165	271	d : 3, s : 1	α : 58 ± 23	$1.6^{+1.5}_{-0.5}$ min	8.54 ± 0.08	8.67 ± 0.08
	163	269	b : 1	α	2^{+10}_{-1} min	8.57 ± 0.10	8.70 ± 0.10
105	165	270	d : 4, t : 2	SF [d]	15^{+10}_{-4} h	–	–
	163	268	d : 27, t : 19, b : 20	SF [d]	26^{+4}_{-3} h	–	–
	162	267	d : 2, t : 1	SF [d]	$1.3^{+1.6}_{-0.5}$ h	–	–
	161	266	d : 1	SF [d]	22^{+105}_{-10} min	–	–
104	163	267	d : 2	SF	$1.3^{+2.3}_{-0.5}$ h	–	–
	161	265	b : 1	SF	2^{+8}_{-1} min	–	–

Note. The following notations are used: E_α is the experimental kinetic energy of the α particle; Q_α^{exp} is the total α-decay energy. [a] The number of decays observed at separators DGFRS (d), SHIP (GSI) (s), BGS (LBNL) (b), TASCA (GSI) (t) and in experiments on aqueous and gas chemistry. [b] The most probable type of decay (α or SF) is presented; the decay probability is not specified if only one type of decay was observed. The error bars correspond to a confidence interval of 68%.

[c] The values combining the results of physical and chemical experiments are given.

[d] Spontaneous fission is observed; however, electron capture or α-decay are not ruled out.

III.1. Synthesis of even-*Z* nuclides

For the first time, superheavy nuclei — two isotopes of elements 114 and 116 — have been synthesized at the FLNR JINR [21, 22] by bombarding ^{244}Pu and ^{248}Cm targets with a ^{48}Ca beam. In the experiment, these nuclides were observed as a sequence of α-decays terminated by spontaneous fission. It was precisely the scenario that was expected for the decay of superheavy nuclei located at the island of stability and separated from the region of lighter nuclei. Noteworthy is the fact that the half-lives of their daughter nuclei — isotopes of elements 110 and 112 (see Table 1) — are ~5 orders of magnitude longer than those of the lighter isotopes synthesized by cold fusion reactions. Recall that the existence of these nuclei is completely due to the effect of the deformed nuclear shells $Z = 108$, $N = 162$.

In later experiments, fusion reactions of ^{238}U, ^{242}Pu, ^{245}Cm and ^{249}Cf targets with ^{48}Ca projectiles have led to other isotopes of even-Z elements 112, 114, 116 and 118.[23]

III.2. Synthesis of odd-*Z* nuclei

The structure of odd-Z nuclei is of separate interest. At an odd number of protons or neutrons in the nucleus, α-decay and spontaneous fission are strongly inhibited (on average, by a factor of 3 and 3000, respectively); for odd–odd nuclei, this effect is even stronger. Therefore, successive α-transitions pass through the 'danger zone' at $N = 170$, and competition from spontaneous fission appears only in dubnium isotopes ($Z = 105$, $N = 161–165$).

In odd–odd isotopes of elements 113, 115 and 117 synthesized in the ^{237}Np, ^{243}Am, ^{249}Bk + ^{48}Ca reactions,[24–26] α-transitions take some time from 0.1 to 50 s, depending on Z and N of the parent nucleus, whereas spontaneous fission begins only after 0.5–30 h. It is most likely that this time does not pertain to spontaneous fission; rather, it pertains to electron capture of odd–odd dubnium isotopes leading to even–even isotopes of rutherfordium ($Z = 104$), which undergo spontaneous fission in seconds or even in a split second.

The nuclear physical properties of new nuclides have been considered in detail in the review paper [13].

IV. Chemical identification and study of chemical properties of superheavy elements

The identification of nuclides in the above experiments is based on the knowledge of their decay properties and the mechanism of reaction, in particular, of the characteristic dependence of the yield of neutron evaporation products from the excited compound nucleus.

At the same time, the chemical determination of the atomic number of some of the isotopes in the observed decay chains would not only make it possible to reliably identify the atomic numbers of all nuclei in the chain but also independently prove the discovery of a new element (elements). The first such experiment was carried out for element 115.[26]

IV.1. Chemical identification of element 115 based on the final decay product, element 105

The isotope of element 115 with a mass of 288 was synthesized for the first time in the reaction [27]

$$^{48}Ca + {}^{243}Am \longrightarrow {}^{288}115 + 3\,n$$

It undergoes five successive α decays

$$115 \xrightarrow{\alpha} 113 \xrightarrow{\alpha} 111 \xrightarrow{\alpha} 109 \xrightarrow{\alpha} 107 \xrightarrow{\alpha} 105 \xrightarrow{SF}$$

ending with the spontaneous fission of the ^{268}Db nucleus. The total time of the five α-transitions was ~20 s. The half-life of the final nucleus (^{268}Db), determined from three observed events was estimated at $T_{1/2} = 16^{+19}_{-6}$ h. It was not ruled out that the observed spontaneous fission could be caused by electron capture of the odd–odd ^{268}Db nucleus with subsequent rapid fission of the even–even ^{268}Rf nucleus ($T_{SF} \approx 1.5$ s). This does not change the conclusion that the large spontaneous fission half-life is determined by the decay of ^{268}Db. Because of the small number of events, it was not ruled out that the ^{268}Db isotope can in some cases undergo α-decay with subsequent spontaneous fission of ^{264}Lr.

The ^{268}Db isotope is not able to form at an energy close to the Coulomb barrier directly through the transfer of 25 nucleons (ten protons and fifteen neutrons) from the ^{48}Ca nucleus to the ^{243}Am target nucleus. The relatively long lifetime of ^{268}Db and its rather characteristic decay (spontaneous fission) enabled the first chemical identification of dubnium ($Z = 105$) as the decay product of element 115 formed in the ^{243}Am + ^{48}Ca reaction.

According to the ground-state electronic configuration ([Rn]5d^{14}6p^{3}7s^{2}), dubnium is a Group 5 element, *i.e.*, a heavier homologue of niobium and tantalum.

For the chemical identification of an element, it should be separated on the basis of its group properties. For this purpose, the procedure of sorption extraction of Group 5 elements as anionic fluoride complexes was used in the experiments. Since the isotope of element 105 undergoes spontaneous fission, special attention was paid to the separation of Group 5 elements from actinides and, first of all, from long-lived fissioning californium isotopes ^{252}Cf ($T_{1/2} = 2.65$ years, SF 3.1%) and ^{254}Cf ($T_{1/2} = 60.5$ days, SF 99.7%). The separation from actinides (including lawrencium) simultaneously answered the question of whether ^{268}Db undergoes additional α-decay with subsequent spontaneous fission of ^{264}Lr.

The experiment was carried out at the U-400 heavy-ion accelerator of the Laboratory of Nuclear Reactions, JINR, in June 2004. The scheme of irradiation is shown in Fig. 3.

The target — a rotating disc made of thin (1.5 μm) titanium foil with a total surface area of 32 cm^2 covered with ^{243}Am (99.9%) oxide 1.2 mg cm^{-2} thick (as calculated for ^{243}Am) — was bombarded with ^{48}Ca projectiles with an energy of 247 MeV (the energy in the centre of the target layer). The irradiated area of the target was limited by a collimator 10 mm in diameter. The average beam intensity of the ions incident on the target was 5×10^{12} s^{-1}. The recoil nuclei — the reaction products knocked out of the target — passed through the second collimator 12 mm in diameter mounted at a distance of 10 mm downstream the target and 'stopped' in a copper catcher block. The catcher of recoil nuclei 50 mm in diameter was placed at a distance of 100 mm from the target along the beam axis. In this

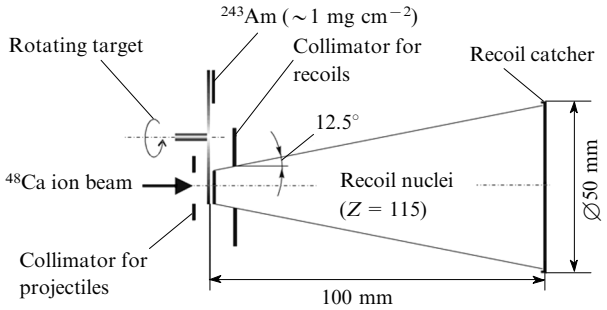


Figure 3. Scheme of the experiment.[26]

geometry of the experiment, the products of the fusion reaction of ^{243}Am and ^{48}Ca nuclei (the capture angle ±12.5°) are stopped in the catcher block with an efficiency close to 100%. The implantation depth of the recoils in the catcher material did not exceed 3–4 μm.

Eight identical experiments were carried out in which the irradiation time was from 20 to 45 h. After irradiation in each experiment, the recoil catcher was transferred to a radiochemical laboratory. The catcher surface was cleaned from aerosol particles containing ^{243}Am; then, the upper 7–10 μm thick layer (120–180 mg Cu) was removed with a micro lathe. Copper chips were dissolved in 10 ml of concentrated nitric acid. The resulting nitric acid solution was a multicomponent system with a high content of copper (the collector material) containing the ^{48}Ca + Cu reaction products, fission fragments of ^{243}Am implanted in the catcher and the products of transfer of different numbers of nucleons from the ^{48}Ca ion nucleus to the ^{243}Am target nucleus, including long-lived spontaneously fissioning isotopes of ^{252}Cf and ^{254}Cf. For spectrometric monitoring of isolation of Group 5 elements and actinides, aliquots of nitrates of ^{92m}Nb ($T_{1/2} = 10.15$ days), ^{177}Ta ($T_{1/2} = 56.6$ h), ^{169}Yb ($T_{1/2} = 32$ days) and ^{167}Tm ($T_{1/2} = 9.25$ days) radionuclides were introduced into the solution.

Group 5 elements were isolated from the nitric acid solution by the scheme involving the following key steps:

— separation of the reaction products from the macro element (copper) by their quantitative coprecipitation with lanthanum hydroxide in an ammonia medium (copper remained in solution as an ammine complex);

— separation of Group 5 elements from lanthanum *via* their joint sorption from the nitric acid solution onto Dowex 50 × 8 cation-exchange resin with subsequent selective desorption of Group 5 elements as anionic fluoride complexes;

— preparation of thin sources (working samples) for measurements by spreading the solution by means of a capillary over a 0.4 μm thick polyethylene film disc 15 mm in diameter with subsequent evaporation in a hot helium stream.

The efficiency of extraction of Group 5 elements was close to 90% with a separation factor from lanthanides of ~10^5.

The entire chemical procedure, from the switching off of irradiation to the start of measurements on the detectors, took 2–3 h; it has been described in detail elsewhere.[26, 28]

For detection of α-particles and fission fragments, a detector assembly composed of four identical chambers

with two semiconducting detectors in each of them was used. The semiconductor detectors, each with a surface area of 6 cm^2, were installed in the chambers in front of each other 4 mm apart. A sample holder with a sample was placed into the gap between the detectors. All chambers were placed into a neutron detector, which counted spontaneous fission neutrons. The neutron detector consisted of 72 ^{3}He-counters in a polyethylene neutron moderator arranged in three rows at different distances from the chambers with the samples. The detector array was calibrated with ^{248}Cm and ^{252}Cf sources. The detection efficiency of the semiconductor detectors was ~90% for fission fragments and ~40% for neutrons. In a 330-h test of the detector block prior to the experiment, no background events mimicking spontaneous fission were detected.

During eight experiments on bombardment of the ^{243}Am target with ^{48}Ca projectiles (total beam dose of 3.4×10^{18}), 15 spontaneous fission events were detected. Measurements were taken for 957 h. All the 15 spontaneous fission events were detected over a period of time of 174 h after the beginning of measurements. In the next 783 h, no spontaneous fission events were recorded. At the separation factor of Group 5 elements from actinides of 10^5, actinide isotopes (including ^{264}Lr) could give no more than 0.002 spontaneous fission event during 174 h of measurements. From the time distribution of events, the half-life was estimated to be 32^{+11}_{-7} h.

The total kinetic energy of the fission fragments ($\overline{\text{TKE}}$), defined as the sum of the amplitudes of coincidence signals from both detectors corrected for absorption in the source and support, was ~230 MeV. This result is consistent with the data of the physical experiment ($\overline{\text{TKE}} \approx 225$ MeV). The average number of neutrons per fission, determined from the coincidences of signals of different multiplicity from the ^{3}He-counters, was $\bar{\nu} \approx 4.2$. Both parameters — the high $\overline{\text{TKE}}$ value and the large neutron multiplicity — are evidence of the fission of a heavy nucleus. It is worth noting that, for the spontaneous fission of ^{248}Cm and ^{252}Cf nuclei, the $\overline{\text{TKE}}$ was 181 and 185 MeV and $\bar{\nu}$ was 3.14 and 3.75, respectively.

It should be noted that Group 5 and Group 4 elements were isolated together in the above experiment. Therefore, the method is applicable to the isotopes of both elements 105 and 104, the final decay products of the parent nuclei with $Z = 115$ and 114, respectively. However, the observation of spontaneous fission of rutherfordium isotopes as the final products in the decay chains of isotopes of element 114 is ruled out because of the negligibly small cross section of the ^{243}Am(^{48}Ca,pxn)$^{290-X}$114 reaction as compared with the cross section of the ^{243}Am(^{48}Ca,xn)$^{291-X}$115 reaction, as well as because of the short lifetimes (a few seconds) of the nuclides in the decay chains of the isotopes of element 114. In this context, all spontaneous fission events recorded by the detectors in the ^{243}Am + ^{48}Ca reaction should be attributed only to the decay chain of element 115. The experimental conditions (separation from actinides) exclude the assumption of the possible additional α-decay of the ^{268}Db isotope with the subsequent spontaneous fission of ^{264}Lr. As a whole, the above experiment is an independent proof of the synthesis of element 115 (as well as of element 113) in the ^{48}Ca + ^{243}Am reaction.

A detailed comparative analysis of the 'physical' and 'chemical' experiments on the synthesis of element 115 in the ^{243}Am + ^{48}Ca reaction has been presented elsewhere.[26] It should be noted that the half-life of ^{268}Db estimated from the data of both experiments was 29 h; this value is roughly coincident with the half-life (26^{+4}_{-3} h) calculated from the results of all experiments aimed at studying the ^{243}Am + ^{48}Ca reaction accomplished to date in Dubna, Darmstadt and Berkeley (see Table 1). Later, a team of radiochemists from PSI[29] has comprehensively studied the samples synthesized in the Dubna experiment and has completely confirmed the high degree of separation from actinides; the researchers have arrived at the conclusion that all 15 SF events in the 'chemical' experiment unambiguously pertain to the final decay product ^{268}105, which confirms the synthesis of 115 in the ^{243}Am + ^{48}Ca reaction.

IV.2. Study of chemical properties of elements 112 and 114

In a superheavy atom, relativistic effects on its electronic structure and especially on its outer electron shell begin to play a considerable role. Elements 112 and 114 belong to, respectively, Group 12 (Zn, Cd, Hg) and Group 14 (Ge, Sn, Pb) of the Periodic Table. Hence, their ground-state configurations should be [Rn]5f^{14}6d^{10}7s^2 and [Rn]5f^{14}6d^{10}7s^{2}7p^2, respectively. Simple extrapolations demonstrate that element 112 is similar in properties to noble metals. At the same time, the inclusion of relativistic effects in the calculations of atomic properties of superheavy elements implies the contraction of spherical electronic orbitals s and $p_{1/2}$. This should lead to an increase in the chemical stability of elements in the elemental state. Moreover, it cannot be ruled out that they can be noble gases similar to radon. Other calculations confirm the strong contraction of the 7s orbitals. However, it is also predicted that, due to the relativistic spin–orbit splitting of 6d orbitals, element 112 will be a noble transition metal or even a semiconductor. Theoretical evaluations of the relativistic effects on the properties of superheavy elements, including analysis of different computational methods, have been presented in review papers.[30, 31] Here, it is only worth noting that most of the calculations for elements 112 and 114 predict the enhanced volatility in the elemental state, but there are differences in the evaluation of their chemical inertness. This issue could be clarified by studying the adsorption of the elements onto the noble metal surface.

By now, the adsorption behaviour has been best studied for superheavy elements with lifetimes of seconds on the gold surface by gas chromatography. The experiments are carried out in the online mode directly during irradiation of the initial targets with an ion beam of desired energy at accelerator complexes. Two approaches have been realized. In the first approach, the reaction products leaving the irradiated target are 'stopped' in an inert gas and transported by a gas jet through a thin capillary to the detector array, and the element under consideration is adsorbed onto the gold-coated surface of semiconductor silicon detectors at definite temperature. The second approach implies the preliminary separation of the reaction products knocked out of the irradiated targets from background elements in gas-filled separators, and only after this operation, they are 'stopped' in a gas medium and transported by a gas jet into the detector module. The preliminary separation noticeably reduces the background, but also significantly decreases the efficiency of the experiment. When using these procedures, it is implied that the element under consideration is volatile and does not interact with the inert surface of the transport capillary (as a rule, Teflon). The adsorption temperature

determined in the experiment is a key parameter for the calculation of the enthalpy of adsorption of the element onto the gold surface and the conclusion about its chemical activity or inertness.

Chemical experiments have become possible only recently. After the synthesis of relatively long-lived elements 112–114 in the above-described reactions of ^{48}Ca with ^{238}U, ^{242,244}Pu. Early attempts to chemically identify and study the properties of element 112 failed.[32] The key reason was the use of the reaction of ^{38}U with ^{48}Ca characterized by the low (~1 pb) cross section of formation of isotopes of element 112. Progress has been achieved with the use of ^{48}Ca reactions with ^{242,244}Pu with a sufficiently high cross section (~10 pb); these reactions lead to isotopes of element 114, which undergo α-decay to give the corresponding isotopes of element 112. The experiments in the period from 2006 to 2010 were performed by a joint research team of the Laboratory of Nuclear Reactions, JINR, and PSI at the U-400 accelerator complex.[33–35]

The ^{242}Pu targets were irradiated with 270-MeV ^{48}Ca ions. The isotopes of element 114, produced by nuclear fusion, left the target and were stopped in an He–Ar medium. Further, two scenarios were possible:

— if element 114 was volatile (at room temperature) and the transport time of the technique (the time it took for an atom from the target chamber to reach the detectors) was comparable with the lifetime of its isotopes (~0.5 s for ^{287}114 and ~0.7 s for ^{288}114), the He–Ar jet would capture the atoms of element 114 and transport them through the Teflon capillary to a distance of ~10 m into a cryodetector;

— if element 114 was not volatile or if the speed performance of the technique was insufficiently high, the He–Ar would capture the atoms of element 112 produced in the decay of element 114.

The cryodetector consisted of 32 pairs of PIPS‡ detectors, which provided nearly 4π counting geometry for detection of α-particles and spontaneous fission fragments. The surface of the upper detector in each pair was covered with a thin gold layer. The temperature of the detectors varied from up to −24 °C (the first pair of detectors) to −184 °C (the last pair) in the first cycle of the experiment and from +35°C to −164 °C in the second cycle of the experiment. Two properties expected for Group 12 and 14 elements — the volatility and ability to form intermetallic compounds with gold — were studied.

In all experiments, natural neodymium (~1 mass %) was introduced into the plutonium targets. Bombardment of such targets with ^{48}Ca ions led to the synthesis of the short-lived (49 s) isotope ^{185}Hg [^{142}Nd(^{48}Ca,5n)], which was used as monitor throughout the whole experiment. In addition, multinucleon transfer reactions produced various isotopes of radon [for example, short-lived (3.96 s) ^{219}Rn]. Thus, the behaviours of element 112 and its possible analogues were simultaneously monitored in the experiments.

In the experiments carried out in 2006, the transport time of the technique was ~4 s (the He–Ar flow rate was ~900 ml min^{-1}). Two decay chains (α→f) were registered analogous to those obtained in the earlier experiments at the gas-filled separator for the ^{283}112 isotope.

‡ Passivated implanted planar silicon.

Adsorption of element 112 was observed when the temperature gradient on detectors was (1) from −24 to −184 °C on the second detector (at −28 °C) and (2) from +35 to −164°C on the seventh detector (at −5 °C). In both cases, atoms were adsorbed onto the gold-coated surfaces. These results[33] have provided unambiguous evidence that element 112, by its behaviour, is essentially closer to mercury than to radon, which was adsorbed at temperature from −150 to −180 °C.

In the second series of experiments (2007), ^{242}Pu and ^{244}Pu targets were irradiated under analogous conditions. The transport time of the technique was ~1 s. The data on the behaviour of ^{283}112 obtained in the first experiment were completely confirmed: three decay chains of this isotope were observed.

Statistical analysis of the results of these experiments[34] made it possible to evaluate the standard enthalpy of adsorption of element 112 onto the gold surface ($-\Delta H_{ads} = 52^{+4}_{-3}$ kJ mol^{-1}) and the enthalpy of sublimation ($\Delta H_s = 38^{+10}_{-12}$ kJ mol^{-1}). The boiling point (T_b) of element 112 was estimated at 357 °C. The changes in the enthalpy of sublimation and boiling temperature for Group 12 elements are shown in Fig. 4. As is seen, element 112 is a typical representative of this group.

In the described experiments, the decay chains of two isotopes, ^{287}114 and ^{288}114, were registered; they completely coincided with the chains observed in the previous experiments at the gas-filled separator. Adsorption of atoms of element 114 was observed at temperature about −80 °C on gold-coated detectors.[35] The standard enthalpy of adsorption of element 114 onto the gold surface was estimated at 30–34 kJ mol^{-1}; *i.e.*, flerovium is more inert than copernicium. This result was accepted with scepticism by some experts,[29] who emphasized that, according to theoretical calculations, flerovium should be more active as compared with copernicium. The 'incorrectness' of the experiments carried out at the FLNR JINR was also pointed out in paper[36] of the TASCA collaboration (GSI), where the adsorption of flerovium onto the gold surface was registered at room temperature. However, the later additional experi-

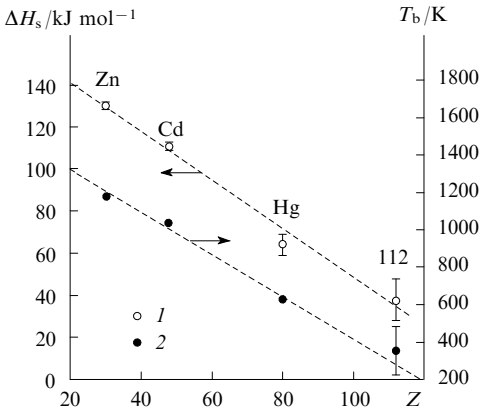


Figure 4. Volatility of Group 12 elements of the Periodic Table.[34] (*1*) Standard enthalpy of sublimation, (*2*) boiling temperature (taken as a measure of the volatility of an element); the error bars for zinc and cadmium are smaller than their symbols; linear trends (dashed lines) are shown for evaluation.

ments performed by the TASCA collaboration have confirmed the results of researchers of the FLNR JINR.[37] Unfortunately, the authors have not commented on such different results. A possible reason (taking into account that the performance of the technique is comparable with the lifetimes of the flerovium isotopes under consideration) could be that, in the first experiment, the decay of flerovium isotopes 'in flight' was observed; *i.e.*, the decay (and, hence, its detection) occurred during the gas-jet transportation before adsorption onto the gold surface. It is worth noting that the theoretical estimates of the flerovium adsorption onto the gold surface[38] also support the conclusion that flerovium is less active than copernicium made from the experiments at the FLNR JINR.

Thus, it can be stated that the adsorption behaviour of element 114 on the gold surface is closer to the behaviour of inert gases than to the behaviour of lead, its closest analogue. On the whole, the above results are the first experimental demonstration of considerable relativistic effects on the properties of elements at the end of the Periodic Table.

IV.3. Study of chemical properties of element 113

The chemical identification of element 113 is based on the assumption that it is a typical member of Group 13 and exhibits the properties of the seventh period, as well as on the result of relativistic DFT calculations of the interaction of element 113 with gold cluster (comprising 4–58 atoms), which predict its adsorption onto the gold surface ($\Delta H_{ads} = 06 \pm 10$ kJ mol^{-1}).[39] The relativistic calculations performed by Pershina *et al.*[40,41] have shown that, because of the strong contraction and stabilization of the outer $7p_{1/2}$ orbital, element 113 will be poorly adsorbed onto inert surfaces. In particular, the calculated value of $-\Delta H_{ads}$ is 14 J mol^{-1} for Teflon and 16 kJ mol^{-1} for polyethylene. At the same time, element 113 should be readily adsorbed (in a He/H_2 atmosphere) onto the gold surface ($\Delta H_{ads} = -158.6$ kJ mol^{-1}); the adsorption temperature is expected to be 400–450 °C. In the presence of oxygen and water traces, the most stable reaction product is presumably hydroxide 113OH, which is assumed to interact more weakly with the gold surface. According to calculations, the expected enthalpy of adsorption is -113 kJ mol^{-1}.

Since Si-detectors cannot be heated considerably above room temperature, the adsorption of element 113, when studied by the above methods, will be observed at the very beginning of a chromatographic column with a negative temperature gradient; *i.e.*, only the lower limit of ΔH_{ads} can be determined.

To date, five isotopes of element 113 with masses 282–286 have been discovered. The ^{282}113 isotope has been synthesized in the hot fusion reaction of ^{48}Ca with ^{237}Np, whereas the other isotopes have been registered as daughter and granddaughter decay products of corresponding 115 and 117 isotopes synthesized in reactions of ^{48}Ca with ^{243}Am and ^{249}Bk, respectively.

The experiment[42] was carried out at the accelerator facility of the FLNR JINR. The ^{243}Am + ^{48}Ca reaction was used, which led to the ^{284}113 and ^{285}113 isotopes with lifetimes of ~1.0 and ~6.0 s, respectively. The experiment layout is schematically shown in Fig. 5. A stationary target was mounted on supporting thin copper grids (~80% transmission) and irradiated with a ^{48}Ca beam of an average

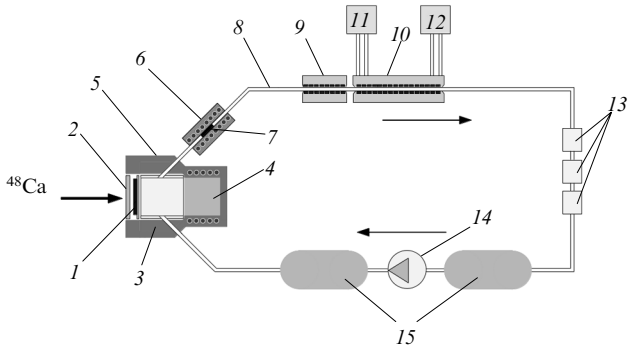


Figure 5. Scheme of the setup for studying chemical properties of element 113.[42]
(*1*) Target: ^{243}Am (1.5 mg cm^{-2}) + ^{nat}Nd (15 μm cm^{-2}) on a Ti support (2 μm); (*2*) vacuum window (Ti foil 4 μm); (*3*) cylindrical quartz insert (2.1 cm in inner diameter, 6 cm in length); (*4*) water-cooled beam stop; (*5*) target chamber (21 cm^3 in volume, 2.1 cm in inner diameter, 6 cm in length); (*6*) oven (T = 600 °C); (*7*) quartz filter; (*8*) transport capillary (Teflon, 2 mm in inner diameter, 4 m in length, volume to detectors 12 cm^3); (*9*) detection module consisting of 16 pairs of Au(Si) detectors at room temperature; (*10*) cryodetector consisting of 32 pairs of Au(Si) detectors, $T_{warm} = +20$ °C, $T_{cryo} = -50$ °C; (*11*) water thermostat; (*12*) cryostat; (*13*) gas purification system containing water-absorbing and aerosol filters; (*14*) pump, gas (30% Ar + 70% He) flow rate of 1.5 litre min^{-1}; (*15*) buffer volumes.

intensity of 3×10^{12} s^{-1}; the ^{48}Ca ion energy in the middle of the target was 242 MeV.

The reaction products knocked out of the irradiated targets were stopped in an inert gas mixture (70% He + 30% Ar, 1.1 atm) in the target chamber and transported by a gas jet through a quartz wool filter heated to 600 °C, located immediately downstream the chamber, and then through a thin Teflon capillary into the detector modules. The gas mixture flow rate in the capillary was 1.5 litre min^{-1}; *i.e.*, the maximum transportation time of the reaction products from the target chamber to the detectors (assuming complete gas exchange in the target chamber and transport capillary) was ~1.5 s. Only volatile and relatively inert reaction products were able to reach the detector module. After passing through the detector module, the gas mixture was pumped through the filters for fine purification from O_2 and H_2O traces and returned into the target chamber. The Teflon capillary was placed into a sealed metallic tube, and a part of it from the SiO_2 filter to the detector was heated to 70 °C.

For detection, two detection modules placed in series were used. The first module consisted of 16 pairs of semiconductor Si detectors placed in front of each other with the surfaces coated with a thin gold layer; all detectors were at ambient temperature. The second module was a cryodetector consisting of 32 pairs of semiconductor Si detectors placed in front of each other with the surfaces coated with a thin gold layer. The temperature of the detector surface changed from 20 °C (the first pair of detectors) to −50 °C (the last pair). The working surface area of each detector in both modules was 1.24 cm^2 (15 × 8 mm); the gap between the detectors in each pair was 2 mm. For this geometry, the efficiency of detection of an α particle and a spontaneous fission fragment by each pair of detectors was 86%, and the

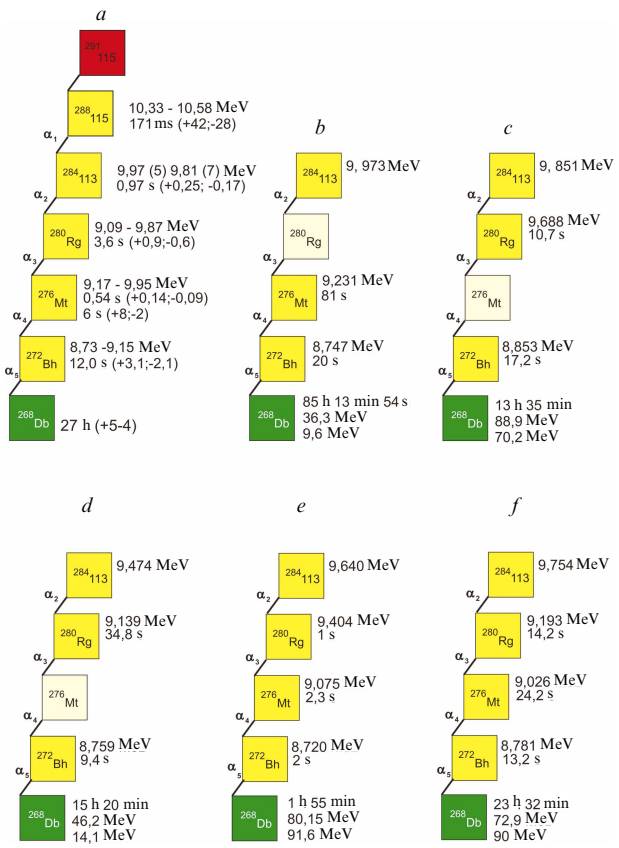


Figure 6. Average lifetimes and decay energies measured in physical experiments at the Dubna gas-filled recoil separator (*a*) and decay chains of element 113 detected in the course of the experiment (*b*–*f*).[42]

energy resolution for detection of α particles in the gas (FWHM)[§] was ~200 keV.

The adsorption behaviour, on the Si detectors, of the short-lived isotope ^{185}Hg formed in the reaction of ^{48}Ca with ^{nat}Nd introduced into the targets was continuously monitored to be sure that the specified conditions of the experiment were met. The change in time of the ^{185}Hg activity registered by the detectors reflected the state of the target subjected to partial destruction on exposure to the ^{48}Ca beam. Multinucleon transfer reactions between ^{48}Ca and ^{243}Am also led to astatine and radon isotopes. The total flux of ^{48}Ca ions on the targets was 8×10^{18}.

In the course of the experiment, five correlated decay chains of the ^{284}113 isotope were detected (Fig. 6). The search was performed over extended time intervals ($0 \leqslant T \leqslant 5\,T_{1/2}$). The following ranges were selected for α-decay energies (E_α):

Element	^{284}113	^{280}Rg and ^{276}Mt	^{272}Bh
E_α/keV	9750 – 10250	9000 – 10 000	8750 – 9250

Analysis of the probability that the observed five decay chains were a result of random coincidences was performed assuming a Poisson distribution of events.[43] The resulting probabilities of random coincidences were 7.6×10^{-3}, 6.6×10^{-5}, 2×10^{-4}, 6.7×10^{-10} and 5.7×10^{-6}, respectively. The direct synthesis of ^{284}113 in the multinucleon transfer reaction of ^{48}Ca with ^{243}Am (18 protons and 23 neutrons) is practically impossible. Based on the above evidence, it can be concluded that the isotopes of elements 113 – 111 – 109 – 107 – 105 detected in this experiment are the daughters of the parent nuclide ^{288}115 formed in the ^{243}Am(^{48}Ca,3n) reaction.

Data on the distribution of ^{185}Hg and ^{211}At, as well as on the distribution of decay events of ^{284}113 in a gas chromatographic detector are shown in Fig. 7. The deposition and decay of element 113 were observed of the gold-coated detector surfaces at room temperature. The resulting sequence of five events does not suffice to accurately quantify the enthalpy of adsorption onto the gold surface. However, the observation of adsorption at room temperature, rather than along the temperature gradient, makes it possible to estimate the lower limit of the enthalpy of adsorption of element 113 onto gold at $-\Delta H_{ads} > 60$ kJ mol^{-1}.

From the results of the experiment,[42] the authors have made a conclusion that the chemical form of element 113 is volatile, slightly interacts with the Teflon surface and is strongly bound to the gold surface. Comparison of the behaviour of element 113 with that of its lighter analogue — thallium — enabled the assumption that either element 113 or its hydroxide 113OH was observed in the experiment. The adsorption behaviour of element 113 under the experimental conditions made it possible to compare its adsorption properties with the properties of mercury and astatine, but just under these experimental conditions: adsorption has been observed at room temperature, whereas more comprehensive study requires the creation of a temperature-gradient detector with an essentially higher initial temperature (100 – 200 °C), which is impossible for modern semiconductor Si detectors.

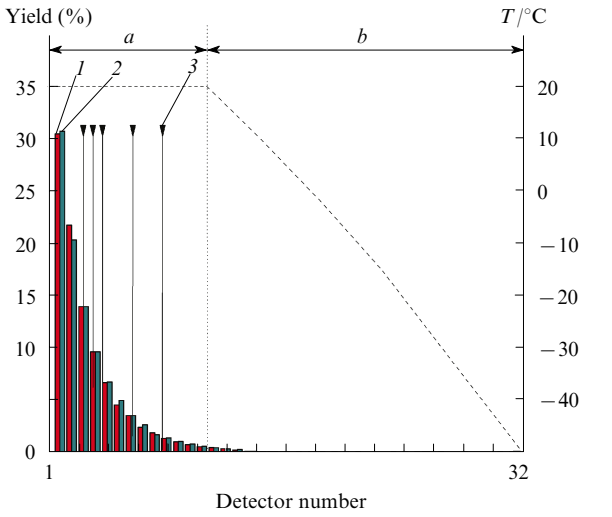


Figure 7. Distribution of ^{185}Hg (*1*) and ^{211}At (*2*) over the detectors as compared with the positions of detection of decay chains of ^{284}113 (*3*); the temperature gradient from 20 °C in the isothermal portion of the detector (*a*) and in the cryodetector (*b*) is shown by the dashed line.[42]

§ Full width at half maximum.

Thus, in recent years, a large series of pioneering studies has been performed dealing with chemical properties of new superheavy elements at the end of Mendeleev's Periodic Table. A new field of modern radiochemistry — chemistry of single atoms — has been developed. However, further progress in research is possible only with the development of new experimental facilities providing a substantial increase in the efficiency of experiments.

V. Factory of Superheavy Elements

The discovery of the new region ('island') of stability and the very fact of the existence of superheavy elements gave rise to new questions pertaining to the fundamental properties of nuclear matter, namely:

— can even heavier nuclei exist; is the 'island of stability of superheavy elements' the last one on the chart of the nuclides?

— can superheavy nuclei be formed through nucleosynthesis similar to the stable and long-lived Pt, Pb and U–Th nuclei formed in nature?

— what is the electronic structure of a superheavy atom in the strong Coulomb field?

— where are the boundaries of Mendeleev's Periodic Table? how much are the chemical properties of superheavy elements similar to the properties of their lighter homologues?

It is evident that, in searching for the answers to these and many other questions, we should significantly enrich our knowledge of the subject. To do this, it is necessary to significantly expand the field of activity with attracting new resources. However, judging by the first attempts, it will be a challenge to go beyond the region of the synthesized superheavy nuclei, which has been the focus of research for the past 15 years. Let us dwell on this in more detail.

Direct synthesis of elements with $Z > 118$ in fusion reactions requires using heavier projectiles than calcium nuclei, since the production of the target material in a nuclear reactor is limited to the californium isotopes (see above). Attempts to synthesize elements 119 and 120 undertaken at different laboratories failed.[44–46] The cross sections of formation of nuclei with $Z = 120$ in the $^{248}Cm + {}^{54}Cr$ reaction and of nuclei with $Z = 119$ in the $^{249}Bk + {}^{50}Ti$ reaction turned out to be $\sim 10-20$ times smaller than the cross section of formation of isotopes of element 114 and 115 in the experiments with ^{48}Ca.

To advance into another region, namely, into the region of more neutron-rich isotopes of the already known superheavy elements, and get closer to the shell $N = 184$ is possible only with the use of more neutron-rich radioactive ions than ^{48}Ca. Unfortunately, the intensities of beams of radioactive nuclei in the state-of-the-art accelerators and even in projected ones are extremely low to perform such experiments.

Advance in the opposite direction, toward neutron deficit in superheavy nuclei, also leads, as noted above, to a strong decrease in the reaction cross section as moving away from the shell $N = 184$.

Taking into account these facts, it seems expedient to comprehensively study the already synthesized nuclei: to measure their masses, shapes and fission barriers; to find excited states; to study their chemical properties; *etc*. However, for these data to have the predictive power, it is necessary to essentially enhance the statistics of measurements. Single events of formation and decay of superheavy nuclides, which are currently detected in the experiment at a rate from one per day to one per month (which is believed to be a great achievement of the recent years), are far from being sufficient for these purposes. The experimental result should be represented by hundreds and thousands of events rather than single events. Only then, it will be possible to trace rare decay channels of superheavy elements and comprehensively study nuclear transitions to different states, in short, to perform complete measurements in spite of very small cross section of formation of superheavy elements.

It is worth noting that the current situation resembles, in some ways, the beginning of efforts to synthesize superheavy elements two decades ago, when a new approach to the synthesis of superheavy elements (An + ^{48}Ca reactions) was found and essential progress in experimental technique was achieved.

After the discovery of the superheavy elements, based on the accumulated knowledge of the synthesis of new elements (nuclear fusion followed by neutron evaporation), the cross sections of formation of superheavy nuclei at different beam energies (excitation functions), the competing reaction channels (background conditions) and decay characteristics of isotopes of superheavy elements (decay modes, energies and times), as well as taking into account the progress achieved over the past two decades in many relevant fields, such as the technique of physical experiment, physics and technology of charged particle accelerators, physics of plasma, design of new high-precision and high-sensitivity nuclear radiation detectors, production of new target materials in high-flux nuclear reactors and development of new target technologies, we have arrived at the conclusion that it is possible to increase nearly 100-fold the production rate of the known isotopes of superheavy elements at a new experimental complex — 'Factory of Superheavy Elements' — and to make a second breakthrough into the world of superheavy elements. Ideas underlying the design of this facility are associated with the development of the experimental base for future research in several areas:

— production of new target materials and development of techniques of making targets with high thermal and radiation stability (running and projected nuclear reactors and enrichment facilities);[47]

— construction of a new powerful accelerator of stable and long-lived isotopes in the mass range $A = 10-100$ with the intensity up to 10 pμA and the energy up to 8 MeV nucleon^{-1};[48]

— construction of a new experimental building and infrastructure for accommodation of the accelerator and beam transport channels;

— development of new separators and detection modules (along with the use of the existing ones) for studying the nuclear, atomic and chemical properties of new elements;

— development of a base for research with intense ion beams in related fields of science and technology.

Currently, the project 'Factory of Superheavy Elements' is implemented at the Flerov Laboratory of Nuclear Reactions and is one of the key projects in the programme of development of perspective directions of the JINR. The launch of the 'Factory' is scheduled for 2017–2018.

In general, studies of heavy and superheavy nuclei fall into the realms of atomic physics, nuclear physics, astrophysics and radiochemistry. These studies cover a wide range of phenomena and are far from being limited by the experiments intended to perform at the 'Factory of Super-

heavy Elements'. However, when experiments are performed with extremely heavy nuclei at the boundary of stability and require the highest ever sensitivity, advantages of the 'Factory of Superheavy Elements' become invaluable. This is a specific feature of the new complex. Its research program will be directly related to the achievements of world science and is designed for broad international cooperation.

'Factory of Superheavy Elements' has no analogues in the world. The factory is designed to operate for 20 – 25 years (as well as all heavy ion accelerators at the JINR) and will be in demand as the experimental complex ensuring leading positions in the science of heavy and superheavy elements.

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References

1. G Gamow *Proc. Roy. Soc. London, A: Mathem. Phys. Eng. Sci.* **126** 632 (1930)
2. O Hahn, F Strassmann *Naturwissenschaften* **27** 11 (1939)
3. N Bohr, J Wheeler *Phys. Rev.* **56** 426 (1939)
4. K A Petrjak, G N Flerov *Phys. Rev.* **58** 89 (1940)
5. W D Myers, W J Swiatecki *Nucl. Phys.* **81** 1 (1966)
6. V M Strutinsky *Nucl. Phys. A* **95** 420 (1967)
7. A Sobiczewski, F A Garee, B N Kalinkin *Phys. Lett.* **22** 500 (1966)
8. H Meldner *Ark. Fys.* **36** 593 (1967)
9. S G Nilsson, C F Tsang, A Sobiczewski, Z Szymanski, S Wycech, C Gustafson, I-L Lamm, P Moller, B Nilsson *Nucl. Phys., A* **131** 1 (1969)
10. Yu Ts Oganessian *Lect. Notes Phys.* **33** 221 (1974)
11. S Hofmann *Lect. Notes Phys.* **764** 203 (2009)
12. K Morita, K Morimoto, D Kaji, H Haba, K Ozeki, Y Kudou, T Sumita, Y Wakabayashi, A Yoneda, K Tanaka, S Yamaki, R Sakai, T Akiyama, Shin-ichi Goto, H Hasebe, M Huang, T Huang, E Ideguchi, Y Kasamatsu, K Katori, Y Kariya, H Kikunaga, H Koura, H Kudo, A Mashiko, K Mayama, Shin-ichi Mitsuoka, T Moriya, M Murakami, H Murayama, S Namai, A Ozawa, N Sato, K Sueki, M Takeyama, F Tokanai, T Yamaguchi, A Yoshida *J. Phys. Soc. Jpn.* **81** 103201 (2012)
13. Yu Oganessian, V Utyonkov *Rep. Prog. Phys.* **78** 036301 (2015)
14. Yu Ts Oganessian, S N Dmitriev *Russ.Chem. Rev.* **78** (12) 1077 (2009)
15. S Hofmann, S Heinz, R Mann, J Maurer, J Khuyagbaatar, D Ackermann, S Antalic, W Barth, M Block, H G Burkhard, V F Comas, L Dahl, K Eberhardt, J Gostic, R A Henderson, J A Heredia, F P Heßberger, J M Kenneally, B Kindler, I Kojouharov, J V Kratz, R Lang, M Leino, B Lommel, K J Moody, G Münzenberg, S L Nelson, K Nishio, A G Popeko, J Runke, S Saro, D A Shaughnessy, M A Stoyer, P Thörle-Pospiech, K Tinschert, N Trautmann, J Uusitalo, P A Wilk, A V Yeremin *Eur. Phys. J., A* **48** 62 (2012)
16. Ch E Düllmann, M Schädel, A Yakushev, A Törler, K Eberhardt, J V Kratz, D Ackermann, L-L Andersson, M Block, W Bröchle, J Dvorak, H G Essel, P A Ellison, J Even, J M Gates, A Gorshkov, R Graeger, K E Gregorich, W Hartmann, R-D Herzberg, F P Heßberger, D Hild, A Hübner, E Jäger, J Khuyagbaatar, B Kindler, J Krier, N Kurz, S Lahiri, D Liebe, B Lommel, M Maiti, H Nitsche, J P Omtvedt, E Parr, D Rudolph, J Runke, B Schausten, E Schimpf, A Semchenkov, J Steiner, P Thörle-Pospiech, J Uusitalo, M Wegrzecki, N Wiehl *Phys. Rev. Lett.* **104** 252701 (2010)
17. J Khuyagbaatar, A Yakushev, Ch E Düllmann, D Ackermann, L L Andersson, M Asai, M Block, R A Boll, H Brand, D M Cox, M Dasgupta, X Derkx, A Di Nitto, K Eberhardt, J Even, M Evers, C Fahlander, U Forsberg, J M Gates, N Gharibyan, P Golubev, K E Gregorich, J H Hamilton, W Hartmann, R D Herzberg, F P Heßberger, D J Hinde, J Hoffmann, R Hollinger, A Hübner, E Jäger, B Kindler, J V Kratz, J Krier, N Kurz, M Laatiaoui, S Lahiri, R Lang, B Lommel, M Maiti, K Miernik, S Minami, A Mistry, C Mokry, H Nitsche, J P Omtvedt, G K Pang, P Papadakis, D Renisch, J Roberto, D Rudolph, J Runke, K P Rykaczewski, L G Sarmiento, M Schädel, B Schausten, A Semchenkov, D A Shaughnessy, P Steinegger, J Steiner, E Tereshatov, P Thörle-Pospiech, K Tinschert, T Torres De Heidenreich, N Trautmann, A Törler, J Uusitalo, D E Ward, M Wegrzecki, N Wiehl, S M Van Cleve, V Yakusheva *Phys. Rev. Lett.* **112** 172501 (2014)
18. P A Ellison, K E Gregorich, J S Berryman, D L Bleuel, R M Clark, I Dragojević, J Dvorak, P Fallon, C Fineman-Sotomayor, J M Gates, O R Gothe, I Y Lee, W D Loveland, J P McLaughlin, S Paschalis, M Petri, J Qian, L Stavsetra, M Wiedeking, H Nitsche *Phys. Rev. Lett.* **105** 182701 (2010)
19. S Dmitriev, A Popeko *Mendeleev Commun.* **23** 1 (2013)
20. P J Karol, R C Barber, B M Sherrill, E Vardaci, T Yamazaki *Pure Appl. Chem.* **88** 139 (2016)
21. Yu Ts Oganessian, V K Utyonkov, Yu V Lobanov, F Sh Abdullin, A N Polyakov, I V Shirokovsky, Yu S Tsyganov, G G Gulbekian, S L Bogomolov, B N Gikal, A N Mezentsev, S Iliev, V G Subbotin, A M Sukhov, G V Buklanov, K Subotic, M G Itkis, K J Moody, J F Wild, N J Stoyer, M A Stoyer, R W Lougheed *Phys. Rev. Lett.* **83** 16 (1999)
22. Yu Ts Oganessian, V K Utyonkov, Yu V Lobanov, F Sh Abdullin, A N Polyakov, R N Sagaidak, I V Shirokovsky, Yu S Tsyganov, A A Voinov, G G Gulbekian, S L Bogomolov, B N Gikal, A N Mezentsev, S Iliev, V G Subbotin, A M Sukhov, K Subotic, V I Zagrebaev, G K Vostokin, M G Itkis, K J Moody, J B Patin, D A Shaughnessy, M A Stoyer, N J Stoyer, P A Wilk, J M Kenneally, J H Landrum, J F Wild, R W Lougheed *Phys. Rev. C* **74** 044602 (2006)
23. Yu Ts Oganessian, V K Utyonkov, Yu V Lobanov, F Sh Abdullin, A N Polyakov, R N Sagaidak, I V Shirokovsky, Yu S Tsyganov, A A Voinov, G G Gulbekian, S L Bogomolov, B N Gikal, A N Mezentsev, V G Subbotin, A M Sukhov, K Subotic, V I Zagrebaev, G K Vostokin, M G Itkis, R A Henderson, J M Kenneally, J H Landrum, K J Moody, D A Shaughnessy, M A Stoyer, N J Stoyer, P A Wilk *Phys. Rev. C* **76** 011601(R) (2007)
24. Yu Ts Oganessian, V K Utyonkov, S N Dmitriev, Yu V Lobanov, M G Itkis, A N Polyakov, Yu S Tsyganov, A N Mezentsev, A V Yeremin, A A Voinov, E A Sokol, G G Gulbekian, S L Bogomolov, S Iliev, V G Subbotin, A M Sukhov, G V Buklanov, S V Shishkin, V I Chepygin, G K Vostokin, N V Aksenov, M Hussonnois, K Subotic, V I Zagrebaev, K J Moody, J B Patin, J F Wild, M A Stoyer, N J Stoyer, D A Shaughnessy, J M Kenneally, P A Wilk, R W Lougheed, H W Gäggeler, D Schumann, H Bruchertseifer, R Eichler *Phys. Rev. C* **72** 034611 (2005)
25. Yu Ts Oganessian, F Sh Abdullin, C Alexander, J Binder, R A Boll, S N Dmitriev, J Ezold, K Felker, J M Gostic, R K Grzywacz, J H Hamilton, R A Henderson, M G Itkis, K Miernik, D Miller, K J Moody, A N Polyakov,

A V Ramayya, J B Roberto, M A Ryabinin, K P Rykaczewski, R N Sagaidak, D A Shaughnessy, I V Shirokovsky, M V Shumeiko, M A Stoyer, N J Stoyer, V G Subbotin, A M Sukhov, Yu S Tsyganov, V K Utyonkov, A A Voinov, G K Vostokin *Phys. Rev. C* **87** 014302 (2013)
26. S N Dmitriev, Yu Ts Oganessian, V K Utyonkov, S V Shishkin, A V Yeremin, Yu V Lobanov, Yu S Tsyganov, V I Chepygin, E A Sokol, G K Vostokin, N V Aksenov, M Hussonnois, M G Itkis, H W Gdggeler, D Schumann, H Bruchertseifer, R Eichler, D A Shaughnessy, P A Wilk, J M Kenneally, M A Stoyer, J F Wild *Mendeleev Commun.* 1 (2005)
27. Yu Ts Oganessian, V K Utyonkov, Yu V Lobanov, F Sh Abdullin, A N Polyakov, I V Shirokovsky, Yu S Tsyganov, G G Gulbekian, S L Bogomolov, B N Gikal, A N Mezentsev, S Iliev, V G Subbotin, A M Sukhov, A A Voinov, G V Buklanov, K Subotic, V I Zagrebaev, M G Itkis, J B Patin, K J Moody, J F Wild, M A Stoyer, N J Stoyer, D A Shaughnessy, J M Kenneally, R W Lougheed *Phys. Rev. C* **69** 054607 (2004)
28. D Schumann, H Bruchertseifer, R Eichler, B Eichler, H W Gäggeler, S N Dmitriev, Yu Ts Oganessian, V P Utyonkov, S V Shishkin, A V Yeremin, Yu V Lobanov, Yu S Tsyganov, V I Chepygin, E A Sokol, G K Vostokin, N V Aksenov, M Hussonnois, M G Itkis *Radiochim. Acta* **93** 727 (2005)
29. R Dressler, R Eichler, D Schumann, S Shishkin *Phys. Rev. C* **79** 054605 (2009)
30. A Türler, V Pershina *Chem. Rev.* **113** 1237 (2013)
31. Y A Demidov, A V Zaitsevskii *Russ. Chem. Bull.* **63** 1647 (2014) [*Izv. Akad. Nauk, Ser. Khim.* 1647 (2014)]
32. A B Yakushev, I Zvara, Yu Ts Oganessian, A V Belozerov, S N Dmitriev, B Eichler, S Hübener, E A Sokol, A Türler, A V Yeremin, G V Buklanov, M L Chelnokov, V I Chepigin, V A Gorshkov, A V Gulyaev, V Ya Lebedev, O N Malyshev, A G Popeko, S Soverna, Z Szeglowski, S N Timokhin, S P Tretyakova, V M Vasko, M G Itkis *Radiochim. Acta.* **91** 433 (2003)
33. R Eichler, N V Aksenov, A V Belozerov, G A Bozhikov, V I Chepigin, R Dressler, S N Dmitriev, H W Gäggeler, V A Gorshkov, F Haenssler, M G Itkis, V Ya Lebedev, A Laube, O N Malyshev, Yu Ts Oganessian, O V Petruschkin, D Piguet, P Rasmussen, S V Shishkin, A V Shutov, A I Svirikhin, E E Tereshatov, G K Vostokin, M Wegrzecki, A V Yeremin *Nature (London)* **447** 72 (2007)
34. R Eichler, N V Aksenov, A V Belozerov, G A Bozhikov, V I Chepigin, S N Dmitriev, R Dressler, H W Gäggeler, A V Gorshkov, M G Itkis, F Haenssler, A Laube, V Ya Lebedev, O N Malyshev, Yu Ts Oganessian, O V Petrushkin, D Piguet, A G Popeko, P Rasmussen, A A Serov, S V Shishkin, A V Shutov, A I Svirikhin, E E Tereshatov, G K Vostokin, M Wegrzecki, A V Yeremin *Angew. Chem., Int. Ed.* **47** 1 (2008)
35. R Eichler, N V Aksenov, Yu V Albin, A V Belozerov, G A Bozhikov, V I Chepigin, S N Dmitriev, R Dressler, H W Gäggeler, V A Gorshkov, R A Henderson, A M Johnsen, J M Kenneally, V Ya Lebedev, O N Malyshev, K J Moody, Yu Ts Oganessian, O V Petrushkin, D Piguet, A G Popeko, P Rasmussen, A Serov, D A Shaughnessy, S V Shishkin, A V Shutov, M A Stoyer, N J Stoyer, A I Svirikhin, E E Tereshatov, G K Vostokin, M Wegrzecki, P A Wilk, D Wittwer, A V Yeremin *Radiochim. Acta* **98** 133 (2010)
36. A Yakushev, J M Gates, A Türler, M Schädel, Ch E Düllmann, D Ackermann, L-L Andersson, M Block, W Brüchle, J Dvorak, K Eberhardt, H G Essel, Ju Even, U Forsberg, A Gorshkov, R Graeger, K E Gregorich, W Hartmann, R Dietmar Herzberg, F Heßberger, D Hild, A Hübner, E Jäger, J Khuyagbaatar, B Kindler, J Kratz, J Krier, N Kurz, B Lommel, L Niewisch, H Nitsche, J P Omtvedt, E Parr, Z Qin, D Rudolph, J Runke, B Schausten, E Schimpf, A Semchenkov, Ju Steiner, P Thörle-Pospiech, Ju Uusitalo, M Wegrzecki, N Wiehl *Inorg. Chem.* **53** 1624 (2014)
37. L Lens, in *Proccedins of the 5th International Conference on the Chemistry and Physics of the Transactinide Elements (TAN 15), Urabandai, Japan, 2015* p. 53
38. A Zaitsevskii, Ch Van Wüllen, A V Titov *J. Chem. Phys.* **132** 081102 (2010)
39. A A Rusakov, Y A Demidov, A Zaitsevskii *CEJP* **11** 1537 (2013)
40. V Pershina, A Borschevsky, E Eliav, U Kaldor *J. Phys. Chem. A* 13712 (2008)
41. V Pershina, J Anton, T Jacob *Chem. Phys. Lett.* **480** 157 (2009)
42. S N Dmitriev, N V Aksenov, Yu V Albin, G A Bozhikov, M L Chelnokov, V I Chepygin, R Eichler, A V Isaev, D E Katrasev, V Ya Lebedev, O N Malyshev, O V Petrushkin, L S Porobanuk, M A Ryabinin, A V Sabelnikov, E A Sokol, A V Svirikhin, G Ya Starodub, I Usoltsev, G K Vostokin, A V Yeremin *Mendeleev Commun.* **24** 253 (2014)
43. V Zlokazova *Eur. Phys. J., A* **8** 81 (2000)
44. Yu Ts Oganessian, V K Utyonkov, Yu V Lobanov, F Sh Abdullin, A N Polyakov, R N Sagaidak, I V Shirokovsky, Yu S Tsyganov, A A Voinov, A N Mezentsev, V G Subbotin, A M Sukhov, K Subotic, V I Zagrebaev, S N Dmitriev, R A Henderson, K J Moody, J M Kenneally, J H Landrum, D A Shaughnessy, M A Stoyer, N J Stoyer, P A Wilk *Phys. Rev. C* **79** 024603 (2009)
45. S Hofmann, S Heinz, D Ackermann, S Antalic, W Barth, H G Burkhard, V F Comas, L D Eberhardt, J Gostic, R Grzywacz, R A Henderson, J A Heredia, F P Heßberger, J M Kenneally, B Kindler, I Kojouharov, R Lang, M Leino, B Lommel, R Mann, J Maurer, K Miernik, D Miller, K J Moody, G Münzenberg, S L Nelson, K Nishio, A G Popeko, J B Roberto, J Runke, K P Rykaczewski, S Saro, D A Shaughnessy, M A Stoyer, P Thörle-Pospiech, K Tinschert, N Trautmann, J Uusitalo, P A Wilk, A V Yeremin *GSI Scientific Report 2011* 205 (2012) GSI Report 2012-1 205
46. Ch E Düllmann, A Yakushev, J Khuyagbaatar, D Rudolph, H Nitsche, D Ackermann, L-L Andersson, M Block, D M Cox, J Dvorak, K Eberhardt, P A Ellison, N E Esker, J Even, C Fahlander, U Forsberg, J M Gates, K E Gregorich, P Golubev, O Gothe, W Hartmann, R-D Herzberg, F P Heßberger, J Hoffmann, R Hollinger, A Hübner, E Jäger, J Jeppsson, B Kindler, S Klein, I Kojouharov, J V Kratz, J Krier, N Kurz, S Lahiri, B Lommel, M Maiti, R R Mändl, S Minami, A Mistry, C Mokry, J P Omtvedt, G K Pang, I Pysmenetska, D Renisch, J Runke, L G Sarmiento, M Schädel, B Schausten, A Semchenkov, J Steiner, P Thörle-Pospiech, N Trautmann, A Türler, J Uusitalo, D Ward, N Wiehl, M Wegrzecki, V Yakusheva *GSI Scientific Report 2011* 206 (2012) GSI Report 2012-1 206
47. S N Dmitriev, A G Popeko *J. Radioanal. Nucl. Chem.* **305** 927 (2015)
48. G Gulbekyan, B Gikal, S N Dmitriev, S L Bogomolov, O N Borisov, I A Ivanenko, N Yu Kazarinov, V I Kazacha, I V Kalagin, N F Osipov, A V Tikhomirov, J Franko, in *Proceedings of IPAC 2011, San Sebastiàn, 2011* p. 2700