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THE EXPERIMENTAL PRESENT AND FUTURE OF SUPERHEAVY NUCLEI SYNTHESIS*

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One of the long-term programs of nuclear physics is to investigate the properties of the heaviest atomic nuclei. The synthesis of nuclei with $Z > 100$ always belonged to experiments at laboratory detection limits. The last large scale upgrade of experimental technique enabled to synthesize new nuclei with $Z = 110, 111, 112$. At these experiments no such a significant shell stabilizing or isospin effect was observed, which could eliminate the continuous decrease of cross sections of both "cold" and "hot" fusion reactions. For the synthesis of nuclei with $Z \geq 113$ cross sections below 1 pb are expected. To synthesize new superheavy nuclei with higher nuclear charge, the laboratory technique, to be used at the proposed reactions, should be again considerably upgraded. New target systems are considered, able to accept higher beam intensities. Some of the new superheavy evaporation residues will probably decay by fission. At present no adequate detection methods are used at superheavy element research, enabling an unambiguous identification of single fissionable evaporation residues. Possibilities to develop such detector systems are presented.

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1 Introduction

The understanding of the structure and properties of the heaviest atomic nuclei and to determine where is the upper end of stability of nuclear matter, to answer the question how many protons and neutrons can create a nuclear system, surviving the process of creation in a nuclear reaction, is one of the long term programs of nuclear physics. Until 1940 ^{238}U was the heaviest known nucleus. From that time 20 transuranium elements were synthesized and more than 200 isotopes of these elements were unambiguously identified. Fig. 1 shows the upper end of the chart of nuclei. The figure contains three type of data: Identified isotopes of new elements, nuclear reactions where only cross section limits were determined and nuclear reactions supposed to

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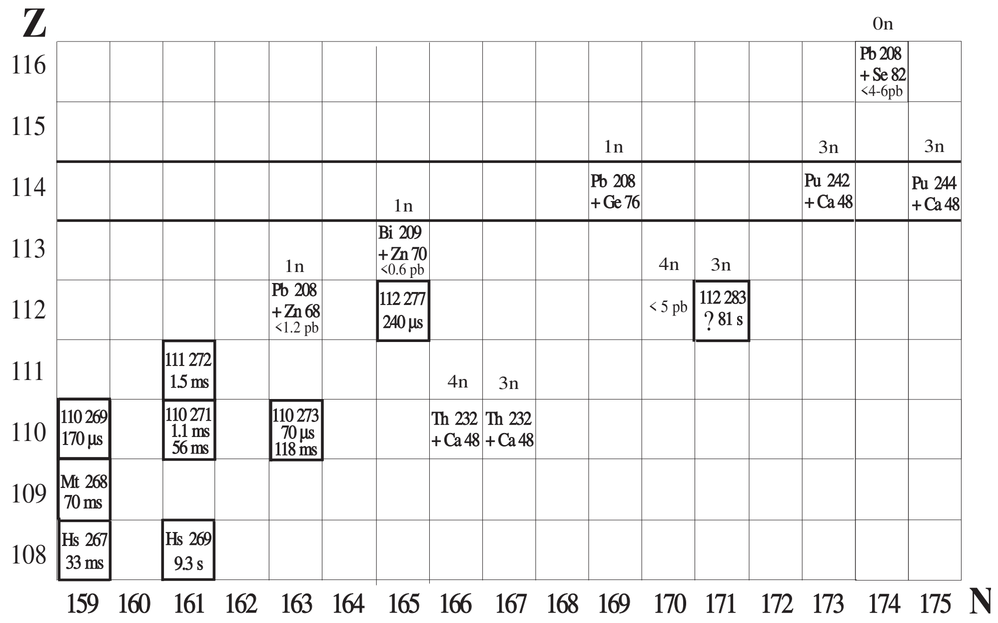

Fig. 1. The upper end of the table of nuclei.

be carried out in a near future. The comparison of experimental and predicted half-life values shows, that recent theoretical calculations based on the Nilsson-Strutinsky model give for even-even nuclei half-life values, which are in good agreement with the measured values [1, 2]. From the experimental point of view it is very important, that the predicted half-life values for the available target-projectile combinations are longer than the experimentally critical 1 μs, and are short enough to apply the powerful $\alpha-\alpha$ correlation method of evaporation residue identification [1–4].

The predictive force of production cross section calculations is worse than in the case of half-lives. Recent calculations made by R. Smolanczuk [5] reproduce the measured production cross sections for the 1n reaction channel of Pb and Bi targets up to $Z=112$. R. Smolanczuk predicts for the synthesis of the hypothetical spherical superheavy nuclei unexpectedly high production cross sections. For the reaction of $^{208}\mathrm{Pb}(^{82}\mathrm{Se},1\mathrm{n})^{289}116$ the predicted production cross section is 32 pb, and for the reaction of $^{208}\mathrm{Pb}(^{86}\mathrm{Kr},1\mathrm{n})^{293}118$ 1.8 nb. These values are in contradiction with the trend of continuous decrease of experimental production cross sections with Z as it is shown in Fig.2. The stabilizing effect of the supposed spherical shape of these nuclei may be overestimated and the role of quasifission is probably underestimated. The predictive force of this calculations cannot be tested with the experimental limit, achieved at the velocity separator SHIP (GSI) for the reaction of $^{82}\mathrm{Se}+^{208}\mathrm{Pb}$, because this experiment was running at excitation energies calculated for the 0n de-excitation channel.

We are still too far from good understanding of all basic physical properties of the heaviest nuclei and the mechanism of their creation. To improve the model images of this area of nuclei more experimental points at the upper end of the chart of nuclei are needed. Especially around $Z=114$, where model calculations, based on the Nilsson-Strutinsky approach [6] predict a closed

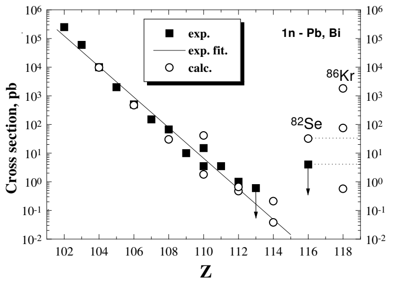

Fig. 2. The highest measured (full squares) production cross sections of isotopes of transfermium elements for the 1n de-excitation channel and Pb and Bi targets and values (open circles) calculated by R. Smolanczuk [5].

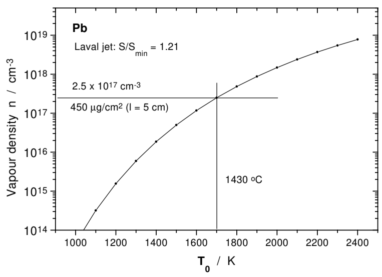

Fig. 3. Saturated Pb vapor density as the function of temperature. Conditions for vapor density, equivalent to 450 $\mu g/\mathrm{cm}^2$ Pb target foil are indicated.

proton shell with strong shell correction energies and spherical shapes of nuclei [2, 4]. Our possibilities for experimental testing of this area of nuclei are limited. First of all by the available combinations of stable or long living target and projectile nuclei. We need more neutron reach combinations of target and projectile nuclei. This can be achieved only with radioactive beams. In spite of the great progress in secondary beam intensities we are today still several orders of magnitude below the necessary level. In the case of Pb and Bi based complete fusion reactions even the known most neutron reach radioactive nuclei of Zn, Ga and Ge do not allow to get close to the supposed double magic nucleus of $^{298}114_{184}$. The situation is similar also for the possible target - projectile combinations for the hot fusion 3n, 4n, 5n de-excitation channels.

2 Cross-section limitations

The primary source of most of the experimental problems, concerned with the synthesis of superheavy nuclei beyond $Z = 110$, is the low production cross section in complete fusion reactions. The cross sections of the cold fusion reactions, based on Pb and Bi targets and 1n de-excitation channel is steadily decreasing. For $Z = 112$ it decreased to the level of 1 pb as it is shown in Fig. 2. Linear extrapolation to $Z = 114$ gives for the 1n channel complete fusion reaction a cross-section of about 0.1 pb. Higher cross-section values can be expected taking into consideration the higher isospin value for the heaviest available projectile nuclei of germanium - ^{76}Ge. The present sensitivity of the UNILAC-SHIP complex (GSI Darmstadt) for the detection of one heavy element α-decay chain is about one decay chain per 10 days at a cross-section of 1 pb. The second facility, designed for heavy element research, the U400-VASSILISSA complex (JINR Dubna) has a similar sensitivity.

To go further and to have a realistic possibility to synthesize several nuclei of elements around $Z = 114$ there is a need to improve the sensitivity to the level of one identified decay chain within 10 – 15 days at a cross section of about 0.1 pb. There are two parameters which can substantially contribute to the sensitivity: the beam intensity on the target and the target ability to accept high beam intensity.

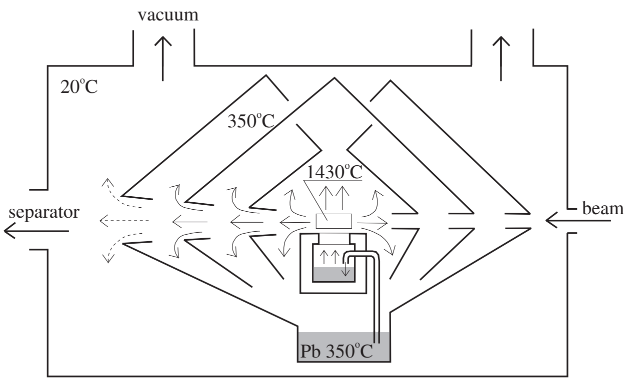

Fig. 4. Schematic view and operation principle of the proposed Pb vapor jet target.

2.1 Beam intensity

The ECR heavy ion sources and injectors are gradually increasing the delivered beam intensities above 10^{13} pps and there are projects to achieve beyond several years intensities above 10^{14} pps. Present heavy ion beam intensities, like Ni or Zn, on the rotating target in front of the velocity filter SHIP can reach about 8×10^{12} pps. This is more than two times higher than the rotating Pb target foil can accept without a significant loss of quality. On the other side in 1999 a new heavy ion source and injector at GSI will be suited to inject into UNILAC as many as 6×10^{13} pps of heavy ions and in a future 3×10^{14} pps for heavy element experiments at SHIP [7]. Similar intensities are expected also in other nuclear research centers, namely at RIKEN.

2.2 Target

There are several possibilities how to create conditions for the irradiation of the rotating Pb or Bi target foils at SHIP with higher beam intensities. The possibilities considered in a previous work [8] are not able to increase the beam intensity more than 2 - 3 times. The only type of Pb or Bi targets, able to bear beam intensities considerably over 10^{13} pps are vapor or cluster jets. The optimum Pb target thickness is about $450\,\mu g/cm^2$. The equivalent Pb vapor or cluster amount is $1.3 \times 10^{18}/cm^3$. The vapor jet can have an effective length of 5 cm and the corresponding vapor density will be $2.6 \times 10^{17}/cm^3$. This vapor density of lead is achieved at 1430 $°C$ as it is shown in Fig. 3.

At this temperature the atoms or molecules of lead have a velocity of 400 m/s, therefore the consumption of lead will be about 65 kg/hour. To have a reasonable consumption the target system is proposed to be closed as much as possible. A schematic view of the possible design of such a Pb or Bi vapor-cluster jet target is shown in Fig. 4. From the oven with a Laval nozzle in top the vapor stream will create a volume of 5 cm^3 with the desired density of $2.6 \times 10^{17}/cm^3$. The expanding material will condense on the surface of a system of condensers, having a temperature slightly above the melting point of lead. The condensed melted lead is collected at the bottom of the vacuum tank and pumped back into the oven. A system of holes in the condensers allow the evaporation residues and the beam to get out from the target vessel.

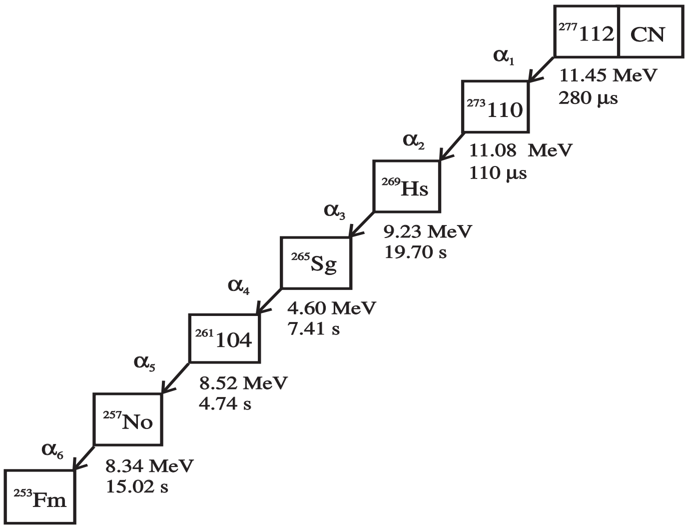

Fig. 5. One of the two alpha decay chains obtained using the $\alpha - \alpha$ correlation method at the identification of the new element $Z = 112$ [10].

According to our estimations the amount of lead, escaping from the target vessel, can be in the case of pulsed regime of operation well below 1 g/day.

3 Identification of reaction products

3.1 The $\alpha - \alpha$ correlation method

The main decay mode of all known nuclei beyond $Z = 106$ is α-decay. This allows the safe identification of both - mass number A and atomic number Z of an evaporation residue. The method is based on the correlation between the known α-decay characteristics of a chain of daughter α-emitters following the α-decay of the unknown mother nucleus. The reliability of the method is increased when the detector system is position sensitive and the pulses caused by α-particles are detected from the same position as the initial pulse from the incoming ER. An additional increase of the reliability of the method is achieved with time and position correlation between the pulse created with the ER in the analyzing detector and pulses from time-of-flight (TOF) detectors in front of the analyzing detector. The $\alpha - \alpha$ correlation method was first time successfully used at synthesis of a new element by G. Münzenberg et al. [9] in 1981 at the identification of the first nuclei of element 107. At all the later discoveries of heavier atomic nuclei this method of identification was used , last time in 1996 at the identification of the first two nuclei of element 112 [10]. In Fig. 5 the $\alpha - \alpha$ correlation chain of $^{277}112$ is shown.

There are two principal limitations for the application of this method. First, the investigated heavy ER have to be an α-emitter and at least some members of the α-decay chain should have known α-particle energies and half-life values. The second limitation are the background conditions. Without any background the method could be used, in principle, for $\alpha - \alpha$ correlation chains of nuclei with half-lives as long as hours, days or even longer. At real background conditions, an unambiguous assignment of detected energy pulses to particular α emitters is limited to minutes. Better background conditions can be achieved for the longer living members of the α-decay chains, when the pulses created by the first fast decaying members of the decay-chain are triggering the switch off the beam for some minutes, or if necessary even for a longer period. At this condition the improvement in the correlation time could help to "bridge" unknown decays of long lifetimes, which finally will end in known decays. It will enable an unambiguous identification of alpha-decay chains with several unknown members.

3.2 Fission fragment identification

There is no physical reason to suppose, that all not yet synthesized nuclei above $Z = 106$ will have a significant α-decay branch. In the last experiment, carried out at the VASSILISSA kinematic separator in Dubna, the reaction $^{238}\mathrm{U}(^{48}\mathrm{Ca},3\mathrm{n},4\mathrm{n})^{283,282}112$ was investigated [11] . At the beam energy of 231 MeV, corresponding to an excitation energy of 33 MeV, two fission events were detected with a position sensitive semiconductor detector array. After a careful analysis of all experimental parameters, related to these two events, the authors came to the conclusion that the observed fission fragments are, with very high probability, the decay products of $^{283}112$. But the used method of identification can not give an unambiguous proof that such rare single fission events have their origin in the decay of the supposed nucleus.

Let us consider, what possibilities we have for an unambiguous identification of a fissionable superheavy nucleus. A nucleus is identified when his atomic number Z and mass number A are identified using a direct or an indirect method of identification. Position sensitive silicon detectors, often used to identify α-decay chains, can not give any information about Z of the impact nucleus. The output energy signal from a silicon detector has a nonlinear deformation for heavy ions caused by the plasma effect. For this reason the correlated TOF and energy measurements will give mass values of heavy ERs, which do not allow to make a definite mass assignment.

3.2.1 Bragg spectrometry

From the point of view of possible methods for A and Z identification it is useful to distinguish between short- and long- living ERs. ERs with a half-life longer than about 20 ms can be slowed down to a thermal velocity and deposited on the surface of a very thin foil. A double Bragg spectrometric ionization chamber could have a resolving power to determine the atomic numbers Z_1 and Z_2 of the independently detected fission fragments. Because of the emission of prompt neutrons, the mass numbers cannot be determined in a Bragg spectrometer. Ten years ago a double ionization chamber was developed (Fig.6) and connected behind the kinematic separator VASSILISSA [12]. The ERs reached the common cathode as drifting positive ions after the process of slowing down in the gas filling. The ERs were collected with an efficiency close to 100%. The fission fragments were detected independently in the ionization chambers. The drift time of the ERs to the common cathode was about 40 ms with the possibility to reduce this time to about 10 ms. Taking into consideration this time limit, this device is proofing the possibility to design a double Bragg ionization chamber for atomic number identification of fission fragments. A possible limitation is connected with the fact, that fission fragments of neighboring very heavy nuclei have their Bragg peaks too close each to other.

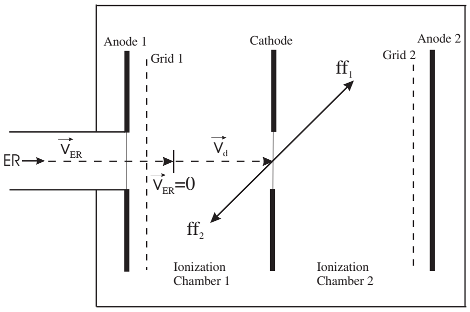

Fig. 6. Schematic view of the double ionization chamber, developed for alpha and fission fragment detection at the kinematic separator VASSILISSA [12].

3.2.2 Penning ion traps

There is a possibility to use a Penning ion trap to identify very heavy reaction products. In a Penning ion trap the mass separated radioactive or stable ions are stored and their mass is determined by a measurement of the cyclotron frequency in a magnetic field. In experiments with ions up to ^{230}Ra the Penning trap mass spectrometer at ISOLDE separator allowed the determination of mass values with an accurateness of $\Delta M/M = 10^{-7}$ for all isotopes [13]. There are planes to install a Penning trap together with a gas-filled laser ion source and a Paul filter behind the velocity separator SHIP. This combination can perform first time atomic, nuclear and mass spectroscopy of transuranium nuclei. The use of a Penning trap behind SHIP could solve the problem of identification of non-alpha decaying heavy nuclei.

In a Penning trap there is a possibility, in principle, to investigate the properties of single ions. This unique property belongs only to the trap itself. The reaction products, emerging from the kinematic separator, have to be first decelerated and after that captured by the trap. The efficiency of this process is rather low, less than one percent, and the stopping process on a foil in a two stage trap takes about 1 second. For the use of Penning ion traps for identification of reaction products, at picobarn cross section levels, the efficiency of the process of cooling and consequent capturing should be increased to a value close to 100%.

3.2.3 Coincidence γ-spectrometry and roentgen-spectrometry of single fission events

The atomic number Z of a heavy fissionable nucleus could be determined, in principle, by γ-spectrometric methods. Coincidence γ-spectra of both fission fragments ($Z1$,$A1$) + ($Z2$,$A2$) can be measured with a γ-sphere. Such γ-spheres are operating in many laboratories. The basic problem of the possible use of γ- spectrometry for the identification of a single fissioning nucleus is the background spectrum of such a spectrometer. Also the level schemes of the fission fragments should be known. At the moment it is not clear, if the background spectrum of a coincidence γ-spectrometer can be suppressed to the desired extremely low level. And probably also the level schemes most of the possible fission fragments are not known.

Better conditions can be expected for the identification of both fission fragments if their coincidence roentgen spectra will be measured and analyzed. Both possibilities, coincidence γ-spectroscopy and coincidence roentgen-spectroscopy of fission fragment should be carefully analyzed.

4 Conclusions

The predictive force of the last half-life calculations is strong enough to expect measurable half-lives for nuclei of elements 113 and 114. Recent theoretical calculations, based on the Nilsson-Strutinsky model predict for the available target-projectile combinations half-lives which are longer than the experimentally critical 1 μs and short enough to use the $\alpha-\alpha$ correlation method of identification.

In spite of new attempts to present more reliable calculated cross section values for the synthesis of superheavy nuclei, created in Pb(HI,1n) reactions, the presented cross section values for Z above 112 remain too uncertain to use them as a guide for future experiments.

New ECR heavy ion sources and injectors under development will deliver in the near future, at least at GSI Darmstadt and at RIKEN, heavy ion beam intensities several times 10^{13} pps and later even more. This gives the possibility to synthesize new superheavy nuclei at a cross-section level of 0.1 pb at a reasonable beam time.

The conditions for high beam acceptance of Pb and Bi targets can be achieved by using vapor- or cluster-jet targets. There are no principal physical or technical limitations to design such a target system.

There is a need to investigate and determine which possibilities we have to develop detector systems, able to determine Z and A of heavy evaporation residues undergoing fission. If the efficiency of the process of slowing down of evaporation residues will be solved, ion traps can give an excellent mass resolution in the case of any heavy nucleus. There are several principal possibilities for Z and A determination, which should be the subject of further investigation.

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