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Synthesis of heaviest nuclei and heaviest chemical elements

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Abstract. Studies of the heaviest nuclei and heaviest chemical elements are shortly described. Methods of synthesis and identification of these nuclei are discussed. Some details of the studies are illustrated on the example of the nucleus ^{277}Cn, the isotope of the element 112 (copernicium) the discovery of which has been recently approved by IUPAC. General results of the research on superheavy nuclei (atomic number Z = 104–118), synthesized within the period from 1969 (discovery of rutherfordium, Z = 104) up to the present are outlined.

Key words: heaviest nuclei • heaviest chemical elements • nuclear reactions • α-decay energy • α-decay half-life • α-decay genetic chains

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Introduction

As we know, only the elements with atomic number Z up to Z = 92 (uranium) appear in the Earth in the natural way. All the heavier ones were produced in the laboratory, with the use of nuclear reactions (see e.g. [15]). The lightest of them, up to Z = 101 (mendelevium), were obtained with light projectiles (neutrons, deuterons and α particles). To produce heavier ones, one needed to use heavy ions. A specific class of heaviest nuclei are the transactinide ones, i.e. with Z > 103 (translawrencium nuclei). Detailed calculations, based on various nuclear models, indicate that these nuclei exist only due to their shell structure. They are called superheavy nuclei. Thus, one would not have superheavy nuclei without their shell structure.

The objective of this paper is to give a short review of the present state of the synthesis and studies of the properties of superheavy nuclei. In description of these studies, we will mainly concentrate on nuclei of two elements. One is copernicium (Cn, Z = 112), the heaviest element, the discovery and name of which are already approved by IUPAC. This element was discovered at GSI-Darmstadt (Germany) in 1996 [7]. The second one is the element 117, observed recently (in 2010) [10] at the Joint Institute for Nuclear Research (JINR) at Dubna (Russia).

Synthesis of superheavy nuclei

Heaviest nuclei are produced in the fusion reactions. There are two classes of these reactions, depending on which targets are used. In one of them, strongly bound, doubly magic (i.e. with both proton and neutron shells closed) nucleus ^{208}Pb, or a near neighbour of it, is used. An example of such a reaction is

$$(1)\qquad {}^{70}_{30}\mathrm{Zn} + {}^{208}_{82}\mathrm{Pb} \rightarrow {}^{278}_{112}\mathrm{Cn}^{*} \rightarrow {}^{277}_{112}\mathrm{Cn} + 1\mathrm{n},$$

i.e. the reaction in which the element 112 (Cn) was obtained [7]. Here, the compound nucleus ^{278}Cn* was formed by the fusion of projectile ^{70}Zn and the target ^{208}Pb nuclei. Due to the strong binding (i.e. relatively small mass) of the nucleus ^{208}Pb, the excitation (denoted by an asterix) of the compound nucleus ^{278}Cn* is relatively small (around 15 MeV) and is sufficient for the emission of only one neutron to produce the final nucleus ^{277}Cn. Reaction (1) represents the class of the **cold-fusion reactions.** All superheavy elements with Z up to 112 were discovered with the use of this kind of reactions.

The second class of the fusion reactions is that in which actinide targets are used. As the actinide nuclei are less bound than ^{208}Pb, the excitation energy of the compound nucleus is larger (35–45 MeV) and usually 3 or 4 neutrons are emitted to reach the final nucleus. Examples of such reactions are:

$$(2a)\qquad {}^{48}_{20}\mathrm{Ca} + {}^{249}_{97}\mathrm{Bk} \rightarrow {}^{297}117^{*} \rightarrow {}^{294}117 + 3\mathrm{n}$$

$$(2b)\qquad {}^{48}_{20}\mathrm{Ca} + {}^{249}_{97}\mathrm{Bk} \rightarrow {}^{297}117^{*} \rightarrow {}^{293}117 + 4\mathrm{n},$$

i.e. the reactions in which the element 117 was obtained [10].

Identification of superheavy nuclei

The identification of a superheavy nucleus is done with the use of the so-called genetic chain. To obtain such a chain, one uses a position-sensitive detector. If position in such a detector is precisely determined, one can say (with a great probability) that all decays observed at this position belong to the decay chain of one specific nucleus, being the origin of this chain. If this is, as usually, the α decay, each member (link) of the chain determines the whole chain and, thus, also the first nucleus which was unknown. Quite often, already the second nucleus in the chain is known and identifies the whole chain. Further known nuclei in the chain only confirm the identification. Figure 1 shows the four genetic chains identifying the nucleus ^{277}112. The first one from the left was obtained in 1996 at GSI-Darmstadt [7] and its observation was the discovery of the element 112. The second one [5], observed also at GSI, and the third and fourth chains, observed at RIKEN (Japan) [8], were the confirmation of the discovery. The symbol CN in the figure denotes the compound nucleus ^{278}112.

Discovery of the element 112 (copernicium)

As mentioned in the Introduction, the element 112 is the heaviest of the elements, the discovery and the name of which have been already approved by IUPAC. It was synthesized in 1996 in the cold-fusion reaction of Eq. (1). The time of the irradiation was around three weeks. The intensity of the ^{70}Zn beam was 3×10^{12} ions/s,

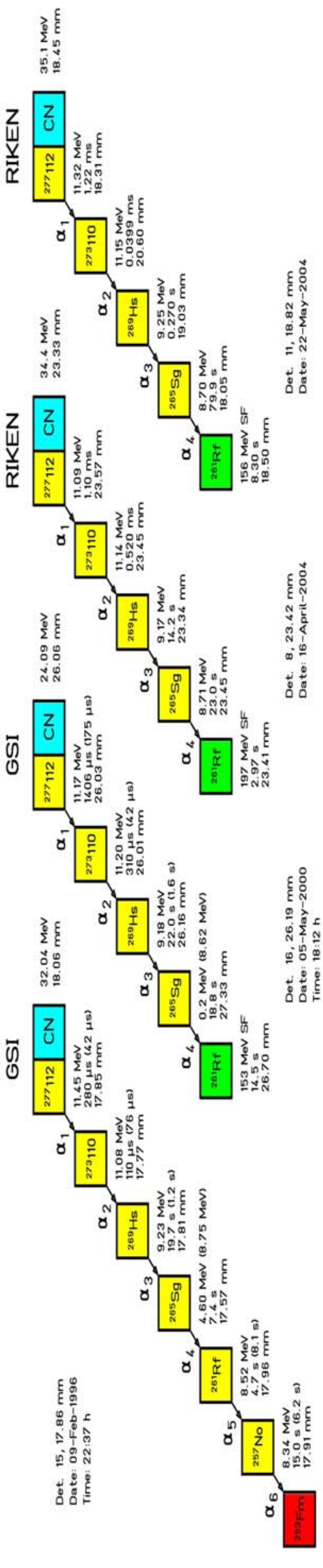

Fig. 1. Four (genetic) α-decay chains of the nucleus ^{277}112 (see text).

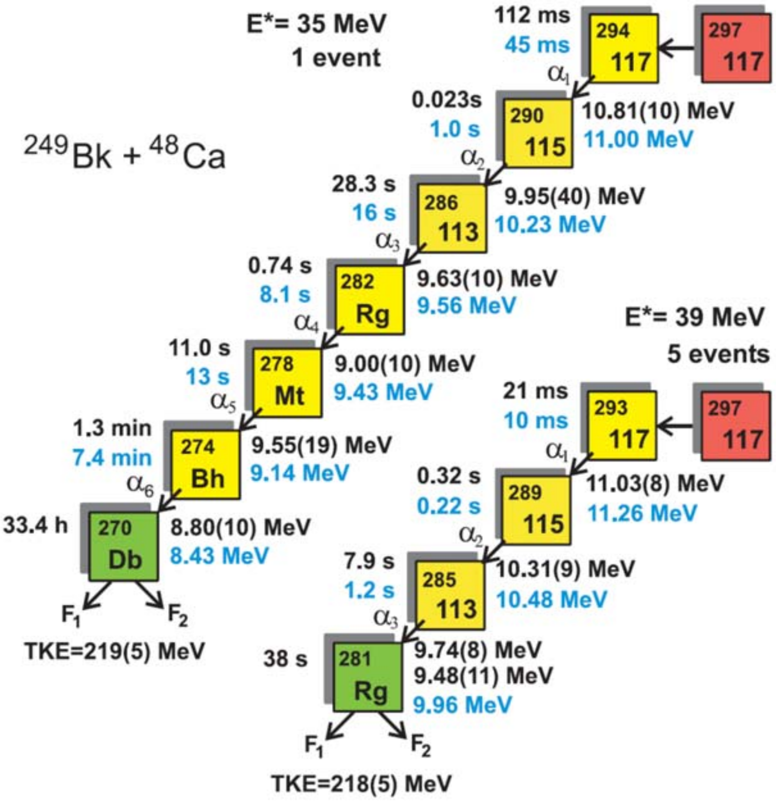

Fig. 2. Genetic chains identifying two isotopes of a new element 117 [10] (see text).

so the total dose of the ions was about 3 × 10^{18}. Only one superheavy nucleus ^{277}112 was observed. The measured cross section was about 1 pb. This illustrates how small is the probability of such synthesis. The measured half-life of ^{277}112 was about 0.2 ns. The small cross section together with the small half-life show that such nuclei (atoms) cannot be collected. They are available only on the scale: one nucleus (one atom) at a time.

Synthesis of the element 117

The element 117 was synthesized most recently (in 2010) at JINR-Dubna [10]. The heaviest element (118) of all produced up to now was observed earlier (in 2006) [12] at the same laboratory. Two isotopes of 117 were obtained in the hot-fusion reactions of Eqs. (2a) and (2b). Single isotope ^{294}117 was produced with a cross section of about 0.5 pb and 5 isotopes ^{293}117 were obtained with a cross section of about 1.3 pb. Measured half-life of the former nucleus was 78 ms and that of the latter one was 15 ms. The decay energies and half-lives of all nuclei in both decay chains were predicted, with a reasonable accuracy, by theoretical calculations [17]. Experimental as well as theoretical results are shown in Fig. 2, taken from Ref. [10]. The measured values (shown in black in the original figure) are given above the predicted ones (shown in blue in the original).

General results

Up to the present, 104 superheavy (i.e. translawrencium) nuclei with Z = 104–118 have been observed. These are isotopes of 15 superheavy chemical elements. Of these nuclei, 51 nuclides (with Z = 104–112 and one, ^{278}113, with Z = 113) were obtained in the cold-fusion reactions and 53 (with Z = 113–118, except ^{278}113) were produced in the hot-fusion ones. Detailed description of respective experiments may be found in, e.g. Refs. [1, 4, 6, 9] and references given there. One should say that a significant contribution to these results have been made by chemists (e.g. [3, 11, 14, 19]). This is because to study chemical properties of superheavy elements (SHE), one needs first to synthesize them and the latter is done by physical methods and brings a knowledge of physical properties of nuclei of these elements. One cannot separate the efforts of these two groups of scientists closely cooperating with each other in the studies of superheavy nuclei and elements.

The experimental research has been accompanied by the theoretical one, done by both more traditional macroscopic-microscopic methods (e.g. [16–18]) and more recent purely microscopic ones (e.g. [2, 13]). The latter represent self-consistent calculations of the Hatree-Fock type with the use of effective density-dependent interactions of both zero (Skyrme) and finite (Gogny) range, and also the relativistic mean field approach.

Conclusions

Studies of superheavy nuclei and of superheavy elements constitute presently fast developing parts of nuclear physics and of nuclear chemistry, respectively. Since 1969, when the element rutherfordium, Z = 104 (isotopes ^{257}Rf and ^{259}Rf) was discovered at Berkeley, 104 superheavy nuclei have been observed. These are isotopes of 15 superheavy elements with Z = 104–118. Despite the fact that the studies are expensive and time consuming, they are being intensively continued. Last year (2010), the new element 117 was synthesized at the JINR-Dubna. At present, an experiment aiming at the synthesis of element 120 is running at GSI-Darmstadt. The studies intend to answer a fascinating question: where is the limit of the periodic table of the chemical elements and the upper boundary of the nuclide chart.

Relating to the International Year of Chemistry 2011, connected with the centenary of the Nobel Prize in Chemistry of Maria Skłodowska-Curie, one can say that the studies of superheavy nuclei and elements are a continuation of her research on radioactivity, as just the radioactivity is used as the method of identification of these heaviest nuclei and elements.

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