Nuclei in Astrophysics

Yu. E. Penionzhkevich
Joint Institute for Nuclear Research, Dubna, Moscow region, 141980 Russia
Federal Research Nuclear University "MEPhI", Moscow, Russia
E-mail: pyuer@mail.ru

Abstract. This work is an attempt to present some problems on the evolution of the Universe: the nucleosynthesis and cosmochronology from the standpoint of physics of particles and nuclei, in particular with the use of the latest results, obtained by means of radioactive nuclear beams. The comparison is made between the processes taking place in the Universe and the mechanisms of formation and decay of nuclei, as well as of their interaction at different energies. Examples are given to show the capabilities of nuclearphysics methods for studying cosmic objects and properties of the Universe. The results of investigations in nuclear reactions, induced by radioactive nuclear beams, make it possible to analyze the nucleosynthesis scenario in the region of light elements in a new manner.

1. BASIC IDEAS ABOUT THE EVOLUTION OF THE UNIVERSE

The studies of microcosm laws where nuclear physics is involved have recently assisted in considerably extending our ideas about phenomena occurring in the macroworld our Universe and contributed enormously to developing the astrophysical and cosmological theories. This is concerned, first of all, with the abundance of elements and scenarios of their formation, as well as with properties of different stars and cosmic objects. Without aspiring in this review to the full description of all cosmology problems, let us dwell only upon those of them that have much in common with nuclearmatter properties manifesting themselves in nuclear interactions.

2. Model of the Expanding Universe.

According to estimates, formation of the Universe was around 10 billion years ago. It is believed that at this epoch the nowobservable Universe arose as a result of a monstrous explosion. The Big Bang, as the explosion is called, initiated the formation not only of the Universe, but also of all physical notions we know, including the notions of space and time. Some authors [1, 2] consider the evolution of the Universe in the form of four consecutive epochs, as a result of replacements of which, according to the newest models, the Universe came to its present state: \( \rho \approx 10^{-30} \text{ g/cm}^3, T = 3 \text{ K}. \) It is supposed in these models that the Universe behaves like a perfect black body, whose initial temperature and density are very high, its initial density is higher than a nuclear one of \( 10^{15} \text{ g/cm}^3 \) and a temperature is higher than \( 1 \text{ GeV} \) \( (10^{13} \text{ K}) \). The density of matter becomes larger than the radiation density (photon’s energy density) and grows during the expansion. This corresponds to the “star epoch” that has been lasting until now. V.L. Ginzburg describes in his book [2] the problems of the expanding Universe as the interaction of a great number of different particles: photons, electrons, neutrinos, muons, \( \pi \) - mesons, protons, neutrons, etc. Though, as he himself notes, this approach is rather subjective because we have no complete understanding of particle physics so far. Everything said above referred to the possible interpretation of the Universe based on strong interactions of elementary particles.
Meanwhile, one of the most interesting corollaries from the modern theory of particle physics is the fact that the Universe could experience a phase transition from one state of the matter to another. This phase transition is connected with shortrange interactions of the other class: weak interactions. Weak interactions in nuclear physics are responsible for certain radioactive-decay processes (e.g., decay of a free neutron) or of any reaction that involves neutrinos. The development of this theory made it also possible to draw important conclusions on problems concerning the study of the early Universe. (In 1998, S. Perlmutter and A. Riess from the USA and B. Schmidt from Australia predicted the acceleration of the expansion of the Universe. They were awarded the Nobel Prize in Physics for this achievement in 2011). This discovery has been made on the basis of changeability of the brightness of supernovas that end their evolution with an explosion. However, the Nobel Prize winners delivered the direct measurement of the acceleration of the expansion of the Universe, which also confirmed a theory of dark energy. However, all this requires the further comprehension and acquisition of new data and new approaches to description of the evolution of the Universe.

3. Nucleosynthesis
At this temperature in the early Universe, consisting of electrons, positrons, neutrinos, anti-neutrinos, neutrons, protons, and photons, different nuclei could form starting with deuteron and ending with helium. The heavier nuclei such as nuclei of carbon, oxygen, etc., could be synthesized only in the course of thermonuclear reactions in stars. The cause of it is that there is a certain interval of instability of light nuclei located near the lithium nucleus, and this interval cannot be surmounted in the course of the primeval nucleosynthesis. Therefore, the synthesis in the early epoch stops at the stage of the helium formation. It is believed that one of the first reactions leading to the formation of heavy nuclei is the reaction $n + p \rightarrow \alpha + \gamma$. As calculations have demonstrated, this reaction goes at the temperature $T = 10^{10}$ K, which corresponds to a ratio between the numbers of neutrons and protons in the Universe of $N_n/N_p = 0.2$ and to the time $\sim 3$ s. Under these conditions, deuterium forms in sufficient quantities for producing nuclei with a mass of 3 in the following reactions: $d + n \rightarrow ^3H + ^3d + p \rightarrow ^4He + \gamma, \gamma,d + d \rightarrow ^4H + p,d + d \rightarrow ^4He + n$ and finally $^4He$ can be formed as a result of the reactions: $^4H + p \rightarrow ^5He + \gamma, ^4He + n \rightarrow ^7He + \gamma$. The binding energy of products of these reactions is larger than that of deuterium (2.225 MeV); then if a photon can form a deuterium, it can conduct other reactions too. Since the stable mass 5 does not exist, $^4He$ is the last nucleus at the initial stage of nucleosynthesis. In principle, it could form the heavier nuclei (A = 7) as a result of the reactions: $^3He + ^4H \rightarrow ^7Li + ^4He + ^4He \rightarrow ^8Be + \gamma$. In this epoch, the formation of hydrogen and helium occurs. With this, the stage of primeval nucleosynthesis ends. The heavier nuclei form now as a result of processes related to the evolution of stars.

4. The stellar nucleosynthesis
The Universe during its evolution is enriched with ever heavier chemical elements. The abundance of chemical elements in the Universe is determined using different methods: by star radiation spectrum, by means of element analysis of terrestrial and cosmic samples (meteorites, lunar samples). The obtained curve of the element abundance is shown in Fig. 1. The curve has maxima for the silicon group and for the iron group, after which the abundance curve splits into two branches, one of which includes neutron-rich isotopes and is characterized by three double peaks near the magic numbers N = 50, 82, and 126, while the other branch includes four less abundant proton-rich isotopes. One of the nucleosynthesis stages is the formation of $^{12}C$. As has been shown above, carbon can be formed as a result of the two step reaction $^4He + ^4He \rightarrow ^7Be + ^7He \rightarrow ^8C + \gamma$. This reaction makes it possible to explain the existence of carbon and the other observable isotopes together with it. At each stage of the nuclear fusion initiated by explosion of the outer shell of stars, the more and heavier nuclei form: $^5He, ^{12}C, ^{16}O, ^{28}S$, and $^{56}Fe$. In so doing, the processes of formation are accompanied by the processes of decay of these nuclei. Somewhat different is a mechanism of
formation of the nuclei heavier than iron. This mechanism is explained by consecutive reactions of radioactive capture of neutrons by the iron-group elements.

Figure 1. The curve of abundance of elements. The top curve with double (r and s) peaks corresponds to neutron-rich isotopes; the bottom curve (p) is appropriate to proton-rich isotopes.

The presence of double peaks in the curve of element abundance (see Fig. 1) evidences that there are two different processes of neutron capture, the so-called r- and s-processes. The two processes correspond to different neutron densities. In case of low densities of neutrons (s-(slow)-process) in the radiation capture \( (A, Z) + n \rightarrow (A+1, Z) \), the isotope forms with a mass that is a unity larger than the target nucleus mass. This process repeats many times and leads to the formation of neutron-poor nuclei with a mass to 200. After this, the nuclear fission occurs at a large probability, which interrupts the s-process. With high densities of neutrons (r (rapid)-process), the nucleus \( (A + x, Z) \) will absorb neutrons before it decays, and new radiation captures occur. The evidence that r- and s-processes exist is the increased concentration of isotopes with \( N = 50, 82, \) and 126. It is experimentally shown that the abundance of elements is inversely proportional to total cross sections of neutron capture. This cross section for nuclei with magic numbers is several orders of magnitude lower than the one for other neighboring nuclei. From the viewpoint of nuclear physics, this result is a manifestation of magic numbers. For astrophysics, it is the proof of s-process existence. The existence of the shell with \( Z = 114 \) and hence the increase in stability of superheavy nuclei near the double-magic nucleus \(^{298}114\) (114 protons and 184 neutrons) were also predicted. Calculations performed according to the shell model showed the possibility of existence of this superheavy nucleus with a half-life to \( \sim 10^8 \) yr [3]. Despite the fact that the accuracy of these calculations is not high and they most likely are of qualitative type, the latest experiments in synthesis of heavy isotopes of elements 112–118 have shown that the increase in stability of superheavy nuclei with respect to decay is observed [4], which is an additional confirmation of the stability of superheavy nuclei near the shells (Fig. 2). If we suppose that the longest-lived superheavy nuclei have a half-life of \( 10^5 \)–\( 10^6 \) yr, which do not disagree much with predictions of the theory that makes its estimations with certain accuracy, then we cannot exclude that they may be revealed in cosmic rays: witnesses of formation of elements on other, younger planets of the Universe. If we also suggest that a half-life of “long-livers” may reach tens of millions of years or more, then they could be available in the Earth, having remained intact in very small quantities from the instant of formation of elements in the Solar System to present days.
the possible candidates, the most real ones are isotopes of element 108 (Hs), nuclei of which contain around 180 neutrons.

Then the decay of a superheavy nucleus will be recorded according to a neutron flare that accompanies a spontaneous fission. Such a facility including a 4π- neutron detector has been created at the JINR Laboratory of Nuclear Reactions, and for reducing the cosmic background of neutrons, it is installed in the underground laboratory located under the Alps in the middle of the tunnel connecting France with Italy at the depth of 4000 m water equivalent. If at least one event of spontaneous fission of a superheavy nucleus is observed for a year of measurements, then it will correspond to a concentration of element 108 in the Os sample around $5 \times 10^{-15}$ g/g on assumption that its half-life is $10^9$ yr. Such a small value amounts only to $10^{-16}$ of the uranium concentration in the Earth’s crust. Despite the superhigh sensitivity of the experiment, chances to detect relic superheavy nuclides are small. The absence of effect will provide only the upper limit of the long-liver’s half-life at a level of $T_{1/2} \sim 3 \times 10^7$ yr. Active searches in the natural objects (cosmic rays, materials, lunar samples, concentrates of heavy chemical elements of terrestrial samples) have yielded so far no positive result. At the present time, experiments are conducted at accelerators in Dubna and Darmstadt (Germany), which are directed at the artificial synthesis of superheavy elements in nuclear reactions with heavy ions, but, naturally, with shorter half-lives.

5. NUCLEAR PHYSICS EXPERIMENTS IN ASTROPHYSICS

The most fundamental problems of astrophysics, i.e., the processes of energy release in formation and explosion of stars, as well as nucleosynthesis, are most closely connected with particle physics and also with studies (using nuclear physics methods) of different nuclear characteristics and nuclear interactions at different energies including the energies near the Coulomb barrier. The primary information for solving one or another astrophysical problem is obtained from the following experimental data:

- half-lives of nuclei near the boundaries of
- nucleon stability (for r- and s-processes);
- probabilities of neutron emission after β-decay;
- characteristics of nuclear reactions leading to the synthesis of new nuclei;
total cross sections of nuclear reactions;  
characteristics of nuclear reactions induced by exotic nuclei;  
binding energy and masses of nuclei far away from the β-stability line;  
characteristics of super-neutron-rich nuclei of the lightest elements (multi-neutron systems, super-heavy isotopes of hydrogen helium \(^{4,5,6,7}_2\)H, heavy isotopes of hydrogen helium \(^{6,8,9,10}_{\text{He}}\), lithium \(^{6,10,11,13}_{\text{Li}}\), etc.;  
nuclear temperature measurement;  
characteristics of neutrino emission from exotic nuclei \((^8_\text{B})\);  
probabilities of proceeding of thermonuclear reactions with light exotic nuclei. A list of these data retrieved from nuclear physics experiments can be continued. However, it is already obvious from the listed above, how much extensive information can be obtained from nuclear experiments for solving many problems of astrophysics.

6. Exotism of nuclei
Exotic states of the nuclear matter i.e., of the nuclei in extreme states (with high spin, large deformation, high density and temperature, the neutron- or proton-rich nuclei on the boundary of nucleon stability) play an important role in studies of fundamental nuclear properties, which bring us closer to deducing the equation of state of the nuclear matter. This is undoubtedly of great significance for extrapolating microcosm characteristics to the macroworld that presents our Universe. Synthesis and study of neutron-rich isotopes have two main goals: finding the position of neutron-stability boundaries and obtaining data on properties of exotic nuclei near these boundaries. The development of accelerator technology has made it possible to obtain the accelerated beams of secondary radioactive nuclei. In this connection, new vast opportunities have opened up for studying both the structure of light exotic nuclei themselves and the peculiarities of nuclear reactions induced by these nuclei. It is extremely important to obtain new information regarding nuclei near the nucleon-stability boundary because considerable deviations of properties of such nuclei from the widely known regularities may be expected (and are already observed). Here the nuclei in a range of small \(Z\) serve as convenient objects for investigation. However, the question of how general the corollaries made for this small number of nuclei is crucial. The experiment alone can give an answer to this question.

7. Nuclear shapes
Problems related to the fact that a deformation may lead to an increase in binding energy of nuclei have been actively discussed recently. The nuclei with the neutron number \(N = 20\), for ground states of which a spherical shape is expected due to filling the closed shell \(N = 20\), are of particular interest from this point of view. However the latest theoretical calculations of their binding energy predict for some of them the presence of the strong longitudinal deformation (~ 0.3) and even the existence of isomeric states. It is supposed that a corollary from this deformation is the experimentally revealed sharp growth in binding energy of two neutrons in the neutron-rich nuclei \(^{31}_{\text{Na}}\) and \(^{32}_{\text{Mg}}\), i.e., the inversion of Nilsson levels that correspond to a large deformation takes place. It is the evidence that the closed shell breaks up and \(N = 20\) is no longer the magic number. The subsequent experiments in studying the nuclei \(^{33-35}_{\text{Al}}, \text{Si}_{\text{35}}, \text{P}_{\text{36}}\) [6] have shown the possibility of finding the nuclei with the spherical and deformed shapes within the region between the magic numbers \(N = 20\) and 28 (a domain of existence of two types of deformation). The experiments for measuring \(T_{1/2}\) for the nuclei \(^{27,29}_{\text{F}}, \text{Ne}_{\text{30}}\) have also shown that they are more stable than was predicted according to the shell model. The measured large value of the probability of the transfer \(B(E2; 0^+ 2^+\) for the nucleus \(^{32}_{\text{Mg}}\) (\(N = 20\)) confirmed that a deformation can exist in magic light nuclei[7]. The detection of the latter strongly-bound neutron-rich isotopes \(^{32}_{\text{Ne}}\) and \(^{40}_{\text{Mg}}\) [8] also demonstrated the validity of the prediction that stability of neutron-rich nuclei increases as their deformation grows. The isotope \(^{28}_{\text{O}}\) is extremely significant in this respect. This doubly magic (\(N = 20, Z = 8\)) nucleus has not been observed so far. However the nucleus \(^{28}_{\text{F}}\) with the same number of neutrons but with one surplus proton (\(N = 20, Z = 9\)) proved to be nucleonstable. If pn-interaction is not a cause of this stability, then we can suppose that
the effect of deformation in the $^{29}$F nucleus is more significant than in $^{31,32}$Na nuclei, which causes its stability. The investigation in properties of nuclei near the magic numbers of neutrons $N = 20, 28$, and $50$ is the most interesting problem of nuclear physics and requires the further development using diverse methods for measuring the deformation and radius of nuclei. The information on properties of these nuclei is needed for calculation of scenarios of nucleosynthesis in r-process.

8. Nuclear sizes

Determination of nuclear sizes was always a fundamental problem of nuclear physics because exact values of nuclear matter distribution (the charge and nucleon radii) are necessary for many calculations. These distributions were mainly investigated in the experiments on electron scattering (data on charge distribution in nuclei were retrieved) and hadron scattering (nucleon distribution in a nucleus was determined). When obtaining the secondary radioactive beams became possible, the region of the nuclei extended considerably, for which sizes could be determined directly from data of experiments in measuring the cross sections of reactions induced by these nuclei. It is known that variations in the binding energy correlate with a nucleus size. This was manifested most vividly in the region of light nuclei: a set of new interesting properties were revealed which were associated with the extremely small binding energy of valence neutrons in the nuclei on the boundary of neutron stability. So, in reactions with secondary radioactive beams of He, Li, Be, and B isotopes, an extremely high value of reaction cross section was detected for certain isotopes [10]. The values of radii of nuclear matter distribution retrieved in these experiments have demonstrated their gradual growth with an increase in the number of neutrons. For the loosely bound nuclei $^{11}$Li, $^{11}$Be, $^{14}$Be, and $^{17}$B that are close to the stability boundary, these radii exceeded substantially the values determined by the standard increment in the dependence on mass $\sim A^{1/3}$ (Fig. 3) [9]. Similar results were also obtained for the region of heavier nuclei [10]. The determination of regularities in the behavior of radii as a function of the mass, isospin, and energy within a broad range makes it possible to define a structure of exotic nuclei and to predict the existence of new nuclei with neutron halo. The systematics of only 7 pairs of mirror nuclei has confirmed the existence of a neutron halo in $^6$He and $^8$He isotopes, predicted a halo in $^9$Be and $^{13}$C nuclei: $R_n - R_p \sim 0.20–0.30$ fm, and also indicates to the inversion of the s and d orbitals in the mirror pair $^{16}$Ne–$^{17}$N [15]. Thus obtained values of nucleon distribution radii allow the probabilities of their interaction with other nuclei to be determined, which is fundamental in calculations of the nucleosynthesis scenario.

![Figure 3. The radii of interaction for light elements He (●), Li (○), Be (■), B (□), C (◊), N (Δ) and F (•), retrieved from the experimental values of cross sections [9].](image-url)
9. Neutron halo

Anomalous radius value of the very neutron-rich nuclei was interpreted as manifestation of the so-called neutron-halo in these nuclei, when valence neutrons in the loosely bound nuclei form a long tail in the neutron-density distribution [5]. The halo is a characteristic of the bound state lying near the threshold of particle emission. Thus, an increase in the rms radius of neutron distribution is the first signature of the halo available in exotic nuclei. Thus, the new phenomena revealed recently during the studies of lightest nuclei near the neutron stability boundary caused a need in revising some ideas on these nuclei. The data on new heavier nuclei with halo are necessary because only several nuclei with two-neutron halo (\(^6^\text{Li}, \(^7^\text{Li}, \(^9^\text{He}, \(^11^\text{Li}, \(^13^\text{B}, \text{ and } \(^15^\text{B}\) and two nuclei with single-neutron halo in all (\(^11^\text{Be} \text{ and } \(^19^\text{C}\) have been known so far. The existence of many other halo-shaped nuclei is predicted. Vast opportunities forthfor formation and investigation are opened up when beams of radioactive nuclei are used. A problem of the order of filling the shells is important. An answer is required to the following question: how do the pairing and the shells, including the deformed ones, influence the nuclear stability? More detailed data on nuclear sizes and their isospin dependence are needed. The use of secondary beams of radioactive nuclei will make it possible to find the isospin dependence of the spatial distribution of nuclear matter for many exotic nuclei. There is a question regarding existence of dineutron and tetraneutron in neutron-halo nuclei. The experimental solution to these and some other problems in the region of light neutron-rich nuclei is associated with the possibility of obtaining these nuclei in large quantities. The development of accelerator facilities producing the stable and radioactive nuclear beams has been successfully accomplishing at the recent time.

10. Nuclear reactions and nucleosynthesis

An important role in the nucleosynthesis processes is played by the nuclear reactions proceeding with the capture of protons and neutrons or heavier particles (\(\alpha\)-particles, heavy ions) by different nuclei, including the unstable ones too. The determination of a rate of proceeding of these reactions is a very difficult experimental task. The cross section of these processes also strongly depends on a temperature of the object. In the process of the nonexplosion evolution of a star, its temperature is relatively low and the effective cross section of reactions is from a few picobarn to several nanobarn (\(10^{-36}\text{–}10^{-33}\text{ cm}^2\)). With a star explosion, the temperature is very high (~\(10^9\text{K}\)) and the effective cross section is several millibarn (\(10^{-27}\text{ cm}^2\)). For simulation of these processes under laboratory conditions, it is necessary to have a wide region of radioactive nuclei that play a main part in the star explosion.

This opportunity has appeared recently with construction of accelerator facilities with radioactive nuclear beams. With the help of these beams, the reaction characteristics are investigated by using the targets of hydrogen and helium. Let us give several examples of these reactions. Reactions of the type of \(^3^\text{Li}(\alpha, n)^4^\text{B}, \(^4^\text{He}(\alpha, n)^5^\text{Be}, \(^5^\text{H}(6^\text{He}, 7^\gamma)^6^\text{Li}, \text{ and } \(^7^\text{H}(\alpha, n)^8^\text{Be}\) are fundamental for nucleosynthesis in this inhomogeneous ("big bang") process. Measurements of the reaction rates of \(^7^\text{Be}(p, \gamma)^8^\text{B}, \(^7^\text{Be}(p, \gamma)^8^\text{C}, \(^8^\text{Be}(p, \gamma)^9^\text{C}, \text{ and } \(^11^\text{C}(p, \gamma)^12^\text{N}\) reactions are of interest for simulation of the hot proton–proton channel that may take place during the supernova explosion. Reactions with light, loosely bound nuclei, which proceed at energies close to the Coulomb barrier, are of particular interest for astrophysics. These reactions have many peculiarities that have been revealed lately by means of radioactive nuclear beams. One of these features is the enhancement in interaction cross sections in the subbarrier region of energies. This effect manifests itself most evidently for cluster nuclei (\(^6^\text{Li} \text{ and } \(^11^\text{Li}\) [12]) and also for neutron-halo nuclei (\(^6^\text{He}\) [11]). The main interaction channels for these nuclei are transfer reactions, breakup reactions, and completfusion reactions. In the case of interaction of loosely bound nuclei, the fusion process is of more intricate nature due to a large probability of breakup of these nuclei with the subsequent capture of the residue nucleus (incomplete fusion). This substantially complicates the description of interaction of these systems and leads to new unexpected effects at energies in the vicinity of the Coulomb barrier: the deepsubbarrier fusion and transfer of clusters from the loosely bound nuclei that have, as a rule, the cluster structure. So, for the neutron transfer reaction in case of interaction of \(^6^\text{He}\) (Fig.5b), the cross section reaches a value of several barns and has a maximum at energy near the Coulomb barrier. The large cross section of a single
neutron transfer and its smooth falling to the low energy region (to 5 MeV) can be an evidence of the mechanism of interaction between a quasi-free neutron of $^6$He nucleus and a target nucleus. These interaction peculiarities manifesting themselves by enhancement in cross section of the cluster transfer reactions and also the complete-fusion reactions in the vicinity of the Coulomb barrier are characteristic of many loosely bound cluster nuclei. Thus, from the observation of reactions with the compound-nucleus formation in the subbarrier energy region, one could draw the conclusion that a substantial (by a factor of several thousands) enhancement in cross sections of fusion reactions with the halo-shaped $^6$He nuclei was observed in the vicinity of the Coulomb barrier. (Fig. 5) also presents the results of calculations according to the two-step model of fusion proposed in [14].

![Figure 4. The energy dependences of cross sections for (a) the complete-fusion reactions of $^6$He nuclei with $^{208}$Pb with formation of the compound $^{210}$Po nuclei and (b) the reactions of one-neutron transfer (●) and of one-neutron stripping (□) on the $^{197}$Au nuclei with beams of $^6$He and $^4$He (▲ and Δ respectively).](image)

Neutron transfer reactions for haloshaped nuclei must proceed with a large probability. Analogous conclusions on the enhancement in cross sections of fusion of $^3$He and $^7$Li nuclei have been recently made in [13]. The obtained results are extremely important for solving astrophysical problems, particularly for understanding of the mechanism of formation of light elements in the Universe. During the nucleosynthesis, a large cross section of interaction of cluster loosely bound nuclei ($^6$He, $^7$Li, and $^7$Be) can change the chains of β-decays leading to formation of different elements [23]. For example, the following channels of reactions: $^1$H($^6$He, n)$^7$Li, $^{12}$C($^6$He, 2n)$^{14}$O, $^1$H($^7$Li, n)$^8$Be, $^3$He($^7$Li, 2n)$^{10}$B, etc. may appear to be most probable for synthesis of light stable nuclei. This example once again confirms that the fundamental nuclear physics not only extends our knowledge of the microcosm, but also assists in development of our ideas about our ambient macroworld and makes a contribution to the adjacent fields of science and technology. The information on the structure of exotic nuclei obtained in nuclear physics experiments with the use of the stable and radioactive beams is extremely important for the solving of these or other problems of astrophysics (nucleosynthesis, cosmochronology, evolution of galaxies, formation and breakups of neutron stars and supernovas, etc.). These are only a few examples of the link between physics of atomic nuclei and physics of macroworld. Despite a small number of particles participating in the atomic nucleus formation (no
more than 300), they present a unique system for simulation of the macroworld problems. Under laboratory conditions using nucleus–nucleus collisions implemented at the modern heavy ion accelerators.

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12. References
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