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# Nuclear reactions in astrophysics

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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 lat est results, obtained by means of radioactive nuclear beams. The comparison is made between the processes taking place in the Universe and the mechanisms of for mation and decay of nuclei, as well as of their interaction at different energies. Examples are given to show the capabilities of nuclear physics 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.

**Keywords:** nuclear reactions, radioactive nuclear beams, cosmic objects, light elements.

## 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.

## Model of the Expanding Universe

In 1965 with the use of the radiotelescope, the existence of the isotropic "noise" was detected, which was identified with the phenomenon called now as the cosmic microwave background radiation, i.e., the radiation that is uniformly distributed over the celestial sphere and corresponds in intensity to the thermal emission of a perfect black body at a temperature of $\sim$ 3 K. This observation was of very great importance for cosmology because earlier Gamow theoretically predicted the similarradiation existence within the model based on Hubble's law: "The red shift of the radiation emitted by galaxies is proportional to the distance from these galaxies". If this shift is explained by the Doppler effect, then this leads to the pattern of the expanding Universe, in which galaxies fly away. If we extrapolate this situation back in the past, then it is possible to conclude that the expansion rate in the past was larger and the density of the Universe was higher than now. How far in the past do we have a right to extrapolate in this manner? Obviously, it is possible to do this to the epoch when the entire Universe was compressed into the single point. According to estimates, this 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: $\rho \approx 10^{-30}\mathrm{g/cm}^3$, T = 3 K (Figure 1). 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 $10^{15}\mathrm{g/cm}^3$ and a temperature is higher than 1 GeV $(10^{13}$ K). The radiation of this perfect black body consists of the known hadrons, leptons, and photons and continues while the temperature is higher than the mass of the lightest hadron, i.e., $\pi$-meson ($mc^2 \approx 140$ MeV, the temperature is $1.6 \times 10^{12}$ K). This corresponds to the "hadron epoch" which lasts approximately $10^{-4}$ s. By the end of it, the density is comparable with the density of nuclear matter. When the temperature becomes lower than 100 MeV ($10^{12}$ K), hadrons still remain but cannot be born spontaneously during the radiation of a perfect black body. Now the radiation mainly consists of leptons and photons and this situation remains while the temperature is higher than a threshold for creation of the pair $\gamma \to e^+ + e^-$, i.e., approximately 1 MeV. Cooling from 100 MeV to 1 MeV takes around 1 s. This time corresponds to the socalled lepton epoch, by the end of which the density becomes $10^4$ g/cm$^3$. Although leptons exist as particles at a temperature below 1 MeV, they already cannot be generated spontaneously during the radiation of a perfect black body. Now the radiation consists mainly of photons. This is the beginning of the "radiation epoch," the end of which is determined as the instant after which the (photon's) radiation exists separately from the matter (hadrons and leptons). The radiation epoch ends after nearly $10^6$ year from the Bing Bang. 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. Figure 1 presents schematically the links among temperature, energy, size, density, and time existing in the early Universe. 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 authors of [3] have demonstrated that intensive neutrino fluxes can be produced as a result of a supernova explosion, which can be interpreted on the

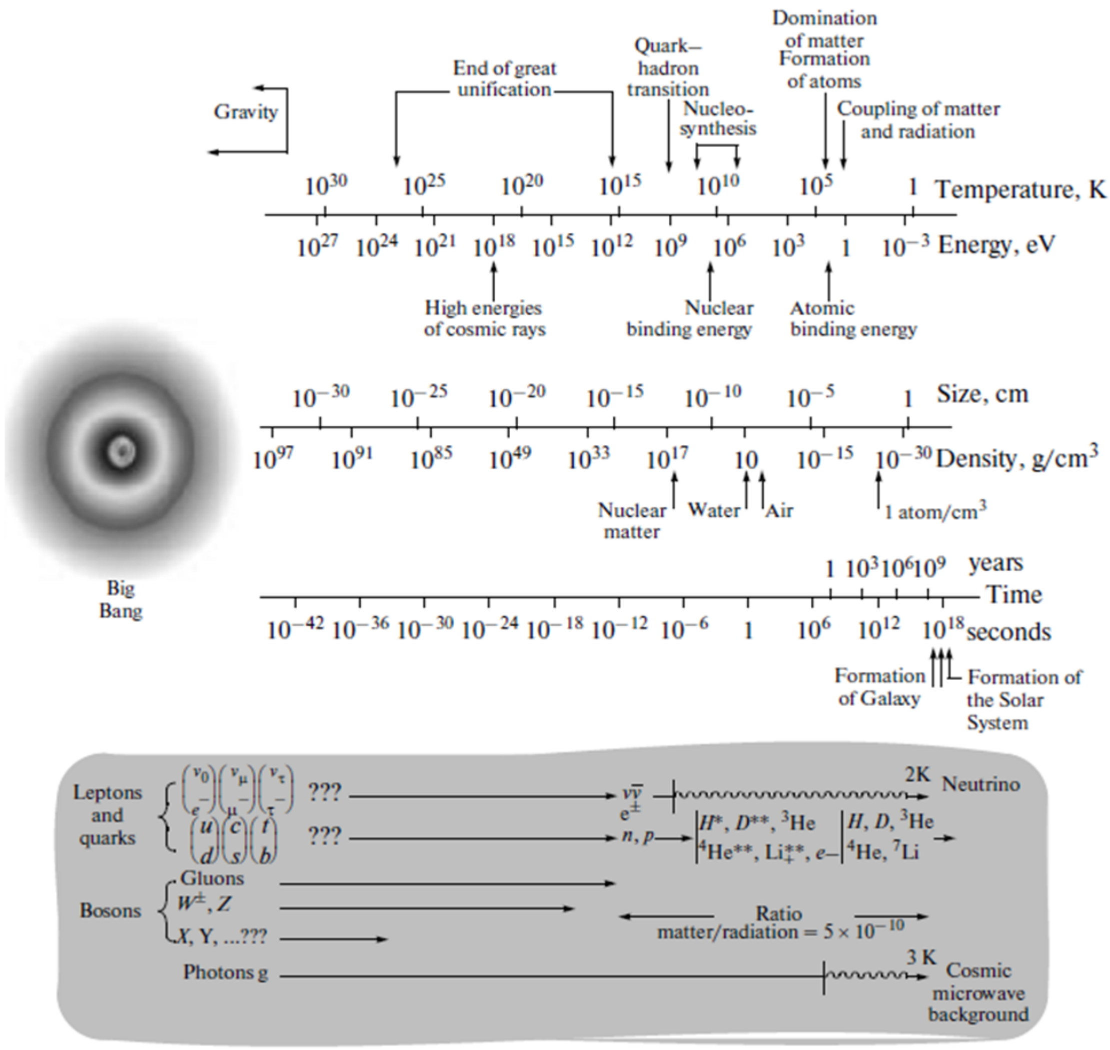


Figure 1. Relations between temperature, energy, size, density, and time in the early Universe. The lower part of the scheme illustrates the quark and lepton composition of matter.

basis of the rotation mechanism. Weak interactions are significantly weaker than the strong, electromagnetic interactions. Meanwhile, there is an intimate connection between the weak and electromagnetic interactions, which has become a basis of the new field theory that unifies these two forces. 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. This result generated a lot of reasoning about the after effects of this expansion of the Universe. If it was supposed earlier that the end of the Universe would become the "world's boiler", with the destruction of planets in the world's ocean of energy, then now we may suggest that the Universe will be cooling: having flown apart through the boundless vacuum, the stars will explode and the planets will freeze. A frozen lake of Cocytus has been waiting for the Universe, as Dante Alighieri wrote in his time. However, all this requires the further comprehension and acquisition of new data and new approaches to description of the evolution of the Universe.

**Nucleosynthesis**

As it was mentioned above, the radiation played an important role in the early Universe. This radiation has a thermal spectrum, therefore it can be characterized by the temperature $T$ according to the relation $U = aT^4$ , where $a$ is the radiation constant. With advancement to the initial stage, the radiation temperature grows according to the law

$$T = T_p(1 + Z), \qquad (1)$$

where $T_p$ is the presentday radiation temperature and $Z$ is the quantity corresponding to the red shift. For the early period when the radiation dominated, a simple relation between the temperature $T$ and the time $t$ passed from the Bing Bang follows from the Einstein equations:

$$T = \alpha 10^{10} K/t, \qquad (2)$$

Here the time $t$ is expressed in seconds, while the temperature $T$ is in Kelvin. The constant $\alpha$ has a value on the order of unity and depends on the state of matter and on the radiation in the Universe. If we assume $\alpha = 1$ , then, according to this relation, the radiation temperature in the Universe was $10^{10}$ K after 1 s from the Bing Bang. 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 $n + p \to \alpha + \gamma$ . 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:

$$d + n \to {}^3\mathrm{H} + \gamma,\ d + p \to {}^3\mathrm{He} + \gamma, \qquad (3)$$

or

$$d + d \to {}^3\mathrm{H} + p,\ d + d \to {}^3\mathrm{He} + n \qquad (4)$$

and finally ${}^4\mathrm{He}$ can be formed as a result of the reactions:

$${}^3\mathrm{H} + p \to {}^4\mathrm{He} + \gamma, \qquad (5)$$

$${}^3\mathrm{He} + n \to {}^4\mathrm{He} + \gamma. \qquad (6)$$

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, $^4$He 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:

$$^4\mathrm{He} + {}^3\mathrm{H} \rightarrow {}^7\mathrm{Li} + \gamma, \tag{7}$$

$$^4\mathrm{He} + {}^3\mathrm{He} \rightarrow {}^7\mathrm{Be} + \gamma. \tag{8}$$

But the Coulomb barrier for these reactions is around 1 MeV, whereas nuclei at the temperature $T = 10^9$ K have kinetic energy of only 0.1 MeV. In [4], the events are given in chronological order, which occurred in the Universe starting with an instant of $10^{-2}$ s after its birth (Figure 1). It can be seen from Figure 1 that the nuclear formation processes terminate at $t$ = 35 min when the temperature in the Universe drops to $3 \times 10^8$ K. This means that protons and neutrons do not fuse any more to form the heavy nuclei. The next stage is implemented when the age of the Universe reaches $7 \times 10^5$ year and the temperature drops to 3000 K. At this temperature, the chemical energy of binding between atomic nuclei and electrons is high enough to keep them together in the form of neutral atoms. 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.

**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 Figure 2. The curve has maxima for the silicon group and for the iron group [5], 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 protonrich 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 reaction $^4\mathrm{He} + {}^8\mathrm{Be} \rightarrow {}^{12}\mathrm{C} + \gamma$. However the nucleus $^8$Be is unstable with respect to decay into two particles and lives for $10^{-16}$ s. Meanwhile, at the temperature close to $10^8$ K and with a density of the order of $10^5$ g/cm$^2$, three $^4$He nuclei can form $^{12}$C nucleus as a result of the twostep reaction $^4\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^8\mathrm{Be} + {}^4\mathrm{He} \rightarrow {}^1 2\mathrm{C} + \gamma$, the second part of which is of resonance nature. 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 more heavy nuclei form: $^4$He, $^{12}$C, $^{16}$O, $^{28}$Si, and $^{56}$Fe. In so doing, the processes of formation are accompanied by the processes of decay of these nuclei. In this case, the most stable isotopes (with the maximum binding energy per nucleon) are under most favorable conditions. Among those are nuclei in a region of A $\approx$ 60. This explains the increase in concentration of iron-group 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 irongroup elements. The presence of double peaks in

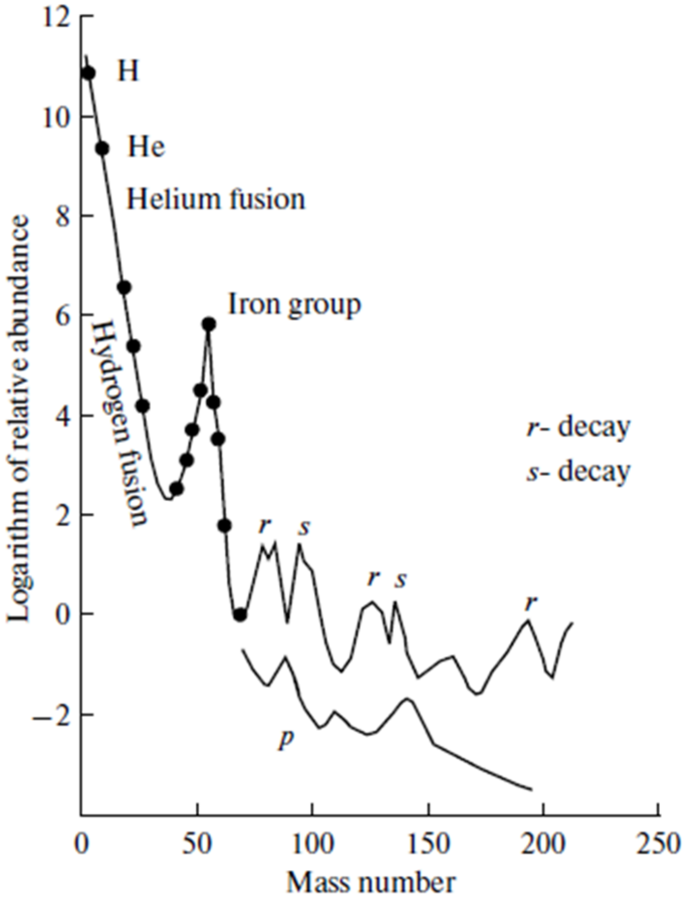


Figure 2. The curve of abundance of elements. The top curve with double ( $r$ and $s$ ) peaks corresponds to neutron-rich isotopes; the bottom curve ( $p$ ) is appropriate to proton-rich isotopes.

the curve of element abundance (see Figure 2) evidences that there are two different processes of neutron capture, the socalled $r$- 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. If the final nucleus (A + 1, Z) is stable, then a radiation capture can also occur on it with formation of the new isotope (A + 2, Z). With small fluxes, the nucleus (A + x, Z) will decay before it absorbs a neutron. It decays mainly by means of decay, which results in formation of the new nucleus (A + x, Z + 1) or a real chain of decays ending with a nucleus whose halflife will be long enough for a new radiation capture to occur. 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. This will continue until a chain of captures ends on the isotope with a very short half-life, and we shall arrive at the previous case. Figure 3 illustrates chains of $r$ and $s$-processes of isotope formation from the $^{56}$Fe nucleus. 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

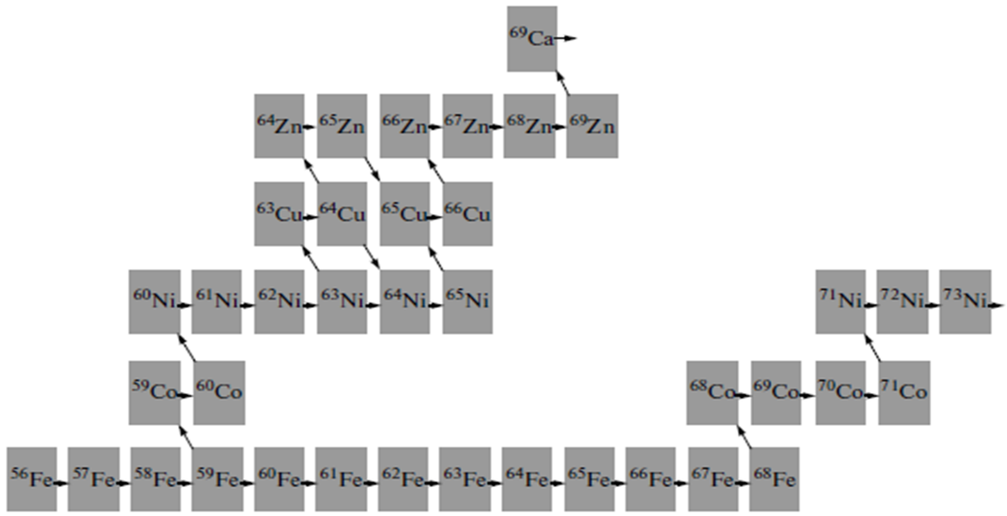

Figure 3. Chains of rapid and slow capture of neutrons ( $r$ - and $s$ -processes) for $^{56}$Fe nucleus. The dashed arrows indicate alternative channels of $^{65}$Cu formation.

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 $\sim 108$ year [6]. 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 [7], which is an additional confirmation of the stability of super-heavy nuclei near the shells (Figure 4). If we suppose that the longest-lived superheavy nuclei have a halflife of $10^5 - 10^6$ year, 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. Among the possible candidates, the most real ones are isotopes of element 108 (Hs), nuclei of which contain around 180 neutrons. Chemical experiments carried out with the shortlived isotope $^{269}$Hs ( $T_{1/2} \sim 9$ s) have shown that element 108, as it was expected, according to the Periodic law, is a chemical homolog of element 76-osmium (Os) [8]. Then a sample of metallic osmium may contain element 108-Eka(Os)-in very small quantities. The presence of Eka(Os) in osmium can be determined by its radioactive decay. The superheavy element will probably experience a spontaneous fission or the spontaneous fission will occur after the preceding $\alpha$ – and $\beta$ –decays (a kind of the radioactive transformation, at which one of the neutrons turns into proton in a nucleus) of the lighter and shorter lived daughter (or $\beta$ granddaughter) nucleus. 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 $4\pi$ -neutron detector has been

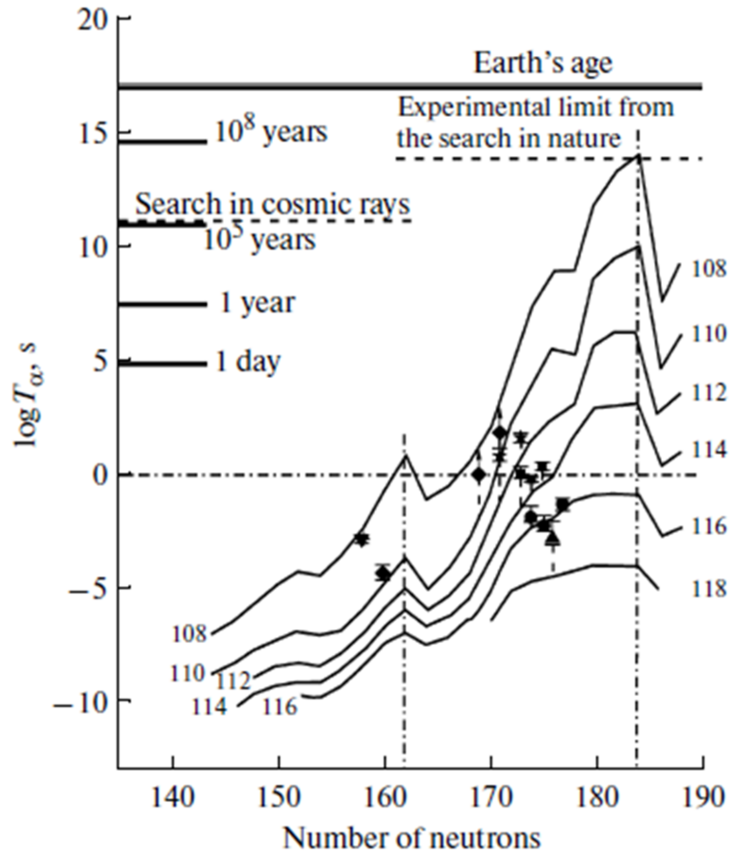


Figure 4. The $\alpha$ –decay half-life of superheavy elements as a function of the number of neutrons N. The solid horizontal lines present certain time marks: the Earth's age (1), $10^8$ year(2), $10^5$ year(3), 1 year(4) and 1 day (5). The dashed lines indicate the experimental limits of search for elements (a) in nature and (b) in cosmic rays.

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 (Figure 5). If at least one event of spontaneous fis-

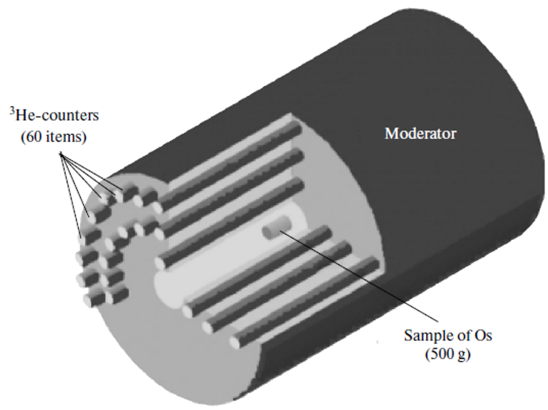


Figure 5. The facility at the Modane underground laboratory (France) for detecting flares of neutrons from the spontaneous nuclear fission upon the decay of element 108 Eka(Os). One event in a year corresponds to formation of $5 \times 10^{-15}$ g of Eka(Os) in 1 g of Os(or $10^{-22}$ of Eka(Os) in 1 g of the Earth's crust, or $10^{-16}$ of the U content).

sion 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 on assumption that its half-life is $10^9$ year. Such a small value amounts only to $10^{-16}$ of the uranium concentration in the Earth's crust. Despite the super-high 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 $T_{1/2} \sim 3 \times 10^7$ year [9]. 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. Thus, an answer will soon be given to a question on existence of superheavy elements. Speaking about the problem of the nucleosynthesis in stars, we also cannot but mention about the certain processes occurring in them and, in the first place, in the Sun, which considerably change the primeval abundance of elements. It mainly concerns the so-called CNOcycle, in which carbon, nitrogen and oxygen play a role of catalyst in the formation $4p$, $^4$He (Figure 6).

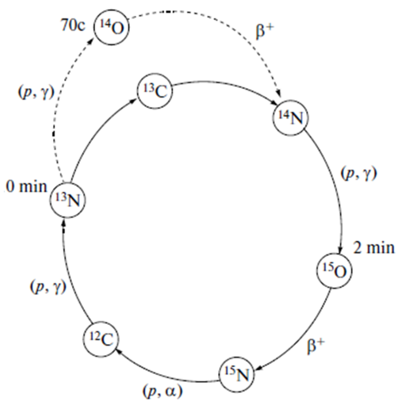


Figure 6. The "cold" and "hot" CNO cycles shown with the solid and dashed lines, respectively. The half-lives $T_{1/2}$ are indicated for the isotopes $^{13}$N and $^{14,15}$O.

## 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 $\beta$–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 $\beta$ stability line;
- characteristics of superneutron-rich nuclei of the lightest elements (multi-neutron systems, super-heavy isotopes of hydrogen helium ($^{4,5,6,7}$H), heavy isotopes of hydrogen helium ($^{6,8,9,10}$He) (He), lithium ($^{9,10,11,13}$Li) etc.;

• nuclear temperature measurement;
• characteristics of neutrino emission from exotic nuclei ( $^{8}$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.

**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.

**Masses of nuclei**

The fundamental characteristic of a nucleus is its mass. A mass value is one of necessary conditions for determining stability and properties of loosely bound nuclei. A binding energy of a nucleus, which displays a balance between the nuclear and Coulomb forces, and hence a configuration of nucleons, is determined on the basis of the measured mass. Measuring nuclear masses also provides the direct information on boundaries of stability. So, for the whole spectrum of nuclei, e.g., for $^{8-10}$He , $^{11}$Li , $^{14}$Be and $^{16}$B , an experiment has shown that they are not only bound more strongly than it is predicted by theory ( $^{9,10}$He , $^{16}$B ), but some of them are always stable ( $^{8}$He , $^{11}$Li , $^{14}$Be ). In the cases when a nucleus is not bound, it is important to find, in what measure it is unstable. A nucleus mass value is also required for determining the energy of all processes, in which the nucleus under study takes part. Measuring of masses of helium isotopes has made it possible to discover the socalled helium anomaly [10]. It is found that the higher the number of neutrons in a nucleus, the less is the binding energy of the last neutron. Due to the effect of nucleon pairing, this relation should be regarded separately for nuclei with the even and odd number of neutrons. In so doing, the monotonous dependence of the binding energy will be modified because of shell effects. The stability for almost all known nuclei of light elements reduces with the addition of two neutrons. An exception to this rule is a nuclear pair of $^{15}N - ^{17}N$, for which the increase in stability is found. Another exception is He isotopes. The largest stability increase with a growth in number of neutrons is observed for $^{6}He - ^{8}He$ pair, for which it is around 1 MeV. The binding energy is also increased in transfer from $^{5}He$ to $^{7}He$. The transfer from $^{5}He$ to $^{9}He$ (i.e., when the mass number is increased by four neutrons) almost do not change the binding energy. The isotope $^{10}He$ ( $E_{2n}$ = 1.07-1.2 MeV) appeared to be considerably more stable than it was predicted. This effect was named "helium anomaly" (Figure 7). There has been no quantitative interpretation of this extraordinary behavior of the neutron-separation energy for these nuclei so far. However, certain

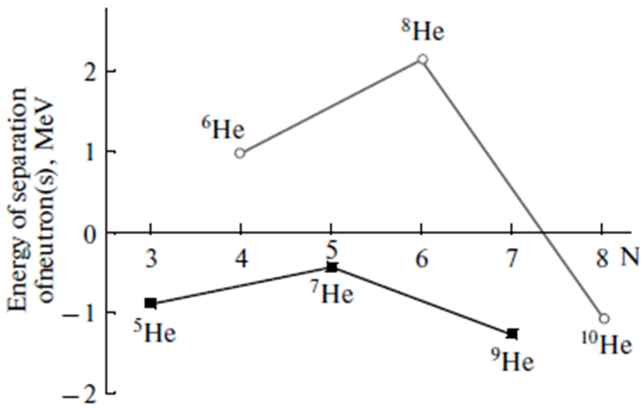


Figure 7. The energy of separation of one and two neutrons in He isotopes ( "helium anomaly").

suggestions are made, particularly that this effect may be associated with a large excess of neutrons in heavy nuclei of helium or explained by the influence of centrifugal barrier on their stability. For interpretation of such "anomalies" arising also in other neutron-rich nuclei, the experimental data are required on masses of the neighboring pairs of isotopes very enriched in neutrons. The nuclear mass measurement also yields the information about the nuclei shape evolution that may occur for nuclei near the nucleonstability boundary [11].

**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 ( $\sim$ 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 neutronrich nuclei $^{31}Na$ and $^{32}Mg$, i.e., the inversion of Nilsson levels that correspond to a large deformation takes place [12]. 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 $^{33-35}Al$, $^{35}Si$, and $^{36,37}P$ [13] 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 $^{27,29}$F and $^{30}$Ne have also shown that they are more stable than was predicted according to the shell model [14]. The measured large value of the probability of the transfer B(E2; 0+ 2+) for the nucleus $^{32}$Mg ( $N = 20$ ) confirmed that a deformation can exist in magic light nuclei [15]. The detection of the latter strongly-bound neutron-rich isotopes $^{32}$Ne and $^{40}$Mg [16, 17] also demonstrated the validity of the prediction that stability of neutron-rich nuclei increases as their deformation grows. The isotope $^{28}$O is extremely significant in this respect. This doubly magic ( $N = 20, Z = 8$ ) nucleus has not been observed so far. However the nucleus $^{29}$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.

**Nuclear sizes**

Determination of nuclear sizes was always a fundamental problem of nuclear physics because exact values of nuclearmatter 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 corre late 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 [18]. 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, while 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 $\sim$ $A^{1/3}$ (Figure 8) [19]. Similar results were also obtained for the region of heavier nuclei [20]. 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 study of mirror nuclei when one of them is unbound is most informative in these investigations. The use of measured qua drupole moments and also of the Coulomb energy differences allows the new kind of systematics to be introduced in the search for extraordinary states

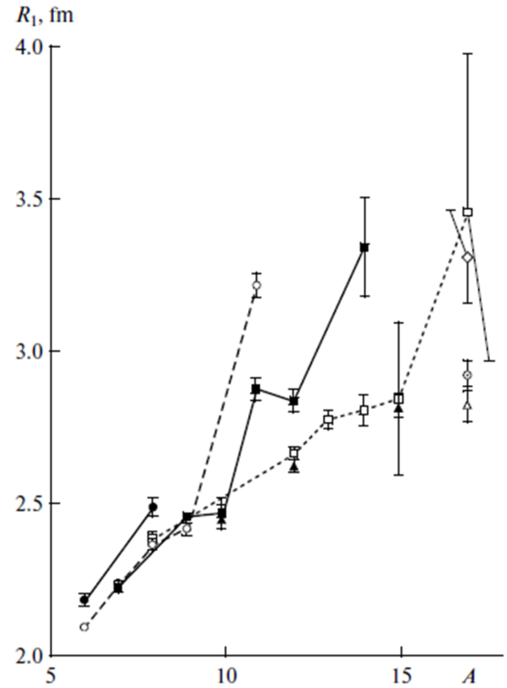


Figure 8. The radii of interaction for light elements He, Li, Be, B, C, N, F, Ne retrieved from the experimental values of cross section[21].

of exotic nuclei. 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 $^{15}$C nuclei: rms – ( $R_n - R_p \sim$ 0.20-0.30) fm, and also indicates to the inversion of the $s$ and $d$ orbitals in the mirror pair $^{17}$Ne – $^{17}$N [21]. 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.

*Neutron halo.* This 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 [22]. The halo is a characteristic of the bound state lying near the threshold of particle emission. Further experiments with application of fragmentation reactions, dissociation reactions in the field of the target nucleus, and also with measuring of momentum distributions of nucleons or fragments being formed as a result of interaction of these nuclei have confirmed the suggestion on the neutron halo existence in light neutron-rich nuclei [23]. Thus, an increase in the rms radius of neutron distribution is the first signature of the halo available in exotic nuclei. The existence of two types of halo was found further [24]. The first type is connected with a general increase in the nucleus size (in case of the nuclei $^{11}$Li, $^{11}$Be, $^{14}$Be, and $^{17}$B). The second type halo takes place in the nuclei with normal sizes (e.g., $^{6}$He and $^{8}$He). The difference between these two kinds of halo is shown in Figure 9 for the nuclei $^{11}$Li and $^{8}$He.

It is believed that the first kind halo is explained by a very small binding energy of valence neutrons, whereas the second kind halo is the result of a very compact ($\alpha$-particle) core of the $^{6}$He and $^{8}$He nuclei. In [25], the cross sections of interaction and fragmentation were measured for $^{4,6,8}$He at energies of

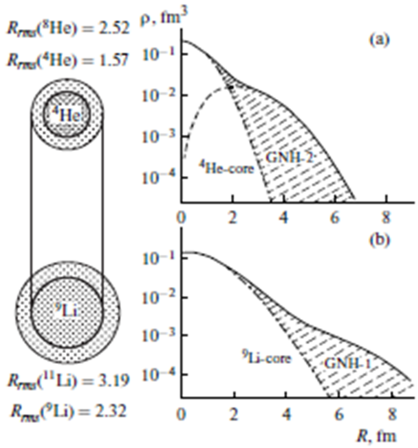


Figure 9. The neutron density distribution in (a) $^8$He and (b) $^{11}$Li nuclei

800 MeV/nucleon and a conclusion was made that the increase in interaction cross section with the massnumber growth was related to the cross section of neutron stripping. Having found the spatial distribution of neutrons and protons, the authors obtained that $R_{rms} \sim 0.9$ fm for $^6$He and $^8$He. This effect of extended neutron distribution as compared to the proton distribution was named the "neutron fur-coat". There is no crisp difference between the neutron fur-coat and neutron halo, though using these notions we can attempt to separate the cases with a very small binding energy of last neutrons (e.g., $S_{2n}$(Li) $\sim$ 0.3 MeV, $S_n$(Be) $=$ 0.5 MeV) from the cases with relatively large values (e.g., $S_{2n}(^6He) = 0.97$ MeV, $S_{2n}(^8He) = 2.14$ MeV) [25]. There is a supposition that a twoneutron halo in the form of dineutron exists. This question is as important as the question on correlations between the halo neutrons and the nucleus core. In [26-28], not only the factological material is set forth, but also the development of comprehension of a neutron halo and properties of the nuclei with neutron halo (that plays a significant role in the structure of these nuclei and also manifests itself in their interaction with other nuclei) is analyzed. 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. Here, several questions remain open which are to be answered by experiments soon. An issue of the level structure of the neutron-halo nuclei is important. A new type of collective excitation [29] at small excitation energies was offered for explanation of the increased cross section of electromagnetic dissociation of these nuclei. This new excitation mode was named the "soft dipole resonance". By the present time, the existence of the low energy E1-dipole in certain nuclei has been verified experimentally; however, a mechanism of its excitation has not yet been explained unambiguously, because a value of the excitation energy appeared to be model-dependent. It is also important to seek the predicted higher-multipolarity excitations. The data on new heavier nuclei with halo are necessary because only several nuclei with two-neutron halo ($^{6,8}$He, $^{11}$Li, $^{14}$B and $^{17}$B) and two nuclei with single-neutron halo in all ($^{11}$Be and $^{19}$C) have been known so far [30]. The existence of many other halo-shaped nuclei is predicted. Vast opportunities for their formation and investigation are opened up when beams of radioactive nuclei are used. A problem of the order of filling the shells is important [31]. 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. The question of correlations of neutron-halo nucleons still remains open. The fragmentation of exotic nuclei that are obtained in the form of beams has appeared to be an effective means for studying correlations between their components. Experiments with using "full kinematics" may answer this question. 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 power ful accelerator facilities producing the stable and radioactive nuclear beams has been successfully accomplishing at the recent time.

**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 ( $\alpha$-particle , 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 non-explosion evolution of a star, its temperature is relatively low and the effective cross section of reactions is from a few picobarn to several nanobarn ( $10^{-36} - 10^{-33}$cm$^2$ ). With a star explosion, the temperature is very high ( $\sim 10^9$ K) and the effective cross section is several millibarn ( $10^{-27}$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 $^8$Li$(\alpha, n)^{11}$B , $^6$He$(\alpha, n)^9$Be , $^1$H($^6$He, $n\gamma)^6$Li and $^1$H($^9$Li, $n\gamma)^9$Be are fundamental for nucleosynthesis in this inhomogeneous ("big bang") process. Measurements of the reaction rates of $^7$Be$(p, \gamma)^8$B , $^7$Be$(p, \gamma)^9$C , $^8$Be$(p, \gamma)^9$C and $^{11}$C$(p, \gamma)^{12}$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 ( $^{6,9,11}$Li ) [32, 34] and also for neutron-halo nuclei ( $^{6,8}$He ) [35-37]. The main interaction channels for these nuclei are transfer reactions, breakup reactions, and complete fusion 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 deep subbarrier 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 $^{6}$He, 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. The analysis of excitation functions for the transfer reactions on $^{6}$Li nuclei confirms the corollary that a basic mechanism of these reactions is the capture of a deuteron from $^{6}$Li by a target nucleus. 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. Figure 10a also presents the results of calculations according to the two-step model of fusion proposed in [38]. The agreement between the experimental and calculated data is the evidence that the process of the consecutive neutron transfer for neutron-halo nuclei is, likely, one of the factors influencing the fusion probability and enhancing the reaction cross section in the deep subbarrier energy region. Therefore, the neutron transfer reactions for haloshaped nuclei must proceed with a large probability. It can be seen from Figure 10b that the neutron transfer reaction from a $^{6}$He nucleus to a $^{197}$Au nucleus at the deep subbarrier energy ($E_{c.m.} - B_{c.m.} \sim 10$ MeV) proceeds with a relatively high cross section (a few barn). This may be the evidence of the dominating mechanism of interaction of the quasi-free neutron in a $^{6}$He nucleus. Analogous conclusions on the enhancement in cross sections of fusion of $^{8}$He and $^{9}$Li nuclei have been recently made in [34-36] (Figure 10).

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, $^{9}$Li, $^{7}$Be) can change the chains of $\beta$-decays leading to formation of different elements. For example, the following channels of reactions: $^{1}\mathrm{H}(^{6}\mathrm{He}, n)^{6}\mathrm{Li}$, $^{12}\mathrm{C}(^{6}\mathrm{He}, 2n)^{16}\mathrm{O}$, $^{1}\mathrm{H}(^{9}\mathrm{Li}, n)^{9}\mathrm{Be}$, $^{3}\mathrm{He}(^{9}\mathrm{Li}, 2n)^{10}\mathrm{B}$, etc. may appear to be most probable for synthesis of light stable nuclei (Figure 11). 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 fundamental science that provides knowledge about the ambient world and the applied science that converts the acquired knowledge into the practical benefit develop together, enriching and supplementing each other.

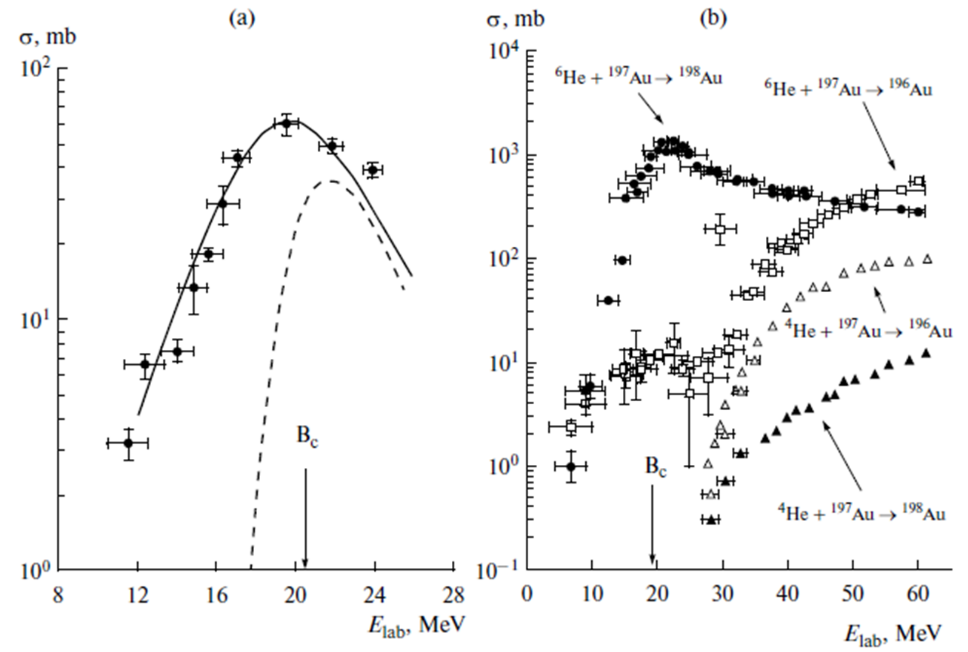


Figure 10. Excitation functions for the reactions (close boxes) $^{206}$Pb ( $^{6}$He, 2$n$ ) $^{210}$Po (a). The dashed curves represent the results of the statistical-model calculations. Solid curve stands of the results of the calculation within the sequential-fusion model. Excitation function for $^{6}$He + $^{197}$Au reactions (b) leading to the production of the isotopes (closed boxes) $^{196}$Au and (open circles) $^{198}$Au . Here, $Bc$ is the Coulomb barrier for $^{6}$He + $^{197}$Au reactions.

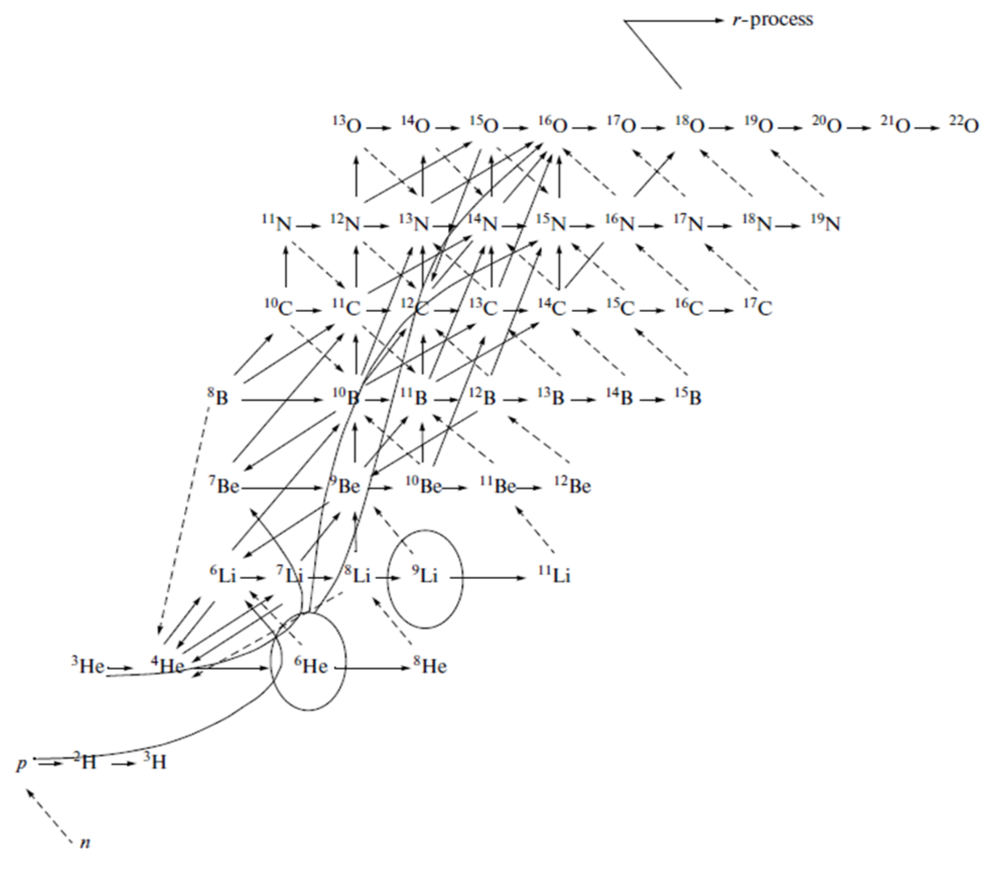


Figure 11. The new scenario of development of fusion of light neutron-rich nuclei for synthesis of light nuclei in the Universe with participation of $^{6}$He and $^{9}$Li nuclei.

**Radiactive nuclear beams in astrophysics**

The examples of investigations in fundamental astrophysical problems with the use of accelerated radioactive nuclear beams were already given above. This research avenue of physics has begun to develop intensely in recent times, which is explained by the advent of powerful accelerator facilities at all leading world laboratories, which allow the secondary beams with the relatively high intensity to be generated. To these radioactive beam factories we should assign, in the first place, the accelerator facility UNILAC-SIS-ESR and the new (under construction) accelerator facility FAIR in Darmstadt (FRG), the accelerator facility GANIL-SPIRAL1 and the new (under construction) facility for radioactive beam acceleration SPIRAL2 in Caen (France), the heavy - ion accelerator facility RIKEN (Japan), the superconducting cyclotron in Michigan and the powerful radioactive-beam factory RIBF to be constructed in Michigan (USA), the heavyion cyclotron with a storage ring in Lanzhou (China), the heavy ion cyclotron facility DRIBs and the new (under construction) facility DRIBs3 at the Flerov Laboratory of Nuclear Reactions of the JINR in Dubna (Russia). This new research avenue in nuclear physics has already made it possible to reveal a number of interesting phenomena connected with properties of the nuclei far away from the $\beta$-stability region. The radioactive nuclear beams with intensity of $10^2 - 10^7$ $s^{-1}$ were used for this purpose. The experiments in studying the interaction of radioactive nuclei with the target matter have been carried out. Their interaction cross sections are measured, and the data on nuclear radii are obtained from their analysis. The anomalously high radius of neutron distribution (neutron halo) is detected in the $^{11}$Li nucleus, the searches are in progress for neutron halo in neutronrich nuclei of $^6$He , $^8$He , $^{14}$Be , etc. and also for proton halo (anoma lously high radius of proton distribution) in neutron poor nuclei of $^8$B , $^{17}$Ne , etc. The accelerated radioactive nuclear beams provide the possibility to obtain and investigate nuclei with a maximum possible number of neutrons (neutron-rich) or of protons (proton-rich). The radically new information can be obtained about the mechanism of nuclear reactions with such beams, on which the structure of the interacting nuclei will have a profound effect. Radioactive beams are efficiently used for research in the field of astrophysics and for applied studies. Interesting data on the extraordinary structure of exotic nuclei were obtained with the use of beams of these nuclei. Figure 12 presents values of the 2+ level energy depending on the number of neutrons in the nuclei.

These dependences demonstrate the manifestation of the shells with N = 20 and N = 28 for Ar, Ca, and Ti isotopes. The measured values of the 2+ level energy for the nuclei $^{32}$Mg (E(2+) = 885.5(7) keV, E(4+) = 1430(3) keV) and $^{44}$S (E(2+) = 1297(18) keV) [38] showed that they were strongly deformed. Additionally, the discovery of the isomeric state of the 43S nucleus with the transfer energy E = 319 keV and the half-life $T_{1/2} = 488 \pm 48$ ns [39] showed that two shapes-spherical and deformed (first predicted by Lyutostantskii for $^{31}$Na [37]) ones-could coexist in this nucleus. The increase in binding energy of neutrons near the numbers N = 20 and N = 26 for Cl, S and P isotopes in comparison with Ca, Na and Ar isotopes is also observed, which can be explained by the deformation that forms the more strongly bound configuration of nuclei. Thus, new deformation regions arise for neutron rich nuclei near the neutron numbers N = 22 and N = 26, which determine the stability of these nuclei. Similar tendencies take place also for other

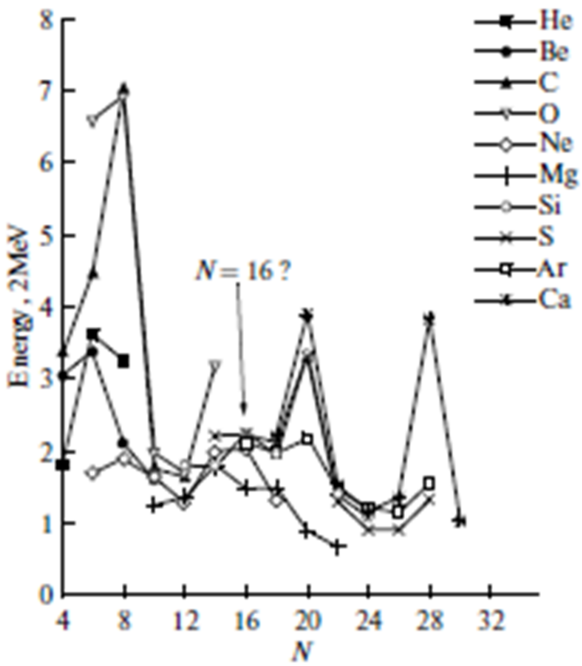


Figure 12. The dependece of 2+ level energy in different nuclei on the number of neutrons.

nuclei, which lead to the magic numbers N = 6, 16, and 34 for neutron-rich nuclei instead of N = 8, 20, and 40 for the nuclei in the stability valley. For example, for the light neutron rich nuclei (the socalled p-shell nuclei), the number N = 6 appears instead of the magic number N = 8. As a consequence, the $^{8}$He nucleus is fairly well-bound, while $^{9,10}$He isotopes are unbound. The same situation takes place for the bound magic $^{24}$O nucleus and for the unbound $^{25-28}$O nuclei.

This result strongly confirmed the conclusions regarding the impact of deformation on the nuclear stability near nucleon-stability boundaries. Obtaining the sufficiently intense beams of radioactive nuclei far from the stability boundaries opens up fresh opportunities for observation of exotic decays. There is a difference between the masses of neighboring isobars (the $\beta$-decay energy may reach 20-30 MeV), therefore the levels with the high energy of excitation can be populated after the . decay, which leads to a rise of a wide energy region for the different decay types: the two-neutron and three-neutron decays, the emission of tritons, $\alpha$-particles and the heavier particles clusters.

**This new type of decay was revealed in the experiment**

The beta delayed triton emission associated with the $\beta$-decay of $^{8}$He nucleus was also observed experimentally [34]. The $\beta$-decay energy for this nucleus $Q_{\beta}$ = 10.653 MeV and thresholds for $^{8}$Li breakup into $\alpha + t + n$ and $^{5}$He are 4.50 and 5.39 MeV, respectively. Both decay branches in the decay of the $^{8}$He nucleus were identified. One of the most important problems of physics of light nuclei is related to the feasibility of emission of the correlated pair of neutrons (dineutron). This process was not observed yet in experiments for investigation in $\beta$-delayed decays. Studying a decay of certain neutron-rich nuclei (e.g., $^{17}$B) has shown that the emission of two, three, and four neutrons occurs with a relatively large probability. An important experimental problem is the investigation in correlations of these neutrons and in feasibility of emission of the whole neutron systems consisting, e.g., of four neutrons (tetraneutron). Such experiments are conducted now in radioactive nuclear beams. Important information was obtained in experiments with radioactive beams of light nuclei regarding the radii of these nuclei and nucleon-density distribu tion. In one of the first experiments using a beam of lithium isotopes, the interaction cross section $\sigma_I$ was measured as a difference between the total reaction cross section $\sigma_R$ and elastic interaction cross section $\sigma_{E1}$ : $\sigma_I = \sigma_R - \sigma_{E1}$ [19]. In other words, $\sigma_I$ was defined as a cross section of reactions, as a result of which the number of protons and/or of neutrons changes in the beam nucleus. The determined value of radii of light nuclei from hydrogen to neon is presented in Figure 8.

The dependence of interaction radius on the $^{24}$O nucleus, in which there are 16 neutrons. It is also experimentally found that the doubly magic $^{28}$O nucleus (N = 20) is unbound. All this testifies once again to the change in the magic numbers 8, 20, and 40 for the nuclei far from the stability valley [40]. These results are important for definition of the nucleosynthesis scenario in the light nuclei region. Significant data on exotic nuclei properties have been obtained recently using gamma-spectroscopy for studying their decay from the excited states (e.g., from the Coulomb energy).

## Conclusion

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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