Nuclei near the boundary of neutron stability

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This article is devoted to the description of the properties of the lightest nuclei with a large excess of neutrons. Light nuclei have always attracted attention due to the wide variety of their properties. While the structural characteristics of medium and heavy nuclei vary fairly smoothly, only single deviations are observed, the structure of light nuclei varies sharply, two neighboring light nuclei are often completely different from each other. This, on the one hand, makes their study a very interesting task, and on the other hand it makes it difficult to identify common trends. Our interest in light neutron-rich nuclei is connected with the desire to observe the characteristic features of nuclei overloaded with neutrons.

Keywords: neutron-rich nuclei, boundary of neutron stability, neutron excess.

Introduction

As will be seen from the following, it is now possible to obtain information on nuclei with a large excess of neutrons ($N/Z/A$) only by studying light nuclei. Only in the region of the lightest nuclei we can reach the boundary of neutron stability and observe nuclei that decay by emitting neutrons. Interest in neutron-rich nuclei with is caused by many factors, but primarily by the fact that the position of the boundary of neutron stability, and even its existence, is, in essence, an open question. Despite numerous calculations of the masses of nuclei, they are all not sufficiently reliable when moving away from the stability valley. The question of the possibility of the existence of nuclei in which the neutron excess is much larger than the predicted one has been repeatedly discussed in the literature, and in the limiting case, the existence of nuclei consisting of neutrons alone is not

excluded. If the possibility of the existence of nuclei with an anomalously large neutron excess (we will call them neutron nuclei) was demonstrated, it would be a qualitative change in our present ideas about the nucleus. This would have an undoubted influence on other sciences, for example, astrophysics.

The properties of unusual nuclear systems with a large excess of neutrons (exotic nuclei) are one of the main lines of research in modern nuclear physics. Progress in experimental techniques, and first of all in the creation of a new generation of heavy ion accelerators, allowing us to produce intense beams of stable and radioactive nuclei of low (near the Coulomb barrier), intermediate and high energies, and subsequent experiments with these beams provided the possibility of synthesizing hundreds of new neutron-rich nuclides in recent years. When studying these nuclei, new interesting phenomena were discovered and unusual information about their structure was obtained. In the region of the lightest nuclei, nuclei located beyond the line of neutron stability (neutron drip line) were discovered, which are neutron-unstable, but live quite long and are observed in the form of resonances in the cross sections of their formation.

The experimental determination of the line of neutron stability reduces to either observation of nuclei that decay by emitting neutrons or to non-observation of nuclei even in a resonant state.

Bound nuclei that live long enough relative to the time of the reaction in which they were formed are radioactive nuclei. The lifetime, when one can say that the nucleus is radioactive, is $t > 10^{-12}$ s. The decay of nuclei with the emission of nucleons turns out to be relatively slow in the nuclear time scales, but rather fast in comparison with radioactive decay. The lifetime of these nuclei cover a wide range: $10^{-12} > t > 10^{-22}$ s. Nuclear states with lifetimes in this interval are sometimes called quasistationary. Such nuclei include ^{7}He, ^{9}He, ^{10}He, ^{10}Li, ^{13}Be, etc. They are observed in the form of resonances in the cross sections of various processes. The resonance width Γ (in MeV) and the lifetime T (in seconds) for the unstable nucleus are related by the equation

$$T = \hbar/\Gamma = (6.6 \cdot 10^{-22})/\Gamma, \tag{1}$$

Based on the maximum possible lifetime of such a nucleus, determined by the characteristic nuclear time (which is $t = 10^{-22}$ s), it is possible to obtain a value of the resonance width $\Gamma < 6.6$ MeV, corresponding to the lower boundary of the lifetime of the nucleus in the quasistationary state. However, we can consider the resonance as a real state of the nuclear system only if $\Gamma < 1$ MeV. The resonance energy is separated from the threshold of the system decay, accompanied by the emission of one or more nucleons, by a value equal to the decay energy. Thus, observation of the resonance makes it possible to immediately determine two important characteristics of the nucleus - the decay energy and the lifetime. When the lifetime of the nuclear system formed is $t = 10^{-22}$ s, it is assumed that this nucleus is unstable, that is, it does not exist as such.

One of the problems of nuclear physics is the study of decay features and properties of nuclei, both stable and unstable with respect to the emission of nucleons. Any prediction of the properties of highly neutron-rich nuclei is made by extrapolating the properties of the known nuclei located in the region of

β-stability, assuming that these properties practically do not change with the increase in the number of neutrons in the nucleus. For the region of medium and heavy nuclei, these changes are really quite smooth. However, the properties of any nuclear system are determined by the number of nucleons as well as by the interaction of only a few of them. As a result, in the region of light nuclei even a small change in the number of nucleons can lead to a significant difference in the properties of neighboring nuclei. Thus, extrapolation of the properties of nuclei near the line of β-stability, as a rule, does not provide information on what can be expected for nuclei far from the stability region. Therefore, direct experiments for studying the structure of light nuclei at the boundary of nucleon stability are of great importance for understanding the properties of such nuclei and predicting the properties of heavier nuclei. The new possibilities for these experiments appeared with obtaining sufficiently intense (up to 10^8 s^{-1}) beams of radioactive nuclei [1].

Experiments on studying the properties of exotic nuclei with extreme values of N/Z (very far from the line of β-stability) conducted in various laboratories around the world revealed a number of unexpected peculiarities: the existence of neutron and proton halos [2], new deformation regions [3, 4], new types of decay, changes in the sequence of shell occupation [5-7], weakening and even disappearance of the known "traditional" shells, appearance of new magic numbers, etc. The most striking discovery in this field is the observation of a giant neutron halo in some light nuclei. The number of discovered halo nuclei becomes higher and higher, and they exhibit absolutely unexpected properties which were not predicted earlier. Therefore, experiments on studying nuclei strongly enriched with neutrons or protons are an important source of information necessary for testing and developing existing theoretical models. The results of studies of such nuclei play an extremely important role in astrophysics. The importance of this problem is justified by a large number of international conferences [8-10], as well as a number of reviews on the properties of light nuclei far from the line of stability [11, 12]. A large number of publications are devoted to the problem of neutron halo [13-16]. Intensive accumulation of new information on the properties of the lightest nuclei is under way, so we considered it necessary to create a present article in which we tried to systematize known data on the properties of neutron-rich isotopes of light elements.

The neutron boundary of stability for light nuclei

Part of the map of nuclides for light nuclei is shown in Figure 1. It can be seen that the greatest neutron excess has been achieved in this region. For instance, in the ^{8}He nucleus, which is stable to neutron emission, the ratio N/Z =3 and $(N-Z)/A$ =0.5. For many light nuclei in this region, the neutron excess $(N-Z)/A$ is close to or even exceeds the boundary value of 0.36. In the beginning, the boundary of neutron stability was assumed to be reached for nuclei with atomic number Z =4 after observation of the heaviest bound beryllium isotope ^{14}Be [17]. Later, with the development of the technique of

obtaining intense beams of heavy ions of intermediate and high energies, it became possible to advance to larger Z. The heaviest bound isotope with $Z=5$, ^{19}B, was synthesized on the ^{56}Fe beam [18]. Subsequent joint Dubna-GANIL experiments on the GANIL accelerator complex using ^{40}Ar and ^{48}Ca beams at energy ≈ 50 MeV/A not only confirmed the earlier results on nucleon stability of ^{14}Be, ^{19}B, ^{20}C, and ^{27}F nuclei [18, 19], but also allowed the synthesis of new bound neutron-rich nuclei, such as ^{22}C, ^{23}N, ^{29}F, ^{29,30,32}Ne.

In the region of the lightest nuclei, nuclei located beyond the neutron boundary of stability were discovered, i.e., nuclei which, being nucleon-unstable, live long enough and are observed as resonances.
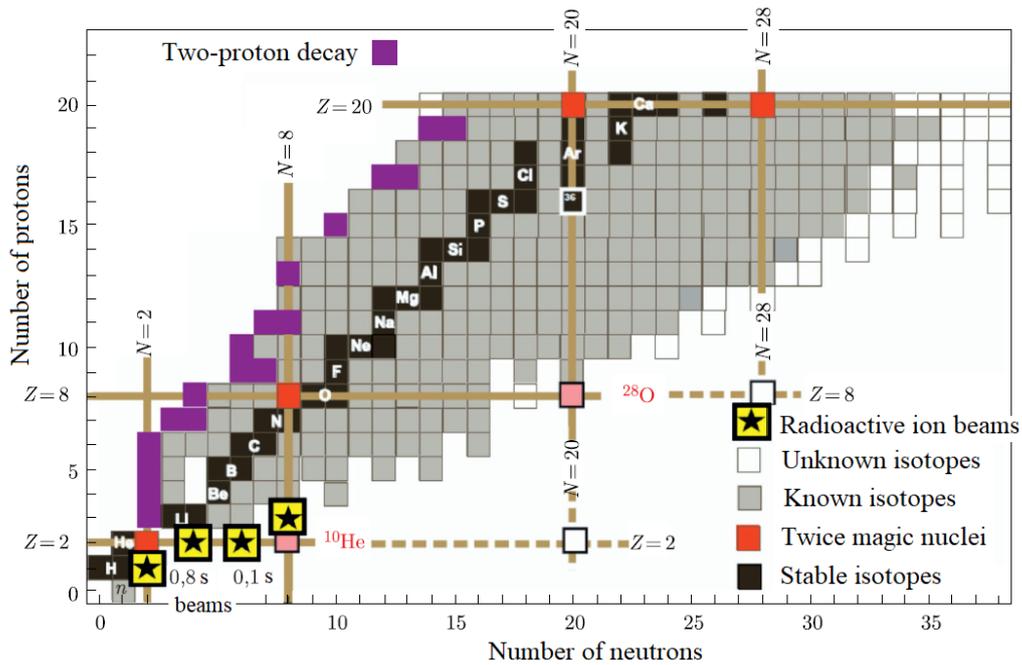

Figure 1. Nuclide map for light elements.

Several reasons can lead to a delay in the decay of nucleon-unstable nuclei. In contrast to proton-unstable nuclei, where penetration through the Coulomb barrier provides a longer lifetime, in the case of neutron-unstable nuclei the situation is different. Their stability can be influenced by the following factors: a) the isotopic spin selection rule; b) the existence of a centrifugal barrier (for neutrons with an orbital angular momentum $l>0$); and c) the need for a strong change in the initial configuration of nucleons in the process of nucleus decay. Under the influence of these factors, the decay rate of neutron-unstable nuclei can decrease, and their lifetime becomes much longer than the characteristic nuclear time ($t \gg 10^{-22}$ s). To date, only about a dozen such nuclei are known (see Table 2): ^{4}H, ^{5}H, ^{6}H, ^{7}H, ^{5}He, ^{7}He, ^{9}He, ^{10}He, ^{10}Li, ^{13}Be, and ^{16}B [18, 19]. For a number of other nuclei - ^{18}B, ^{21}C, ^{24}N, ^{25,26,28}O, and ^{28}F - only instability with respect to neutron emission was experimentally established [20, 21]. Multiple attempts to observe ^3n and the ^4n nuclei also did not yield a positive result - they were not observed even in the form of a short-lived quantum system, i.e., a resonance.

The boundary of nucleon stability is not a smooth line. This is due to the

influence of the neutron pairing energy on the stability of nuclei. In many cases, the pairing energy is 2-3 MeV and exceeds the binding energy of the last neutron in the nucleus, which should be manifested as an even-odd effect. This means that adding one neutron to an unstable (unbound) nucleus with an odd number of neutrons leads to a significant increase in stability, up to the point that the sign of the binding energy can change. This can explain the alternation of nucleon-stable nuclei with an even number of neutrons and nucleon-unstable nuclei with an odd number of neutrons. The long chain of isotopes of boron serves as a good illustration of the experimental observation of the pairing effect (^{15}B, ^{17}B, ^{19}B nuclei having 10, 12 and 14 neutrons, respectively, are nucleon-stable, but the ^{16}B, ^{18}B nuclei with 11 and 13 neutrons, respectively, are unstable with respect to the emission of neutrons).

Table 1.
Properties of nucleon-unstable light nuclei.

Nucleus	$\eta=(N-Z)/A$	Decay type	Decay energy, MeV	Width Γ, MeV
^{4}H	0.50	^{3}H+n	3.19	5.42*
^{5}H	0.60	^{3}H+2n	1.8(1)	< 0.5
^{6}H	0.67	^{3}H+3n	2.6(5)	1.3(5)
^{7}H	1	^{3}H+4n	+0.42	+0.94
^{5}He	0.20	^{4}He+n	0.89(5)	0.60(2)
^{7}He	0.42	^{6}He+n	0.44	0.15(2)
^{9}He	0.56	^{8}He+n	1.27(8)	0.30(7)*
^{10}He	0.60	^{8}He+2n	1.07(7)	0.3(2)
^{10}Li	0.40	^{9}Li+n	0.24(4)	0.10(7)*
^{13}Be	0.39	^{12}Be+n	0.80(9)	$\approx$1.0*
^{16}B	0.38	^{15}B+n	0.04(6)	< 0.10
* Experimental data				

Comparing the experimental data with various model predictions, we can say that the boundary of neutron stability was reached for all elements with Z <10. However, some authors suggest that in principle a number of circumstances may occur, in which the boundary of neutron stability does not exist at all or in which we cannot exclude the existence of "islands of stability" far beyond its limits, where N/Z is very large [22, 23]. This is indicated by the systematics of the binding energies of one and two neutrons [24], from which it is evident that for certain heavy isotopes of light elements near the boundary of stability, with an increase in the mass number, the binding energy values decrease smoothly and approach the value $S_n, 2n$ =0 almost tangentially. In addition, as for nuclei with a two-particle halo, it may turn out that neutron clusters containing a larger number of neutrons may be bound to the core and form even heavier loosely bound systems.

Thus, the precise determination of stability boundaries (both neutron and proton ones) is a very complicated theoretical problem. This is due to the fact that the parameters of mass formulas are determined by extrapolation of known

nuclear properties near the line of β-stability to the region of nuclei with much higher N/Z ratios. A detailed analysis of different mass calculations [25] shows that they can differ substantially in predicting the stability of the same nucleus. The results sometimes differ by 5 MeV and more in magnitude of the binding energy of valence nucleons in the nucleus. Thus, the position of the boundary of stability with respect to the emission of nucleons is model-dependent. Therefore, only experiments can provide an answer to the question of the stability of nuclei with a large excess of neutrons and about their structure. In this sense, any new experimental result for nuclei with an unusual N/Z ratio makes it possible to draw important conclusions about existing theoretical models.

This is evidenced by a number of the following examples. For instance, ^{14}Be and ^{29}Ne nuclei were observed experimentally [26, 27], although earlier different models predicted their instability with respect to the emission of nucleons. In experiments using a ^{48}Ca beam (44 MeV/A), the isotope ^{26}O was not observed, but the heaviest nucleon-stable ^{32}Ne isotope was synthesized [21], which contradicts the predictions of different mass formulas [24]. Meanwhile, direct non-observation of the nucleus in the experiment cannot be an unambiguous answer to the question of its nucleon stability. An illustration of this is the non-observation of ^{14}Be and ^{31}Ne in some experiments [28], which were later uniquely identified by using other reactions [29].

Attempts to test the existence of islands of nucleon-stable nuclei located far beyond the predicted boundary of stability, as well as the possibility of the existence of nuclei consisting of neutrons alone may be considered as particular cases of the problem of determining the location of the boundary of neutron stability.

Despite the fact that the calculation of the masses of finite nuclei yields ambiguous predictions about the existence of nuclei with an anomalously large neutron excess, theoretically, this possibility cannot be excluded.

The analogy between neutron matter and liquid helium is well known. Two neutrons, as well as two helium atoms, do not form a bound system. Their interaction potentials are very similar; they are attractive, but not strong enough to form a stable nucleus or molecule, respectively. At the same time, a very large number of helium atoms form a liquid drop. The question arises as to whether a similar situation with neutrons can take place. A.I. Baz with colleagues [11] tried to solve the problem of the appearance of a bound multineutron system at the microscopic level. The main conclusion they made was that a small change in the potentials, which practically does not change the nucleon-nucleon scattering phase at low energies, can stabilize the nucleus if the number of neutrons is not less than several tens.

In the framework of the K-harmonics method, accurate calculations were made for five different sets of potentials. The results of calculations showed that if the number of neutrons is less than 100, then none of these potentials leads to the existence of a bound multineutron state. For $N > 112$, the bound state arose for three of the five potentials. All these potentials were not arbitrary, but were tested in calculations of the binding energies and the radii of many nuclei, although located near the valley of stability.

Calculations of A.I. Baz show the possibility of an alternative approach to the problem of the existence of neutron nuclei, in comparison with the generally accepted ones, and confirm the above statement that at the present time none of the theoretical calculations gives an unambiguous conclusion about the existence or absence of purely neutron nuclei. Thus, the problem of the existence of neutron nuclei can only be solved experimentally. This path should include two directions. The first is a direct advance towards the expected boundary of stability by the synthesis of new nuclei with an ever larger neutron excess, up to the discovery of neutron-decaying nuclei. The second is the measurement of their masses and the corresponding binding energies by the missing mass method, which will be discussed below.
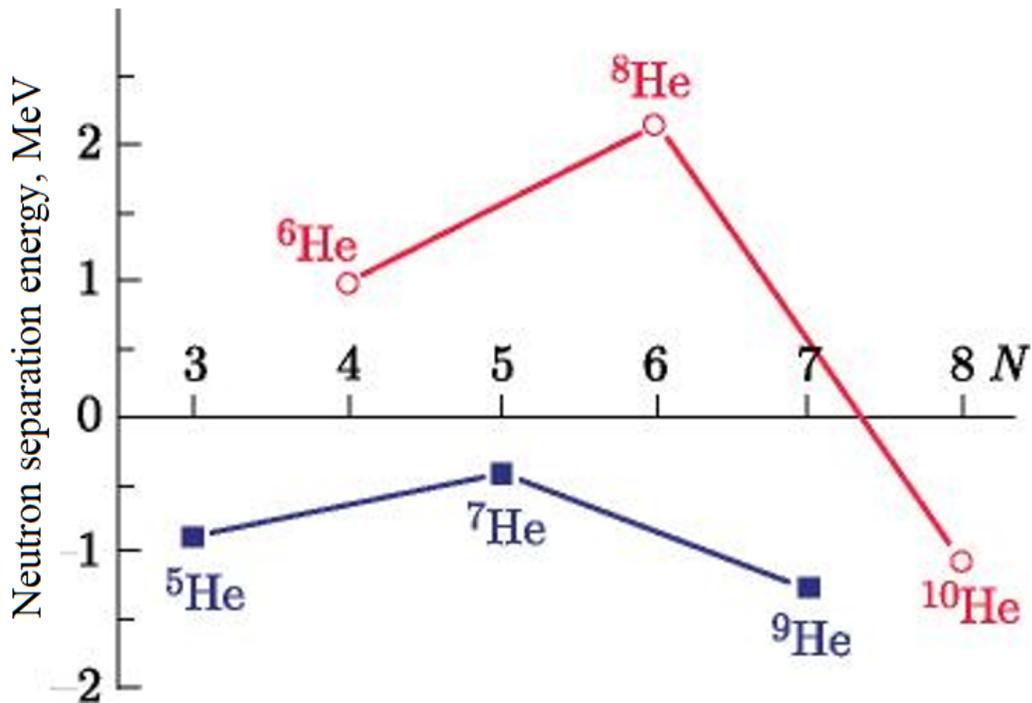

Figure 2. The energy of separation of one and two neutrons in helium isotopes (helium anomaly).

It is obvious that nucleon-stable neutron-rich nuclei will be β-radioactive, and it is very probable that β-decay into the excited states of the daughter nucleus will be accompanied by the emission of delayed neutrons. With the growth of the neutron excess, the binding energy of the last neutron will decrease and at the very boundary of stability, it can be very small. It is clear that the discovery of all kinds of anomalous behavior of the binding energy with increasing neutron excess is of particular interest, since this can serve as an indication of the manifestation of fundamentally new properties.

Calculations of the structure of neutron-rich nuclei are a complicated theoretical task. Because of the low binding energy, the tails of the wave functions of the last neutrons must be sufficiently extended, as a result of which the nuclear boundary will be smoothed and the rms radius will increase. In this case, the neutron radius may be much larger than the proton radius (neutron halo), although in a number of cases, as the comparison of ^{40}Ca and ^{48}Ca isotopes shows, this difference may be small.

A pairing interaction must play a special role near the boundary of neutron stability. In many cases, the pairing energy (2-3 MeV) is greater than the binding energy of the last neutron, which leads to pronounced even-odd effects. Adding only one neutron to the nucleus with an odd number of neutrons leads to a significant increase in its stability, up to a change in the sign of the binding energy. It should be expected that odd (in terms of the number of neutrons) nucleon-unstable nuclei will alternate with even nucleon-stable nuclei. Thus, the boundary of neutron stability in the $N-Z$ diagram is not a line, but a strip of a greater or lesser width. The dimensions of this strip with respect to N are determined by the competition between the decrease in stability with increasing number of neutrons and the stabilizing effect of the pairing forces.

As already noted above, neutron decay can be slowed down for two reasons: because of the need to overcome the centrifugal barrier (for neutrons with $l>0$) and in the case when the initial neutron configuration must change greatly as a result of the decay.

Estimates of the penetrability of the centrifugal barrier show that at $l=6$ and the decay energy $E=0.5$ MeV, the lifetime can reach 10^{-16} s. Structural forbiddance can increase this time even more. Although the lifetimes of neutron-decaying nuclei are much smaller than those of proton-decaying nuclei in the $A \approx 100$ region, and cannot be directly measured, the only physical reason of their existence is the probability of penetration through a potential barrier. From this point of view, there is every reason to speak of neutron radioactivity.

For neutron radioactivity, it is difficult to expect competition from other types of decay. With the growth of the neutron excess, the decay energy of neutron-radioactive nuclei should increase, and the lifetime should decrease, gradually reaching the time of free separation. The search for neutron radioactivity is one of the fundamental problems of nuclear physics and is included in the scientific programs of modern factories of beams of radioactive nuclei.

As mentioned above, from the known experimental data it follows that only for the region of the lightest elements ($Z<10$) can we draw definitive conclusions about the position of the neutron boundary of stability. For the region $Z>10$, it is difficult to say anything for certain about the boundary of stability. Recently, the heaviest neutron-rich nuclei with 10< Z <13: ^{32}Ne, ^{39}A1 [21], and also ^{31}Ne, ^{37,38,40}Mg, ^{40,41,42}A1 in reactions with ^{50}Ti and ^{48}Ca ions [29] were discovered. These results once again confirmed that the exact position of the neutron stability boundary remains quite uncertain and is one of the most important problems in studying nuclei far from the line of β-stability.

Exotism of light nuclei

Synthesis and study of neutron-rich isotopes have two main goals: establishing the location of neutron boundaries of stability and obtaining information on the properties of nuclei with an extreme ratio of the number of neutrons to the number of protons (exotic nuclei) near these boundaries. With the development of accelerator technology, it became possible to obtain accelerated beams of

secondary radioactive nuclei. Therefore, new broad opportunities were opened for studying both the structure of the light exotic nuclei themselves and the peculiarities of nuclear reactions with their participation.

It is extremely important to obtain new information on nuclei near the boundary of nucleon stability, since it may be expected that the properties of such nuclei significantly deviate from well-known regularities (and this is already observed experimentally). In this respect, the nuclei in the region of small Z are convenient objects for investigation. The key question here is how general the conclusions made for such a small number of nuclei can be. The answer to this question can also be given only by experiment.

Mass and binding energy of nuclei at boundaries of neutron stability

The fundamental characteristic of the nucleus is its mass. Knowledge of the mass is one of the necessary conditions for determining the stability and properties of loosely bound nuclei. Based on the measured mass, the binding energy of the nucleus is determined, which reflects the balance between nuclear and Coulomb forces and, consequently, the configuration of nucleons. The measurement of the mass of the nuclei also gives direct information on the boundaries of stability. For a number of nuclei, for example, $^{8-10}$He, ^{11}Li, ^{14}Be, ^{16}B, the experiment showed not only that they are more bound compared to theoretical predictions (^{9,10}He, ^{16}B), but also that some of them are even stable (^{8}He, ^{11}Li, ^{14}Be). In the cases when the nucleus is not bound, it is important to determine how unstable it is. The value of the mass of the nucleus is also necessary for determining the energy of all processes in which the studied nucleus participates.

Measurement of the masses of helium isotopes allowed the discovery of the so-called helium anomaly [30]. It is established that the greater the number of neutrons in the nucleus, the lower the binding energy of the last neutron. Because of the effect of nucleon pairing, this dependence should be considered separately for nuclei with even and odd number of neutrons. In this case, the monotonic dependence of the binding energy will be modified due to shell effects. Practically for all known nuclei of light elements, stability decreases with the addition of two neutrons. The exception to this rule is the pair of ^{15}N-^{17}N nuclei, for which the increase in stability is beyond the experimental error. The isotopes of helium were the next exception. An increase in stability with an increase in the number of neutrons is observed for the ^{6}He-^{8}He pair, for which the neutron separation energy is about 1 MeV. In the transition from ^{5}He to ^{7}He, the separation energy also increases. The transition from ^{5}He to ^{9}He (i.e., an increase in the mass number by four neutrons) practically does not change the binding energy. The ^{10}He isotope turned out to be much more stable than predicted (E_{2n} =1.07-1.2 MeV [31, 32]). This effect was called the helium anomaly (Figure 2). There is still no exact explanation for this unusual behavior of the neutron separation energy for these nuclei. However, some assumptions are made, in particular, that this effect can be connected with a large excess of neutrons in heavy helium nuclei or due to the influence of the centrifugal barrier on their stability. To interpret such "anomalies" that also arise in other neutron-rich nuclei, it is important to have experimental data on the masses of neighboring pairs of isotopes highly enriched

in neutrons.

The measurement of nuclear masses also provides information on the evolution of the shape of the nuclei. This will be discussed below.

Peculiarities of filling of energy levels

Level schemes of light neutron-rich nuclei, both bound and unbound with respect to neutron emission, provide important information about their properties. Until recently, information about the energy levels in such nuclei was rather scarce. Even the very existence of excited states for most such nuclei was not established. For instance, for the heaviest stable isotopes ^{8}He, ^{11}Li, ^{14}Be and unstable ^{10}He, ^{10}Li, ^{16}B the existence of excited levels was discovered only recently. Experimental information on levels with their quantum characteristics makes it possible to determine the order of shell filling and, thus, the applicability of a particular theoretical model, the presence of collective excitation (for example, a soft dipole mode), the type of decay of levels, etc. These topics will be discussed in more detail below.

Change in the shape of nuclei when approaching boundaries of stability

In many recent works, the problem of dependence of deformation on the binding energy of nuclei is discussed. From this point of view, of special interest are nuclei with the number of neutrons N =20, for the ground state of which a spherical shape is expected due to the filling of the closed shell N =20. However, the latest theoretical calculations of their binding energies predict a strong longitudinal deformation ($\beta \approx 0.3$) for some of them and even the existence of isomeric states. It is assumed that the consequence of this deformation is the experimentally observed sharp increase in the binding energy of two neutrons in neutron-rich nuclei of ^{31}Na and ^{32}Mg, i.e., the presence of an inversion of the Nilson levels corresponding to a large deformation [33-35]. This indicates that the closed shell N =20 is destroyed and it is no longer a "magic" number for strongly neutron-rich nuclei. Following experiments on the structure of nuclei $^{33-35}$Al, ^{35}Si, ^{36,37}P [36, 37] showed the possibility of finding nuclei in the region between the magic numbers N =20 and 28 with both spherical and deformed shapes (the region of coexistence of two types of deformation).

The results of measuring the half-life Tw_2 for ^{27,29}F, ^{30}Ne nuclei have shown that they are also more stable than predicted by the shell model [38]. The large value of the reduced transition probability $B(E2; 0^+ \rightarrow 2^+)$ for the ^{32}Mg nucleus (N =20) measured in [4] showed the possibility of the existence of deformation in light magic nuclei. The observation of highly neutron-rich isotopes ^{31}Ne and ^{37}Mg [29] confirms an increase in the stability of neutron-rich nuclei with an increase in their deformation.

Finally, the ^{28}O isotope is very representative in this respect. This doubly magic (N =20, Z =8) nucleus has not yet been experimentally observed. However, the nucleus ^{29}F with the same number of neutrons, but one proton larger (N =20, Z =9), turned out to be nucleon-stable. If the *pn* -interaction is not the reason for this stability, it can be assumed that the deformation effect in the ^{29}F nucleus is more significant than in the ^{31,32}Na nuclei, which determines its stability. The study of the properties of nuclei near the magic number of neutrons, N =20, is a very interesting problem in nuclear physics and requires its further development

using various methods for measuring deformations of nuclei and their radii.

Systematics of nuclear radii for light nuclei

The determination of the sizes of nuclei has always been a fundamental task of nuclear physics, since many calculations require exact values for the distribution of nuclear matter (charge and matter radii). These distributions were studied predominantly in experiments on electron scattering (information on the charge distribution in nuclei was extracted) and hadrons (the matter distribution in the nucleus was determined).

With the advent of beams of radioactive nuclei, the possibilities of determining the sizes of the nuclei have significantly expanded, in particular, in experiments on the measurement of the cross sections of reactions caused by such nuclei. It is well known that changes in the binding energy correlate with the size of the nucleus. Investigations in the region of light nuclei have revealed a number of new interesting properties of nuclei with low binding energy of valence neutrons. For instance, in reactions with secondary beams of radioactive isotopes of helium, lithium, beryllium, and boron, an anomalously high value of the reaction cross section for some isotopes was observed [1]. The radii of the nuclear matter distribution obtained in these experiments showed the gradual increase with the number of neutrons, and for such weakly bound nuclei as ^{11}Li, ^{11}Be, ^{14}Be, and ^{17}B, close to the boundary of stability, these radii significantly exceeded the values determined by the dependence $\approx A^{1/3}$ (Figure 3) [39-42].

A similar increase in the radii was also obtained for neutron-rich isotopes of heavier elements [43].

Regularities in the behavior of radii as a function of mass, isospin, and energy over a wide range make it possible to determine the structure of exotic nuclei and predict the existence of new nuclei with a neutron halo. In this sense, it is especially informative to study mirror nuclei in the case when one of these nuclei is unbound. The use of the measured values of quadrupole moments, as well as the difference in the Coulomb energy, made it possible to obtain a new type of systematics for radii when searching for unusual states of exotic nuclei. The resulting systematics for seven pairs of mirror nuclei confirmed the existence of a neutron halo in ^{6}He and ^{8}He isotopes, predicted the halo in ^{9}Be and ^{15}C nuclei (R_{ms}^{TM} - $R_{rms} \approx 0.20$-0.30 fm), and also led to conclusions that there is an inversion of s- and d-orbits in the mirror pair ^{17}Ne-^{17}N.

The neutron halo

The anomalous increase in the radius of some highly neutron-enriched nuclei was interpreted as the existence of the so-called neutron halo in these nuclei, manifested in the tails of the density distribution of valence neutrons of weakly bound nuclei [6]. The halo is a characteristic of the bound state lying near the particle emission threshold. This unusual property of some light highly neutron-enriched was not previously observed. Further experiments on the measurement of momentum distributions of nucleons or fragments formed as a result of the interaction of such nuclei confirmed the assumption of the existence of the neutron halo in the light neutron-rich nuclei [44-46].

Thus, the increase in the radius in comparison with the standard increment described by the dependence ($A^{1/3}$), is the first sign of the presence of halo in
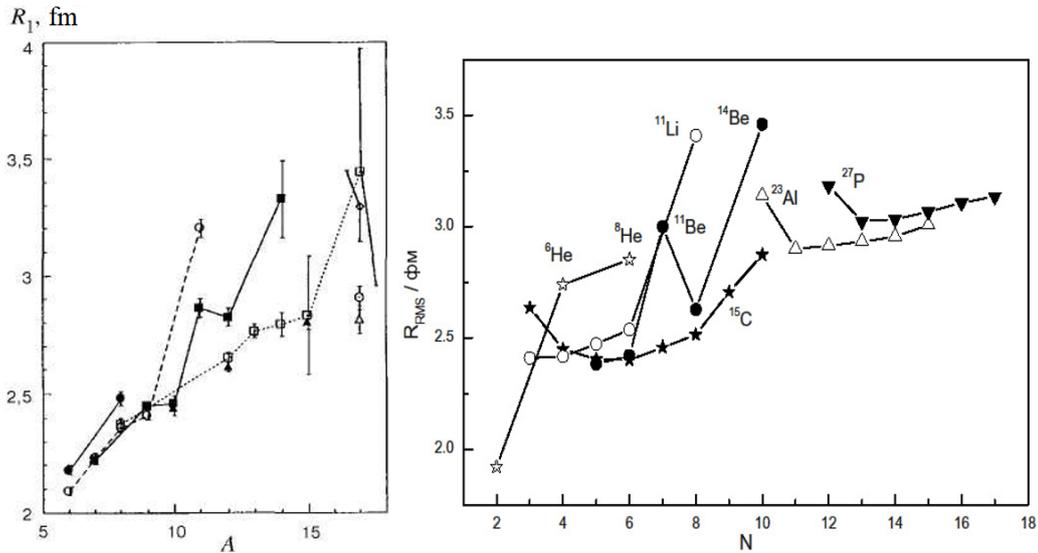
Figure 3. The interaction radii for light nuclei extracted from the experimentally obtained values of interaction cross sections [39-42].

exotic nuclei. Later on, the existence of two types of halos was found [44]. The first type (GNH-1) is associated with an overall increase in the nuclear size (in the case of nuclei ^{11}Li, ^{11}Be, ^{14}Be, ^{17}B). The second type of halo (GNH-2) occurs in nuclei with normal dimensions (for example, ^{6}He, ^{8}He). The difference between these two halo types is shown in Figure 4 for the ^{11}Li and ^{8}He nuclei. It is believed that the halo of the first type is associated with a very low binding energy of valence neutrons, whereas the second type halo is the result of a very compact (α-particle) core of ^{6}He and ^{8}He nuclei. In [45], based on the measured cross sections for the fragmentation of ^{4,6,8}He nuclei at the energy 800 MeV/A, it was concluded that the increase in the interaction cross section with the increasing mass number is connected with the cross section of stripping of valence neutrons. From the spatial distribution of neutrons and protons, it was found that R^n_{rms}-$R^p_{rms} \approx 0.9$ fm for ^{6}He and ^{8}He. This effect of the extended neutron distribution, in comparison with the proton one, was called a neutron "skin". The existence of the neutron "skin" in the ^{8}He nucleus was also confirmed in work [46]. There is no clear difference between the neutron "skin" and the neutron halo, although with the help of these concepts one can try to distinguish the cases of very low binding energies of the last neutrons (for example, S_{2n} (^{11}Li) ≈ 0.3 MeV, S_n (^{14}Be)=0.5 MeV) and the cases of comparatively large values (for example, S_{2n} (^{6}He)=0.97 MeV, S_{2n} (^{8}He)=2.14 MeV). There is an assumption about the existence of a two-neutron halo, which can result from the pairing of two valence neutrons, for example, for the ^{6}He nucleus with the formation of a dineutron. This extremely interesting problem, as well as the question of correlations between neutrons of the halo and the core of the nucleus, is the subject of intensive research. In the works [6, 11, 47] the factual material is described in detail and the development of the ideas about the neutron halo is traced. The neutron halo plays an important role in the structure of nuclei, as well as in the peculiarities of their interaction with other nuclei.

Thus, the recently discovered manifestation of new properties when studying
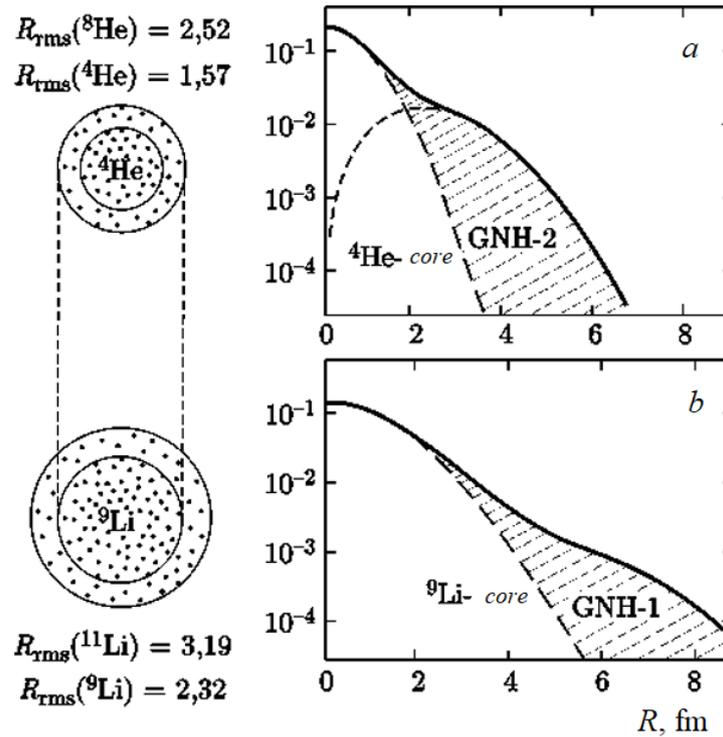
Figure 4. The neutron density distribution in the nuclei ^{8}He (a), ^{11}Li (b).

of the lightest nuclei near the boundary of neutron stability led to the need of revision of a number of ideas about these nuclei. There remain a number of open questions for which an experimental answer should be obtained in the nearest future.

First, these are the features of the structure of nuclei with the neutron halo. To explain the increased cross section of the electromagnetic dissociation for such nuclei, a new type of collective excitation was proposed [6, 11] at low excitation energies. This new mode of excitation was called a "soft dipole resonance". To date, the existence of a low-energy E1-dipole in some nuclei has been experimentally confirmed [47]. The mechanism of its excitation did not find an unambiguous explanation because of the fact that the value of the excitation energy is model-dependent [48]. Of great interest is the search for excitations of a higher multipolarity.

Second, it is necessary to obtain data on new, heavier nuclei with a halo. So far only a few nuclei with a two-neutron halo (^{6}He, ^{8}He, ^{11}Li, ^{14}Be and ^{17}B) are known, and only two nuclei with a single-neutron halo (^{11}Be and ^{19}C) [49]. Meanwhile, the existence of many other halo nuclei is predicted. Large opportunities for their investigation open with the use of beams of radioactive nuclei.

Third, the question of the sequence of shell filling is important from the point of view of the structure and stability of exotic nuclei. It is also required to answer the question, for which N and Z shells are filled, as well as what effect pairing and shells, including deformed ones, have on the stability of the nuclei.

Fourth, this is the question of the dependence of the radii of nuclei on the neutron excess. The use of secondary beams of radioactive nuclei will make

it possible to determine the isospin dependence of the spatial distribution of nuclear matter for many exotic nuclei.

Fifth, there remains the question of the correlations of the neutron halo nucleons. Fragmentation of exotic nuclei, obtained in the form of beams, provided the possibility of studying the correlations between their components. It is expected that experiments using "full kinematics" [50, 51] can yield an answer to this question.

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