A note on the history of research on light nuclei in the boundary region

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Research on light nuclei has become a separate and distinctive branch of nuclear physics. The number of nucleons in light nuclei is too low for statistical methods to be used to describe the nuclei, and the addition of a single nucleon to a light nucleus can lead to important changes in properties.

Since there are so few nucleons, it is a comparatively simple matter experimentally to reach the nuclear stability boundary. Although the absolute difference between the numbers of protons and neutrons in the light nuclei of the boundary region is not very large, the ratio between the numbers of protons and neutrons is unusual. The isotope ^{8}He, for example, has three times as many neutrons as protons, while this ratio does not exceed 1.6:1 for the nuclei at the heavy end of the scale. The properties of nuclei near the stability boundaries can thus furnish unique opportunities for testing nuclear theories based on the properties of ordinary nuclei. Furthermore, the light nuclei near the stability boundaries exhibit some unusual decay modes. The properties of light nuclei are very important to the rapidly developing field of astrophysics as well as being of independent interest in nuclear physics. As an example of the astrophysical applications, we note that the sun consists of 98% hydrogen and helium and only 2% heavier elements. Its energy comes primarily from the hydrogen-cycle reactions $p+p \to D+e^+ +\nu$, $D+p \to \mathrm{He}^3+\gamma$, $\mathrm{He}^3+\mathrm{He}^3 \to \mathrm{He}^4+2p$, i.e., reactions among extremely light nuclei. This preponderance of hydrogen and helium extends to the entire local galaxy. The situation can be explained in a simple fashion on the basis that there is no stable nucleus of mass 5 and that the ^{8}Be nucleus is unstable. A detailed description of the present abundances of the elements and of the evolution of the universe, however, would require extensive information on reactions involving light nuclei, analysis of their stability, and analysis of their decay modes. Finally, hopes for the future availability of fusion energy are based on reactions among light nuclei: $D+D \to \mathrm{He}^3+n$, $D+D \to T+p$, and $D+T \to {}^4\mathrm{He}+n$. Tritium recovery requires reactions like $n+\mathrm{Be}^9 \to 2\,{}^4\mathrm{He}+2n$, $n+\mathrm{Li}^6 \to T+\mathrm{He}^4$, and $n+{}^7\mathrm{Li} \to n+{}^4\mathrm{He}+T$. The importance of this branch of nuclear physics was not always obvious, but in the early 1960's some fundamental predictions were made regarding the stability boundary, and methods were developed for estimating the masses of the nuclei in the boundary region. These predictions, which required an unharnessed imagination and a lot of difficult work, were made long before the corresponding experiments were carried out. Soviet physicists led the effort.

The concept of isotopic invariance of nuclear forces, which is justified particularly well in the case of light nuclei, and the general laws regarding the interaction of weakly bound nucleons in nuclei formed the heart of the theory which was developed and of the predictions which were made regarding the properties of light nuclei.

Since the Coulomb interaction between the protons in light nuclei can be treated as a small perturbation in comparison with the isotopically invariant nuclear interaction, the total energy of a nucleus (Z,N) can be written as the sum of three terms:

$$c^2{}_ZM_N^A = E^A(T) + E_C(Z, N) + c^2(Nm_\mathrm{n} + Zm_\mathrm{p}), \tag{1}$$

where m_n and m_p are the neutron and proton masses, E_C is the energy of the Coulomb interaction between protons in the nucleus, and $E^A(T)$ is that part of the binding energy which results from the nuclear, isotopically invariant interaction between nucleons.

Because of charge invariance of nuclear forces, $E^A(T)$ depends only on A (the total number of nucleons in the nucleus) and the isospin T of the ground state of the nucleus.[1] This part of the total energy is the same for (Z_1, N_1) and for the isotopically conjugate nucleus (N_1, Z_1); for example, it is the same for ^{14}C and for ^{14}O. The last term in Eq. (1) is known. It corresponds to the mass defect in the scale $^{12}\mathrm{C}(N\cdot 8.071+Z\cdot 7.288)$ MeV. The second term in the equation for the mass is the Coulomb energy, and it is well known also.

By evaluating these two terms, we can predict the mass difference of isotopically conjugate nuclei, and if we know the mass of one of a pair we can easily evaluate the stability of the other.

The talented Soviet physicist A. I. Baz', who recently suffered an untimely death, was the first to use an equation like this, based on the isotopic invariance of nuclear forces and experimental data on the masses of neutron-rich nuclei, to predict the nuclear stability of several neutron-deficient nuclei. He later analyzed the possible existence of purely neutron nuclei, for various nucleon-nucleon potentials; such nuclei apparently do not exist.

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[1] We recall that the lowest value of T for a given nucleus is $T_\mathrm{min} = |(N-Z)/2|$ and usually corresponds to the ground state, i.e., the most stable state, of the nucleus.

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The concept of isotopic invariance was developed most extensively in a series of papers by Gol'danskiĭ.[2-4] He predicted the properties of many tens of neutron-deficient isotopes. Working from these properties, he predicted a new property: radioactivity involving the emission of two protons, which has not yet been observed experimentally. The equation which Gol'danskiĭ derived for calculating nuclear masses[3,4] anticipated the later Garvey–Kelson version. Gol'danskii predicted that nuclei with suitable Z and an isospin projection $T_z=-\frac{3}{2}$ (as well as other nuclei with $Z>N$) would exhibit a superallowed β^+ decay which would lead to proton emission from an analogue state of the daughter nuclei.[5] This effect was subsequently observed in several experimental studies.

Ya. B. Zel'dovich made a very important contribution to the study of the unusual properties of light nuclei. Developing some shell-model concepts, he predicted nuclear stability for tens of neutron-rich nuclei.[6] He was the first to point out that the isotope ^{8}He was stable, and he estimated its mass (his paper was soon followed by one by Gol'danskiĭ,[7] who refined the mass and the decay modes of ^{8}He, the heaviest isotope of helium). Experimentally, this isotope was first observed in 1961, by Lozhkin and Rimskiĭ-Korsakov. The stability of ^{6}He indicates that there is no dineutron (^2n) with binding energy greater than 0.6 MeV (otherwise, ^{6}He would decay into ^{4}He and ^2n). However, this is a trivial result, since there is extensive experimental evidence on the two-nucleon interaction in various isotopic states. Analogously, the existence of ^{8}He rules out the possibility of ^4n with a binding energy greater than 3.2 MeV, and this conclusion is not trivial. Zel'dovich was again the first to study the existence of purely neutron nuclei,[6] and he drew attention to the possibility of searching for and studying states with high isospin in resonant reactions forbidden by isospin conservation.[9] Working from the properties of such states, it turned out to be possible to predict the properties of the ground states of other nuclei far from the stability boundary. This method has become the most common one for detailed study of high-isospin states in resonant reactions. Baz', Gol'danskiĭ, and Zel'dovich published several reviews in this journal which reflected the thrust of research in this branch of nuclear physics. The last review[2] (written in collaboration with B. Z. Gol'dberg) appeared as a separate monograph in 1972 and pointed out, in particular, that such an unusual hydrogen isotope as ^{7}H might exist. Earlier, before the discovery of ^{8}He, it had been predicted that ^{7}H would be unstable. This conclusion was reached on the basis of the nucleon instability of ^{5}H and the systematic decrease in the binding energies of the excess neutron pairs in the known neutron-rich heavier isotopes.

Since it is now known that the binding in ^{8}He is tighter than that in ^{6}He, the ^{7}H question has attracted a closer look, but a final resolution of this question must await further experiments.

Finally, we should cite the important work by P. É. Nemirovskiĭ on the stability of light nuclei in the boundary region. The first paper[10] appeared in 1959. In his series of papers, Nemirovskiĭ estimated the stability boundaries for neutron-rich nuclei, using a potential incorporating the isotopic effect which he had developed himself. Although this approach proved more satisfactory for nuclei of intermediate weight, the calculations yielded binding energies more accurate than those found by the Garvey–Kelson method for several light nuclei.

Much attention was drawn to the field by some early papers by B. S. Dzhelepov[11] and V. A. Karnaukhov,[12] who analyzed the properties of proton radioactivity and the outlook for detecting this effect among light nuclei.

G. N. Flerov's laboratory at Dubna made a huge contribution to our understanding of exotic light nuclei (in addition to winning distinction for itself in research on very heavy nuclei). Delayed protons were observed there first,[13] and a group led by V. V. Volkov has used a novel method to discover several neutron-rich isotopes of light nuclei.[14]

Also in this issue, a translated paper by the American physicists J. Cerny and A. M. Poskanzer introduces the reader to some surprising transformations of exotic light nuclei. That paper was written at a very popular level, for publication in *Scientific American,* and it deals mostly with work in the USA.

We should also note a very recent paper by Azuma *et al.*,[15] which reports the first observation of the delayed emission of two neutrons accompanying the β decay of the nucleus ^{11}Li. The possibility of this process was first pointed out by Gol'danskiĭ.[4]

In the decay of ^{11}Li, some reaction channels which have not yet been observed experimentally are energetically possible: $^{11}\mathrm{Li}\to{}^6\mathrm{He}+{}^4\mathrm{He}+n$ and $^{11}\mathrm{Li}\to{}^4\mathrm{He}+{}^4\mathrm{He}+3n$. The latter channel leads to the simultaneous emission of three neutrons and may occur either directly or through the formation of an intermediate ^{8}Be nucleus which is unstable with respect to decay into two α particles.

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