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FINAL REPORT ON THE START PROGRAMME

Cluster Structure of Light Atomic Nuclei

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Annotation

A review of existing views on the definition of the atomic nucleus has been conducted, as well as an examination of the features of the structure of light nuclei, including the cluster nature of some of them.

Introduction

Studies of various properties of nuclei and nuclear forces are a very relevant topic. However, this is impossible without a good understanding of the object of research, its definition, basic properties, their nature and other fundamental things.

The purpose of the presented literature review is to present and discuss the known experimental data about the nature atomic nuclei.

Project goals

The result of the project will be an summary covering the following topics:

- the concept of the atomic nucleus and its stability, including their definition through the lifetime and binding energy;
- halo structure, example of remarkable phenomenon in the atomic nuclei.

In addition, the aim was to emphasize the relevance and validity of the cluster approach in the study of nuclei.

Definition of atomic nucleus

Atomic nuclei are systems of interacting nucleons: protons and neutrons. The properties of atomic nuclei are determined by the combined action of strong, electromagnetic, and weak interactions.

However, the answer to the question of which specific system of interacting nucleons should be considered as a nucleus is not entirely clear, as it can have different lifetimes. For example, the emission of a proton by a proton-rich nucleus can be hindered by the presence of a Coulomb barrier, while the emission of a neutron by neutron-rich nuclei can be hindered by the presence of a centrifugal barrier.

Different definitions can be given for the lower limit of the existence time of a nuclear system, and if the system lives longer than this time, it can be called an atomic nucleus. One definition can be associated with the phenomenon of radioactivity. As proposed by Goldanskii [1] and supported by Cherni and Hardy [2], timescales on the order of 10^{-12} s correspond to the lower limit of a process that can be called radioactivity, and the nucleus must exist long enough for radioactive decay to occur.

Another definition could be associated with the characteristic time of atom formation and the emergence of chemical properties in the nucleus. The International Union of Pure and Applied Chemistry (IUPAC) has published a guide to the discovery of chemical elements [3]. In addition to other criteria, they agreed that "the discovery of a chemical element is an experimental demonstration of the existence of a nuclei with atomic number Z, not previously identified, existing for at least 10^{-14} s," since realistic estimates suggest that during this time the nucleus acquires an electron shell, along with its chemical properties.

Similarly, the definition of a nucleus should be related to the time duration of nuclear processes. The transit time of a particle through an object of the nucleus size is approximately 10^{-22} s. Nucleon systems that exist for many orders of times longer than this scale can be considered as nuclei [4].

Fundamental Interactions

There are four fundamental interactions in nature: strong, weak, gravitational, and electromagnetic.

Table 1 - Fundamental Interactions And Their Strength

Interactions	Quantum	Characteristic Radius, cm	Relative Strength of Interaction	Example
Strong	gluons	10^{-13}	$\backsim 1$	nucleus, hadrons
Electromag.	γ-quantum	∞	$\alpha_{el} = 1/137 \approx 10^{-2}$	atom
Weak	W, Z	10^{-16}	$\backsim 10^{-6}$	β-decays
Gravitational	graviton	∞	$\backsim 10^{-40}$	gravity

In nuclear systems, the most significant interactions are the strong, electromagnetic, and weak forces. The strong and electromagnetic forces influence the structure of the nucleus, while the weak force affects its stability.

The gravitational interaction is not considered because it is negligible in compared with the other forces.

Briefly about nuclear decays

Table 2 - Important dates in the study of radioactive decay of nuclei [6]

Discovery	Emitted particles	Year of discovery	Authors
Radioactivity of atomic nuclei	Radiation that caused by darkening of photographic plates	1896	A. Becquerel
Existence e^-	–	1897	J. Thomson
α-decay	^{4}He	1898	E. Rutherford
β-decay	e^-	1898	E. Rutherford
γ-decay	γ-quantum	1900	P. Villard
Discovery of the nucleus	–	1911	E. Rutherford
Nuclear isomerism	γ, e^--capture, β^-, β^+, nuclear fission	1921	O. Hahn
Discovery of the neutron	–	1932	J. Chadwick
β^+-decay	$e^+\nu$	1934	I. et F. Joliot-Curie
e^--capture	ν	1938	L. Alvarez
Spontaneous fission	Two fragments of comparable mass	1940	G.N. Flerov, K.A. Petrzhak
Double β-decay	e^- , ν_e	1950	M.G. Ingram, J.H. Reynolds
Prediction of two-proton radioactivity	2p	1960	V.I. Goldansky
Proton radioactivity	p	1981	S. Hofmann

Cluster radioactivity	14C	1984	H. Rose, G. Jones, D.V. Alexandrov
β^--decay of an ionized atom	e^-	1992	H. Jung et al.
Two-proton radioactivity	2p	2002	J. Giovinazzo, B. Blank et al. M. Pfutzner, E. Badura et al.

Stable nuclei are nuclei that do not undergo decay over a time comparable to the age of the Earth or the universe.

Alpha decay $X \to Y + {}^4\mathrm{He}$ is observed mainly in heavy nuclei $A > 100$, and also for nuclei located "above" the stability line on the NZ-diagram (see below).

Beta decay is a result of weak interaction and is observed in a wide range of nuclear masses, starting from neutrons to the heaviest nuclei. This process represents the decay in which a single nucleon decays within the nucleus. The two types of the beta decay are know as β^- decay, $\mathrm{n}^0 \to \mathrm{p}^+ + \mathrm{e}^- + \overline{\nu_e}$ and β^+ decay – $\mathrm{p}^+ \to \mathrm{n}^0 + \mathrm{e}^+ + \nu_e$. In the case of electron capture $\mathrm{p}^+ + e^- \to \mathrm{n}^0 + \nu_e$, the nucleus captures one of the electrons from the atomic shell, usually from the K-shell, and emits a neutrino.

Double beta decay is a very rare radioactive decay process that was first observed by physicists in 1986. It occurs in a small number of isotopes whose nuclei have higher binding energy than neighboring nuclei with an atomic number increased by one and lower binding energy than nuclei with an atomic number increased by two. In such cases, single beta decay is energetically forbidden, but double beta decay is allowed. The half-lives for all isotopes where this type of decay has been observed are more than 10^{18} years, which significantly exceeds the age of the universe.

The lifetimes of excited bound states of nuclei have a wide range. In some cases, when a high degree of forbiddings is combined with a low energy of the gamma-transition, the photon emission from the excited nuclear states after a macroscopic lifetimes (up to several hours) can be observed. Such long-lived excited states of nuclei are called isomers. The presence of isomeric states is expected in cases where shell levels close in energy have significantly different spin values. It is in these regions that the so-called "islands of isomerism" are located. The islands of isomerism are found just before the magic numbers 50, 82, and 126 from the side of smaller Z and N.

NZ-map

Currently, about 3000 nuclei have been discovered, representing various combinations of proton number Z and neutron number N. According to some estimates, the total number of nuclei could be around 6500 [7].

The neutron-proton or NZ diagram of atomic nuclei is a map that visually shows nuclei and nuclear systems with different numbers of neutrons and protons. Despite the different ways for labeling of nuclei and nuclear systems (such as by lifetime, decay modes, etc.), all such diagrams have a similar appearance and common elements.

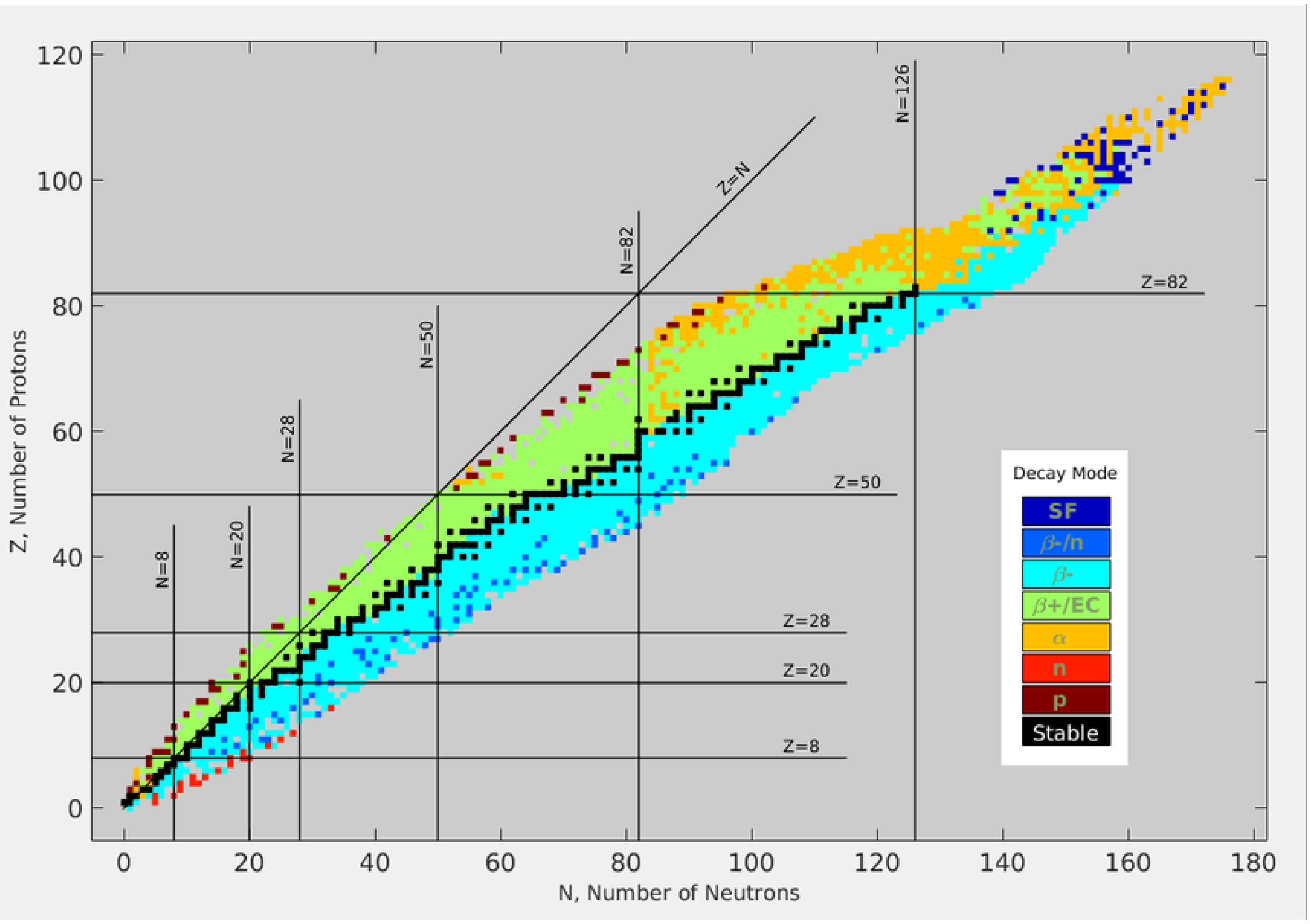

Figure 1: Neutron-proton diagram with color labeling of decay modes. Notations: vertical and horizontal lines – magic numbers of stable nuclei, black – stable nuclei, dark-red – proton decay, bright-red – neutron decay, yellow - alpha decay, green – β^+ decay or electron capture; blue – β^- decay, light-blue – β^-/n decays, bright-blue – spontaneous fission.

Stable nuclei are marked in black colors on the diagram 1 and form the line or valley of a stability.

The behavior of this stability line is determined by strong and electromagnetic interactions. In light stable nuclei (with $Z \lesssim 20$), the number of neutrons is approximately equal to the number of protons. However, as the mass of the nucleus increases, the ratio of neutrons to protons in stable nuclei starts to increase and reaches the value of 1.6 at A = 250. This change can be explained by the short-range nature of nuclear forces and the increasing role of the long-range Coulomb repulsion in heavy nuclei that forces the stability line to bend down.

The last element after which the line of stability is interrupted is ^{209}Bi, and the radioactive nuclei ^{232}Th, ^{235}U, ^{238}U, and ^{244}Pu are separately highlighted on the map, because they have too long half-lives.

To the left from the stable nuclei on the NZ-map are nuclei with an excess of protons (proton-rich nuclei), and to the right are nuclei with an excess of neutrons (neutron-rich nuclei). Nuclei with a strong excess of neutrons or protons are usually called exotic. Exotic nuclei with an excess of neutrons are predominantly decay by the β^-, while isotopes with an excess of protons undergo an electron capture.

The boundaries of nuclear stability for a nucleon emission are called "drip lines" and are determined by the separation energy of nucleons. The neutron separation energy S_n and the proton separation energy S_p can be calculated from the difference in binding energies of two neighboring nuclei:

$$\begin{aligned} E_B &= (Zm_p + Nm_n - M)c^2, \\ S_n &= E_B(Z,N) - E_B(Z,N-1), \qquad (1) \\ S_p &= E_B(Z,N) - E_B(Z-1,N), \qquad (2) \end{aligned}$$

where E_B is the binding energy, m_p, m_n, M are the masses of proton, neutron and nucleus, respectively, and these values determine the boundary beyond which atomic nuclei are unbound ($S_n < 0$ or $S_p < 0$) with respect to proton or neutron emission.

However, nuclear structures beyond drip lines can also be of interest for research, for example such as neutron-rich hydrogen systems.

Table 3 lists nuclei up to $A \lesssim 20$ (first column), their lowest breakup thresholds (second column) into corresponding fragments (third column). Stable nuclei are highlighted in red. Negative breakup threshold energy indicates that the nucleon system is beyond the drip lines. In the case of an unstable nucleus, the most probable decay modes from its ground state are indicated in the last column.

Table 3 - Lowest breakup thresholds E for nuclei up to $A = 20$

Nuclear System	E, МэВ	Breakup	Mode of decay from the g.s.
$^{3}\mathrm{H}$	6.257	$^{3}\mathrm{H} \to {}^{2}\mathrm{H} + \mathrm{n}$	β^{-}, $\tau = 12.32$ y
$^{3}\mathrm{He}$	5.493	$^{3}\mathrm{He} \to {}^{2}\mathrm{H} + \mathrm{p}$	stable
$^{4}\mathrm{H}$	-3.19	$^{4}\mathrm{H} \to {}^{3}\mathrm{H} + \mathrm{n}$	–
$^{4}\mathrm{He}$	19.815	$^{4}\mathrm{He} \to {}^{3}\mathrm{H} + \mathrm{p}$	stable
$^{4}\mathrm{Li}$	-4.07	$^{4}\mathrm{Li} \to {}^{3}\mathrm{He} + \mathrm{p}$	–
$^{5}\mathrm{He}$	-0.798	$^{5}\mathrm{He} \to {}^{4}\mathrm{He} + \mathrm{n}$	–
$^{5}\mathrm{Li}$	-1.69	$^{5}\mathrm{Li} \to {}^{4}\mathrm{He} + \mathrm{p}$	–
$^{6}\mathrm{He}$	0.973	$^{6}\mathrm{He} \to {}^{4}\mathrm{He} + 2\mathrm{n}$	β^{-}, $\tau = 806.7$ ms
$^{6}\mathrm{Li}$	1.474	$^{6}\mathrm{Li} \to {}^{4}\mathrm{He} + \mathrm{d}$	stable
$^{6}\mathrm{Be}$	-1.3711	$^{6}\mathrm{Be} \to {}^{4}\mathrm{He} + 2\mathrm{p}$	–
$^{7}\mathrm{He}$	-0.445	$^{7}\mathrm{He} \to {}^{6}\mathrm{He} + \mathrm{n}$	–
$^{7}\mathrm{Li}$	1.474	$^{7}\mathrm{Li} \to {}^{4}\mathrm{He} + \mathrm{t}$	stable
$^{7}\mathrm{Be}$	1.586	$^{7}\mathrm{Be} \to {}^{4}\mathrm{He} + {}^{3}\mathrm{He}$	e^{-}-cupture, $\tau = 53.22$ days
$^{7}\mathrm{B}$	2.21	$^{7}\mathrm{B} \to {}^{6}\mathrm{Be} + \mathrm{p}$	–
$^{8}\mathrm{He}$	2.14	$^{8}\mathrm{He} \to {}^{6}\mathrm{He} + 2\mathrm{n}$	β^{-}, $\tau = 119$ ms
$^{8}\mathrm{Li}$	2.033	$^{8}\mathrm{Li} \to {}^{7}\mathrm{Li} + \mathrm{n}$	β^{-}, $\tau = 839$ ms
$^{8}\mathrm{Be}$	-0.0918	$^{8}\mathrm{Be} \to {}^{4}\mathrm{He} + {}^{4}\mathrm{He}$	α, $\Gamma = 6.8 \pm 1.7$ эВ
$^{8}\mathrm{B}$	0.137	$^{8}\mathrm{B} \to {}^{7}\mathrm{Be} + \mathrm{p}$	β^{+}, $\tau = 770$ ms
$^{8}\mathrm{C}$	-2.141	$^{8}\mathrm{C} \to {}^{6}\mathrm{Be} + 2\mathrm{p}$	–
$^{8}\mathrm{C}$	0.065	$^{8}\mathrm{C} \to {}^{7}\mathrm{B} + \mathrm{p}$	–
$^{9}\mathrm{Li}$	4.0639	$^{9}\mathrm{Li} \to {}^{8}\mathrm{Li} + \mathrm{n}$	β^{-}, $\tau = 178.3$ ms
$^{9}\mathrm{Be}$	1.5736	$^{9}\mathrm{Be} \to {}^{4}\mathrm{He} + {}^{4}\mathrm{He} + \mathrm{n}$	stable
$^{9}\mathrm{B}$	1.689	$^{9}\mathrm{B} \to {}^{5}\mathrm{Li} + {}^{4}\mathrm{He}$	p, $\Gamma = 0.54 \pm 0.21$ ms
$^{9}\mathrm{C}$	1.3	$^{9}\mathrm{C} \to {}^{8}\mathrm{B} + \mathrm{p}$	β^{+}, $\tau = 126.5$ ms
$^{10}\mathrm{He}$	-1.069	$^{10}\mathrm{He} \to {}^{8}\mathrm{He} + 2\mathrm{n}$	n, $\Gamma = 0.3 \pm 0.2$ МэВ

continuation of the table 3

$^{10}\mathrm{Li}$	-0.025	$^{10}\mathrm{Li} \to {}^{9}\mathrm{Li} + \mathrm{n}$	–
$^{10}\mathrm{Be}$	6.81	$^{10}\mathrm{Be} \to {}^{9}\mathrm{Be} + \mathrm{n}$	β^-, $\tau = (1.51 \pm 0.04) \cdot 10^6$ y
$^{10}\mathrm{Be}$	7.41	$^{10}\mathrm{Be} \to {}^{6}\mathrm{He} + {}^{4}\mathrm{He}$	β^-, $\tau = (1.51 \pm 0.04) \cdot 10^6$ y
$^{10}\mathrm{B}$	4.46	$^{10}\mathrm{B} \to {}^{6}\mathrm{Li} + {}^{4}\mathrm{He}$	stable
$^{10}\mathrm{C}$	3.82	$^{10}\mathrm{C} \to {}^{8}\mathrm{Be} + 2\mathrm{p}$	β^+, $\tau = 19.29$ c
$^{11}\mathrm{Li}$	0.3691	$^{11}\mathrm{Li} \to {}^{9}\mathrm{Li} + 2\mathrm{n}$	β^-, $\tau = 8.75 \pm 0.14$ ms
$^{11}\mathrm{Be}$	0.5016	$^{11}\mathrm{Be} \to {}^{10}\mathrm{Be} + \mathrm{n}$	β^-, $\tau = 13.76 \pm 0.07$ ms
$^{11}\mathrm{B}$	8.6641	$^{11}\mathrm{B} \to {}^{7}\mathrm{Li} + {}^{4}\mathrm{He}$	stable
$^{11}\mathrm{C}$	7.5436	$^{11}\mathrm{C} \to {}^{7}\mathrm{Be} + {}^{4}\mathrm{He}$	β^+, $\tau = 20.36$ min
$^{11}\mathrm{N}$	-1.4893	$^{11}\mathrm{N} \to {}^{10}\mathrm{C} + \mathrm{p}$	–
$^{12}\mathrm{Be}$	3.171	$^{12}\mathrm{Be} \to {}^{11}\mathrm{Be} + \mathrm{n}$	β^-, $\tau = 21.46 \pm 0.05$ ms
$^{12}\mathrm{B}$	3.37	$^{12}\mathrm{B} \to {}^{11}\mathrm{B} + \mathrm{n}$	β^-, $\tau = 20.20 \pm 0.02$ ms
$^{12}\mathrm{C}$	7.367	$^{12}\mathrm{C} \to {}^{4}\mathrm{He} + {}^{4}\mathrm{He} + {}^{4}\mathrm{He}$	stable
$^{12}\mathrm{N}$	0.601	$^{12}\mathrm{N} \to {}^{11}\mathrm{C} + \mathrm{p}$	β^+, $\tau = 11.000 \pm 0.0166$ ms
$^{12}\mathrm{O}$	-1.638	$^{12}\mathrm{O} \to {}^{10}\mathrm{C} + 2\mathrm{p}$	–
$^{12}\mathrm{O}$	-0.326	$^{12}\mathrm{O} \to {}^{11}\mathrm{N} + \mathrm{p}$	–
$^{13}\mathrm{B}$	4.878	$^{13}\mathrm{B} \to {}^{12}\mathrm{B} + \mathrm{n}$	β^-, $\tau = 17.36 \pm 0.16$ ms
$^{13}\mathrm{C}$	4.946	$^{13}\mathrm{C} \to {}^{12}\mathrm{C} + \mathrm{n}$	stable
$^{13}\mathrm{N}$	1.9435	$^{13}\mathrm{N} \to {}^{12}\mathrm{C} + \mathrm{p}$	β^+, $\tau = 9.965 \pm 0.004$ min
$^{13}\mathrm{O}$	1.514	$^{13}\mathrm{O} \to {}^{12}\mathrm{N} + \mathrm{p}$	β^+, $\tau = 8.58 \pm 0.05$ ms
$^{14}\mathrm{B}$	0.97	$^{14}\mathrm{B} \to {}^{13}\mathrm{B} + \mathrm{n}$	β^-, $\tau = 13.8 \pm 1.0$ ms
$^{14}\mathrm{C}$	8.1765	$^{14}\mathrm{C} \to {}^{13}\mathrm{C} + \mathrm{n}$	β^-, $\tau = 5730 \pm 40$ y
$^{14}\mathrm{N}$	7.551	$^{14}\mathrm{N} \to {}^{13}\mathrm{C} + \mathrm{p}$	stable
$^{14}\mathrm{O}$	4.628	$^{14}\mathrm{O} \to {}^{13}\mathrm{N} + \mathrm{p}$	β^+, $\tau = 70.606 \pm 0.018$ c
$^{15}\mathrm{C}$	1.218	$^{14}\mathrm{C} \to {}^{14}\mathrm{C} + \mathrm{n}$	β^-, $\tau = 2.449 \pm 0.005$ c
$^{15}\mathrm{N}$	10.207	$^{15}\mathrm{N} \to {}^{14}\mathrm{C} + \mathrm{p}$	stable
$^{15}\mathrm{N}$	10.833	$^{15}\mathrm{N} \to {}^{14}\mathrm{N} + \mathrm{n}$	stable
$^{15}\mathrm{O}$	7.297	$^{15}\mathrm{O} \to {}^{14}\mathrm{N} + \mathrm{p}$	β^+, $\tau = 122.24 \pm 0.16$ c
$^{15}\mathrm{F}$	-1.47	$^{15}\mathrm{F} \to {}^{14}\mathrm{O} + \mathrm{p}$	–
$^{16}\mathrm{C}$	4.251	$^{16}\mathrm{C} \to {}^{15}\mathrm{C} + \mathrm{n}$	β^-, $\tau = 0.747 \pm 0.008$ c

continuation of the table 3

^{16}N	2.491	$^{16}\mathrm{N} \to {}^{15}\mathrm{N} + \mathrm{n}$	β^-, $\tau = 7.13 \pm 0.02$ c
^{16}O	7.162	$^{16}\mathrm{O} \to {}^{12}\mathrm{C} + {}^{4}\mathrm{He}$	stable
^{16}F	-0.535	$^{16}\mathrm{F} \to {}^{15}\mathrm{O} + \mathrm{p}$	–
^{17}N	5.882	$^{17}\mathrm{N} \to {}^{16}\mathrm{N} + \mathrm{n}$	β^-, $\tau = 4171$ ms
^{17}O	4.1436	$^{17}\mathrm{O} \to {}^{16}\mathrm{O} + \mathrm{n}$	stable
^{17}F	0.6005	$^{17}\mathrm{F} \to {}^{16}\mathrm{O} + \mathrm{p}$	β^+, $\tau = 64.49 \pm 0.16$ c
^{18}O	6.227	$^{18}\mathrm{O} \to {}^{14}\mathrm{C} + {}^{4}\mathrm{He}$	stable
^{18}F	4.415	$^{18}\mathrm{F} \to {}^{14}\mathrm{N} + {}^{4}\mathrm{He}$	β^+, $\tau = 109.77 \pm 0.05$ min
^{18}Ne	3.922	$^{18}\mathrm{Ne} \to {}^{17}\mathrm{F} + \mathrm{p}$	β^+, $\tau = 1672 \pm 8$ ms
^{19}O	3.957	$^{19}\mathrm{O} \to {}^{18}\mathrm{O} + \mathrm{n}$	β^-, $\tau = 26.91 \pm 0.08$ ms
^{19}F	4.0138	$^{19}\mathrm{F} \to {}^{15}\mathrm{N} + {}^{4}\mathrm{He}$	stable
^{19}Ne	3.5294	$^{19}\mathrm{Ne} \to {}^{15}\mathrm{O} + {}^{4}\mathrm{He}$	β^+, $\tau = 17.22 \pm 0.02$ c
^{19}Na	-0.321	$^{19}\mathrm{Na} \to {}^{18}\mathrm{Ne} + \mathrm{p}$	–
^{20}O	7.608	$^{20}\mathrm{O} \to {}^{19}\mathrm{O} + \mathrm{n}$	β^-, $\tau = 13.51 \pm 0.05$ c
^{20}F	6.601	$^{20}\mathrm{F} \to {}^{19}\mathrm{F} + \mathrm{n}$	β^-, $\tau = 11.163 \pm 0.008$ c
^{20}Ne	4.730	$^{20}\mathrm{Ne} \to {}^{16}\mathrm{O} + {}^{4}\mathrm{He}$	stable
^{20}Na	2.195	$^{20}\mathrm{Na} \to {}^{19}\mathrm{Ne} + \mathrm{p}$	β^-, $\tau = 447.9 \pm 2.3$ ms
^{20}Mg	2.314	$^{20}\mathrm{Mg} \to {}^{18}\mathrm{Ne} + 2\mathrm{p}$	β^-, $\tau = 90.8$ ms

One can observe the following fact: the lowest threshold in the lightest nuclei corresponds to the breakup with cluster or few-nucleon emission. And only the stable nuclei that heavier then ^{12}C have the lowest threshold with one nucleon emission. This fact indirectly suggests that if the energy for cluster threshold is small then the nucleus has a cluster nature.

Halo Nucleus

Of particular interest are nuclei that have the "halo" structure. Signs of a halo in the nuclear systems are shown in peculiarities of the ground state and the low-energy continuum:

- weakly bound nuclei (nucleon separation energy $\lesssim 1$ MeV): for example, in ^{11}Li this energy is ~ 400 keV while in stable nuclei is few times large;

- large nuclear sizes: the reaction cross sections for halo nuclei are significantly enhanced in comparison with cross sections caused by the neighboring nuclei;
- very narrow fragment (nucleons and core) momentum distributions measured in breakup reactions in comparisons with fragment momentum distributions obtained for the stable nuclei;
- Electromagnetic dissociation cross sections per unit charge are orders of magnitude larger than for stable nuclei;
- Ground state properties (quadrupole and magnetic moments) are close to properties of the core nucleus;

These peculiarities can be consistently explained by the halo structure model which based on assumptions that nucleus has pronounced clusterization on the core nucleus and peripheral (halo) nucleons. Due to weak binding the halo nucleons are localized far away from the core which leads to the large space extension of the halo wave function. This phenomenon is associated with a nucleon tunneling into peripheral domain and often called as "the residence in forbidden regions". Such possibility depends on the angular momentum of the valence neutrons since the high angular momentum prevent them from tunneling through the centrifugal barrier. Hence, halo nuclei, as a rule, are in states with low relative orbital angular momentum (s or p).

The known halo nuclei are shown in the table 4. It also includes nuclei with a proton halo, but below we will talk mainly about neutron one.

Halo nuclei first came into focus after the interaction cross section measurements made by Tanihata [9] and the extraction of the nuclear matter radii from them. Two year later the key ingredients of the halo structure model were identified in the paper by Hansen and Jonson [10]. In this article the existence of low-energy excitations (soft modes), that leads to the large cross section for Coulomb dissociation, was also predicted. After these works the intensive explorations of the halo phenomenon are started around the world both experimentally and theoretically.

The shell model has some difficulties in consistent descriptions of the halo structures. The more simple and transparent approach can be obtained within a few-body cluster model: core + nucleons. It has proved successful in describing their essential characteristics.

Table 4 - Halo Nuclei

Nucleus	Number of Halo Isotopes	Halo Isotopes	Composition	Half-life (ms)
He	1	^{6}He	^{4}He + 2n	801(10)
Li	1	^{11}Li	^{9}Li + 2n	8.75(14)
Be	2	^{11}Be	^{10}Be + n	13810(80)
		^{14}Be	^{12}Be + 2n	4.35(17)
B	3	^{8}B	^{7}Be + p	770(3)
		^{17}B	^{15}B + 2n	5.08(5)
		^{19}B	^{17}B + 2n	2.92(13)
C	2	^{19}C	^{18}C + n	49(4)
		^{22}C	^{20}C + 2n	$6.1^{+1.4}_{-1.2}$
Ne	1	^{17}Ne	^{15}O + 2p	109.2(6)
P	1	^{26}P	^{25}Si + p	43.7(6)
S	1	^{27}S	^{25}Al + 2p	15.5(15)

There are two types of the halo systems with one and two halo neutrons. The two-neutron halo nuclei have the interesting feature: all of them break up into three fragments (core and two neutron) and any two-body subsystems (core + n or n + n) have no bound states. Such systems are called "Borromean" [11]. Simple cluster models with few-bodies allows account the main features of halo nuclei. Model assumes that the nuclear wave function is presented by a product of two function. One describes the core nucleus and the other describes a relative motion of the halo neutrons and the core center of mass. The cluster three-body model allows fully account the dynamic features of the borromean systems including the correct asymptotic behaviour of the nuclear wave functions. However, they also have disadvantages. Antisymmetrization between the core and halo nucleons has often been considered only approximately and the effects of the core nucleus excitation and polarization have often been ignored. Although a number of studies to address these shortcomings are ongoing.

Nowadays, fully microscopic (ab initio) models of the structure appears. These models are completely antisymmetric, starting with realistic nucleon-nucleon interactions including the three bodies forces. However, they only approximately account the few-body continuum dynamics.

Conclusion

The nucleus is a system which consists from neutrons and protons. In spite of this fact some light nuclei show a pronounced cluster structure. This is indirectly manifested by breakup of the nuclei into clusters at lowest thresholds (see Table 3). Halo nuclei are a remarkable example of the exotic nuclear structure, where this phenomenon of the nucleon clusterization is very pronounced. The cluster few-body models allows to give a simple and transparent description of these systems.

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