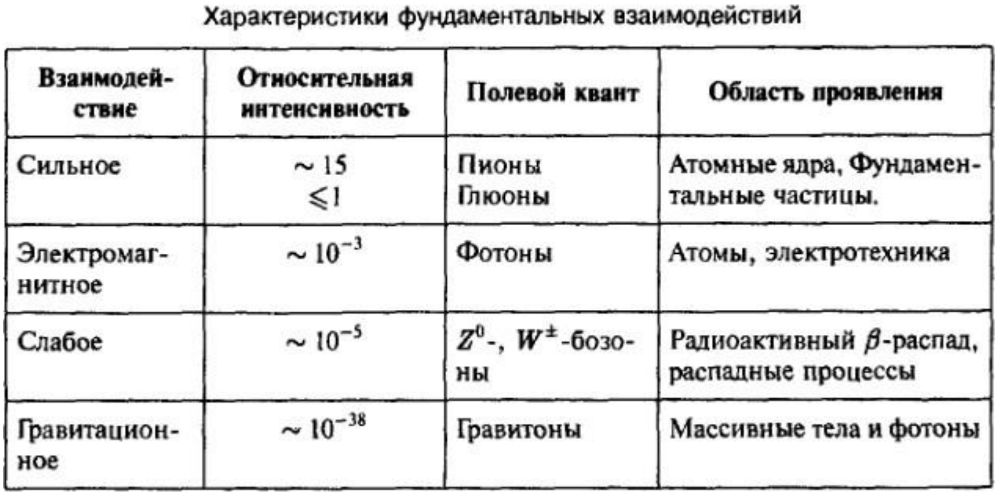
Brief summary of lectures on discipline
"Introduction to the theory of the nucleus"

Lecture 1. Gravitational interaction.

This interaction is of a universal nature, it involves all kinds of matter, all objects of nature, all elementary particles. The generally accepted classical theory of gravitational interaction is Einstein's general theory of relativity. Gravity, in particular, determines the motion of planets in stellar systems, plays an important role in the processes occurring in stars, controls the evolution of the universe, under terrestrial conditions, manifests itself as the force of gravity.



Характеристики фундаментальных взаимодействий

Взаимодействие	Относительная интенсивность	Полевой квант	Область проявления
Сильное	~ 15 $\leqslant 1$	Пионы Глюоны	Атомные ядра, Фундаментальные частицы.
Электромагнитное	$\sim 10^{-3}$	Фотоны	Атомы, электротехника
Слабое	$\sim 10^{-5}$	Z^0-, $W^{\pm}$-бозоны	Радиоактивный β-распад, распадные процессы
Гравитационное	$\sim 10^{-38}$	Гравитоны	Массивные тела и фотоны

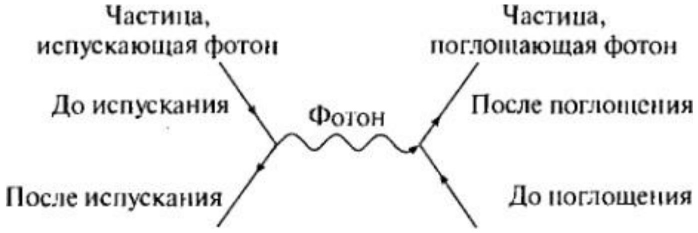
Lecture 2. Weak interaction.

For the first time, weak interactions were observed in the beta decay of atomic nuclei. The need for introducing a weak interaction is due to the fact that in nature processes occur in which electromagnetic and strong decays are forbidden by conservation laws. Weak interaction is short-range. It was experimentally established that the characteristic radius of its order is 10-15 cm, i.e. it is concentrated at distances smaller than the dimensions of the atomic nucleus. Weak interaction plays an important role in the thermonuclear reactions responsible for the mechanism of energy release in the stars.

Currently, a number of laboratories in the world are conducting experiments to obtain and study the anti hydrogen atoms. CERN is leading in this direction. The main purpose of the experiments is to directly test CPT in variance on the basis of a comparison of the spectra of hydrogen atoms and anti hydrogen.

Lecture 3. Electromagnetic interaction.

In the electromagnetic interaction involve all charged bodies, all charged elementary particles. Perhaps this is the most important interaction, since it not only unites all electrical phenomena, but also provides forces through which matter at the atomic and molecular level exists as a whole. The classical theory of electromagnetic interaction is Maxwell's electrodynamics. From the point of view of the quantum theory the vector of the electromagnetic interaction is an elementary particle of a photon - a mass less boson with spin 1. The quantum electromagnetic interaction between charges is conditionally represented as follows:



A charged particle emits a photon, so that the state of its motion changes. Another particle absorbs a photon and also changes its state of motion. As a result, the particles seem to feel each other.

Lecture 4. Strong interaction.

Strong interaction is responsible for the stability of atomic nuclei. Since the atomic nuclei of most chemical elements are stable, it is clear that the interaction that keeps them from decay must be strong enough. In order for positively charged protons not to scatter in different directions, it is necessary to have forces of attraction between them that exceed the forces of electrostatic repulsion. It is strongly the interaction is responsible for these forces of attraction.

The theory of strong interaction is analogous to electrodynamics and is called quantum chromodynamics. According to this theory, particles participating in a strong interaction are called hadrons, consist of elementary particles, called quarks. The hypothesis of their existence was expressed in 1964. It was confirmed in experiments that showed that the nucleons are not pointlike objects, but consist of quarks.

Lecture 5. On some problems in the physics of elementary particles.

In quantum chromodynamics there are a number of unresolved dynamic problems, among which the problem of confinement, the mechanism of color confinement, is highlighted. In this area an important role should be played by the discovery and investigation of exotic hadrons. The search and investigation of exotic hadronsare being intensively carried out in experiments at the U-70 accelerator in Protvino (Russia), at the SPS accelerator at CERN (Geneva) and in other laboratories.

Another direction in the physics of elementary particles is the study of exotic atoms. Some results of the physics of exotic atoms have now turned into important practical directions:
1) meson chemistry;
2) the method of muon spin relaxation.

Another problem of elementary particle physics is the combination of interactions. Also, of particular interest to researchers are neutrinos produced in nuclear fusion reactions, which are realized in the bowels of the Sun and which are the source of the internal energy of our luminary.

Lecture 6. The concept of mass in modern physics.

According to modern terminology, both terms "relativistic mass" and "rest mass" are obsolete, it is not recommended using them. It should be said simply about the mass without any adjectives or other additional words. Such a mass is given by $m^2=\frac{E^2}{c^4}-\frac{\vec{p}^2}{c^2}$, whereE – the total energy of a free body, $\vec{p}$- is its momentum, and c – is the speed of light. Such a mass does not change during the transition from one inertial frame of reference to the other.The physical meaning of the mass was discovered by Einstein in 1905, when he introduced the concept of rest energy. From the above relation for a resting body($\vec{p}=0$), we obtain:$m=\frac{E_0}{c^2}$Consequently, the mass is proportional to the rest energy. It is the energy of rest, "dormant" in the bodies, partially released in chemical and especially nuclear reactions.

The main change is due to the fact that physics has come close to the question of the nature of the mass as truly elementary particles, such as leptons and quarks, and particles of the proton and neutron type, called hadrons. This question is closely related to the search for so-called bosonsand with the structure and evolution of the vacuum. Once again, it can be clarified that here the words about the nature of the mass refer to the invariant mass, and not to the relativistic mass, which simply represents the total energy of a free particle.

Lecture 7. Physical experiment: current state and development prospects.

In this lecture, we discuss the sensitivity (resolution) in experiments that lead to the measurement of small displacements, small forces (accelerations), and also to the detection of small frequency shifts.

Physical experiments in which sensitivity (resolution) played a decisive role, first began to be carried out at the end of the 18th century. G. Kavendish and S. Kulon. In the experiments of these outstanding physicists, the force (acceleration) was measured by the magnitude of the mechanical displacement (the amplitude of the oscillations). In numerous subsequent experiments of other experimenters, the sensitivity in measurements of small displacements and, independently, in the measurement of small forces, increased.

Somewhat later, a culture of measurement arose in which the physical quantity was recorded by changing the time interval (frequency difference). Measurements with high resolution of small mechanical displacements, small accelerations and small frequency changes (time intervals) led to the discovery of the most important physical laws. It can be expected that in the future, an increase in sensitivity in these three types of measurements will lead to new nontrivial results.

Experimenters in the past few years have been intensively preparing the replacement of some key antenna elements, which will significantly reduce the technological limitations of sensitivity. As a result, fundamental information will be obtained, which can be summarized in the following paragraphs:

1) An estimate will be made of populations of neutron stars in the megalaxy and, correspondingly, the contribution of these stars to dark matter.
2) In the form of a burst of gravitational radiation from neutron stars, it will be possible to find out which of the equations of state for a substance of neutron stars is valid (of several already available).
3) Analysis of the shape of the burst from the fusion of black holes is a very likely way of testing the general theory of relativity in the ultrarelativistic case. In this case, the experimenters will not observe matter as such, but only the behaviour of space-time.

Lecture 8. Quarks in nuclei.

To describe the matter at the atomic-molecular level, valence plays an important role, at the level of the atomic nuclei, the mass defect. The latter concept allowed us to consider light objects constructed from heavier particles. At the next level, the concept of a virtual particle has been established; one that exists for a very short time.

The substance surrounding us and ourselves are built of atoms consisting of electrons and nuclei, and the latter, in turn, consist of protons and neutrons. Protons and neutrons belong to the class of particles participating in strong interaction, called hadrons. The electron, which does not participate in the strong interaction, is part of the lepton group. Like the nuclei of atoms, hadrons, in turn, are compound particles. Their constituents are called quarks; they have peculiar properties. The most unusual of them is that quarks exist only inside hadrons and are not observed as isolated objects. Thus, quarks are an example of virtual particles.

In the proton and neutron composition there are two types of quarks: u and d; The u-quark has an electric charge (+ 2 / 3e), and the d-quark is (-1 / 3e), respectively, where e is an elementary charge.

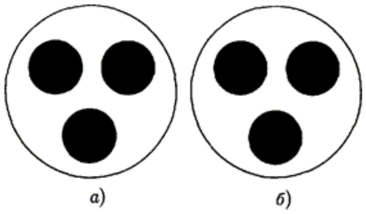


Рис. 9.1. Кварковый состав протона (*а*) и нейтрона (*б*). Темный кружок соответствует кварку u, светлый кружок — кварку d

The neutron consists of three quarks (u, d, d), a proton - also of three, but in another combination (see Fig.).

Other hadrons also consist of quarks. Quarks are held inside the particle due to the strong interaction between them. The reason for this interaction is that in addition to the electric charge, the quarks have another very peculiar charge, called the "coloured" charge, which leads to the appearance of forces that bind quarks to hadrons.

Lecture 9. Particle accelerators.

The main tool that makes it possible to study the structure of matter is an accelerator that creates particles of such high energy that they are able to penetrate into the deep regions of the microobject studied. At present, several such machines are operating in the world, accelerating charged particles to very high energies. Such accelerators can act both in the mode of the extracted beams (when the accelerated particles are directed to a stationary target) and in the collider mode (when two particles accelerated to high energies collide with each other). The collider mode is energetically more favorable. The energy of 900 GeV of each of the colliding particles (in this case, these are protons) is the maximum for today; It was achieved at an accelerator in the E. Fermi National Laboratory (USA). For the first time, a collider in which electrons and protons collided was built in Novosibirsk (VEP-2M). the energy of each of the beams reached 0.7 GeV. Since 1994, the energy of electrons and positrons in the collider is 6 GeV (VEP-4M). the European Center for Nuclear Research operates a complex of accelerators, in which electrons and positrons are accelerated to an energy of 100 GeV.

In order to study the structure of microobjects in addition to high energies, irradiating particles it is desirable that these projectile particles be as simple as possible nonstructural formations. At the modern level of our knowledge, such particles are leptons; among them the electron is most accessible for experiments. According to modern concepts, they have no structure, at least up to distances~10^{-16} cm.

Lecture 10. Energy properties of nuclei.

In accordance with existing concepts, the forces acting between nucleons are short-range, and practically the same density of matter in different nuclei indicates an extremely low compressibility of nuclear matter. Liquid possesses the same small compressibility, while intermolecular forces are short-range. These similarities have given the description of likening the core of a charged droplet of liquid and suggest on this basis a drop model for describing the structure and dynamics of atomic nuclei.On the basis of this approach, using the semiempirical calculations, the following expression was obtained, which describes well the experimental values of the binding energy of nuclei:

$$E_{\text{св}} = 14{,}0A - 13{,}1A^{2/3} - 0{,}585Z(Z-1)A^{-1/3} -$$
$$- 18{,}1(A-2Z)^2A^{-1} + \delta A^{-1}.$$

Here,$E_{св}$is the total binding energy (in MeV), i.e. the energy necessary for the splitting of the nucleus into individual nucleons. It is also pertinent to note here that if a nucleus is collected from individual nucleons, then the energy equal to the binding energy of the nucleus will be released.

Experiments show that the average binding energy per nucleon for all elements, except the lighter ones, differ insignificantly (see Fig.).

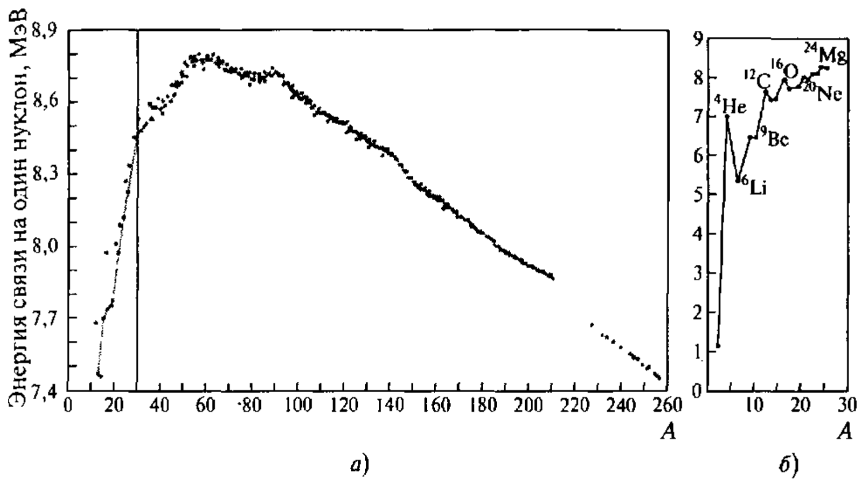


Рис. 9.2. Зависимость энергии связи на один нуклон для области $15 < A < 255$ (*а*) и для области $2 < A < 30$ (*б*)

In a number of cases, not the binding energy is considered, but the kernel mass given by expression$M = ZM_H + (A - Z) M_n - E_{св}$.

Lecture 11. Kernels removed from the stability area.

The vast majority of our knowledge of nuclear matter is derived from studies of the properties of nuclei lying in a narrow region near the valley of nuclear stability. However, in the late 80's. In the 20th century, intensive investigations of nuclei in various parts of the parabola began in nuclear physics, far from the stability valley, the so-called exotic nuclei. The areas of such studies that have already made it possible to discover new properties of nuclear matter can, at least, be described as follows. Consider the evolution of the lithium nucleus as the number of neutrons increases with respect to the stable state^{6}Li (see Fig.).

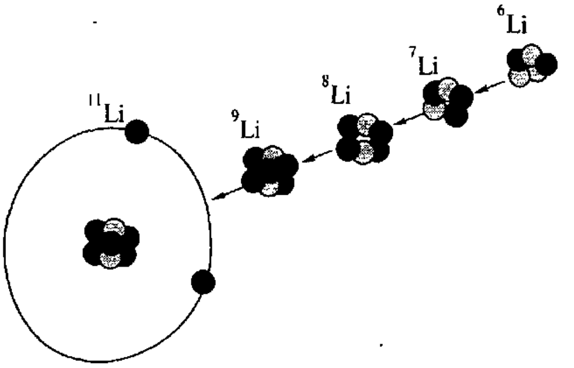


Рис. 9.4. Схематическое изображение эволюции ядра лития по мере увеличения числа нейтронов

Examinations of exotic nuclei performed so far allow us to assume that the results obtained can be used to solve certain problems of astrophysics. This applies both to the problem of the synthesis of elements in the early stages of the evolution of the universe, and to the question of the energy balance in the stars.

It is possible to obtain and study nuclei located far from the stability valley by using beams of radioactive nuclei. It is believed that this direction is in fact the general line for the development of nuclear physics for the coming decades.

Lecture 12. Radioactivity.

Radioactive processes are spontaneously occurring nuclear decays, accompanied by the emission of elementary particles or nuclear fragments over a measurable time (in accordance with the capabilities of modern techniques for at least 10-12 s). At present, about twenty nuclear-physical processes, one part of which occurs with nuclei in the ground state, the other with nuclei in the excited state, is considered radioactive. All these processes can be divided into four groups.

The first group includes all the radioactive processes that are possible (and indeed discovered) for nuclei in the ground state. These include alpha, beta and proton decays, the emission of nuclei is heavier than alpha particles (cluster decay) and spontaneous fission. The second group includes a large number of different retarded processes occurring with highly excited atomic nuclei arising as a result of the preceding$\beta^{\pm}$-decays.

Radioactive processes in the third group are related to nuclei that have long-lived (metastable) isomeric levels. Three types of isomeric transitions are known: the hindered transition is a transition often accompanied by the emission of conversion electrons, isomeric proton decay, and isomer spontaneous fission.

The fourth, the smallest group consists of only one radioactive process, which, however, occurs most often. This is the decay, by means of which the excess excitation energy of the nuclei is removed in practically all the radioactive processes listed above.

There are no fundamental differences between the radioactivity of nuclei in the ground and excited states.

Lecture 13. Spontaneous fission of nuclei and spontaneously fissioning nuclear isomers.

Spontaneous fission of nuclei is the process of tunnelling of nuclei through the fission barrier. The minimum of the potential energy corresponds to the ground state of the nucleus, in which it experiences only zero-point vibrations.

A drop of water in the lowest energy form, for the creation of which the least energy is required, is a sphere.

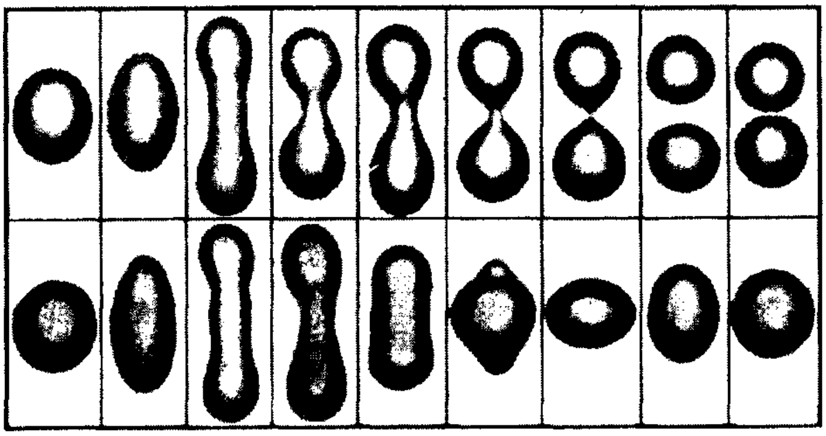


Рис. 9.7. Фотографии последовательных деформаций жидкой капли

The large energy release and emission of secondary neutrons in the fission process is of great practical importance. In particular, the process of nuclear fission, as is known, is based on the work of nuclear reactors.

Lecture 14. Proton and two-proton radioactivity. Clusterradioactivity.

Until a certain time, it was believed that the emission of a proton, unlike alpha decay, is energetically unprofitable. This was proved by the fact that four nucleons in a free alpha particle are much more strongly bound than in any heavy nucleus. Advances in accelerator technology made it possible to obtain superprotonically excess nuclei and for the first time observe proton radiators such as ^{165,166,167}Ir, ^{171}Au, ^{185} Bi, 16-18 nucleons away from stable nuclei.

In 1960, Academician V.I. Goldansky predicted the possibility of the existence of another radioactive process - two-proton decay. This process should be observed for proton-abundant light nuclei (Z <50) with even Z. At present several confirmations of the existence of two-proton radioactivity (both for excited nuclei and for those in the ground state).

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Since the mid-80's. A new type of radioactive decay is widely studied, consisting in the fact that the atomic nuclei that are in the ground states spontaneously emit heavy constituent particles (clusters), such as^{14}C, ^{24}N, ^{28}Mg,^{32}Si.Clusters in this case are understood to mean various compact structures consisting of two or more particles (these include not only protons and neutrons, but also mesons, quarks, and also other elementary particles) that can arise inside the atomic nucleus. Since the discovery of this type of radioactivity, more than twenty nuclei from ^{221}Fr to ^{241}Am have been detected that emit clusters from ground states. This discovery raised the question of its place in the general picture of radioactive decay.

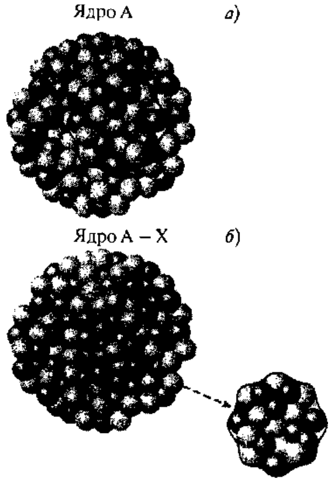

Рис. 9.10. Схема выхода кластера из атомного ядра: *а*) кластер X находится внутри ядра A; *б*) кластер X вылетел из ядра

Lecture 15. Super Dense Nuclear Matter. Transitionradiation.

The dimensions of the nuclei depend on the number of nucleons contained in them. The average density of nucleons in the nucleus is practically the same for all multinucleon nuclei, i.e. the nucleons in the nucleus are at the same distance from each other. In 1971, the Soviet physicist A.B. Migdal developed a theory in which the interaction of nucleons depends to a large extent on the density of nuclear matter. To date, it has not been possible to experimentally detect a stable superdense nuclear matter. Transition radiation is an extremely common phenomenon, constituting a vast section of modern physics. If the medium is inhomogeneous or not stationary, then with a uniform motion of the source, transitional radiation appears.

Just as it once seemed self-evident that "a uniformly moving particle does not radiate", it now seems self-evident that any moving particle radiates. The point is that the particle would not radiate only in the case of motion in empty space without external fields. In real conditions, the motion of charged particles occurs in the medium and in the presence of external fields. Moreover, most often the conditions for the manifestation of several elementary electromagnetic radiation mechanisms are fulfilled, which can complicate not only the analysis of the experimental data, but also the interpretation of natural radiation (for example, in astrophysics).

Information on the methodical provision of the discipline

Recommended:

1. Bethe H.A., Morrison P. Elementary Nuclear Theory, 1st ed. New York: Wiley, 1947. 147 p.
2. Heyde K. Basic Ideas and Concepts in Nuclear Physics: An Introductory Approach, 2nd Edition. Institute of Physics Publishing Bristol and Philadelphia, 1999. 547 p.
3. Iliadis Ch. Nuclear Physics of Stars, WILEY-VCH Verlag, Weinheim, 2007, 666 pages Martin B.R. Nuclear and Particle Physics: An Introduction, Wiley, 2006. — 415 p.
4. Kamal A. Nuclear Physics, Springer, 2014. — 612 p. — (Graduate Texts in Physics).
5. Takigawa N., Washiyama K., Fundamentals of Nuclear Physics, Springer, Japan, 2017. – 277 p.

Additional:

1. Shultis J.K., Faw R.E. Fundamentals of Nuclear Science and Engineering, Kansas State University Manhattan, Marcel Dekker, New York, Basel, 2002, 506 pp.
2. Frobrich P., Lipperheide R., Theory of nuclear reactions, Clarendon Press, Oxford. 1996 - 476 p.
3. J.M.Blatt and V.F.Weisskopf, Theoretical Nuclear Physics, Springer, 1979, VII.5
4. Nuclear Physics by Irving Kaplan 2nd edition1962 Addison-Wesley