Lecture 1

Subject of Nuclear Physics

The nuclear physics is the science, which deals with the structure and properties of nuclei, laws of change and transformation of nuclei, properties of nuclear forces, mechanism of nuclear reactions, interaction of nuclear radiation with substance, physics of elementary particles.

The history of evolution of nuclear physics:

1895 - The discovery of X-ray radiation.

2005 - Up-to-day problems of nuclear physics.

Nowadays four types of fundamental interactions: strong, electromagnetic, weak and gravitational are known. Strong interaction is carried out between nucleons in atomic nuclei. It is also inherent in a plenty of elementary particles, so-called hadrons (protons, neutrons, hyperons, mesons, etc.). The electromagnetic interaction is carried out between electric charges. Chemical, molecular, elastic, viscous and other forces relate to electromagnetic interactions. Weak interactions generate β- decay of radioactive nuclei and together with electromagnetic forces they are inherent in leptons, elementary particles, not participating in strong interactions and possessing spin $s = 1/2$ (electron, muon, neutrino, etc.). Neutral leptons do not participate in electromagnetic interactions. Gravitational interaction is inherent in all particles.

Objects of the microcosm - atoms, nuclei and elementary particles obey the laws appreciably distinguished from laws of the macrocosm.

Scales and units of values, which are characteristic for nuclear physics:

Length

The radius of an atom is about 10^{-8} *cm*. This size characterizes the radius of an orbit of outer electrons. The radius of a nucleus is about $10^{-12} \div 10^{-13}$ *cm*. The distance of 10^{-13} *cm* is called 1 *Fermi (Fm)*.

Energy

The unit of electron-volt (*eV)* is widely used as the energy unit.

1 *eV* represents the energy got by the electron accelerated by a potential difference of 1 *volt*. The binding energy of protons and neutrons in a nucleus is equal, on average, to $8 \cdot 10^6$ *eV*.

Mass

In nuclear physics the mass of a nucleus and an atom is often measured by atomic mass units. One atomic mass unit *(amu)* equals one-twelfth of the mass of the carbon atom *(amu* = 931.4 *MeV*; 1 *amu* = $1.66 \cdot 10^{-24}$ *g*).

Time

In nuclear physics the time scale differs from the habitual time. The characteristic or nuclear time is considered to be the time for which the particle traveling with the velocity of light will cross a diameter of a nucleus. It equals 10^{-23} *sec*.

Lecture 2
Features of Physical Phenomena in the Microcosm

The Corpuscular-wave Dualism

The distinctive property of elementary particles consists in that the same particle has simultaneously both corpuscular and wave properties. The energy of quantum of the electromagnetic radiation is determined by a relation

$$E = h\nu$$

where ν is the radiation frequency, $h = 6.6252 \cdot 10^{-34}$ *joule·s* is the Planck's constant. A certain wave of a length λ, the frequency ν and the wave number $k = 2\pi/\lambda$ can be put in conformity to each particle with a pulse p. The de Broglie relation can be written down in the following kind:

$$\lambda p = h.$$

The evolution of a question on dualism has led to creation of the quantum field theory, which generalizes conclusions about the corpuscular and wave nature of particles.

The Indeterminacy Relation

Under laws of classical mechanics any particle at any moment strictly takes a certain place in space and possesses the certain pulse. Wave properties bring significant restrictions in an opportunity to describe the indeterminacy and parameters of particles. Indeterminacies in coordinate (Δx) and in a pulse (Δp) are related by the *indeterminacy relation (the Heisenberg uncertainty)*

$$\Delta x \Delta p \geq \hbar, \text{ here } \hbar \qquad .$$

This relation shows that in quantum mechanics the habitual idea about a trajectory is lost.

Except for the indeterminacy relation for a coordinate and a pulse, in quantum physics there is the indeterminacy relation for the energy E and time t: $\Delta E \Delta t \geq \hbar$, which is related to the former. The energy of the system, which is in the excited state for the time Δt, cannot have the exact value. The uncertainty of the energy value ΔE refers to as the width of the excited level. The time Δt, for which the system is in the excited state, refers to as the mean time of a life. The less the mean time of a life in the given state, the more the energy uncertainty of this state is.

Discreteness

The basic parameters of elementary particles, such as a mass and a charge, for each sort of particles are constant and well defined. Atoms and nuclei are compound particles. However, as they consist of quite certain elementary particles, their parameters also possess quantum (discrete) properties. Internally the energy state of a nucleus changes only discretely. The state with the least possible energy refers to as basic or normal (basic). Other states with high energies are called excited. *Discreteness* of states of compound particles is one of the major features of the microcosm.

Lecture 3
The Structure of an Atomic Nucleus

Atomic nuclei consist of nucleons - protons and neutrons. ***The proton*** (^1_1p) possesses a charge equal to an electron charge e and a mass $m_p = 1836.1 \cdot m_e$, where m_e is the electron mass. The proton has the spin, which is equal to $s = 1/2$, and the intrinsic magnetic moment, which equals $\mu_p = +2.79\mu_{nuc}$, where μ_{nuc} is a unit of the magnetic moment called the nuclear magneton. The neutron (^1_0n) has the charge, which is equal to zero, and a mass of a neutron $m_n = 1838.6 \cdot m_e$. The mass difference of a neutron mass and a proton mass is $2.5 \cdot m_e$. The neutron possesses spin, which equals $s = 1/2$, and despite lacking an electric charge it has an intrinsic magnetic moment $\mu_n = -1.91\mu_{nuc}$. The minus sign specifies that directions of intrinsic mechanical and magnetic moments are opposite.

The mass number A is determined by the number of nucleons (protons and neutrons) in a nucleus. *The charge of the atomic nucleus* Z is defined by the quantity of protons in a nucleus, which coincides with the number of electrons in nuclear shells and the ordinal number in the Mendeleyev's Table. The relation between the frequency of characteristic X-ray radiation of an atom ν and a charge of a nucleus is determined by the Moseley's law.

$$\sqrt{\nu} = AZ - B,$$

where A and B are constants for the given series of radiation independent on the element.

As the charge of a nucleus Z is numerically equal to the number of protons in a nucleus, and the mass number Z - to total number of nucleons, the number $N = A - Z$ determines the quantity of neutrons in a nucleus. Nuclei with the identical mass number A are called *isobars* and with an identical charge Z - *isotopes*, and with identical number N - *isotones*. The concrete nucleus (atom) with the data A and Z and other characteristics can be called *a nuclide*.

The sizes of atomic nuclei. Owing to quantum properties of atomic nuclei the idea about their sizes has some uncertainty. Heavy nuclei have the greatest definiteness in their sizes. If a nucleus to consider spherical, all experimental methods result in the empirical formula establishing relation between a radius of a nucleus R and the number of nucleons in a nucleus A:

$$R = r_0 \cdot A^{1/3}$$

The constant r_0 determined for heavy nucleus by various methods has a little bit distinguished values. However, all of them are in the limits of $r_0 = (1.2 \div 1.5) \cdot 10^{-13}$ *cm*. Distinctions in the value r_0 are defined by physics of measurement processes.

Lecture 4
Nuclear Moments

The total angular momentum is called a nuclear mechanical moment (the nuclear spin). The total mechanical moment of a compound particle consists of angular momenta of its particles. The latter, in turn, possess the spin and the orbital momentum, which are accounted for revolving the general centre of inertia of a compound particle. Summation of all the moments is carried out by the laws of addition of quantum-mechanical vectors.

The magnetic moment of the nucleus, which consists of A nucleons, is due to spin magnetic moments of nucleons and the magnetic moments caused by the orbital motion of protons. The vector of the magnetic moment does not coincide with a vector of the mechanical moment of the momentum. From the experience it is known that the magnetic moments of a nucleus either are equal to zero, or have values about the nuclear magneton.

Except for the magnetic moments atomic nuclei possess also *the electric moments,* which depend on distribution of a charge in a nucleus. The experience shows that the dipole moment at nuclei is absent. This means that the centre of gravity of protons coincides with the centre of gravity of a nucleus, i.e. neutrons and protons in a nucleus are mixed up enough. Many nuclei have the so-called *quadrupole moment*. It arises owing to breaking of spherical symmetry of charges. The quadrupole electric moment at spherical and symmetric distribution of charges is equal to zero.

The positive sign of the quadrupole moment means that distribution of charges is extended in a direction a spin, i.e. it has the cigar-shaped form. The negative sign of the quadrupole moment means that the nucleus "is flattened" in a direction of a spin, i.e. it has a disc-shaped form. These deviations from spherical distribution of a charge in a nucleus do not exceed 10 % of the size of a nucleus radius.

Heavy nuclei have the most extended form, but all nucleus with $Z = N$ are symmetric.

Lecture 5
Mass and a Binding Energy

Comparison of nuclear mass with the sum of masses of all nucleons contained in these nuclei shows that the mass of a nucleus is always less than the sum of masses of all protons and neutrons. The value

$$\Delta M = \left[Zm_p + (A - Z)m_n - M_{nuc}(A,Z) \right]$$

is called a nucleus mass defect. According to the known Einstein's relation

$$\Delta E = \Delta M \cdot c^2 = \left[Zm_p + (A - Z)m_n - M_{nuc}(A,Z) \right] \cdot c^2$$

refers to *as a binding energy of a nucleus* concerning all of its consisting nucleons. The binding energy is the value of the energy, which needs to be spent in order to fission the given nucleus into all nucleons composing this nucleus. The mass of an atom differs from the mass of a nucleus by Z mass electron (to within the binding energy of electrons).

For comparison of stability of nuclei, we use the concept of a specific binding energy ε describing the average binding energy of one nucleon in a nucleus:

$$\varepsilon = \Delta E / A = \Delta M c^2 / A .$$

The value ε shows what energy on average is necessary to spend for removing one nucleon from a nucleus, not imparting the kinetic energy to it. The size ε has the value for each nucleus. The more ε, the more stable the nucleus is. The nuclei with the mass numbers of 50-60 possess the highest specific binding energy. With decrease or increase of A, the specific binding energy decreases with different intensity.

The major feature of the binding energy appears its proportionality to the number of particles in a nucleus, i.e. approximate constancy of a specific binding energy. Such a character of a behavior of a specific binding energy specifies the property of nuclear forces to reach saturation. The nucleon in a nucleus interacts only with the limited number of the neighboring nucleons. If nuclear forces did not possess the property of saturation, the energy of nucleon interaction and consequently the binding energy of a nucleus would increase proportionally to a square of a mass number. Saturation of nuclear forces interferes with tightening of nuclei till very small sizes at increase of A, and volumes of nuclei appear to be proportional to the number of particles in a nucleus

$$V \; \square \; \frac{4}{3} \quad \square \; \frac{4}{3} \quad \square \qquad .$$

Lecture 6
Stability of Atomic Nuclei

The detailed research showed that stability of nuclei essentially depended on the parameter $(A-Z)/Z$ - relations of neutrons and protons numbers. Nuclei of light nuclides are more stable at $(A-Z)/Z=1$. With growth of the mass number there is more and more noticeable the electrostatic repulsion between protons, and the area of stability is shifted to values $(A-Z)/Z>1$. For the heavier nuclides $(A-Z)/Z \approx 1.5$.

While considering tables of stable nuclides it is necessary to pay attention to their distribution of even and odd values Z and $(A-Z)$. All nucleus with odd Z and $(A-Z)$ are nuclei of light nuclides ${}_1H^2$, ${}_3Li^6$, ${}_5B^{10}$, ${}_7N^{14}$. Among isobars with odd A only one, as a rule, is stable. In a case of the even A, two, three and more stable isobars often meet. Hence, even-even nuclei are the most stable, the least stable are odd-odd. The phenomenon of the increased stability of even-even nuclei testifies that both neutrons and protons show the tendency to be grouped in pairs with anti-parallel spins. It results in infringement of smoothness of dependence of the average binding energy on A.

The given effect refers to as the effect of paired relationship: especially pairs of protons and pairs of neutrons are strongly connected in the nucleus. The difference in ε of a pair and unpaired nucleon is $1 \div 3$ *MeV*, and at some light nuclei this difference is more. Even-even nuclei have the greatest value ε, then even-odd, and odd-odd nuclei have the least value ε. The consequence of the effect of the paired relationship is prevalence of stable nuclides in the nature: even-even nuclei - 168; even-odd and odd-even -108; odd-odd - 4.

Lecture 7
Nuclear Forces

One of the primary goals of nuclear physics from the moment of its appearance is the physical explanation of nuclear forces. As a result of experimental researches the following basic properties of nuclear forces are established.

The Attraction Forces. The forces acting between nucleons are basically characterized by attraction forces. This follows from the fact of the existence of stable nuclei.

The forces possessing the greatest intensity of all kinds of interactions.

Short-range forces. The important property of nuclear forces is their small range, under the order of size equal $(1.2 \div 1.5)\cdot 10^{-13}$ *cm* and their sharp decrease with increase of the distance between nucleons.

Forces not depending on electric charges of interacting particles. This property of nuclear forces has a fundamental character and specifies the deep symmetry existing between two particles: a neutron and a proton. The charge symmetry allows considering a proton and a neutron as two states of the same particle - a nucleon.

Nuclear forces depend on a spin. Dependence of nuclear forces on a spin follows from the following factors. The same nucleus in states with various spins possesses various binding energies

Nuclear forces possess the property of saturation. Nuclear forces possess the property of saturation: one nucleon in a nucleus interacts only with the limited number of other nucleons; other nucleons either are not subject to its influence at all or are repelled by it.

Non- central nuclear forces. In contrast to gravitational and electromagnetic forces, nuclear forces contain non- central components.

Nuclear forces have the exchange character. The exchange property of nuclear forces is shown while colliding the nucleons can transfer each other such characteristics as a charge, spin projections and others.

The meson theory is based on the assumption that nuclear interaction is carried out by means of an exchange of virtual particles with the mass of a rest $\approx 270 m_e$. Particles matched with the meson theory are found out experimentally and called π -mesons.

Lecture 8
Models of Atomic Nuclei

One of the basic and not for a while yet unsolved problems of nuclear physics is the development of the theory of an atomic nucleus. All attempts of developing the theory of a nucleus encounter two serious difficulties:

1) Insufficiency of knowledge of nuclear forces and incompleteness of the theory of nuclear forces;

2) Extreme bulkiness of a quantum problem of many bodies (the nucleus is the quantum- mechanical system consisting of A nucleons).

These difficulties compel to go on a way of development of nuclear models allowing describing with the help of rather simple mathematical means the certain set of properties of a nucleus. For a basis of this or that model one take some singled out properties of a nucleus, which are considered to be main properties in developing the given model. Other properties of a nucleus in this model are neglected. It is natural that the model of a nucleus constructed by such a principle has the limited field of application. However, within the limits of this range each model allows to receive a number of interesting results.

By present time a large enough number of models of a nucleus is developed, but any of them cannot explain all the set of the skilled facts. All existing models can be conventionally divided into two types being as though the approach to the validity from the different sides.

Models of independent nucleons (one-partial models), in which nucleons in zero approximation are considered to be moving independently from each other in some general for all nucleons a potential field of a nucleus.

Models with a strong interaction of nucleons (collective models), in which nucleons are supposed to interact intensively with each other.

The elementary model of the first type is a model of the Fermi-gas, the second - the model of a liquid drop. By combining the one-partial and collective models one obtain *the generalized models of a nucleus,* in which both one-partial, and the collective degrees of freedom essential for the considered group of the phenomena, are simultaneously taken into account.

Lecture 9
Collective Models

The most elementary and historically first of collective models is the drop model of a nucleus. There is some analogy between the behavior of nucleons in a nucleus and the behavior of molecules in a droplet of a liquid. Both in that and in other cases the forces quickly conterminous with increase of the distance act on each particle from the side of the nearest neighbor particles. For separation of each molecule from a drop (for evaporation of this molecule) on average the identical energy is required. As the specific binding energy of nuclei is almost constant, for separation of each nucleon from a nucleus it is also necessary to spend on average the same energy. At last, the volume of a drop as well as the volume of a nucleus is proportional to the number of particles. Due to such similarity it is possible to find a number of common laws for nuclei, not resorting to detailed consideration of interaction of nucleons among themselves.

On the basis of concepts about a nucleus as about a drop of a nuclear liquid have allowed obtaining the expression, which we call semi-empirical formula for Bete-Weitzeker mass atoms

$$M_a(A,Z) = Zm_H + (A-Z)m_n - a_1 A + a_2 A^{2/3} + a_3 \frac{Z^2}{A^{1/3}} + a_4 \frac{\left(\frac{A}{2} - Z\right)^2}{A} + \delta$$

in which masses of hydrogen atom m_H and a neutron m_n are already known and factors a_1, a_2, a_3, a_4 and a_5 (the latter enters into the value δ) are selected so that values of atom masses found by experiments and defined according to the given relation would be close among themselves for the possible greater number of isotopes with various values Z and A (except for the easiest).

Having made a number of simple transformations from a relation for atom masses it is possible to obtain the expression for the binding energy of a nucleus

$$E_{св} = a_1 A - a_2 A^{2/3} - a_3 \frac{Z^2}{A^{1/3}} - a_4 \frac{\left(\frac{A}{2} - Z\right)^2}{A} - \delta .$$

The given relations allow calculating the atom mass and the binding energy of their nucleus at $A \geq 15$ with sufficient accuracy for many purposes. In particular, they find application for definition of stability of isotopes in relation to various types of disintegration and an explanation of fission of nucleus. The drop model of a nucleus is involved also for the description of some types of nuclear reactions.

There are some properties of atomic nucleus, which are impossible to explain on the basis of a drop model. The given properties of nucleus rather originally depend on the number of nucleons in a nucleus. This originality consists in the periodicity of their change.

Lecture 10
One-partial Models

The typical representative of one-partial models is the model of nuclear shells. We shall consider positions, which are put in its basis:

1. It is considered that all nucleons are quasi-independent and move in the average potential field of a nucleus created by other nucleons and their motion can be calculated according to laws of quantum mechanics. The nucleon moving in a potential field of a nucleus can have the final number of states with quite certain energy. Thus, by virtue of Pauli's principle in each state there can be only one nucleon. To various $2l+1$ orientations of a vector of the orbital angular momentum and two possible orientations of the spin, there corresponds the same value of energy. Thus, at each power level there can be $2(2l+1)$ nucleons of the given type.

2. The shells possessing the increased stability are formed by 2, 8, 20, 50, 82 and 126 neutrons or protons. These shells have the same value for nucleus, as the filled shells of an atom. Properties of atomic nuclei should be determined appreciably by surplus or lack of nucleons in comparison with the closed shells.
In a nucleus a strong spin-orbital interaction (interaction between a spin s and the orbital moment l) takes place. In the result the level of the energy of a nucleon for the given value of quantum number l (besides $l=0$) is splitted in two sublevels characterized by values of the total orbital angular momentum j equal $l+\frac{1}{2}$ and $l-\frac{1}{2}$. On each of these sublevels $2j+1$ nucleons (protons or neutrons) can be placed. At gradual filling, levels $l+\frac{1}{2}$ are filled, and then $l-\frac{1}{2}$.

3. Identical nucleons tend to be united in pairs with the zero total moment. Therefore, spins of the basic states at even-even nucleus are equal to 0, and spins with odd A are equal to a spin of the latter, not coupled, or a so-called free nucleon.

Disadvantages of shell models:

-it does not allow receiving correct values of quadrupole moments of a nucleus;

- it does not give a satisfactory explanation to the behavior of high-excited nucleus;

- at consecutive filling levels, divergences between the predicted and experimental values of spins for some nucleus are observed. Attempts of elimination of the given lacks have led to developing the generalized model of atomic nuclei being synthesis of collective and one-partial approaches.

Lecture 11
Radioactivity

Spontaneously occurring nuclear processes refer to as *radioactive* for they proceed under laws of radioactive disintegration. The radioactivity covers the number of radioactive processes, such as α-decay, β-decay (including K-capture), γ-radiation, spontaneously fission of heavy nuclei, and also emission of delayed neutrons and protons.

α - decay: ${}_{Z}X^{A} \rightarrow {}_{Z-2}X^{A-4} + {}_{2}He^{4}$;

β^{-} - decay: ${}_{Z}X^{A} \rightarrow {}_{Z+1}X^{A} + e^{-} + \tilde{\nu}$;

β^{+} - decay: ${}_{Z}X^{A} \rightarrow {}_{Z-1}X^{A} + e^{+} + \nu$;

K - capture: $e^{-} + {}_{Z}X^{A} \rightarrow {}_{Z-1}X^{A} + \nu$.

The probability of radioactive disintegration λ in unit of time is constant. If for the initial moment of time N_0 radioactive nuclei existed, the change of their number would be described by the law of a simple radioactive disintegration

$$N = N_0 e^{-\lambda t}.$$

Characteristics of radioactive nuclei are: a constant of disintegration λ; a half-life period $T_{1/2} = \ln 2/\lambda$; the mean life time of radioactive nuclei $\tau = 1/\lambda$.

In a case if as a result of disintegration of nuclei N_1 with a constant of disintegration λ_1, new radioactive nuclei N_2 with a constant of disintegration λ_2 are formed, the law of change of nuclei quantity $N_2(t)$ looks like

$$N_2 = N_{20} \cdot e^{-\lambda_2 t} + N_{10} \cdot \frac{\lambda_1}{\lambda_2 - \lambda_1} \cdot \left(e^{-\lambda_1 t} - e^{-\lambda_2 t}\right).$$

The rate of radioactive disintegration of nuclei (quantity of disintegrations per unit time) - refers to *as activity* A

$$A(t) = \frac{dN(t)}{dt} = \lambda N(t),$$

The unit of activity measurements is the value 1 *Becquerel* [*Bq*] - corresponding to one disintegration per second [1/*sec*.] The nonstandard unit of activity *Curie*, is often used, 1 *Cu* = $3.7 \cdot 10^{10}$ *Bq*.

Lecture 12
Alpha Decay

An alpha-decay is characteristic for heavy nucleus at which with growth A the decrease of specific binding energy is observed. The alpha- decay is possible when the necessary energy *condition* satisfies:

$$E_\alpha = \left[M(A,Z) - M(A-4,Z-2) - M_\alpha\right]\cdot c^2 > 0.$$

However, the Coulomb potential barrier prevents the emission from a nucleus, the probability of passing it by an α - particle is negligible and it very quickly falls at decreasing the energy of a particle. In a theory the mechanism of alpha-decay is accounted for an opportunity of a quantum-mechanical *tunnel* effect. Regular dependence of a constant of disintegration on the energy E_α emitted by an alpha particles, which is explained by the Geiger-Nettol relation.

$$\lg\lambda = a + b\lg E_\alpha,$$

where a and b are constants. Strong dependence λ on E_α is defined by the tunnel mechanism of overcoming a Coulomb potential barrier by an α-particle.

The number of nucleons as a result of alpha decay changes by four units, therefore, the existence of four independent chains of disintegration - *radioactive families* is possible. Three of them are natural and are formed by long-living α-active nuclides: ^{232}Th, ^{235}U and ^{238}U. The fourth family is artificial and is formed by the nuclide ^{237}Np.

As a result of alpha decay the new nucleus and one particle are formed, the energy of each α-particle is always identical. Spectra of α-radiation are linear. Except for the basic group of particles, there can be submitted groups of α-particles with lower energies (short-range particles), each of which belongs to a strictly certain value of energy. The given fact is explained by an opportunity of formation owing to disintegration of nucleus in the excited state and discrete behavior of their power structure. In a case if α decay occurs from the excited state of a nucleus, in an alpha-spectrum the occurrence of α-particles with the energy exceeding the energy of α-decay (long-range particles) is observed.

Lecture 13
Beta-decay

The deviation of the proton-neutron structure of a nucleus from optimum results in an opportunity of processing a spontaneous change of a nucleus structure for the most energy-wise efficient. The mechanism of change of the proton-neutron structure is the interconversion of nucleons - β-decay. At surplus of neutrons the transformation inside a nucleus ${}_0^1 n$ is realized in ${}_1^1 p$

β^-- decay: $(A,Z) \rightarrow (A,Z+1) + e^- + \tilde{\nu}$.

In case of surplus of protons two processes are possible

β^+- decay: $(A,Z) \rightarrow (A,Z-1) + e^+ + \nu$,

K- capture: $e^- + (A,Z) \rightarrow (A,Z-1) + \nu$.

The power condition of the possibility of processes β^-- decay and K-capture is the following:

$$E_\beta = \left[M_a(A,Z) - M_a(A,Z \pm 1)\right] \cdot c^2 > 0,$$

At β^+- decay

$$E_\beta = \left[M_a(A,Z) - M_a(A,Z-1) - 2m_e\right] \cdot c^2 > 0.$$

The power spectrum of particles emitted as a result of β-decay is continuous. The average energy of a spectrum is $(1/3)E_\beta$. The most part of the energy is carried away by a neutrino. *The neutrino is* the elementary particle with a very small mass, it has no electric charge and participates only in the weak interaction.

As a result of radioactive transformations, nuclei - products are basically formed in the excited state. The basic process of discharging a nucleus from a superfluous energy (if this energy does not surpass the binding energy of a nucleon in a nucleus) is *radiation* of γ-quantum. In a case if the exciting energy of a nucleus surpasses the binding energy of nucleons, the basic process of release of superfluous energy is the emission of nucleons. Thus, the neutron emission is more probably because of the absence of the Coulomb energy barrier. For example, the given mechanism is realized at formation of the neutron- overloaded fragments in the reaction of fission. Neutrons emitted by fission products refer to *as delayed*.

Lecture 14
Gamma- radiation

γ-quantum radiation is the basic process of releasing a nucleus from a superfluous energy if this energy does not surpass the binding energy of a nucleon in a nucleus. The formation of γ-quanta occurs only by acting the electromagnetic forces and is accompanied by redistribution in a nucleus either an electric charge, or the magnetic moments. In this case the nuclear spin or its constituents necessarily change or reorient, as the quantum carries away the mechanical moment l at least equal to unit. Radiation with $l = 1$ is called dipole, and a life time of a nucleus relative the dipole transition is □ *sec*. A life time of a nucleus in the excited state quickly increases with growth of the mechanical moment l carried away by the γ-quantum. Besides, a life time of a nucleus depends on the transition of the energy and grows with decrease of a difference between energies of initial and final states. If between the basic and excited states with the great spin difference there are no intermediate levels (the absolute energy value of the excited level is low), the given level appears to be long-living, *metastable*. The time of transition between such levels can be equal to seconds, hours and even years. Identical nuclei, one of which is in the metastable excited state, are called isomers.

Emission of γ-quanta is not the only process resulting in releasing an atomic nucleus from the energy surplus.

Electrons of internal conversion. The Coulomb field of a nucleus transfers all the excitation energy directly to the atomic electron. Here radiation of γ-quanta does not occur, and the electron of internal conversion is emitted from the atom.

X-ray radiation and Auge-electrons. When emissing conversion electrons the atom loses the electron in an inner shell. As a result of transition from the outer shell to the vacant inner shell, the atom emits *characteristic X-ray radiation*. Such a transition can be accompanied by emission of one more electron *(the Auge-electron)* instead of X-ray quantum.

Pair formation conversion. If the excitation energy of a nucleus surpasses the value $E^* > 2m_e c^2 = 1.02$ *MeV* in the Coulomb field of a nucleus, the electron-positron pair can be formed. The given process is the additional way of transfer of the excitation energy of a nucleus in the external space and occurs without emission of γ-quanta. The probability of the given process is 10^{-4} of decay with radiation of γ-quanta.

Lecture 15
Interaction of Ionizing Radiation with the Substance

The ionizing radiation is the radiation consisting of charged or neutral particles, which interaction with atoms of the medium results in formation of ions of different signs. Particle fluxes emitted at radioactive disintegration is called *radioactive emission.* The space is penetrated with fluxes of various particles, which energies reach very high values (up to 10^{20} *eV*). This is the *space radiation*. Accelerators and nuclear reactors are also the sources of various particles, including neutrons. Fluxes of all listed particles arising at natural processes and obtained artificially are united by the common name *of nuclear radiation*. The nuclear radiation is one of versions of the ionizing *radiations* to which *ultra-violet radiation*, *Roentgen beams* and some other kinds of radiation also concern.

Passing through the substance all kinds of a nuclear radiation, anyhow, interact with it. The character of interaction depends on the type of radiation and its energy. The common for all kinds of interaction of a nuclear radiation with the substance is that the energy of incident particles is transferred to the substance atoms. This energy is spent for excitation and ionization of the medium atoms. In the process of penetration into a depth of a substance, the energy and radiation intensity decrease.

Depending on a grade of particles interacting with a substance two limiting kinds are considered.

Many weakly deflecting interactions: Each interaction results in the energy loss and a small deviation of a trajectory of a particle. Losses and deviations are developed as random variables. After passage of a beam of particles through a layer of the absorbing substance, its energy decreases, it stops to be monoenergetic and becomes divergent. At the greater thickness of an absorbing layer separate particles of a beam are stuck in the thickness R_0 called *the mean length of a run*.

Interactions such as « all or nothing ». The particle either passes through a layer of a substance without interaction with it, or is absorbed in a substance of a layer, having experienced the "catastrophic" collision. If passed particles have not experienced any interaction with the substance, the passed beam has the same energy and the same angular divergence, as well as the incident one. The number of the particles passed through the given layer of a substance decreases exponentially with increasing a thickness of a layer

$$N(x) = N(0)e^{-\mu x},$$

here μ is the *factor of absorption.* The average distance, passable by a particle in a substance before interaction with it, is called *the mean length of a free run* and is equal to $1/\mu$.

Lecture 16
Interaction of the heavy charged particles with a substance

The mechanism of interaction of the heavy charged particles with a substance can be presented as follows. The particle, penetrating through a substance, "pushes aside forcibly" atomic nuclei by its Coulomb field. Due to it the particle gradually loses energy, and atoms either are ionized, or raised. Having lost the energy, the particle stops. Because of a long-range character of Coulomb forces, the penetrating particle has the time "to push aside forcibly" a plenty of electrons. The incident particle itself while colliding with a separate electron a little deviates from the path because of its big mass. Besides, these negligible deviations almost entirely compensate each other at the huge number of statistically focused collisions. Therefore, the trajectory of the heavy charged particle in a substance is practically rectilinear.

Thus, the heavy charged particles lose their energy basically in the result of Coulomb interactions at collisions with the fixed atomic electrons. Here electrons can jump on higher discrete levels (at excitation), and can detach from the atom (at ionization). If the particle penetrating through the substance possesses energy more than the binding energy of the electron in the atom, there prevail processes of ionization. The rate, with which the energy of a heavy particle is lost at collisions with electrons of a substance, has been calculated in the classical theory by Bohr and in the quantum theory – by Bete and Bloche. The final formula for definition *ionization losses* of the energy of the heavy charged particle is called «The Bete-Bloche Formula»:

$$-\frac{dE}{dx}=\frac{4\pi n Z^2 e^4}{m_e \upsilon^2}\left\{\ln\frac{2m_e\upsilon^2}{\bar{I}\left[1-(\upsilon/c)^2\right]}-\left(\frac{\upsilon}{c}\right)^2\right\}$$

where, dE is the energy lost by a particle at length dx; n is the number of electrons per 1 cm^3 of a braking substance; m_e is the electron mass; Ze and υ are accordingly a charge and velocity of the heavy charged particle; $\bar{I}$ is the average potential of ionization and excitation of decelerating substance atoms.

Expression for the length of a particle path in the given substance can be received, having integrated a the Bete-Bloche relation

$$R=\int_{E_0}^{0}\frac{dE}{(dE/dx)}.$$

Lecture 17
Interaction of the Light Charged Particles with the Substance

Interaction of electrons and positrons with the substance qualitatively differs from passage of other charged particles. The main reason of it is a small mass of an electron and a positron. Because of a low mass for the incident electron (positron), the change of a pulse is rather great at each collision. And this, in turn, results to that the electron, first, can significantly deviate from the initial direction of motion, and, second, at collisions it can generate quanta of electromagnetic radiation. The former of just mentioned effects is shown in that the electron travels in the substance not on a straight line; owing to the second effect there are essential *radiation losses* for electrons, i.e. losses of the energy by the electromagnetic radiation.

Ionization losses. Taking into account the low electron mass and action of relativistic and quantum-mechanical effects, for ionization losses of electrons the expression turns out to be

$$-\frac{dE}{dx}=\frac{2\pi e^4 n}{m_e \upsilon^2}\left\{\ln\frac{m_e \upsilon^2 E}{2\bar{I}^2(1-\beta^2)}-(2\sqrt{1-\beta^2}-1+\beta^2)\ln 2+1-\beta^2+\frac{1}{8}(1-\sqrt{1-\beta^2})^2\right\},$$

where under E we mean the relativistic kinetic energy of the electron, and $\beta=\upsilon/c$.

Radiation losses. Radiation losses of the electron energy are defined by the expression

$$-\left(\frac{dE}{dx}\right)_{rad}\approx\frac{E}{x_0},$$

where the constant x_0 refers to *as radiation length*.

Total losses of the electron energy in an absorber are developed from ionization and radiation losses:

$$-\left(\frac{dE}{dx}\right)_{sum}=-\left(\frac{dE}{dx}\right)_{ion}+\left[-\left(\frac{dE}{dx}\right)_{rad}\right].$$

The path of electrons in a substance. The concept of a path for electron of the given energy in the given substance is not simple. For electrons there are two values corresponding to the path: the maximum path and the extrapolated path. The minimum thickness of a layer of substance, in which all the electrons are delayed refers to *as the maximum path*. The maximum path coincides with complete, usually curvilinear path, which the electron passes in a substance. It is difficult to calculate *the extrapolated path* R_{extr} theoretically. Therefore, for estimations one usually use tables and semi-empirical formulas.

Lecture 18
Interaction of Gamma - quanta with a Substance

The electromagnetic waves, which length is much less than the interatomic distances $\lambda << a$ where $a \approx 10^{-8}$ *cm*, refer to γ-radiation. In a corpuscular picture this radiation represents a flux of particles called γ-quanta. The bottom limit of energy of γ-quanta is of the order of tens *keV.* Similarly to the charged particles, the beam of γ-quanta is absorbed by a substance basically owing to electromagnetic interactions. However, the mechanism of this absorption is essentially other. They either do not interact with particles of a substance (do not change the velocity and directions) or, if the interaction has taken place, are absorbed.

Absorption of γ-radiation by a substance basically occurs due to three processes:

The photoeffect is the process, at which an atom absorbs γ-quantum and emits an electron. With sufficient accuracy for practical appendices it is possible to consider that each quantum is absorbed by one atomic electron.

The Compton effect is the effect when the absorption of γ-quantum is accompanied by immediate emission of a new γ-quantum.

The process of pair formation is the process when transformation of γ-quantum energy to the energy of the rest $2m_ec^2$ and a kinetic energy of the electron-positron pair occurs in a Coulomb field of a nucleus. As the mass of the rest of γ-quantum is equal to zero, it can turn into a pair only if it has the energy more than the sum of energies of electron and positron rest $h\nu > 2m_ec^2 = 1.02$ *MeV.*

The absorption factor μ of γ-radiation in a substance is the sum of absorption factors owing to all possible mechanisms.

$$\mu = \mu_f + \mu_c + \mu_\pi$$

There are no concepts of the path, the maximum path, energy losses per unit of length for γ-quanta. At passage of a beam of γ- quanta through a substance the number of quanta in a beam in the result of "catastrophic" collisions gradually decreases. *The attenuation law of intensity of the γ- radiation beam* in a substance looks like

$$I = I_0 e^{-\mu x},$$

where I_0 is the initial intensity; μ is the *factor of absorption.*

Lecture 19
Additional Mechanisms of Interaction between Nuclear Particles and a Substance

In considering questions on interaction of ionization radiation, the additional mechanisms of absorption are of great importance and different secondary processes turn to be essential.

Coulomb nuclear collisions. The charged particles passing through the substance experience Coulomb collisions not only with electrons, but also with nuclei. Because of the big mass of a nucleus, the Coulomb scattering takes place at large corners (even back) within the nucleus.

Strong nuclear interaction. Protons, pions and the majority of other charged particles, except for electrons and muons, are capable to start a strong interaction with nuclei. Because of a short – range, nuclear forces of collision with their participation occur approximately 10^{12} times less than Coulomb collisions with electrons. On the other hand, if at a single Coulomb collision with an electron the particle only loses very low energy, at a nuclear collision the particle almost always leaves a beam (either scatters at the large angle, or it is absorbed, or turns into other particle).

Annihilation losses. On passing positrons through a substance losses are realized owing to two-photon annihilation of positrons with electron substances $e^{+}+e^{-}\rightarrow\gamma+\gamma$.

The Cherenkov radiation. The particle of high energy can travel faster than the light in the given medium. Such a particle if it is charged, will radiate even at non-accelerated motion. This radiation is called the Cherenkov radiation.

The nuclear photoeffect. Gamma - quanta with the energy $>10\ MeV$ can start the inelastic interaction with nucleus, knocking out protons, neutrons and other particles. This process (a nuclear photoeffect) makes a negligible contribution to the total factor of absorption, but it is characterized by occurrence of secondary nucleons.

Secondary effects are:

Secondary fluxes of γ *-quanta*;

Electron-positron showerrs;

Decelerationof the secondary charged particles;

Radioactivation of nuclis.

Lecture 20
Nuclear Reactions

The typical example of a nuclear reaction is the process of interaction of fast α-particles with nitrogen nuclei, at which the escape of protons is observed,

$$^4_2\alpha + ^{14}_7N \rightarrow ^{18}_9F^{**} \rightarrow ^1_1p + ^{17}_8O.$$

A nucleus $^{18}_9F$ produced during the given nuclear reaction for a short time is called *an intermediate nucleus,* or *a compound nucleus*. The circuit of a nuclear reaction in a general view can be written down so:

$$a + A \rightarrow C \rightarrow B + b,$$

where a and b are initial and emerging particles; A and B are initial and final nuclei; C is a compound nucleus. For brevity the compound nucleus is not very often indicated:

$$a + A \rightarrow B + b.$$

Besides, nuclear reactions, at which the compound nucleus is not formed, are known. For example, the fast proton can knock out one of nucleons from a surface of a nucleus and to emerge together with it having left a nucleus almost in an unexcited state. Such processes are called direct nuclear reactions.

Nuclear reactions can *be classified* as the particles causing a reaction, or as the particles formed during a reaction.

When considering nuclear reactions, as well as other processes discussed in nuclear physics, the following exact laws of conservation are used:

1) *The law of conservation of energy;*
2) *The law of conservation of a pulse;*
3) *The law of conservation of momentum*
4) *The law of conservation of an electric charge;*
5) *The law of conservation of a baryon charge;*
6) *The law of conservation of lepton charges.*

Laws of conservation allow predicting what of mentally possible reactions can really be carried out, and what are impossible or as speak, "are forbidden" by virtue of default of one or several laws of conservation. In this respect with reference to nuclear reactions the laws of conservation play the especially important role.

Lecture 21
The Basic Characteristics of Nuclear Reactions

The quantitative description of nuclear reactions from the quantum-mechanical point of view can be only statistical, i.e. such, in which it is essentially possible to speak only about probabilities of the various processes describing the nuclear reaction. Thus, the probability of realization of a nuclear reaction without detailed elaboration of its results is characterized by the general *effective section* σ. Dependence of a differential effective section on azimuth and polar angles of scattering refers to as angular distribution of particles in the reaction. Dependence of differential effective section on the kinetic energy of products of the reaction (basically of a light particle) refers to as energy distribution (or a spectrum).

The portion of particles of a beam, which has experienced the nuclear interaction with particles of a target refers to *as an output of a nuclear* reaction Y. $Y = \Delta N / N = \sigma n$, where n is the concentration of nuclei in a target.

The basic mechanisms of nuclear reactions:

1. *The mechanism of a compound Bohr nucleus.* It is based on the assumption that reaction proceeds in two stages with formation of the intermediate excited nucleus $a + A \to C^* \to b + B$.

2. The mechanism of a compound nucleus assumes that the time of reaction processing is much more than the characteristic nuclear time (time of transit of a particle through a nucleus □ 0^{-23} *sec*).

3. *The mechanism of a direct nuclear interaction.* There are processes, in which interaction of a fast nucleon with a nucleus occurs as a collision of the incident particle only with one or two nucleons of a nucleus-target or as an exchange of any particle. In these cases the formation of a compound nucleus does not occur.

4. *The mechanism of the Coulomb excitation.* In some processes the transiting charged particle interacts with a nucleus only by its electric field. It is enough to excite a nucleus and to cause a reaction.

5. *The mechanism of a single or plural birth of particles.* At ultra-high energies of bombarding particles ($>10^9$ *eV*) the plural birth of mesons and sometimes and baryon – anti-baryon pairs are observed. This phenomenon plays an important role at interaction of space beams with a substance.

Lecture 22
Nuclear Reactions at Different Energies of Interacting Particles

The range of low energies. At low energies only the probability of a reaction for the particles experiencing a head-on collision with a nucleus is different from zero. In this range of energies the nuclear reactions under action of neutrons are play the main role , as for the slow charged particles the probability of penetration through the Coulomb barrier (especially for heavy nuclei) is extremely small. The section of formation of a compound nucleus in this range is determined by a length of a wave of incident neutrons $\sigma_a = \pi\bar{\lambda}^2$ and can reach great values. The section behavior of formation by a neutron of a compound nucleus in a vicinity of one of levels of this nucleus is described by the Breit-Wigner formula

$$\sigma_n = \pi\bar{\lambda} \frac{\Gamma_1 \cdot \Gamma}{(E - E_{res})^2 + \frac{\Gamma^2}{4}},$$

The range of high energies. High energies are called such energies, at which the length of a wave of an incident particle $\bar{\lambda}$ is far less than the values of the nucleus characterized by a radius R ($\bar{\lambda}$. Particles with energies about several *MeV* and higher satisfy to this condition. It is possible to consider that at such energies the probability of penetration through potential barriers is already close to unit. If the nucleus absorbed all particles, which have got on it, i.e. behaved as the absolutely black body, the section of absorption would be calculated as $\sigma_a = \pi R^2$, i.e. it would be equal to geometrical section of a nucleus. The section of absorption σ_a is always much less than geometrical values of a nucleus and approaches to it in the range of ultra-high energies.

Energetic and angular distributions of products of a nuclear reaction. At low energies of excitation the course of nuclear reactions depends on properties of separate levels. In the energy distribution of emerging particles there is a number of the maxima corresponding to levels of a final nucleus. The angular distribution of emerging particles dependent on the angular momentum carried away by a particle is typical for each transition. For example, when particles carry away the orbital momentum $l = 0$, they emerge isotropically.

At high energies levels of nuclei are overlapped. The energy distribution of particles emerging from a heavy-excited compound nucleus is externally similar to the energy distribution of molecules evaporating from a surface of a liquid:

$$N(E) \approx E\sigma(E)e^{-E/T},$$

where the temperature $T \sim \sqrt{E_{ex}}$ is expressed by energy units, E - energy of a the emerging particle. In the field of overlapped levels the angular distribution of emerging particles approaches to isotropic as properties of separate levels are averaged.

Lecture 23
Features of Course of Nuclear Reactions under the Action of Various Particles

Reactions under the action of α-particles. In a large number of cases of a reaction under the action *of α-particles* are reduced to formation of a compound nucleus, which then decays. By this they are similar to the reactions going under the action of neutrons and protons. The existing distinction in charges affects only the permeability of the Coulomb potential barrier. The section of the nuclear reactions caused by the capture *of α-particles* in the range of low energies is insignificantly and quickly grows with increase in energy. Under the action *of α-particles* there are mainly reactions of type (α, n) and (α, p).

Reactions under the action of protons. Under the action of protons there are reactions (p, α), (p, n), (p, p), (p, α) and with the less probability (p, d).

Nuclear reactions under the action of deutons. Nuclear reactions under the action of deutons are very important. The output of these reactions is usually greater than outputs of corresponding reactions under the action of other charged particles. Besides, the consequence of a low value of the binding energy of deuton is the high excitation energy of an intermediate nucleus, and, as a rule, reactions with absorption of deutons are exoenergetic ($Q > 0$).

Photonuclear reactions (reactions under the action of gamma-rays). Under the action of gamma-rays reactions of type (γ, n), (γ, p) and (γ, α) are possible. All of them are similar to the process of photo-electric absorption of gamma-rays considered earlier by atom and consequently refer to as a nuclear photoeffect. In order that one of such reactions could go, it is necessary that the energy of gamma-quantum were more than the binding energy of a corresponding particle in a nucleus.

Reactions under the action of neutrons. Neutrons have no electric charge and do not participate in the Coulomb interaction. All processes caused by neutrons are determined only by nuclear forces. Under the action of neutrons processes are possible: (n,n) is the elastic scattering; (n,n') is inelastic scattering; (n,γ) is the radiation capture; and fission (n,f). Besides, at these energies neutrons $\approx 0.5 \div 10$ MeV reactions (n,p) and (n,α) are observed.

Lecture 24
Fission of Heavy Nuclei

From dependence of a specific binding energy ε on a mass number A follows that two types of nuclear processes resulting in the energy release are possible.

a) Fission reaction, i.e. fission into parts of nuclei of heavy elements (for example uranium and plutonium);

б) *Fusion reaction* i.e. the process of producing heavier nuclei from two lighter ones.

Basic features of the fission reaction:

1.) The fission reaction, in which heavy nuclei are disintegrated into two fragments, is energetically favorable. Therefore, the fission can be realized as the forced nuclear process (at capture of some particle by a heavy nucleus), and as a spontaneous nuclear transformation;

2) The energy released at fission is about 200 MeV that essentially exceeds the release of the energy in the majority of nuclear processes. The energy $Q \approx 200\ MeV$ liberated at fission is released in three forms: the kinetic energy of fragments Q_f, the energy of radioactive transformations of fragments Q_β overloaded with neutrons and the energy of the fission neutrons (emitted directly at fission) and secondary (delayed) neutrons (emitted fragments at β transformations) Q_n.

3) Fission of nuclei can occur in the most various channels in relation to formation of fission products (For example, for nucleus U^{235} under the action of thermal neutrons it is observed about 30 different ways of fission producing about 60 different fragments). The relative probability of producing various fragments has strongly pronounced asymmetry, i.e. the formation of two fragments , heavy and light, with mass numbers about 140 and 95 accordingly is mainly observed;

4) At fission of nuclei simultaneously with production of fragments several fast neutrons are also emitted. These neutrons are capable to cause new processes of fission and by that their formation will determine an opportunity of realization of the chain fission reaction.

Lecture 25
Thermonuclear Reactions

The fusion reaction is the process of formation of heavier nuclei from two lighter ones. The most known fusion reactions are

$$H_1^2 + H_1^2 \rightarrow He_2^3 + {}_0^1 n + Q = 3.25\ MeV$$

$$H_1^2 + H_1^2 \rightarrow H_1^3 + {}_1^1 p + Q = 4.03\ MeV$$

$$H_1^2 + H_1^3 \rightarrow He_2^4 + {}_0^1 n + Q = 17.6\ MeV$$

which differ by high values of the reaction energy Q very much. The thermonuclear energy release per one nucleon essentially surpasses the energy release per one nucleon during fission processes of heavy nuclei.

The necessary condition of realization of fusion reactions is the very high temperature of a substance as in these processes the Coulomb barrier (about 0.1 *MeV*) interfering the fusion of two nuclei plays an essential role. To obtain the average energy about 0.1 *MeV,* heating a substance to a temperature of $10^9\ {}^oK$, i.e. to *a plasma state, is required*. To reduce the necessary for realization of thermonuclear fusion temperature, it is possible when increasing the density of a substance.

A thermonuclear fusion is the energy source of stars. For example, on the Sun where the temperature is about □ ${}^oK$, and the density of a substance is 100 g/cm^3, two thermonuclear cycles, proton - proton and carbon –nitric, are realized.

In terrestrial conditions, a self-sustaining chain reaction of fusion is carried out in a so-called hydrogen bomb. It is much more difficult to obtain the controlled chain process of fusion. The basic difficulties are connected with necessity of obtaining the high temperature and confinement of plasma for a long time in the set volume. Kinetics of thermonuclear reactions is that the most part of the released energy is carried away by neutrons. This energy can be practically used only with the help of nuclear reactions, for example

$$Li_3^6 + {}_0^1 n \rightarrow H_1^3 + He_2^4$$

Here the energy of neutrons will be transformed to the kinetic energy of the charged particles, which then can be transformed to the heat energy.

Now two directions of realization of controlled fusion reaction are intensively developed: the magnetic confinement of plasma both its heating up (TOKAMAK) and inertial thermonuclear fusion by using lasers and beams of particles.

Lecture 26
Elementary Particles

Elementary particles are now conditionally called the large group of the minute micro particles which are not being atoms or atomic nuclei (except for protons - hydrogen atom nuclei). The common that relates all elementary particles is specific forms of the matter, which have not been associated in atoms and atomic nuclei.

Nowadays the following particles (and their antiparticles): 1) *leptons* (e, μ, τ and corresponding to them neutrinos); 2) quarks; 3) photons and intermediate bosons $W^{\pm}, Z^0$ are referred as to "truly" elementary particles. The most typical property of elementary particles related with the up-to-day conceptions of corpuscular - wave dualism is their *ability to be born and to be interconvertible* at collisions. The second characteristic feature of elementary particles is the overwhelming part of them *is unstable.* Particles spontaneously decay. The mean time of life of a tau-particle in a free state varies over a wide range: from 10^{-24} up to indefinitely (for a proton, for example, it is experimentally found that $\tau > 10^{32}$ years).

All particles (including non-elementary particles and quasi-particles) are divided into bosons and fermions. Bosons (or *Bose-particles*) *are called* such particles or quasi-particles possessing zero or the integer spin. Bosons subject to Bose-Einstein's statistics (from here and there is their name). *Hypothetical graviton, a photon, intermediate vector bosons, gluons, mesons* and *meson resonances,* and also *antiparticles* of all listed particles refer to as bosons. Particles or quasi-particles with a half-integer spin refer to as *fermions.* For them the Pauli's principle is fair, and they subject to Fermi–Dirac statistics. *Leptons,* all *baryons* and *baryon resonances, quarks*, and also corresponding *antiparticle refer to as fermions.* As to the life time *t,* one distinguishes *stable, quasi-stable* and *resonant particles.*

In a microcosm to each *particle* there corresponds *an antiparticle.* In some cases the particle coincides with the antiparticle, i.e. all properties of a particle and an antiparticle are identical. Such elementary particles are called *truly neutral particles.* The *photon* γ, π^0-meson, η^0 *-meson*, I/ψ-meson, *epsilon-particle* ϒ refer to as *truly neutral particles..* If the particle and an antiparticle do not coincide, masses, spins, isotopic spins, the life time of a particle and antiparticles are identical, and other characteristics (an electric charge, the magnetic moment, lepton and baryon charges, a strangeness, a charm) are identical by the absolute value, but opposite by a sign.

Lecture 27
Particle Sources of Ionizing Radiation

Radioisotope sources. Sources of an alpha-radiation. Nowadays about thirty alpha-active nuclei in chains of consecutive disintegrations of nuclei belonging to uranium, actinium and thorium family are known. Except for the natural alpha-active nuclei the overwhelming majority is the artificially obtained nuclides elements followed by lead and the group of lighter nuclei, which emit the alpha-particle, decay. In general more than hundred alpha-active nuclei are obtained artificially. One of the most remarkable properties of an alpha-radioactivity is the huge range of possible values of half-life periods at negligible change of the energy of alpha-particles.

Beta-radiation sources. In total it is known three types of beta-decay of stable nuclei: an electron radiation, a positron radiation and a capture of a nuclear electron. In most cases the final nucleus at beta-decay remains in the excited state that results, first, in complication of a spectrum of beta-particles and, second, to occurrence of gamma-quanta emitted by a final nucleus. To construct the beta-sources, which do not radiate gamma-quanta at all, is not possible by two reasons: 1) presence of bremsstruhlung 2) characteristic X-ray radiation of an atom of a decay product. In emitting positrons by the source and annihilating them in a material of a source or a substrate, gamma-quanta of the energy $\geq$ 0.511 appear.

Gamma-radiation sources. Gamma - radiation arises at transitions between different energy levels of excited nuclei. Except for the gamma-radiation formed while changing the inner state of a nucleus, the short-wave electromagnetic radiation arises at deceleration of fast electrons in a substance. There is one more important mechanism of occurrence of gamma-quanta – annihilation of electro-positron pairs, which is used for construction of sources of almost monochromatic gamma-quanta of the energy of tens *MeV*. Gamma - quanta of the energy of hundreds *MeV* arise at disintegration of π^0-mesons. Monochromatic gamma-quanta can be obtained also by using the reverse Compton Effect.

The neutron sources. The neutron-radioactive nucleus does not exist; therefore, all sources of neutrons are artificial. Sources of neutrons are (α, n), (γ, n), (p, n) and (d, n) reactions in which *sources α -, γ-, p-*and *d-radiations* can be various (particle accelerators, radioisotope sources and so on). Besides, as a neutron source is the nuclei fission: spontaneous fission of super-heavy nucleus (^{252}Cf); in nuclear reactors; as a result of nuclear explosion.

Lecture 28
Charged Particle Accelerators

Generation of beams of the charged particles is made in special plants, which have received the name of accelerators. Besides physical applications, accelerators start more and more to be used beyond physics (chemistry, biophysics, geophysics) and for the applied purposes (sterilization of products, flaw inspection, beam therapy, etc.). Accelerators allow to obtain beams of the charged particles of energies from several *MeV* up to several hundreds *GeV*, and the top limit is defined not by the basic difficulties, but a level of development of acceleration technique. This limit constantly increases approximately by the order for a decade. Intensity of beams achieves 10^{16} particles per second, and these beams can be focused on a target of some square millimeters.

To obtain beams of the accelerated charged particles, two groups of methods based on different principles are applied. In one of them to accelerate particles, the great constant potential difference is used. In other group of methods acceleration of particles is carried out by means of an electric field of high frequency. One makes a beam of particles to pass many times in vacuum through the accelerating field and to accumulate the energy of separate small portions. The idea *of the linear accelerator* consists in that the accelerated particles did not require a source of a high voltage, which opportunities are limited (charge leakage, breakdown), and would repeatedly be accelerated from a source of alternating and a rather low voltage. *A cyclotron and a betatron* are realization of a principle of cyclic acceleration in view of features of the charged particles motion in variable electric and magnetic fields.

The necessity of obtaining ultrahigh energies of accelerated particles has led to development of various modifications of cyclotrons (*a microtrone, a phasotron*) and betatrons *(synchrotron)*, and hybrid plants – *synchrophasotrons*, as well

The up-to-date huge accelerators of ultrahigh energy consist of several bodies: the preinjector (a preaccelerator), the linear accelerator, the basic electromagnetic ring and experimental cases.

Nowadays the most serious attention is given to creation of accelerators of other type, which operation is based on the use instead of a motionless target of a beam of the accelerated particles moving towards to the basic beam (counter beams). Such accelerators for electron-electron, electron-positron, proton - proton, proton - anti-proton beams have been already constructed and operate.

Lecture 29
Bases of Detecting the Elementary Particles (Part 1)

Devices for registration of particles refer to *as detectors of particles*. The effect of influence of a separate particle on a substance from the microscopic point of view is very small. The most appreciable such effect is ionization of a substance by the charged particle. Therefore, the operation of the overwhelming majority of existing types of detectors of the charged particles is based on a principle of use ionization ability of particles. In some types of detectors the electromagnetic radiation of the charged particles in the medium is used. Action of neutral particles on a substance is too insignificant that they could be registered directly. Therefore, neutral particles are registered on secondary processes: researched neutral particles generate charged ones, which are registered by their ionization action.

The existing detectors can be subdivided into *counters* and *track detectors*. With the help of counters, the passage of a particle through the certain site of space for a certain moment of time with macroscopic accuracy is registered. Besides in various types of counters one can define some characteristics of a particle, such as energy, a charge, a speed, and a mass. In track detectors the charged particle leaves a trace named a track. Tracks are fixed by that or a different way. Therefore, in track detectors it is possible to obtain the incomparably large, than in counters, information about a direction of a particle motion, processes of its collisions with other particles, about its disintegration and a lot of other characteristics of a particle. Neutral particles of tracks are not formed. Nevertheless, with the help of track detectors one obtain the richest information about neutral particles, as well.

The ionization chamber is a thin-walled closed volume filled with gas. There are two electrodes of 100-1000 V- voltage in this volume. The charged particle, getting in the chamber, ionizes the gas filling it. Formed by a particle positive and negative ions direct to electrodes, creating an electric current by which a registration is made. There are two types of ionization chambers: continuous action and pulse.

Discharge counters are similar to ionization chambers, that is, in all these detectors the working substance is the gas, to which the electric voltage is applied, but the pulse of a voltage, arising as a result of the discharge in the gas at passage of a particle, is registered. The main difference of gas-discharge counters from ionization chambers is that in the former the secondary ionization plays an essential role caused by collisions of primary ions with atoms and molecules of a gas and walls. Discharge counters are divided into proportional and Gejger-Muller counters.

Lecture 29
Bases of Detecting the Elementary Particles (Part 2)

The operation principle of *the scintillation counter* is based on that in a number of substances (for example, a crystal of iodide sodium NaI) the passing nuclear particles cause the flashes of the visible light called *scintillations*. Photons of flash, getting on the photocathode, knock out photoelectrons from it. The electron flux amplifies by the photoelectron multiplier, the electric pulse registered by radio engineering methods is formed. Advantages of *scintillation* counters are the following. First, high efficiency of registration (100 % for charged particles). In the second, a negligible resolution time, which limit is defined by duration of a luminescent flash. The third advantage is the opportunity of measurement of the energy both charged particles and gamma-quanta.

Original by an operating principle is *Cherenkov's counter* based on registration of Cherenkov's radiation. The distinctive feature of Cherenkov's radiation is its sharp orientation. Practically all radiation emits in a thin surface of a cone at an angle concerning the particle motion. If one knows an angle, it is possible to define a velocity of a particle. At the known mass the measurement of a velocity is equivalent to the measurement of the particle energy. If a mass of a particle is not known, it can be determined by measuring independently the energy of a particle. The main purpose of Cherenkov's counters is measuring the energy of particles and fission of particles by masses. Cherenkov's counters have found wide application in physics of high energies. They are especially convenient that Cherenkov's radiation has the bottom threshold of a particle velocity. Sensitivity and the resolution time of Cherenkov's counters are the same, as at scintillation counters, i.e. very good.

Counters, in which working substance is the semiconductor, are *semiconductor counters*. The basic part of a semiconductor counter is *the monocrystal* of a size about a small coin. The crystal is a semiconductor diode. The semiconductor counter operates as the ionization chamber, with that difference, that a working environment is not a gas, but a firm body. The mean ionization energy in a semiconductor is higher by the order, it facilitates registration and increases accuracy of measuring the energy, reaching up to fractions of percent. The small sizes of working area result in that the resolution time can be reduced up to 10^{-7} *sec*. In the field of low energies semiconductor counters possess practically the absolute efficiency, the good time of resolution and surpass counters of other types by compactness and accuracy of the energy measurement.