TOMSK POLYTECHNIC UNIVERSITY

SUMMARIES OF LECTURES IN THE FIELD OF PHYSICAL PROTECTION, CONTROL AND ACCOUNTING (MPC&A) OF NUCLEAR MATERIALS

Part I

Study Aid

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The maintenance of a lecture part of special disciplines (abstracts of lectures) which in 6th and 7th semestres are studied by the students of the Tomsk Polytechnic University, trained on a speciality “Safety and non-distribution of nuclear materials”, is stated. The Manual can be used as a management on self-preparation at studying of some sections of such special disciplines, as “Nuclear physics”, “Theoretical physics”, “Introduction in the account, the control and physical protection of nuclear materials”, “Account and control of sharing materials in manufacture of nuclear fuel”, “Analytical chemistry of uranium, plutonium and thorium”, “Dosimetry and spectrometry of fields of an ionising radiation”.

The study aid is developed in the framework of Innovative Educational Programme of the TPU on the direction “Atomic power engineering, nuclear fuel cycle, safe handling with radioactive waste and spent nuclear fuel, accident prevention and counter-terrorism”.

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PREFACE

Since 2002, in the TPU is carried out training of students on a speciality “Safety and non-distribution of nuclear materials”. In 2005 the frame agreement between the TPU and Northwest Pacific national laboratory of the USA (PNNL) about cooperation within the limits of Engineering educational program on realisation in the TPU process of preparation of engineers on Physical protection, the account and the control of nuclear materials is signed. According to the programme in the TPU with the assistance of the organisations designated by the Department of Energy of the USA (DOE), actions for formation and perfection of process of training for a new speciality are carried out.

Preparation of engineers on Physical protection, the account and the control of nuclear materials in Russia is carried out in two leading higher technical educational institutions – at the Moscow engineering-physical institute (technical university) and the Tomsk Polytechnical University. Preparation curricula in them differ a little. In TPU by the preparation plan deeper studying of the questions connected with technical aspects of realisation of the concept of non-distribution of nuclear materials that is the questions, concerning technologies of a nuclear fuel cycle is provided.

The given manual represents the collection of abstracts of lectures on a number of sections of the special disciplines studied by students of a new speciality in 6th and 7th semesters. Its use will allow orienting at a choice of those sections of disciplines to which it is necessary to pay especial attention at studying. For example, at course studying “the Nuclear physics” to the students trained on a speciality “Safety and non-distribution of nuclear materials”, it is necessary to focus the attention on questions of physics of simple and difficult radioactive disintegrations, physics of interaction of the charged particles, gamma quanta and neutrons with substance. At course studying “the Theoretical physics” it is necessary to understand appendices (methods) of mathematical statistics which are used at interpretation of results of measurements in details.

The manual can be used as a management at independent studying of theoretical sections of special disciplines and at studying of professional English language.

NUCLEAR PHYSICS

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, $h = 6.6252 \cdot 10^{-34}$ $joule \cdot s$ 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)*

$$\Delta x \Delta p \geq \hbar, \text{ here } \hbar = h/2\pi.$$

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 $r_0 = \left(1.2 \div 1.5\right) \cdot 10^{-13}$ *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

$$V = \frac{4}{3}\pi R^3 = \frac{4}{3}\pi r_0{}^3 A = const \cdot A .$$

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 $_0^1n$ is realized in $_1^1p$

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

In case of surplus of protons two processes are possible

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

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

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

$$E_\beta=\left[M_a(A,Z)-M_a(A,Z\pm1)\right]\cdot c^2>0,$$

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 $\sim 10^{-14}$ *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»:

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

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

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

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 $e^+ + e^- \to \gamma + \gamma$.

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,

$$^{4}_{2}\alpha + ^{14}_{7}N \rightarrow ^{18}_{9}F^{**} \rightarrow ^{1}_{1}p + ^{17}_{8}O.$$

A nucleus $^{18}_{9}F$ 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 $\sim 10^{-22} \div 10^{-23}$ *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 $\sigma_a = \pi\lambdabar^2$ 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

$$\sigma_n = \pi\lambdabar^2 \frac{\Gamma_n \cdot \Gamma}{(E - E_{res})^2 + \frac{\Gamma^2}{4}}.$$

The range of high energies. High energies are called such energies, at which the length of a wave of an incident particle $\lambdabar$ is far less than the values of the nucleus characterized by a radius R $(\lambdabar << R)$. 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 $: 2 \cdot 10^7\ {}^oK$, 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 ≥ 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 characterisëtics 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 30
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.

THEORETICAL PHYSICS

LECTURE 1
ELEMENTS OF THE ERROR THEORY

The measurement can be determined as the cognitive process consisting in comparing the value received by the physical experiment with its some meaning accepted for a unit of measurement. As a result of measurement we know how many times the measured value is more or less than the corresponding value accepted for unit (etalon).

It is necessary to remember that any measurement cannot be carried out absolutely precisely. Its result always contains some errors. It is obvious that measuring some value we, as a rule, cannot do an error minuter than that one, which is determined by an error of the measuring device.

The problem of measurements consists not only in finding the value, but also in estimating the error permitted at measurement, i. e. the processing of measurement results is necessary.

The difference between exact (true) and approximated values of the measured (determined) value refers to as an error or a mistake of measurement (the approximated calculation). Generally concerning an error of measurement we can say that it is a deviation of the measuring result from the true value of the magnitude being measured.

Errors of measurements can be divided into *random* and *systematic*.

Random errors are the errors caused by the multitude of the chance reasons, which action on each measurement is different and also cannot be taken into account beforehand. The value of random errors is different even for measurements executed in the same manner.

The systematic errors are the errors distorting the result to a certain side and having the regular character. As to the value of the size, systematic errors remain constant or naturally change in all measurements carried out by the same method and by the same measuring devices.

As the role of computers in processing of the various data is rather great, there are some more errors, which are brought both by methods of data processing and that fact that the COMPUTER introduces errors *of a rounding off,* which are caused by limitation of a digit grid of the machine.

We shall consider mathematical characteristics of the task accuracy of the problem initial data. We shall designate in terms of x the exact value of some magnitude, and in terms of x^* – its approximated value. We shall designate $x^* - x = \alpha_{x^*}$. The error of the approximated value x^* is usually unknown. *The estimation of an error* x^* is understood as an establishment of an inequality of a kind:

$$\left|x - x^*\right| \le A_{x^*}, \tag{1.1}$$

where A_{x^*} refers to *as an absolute error* of the approximated value x^*. As A_{x^*}, one tries to specify the least number, which will satisfy an inequality (1.1), or else it can be copied as:

$$x^* - A_{x^*} \le x \le x^* + A_{x^*}$$

Let's note that the absolute error is the denominate quantity having dimension x^*.

The relation of its absolute error A_{x^*} to the absolute value of number x^* refers to *as a relative error* Δ_{x^*} of the approximated value x^*, i. e.:

$$\Delta_{x^*} = \frac{A_{x^*}}{\left|x^*\right|}, \left(x^* \ne 0\right)$$

or

$$\frac{\left|x^* - x\right|}{\left|x^*\right|} \le \frac{A_{x^*}}{\left|x^*\right|} = \Delta_{x^*}$$

The relative error is the dimensionless value and is usually expressed in percentage. It can be written down with two, three signs to a side of increasing.

LECTURE 2
THE BASIC CONCEPTS OF PROBABILITY THEORY

All events observable by us can be divided into three kinds: *authentic, impossible and random.* As *event* we shall understand *an outcome* of a certain experiment.

The authentic event we shall call such an event, which will take place if the certain set of conditions is carried out.

The impossible event is called such an event, which obviously will not take place if the certain set of conditions is carried out.

The random event is called such an event, which at realization of a complex of conditions can either take place, or cannot take place.

Let's consider some examples demonstrating concepts of the authentic, impossible and random event. We assume that we have some urn, in which there are 10 spheres of white color. During the experiment, some experimentalist takes out one sphere from this urn. In this example the urn the specified quantity of spheres and their color make itself the population S. Now we shall consider the result of the experiment (experience). Its result is the sphere taken out from the urn. The event «the sphere taken out from the urn has a white color» is *authentic*. The event «the sphere taken out from the urn has a black color» is *impossible*, for the reason, that spheres of a black color are not present in our urn. We shall change now the population S that the urn will contain 5 black and 5 white spheres. Then the event «the sphere taken out from the urn has white color» will be *casual*.

Let's consider an example. Let the urn contain 10 identical, carefully hashed spheres, and 3 of them are red, 5 are dark blue and 2 are white. It is obvious that opportunity to take out at random a color sphere, it is more than an opportunity to take out a white sphere. This opportunity can be characterized by the number. This number is called the *probability of event*.

Let's try to state a quantitative estimation of an opportunity of that the sphere taken at random will be colored. Occurrence of a color sphere we shall consider as *event A*. Each event of the *elementary outcomes* we shall designate by ω_i. Then for our example $\omega_1, \omega_2, \omega_3$ are outcomes, at which we take out *a red* sphere, $\omega_4, \omega_5, \omega_6, \omega_7, \omega_8$ are outcomes, at which we take out *a dark blue* sphere, and ω_9, ω_{10} are outcomes, at which we take out *a white* sphere. Those elementary outcomes, in which our event comes, we shall call *favorable* for this event. In our example 8 outcomes favor for *event A*. Hence, it is possible to assert that the following *relation of the number of elementary outcomes being favorable for event A to their common number will be* ***the probability*** *of event A,* which is designated by $P(A)$. Thus, the probability of event A is defined by the formula $P(A) = m/n$, where m is the number of elementary outcomes favorable for *event A*, and n is the number of all possible elementary outcomes. We shall pay attention to some properties of probability:

1. The probability of the authentic event equals 1, i. e. $P(A) = m/n = n/n = 1$

2. The probability of the impossible event equals 0, i. e. $P(A) = m/n = 0/n = 0$

3. The probability of the random event is the positive number put between 0 and 1, i. e. $0 < P(A) < 1$. The probability of any event is also put between 0 and 1, but concluding 0 and 1 i. e. $0 \le P(A) \le 1$.

Let's consider one more example. Let us have an ordinary playing dice. At its throwing there can be numbers 1, 2, 3, 4 and 6. Beforehand to define the number of dropped out points it is impossible, as it depends on many casual reasons, which completely cannot be taken into account. In this sense the number of points is the random variable, numbers 1, 2, 3, 4, 5 and 6 are *possible values* of this magnitude.

The random variable is called such a value, which as a result of a test takes one and the only possible value, beforehand unknown, and dependent on the casual reasons, which cannot be taken into account. Random variables can be designated by capital letters, for example, X,Y,Z and their possible values – by the corresponding small letters x,y,z. For example, if the random variable X has three possible values, they will be designated so x_1,x_2,x_3, and probabilities of these values are designated as p_1,p_2,p_3. It is possible to divide random variables into two kinds – *a discrete* and *continuous* random variable.

The discrete random variable is called a variable, which accepts separate, isolated possible values with the certain probabilities. The number of possible values of a discrete random variable can be final or infinite.

Continuous is called a random variable, which can accept all values from some final or infinite interval. It is obvious that the number of possible values of a continuous random variable is infinitely.

LECTURE 3
NUMERICAL CHARACTERISTICS OF RANDOM VARIABLES

Before speaking about numerical characteristics of random variables, it is necessary to introduce the concept *of the law of distribution* of a random variable. We shall introduce the following definition: *any relation establishing connection between possible values of a random variable and probabilities corresponding to them refers to as the law of distribution of a random variable.*

It is possible to tell about a random variable, that it is «distributed» under the given law of distribution or «subordinated» to this law of distribution. For *a discrete random variable* the law of distribution can be set as the table, analytically and graphically. For example, the following table

x	x_1	x_2	$\ldots$	x_n
p	p_1	p_2	$\ldots$	p_n

can be considered as the law of distribution of size of a random variable X with probabilities $p_i, i=\overline{1,n}$, which correspond to values of a random variable $x_i, i=\overline{1,n}$. *For any random variable:*

$$\sum_{i=1}^{n} P\left(X=x_i\right)=\sum_{i=1}^{n} p_i=1 .$$

This unit *is distributed* between values of a random variable; from here we have the term «distribution».

It often happens that the law of distribution of a random variable is unknown and it is necessary to be limited of minute data, which describe a random variable totally; such numbers are called *numerical characteristics of a random variable. The population mean* and *a dispersion* of a random variable concern to number of the important numerical characteristics.

The population mean of random discrete variable is called the sum of products of all of its values on their probability, i. e.

$$M(X) = x_1p_1 + x_2p_2 + \ldots + x_np_n = \sum_{i=1}^{n} x_ip_i\ .$$

Let X be a random variable and $X - M(X)$ be its population mean. We shall consider a difference $X - M(X)$ as a new random variable. *A deviation* is called a difference between a random variable and its population mean. *A dispersion (variance) of a discrete random variable is called a population mean of a random variable deviation square from its population mean, i. e.*

$$D(X) = M\left[X - M(X)\right]^2 .$$

Let's specify some properties of a population mean:

1. *A population mean of a constant equals the constant itself:* $M(C) = C$.

2. *The constant multiplier can be put outside a sign of a population mean:* $M(CX) = CM(X)$.

3. *A population mean of a product of two independent random variables equals the product of their population means:* $M(XY) = M(X)M(Y)$

and dispersion.

1. The dispersion of a constant value is equal to zero: $D(C) = 0$.

2. The constant multiplier can be put outside a sign of a dispersion, squaring it $D(CX) = C^2D(X)$.

3. The dispersion of the sum of two independent random variables is equal to the sum of dispersions of these values $D(X+Y) = D(X) + D(Y)$

4. The dispersion of a difference of two independent random values is equal to the sum of dispersions of these values: $D(X-Y) = D(X) + D(Y)$.

LECTURE 4
DISTRIBUTION FUNCTION OF PROBABILITIES OF A RANDOM VARIABLE. DENSITY OF DISTRIBUTION OF PROBABILITIES OF A RANDOM VARIABLE

Earlier, to describe a discrete random variable, we considered the law of its distribution representing a number of distributions or the formula allowing finding probabilities of any values of a random variable X. However, such a description of a random variable is not the only thing, and, it is not universal.

To describe the law of distribution of a random variable X, the other approach is also possible: to consider not only probabilities of events $X = x$ for different x (as it takes place in a number of distributions), but probabilities of event $X < x$, where x is the current variable. The probability $P(X < x)$, obviously, depends on x, i. e. is a certain function of x.

Proceeding from this it is possible to speak that *function of distribution of the random variable X is called the function $F(x)$ expressing for every x the probability of that the random variable X will take the value lower than x:*

$$F(x) = P(X < x).$$

The function $F(x)$ is sometimes called the *integrated function of distribution* or *the integrated law of distribution.*

Let's consider the common properties of the distribution function:

1) The distribution function of a random variable is ***the non-negative*** *function put between zero and unit:* $0 \le F(x) \le 1$

2) The distribution function of a random variable is not a decreasing function on the all numerical axis.

3) On a minus of infinity the distribution function is equal to zero, and on a plus of infinity – to unit, i. e. $F(-\infty) = \lim\limits_{x \to -\infty} F(x) = 0, F(+\infty) = \lim\limits_{x \to +\infty} F(x) = 1$

4) The probability of hit of a random variable in an interval $[x_1, x_2)$ is equal to an increment of its distribution function on this interval, i. e. $P(x_1 \le x \le x_2) = F(x_2) - F(x_1)$.

The random variable X refers to ***continuous*** *if its distribution function is continuous in any point and is differentiated everywhere, except for, maybe, separate points.*

The derivative of its distribution function $\varphi(x) = F'(x)$ refers to ***as a density of probability (density of distribution)*** *or simply* ***density*** *$\varphi(x)$ of a continuous random variable X.*

The density of probability variable is sometimes called *differential function* or *the differential law of distribution*.

We shall note properties of probability density of a continuous random variable.

1. Density of probability is a non-negative function, i. e. $\varphi(x)\ge 0$.

2. The probability of hit of a continuous random variable in an interval $[a,b]$ *is equal to the certain integral of its probability density within the limits of* a *to* b*, i. e.* $P(a\le X\le b)=\int\limits_a^b \varphi(x)dx$.

3. The probability function of a continuous random variable can be expressed in terms of probability density by the formula: $F(x)=\int\limits_{-\infty}^{x}\varphi(x)dx$.

4. The improper integral from the probability density of a continuous random variable to infinite limits is equal to unit: $\int\limits_{-\infty}^{+\infty}\varphi(x)dx=1$.

Most frequently used functions of distribution are functions of the Gauss distribution (the distribution set by this function is often called «normal») and the Poisson one.

The density of probability of a continuous random variable X, which has the normal law of distribution (the Gauss Law) with parameters a and σ^2 looks like:

$$\varphi_N(x)=\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{(x-a)^2}{2\sigma^2}}.$$

The normal law of a random variable distribution with parameters a and σ^2 is designated by $N(a,\sigma^2)$. If $a=0,\sigma^2=1$, i. e. $N(0;1)$, such a normal law of distribution refers to *normalized* or *standard.*

The discrete random variable X has the law of the Poisson distribution if it takes values $0,1,2,\ldots,m,\ldots$ (infinite, but countable set of values) with probabilities

$$P(X=m)=\frac{\lambda^m e^{-\lambda}}{m!}.$$

LECTURE 5
THE BASIC CONCEPTS OF MATHEMATICAL STATISTICS

The establishment of laws, to which the mass random phenomena submit, is based on studying the methods of probability theory of the statistical data – the results of observation.

The first problem of mathematical statistics is to specify ways of gathering and grouping the statistical data received as a result of observation or in the result of specially carried out experiments.

The second problem of mathematical statistics is to develop the analysis methods of the statistical data depending on the research purposes. Here concern:

a) An estimation of unknown probability of the event; an estimation of the unknown function of distribution; an estimation of distribution parameters, which kind is unknown; an estimation of a random variable dependence on one or several random variables, etc.;
b) Check of statistical hypotheses about a kind of unknown distribution or about size of parameters of distribution, which kind is unknown.

So, the problem of the mathematical statistics will consist in creating the methods of gathering and processing of the statistical data for reception of scientific and practical conclusions.

Let it be required to study a set of homogeneous objects concerning some *qualitative* or *quantitative attribute* describing these objects. For example, if there is a set of details, standardized details can serve as a qualitative attribute, and the quantitative one – the controllable size of a detail. Then the set of details will serve as some *population,* and standardization of a detail or the controllable size of a detail – *attributes.* Concerning a notorious set of details it is possible to carry out continuous examination, i. e. to examine *every* object of the set concerning an attribute, in which we are interested. However, in practice it is seldom used, as the set often contains a plenty of objects. It is more practical to select some, a small amount of objects, from the population by chance and to subject them to studying.

Sampling population or simply sampling is called a set *of casually selected objects*. *General population* is called a set of objects *from which* sampling is carried out. *The population volume* (selective or general) is called the number of objects of this population.

LECTURE 6
A METHOD OF SAMPLING (PART 1)

Let's remind that *sampling is* called a population *of casually selected objects*.

Making up a sample it is possible to act in two ways: after the object has been selected and observed, it can be returned or is not returned to a general population. As mentioned above samplings are divided into repeated and non-repeated.

The *repeated* sampling is called such a sampling, at which the selected object (before selection of the following one) comes back to a general population.

The non-repeated sampling is called such a sampling, at which the selected object does not come back to a general population.

In order to judge confidently enough about the characteristics of general population, which we are interested in, according to sampling data, it is necessary that objects of sampling should correctly represent it. In other words, sampling should represent proportions of general population correctly. This requirement is shortly formulated so: sampling should be *representative.*

Small samplings are convenient for representing as tables consisting of two lines. In the first line sample units are written (they refer to *as variants*) located in an ascending order. In the second line *frequencies* of variants are given. The number equal to quantity of variant recurrences in sampling refers to *as frequency*. If n_i is the frequency of variants x_i, a total number in a sampling is k of different variants, $n_1+n_2+n_3+\ldots+n_k=n$ where n is a sampling volume. The described table refers to *as the table of frequencies.*

It is not always convenient to consider sampling as the table or some set of tables, therefore, for presentation of various diagrams of statistical distribution and, in particular, the range (polygon) and the histogram are plotted.

The polygon of frequencies is called a broken line, which segments connect points $(x_1;n_1),(x_2;n_2),\ldots,(x_k;n_k)$. To construct the polygon of frequencies variants x_i are plotted on an abscissa axis, and on an axis of ordinates – the frequencies n_i corresponding to them. Points (x_i,n_i) are connected by segments of straight lines and the polygon of frequencies is obtained.

In case of *a continuous attribute* it is expedient to build *the histogram* for what an interval, in which all observable values of an attribute are put, is broken into some partial intervals of length h. Then for each partial interval n the sum of frequencies of variants, which have got in an i – interval, is found.

*The histogram of frequencie*s is often called the step figure consisting of rectangulars, which bases are partial intervals of length h, and heights are equal to the relation of n_i/h (the frequency density).

To construct the histogram of frequencies, partial intervals are plotted on an abscissa axis, and above them the segments parallel to an abscissa axis are plotted in a distance of n_i/h.

Besides the graphic representation, sampling can also be characterized by *numerical characteristics*. A *selective mean, a mode, a median, quartiles, decatyls and percentiles are referred to them.*

A selective mean $\bar{x}$ is an average arithmetic variant of sampling. If the volume of sampling is equal to n,

$$\bar{x} = (1/n)\sum_{j=1}^{n} x_j = (1/n)\sum_{i=1}^{n} n_i x_i,$$

where k is the number of different variants, n_i is frequency of the variant x_i, $i = 1, 2, 3, \ldots, k$.

The mode (x_{mod}, M_0) of a discrete random variable is called such its value, which has a maximal probability. The mode of continuous random variable is called such its value, at which the maximum of probability density function is achieved. More simply the mode can be understood so – *a variant, which has the greatest frequency.* For example, for lines:

variant	1	4	7	9
frequency	5	1	20	6

The mode is equal to 7.

A median m_e is called that variant, which divides a variation line into two parts equal in the number of variants. If the number of variants is odd, i. e. $n = 2k+1$, $m_e = x_{k+1}$, at even one $n = 2k$ - a median is $m_e = (x_k + x_{k+1})/2$.

The median divides sampling into two parts. It is possible to find such three numbers Q_1, Q_2, Q_3, which will divide a sample into four parts in the same manner, such numbers are called *quartiles* . The number $Q_2 = m_e$, i. e. coincides with a median, the number Q_1 – refers to *a bottom quartile,* the number Q_3 – *a top quartile.* It is also possible to find 9 numbers: $D_1, D_2, \ldots, D_9$, which will divide a sample into 10 equal parts. Such numbers *are called de-*

catyls. If to break a sample into 100 different parts, points of division refer to *percentyls* and are designated as $P_i, i = \overline{1,99}$.

LECTURE 7
A METHOD OF SAMPLING (PART 2)

Let a sampling be taken from a general population, x_1 being observed n_1 times, x_2 – n_2 times, x_k – n_k times and $\sum_{i=1}^{k} n_i = n$ is a volume of a sampling. Observable values x_i are called variants, and sequence of variants written down in the growing order is called *a variation line*. Numbers of observations are called frequencies, and their relations to the volume of sampling $n_i/n = W_i$ are called *relative frequencies*.

The statistical distribution of a sampling is called the list of variants and frequencies corresponding to them or relative frequencies. It is possible to set the statistical distribution also as sequence of intervals and frequencies corresponding to them or relative frequencies. It is possible to set statistical distribution also as sequence of intervals and frequencies corresponding to them (as the frequency corresponding to an interval is taken the sum of the frequencies, which have got in this interval).

We shall notice that in the probability theory under *distribution* we understand conformity between possible values of a random variable and their probabilities, and in mathematical statistics – conformity between observable variants and their frequencies or relative frequencies.

Let the primary known statistical distribution of frequencies of a quantitative attribute be X. We shall introduce a designation n_x – the number of observations, at which there was observed the value of an attribute, which is lower than *x*; *n* is the general number of observations (the volume of a sampling).

The *empirical function of distribution* (the distribution function of a sampling) is called the function $F^*(x)$ determining for each value *x* the relative frequency of the event $X < x$.

Making a start from this definition, we receive:

$$F^*(x) = n_x/n,$$

where n_x is the number of variants, which is lower than x, *n* is the volume of a sampling.

As against the empirical function of a sample distribution, the distribution function $F(x)$ of a general population is called *a theoretical function of* *distribution.* Distinctions between empirical and theoretical functions consist in the following: the theoretical function $F(x)$ defines the probability of the event $X < x$, and the empirical function $F^*(x)$ determines the relative frequency of this event.

From the definition of the function $F^*(x)$ its following properties follow:

1. Values of the empirical function belong to a segment [0,1].
2. $F^*(x)$ – a nondecreasing function.
3. If x_1 is the least of a variant, $F^*(x)$ at $x \leq x_1$; if x_k is the greatest value, $F^*(x) = 1$, at $x > x_k$.

LECTURE 8
STATISTICAL ESTIMATIONS OF DISTRIBUTION PARAMETERS

Let it be required to study a quantitative attribute of a general population. We assume that from theoretical reasons it was possible to find which distribution has an attribute. Naturally there is a problem of an estimation of parameters by which this distribution is defined. For example, if beforehand it is known that the investigated attribute is distributed in a general population normally, it is necessary to estimate (approximately to find) a population mean and a root-mean-square deviation, as these two parameters completely define the normal distribution. If there are grounds to consider that the attribute has, for example, the Poisson distribution, it is necessary to estimate parameter X by which this distribution is determined.

Usually at the disposal of the researcher there are only the given samples, for example values of a quantitative attribute $x_1, x_2, \ldots, x_n$ received as a result of n observations (hereinafter observations are assumed independent). The estimated parameter is expressed by these data. Considering $x_1, x_2, \ldots, x_n$ as independent random variables of $X_1, X_2, \ldots, X_n$ it is possible to say that to find a statistical estimation of an unknown parameter of a theoretical distribution is to find the function of observable random variables, which gives the approximated value of the estimated parameter. For example, for an estimation of a population mean of a normal distribution the function (average arithmetic observable values of an attribute) $\bar{X} = (X_1 + X_2 + \ldots + X_n)/n$ is used.

So, a statistical estimation of an unknown parameter of a theoretical distribution is called the function of the observable random variables.

Let Θ^* be a statistical estimation of an unknown parameter Θ of a theoretical distribution. We assume that the estimation Θ_1^* is found due to a sample of a volume n. We shall repeat the experiment, i. e. we shall take from a general population the other sample of the same volume and due to its data we shall find estimation Θ_2^*. Repeating the experiment repeatedly we shall receive numbers $\Theta_1^*, \Theta_2^*, \ldots, \Theta_k^*$ which, generally speaking, are different between themselves. Thus, the estimation Θ^* can be considered as a random variable, and numbers $\Theta_1^*, \Theta_2^*, \ldots, \Theta_k^*$ – as its probable values.

Unbiased is called a statistical estimation Θ^*, which the population mean is equal to the estimated parameter Θ at any volume of a sample, i. e. $M(\Theta^*) = \Theta$.

Displaced is called such an estimation, which the population mean is not equal to the estimated parameter.

Effective is called a statistical estimation, which (at the set volume of a sampling n) has the least probable dispersion.

Considering the great volume of samples (n it is great!) the requirement of a solvency is given to statistical estimations.

Independent is called a statistical estimation, which at $n \to \infty$ tends in probability to the estimated parameter. For example, if the dispersion of the unbiased estimation $n \to \infty$ tends to zero, such estimation appears to be *independent.*

Let the discrete general population concerning a quantitative attribute X be studied. *The General mean* $\overline{x}_G$ is called the average arithmetic values of an attribute of a general population. If all values $x_1, x_2, \ldots, x_N$ of an attribute of a general population of a volume N ***are different***,

$$\overline{x}_G = (x_1 + x_2 + \ldots + x_N)/N .$$

If values of an attribute $x_1, x_2, \ldots, x_k$ have accordingly frequencies $N_1, N_2, \ldots, N_k$, in which connection $N_1 + N_2 + \ldots + N_k = N$, we have

$$\overline{x}_G = (x_1 N_1 + x_2 N_2 + \ldots + x_k N_k)/N ,$$

i. e. the general mean is the average weighed of values of an attribute with the weights equal to corresponding frequencies.

A *selective mean* $\overline{x}_s$ is called the mean arithmetic value of an attribute of a sample. If all values $x_1, x_2, \ldots, x_k$ of an attribute of sample of a volume n are different,

$$\overline{x}_s = (x_1 + x_2 + \ldots + x_n)/n .$$

If values of an attribute $x_1, x_2, \ldots, x_k$ have accordingly frequencies $n_1, n_2, \ldots, n_k$, in which connection $n_1 + n_2 + \ldots + n_k = n$, we have $\overline{x}_s = (n_1 x_1 + n_2 x_2 + \ldots + n_k x_k)/n$.

i. e. a selective average is the average weighed of values of an attribute with the weights equal to corresponding frequencies.

A general dispersion D_G is called the mean arithmetic of deviations squares of attribute values of a general population of their mean value $\overline{x}_G$

If all values $x_1, x_2, \ldots x_n$ of an attribute of a sample of volume N are different,

$$D_\Gamma = \left(\sum_{i=1}^{N} \left(x_i - \overline{x}_\Gamma \right)^2 \right) \Big/ N .$$

If values of an attribute $x_1, x_2, \ldots x_n$ have accordingly frequencies $N_1, N_2, \ldots, N_k$, in which connection $N_1 + N_2 + \ldots + N_k = N$, we have

$$D_G = \left(\sum_{i=1}^{k} N_i \left(x_i - \overline{x}_G \right)^2 \right) \Big/ N .$$

A selective dispersion D_s is called the mean arithmetic of deviation squares of observable values of an attribute of their average value $\overline{x}_s$.

If all values $x_1, x_2, \ldots x_n$ of an attribute of sample of volume n are different,

$$D_s = \left(\sum_{i=1}^{n} \left(x_i - \overline{x}_s \right)^2 \right) \Big/ n .$$

If values of an attribute $x_1, x_2, \ldots x_k$ have accordingly frequencies $n_1, n_2, \ldots, n_k$, in which connection $n_1 + n_2 + \ldots + n_k = n$, we have

$$D_s = \left(\sum_{i=1}^{k} n_i \left(x_i - \overline{x}_s \right) \right) \Big/ n .$$

LECTURE 9
CONCEPT OF THE INTERVAL ESTIMATION. CONFIDENTIAL PROBABILITY

To receive representation about accuracy and reliability of an estimation Θ of a parameter Θ, an interval estimation of a parameter is used.

The numerical interval $\left(\Theta_1^*, \Theta_2^*\right)$, *which with the set probability* γ *«covers» the unknown value of a parameter* Θ *refers to as an interval estimation of a parameter* Θ.

Borders of an interval and its value are according to selective data and consequently are *random variables* as against of the estimated parameter Θ – the nonrandom value, therefore, to say that the interval $\left(\Theta_1^*, \Theta_2^*\right)$ *«covers»* is more correctly, instead of «contains» the value Θ.

Such an interval $\left(\Theta_1^*,\Theta_2^*\right)$ *refers to* ***confidential****, and a probability* γ *–* ***as a confidential probability*** *or* ***the reliability of an estimation.***

The size of a confidential interval essentially depends on the volume of a sample n (decreases with growth n) and on the value of a confidential probability γ (increases with approximation to unit).

It is very often (but not always) the confidential interval is picked out symmetric relative to Θ i. e. $(\Theta-\Delta,\Theta+\Delta)$.

The greatest deviation Δ *of a selective mean (or a fraction) from a general mean (or a fraction), which is possible with the set confidential probability* γ*, refers to* ***as a limiting accuracy of sampling.***

The error Δ is *a mistake of representativeness* of sampling. It arises because not all the population but only a part of it (a sample) casually selected is investigated. This error is often called a random error of representativeness.

To construct confidential intervals for parameters of general populations two approaches based on the value of *exact* (at the given volume of a sample *n*) or *asymptotic* (at $n\to\infty$) distribution of selective characteristics (or some their functions) can be realized.

LECTURE 10
A PRINCIPLE OF PRACTICAL CONFIDENCE. A STATISTICAL HYPOTHESIS AND THE GENERAL DIAGRAM OF ITS CHECK

Before considering the concept *of a statistical hypothesis*, we shall formulate the so-called principle of a practical confidence underlying application of conclusions and recommendations with the help of the probability theory and mathematical statistics:

If the probability of the event A in the given test is very little, at a single performance of a test it is possible to be confident that the event A will not happen, and in practice you should behave as if the event A were generally impossible.

This principle cannot be proved mathematically; it is proved by all the experience of the practical human activity and we are always (though unconsciously) guided by it. For example, being sent by plane to the other city, we do not consider on an opportunity to be lost in an aviation accident though some (rather little) probability of such an event is nevertheless present.

Any assumption of a kind or parameters of the unknown law of distribution refers to ***as a statistical hypothesis****.*

We distinguish *simple* and *complex* statistical hypotheses. The simple hypothesis, as against a complex one completely defines a theoretical function of a random variable distribution. For example, hypotheses «the probability of occurrence of the event in the Bernoulli scheme is equal to 1/2», «the law of distribution of a random value normal with parameters $a = 0, \sigma^2 = 1$ «are simple, and hypotheses» the probability of occurrence of the event in the Bernoulli scheme is put between 0.3 and 0.6», «the law of distribution is not normal» – complex.

The checked hypothesis is usually called *zero* and designated by H_0. Alongside with a zero hypothesis H_0 *the alternative* or *competing* hypothesis H_1 being a logic denial H_0 is also considered. *Zero* and *alternative hypotheses represent two opportunities of the choice, which is carried out in problems of checking the statistical hypotheses.*

The essence of checking a statistical hypothesis consists in the following: specially made selective characteristic *(statistics)* $\Theta^*(x_1, x_2, \dots, x_n)$ received by a sample $X_1, X_2, \dots, X_n$ with the known exact or approximated distribution is used. Then according to this selective distribution such a critical value Θ_{cr} is defined that if the hypothesis H_0 is true, the probability $P(\tilde{\Theta}_n > \Theta_{cr}) = \alpha$ is little; so according to a principle of a practical confidence under conditions of the given research the event $\tilde{\Theta}_n > \Theta_{cr}$ can be practically considered to be impossible. Therefore, if in the given concrete case the deviation $\tilde{\Theta}_n > \Theta_{cr}$ occurs, the hypothesis H_0 is rejected or accepted whereas the occurrence of the value $\tilde{\Theta}_n \le \Theta_{cr}$ is considered to be compatible with a hypothesis H_0, which then is accepted (more precisely it is not rejected). *The law, according to which the hypothesis H_0 is rejected or accepted, refers to* ***as statistical criterion.***

Thus, the set of possible values of statistics of criterion (critical statistics) $\tilde{\Theta}_n$ is broken into two not crossed subsets: *the critical area (area of a deviation of a hypothesis)* W and *the area of allowable values (the area of hypothesis acceptance)* $\overline{W}$. If actually the observable value of statistics of the criterion $\tilde{\Theta}_n$ gets in the critical area W, a hypothesis H_0 is rejected. Thus, four cases are possible.

The hypothesis H_0	*It is accepted*	*It is rejected*
It is true	*The correct decision*	*The error of the 1-st sort*
It is wrong	*The error of the2-nd sort*	*The correct decision*

Definition. *The probability α to make an error of the 1-st sort i. e. to reject a hypothesis H_0 when it is true refers to* ***as a significance value of criterion****.*

The probability to make an error of the 2-nd sort i. e. to accept a hypothesis H_0 when it is incorrect is usually designated by β.

Definition. *The probability* $(1-\beta)$ *to not make a mistake of the 2-nd sort i. e. to reject a hypothesis* H_0 *when it is incorrect refers to **as capacity** (or **the function of capacity) of a criterion**.*

LECTURE 11
CHECK OF HYPOTHESES OF THE EQUALITY OF THE AVERAGE OF TWO AND MORE POPULATIONS.
CHECK OF HYPOTHESES OF THE EQUALITY OF DISPERSIONS OF TWO AND MORE POPULATIONS

Let's formulate a problem. Let us have two sets characterized by general means $\overline{x}_0$ and $\overline{y}_0$ and *by the known dispersions* σ_x^2 and σ_y^2. It is necessary to check up the hypothesis H_0 about the equality of a general mean, i. e. $H_0 : \overline{x}_0 = \overline{y}_0$. To check up the hypothesis H_0, two independent samples of volumes n_1 and n_2, on which the average arithmetic $\overline{x}$ and $\overline{y}$ and selective dispersions s_x^2 and s_y^2 are found, are taken from these populations.

At enough great volumes of a sample, selective average $\overline{x}$ and $\overline{y}$ have approximately the normal law of distribution, accordingly $N\left(\overline{x}_0, \sigma_x^2\right)$ and $N\left(\overline{x}_0, \sigma_y^2\right)$.

In case of validity of the hypothesis H_0 the difference $\overline{x}-\overline{y}$ has the normal law of distribution with a population mean $M\left(\overline{x}-\overline{y}\right) = M\left(\overline{x}\right) - M\left(\overline{y}\right) = x_0 - y_0 = 0$ and dispersion $\sigma_{\overline{x}-\overline{y}}^2 = \sigma_{\overline{x}}^2 + \sigma_{\overline{y}}^2 = \dfrac{\sigma_x^2}{n_1} + \dfrac{\sigma_y^2}{n_1}$. Therefore, while performing the hypothesis H_0 the statistics

$$t = \frac{\left(\overline{x}-\overline{y}\right) - M\left(\overline{x}-\overline{y}\right)}{\sigma_{\overline{x}-\overline{y}}} = \frac{\overline{x}-\overline{y}}{\sqrt{\dfrac{\sigma_x^2}{n_1} + \dfrac{\sigma_y^2}{n_1}}} \tag{11.1}$$

has a standard normal distribution $N(0;1)$.

In case of a competing hypothesis $N_1 : \overline{x}_0 > \overline{y}_0$ (or $H_1 : \overline{x}_0 < \overline{y}_0$), the *unilateral* critical area is chosen and a critical value of statistics is found from a condition

$$\Phi\left(t_{cr}\right) = \Theta\left(t_{1-2\alpha}\right) = 1 - 2\alpha. \tag{11.2}$$

And at a competing hypothesis $H_2 : \overline{x}_0 \neq \overline{y}_0$, *a bilateral* critical area is chosen and a critical value of statistics is found from a condition

$$\Phi\left(t_{cr}\right) = \Phi\left(t_{1-\alpha}\right) = 1 - \alpha. \tag{11.3}$$

If the actually observable value of statistics t is more than the critical t_{cr} *determined by a value* α *(by the absolute value, i. e.* $|t| > t_{cr}$*, the hypothesis* H_0 *is rejected. If* $|t| \le t_{cr}$*, we come to conclusion that the zero hypothesis* H_0 *does not contradict available observations.*

Example 11.1:

To check up the new detector of a threshold of Pu^{329} concentration, two lines of the control are selected: the first line of the control is on the base of 3 detectors of a new type and the second line of the control is on the base of 5 detectors. A selective mean, which represents an excess of permissible concentration of Pu^{329}, is $\bar{x} = 10$ for the first line, for the second line is $\bar{y} = 5$. It is preset that dispersions of the first and second lines are equal to $\sigma_x^2 = 6$ and $\sigma_y^2 = 8$, respectively. With a value of $\alpha = 0.05$ it is necessary to find out the influence of application of new detectors on a quality of measurement of concentration Pu^{329} in the made product.

The decision:

The checked hypothesis $H_0 : x_0 = y_0$, i. e. the average excess of permissible concentration measured by new and old detectors, are identical. As a competing hypothesis it is possible to take $H_1 : \bar{x}_0 > \bar{y}_0$ or $H_2 : \bar{x}_0 \ne \bar{y}_0$ (in the given example it is more natural to use the hypothesis H_1, as its validity will mean the efficiency of application of a new detector).

According to (11.1) the physical value of statistics of a criterion

$$t = \frac{10-5}{\sqrt{\frac{6}{3}+\frac{8}{5}}} = 2.64.$$

At a competing hypothesis H_1 the critical value of statistics is found from a condition (11.2), i. e. $\Phi(t_{cr}) = 1 - 2 \cdot 0.05 = 0.9$, whence (under the table of values of the Laplace function) $t_{cr} = t_{0.9} = 1.64$, and at a competing hypothesis H_2 from a condition (11.3), i. e. $\Phi(t_{cr}) = 1 - 0.05 = 0.95$, whence (under the same table) $t_{cr} = t_{0.95} = 1.96$.

As the actually observable value $t = 2.64$ is more than the critical value t_{cr} (at any of taken competing hypotheses), the hypothesis H_0 rejects, i. e. at 5% – level of the value it is possible to come to conclusion that the new detector allows to measure the concentration of Pu^{329} more effectively.

Hypotheses about dispersions rather often arise since the dispersion characterizes such important parameters as accuracy of machines, devices, technological processes, etc.

Let there be two normally distributed populations, which dispersions are equal σ_1^2 and σ_2^2. It is necessary to check up a zero hypothesis about the equality of dispersions, i.e $H_0 : \sigma_1^2 = \sigma_2^2$ concerning the competing $H_1 : \sigma_1^2 > \sigma_2^2$ or $H_1' : \sigma_1^2 < \sigma_2^2$.

To check up the hypothesis H_0, independent samples of volume n_1 and n_2 are taken from these populations and, to estimate dispersions σ_1^2 and σ_2^2, the «corrected» sample variances $\hat{s}_1^2$ and $\hat{s}_2^2$ are used. Hence, the problem of checking a hypothesis is reduced to comparison of dispersions $\hat{s}_1^2$ and $\hat{s}_2^2$.

At validity of the hypothesis $H_0 : \sigma_1^2 = \sigma_2^2 = \sigma^2$ as estimation σ^2 it is possible to take the same dispersions $\hat{s}_1^2$ and $\hat{s}_2^2$ designed on elements of the first and the second samples.

It is necessary to say that a random variable

$$F = \frac{\hat{s}_1^2}{\hat{s}_2^2} \tag{11.4}$$

equal to the relation of the «corrected» sample variances $\hat{s}_1^2$ and $\hat{s}_2^2$ has F – the Fisher – Snedekor distribution with $k_1 = n_1 - 1$ and $k_2 = n_2 - 1$ degrees of freedom.

At formation of criterion of a rejection (acceptance) of a hypothesis H_0 it is necessary to take into account that distribution of statistics F is asymmetrical.

Therefore, the hypothesis H_0 is rejected, if $F > F_{\alpha;k_1;k_2}$ (in case of a right-hand critical area), or if $F < F_{\alpha;k_1;k_2}$ in case of a left-hand, or if $F < F_{1-\alpha/2;k_1;k_2}$ or $F > F_{\alpha/2;k_1;k_2}$ (in case of a bilateral critical area). Otherwise, the hypothesis H_0 is not rejected.

For calculation of values $F_{\alpha;k_1;k_2}$ it is necessary to use the table of values $F_{\alpha;k_1;k_2}$ – Fisher – Snedekor criterion.

LECTURE 12

CHECK OF HYPOTHESES ABOUT THE EQUALITY OF FRACTIONS OF AN ATTRIBUTE IN TWO AND MORE POPULATIONS

We shall formulate a problem. There are two populations, where general fractions of an attribute are accordingly equal p_1 and p_2. It is necessary to check up a zero hypothesis about the equality of general fractions, i. e $H_0 : p_1 = p_2$. To check up the hypothesis H_0, two independent samples of a rather great volume n_1 and n_2 are taken from these populations. Selective fractions of an attribute are accordingly equal $w_1 = \frac{m_1}{n_1}$ and $w_2 = \frac{m_2}{n_2}$, where m_1 and

m_2 are accordingly the number of elements of the first and the second samples possessing the given attribute.

At validity of a hypothesis $H_0 : p_1 = p_2 = p$ the difference $w_1 - w_2$ has the normal law of distribution with a population mean $M(w_1 - w_2) = p - p = 0$ and dispersion is $\sigma^2_{w_1-w_2} = \sigma^2_{w_1} + \sigma^2_{w_2} = p(1-p)\left(\frac{1}{n_1} + \frac{1}{n_2}\right)$. Therefore, statistics

$$t = \frac{w_1 - w_2}{\sigma_{w_1-w_2}} = \frac{w_1 - w_2}{\sqrt{\hat{p}(1-\hat{p})\left(\frac{1}{n_1} + \frac{1}{n_2}\right)}} \tag{12.1}$$

has the normal distribution $N(0;1)$.

As the unknown value p, which is included in the expression (12.1), its best estimation $\hat{p}$ equal to a selective fraction of an attribute if two samples to mix in one, i. e.

$$\hat{p} = \frac{m_1 + m_2}{n_1 + n_2} \tag{12.2}$$

is taken.

The choice of a critical area type and checking the hypothesis H_0 is carried out in such a way as mentioned above at checking the hypothesis about the equality of the averages.

Example 12.1:

The control of allowable quantity of a fissionable material was carried out with the help of two techniques, (neutron-activation analysis, a method of γ – spectrometry of a fissionable material radiation). By the first technique it has been checked up 105 fuel elements, in which the excess of concentration of a fissionable material, which is more than the allowable ($C_{FM} > C_{poss}$), has been fixed in 60 fuel elements. By the second technique it has been checked up 140 fuel elements, in which the excess of concentration of a fissionable material, which is more than allowable ($C_{FM} > C_{poss}$), has been fixed in 69 fuel elements. At the level of the value $\alpha = 0.02$ – to check up a hypothesis about the absence of essential distinctions in the quantity of concentration excess of a fissionable material, which is more than allowable, revealed by the first and the second techniques.

***The decision*:**

We have a hypothesis $H_0 : p_1 = p_2 = p$ i. e. fractions of the concentration excess, in the first and second techniques are equal. As alternative hypothesis, we shall take the hypothesis $H_1 : p_1 \neq p_2$.

At validity of the hypothesis H_0, according to (12.2) the best estimation p will be $\hat{p} = \frac{60+69}{105+140} = \frac{129}{245} = 0.547$. Selective fractions of the fixed excesses for each group are $w_1 = \frac{m_1}{n_1} = \frac{60}{105} = 0.571$ and $w_2 = \frac{m_2}{n_2} = \frac{69}{140} = 0.493$. Statistics of a criterion by (12.1) is

$$t = \frac{0.571 - 0.493}{\sqrt{0.527\left(1-0.527\right)\left(\frac{1}{105} + \frac{1}{140}\right)}} = 1.21 .$$

At the competing hypothesis H_1 it is chosen the critical bilateral area, which borders it is determined from a condition (11.3) $\Phi\left(t_{cr}\right) = 1 - 0.02 = 2.33$, whence (according to the table of values of the Laplace function) we have $t_{cr} = t_{0.98} = 2.33$. The actual value of criterion is less than critical, i. e. $t < t_{cr}$, hence, the hypothesis H_0 is accepted, i. e. the received data do not contradict a hypothesis about the absence of essential distinctions in the quantity of the concentration excess of a fissionable material, which is more than allowable one, revealed by the first and the second techniques.

In a case when more than three populations are present, the hypothesis about the equality of general fractions in all populations is put forward. As well as in the previous example the selective fractions of an attribute are calculated. To tell the truth, at validity of a hypothesis $H_0 : p_0 = p_1 = \ldots = p_l = p$ and at $l \to \infty$ statistics

$$\chi^2 = \frac{1}{\hat{p}\left(1-\hat{p}\right)} \sum_{i=1}^{l} n_i \left(w_i - \hat{p}\right)^2 \qquad (12.3)$$

has χ^2 – distribution with a $l-1$ degree of a freedom.

LECTURE 13
CHECKING THE HYPOTHESES ABOUT NUMERICAL VALUES OF PARAMETERS

Generally hypotheses about numerical values of parameters look like $H_0 : \Theta = \Delta$, where Θ is some parameter of the distribution being investigated, and Δ_0 is the area of its concrete values consisting, in that specific case, of one value.

Criteria of checking the hypotheses about numerical values of parameters of the normal law are resulted in tab. 13.1.

Table 13.1

Zero hypothesis	Assumptions	The statistical characteristic	An alternative hypothesis	Criterion of a rejection of a hypothesis
$a = a_0$	σ^2 is known	$t = \dfrac{\overline{x} - a_0}{\sigma/\sqrt{n}}$	$\left.\begin{matrix} a = a_1 > a_0 \\ a = a_1 < a_0 \end{matrix}\right\}$ $a = a_1 \neq a_0$	$\lvert t\rvert > t_{1-2\alpha}$ $\lvert t\rvert > t_{1-\alpha}$
	σ^2 is unknown	$t = \dfrac{\overline{x} - a_0}{s/\sqrt{n}}$	$\left.\begin{matrix} a = a_1 > a_0 \\ a = a_1 < a_0 \end{matrix}\right\}$ $a = a_1 \neq a_0$	$\lvert t\rvert > t_{1-2\alpha,n-1}$ $\lvert t\rvert > t_{1-\alpha,n-1}$
$\sigma^2 = \sigma_0^2$	a is unknown	$\chi^2 = \dfrac{ns^2}{\sigma_0^2}$	$\sigma^2 = \sigma_1^2 > \sigma_0^2$ $\sigma^2 = \sigma_1^2 < \sigma_0^2$ $\sigma^2 = \sigma_1^2 \neq \sigma_0^2$	$\chi^2 > \chi^2_{\alpha;n-1}$ $\chi^2 > \chi^2_{1-\alpha;n-1}$ Or $\left\{\begin{matrix} \chi^2 > \chi^2_{\alpha/2;n-1} \\ \chi^2 > \chi^2_{1-\alpha/2;n-1} \end{matrix}\right.$
$p = p_0$	It is rather great *n*	$t = \dfrac{w - p_0}{\sqrt{p_0 q_0/n}}$	$\left.\begin{matrix} p = p_1 > p_0 \\ p = p_1 < p_0 \end{matrix}\right\}$ $p = p_1 \neq p_0$	$\lvert t\rvert > t_{1-2\alpha}$ $\lvert t\rvert > t_{1-\alpha}$

***Example 13.1*:**

On the basis of the forecast the average of a saved up Pu^{329} in the same nuclear steam producing apparatus B-320 (the water cooled and water-moderated reactor-1000) should be $a_0 = 120$ g/HGA (g/heat generating assembly) for the operating period. The random inspection of 10 reactors has shown that $\overline{x} = 135$ g/HGA, and the average quadratic deviation of the contents of Pu^{329} is $s = 20$ g/HGA. At the value of $\alpha = 0.05$: a) to find out whether it is possible to accept the given forecast; b) to find capacity of criterion if actually the average deviation of the contents of all reactors is 130 g/HGA.

The decision:

a) The checked hypothesis $H_0 : \overline{x}_0 = a = 120$. As an alternative hypothesis, we shall take the hypotheses $H_1 : a > 120$. The general dispersion σ^2 being unknown, t - the Student criterion is used. The statistics of criterion according to table 13.1 is equal to $t = \dfrac{\overline{x} - a_0}{s/\sqrt{n-1}} = \dfrac{135 - 120}{20/\sqrt{10-1}} = 2.25$. The critical value of statistics is $t_{1-2\cdot 0.05;10-1} = t_{0.9;9} = 1.83$. As $\lvert t\rvert > t_{0.9;9}\,(2.25 > 1.83)$, the hypothesis H_0 is rejected, i. e. at 5% – value the made forecast should be rejected.

b) The alternative hypothesis $H_1 : \bar{x}_0 = a_1 = 120$. As $a_1 = 130 > a_0 = 120$, the critical area is right-hand and the critical value of the sample average is

$$\bar{x}_{cr} = \bar{x}_0 + t_{1-2\alpha;n-1}\frac{s}{\sqrt{n-1}} = a + t_{0.9;9}\frac{s}{\sqrt{n-1}} = 120 + 1.83\frac{20}{\sqrt{10-1}} = 132.2$$

i. e. the critical area for $\bar{x}$ is an interval $(132.2, +\infty)$. The capacity of criterion is equal to the probability P to reject a hypothesis H_0 when the hypothesis H_1 is true, i. e.

$$P = P(132.2 < \bar{x} < +\infty) = \frac{1}{2} + \frac{1}{2}\Theta(t, n-1),$$

where $t = \frac{\bar{x} - a_1}{s/\sqrt{n-1}} = \frac{132.2 - 130}{20/\sqrt{10-1}}0.33$.

According to the table of values $t_{\gamma,k}$ – the Student criterion $\Theta(0.33;9) \approx 0.25$.

So $P = \frac{1}{2} + \frac{1}{2}\Theta(0.33;9) \approx \frac{1}{2}(1 + 0.25) \approx 0.62$.

Other hypotheses about numerical values of parameters are also similarly checked up according to the criteria of checking resulted in table 13.1.

LECTURE 14
DEVELOPMENT OF THE THEORETICAL DISTRIBUTION LAW ACCORDING TO EXPERIMENTAL DATA

One of the important problems of mathematical statistics is *the ascertainment of the theoretical law of distribution of the random variable* describing the investigated attribute by the experimental (empirical) distribution representing a variation line.

For the decision of this problem it is necessary to determine a kind and parameters of the distribution law.

The assumption of *a kind of the distribution law* can be put forward proceeding from theoretical preconditions, experience of similar previous researches and, at last, on the basis of a graphic representation of the empirical distribution.

Parameters of distribution, as a rule, are unknown; therefore, they are replaced by the best estimations of sampling.

However the theoretical law of distribution might be well chosen, divergences between empirical and theoretical distributions will be inevitable. Naturally, there is a question: whether these divergences are explained only by the casual circumstances connected to the limited number of observations, or they are essential and are connected with that fact the theoretical law is chosen unsuccessfully. To answer this question, there are *criteria of concordance*.

Let it be necessary to check up a zero hypothesis H_0 that the random variable X being studied submits to the certain law of distribution. To check up the hypothesis H_0, it is necessary to choose some random variable U, which characterizes a degree of a divergence of theoretical and empirical distributions, which law of distribution at a rather high n is known and practically does not depend on the law of distribution of a random variable X.

χ^2 is the Pirson criterion. In the Pirson criterion χ^2, which is often used in practice, as a measure of a divergence the value χ^2 is taken equal to the sum of squares of deviations of relative frequencies (statistical probabilities) w_i from hypothetical p_i calculated on the suggested distribution taken with some weights c_i:

$$U=\chi^2=\sum_{i=1}^{m}c_i\left(w_i-p_i\right)^2. \tag{14.1}$$

Weights c_i are introduced so that at the same deviations $\left(w_i-p_i\right)^2$ the deviations, at which p_i is low, had the greater weight and deviations, at which p_i is great, had the less weight. If we take $c_i=\dfrac{n}{p_i}$, we shall obtain at $n\to\infty$ statistics:

$$U=\chi^2=\sum_{i=1}^{m}\frac{n}{p_i}\left(w_i-p_i\right)^2 \text{ or } U=\chi^2=\sum_{i=1}^{m}\frac{\left(w_i-np_i\right)^2}{np_i} \tag{14.2}$$

has χ^2- distribution with $k=m-r-1$ degrees of freedom, where m is the number of intervals of empirical distribution, r is the number of parameters of theoretical distribution.

Numbers $n_i=nw_i$ and np_i are called *empirical* and *theoretical frequencies, respectively*

The method of application of criterion χ^2 is the following:

1. The measure of a divergence of empirical and theoretical frequencies χ^2 is defined according to (14.2).
2. For the chosen level of a value α the critical value $\chi^2_{\alpha;k}$ is found according to table $\chi^2$of distribution at the number of degrees of freedom $k=m-r-1$.
3. If the actually observable value $\chi^2$is more than the critical one, i. e. $\chi^2>\chi^2_{\alpha;k}$, the hypothesis H_0 is rejected, if $\chi^2\le\chi^2_{\alpha;k}$, the hypothesis H_0 does not contradict the experimental data.

In *Kolmogorov's criterion* as a measure of a divergence between theoretical and empirical distributions the maximal value of the absolute value of a difference between the empirical function of distribution $F_n(x)$ and the corresponding theoretical function of distribution is considered:

$$D = \max\left|F_n(x) - F(x)\right| \tag{14.3}$$

The way of Kolmogorov's criterion application is the following:

1. The empirical function of distribution $F_n(x)$ and a prospective theoretical function of distribution $F(x)$ are developed.

2. The measure of a divergence between theoretical and empirical distribution D is defined according to the formula (14.3) and the value $\lambda = D\sqrt{n}$ (14.4) is calculated.

If the calculated value appears to be more than the critical λ_α, which is determined at the level of a value α, the zero hypothesis H_0 that the random variable X has the set law of distribution is rejected. If $\lambda \le \lambda_\alpha$, the hypothesis H_0 is not considered to contradict the experimental data.

LECTURE 15
CHECK OF HYPOTHESES ABOUT UNIFORMITY OF SAMPLES

Hypotheses about uniformity of samples are hypotheses that the examined samples are taken from the same general population.

Let it be two independent samples made of general populations with unknown theoretical functions of distribution $F_1(x)$ and $F_2(x)$. The zero hypothesis being checked up looks like $H_0 : F_1(x) = F_2(x)$ against the competing $H_1 : F_1(x) \ne F_2(x)$. We shall assume that functions $F_1(x)$ and $F_2(x)$ are continuous.

Statistics of Kolmogorov – Smirnov criterion looks like:

$$\lambda' = \sqrt{\frac{n_1 n_2}{n_1 + n_2}} \cdot \max\left|F_{n_1}(x) - F_{n_2}(x)\right|, \tag{15.1}$$

where $F_{n_1}(x)$ and $F_{n_2}(x)$ are the empirical functions of distribution constructed by two samples of volumes n_1 and n_2.

The hypothesis H_0 is rejected, if the actually observable value of statistics λ' is more than the critical λ'_{cr}, i. e. $\lambda' > \lambda'_{cr}$, and, otherwise, is accepted.

***An example 15.1*:**

The check of $C_{U^{235}}$ (concentration) in UF_6 on the outlet from a centrifuge was selectively carried out for a month. Results of two checks on deviations of device indications from the expected ones according to certificate characteristics of a centrifuge are resulted in table 15.1.

Table 15.1

Number of an interval	Intervals of underweight, %	Frequencies	
		n_{i_1} for sample 1	n_{i_2} for sample 1
1	0–10	3	5
2	10–20	10	12
3	20–30	15	8
4	30–40	20	25
5	40–50	12	10
6	50–60	5	8
7	60–70	25	20
8	70–80	15	7
9	80–90	5	5
		$n_1 = 110$	$n_1 = 100$

Is it possible to consider that at the level of a value of $\alpha = 0.05$ deviations of indications are described by the same function of distribution by results of two checks (random samples)?

The decision:

We shall designate $n_{i_1}^{cum}$ and $n_{i_2}^{cum}$ – the cumulative frequencies of samples 1 and 2, accordingly; $F_{n_1}(x_i) = n_{i_1}^{cum} / n_1$, $F_{n_2}(x_i) = n_{i_2}^{cum} / n_1$ are the values of these empirical functions of distribution. Results of calculations we shall reduce in table 15.2.

Table 15.2

x_i	$n_{i_1}^{cum}$	$n_{i_2}^{cum}$	$F_{n_1}(x_i)$	$F_{n_2}(x_i)$	$\lvert F_{n_1}(x_i) - F_{n_2}(x_i) \rvert$
10	3	5	0.027	0.050	0.023
20	13	17	0.118	0.170	0.052
30	28	25	0.254	0.250	0.004
40	48	50	0.436	0.500	0.064
50	60	60	0.545	0.600	0.055
60	65	68	0.591	0.680	0.089
70	90	88	0.818	0.880	0.072
80	105	95	0.955	0.950	0.005
90	110	100	1.000	1.000	0.000

From the last column it is visible that $\max\left|F_{n_1}(x_i)-F_{n_2}(x_i)\right|=0.089$. According to the formula (15.1) the statistics observable value at $n_1=110$ and $n_2=100$, $\lambda'=\sqrt{\frac{110\cdot100}{110+100}}\cdot0.089=0.644$. At the value of $\alpha=0.05$, $\lambda_{0.05}=1.36$ (the critical value according to the Kolmogorov's criterion).

As $\lambda'<\lambda_{0.05}$, $(0.644<1.36)$, the zero hypothesis H_0 is not rejected, hence, deviations of indications are described by the same function of distribution, i. e. they are steady and the natural process in the given centrifuge.

LECTURE 16

A CONCEPT OF THE VARIANCE ANALYSIS. A SINGLE-FACTOR ANALYSIS OF VARIANCE. A CONCEPT OF THE TWO-FACTOR ANALYSIS OF VARIANCE

The variance analysis is determined as the statistical method intended for estimating the influence of various factors on the result of the experiment, and also, for the following planning of similar experiments.

On the number of factors, which influence is being investigated, there are the one-factor and multi-factor analysis of variance.

The one-factor variance model looks like:

$$x_{ij}=\mu+F_i+\varepsilon_{ij},$$

where x_{ij} is the value of the investigated variable received at the i – level of a factor $(i=1,2,\ldots,m)$ with a j – order number $(j=1,2,\ldots,n)$;

F_i is the effect caused by influence of the i – factor;

ε_{ij} is a random component, or the perturbation caused by influence of uncontrollable factors, i. e. a variation of a variable inside a separate level.

The level of a factor is understood as its some measure and standing, for example, quantity of brought fertilizers, a kind of melting the metal or a number of a set of details, etc. The Basic preconditions of the analysis of variance:

1. The population mean of perturbation ε_{ij} is equal to zero for any i, i. e. $M(\varepsilon_{ij})=0$

2. ε_{ij} perturbations are mutually independent.

3. The variance of a variable x_{ij} (or perturbations ε_{ij}) is constant for any i, j i. e. $D(\varepsilon_{ij}) = \sigma^2$

4. The variable x_{ij} (or perturbations ε_{ij}) has the normal law of distribution $N(0;\sigma^2)$

Influence of levels of a factor can be as *fixed* or *regular* (model I), and random (model II). In multi-factor complexes the mixed model (model III), in which certain factors have random levels and others – fixed, is possible.

The two-factor variance model looks like:

$$x_{ijk} = \mu + F_i + G_j + I_{ij} + \varepsilon_{ijk},$$

where, x_{ijk} is the value of observation in a cell ij with the number k

μ is a general mean;

F_i is the effect caused by influence of the i – level of a factor A;

G_i is the effect caused by influence of the j - level of a factor B;

I_{ij} is the effect caused by interaction of two factors, i. e. a deviation from the average according to observations in a cell ij from the sum of the first three items in a model;

ε_{ijk} is the perturbation caused by a variation of a variable inside a separate cell.

We believe that ε_{ijk} has the normal law of distribution $N(0,\sigma^2)$, and all population means F_*, G_*, I_{i*}, I_{*j} are equal to zero.

LECTURE 17
FUNCTIONAL, STATISTICAL AND CORRELATION DEPENDENCES

In natural sciences we often speak about the *functional* dependence (connection}) when each value of one variable meets a quite certain value of another (for example, speed of a free falling body in vacuum depending on time, etc.).

But at the analysis each value of one variable meets a certain (conditional) distribution of other variable. Such dependence has received the name statistical (or stochastic, probabilistic). Occurrence of statistical connection concept is conditioned by that the dependent variable is subject to influence of some uncontrollable or uncounted factors, and also that measurement of variable values is inevitably accompanied by some random errors. An example of statistical connection is dependence of productivity on quantity of applied fertilizers, labor productivity at the enterprise of its installed power per employee, etc.

By virtue of ambiguity of statistical dependence between Y and X for the researcher, in particular, the circuit of dependence averaged on x is of interest, i. e. the law in change of a conditional population mean $M_x(Y)$ (the population mean of a random variable Y calculated in the assumption that the variable X has accepted the value x) depending on x.

Definition. *The functional dependence between values of one of them and a conditional population mean of another refers to as correlation dependence between two variables.*

Correlation dependence can be represented as:

$$M_x(Y)=\varphi(x) \text{ or } M_y(X)=\psi(y), \text{ where } \varphi(x)\neq const,\ \psi(y)\neq const.$$

These equations also refer to the *modeling equations of regress* (or simply – the equations of regress) accordingly Y on X, and X on Y, functions $\varphi(x)$ and $\psi(x)$ – *as modeling functions of regress* (or *functions of regress*).

At a large quantity of observations the same value x can meet n_x times, the same value y – n_y times, the same pair of numbers (x,y) can be observed n_{xy} times. Therefore, the data of observation are grouped, i. e. frequencies n_x, n_y, n_{xy} are counted. All grouped data are written down as the table, which is called *correlation.*

We shall explain the contents of the table by an example.

Y	X				
	10	20	30	40	n_y
0.4	5	–	7	14	26
0.6	–	2	6	4	12
0.8	3	19	–	–	22
n_x	8	21	13	18	60

In the first column of a table observable values (10, 20, 30, 40) of an attribute X are given, and in the first column – the observable values (0,4; 0,6; 0,8) of the attribute *Y*. On crossing of lines and columns there are frequencies n_{xy} of observable values of the attribute pairs.

In the last column the sums of frequencies of lines are written down. For example, the sum of frequencies of the first line is equal to

$n_y = 5+7+14 = 26$; this number specifies that the value of an attribute Y equal 0,4 (in a combination to various values of an attribute X) was observed 26 times.

In the last line the sums of frequencies of columns are written down. For example, the number 8 specifies that the value of an attribute X equal 10 (in a combination to various values of an attribute Y) was observed 8 times.

In a cell of the table located in the bottom of the right corner, the sum of all frequencies (the general number of all observations *n*) is placed. Obviously, $\sum n_{xy} = \sum n_y = n$. In our example

$$\sum n_x = 8+21+13+18 = 60 \text{ and } \sum n_y = 26+12+22 = 60.$$

LECTURE 18
SUBSTANTIVE ASPECTS OF THE CORRELATION ANALYSIS

The correlation analysis *(correlation model) is the method used when the data of observation or the experiment can be considered random and chosen from the population distributed according to the multivariate normal law.*

The basic goal of the correlation analysis *consists in revealing connection between random variables by dot and interval estimations of various (pair, multiple and partial) factors of correlation.* The additional problem of the correlation analysis (being the basic one in the regress analysis) consists in estimating the equations of regress of one variable by another.

Let's consider the elementary model of the correlation analysis – two-dimensional. The density of combined normal distribution of two variables X and Y looks like:

$$\varphi_N(x,y) = \frac{1}{2\pi\sigma_x\sigma_y\sqrt{1-\rho^2}} e^{-L(x,y)},$$

where $L(x,y) = -\frac{1}{2(1-\rho^2)}\left[\left(\frac{x-a_x}{\sigma_x}\right)^2 - 2\rho\frac{x-a_x}{\sigma_x}\cdot\frac{y-a_y}{\sigma_y} + \left(\frac{y-a_y}{\sigma_y}\right)^2\right]$;

a_x, a_y – population means of variables X and Y;

σ_x, σ_y – variances of variables X and Y;

ρ – the factor of correlation between variables X and Y, or *the general factor of correlation* determined by *the correlation moment (covariation)* K_{xy} under the formula:

$$\rho = \frac{K_{xy}}{\sigma_x\sigma_y} = \frac{M\left[(X-a_x)(Y-a_y)\right]}{\sigma_x\sigma_y};$$

or

$$\rho = \frac{M(XY) - a_x a_y}{\sigma_x \sigma_y}.$$

The size ρ characterizes tightness of connection between random variables X and Y in general population. The specified five parameters give exhaustive data on correlation dependence between variables.

At the combined normal law of distribution of random variables X *and* Y expressions for conditional population means, i. e. the modeling equations of regress, are expressed by linear functions:

$$M_x(Y) = a_y + \rho \frac{\sigma_y}{\sigma_x}(x - a_x); \tag{18.1}$$

$$M_y(X) = a_x + \rho \frac{\sigma_x}{\sigma_y}(y - a_y). \tag{18.2}$$

ρ is a parameter of tightness of connection only in case of linear dependence (linear regress) between two variables received in particular according to formulas (18.1), (18.2) at their combined normal distribution.

LECTURE 19
THE FACTOR OF CORRELATION

For the description of the system of two random variables except for population means and variances of components, other characteristics are also used; the correlation moment and factor of correlation is among them.

The correlation moment μ_{xy} of random variables X and Y is called a population mean of the product of these values deviations:

$$\mu_{xy} = M\{[X - M(X)][Y - M(Y)]\}.$$

To calculate the correlation moment *of discrete values,* the following formula is used:

$$\mu_{xy} = \sum_{i=1}^{n}\sum_{j=1}^{m}[x_i - M(X)][y_j - M(Y)]p(x_i, y_j),$$

The formula

$$\mu_{xy} = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}[x - M(X)][y - M(Y)]f(x,y)\,dxdy$$

is used for continuous values.

The correlation moment serves for the characteristic of connection between values X and Y. As it will be shown below, the correlation moment is equal to zero if X and Y are independent; hence, if the correlation moment is not equal to zero, X and Y are dependent random variables.

The correlation moment of two independent values X and Y is also equal to zero.

From definition of the correlation moment it follows that it has the dimension equal to the product of dimensions of values X and Y. In other words, the value of the correlation moment depends on units of measurements of random variables. For this reason for the same two values the quantity of the correlation moment has various values depending on in what units they have been measured. To remove this lack, the new numerical characteristic – the factor of correlation is used.

The *factor of correlation* r_{xy} of random variables X and Y is called the relation of the correlation moment to the product of average quadratic deviations of these values:

$$r_{xy} = \frac{\mu_{xy}}{\sigma_x \sigma_y}.$$

As dimension μ_{xy} is equal to the product of dimensions of values X and Y, σ_x has dimension X, and σ_y has dimension of the value Y, r_{xy} is a *dimensionless value* Thus, the value of the factor of correlation does not depend on a choice of measurement units of random variables. This is the advantage of the correlation factor over the correlation moment.

It is obvious that the correlation factor of independent random variables is equal to zero.

LECTURE 20
CHECK OF THE IMPORTANCE AND AN INTERVAL ESTIMATION OF CONNECTION PARAMETERS

In practical researches the tightness of correlation dependence between the considered variables is actually judged about not by the value of a general factor of correlation ρ (which it is usually unknown), but by the value of its selective tax r. As r is calculated by the values of the variables, which casually have fallen in a sample from the general population, the parameter r is *the random variable* as against the parameter ρ .

For a significant factor of correlation r it is expedient to find *a confidential interval (a confidential estimation),* which with the set reliability $\gamma = 1-\alpha$ contains (more precisely, «covers») the unknown general factor of correlation ρ. For construction of such an interval it is necessary to know the selective distribution of the correlation factor r, which at $\rho \neq 0$ is asymmetrical and very slowly (with the growth of n) converges to the normal distribution. Therefore, one resorts to a specially selected functions from r, which converge to well investigated distributions. *Z - Fisher's transformation* , is often used for selection of the function.

$$z=\frac{1}{2}\ln\frac{1+r}{1-r}. \qquad (20.1).$$

Even at small n the distribution z is approximately normal with the population mean

$$M(z)=\frac{1}{2}\ln\frac{1+\rho}{1-\rho}+\frac{\rho}{2(n-1)} \qquad (20.2)$$

and a dispersion

$$\sigma_z^2=\frac{1}{n-1}.$$

Therefore, in the beginning a confidential interval is built for $M(z)$:

$$z-t_{1-\alpha}\frac{1}{\sqrt{n-3}}\le M(z)\le z+t_{1-\alpha}\frac{1}{\sqrt{n-3}},$$

where $t_{1-\alpha}$ is the normalized deviation determined with the help of the Laplace function:

$$\Phi(t_{1-\alpha})=\gamma=1-\alpha.$$

To determine the confidential interval for, i. e. for the transition from z to ρ, there is a special table. At its absence the transition can be carried out under the formula:

$$r=th\,z=\frac{e^z-e^{-z}}{e^z+e^{-z}},$$

where $th\,z$ is a hyperbolic tangent.

If the correlation factor is significant, factors of regress b_{yx} and b_{xy} also significantly differ from zero, and interval estimations for corresponding *general factors of regress* β_{yx} and β_{xy} can be obtained by the formulas, based on that statistics $\frac{(b_{yx}-b_{xy})}{s_{b_{yx}}},\frac{(b_{xy}-b_{yx})}{s_{b_{xy}}}$ have the Student's t – distribution with $(n-2)$ degrees of freedom:

$$b_{yx}-t_{1-\alpha;n-2}\frac{s_y\sqrt{1-r^2}}{s_x\sqrt{n-2}}\le\beta_{yx}\le b_{yx}+t_{1-\alpha;n-2}\frac{s_y\sqrt{1-r^2}}{s_x\sqrt{n-2}}\ ;$$

$$b_{xy}-t_{1-\alpha;n-2}\frac{s_x\sqrt{1-r^2}}{s_y\sqrt{n-2}}\le\beta_{xy}\le b_{xy}+t_{1-\alpha;n-2}\frac{s_x\sqrt{1-r^2}}{s_y\sqrt{n-2}}.$$

LECTURE 21
THE CORRELATION RELATION AND A CORRELATION INDEX

As it has been stated, the correlation factor is a valuable parameter of connection tightness only in case of linear dependence between variables. However, a necessity for an authentic parameter of connection intensity at any form of dependence arises very often.

To obtain such a parameter we shall recollect a rule of dispersion summation:

$$s_y^2 = s_{iy}'^2 + \delta_{iy}^2, \tag{21.1}$$

where s_y^2 is a general dispersion of a variable

$$s_y^2 = \frac{\sum_{j=1}^{m} \left(y_j - \bar{y}\right)^2 n_i}{n}; \tag{21.2}$$

$s_{iy}'^2$ is the average group of dispersions s_{iy}^2, or a residual dispersion-

$$s_{iy}'^2 = \frac{\sum_{i=1}^{l} s_{iy}^2 n_i}{n}, \tag{21.3}$$

where $$s_{iy}^2 = \frac{\sum_{j=1}^{m} \left(y_j - \bar{y}_i\right)^2}{n}; \tag{21.4}$$

δ_{iy}^2 is an among-groups dispersion

$$\delta_{iy}^2 = \frac{\sum_{i=1}^{l} \left(\bar{y}_i - \bar{y}\right)^2 n_i}{n}. \tag{21.5}$$

That part of variability, which arises because of variability of unaccounted factors independent on X, is measured by the residual dispersion. The among-groups dispersion expresses that part of a variation Y, which is caused by the variability X. The value

$$\eta_{yx} = \sqrt{\frac{\delta_{iy}^2}{s_y^2}} \tag{21.6}$$

is called *the empirical correlation relation* Y *on* X. The more closely connection, the greater influence on a variation of a variable Y the variability X exerts in comparison with the unaccounted factors, the more η_{yx}. The value η_{yx}^2 called *the empirical factor of determination* shows what part of the general variation Y is caused by a variation X. *The empirical relation* X is similarly introduced *by* Y*:*

$$\eta_{xy} = \sqrt{\frac{\delta_{ix}^2}{s_x^2}}. \qquad (21.7).$$

We shall note **the basic properties of correlation relations** (at enough great volume of a sample n):

1. *The correlation relation is a non-negative value not over than 1:* $0 \le \eta \le 1$
2. *If* $\eta = 0$, the *correlation connection is absent.*
3. *If* $\eta = 1$, *there is a functional dependence between variables.*
4. $\eta_{yx} \ne \eta_{xy}$, i. e. as against the correlation factor r, (for which $r_{yx} = r_{xy} = r$), when calculating the correlation relation it is essential to consider what variable is independent and what variable is dependent.

The empirical correlation relation η_{yx} *is a parameter of points dispersion of a correlation field concerning an empirical line of the regress* expressed by a broken line connecting values $\bar{y}_i$. However, in connection with that the natural change $\bar{y}_i$ is broken by casual zigzags of the broken line, η_{yx} arising owing to residual action of uncounted factors exaggerates the tightness of connection. Therefore, alongside with n_{yx}, the parameter of tightness of the connection describing *the point dispersion of a correlation field concerning a line of regress* y_x is considered. The parameter R_{yx} was called ***the theoretical correlation relation*** *or* ***an index of correlation*** Y ***by*** X***:***

$$R_{yx} = \sqrt{\frac{\delta_y^2}{s_y^2}} = \sqrt{1 - \frac{s_y'^2}{s_y^2}} \qquad (21.8)$$

where dispersions δ_y^2, $s_y'^2$ are defined under formulas (21.2) – (21.4).

Likewise R_{yx} *the index of correlation* X is introduced *by* Y*:*

$$R_{xy} = \sqrt{\frac{\delta_x^2}{s_x^2}} = \sqrt{1 - \frac{s_x'^2}{s_x^2}} \qquad (21.9)$$

The advantage of the considered parameters η and R is that they can be calculated at any form of connection between variables. Though η overestimates the tightness of connection in comparison with R, but for its calculation it is not necessary to know the equation of regress. Correlation relations η and R are connected with the correlation factor r by the following way:

$$0 \le |r| \le R \le \eta \le 1.$$

LECTURE 22
THE CONCEPT OF THE MULTIVARIATE CORRELATION ANALYSIS

Many phenomena are more often adequately described by multiple-factor models. Therefore, there is a necessity to generalize the two-dimension correlation model considered above in case of several variables.

Let there be a population of random variables $X_1, X_2, \dots, X_i, \dots, X_j, \dots, X_p$ having normal joint distribution. In this case we shall make a matrix:

$$Q_p = \begin{pmatrix} 1 & \rho_{12} & \dots & p_{1p} \\ \rho_{21} & 1 & \dots & p_{2p} \\ \dots & \dots & \dots & \dots \\ \rho_{p1} & \rho_{p2} & \dots & 1 \end{pmatrix}$$

made of pair factors of correlation $\rho_{ij}\left(i, j = 1, 2, \dots, p\right)$, which we shall call the correlation. *The primary goal* ***of the multivariate correlation analysis*** *consists in estimating the correlation matrix Q_p by a sample.* This problem is solved by definition *of a matrix of selective correlation factors:*

$$q_p = \begin{pmatrix} 1 & r_{12} & \dots & r_{1p} \\ r_{21} & 1 & \dots & r_{2p} \\ \dots & \dots & \dots & \dots \\ r_{p1} & r_{p2} & \dots & 1 \end{pmatrix},$$

where $r_{ij}\left(i, j = 1, 2, \dots, p\right)$ are determined under the formula $r = \dfrac{\overline{xy} - \overline{x} \cdot \overline{y}}{s_x s_y}$ or its modification.

In the multivariate correlation analysis two typical problems are considered:

a) Definition of connection tightness of one of variables with population of other $(p-1)$ variables included in the analysis.

b) Definition of connection tightness between variables at fixation or exception of influence of other q variables, where $q \le (p-2)$.

These problems are solved with the help of plural and partial factors of correlation.

The tightness of linear interrelation of one variable X_i with the set of other $(p-1)$ variables of X_j considered as a whole is measured with the help *of plural factor of correlation* $\rho_{1,2,\dots,p}$, which is generalization of the pair factor of correlation ρ_{ij}. *The selective plural* or *cumulative factor of correlation*, being estimation $R_{i,12\dots p}$, can be calculated under the formula:

$$R_{i,12\ldots p} = \sqrt{1 - \frac{|q_p|}{q_{ii}}},$$

where $|q_p|$ is a determinant of a matrix q_p; q_{ii} is algebraic addition of an element r_{ii} of the same matrix (it equals 1).

With the help of a plural factor of correlation (as approaching R to 1) *one can judge about the tightness of interrelation, but not about its direction. The value* R^2 called a *selective plural (or cumulative) factor of determination* shows what share of a variation of the investigated variable the variation of other variables explains.

If variables correlate with each other, the influence of other variables partially affects the value of the pair factor of correlation. In this connection it is necessary to investigate *the partial correlation* between variables with the exception of influence of one or several variables.

The following expression

$$r_{ij,12\ldots p} = \frac{-q_{ij}}{\sqrt{q_{ii} q_{jj}}},$$

where q_{ii} and q_{jj} are algebraic additions of elements r_{ii} and r_{jj} of the matrix q_p we call *a selective partial correlation factor between variables* X_i *and* X_j at the fixed values of other $(p-2)$ variables.

LECTURE 23
THE CONCEPT OF THE REGRESS ANALYSIS

The basic statements of the regress analysis. An interval estimation and check of the importance of the regress equation.

Problems of the regress analysis are an establishment of the form of dependence between variables, the estimation of the regress function, an estimation of unknown values (the prediction of values) of a dependent variable.

In the regress analysis *one-sided dependence of a random dependent variable* Y *on one (or several) nonrandom independent variable X,* which is often called *the explaining variable,* is considered. Such dependence can be submitted as the modeling equation of regress: $M_x(Y) = \varphi(x)$, where $\varphi(x) \neq const$. By virtue of influence of unaccounted random factors and reasons, separate observations y will deviate the function of regress $\varphi(x)$ in the greater or less degree. In this case *the equation of interrelation of two variables (a pair regress model)* can be expressed by the formula: $y = \varphi(x) + \varepsilon$ where ε is the random variable describing a deviation from a function of regress. This variable we shall call *disturbing* or simply *disturbance*. Thus, *in the regress model the dependent variable Y is a certain function $\varphi(x)$ to within the random disturbance ε..*

We shall consider *the linear regress analysis,* for which the function $\varphi(x)$ ***is linear*** concerning estimated parameters:

$$M_x(Y) = \beta_0 + \beta_1 x. \tag{23.1}$$

Let's assume that to estimate parameters of a linear function of regress (23.1), the sample containing *n* pairs of values of variables (x_i, n_i), where $i = 1, 2, 3, \ldots, n$, is taken. In this case *the linear pair model* looks like: $y_i = \beta_0 + \beta_1 x_i + \varepsilon_i$.

We shall note **the basic preconditions of the regress analysis:**

1) *A dependent variable y_i (or disturbance ε_i) is the random variable, and an explaining variable x_i is the nonrandom value.*

2) *The population mean of disturbance ε_i is equal to zero:* $M(\varepsilon_i) = 0$.

3) *The dispersion of a dependent variable y_i (or disturbance ε_i) is constant for any i:* $D(\varepsilon_i) = \sigma^2$.

4) *Variables y_i and y_j (or disturbances ε_i and ε_j) are not correlated:* $M(\varepsilon_i \varepsilon_j) = 0 (i \neq j)$.

5) *A dependent variable y_i (or disturbance ε_i) is a normally distributed value.*

The relations between the phenomena and processes can be not always expressed by linear functions as there can be unwarrantable great errors. In such cases the nonlinear regress is used.

The choice of the equation of regress (this stage is called *the specification* or *parameterization of a model is carried out* on the basis of the experience of the previous researches, references, other reasons of professional character, and also visual observations of points of a correlation field. The following kinds of the equations of nonlinear regress occur more often:

- *polynomial* $y_x = b_0 + b_1 x + \ldots + b_k x^k$;
- *hyperbolic* $y_x = b_0 + \dfrac{b_1}{x}$;
- *exponential* $y_x = b_0 \cdot x_1^{b_1} \cdot \ldots \cdot x_p^{b_p}$.

INTRODUCTION IN THE ACCOUNT, THE CONTROL AND PHYSICAL PROTECTION OF NUCLEAR MATERIALS

LECTURE 1
INTRODUCTION

Nonproliferation of mass destruction weapons: introduction in a problem. The history of development and distribution in the world of nuclear technologies of the military and peace purpose.

In 40th years of the XX-th century the process of mastering by secrets of an atomic energy has led the mankind to practical application of nuclear technologies. Start-up of the first nuclear reactor on December 2, 1942 and the first nuclear bomb test on July 16, 1945 in Alamogordo (USA) in an equal measure can be considered as a reference point of a nuclear century. Sides of its contradictions were designated sharply: triumph of a science – tragedy of Hiroshima and Nagasaki in August, 1945; power of the person, made an atomic energy to serve to a man, – powerlessness of mankind before a threat of nuclear catastrophe.

After the USA the Soviet Union has seized the nuclear weapon (the first nuclear test – on August 29, 1949), then England (on October 3, 1952), France (on February 13, 1960), Chinese People's Republic (on October 16, 1964). The possession by a super bomb was perceived as an attribute of the geostrategic full value fixing the status of great powers – constant members of Security Council of the United Nations. However, for similar reasons a number of other countries also aspired to master the nuclear weapon.

Many states (from Sweden up to the republic of South Africa and from Brazil up to Japan) in different years carried out confidential nuclear programs for the military purposes. Before the world community there was a question: how to take the most of peace potential of an atomic energy, having reduced thus to a minimum threat of its military application. The more the countries got access to the nuclear weapon after occurrence of a situation of «mutual containment» of the USA and the USSR, the more risk of nuclear war was. It became much more difficult to control its distribution. Full prohibition of the nuclear weapon with the subsequent destruction of its stocks would be optimum. Such a decision would remove a threat of a nuclear war and discrimination of the states on the basis of possession the super-weapon. As realities of «cold war» blocked this way, nuclear powers have selected the more difficult variant. The essence of it is to simplify an access to the peace nuclear technologies of all states under condition of guarantee observation of not directing the obtained materials and the equipment to the military sphere, refusal of uncontrolled re-export, etc.

In the beginning of 50th the states importing the nuclear materials came to conclusion that it would be much easier to agree that the use of nuclear materials and the equipment in peaceful purposes should be supervised by employees of foreign states

Realization of control functions in the field of safety, or guarantees, has been delegated to the International Atomic Energy Agency (IAEA), which Charter has come into force on July 29, 1957.

In 60th years there was a prompt evolution of system of IAEA guarantees. It in many respects was explained by that fact the interest to the nuclear power, the peak of which was in the end of 70th years, has quickened. The danger of spreading the military nuclear technologies has simultaneously increased. The number of «the threshold countries», that is the states, technically capable to create a nuclear bomb grew. Threat of distribution was especially sharp in the advanced countries, including that have suffered defeat in the world war. All this demanded radical change of a policy of nuclear powers, creation of an effective mode of non-proliferation in the world.

After long negotiations for signing the Nonproliferation treaty of the nuclear weapon, which became a symbol of the established mode of non-distribution on July 1, 1968, was opened .

LECTURE 2

NON-PROLIFERATION BASICS OF MASS DESTRUCTION WEAPONS AND NUCLEAR MATERIALS (MDW&NM)

Studying the nuclear nonproliferation. Education of experts in Russia (high schools, programs, systems of vocational training and improvement of professional skill) and abroad. Literature and review of printed and electronic sources. Search and an estimation of the information on nonproliferation.

Problems of *nonproliferation* – problems of political and technological character:

- The political superiority – the certain military superiority.
- The military superiority – the certain technological superiority.
- The technological superiority – the certain economic superiority.
- The economic superiority – resources and the legal form of their disposal.

Why do problems of nonproliferation take a special place in a human society?

- Non-distribution – preservation of the certain superiority and various kinds of independence. (Non-distribution of the high technologies).
- Distribution – preservation of the certain superiority and deprivation of other countries of the certain independence. (Political and economic actions).
- Use of the technological superiority with a view of terrorism.
- Why did the problem of introducing the education in systems of training experts, who should work in various fields of nuclear technologies, arise?
- The necessity of increasing the culture of the personnel working in the sphere of NM application.
- The necessity of increasing the safety of nuclear technologies in which NM are used.
- The necessity of training of the personnel for work with the new equipment and systems of NM protection from the non-authorized actions.
- The necessity of expert adaptation to work with NM of increased requirements.
- Presence of a large number of the nuclear enterprises in Siberian region.
- Studying the international and legal aspects of problems of nonproliferation.

Nonproliferation Sites:

- Center for Nonproliferation Studies http://cns.miis.edu/
- Carnegie Endowment http://www.ceip.org/files/nonprolif/default.asp
- Federation of American Scientists http://www.fas.org/index.html
- Henry L. Stimson Center http://www.stimson.org/
- CNS Educational Resources Guide
  http://nsdl.miis.edu/cnserd/results.asp
  http://cnsdl.miis.edu/cnserd/results.asp
- Nuclear Control Institute Terrorism Website
  http: // www.nci.org/nci-nt.htm/
  sites2 http: // www.nci.org/nci-nt.htm

Russian Nonproliferation Sites:

- PIR Center: http: // www.pircenter.org/
- Carnegie: http: // www.carnegie.ru/
- Yadernaya bezopasnost: http://www.npi.ru/nucrep/
- Minatom Sites: http://www.minatom.ru/links/

- Compilation of nuclear news:
  http://www.minatom.ru/presscenter/news.html
  http://www.laes.sbor.ru/
  http://www.laes.sbor.ru/ciso/work/razdel/pressa/obzor/current.htm
- Moscow Institute of Physics and Technology Center for Arms Control,
- Energy and Environmental Studies: http://www.armscontrol.ru/
- Nuclear.ru: http://www.nuclear.ru/index.shtml
- Environmental organizations: http://www.antiatom.ru/;
  http://www.ecodefense.ru/; http://www.atomsafe.ru/

LECTURE 3
LEGAL BASICS OF NUCLEAR NONPROLIFERATION (1)

The Russian legal and normative base in the field of nonproliferation. The basic concepts. Normative documents.

- THE LAW OF THE RUSSIAN FEDERATION «ABOUT USE OF THE ATOMIC ENERGY» OF NOVEMBER 21, 1995 (IN EDITION OF FEBRUARY 10, 1997)
- REGULATIONS ABOUT THE MINISTRY OF THE RUSSIAN FEDERATION REGULATIONS ON THE ATOMIC ENERGY OF APRIL 5, 1997.
- ABOUT LICENSING ACTIVITY IN THE FIELD OF USE OF THE ATOMIC ENERGY OF JULY 14, 1997.
- THE CRIMINAL CODE OF THE RUSSIAN FEDERATION OF JUNE 13, 1996 (IN EDIT. FROM JUNE 19, 2001)
- THE RESOLUTION OF THE RUSSIAN FEDERATION OF OCTOBER 14, 1996 N 1205
- THE SYSTEM CONCEPT OF THE STATE ACCOUNT AND THE CONTROL OF NUCLEAR MATERIALS
- THE RESOLUTION OF THE RUSSIAN FEDERATION OF JULY 10, 1998 N 746
- THE ORGANISATION REGULATIONS OF THE SYSTEM OF THE STATE ACCOUNT AND THE CONTROL OF NUCLEAR MATERIALS
- THE RESOLUTION OF THE RUSSIAN FEDERATION OF DECEMBER 15, 2001Г. N 962
- REGULATIONS ABOUT THE STATE ACCOUNT AND THE CONTROL OF NUCLEAR MATERIALS

The basic concepts:

«Nuclear materials» – the materials containing or capable to reproduce fissionable (splitting) nuclear substances;

«Special non-nuclear materials» – the materials, which are not containing or not capable to reproduce nuclear materials but which can be used in the devices intended for realization of explosive allocation of a nuclear energy (nuclear explosion);

«Nuclear installations» – constructions and complexes with nuclear reactors, including nuclear stations, water crafts and others water means, space vehicles, other transport and transportable means; constructions and complexes with industrial, experimental and research nuclear reactors, critical and sub-critical nuclear stations; constructions, complexes and ranges with the nuclear charges placed on them, a nuclear ammunition; other containing nuclear materials of a construction, complexes, installations for manufacture, uses, processing and transportation of nuclear materials;

«The nuclear weapon» – nuclear charges, nuclear ammunition, and also the carriers of nuclear ammunition equipped with them, complexes of the nuclear weapon and carriers of the nuclear weapon;

«The account of nuclear materials» – definition of actual quantity of nuclear materials, making up, registration and conducting registration and accounting documents;

«The control of nuclear materials» – the administrative control over presence and moving of nuclear materials with the purpose of prevention of their non-authorized use.

Nuclear materials and special non-nuclear materials are subject to the state account and the control without regard to a chemical compound, to which they belong, and their physical condition.

LECTURE 4
LEGAL BASICS OF NONPROLIFERATION (2)

The legislative and normative principles of the system of the state account and control of nuclear materials (NM). A structure and functions of the system of the state account and the control of nuclear materials. The concept of national security of the Russian Federation. The list of measures on the program realization of raising the account level, the control and physical protection of NM.

The main functions of the system of the state account and the control of nuclear materials are development and introduction of well-founded norms and rules of account and control of nuclear materials, supervision of system of the state account and control of NM.

The state account and the control of the nuclear materials intended for use in the peaceful purposes are fulfilled by Rosatom.

The state account and the control of the nuclear materials intended for use in the defense purposes are fulfilled by Rosatom and by the Ministry of the Russian Federation Defense.

The state account and the control of the nuclear materials intended for use in the peaceful and defense purposes are fulfilled by the Federal bodies of the executive power, in which disposal the nuclear materials are.

The main goal of the system of ensuring the security is Overall objective of system of a safety is maintenance of steady functioning of nuclear object and prevention of threats of his safety, protection of legitimate interests of subjects of a safety (the state, institutions of local government, administration, the personnel, citizens) from illegal encroachments, protection of a life and health of the personnel and citizens, недопущение plunders and destructions of property and values and, first of all, nuclear materials and radioactive substances, infringement of industrial activity (technological processes and work of means), disclosure, loss, outflow, distortion and destruction of the information.

Threats of safety of nuclear objects are:

- Certificates of illegal intervention in activity of subjects in the field of use of an atomic energy.
- Plunders and illegal circulation of nuclear materials, radioactive substances, materials of nuclear technologies, other material and information resources.
- Diversions and acts of terrorism concerning objects and subjects of safety.
- Personnel threat.

Principles of a safety:

- Legality of creation and functioning of system of a safety.
- Timeliness, or anticipatory character of measures of a safety on the basis of the analysis and forecasting of threats.
- Constant readiness of protective measures.
- Validity of used opportunities and means of protection on a modern level of development of a science and technical equipment.

LECTURE 5
BASES OF THE EXPORT CONTROL OF NUCLEAR MATERIALS (1)

Definition of System of the Export Control. The Structure of the system of the Export Control. Participation in the International Modes of Nonproliferation. Control Lists.

The export control (EC) is a set of measures providing realization established legislatively or through other normative legal certificates of the procedure of foreign trade activities concerning the goods, information, works, services, results of intellectual activity, which can be used at creation of the mass destruction weapons (MDW), means of its delivery, other kinds of arms and military technical equipment.

Thus, foreign trade activities is understood as a foreign trade, investment and other activity in the field of the international exchange of the goods, the information, works, services, results of intellectual activity, including the exclusive rights to them (the intellectual property).

Thus, the EC operates with reference to materials, technologies and information, which could be used at creation of the nuclear weapon, chemical weapon, biological weapon, toxin weapon, the MDW based on other physical principles, means of delivery (carriers) of any MDW, and also, on occasion, it can be applied to conventional armaments and military technical equipment.

The EC is one of the basic tools on prevention of distribution and means of its delivery, technologies of their manufacture and other information and knowledge about them, and also materials and technologies of a double use – that is what can be used both in the civil purposes, and for manufacture of the MDW, its components and means of its delivery.

The EC mode takes a special place in a policy of the external economic regulation of any advanced country as it is simultaneously the important tool of the foreign policy. It is based on the license order of the export of certain goods and the technologies, which have got in special control lists. Thus, the export is understood, more widely, actually the question is about all external economic operations touching the transfer of the controllable goods or technologies.

The EC is carried out through creation of the international EC system and national EC systems of the states.

LECTURE 6
BASES OF THE EXPORT CONTROL OF NUCLEAR MATERIALS (2)

The universal control (a mode «catch-all») Procedures of the export control. Check (verification). Information interchange.

The idea of the universal control consists that any export should not be carried out if it can be somehow directed on the manufacture of the MDW even if the exported material or technology are not included in control lists. The politics of the universal EC has been initiated in 1975 in frameworks of GNS by the Great Britain and the Soviet Union, and then maintained by the United States, which have included this concept in the national system of the EC. Thus, the international legally obligatory arrangements under the universal control are absent.

According to the rules of the universal control working in a number of the states (in particular, in Russia), juridical or physical persons are forbidden to conclude, make the external economic transactions with the goods, the information, works, services, results of intellectual activity or to participate in them in any form otherwise in case such persons authentically know that the given goods, the information, works, services, results of intellectual activity will be used by the foreign state or the foreign person for the purposes of creation of the MDW and means of its delivery.

Exporters are obliged to receive the special sanction of a national body on EC on realization of the external economic operations with the goods, the information, works, services, the results of intellectual activity, which are not falling under action of control lists if they are informed by this or other competent state body or have the bases to believe, that the given goods, the information, works, services, results of intellectual activity can be used with a view of nuclear distribution.

LECTURE 7
BASES OF THE EXPORT CONTROL OF NUCLEAR MATERIALS (3)

Customs service (procedural actions on the basis of legislative base on nonproliferation of the MDW and NM). The enforcement – as a basis of the state guarantees. The in-house service of the export control (ISEC). An element «training» of the system of the export control.

The ISEC procedures include the organization of work of the device participating during the control; provide updating the existing procedures, development and introduction new, and also compulsion to their performance. The legal base of EC should define what establishments, the organizations and agencies are included in process of the export control.

The mechanism of interdepartmental coordination is necessary for effective realization of EC procedures.

The element of check includes a legal basis, bodies, rules and the actions connected to confirmation of reliability of the end user, a place and the purpose of use of the goods how they have been declared in the license as possible action – inspection of places of use.

The information exchange in the legal and organizational area with the purpose of informing in regarding the EC, legislations and realizations of the EC, and also its internal and international regulation. The widest element of the EC.

The customs house is a specially established state law-enforcement department, developing and carrying out measures by definition and crossing of illegal export / import.

The place and role of customs house within the framework of a policy of nonproliferation should be determined and fixed legislatively.

The state should provide a strict enforcement in the EC sphere, in particular – criminal and civil punishment for infringements of its requirements.

The in-house service of the export control (ISEC) is a structural unit of the enterprise (firm), and its major problem is to provide observance by the enterprise of norms and rules of the EC .Сотрудники of the ISEC are obliged to accompany with the goods from the very beginning of its manufacture and till the moment of its export abroad. The export control begins with the ISEC activity.

The element «training» of EC system provides the system with the qualified employees of all levels, includes a network of educational establishments, and provides informing exporters. For effective functioning of the EC system the system of a professional training on each of the listed above elements of the EC including licensing and the customs control.

LECTURE 8

THE SYSTEM OF PHYSICAL PROTECTION (SPHP)

Basic notions. The history of developing the system of Physical Protection. Bases of designing and the analysis of systems of physical protection.
The Structure of SPhP.

«The Physical protection» (in the historical point of view) is the system of regime – army measures aimed at the provision of a security regime of the carried out, a defence works, and also a security and a defense of particularly important state objects from the probable actions from army of NATO.

Factors of Developing SPhP requirements:

- deideologization of the notion «enemy» (the offender);
- criminalization of the most part of a society;

- the increase of vulnerable of «the human factor» due to negative processes in the sphere of ideology, «flooding» of the patriotism bases;
- the danger in crease of the «internal enemy»;
- the physical and moral aging of the existing against the undoubted technical progress of foreign means;
- technical protection of the dangerous objects;
- lagging behind the life and the military charter;
- trying to attain the conformity of the international standards in the speare of the nuclear security.

The Federal bodies of the executive power providing the functionality of SPhP:

- Rosatom of RF.
- The Federal Security Service of RF.
- The Ministry for Internal affairs of RF.
- The Ministry of Defence of RF.
- The State Atom Supervision of RF (Gosatomnadzor).
- The Ministry of the Fire Service of RF.
- The Ministry of Transport of RF.
- The State Customs Committee the Russian Federation.

LECTURE 9
THE FUNDAMENTALS OF PROJECTING THE SYSTEM OF PHYSICAL PROTECTION

<u>The SPhP projecting technique:</u>

1. The definition of goals of developing SPhP.
2. SPhP designing.
3. The estimation of SPhP.

<u>Understanding what is to be defended and who is to be defended of:</u>

1. Definition of the object characteristics.
2. Definition of possible threats.
3. Definition of sabotage aims.

<u>The following object characteristics are defined:</u>

1. The borders of the object territory.
2. Characteristics of buildings.
3. Allocation of premises.
4. Allocation of points of access into the premises.
5. Characteristics of the processes occurring at the object.
6. The exploitation conditions of the object (working hours, unworking hours, potential emergencies).
7. The existing protection means.

Definition using all available sources:

1. The Sort of offenders:
    - external offenders;
    - internal offenders;
    - conspiracy of external and internal offenders.
2. The tactical methods of offenders:
    - The disguised attempt of actions.
    - The force attack.
    - Deception.
3. Possibilities of offenders:
    - Knowledge and experience.
    - Causes and motives of actions.
    - Practical knowledge and skills.
    - Armed means and other means to carry out Sabotage.

Definition of possible goods of the following kinds of diversions:

- Radiation sabotage.
- Definition of critical sites needed in protection.
- Theft at nuclear materials.
- The definition of placing the nuclear materials needed in protection.

The Basic Principles of SPhP Design:

- Combination of components of SPhP in accordance with restrictions concerning characteristics of the object.
- Using such system components, which are in complement of one another and permit eliminating of «weak spots» in the system configuration.
- Arrangement of detection means (detectors) nearer to the perimeter and detection means nearer to the diversion target.

Basic principles of Estimation of SPhP:

- Verification of the required characteristics of the System.
- Use of the technology of the system modeling (The preferable estimation method of the project).

As a result of the carried out analysis of the system:

- Vulnerability of the SPhP is defined («weak spots»).
- The repeated projecting with the purpose of eliminating the noticed «weak spots» is made.
- The re-estimation of the system in confirming the final estimation of «weak spots» is carried out.

LECTURE 10
PHYSICAL PROTECTION OF FISSIONABLE MATERIALS

The Physical protection is the set of organization methods of engineering means and actions security departments with the purpose of preventing diversions or misappropriation of nuclear materials.

Problems of SPhP:

- foreseeing of the non-sanction access;
- finding the non-sanction action in time;
- delay of the enemy penetration;
- stopping of non-sanction actions;
- detention of person concerned with preparation or caring out of the diversion or misappropriation of NM.

The diversion or any premeditated action concerning NM, nuclear plants, storage premises for NM or transportation means for NM or nuclear plants, with are able to results in emergency and create the threat for people's health in the result of radiation effects or lead to the radioactive pollution of the environment.

The non-sanction action is performing or an attempt of performing diversion, NM misappropriation, non-sanction access, transportation or importation of prohibited objects, putting out of operation physical protection means.

The head is responsible for ensuring the physical protection of a nuclear-dangerous object.

While creating the SPhP it is necessary:

- to take into consideration the object features and measures of nuclear, radiation, ecological, fire, technical or other kinds of security;
- to provide a stable system work, at the fault of any element did not disturb functionality of the SPhP an a whole;
- to limit the number of persons having an access to the NM and nuclear plants up to the minimum.

LECTURE 11

THE SYSTEM OF ACCOUNT AND CONTROL OF THE FISSIONABLE MATERIALS

Account and control of nuclear materials at the nuclear plant.

Security of NM:
- misappropriation;
- use for not its proper purposes;
- radiation sabotage or any hostils, which can result in inadmissible consequences the state security, health or safety of population or ecology;
- physical security of nuclear materials, plants and sites;
- personnel security;
- information security;
- account and control of NM.

The System of NM security:
- to with stand threat;
- to reveal the non-sanction acts;
- to react for acts of criminals immediately after their discovery;
- to return nuclear materials;
- to watch that NM should not be directed not for the proper purpose or should not be lost.

NM information security:
- Facts, information data about nuclear materials or about their security.
- Computer security.
- Information sources control, physical security, security of personnel and administration, protection of communication lines.
- Software and hardware security.

The system of NM account:

The NM account is based on the results of measuring the quantitative characteristics and NM attributive signs.

Means of access control (MAC) are applied to NM. These MAC prolong the authenticity of the results of measurement carried out carlier. It is permitted using the results of the previous measurement of quantitative characteristics of NM, if their reliability is confirmed:
- the proper use of MAC;
- the corresponding confirmed measurements.

LECTURE 12
THE INTERNATIONAL REGIMES WITH THE PURPOSE OF NONPROLIFERATION OF MDW AND NM

The international regime of nonproliferation: the history of development and evolution. The Treaty of nonproliferation of Nuclear weapons (TNNW).

Theorists of international relations usually spoke about the policy peace by the notions of anarchy and conflicts. The loss of political power, which exceeds the frames of one state, meant that relations between countries were constructed on the base of «The jungle laws»: the strong one acts as he likes, the weak one as he can. At such approach the theorists of 1970-th came to bewilderment observing the certain samples of improving cooperation between countries. To account for this unusual cooperation, they introduced such notion as a conglomerate of societies, treaties, laws and decretes based on the existing principles and notions about social values.

The mutual interaction and strengthening of these elements should conduce to certain corroboration of countries, even those ones, the history of with has many conflicts.

Nowadays the regime of nonproliferation is one of the most successful regimes in the policy of peace. In accordance with the TNNW the freely signed agreement between countries possessing the nuclear weapons.

How to extract the benefit from the peaceful use of a nuclear energy, at the same time to apply all the attempts in order not to undermine the peace and security.

The regime of nonproliferation is based on the Treaty of nonproliferation, Tlatelocco and Paratongo Treaties, the International Agency on the nuclear control, national agencies and resolutions about the nuclear control.

All these are penetrated in more or less degree by social persuasion in that distribution of nuclear weapons in danger for the peace and security of states is in danger too.

These components of the regime, which are independent in their development and functionality actively interact and are united in regards to strengthening the norms of nonproliferation. For example, some agreements trust IAEA to realize their resolutions.

Nuclear suppliers of the whole world cooperate helping to set the exact sense of some not absolutely definite paragraphs of the nonproliferation Treaty, the national Departments of the nuclear control submit to the principles of the inner legislation.

The interconnection nature of various elements of the regime serves to strengthening the nonproliferation regimes and its protection of ruining of this regime.

LECTURE 13
THE INTERNATIONAL MODES WITH THE PURPOSE OF NONPROLIFERATION OF MDW AND NM (2)

The international mode of nuclear nonproliferation at the present stage. The contract about general prohibition of nuclear tests

In first half of 90th years impressing results in prevention of nuclear distribution have been achieved. The center of it formed as a result of disintegration of the USSR, has been extinguished – Ukraine, Byelorussia and Kazakhstan, in which the territory the Soviet nuclear arms were deployed, became participants of TNNW. The Northern Korea, trying to come out of it, has undertaken re-profile the nuclear objects so that they could not be used in the military purposes. The Southern Africa has refused to possess the nuclear weapon and dismantled the created illegal nuclear devices. After the defeat in war in the Persian Gulf Iraq has been forced by the Security Council of the United Nations to dismantle the industrial potential for creation of the weapon of mass destruction. In 1995 the TNNW, the basis of all mode of nonproliferation, has been prolonged term less and became permanent. In September, 1996 the text of the Contract about universal prohibition of nuclear tests was prepared and open for signing.

So, it seemed to achieve quite good results. All five nuclear powers and more than 170 non-nuclear states of the world have joined to the TNNW. After denuclearized zones in the Latin America and in a southern part of the Pacific Ocean denuclearized zones in Africa and in the South-East Asia have appeared. More than 100 countries became participants of denuclearized zones. The main achievement of a policy in this key sphere of the international safety there appeared also the acceptance by the majority of the countries in the world community of norms of the behavior forbidding and condemning any expansion of «the nuclear club».

At the same time the achieved results cannot be an occasion for complacency and curtailing of efforts on strengthening a mode of nonproliferation. On horizon opportunities to turn nuclear distribution back in the Far East and in the Southern Asia are not looked through yet. Israel, India and Pakistan flatly refuse to join the Nonproliferation treaty of the nuclear weapon and to stop escalating nuclear potential available at their order. The main question is how to prevent the threat, because these countries officially announced them to be the nuclear states. In the Far East a number of the Arabian countries and Iran are not going to be reconciled with nuclear monopoly of Israel and as a counterbalance try to master the peace nuclear technology, to get the chemical and rocket weapon. India and Pakistan intensify the programs of rocket production for creation of means of delivery of the nuclear weapon. It is not clear how far there will be the Northern Korea is in business of liquidation of the saved up potential in the nuclear and rocket spheres.

LECTURE 14

THE INTERNATIONAL MODES WITH THE PURPOSE OF NONPROLIFERATION OF THE MDW AND NUCLEAR MATERIALS (3)

The Treaty about prohibition of manufacture of split materials. Conferences 1995, 2000, 2005 on distribution of action and prolongation of TNNW. Problems and prospects. Zones, free from the nuclear weapon

The great value in business of nonproliferation of the nuclear weapon and maintenance of global safety has process of creation of denuclearized zones.

The idea of denuclearized zones gets the increasing appeal not only as a measure promoting nuclear nonproliferation and disarmament in general, but also as the essential factor of discharge and settlement of regional disputed situations. Important thus to note, that denuclearized zones in the certain relation give the states participating in them some advantages in comparison with the TNNW: they establish completely the denuclearized status, forbidding presence of the nuclear weapon belonging to nuclear powers (that the TNNW does not provide); participants of zones besides receive from nuclear powers in conformity with already developed practice legally obligatory guarantees of safety (that are deprived non-nuclear participants of the TNNW).

For today denuclearized zones are already created or are in process of creation in Latin America, a southern part of the Pacific Ocean, Africa, and the South-East Asia. Besides, there are offers on creation of a denuclearized zone in Southern Asia and on the Korean peninsula. At last, recently Uzbekistan had been put forward idea of formation of a free zone from the nuclear weapon in the Central Asia.

«Any zone recognized by the General Assembly of the United Nations, which any group of the countries in free sovereignty has formed by virtue of the contract or the convention», has been determined as the zone, free from the nuclear weapon. Such contract should provide «full absence of the nuclear weapon, as should be applicability of a zone», and also is free to provide «the international system of checks and the control over warranting conformity to the obligations established by this Treaty». Besides the United Nations recommend the nuclear states in view of full absence of the nuclear weapon in such zones to not resort to any sort to infringements of a denuclearized mode of zones.

The United Nations already 30 years ago have recognized zones, free from the nuclear weapon, useful means for maintenance of regional and international safety, in every possible way encouraging their creation, and the General Assembly has accepted corresponding resolutions, calling the states to undertake necessary efforts for end of registration of the existing zones and creating the new ones

LECTURE 15

GUARANTEES AND ENSURING THE NONPROLIFERATION MODES OF MDW AND NM (1)

The IAEA and guarantees of nonproliferation of the nuclear weapon.

Realization of control functions in the field of safety, or guarantees, has been delegated to the International agency on atomic energy (IAEA), based in 1957 as the organizational center of the Program of Eisenhower «Atom for the world». The IAEA is now the most significant in the world the intergovernmental nuclear organization numbering 122 states – participants.

The charter of agency has been accepted on October 26, 1956 at the international conference in New York and has come into force after ratification of it by 18 states – participants on July 29, 1957. The IAEA charter is the international contract of the sovereign states, signed irrespective of their membership in the United Nations and other obligations. At the same time under the IAEA agreement and the United Nations of November 14, 1957 the Agency has occupied the position, in much similar to the position of the specialized establishments of the United Nations.

According to the Charter the IAEA objectives are: to aspire to achievement of faster and wide use of an atomic energy for maintenance of the world; to promote peace use of a nuclear energy; to help to protect from switching civil nuclear materials in area of military application; to promote and develop that the nuclear power for maintenance of the world can give, health and well-being.

In the performance of mandate the IAEA has developed guarantees so that the material would not be switched from use in the peace purposes to creation of the nuclear weapon or nuclear explosives. All IAEA guarantees demand from the corresponding state of representation in the IAEA for the analysis:

1. The design documentation concerning its nuclear objects, both already available, and planned.
2. The correct and full information concerning a nuclear material, falling under guarantees.
3. Special reports at occurrence of unusual events or the supernumerary situations provided by the agreement on guarantees.

The extremely important point is that the states concluded the universal agreement on guarantees should create the national organization responsible for the account of nuclear materials and the control over their use. On heads of objects it imposes a duty through corresponding bodies of the state to represent reports according to requirements of the IAEA. It besides promoted the development of the national legislation regarding, concerning a nuclear material and its account. One more moment peculiar of all system of guarantees of the IAEA is the requirement of granting to official representatives of Agency of access on objects for carrying out of inspections.

LECTURE 16

GUARANTEES AND ENSURING THE NONPROLIFERATION MODES OF MDW AND NM (2)

The international organizations in the field of use of an atomic energy, nonproliferation and the control of nuclear arms. The Group of Nuclear Suppliers (GNS). Tsanger’s List.

In 1971 the group of states – participants of the IAEA had been created the Tsanger’s Committee, which has made an attempt to come to the consent concerning uniform interpretation of terms «the equipment and the materials specially developed or prepared for processing, use or manufacture of special split materials». The Tsanger’s Committee treated clause III (2) as demanding of countries – exporters to provide that the importer established guarantees of safety on the certain materials concerning manufacture of a nuclear energy or to research laboratories. The committee carries out information interchange between the members about corresponding export licenses, which have been given, and about those, in which delivery is refused. The committee informs the IAEA on its activity.

The group of suppliers of nuclear materials («The London club»). In 1975 one more attempt for protection of nuclear materials against possible use not in the peace purposes has been undertaken. The informal group of states – suppliers of nuclear materials, which sessions passed within 1975 - 1977 in London and which later became known as Group of suppliers of nuclear materials, has developed the list of export materials, the equipment and technologies, which delivery demanded from addressees of creation the necessary protection and obligations to not use them differently as in the peace purposes. Known as the London rules for transactions with nuclear materials, these coordinated list and conditions of application of the given rules have been accepted in 1977 and reconsidered in 1993.The finishing session in Poland in April, 1992, the Group of suppliers of nuclear materials has approved the additional measures, which have expanded a spectrum of the existing rules. The group has formally made the list of the equipment, materials and corresponding technologies of double use – named subsequently the Warsaw rules, which transfer its members should limit under the national export legislation. They also have agreed to export such goods only to the states, which are participants of the IAEA or have agreed with universal safety rules of the IAEA. Besides, the advisory forum for consideration of inquiries about reception of export licenses has been formed.

LECTURE 17

THE CONCLUSION

THE CURRENT CONDITION IN THE RUSSIAN FEDERATION

Rosatom in the Russian Federation, the Russian nuclear centers and the atomic power stations and problems of nonproliferation.

The analysis of a present day problems of nonproliferation directly in the end of a given course is necessary.

SUMMARIES OF LECTURES FOR 7TH SEMESTER

ACCOUNTING AND CONTROL OF FISSILE MATERIALS IN PRODUCTION OF NUCLEAR FUEL

LECTURE 1

ROLE OF SYSTEMS OF NUCLEAR MATERIALS ACCOUNT, CONTROL AND PHYSICAL PROTECTION

The purpose of this lecture is to give a general idea of systems and measures that are used for safety maintenance of nuclear materials (NM) in the production of nuclear fuel (NF).

In this lecture, the systems and measures ensuring safety of NM are considered. The emphasis is on the system for physical protection as well as on the system for the account and control of nuclear materials (PhP&ACS). The objective and function of PhP&ACS are considered. The basic principles and structure of the two systems are presented. The mutual integration of the above systems and measures for safety provision of NM is considered. The present condition of the state AM system and PhP system at the enterprises of Russian Federation NFC is shown. The elements of the accountability in uranium production are considered: stocktaking, reports and helps, control of timely material use.

The list of failures and accidents at the NFC enterprises is offered. The programs on PhP&ACS improvement at the NFC enterprises of Russian Federation are presented, including the cooperation of USA and Russia in the field of PhP&ACS advancement.

LECTURE 2

THE OBJECTIVE AND FUNCTION OF THE ACCOUNT AND CONTROL SYSTEM FOR NUCLEAR MATERIALS

The purpose of the lecture is to give a general idea of the role of ACS for NM in the security system and NM non-proliferation measures.

In this lecture, ACS is considered in more detail. The objective and function of ACS for NM are presented. The components of ACS are considered. The definitions of such terms as account and control are given in the context of safety and non-proliferation of NM. The differentiated approach to provision of safety, account and control of nuclear materials is considered. The account system and control system for NM are considered separately. The mutual integration and overall efficiency of these systems are described.

LECTURE 3
THE ATTRACTIVENESS OF NUCLEAR MATERIALS AT DIFFERENT STAGES OF A NUCLEAR FUEL CYCLE

The purpose of this lecture is to give a concept of this nuclear fuel cycle (NFC), its phases and process stages, to give qualitative estimation of the attractiveness of NFC stages in respect to risk of NM proliferation.

In the lecture, the nuclear fuel cycles of industrial complexes participating in production of nuclear fuel (NF) are considered. The main phases and process stages of the industrial complexes are considered. The open and closed schemes of NFC are given. Using the schemes as an example, the analysis of factors describing attractiveness of nuclear materials (NM) for stealage at various stages of NFC is carried out. Most attention is given to the phase of nuclear fuel production. The comparative analysis of danger of NFC stages is carried out with respect to risk of proliferation and attractiveness of NM.

LECTURE 4
METHODS OF NONDESTRUCTIVE AND DESTRUCTIVE ANAL YSES USED FOR CONTROL OF NUCLEAR MATERIALS AT DIFFERENT STAGES OF NFC

The purpose of the lecture is to give a general idea of existing methods and instruments for nondestructive (NDA) and destructive analyses (DA) used for control in uranium production.

In the lecture, an overview of the most important destructive physical and chemical methods (DA) used for control of NM is presented. The emphasis is on gravimetry, various titrimetric methods, coulometry, fluorometry, methods based on photocolometry and spectrometry.

An overview of the principal methods of NDA for NM is presented. They include various weight measurements, calorimetric measurements, gamma- and neutron measurements. Most attention is given to the gamma-spectrometric equipment which is used for determination of uranium enrichment or fuel isotopic composition, as well as to instruments and methods of nondestructive neutron control, which enable one to determine a mass of NM; to instruments based on radiation control (gamma-radiation or neutron radiation) or on visual observation by means of which the check of hard-to-reach NM is carried out; to instruments for radiation control (radiation portals) that monitor the replacement of nuclear materials both during phase of NF production, and within a separate processing line.

The general problems connected with the description and fixing of material balance on uranium being at the phase of nuclear fuel production are considered. The methods of physical inventory permitting the realization of reliable control in uranium production are presented.

LECTURE 5
THE PHASE OF PRODUCTION OF NUCLEAR FUEL BASED ON CERAMIC URANIUM DIOXIDE

The purpose of the lecture is to give a concept of a phase of the nuclear fuel production. We are going to identify those technological sites at a phase of NF production where it is the most vulnerable (exposed), which calls for the use of methods and measures of AM system.

In the lecture, some types of fuel elements and fuel elements assembly (FEA) are considered. Their design, geometric and material parameters are represented. The process scheme of prevailing fuel elements and FEA from uranium dioxide (UO_2) (a phase of NF production) is described. The given process scheme of NF based on ceramic UO_2 includes the following phases and process stages: 1) preparations of nuclear fuel; 2) preparations of tubular casing for fuel elements and end pieces; 3) provision of fuel elements with fuel; 4) assembly of fuel elements in HGS, control bench tests.

The considered engineering processes and operations occurring at each phase of NF production are analyzed in the view of attractiveness and risk of NM proliferation.

LECTURE 6
A MANUFACTURING METHOD FOR CERAMIC URANIUM DIOXIDE

The purpose of the lecture is to give a general idea of a manufacturing method for pelleted uranium.

In the lecture, the review of engineering processes and operations of NF production is given. The stage of NF preparation is considered, namely: the instrumental-and-technological scheme for production of pellets from UO_2. The basic methods of ceramic UO_2 production are presented, with setting off those brought to a commercial stage. They include both the production of ceramic uranium dioxide by way of the intermediate stage of ammonium polyuranate sedimentation (ADU-process) and the production of ceramic uranium dioxide through the intermediate stage of tricarbonate-uranylate sedimentation (AUK-process). Advantages and disadvantages of both ADU- and AUK-processes are analyzed.

The review of some leading enterprises in Russia and abroad is carried out, where ADU- and AUK-processes are realized, with presenting their performance data.

LECTURE 7
THE PRODUCTION OF CERAMIC URANIUM DIOXIDE BY WAY OF THE INTERMEDIATE STAGE OF AMMONIUM POLYURANATE SEDIMENTATION (ADU-PROCESS)

The purpose of the lecture is to give a concept of ceramic UO_2 production by way of the intermediate stage of ammonium polyuranate sedimentation (ADU-process)

The general principles of ADU-process are stated. The classical scheme of preparing UO_2 from UF_6 is considered (hydrolysis of UF_6 in water or dissolution of ammonia – sedimentation of ammonium – drying – glowing – restoring) that was implemented at Mallincroud factory in USA.

The first variant of ADU-process is considered (that is realized in fluoride systems), which uses the classical scheme of preparing UO_2 from UF_6. The destination and production technique for powder UO_2 preparation by this variant of ADU-process are described.

The second variant of ADU-process based on ammonium polyuranate sedimentation from nitrate solutions is considered. Destination and technique of preparing powder UO_2 by the given variant of ADU-process are described. Most attention is given to the first variant of ADU-process implemented in fluoride systems, for it is intended for processing UF_6 with an increased concentration of U^{235}. The comparative analysis of the two variants of ADU-process is represented.

LECTURE 8
METHODS AND INSTRUMENTS FOR NONDESTRUCTIVE AND DESTRUCTIVE ANALYSES USED IN PRODUCTION OF CERAMIC URANIUM DIOXIDE BY THE ADU-PROCESS

The purpose of the lecture is to familiarize students with the engineering process of preparing ceramic UO_2 by ADU-process and to give general idea of methods and instruments for NDA and DA used at the given NF production phase.

In this lecture, the first stage of nuclear fuel production based on UO_2 of low concentration rate is considered. The instrumental-and-technological scheme of production of pellets from UO_2 is given. The preparing ceramic UO_2 through an intermediate stage of ammonium polyuranate sedimentation (ADU-process) is considered. The main attention is given to the technological scheme of preparing ceramic UO_2 for light-water reactors (LWR) by the ADU-process.

Two examples of the scheme implementation are considered: one at «Kerr-Mc-G Corporation» factory in the town of Symarron, another one at the Colombian factory owned by «Vestighaus Electric».

The account and control (A&M) operations during NF production (methods and instruments for NDA and DA, material balance) are considered by the example of the operating plant of «Kerr-Mc-G Corporation». The emphasis is placed on gamma- and mass-spectroscopy, and on instruments and methods based on neutron measurement methods.

LECTURE 9

THE PRODUCTION OF CERAMIC URANIUM DIOXIDE BY THROUGH THE INTERMEDIATE STAGE OF TRICARBONATE-URANYLATE SEDIMENTATION (AUK-PROCESS)

The purpose of lecture is to give a concept of production of ceramic UO_2 by way of the intermediate stage of tricarbonate-uranylate sedimentation (AUK-process).

The general principles of AUK- process are stated. The emphasis is placed on the theoretical background of AUK-process. The shortcomings peculiar to both ADU- and AUK-processes are considered. The comparative analysis of technologies using ADU- and AUK-processes is carried out.

LECTURE 10

METHODS AND INSTRUMENTS FOR NONDESTRUCTIVE AND DESTRUCTIVE ANALYSES USED IN PRODUCTION OF CERAMIC URANIUM DIOXIDE BY THE AUK-PROCESS

The purpose of the lecture is to familiarize students with the engineering process of preparing ceramic UO_2 by AUK – process and to give general idea of methods and instruments for NDA and DA used at the given NF production phase as applied to AUK-process.

In this lecture, the first stage of nuclear fuel production based on UO_2 of low concentration rate is considered. The deriving ceramic UO_2 from UF_6 is carried out through an intermediate compound of tricarbonate-uranylate ammonium (AUK-process). The technology of deriving powder UO_2 is described. The realization of the technology is considered by the example of a factory in Volfgange unter Hanau (Germany) owned by «Nuclear Chemie und Metallurgy».

A&M operations for NM during NF production (methods and instruments for NDA and DA, material balance) are considered by the example of an operating plant of «Nuclear Chemie und Metallurgy» (Germany). The emphasis is placed on gamma- and mass – spectroscopy, and on instruments and methods based on neutron measurement methods. The technique of material balance description and fixing on the process stages is considered.

LECTURE 11

METHODS AND INSTRUMENTS OF ACCOUNT AND CONTROL SYSTEM FOR LARGE LOTS OF NM

The purpose of the lecture is to give the overview of quality control techniques for prepared pellets. We are going to give a general idea of ACS methods (NDA and DA methods, accounting, engineering data, etc.) for large lots of NM both in storage and during transportation from one factory to another.

Before provision of fuel elements, the pellets are subjected to careful quality control. This lecture reviews methods of quality control for prepared pellets. The methods of ACS for NM during storage of pelleted uranium in finished-product storehouses are considered. The emphasis is on the methods and instruments based on registration of gamma- and neutron radiation (various gamma- and neutron counters). The methods and instruments of gamma-spectrometry are considered. The review of ACS methods for transportation of ready pellets from one factory to another is given. They include portal screen monitors for staff and transport means, various manual control instrumentation based on gamma- and neutron counters.

The review of methods for NM control inside a nuclear object is given. They include various radiation portals, manual control instrumentation based on gamma- and neutron counters. Methods of physical inventory in operating with large quantity of NM (inventory list, list of kinds of shipped compounds, and other documents accompanying replacement of nuclear materials) are represented.

LECTURE 12
MANUFACTURE OF TUBULAR CASINGS FOR FUEL ELEMENTS AND END PIECES

The purpose of the lecture is to familiarize students with methods and instruments for quality control of tubular casings for fuel elements and end pieces.

In this lecture, the production engineering of thin-walled pipes for fuel element casing (the second stage of NF production) is considered. The emphasis is on production of thin-walled zirconium pipes for domestically-produced reactors of PWR and RBMK types. The various methods of quality control of complete products are considered. Most attention is centered on radiation control techniques permitting one to detect voids, cracks, thickness of casings; also on acoustic methods used for determination of casing thickness; and on methods based on magnetic and electrical properties of materials and products under study, which are used for detection of cracks and determination of covering on uranium rods and pipes.

LECTURE 13
METHODS AND INSTRUMENTS FOR NONDESTRUCTIVE AND DESTRUCTIVE ANALYSES USED IN OPERATIONS OF PROVISION OF FUEL ELEMENTS WITH PELLETED URANIUM

The purpose of the lecture is to familiarize students with methods and instruments for NM control used in operations of provision of fuel elements with pelleted uranium.

In the lecture, the third phase of NF production is considered, namely provision of fuel pins with fuel. The following problems are covered: dosage and packing of pellets in tubular casings prepared to assembly; setting up of end pieces, filling them with helium, capsulation (by welding), control operations and transfer fuel pins to assembly. As noted above, various methods and instruments for nondestructive and destructive control are used in the course of NF production. At the given stage of NF production, however, the use of DA methods is undesirable; therefore, main attention is given to methods and instruments for NDA. The gamma-spectrometric equipment is considered; instruments and methods based on radiation control (gamma-radiation or neutron radiation), or on visual observation by means of which the examination of hard-to-reach NM is carried out; instruments of radiation control (radiation portals, screen monitors) monitoring the replacement of nuclear materials on phases of NF production. The material balance and methods of nuclear materials inventory are represented.

LECTURE 14
QUALITY CONTROL AND METHODS OF FUEL ELEMENTS TESTING

The purpose of lecture is to give a general idea of testing methods and quality control of ready fuel elements and other constructional materials positioned in the active zone of NR.

Before assembly of fuel pipes in FEA, fuel elements should be carefully inspected and tested. Only in this case, are proper work of the reactor, its safety and economical efficiency assured. In this lecture, the general data on quality control and test methods for fuel elements are presented. Most attention is concentrated on various radiation methods of control permitting voids, cracks, casing thickness to be detected; on various acoustic methods used for determining thickness of fuel element casings as well as for control of the mechanical contact and adhesion of a core with a casing; on optical methods (methods of visual control and microscopic methods of metallography and spectrometry) used for control of ready fuel elements; on methods based on magnetic and electrical properties of materials and products under study used for observation and locality of cracks and determination of coverings on uranium rods and pipes.

The various thermal tests used for determination of temperature distribution in a fuel element are presented.

LECTURE 15
FUEL ELEMENTS ASSEMBLY (FEA)
METHODS OF ACCOUNT AND CONTROL SYSTEM AT THIS STAGE

The purpose of the lecture is to familiarize students with the final phase of NF production and with A&C methods at this stage.

This lecture presents general data on preparation, gathering of parts for the assembly of fuel pins in FEA (covers, end pieces, grids, rods). The operation of fuel pins replacement to assembly and FEA as such are considered. The control bench tests of FEA are presented.

The methods of DA and NDA used at this phase of NF production are presented. For NM monitoring at this stage, DA are used only in exceptional cases, because of this, most attention is concentrated on instruments and methods for NDA based on gamma- and neutron radiations. The problems related to the description and fixing of material balance on uranium being at the phase of production of nuclear fuel are considered. The methods of physical inventory permitting one to exercise reliable control in uranium production at the given stage are represented.

LECTURE 16
REACTOR TESTING (IRRADIATION TEST) OF FUEL ELEMENTS

The purpose of the lecture is to familiarize students with a quality control technique for fuel elements and FEA based on the irradiation test.

In this lecture, one of the destructive control techniques used for quality estimation of both fuel elements and constructional elements situated in NR active zone is considered. This method is based on the irradiation test (reactor testing). There are presented experimental device designs and loopback channels for irradiation of various samples (fuel pins, FEA, and other constructional elements).

In addition, the list of research reactors intended for irradiation testing is given and their performance data are considered.

ANALYTICAL CHEMISTRY OF URANIUM, PLUTONIUM AND THORIUM

LECTURE 1
INTRODUCTION
SUBJECT OF ANALYTICAL CHEMISTRY

Any substance consists of one or several chemical elements. To determine structure of substance – it means to determine, what chemical elements form this substance. Such task is solved by methods of the chemical analysis. However these methods enable to determine not only, what elements are a part of any substance, but also in what quantitative parities.

Now tasks of the analysis considerably become complicated. There was a necessity to define not only chemical elements, but also their isotopes. The concept – «structure of substance» has extended. It includes definition of chemical elements, functional groups, ions, molecules, isotopes.

Analytical chemistry – it is a science about methods of the analysis of substance. A subject of this science is the theory and practice of the analysis. The chemical analysis – it is a reception by practical consideration data about a chemical compound of substance.

BRIEF HISTORY OF DEVELOPMENT OF ANALYTICAL CHEMISTRY

The analytical chemistry as scientific discipline starts to develop with the middle of XVII century. The founder of the qualitative analysis is English scientist Robert Bojl (1627–1691.) Boil has entered the term «the chemical analysis», has defined concept «element» as a simple body which is a part of the mixed bodies.

Bases of the regular analysis of cations of metals were developed by Swedish chemist T.U.Bergman (1735–1784).

The special place in history of development of analytical chemistry occupies XIX century. Cardinal value both for chemistry, and for the chemical analysis D. Dalton's atomic theory (1766–1844) has got.

I.J. Bertselius has opened a series of new elements: selenium, silicon, zirconium, thorium, and together with pupils-lithium, vanadium, the titan and cerium.

In most, the beginning of XIX century (1778–1829) first works on electrolysis of chemical compounds have been executed by Russian scientist V.V. Petrov (1761–1834) and English scientist G. Devy. Application of this method has allowed to G. Devy to open potassium, sodium, barium, calcium, strontium and magnesium and also to prove the element nature of chlorine as which considered as complex substance. He has created the hydrogen theory of acids.

The big contribution to the theory of analytical chemistry was brought by the Norwegian scientists K. M-Guldberg (1836–1902) and G. Vaague (1833–1900) which have opened in 1867 the law of operating masses, and the Swedish scientist S. Arrenius (1859–1927) who have offered the theory of electrolytic dissociation in 1887.

The founder of Russian school of chemists-analysts is N.A. Menshutkin (1842–1907).

THE BASIC DIRECTIONS OF MODERN ANALYTICAL CHEMISTRY

For modern analytical chemistry exclusive rates of development are characteristic. Primary development is received with physical-chemical and physical methods of the analysis which are named **tool methods of the analysis**. In analyses apply nuclear reactions at action of the neutrons, the charged particles and gamma-radiations, and also optical quantum generators of light (lasers).

In modern analytical chemistry widely are used not water solvents. Earlier the basic solvent in the analysis was water. Water as solvent is applied and now, but simultaneously use also various not water solvents, as, for example, a waterless acetic acid, acetic anhydride, glycols and many other things. Methods of not water titration have got and get the increasing value. For the first time N.A. Menshutkin began to develop these methods.

In the modern analysis wide application was received with synthetic organic reactants. The beginning to this direction have put M.A. Ilinsky's (1885) which have offered A-nitroso-R-naftol and L.A. Chugaev (1905), offered dymetilglyoxim. The reagent arsenaso III which was applied by S.B. Savvin(1966) has very quickly entered into a practical work.

In the middle of XX century ultramicromethods of the analysis began to develop. Extremely small weights of substance are necessary for research (10^{-6}–10^{-12} g), work with which demands special technical equipment. The technical equipment of experiment in the ultramicroanalysis has been developed by P. Kirk and I.M. Korenman. To the further development of this techniques are devoted works of I.P. Alimarin and M.I. Petrikova. I.P. Alimarin has offered methods of the analysis of mineral raw material, has developed microchemical methods of research of structure of minerals and ores.

In the modern analysis even more often resort to extreme conditions, to the conditions sharply differing from usual. It can be very high or, on the contrary, very low temperatures, very high pressures or space vacuum.

CHEMICAL, PHYSICAL AND PHYSICAL-CHEMICAL METHODS OF THE ANALYSIS

The analysis of substances is carried out by means of chemical, physical or physical-chemical methods. Chemical methods are based on chemical reactions. For the analysis use only such reactions which are accompanied by observed outward effects, for example change of painting of a solution, allocation of gases, loss or dissolution of deposits. These outward effects will be in the given case analytical signals. Occurring chemical changes are named analytical reactions, and the substances causing these reactions,-chemical reagents. If the reaction is carried out in a solution such way of performance name «wet by». A way, performance of the analysis with firm substances without use of solvents name «dry by». It is the pyrotechnical analysis and the analysis by method of grinding. At the pyrotechnical analysis researched substance is heated up in a flame of a gas torch. Thus flying salts (chlorides, nitrates, carbonates) of some metals give to a flame the certain painting. For example, salts of sodium paint a flame in yellow color, potassium – in violet, barium-in yellow-green, strontium – in purple – red. Other variety of the pyrotechnic analysis – reception of the painted glasses (pearls). For reception of pearls salts and metals oxides are alloyed with sodium tetraborat and observe painting of formed glasses (pearls).

At the analysis by physical methods do not resort to chemical reactions, and investigate physical properties of substance by means of devices. Among to physical methods are spectral analysis, luminescent, roentgen – structure and other ways of analyses.

By means of physical and chemical methods the physical phenomena which occur at chemical reactions are studied. For example, in calorimetric method intensity of painting depending on concentration of substance is measured, in conductometric analysis change of electric conductivity of solutions is measured, etc.

LECTURE 2
THE BASIC STAGES OF THE ANALYTICAL CYCLE

The general statement of a problem is usually outside of the competence of an analyst. The customer can not have at all representation about opportunities and technical aspects of the chemical analysis. Result of discussion of a task between the customer and an analyst the clear understanding of the general basis of forthcoming analytical procedure should be.

Statement of a concrete analytical task. The customer and an analyst should be defined in common with an object of research: that it is necessary to determine and what probably to determine. At this stage it is necessary to receive answers to the questions similar to the following:

- what represents object or the sample that it is necessary to determine: molecular, element composition, or, for example, functional groups?
- the qualitative or quantitative analysis is required? What is necessary accuracy of the quantitative analysis?
- what quantity of a material is accessible to the analysis? What provisional maintenances of a determined component?
- what the matrix of the sample represents?
- whether it is enough to determine only one component or it is required the multy-componential analysis?
- it is required to lead the analysis to what terms? In other words: what as much as possible admissible time can pass from a capture of test before delivery of ready results? Whether the repeated analysis of similar samples and, if yes, is supposed with what periodicity? Or it is the individual analysis?
- it is admissible or not destruction of the sample during the analysis?

This list of questions is not exhaustive. It only shows, in what channel there should be a dialogue to receive all necessary information for a correct choice of an analytical method and a technique.

The choice of a technique has crucial importance. Technique defines the general expenses for performance of the analysis, including as cost of the equipment, so payment of the personnel labor. The choice of a technique is inevitably limited by certain frame conditions, such, as amount of the sample, admissible time of the analysis, and also, probably, additional information. The method of the analysis, capable to provide necessary analytical characteristics taking in account all of probable restrictions, is optimum.

Sample cutting consists of two stages: development of the plan of sample cutting and sampling as those. Depending on a way of sampling, the nature of a determined component and its maintenance, structure of a matrix, measures depend, which are necessary for accepting to avoid any change of structure of test.

Firm materials. Test should be representative, but for economic reasons its size should not be more, than it is strictly necessary. The size of test depends on demanded accuracy of the analysis, a degree of heterogeneity of a material and the size of its particles. Sometimes for maintenance of imposing appearance tests in weight some kgs or even hundreds kgs are required.

Liquids and gases. Usually liquids and gases are homogeneous enough or their tests can be easy homogenized, therefore, as a rule, are not big. However vessels used for their storage have small volume and accordingly the big size of the relation of a surface of cover to volume. It can cause great losses due to adsorption. Therefore it is necessary to achieve an establishment of balance between test and walls by long-time rinsing of vessel (this operation is named an equilibration).

Interaction between test and walls of the container can change structure of test. Therefore walls of the container are necessary for processing preliminary so that to exclude this opportunity. Pollution of test from devices for sample cutting and vessels for storage of test should be completely excluded. All tests should be precisely signed with the indication of a source, date and time of selection, and also determined components.

Transportation and storage can change structure of tests owing to passing of the reactions caused by intensive hashing. At transportation of test in pipelines diffusion of gases through walls of pipes and the losses caused by this or pollution of test is possible.

Between selection of test and its research can pass significant time. For example, tests of the Antarctic ice can be analyzed in other part of globe.

Thus losses of components due to adsorption on walls or pollution of test also are possible.

Sample cutting pursues some the aims. One of them – transfer of test in the physical condition demanded for the chosen technique One more problem task – to take care of that the maintenance of a determined component corresponded to an optimum range for the given technique. At definition of scent components initial concentration are often so low, that direct definition is impossible for any of existing methods. In these cases it is necessary concentration, more often by means of extraction, sorption or an ionic exchange. The same methods can be used as methods of separation for disjointing of stirring components. Stirring influence of extraneous components can be removed by addition of special reagents. This way refers to as masking.

Measurement. In a basis of the majority of methods of the analysis comparison of a signal of the sample with signals of one or several samples of comparison which have precisely known structure is used. Indications of measuring devices are subject undesirable, but to the inevitable fluctuations named by noise. Noise level is usually characterized by standard deviation of fluctuation of a signal. For improvement of quality of results the increase in the relation a signal/noise is necessary.

Conclusions and the report. The analyst bears the full responsibility for results which is going to inform. He should specify precisely with what accuracy data are obtained all, to avoid any probable ambiguity in their interpretation. For maintenance of quality of results it is necessary to check applied techniques on the certified standard samples. The analyst should be assured that data obtained by him are really necessary for the decision of the general problem which is formulated by the customer.

LECTURE 3
ANALYTICAL CHARACTERISTICS OF TECHNIQUES FOR ANALYSIS

Regularity is the characteristic of proximity of an average value of the measured magnitude to the postulated true value.

Reproducibility is the characteristic of measuring results scatter relative to the average value. As a reproducibility measure, the following magnitudes are widely used: sample standard deviation, relative standard deviation, dispersion, and relative mean deviation.

Sensitivity. It is characterized by the sensitivity coefficient – a measure of the modification of an analytical signal with a change in concentration.

Detection limit. If an analytical signal is only close to the average value of a check experiment signal (background signal), then the question arises as to whether this exceeding is caused by the presence of the substance to be determined or by the background signal fluctuation called noise. The detection limit corresponds to a signal exceeding the average background value by the factor **k**. As a rule, the value **k** is set equal 3. If the signal is higher than the detection limit, it points to the presence of the substance to be determined, but if it is lower than the detection limit – to its absence.

The low bound of determined contents. In contrast to the qualitative analysis where it is required only to establish the fact of the substance presence, in the quantitative analysis it is necessary to determine its content. In this case the numerical values specifying this content should satisfy the necessary exactness requirements. Therefore, the low bound of the contents to be determined (characterizing possibilities of the method in terms of quantitative analysis) is always higher in magnitude than the detection limit (possibility of the qualitative analysis).

The selectivity characterizes to what extent the irrelevant constituents of a test sample affect the analysis results. In different methods of the analysis various methods of quantitative selectivity evaluation are used.

LECTURE 4
CHEMICAL METHODS OF ANALYSIS

In a system consisting of two or more substances, chemical conversions occur until a stable condition is reached. This final condition is said to be an equilibrium condition. An equilibrium condition is characterized by the equality of rates of direct and reverse reactions. The chemical equilibrium can be described by the equilibrium constant that is related to main thermodynamic functions:

$$\ln K = \frac{\Delta G}{RT}.$$

On the other hand, the equilibrium constant is related to concentration of reacting substances by the law of mass action. So for the reaction **A + B = C.**

$\mathrm{K} = \dfrac{\mathrm{a(C)}}{\mathrm{a(A)} * \mathrm{a(B)}}$, where a (C), a (A) and a(B) are concentrations of substances A, B and C multiplied by the activity factor.

For ions of uranium, plutonium and thorium in solutions, the formation of complex compounds is characteristic, in which anions-ligands are bound to them by the donor-acceptor bond.

Oxidation-reduction reactions refer to reactions with electron exchange between reagents. In this case, one of the reactant is oxidized (i. e. loses electrons), and another reactant is reduced (gains electrons). The titrimetric and electrochemical methods of analysis are based on oxidation-reduction reactions.

LECTURE 5
CHEMICAL METHODS OF ANALYSIS (2)

By the gravimetric analysis is meant a method of quantitative chemical analysis based on the precise measurement of mass of the substance being determined or of its constituents isolated as compounds of the known stable composition. The gravimetric determinations can be classified into three groups: the sedimentation , distillation and isolation methods.

The sedimentation methods are based on sedimentation of the constituent being determined in the form of a poorly soluble chemical compound, its filtering, calcination (or drying) up to a constant mass, followed by mass determination of the obtained substance.

The gravimetric form should satisfy the following main requirements: 1) to have well-determined stable stoichiometric composition; 2) to be unaffected by an environment; 3) a gravimetric form obtained by calcination should be stable at high temperatures; 4) in selecting a gravimetric form, it is necessary that its molecular mass should be as great as possible in comparison with the atomic or molecular mass of the constituent being determined, that ensures a low detection limit and a less determination error.

The gravimetric analysis by the sedimentation method is used both in the analysis of etalons for calibration and in control of the physicochemical methods of analysis, as well as in determination of a synthesized compound structure etc.

The titrimetric method of analysis was offered by J.L. Gay-Lussac in the last century and because of execution simplicity, rapidity, and high accuracy it has received wide acceptance.

By a titrimetric method of the quantitative chemical analysis is meant a method based on measurement of the amount of reactant **B** expended for the reaction with a constituent **A** to be determined. In carrying out the analysis, to a precisely measured volume of the substance being analyzed someone gradually adds the continually monitored amount of a reactant until the moment when the mole quantity of the added reactant equivalent **B** becomes equal to the mole quantity of the determined equivalent **A**.

For the titrimetric determinations, reactions of various types can be used, but all of them should satisfy the following requirements.

1. A reaction should proceed by the strictly determined stoichiometric equation, side reactions should be excluded.
2. A reaction should proceed quantitatively.
3. A reaction should proceed fast, for at any titration moment the equilibrium condition to occur practically instantly.

The following reactions satisfy the requirements mentioned above.

1. An acid-base reaction
2. An oxidation-reduction reaction
3. A complexation reaction
4. A sedimentation reaction

In titrimetry, three titration techniques are used: direct, back and titration of a substituent.

LECTURE 6
CHEMICAL PROPERTIES OF URANIUM AND ITS COMPOUNDS

Metallic uranium is extremely an reactive element. It cooperates with all nonmetals. The basic chemical property of uranium is its strong regenerative ability. On air at a room temperature the compact metal is slowly oxidized. Uranium is steadier against gaseous nitrogen, than to oxygen. Appreciable interaction of uranium to nitrogen occurs at temperature above 880 °C. With hydrogen the compact uranium cooperates at 200–300 °C with formation of the hydride of uranium UH_3. Reaction of metal uranium with gaseous fluorine intensively proceeds. With gaseous fluorine reaction begins already at a room temperature. As a result of reaction it is formed uranium hexafluoride. Metallic uranium slowly reacts with water with formation dioxide:

$$U + 2H_2O = UO_2 + 2H_2.$$

At dissolution of uranium in hydrochloric acid chlorides of three – both tetravalent uranium and the black rest of hydrated oxides of uranium are formed. Full dissolution of uranium in a hydrochloric acid is achieved by addition of an oxidizer. The concentrated sulfuric acid slowly dissolves uranium with $U(SO_4)_2$. At presence of an oxidizer sulfate of uranil is formed:

$$U + 4\,H_2SO_4 + 3\,MnO_2 = UO_2SO_4 + 3\,MnSO_4 + 4\,H_2O.$$

In nitric acid uranium is dissolved with formation of nitrate of uranil. In alkaline solutions uranium is insoluble.

Oxides of uranium. The greatest significance have: UO_2, U_3O_8, UO_3. On reduction of chemical activity oxides are settling down in a line: UO_3, U_3O_8, UO_2. Gaseous fluorine has fluorinates all oxides up to hexafluoride:

$$U_3O_8 + 9\,F_2 = 3\,UF_6 + 4\,O_2.$$

At interaction with the fluoric hydrogen dioxide of uranium gives tetra-fluoride, trioxide of uranium gives uranil-fluoride, and protoxide-oxide gives two moles of uranil-fluoride and one mole of tetra-fluoride:

$$U_3O_8 + 8\ HF = 2\,UO_2F_2 + UF_4 + 4\,H_2O.$$

With the water only trioxide of uranium cooperates, forming acids. In the concentrated acids are dissolved all oxides, but with various speed. Carbonates solutions cooperate with UO_3 and partially with U_3O_8. With the bases reacts only trioxide of uranium. Thus are formed diuranats. In the industry oxides are received by thermal decomposition of salts of uranium, and from some salts it is possible to receive all oxides, changing conditions of thermal decomposition.

UF_4 is one of the major compounds of uranium. Tetra-fluoride of uranium is inert enough substance. By oxygen of air it is oxidized up to uranil-fluoride:

$$UF_4 + O_2\ \text{air} = UO_2\,F_2 + F_2.$$

In the water it is not dissolved. Not oxidizing acids do not act to UF_4. Tetra-fluoride of uranium is dissolved in the concentrated nitric acid and also in solutions of a carbonate or oxalate of ammonium.

Hexafluoride of uranium is one of chemically active compounds of uranium. On air it smokes as a result of allocation of HF when hydrolysis in vapour of water:

$$UF_6 + 2\,H_2O = UO_2F_2 + 4\ HF.$$

Hydrogen restores hexafluoride up to tetra-fluoride:

$$UF_6 + H_2 = UF_4 + 2\ HF.$$

Hexafluoride of uranium in the industry is received by fluorination of oxides, tetra-fluoride, metallic uranium:

$$U_3O_8 + 9\,F_2 = 3\,UF_6 + 4\,O_2, UF_4 + F_2 = UF_6.$$

LECTURE 7
CHEMICAL PROPERTIES OF URANIUM AND ITS COMPOUNDS

SALTS of U(IV). Among the salts of tetravalent uranium, uranium (IV) sulfate is of the chief practical importance. $U(SO_4)_2$ represents green crystals with density of 4.6 g/cm^3.

$U(SO_4)_2$ is easily oxidized to UO_2SO_4 with such oxidizers as O_2, HNO_3, MnO_2.

$$2U(SO_4)_2 + O_2 + H_2O = 2UO_2SO_4 + 2H_2SO_4.$$

Uranium sulfate tends greatly to complexation. For example in excess of sulfuric acid, the complex compounds $H_2 [U (SO_4)_3]$ and $H_2 [U_2 (SO_4)_5]$ arise.

With insufficient acidity of a medium $U (SO_4)_2$ is subjected to hydrolysis:

$$U(SO_4)_2 + H_2O = UOSO_4 + H_2SO_4.$$

The action of alkalis on uranium sulfate solution results in sedimentation of insoluble uranium U(IV) hydroxide

$$U(SO_4)_2 + 4NaOH = U(OH)_4 + 2Na_2SO_4.$$

SALTS of U(VI). Because of amphoterism **UO_3** is capable to form the salts of two types: uranyl salts and uranates.

URANYL SALTS. U^{+6} is the most stable uranium state in water solutions. In this case, uranium exists exclusively as the ion complex UO_2^{2+} – uranyl.

All the uranyl salts are yellow – green in colour and fluoresce. Most of them are very soluble in water and polar organic solvents, since in water they poorly dissociate into ions. Among poorly soluble salts are uranyl oxalate, uranyl carbonate, and uranyl phosphate. Uranyl nitrate, uranyl sulphate, and uranyl fluoride are of chief importance among all the uranyl salts.

UO_2SO_4 is easily reduced to tetravalent uranium sulphate.

$$UO_2SO_4 + Zn + H_2SO_4 = U(SO_4)_2 + ZnSO_4 + H_2O.$$

Any soluble uranyl salt under the action of a base forms insoluble polyuranates:

$$2UO_2SO_4 + 6\ NaOH = Na_2U_2O_7\downarrow + 2\ Na_2SO_4 + 3\ H_2O.$$

The interaction of uranyl salt solutions with hydrogen peroxide results in the sedimentation of uranium peroxide that is insoluble in neutral and subacid media.

$$UO_2SO_4 + H_2O_2 + 2H_2O = UO4\cdot 2H2O + H_2SO_4.$$

Uranyl-ion tends greatly to complexation. So in excess of acid, the formation of compounds occurs:

$$UO_2SO_4 + H_2SO_4 = H_2[UO_2(SO_4)_2];$$
$$UO_2SO_4 + 2H_2SO_4 = H_4[UO_2(SO_4)_3].$$

Of great practical importance is tricarbonate complex that is formed in solutions containing carbonic acid ions **CO_3^{2-}:**

$$UO_2F_2 + 3\ (NH_4)_2CO_3 = (NH_4)_4[UO_2(CO_3)_3] + 2\ NH_4F.$$

URANATES. Uranates are insoluble in water salts of both uranium and polyuranium acids, usually of yellow colour.

All the uranates are dissolved in acids with the formation of uranyl salts:

$$Na_2U_2O_7 + 6HNO_3 = 2UO_2(NO_3)_2 + 2NaNO_3 + 3H_2O.$$

Uranates are insoluble in bases, but they are readily dissolved in soda solutions with the formation of complex uranyl carbonates:

$$Na_2U_2O_7 + 6Na_2CO_3 + 3H_2O= 2Na_4[UO_2(CO_3)_3] + 6NaOH.$$

Of special importance are ammonium uranates that are thermally unstable, and on calcination they are decomposed to uranium oxides:

$$(NH_4)_2U_2O_7 = 2UO_3 + 2NH_3 + H_2O \text{ at } \mathbf{t} = 250 – 400\ °C;$$

$$9(NH_4)_2U_2O_7 = 6U_3O_8 + 14NH_3 + 15H_2O + 2N_2 \text{ at } \mathbf{t} = 600 – 900\ °C.$$

LECTURE 8

ISOLATION OF URANIUM FROM ACCOMPANYING ELEMENTS

Most of methods of isolation of uranium from accompanying elements are based on isolation of uranium itself from a solution being analyzed, and minority of them – on isolation of impurity substances.

The sedimentation, extraction and chromatographic methods are the most-used for uranium isolation. In addition, there are sometimes applied distillation, sublimation, electrolysis, electrodialysis etc. For isolation of small amounts of uranium, coprecipitation with a carrier and extraction are more appropriate, and chromatography as well.

The choice of one or other isolation technique depends on the selected method of determination, on the composition of solution being analyzed, and first of all on the nature of accompanying elements and their concentration, on the uranium content in the solution, and on the required accuracy of determination. It is impossible, therefore, to indicate such a technique which would ensure the best results in all cases.

Among techniques for uranium isolation by sedimentation, ones most extensively employed are: (1) the carbonate technique involving sedimentation of majority of hindering accompanying elements by ammonium carbonate or by alkaline metal carbonates reacting with uranium (VI) to form a soluble carbonate complex, and also (2) uranium sedimentation by phosphates, hydrogen peroxide, cupferron, fluorides and 8-oxyquinoline. Sedimentation by oxalates, caustic alkalis, urotropine, pyridine and other organic bases is less significant.

Among all the well-known extraction techniques of uranium isolation, used both for analytical purposes and in technology, the most important are extraction of uranyl-nitrate by certain oxygen-containing extractive agents such as ethers, ketones, esters and the like. Extraction isolation of uranium in the form of uranyl-nitrate has the advantage that in this case just a few elements together with uranium are extracted as nitrates.

The substance most extensively employed for extraction isolation of uranium is tributyl phosphate.

LECTURE 9

QUALITATIVE DETERMINATION OF URANIUM

The characteristic reactions of uranium ions, which can be used for its fast qualitative detection are, first of all, the colour reactions with inorganic and organic reactants and the luminescence reactions.

In the absence of other radioactive elements, uranium can be fast determined by its radioactivity. The very small amounts of uranium can be determined by the microradiography.

Some other methods are more rarely used for uranium detection: polarographic, spectral, the neutron-activated analysis. These rather complicated instrumental methods are mainly used for the quantitative determination of uranium.

The sedimentation reactions are little characteristic of uranium in most cases and are not applied for fast qualitative analyses. The exception is some microcrystalline reactions, for example with anthranyl acid. If on uranium sedimentation by organic compounds the sediments are intensively coloured, they can be used for detection of uranium. In this case nonaqueous solvents are preferable, in which these sediments are dissolved and then subjected to photometric procedure by the standard scheme.

Almost exclusive peculiarity of the system UO_2-NaF to give bright yellow – green fluorescence under the action of ultra-violet radiation makes the fluorescence method so selective that preliminary impurities isolation is not usually required.

With concentrations in the order of some milligrams per millilitre in solutions free of coloured substances, the uranium can be identified by colour of its own simple inorganic salts. Uranyl solutions are of yellow colour, tetravalent uranium solutions are of much more intensive green colour. The colouring of salts of both hexavalent and tetravalent uranium intensifies in solutions of concentrated acids.

There exist many well-known characteristic reactions of uranium with oxygen- and sulfur-containing reactants.

LECTURE 10
QUANTITATIVE DETERMINATION OF URANIUM

The chemical methods for quantitative determination of uranium that include gravimetric and titrimetric techniques are characterized by the wide variety. This variety is caused by the fact that the uranium belongs to elements capable of exhibiting easily various valences and has a pronounced tendency to form not readily soluble compounds and complexes.

All known now gravimetric methods of uranium determination are based on sedimentation of it from solutions in which it is either tetravalent or hexavalent. The most widespread weight form for uranium determination is uranium protoxide-oxide **U_3O_8.** The weighing of uranium content is carried out by sedimentation of it by means of ammonium hydroxide, hydrogen peroxide, ammonium sulphide, hydrofluoric acid or ammonium fluoride and also with organic reactants, followed by weighing it as protoxide-oxide.

In comparison with some other methods of uranium determination, weight (gravimetric) methods are characterized by higher accuracy of 0.1 %. One of drawbacks is that the minimum quantity of uranium required for gravimetric determination measures about 5 mg. The second essential drawback of gravimetric methods of uranium determination is their long duration and labouriousness.

The titrimetric techniques of uranium determination in a number of cases are highly competitive with the gravimetric methods in accuracy, but offer a few advantages over them. To advantages of titrimetric techniques should be referred the possibility of uranium determination over a wide range of its contents including microamounts, making the analysis in much shorter times, as well as the considerable opportunities of uranium determination in the presence of other elements hindering their gravimetric determination

The titrimetric techniques of uranium determination are classified into some groups, each of them being based on the use of a certain chemical property of uranium. Of very widespread use are the titrimetric techniques of uranium determination based on oxidation-reduction properties of uranyl and uranium ions. Less common methods are based on titration of either uranium or uranyl salts with solutions of precipitants or complexing substances. Lastly, of even lesser importance are all the indirect methods consisting in sedimentation of uranium with precipitants, which content in the resulting precipitate is determined by one or other titrimetric procedure.

Most widespread are the methods of titration with potassium permanganate and potassium dichromate.

LECTURE 11
CHEMICAL PROPERTIES OF THORIUM AND ITS COMPOUNDS

Thorium is a silvery white metal with the density of …. g/cm^3. The melting temperature is 1750 °C.

The boiling point is 3500–4200 °C.

Thorium is a reactive electropositive metal. Thorium reacts with hydrogen forming solid solutions and hydrides. On heating thorium with nitrogen up to 800 ^{o}C, nitrides formation occurs. Thorium metal is slow to react with water. Diluted HF, HNO_3, H_2SO_4, and concentrated H_3PO_4 are slow to interact with the compact metal. Concentrated HNO_3 passivates the metal. Thorium is easily dissolved in hydrochloric acid and in aqua regia. Alkali solutions do not react with thorium metal.

Thorium dioxide ThO_2. ThO_2 can be obtained by burning thorium metal in air, and also by calcination of thermally unstable thorium compounds: $Th(OH)_4$, Th_2O_7, $Th(NO_3)_4$ etc. ThO_2 dissolves in acids and is insoluble in water and alkalis.

$ThOH_4$ is precipitated from solutions in the pH range of 3.5–3.6 in the form of amorphous precipitate. It is a basic hydroxide.

Thorium fluoride. ThF_4 is practically insoluble in water and acids.

$ThCl_4$ is a white crystalline hygroscopic substance, it is easy soluble in water.

Thorium sulphate is moderately soluble in water.

Thorium nitrate is the most soluble salt – at 20 °C the solubility of $Th(NO_3)_4$ measures 65.6 %. Besides, this salt has great solubility in alcohol, ketones, ethers , organophosphorous compounds.

Thorium oxalate. Solubility of thorium oxalate is one of the least and measures 0.07 mg/l at 25 °C.

LECTURE 12
ISOLATION OF THORIUM FROM ACCOMPANYING ELEMENTS

The main accompanying elements of thorium are REE, uranium, iron, silicon, phosphorus, titanium, zirconium, hafnium, calcium etc.

Methods of separation for thorium and rare-earth elements are based on distinctions of their chemical basicity, solubility of the compounds, relation to organic solvents and volatility of the compounds. For this purposes, hydrolytic sedimentation, iodate sedimentation, ion-exchange chromatography, and extraction are used.

To isolate thorium from titanium, sedimentation by oxalic acid, sedimentation by hydrofluoric acid are used, as well as sedimentation in the form of not readily soluble salicylate, and the chromatographic separation. Thorium and zirconium are separated in a similar way.

Most frequently used method of thorium separation from chromium is distillation of chromium in the form of chromyl-chloride.

Thorium separation from alkaline and alkaline-earth metals can be carried out by ammonia sedimentation or by the chromatographic method.

Thorium from beryllium is separated with hydrofluoric acid by means of sedimentation of not readily soluble thorium fluoride.

Separation of thorium from Co, Ni and Zn is achieved by sedimentation of thorium fluoride with hydrofluoric acid or by electrolytic reduction of Co, Ni and Zn.

The methods of separation of thorium from niobium and tantalum are based on sedimentation of thorium fluoride, peroxide, hydroxide or oxalate.

To separate thorium from phosphorus, sedimentation with oxalic acid is most commonly used.

LECTURE 13
DETERMINATION OF THORIUM IN NATURAL AND INDUSTRIAL OBJECTS

Qualitative determination. Since a thorium ion is colourless, only a few characteristic reactions are known for it. There is a number of qualitative colour reactions for a thorium ion. These reactions, however, are not specific, since REE and zirconium react similarly.

Quantitative determination. The determination of thorium, not presenting a considerable problem in itself, becomes durational and complicated in the presence of accompanying elements. The majority of offered methods involve preliminary separation of impurities, and only few of them can be applied immediately.

Depending on the formulated problem, gravimetric, volumetric, colorimetric and other techniques are used in determination of thorium.

For precise determination, the gravimetric techniques are most often used. As a weight form, thorium dioxide is commonly used.

The volumetric methods ensuring rapidity and convenience of work are applied for the mass analyses when too high precision is not required. These methods, mainly indirect, are based on sedimentation of thorium in the form of not readily soluble compounds of stable composition (oxalate, iodate, molybdate etc.) and its determination either by an anion bonded to it or by excess of a precipitant. The most accurate of them are the iodate and molybdate techniques.

For determination of very small amounts of thorium (up to 1 mg), the colorimetric (spectrophotometric) procedures are used.

The radiometric methods are suitable for analysis of samples containing thorium only under the condition of establishment of radioactive equilibrium. The determination of thorium is hindered in the presence of uranium.

Spectral and X-ray spectral methods are used for determination of thorium quite seldom.

LECTURE 14

CHEMICAL PROPERTIES OF PLUTONIUM AND ITS COMPOUNDS

Plutonium metal is a heavy brittle metal of silvery-white colour. On heating from room temperature up to the melting point, plutonium undergoes five phase transformations and accordingly can exist in six allotropic modifications.

In its chemical properties, plutonium is a rather active element. Oxygen of the air oxidizes plutonium metal. Plutonium metal reacts appreciably with hydrogen even at 25–50 °C. At 900 °C plutonium is slow to reacts with nitrogen. Plutonium metal vigorously reacts with halogens and hydrogen haloids with formation of corresponding plutonium trihalogenides. With gaseous compounds of sulfur, plutonium metal forms sulphides. The interaction of the metal with carbon dioxide results mainly in formation of PuO_2.

Plutonium easily and fast dissolves in hydrochloric acid of various concentrations. Dissolving plutonium in 72 % chloric, 85 % phosphoric and concentrated trichloroacetic acids proceeds slightly slower. The metal is inert in relation to concentrated H_2SO_4 and CH_3COOH, but is slow to react with diluted solutions of these acids. In nitrogen acid, plutonium passivates and even prolonged action of the acid for several hours practically does not result in dissolution of the metal. In solutions of alkalis, appreciable dissolution of plutonium does not occur.

Plutonium dioxide is widely used in analytical chemistry as the most stable weight form, and in a process as an initial material for production of halogenides and other compounds as well. Plutonium dioxide represents a fine-grained powder of colour ranging from greenish-grey to dark brown. Plutonium dioxide is practically insoluble in water and diluted mineral acids.

$Pu(NO_3)_4$–$5H_2O$ is easily dissolved in water producing the solution of brown colour. Plutonium nitrate PuO_2 $(NO_3)_2 \cdot 6H_2O$ is very soluble in water, nitrogen acid and spirit, but insoluble in chloroform. Plutonium sulphates are very soluble in diluted mineral acids. Anhydrous sulphate is stable in the air. Adding the excess of alkalis or ammonia to solutions of salts of plutonium (III) and (IV) yields poorly soluble hydroxides precipitates. Adding the plethora of hydrogen peroxide to acid liquor of plutonium in any valence state produces the sedimentation of plutonium (IV) peroxide. Under the action of hydrofluoric acid on water solutions of plutonium (III), the salt PuF_3–H_2O precipitates. In response to adding hydrofluoric acid to acid liquors of tetravalentoго plutonium, the crystalline precipitate of pink colour PuF_4–$2,5H_2O$ occurs. The plutonyl fluoride PuO_2P_2 is very soluble in water. Plutonium phosphates are assigned to not readily soluble compounds. Under the action of oxalic acid on acid liquors of plutonium (III), (IV) and (VI), the appropriate not readily soluble plutonium oxalates are produced.

LECTURE 15

SEPARATION OF PLUTONIUM FROM ACCOMPANYING ELEMENTS

The determination of plutonium is made in various products of technological processing of nuclear fuel, in which the contents of plutonium, fission products and various impurities can vary over the widest limits. The impurities present in the products to be analyzed, hinder the quantitative determination of plutonium. In this connection the determination is usually preceded by isolation of plutonium from hindering elements using any **appropriate chemical procedure.**

The lanthanum-sulphate technique. The procedure is based on the property of Pu(III) and Pu(IV) to coprecipitate from water solutions with addition of double potassium and lanthanum sulphate. The hexavalent plutonium does not coprecipitate in the same conditions.

The bismuthphosphate technique. As the carrier, $BiPO_4$ is used. Pu(IV) is quantitatively coprecipitated with bismuth phosphate precipitate from the solution with concentration of HNO_3 from 0.1 to 1.0 N. The isolation of plutonium by this technique can be conducted in the presence of large amounts of iron.

Coprecipitation with zirconium phosphate. Similar to tetravalent thorium and cerium, Pu(IV) is quantitatively coprecipitated with zirconium phosphate (tri- and hexavalent plutonium remain in the solution in this case). The zirconium-phosphate technique enables one not only to separate plutonium and neptunium from fission products, but also to isolate these elements between themselves.

The lanthanum-fluoride technique. According to this scheme, from neutron irradiated uranyl nitrate were first isolated the weight amounts of plutonium. The technique is based on quantitative coprecipitation of neptunium(VI), Pu (III) and (IV) from acid liquors with the precipitate of lanthanum fluoride. Plutonium(VI) is not entrained by LaF_3 precipitate.

Coprecipitation on hydroxides. This technique is one of the most convenient and widespread for plutonium concentrating. Lanthanum or nickel are usually used as the carrier.

The sodium-uranyl-acetate technique. In this method the ability of hexavalent plutonium to produce poorly soluble sodium-plutonyl-acetate isomorphic with sodium-uranyl-acetate is used. Tri- and tetravalent plutonium does not coprecipitate with sodium–uranyl–acetate.

The extraction of plutonium in the form of molecular compounds with an extractive agent. The majority of extraction techniques of isolation are based on solubility of plutonium nitrates in various organic solvents.

The ethers are used for extraction isolation of plutonium in tetra- and hexavalent states. At the first stages of actinide elements production, for their purification and separation the extraction of Pu(IV) by diethyl ether was used.

The extraction of plutonium by tributyl phosphate. The main merit of the extraction of plutonium by TBP consists in high distribution coefficients.

The chromatographic isolation of plutonium. In technology and chemical-analytical control of plutonium, methods of ion-exchanging and partition chromatography are commonly used. The ion-exchanging techniques of elements separation consists in the selective absorption of ions from solutions by exchange them with ions of ionite active groups, followed by ions eluating (desorption) from the ion-exchange reactor.

LECTURE 16

QUALITATIVE AND QUANTITATIVE DETERMINATION OF PLUTONIUM

QUALITATIVE DETERMINATION OF PLUTONIUM. For plutonium detection, the radiometric method has taken the greatest significance, which is based on measurement of total **α**-radiation of plutonium and its energy. The radiometric method allows 0.0001 mkg of plutonium to be detected.

For plutonium detection, the reactions with intensively coloured reactants like arsenazo and thoron can be used.

QUANTITATIVE DETERMINATION OF PLUTONIUM. The radiometric method of plutonium determination is wide-spread. The reason is that the main plutonium isotope, Pu239, has very high **α**-radioactivity.

Methods based on light-absorbtion in water solutions of inorganic acids are frequently used.

The titrimetric methods are used quite seldom. The titrimetric methods are suitable for the analysis of quite pure products containing plutonium, and they are applied mainly to control products at final stages of nuclear fuel processing. The redox titration (with use of potassium bichromate, ammonium vanadate, potassium permanganat) are applied as well as the chelatometric titration with use of ethylene-diamine-tetraacetic acid (EDTA, complexon II).

The (gravimetric) determination is based on the sedimentation of plutonium from solutions in the form of tetravalent plutonium compounds. In most cases, plutonium dioxide serves as the weight form.

METROLOGY AND SPECTROMETRY OF IONIZING RADIATION FIELDS

LECTURE 1

INTRODUCTION TO DOSIMETRY AND SPECTROMETRY OF FIELDS OF IONIZING RADIATIONS

In the lecture, the purpose and basic problems of this course are defined.

The aim of the course is the acquirement of basic knowledge in the area of dosimetry and spectrometry of fields of ionizing radiations forming the theoretical basis for all dosimetric, radiometric and spectrometric methods of the analysis.

The course covers the following items:

1. Definition and classification of natural and artificial sources of ionizing radiations.
2. Definition of concept of radiation safety. Study of main terms and definitions in the field of radiation safety: radiation, activity, flux, fluence, radiation rate, source strength, etc.

3. Study of basic physics of dosimetry and spectrometry of ionizing radiations on the basis of the contents and features of physical processes responsible for their interaction with substance.
4. Study of theoretical fundamental of registration techniques for ionizing radiations.
5. Study of physical contents and principals of making dosimetric, radiometric and spectrometric investigations by various methods.

LECTURE 2
BIOLOGICAL EFFECTS OF IONIZING RADIATIONS

The purpose of the lecture is to become familiar with major factors of biological effect of ionizing radiations and principles of radiation safety.

The concept of a radiation doze is introduced. The features of absorbed, equivalent and exposition dozes as well as distinctions between them are defined. The concept of kerma is given. The relations between kerma and both absorbed and exposition dozes are determined.

The main consequences of exposure of biological organisms to ionizing radiations are considered: somatic, stochastic, and genetic.

The various ways of influence of ionizing radiations on living organisms are considered. Information about sources, contents and concentration of radionuclides in the environment is presented. Average annual dozes received from various radiation sources with various routes of exposure.

LECTURE 3
BASIC PHYSICS OF DOSIMETRY AND SPECTROMETRY OF IONIZING RADIATIONS

The first lecture in the section concerned with study of basic physics of dosimetry and spectrometry of ionizing radiations, it is devoted to revision and study of basics of interaction of charged particles with substance. The physical interaction features of primary interest in view of possibility of radiation registration are considered.

As the object of study, alpha-, beta-particles and positrons are selected The main features of radioactive decay schemes resulting in occurrence of the cited particles are analyzed.

The average energy loss due to ionization and excitation calculated per unit track length of alpha-particle is determined by Bethe formula. Alpha-particle track length is determined by the Geiger empirical relation. The concepts of bremsstrahlung and linear ionization density are introduced. The possibilities of Wilson chamber and ionization chambers for registration of alpha-particles are considered.

The average energy loss of electrons is given in terms of Bohr-Bethe theory. Except for losses in excitation and ionization, the losses due to bremsstrahlung occurrence (radiation losses) should be taken into account. The average radiation losses can be determined in terms of Haitler equation. The total losses of electron energy in substance are determined as the sum of ionization and radiation losses. The difference in the reduction law between monoenergetic electrons and beta-particles in substance is given.

LECTURE 4

BASIC PHYSICS OF DOSIMETRY AND SPECTROMETRY OF IONIZING RADIATIONS

The second lecture in the section concerned with study of basic physics of dosimetry and spectrometry of ionizing radiations, it is devoted to revision and study of basics of interaction of x-ray and gamma-radiation with substance. The physical interaction features of principal interest in view of possibility of the radiation registration are considered.

Starting from consideration of basic physics of x-ray and gamma-radiation nature, their principal distinctions are established. The main sources of x-ray and gamma-radiation are presented.

For X-radiation, the sources, condition and ways of origin of bremsstrahlung and characteristic radiations are determined. The reduction law of x-ray and gamma – radiation in substance is considered. The concepts of reduction factor and of half- reduction layer are introduced, as well as geometry of a broad and narrow radiation beam.

There are considered and described the main processes of gamma – radiation interaction with substance:

- photo-electric effect;
- Compton effect;
- pairing effect;
- nuclear photoeffect.

The features of total reduction factor of gamma-radiation are determined depending on radiation energy for various materials.

The physical meanings of effective atomic number of substance as well as of average ion production energy are introduced and elucidated.

LECTURE 5
BASIC PHYSICS OF DOSIMETRY AND SPECTROMETRY OF IONIZING RADIATIONS

The last lecture in the section concerned with study of basic physics of dosimetry and spectrometry of ionizing radiations, it is devoted to revision and study of basics of interaction of neutron radiation with substance. The physical interaction features of principal interest in view of possibility of the radiation registration are considered.

The description of elastic and inelastic interactions of neutrons with substance nuclei is given. The possible nuclear reactions are defined. The concepts of microscopic and macroscopic cross- section of neutrons are introduced.

The neutrons are classified into groups according to pattern of their interaction with substance: ultracold; cold; thermal; epithermal; intermediate energy neutrons; fast; ultraspeed ones. The interaction features of neutrons of various groups are considered on the basis of study of dependence of effective cross-section on energy for various materials.

The various materials are compared in their pattern of interaction with neutrons: moderators and absorbers. For this purpose, some concepts are introduced: average logarithmic energy loss, moderating ratio; average track length; relaxation distance; average path length before absorption; diffusion constant; diffusion length etc.

LECTURE 6
METHODS OF DOSIMETRY AND RADIOMETRY FOR PHOTON RADIATION

The aim of the first lecture in this section is to study the theoretical material concerning the principles of operation of ionization chambers and gas counters, as well as their performance.

The scheme and main principles of operation of ionization chambers are considered. At current-voltage diagram of the camera, the area of its working use – area of saturation current – is set off. On the basis of ionic pattern condition equation, the chamber operation and its order of magnitude of the response to external ionizing effect is considered. The classification of ionization chambers by various parameters is introduced, namely: by the function impulse and integrating), and by the design (with the internal source position, barrier chambers including thimble ones, diaphragmal or normal chambers.

Electron equilibrium and Grey theory are considered as theoretical grounds relating radiation dose data to current characteristics of ionization chambers.

The principles of operation of gas counters based on gas amplification due to impact ionization of gases are studied. The counters are categorized as either proportional or Geiger-Muller counter according to the character of gas ionization (the discharge type) in the internal space. The counters with self-quenched and non-self-quenched discharge are considered.

On the basis of counter response function, the main timing performances of its operation are introduced: signal shaping time, dead time, rehabilitation time, pulse duration.

The area of application of ionization chambers and gas counters is determined. The typical values of efficiency of radiation registration are given.

LECTURE 7

METHODS OF DOSIMETRY AND RADIOMETRY FOR PHOTON RADIATION

The aim of the second lecture in this section is to study the theoretical material concerning the principles of operation of fluorescent (including scintillation) dosimeters and spectrometers, as well as methods of registration of ionizing radiations based on coloration of glasses and plastics.

The concept of luminescence is introduced with defining the types of luminescence: photoluminescence, radiophotoluminescence, thermoluminescence etc. The principles of luminescence origin in materials are considered along with stimulated and unstimulated luminescences.

The principles of operation of scintillation detectors are presented. The scheme and principles of operation of scintillation radiation counters are given. The general properties of scintillators are given: de-excitation time, conversion efficiency, technical efficiency, amplification factor of the photoelectronic multiplier. Various scintillation materials are characterized: inorganic, organic and combined, liquid and solid.

The characteristic curve of thermal de-excitation for thermoluminescence dosimeters is considered. The characteristic area for their application is determined.

The modification of optical properties of materials under the action of ionizing radiation is characteristic of some glasses and plastics. The glasses are colored and change their optical properties on exposure to dozes exceeding several rad, and they are used for determination of considerable dozes. The performance data of the most used glasses and plastics are given.

LECTURE 8
METHODS OF DOSIMETRY AND RADIOMETRY FOR PHOTON RADIATION

The purpose of the final lecture in this section is to study the theoretical material concerning the essentials of techniques of photographic and chemical dosimetry, and calorimetric techniques as well.

The photographic method was historically among the first, and it is closely related to the discovery of X-radiation. For registration of the radiation, various photoemulsions are used. Sensitometric characteristics of photographic materials associated with the optical denseness of darkening are considered. Some grounding in theory of photographic action of x-ray and gamma- radiation is provided. As an example, employment of the dosimeters for individual dosimetric control is considered.

The calorimetric methods are based on registration of amount of heat transmitted by a radiation during interaction with materials. According to operating mode, the calorimetric methods are subdivided into isothermal, adiabatic and statical calorimeters of a heat flow. The principles of their work and main performances are considered.

The chemical dosimetric techniques are based on observation of irreversible chemical modifications made by radiation in a substance. The products of chemical reactions are determined with the help of chemical analysis (titration, electroconductivity measurement, spectrophotometry etc.). The liquid and gas chemical dosimeters are considered in regard to principles of their operation and major performances.

LECTURE 9
BASICS OF GAMMA-SPECTROMETRIC METHOD OF ANALYSIS WITH A SEMICONDUCTOR DETECTOR

The aim of the first lecture in this section devoted to gamma- spectrometric method of analysis is to study the theoretical background of the method and areas of its application.

The method is based on registration of characteristic x-ray and gamma-radiations. Distribution of the semiconductor method of measurement is connected with broad implementation of the spectrometric analysis.

A semiconductor detector may be considered as a solid-state ionization chamber. The principles of the detector operation are described with the help of the zone-theory of semiconductors, the basics of which are presented. By the use of extrinsic conductivity (donor and acceptor), it is possible to achieve improvements in semiconductor crystal performance for registration of radiations.

The peak of total radiation photoabsorption in a crystal is the dominant source of information in a spectrum. The process of Compton scattering creates a continuous background spectrum complicating performance of the analyses. The pairing is an additional source of information about some radionuclides which decay with emission of a positron.

Main types of semiconductor detectors include planar, coaxial and improved (well-type) ones. Each type of the detectors has its peculiarities and the specific area of application.

In the lecture, typical schemes of spectrometric tracts are considered. The performance data of its individual elements are given.

LECTURE 10

BASICS OF GAMMA-SPECTROMETRIC METHOD OF ANALYSIS WITH A SEMICONDUCTOR DETECTOR

The aim of the second lecture in this section devoted to gamma- spectrometric method of analysis is to study the theoretical background related to parameters of radiation registration.

The gamma-spectrometric tract is characterized by a number of features. One of the principal peculiarities is the detector resolution which is characterized by a half-width of peak at its half- height for given emitter energies.

Other major performances are determined by the response function of a spectrometric tract to external radiation exposure. Those are timing performances, and the dead time above all.

To make a spectrometric tract serviceable, the specific procedures are to be executed, namely calibration against energy and efficiency. A special feature of semiconductor detectors is the linearity of energy characteristic. Various forms of the efficiency curve distinguish the various kinds of detectors.

For calibration, the calibrating sources of gamma- and x-ray radiations are used. The calibrating sources are produced on the basis of various radionuclides. The radionuclides with one line have the best performances for calibration, for they have only one line of the characteristic gamma-radiation. The calibrating sources are classified as standard and control according to their accuracy rating. In shape, the sources are subclassed as either point or volume. The manufacturing and certification of calibrating sources of the complicated form is a labour-consuming problem that involves special standard materials.

LECTURE 11
BASICS OF GAMMA-SPECTROMETRIC METHOD OF ANALYSIS WITH A SEMICONDUCTOR DETECTOR

The aim of the final lecture in this section devoted to gamma- spectrometric method of analysis is to consider specific problems pertaining to various kinds of the analyses, executed with the help of indicated method.

The semiconductor gamma-спектрометрия is a basis for performing a number of analyses with specific execution features. Using this method, the radioecological investigations related to determination of radionuclide microquantities in the environment can be performed. The same method is used for measurements of highly-active material samples arriving for research after exposure in a nuclear reactor.

In the method, the geometry of measurements is of great importance. For due account of geometry, quite often it is required to manufacture special standard materials or to use semiempirical methods permitting the calibration based on efficiency to be performed correctly.

The form of a registered spectrum depends on many factors, including geometry of measurements and elemental composition of used and researched materials. The basic challenge is the arrangement of measurement conditions that provide the best – in shape and intensity – total absorption peak in question against the backgrounds of other peaks and scattered radiation. The relationship between the peak and the background determines sensitivity of analyses carrying out and may be either stationary or dynamically varying parameter.

An independent problem is determination of analysis error. The difficulty of correct determination of error is determined not only by the measurement process in itself and statistical error of the analyses, but by all the components of its performance – preparation of samples, exposure (if it is), correct account of geometry etc.

LECTURE 12
METHODS OF DOSIMETRY AND RADIOMETRY FOR CHARGED PARTICLES. METHODS OF RADIOACTIVITY MEASUREMENT FOR AEROSOLS AND GASES

The aim of the lecture is to study the peculiarities of parameter measurements of charged particle fields and the basics of methods of radioactivity measurement for aerosols and gases.

The charged particles have short free length as compared with gamma-radiation and neutrons. Because of this, for their registration the special detectors are used, or, for example, scintillation detectors of a small thickness.

The performances of these detectors and methods of charged particle measurements are discussed in this lecture.

The radioactive aerosols arise during production and handling with radioactive materials and represent the suspended particles of various size, with radionuclides deposited on their surfaces. For registration of such particles, the methods of their sedimentation from gas medium on filtering materials are developed. Thereafter the filters are controlled by means of radiometric or spectrometric instruments. The performances of most frequently used filtering materials are given.

Much more serious problem is determination of content of radioactive gases. Among these are noble gases which are chemically passive. The cryogenic sedimentation is the most effective technique for their sampling from a gas medium. The designs of electrofilters, cryogenic filters and filters based on various sorbents are considered here.

The applicability of direct radiometry and spectrometry of radioactive gases in technological tracts is discussed.

LECTURE 13
SPECTROMETRY OF ALPHA- AND BETA-RADIATIONS

The purpose of the lecture is to become familiar with technologies and techniques of beta- and alpha-spectrometric measurements.

Among radionuclides, pure beta-emitters occur, or emitters, the identification of which in specific analysis conditions may be possible and reasonable by means of beta-spectrometric method. The chief drawback of this method is the difficulty of obtaining the analyses results of good quality for mixture of great number of emitters, because the beta-radiation spectrum is continuous, in contrast to characteristic x-ray and gamma- radiations. Nevertheless, the identification, for example, of such radionuclides as $^{90}\mathbf{Sr}$ with the help of beta-spectrometry is justified, since alternatively it is possible to use only method of radiochemical isolation followed by beta-radiometry of the sample. The principles of beta-spectrometers operation and their performances are considered.

Alpha spectrometry is frequently used for precise determination of small amounts of alpha-emitters in samples. It is preceded by radiochemical isolation of a mixture of emitters to be determined. The alpha radiation spectrum is discrete, but it has peculiarities in the form of peaks. The composition of alpha-spectrometric tracts, description of its elements as well as the parameters obtainable in making analyses are discussed.

LECTURE 14
BASICS OF METHODS FOR MASS-SPECTROMETRIC AND ROENTGEN-FLUOROMETRIC ANALYSES

The purpose of the lecture is to become familiar with technologies and techniques of the mass-spectrometric and roentgen – fluorometric analyses.

The mass-spectrometric method is the most accurate of all analytical methods for element and isotope compositional analysis of materials. The structural design of mass-spectrometers (ion sources, analyzers, detectors, and vacuum systems), their advantages and advantages are discussed. The main types of the most frequently used mass-spectrometers and their performance are given. Merits and demerits of various systems of gas ionization and measurements are identified.

The roentgen – fluorescent analysis belongs to the category of widely used analytical procedures for determination of elemental composition of substances. The basic physics of the method relating to attainment of minimum critical potential of electron shells are considered. The possibilities of reaching the greatest intensity of characteristic lines are discussed. The various optical and monocrystal systems for registration of radiation are considered, and also various sources of X-radiation. The analysis of complex x-ray spectra is a rather intricate problem defining sensitivity of the analyses. Despite the complexity of execution, the method allows one to determine traces of elements down to 10^{-6} g/sg. The sample preparation is of principal importance in the method, for it defines reproducibility of the results and, as a consequence, their representativeness.

LECTURE 15
BASICS OF DOSIMETRY AND SPECTROMETRY OF NEUTRON RADIATION

The purpose of the lecture is to become familiar with principal methods of registration of neutron radiation.

The dosimetry of neutrons is based on the concepts of biological tissue and equivalent dozes. By biological tissue doze is meant a total doze produced by all kinds of secondary radiation (by recoil protons, recoil nuclei, ionizing particles produced in nuclear reactions, gamma – quanta originating in neutron capture).

For registration of neutrons, the secondary radiation is used, which arises due to their interaction with substance. One of the types of fast neutrons ionizing effect is the occurrence of recoil nuclei during their scattering. For registration of the recoil nuclei, the large, average and small ionization chambers are used, the elementary theory of which is considered. The design, principles of operation, and parameters of various types of neutron dosimeters (boron chambers, fission chambers, track dosimeters, scintillation counters, the photodosimeters) are discussed. The areas of their potential application are compared.

LECTURE 16

BASICS OF DOSIMETRY AND SPECTROMETRY OF NEUTRON RADIATION

The purpose of the lecture is to become familiar with methods of spectrometry of neutron radiation.

Spectrometry of neutrons is a specific, complex problem. One of the most frequently used methods of its solution is the sample activation technique. The method is standardized. For its implementation, sets of commercial activation detectors (AKN) are used and sets of fission detectors (DKN). The irradiated samples are measured by methods of radiometry, spectrometry and track analysis. The restoration of spectra is executed by means of specially developed techniques.

The simplest method for the multigroup analysis of a neutron field is the three-group method subdividing the neutron spectrum into thermal, epithermal and fast. The determination of thermal and epithermal neutron group is carried out by the method of cadmium difference. The method is considered in detail. Fast component of a spectrum is determined with the help of threshold detectors activation.

Some methods are used for the absolute calibration of neutron sources: the correlating particles technique; direct flux measurement; the complete absorption technique. For the spectral analysis, the following methods are used: time of flight, interrupter, intermittent source.

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