The aim of the course “Atomic nucleus fission” is to introduce future physicists-experimentalists to a range of scientific problems, which determine the development of modern idea of atomic nucleus fission. We provide a basic insight into the process of fission, which follows from the model of drop of liquid, and show the inability of this model to explain mass asymmetry of fission, the existence of subbarrier resonances and spontaneously fissile isomers. In the lectures we set out systematically modern knowledge of fission physics and research prospects in this field. The material, which is set out, includes: experimental data and the basics of theoretical models of deformation energy and fission barriers of heavy nuclei, knowledge about the conditions of passing the fission barrier, data about nucleus lifetime in relation to fission and explanation of these data, the existing idea of different aspects of fission dynamics and their relation to the experimentally measured quantities. The lectures also give detailed description of methods and results of the study of level structures in the second well of the potential barrier, experimental methods of atomic nucleus fission study, works on ternary fission, and explanation of the connection between these works and the main problems of binary fission. The concluding part contains the results and prospects of the study of characteristics and dynamics of the processes of fission, observed in nuclear reactions in the heavy ion beam.

After studying this course, a student should:

- receive basic knowledge about the process of fission, which we have know;
- have a clear idea of basic approaches to and methods of studying nucleus fission and understand the sense of the experimental data about fission;
- be trained enough for creative work in a team, which deals with modern experimental research on different branches of fission physics;
- be able to deal with modern scientific articles on nucleus fission by themselves.

The review of main results in the field of nucleus fission

Deformation energy and fission barriers for heavy nuclei

Deformation energy pattern in the drop nuclear model. Disadvantages of the drop nuclear model. The absence of explanation of nuclear deformation in the fundamental state. Stability of the charged drop of liquid in relation to asymmetric deformation modes and incapability to explain asymmetric nucleus fission. Difficulties in explaining fission barrier height. The necessity to explain the nature of long-lasting resonances below fission barrier and spontaneously fissile isomers. The model of shells with nuclear deformation. Strutinsky shell correction method. Testing of the method through the calculation of nuclear deformation in the fundamental state and asymmetry of masses of fission fragments. Potential energy surface of heavy nuclei. Nuclear deformation parameters, which are essential for the description of basic fission properties. Dependency of fission barriers on nuclear fission parameters. Stability island of superheavy elements. The discovery and study of superheavy nuclei. Stability island of deformed nuclei about magic number of neutrons N=164.

Passing of fission barrier


Parameters of double-peaked fission barriers and lifetime of shape isomers

Zone of spontaneously fissile isomers on nuclide map. The influence of the odd nucleon on the increase of lifetime in relation to fission. Specialization energy. Phenomenology of half-life periods of spontaneously fissile isomers. Other types of decay of shape isomers. Explanation of low probability of gamma-decay of spontaneously fissile isomers. Experimental methods to find parameters of the form of double-peaked fission barrier. Information about lifetime of shape isomers and height of the first and of the second barriers. Compound-nucleus formation and decay as a way of studying spontaneously fissile isomers. Formation pattern of shape isomers during the decay of excited compound-nucleus. Statistical model and evaluation of the competition of processes of instantaneous fission neutron evaporation, gamma decay and transfer to the second well of potential barrier (formation of shape isomers). Dependency of shell correction of nuclear energy on energy. Level density at the saddle point. Regard for the influence of giant resonance on the value of matrix element of gamma transition. Evaluation of cross-sections of evaporation reactions, which result in formation of shape isomers, comparison with experiment. Two classes of levels of compound nucleus,
responding to deformations of the fundamental and isomeric state. Density of states in the second well. Information about energy of shape isomers and height of the first and second barriers.

**Nuclear state in the second well of fission barrier**

Types of state in the second well: particle-hole states, levels of rotary bands, vibration states. Calculation of one-particle states in the second well. Energy gap, energy of decay of the pair, K-isomers. Ways of settling and studying nuclei with excitation energy below fission barrier: reactions of neutron evaporation from compound nuclei, neutron capture, photofission, inelastic scattering of protons, alpha-particles, etc., straight reactions: (d,p), (t,d), (t,p) etc. Distribution of compound nuclear states according to the impulsive moment strength; evaluation of angular distribution of fission fragments. Photofission of even-even nucleus. Production of weakly excited nuclei in reaction d, p. Nuclear fission, caused by resonance neutrons. Reactions \((n,\gamma)\), \((n,n')\), \((n,f)\). Beta- and gamma-vibrations. Vibrational beta-resonance in the second well and its role in subbarrier fission. Examples of vibrational resonances in the second well. Fission in resolved resonance region of the levels of class I. Data about density of levels of classes I and II. Spectroscopy of the levels of the third well of uranium-234. Depth of the third minimum. Gamma-spectroscopy of the levels in the second minimum of potential energy. Data about the levels of rotary bands of shape isomer and direct determination of deformation (inertia moments) of states in the second well \(^{240}{\text{Pu}}\).

**Dynamics of fission**

The notions of saddle point, point of exit from classical forbidden region below fission barrier and breaking point. Evaluation of energy of transition from the saddle point (point of exit) to the breaking point. The influence of the dynamics of the process on the distribution of kinetic energy, excitation energy and impulsive moment strength of fission fragments. Role of the process of fall in evaluating mass distribution (including odd-even effect magnitude), asymmetries of masses of fission fragments. Microscopic models. Time-dependent nuclear Hamiltonian in Hartree-Fock approximation. Examples of microscopic and macroscopic calculations of fissile nucleus shapes. Calculations, which presuppose scholastic nature of fission. Calculations of lifetime in relation to fission according to Bohr-Willer statistic model and Cramers. Multiplicity of neutrons, released before the rupture of the neck. Diffusion fission model. Deterministic description of fission. The choice of deformation parameters. Coordinate frame, based on Cassinian ovals. Shell effect in energy of strongly deformed nucleus. Comparison of calculated masses of fission fragments asymmetries with experimental data. Model analysis of inertia and friction tensors. Comparison of calculated values of kinetic energy of fragments with experiment. Evaluation of the values of energy before rupture. Insight into provisional scale of the processes of fall, rupture of the neck, fragments acceleration. Empiric formulas for the mean value of full kinetic energy of fission fragments. Static fission model, based on the analysis of
the properties of the fissile nucleus at the point of rupture of the neck. Balance of energy, released in passing to breaking point. Search for neutrons, released before the rupture of the neck. Collective degrees of freedom at the point of the rupture of the neck, impulsive moment of fission fragments.

Experimental methods of researching nuclear fission

Methods of measurement of fission fragments mass and energy. Determination of nuclear charge of fragments. Data of experiments on measuring spectra of kinetic energy and mass distribution of fission fragments. Fission modes of nuclei with Z>90. Study of the “cold” nuclear fission. Cold symmetric nucleus fission. Cold, symmetric fission of nucleus \(^{258}Fm\) and other nuclei, similar to \(^{264}Fm\). Registration of instantaneous neutrons of fission, the average number of neutrons, multiplicity distribution, neutrons, released before the eruption of the neck and from accelerated fragments. Independent exits of fission fragments. Gamma emission of fission fragments. Independent exits of pairs of fragments. Balance of energy of nuclear fission. Measurement of impulsive moments of fission fragments.

Ternary fission

Search for fission of heavy nuclei into 3 fragments, with almost equal masses. Observed ternary fission as a process, which represents a weak branch of fission into two fragments. Exits of ternary fission of weakly excited nuclei of actinides. Probability of emission of the third particle, light nucleus, depending on its mass and charge. Information about power consumption, caused by ternary fission. Energy spectra and angular distribution of light nuclei of ternary fission. About the connection of these spectra with collective movement modes movement at the point of the rupture of the neck. Calculation of energy spectra and jump angles of light nuclei of ternary fission. Measuring the temperature in the neck of the fissile nucleus \(^{252}\text{Cf}\) through the measuring of the exit of \(^{10}\text{Be}\) in the fundamental and excited states during ternary fission. Independent exits of fragments, measured during ternary fission \(^{252}\text{Cf}\). Fission modes, contributing to ternary fission with exits of different light nuclei.

Heavy ion beams and nucleus fission

New possibilities of studying nuclear fission, which appeared due to the use of nuclear reactions at heavy ion beams. Fission of nuclei with high fission barriers in comparison to nuclei Z>90. Fission of hot rotating nuclei. Study of emission pre- and post-fissile fissile neutrons. Resulting temperature of fissile nucleus. Dependency of the height of fission barrier on nuclear angular moment. Impulsive moment and mass and energy spectra of fragments. Study of mass spectra of fragments about Бусиаро-Галлоне point. Properties of quasi-fission. Study of fission of weakly excited nuclei, formed in fusion reactions. Multimodal nuclear fission near plumbum and thorium-actinium. Fission of
nuclei, which are far from $\beta$-stability. Delayed fission. Significance of the results for calculation of nucleosynthesis of heavy and superheavy nuclei.