NUCLEAR REACTIONS WITH HEAVY IONS

Prof. Valery Zagrebaev (Flerov Laboratory of Nuclear Reaction)

9th semester, Lectures: 34 hours, Seminars: 17 hours

The aim of the course “Nuclear reactions with heavy ions” is the study by the students of the basic processes, that take place during the collision of atomic nuclei at low energies. Low-energy nuclear reactions are the basic instrument in the investigation of the atomic nuclei and nuclear dynamics, in the production and study of the exotic nuclear states and matter, in the synthesis of new elements and isotopes.

During the course a student should acquire a clear idea of nucleus-nucleus interaction and of basic peculiarities of nuclear reactions. The study of different mechanisms of nuclear reactions presupposes the mastering of the experimental methods of the measurement of cross-sections of different processes, the analysis of the experimental data and introduction to the modern models of nuclear dynamics, which are used for their description. This course includes the study of peculiarities of elastic and inelastic scattering of nucleons and heavy ions by nuclei, the processes of fragmentation, deep inelastic scattering and fusion, reactions with radioactive nuclei. This course presupposes that students have already studied general courses “Nuclear physics” and “Quantum mechanics”, as well as special courses “Scattering theory” and “Nuclear radiation detectors”.

<u>The contents of the sections of the discipline</u>

1. Nucleus interaction and general regularities of nuclear reactions.

1.1 Nucleon-nucleon and nucleon-nucleus interaction, nuclear mean field.

1.2 Nucleus-nucleus interaction: folding-potential, proximity-potential, phenomenological potentials.

1.3 Nuclear reactions. Their classification according to their energy and basic mechanisms.

1.4 Setting-up of experiments for the study of nuclear reactions.

1.5 Conservation laws and kinematics of nuclear reactions.

1.6 Differential cross-sections of nuclear reactions.

2. Elastic scattering of nucleons and heavy ions.

2.1 Elastic scattering of protons and neutrons by nuclei.

2.2 Cloudy crystal ball model.

2.3 Elastic scattering of light ions.

2.4 Applicability of classical mechanics and trajectory analysis.

2.5 Coulomb and nuclear rainbow, diffraction scattering.

2.6 Elastic scattering of heavy ions.

3. Quasi-elastic scattering and reactions of few-nucleon transmission.

3.1 Straight reactions of few-nucleon transmission.

3.2 Method of distorted waves for the description of forward processes.

3.4 One-particle and cluster states in nuclei, spectroscopic factors.

3.5 Quasi-elastic scattering of nuclei and heavy ions.

3.6 The study of vibratory and rotational nuclear states.

4. Deep inelastic scattering of nuclei

4.1 Experimental regularities of deep inelastic scattering of nuclei.

4.2 Description of processes of deep inelastic scattering of nuclei.

4.3 Multidimensional surface of potential energy of the heavy nuclear system.

4.4 Diabatic and adiabatic driving-potential.

4.5 Transport equations, which are used for the description of deep inelastic collisions of nuclei, nuclear frictional force.

4.6 Analysis of regularities of deep inelastic scattering with the help of multidimensional Langevin equations.

4.7 The prospective usage of deep inelastic transmission reactions for the production of new isotopes and elements.

5. Nuclear fusion reactions.

5.1 Nuclear fusions at over-barrier energies.

5.2 Statistical model of decay of the excited compound nucleus.

5.3 Registration of fusion fragments and evaporation products of the compound nucleus.

5.4 Sub-barrier nuclear fusion.

5.5 Model of the one-dimensional barrier, Hill-Willis formula.

5.6 The connection of channels, empirical and quantum description of the fusion process.

5.7 Barrier distribution function.

5.8 The role of nucleon transmission in the process of sub-barrier fusion.

5.9 Fusion of light neutron-excess nuclei.

5.10 Synthesis of super heavy nuclei in fusion reactions.

5.11 Processes of quasi-fission.

6. Processes of fragmentation and massive transmission.

6.1 Processes of decay of light ions.

6.2 Nuclear fragmentation reactions at intermediate energies.

6.3 Production of pre-equilibrium light particles.

7. Reactions with radioactive nuclei.

7.1 Nuclear chart and limits of nuclear stability.

7.2 Exotic qualities of weakly bound nuclei, neutron halo.

7.3 Production of nuclei near the limit of nuclear stability, mass-separators.

7.4 Production of accelerated beams of radioactive nuclei.

7.5 Elastic scattering and spectroscopy of exotic nuclei.

7.6 Fragmentation of weakly bound nuclei.

7.7 Near-barrier fusion of weakly bound nuclei.

Methodical recommendations to the tutor

It is noteworthy that this special course is given to the students after they have studied "Collision theory". The focus is made here on the study of experimental regularities of nuclear reactions with heavy ions at low energies and on the understanding of difficult dynamics of nucleus-nucleus interaction. That is why the study of each process begins with the discussion of the setting up of the relevant experiment, including the explanation of the difficulties and problems. Then we demonstrate observed experimental cross-sections and regularities of the studied reaction and give qualitative explanation of them. In conclusion, we compare calculations, made on the basis of modern theoretical models, with experimental findings, and discuss those physical conclusions, which can be drawn from the analysis of those data.

At practical lessons and as a self-study, each student makes two course papers, aimed at the analysis of experimental data on a certain nuclear reaction (elastic scattering and fusion in different combinations). In the case of elastic scattering the trajectory analysis of the process of collision (rainbow, diffraction, close and far components) is performed, and in the cloudy crystal ball model the analysis with the adjustment of parameters of the optical potential is carried out. For the fusion reaction we create multidimensional potential surface of the nuclear system and perform the analysis on the basis of the model of one-dimensional barrier penetration, with the help of empirical barrier distribution function and on the basis of the quantum method of connected channels. The work is performed with help of the software, adjusted to the work in the Web-browser environment. On each paper a report should be made, where the choice of physical quantities should be justified and the conclusions should be drawn (from the analysis of experimental data).

Methodical recommendations to the students

First of all, a student should get used to the idea that it's necessary to learn nuclear physics terminology as soon as possible, because the basic literature on this course (as well as on other courses, by the way) and nuclear databases are written in English. By making course-papers a student should not only master the application of modern theoretical models and software for the analysis of actual experimental data, but also to learn to search on his/her own (in literature or nuclear databases) additional information, which is required for this analysis, about the qualities if nuclei, taking part in the reaction (binding energy, spins, excited states and their qualities, etc.), and also learn to carry out the simplest kinematical analysis of nuclear reactions.