

NUCLEAR REACTIONS AT INTERMEDIATE ENERGIES

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10th semester, Lectures: 34 hours

It has been found out in the last years that there is a connection between nucleon interaction at low and intermediate energies below the threshold of pion production and basic theory of strong interaction - quantum chromodynamics (QCD), specifically chiral symmetry of QCD. One of the main aims of this course is to carry to the students the contents and the importance of this achievement for nuclear physics. The choice of experimental data and minimal theoretical information are aimed at the solving of this problem. The focus is made on the question of nuclear potentials. We set out purely phenomenological models of NN-forces, which are widely used in nuclear physics, but have no theoretical status, and modern NN-forces from effective chiral theory. We bring forward the results of the experimental testing of nuclear forces on the basis of the study of two- and three-nucleon systems, and of reactions of pion production during NN-collisions in accelerators COSY, TRIUMPH, RIKEN, etc. At the same time a wide range of important questions of nuclear physics lies beyond the applicability of chiral theory, and some of them are also discussed in the course. Here belong experiments on deep inelastic nuclear reactions (cumulative processes) and electron scattering at large momentum transfer. There is no consistent theory of these processes. We also discuss a wide class of diffraction processes, which are successfully described by Glauber-Sitenko theory of multiple scattering.

This course is aimed at teaching students to understand basic trends, key tasks and established theoretical methods in the field of studying nuclear reactions at intermediate energies at the level, which is enough for self-work with modern scientific literature on this branch of experimental nuclear physics. A student should know basic experimental facts from low-energy pion physics, low-lying nucleon resonances and their manifestation in nuclear reactions, and be able to make the simplest assessment of the characteristics of nuclear reactions, which are studied in the special course.

The contents of the sections of the discipline

1. Small parameters in strong interaction theory. High, low and intermediate energies in the physics of nuclear reactions. Left and right fermions. Chirality and helicity. Conservation of helicity at the chiral limit and decay probability ratio for $\pi \rightarrow \mu + \nu_\mu$ and $\pi \rightarrow e + \nu_e$. Chiral $SU(3)_L \times SU(3)_R$ and $U(1) = U(1)_L \times U(1)_R$ symmetries of classical Lagrangian QCD. Spontaneous alteration of chiral symmetry. Pion as Goldstone boson. Mass formulas for pseudoscalar mesons. Vector and axial-vector currents. Isospin symmetry and conservation of vector current. Partial conservation of axial-vector currents. The derivation of Goldberg-Treiman ratio from the condition of conservation of axial current. Physical sense of constants g_A and f_π . $\pi\pi$ -scattering length. Experiments DIRAC and NA48.

2. Pion and nucleon coupling – analogy with electrodynamics. Lagrangian of pseudoscalar and pseudovector coupling. Constants πNN -coupling. Vertex function πNN . Nucleon-nucleon interaction. Static potential of one-pion exchange (OPE) in coordinate representation. Central and tensor part of the potential. Static characteristics of deuteron and OPE potential. Phase shifts in the highest partial waves of NN-scattering and OPE potential. Contribution of the polar diagram of pion exchange into elastic NN-scattering. OPE potential in impulse representation. Potentials of one-boson exchange (OBE). Scalar meson exchange. Vector boson exchange. Comparison of the spin parts of potentials V^π and V^ρ . Spin-orbit coupling. Modern high-accuracy potentials of NN-interaction. CD Bonn model of NN-interaction.

3. The idea of chiral effective perturbation theory (CEPT). Effective chiral Lagrangian. Nucleon forces in chiral effective theory. Pion exchanges and contact interaction. Three-nucleon and multinucleon forces. Main achievements of CEPT. Description of data about NN-, nd-scattering in chiral effective theory.

4. The lowest nucleon resonances: $\Delta(1232)$, $N^*(1232)$, $N^*(1440)$, $N^*(1520)$, $N^*(1530)$, and their quantum numbers. Excitation of nucleon resonances in πN -scattering. Clipping of the galactic cosmic rays spectrum through the interaction with relict photons through Δ -isobar. P -wave πN -scattering amplitude in Born approximation. Δ -isobar model of πN -scattering. Comparison of p -wave amplitudes with the experiment. S -wave πN -scattering. Quantum numbers of effective bosons in s -wave πN -scattering. Spin structure of the amplitude of the reaction $0 + \frac{1}{2} \rightarrow 0 + \frac{1}{2}$. Spin observables in terms of invariant amplitudes: unpolarized cross-section $d\sigma_0$ and spin correlation.

5. Scattering of pions by deuterons. Impulse approximation for the calculation of full cross-section of this reaction. Charge invariance violation in πd -interaction. Reaction $pp \rightarrow d\pi^+$ in Δ -resonance region. Isotopic ratio for the cross-section of reactions $pp \rightarrow d\pi^+$ and $pp \rightarrow d\pi^0$. Counting of pion quantum numbers from the reactions $\pi^+ d \rightarrow pp$ and $\pi^- d \rightarrow nn$. Generalized Pauli principle for the system of two nucleons. Allowed transitions into reactions $pp \rightarrow \{pp\}, \pi^0$. Rejection of Δ -isobar contribution in the process $pp \rightarrow \{pp\}, \pi^0$.

6. Elastic pd -backscattering at energies \sim GeV. Impulse approximation. Problem t_{20} . Reaction of production of biproton $pd \rightarrow \{pp\}, n$ in kinematics of pd -backscattering at 0.5-2 GeV. Sensitivity of this process to NN -potential behaviour at tight spacing. Cumulative effect. Nuclear scaling. Search for multi-quark configurations in nuclei. The rules of quark counting for binary reactions.

7. Electron scattering by nuclei. Meson exchange currents (MEC). Manifestation of MEC in reactions of deuteron fission near the threshold at large momentum transfer $d(e, e')pn$.

8. Diffraction interaction of protons of intermediate energies with nuclei. The idea of Glauber-Sitenko diffraction theory of multiple scattering.

Methodical recommendations for the tutor

The problems, which are discussed in this special course, lie at the intersection of traditional nuclear physics and elementary particle physics. This fact determines the choice of material for this course. This course presupposes minimal use of mathematical formalism of quantum field theory and quantum scattering theory, which students already know from the previous courses. The use of mathematical apparatus is aimed at decreasing time and efforts, which are necessary for acquiring the material. The focus is made on physical significance of basic mathematical ratios; for this purpose we draw analogies with solid state physics (as far as, for example, spontaneous symmetry violation is concerned) and quantum electrodynamics – in case of pion-nucleon interaction. One of the basic concepts – the concept of chirality – is illustrated with experimental facts of pion decay and lepton scattering at the ultra-relativistic limit. Formalism of spin observables is demonstrated at the simplest example of scattering $0 + \frac{1}{2} \rightarrow 0 + \frac{1}{2}$. Experimental data, which relate mostly to few-nucleon systems, are also used in minimal amount, which is quite enough to illustrate basic results of chiral theory. Data, which lie beyond the applicability of this theory (resonance mechanisms, deep inelastic reactions, cumulative effect) are studied in a more thorough way.

Methodical recommendations for students

The main technical difficulty of working out and acquiring this course is connected with the fact that necessary literature on chiral theory is still scattered in digests in digests in journals. The synopsis of this part of the special course is under preparation.