Particle and nuclear physics

Coordinated by: Institute of Particle and Nuclear Physics
Study programme coordinator: prof. RNDr. Pavel Cejnar, Dr., DSc.

Characterization of the study program:

Particle physics (high-energy, subnuclear physics) investigates the structure of matter on the level of elementary particles and their fundamental interactions. Nuclear physics studies the structure of atomic nuclei and, more generally, the behaviour of finite quantum systems of mutually interacting particles. The study is based on comprehensive courses of theoretical and experimental particle and nuclear physics, based on extensive courses of quantum mechanics and quantum field theory. The emphasis is put on mastering the relevant computational techniques and managing the methods of acquisition and evaluation of experimental data, including an efficient use of computing and advanced software tools. With the aid of optional courses and the Master project, the students gain deep knowledge in a selected area and choose orientation to theory or experiment.

Profile of the graduates and aims of the study:

The graduates have advanced knowledge of particle and nuclear physics, in both experimental and theoretical domains. They comprehend quantum theory, understand basic approaches to the description of the microscopic world and manage experimental techniques of its study. They find employment mainly in fundamental experimental and theoretical research, but also in relevant applied research, e.g., in detector physics, nuclear medicine etc. The graduates are prepared to creatively develop the field of their scientific focus and to join international research teams. Experience in application of advanced software tools opens possibilities also for employment in the field of information technologies.

Recommended plan of the study

A pre-requisite of the study in this program is knowledge of general physics, experimental methods, non-relativistic quantum mechanics, calculus and algebra on the Bachelor level.

First year of the of the Master study

Code	Subject	Credits	Winter	Summer
NJSF041	**Experimental and Applied Nuclear Physics**	6	4/0 Ex	—
NJSF064	**Nuclear Physics**	7	3/2 C+Ex	—
NJSF105	**Elementary Particle Physics**	7	3/2 C+Ex	—
NJSF068	**Quantum Field Theory I** [1]	9	4/2 C+Ex	—
NJSF145	**Quantum Field Theory I** [1]	9	4/2 C+Ex	—
NJSF086	**Quarks, Partons and Quantum Chromodynamics**	6	—	2/2 C+Ex
NJSF037	**Microscopic Theory of Nuclei**	6	—	4/0 Ex
NJSF085	**Fundamentals of Electroweak Theory**	6	—	2/2 C+Ex
NSZZ023	**Diploma Thesis I**	6	—	0/4 C

[1] The students enroll only in one of these alternating courses.

Second year of the of the Master study

Code	Subject	Credits	Winter	Summer
NJSF191	**Seminar on Particle and Nuclear Physics III**	3	0/2 C	—
NJSF192	**Seminar on Particle and Nuclear Physics IV**	3	—	0/2 C
NSZZ024	**Diploma Thesis II**	9	0/6 C	—
NSZZ025	**Diploma Thesis III**	15	—	0/10 C

Compulsory-optional courses

Code	Subject	Credits	Winter	Summer
Quantum field theory				
NJSF069	Quantum Field Theory II [1]	9	—	4/2 C+Ex
NJSF146	Quantum Field Theory II [1]	9	—	4/2 C+Ex
NJSF139	Beyond Standard Model Physics I	4	2/1 Ex	—
NJSF140	Beyond Standard Model Physics II	4	—	2/1 Ex
NJSF082	Selected Topics on Quantum Field Theory I	4	3/0 Ex	—
NJSF083	Selected Topics on Quantum Field Theory II	4	—	3/0 Ex
NTMF022	Theory of Gauge Fields	4	3/0 Ex	—
NJSF084	Chiral Symmetry or Strong Interactions	3	—	2/0 Ex
NJSF030	Quantum Field Theory at Finite Temperature	3	—	2/0 Ex
NJSF129	Advanced Concepts of Symmetry	5	—	2/2 Ex
NJSF142	Theory of groups and algebras in particle physics	4	—	2/1 Ex
Theory of many-body systems				
NJSF196	Microcopic Theory of Nuclei II	3	2/0 Ex	—
NJSF107	Statistical Nuclear Physics	3	2/0 Ex	—
NJSF193	Collective Dynamics of Manybody systems	3	2/0 Ex	—
NJSF031	Classical and Quantum Chaos	3	—	2/0 Ex
NJSF157	Physics of few-body nuclear systems	3	2/0 Ex	—
NJSF158	Introduction to computational nuclear physics	3	1/1 Ex	—
Experimental particle physics				
NJSF073	Experimental Checks on Standard Model	4	—	2/1 C+Ex
NJSF195	Strong Interaction at High Energies	3	2/0 Ex	—
NJSF102	Nuclear Astrophysics	3	2/0 Ex	—

NJSF130	Cosmic Rays	3	—	2/0 Ex
NJSF131	Diffraction in particle physics	4	2/1 Ex	—

Experimental methods, data evaluation, applications

NJSF070	Particle Detectors and Accelerators	3	2/0 Ex	—
NJSF159	Physics of particle accelerators	4	2/1 Ex	—
NJSF101	Semiconductor Detectors in Nuclear and Subnuclear Physics	3	2/0 Ex	—
NJSF081	Software and data processing in particle physics I	3	1/1 Ex	—
NJSF109	Software and data processing in particle physics II	4	—	2/1 Ex
NJSF143	Statistical methods in high energy physics	4	3/0 Ex	—
NJSF067	Data acquisition methods in particle and nuclear physics	4	2/1 Ex	—
NJSF138	Neural nets in particle physics	4	2/1 Ex	—
NJSF024	Radioanalytical Methods	3	2/0 Ex	—
NJSF008	Biological Effects of Ionizing Radiation	3	—	2/0 Ex
NJSF141	Experimental data evaluation	3	—	2/0 Ex

Other

NJSF091	Seminar on Particle and Nuclear Physics I	3	0/2 C	—
NJSF092	Seminar on Particle and Nuclear Physics II	3	—	0/2 C

[1] The students enroll only in one of these alternating courses.

Recommended optional courses

Code	Subject	Credits	Winter	Summer
NJSF079	*Quantum Field Theory III*	9	4/2 C+Ex	—
NJSF132	*Theory of nanosccopic systems I*	3	2/0 Ex	—
NJSF133	*Theory of nanoscopic systems II*	3	—	2/0 Ex

Conditions that must be satisfied to register for the final oral exam

– gain of at least 120 credits
– passing all compulsory courses
– passing the compulsory-optional courses in the extent of at least 25 credits
– submission of the completed diploma thesis within the given deadline

Requirements for the state final exam

The committee asks the student to explain 3 topics from the following 3 sectors (one topic from each sector):

A. Quantum theory

1. Formalism of quantum theory

Hilbert space. Pure and mixed states. Compatible and incompatible observables. Discrete and continuous spectra. Open systems. Classical limit.

2. Evolution of quantum systems

Schroedinger equation and the evolution operator. Green operator. Schroedinger, Heisenberg and Dirac representations of time evolution. Evolution generated by a time-dependent Hamiltonian.

3. Symmetries and conservation laws in quantum mechanics

Continuous space-time symmetries and their generators. Space inversion and time reversal. Conservation laws. Scalars, vectors, spinors.

4. Perturbation methods in quantum mechanics

Stationary perturbation theory for a non-degenerate and degenerate spectrum. Non-stationary perturbation method, step and periodic perturbations, Fermi golden rule.

5. Angular momentum in quantum mechanics

Quantization of angular momentum. Addition of two or more angular momenta. Tensor operators, selection rules.

6. Scattering theory

Lippmann-Schwinger equation. Scattering amplitude, Born series. The method of partial waves.

7. Systems of indistinguishable particles

Bosons and fermions. Fock space, occupation number representation. Creation and annihilation operators, n-body operators.

8. Equations of relativistic quantum theory for free particles with spin 0, 1/2 and 1

Klein-Gordon and Dirac equations, solutions with positive and negative energies, continuity equation, symmetry properties. Weyl and Proca equations.

9. Dirac equation for a particle in electromagnetic field

Transition to the Pauli equation and the spin magnetic moment. Hydrogen type atoms and the fine structure of energy spectra.

10. Quantization of free fields and their particle interpretation

Canonical quantization method. Energy and momentum of a quantum field. Particles and antiparticles. Dirac field, anticommutation rules. Electromagnetic and Proca fields. Propagator of a quantum field.

11. Interactions of fields, perturbative expansion of the S-matrix and Feynman diagrams

Examples of interaction Lagrangians, gauge symmetry principle. Dyson expansion in the interaction representation. Feynman diagrams on the tree level. Decay probabilities and cross sections.

12. Foundations of quantum electrodynamics

Scattering of a charged particle in an external electromagnetic field. Second-order processes. Examples of diagrams with a closed loop.

B. Physics of elementary particles

1. Classification of elementary particles

Leptons, hadrons, interaction mediators. Approximate SU(3) symmetry, hadron multiplets. Quark model. Color of quarks, its experimental evidence. Quarks u, d, s. Heavy quarks c, b. Decays of hadrons (neutron, pion, strange particles).

2. Properties of hadrons and their experimental determination

Spin, magnetic moment, spatial-, charge- and G-parity, isospin, strangeness, hypercharge. Conservation laws for individual interaction types. Examples of experiments.

3. Properties of leptons

Weak and electromagnetic interactions of leptons: mion pair production in electron-positron annihilation, scattering of neutrinos, decays of muons and tau leptons. Helicity of neutrinos, neutrino oscillations, P and CP violation. Neutrino experiments.

4. Methods of measurement and identification of particles in experiments

Measurement of energy, momentum, time of flight, Cherenkov and transition radiation, invariant mass of decay products. Examples of detection techniques in particle discoveries.

5. Experiments with particle accelerators

Linear and circular particle accelerators, colliders, luminosity. Present-day accelerators. Particle production in hadronic and leptonic collisions.

6. Conceptual foundations of the standard model of electroweak interactions

Gauge invariance. Yang-Mills field. The Higgs mechanism.

7. Types of particle interactions in the standard model of electroweak interactions

Interactions of vector bosons, interactions of the Higgs boson, neutral and charged currents. Discovery of vector bosons W and Z, discovery of the Higgs boson.

8. Mixing in the quark sector of the standard model

Generation of masses through the Yukawa interactions. Cabibbo-Kobayashi-Maskawa matrix, CP violation. Discovery of quarks c, b, t.

9. Systems of neutral mesons

Oscillation and regeneration. Direct and indirect CP violations and their signatures.

10. Structure of nucleons and the parton model

Elastic scattering of electrons on the proton, formfactors. Deep inelastic scattering, structure function, Bjorken scaling. Formulation of the parton model and the concept of parton distribution function.

11. Applications of the parton model

Basic processes in the parton model: hadron production in electron-positron annihilation, Drell-Yan process. Fragment function, deep inelastic scattering, measurement of parton distribution functions. Jet production, discovery of gluon.

12. Quantum chromodynamics

QCD Lagrangian and the gauge invariance principle. Running coupling constant, asymptotic freedom, color confinement. Description of quarkonia. Infrared and collinear singularities, jets, evolution equation for parton distribution functions.

C. Nuclear physics

1. *Characteristics of nuclei and their experimental determination*

Binding energy, von Weizsaecker formula. Spin, parity. Magnetic dipole and electric quadrupole moments. Deformation parameters.

2. *Nuclear decays and radioactivity*

Beta decay, spectra of electrons/positrons, selection rules, electron capture. Alpha decay, decay chains. Gamma decay, elements of the theory of electromagnetic transitions, their types and multipolarities, selection rules.

3. *Nucleon-nucleon interactions*

Phenomenological and microscopic nucleon-nucleon potentials, symmetry principles, isospin, meson exchanges and their quark interpretation. Effective interactions in nuclear environment. Deuteron.

4. *Mean field and single-particle motions in nuclei*

Hartree-Fock construction of the mean field. Spin-orbit coupling, magic numbers. Nilsson model, deformation.

5. *Pairing of nucleons and its consequences*

Short-range residual interactions. Bardeen-Cooper-Schrieffer theory of superconductivity. Signatures of pairing in nuclei.

6. *Collective motions of nuclei*

Rotational and vibrational spectra of nuclei and their phenomenological and microscopic description. Giant resonances. Nuclear fission.

7. *Nuclear reactions and highly excited states*

Direct and compound-nucleus reactions, examples, typical properties, elements of their theoretical description. Population of excited states, statistical modelling of their decays, yrast line.

8. *Passage of ionizing radiation through matter*

Processes during the passage of heavy and light particles through matter. Interaction of gamma particles. Passage of neutrons.

9. *Principles of detection of nuclear radiation*

Spectrometry of charged and neutral particles. Basic types of particle detectors and their characteristics.

10. *Application of nuclear physics in material analysis and dating*

Measurement of elemental and isotopic abundances. Nuclear probes in materials. Nuclear methods of age determination.

11. *Application of nuclear physics in medicine*

Methods of imagining based on nuclear radiation, functional tomography. Radiotherapy and hadron therapy.

12. *Nuclear energy*

Nuclear fission and fusion. Nuclear reactor, tokamak. Nuclear processes in stars.