Elementary Particle Physics Laboratory (EPPL)
Main physics results obtained with the participation of EPPL physicists

The "Elementary Particle Physics Laboratory" (EPPL) named in the past as "The Nuclear Structure Laboratory" was formed in 1963 at PNPI (at that time PNPI was a branch institute of the Leningrad Physico-Technical Institute). Up to 2002, this laboratory was headed by Prof. A.A. Vorobyov. In 2002, G.D. Alkhazov was elected head of EPPL.

1. Proton diffraction scattering on nuclei and nuclear matter distributions

The 1 GeV proton scattering from nuclei has been proven to be a very useful tool for studying the nuclear structure. The first high precision measurements of the differential cross sections for elastic scattering of 1 GeV protons on nuclei were performed at PNPI (LNPI) in 1972. It was demonstrated that with this method one can obtain information on the nuclear matter distributions with the accuracy comparable to that reached in studying nuclear charge distributions by the method of electron scattering. A number of nuclei, from ^{3}He to ^{208}Pb, including all doubly magic nuclei, were studied at PNPI. Starting from 1973, similar investigations were performed in joint PNPI-Saclay experiments (at E_p = 1 GeV), and later (from 1977) at Los-Alamos (at E_p = 0.8 GeV). Thus, the study of diffraction scattering of ~1 GeV protons on nuclei became a new branch of experimental research in nuclear physics, and it is due to these studies that the most accurate information on nuclear matter distributions has been obtained by present.

2. Small-angle diffraction scattering of hadrons on the lightest nuclei

A serious of experiments at Gatchina, Saclay, Serpukhov and CERN have been performed where small-angle scattering of pions and nucleons on hydrogen, deuterium, and helium nuclei were studied at intermediate and high energy. A dedicated ionization chamber recoil detector IKAR developed at PNPI was the main part of the experimental setup. The advantage of the applied method was a possibility to measure differential cross sections at small momentum transfers with high absolute accuracy of 1-2%. The differential cross sections for elastic scattering and the analysing powers have been measured. The total cross sections and the ratios of the real to the imaginary parts for the scalar amplitudes of the studied processes have been found. Experimental upper bounds for the nucleon-nucleon (NN) spin-spin amplitudes have been determined. The obtained experimental data are useful in the NN-scattering phase-shift analyses, and in many cases clarify the problem of the dibaryon resonances which are a matter of interest up to now. Also, the measured hadron-nucleus total cross sections permit to get information on the inelastic shadowing corrections to the cross sections calculated in the framework of the Glauber theory.

3. Study of nuclear structure with quasielastic proton scattering at 1 GeV

The shell structure of nuclei was studied at PNPI by (p, 2p) and (p, np) reactions using the 1 GeV proton beam of the PNPI synchrocyclotron. Both reactions were studied in identical kinematical conditions. The scattered proton was detected with a magnetic spectrometer, while the knocked out nucleon (p or n) was detected with a time-of-flight spectrometer. A number of nuclei (more than 20, from ^{6}Li to ^{208}Pb) were studied, and detailed information on the proton- and neutron-shell energies was obtained. Prior these measurements, the neutron shell energies were in most cases unknown. An important result of these studies was the observation of the $1s_{1/2}$ and $1p_{1/2}$ proton and neutron shells in heavy nuclei including ^{90}Zr and ^{208}Pb. The shell splitting was observed in many of the studied nuclei. This shell spliting was explained in terms of the spatial deformation of the self-consistent nuclear field. It was shown that the data on the proton and neutron shell energies allow one to study the deformation parameters of the nuclear density distributions both for protons and neutrons. Also, the measured spectra show high sensitivity to the differences between the proton and neutron root-mean-square radii. The obtained data can serve as a solid basis for testing the existing nuclear models and for developing new theoretical approaches to microscopic descriptions of the nuclear structure.

4. Muon catalized *dd*- and *dt*-fusion

A new experimental method was proposed at PNPI, which occurred to be very efficient for studying muon catalized *dd*-fusion. The basis of the method was the time-projection ionization chamber (IC) filled with hydrogen (deuterium) at 120 bar. The IC operated in the temperature range of 28–350 K. The IC registered muons stopped in the IC sensitive volume and all charged products of the *dd*-synthesis. Thus, all channels of the *dd*-synthesis, that is $dd\mu \rightarrow {}^{3}\mathrm{He}+n+\mu$, ${}^{3}\mathrm{He}\mu+n$ and $t+p+\mu$, could be registered for the first time.

The first experiments with this new method were performed at PNPI, then they were continued at the Swiss meson factory. The main measurements were performed in 1994–1996. As a result, all parameters of the muon catalized *dd*-synthesis were determined. These results form the modern basis of the data which are used to test the theory of the muon catalysis. One of the important results of these investigations was the measurement of the probability of the muon sticking to the ^{4}He nucleus in the reaction $dt\mu \rightarrow {}^{4}\mathrm{He}\mu+n$. The measured probability has allowed to determine the maximum number of the cycles of the muon catalized *dt* fusion initiated by one muon. This number has occurred to be 178±13.

5. Ternary fission

A serious of experiments on ternary nuclear fission were performed at the Gatchina WWR-M neutron reactor. Two alternative approaches in description of the nuclear fission process were discussed in the 60s. Within the framework of the statistical fission model, descending from the saddle point was considered to be adiabatically slow, so that formation of the fragments occurs just before the scission point. On the contrary, in the dynamical model of fission the formation takes place at the barrier, and further separation of the fragments goes so rapidly that no significant redistribution of the fragment masses occurs. The ternary fission has occurred to be useful to tell between these two fission models.

The inclusive spectra of light nuclei (^{2,3}H, ^{4,6,8,}He, ^{7,8,9}Li, ^{9,10,11}Be, ^{11,12,13,14}B, ^{14,15,16}C, ^{20}O) formed in the ternary fission were measured with a magnetic time-of-flight mass-spectrometer. The experiments were carried out with the ^{233}U, ^{235}U, ^{239}Pu, and ^{242m}Am targets exposed to thermal neutron fluxes. The next stage was the correlation experiment with a special set-up which enabled simultaneous detection of the heavy fragments and the light nuclei ^{3}H, ^{4}He, ^{6}He, ^{10}Be. Detailed studies of the

^{235}U and ^{239}Pu thermal neutron induced fission, as well as spontaneous fission of ^{252}Cf, were performed. As a result of these studies, the experimental data were obtained which formed the basis for a detailed kinematics analysis aimed at determination of the initial conditions of the fragment separation. Such an analysis resulted in a rather large value (~30 MeV) of the fragments initial energy. This value excludes the statistical model of nuclear fission.

6. Diffraction scattering of high energy hadrons

In the end of 60s, the study of the global characteristics of the hadron interactions was of common interest. The behaviour of the total cross sections for the hadron interactions and the shrinkage of the diffraction cone with the energy increasing were hot topics at that time. In particular, the theory of Regge poles predicted constancy of the total cross sections in the asymptotic region of high energies accompanied by the logarithmic shrinkage of the diffraction cone. Also, it was a question whether the dispersion relations between the real part of the forward scattering amplitude and the total cross section remain valid. In 1969, a new experimental method was suggested and worked out at PNPI for studies of small-angle scattering of high energy hadrons. A hydrogen-filled ionization chamber (IKAR) used as a recoil detector was the base of the method. This method provided precise measurements of the differential cross sections for small-angle scattering of various hadrons with the absolute normalization at the ~1% precision level.

First experiments using this method were carried out at PNPI in 1972. The *pp* scattering in the energy internal from 600 to 1000 MeV was investigated. In these experiments, the "puzzle of Dutton" was solved, and the validity of the dispersion relations in *pp* scattering at this energy was restored. Then, πp scattering at the energy of 40 GeV was studied at IHEP (Serpukhov). Later, πp scattering was studied at the energy up to 140 GeV (CERN, WA9 experiment), and at the energy to 400 GeV (CERN, NA8 experiment). These experiments yielded important results concerning the hadron interaction at available at that time energies. The most important results were the observation of the universal rise of the total cross sections and the universal shrinkage of the diffraction cone with the energy increasing. The obtained results agree with the conclusions of the general theorems formulated on the basis of the local quantum theory axioms.

7. Study of rare hyperon decays

PNPI was an active participant in the study of rare hyperon decays at the FNAL hyperon beams. The beginning of the PNPI – FNAL collaboration goes back to the year 1981. The basis of the collaboration was the PNPI suggestion of an experiment for studying the Σ^--hyperon β-decay in view of a strange situation in investigation of this process. The existing at that time experimental information on the asymmetry in the decay of polarized Σ^--hyperons was in contradiction with the Cabibbo model prediction while the β-decay of the other baryon octet members were well described by this model. The most difficult task in the study of the reaction $\Sigma^- \to ne\tilde{\nu}_e$ was the separation from the 10^3 times more intense reaction $\Sigma^-\to n\pi^-$. To overcome this difficulty, the PNPI group proposed to use a Transition Radiation Detector sensitive to electrons and less sensitive to π mesons. This detector occurred to be a very important part of the E715 experiment dedicated to the study of the Σ^--hyperon β-

decay. The measured electron asymmetry in the β-decay of polarized Σ^- proved to be in good agreement with the Cabibbo model prediction. So, the long time contradiction between experiment and theory was settled in favour of the Cabibbo model.

Following the PNPI initiative, in 1986 a new experiment (E761) was proposed. The existed at that time experimental data revealed a strong asymmetry in the radiative decay $\Sigma^+ \to p\gamma$, and none of the theoretical attempts succeeded in explanation of that fact. In the E761 experiment, the data on the radiative decay of $\Sigma^+ \to p\gamma$ were obtained with high statistical accuracy. A possible admixture of the more intensive background reaction $\Sigma^+ \to p\pi^0 \to p2\gamma$ was suppressed with a new specially developed Transition Radiation Detector. The E761 data demonstrated that the asymmetry in the Σ^+-hyperon radiative decay was indeed large and negative, the observed decay rate being in agreement with the world data. In the E761 experiment, the data on the radiative decays $\Xi^- \to \Sigma^-\gamma$ and $\Omega^- \to \Xi^-\gamma$ were also obtained and the polarization of Σ^+ and Σ^- produced in the interaction of high energy protons with nuclei was measured.

In addition to the main program of the E715 and E761 experiments, the magnetic moments of Σ^-, Σ^+, $\overline{\Sigma}^+$, and Ξ^- hyperons were also measured.

8. Participation in the L3 experiment

The L3 experiment at the Large Electron-Positron collider at CERN was one of the largest in the high energy physics. PNPI made a significant contribution to the L3 experimental complex. A half of the electromagnetic calorimeter crystals were fabricated by joint efforts using the material supplied by PNPI, the muon spectrometer high-voltage monitor was designed, produced and installed by the PNPI group. All the L3 data taking and experimental control electronics (about 1000 CAMAC and FASTBUS crates) were installed in the water-cooled racks (250 racks) designed (jointly with CERN) and fabricated at PNPI. Finally, the forward-backward FTC detectors, together with the electronics, have been designed and produced at PNPI. The PNPI physicists performed the FTC exploitation, including its calibration and alignment. The PNPI group participated in the data taking and the analysis of the collected data. More than 100 papers were published by the L3 collaboration. One of the main results of the L3 experiment was the high precision confirmation of the validity of the Standard Model.

9. Precision measurement of the nuclear muon capture by ^{3}He

In 1993, the PNPI group in collaboration with physicists from Switzerland, Germany, Austria, Belgium and the USA accomplished a new high-precision measurement of the muon capture rate by ^{3}He.The experiment was carried out in the muon beam of the Swiss meson factory using a new experimental method developed at PNPI. The muons were stopped in a high-pressure gridded ionization chamber (IC) filled with isotopically ultra-pure ^{3}He gas at 120 bar. The IC allowed to detect both the stopped muons and the charged reaction products, that is tritons, deuterons and protons. The muon capture rate was measured in this experiment with a precision of ~0.3%, that is an order of magnitude better than in previous experiments. As a result, the induced pseudoscalar form factor in this process was reliably determined. The obtained result has stimulated the development of the muon capture microscopic theory.

10. Meson spectroscopy

The search for the tensor glueball is one of primary objectives of the meson spectroscopy in the mass region 1900–2400 MeV. There are rather strong proofs that the scalar glueball exists with mass 1500–1650 MeV. It mixes with nearby $q\bar{q}$ states and physical resonances carry a large content of this state. The lattice QCD calculations give the ratio of tensor and scalar glueball masses ~1.4 with rather small errors. It corresponds to a mass for the tensor glueball 2150–2350 MeV. The first step in the tensor glueball search is to locate meson resonances in this mass region. The indication of an exotic state could be an appreciable deviation of the pole positions from the linear trajectories or the presence of a state which does not match linear trajectories at all. The real progress was made in the analysis of new data on $\bar{p}p$ annihilation in flight taken by Crystal Barrel collaboration at LEAR over the momentum range of antiproton 600–1940 MeV/c. The neutral particle production channels were analysed by PNPI (Theoretical Physics Division and High Energy Physics one) group in collaboration with D.V. Bugg (Queen Mary and Wiestfield college, London), B.S. Zou (IHEP, Beijing) and group of C. Batty from Rutherford Appleton Laboratory (England). The following final neutral channels have been processed: $p\bar{p} \to \pi^0\pi^0, \eta\eta, \eta\eta', \pi^0\eta, \pi^0\eta'$; $\pi^0\omega, \eta\omega, \eta'\omega$; $3\pi^0, 2\pi^0\eta$; $\pi^0 2\eta, \pi^0\eta\eta'$; $4\pi^0, 3\pi^0\eta, 2\pi^0 2\eta$.

The first stage was a separate partial-wave analysis of two body and three body final states. At the next stage all relevant data production channels were investigated in the framework of a combined analysis. The analysis allows us to determine a considerable number of meson states over the range 1900–2400 MeV that makes it possible to carry out the systematics of $q\bar{q}$ states in the (n, M^2) and (J, M^2) planes.

11. Experiment SPES4-π

In order to investigate the Roper resonance, the one-pion and two-pion production in the $p(\alpha,\alpha')X$ reaction at an energy of $E_\alpha = 4.2$ GeV was studied by simultaneous registration of the scattered α' particle and the secondary proton or pion. The experiment was performed at the Saturn-II accelerator at the nuclear centre Saclay using the magnetic spectrometer SPES4 and the forward tracking detector fabricated at PNPI, which consisted of a scintillator hodoscope and multiwire drift chambers with a hexagonal structure. The obtained results demonstrate that the inelastic α-particle scattering on the proton at the energy of the experiment proceeds either through excitation and decay of the Δ resonance in the projectile α particle, or through excitation in the target proton of the Roper resonance, which decays mainly on a nucleon and a pion, or a nucleon and a σ meson – a system of two pions in the isospin $I = 0$, S-wave state.

12. Experiment D0

Since 1996, PNPI took part in a large international experiment D0 at the FNAL Tevatron with the total energy of colliding particles of 1.96 TeV. D0 was a universal collider detector that allowed one to study a wide range of processes that occured when protons collided with antiprotons. Main physics goals were precision tests of the Standard Model (SM), the weak bosons physics, top quark physics, QCD, *B* physics and a search for particles and forces beyond the SM: super-symmetric particles, gravitons, candidates for the cosmic dark matter, and a search for extra dimensions.

PNPI was involved in the D0 project through the design and programming of the electronic readout for mini drift tubes (50,000 channels) and operation of the Forward Muon System. PNPI physicists took part in the data analysis, including QCD, *B* physics, and Electroweak physics studies. Main D0 physics results are the top-quark mass, B_s mixing frequency, cross section for single top-quark production and inclusive cross section.

13. Experiment MuCap

In the international experiment MuCap, precision measurements of the muon capture rate in hydrogen were performed at the Swiss muon factory using a new method proposed by PNPI. As a result, an important nucleon characteristic, the pseudoscalar form factor g_p, was determined with high accuracy for the first time. The determined value of g_p occurred to be in agreement with the prediction of the Standard Model.

14. Investigation of the nuclear matter distributions in exotic nuclei by small-angle proton elastic scattering in inverse kinematics

In order to study the spatial structure of light exotic nuclei, it was proposed at PNPI to measure the cross sections for small-angle proton-nucleus elastic scattering in inverse kinematics. The measurements were performed at the beams of exotic nuclei at an energy of 0.7 GeV/u at the nuclear centre of heavy ions GSI (Darmstadt). The measured cross sections were analysed within the frames of the Glauber theory using phenomenological matter density distributions with two free parameters. As a result, the nuclear matter density distributions and the corresponding root-mean-square matter radii were determined for the nuclei of He, Li, Be, B, and C isotopes. The experimental data indicate existence of a neutron halo in ^{6}He, ^{8}He, ^{11}Li, ^{14}Be, ^{15}C and a proton halo in ^{8}B. The largest halo is observed in the ^{11}Li nucleus. Also, a significant neutron skin is observed in neutron-rich ^{8}Li, ^{9}Li, ^{12}Be, and ^{16}C nuclei.

15. Participation in the experiments LHCb and CMS at the Large Hadron Collider

The main physics goals of the LHCb experiment at the Large Hadron Collider (LHC) at CERN are studies of CP violation effects in various decays of *B* and *D* mesons and also searches for rare *B* decays suppressed in the Standard Model (SM). One of the most important elements of the LHCb detector is the muon system. The HEPD group has proposed the basic scheme for constructing the muon system and the technical solution for its implementation. 660 multi-wire proportional chambers covering an area of 435 m^2 were manufactured at PNPI. HEPD physicists are involved in the data taking and data analysis as well as in the LHCb detector upgrade program. One of the important results of the LHCb experiment was the observation of a super-rare decay of the B_s meson into two muons. According to the Standard Model, such a decay can occur with a very low probability. According to new theories beyond the SM, the probability of B_s meson decay into two muons may be larger than that which follows from the SM. The probability of B_s meson decay into two muons, determined in the LHCb experiment and then confirmed in the CMS experiment, is consistent with the SM. This result closes a number of new theories and is a strong argument in favour of extension of the applicability of the SM.

CMS is a collider detector designed to study the physics of proton-proton collisions at an energy in the centre-of-mass system up to 14 TeV at the full luminosity of the LHC accelerator. PNPI has made a significant contribution to the creation of the CMS detector. For the CMS muon system, 120 large muon chambers, a 10,000-channel high-voltage supply system for the muon chambers, and a muon trigger of the first level were manufactured at PNPI. HEPD physicists participate in the data taking and in the analysis of the collected data, as well as in the implementation of the CMS detector upgrade program. The most important result of the CMS experiment was the discovery (together with the ATLAS experiment) of the Higgs boson, a key particle in the modern theory of elementary particles.