PARTICLE AND HIGH-ENERGY HEAVY-ION PHYSICS

The Standard Model of the weak, electromagnetic and strong interactions is one of the most successful theoretical schemes ever developed in particle physics. The Standard Model explains to a high accuracy almost all relevant experimental observations. Nevertheless, it is not a fundamental theory, but a low-energy limit of some underlying theory which probably originates from the very high-energy scales like the Planck scale (of the order of 10^{19} GeV). There are some experimental results which can be treated as arguments for new physics beyond the Standard Model:

- The neutrino oscillations and perhaps neutrinoless nuclear double-beta decay data show that neutrinos have mass, neutrinos have mixing, neutrino properties are a mystery;
- There is missing mass in the Universe and there is acceleration of the Universe (dark matter and dark energy);
- LEP and Tevatron experiments have given strong indications to new physics at the TeV scale;
- There are too many external parameters and unsolved problems in the Standard Model; in particular, the gravity is not included, the electroweak symmetry breaking is not clear, there are hierarchy problems (Higgs mass diverges), etc.

The main problems beyond the Standard Model very generally and very shortly can be grouped into three large classes with labels of Mass, Unification and Flavor. In more details they can be cast into the following basic questions:

- What is the origin of the particle masses, are they indeed due to the Higgs boson?
- What is the nature of new particles and new principles beyond the Standard Model? Are there undiscovered principles of Nature — new symmetries, new laws?
- Why are there so many types of quarks and leptons, and how can one understand their weak mixing and CP violation?
- Do all the forces of Nature become one? How does gravity fit in? Is there a quantum theory of gravity? Is the proton unstable?
- What is the nature of dark matter that makes up about one quarter of the contents of the Universe? Can we produce and detect it in laboratory?

- What is the nature of dark energy that makes up almost three quarters of the Universe? How can we solve the mystery of dark energy?

- Why is the Universe as we know it made of matter, with no antimatter present? What is the origin of this matter-antimatter asymmetry? What happened to the antimatter?

- What are the masses and properties of neutrinos and what role did they play in the evolution of the Universe? How are they connected to the matter-antimatter asymmetry?

- How did the Universe appear? What is the role of very dense quark-gluon matter here? Do indeed both dense baryonic matter (DBM) and quark-gluon plasma (QGP) exist? How are these substances interconnected with each other and with ordinary hadronic matter (HM)? What happens on the borders? How can we study them experimentally?

- Are there extra dimensions? String theory predicts seven undiscovered dimensions of space that give rise to much of the apparent complexity of particle physics.

Addressing the above-mentioned key questions of particle and high-energy heavy-ion physics requires a broad, strongly integrated, programme of theoretical and experimental research using a wide variety of modern tools and techniques that can be classified mainly into four interrelated directions – the **energy-increasing accelerator** direction (**the Energy Border**), the **intensity-increasing accelerator** direction (**the Intensity Border**), the **accuracy-increasing non-accelerator** direction (**the Accuracy Border**), and the **particle astrophysics** direction (**the Cosmic Border**).

1. In the energy-increasing accelerator direction (**Energy Border**) JINR is involved in the world-wide long-perspective activities. JINR physicists participate in the experiments at the Tevatron collider. Experience gained by JINR scientists under the Tevatron programme will be extremely important for their future participation in similar experiments at the LHC.

JINR groups participate in three experiments at the LHC: ATLAS, CMS and ALICE, which are designed to make excellent measurements of many possible (known and unknown) products of collisions at the unprecedented centre-of-mass energy of 14 TeV.

JINR also actively participates in both accelerator and detector activities within the ILC project. In particular, Dubna is officially considered to be one of the possible places for ILC siting. The natural continuation of this effort is the involvement in the R&D for detectors and preparation of the ILC physics programme. JINR intends to participate in internationally coordinated R&D efforts for the conventional and alternative accelerator technologies that a lepton collider of higher energy would require. It is also important to continue R&D of modern particle detectors.

The long-term research plan for JINR in the direction to the Energy Border accelerator-based particle physics is coherent with world-wide ones. It goes mainly from experiments at FNAL to LHC experiments at CERN with future perspectives of high-luminosity LHC and ILC. In accelerator science it goes from the LHC to the Super-LHC and ILC.

2. The Intensity Border

a. To provide the necessary domestic instrumental base for the study of hot and dense strongly interacting QCD matter it is proposed to construct, at JINR, a new accelerator complex of high-energy heavy ions — NICA (Nuclotron-based Ion Collider fAcility) with a dedicated MultiPurpose Detector (MPD), placed at one of the several interaction points of the NICA collider. This is JINR's new flagship project. The proposed facility should provide much higher luminosity (more than 100 times) for experiments with heavy ions in the energy region $\sqrt{s_{NN}}$=4-9 GeV/nucleon than it is possible at the existing collider facilities such as RHIC. As compared with the fixed target experiments at SPS (CERN) and FAIR (GSI), experiments with the MPD detector at the NICA collider will provide almost full 4π acceptance and avoid the problem of strongly energy-dependent detector acceptance and occupancy.

The NICA facility will include two superconducting collider rings with several (more than two) interaction points. For luminosity preservation, an electron or stochastic cooling system is planned for construction. The Nuclotron accelerator will function as injector for the collider rings and will provide ion acceleration to the experiment energy. A new ESIS-type heavy-ion source will be developed; it will have to provide U^{32+} ions at the intensity of $2 \cdot 10^9$ ions per pulse. New key elements of the injection system (Linac and Booster) are planned for construction in order to provide the necessary level of luminosity for heavy-ion experiments. During the construction period, the existing extracted beams from the Nuclotron will be used both for experiments at lower centre-of-mass energies and for the R&D work necessary for the NICA/MPD project.

In the study of hot and dense matter produced in relativistic heavy ion collisions, JINR plans to participate in ongoing experiments at SPS, RHIC, and LHC, and to use gained experience in future experiments at NICA and FAIR.

b. With the NICA facility, JINR will have a chance to provide polarized beams of protons (in the proton-proton mode the proposed collider will provide $\sqrt{s_{NN}}$ up to 20 GeV), neutrons and deuterons with energies $\sqrt{s_{NN}}$ up to 9 GeV, i.e. in the laboratory energy region from hundreds of MeV up to a hundred GeV. Such a spectrum of polarized beams in this energy domain is unique. The collision energy variation over 3 orders of magnitude will give the possibility to follow the transition regime from nucleon-meson degrees of freedom to the quarks and gluons. The high intensity of the polarized beams (about 10^{10} particles/s) will make it possible to reach unprecedented precision in measurements of the spin-dependent observables. There are three main directions of research in the field of spin physics.

The JINR ambiguous spin physics programme contains two main directions. The first one is investigations of the high-energy region and **particle structure probed with spin degrees of freedom**.

The study of the open questions listed above is a first-priority task for the scientific programme at the second interaction point of the NICA facility with intense polarized beams of protons and deuterons, which is to be realized with the help of a Special Spin Detector (SPD). The first-stage experiments are aimed at measurements of the Matveev-Muradyan-Tavkhelidze-Drell-Yan (MMTDY) processes and quarkonia production (first of all, J/ψ) with decay modes to a lepton pair (e^+e^- or $\mu^+\mu^-$). The main research topics are: study of the MMTDY processes with transversely and longitudinally polarized proton and deuteron beams, and study of J/ψ and other quarkonia production processes with decay to a lepton pair in polarized p and D collisions

The second-stage experiments imply upgrade of the SPD detector to allow for studies of spin-dependent effects in inclusive processes in collisions of polarized protons and deuterons, spin effects in various exclusive reactions, diffractive processes and double spin asymmetries in elastic reactions in collisions of polarized protons and deuterons and quarkonia spectroscopy.

The second direction in the JINR spin physics programme is the **study of spin structure of cold dense matter** and search for **formation of rotating nuclear and nucleon clusters**.

The first item implies studies of processes with large momentum transfers where few nucleons are involved. This allows one to reach the density several times higher than in normal nuclear matter without its heating, namely, the state of cold dense matter. Therefore, these investigations make it possible to explore the new region of the phase diagram compared with heavy-ion collisions at NICA. The spin structure of cold dense matter for two- and three- nucleon interactions is a very essential input for the equation of state. The main tools to address this region of the phase diagram are the study of nucleon-nucleon scattering in a wide range of transverse momenta, of the spin structure of few-nucleon **short range correlations**, and a search for effects of non-nucleonic degrees of freedom in reactions induced by light nuclei.

Search for formation of rotating nuclear and nucleon clusters is a new proposal to study the formation of twisting baryonic matter in interactions of polarized deuteron and more heavy polarized particle beams (e.g. ^3He) at NICA conditions. Such a possibility can, in principle, appear when external angular momentum is implemented into strongly interacting hadronic matter at the formation stage.

c. The project FAIR (Facility for Antiproton and Ion Research) at Darmstadt is an international accelerator facility of the next generation. The existing GSI accelerators serve as injector for the new facility. The double-ring synchrotron will provide ion beams of unprecedented intensities as well as of considerably increased energy. Thereby intense secondary beams — unstable nuclei or antiprotons — can be produced. JINR substantially participates in both accelerator and detector (CBM and PANDA) activities at FAIR (taking into account the complementarity both between the CBM and NICA/MPD physics programmes and between the NICA and FAIR accelerator programmes).

d. Investigation of neutrino properties has a long tradition established by Bruno Pontecorvo in the middle of the 20th century. Since that time the comprehensive study of neutrino physics has been a major activity and key feature at the Dzhelepov Laboratory of Nuclear Problems. Observation of neutrino oscillations requires neutrinos to have mass and implies lepton flavor non-conservation. JINR takes part in the tau-neutrino appearance oscillation experiment OPERA at Gran Sasso with muon-neutrino beam from CERN's accelerator. In the neutrino mixing sector, the most advanced projects to study neutrino oscillations are the Daya Bay reactor and T2K accelerator experiments. There are very good prerequisites for JINR's involvement in these experiments. In particular at Daya Bay, the contribution to the detector instrumentation is based on facilities of JINR Member States. For T2K, an important input to the experiment will be from data analysis conducted by the JINR group in the NA61 experiment.

e. Precision studies of rare muon and pion decays allow one to test the Standard Model of electroweak interaction and μ-e universality. It is proposed at DLNP to search for the μ^+ decay into $e^+\gamma$, which violates the leptonic number conservation law (MEG project). The non-zero neutrino masses and mixing lead to violation of this conservation law. On the other hand, such fundamental theories as supersymmetry predict a measurable lepton-flavour-violating μ^+ decay into $e^+\gamma$. Therefore, the proposed experiment with the accuracy of 10^{-14} relative to the main decay mode provides a good chance to make a discovery which will bring evidence for existence of new physics beyond the Standard Model. In 2007 the measurement of the $\pi^+ \to e^+\nu$ branching ratio was carried out at the PIBETA detector (PSI). A test run of new $\mu^+ \to e^+\nu$ detector was accomplished.

f. Measurements of CP violation are now imposing significant constraints on the description of CP violation within the Standard Model. Since it is generally thought that the origin of the matter-antimatter asymmetry in the Universe requires physics beyond the Standard Model, the investigation of CP violation is now entering an era of searching for new physics phenomena. Currently there is a very strong participation of JINR in the NA48/2 experiment at CERN. Future plans are related with the experiments OKA and KLOD at IHEP (Protvino), the NA62 experiment at CERN, and B-meson physics at the LHC. The results obtained with JINR's participation in the E391a experiment at KEK on the decay of a neutral kaon to a pion and neutrino-antineutrino pair allowed one to consider the continuation of this research at a higher precision level, giving access to new physics. As a result of this feasibility study, the project KLOD has been prepared which anticipates measurements at the U-70 accelerator of IHEP. The project is competitive provided the detector and data taking parameters are achieved.

3. In the accuracy-increasing non-accelerator direction (Accuracy Border) JINR participates in studies of extremely important rare physics processes of lepton number non-conservation (neutrinoless double-beta decays, muon to electron conversion, etc), rare neutron, kaon, muon, pion and heavy-quark meson decays, including CP-violating decays. Neutrinoless double-beta decay and nonbaryonic dark matter are being studied and searched for in the underground laboratories at Gran Sasso, Italy (GERDA experiment); Modane, France (NEMO/ SuperNEMO, TGV and EDELWEISS experiments), and Baksan, Russia (IGEX-DB, IGEX-DM) with JINR's active participation. Measurements of the neutrino magnetic moment are being performed with the GEMMA spectrometer at reactors of the Kalinin Nuclear Power Plant.

The study of double-beta decay processes has highest priority, and will be carried out for the first three years (2008-2010) within the framework of the NEMO and TGV projects and later within the GERDA-MAJORANA (G&M) and Super-NEMO projects. It is planned to complete the full-scale Super-NEMO detector in 2013 and with data taking up to 2016 to achieve with ^{82}Se the limit on the lifetime up to $T_{1/2} > 2 \times 10^{26}$ years or the limit on an effective neutrino mass, $m_\nu < 0.04 - 0.11$ eV, depending on the nuclear matrix element used. The main purpose of the GERDA experiment is to search for the neutrinoless double-beta decay of ^{76}Ge. GERDA will operate with bare germanium semiconductor detectors (enriched in ^{76}Ge) situated in liquid argon; the experiment is under preparation in the Gran Sasso underground laboratory.

At the GEMMA spectrometer (situated at the Kalinin Nuclear Power Plant), experiments on measurement of the **neutrino magnetic moment** are performed. With the unique parameters of this instrument, the sensitivity is expected to be at the level of 3.5×10^{-11} μ_B after data taking up to 2009. At the end of 2010, the new detector GEMMA-2 (with 3 times more effective mass and one order of magnitude reduced background) will start to operate with an increased neutrino flux from the reactor. It is planned to achieve with GEMMA-2 the sensitivity on the neutrino magnetic moment at the level of $(9\text{-}7)\times10^{-12}$ μ_B after operation during 2010-2012.

4. In the particle astrophysics direction (Cosmic Border) JINR participates in the study of the ultra-high-energy cosmic rays (within the projects TUS, NUCLEON and Baikal), in direct and indirect dark matter search (within the projects EDELWEISS and Baikal) and in some theoretical and experimental investigations which are relevant to the main problems of particle astrophysics (projects DRIBs, the neutron programme at FLNP, etc). The Accuracy and Cosmic Borders are interrelated. In particular, it concerns the dark matter search experiments.

A direct observation of the interaction of **Weakly Interacting Massive Particles** (WIMP) in a terrestrial detector would be of tremendous importance to particle physics and cosmology. The EDELWEISS collaboration is searching for WIMP dark matter using cryogenic detectors. To reject background caused by cosmic radiation, the experiment is located in the underground laboratory in the Frejus tunnel between France and Italy. The goal of the experiment is to reach (in 2009) a sensitivity level at 10^{-8} picobarn for cross section of interaction of nonbaryonic dark matter in a range of prediction of some modern SUSY models. The development of EDELWEISS will be continued in the project called EURECA (European Underground Rare Event Calorimeter Array), which will unite EDELWEISS and CRESST experiments. The aim is to explore cross sections in the 10^{-9} – 10^{-10} picobarn region with a target mass of up to one tonne. EURECA plans to start as an executable project in 2009 and achieve the desired target by 2015.

The most important practical result for JINR in the course of realization of the proposed long-term research plan will be the creation at JINR, for in-house experiments, of the newest instrumental complex, comprising a modern superconducting accelerator facility – Nuclotron/NICA and multipurpose detectors, built using the most advanced technologies. It will replace the old machines constructed decades ago.

This accelerator complex will fill the gap existing in the world between modern machines with high-quality hadron and heavy-ion beams with energies of several hundred MeV and a high-energy region above 50 GeV; in particular, it concerns polarized beams. This gap appeared after the closure of both SATURNE-II and the Synchrophasotron; actually, it has not been filled by the COSY accelerator which is to be closed soon. It will be complementary to the future facilities like FAIR and J-PARC.

Reaching the following new frontiers: (1) in the luminosity for experiments in high-energy heavy-ion physics (up to 100 times more in the energy region of $\sqrt{s_{NN}}$ =4-9 GeV at A>100 than at existing facilities), (2) in the set of beams (high intensity of polarized beams of protons and deuterons with energies from hundreds of MeV up to a hundred GeV, which are not available elsewhere in the world), (3) in the techniques of physics experiments (in particular, polarimetry of multi-GeV beams), JINR will be able to conduct in-house experiments on the hottest problems of modern particle and nuclear physics, making this Laboratory one of the most attractive scientific centres in the world for research in these fields. One should also emphasize the importance of the modern home experimental base for attracting young scientists and engineers to JINR and for developing the educational programme of this Institute.

The Nuclotron/NICA acceleration complex will be, in fact, the first new one for JINR since the 1950s and for Russia since the mid-1960s (when U-70 was built). Its construction will definitely have a significant positive impact on the industries of all the JINR Member States.