Nuclear Physics. Low and Intermediate Energy Physics

1. Nuclear Physics with Neutrons

At present, nuclear physics with neutrons has become an integral part of investigations carried out in various fields of nuclear physics, particle physics, astrophysics and cosmology, in interpretations of quantum mechanics. Various methods and techniques including the methods of condensed matter physics, low-temperature physics, optics, atomic and nuclear physics are used in experiments. Notwithstanding the diversity of directions of investigations and experimental approaches, nuclear physics with neutrons preserves logicality and conformity determined by the properties of the neutron itself – electrically neutral, strongly interacting particle having long lifetime in free state; the particle, which is used as an object of investigations or probe.

The present-day neutron physics, like many other fields of physics includes fundamental and applied investigations. Fundamental tasks of neutron physics are in the field of experiments, which make the check-up of validity range of the Standard Model of electroweak interaction their aim, as well as of the peculiarities of strong and gravitational interaction, of their connection with the problems of astrophysics and cosmology. Applications of neutron physics range from the study of atmospheric depositions of contaminants and quality of foodstuffs by neutron activation analysis to the study of elemental content of surface of planets of the Solar system by neutron detectors.

The necessary condition for the development of neutron physics is the presence of an up-to-date high-intensity neutron source. Within the next 20-35 years such a source at JINR will be the modernized IBR-2M reactor, the facility which will be one of the world’s three sources with the highest neutron-flux density. As an additional source having a considerably smaller neutron-flux density, though with a considerably better energy resolution, the IREN facility will be used.

A series of investigations will be carried out on external neutron sources, in the first place, the experiments using ultra cold neutrons (UCN). In the nearest time the UCN sources will be commissioned with the densities exceeding the up-to-date values by the order of 2-3 (PSI and FRMII), which will make it possible to increase no less than by an order the parameters of neutron beta decay, electric dipole neutron moment.

1.1. Investigation of the neutron properties

1.1.1. Neutron lifetime

Decay of the free neutron is an important process to check-up the Standard Model of electroweak interaction. As an elementary example of beta decay, this process is sensitive to certain expansions of the Standard Model into the sector of charged weak currents. Measurements of characteristics of neutron beta decay, namely the lifetime and angular correlations with high accuracy, will make it possible to determine the value $/V_{ud}/$ of element of the Cabibbo-Kabayashi-Maskawa matrix (CKM). At present, the most accurate value of this element has been obtained from the experiments to measure times of superresolved $0^+ \rightarrow 0^+$ beta transitions between isobaric analog states of nuclei. These studies give the value $|V_{ud}| = 0.0738 \pm 0.0004$, simultaneously, the uncertainty is mainly related to theoretical corrections. If one uses the values $/V_{us}/$ and $/V_{ub}/$ taken from the current recommended values of the Particle Data Group, than the value $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9966 \pm 0.0014$ differs from unit per 2.1 standard error. Neutron beta decay gives an opportunity to obtain a result with smaller inaccuracy due to the theoretical corrections. At present, the value $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2$ obtained with the help of the data obtained from the neutron lifetime is 0.9971 ± 0.0039, and it is in accord with unit but is less accurate. Experiments to measure neutron lifetime have been carried out at FLNP in common with PNPI since late 80s of the past century. Currently, the facility "KOVSH" has been constructed, which will make it possible to reach the precision in measurement of neutron lifetime 0.1 s (at present, averaged value over the data of seven most precise experiments equals to (885.7±0.8) s) at new UCN sources.

1.1.2. Direct measurement of neutron-neutron scattering length

The nn-scattering experiments are directly connected with the problem of charge symmetry of nuclear forces. For thermal neutrons the scattering cross section is determined by the value of nn-scattering length, which is compared with the length of pp and np-scattering to check up the symmetry of isospin. The scattering length is maximally sensitive to small differences of nuclear potentials. The indirect determination of amplitude of neutron-neutron scattering from nuclear reactions with three particles in the final state, two of which are neutrons, has given contradictory results for a long time. The situation has changed over recent years after experiments at TUNL and LANL, which have provided the agreement of results of indirect measurements of scattering amplitude a_{nn}: –18.7±0.6 Fm for the D(n,p)2n reaction and -18.55±0.005 stat. ±0.3 syst Fm for the D(π,γ)2n reaction.

These results show that nn-interaction is stronger than the nuclear part of pp-interaction. The Charge Symmetry Breaking (CSB) in the scale of scattering lengths has the value $\Delta a_{CSB}=a_{pp}-a_{nn}=1.6\pm0.6$ Fm. There is a theoretical justification of CSB developed both in terms of the meson exchange theory of nuclear forces and at the quark level. In the meson exchange theory, CSB is related to mixing of ρ and ω mesons; within the framework of the quantum chromodynamics (QCD) the breaking of symmetry occurs due to the difference of masses of u- and d- quarks. As shown in paper in both theories the predictable degree of breaking varies in the range 0.5 – 2.5 Fm depending on the specific model of theory. The choice of theoretical model is possible at an increase of the accuracy of experiment, which is a new important argument in favour of the direct measurement of the nn-scattering cross section.

Proposals on the direct measurement of the nn-scattering length have a long history, however, none of them has been implemented. At FLNP, practical realization of the experiment on the direct measurement of the neutron-neutron scattering cross section at the YAGUAR reactor (Snezhinsk, Russia) has been proposed. The YAGUAR reactor provides optimal conditions to carry out the nn experiment. It has:

1. High (at the level of 10^{18} $cm^{-2}s^{-1}$) pulsed density of the neutron flux.
2. Transparent channel passing through the centre of the reactor core, which allows one to use maximal neutron fluxes and creates high symmetry of neutron fields, which must lead to the simplification of experimental data processing.
3. Possibility of placement of the neutron moderator into the central channel with no risk of local overheating of the reactor core near the moderator.
4. Relatively short pulse, which allows one to use the time-of-flight technique to separate thermal neutrons from fast ones.

The use of high density of thermal neutrons reduces the rigidity of requirements to the background, because the effect depends quadratically on the flux density, whereas the background – linearly. The aim of the project is the construction of experimental facility and first direct observation of the neutron-neutron scattering. Within the framework of the given project it is planned to obtain the value of scattering amplitude at the level of 5%.

1.1.3. Investigations of breakings of fundamental symmetries in reactions with neutrons

The physical cause of the CP symmetry breaking discovered in decays of neutral K-mesons remains obscure so far. The CP breaking presupposes also the breakdown of time invariance on the assumption that the CPT theorem is correct. In the Standard Model the opportunity of the CP symmetry breaking may be obtained by way of introducing the complex phase δ_{KM} into CKM. By now there is no firm belief that the observed effects are caused by the presence of this phase and the question, if there are other mechanisms leading to the CP symmetry breaking, remains unanswered, especially because the presence of the complex phase is insufficient to explain the baryon asymmetry of the Universe within the framework of the Big Bang model. One of the spheres, in which one may look for the breakdown of time invariance is the interaction of systems formed by quarks of the first generation, for which the contribution from δ_{KM} is considerably suppressed. The presence of time non-invariance in processes of interactions of polarized neutrons with polarized and aligned nuclear targets will lead to the appearance of non-zero correlation coefficients before the terms in decomposition of the forward scattering amplitude $\vec{s}(\vec{k}\times\vec{I})$ and $\vec{s}(\vec{k}\times\vec{I})(\vec{k}\vec{I})$, the so-called triple and quinary correlations. Performing of experiments to search for these correlations is one of the priority tasks in neutron physics, and these studies will continue within the framework of already existing and planned collaborations. In particular, within the framework of the FLNP-KEK collaboration (Tsukuba, Japan) preparation for the experimental check-up of time invariance at the interaction of polarized neutrons with polarized nuclei will continue. The method proposed at FLNP and developed in common with the LPI RAS specialists was tested in the first test experiments at IBR-30 in 2001 and developed over recent years on the KEK basis. The experiments will be carried out on the new neutron source JPARC beginning 2008.

1.1.4. Investigations with neutrons in astrophysics

Properties of the neutron and nuclear reactions with its participation play the key role in a number of astrophysical processes. Neutron lifetime and cross sections of reactions played in the period after the Big Bang and still play the decisive role in the processes of nucleosynthesis in stars. The investigation of abundance of chemical elements in the Solar system has determined the reactions of neutron capture, which are essential at formation of isotopes in stars. For many reactions the existing experimental data on cross sections are insufficient. Measurements of these cross sections in the region of neutron energies corresponding to star temperatures (fractions eV – hundreds keV) are included, along with other investigations, in the programmes of a number of neutron sources (ORELA; GELINA [; nTOF].

These investigations will also be carried out at the first stage of the IREN facility in FLNP. The calculations show that for a number of available isotopes the intensity and energy resolution will be enough for essential refinement of the existing experimental data. Experiments to measure mean cross sections of the reactions (n,p), (n,α) in the region of neutron energies from several eV to ~1 MeV on nuclides ^{14}N, $^{20,21}Ne$, $^{32,33}S$, ^{35}Cl, ^{36}Ar of light and mean masses are planned. These data are necessary for a more detailed study of star nucleosynthesis and are directly related to such problems as neutron balance at various stages of evolution of stars, origin of rare neutron-excess isotopes of mean masses, determination of contribution of various processes of nucleosynthesis (s-, r-, p-processes) into the abundance of elements of the Solar system, meteorite anomalies.

With the application of a new technique, it is planned to start the realization of a wide programme to measure cross sections of the reactions (n,α) to study the r-process of star nucleosynthesis. The existing not numerous measurements of the reaction (n,α) on nuclei heavier than iron show that they differ very much (sometimes more than by an order) from the calculated reaction rates used in models of the r-process. New experimental data will allow one to adjust more precisely the parameters of alpha particle potentials used in calculations. On the whole, there are 20-30 candidates of rare isotopes, for which it is necessary and possible to measure cross sections of the (n, α) reactions, for example ^{67}Zn, ^{95}Mo, ^{99}Ru, ^{123}Te, ^{143,145}Nd, ^{149}Sm, at IREN. Measurements of the reactions (n, p) and (n, α) will be continued on a number of radionuclides, which play the key role in understanding certain astronomic observations and isotopic anomalies in meteorites: ^{57}Ni(n, p); ^{22}Na(n, p) and (n, α); ^{36}Cl(n, p) and (n, α); ^{37,39}Ar(n,p) and (n, α), etc.

1.1.5. Nuclear fission

Spontaneous and induced nuclear fission has been studied actively for more than fifteen years; however, thorough understanding of the dynamics and mechanism of the phenomenon is still not achieved. This is determined, first of all, by the reason that nuclear fission is one of the most complicated nuclear transmutations related to the deep redistribution of mass and charge of the initial nucleus, to the formation of strongly deformed and excited fragments having high spin and the excitation energy sufficient for emanation of several neutrons and around ten gamma-quanta. The second essential circumstance is that in the majority of experiments nuclear fission is studied under the conditions when it is impossible to obtain information on basic amplitudes of the process characterized by the π parity, the total spin J of the fissionable system and its projection to the fission axis K. Only the fission induced by resonance s- and p-wave neutrons allows one to obtain information on the $J^{\pi}K$ fission amplitudes themselves for collecting excited states of the fissionable system available for experimental study at a rather high neutron energy resolution. This opportunity is related to the circumstance that in the total cross section of the (n,f)-reaction and in the energy dependence of angular distributions of fission fragments the interference of $J^{\pi}K$ amplitudes belonging to various neutron resonances (compound states) manifests itself. Measurements of various characteristics of the nuclear fission process will be carried out at the IBR-2M reactor, external neutron sources and at the IREN facility.

Within the framework of the programme on nuclear data, the investigations of yields and time characteristics of delayed neutrons for minor actinides are planned. The integration of efforts with VNIIEF (Sarov) and IPPE (Obninsk) will allow one to carry out measurements with rare isotope targets, and the original experimental technique using the unique abilities of the reactor will make it possible to provide the high competitive level of results.

The n-TOF source (CERN) possessing a high-energy distribution has a small neutron flux intensity, firstly, due to the low off-duty ratio (<1Hz) and, secondly, due to the only and rather long flight path (185 m). Therefore, investigation of the fission physics, namely of the properties of fission states, including their interference and relation with fission modes, will be continued after construction of the additional shorter flight path, and also of the new measuring complex and the first-class radiochemical laboratory. Measurements of the mass-energy and angular distributions of fission fragments from vibration resonances at the threshold of the (n,f)-reaction will be performed, the thin structure of which has been investigated by the JINR-IPPE-CERN collaboration in 2002-2004. New measurements will make it possible to obtain fundamentally new information on multimodal fission barriers.

1.1.6. Applied investigations

1.1.6.1. Neutron activation analysis

In recent years the studies of atmospheric depositions of heavy metals using the biomonitoring technique have been finished in Central Russia (Tula, Tver, Yaroslavl and the north of Moscow region) and also in a number of European countries (Bulgaria, Slovakia, Romania, Ukraine, Poland, Serbia, Bosnia, Macedonia). The results of these studies have been published in the European Atlas (2003). Similar studies have been carried out in the Republic of Korea, China and the European part of Turkey. The analysis of data to evaluate the pollution of the Chelyabinsk region by heavy metals and radionuclides has been continued

The investigation of soil pollution by heavy metals and other toxic elements under the action of road transport (Minnesota, USA) has been completed.

In collaboration with the Geological Institute of RAS, within the framework of the IAEA Coordination Programme and Technical Cooperation with IAEA, the comparative analysis of elemental content of a number of foodstuffs grown in conditions of strong anthropogenic influence has been performed.

The work on the project “Monitoring of the work place and health of the staff engaged in phosphate fertilizer production at a number of plants of Russia, Uzbekistan, Poland, and Romania” (European Programme 5 Copernicus) has been carried out.

These directions will be continued at the IBR-2M reactor after the completion of modernization and at the first stage of the IREN facility.

1.1.6.2. Development, construction and testing of neutron detectors for orbital spacecrafts and rovers

Since 1997 to the present day, FLNP collaborates with the Space Research Institute (SRI RAS) in the construction of wide-range neutron detectors for spectral analysis of neutron radiation of Mars and other objects of the Solar system aimed at determining the elemental content and the presence of water in the superficial layer of soil. The concept of high-energy neutron detector (HEND) proposed at FLNP has been realized by SRI in collaboration with other Russian and American organizations. At FLNP, calibrations of neutron sensors of the HEND device have been carried out using homoenergetic neutrons obtained in the reaction of interaction of protons and deuterons with light nuclei. The HEND device has successfully been operating for more than 4 years on board the American spacecraft Mars Odyssey 2001. The obtained data unambiguously testify to the presence of a meter layer of water ice at the minimum in the Martian polar regions. At the same time, there are regions in equatorial area with an increased (up to 20 %) water content in the superficial layer of soil.

Together with SRI RAS, FLNP specialists have participated in applications for the construction of neutron spectrometers for two NASA missions. In 2004, both applications passed the competition and were accepted for realization. For the rover Mars Science Laboratory (the launching is planned at the end of 2009), a device will be developed and constructed consisting of a pulsed neutron generator and detector of thermal and epithermal neutrons, which will make it possible to determine the content of water ice in the superficial layer of the Martian soil during the moving of the device along the planet surface. At FLNP, calculations of functions of the device sensitivity and calibrations of the device will be performed in the laboratory conditions, also a model of the Martian soil will be developed and created. FLNP specialists will also take part in the field tests of the device.

The second device, included in the SRI application in common with FLNP, is an orbital detector of fast neutrons with a collimator. The device will be installed on board the spacecraft Lunar Reconnaissance Orbiter (the launching is planned for November 2008). At FLNP, calculations of functions of the device sensitivity, physical simulation and calibrations of separate sensors of the device and also of the device as a whole will be performed.

2. HEAVY-ION PHYSICS

2.1. Introduction

The scientific programme of the Flerov Laboratory of Nuclear Reactions in the field of heavy-ion physics includes experiments on the synthesis of heavy and superheavy elements, exotic light nuclei, studies of nuclear reaction mechanisms, accelerator technology and heavy-ion interaction with matter.

During the last decade, heavy-ion physics is becoming the most intensively developing field of low- and intermediate-energy nuclear physics. The main directions of progress are: synthesis and investigation of nuclear, physical and chemical properties of transfermium (Z>100) and superheavy (SHE) elements, production and study of properties of exotic light nuclei, investigation of fission-fusion and quasi-fission processes in interactions of massive heavy ions, studies of reaction mechanisms with accelerated ions of stable and radioactive isotopes.

2.1.1. Synthesis and investigation of properties of superheavy elements

A fundamental outcome of the macro-microscopic theory is the prediction of an "island of stability" of superheavy elements. Theoretical predictions of the position of this "island" vary strongly depending on the model. The shell correction amplitude has a maximum for the superheavy nucleus ^{298}114 in macro-microscopic models. After calculations performed using the Hartree–Fock method or using a self-consistent relativistic mean-field model, the proton shells are predicted at Z=120 or 126. Following the well-known neutron shell with N=126 (^{208}Pb), the next closed neutron shell is expected at N=184. For nuclei with Z > 120 the unusual bubble structure has been predicted.

Complete fusion reactions ^{238}U+^{48}Ca, ^{242,244}Pu+^{48}Ca, ^{243}Am+^{48}Ca, ^{245,248}Cm+^{48}Ca and ^{249}Cf+^{48}Ca were investigated in attempts to synthesize superheavy nuclei located in the immediate vicinity from the predicted proton and neutron magic numbers. The results obtained during 2000–2006 demonstrate that in ^{48}Ca-induced reactions one can produce and study new nuclei in a wide range of Z and N. Decays of the heaviest isotopes of Rf, Db, Bh, Hs, Mt, Ds, Rg and isotopes of the new elements 111 ÷ 116 and 118 were observed.

In 2008–2017 the efforts will be concentrated both on the further more detailed studies of now discovered isotopes of superheavy elements and on the searches for new methods for the synthesis of heavier ones. The planned experiments will be aimed at the synthesis of nuclei with Z=110–120 in reactions of ^{232}Th, ^{236,238}U, ^{237}Np, ^{242,244}Pu, ^{241,243}Am, ^{246,247,248}Cm, ^{249}Cf with ^{36}S, ^{48}Ca, ^{50}Ti, ^{58}Fe ^{64}Ni.

Symmetric combinations like $^{86}Kr+^{180}Hf$, $^{136}Xe+^{136}Xe$, $^{150}Nd+^{150}Nd$ and in quasi-fission reactions like U + U will be studied using combined physical and radiochemical techniques.

The experiments aimed at the search of primordial superheavy elements in terrestrial samples will be continued using neutron multiplicity counters.

Whatever method is used for the superheavy element production, cold or hot fusion, their formation cross section is expected to be in the range of 1 pb, which corresponds to approximately 1 event per week with the present state of recoil separators, available ion beams, and constitutes a practical limit to the search of new elements. Thus the upgrade of the existing separators at the beams of the U400R cyclotron and construction of a special gas-filled separator at the U400MR cyclotron together with the developing of new target systems, improving the intensity and the quality of ion beams are planned.

2.1.2. Nuclear fusion and fission, exotic decay modes

Nuclei in the vicinity of At-Th and of transfermium isotopes with $Z \geq 100$ are of true interest in the study of the fission mode phenomenon. On the other hand, the study of the fusion-fission cross sections of nuclei at low excitation is of importance in predicting the survivability of those nuclei and in deciding on the optimum way for their synthesis.

Mechanisms of formation and decay of heavy and superheavy nuclei in the reactions with ^{12}C, ^{18}O, ^{22}Ne, ^{26}Mg, ^{48}Ca, ^{58}Fe, ^{86}Kr ions were investigated using the CORSET + DEMON +HENDES set-up which allows measurements of mass-energy distributions of fission fragments, pre-equilibrium, pre- and post-scission neutrons, multiplicities and γ-quanta energies. New evidence of the shell influence on the nuclei fission dynamics has been obtained in the research of spontaneous and induced fission at low excitation energy.

In 2008–2017 it is planned to investigate fusion-fission and quasi-fission reactions between ^{40}Ar, ^{48}Ca, ^{50}Ti, ^{58}Fe, ^{64}Ni, ^{86}Kr ions and ^{238}U, ^{244}Pu, ^{248}Cm and ^{249}Cf targets, leading to the formation of nuclear systems with Z=112–122.

Measurements of characteristics of low-energy fission of neutron-rich Th, Cm and Cf isotopes, produced in the RIB reactions with ^{226}Ra, ^{244}Pu and ^{248}Cm targets. Using the light RI-beams produced at the DRIBs complex it is planned to study fission and fusion reactions induced by ^{6}He and ^{8}He, the probability of the full momentum transfer, fission modes of the heaviest Pu–Cf isotopes.

Study of the influence of the shell structure in the entrance channel in a range from deep subbarrier energies to energies above the Coulomb barrier will be performed in reactions like $^{86}Kr+^{124}Sn$, $^{136}Xe+^{124}Sn$, $^{136}Xe+^{136}Xe$ and in quasi-fission reactions like U + U with the beams produced by the modernized U400R cyclotron.

The mini-FOBOS set-up will be used for investigations of exotic decay modes of excited nuclei at the beams of the U400MR cyclotron.

The study of multiplicities of prompt fission neutrons in spontaneous fission of transfermium isotopes will be continued using the special designed neutron counter installed at the VASSILISSA set-up.

2.1.3. Nuclear spectroscopy of isotopes of transfermium elements

The JINR (Dubna)—IN2P3 (France) collaboration project aimed at the α-, β- and γ- spectroscopy of the transfermium element isotopes using heavy ion beams of the U400 cyclotron and the modernized recoil separator VASSILISSA was launched at Dubna. During the first full-scale experiments, nobelium and lawrencium isotopes produced in the ^{48}Ca+ ^{207,208}Pb → ^{255,256}No* and ^{48}Ca+ ^{209}Bi → ^{257}Lr* reactions were studied. More neutron-rich No isotopes will be produced using a radioactive ^{210}Pb target. The design of a special electromagnetic separator is planned for Recoil Decay Tagging spectroscopy in investigations of Rf and Db isotopes.

2.1.4. Mass- and laser spectroscopy of heavy nuclei

One of the most important tasks for the future will be the exact determination of Z and A of the isotopes synthesized in reactions with ^{48}Ca. The traditionally used α–α-correlation method is inapplicable in that case.

Long lifetimes of the isotopes synthesized in reactions with ^{48}Ca make it possible to change the approach to the synthesis of superheavy nuclei. The properties of superheavy elements are predicted to be similar to those of volatile elements Hg, Tl, Pb, Bi, Po, At or Rn. Now one can use an off-line separator. For precise measurements of masses and the investigation of chemical and physical properties of superheavy elements, the Mass Analyzer of Super Heavy Atoms "MASHA" was designed at FLNR. In experiments with an ECR-ion source, the mass resolution $\Delta m/m$ of $3\cdot10^{-4}$ was achieved for Kr, Xe and Hg isotopes. The set-up MASHA surpasses all known facilities in efficiency of the production of superheavy atoms and in extracting information on their masses and decay characteristics. First on-line experiments with the use of this separator at the beams of the U400MR cyclotron are scheduled for 2008.

In the laboratory of low-energy radioactive beams, investigations in nuclear and laser spectroscopy of neutron-rich isotopes will be performed. The possible construction of an ion trap is under discussion.

2.1.5. Reactions induced by stable and radioactive ion beams of light elements

Experiments with radioactive beams produced in direct reactions were carried out at the ACCULINNA, COMBAS and MULTI set-ups.

Secondary beams of 25-35 MeV/amu ^{6,8}He, ^{9,11}Li, ^{12,14}Be, ^{8}B nuclei are produced using primary U400M cyclotron beams of ^{7}Li, ^{11}B, ^{13}C, ^{15}N and ^{18}O. Intensities of $1.5\cdot10^{6}$ and $7\cdot10^{3}$ pps, respectively, were obtained for 25 MeV/amu ^{6}He and ^{8}He nuclei. After the reconstruction of this accelerator the intensity and the quality of the beams will be significantly improved.

Manifestations of the ^{6}He-nucleus structure in elastic scattering and transfer reactions of 150 MeV ^{6}He from hydrogen and helium nuclei have been studied. This study provided the first direct experimental verification for the theory predicted "di-neutron" configuration of the neutron halo in ^{6}He. The ground-state resonance of ^{5}H was obtained in the reaction ^{6}He+p$\rightarrow$^{5}H+2p.

Experiments with the upgraded cryogenic ^{1,2,3}H targets are planned for the period of 2008–2017 within the project DRIBs. Elastic scattering of ^{6}He and ^{8}He on the tritium target to the backward hemisphere will be studied in order to obtain information on the clustering configurations of ^{6}He in t+t and that of ^{8}He in the ^{5}H+t clusters. The study of transfer reactions will be extended to the study of such transfers as: ^{8}He+^{3}H$\rightarrow$^{10}He+p, ^{9}Li+^{3}H$\rightarrow$^{11}Li+p, ^{6}He+^{3}H$\rightarrow$^{8}He+p. The aim is to investigate the halo clustering in ^{6,8}He and to search for possible structures in the tetra-neutron system. New excited states in ^{4}H, ^{5}H, ^{7}H, ^{11}Li and ^{8}He populated in the reactions will also be searched for. Further investigation of resonance states of unstable nuclear systems ^{4}H and ^{5}H in transfer reactions occurring in bombardment of a liquid tritium (deuterium) target with tritons will be conducted.

Experiments aimed at the search for the ^{7}H nucleus will include direct detection of the long lived ^{7}H nuclei. A limit of $1\cdot10^{-32}$ cm^{-2} was obtained for the cross section of the reaction ^{2}H(^{8}He,^{7}H)^{3}He, which could result in the formation of ^{7}H nuclei with the life time $\tau \geq 3\cdot10^{-9}$ s. New experiments will allow a significant improvement of this result.

Using the in-flight fragment-separator COMBAS experiments aimed at the study of the reaction mechanisms in nucleus-nucleus collisions near the Fermi energy domain and the determination of intensity of secondary radioactive beams of neutron-rich nuclei with atomic numbers $2 \leq Z \leq 11$ are planned. Using intermediate energy projectiles, the yields and cluster properties of the heavy neutron-rich isotopes like $^{10\text{-}14}$Be, $^{14\text{-}17}$B, $^{16\text{-}20}$C, $^{20\text{-}24}$O, $^{23\text{-}26}$F and properties of the proton-rich isotopes like ^{8}B will be studied.

Investigations of the structure of very neutron-rich isotopes of light elements like $^{7\text{-}10}$He, ^{10,11}Li, ^{13,14}Be, ^{16}B are of great interest for the understanding of cluster structure, the neutron halo and of the stability of neutron-rich light nuclei. The experiments are planned with the MULTI set-up at the beams of the U400MR cyclotron.

For investigations of properties and mechanisms of interactions of exotic light nuclei produced in direct reactions, the construction of a new high-resolution beam line and a dedicated separator is under discussion.

2.1.6. Theoretical study of mechanisms of heavy ion induced reactions

A systematic analysis of reaction dynamics of the superheavy nucleus formation and decay at beam energies near the Coulomb barrier will be continued. Dynamical calculations were carried out using the Langevin equations combined with the statistical model for pre-scission neutron evaporation. Several projectile-target combinations leading to the formation of superheavy nuclei were studied within the model. A new mechanism – "sequential fusion" – was proposed and studied for near-barrier fusion of weekly bound neutron-rich nuclei. The studies in this direction will be continued.

Developing and supporting the "Knowledge Base on Low-Energy Nuclear Physics" allocated in the Web has been started. There are two main objectives of the project. (1) Fast and visual getting of experimental data on nuclear structure and cross sections of nuclear reactions. (2) Analysis of experimental data and modeling of the processes of nuclear dynamics.

2.2. Radiochemical Investigations

2.2.1. Chemical properties of transactinides and identification of superheavy elements

For the comparative studies of chemical compounds of transfermium elements and of their light homologues, thermochromatographic technique in gas phase and ion exchange and extraction techniques in solutions are used.

First experiments on the chemical identification of element 112 produced via $^{48}Ca+^{238}U$ were carried out using the gas transportation method. The experimental data point to "Hg-like" behaviour of element 112 and rather "noble gas like" behaviour of element 114. This observation is the first indication of the influence of relativistic effects on the properties of superheavy atoms. This problem is fundamental for modern chemistry.

Another important result on the study of the physical and chemical properties of superheavy elements and the identification of their atomic number is the chemical identification of Dubnium (Db) as a final product in the alpha-decay chain of element 115.

Experiments aimed at the precise measurement of the mass of superheavy elements have been started at the unique mass analyzer MASHA.

New complex methods working in a broad temperature region up to 2500°C for express isolation of superheavy elements will be developed. Planned for 2008–2017 are the on-line chemical isolation and identification of heavy isotopes and detection of α-decay and spontaneous fission fragments in coincidence with neutrons.

2.2.2. Radiation chemistry and material studies.

This studies will be performed to improve the radiation control in the environment and the technological safety in nuclear plants, to develop novel technologies of the radioactive materials treatment, to apply nuclear methods in nuclear medicine (diagnostics and therapy) using thefollowing isotopes: ^{67}Cu, ^{73}As, ^{88}Zr, ^{99}Mo(^{99}Tc), ^{97}Ru, ^{149}Tb,^{178}W(^{178}Ta), ^{186}Re, ^{188}Re, ^{211}At, ^{225}Ac, ^{237}U, ^{236}Pu, ^{237}Pu.

Special attention will be given to the development of methods of radioisotope production in (α, xn) reactions at the U200 cyclotron and in photonuclear reactions at the MT-25 microtron.

2.3. Accelerator physics and development of basic and new facilities

2.3.1. Presently, at the Flerov Laboratory of Nuclear Reactions there are four heavy-ion cyclotrons—U400, U400M, U200 and DC40, which deliver necessary beams both for basic and applied research.

The first stage of the DRIBs project (Dubna Radioactive Ion Beams) has been realized at the U400-U400M accelerator complex. The regular experiments with radioactive ^{6}He ions started in December 2004. The U400 cyclotron accelerated the secondary $^{6}He^{+}$ ions produced at U400M from the energy of 3.5 keV/amu to 5÷20 MeV/amu. The DRIBs-I complex started the routine operation, and 1.5–2 months per year are scheduled for experiments with RI-beams.

In 2007, the reconstruction of the U400M cyclotron started. The goals of this modernization are to accelerate low-energy 3–12 MeV/A Li – U ions and to improve the intensity and the quality of available beams. The realization of this project will allow not interrupting low-energy experiments during the long lasting reconstruction of the U400 cyclotron and will provide additional areas (up to 300 m^2) for new facilities. First experiments at the modernized cyclotron are scheduled for the end of 2007.

Three sources of ions will be installed at the U400MR cyclotron: an ECR and superconducting ECR—for the production of heavy ions, and a high-frequency ion source for the generation of tritium and deuterium ion beams. These beams are required for the study of resonance states of light exotic nuclei.

The reconstruction of U400 is proposed for the improvement of the cyclotron parameters and is scheduled for 2009 – 2010. The aims of the modernization are:

- Decreasing the magnetic field level at the cyclotron centre from 1.93÷2.1 T to 0.8÷1.8 T which allows to decrease the electrical power of the U400R main coil power supply by four times.
- Providing the smooth ion energy variation at the factor of 5 for every mass to charge ratio A/Z at an accuracy of $\Delta E/E=5\cdot10^{-3}$;
- Increasing the intensity of accelerated ions of rare stable isotopes by the factor of 3.

The possibility of increasing the injection voltage from 13÷20 kV to 40÷50 kV is under study. The reconstruction will provide increasing the U400R accelerating efficiency by 1.5÷2 times, which is particularly important for rare ions like ^{36}S, ^{48}Ca, ^{58}Fe.

The modernization of the U400–U400M accelerator complex and the full-scale realization of the DRIBs project will allow continuing the investigations in heavy-ion physics, including experiments on the synthesis of heavy and exotic nuclei using ion beams of stable and radioactive isotopes and studies of nuclear reactions, heavy-ion interaction with matter and applied research on the world level during the next 20 years.

3. LOW- AND INTERMEDIATE ENERGY PHYSICS

3.1 Neutrino physics and astrophysics

One of the main directions in research field under the topic is probing of the new physics beyond the Standard Model of electro-weak interactions. Neutrinoless double beta decay and nonbarionic dark matter is 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, GERDA and others) with an active participation of the scientists from JINR. Measurements of the neutrino magnetic moment are being performed with GEMMA spectrometer at reactors of the Kalinin Nuclear Power Plant. LESI project aims to obtain new information about astrophysical S-factors and effective cross sections for pd, dd, d^3He and $^3He^4He$ reactions in the region of astrophysical energies. The LESI is planned to be implemented at the TEMP-3 facility with the Hall accelerator, now under development at the Nuclear Physics Institute, Polytechnic University (Tomsk), and at the TEMP facility with plasma counter-flows generated in powerful electric discharges in the external magnetic field.

Methodological basis of all the above mentioned experiments is the YASNAPP complex at JLNP JINR combining precision nuclear-spectroscopy technology and methods for production and separation of a wide variety of radioactive isotopes. One of the main achievements is manufacture of unique radioactive sources (including those of mono-atomic thickness) for testing and calibration of the developed experimental set ups. A wide program performed at JLNP JINR aimed to research and develop new types of detector materials made it possible to produce several tons of the high quality plastic scintillators for the NEMO-3 spectrometer, half a hundred semiconductor Ge detectors for the TGV-1 and TGV-2 spectrometer, and tens of Si detectors for the AnCor experiment. All this existing (and thus not requiring considerable investments) potential will be used in new projects G&M, SuperNEMO, EDELWEISS, GEMMA, etc.

3.1.1.Study of the double beta decay

The discovery of neutrino oscillations in experiments with atmospheric and solar neutrinos, observation of neutrino oscillations in the KamLAND experiment with reactor neutrinos, and new SNO results have become impressive experimental evidence for the nonzero mass of the neutrino. However, the above-mentioned neutrino oscillation experiments only yield information on neutrino mass difference squared Δm^2, but they are insensitive to the nature of the neutrino mass (Dirac or Majorana) and cannot provide information on the absolute neutrino mass scale. This problem can be solved in experimental studies of the tritium beta spectrum and, in the case of the Majorana neutrino, the neutrinoless double beta decay ($\beta\beta 0\nu$). Observation and study of the neutrinoless double beta decay will also allow the type of the neutrino mass hierarchy (normal, inverted, or degenerate) to be determined. Analysis of the results of experiments on neutrino oscillations allows the following important conclusion: if the scenario with the inverted or degenerate hierarchy of neutrino masses is valid, the present-day experiments on the search for the neutrinoless double beta decay can, in the case of the Majorana neutrino, allow observation and study of this phenomenon with the imposing of the limitation on the neutrino mass.

Apart from searching for $\beta\beta 0\nu$, an important aspect of the study of double beta processes is thorough study of the two-neutrino double beta decay allowed within the Standard Model. Precise measurement of its half-life will allow more accurate calculation of nuclear matrix elements (NME), the uncertainty of which for various nuclei is very large at present. In their turn, nuclear matrix elements are necessary for correct interpretation of the results of the experiments on the neutrinoless double beta decay. The NME for the $\beta\beta 0\nu$ and $\beta\beta 2\nu$ processes are calculated in different way, and yet they have much in common. Studies of the allowed double beta decay will make it possible to study NME and extend their determination technique to the neutrinoless beta decay, which has not been experimentally verified yet.

By analogy with the two-neutrino double beta decay, study of double beta decays to excited levels of the daughter nucleus will allow additional information on ββ0ν processes. In most nuclei resulting from the ββ0ν decay the characteristics of the first excited levels are 2^+. A transition to this level (and to the 0_1^+ level) is allowed only if there are right-handed currents.

In this connection the study of double beta decay processes has an undisputable 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 SuperNEMO projects.

The NEMO and TGV projects involve studies of ββ processes for a wide range of nuclei. The NEMO-3 detector is a combined (track gas detectors + scintillation calorimeters + magnetic field) assembly capable of measuring not only the total energy of ββ decay electrons but also all other parameters of this process for seven ββ-isotopes (^{48}Ca, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{130}Te, ^{150}Nd) with total mass of about 10 kg . The main isotopes in NEMO-3 are ^{100}Mo (7kg) and ^{82}Se (1kg). The ongoing NEMO-3 experiment will continue data taking up to 2010 year and could confirm the observation of ββ0ν decay signal, for instance, for ^{100}Mo with sensitivity of $T_{1/2} = 2 \times 10^{26}$ y at the level of $<m_\nu> =$ 0.3 – 0.7 eV, but cannot definitely refute the H. Klapdor's et al. (KKGH) claim $T_{1/2} = 1.2 \times 10^{25}$ y or $<m_\nu> =$ 0.44 eV (obtained with ^{76}Ge) in case of a null result due to the uncertainties of the nuclear matrix elements (NME).

The next stage of the NEMO-3 experiment will be the Super-NEMO detector, currently conceived to contain of about 100 kg ^{82}Se or ^{150}Nd. Starting from 2007 extensive program to develop new modules for the Super-NEMO is under way. It is planned to complete the full scale Super-NEMO detector in 2013 year and with data taking up to 2016 to achieve with ^{82}Se the limit on the half life up to $T_{1/2} > 2 \times 10^{26}$ y or, the limit on an effective neutrino mass, m_ν < 0.04 - 0.11 eV, depending on nuclear matrix element used.

Main purpose of the GERDA experiment is to search for the neutrinoless double beta decay of ^{76}Ge. The experimental set up is under construction in the underground laboratory of LNGS (Italy). The commissioning of the completed setup of GERDA is scheduled for 2008. GERDA will operate with bare germanium semiconductor detectors (enriched in ^{76}Ge) situated in liquid argon. In Phase I of GERDA the existing 18 kg of enriched germanium detectors from the previous IGEX and Heidelberg-Moscow experiment will be used. After two years of data taking (2009 – 2011), corresponding to an exposure of 30 kg x years, the GERDA can either confirm the claimed observation of ββ0ν decay or refute it at the high statistical level without problems with uncertainties in NME. If no events will observed, the limit on the half life would amount to $T_{1/2} > 3 \times 10^{25}$ y or, tranlated into an effective neutrino mass, m_ν < 0.3 eV, depending on NME used. For Phase II (2012 – 2016) about 22 kg of new 76Ge detectors will be added and the total mass will be approximately 40 kg. After data taking corresponding to an exposure of 150 kg x years and with the background reduced up to 10^{-3}counts/(keV kg y), the limit on $T_{1/2}$ would improve to > 1.5 x10^{26} y. This translates to an upper limit on the effective neutrino mass of 0.09 - 0.29 eV. Phase I will cover the area of sensitivity required to scrutinize the claim and Phase II will cover the degenerate neutrino mass hierarchy. If no signal for the ββ0ν decay is found, a ton scale ^{76}Ge experiment (Phase III, starting from 2015 year) with further background reduction up to 10^{-4}counts/(keV_kg_y) undertaken in a worldwide collaboration (GERDA-MAJORANA) will be required to cover the inverted hierarchy region.

3.1.2. Search for dark matter in the Universe.

Analysis of recent experimental data on the cosmic microwave background, combined with other astronomical and astrophysical data, gives undoubted evidence that Universe comprise non-luminous, nonbaryonic matter. Cosmological data indicate that only 5% of the mass in the Universe are accounted for by ordinary substance and another 0.3–3% by neutrinos. The unknown rest composition is dark energy (65–70%) and dark matter (about 25%). A direct observation of the interaction of WIMPs in a terrestrial detector would be of tremendous importance to particle physics and cosmology. The EDELWEISS collaboration is searching for WIMP dark matter using natural HpGe cryogenic detectors. Measurement both heat and ionization channels allows highly efficient identification of nuclear recoils (caused by WIMP). To reject background caused by cosmic radiation experiment is located in underground laboratory in the Frejus tunnel between France and Italy. Now test experiments have been accomplished at EDELWEISS-1 setup and direct search of dark matter particles began with the EDELWEISS-2 spectrometer. EDELWEISS-2 was initially been funded for a 28 detectors stage with total weight of detectors about 10 kg. Data is acquired starting from the 2007 year summer with this setup. Forty additional detectors will be added in the two incoming years to enhance progressively the sensitivity. To 2009 EDELWEISS-2 will be biggest cryogenic system for direct search of dark matter. The goal of this phase of the experiment is to reach to 2009 a sensitivity level at 10^{-8} picobarn for cross section of interaction of nonbaryonic dark matter with ordinary one in a range of prediction of some modern SUSY models. The development of EDELWEISS-2 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 scalar cross sections in the $10^{-9} - 10^{-10}$ picobarn region with a target mass of up to one tonne. This will cover almost all predictions of SUSY models. A major advantage of EURECA is our planned use of more that just one target material (multi target experiment for WIMP identification). In preparation for this large-scale experiment, R&D for EURECA is provided through the current phases of CRESST and EDELWEISS. EURECA plans to start as an executable project at 2009 and achieve the desired target to 2015.

3.1.3. Magnetic moment of neutrino

At the GEMMA spectrometer (situated at the Kalinin Nuclear Power Plant), experiments on measurement of neutrino magnetic moment are performed. Now the best limit on the neutrino magnetic moment $\mu_\nu \leq 5.8\times10^{-11}$ μ_B has been obtained at the GEMMA spectrometer. With the unique parameters of this setup, the sensitivity is expected to be at the level of $3.5\bullet10^{-11}$ μ_B after data taking up to 2009 year. 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 increased neutrino flux from reactor. It is planned to achieve with GEMMA-2 the sensitivity on the neutrino magnetic moment at the level of $(9\text{ -}7)\bullet10^{-12}$ μ_B after operation from 2010 to 2012 years.

3.2 Experiments with pions, muons and spin physics at storage rings

Investigation of the properties and interactions of nuclei and particles at intermediate energies, aimed at obtaining new data on fundamental symmetries, processes of strong, weak and electromagnetic interactions of elementary particles, the lightest nuclei and properties of matter. Within the framework of the present topic, investigation is planned of a series of pion and muon decay processes, of spin characteristics of reactions involving the production of light mesons in proton-proton and proton-deuteron interactions, as well as investigation of NN-interaction dynamics at small distances between the nucleons, preparation of the PAX experiment at GSI for measurement of the transverse component of the quark distribution in a transversely polarized proton, and studies of slow pion interactions with the lightest nuclei, searches of meson decays, forbidden by the Standard Model, searches for the forbidden reaction of radiative deuteron capture from the state of a muonic deuterium molecule, and, also, the interaction of muons with matter.

Work on topic 1040 is carried out within the framework of a broad international collaboration at accelerators of JINR, PINP (Gatchina), PSI (Switzerland), and COSY (Germany).

3.2.1 Precision studies of rare muon and pion decays (PEN-MEG)

Precision studies of rare muon and pion decays allow one to test the Standard Model (SM) of electroweak interaction, μ-e universality and V-A version of electroweak interaction.

It is proposed to search for the decay $\mu^+ \to e^+\gamma$, which violates the leptonic number conservation law (MEG project). It should be mentioned that in the SM leptonic number conservation is artificially introduced on the assumption of the neutrino mass. Introduction of neutrino masses and mixing leads to immeasurably small violation of this conservation law. On the other hand, such fundamental theories as supersymmetry, predict a measurable lepton-flavour-violating decay $\mu^+ \to e^+\gamma$. Therefore, the proposed experiment with the accuracy of 10^{-14} relativ to the main decay mode (now it is $1.2*10^{-12}$), provides a good chance to make a discovery which will bring evidence for existence of new physics beyond the Standard Model. A failure to detect the $\mu^+ \to e^+\gamma$ decay at the given accuracy level will impose strong limitations on the fundamental theories and thus will greatly affect future investigations in particle physics. In addition, studies of μ→e conversion are proposed at FNAL and J-PARC.

Since one of the most important research directions in modern elementary particle physics is the search for SM applicability limits, the goal of the PEN project is to increase the measurement accuracy for the branching ratio of the leptonic pion decay $\pi \to e\,\nu$ ($R_{e/\mu}^{exp}$) by approximately an order of magnitude. Now the accuracy of the experimental measurements of this probability is

$$R_{e/\mu}^{exp} = [\Gamma(\pi^+ \to e^+\nu) / \Gamma(\pi^+ \to \mu^+\nu)]_{exp} = (1{,}230 \pm 0{,}004) \times 10^{-4},$$

which is about an order of magnitude lower, than the accuracy of SM calculations.

Therefore a stringent experimental test of electron-muon universality will remain relevant regardless of the path that future theoretical and experimental developments may take.

In 2007 the first data taking run for measurement of the $\pi^+ \to e^+\nu$ branching ratio was carried out at the PIBETA detector (PSI). Also in 2007 a test run of new $\mu^+ \to e^+\gamma$ detector was accomplished.

3.2.2 Study of properties of muons and their behavior in matter (MUON)

The project is aimed at studying the main characteristics of the (μ^- +Z) and (μ^+,e^-) systems and their interaction with a medium. In particular, it is planned to study relativistic corrections to the magnetic moment of the negative muon bound in the atom. The relativistic correction to the magnetic moment of the electron (Dirac particle) at the 1s level in the atom was predicted by Breit. By now the magnetic moment of the electron has been measured to a high accuracy at the 1s level in a few light atoms. The relativistic correction for the negative muon is considerably larger than for the electron. There are additional radiative corrections and the correction caused by the fact that the Bohr radius of the muon in the atom is 207 times smaller than that of the electron and in heavy atoms the muon spends some time inside the nucleus. Apart from checking of theoretical calculations, to know the accurate value of the magnetic moment of the negative muon bound in the atom is important for correct analysis of the results of such precision experiments as, for example, measurement of the Lamb shift in the muon atom. It is planned to measure the magnetic moment of the negative muon at the 1s level in medium and heavy atoms by the μSR method.

Earlier pioneering studies at the DLNP accelerator were crucially important for the μSR method to become established as a unique technique for investigation of matter with unstable elementary particles, muons, used as a tool. The priority of Russia and the contribution of JINR in this field are acknowledged in the world.

Within this project it is planned to use the μSR method for studying the electron structure of shallow acceptor impurities in diamond-like semiconductors (silicon, germanium, diamond), properties of heavy-fermion systems and magnetic properties of ferroliquid based on monodomain (superparamagnetic) nanoparticles about 10–15 nm in size. The use of traditional methods for investigation of acceptor centers in the above semiconductors is limited by the high spin-lattice relaxation rate of magnetic moments of these centers. Recent considerable advances in technology for production of synthetic diamonds, their high thermal conductivity and radiation hardness have considerably increased interest in development of diamond-based detectors and electronic elements. Practical application of diamonds in the above fields requires thorough studies of the electron structure of boron impurity in the diamond because boron is the only impurity that forms an acceptor centre in the diamond and extensively affects conductivity of the sample.

The systems of ultrafine particles and clusters are interesting from a fundamental point of view for study the effect of finite size on the material properties. The magnetic nanoparticles are also of technological importance due to their practical applications in high-density information storage, ferroliquid technology, magnetocaloric refrigeration, magnetically guided drug delivery, magnetic imaging contrast enhancement agents, etc. We have started the experiments on the ferroliquid with the nanoparticles on the DLNP Phasotron in collaboration with scientists from the Member States.

Measurements are carried out at the accelerators of JINR DLNP, PINP (Gatchina), and PSI(Switzerland).

Now the upgrade of the μSR facility MUSPIN installed on the muon beam line of the DLNP Phasotron is under way.

3.2.3. Study of interaction of pions with light nuclei (DUBTO)

DUBTO is the joint JINR-INFN (Italy) experiment aimed at studying pion-nucleus interactions at energies below 100 MeV using a self-shunted streamer chamber filled with helium at atmospheric pressure. The physics results are based on measurement of the momenta of all (including slow) charged secondaries resulting from pion-nucleus reactions and complete reconstruction of the kinematics of each secondary. Branching ratios of various reaction channels, including (for the first time) the gamma-production channel, are determined. Direct Δ^--resonance production has been observed for the first time at a pion energy around 100 MeV. Future plans include measurement and analysis of all the available pion-helium interaction statistics (about 25 000 events), further systematic studies of various reaction channels to reveal effects associated with the structure of nuclear matter in the highest-density helium nucleus (possible manifestation of quark bag states) and final-state interaction. It is also planned to determine directly the upper limit for the muon neutrino mass by analyzing individual in-flight pion decays (the only such measurement was performed by the DUBTO experiment using a neon-filled streamer chamber at CERN).

3.2.4. Nuclear fusion reactions in muonic deuterium and tritium (Mu-CATALYSIS)

Studying nuclear Muon Catalyzed Fusion (MCF) reaction in hydrogen isotope media makes one deal with nuclear, atomic and molecular physics simultaneously by means of theoretical, experimental and technical methods. Since 1996 and up to now DLNP takes leading part in the international collaboration “Mu-CATALYSIS”: DLNP – INP (Poland) – ITEP (Moscow) – TUDelft (Netherlands) – VNIIEF (Sarov). During past years a vast variety of muon catalyzed fusion processes (H, D, T) have been studied in Dubna using installation TRITON. MCF gives unique opportunity in revealing mechanism of light nuclei fusing (because of a determined quantum state in the input channel of nuclear reaction). Therefore MCF allows checking the results of a beam-target experiment (for $1<A<7$) especially in the low energy limit. The last result of the collaboration (2008 year) is the mechanism of tritium fusion coming through intermediate ^5He nucleus formation.

In the years 2008-2009 by means of muon catalysis DLNP addresses phenomena in dd fusion, which have not been previously investigated and are at the frontier of nuclear few-body physics and astrophysics. For this purpose DLNP performs an experiment to study the MCF radiative deuteron capture from muonic deuterium molecules:

$dd\mu \rightarrow {}^4He\mu + \gamma$ +23.8MeV.

Using advances of MCF method will clear specific questions arisen in beam-target TUNL (USA) experiment toward the determination of astrophysical S-factor.

The obvious neutron/proton asymmetry of the p-wave branches of mirror reactions $d(d,n)^3He$ and $d(d,p)^3H$ was found in experiments with polarized deuteron beams and directly measured by means of MCF. These effects were accounted for by the internal Coulomb mixing of the 1^- highly excited states of ^4He with isospin I=0. Finding electromagnetic transitions in the reaction that are forbidden by the isotopic spin selection rule will stimulate further theoretical searches for possible transition mechanisms, such as mesonic exchange current effects in matrix elements. These problems are on the agenda of modern few-body physics. Evermore elaborate theoretical methods (multi-channel resonating group method (MCRGM) and variational Monte Carlo method (VMCM)) are applied to describe the available cross section and polarization data in dd reactions and explain the nature of the reaction.

DLNP will measure the relative yield of this rare reaction from the p-wave state of deuterons in a muonic deuterium molecule with sensitivity of 10^{-7} with respect to main fusion channels. The achievement of this level of accuracy is only possible using the collaborative effort of the parties: electronics of the experiment and low-noise gamma-detector of special design (DLNP), high pressure deuterium target (VNIIEF), GEANT-4 Monte Carlo support (TUDelft).

In the years 2010-2017 DLNP will prolong the study of the radiative capture rate in muon-catalyzed dd fusion at improved level of accuracy, using PSI muon facility.

Another task for the period is to ascertain the exotic MCF mechanisms in deuterium $d(d,n)^3He$, revealing at very low temperatures. This task consists in the measurements of MCF parameters in solid, liquid and gaseous normal and ortho-deuterium (T=6-35 K) and determination of the role of different mechanisms influencing on ddμ molecule formation.

Upon severe financial support (300k$ - for target production) DLNP will be able to determine parameters of MCF reaction:

$t\mu + d \rightarrow dt\mu \rightarrow {}^4He + n + \mu + 17.6$ MeV

at high temperatures (900-1600 K), where theory predicts the high intensity of the process and experimental data are absent. Investigation of MCF d+t reaction is of special interest, because it has high intensity and manifests much richer physical phenomena of chain of MCF in D/T and H/D/T mixture.

3.2.5. **Spin physics at storage rings (SPRING)**

3.2.5.1 Spin structure of nucleons

Study of the quark spin structure of nucleons is one of the main topics of the contemporary physics of elementary particles. There are three fundamental quantities necessary to achieve a full understanding of the nucleon quark structure: the unpolarized quark structure, the helicity distribution and the transversity distribution. One cannot claim to understand the spin structure of the nucleon until all three structure functions have been measured. Whereas the unpolarized distributions are well known, and more and more information is becoming available on the helicity distribution, nothing is experimentally known on the nucleon transversity distribution. Such measurements are possible in the polarized Drell-Yan process , where one obtains the product of two transversity distributions via measurement of the double spin asymmetry. The planned experiments at RHIC with double polarized proton-proton collisions cannot solve the problem since the expected asymmetry is very low and kinematics of the experiments allows to explore only the sea quark proton content. Essencially other way, much more promising, consists in study of transversity in collisions of polarized antiprotons with polarized protons. Just such kind of experiments is proposed in the project PAX. It should be realized at the accelerator complex FAIR (Darmstadt). The study requires development of an intensive polarized antiproton beam which has not been realized anywhere until now. At the first stage of the PAX experiments the suggested spin filtering method has to be studied at the hadron storage rings COSY in Juelich (with protons and deuterons) and AD at CERN (with antiprotons). A special facility is being built at present on the basis of multichannel silicon detectors for detection of scattered low-energy protons and antiprotons. Development of the needed experimental methods and preparing of the experienced scientific personal for the PAX project proceed essentially in the course of the ANKE-COSY collaboration experiments involving polarized beams and targets.

3.2.5.2 Nucleon-nucleon interaction at short distances.

Short-range nucleon-nucleon interaction is a fundamental problem of the hadron physics. Interplace between meson-baryon and quark-gluon description of nucleon-nucleon interaction stays to be an important way for development of the non-perturbative QCD. A creative break in such development requires accumulation of detailed experimental data on the NN interactions at intermediate energies and high momentum transfers. In this respect, very important is study of such relatively simple, “elementary” processes of nucleon-nucleon interactions as a single meson production, hard bremsstrahlung , few-nucleon reactions in cumulative kinematics. Few-particle final states and possibility of measurement of polarization observables in such processes make them an effective tool for the thorough study of the short-range process dynamics. For this aim the project SPRING uses the excellent conditions, unique at present, provided by the setup ANKE at the proton synchrotron COSY. The program includes, in particular, polarization study of several processes launched last years : $p + p \rightarrow \{pp\}_s + \pi^0$, $p + p \rightarrow \{pp\}_s + \gamma$, $p + d \rightarrow \{pp\}_s + n$, where $\{pp\}_s$ is a proton pair in the $^1S_0$ state (diproton), produced at small angles to the beam. The measurements will be done both in single- and double-polarized approaches, i.e. with use of polarized beams and/or gas polarized target. Investigation of the diproton channel in such processes is completely new, earlier unexplored, way of study. It is worth to stress also that this study of the mesonless deuteron breakup is a continuation, at the new, contemporary level, of the cumulative process phenomenon, first observed and extensively explored in Dubna.

3.3 Light Nuclei Cross Sections

The main purpose of the LESI project is cross section and astrophysical S-factor measurements for pd, dd, d^3He and $d^{6,7}Li$ reactions in the ultralow energy(~ keV) region using Hall ion accelerator and colliding plasma fluxes. This information will be obtained for the first time and needed for solving a number of problems in the astrophysics(testing the models of stars dynamics and evolution) and nuclear physics. In the period 2008 – 2014 it is planned to carry out the precision study of the energy dependence of the astrophysical S-factors and cross sections for indicated above reactions in the collision energy range 2-15 keV with using Hall accelerator and the method of opposite colliding plasma flows.