NUCLEAR PHYSICS

I. LOW-ENERGY HEAVY-ION PHYSICS

In the last few decades, heavy-ion physics has become 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.

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 2009–2017 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 of 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 development of new target systems, improvement of the intensity and quality of ion beams are planned.

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 these nuclei and in deciding on the optimal 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 2009–2017 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, and 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 specially designed neutron counter installed at the VASSILISSA set-up.

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 $^{48}Ca + ^{207,208}Pb \rightarrow ^{255,256}No^*$ and $^{48}Ca + ^{209}Bi \rightarrow ^{257}Lr^*$ 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.

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 for investigations 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 $3 \cdot 10^{-4}$ was achieved for Kr, Xe and Hg isotopes. The MASHA set-up surpasses all known facilities in efficiency of the production of superheavy atoms and in extracting information on their masses and decay characteristics.

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.

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 predicting "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 2009–2017 within the DRIBs project. 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 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.

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.

6. Theoretical study of mechanisms of heavy ion induced reactions

The 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.

7. Radiochemical investigations

a. 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 2009–2017 are the on-line chemical isolation and identification of heavy isotopes and detection of α-decay and spontaneous fission fragments in coincidence with neutrons.

b. 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 the following 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.

8. Accelerator physics and development of basic and new facilities

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 its 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 quality of the 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.

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 the electrical power of the U400R main coil power supply to be decreased 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 a 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 further 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 at the world level during the next 20 years.

II. NUCLEAR PHYSICS WITH NEUTRONS

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 ultracold 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. Investigation of neutron properties

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. Experiments to measure neutron lifetime have been carried out at FLNP in common with PNPI since late 1980s. 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 new UCN sources (at present, averaged value over the data of seven most precise experiments equals to (885.7±0.8) s.

2. Direct measurement of neutron-neutron scattering length

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 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 construction of an experimental facility and first direct observation of the neutron-neutron scattering. Within the framework of this project it is planned to obtain the value of scattering amplitude at the level of 5%.

3. Investigations of fundamental symmetry breaking in reactions with neutrons

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 $\vec{s}\left(\vec{k}\times\vec{I}\right)$ and $\vec{s}\left(\vec{k}\times\vec{I}\right)\left(\vec{k}\vec{I}\right)$, the so-called triple and quinary correlations. Performing 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 jointly 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 J-PARC.

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. In particular, cross sections of neutron capture reactions are essential at formation of isotopes in stars. Measurements of these cross sections will be carried out at the first stage of the IREN facility.

The calculations show that for a number of available isotopes the intensity and energy resolution will be sufficient 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.

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.

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 fact 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 about ten gamma-quanta. 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.