**Extended annotation**

**of the proposal for the opening of the project “Investigations of Neutron Nuclear Interactions and Properties of the Neutron”**

The scientific program of the project "**Investigations of Neutron Nuclear Interactions and Properties of the Neutron**" will be implemented within the framework of four **subprojects**:

1. **Subproject "Nuclear Reactions with Neutrons".**

The main tasks that are planned to be solved within the framework of this subproject:

1.1. Study of the properties of neutron resonances, search and study of the effects of parity violation and effects indicating the violation of T-invariance.

Experiments are planned to measure the angular correlations of gamma-ray emission both for already known p-wave and s-wave resonances and aimed at searching for new resonances in various isotopes with the following list of aims:

- measurement of the characteristics of p-wave resonances, including for the purpose of subsequent verification of the compliance of the distributions of these characteristics with standard statistical models;

- study of interference effects of both p- and s-wave resonances and s-wave resonances with each other;

- study of the characteristics of "negative" s-wave resonances, which manifest themselves in interference with p-wave resonances close to the thermal point;

- search for T-non-invariant effects.

For resonances in actinide nuclei, the measured quantities can also include those observed in the fission channel. Work is planned at the IREN resonance neutron source.

1.2. Investigation of TRI and ROT effects in fission

Experiments to study the TRI and ROT effects in fission can be started at the beam of polarized neutrons of the IBR-2 reactor. The ROT effect is explained by the collective rotation of the compound nucleus up to the breaking point. The TRI effect reflects the influence of a rotating nucleus on the probability of emission of ternary particles. It was shown that both effects are present in parallel with different weights for all actinides studied. At present, the greatest interest is in measuring these effects in resonances, where the influence of (J,K) quantum numbers on transition states at the saddle point is most pronounced. Despite the long duration of the IBR-2 reactor pulses, the resolution of the time-of-flight technique makes it possible to resolve low-lying resonances up to several electronvolts at flight paths of the order of 15–30 m. Further work can be continued on external neutron sources such as nTOF (CERN) CSNS (China) or ESS (Sweden).

1.3. Investigation of reactions induced by neutrons with emission of charged particles.

Work will continue on measuring the cross sections for the reactions (n,p), (n,α) on various isotopes. Experiments can be set up at IREN (En = thermal-100 keV); electrostatic accelerators EG-5 FLNP, EG-4.5 PKU, Beijing (En=3-6 MeV); HI-13 tandem accelerator CIAE, Beijing (En=8-11 MeV) and CSNS in China.

One of the priorities is the task of elucidating the nature of the anomaly of neutron resonances in the reaction 147Sm(n,α)144Nd. Such work is planned on a high-aperture time-of-flight neutron source CSNS (China spallation neutron source). Preliminary tests of the equipment can be performed on the neutron beams of the IREN facility at the FLNP JINR.

It is also planned to conduct a cycle of measurements of P-even forward-backward correlations and anisotropy of angular distributions in the reactions 14N(n,p)14C and 35Cl(n,p)35S in a wide range of neutron energies, including low-lying p-wave resonances, and analyze the data jointly with previously defined P-odd and P-even left-right correlations.

**2. Subproject ENGRIN**

The objective of the subproject "Emission of Neutrons and Gamma-quanta in Reactions Induced by Neutrons" (ENGRIN) is to study correlations between variations in neutron multiplicity and mass-energy distributions in fission induced by resonance neutrons.

Experiments within the framework of the subproject are planned on the 2nd channel of the IREN facility. The experimental setup was created as part of the ENGRIN project in 2021-23 and consists of 32 neutron detector modules with a BC501 liquid scintillator located around the fission ionization chamber. It is convenient to divide the studies of correlations of total kinetic energy variations with neutrons into two experiments: in the first experiment, neutron variations are measured with a “thick” target, and the correlations of mass-energy distributions and neutron/gamma multiplicity are measured with a thin target and a position-sensitive ionization chamber.

**3. Subproject "Physics of UCN and VCN"**

Within the framework of the study of the physics of ultracold and very cold neutrons (UCN and VCN), three main areas can be distinguished:

3.1 Neutron optics.

It is planned to continue work on the study of non-stationary diffraction by surface acoustic waves (SAW). The measurements will be carried out for a wide range of samples in which both moving and standing surface waves are excited. It is assumed that the wave frequencies can reach values of the order of Gigahertz. The energy transferred to neutrons will reach a value of the order of 4 μeV. The transfer of such a large energy to neutrons as a result of non-stationary action has not been observed before.

Also works are planned aimed at the development of neutron spin interferometry (NSI) with ultracold neutrons (UCN). The physical basis of the phenomenon is closely related to the quantum picture of spin precession in the presence of both a constant magnetic field and a perturbing potential with which the neutron interacts. To measure the interaction time of a neutron with quantum objects, it is planned to use the Larmor clock method. This method was proposed as a theoretical technique for calculating the neutron scattering time, and much later the possibility of its practical application was demonstrated in experiments with cold neutrons.

3.2 Study of the interaction of low-energy neutrons with diamond nanoparticles.

One of the innovative solutions aimed at creating neutron reflectors in the energy range from ~0.3 μeV to ~5.0 meV is the development of detonation nanodiamonds (DND) based on powders. Scientific tasks that still need to be solved in this area of research within the project:

• Determination of optimal technologies for the synthesis and modification of DND powders to create nanomaterials with known properties.

• Determination of the optimal density of DND powders to achieve the maximum albedo of VCN and CN.

• Development of models for calculating the transport of VCN and CN in the material of nanodiamond reflectors.

• Extension of the range of applicability of the developed models to the range of thermal neutrons.

• Study of the resistance of DND reflectors to external influences.

• Study of the radiation resistance of nanodiamond powders when irradiated with high doses of gamma rays and fast neutrons.

3.3 Study of the interaction of cold neutrons with intercalated graphite.

Not so long ago, a technology appeared for introducing a whole plane (or two planes) of fluorine atoms between graphite planes. In this way, intercalated graphite is obtained, which can effectively scatter cold neutrons. Such a material seems to be promising as a cold neutron reflector, which can be used in strong fields of ionizing radiation. The study of such material is one of the potential areas of activity.

**4. Subproject "Applied Research"**

As part of analytical studies at the REGATA facility of the IBR-2 reactor, it is planned to continue monitoring air quality and the state of water objects bodies in the JINR Member States using a number of analytical methods, in particular, neutron activation analysis. The direction of nanotoxicology will also be developed, where microorganisms, plants and animals will be used as objects of research. Particular attention will be paid to the development of methods for cleaning water and soil, as well as assessing the quality of food.

To conduct a mass multi-element neutron activation analysis to study monumental painting, building materials of the past, archaeological artifacts, ecological, geological and other samples, the capabilities of the IREN facility and the IBR-2 reactor will be used, in particular, using the REGATA-2 pneumatic transport system at the IREN facility, installations on the 3rd channel of the IBR-2 reactor, as well as directly on the surface of the moderator of the IREN facility. In addition, channel 11b of the IBR-2 reactor will be used for fully non-destructive activation analysis on prompt gamma quanta, and for non-destructive analysis using the method of neutron resonances, the source of resonance neutrons IREN will be used.

The EG-5 electrostatic accelerator available at FLNP JINR after modernization will be used to solve the following tasks:

1) Obtaining intense (about 109 n/sec) fluxes of fast neutrons using the reactions d(d,n)3He, d(t,n)4He, 7Li(p,n)7Be

2) Perform elemental analysis of surface layers of various objects using α-particle beams using non-destructive RBS, ERD and PIXE techniques.

3) Carrying out the implantation of ions into the surface layers of various materials

**Expected scientific results:**

● Refinement of characteristics of known resonances, detection of previously unknown ones. Measurement of reaction cross sections and product correlations in the resonance region with an accuracy sufficient to study P- and T-odd effects.

● Perform experiments to study TRI and ROT effects in fission, measure mass-energy and angular distributions of fission fragments, prompt neutrons and gamma quanta; search for rare and exotic fission modes, both using IBR-2 and third-party sources.

● Conducting experimental and theoretical studies of neutron-nuclear reactions in a wide range of projectile particle energies.

● Study of the pattern of non-stationary neutron diffraction on surface acoustic waves. Verification of the validity of generally accepted laws of neutron optics in the case of large accelerations.

● Development of models for calculating the transport of VCN and CN in the material of nanodiamond reflectors and expanding their range of applicability to the range of thermal neutrons.

● Study of the structure of graphites after their intercalation and measurement of cold neutron scattering cross sections by intercalated graphites.

● Acquisition of data for nuclear power engineering and astrophysics: measurement of integral and differential neutron cross sections, angular correlations in the energy range from cold neutrons to hundreds of MeV.

● Study of the radiation resistance of various materials, including those promising for use as neutron reflectors and moderators. Study of the radiation resistance of electronic components, including those operating on new physical principles.

● Obtaining new data and monitoring the environmental situation in certain regions of the JINR Member States with the help of NAA.

● Study of the effect of neutron irradiation on the properties of living objects

● Investigation of layered structures, including high-temperature superconductors using RBS, ERD and PIXE techniques.

● Perform elemental analysis of various cultural heritage sites.

**Expected methodical results:**

● Development of the method of neutron spin interferometry with UCN.

● Determination of optimal technologies for the synthesis and modification of substances for use as UCN and CN reflectors.

● Development of methods for water and soil purification, assessment of food quality.

● Study of the processes of accumulation of nanoparticles in the organs of animals and plants, assessment of their impact on the health of the studied living objects.

● Development of a technique for non-destructive elemental analysis based on prompt gamma quanta. Improvement of existing methods of activation analysis on thermal and resonance neutrons.

● Implementation of work on the creation of electronics and ionizing radiation sensors based on new physical principles.

**Brief SWOT Analysis**

The implementation of the project is supposed to be carried out by the staff of the DNP FLNP, which has extensive experience in studying neutron-nuclear reactions and conducting applied research. It includes both a large number of young (up to 35 years old, 44 people) and more experienced (77 people) employees. Many have Ph.D. and Doctor of Science degrees. The team has at its disposal a significant number of detectors of various types, which make it possible to register practically any products of neutron-nuclear interactions. Some equipment (detector assemblies, ionization chambers, targets for accelerators, digitizers, automation devices) can be created by the team. This is undoubtedly the strength of the project.

During the research program, it is planned to use a large number of scientific infrastructure facilities, both FLNP JINR (IBR-2, IREN, EG-5, TANGRA), and third-party organizations: n\_TOF (CERN), EG-4.5 (Peking University, China), HI-13 tandem accelerator (CIAE, China), which may lead to risks of reducing the scientific program due to changes in the international situation, which can be attributed to the moderately weak side of the project. At the same time, a significant part of the experiments can be carried out on the facilities available at JINR.

The facilities available at FLNP are in need of ongoing repairs, modernization and certification, which may be a factor hindering the implementation of the project. However, to date, there are no significant problems in acquiring critical components for repairs and certification of scientific infrastructure, so in case of complications, one can only expect research to slow down.

*Estimated project completion time: 2024 - 2028.*

*Estimated cost of the project is 4635 k$.*