**Extended annotation**

**of the proposal for the opening of the theme "Nuclear physics with neutrons"**

Nuclear physics research with neutrons is traditionally one of the priority fields developed at JINR. The integrated use of the basic FLNP facilities - the IREN pulsed source of resonance neutrons, the IBR-2 pulsed reactor and the EG-5 electrostatic generator, as well as the TANGRA facility - makes it possible to conduct experiments in a wide range of neutron energies - from cold to ~20 MeV, and the use of external neutron sources, such as n\_TOF (CERN), allows one to expand the energy range to several hundreds of MeV.

Works and studies within the framework of the theme are aimed at the implementation of the tasks formulated in the proposals for the JINR Seven-Year Development Plan 2024-2030 in the direction of "Nuclear Physics". Physics research can be divided into three areas:

* Study of violations of fundamental symmetries in the interactions of neutrons with nuclei, obtaining nuclear data.
* Study of the fundamental properties of the neutron, physics of ultracold and very cold neutrons.
* Applied and methodical research.

The scientific program of the theme "Nuclear Physics with Neutrons" will be implemented within the framework of three projects: two scientific ones ("Investigations of Neutron Nuclear Interactions and Properties of the Neutron" and "TANGRA") and one scientific and technical one ("Modernization of the EG-5 accelerator and its experimental infrastructure"). Work on the development of the concept of a UCN source at pulsed reactors is planned to be singled out as a separate *activity*.

**1. Project "Investigations of Neutron Nuclear Interactions and Properties of the Neutron"**

Within the framework of this project, the following main tasks will be solved:

* Study of the properties of neutron resonances, search and study of the effects of parity violation and effects indicating the violation of T-invariance.
* Comprehensive study of nuclear fission process: study of TRI and ROT effects in fission; measurement of mass-energy and angular distributions of fragments, prompt neutrons and gamma rays; measurements of delayed neutrons and gamma rays; search for rare and exotic fission modes (quaternary and quinary fission; fission into three fragments of comparable mass).
* Investigation of reactions induced by neutrons with emission of charged particles.
* Obtaining 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.

It is planned to resume measurements of angular correlations and gamma-ray yields for already known p-wave resonances in various nuclei, as well as to search for new p-resonances and new effects indicating parity and T-invariance violation. The main work is supposed to be carried out at the IREN resonance neutron source.

Experiments to measure the formally T-odd TRI and ROT effects in fission, carried out at the high-flux reactors ILL (Grenoble) and FRM-II (Garching), will be continued at JINR using the beam of polarized neutrons at the IBR-2 reactor. Despite the relatively long pulse of the IBR-2 reactor, 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).

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=th-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. 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 obtained P-odd and P-even left-right correlations.

Within the framework of the theme, it is planned to study the correlations between variations in the prompt fission neutron multiplicity and mass energy distributions in fission induced by resonance neutrons. The experiments are planned to be carried out on channel No. 2 of IREN using the ENGRIN facility, created in 2021-23.

Within the framework of the study of the physics of ultracold and very cold neutrons (UCN and VCN), three main directions can be outlined: study of quantum phenomena in neutron optics; study of the interaction of slow neutrons with diamond nanoparticles, and study of the interaction of cold neutrons with intercalated graphite.

It is planned to continue work on the investigation of non-stationary diffraction by surface acoustic waves (SAW). The measurements will be carried out for a wide range of samples in which both traveling and standing surface waves are excited. Also planned are works aimed at the development of neutron spin interferometry (NSI) with ultracold neutrons (UCN). To measure the interaction time of a neutron with quantum objects, it is planned to use the Larmor clock method.

It is planned to study the properties of detonation nanodiamond (DND) powders, which can be used as effective reflectors of very cold neutrons (VCN). The use of such reflectors is most efficient for neutrons in the energy range from ~0.3 μeV to ~5.0 meV. In particular, the most important task is to study the radiation resistance of nanodiamond powders when they are irradiated with high doses of gamma rays and fast neutrons.

Not so long ago, a technology appeared for introducing a whole plane (or two planes) of fluorine atoms between graphite planes, resulting in the so-called intercalated graphite, 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 intercalated graphite is one of the potential activities of the topic.

As part of applied research, it is planned to continue monitoring the air quality and the state of water bodies in the JINR Member States using a number of analytical methods, in particular, neutron activation analysis at the REGATA facility of the IBR-2 reactor. 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. The use of nuclear and complementary methods will continue to study monumental painting, building materials of the past, archaeological artifacts, environmental, geological and other samples.

In addition, channel 11b of the IBR-2 reactor will be used for fully non-destructive prompt gamma activation analysis, and for non-destructive analysis using the method of neutron resonances, the source of resonance neutrons IREN will be used. Also, X-ray fluorescence analysis will be used to determine the elemental composition. It is planned to use complementary methods of infrared and Raman spectroscopy, optical and polarization microscopy, chemical microanalysis, and other methods and approaches.

The electrostatic accelerator EG-5 available at FLNP JINR will be used after modernization to obtain intense fluxes of fast neutrons; elemental analysis of surface layers of various objects using α-particle beams using non-destructive RBS, ERD and PIXE techniques; carrying out implantation of ions into the surface layers of various materials

**2. Project "TANGRA".**

The project is dedicated to solving fundamental and applied problems using the tagged neutron method (TNM). The area of interest of the project is nuclear reactions that occur after interaction of neutrons with an energy of about 14 MeV with nuclei. The main tasks to be solved within the framework of the project:

* Performing experiments to study the angular distributions of scattered neutrons.
* Experimental study of (n,γ) and (n',γ)-correlations.
* Theoretical description of the investigated reactions.
* Carrying out experiments to study the reaction (n,2n).
* Development of methods for soil elemental analysis, in particular, determination of carbon concentration in soil. Creation of prototypes of stationary and mobile devices, as well as methodical recommendations for their use for agricultural and environmental monitoring purposes.

**3. Project “Modernization of the EG-5 accelerator and its experimental infrastructure”.**

As a result of the project, the parameters of the accelerator will be significantly improved, the infrastructure of the accelerator complex will be updated, and the development of installations for non-destructive elemental and structural analysis of various objects will continue.

The main technical task of the project is to restore the energy range of accelerated particles: 900 keV - 4.1 MeV and increase the ion beam current to 100-250 μA while maintaining the energy stability of the ion beam at a level no worse than 15 eV, ensuring the spatial stability of the ion beam, sufficient for the implementation microbeam spectrometer / nuclear microprobe options. The objectives of the project also include the improvement of the main systems of the electrostatic charged particle accelerator EG-5, the creation of a neutron source on its basis, which makes it possible to study neutron-nuclear reactions and carry out the study of various objects using nuclear physics methods. Also, within its framework, it is planned to develop complementary experimental methods for studying the elemental composition and physical properties of near-surface layers of solids.

The unique property of a single-stage accelerator is the high energy stability (over 0.01%) of the ion beam, which makes it possible to carry out studies of the elemental composition of the surface layers of materials with very high accuracy and ble to create a unique microbeam method based on EG-5 spectrometer with a beam diameter of less than 1 µm. Such beams cannot be obtained, for example, at the currently popular charge-exchange accelerators—tandetrons. Within the framework of the proposed project, it is planned to carry out, with the support of the Budker INP (Novosibirsk), work to replace the obsolete and out-of-service high-voltage system (HF ion source and accelerating tube), upgrade and automate the service systems of the accelerator, launch the neutron generator, modernize a complex of ion-beam spectrometers and develop a complementary methodical base.

**Activity: "Development of the concept of a UCN source at a pulsed reactor"**

The purpose of this activity is to create a conceptual design for an ultracold neutron (UCN) source on a pulsed reactor. This can be the IBR-2M reactor available at FLNP, as well as the projected NEPTUNE reactor.

A specific feature of the future UCN source at JINR is the pulsed filling of the trap, when neutrons enter it only during the pulse, while the rest of the time the trap remains closed. The practical implementation of this idea is hampered by the fact that, due to the presence of biological shielding, the trap turns out to be remote from the moderator, while the spread of transport transit times can significantly exceed the intervals between pulses, making the very idea of accumulation meaningless. To solve this problem, it is proposed to use a special device, a time lens, which changes the energy of neutrons as they arrive at this lens in such a way that the pulse structure of the neutron beam is restored at the entrance of the trap.

The result of the activity will be the formulation of the concept of an intense UCN source at JINR pulsed reactors. The main goal of the work is to create at JINR a UCN source with parameters corresponding to the modern world level.

**Brief SWOT Analysis**

The work on the topic 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 consists of both a large number of young and more experienced 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 designed and constructed 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 accelerators -13 (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.

*The term for the implementation of the theme will be determined by the terms of implementation of the projects.*

*The total estimated cost of the theme is 5925 k$.*