**SCIENTIFIC AND TECHNICAL REASONING FOR THE OPENING / RENEWAL OF PROJECT/SUB-PROJECT OF A LARGE RESEARCH INFRASTRUCTURE PROJECT IN THE RESEARCH AREA WITHIN THE TOPICAL PLAN FOR JINR RESEARCH**

**1. General information on the project/subproject of the large research infrastructure project (hereinafter LRIP)**

**1.1 Theme code / LRIP** (for renewable themes) - *the theme code includes the opening date, the closing date is not given, as it is determined by the completion dates of the projects in the topic.*

“Nuclear physics with neutrons”

**1.2 Project/sub-project of a MIP code** (for renewed themes)

**1.3 Laboratory**

FLNP

**1.4 Scientific field**

Nuclear physics

**1.5 The name of the Project/subproject of the LRIP**

Investigations of Neutron Nuclear Interactions and Properties of the Neutron

**1.6 Project/ sub-project of the LRIP Leader(s)**

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**1.7 Project/sub-project of the LRIP Deputy Leader(s) (scientific supervisor of the project/subproject of the LRIP)**

**2 Scientific rationale and organizational structure**

**2.1 Annotation**

Nuclear processes induced by slow, resonant, and fast neutrons are traditionally studied at FLNP JINR. The interaction of neutrons with atomic nuclei is of interest to both fundamental and applied research.

The integrated use of the FLNP basic facilities - the IREN pulsed source of resonant neutrons, the IBR-2 pulsed reactor, and the EG-5 electrostatic generator - makes it possible to carry out a wide range of nuclear physics studies in a wide range of neutron energies - from cold neutrons to ~14 MeV, and the use of external sources neutrons, such as n\_TOF (CERN), allows you to expand the energy range to several hundred MeV. Fundamental research carried out at the Department of Nuclear Physics of the FLNP includes the violation of spatial and temporal symmetry, the study of the mechanism of nuclear reactions, the structure of atomic nuclei, fission processes induced by neutrons, neutron-induced reactions with the emission of light particles, the properties of the neutron as an elementary particle, the properties of ultracold and very cold neutrons, quantum mechanical effects involving neutrons.

FLNP has also developed research programs for applied research, such as obtaining nuclear data for nuclear technologies, energy, ~~and~~ transmutation, neutron activation analysis on thermal and epithermal neutrons, neutron activation analysis on prompt gamma quanta, elemental analysis using neutron resonances, elemental analysis on fast neutrons, analysis of thin films on beams of an electrostatic accelerator.

**2.2 Scientific justification** (purpose, relevance and scientific novelty, methods, approaches, methodologies, expected results, risks)

The scientific program of the project "Investigation of the neutron nuclear interactions and neutron properties" will be implemented within the framework of four subprojects:

1. Nuclear reactions with neutrons

2. ENGRIN

3. Physics of UCN and VCN

4. Applied research

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

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

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

● Comprehensive study of nuclear fission process: the investigation 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 (quadruple and quintuple fission; fission into three fragments of comparable mass).

● Study of neutron-induced reactions with the emission of charged particles.

● 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.

**2.2.1.1. Study of the properties of neutron resonances, of the effects of parity violation, and effects indicating the violation of T-invariance.**

Neutron resonance is a long-lived level of a compound nucleus, a very complex system. Interest in resonances arose immediately after their discovery, even if initially it had a predominantly applied character. In particular, the subjects of the research were not only the characteristics of resonances, but also the statistical features of these parameters (distances between resonances, resonance widths). However, this study of complexity at a quantitative level has so far been mainly based only on data obtained for s-wave resonances. Very little amount of information is known about the characteristics of the p-wave resonances of most nuclei, even such as positions and total widths. Moreover, only for few p-wave resonances excited during the interaction of neutrons with nuclei with non-zero spins, partial neutron widths have been established corresponding to the population (and decays) through the p1/2 and p3/2 waves, so that a statistical analysis of these partial widths is generally impossible.

But even for s-wave resonances, the situation is not so unambiguous. A relatively recent experimental work [1], in which significant deviations of the distributions of s-wave neutron widths from standard expectations were found, caused a lengthy discussion. In [2], a solution to this problem was proposed, which is related to some special properties of the 192,194Pt isotopes studied in [1]. There are other published examples of unusual statistical dependences of the characteristics of s-wave resonances.

The complexity of compound-nuclear states is revealed in a non-trivial way in the so-called dynamic amplification of the effects of spatial (P) parity violation in neutron resonances of heavy nuclei. The effects are caused by small P-violating components of the nuclear forces, which are connected with weak interaction. These forces mix s- and p-wave resonances and it is revealed in numerous characteristic effects in the interaction of polarized neutrons with nuclei, both in elastic and inelastic (radiative and fission) channels. Dynamic amplification gives a scale factor of 103, while some factors (“structural” or “kinematic” nature) that arise when measurements are taken directly at p-wave resonance give an additional amplification in some cases up to 103. Thus, in the low-energy interaction of neutrons with heavy nuclei found a lot of P-odd effects with values from 10-4 and higher, i.e. much more pronounced than, for example, in the interaction of neutrons with light nuclei or light with atoms, where the corresponding characteristic effects have a scale of 10-7 - 10-8.

It is important to notice that additional factors of amplification of P-odd effects in p-wave resonances stimulated the search for such resonances and the measurement of the simplest P-odd effect in them - the dependence of the total interaction cross section on the helicity of incident neutrons (“neutron dichroism”). The most complete summary of measurements of this kind, performed on 20 isotopes, is given in the review article [3]. To process these data, standard statistical approaches were used (for example, the equality of the average partial widths corresponding to the p1/2 and p3/2 waves), although, as noted above, their applicability to p-wave resonances is experimentally not substantiated.

As is known, weak interactions do not conserve the P, CP, and T-parities of the wave functions of the participating objects. At present, P-violation phenomena are well known, which are observed in weak decays of free hadrons, in the β-decay of radioactive nuclei, and nuclear reactions. CP-parity violation (or, equivalently, T-invariance violation) has been studied much worse and has been observed only in the decays of K0 and B0 mesons. Violation of T-invariance should also lead to the presence of electric dipole moments (EDM) of neutrons, electrons, and other simple systems, but their search has not yet been successful. It is highly probable that in nuclear interactions there may exist small forces that violate T-invariance and additionally violate P-parity (a more probable option), or preserve P-parity (an unlikely case, but categorically not rejected). If in the next few years, the EDM of some elementary system will be discovered, then this will rather be evidence in favor of the 1st option, but this will not be completely “close” the 2nd possibility. In any case, the detection of, for example, neutron EDM, will lead to intensification of the search for independent indications of T-invariance violation in nuclear interactions at low energies.

It is clear that small T-non-invariant forces, like small P-odd ones, can only be detected by the specific effects that arise due to the mixing of nuclear states under the action of these forces. Therefore, it is clear that the dynamic enhancement of any mixing of states of heavy nuclei (on a scale of 103!) puts T-violation effects in neutron resonances in first place in importance in the list of all other ways to search for nuclear interactions that break T-invariance. By now, not only is a list of the main effects in neutron resonances known but there is also a qualitative understanding of why the violation of T-invariance leads to these effects. Namely, in any case, the violation of T-invariance entails a violation of the detailed balance, i.e. equality of amplitudes of transitions from state A to state B and vice versa. So, in particular, if T-noninvariant forces break P-parity, then they violate the equality of the amplitudes of transitions from the s-to p-states and vice versa, while T-noninvariant and P-even forces violate the equality of the amplitudes of transitions from the states p1/2 to p3/2 and vice versa. Moreover, in both cases, violation of the equality of amplitudes can manifest itself only in the appearance of a relative phase in them, so that any effects that are sensitive to such phases become sensitive to T-violating forces.

This means that, in addition to “pure” and rather complex methods for studying T-invariance in p-wave resonances by searching for the so-called 3-vector and 5-vector correlations in the total cross section for the interaction of polarized neutrons with oriented (polarized or aligned) nuclei, up to a certain level of accuracy, it is possible to search for T-non-invariant effects by simpler methods that are sensitive to the above-mentioned T-non-invariant phase factors. The simplest methods of this kind can be attributed to the search for the “forward-backward” asymmetry in the emission of gamma quanta after neutron capture in p-wave resonance, where in the case of T-noninvariant and P-even forces, the “axis” is set by the momentum of the incident neutrons [4], while in the case of T-non-invariant and P-odd forces, the “axis” is given by the direction of the spin of the incident neutrons; see, for example, [5].

In general, it should be especially noted that the study of angular correlations in the radiative capture of neutrons in p-wave resonances is an unusually wide and prospective area of activity, which was little developed. Even in the simplest case, when neutrons are unpolarized and the nuclei are not oriented, measuring the angular distribution of gamma rays can provide not only information about neutron amplitudes (including partial ones associated with p1/2 and p3/2 waves) and gamma amplitudes in the input and output channels, but also about the position of neighboring s-wave resonances (this information is contained in the asymmetry of the emission of gamma rays relative to the momentum of the incident neutrons), including in the region of "negative" energies (below the neutron binding energy). Moreover, information about the interference of several neighboring s-wave resonances can be obtained using formulas that go beyond the standard approximation of isolated Breit-Wigner resonances. The use of polarized neutrons (not to mention the polarization or alignment of nuclei) will only expand the possibilities of this method. Moreover, such a thorough preliminary study of all the characteristics of the selected p-wave resonance and neighboring s-wave resonances is necessary for the correct interpretation of the results of subsequent studies of the effects caused by violation of T-invariance.

Such studies of angular correlations in radiative neutron capture in p-wave resonances of 139La, 117Sn, and 81Br nuclei, aimed at future searches for T-violationgt effects, in particular, have recently begun in Japan [6–9]. In the 1980s, similar studies were carried out at FLNP on p-wave resonances of 113Cd and 117Sn nuclei, but they were not continued, although without these studies there would be no work [4].

The resumption of such studies at already known p-wave resonances (see the list of isotopes studied in [3]) could be the beginning of a broad program of studying compound nuclear states with the following (incomplete) list of goals:

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

- the study of interference effects of both p- and s-wave resonances, and s-wave resonances with each other, going beyond the simplified approximation of isolated Breit-Wigner resonances,

- the 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.

Investigations of the angular distributions of gamma quanta will be started on unpolarized neutrons, but subsequent development towards adding neutron polarization, the spin orientation of target nuclei, and measurements of the interaction of neutrons with nuclei observed in an elastic channel, including the total interaction cross sections, would be very prospective. For resonances on actinide nuclei, the measured quantities can also include those observed in the fission channel.

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**2.2.1.2. Investigation of TRI and ROT effects in fission**

The study of nuclear fission reactions with oriented or polarized targets and polarized neutrons revealed interesting features of this process. These studies were carried out on pulsed neutron sources in the resonant region and on high-flux research reactors for neutron energies near the thermal point. From the angular distributions of fission fragments of oriented nuclei, the (J, K) quantum numbers of transition states at the saddle point were determined for individual resonances of the cross-section in 235U(n,f) reaction [1]. For the same process, spin-dependent fission cross-sections were obtained in the study with polarized neutron irradiation of polarized 235U targets [2]. A new direction of research was initiated by the discovery of parity violation in fission reactions [3]. Fragments parallel and antiparallel to the neutron spin σn were registered in these experiments. Parity nonconservation (PNC) manifests itself in the asymmetry of the angular distribution of fragments depending on the pseudoscalar product (σn ∧ pLF ) for the light fragment momentum pLF. With the observed asymmetry of about 10-4 in the 235U(n,f) reaction, the magnitude of the PNC effect turned out to be unexpectedly large. This is due to the mixing of the s1/2 and p1/2 states near the P resonances, which are not otherwise visible. After successfully observing the violation of fundamental laws of physics, such as PNC in fission, the idea arose whether it was also possible to test the invariance to time reversal [4]. By analogy with the search for the violation of invariance to time reversal in the decay of free polarized neutrons, it is necessary to analyze the triple correlation between the neutron spin σn and the momenta of fragments and ternary particles emitted in a ternary fission. Several series of experiments were carried out, mainly at the high-flux reactors ILL in Grenoble and FRM-II in Garching. As a result of these measurements the expected correlations were observed, but the hope of finding a violation of T-invariance did not materialize. However, two different phenomena have been discovered and thoroughly studied, which are called ROT and TRI effects [5,6]. The ROT effect is explained by the collective rotation of the compound nucleus up to the break. The TRI effect reflects the influence of a rotating nucleus on the probability of emission of triple particles. It was shown that both effects are present in parallel with different weights for all actinides studied.

Most of the experiments were carried out on beams of cold polarized neutrons, which limited the interpretation of the results in terms of determining the (J, K) quantum numbers for transition states at the saddle point. In 2018, for the first time, it was possible to measure the ROT effect for gamma rays in 235U fission at a low-lying resonance of 0.3 eV. The results obtained agree with the theory, however, for further study of the quantum mechanical properties of the fission process, it is advisable to continue these works to obtain data for higher-lying resonances, as well as for other nuclei. In particular, the 241Am and 245Cm nuclei were proposed as candidates [7].

Such experiments can be started with the beam of polarized neutrons from the IBR-2 reactor. Despite the long duration of the 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).

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**2.2.1.3. Investigation of reactions induced by neutrons with emission of charged particles.**

The measurement of cross-sections for neutron-induced reactions with the emission of charged particles is important for several fields of science and technology. This data is important for various structural materials, neutron absorbers, and other applications of nuclear technology. Requirements for accuracy vary within 1-10 percent in energy range from thermal to 8 and sometimes up to 20 MeV, respectively.

We are planning to continue measuring the cross sections for the reactions (n,p), (n,α) on various isotopes. The experiments are important both for fundamental nuclear physics and for nuclear astrophysics (refining the parameters of the global α-particle potential used in calculations of various astrophysical scenarios). In astrophysics, the reaction cross sections (n,α) are very important for scenarios of nucleosynthesis of elements. It is proposed that most elements heavier than iron are produced by neutron capture and beta decay (s- and r-processes), while rare proton-rich isotopes are mainly produced by photodissociation reactions (p-process). Measurements of the reaction (n,α) are necessary for a better understanding of the s-process in the case of light nuclei, and for heavy nuclei, to construct the α-particle potential used to calculate the reactions occurring in the p-process. Experiments can be made at IREN (En=th-100 keV); electrostatic accelerators EG-5 (FLNP) and EG-4.5 (PKU, Beijing, En=3-6 MeV)); HI-13 tandem accelerator CIAE, Beijing (En=8-11 MeV) and CSNS in China.

The problems of detecting and measuring neutron resonances, in particular, their α-widths, remain relevant for nuclear physics. The task of understanding the nature of the anomaly of neutron resonances in the reaction 147Sm (n,α)144Nd seems to be a top priority. The study of this reaction began at the FLNP JINR in the 70s of the last century, when attention was focused on the anomalously large value of the α-width of the resonance with E0 = 184 eV, which significantly distorted the statistical distribution of the total α-widths. Further experiments showed that in this reaction the α-widths averaged over the intervals of 200–500 eV, are not constant, but indicate their noticeable growth with increasing neutron energy, which contradicts the statistical theory of the compound states of the atomic nucleus. In recent years at ORNL (Oak Ridge), measurements of total α-widths have been continued over a wider range of neutron energies, but so far without analysis of α-particles energy spectra. The Oak Ridge measurements confirmed the anomalous nature of the resonance with E0 = 184 eV in the 147Sm(n,α)144Nd reaction, and also revealed several new anomalous resonances at higher energies. In addition, it was found that for resonances with spins 4- and En > 300 eV, the average values of α-widths are three times greater than for resonances with spins 3-. It contradicts the theoretical predictions because for 4- resonances the most probable α-decay to the ground state of the final 144Nd nucleus with spin 0+ is forbidden by the conservation of momentum and parity. Indeed, for the energy range En < 300 eV, resonances 4- have average values of α-widths three times smaller than for resonances 3-. Mechanisms that could explain such an increase in α-widths for resonances with 4- spins are currently unknown. To establish the nature of these anomalies (possibly, this is a new phenomenon in neutron physics), it would be extremely important to analyze the energy spectrum of α-particles in these resonances or to measure the averaged partial cross sections of this reaction in the energetic windows corresponding to α-transitions to the ground and excited states of the final nuclei. This can become one of the priority tasks for a high-aperture time-of-flight neutron source CSNS (China spallation neutron source). Similar measurements of the α-particles spectra in resonances for other nuclei are also interesting. If the (n,α) program is adopted, a lot of work remains to be done on the creation of some special detectors for α-spectrometry, and the production of samples and the adaptation of the data acquisition electronics for the research. Preliminary tests of the equipment can be performed using the neutron beams of the IREN facility at the FLNP JINR.

Experimental study of angular and polarization correlations and angular distributions of nuclear reaction products, acquiring complete spectroscopic information about p-resonances, in particular, the values and signs of the amplitudes of the widths of the input and output channels of the reaction, necessary both for interpreting the results of studies of P-odd effects and to check the adequacy of the used formalism in the framework of the concept of the compound nucleus seems to be an important task. The proposed research aims to carry out 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 to analyze data together with previously defined P-odd and P-even left-right correlations. The measurement of all these correlations makes it possible to determine the amplitudes of the widths for different spins of the reaction channels and the matrix element of the weak interaction. Since the results of most experiments on the phenomenon of parity violation in reactions with polarized neutrons are interpreted in a two-level approximation, special attention will be paid to the analysis of correlations within the framework of the standard resonance theory. Experiments specifically dedicated to determining the values and signs of the width amplitudes for different channel spins by measuring P-even angular correlations in radiative capture by 117Sn and 113Cd revealed a significant discrepancy between the data. Since the width amplitudes are related quadratically to the neutron width, two sets of width amplitude values are obtained by fitting experimental data for each coefficient. It turned out that one set of values obtained in the measurements of one coefficient quite accurately describes the other coefficient quantitatively, but gives a sign opposite to the observed effect, and the other set, with the correct sign, gives a too-high value. It should be emphasized that such a discrepancy turned out to be common for both nuclei. An indication of a similar uncertainty in the values and signs of the amplitudes of the widths of the channels with moments 1/2, and 3/2 was noticed by us in the reaction 35Cl(n,p)35S. Due to experimental errors, without additional measurements, it is still premature to state that the discrepancy has been unambiguously established. Finding out the reasons for the inadequacy of the analytical description of the real process is extremely important both for the correct interpretation of the results of studies of P-odd effects and for planning future experiments to search for T-parity violation. Measurements are supposed to be carried out on IREN, also on EG-5, and EG-4.5 using 7Li and 3H neutron-generating targets, respectively, and CSNS if necessary.

Measurement of the fission reaction cross section (n,f) in the neutron energy range of 1-20 MeV is planned to be carried out on several isotopes using detectors based on a special ionization chamber (GIC) and Time Processing Chamber (TPC).

**2.2.2. Subproject ENGRIN**

The subproject "Emission of Neutrons and Gamma-quanta in Reactions Induced by Neutrons'' (ENGRIN) is aimed at the experimental study of the properties of prompt neutrons and gamma-quanta in fission induced by resonant neutrons. The study of the properties of prompt fission neutrons (PFN) is of great interest for a general understanding of the fission process and the distribution of excitation energy between fission fragments, in particular. PFN studies in fission reactions at low energies have been carried out at JINR for more than 20 years. The main object of these studies was PFN in the reactions 252Cf(sf) and 235U(nres,f) in the region of allowed resonances. In the 235U(nres,f) reaction, fluctuations were observed in the fission fragments mass and energy distributions depending on the energy of resonance neutrons [1, 2]. Similar fluctuations in the PFN multiplicity depending on the incident neutron energy were also observed in [3]. This project aims to investigate the correlations between PFN multiplicity variations and mass-energy distributions (MEDs) in fission induced by resonance neutrons. This problem attracted attention after the publication of the results of [4], where it was found that there were no variations in the PFN multiplicity in the strongest resonances of the 235U(nres,f) reaction.

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 project in 2021-23 and consists of 32 modules of neutron detectors with a BC501 liquid scintillator, located in such a way that the ends of the detectors are located on the surface of a sphere with a diameter of 1000 mm and with a center coinciding with the center of the ionization chamber (IC). The geometric efficiency of the neutron detection system is 0.18. The position-sensitive ionization chamber [5] can be used as a fission fragment spectrometer, which allows one to measure the kinetic energies, masses of fission fragments, and orientation of the fission axis (the angles of the fission axis to the axes of the Cartesian coordinate system with the origin at the center of the IC). In this case, the neutron beam axis passes through the geometric center of the IC, and the neutron detectors are arranged compactly around the neutron beam axis. The PFN and MED studies impose opposite requirements on the fissile target: in the first case, it is suitable to use a relatively thick target to increase the neutron yield. In the second case, a thin target is needed to ensure the exit of fission fragments from it and the possibility of their separate registration. Thus, it is convenient to divide the studies of correlations of total kinetic energy variations with PFNs into two experiments: in the first experiment, PFN multiplicity variations with a “thick” target are measured, while the correlations of mass-energy distributions and PFN multiplicity are measured with a thin target and a position-sensitive ionization chamber.

Is proposed to use for the experiment a double fission ionization chamber designed at FLNP with a “thick” (0.5 mg/cm2) target 17 cm in diameter. A 235U preparation (99.999% enrichment) is deposited on both sides of the aluminum foil cathode. The cathode is located in the center of the stainless steel cylinder at the same distance of 12 mm from the flange and the bottom of the cylinder. To analyze variations in the PFN number in strong resonances with an accuracy of about 3%, 240 hours (2 weeks) of measurements with a thick target (230 mg) at a resonant neutron flux intensity of ~2\*1011n/sec are sufficient. To measure variations in the mass-energy distributions with an accuracy of ~3%, about 50 weeks of measurements with a “thin” target (1 mg) and the above neutron flux intensity will be required. Approximately 50-70 weeks are required for the development of hardware and software for measuring and the preparation of IREN channel No. 2.

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**2.2.3. 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: the study of quantum phenomena in neutron optics; the study of the interaction of slow neutrons with diamond nanoparticles and study of the interaction of cold neutrons with intercalated graphite.

**2.2.3.1. Neutron optics.**

FLNP has many years of experience in studying quantum phenomena in neutron optics [1–18]. Among the theoretical results [1-11], there are several that served as a basis for subsequent experiments. Nonstationary neutron diffraction by a moving grating [3] was observed in experiments [12–14]. This phenomenon formed the basis of the idea of temporal focusing of neutrons [15], which was experimentally confirmed in [16], and a new approach to the experiment to test the equivalence principle [17]. As for the hypothesis of I. M. Frank [1] about the possibility of non-stationary energy transfer to a neutron during diffraction by surface waves, received experimental confirmation in 1987 [19]. Recently, FLNP researchers carried out a more detailed experiment on observing neutron diffraction by surface acoustic waves (SAWs) [18].

The continuation of the development of this line of research within the framework of the proposed topic project is relevant.

It is planned to continue work on the study of non-stationary diffraction by SAW. The scientific objectives of such a study are outlined below. First of all, the modern technique of reflectometric experiments makes it possible to measure with high accuracy the angular distribution and absolute amplitudes of diffracted waves of both the first and higher orders in the reflection geometry. The measurements will be carried out for a wide range of samples in which both traveling and standing surface waves are excited. Comparison of experimental data with the results of quantum calculations is of undoubted interest. It is assumed that the wave frequencies can reach values of the order of Gigahertz. The energy transferred to neutrons will reach a value about 4 μeV. The transfer of such large energy to neutrons as a result of non-stationary action has not been observed before.

Experimenting with extremely high vibrational frequencies of matter will also provide answers to two more important questions. First of all, the fact of observing the effect of non-stationary diffraction in the reflection indicates that the time of formation of the reflected wave in the substance is at least less than the period of the surface oscillation. At the same time, the question of the reflection time of neutron and X-ray waves when the glancing angle exceeds the critical angle of total internal reflection remains open today [20–21]. Any experimental information shedding light on this problem is very important.

The second important circumstance is that when a SAW is excited on the surface of a substance, a relatively thick layer of substance is involved in the oscillatory motion, in which the reflected wave is formed. In this case, the matter moves with a periodically changing acceleration, the value of which reaches gigantic values. In particular, at a SAW frequency of hundreds of MHz, this acceleration reaches 108g. Therefore, an experimental study of neutron diffraction by SAW can also be considered a sensitive test for verifying the validity of generally accepted laws of neutron optics in the case of high accelerations [22].

In addition to the study of non-stationary diffraction by SAW, within the framework of the proposed topic, it is planned to undertake work aimed at the development of neutron spin interferometry (NSI) with ultracold neutrons (UCN) [10]. 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. Technically, we are talking about the creation of a miniature UCN spin-echo spectrometer, which is a rather difficult task. Some ways to solve it are outlined in [23]

Also, we are going to use the developed NSI technique both for fundamental research and for creating new methods of applied research. In particular, it is planned to use the Larmor clock method to measure the interaction time of a neutron with quantum objects. This method was proposed as a theoretical technique for calculating the neutron scattering time in [24, 25] and much later, the possibility of its practical application was demonstrated in experiments with cold neutrons [23, 26]. Since the sensitivity of the method is proportional to the cube of the wavelength, the usage of UCN in such experiments will open up completely new experimental possibilities.

Another option arising due to the development of the NSI technique with UCN is the possibility of a new approach to the problem of phase contrast in neutron optics [23, 27].

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

Low-energy neutrons, the so-called cold neutrons, with a wavelength of more than 0.4 nm, or an energy of less than 5 meV, are especially important for research on the structure of matter, including the magnetic structure. The large wavelength of such neutrons allows one to use them to study structural features ranging in size from fractions of a nanometer or more.

To extract neutrons from neutron sources, such as the core of a reactor, neutron reflectors are often used, which make it possible to significantly (in some cases many times) increase the intensity of neutron beams available for scientific research. However, there are currently no effective cold neutron reflectors. One of the innovative solutions proposed by the members of our group is the development of neutron reflectors based on detonation nanodiamond (DND) powders. The use of such reflectors is most efficient for neutrons in the energy range from ~0.3 μeV to ~5.0 meV. Over the past 15 years, our group has carried out a whole layer of both theoretical and experimental studies on the creation of such reflectors [28–35].

Depending on the scientific problems being solved, the energy range of cold neutrons is usually divided into two regions: from ~0.3 μeV to ~0.1 meV - very cold neutrons (VCN); and from ~0.1 meV to ~5.0 meV - cold neutrons (CN). Theoretical estimates show that for each of these energy ranges, several different types of effective DND reflectors can be obtained. For VCN, one can obtain reflectors with a reflection coefficient (albedo) of ~99.5% even at normal neutron incidence on the DND powder surface [36]. For CNs, effective reflection is possible only when neutrons are incident at a small glancing angle to the DND powder surface, less than 5 degrees. In this case, the angle of reflection is close to the angle of incidence - the so-called. quasi-mirror reflection [37].

As a result of comprehensive research with the participation of FLNP staff, technologies and methods were developed that made it possible to significantly improve the quality of DND powders: to reduce the concentrations of impurities that reduce the neutron albedo and impurities that are activated in intense neutron fields. To reduce the content of chemically bound hydrogen by a factor of 30 (the source of the main losses of VCN and CN), a method was proposed and implemented to replace hydrogen atoms from the surface of nanodiamonds with fluorine atoms [38]. In this case, the structure of the powder and individual nanoparticles does not change as a result of this procedure [39]. Procedures for DND structural changes were also carried out: splitting large DND clusters into separate nanoparticles (deagglomeration) [40] and DND separation by size [41]. All of the listed modifications of DND powders should potentially improve the albedo of the VCN and CN nanodiamond reflectors.

Scientific tasks that are planned to be solved in this area of research within the framework of the project:

1) Determination of the optimal technologies for the synthesis and modification of DND powders for the creation of nanomaterials with determined properties, which will make it possible to create on their basis the most effective reflectors of VCN and CN. The planned work will help to select DND powders with the highest albedo to use them in full-scale reflectors, and in the designs of VCN and CN sources [42].

2) Determination of the optimal density of DND powders to achieve the maximum albedo of VCN and CN. The point is that the concentration of nanoparticles in a low-density DND powder may not be sufficient to effectively reflect VCN and CN. At the same time, with an increase in the powder density, the probability of neutron scattering at large angles decreases due to a decrease in the probability of scattering on individual nanoparticles. At the same time, the probability of scattering at small angles increases, due to an increase in the probability of scattering on agglomerates (large clusters of “sticky” particles), their sizes will grow with increasing powder density, and the scattering angles will decrease. Thus, there should be an optimum powder density that would give the maximum reflection at fixed sizes of DND samples.

3) Development of models for calculating the transport of VCN and CN in the material of nanodiamond reflectors. FLNP researchers have previously proposed models for the transport of low-energy neutrons in nano-dispersed media. They are implemented in the form of original computational complexes [43, 44], which require the preliminary creation of a structural model of the DND powder [45]. An algorithm for the formation of a DND powder model by the structure was also previously proposed: it is based on the data of small-angle neutron scattering. To increase the productivity of calculations of the transport of VCN and CN in the material of nanodiamond reflectors of complex geometries, it is required to integrate the proposed models and algorithms into existing programs for modeling the interaction of neutrons with matter (Geant4, MCNP, etc.).

4) Extension of the range of applicability of the developed models to the range of thermal neutrons. For such neutrons, an important process of interaction with DND is diffraction on the crystal lattice, which is not taken into account in the currently existing models of transport of VCN and CN. The level of influence of this mechanism on the propagation of neutrons has not yet been assessed by anyone. For this reason, it is currently impossible to simulate quasi-mirror reflection from neutron DND powders with wavelengths below the Bragg limit for diamond ~0.4 nm [35]. The planned studies with thermal neutrons will make it possible to evaluate the effect of Bragg diffraction on diamond nanocrystals and create new models that take into account this contribution to neutron transport.

5) Study of the resistance of DND reflectors to external influences. It was assumed that, as a result of fluorination, nanodiamond powders become hydrophobic, which was confirmed by the results of thermogravimetry. However, additional measurements performed three years later on the registration and analysis of prompt gamma quanta showed a significant, 6-fold, increase in chemically bound hydrogen in the samples. This was additionally confirmed by the results of Raman scattering and X-ray photoelectron spectroscopy. Thus, it is required to study the mechanism of the reverse substitution of fluorine for hydrogen on the surface of nanodiamonds, how much nanodiamond powders retain their physicochemical characteristics during fluorination, and how stable they are under the influence of the environment (temperature, humidity, elemental composition of the atmosphere).

6) Study of the radiation resistance of nanodiamond powders when irradiated with high doses of gamma rays and fast neutrons. Since nanodiamond powders are planned to be used as neutron reflectors, and this is due to the placement of equipment near the reactor core, such placement leads to significant radiation loads caused by both a large gamma-ray flux and exposure to high-energy neutrons (fast neutrons).

**2.2.3.3. Study of the interaction of cold neutrons with intercalated graphite.**

Bragg scattering on a crystal is possible only if the radiation wavelength does not exceed twice the distance between the crystal planes. Usually, in natural crystals, the interplanar spacing does not exceed ~2 Å; therefore, neutrons with wavelengths longer than ~4 Å are no longer scattered by them. Therefore such neutrons were allocated into a separate group called cold neutrons. However, it is possible to create artificial crystals with multiple interplanar spacing. Usually, in their production, a single crystal of graphite is used as a basis, and atoms of another substance are introduced between its crystal planes and pushing them apart. Intercalated graphite is produced with this technology. Such crystals can effectively scatter cold neutrons, however, they are not radiation resistant enough to be used near the reactor core.

Recently, a technology has appeared for introducing a whole plane (or two planes) of fluorine atoms between graphite planes. 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.

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**2.2.4. Subproject "Applied Research"**

Analytical studies at the REGATA facility

Within the framework of the project, it is planned to continue monitoring the air quality and the state of water bodies in the JINR Member States using several analytical methods, in particular, neutron activation analysis at the REGATA facility of the IBR-2 reactor. Another branch of studies, nanotoxicology, will also be performed, 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 neutron activation analysis method has several advantages over other approaches to elemental analysis due to its high sensitivity and selectivity, ease of sample preparation for analysis, and the ability to determine more than 50 chemical elements in a wide range of concentrations.

The results of the subproject will be:

- new data on the ecological state of the studied regions will be acquired, pollution areas in the studied territories will be identified and compared with previously obtained data;

- the process of accumulation of nanoparticles in the organs of animals and plant segments will be studied, as well as their impact on the health of the studied living objects;

- new eco-friendly methods of remediation of soils and water bodies will be proposed.

Applied research at the IREN facility

The study of cultural heritage objects by physical and chemical methods is important both from a scientific and practical point of view. The capabilities of the traditional methods of the humanities in this area are currently not enough, so art critics, restorers, and archaeologists are increasingly joining their scientific efforts with physicists and chemists. The analyzed results of natural science research open up new possibilities and approaches to the study of cultural heritage objects. In addition, within the framework of the modern method of scientific restoration, the possibility of preparing restoration projects without a preliminary study of the monuments by instrumental methods is excluded.

To date, FLNP JINR has accumulated considerable experience in the study of cultural heritage objects of various origins. The use of neutron methods for studying monumental paintings, ancient building materials, archaeological artifacts, ecological, geological, and other samples will be continued. The capabilities of the IREN facility and the IBR-2 reactor will be used for neutron activation analysis purposes. The elemental composition by short-lived isotopes will be determined using the REGATA-2 pneumatic transport system at the IREN facility. Irradiation of samples for elemental analysis based on medium- and long-lived isotopes will be carried out using the facility 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 prompt neutron-gamma quanta activation analysis.

Another original approach for absolutely non-destructive elemental and isotope analysis is the method of neutron resonance analysis. It is based on detecting neutron resonances during radiative capture and measuring the yield of reaction products in these resonances. This requires a pulsed source of resonance neutrons (in our case, IREN) and the usage of time-of-flight neutron spectrometry. It is planned to continue joint research work on the study of materials provided by the Institute of Archeology of the Russian Academy of Sciences and other organizations. As part of these studies, work is planned to create a multi-section plastic scintillation detector. For the collection and preliminary analysis of data, the digitizer CRS - 2/6/32 will be used.

Along with neutron methods for determining the elemental composition, X-ray fluorescence analysis will be used. Complementary methods of infrared and Raman spectroscopy, optical and polarization microscopy, chemical microanalysis, and some others with the usage of additional laboratory equipment will be applied to increase the efficiency and accuracy of results.

As part of the topic, methodological work is planned to determine the potential for gamma activation analysis using the REGATA-2 pneumatic transport system and activation analysis on prompt gamma quanta on the 6th channel of the IREN facility, as well as the creation of appropriate methods.

Applied work at the EG-5 accelerator

The electrostatic accelerator EG-5 after modernization will be able to generate beams of light-charged particles (p, d, α) with high stability of characteristics (energy up to 4.1 MeV, current up to 250 μA, parameters can be changed over a wide range depending on the needs of the experiment). With this setup, one can perform the following tasks:

1) Obtain 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 with non-destructive RBS, ERD, and PIXE techniques.

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

Data on the characteristics of reactions induced by fast neutrons is needed for studying the mechanisms of nuclear reactions, the structure of atomic nuclei, and performing calculations when creating new facilities for nuclear power. Acquiring nuclear data and developing nuclear physics techniques for elemental analysis is one of the priority tasks of the project. It is possible to create a setup for non-destructive elemental analysis on prompt characteristic gamma quanta emitted by the products of nuclear reactions with fast neutrons. Its advantage will be the ability to vary the spectrum of neutron radiation over a wide range using changing the energy of incident charged particles and by replacing the neutron-producing target, which if needed for study the energy dependence of the cross sections and prospective for refining the results of the elemental composition determination.

The high intensity of the neutron flux allows one to study the radiation resistance of various objects, including electronic components, based on new physical principles developed by the group. Within the framework of the subproject, investigation of the effect of neutron irradiation on living objects (lipid membranes, cereal grains, molds) and inanimate nature (silicon multilayer architectures, oxide ceramics, metals, superconducting alloys) is also planned.

Alpha-particle beams of EG-5 allows one to obtain element concentration profiles with a depth resolution of up to 10 nanometers. There is a unique opportunity to study layered structures using the RBS, ERD, and PIXE techniques, which is especially promising for studying multilayer high-temperature superconducting systems. Studying the processes of ion implantation on the surface of solids is also underway.

Expected scientific results:

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

● Performing experiments to study TRI and ROT effects in fission, measuring the mass-energy and angular distributions of fragments, prompt neutrons and gamma rays; searching 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 basic 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 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 methodological 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, and 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 resonant neutrons.

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

The fundamental results obtained during the implementation of the project will be of great importance for understanding the mechanisms of neutron-nuclear reactions and the development of theoretical ideas about these processes. The study of P- and T-odd effects will provide information on the contribution of the weak interaction to nuclear forces and can serve as an alternative method for determining the mixing coefficient Vud of an SKM matrix. Obtaining new information about ROT and TRI effects, as well as exotic fission modes, will clarify the features of one of the stages of this process - the break-up of a fissile nucleus into fragments. The data obtained during the implementation of the neutron-optical part of the project will be needed to create new neutron moderators and reflectors. In addition, they could lead to significant progress in the development of neutron microscopy methods and studies of the magnetic structure of various objects.

The implementation of the applied program of the project will contribute to the progress of environmental, materials science, archaeological, and nanotechnological research. Techniques of elemental and structural analysis created and modernized will be in demand in many branches of human activity.

**Risks**

**SWOT analysis**

The implementation of the project is supposed to be carried out by the staff of the OLNP 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. The team has a significant number of detectors of various types, which are able 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 (Beijing 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.

**2.3 Estimated completion date**

Project implementation timeline: 2024 - 2028.

The scientific program of the project will be systematically implemented during the specified period.

**2.4 JINR’s laboratories**

During the implementation of the project, cooperation with other JINR laboratories is planned: MLIT, BLTP, FLNR, DLNP, VBLHEP, and LRB.

**2.4.1** **MICC resource requirements**

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Computing resources** | **Distribution by year** | | | | |
| 1st year | 2nd year | 3rd year | 4th year | 5th year |
| Data storage (TB)  - EOS  - Tapes |  |  |  |  |  |
| Tier 1 (CPU core hours) |  |  |  |  |  |
| Tier 2 (CPU core hours) |  |  |  |  |  |
| SC Govorun (CPU core hours)  - CPU  - GPU |  |  |  |  |  |
| Clouds (CPU cores) |  |  |  |  |  |

**2.5. Participating countries, scientific and educational organizations**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Country or**  **international**  **organization** | **City** | **Institute or**  **laboratory** | **Members** | **Status** |
| Australia | Melbourne | University | Klein A.G. + 3 pers. | Collaborations |
| Austria | Innsbruck | University | Zeilinger + 1 pers. | Collaborations |
| Azerbaijan | Baku | BSU | Gadzhieva S.R. | Collaborations |
| IGG ANAS  IRP ANAS | Huseynov D.A.  Samedov O.A. | Collaborations |
| Collaborations |
| Albania | Tirana | UT | Lazo P. + 3 pers. | Collaborations |
| Armenia | Yerevan | NITSIKN | Simonyan A.E.  Khanzatyan G.A. | Protocol |
| Belarus | Minsk | BSU | Ksenevich V.K. + 2 pers. | Collaborations |
| Research Institute NP BSU | Maksimenko S.A. + 2 pers. | Collaborations |
| SPC NASB for Materials Science | Ignatenko O.V. + 3 pers. | Collaborations |
| Germany | Mainz | JGU | Rhys D. | Collaborations |
| Munich | TUM | Klenke J. Lauer | Collaborations |
| Georgia | Tbilisi | AIP TSU | Japaridze G. + 4 pers. | Collaborations |
| Sapozhnikova N.A. | Protocol |
| TSU | Shetekauri Sh. + 5 pers. | Collaborations |
| Egypt | Alexandria | University | Badavi M.S. + 3 pers. | Collaborations |
| Giza | CU | Sheriff M. | Collaborations |
| Cairo | NRC | Ibrahim M. + 3 pers. | Collaborations |
| Shibin El Kom | MU | El Samman H. + 5 pers. | Collaborations |
| El Mansoura | MU | Sallah M. + 2 pers. | Collaborations |
| India | Varanasi | BHU | Kumar A. + 3 pers. | Collaborations |
| Italy | Rome | ENEA | Map M. + 2 pers. | Collaborations |
| Kazakhstan | Alma-Ata | INP | Glushchenko V.N. | Collaborations |
| Astana | ENU | Lennik S.G. | Protocol |
| Omarova Nu + 5 pers. | Collaborations |
| Kyzylorda | KazRIR | Duysembekov B.A. | Protocol |
| China | Beijing | IHEP CAS | Zifang tea + 3 pers. Zhang Guahui + 5 people | Collaboration Protocol |
|  | Xi'an | NINT | Song Zhaohue + 3 people |  |
| IAEA | Vein | IAEA | Fesenko S. | Collaborations |
| Moldova | Kishinev | IMB ASM | Rud L.B. | Protocol |
| IC | Chokyrlan A.G. | Protocol |
| Mongolia | Ulaanbaatar | CGL | Balzhinnyam N. + 2 pers. | Exchange of visits |
| Collaborations |
| NRC NUM | Huuhenhuu G. + 3 pers. | Collaborations |
| Poland | Wroclaw | UW | Kosior G. + 5 pers. | Collaborations |
| Gdansk | GUT | Bizyuk M. + 4 pers. | Collaborations |
| Krakow | INP PAS | Godzik B. + 4 pers.  Jurkovski J. + 1 pers. | Collaborations |
| Lodz | UL | Andrzejewski J. + 3 pers. | Collaborations |
| Lublin | UMCS | Zhuk E. + 3 pers.  Yasinskaya B. + 7 pers. | Collaborations |
| Opole | UO | Vaclavek M. + 5 pers. | Collaborations |
| Otwock (Sverk) | NCBJ | Miyanovsky C.  Polansky A. + 2 pers. | Collaborations |
| Poznan | AMU | Blashak Z. + 4 pers. Navrotsyk V. + 4 pers. | Collaborations |
| The Republic of Korea | Pohang | PAL | Kim G. + 3 pers. | Collaborations |
| seoul | Dawonsys | Kim Dong-soo | Collaborations |
| Daejeon | KAERI | Chang D. | Collaborations |
| Russia | Arkhangelsk | NArFU | Yeseev M.K. | Protocol |
| Borok | IBIW RAS | Tselmovich V.A. + 2 pers. | Collaborations |
| Vladikavkaz | NOSU | Labrinenko Yu.V.  Tvauri I.V. | Collaborations |
| Voronezh | VSU | Vakhtel V.M.  Kadmensky S.G. + 3 pers. | Collaborations |
| Gatchina | NRC KI PNPI | Vorobyov A.S. + 3 pers.  Voronin V.V. + 10 people | Collaborations |
| Grozny | ChSPU | Okazova Z.P. | Collaborations |
| Dolgoprudny | MIPT | Rogachev A.V. | Protocol |
| Dubna | State. University "Dubna" | Morzhukhina S.V. + 5 pers.  Senner A.E. + 3 pers. | Collaborations |
| Diamond | Syrovatskaya T.N. | Collaborations |
| Ekaterinburg | UrFU | Kruzhalov A.V. + 5 pers. | Collaborations |
| Ivanovo | ISUCT | Grinevich V.I.  Dunaev A.M. | Collaborations |
|  |  |  |  |
| Izhevsk | UdSU | Bukharina I.L.  Zubtsovsky N. | Collaborations |
| Irkutsk | LIN SB RAN | Hodger T.V. | Collaborations |
| Moscow | JSC "MNRHU" | Seregina E.I. | Protocol |
| VNIIA | Bogolyubov E.P. + 1 pers. | Collaborations |
| SIAS | Tsarevskaya T.Yu. | Protocol |
| GIN RAS | Lyapunov S.M. + 3 pers. | Collaborations |
| IA RAS | Vdovichenko M.V. | Protocol |
| SRI RAS | Mitrofanov I.G. + 5 pers. | Collaborations |
| GPI RAS | Mikhailova G.N. | Collaborations |
| ITEP | Trouble A.G.  Danilyan G.V. + 3 pers. | Collaborations |
| IPChE RAS | Safonov A.S. + 3 pers. | Collaborations |
| MSMU | Karalkin P.D. | Protocol |
| Moscow State University | Batsevich V.A. + 2 pers. | Collaborations |
| Belokhin V.S. | Protocol |
| Bushuev V.A. | Collaborations |
| Krasnushkin A.B. + 1 pers. | Collaborations |
| SINP MSU | Tretyakova T.Yu. + 2 pers. | Protocol |
| Chuvilsky Yu.M. + 1 pers. | Collaborations |
| NRC KI | Barabanov A.L. + 2 pers. | Collaborations |
| FRC “Soil Institute” | Bolotov A.G. | Protocol |
| Moscow, Troitsk | INR RAS | Dzhilkibaev R.M. | Protocol |
| Kuznetsov V.L. | Collaborations |
| Nizhny Novgorod | IPM RAS | Salashchenko N.N.  Chkhalo N.I. + 1 pers. | Collaborations |
| Obninsk | IPPE | Grudzevich O.T. + 10 people | Collaborations |
| Perm | PSU | Gatina E.L. | Agreement |
| St. Petersburg | KBI RAS | Tkachenko K.G. + 3 pers. | Collaborations |
| FIP St. Petersburg State University | Bunakov V.E. + 1 pers. | Collaborations |
| RI | Smirnov A.N. + 1 pers. | Collaborations |
| SPbFTU | Alekseev A.S. + 10 people | Collaborations |
| SPMU | Vasilenko T.A. | Protocol |
| IPTI | Vul A.Ya. + 5 pers. | Collaborations |
| Sevastopol | IBSS | Milchakova N.A. + 2 pers. | Collaborations |
| Tula | TulSU | Gorelova S.V. | Collaborations |
| Romania | Baia Mare | TUCN-NUCBM | Todoran R. + 3 pers. | Collaborations |
| Bucharest | IFIN-HH | Gita D. | Collaborations |
| Dima O.  Michael O. | Protocol |
| Pantelika A. + 3 pers.  Setnescu R. | Collaborations |
| IGR | Douliou O. | Protocol |
| INCDIE ICPE-CA | Mirela M. + 5 pers. | Collaborations |
| UB | Grue I.  Douliou O.  Lived A.  Lazanu I.  Tudora A. | Collaborations |
| UPB | Fikay A. | Protocol |
| Galati | UG | Ene A. + 3 pers. | Collaborations |
| Cluj-Napoca | INCDTIM | Soran N.L. | Collaborations |
| Constanta | UOC | Belk M. + 2 pers. | Collaborations |
| Magurele | ISS | Potlog P.M. | Collaborations |
|  | NIMP | Badika P. + 6 pers.  Stanculescu A. + 4 pers. | Collaborations |
| Oradea | UO | Oprea A. + 3 pers.  Philip S. | Collaborations |
| Pitesti | ICN | Preda M. | Collaborations |
| Ramnicu Valcea | ICSI | Kuruya M. + 3 pers.  Oprah K.  Stefanescu I. | Collaborations |
| Sibiu | ULBS | Bondrea I. | Protocol |
|  |  | Chisea D. + 8 pers. | Collaborations |
| Timisoara | UVT | Stef M. + 4 pers. | Collaborations |
| Targovishte | VT | Bamwak M.  Bamkuta I.  Radulescu K.  Setnescu T. | Collaborations |
| Poetry S. + 4 pers. | Protocol |
| Iasi | NIRDTP | Chirakh H.+ 2 pers. | Collaborations |
| UAIC | Carmen M. + 5 pers. | Collaborations |
| Northern  Macedonia | Skopje | UKiM | Stafilov T. + 3 pers. | Collaborations |
| Serbia | Belgrade | IPB | Anicic M. + 5 pers. | Collaborations |
|  | University | Popovich D. | Collaborations |
| Novi Sad | UNS | Krmar M. + 3 pers. | Collaborations |
| Slovakia | Bratislava | CU | Kucherka N. + 5 pers. | Collaborations |
|  | Holly K. | Collaborations |
| IEE SAS | Guran E. |  |
| IP SAS | Kliman Ya. + 3 pers. | Collaborations |
| Slovenia | Ljubljana | GeoSS | Shane R. | Collaborations |
| USA | Durham, NC | Duke | Gould K. + 2 pers.  Thornow W. | Treaty |
| Los Alamos | LANL | Systrem S. + 5 pers. | Collaborations |
| Oak Ridge | ORNL | Keler P. | Collaborations |
| Thailand | Hat Yai | PSU | Bongsuwan T. | Collaborations |
| Türkiye | Canakkale | COMU | Koskun M. + 3 pers. | Collaborations |
| Uzbekistan | Tashkent | INP AS RUz | Artemov S.V. | Collaborations |
| Finland | Jyväskylä | UJ | Trzaska V. | Collaborations |
| Oulu | UO | Keronen A. + 3 pers. | Collaborations |
| France | Grenoble | ILL | Geltenbort P.  Yenchel M.  Nesvizhevsky V. | Collaborations |
|  | LPSC | Protasov K.V. + 2 pers. | Collaborations |
| Cadarache | CC CEA | Soul R. + 5 pers. | Collaborations |
| Saclay | LLB | Leroy S. + 2 people | Collaborations |
| Strasbourg | IPHC | Stuttje L. + 2 pers. | Collaborations |
| Croatia | Zagreb | Oikon IAE | Spirich Z. + 5 pers. | Collaborations |
|  | RBI | Valkovich + 2 pers. | Collaborations |
| CERN | Geneva | CERN | Chiaveri E. + 12 pers. | Collaborations |
| Czech Republic | Ostrava | VSB-TUO | Yanchik P. | Collaborations |
| Prague | CEI | Kuchera Ya. + 2 pers. | Collaborations |
| CTU | Shtekl I. + 15 pers. | Collaborations |
| Rzhezh | CVR | Patrick M. | Protocol |
| Switzerland | Willigen | PSI | Lauss B. | Collaborations |
| Schmidt-Welenburg F. | Collaborations |
| South Africa | Bellville | UWC | Petrik L. + 5 pers. |  |
| Pretoria | UNISA | Sofianos S. | Collaborations |
| Stellenbosch | SU | Bezudenot J. + 3 pers. | Collaborations |
| Japan | Kyoto | KSU | Kimura I. + 3 pers. | Collaborations |
| Tsukuba | KEK | Masuda Ya. + 5 pers. | Collaborations |

**2.6. Co-executing organizations** *(those collaborating organizations/partners without whose financial, and infrastructural participation the implementation of the research program is impossible. An example is JINR's participation in the LHC experiments at CERN).*

**3. Staffing**

**3.1. Staffing needs in the first year of implementation**

|  |  |  |  |
| --- | --- | --- | --- |
| **№** | **Category** | **Main/Core staff,**  **Total FTE** | **Associate staff,**  **Total FTE** |
| 1. | research scientists | 55 |  |
| 2. | engineers | 35 |  |
| 3. | specialists | 10 |  |
| 4. | office workers | 0 |  |
| 5. | workers | 2 |  |
|  | **Total:** | **102** |  |

**3.2. Human resources available**

**3.2.1. JINR core/main staff**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Category** | **Full name** | **Division** | **Position** | **FTE** |
| research scientists | Lychagin E.V. | FLNP | Laboratory director |  |
| Kopach Yu.N. | FLNP | Deputy laboratory director for research |  |
| Shvetsov V.N. | FLNP | Head of department |  |
| Sedyshev P.V. | FLNP | Deputy head of department |  |
| Fedorov N.A. + 58 people | FLNP | Head of sector |  |
| Kulin G.V. + 18 people | FLNP | Head of sector |  |
| Zinkovskaya I. + 23 people | FLNP | Head of sector |  |
| Specialists | Pyataev V.G. + 28 people | FLNP | Chief engineer |  |
| Workers |  |  |  |  |
| Total | | | |  |

**3.2.2. JINR-associated personnel**

|  |  |  |
| --- | --- | --- |
| **Category of workers** | **Partner organization** | **Total FTE** |
| Scientific workers |  |  |
| engineers |  |  |
| specialists |  |  |
| workers |  |  |
| **Total:** |  |  |

**4. Financial support**

**4.1 Total estimated cost of the project/sub-project of the LRIP**

Forecast of the total estimated cost (specify cumulatively for the whole period, excluding FPC). The details are given in a separate form.

4635 thousand dollars

**4.2 Extrabudgetary funding sources**

Estimated funding from co-executors/customers - total.

**Project (sub-project of the LRIP) Leader** \_\_\_\_\_\_\_\_\_\_/\_\_\_\_\_\_\_\_\_\_\_/

Date of submission of the project (sub-project of the LRIP) to DSOA: \_\_\_\_\_\_\_\_\_

Date of decision of the laboratory's STC: \_\_\_\_\_\_\_\_\_ document number: \_\_\_\_\_\_\_\_\_

Year of the project (subproject of the LRIP) opening: \_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_

(for renewable projects) -- Project start year: \_\_\_\_\_\_\_

**Schedule proposal and resources required for the implementation of the Project / Sub-project of the LRIP**

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Expenditures, resources,**  **funding sources** | | | **Cost (thousands**  **of US dollars)/**  **Resource requirements** | **Cost/Resources,**  **distribution by years** | | | | |
| 1st year | 2nd year | 3rd year | 4th year | 5th year |
|  | | International cooperation | 410 | 65 | 65 | 75 | 90 | 100 |
| Materials | 1000 | 200 | 200 | 200 | 200 | 200 |
| Equipment, Third-party company services | 2755 | 425 | 525 | 555 | 600 | 650 |
| Commissioning |  |  |  |  |  |  |
| R&D contracts with other research organizations | 75 | 15 | 15 | 15 | 15 | 15 |
| Software purchasing | 410 | 70 | 70 | 80 | 90 | 100 |
| Design/construction |  |  |  |  |  |  |
| Service costs (planned in case of direct project affiliation) |  |  |  |  |  |  |
| **Resources required** | **Standard hours** | Resources |  |  |  |  |  |  |
| * the amount of FTE, | 945000 | 189000 | 189000 | 189000 | 189000 | 189000 |
| * accelerator/installation (EG-5 and IREN), | 12500 | 2500 | 2500 | 2500 | 2500 | 2500 |
| * IBR-2 reactor | 12500 | 2500 | 2500 | 2500 | 2500 | 2500 |
| **Sources of funding** | **JINR Budget** | JINR budget (budget items) | 4635 | 775 | 875 | 925 | 995 | 1065 |
| **Extra fudning (supplementary estimates)** | Contributions by  partners  Funds under contracts with customers  Other sources of funding |  |  |  |  |  |  |

Project (sub-project of the LRIP) Leader\_\_\_\_\_\_\_\_\_/\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_/

Laboratory Economist \_\_\_\_\_\_\_\_\_/\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_\_/

**APPROVAL SHEET FOR PROJECT / LRIP SUBPROJECT**

TITLE OF THE PROJECT/LRIP SUBPROJECT

SHORT DESIGNATION OF THE PROJECT / SUBPROJECT OF THE LRIP

PROJECT/LRIP SUBPROJECT CODE

THEME / LRIP CODE

NAME OF THE PROJECT/ LRIP SUBPROJECT LEADER

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  |  |  |  | |
| AGREED |  |  |  | |
| JINR VICE-DIRECTOR | \_\_\_\_\_\_\_\_\_\_\_  SIGNATURE | \_\_\_\_\_\_\_\_\_  NAME | \_\_\_\_\_\_\_\_\_  DATE |  |
| CHIEF SCIENTIFIC SECRETARY | \_\_\_\_\_\_\_\_\_\_\_  SIGNATURE | \_\_\_\_\_\_\_\_\_  NAME | \_\_\_\_\_\_\_\_\_  DATE |  |
| CHIEF ENGINEER | \_\_\_\_\_\_\_\_\_\_\_  SIGNATURE | \_\_\_\_\_\_\_\_\_  NAME | \_\_\_\_\_\_\_\_\_  DATE |  |
| LABORATORY DIRECTOR | \_\_\_\_\_\_\_\_\_\_\_  SIGNATURE | \_\_\_\_\_\_\_\_\_  NAME | \_\_\_\_\_\_\_\_\_  DATE |  |
| CHIEF LABORATORY ENGINEER | \_\_\_\_\_\_\_\_\_\_\_  SIGNATURE | \_\_\_\_\_\_\_\_\_  NAME | \_\_\_\_\_\_\_\_\_  DATE |  |
| LABORATORY SCIENTIFIC SECRETARY | \_\_\_\_\_\_\_\_\_\_\_  SIGNATURE | \_\_\_\_\_\_\_\_\_  NAME | \_\_\_\_\_\_\_  DATE |  |
| THEME LEADER | \_\_\_\_\_\_\_\_\_\_\_  SIGNATURE | \_\_\_\_\_\_\_\_\_  NAME | \_\_\_\_\_\_\_  DATE |  |
| THEME LEADER | \_\_\_\_\_\_\_\_\_\_\_  SIGNATURE | \_\_\_\_\_\_\_\_\_  NAME | \_\_\_\_\_\_\_  DATE |  |
| THEME LEADER | \_\_\_\_\_\_\_\_\_\_\_  SIGNATURE | \_\_\_\_\_\_\_\_\_  NAME | \_\_\_\_\_\_\_  DATE |  |
| PROJECT / LRIP SUBPROJECT LEADER | \_\_\_\_\_\_\_\_\_\_  SIGNATURE | \_\_\_\_\_\_\_\_\_  NAME | \_\_\_\_\_\_\_\_\_  DATE |  |
| PROJECT / LRIP SUBPROJECT LEADER | \_\_\_\_\_\_\_\_\_\_  SIGNATURE | \_\_\_\_\_\_\_\_\_  NAME | \_\_\_\_\_\_\_\_\_  DATE |  |
|  |  |  |  |  |
| APPROVED BY THE PAC | \_\_\_\_\_\_\_\_\_\_\_  SIGNATURE | \_\_\_\_\_\_\_\_\_  NAME | \_\_\_\_\_\_\_\_\_  DATE | |