**Annex 3.**

***Form of opening (renewal) for Project /***

***Sub-project of LRIP***

**APPROVED**

**JINR DIRECTOR**

**/**

**" " 2023**

**PROJECT PROPOSAL FORM**

Opening/renewal of a research project/subproject of the large research infrastructure project within the Topical plan of JINR

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

* 1. **Theme code / LRIP** (for extended projects) - *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.*

**"Neutron nuclear physics"**

**1.2 Project/LRIP subproject code** (for extended projects)

**1.3 Laboratory** **FLNP**

**1.4 Scientific field: Nuclear physics**

**1.5 Title of the project/LRIP subproject**

**Development of the tagged neutron method for determining the elemental structure of matter and nuclear reactions research (project TANGRA - Tagged Neutrons and Gamma Rays)**

**1.6 Project/LRIP subproject leader(s)**

**Kopatch Yu.N.**

**1.7 Project/LRIP subproject deputy leader(s) (scientific supervisor(s))**

**Deputy leader: Fedorov N.A.**

**2 Scientific case and project organization**

**2.1 Annotation**

Information about neutron-nucleus interactions is extremely important for both fundamental and applied physics. The absence of an electric charge on the neutron makes it a unique probe for studying nuclear forces. Due to electrical neutrality, the high penetrating power of neutron radiation makes it promising for studying the structure of matter both at the nuclear and at the molecular levels. Neutrons are widely used for applied purposes: in inspection complexes, non-destructive elemental analysis setups, in devices for studying surrounding rocks in boreholes (logging), as well as in the creation of neutron and gamma-ray detectors used on orbital and descent spacecraft for analysis of soil and atmosphere of planets. Information about neutron-nuclear reactions is also necessary for designing prospective nuclear power stations, as well as for modeling various devices and objects that interact with neutron radiation. An indicator of the relevance of studying the characteristics of neutron-nucleus interactions can be the fact that the large part of the high priority nuclear datarequestlist for the most part consists of queries directly related to neutron-nuclear reactions [1].

The TANGRA (TAgged Neutrons and Gamma Rays) project is aimed at research of the neutron-nuclear reactions using the tagged neutron method, finding new ways to use neutron methods in fundamental and applied research, improving existing and creating new approaches for processing of the data collected in nuclear physics experiments. An important task of the project is the interpretation of existing experimental data on the nuclear reactions with fast neutrons, their systematization and validation. The priority area of work is the acquisition and update of nuclear data.

**2.2** **Scientific justification** (purpose, relevance and scientific novelty, methods and approaches,

methodologies, expected results, risks)

Information about the features of neutron-nucleus interactions is important for both fundamental and applied physics. The absence of an electric charge in the neutron makes it a unique test particle for the study of nuclear forces. Due to electrical neutrality, the high penetrating power of neutron radiation makes it promising to use it to study the structure of matter at different levels of organization: from atomic nuclei to large molecules and crystals. Neutrons are also widely used for applied purposes: in inspection complexes, setups for non-destructive elemental analysis, in devices for well logging. Information about neutron-nuclear reactions is also necessary for designing prospective nuclear power stations, as well as for modeling various devices and objects that interact with neutron radiation.

The most convenient processes for studying the interaction of neutrons with nuclei are inelastic scattering and radiative capture, which result in the emission of γ-quanta.There are no technical difficulties in their registration and it makes the usage of these reactions for applied purposes more attractive. The study of inelastic scattering of neutrons can provide information on the properties of bound states of nuclei [2], especially heavy ones, since the neutron is not affected by the Coulomb barrier and can penetrate into the nucleus with an arbitrarily low energy [3]. In addition, the study of (n′ ,γ) angular correlations and anisotropy of γ-radiation makes it possible to clarify the mechanism of inelastic scattering (direct or compound) [4], refine the parameters of the optical potential used to describe a reaction on the particular nucleus [5]. The study of the interaction of 14.1 MeV neutrons, produced in the reaction d + t → α + n, with with matter is relevant due to the fact that it is the most promising for controlled thermonuclear fusion [6]. Another application of this reaction is the production of neutron radiation using compact sources - neutron generators, which are currently actively used both to search for hazardous substances inside various objects, and in geology when studying the composition and moisture content of rocks (the so-called neutron logging) [7]. An important advantage of neutron generators, in addition to compactness, is the possibility of implementing the so-called tagged neutron method (TNM), which consists in detecting charged particles produced together with a neutron in a binary reaction using an α-detector built into the generator. The use of the TNM makes it possible to estimate the direction of motion of the emitted neutron and obtain a time reference to the moment of its emission. The registration of signals from the detectors of secondary radiation together with the pulses from built-in α-detector makes it possible to select events by the time-of-flight. The advantage of this approach is the ability to identify events corresponding to reactions in the irradiated object, and its usage leads to a significant background reduction. The listed features of neutron generators with the implementation of neutron tagging make them promising for use in experimental setups for studying neutron-nuclear reactions. Styding of the γ-radiation emitted in (n,xγ)-type reactions is the easiest task, since only γ-detectors are required for their registration, and there is no need for vacuum equipment and long flight bases.Secondary particles which are emitted together with γ-rays are designated as x: n, p, α. To study these reactions in the Frank Laboratory of Neutron Physics of the Joint Institute for Nuclear Research (FLNP JINR, Dubna), the TANGRA facility (TAgged Neutrons and Gamma Rays) was created, and, after some time, a collaboration of the same name was formed.

**Aims of the project:**

1. Styding of (n,xγ) reactions using TNM;
2. Development of algorithms and programs for the analysis of experimental information coming from neutron and γ-radiation detectors;
3. Testing of various theoretical approaches describing the neutron-nucleus reactions.
4. Creation and development of a database on the cross sections of (n,xγ)-reactions for 14.1 MeV neutrons, expanding the applicability of the tagged neutron method for identifying a wide range of complex chemicals;
5. Development of a methodology for studying the elemental composition of various objects on the basis of TNM in order to determine the content of a wide range of chemical elements in them.
6. Experimental and theoretical study of (n,γ) and (n’,γ) - correlations in inelastic neutron scattering reactions
7. Study of reactions (n,α) and (n,2n) whose characteristics are necessary for the needs of astrophysics

**Actuality:**

Information about the cross sections of γ-quanta emission by matter under the neutron irradiation with an energy of 14.1 MeV is currently becoming more and more relevant. Modern compact neutron generators make it possible to create devices for fast elemental analysis of various substances that are in demand in various industries (metallurgy, production of mineral fertilizers), security (analysis of potentially hazardous objects), geological exploration (analysis of samples, well logging) and agriculture (analysis of the chemical composition of soils) . To date, one of the main obstacles to the widespread use of these devices is the lack of a relevant database on the γ-radiation cross sections of for the nuclei of various elements. The currently available data are replete with inaccuracies and incomplete. In addition to information on the γ-quanta spectra, information on their angular distributions is also in demand, which is necessary, on the one hand, for accurate modeling of nuclear physics experiments and optimization of the geometry of setups for elemental analysis in order to increase their efficiency. Angular correlations (n,γ) and (n,n',γ) are useful for understanding the properties and mechanisms of nuclear reactions. The currently used neutron generators are capable of producing a sufficiently intense neutron flux, which makes it possible to use these devices to obtain nuclear data on the reactions (n,n'), (n,p), (n,a) and ( n,2n) at relatively low financial costs.

**Methodology and approaches:**

The main idea of the tagged neutron method (MTN) [6] (the term API-method (Associated Particles Imaging) is also used in the English literature) is to detect the products of a neutron-nuclear reaction in coincidences with an α-particle formed in the reaction

d + 3Н → 4He (3.5 MeV) + n (14.1 MeV). (1)

In the binary reaction (1), the α-particle and the neutron fly apart in almost opposite directions, and therefore, information about the direction of the momentum of the α-particle allows one to determine the direction of the neutron momentum with good accuracy. Thus, neutron tagging is carried out using a position-sensitive α-detector placed inside the neutron tube of a portable neutron generator. The accelerating structure of the neutron tube ensures the acceleration of deuterons to energies of 80-100 keV and subsequent focusing on a tritium target.

The most convenient process for investigation is the (n,Xγ)-type reaction. In this case, the measurement of the time interval between the signals from the α- and γ-detectors makes it possible to determine the distance from the point of neutron emission in reaction (1) to the point at which the tagged neutron interacted with the nucleus of the substance under study (the velocity of a neutron with an energy of 14.1 MeV is 5 cm /ns). Thus, with the application of the TNM, it is possible to determine all three coordinates of the point at which the reaction take place. Due to the usage of (α-γ)-, (α-n')-, (α-n'γ)-coincidences, it becomes possible to effectively separate useful and background events, while, depending on the configuration of detector systems and data processing algorithms used, the background suppression can be up to 200 times compared to the experiment without neutron tagging.

In the experiments of the project, two types of detector systems are traditionally used: "Romashka" and "HPGe". The first one is a set of detectors located in a horizontal plane around the sample and designed to measure the angular distributions of secondary particles (γ-quanta or neutrons), and consisting, depending on the purpose of the experiment, of NaI(Tl), BGO detectors or plastic scintillators. A large number of combinations of "neutron beam-detector of secondary radiation" allows one to measure the angular distributions of secondary particles and their correlations with good angular resolution without moving the detectors. The second system is designed to study the γ-radiation cross sections with the maximum achievable energy resolution, for which high-purity germanium detectors are used. Previously, we have measured the γ-radiation yields for a number of elements using a single HPGe detector. At present, the setup for measuring the cross sections for the emission of γ-quanta in neutron-nuclear reactions, which will include 2 HPGe spectrometers, is being assembled.

To develop a soil elemental analysis methodology, it is planned to carry out a phased work, which will be completed with the receipt of the results of field measurements. It will be necessary to design and construct several experimental facilities, each of which will solve its own problem. When designing, it is planned to actively use digital modeling to determine the configuration of each unit, taking into account the specifics of its operation. At least one unit will be designed for laboratory work with prepared samples, another unit will be created to work directly in the field, in the conditions of a carbon test areas. All setups will include a portable neutron generator (NG) ING-27 and a set of gamma detectors. We are planning to use samples with a controlled chemical composition as well as specimens of real soils. It is supposed to compare the values and accuracy of determining the mass concentrations of elements, obtained by traditional chemical methods of analysis, with the values measured on the created experimental devices in order to verify the method being developed at the stage of laboratory research. An important factor affecting the applicability of this method in the field and the achievable accuracy is the presence of plants parts and other organic matter in the soil. To assess the influence of this factor, it is planned to measure purified soil samples with and without plant material, as well as individual vegetation samples in order to study the possibility of taking into account the presence of vegetation by introducing appropriate correction factors.

**Expected results:**

1. Performing experiments to study the angular distributions of scattered neutrons
2. Experimental study of (n,γ) and (n’,γ)-correlations.
3. Theoretical description of the studied reactions.
4. Conducting experiments to study the reaction (n,2n)
5. Conclusion on the applicability of the MMN for elemental analysis of soils. In case of a positive result, the creation of prototypes of stationary and mobile installations, as well as methodological recommendations for their use for agricultural and environmental monitoring purposes.

The results obtained during the implementation of this project will be valuable for both fundamental and applied science. The obtained experimental data on the yields and angular distributions of γ rays can be used to increase the accuracy of the Monte Carlo simulation of various physical installations. Another planned application of the obtained experimental results is fast elemental analysis. Optimized model parameters can be used to theoretically describe previously unstudied reactions. The developed prototypes of plants for elemental analysis of soils can become the basis for creating devices useful for intensifying agriculture and monitoring the state of the environment

**Risks:**

*Strengths of the project:*

When implementing the project, it is supposed to use a fairly well-established MMP technology. Used as neutron sources, D-T generators are relatively inexpensive and safe when used correctly. The project team is highly qualified, although it includes a significant number of young (under 35) specialists. The team has at its disposal equipment that is already sufficient to carry out a minimum research program. The employees participating in the project have extensive experience in studying reactions of the (n,Xγ) type, the feasibility of the program for studying the cross sections for the radiation of γ-quanta in these reactions is beyond doubt if it is possible to purchase all the samples planned for research.

*Weaknesses of the project:*

The insignificant disadvantages of the technique used include the finite service life of neutron generators and the need to replace them when the resource is exhausted. Potential risks in the development of soil elemental analysis methods are the impossibility of direct separation of carbon contained in organic and inorganic compounds, as well as the presence of a large number of factors (density, moisture, vegetation, parent rock composition, etc.) that affect the accuracy of the results obtained. . There is a risk that the application of the created methodology will be inappropriate for economic reasons. However, there is no information on the fundamental unsolvability of these problems.

Bibliography:

1. NEA Nuclear Data High Priority Request List. URL: https://www.oecd-nea.org/dbdata/hprl/.
2. Phillips G. C., Marion J. B., Risser J. R. Progress in Fast Neutron Physics. University of Chicago Press, Chicago, 1963.
3. Benetskii B. A., Frank I. M. Angular correlation between gamma rays and 14 MeV neutrons scattered inelastically by Carbon // JETP. 1963. Vol. 17. P. 309.
4. Van J. J., Lind D. A. Measurements of Inelastic Scattering Cross Sections for Fast Neutrons. // Phys. Rev. 1956. Vol. 101. P. 103.
5. Sheffield J. Fun in Fusion Research. Elsevier, 2013.
6. V Valkovic. 14 MeV Neutrons. Physics and Applications. CRC Press, New York. 2015. 516 p.

**2.3 Estimated completion date**

The project realization period is 2024 – 2028. The scientific program of the project will be systematically implemented during the specified period.

**2.4 Participating JINR laboratories**

A cooperation with following JINR Laboratories is planned: MLIT, DLNP, FLNR, VBLHEP.

**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**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Organization** | **A country** | **City** | **Members** | **Agreement type** |
| IGG ANAS | Azerbaijan | Baku | Huseynov D.A. | Collaborations |
| INRNE BAS | Bulgaria | Sofia | Ruskov I. + 4 people | Protocol |
| AU | Egypt | Alexandria | Badavi V.M. + 3 people | Collaborations |
| BHU | India | Varanasi | Kumar A. + 3 pers. | Collaborations |
| IH ASM | Moldova | Kishinev | Chokyrlan A.G. | Protocol |
| Diamant | Russia | Dubna | Syrovatskaya T.N. | Collaborations |
| VNIIA |  | Moscow | Bogolyubov E.P. + 1 person | Collaborations |
| Moscow State University |  |  | Belokhin V.S. | Protocol |
| SINP MSU |  |  | Tretyakova T.Yu. + 2 people | Protocol |
| NRC KI |  |  | Barabanov A.L. + 2 people | Collaborations |
| FRC “Soil Institute” |  |  | Bolotov A.G. | Protocol |
| UO | Romania | Oradea | Oprea A. | Collaborations |
| UNS | Serbia | Novi Sad | Krmar M. + 3 pers. | Collaborations |
| RBI | Croatia | Zagreb | Valkovich V. + 2 pers. | Collaborations |

**2.6. Key partners** *(those collaborators whose financial, infrastructural participation is substantial for the implementation of the research program. An example is JINR's participation in the LHC experiments at CERN).*

**3. Manpower**

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

|  |  |  |  |
| --- | --- | --- | --- |
| **№№**  **n/a** | **Category of personnel** | **JINR staff,**  **amount of FTE** | **JINR Associated**  **Personnel,**  **amount of FTE** |
| 1. | research scientists | 5 |  |
| 2. | engineers | 3 |  |
| 3. | specialists | 2 |  |
| 4. | office workers | 0 |  |
| 5. | technicians | 1 |  |
|  | **Total:** | **11** |  |

**3.2. Available manpower**

**3.2.1. JINR staff**

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Category of personnel** | **Full name** | **Division** | **Position** | **Amount**  **of FTE** |
| Scientific workers | Kopatch 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. + 10 people | FLNP | Head of sector |  |
| Sapozhnikov M.G. | VBLHEP | Main researcher |  |
| Rogov Yu.N. | VBLHEP | Researcher |  |
| workers |  |  |  |  |
| Total | | | |  |

**3.2.2. JINR associated personnel**

|  |  |  |  |
| --- | --- | --- | --- |
| **No.** | **Category of personnel** | **Partner organization** | **Amount of FTE** |
| 1. | research scientists |  |  |
| 2. | engineers |  |  |
| 3. | specialists |  |  |
| 4. | technicians |  |  |
|  | **Total:** |  |  |

**4. Financing**

**4.1 Total estimated cost of the project/LRIP subproject**

The total cost estimate of the project (for the whole period, excluding salary).

The details are given in a separate table below.

675 kUSD.

**4.2 Extra funding sources**

Expected funding from partners/customers – a total estimate.

**Project (****LRIP subproject) Leader** \_\_\_\_\_\_\_\_\_\_/\_\_\_\_\_\_\_\_\_\_\_/

Date of submission of the project (LRIP subproject) to the Chief Scientific Secretary: \_\_\_\_\_\_\_\_\_

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

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

(for extended projects) – Project start year: \_\_\_\_\_\_\_

**Proposed schedule and resource request for the Project / LRIP subproject**

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **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 | 100 | 20 | 20 | 20 | 20 | 20 |
| Materials | 150 | 30 | 30 | 30 | 30 | 30 |
| Equipment, Third-party company services | 350 | 100 | 50 | 100 | 50 | 50 |
| Commissioning |  |  |  |  |  |  |
| R&D contracts with other research organizations | 25 | 5 | 5 | 5 | 5 | 5 |
| Software purchasing | 50 | 10 | 10 | 10 | 10 | 10 |
| Design/construction |  |  |  |  |  |  |
| Service costs (*planned in case of direct project affiliation)* |  |  |  |  |  |  |
| **Resources required** | **Standard hours** |  |  |  |  |  |  |  |
| 101900 | 20380 | 20380 | 20380 | 20380 | 20380 | 139 728 |
| 2500 | 500 | 500 | 500 | 500 | 500 | 2500 |
|  |  |  |  |  |  | 2500 |
| **Sources of funding** | **JINR Budget** | 675 | 165 | 115 | 165 | 115 | 115 | 1190 |
| **Extra fudning (supplementary estimates)** | Contributions by  partners  Funds under contracts with customers  Other sources of funding |  |  |  |  |  |  |

Project (LRIP subproject) 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 |  |
|  |  |  |  |  |
|  |  |  |  |  |
| APPROVED BY THE PAC | \_\_\_\_\_\_\_\_\_\_\_  SIGNATURE | \_\_\_\_\_\_\_\_\_  NAME | \_\_\_\_\_\_\_\_\_  DATE | |