**Extended annotation**

**of the proposal for the extension of the project “Development of the tagged neutron method for determining the elemental structure of matter and nuclear reactions research”**

**(project TANGRA - Tagged Neutrons and Gamma Rays)**

The TANGRA (TAgged Neutrons and Gamma Rays) project is aimed at studying 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 to processing the results of nuclear physics experiments. One of the tasks to be solved within the framework of the project is the interpretation of existing experimental data on the reactions of interaction of fast neutrons with atomic nuclei, their systematization and validation. The priority area of work is the acquisition of nuclear data.

The study of the interaction of neutrons with energies of 14.1 MeV with matter, produced in the reaction d + t → α + n, is currently of particular relevance due to the fact that this reaction is the most promising for controlled thermonuclear fusion. Another application 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). 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 birth. The registration of signals from the detectors of secondary radiation together with the operation of the α-detector built into the generator makes it possible to select events by the time difference between the signals in the detectors. The advantage of this approach is the ability to identify events corresponding to reactions in the object under study, and its application leads to a significant reduction in the contribution of background events to the results obtained.

Reactions (n,xγ) with the emission of γ-quanta are the most accessible for study, since only γ-detectors are required for their registration, and there is no need for vacuum equipment and long flight paths. In addition to γ-rays, these reactions emit secondary particles 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.

The objectives of the proposed project are:

1) Investigation 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 processes under study.

4) Creation and development of a database on the cross sections of reactions of interaction of neutrons with an energy of 14.1 MeV with nuclei of various elements and characteristic γ-lines emitted in these reactions, to expand 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

Despite the rather long history of the study of neutron-nuclear reactions, information about the individual channels of the interaction of fast (14 MeV) neutrons with atomic nuclei remains incomplete. Thus, the most complete collection of information on the cross sections of radiation of γ-quanta by nuclei of various elements at an energy of incident neutrons of about 14 MeV is (Simakov S.P. et al. IAEA, 1998). This compilation contains data for 36 elements and is replete with many inaccuracies and uncertainties. It should be noted that most of the earlier experiments of this type were carried out in the 60s - 80s of the XX century, the completeness and accuracy of the data obtained are insufficient for the needs of modern research. As part of the planned work, it is expected to measure the radiation cross sections of γ-quanta for more than 50 elements, including for 24 elements - for the first time. On the basis of the obtained information, for the first time, a database of sections suitable for the purposes of elemental analysis will be created.

The information obtained in the study of angular correlations of the products of neutron-nuclear reactions is useful for the development of theoretical ideas about the features of these processes. Currently, there is an acute shortage of data on correlations (n, γ) and (n, n’, γ) for inelastic scattering of 14 MeV neutrons: angular distributions with respect to the direction of incident neutrons are unknown for a large number of nuclei, for correlations of the type (n, n ', γ) only a few experiments are known, conducted in the 60 – 80 years of the last century, while a large number of similar data on reactions with protons are known.

One of the new applications of the tagged neutron method is the determination of carbon content in soil, which is one of the most significant natural carbon reservoirs. The need to increase the coverage of monitoring simultaneously with increasing its accuracy and detail in the description of soil organic carbon variability generates a request for the development of a tool base that reduces the amount of sample preparation, the creation of field / mobile versions of instruments / laboratories, automation of analysis, the ability to determine several characteristics in one measurement at once.

The study of reactions of inelastic scattering of neutrons on nuclei will provide additional information on the mechanism of reactions (n,n`), (n,2n`), (n,xn`), for example, the study of the 10B(n, 2n)9B process, and will allow testing and improve the theoretical description of these processes. The implementation of the experimental program of the project is also important for fundamental nuclear physics: neutron-nuclear reactions are one of the main sources of information about the deformation of nuclei, the depth, radius and diffuseness of the potential of nuclear forces. The information obtained from such experiments allows us to refine our understanding of the structure and properties of atomic nuclei.

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 under study 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 emission cross sections of γ-quanta with the maximum achievable energy resolution, for which high purity germanium detectors are used. At present, the installation 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 staged work, which will be completed with obtaining 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 landfill.

As targets, it is planned to use both samples with a controlled chemical composition and samples of real soils. It is supposed to compare the values and accuracy of determining the mass concentrations of elements, obtained by traditional methods of analysis, with the values measured on the created experimental facilities in order to verify the method being developed at the stage of laboratory research.

**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 TNM 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. The developed prototypes of facilities for elemental analysis of soils can become the basis for creating devices useful for intensifying agriculture and monitoring the state of the environment.

**Brief SWOT Analysis**

Strengths of the project:

When implementing the project, it is supposed to use a fairly well-established TNM technique. 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 scientists (up to 35 years). 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 developed techniques will be inappropriate for economic reasons. However, there is no information on the fundamental unsolvability of these problems.

*Estimated project completion time: 2024 - 2028.*

*Estimated cost of the project is 675 k$.*