

## Abstract of the report

E.Lychagin

### Report on the theme

#### **"Investigations of Neutron Nuclear Interactions and Properties of the Neutron" (2020-2021) and a proposal for its extension until the end of the seven-year plan.**

The theme was extended by 3 years (2020-2022) at the 50th meeting of the PAC for Nuclear Physics. Since a decision to extend scientific themes only within the current seven-year plan has been made by the JINR Directorate, the leaders of the theme propose to extend it until the end of the seven-year plan - by 2023. At the same time, during 2022-2023, a scientific research program for the next seven-year period will be drafted and proposed, which will be presented at one of the meetings of the PAC in 2023.

Three projects are being implemented within the framework of the theme. Since 2017 the TANGRA project has been opened and in 2022 two new projects will be opened: the ENGRIN project and the EG-5 Modernization project. These projects will also be proposed to extend for 2023. It is planned that a report on the results of the TANGRA project, as well as on the interim results of the other two projects will be made at the 56th meeting of the PAC.

The most interesting results obtained in 2020 and 2021 in the main research areas of the theme will be presented in the report

#### ***Study of nuclear reactions with neutrons.***

1. The planned measurement of the P-even but pseudo T-odd correlation in triple fission of the form  $\vec{\sigma}_n \cdot [\vec{p}_l \times \vec{p}_t]$ , where  $\vec{\sigma}_n$  is the neutron spin,  $\vec{p}_l$  - is the momentum of a light fission fragment,  $\vec{p}_t$  - momentum of the third particle ( $\alpha$ -particle, neutron or  $\gamma$ ) at a resonance of 1.14 eV of compound nucleus  $^{236}\text{U}$  has not been implemented because of the impossibility of carrying out the required modernization of the neutron beam of the POLIFRM2 facility, resulting from the pandemic. A detailed analysis of the previously obtained results at a neutron energy of 0.06 eV was carried out. The analysis has for the first time allowed to determine and compare the angles of division axis rotation for fission by neutrons with different energies. The results of this analysis were included in the Ph.D. thesis, defended at the end of 2020.
2. Within the framework of the TANGRA project, the angular distributions of gamma quanta in the reaction (n, n' $\gamma$ ) for neutrons with an energy of 14 MeV were obtained for the nuclides  $^{12}\text{C}$ ,  $^{24}\text{Mg}$ ,  $^{52}\text{Cr}$ ,  $^{56}\text{Fe}$  using the "Romasha" detector (out of 18 BGO detectors). In 2021 a PhD dissertation was prepared and defended based on the obtained results. A new setup configuration with a HPG detector has been tested. The angular distributions of inelastically scattered neutrons at  $^{12}\text{C}$  nucleus have been measured. Methodological work is underway to develop a quantitative analysis of the carbon content in soils using the tagged neutron technique.
3. In accordance with the requests of the BROND library and the SSC IPPE, the cross sections of reactions (n, $\alpha$ ) were measured for  $^{14}\text{N}$ ,  $^{35}\text{Cl}$ ,  $^{91}\text{Zr}$ ,  $^{58}\text{Ni}$ ,  $^{60}\text{Ni}$ ,  $^{61}\text{Ni}$  in the energy range 3-5.5 MeV. All these reactions are of great practical importance for nuclear power and even for agriculture (product  $^{32}\text{P}$  can be used to study the absorption of phosphate fertilizers by plants using the radionuclide tracking method). Results in this energy range for  $^{60}\text{Ni}$ ,  $^{61}\text{Ni}$  were obtained for the first time.
4. In collaboration with colleagues from Charles University, Prague, theoretical processing of experimental data on the multiplicity spectra of cascade gamma decay of neutron resonances of the  $^{196}\text{Pt}$  compound nucleus, obtained at the DANCE facility in the Los Alamos laboratory, was carried out. An analysis of these spectra shows that the previously used parameters of the models for describing the radiative strength function and the level density of excited states should be corrected considering the obtained results.
5. Measurements of rare spontaneous fission modes were carried out with a highly active ( $\sim 400$  kBq) sample of Cf-252 together with TU Praga in 2021. Timepix detectors with

modernized electronic boards are used to register light particles. The main goal of the study is to detect quinary fission. The set of statistics within 2 months allowed to confidently distinguish p, d, t,  $\alpha$ , Li, Be, B, C as the lightest particle in triple fission and to determine the spectra of the registered p, d, t,  $\alpha$ . Timepix cluster resolutions makes it easy to separate the ( $\alpha$ ,  $\alpha$ ) and ( $\alpha$ , t) pairs from quadruple fission. In the available results there are events indicating the possibility of the existence of the quinary fission. The set of statistics and data processing will continue.

***Research of quantum-mechanical phenomena with ultracold and cold neutrons, study of neutron properties.***

1. The study of nonstationary phenomena in interaction of slow neutrons by the example of reflection from a traveling surface wave was further carried out. The results obtained in 2019 on a reflectometer with a fixed neutron wavelength (4.3 Å) are satisfactorily described by theory, however, the amplitude of the scattered wave in the new measurements of 2020 by the TOF method (wavelengths 5-20Å) at a fixed scattering angle differs from the expected ones by almost 2 times.
2. The change observed in the energy and velocity of UCN after passing through a refractive sample, oscillating with variable acceleration, led to the statement that the result of the interaction of a particle with any object moving with acceleration should lead to change in its energy and frequency, determined by the relation  $\Delta\omega = ka\tau$ , where  $k$  is the wavenumber,  $a$  is the acceleration of the object, and  $\tau$  is the interaction time. To verify this statement, a series of calculations of neutron reflection from various potential structures were carried out. The obtained results indicate the validity of the conclusion. Simulation of reflection from an oscillating potential structure using various methods has shown that in resonance (when a large group delay occurs), the results of numerical calculations differ from calculations in approximations that admit an analytical solution. The discrepancy requires additional analysis.
3. Activities have started on the preparation of a test experiment at IBR-2 to demonstrate the possibility of temporal focusing of UCN. A moving diffraction grating was chosen as the focusing device. Its parameters have been determined, and the neutron guide system is being calculated. Successful implementation of the test measurement opens prospects for creating a high-density UCN source at the IBR-2 reactor (and furtherly at the new pulsed neutron source of JINR).
4. As a part of creating a very cold neutron source (VCN) prototype based on nanodiamond reflectors, a procedure has been developed that allows one to compare the reflectivity of various nanodiamond powders. Experimental determination of albedo requires a lot of material. The amount of synthesized material is not large. Having 1-10 grams of diamond powder, it can be characterized by the SANS method using a cold neutron beam. From this measurement, the parameters of the physical model used to describe the transport of VCN in the powder are extracted and then a model calculation of the albedo is carried out. The correctness of this procedure was verified using experimental data on the transmission of CN through a thick sample. A comparison is made of powders with different dimensional and structural characteristics. A powder with optimal properties for use as a nanodiamond reflector in the design of a prototype of an VCN source has been determined.

A large number of analyzes of micro-impurities of powders were carried out during their modification and during development of the procedure of powder purification from impurities.

An experimental setup for a prototype is being designed.

***Applied research with the use of nuclear physics methods***

Activities are widely performed using various nuclear physics techniques for problems of ecology, materials science, archeology, art history, medicine, research of objects of extraterrestrial origin, etc. These activities are carried out in collaboration with a great number of researchers from various research institutes of the JINR member states and Russia. Several examples of these studies will be presented in the present report.

1. In 2020, an atlas of atmospheric fallout of heavy metals "Mosses as Biomonitors of Air Pollution: 2015/2016 survey on heavy metals, nitrogen and POPs in Europe and beyond" was published at JINR, which included the results for 36 countries, including 14 JINR member states: Armenia, Azerbaijan, Belarus, Bulgaria, Vietnam, Georgia, Kazakhstan, Moldova, Mongolia, Poland, RF, Romania, Slovakia, Ukraine and Czech Republic. The data on the immediate collection of biomonitor moss over large areas, presented in the atlas, allowed to assess both spatial and temporal trends in changes in the concentrations of heavy metals, as well as to identify areas with a high level of pollution as a result of local and transboundary transfer of metals.
2. A cotton roll of cloth located by cosmonauts on the outer surface of the ISS and kept there for 10 years has been investigated. Using neutron activation analysis (NAA), it was possible to determine the content of 39 elements in a contaminated fragment of tissue and 19 elements in a clean fragment. Three main sources of elements deposited on the cloth have been identified. One of the important sources can be considered dust particles formed during the fall of meteorites, asteroids or comets. The second source is the materials of the station itself (Al, Ti, etc.). The third source of deposition of elements on the convolution can be considered particles ejected from the Earth, for example, volcanic ash. Ionized particles from the volcano's gas and dust emissions can enter the upper part of the ionosphere at the altitude of the ISS orbit from the ascending branch of the global electrical circuit.
3. In cooperation with the Institute of Microbiology and Biotechnology, in Chisinau, the effect of unmodified (AgNPs) and modified by *Spirulina platensis* biomass silver nanoparticles (AgNPs-Spirulina) on rats was studied. The silver content in the organs was determined by the NAA method. In animals that were injected with unmodified nanoparticles, the highest silver content was found in the brain and kidneys, while in animals that were injected with AgNPs-Spirulina, silver was mainly accumulated in the brain and testes. After a half-life, silver is rapidly cleared from the spleen and kidneys; however, clearance from the brain was very low, regardless of the type of nanoparticles.
4. The results of elemental and complementary methods of analysis of cultural heritage samples are used to solve pressing problems in the humanitarian sciences. Cooperation with the Institute of Archeology of the Russian Academy of Sciences, the State Institute of Art Studies, the Museum and Exhibition Complex "Volokolamsk Kremlin", the Museum of Dubna is performed.

A unique pre-Mongolian fresco painting of the 12th century of one of the most ancient monuments of Russian architecture - the St. George Cathedral of the Yuriev Monastery in Veliky Novgorod (1119) was investigated, the painting technology was determined (mixed: al fresco and al secco), the use of an extremely expensive imported lapis lazuli was revealed, on the basis of which important conclusions were made about the status of customers. The analysis of the process of changing the color of paintings during aging and under fire conditions has been carried out. The information obtained is necessary for the justified conduct of experiments on digital reconstruction of the original color. The issue of searching for criteria for determination of the place of origin of archaeological ceramics by analyzing its elemental composition with the use of the methods of mathematical statistics is widely performed.

***Operation and development of the IREN facility.***

1. In 2020 - 2021 IREN worked 2700 hours for a physical experiment, of which 100 hours in 2021 at a frequency of 50 Hz. At the end of November 2021, the klystron of the first accelerating section failed. Work is underway to replace it. The facility is scheduled to resume operation in the first quarter of 2022.
2. In 2020, a set-up for activation analysis at IREN with a pneumatic transport was put into operation. In 2021, for the first time at IREN, test measurements of gamma activation were carried out on a gamma-producing target.
3. The stage-by-stage implementation of the project for the reconstruction of the premises of the beam infrastructure of the IREN experimental areas has been started. The cranes in the experimental halls were replaced, which allows to start dismantling activities of the old equipment. the reconstruction on beamlines 1, 6 is almost over.

The tasks for 2023, that will be solved within the framework of the theme are also presented in the report. In the field of scientific research, these tasks are:

1. Measurement of gamma-ray spectra in s- and p-resonances, to search for P-even and P-odd effects in reactions with slow polarized neutrons.
2. Obtaining nuclear data for nuclear power and astrophysics: measuring integral and differential neutron cross sections, angular correlations in the energy range from cold neutrons up to  $\sim 1$  GeV.
3. Measurement of mass-energy and angular distributions of fission fragments, neutrons, and gamma-quanta from fission; search for rare fission modes.
4. Measurement of cross sections and angular correlations in reactions  $(n, n'\gamma)$  and  $(n, 2n)$  in the interaction of fast neutrons with nuclei (TANGRA project).
5. Development of the experimental technique for measuring of the neutron lifetime on the extracted beams of the IBR-2 and IREN reactors (original, beam method).
6. Investigation of nonstationary quantum effects and models of interaction with diamond nanostructures for slow neutrons.
7. Determination of the elemental composition and surface structures of various samples by nuclear-physical methods for solving problems of materials science, ecology, history, archeology, art history, restoration, and life sciences.

In the field of methodological and applied work:

1. Regular and stable work of IREN for a physics experiment. Increasing the IREN intensity by increasing the pulse frequency.
2. Developing of neutron polarization methods for experiments to search for the effects of parity violation and time invariance in neutron-nuclear interactions.
3. Modernization of the EG-5 electrostatic generator, increasing of the instrumental base of the accelerating complex.
4. Creation of a prototype of a very cold neutron source and its testing on the extracted neutron beam of IBR-2 or the HFR reactor (Grenoble, France).
5. Preparation of a test experiment for UCN time focusing feasibility at IBR-2.
6. Creation and development of neutron and gamma detectors for spacecraft.
7. Creation of methodology for gamma-activation analysis and PGAA technique for the IREN facility.

The PAC members will also be informed about the current state of work on the development of a new neutron source at JINR.