“Research activities under the theme “Investigations of neutron nuclear interactions and properties of the neutron”: status and prospects”

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Annotation.

At the 50th meeting of the PAC for Nuclear Physics, a rather detailed report on the theme was presented and the main results obtained during 2017-2019 were shown in the report presenting materials for the theme extension for three years.

This report will present the results obtained in recent months and the prospects for the further development of scientific works in various areas:

– Research of quantum-mechanical phenomena with ultracold and cold neutrons, the study of the properties of a neutron;

– Study of nuclear reactions caused by neutrons;

– Applied research using nuclear physics methods.

of quantum-mechanical phenomena with ultracold and cold neutrons, the study of the properties of a neutron.

1. Three active groups work in these areas. Prof. A. Frank’s group is engaged in the study of neutron interaction with a substance moving with giant acceleration in order to determine the limits of applicability of the standard dispersion law for a neutron in a medium. They prepared an experiment, which was postponed to the beginning of 2020 and carried out simulations that can be used to interpret the experimental data. Prospects for the development of this direction will be clear after the experiment and analysis of the results.

An interesting and promising research area of this group is the theoretical study of time focusing of UCNs using a moving interference grating in a wide range of velocities. The possibility of such focusing has been demonstrated experimentally earlier. A practical solution to the issue of time focusing of UCNs opens a way to the creation of a high density UCN source at a pulsed neutron source and is an extremely promising and important research area for FLNP.

2. A group headed by the leading researcher A. Strelkov has recently been studying the processes of scattering of ultracold, very cold and cold neutrons by diamond nanoparticles and powders. The study of the interaction of UCNs with surface nanoparticles is associated with the problem of small energy increase of UCNs at a trap surfaces reflection. The group plans to realize measurements with specially prepared samples to confirm its assumptions regarding the mechanism of low energy transfer. The experiment is scheduled for 2021.

Considerable work has been done to determine the optimal parameters of diamond nanopowders aimed at creating effective reflectors for VCN and CN. This work includes a significant amount of measurements (activation analysis, X-ray diffraction, small-angle neutron scattering, determination of hydrogen impurities by prompt gamma analysis) performed to determine the characteristics of different powders and the development of theoretical models that allow calculations of neutron transport in powders with parameters extracted from the experiments. This study should be finalized by the creation of a prototype of very cold neutron source. It should be based on a nanoparticle reflector and its effectiveness should be illustrated at an extracted beam of thermal or cold neutrons experimentally. The current work is a part of the European grant CREMLIN + with the participation of European and American concerned researchers.

3. At the 50th meeting of the PAC, a report was presented on the intention of opening a project within the framework of a topic dedicated to the study of the possibility of measuring the neutron lifetime on the IBR-2 reactor beam. The original idea of Dr. V. Kuznetsov is based on the determination of the change in the shape of the neutron spectrum obtained by the time-of-

flight method with an increase in the flight pass. Following the recommendations of the PAC, measurements have been carried out in the 7 - 9th cycles of the IBR-2 reactor with a point detector in order to demonstrate the stability of the recorded spectra. The achieved results are being processed, the preliminary analysis and a plan for the further work will be presented in the report. The issue on the appropriateness of allocation of these studies will be decided based on test measurements in the form of a project.

Study of nuclear reactions caused by neutrons.

In this area, studies are carried out related to the issues of fundamental symmetries breaking, studying reaction mechanisms and accumulating nuclear data.

1. In 2015-2016 a set of measurements of spatially odd (P-odd) asymmetries were carried out at low-nucleon systems. These were, namely, the asymmetries of products emission relative to the direction of the neutron spin at reaction with cold polarized neutrons. Investigations of low-nucleon systems make it possible to describe weak nucleon-nucleon interactions from the "first principles".

Unique results in accuracy were obtained in the experiments for three reactions performed by the PNPI-JINR-ILL collaboration., From the results, a constraint on the weak π-meson coupling constant of the weak nucleon-nucleon potential was obtained. The working equipment still exists at FLNP and a measurement procedure has been developed and used successfully. Using new methodological developments in neutron polarization it is possible to improve the accuracy of the implemented experiments. The possibility of measuring the asymmetry of particle ejection in the output channel relative to the direction of the neutron spin in the ^{3}He(n,p)^{3}H reaction is considered in the future. Such kind of measurement can be realized at high-flux reactors as the ILL reactor and/or PIK (Gatchina). The preparation activities to this measurement require significant modernization in the existing equipment. In 2020, it is planned to carry out model calculations to select the design of the installation and determine its sensitivity.

Another approach is possible to determine the contribution of weak interaction in reactions with heavier nuclei. It has been shown theoretically and experimentally that near the p-wave resonances, both P-odd effects and P-even effects, for example, "forward-backward" and "left-right" correlations, are amplified. The first ones contain information about the matrix elements of the weak interaction of Hamiltonian, and the second ones - about the resonance parameters that must be known to extract these matrix elements. For more accurate interpretation of the previously obtained data, at present, one can start measuring P-even correlations of the "forward-backward" type at the IREN facility. The necessary equipment for such experiments is available. The measurements of left-right correlation require polarized neutrons.

2. Experiments are carried out to study the P-even but T-odd correlation in triple fission of the form $\overrightarrow{\sigma_n} \cdot [\overrightarrow{p_l} \times \overrightarrow{p_t}]$, where $\overrightarrow{\sigma_n}$ is the neutron spin, $\overrightarrow{p_l}$ is the momentum of light fragment fission, $\overrightarrow{p_t}$ is momentum of the third particle (α-particle, neutron or γ). The existence of this correlation has been established in all its forms while studying polarized cold and thermal neutrons at beams. This correlation is not perceived as significant evidence of violation of T-invariance, since its appearance can be caused by interaction in the final state. The most attractive explanation of the phenomenon is the hypothesis of the transition of the compound nucleus spin to the rotation of fission fragments (the so-called ROT effect), which leads to a shift in the angular distributions $\overrightarrow{p_t}$ for third particles relative to the final direction $\overrightarrow{p_l}$ being formed at the moment of fission. The observed effects have many features that require explanation: a) what is the mechanism of spin transfer of the compound nucleus to the orbital moment of fragments; b) why do the effects for α particles on the ^{233}U and ^{235}U nuclei have the same signs and are different for the γ quanta; c) what is the reason for the appearance of an impurity of the double-angle dependence, which is particular to the T-odd five-vector correlation in the angular

distributions: $\overrightarrow{\sigma_n} \cdot (\overrightarrow{p_l} \cdot \overrightarrow{p_t}) \cdot [\overrightarrow{p_l} \times \overrightarrow{p_t}]$. Outside resonances, effects are considered to be a mixture of effects from two spin components of the compound nuclei $J^+ = I + 1/2$ and $J^- = I - 1/2$. Therefore, due to their opposite directions of polarization, the effects are different in nature. In addition, knowledge of the contributions of these states to the cross section of the fission reaction is necessary. Further, for these states there can be different efficiency of the spin transfer of the compound nucleus to the orbital moment of fragments. Determination of this efficiency for different spin states, in fact, is one of the goals of the research. This suggests that the mentioned effects must be investigated in resonances.

In 2019, an analysis of the experimental data previously obtained at the MEPHISTO and POLI facilities at the FRM-II reactor in Germany was carried out, as well as methodological work was performed to prepare measurements at a resonance of 1.14 eV of 235U. The values of the angular correlation coefficients for the gamma rays ROT effect were obtained for 235U at neutron energies 0.004, 0.06, and 0.3 eV. The design of a new collimator for the POLI facility has been developed. It allows to perform measurements at neutron energies up to 1.5 eV. The modernization of the experimental facility is realized which allows to increase the effect accumulation rate nearly by an order of magnitude.

In 2020-2022 comparative measurement of the T-odd ROT effect for nuclei ^{235}U and ^{233}U, preparation and realization of the experiment at the second resonance ^{235}U (1.14 eV), implementation of test measurements at the IBR-2 reactor with the purpose of studying the possibility of research of similar T-odd effects using the time-of-flight technique are planned.

3. To expand the methods and capabilities in realization of the experiments, it is planned to create a polarized nuclear target obtained by dynamic pumping of polarization (DPP). The availability of such target will allow to carry out experiments with polarized neutrons and polarized nuclei. For example, the study of P-odd effects and ROT effects can be performed at a new qualitative level. It will become possible to obtain spin-separated cross sections of various nuclear reactions and, firstly, of (n, f) reactions. They are very important for fundamental and applied applications. At the previous meeting of the PAC the report of Dr. V. Novitsky was dedicated to the intention of singling out the work directed to creating a polarized nuclear target in a separate project within the framework of the topic. Currently, a schedule of necessary activities and determination of necessary resources are prepared.

4. The experimental investigations of various characteristics of PFN emission are necessary to understand the nuclear fission dynamics from the scission point to the rupture. One of the interesting observations is the increase in the PFN multiplicity from the heavy fragment with an increase in the excitation energy of the fissile system, which still lacks clear explanation. For systematic study of correlations between the characteristics of fragments and neutrons an experimental facility was developed and tested to which Dr. Sh.Zeinalov's report is dedicated. The first experiments with the new facility at IREN were planned with ^{252}Cf and ^{235}U targets, a target that was used to obtain reference distributions of the MND in the ^{235}U (n_{th},f) reaction.

5. In the framework of the TANGRA project, measurements of the yields and angular correlations of gamma rays generated by the interaction of 14.1 MeV neutrons with various nuclei were carried out furtherly using the tagged neutron method. The main objectives of this study are:

- Creation of a theory that describes the angular distributions of gamma rays in inelastic neutron scattering, obtaining acceptable agreement between the experimental data on angular correlations and theoretical calculations.

• Creation of a database of gamma rays generated from various isotopes by irradiation of 14.1 MeV neutrons. Development of the method of non-destructive elemental analysis based on the method of tagged neutrons.

In 2020-2022 modernization of the TANGRA facility using a detector from ultrapure Germanium, further measurements of yields and angular correlations of gamma rays, measurement of reactions (n, 2n) and (n, f), theoretical analysis of experimental data, development of methods for the analysis of kimberlite ores in order to detect large diamonds are planned.

6. Research of the reactions (n, p) and (n, α) on resonant and fast neutrons is underway. In October-November, measurements were carried out on the reaction $^{14}N(n,\alpha)^{11}B$ at E_n=4,25-6,0 MeV, $^{58}Ni(n, \alpha)$ at 4.75, 5.0, 5.25, 5.5 MeV and $^{60,61}Ni(n, \alpha)$ at 5.0, 5.5 MeV. The data is being processed. These studies are motivated both by the needs of astrophysical research, and by a request for nuclear data from nuclear power. As it is known, the creation of nuclear databases is overseen by IAEA and national centers. FLNP JINR participates in the creation of the national library of nuclear physical data BROND. The subject of research and development on the part of FLNP is to obtain new experimental information on the reaction cross sections (n, α) for the following nuclei: ^{14}N, ^{35}Cl, ^{56}Fe, ^{91}Zr, ^{6}Li. As a part of the work, methodological studies are carried out aimed at improving the metrological characteristics of the measuring devices used to obtain experimental data for the reactions mentioned above.

At the IREN beam Dr. Yu. Gledenov and his team plan to measure the cross sections of the reactions $^{6}Li(n,\alpha)^{3}H$, $^{3}He(n,p)^{3}H$, $^{14}N(n,p)^{14}C$, $^{35}Cl(n,p)^{35}S$ iside the neutron energy range of 1 eV-100 keV.

Applied research using nuclear physics methods

1. On a full-scale, work is underway using the NAA technique. Within the framework of the international program “Atmospheric Deposits of Heavy Metals in Europe - Estimation Based on the Analysis of Biomonitor Mosses,” the biomonitoring work was completed in the Moscow Region, Georgia, Tajikistan and Vietnam. The method of active biomonitoring using the technology of moss transplants was applied for the first time in the territory of recreational areas of Moscow in order to determine air pollution by heavy metals. These activities will be performed fourthly.

Concentrations of 40 elements in the tissues of mussels selected at various points along the coast of South Africa were determined as a part of biomonitoring program. Preliminary results showed that the concentrations of Ti, Cr, V, Sc, Th reached high values at almost all stations and areas along the coast of South Africa. This study will continue as a part of the Mussel Watch project, expanded to new areas on the African coast and other mollusk species.

A range of activities was carried out to extract metals from complex chromium and copper-containing wastewaters using several types of biological sorbents: yeast *Saccharomyces cerevisiae* (brewing waste), a combined sorbent - bacteria *Shewanella xiamenensis* immobilized on zeolites, and the biomass of cyanobacteria *Spirulina platensis*. The work will be continued in order to assess the effectiveness of the use of the proposed sorbents for the extraction of metals from other types of metal-containing wastewater.

For the first time, the effects on the offspring of silver nanoparticles from the mother’s body during the prenatal and lactation periods were investigated. Comparison of the levels of cognitive functions of young animals, as well as the silver content in various organs (blood, liver, lungs, kidneys and brain) of females and their offsprings was determined by neutron activation analysis. The accumulation of titanium dioxide nanoparticles by medical plants was studied using various methods of introducing nanoparticles. Further research as carried out in a new promising area - the determination of the elemental composition of plants used in medicine.

The chemical composition of the composite materials in the B-N-Al-Ti system obtained by exposure to high pressures and temperatures was determined by the NAA method. 28 elements were identified in the synthesized samples, including five ones transferred from the equipment for synthesis. The elemental composition of the filters delivered from the international space station was measured in order to determine the elements leading to corrosion of the station coating.

2. In the second half of 2019, the new administrative group “EG-5 Facility” was formed as a part of the Neutron-nuclear interaction research sector at Nuclear Physics Department in order to expand the functionality of the EG-5 accelerator and to strengthen the related research areas at FLNP and JINR as a whole.

A concept for the development of the group for the near future is worked out, a draft project of the accelerator modernization is prepared. This information will be presented in the report of A. Doroshkevich.

3. Currently, a method of neutron resonance spectroscopy determining the elemental composition of samples is developed at the Frank Laboratory of Neutron Physics. The method is based on recording neutron resonances in radiation capture and measurement of the yield of reaction products in these resonances. Research is performed on the neutron beam of the IREN pulsed neutron source using the time-of-flight technique. A cylindrical multisection liquid scintillation detector is used for registration of gamma-quanta. A new detector with a high aperture is being created.

The main advantages of the neutron resonance analysis are: non-destructive nature, sensitivity to the isotopic content of the element, the fundamental possibility of studying samples of any shape and size, the practical absence of induced activity. This makes it a promising method for the research of cultural heritage items and archaeological artifacts.

4. It is planned to create a facility based on the HPG detector for measuring the isotopic composition of samples by prompt gamma analysis at the 11b channel of the IBR-2 reactor. This technique is widely demanded in various fields of research.