NEUTRON NUCLEAR PHYSICS

In 2015, in FLNP the scientific activity in the field of neutron nuclear physics was carried out in the following traditional directions: investigations of time and space parity violation processes in neutron-nuclear interactions; studies of the fission process; experimental and theoretical investigations of fundamental properties of the neutron; gamma-spectroscopy of neutron-nuclear interactions; atomic nuclear structure, obtaining of new data for reactor applications and for nuclear astrophysics; experiments with ultracold neutrons, applied research using NAA. The scientific program to study the inelastic scattering of fast neutrons made into a separate project "TANGRA" was successfully implemented. A number of investigations in the field of fundamental physics and ultracold neutron physics were performed on the neutron beams of nuclear research centers in Germany, China, USA, France, Switzerland.

Of particular note is the accurate implementation of the planned activities on the modernization of the IREN facility aimed to ensure that in 2016 two accelerating sections of the accelerator will operate.

Experimental and methodological investigations

Investigations of prompt fission neutrons

In 2015, the first stage of works on the development of a facility for studying prompt neutrons from fission induced by low-energy neutrons was completed, which resulted in the construction of a setup consisting of a double ionization chamber (DIC) with Frisch grids (see **Fig. 1**). DIC is designed to measure masses, kinetic energies of correlated fission fragments and angles between the fission axis and the normal to the target plane.

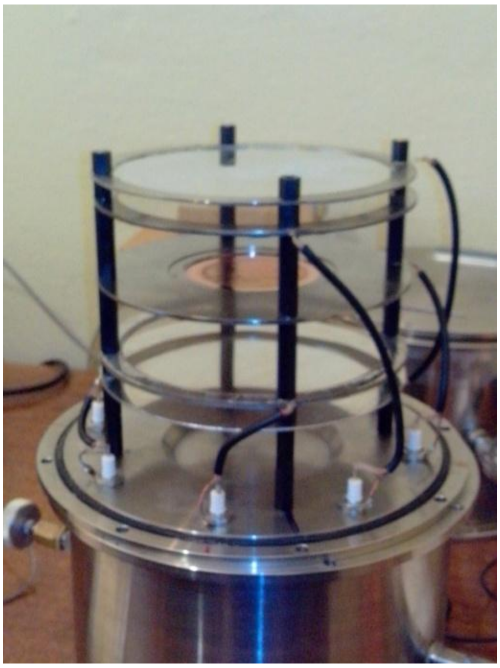


Fig. 1. *Double ionization chamber with Frisch grids with a target mounted on a common cathode.*

A fast neutron detector (FND) on the basis of liquid scintillator BS-501A from Saint-Gobain is located at a distance of ~0.7 m from the target along the normal to its center and allows one to determine the angle between the direction of motion of prompt fission neutrons and fission fragments.

The determination of energy of prompt fission neutrons is realized by measuring the time of flight using a cathode signal as a "T-zero" signal and an FND signal as a "Stop" signal. A schematic of electronic equipment and acquisition system is shown in **Fig. 2**.

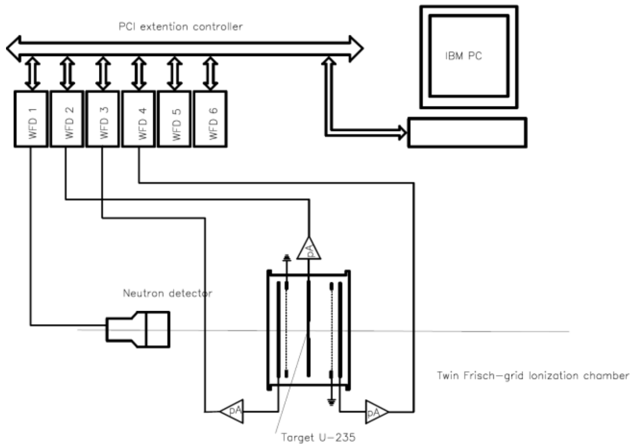


***Fig. 2**. Schematic of a setup for studying prompt fission neutrons.*

It consists of current amplifiers with cathode and two anode circuits. Signals from the outputs of amplifiers and fast neutron detector arrive to the inputs of digitizers from "SPECTRUM-INSTRUMENTATION". The digitizers are mounted on an autonomous bus PCI-Express, which is connected to a PC via a fiber-optic communication line SONET.

The detector signals are digitized simultaneously in six channels at a rate of 250 MHz and amplitude resolution of 12 bits. The start of ***digitization*** is given during the registration of a fission fragment using the signal from the DIC common cathode. The setup was tested on thermal neutron beamline 11B of the IBR-2 reactor. Some preliminary results of the measurements are shown in **Figures 3, 4**.

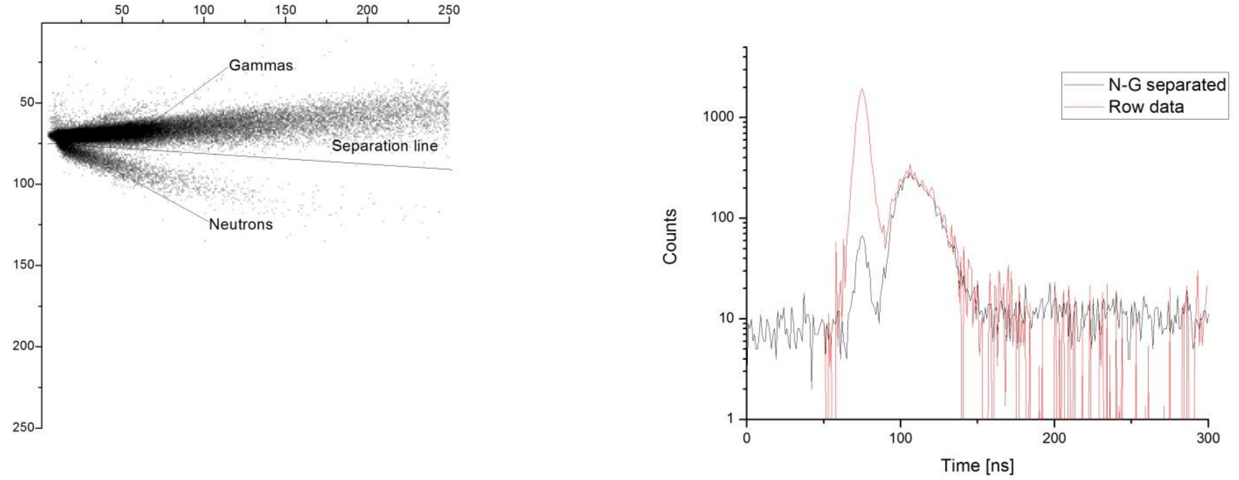


***Fig. 3.** Separation of events of registration of neutrons and γ-rays using the two integral method (left). TOF spectra of prompt fission neutrons (right): initial data (red line) and after separation of neutrons and γ-rays (black line).*

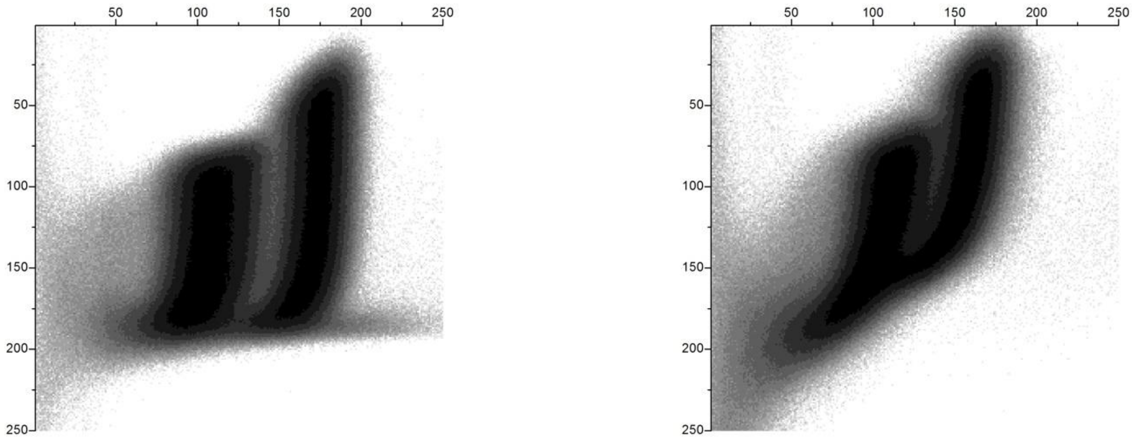


Fig. 4. Two-dimensional distributions of fission fragments in the coordinates of amplitude-time of charge collection on the anodes of DIC: for the anode from the side of the target layer (left) and for the anode from the side of the substrate (right).

Monte-Carlo calculations of angles between directions of motion of two light charged particles in "pseudo"-quaternary fission

A lot of experiments have been devoted to the study of charged particles from ternary and quaternary fission, in which in addition to two heavy fragments, one or two lighter charged particles are emitted. If the emitted particle is unstable, it may in turn decay during its travel. The use of position-sensitive detectors makes it possible to identify such events by finding two particles detected simultaneously in different parts of one or two detectors. Timepix detectors are convenient for detecting such events. We have developed two ΔE-E telescopes to study light unstable charged particles from the spontaneous decay of ^{252}Cf. Of particular interest is the study of the emission of two unstable particles: ^{8}Be and ^{7}Li. In the decay of ^{8}Be two alpha-particles should be detected, and in the decay of ^{7}Li — an alpha-particle and tritium nucleus. The decay of ^{8}Be has three channels, which can be separated. These channels are the decay of ^{8}Be in the ground state, and two variants of decay when ^{8}Be is in the first excited state and the second excited state. In the case of ^{7}Li it makes sense to consider three variants of decay: when ^{7}Li is in the first, second and third excitation levels. Decay channels of particles under study are separated by the registration of the distance between two charged particles simultaneously detected by position-sensitive detectors. Knowing the energy of flying particles and the positions and sizes of telescopes, one can calculate the distances. Monte Carlo calculations of three variants of ^{8}Be decay and three variants of ^{7}Li decay have been performed. As a result of the calculations it has been found that in a real experiment in the case of ^{8}Be the events from two decay channels can be obtained: from decay of ^{8}Be in the ground and first excited states. In the case of ^{7}Li it has been revealed that three decay channels cannot be separated using the developed setup, and one can only study the total contribution of these channels.

Measurement of T-odd effects in ^{235}U fission on a hot source of polarized neutrons

In the framework of the FLNP-ITEP collaboration a series of experiments have been conducted to measure the ROT-effect for studying prompt γ-rays and neutrons in binary fission of ^{235}U and ^{233}U induced by polarized cold neutrons. In 2015, at the facility POLI (FRM-2, Garching) beam time (11 days) was allocated to conduct an experiment to measure the effect of rotation of the fissioning nucleus in the resonance region of ^{235}U at an energy of 0.3 eV on the beam of polarized resonance neutrons being constructed (hot source of neutrons). In July of 2015 the first experiment to measure the ROT-effect in the resonance region was carried out. The experimental setup is shown in **Fig. 5**.

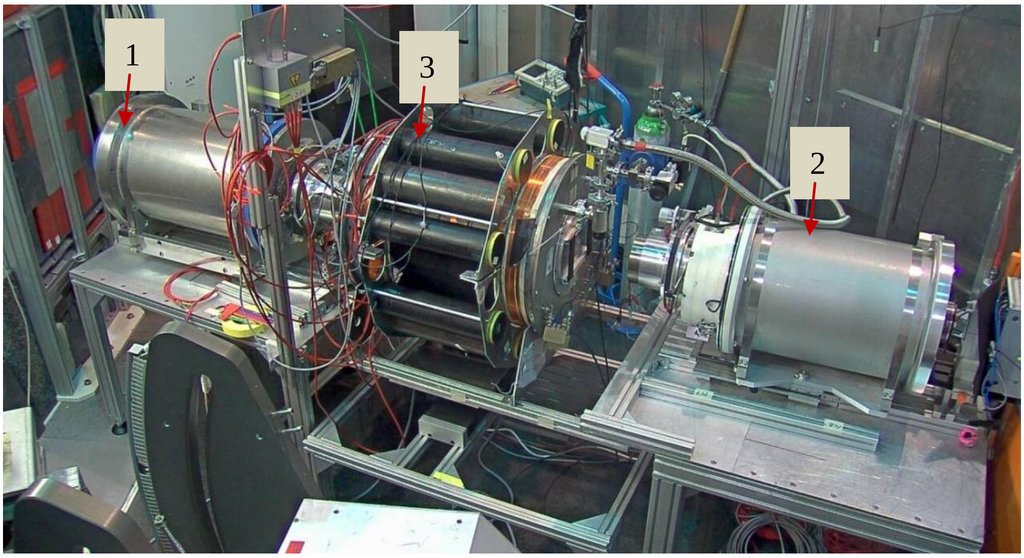


Fig. 5. A setup for measuring the ROT-effect on the POLI instrument (FRM-2, Garching). 1 – neutron polarizer, 2 – analyzer, 3 – fission chamber surrounded by detectors of gamma-rays and neutrons.

The neutron beam with an energy of 0.3 MeV was cut using a mosaic single crystal diffractometer and focused on the target. A neutron polarizer on the basis of a polarized ^{3}He cell with an average polarization of ~70% was placed between the diffractometer and the target. The polarized neutron flux density at the target was ~5x10^{6} n/cm^{2}/s. The polarization was controlled by a similar analyzer and measured using the readings of neutron counters.

Since the neutron beam should be longitudinally polarized at the target and a ^{3}He polarizer produces a vertically polarized beam, additional magnetic coils have been installed, thus providing an adiabatic spin rotation by 90° in the target. The direction of the magnetic field in the coils changed once per second, which created an analogue of a spin-flip and allowed us to measure the difference effect.

A schematic of the fission chamber is shown in **Fig. 6**.

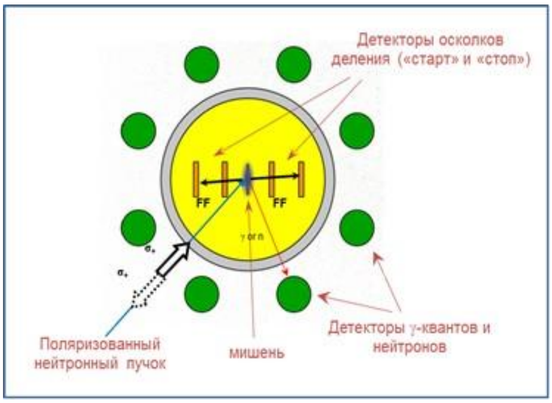


Fig. 6. Fission chamber with a ^{235}U target.

Fragments were detected using fast multiwire detectors and separated into light and heavy ones by the time of flight. Gamma-rays and neutrons were detected by scintillation counters (plastic, NaI(Tl)) positioned at specific angles to the direction of emission of the fragments. We measured the so-called TRI-effect (up-down emission asymmetry) and the ROT-effect (rotation of the fissioning system in or against the direction of the angular momentum transferred by a polarized neutron).

The search for the effect was conducted during 48 hours with a polarized beam and 12 hours with a non-polarized beam (measurements of zero-effect). The statistical accuracy achieved was of the order of $2\text{-}5\times10^{-3}$ (depending on the detector), which was not enough to observe the desired effect. Nevertheless, the experiment has demonstrated a principal possibility to measure such an effect with the POLI instrument with the required accuracy of better than 10^{-3}. The adjustment of the equipment, as well as the check of the background conditions and the rate of statistics collection have been carried out. On the basis of the results of this experiment, a new proposal to the POLI instrument for a longer beam time has been submitted and approved by the Program Committee. In 2016, a new experiment is planned, in which we expect to observe the effect or determine its upper limit with the accuracy comparable to that obtained on the cold neutron beam.

Measurement of the angular distribution of γ-rays with an energy of 4.43 MeV produced in the inelastic scattering of neutrons with an energy of 14.1 MeV by carbon

One of the first experiments planned in the framework of the project «TANGRA» (TAgged Neutrons and Gamma RAys), is the measurement of angular correlations of γ-rays and neutrons produced in the reaction of inelastic scattering of neutrons with an energy of 14.1 MeV by carbon nuclei:

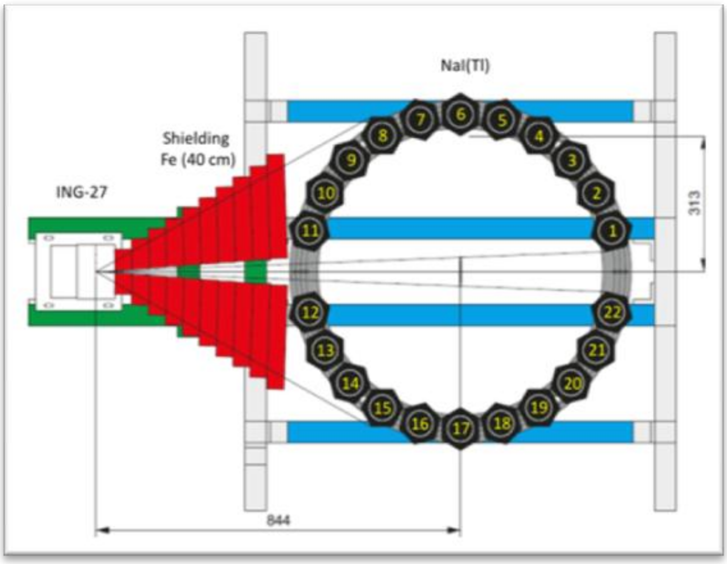
$$^{12}C(n,n')^{12}C^* \xrightarrow{\gamma} {}^{12}C$$

The result of this experiment will make it possible not only to make a correct comparison with the experimental data obtained earlier in the experiments studying the characteristics of the reaction and significantly differing among themselves, but also to obtain information on the mechanism of inelastic scattering of fast neutrons by carbon nuclei. It should be noted that in the framework of the project «TANGRA» it is planned to carry out a series of experiments for a detailed study of the inelastic scattering of fast neutrons by ^{12}C, ^{14}N, ^{16}O, ^{27}Al, ^{56}Fe, ^{37}Cl, ^{32}P and other nuclei using the tagged neutron method (TNM).

In addition, the interest in the study of these reactions is dictated by the need to address many applied problems basing on the use of TNM and connected with mineralogy and geology of the Earth, determination of the elemental composition of rocks, as well as with the creation of algorithms and devices for detection of hidden dangerous substances (explosives, narcotic and highly toxic substances).

A schematic of the experimental setup is presented in **Fig. 7a**, and its general view is given in **Fig. 7b**.

As a source of neutrons with an energy of 14.1 MeV, we used a portable neutron generator ING-27 developed and manufactured at the *N.L.Dukhov* All-Russia Research Institute of Automatics (VNIIA). To form a tagged neutron flux, the generator comprises a built-in silicon double-sided strip detector that consists of 8 mutually perpendicular strips on each side forming an 8x8 matrix of 4x4 mm^2 pixels. The total active area of the 64-element α-detector is 32x32 mm^2. The alpha-detector is located 62 mm away from the tritium target of the neutron generator and intended to detect α-particles with an energy of 3.5 MeV produced in the reaction $d + t \rightarrow \alpha(3.5\,\text{МэВ}) + n(14.1\,\text{МэВ})$.



a) b)

Fig. 7. ***a)**. A schematic of the experimental setup;* ***b)** A general view of the setup.*

Twenty two detectors of γ-rays on the basis of NaI(Tl) crystals shaped as hexahedrons (distance between the crystal faces – 85 mm, the crystal height – 200 mm) were used as detectors of characteristic nuclear γ-radiation with an energy of 4.43 MeV from carbon. The γ-ray detectors were arranged perpendicularly to the horizontal plane in a circle of radius of 370 mm with a carbon target placed in its center. The angle between the axes of two adjacent NaI(Tl) crystals in the horizontal plane was 15º.

In the experiment, for each detector the number of detected events corresponding to the total absorption peaks for gamma-rays with an energy of 4.43 MeV (detected in coincidence with the central pixel of alpha-detector) was determined. Then, the obtained number of events was averaged for each pair of γ-detectors located symmetrically at a specified polar angle relative to the axis of the central tagged neutron beam.

To describe quantitatively the anisotropy of the angular distribution for γ-rays generated in the inelastic scattering reaction, the anisotropy parameter W is used. It is defined as the ratio of the number of events detected by the detector positioned at an angle θ to the number of events detected by the detector positioned at an angle of 90º:

$$W(\theta) = 1 + a\cos^2\theta - b\cos^4\theta \, .$$

Figure 8 shows the anisotropy parameter for γ-rays generated in the course of the reaction of inelastic neutron scattering from carbon as a function of the polar angle obtained from the experimental data processing. The errors in the angle (angular resolution of the detector) were obtained by the Monte Carlo simulations using the Geant4 package. The obtained angular dependence can be described using the above formula with the parameters $a = 2.47 \pm 0.10$ and $b = 2.04 \pm 0.12$. The Figure also shows a comparison with the experimental data obtained in other studies and a theoretical curve from the ENDF/B-VII.1 library.

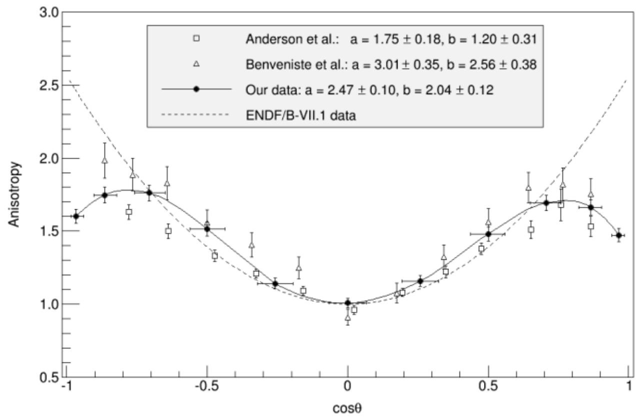


***Fig. 8**. Angular dependence obtained from the experimental data in comparison with the evaluated and other experimental data.*

Investigations of (n,p), (n,α) reactions

The experimental and theoretical investigations of the (neutron, charged particle) reactions induced by fast neutrons have been conducted. The experiments were carried out at the Van de Graaf accelerators EG-5 in FLNP JINR and EG-4.5 of the ***Institute of Heavy Ion*** Physics of Peking ***University***. Data on the neutron reactions with the emission of charged particles induced by fast neutrons are of much interest for studying the mechanisms of nuclear reactions and atomic nuclear structure as well as in choosing engineering materials and in performing calculations in the development of new facilities for nuclear power engineering.

In 2015, the data treatment for the measurements of the ^{40}Ca(n,α)^{37}Ar and ^{54,56,nat}Fe(n,α) reactions was completed; the results were published [1,2]. Taking into account the results of the previous study on ^{57}Fe, a full cycle of measurements for this element in the neutron energy range of 4-6.5 MeV has been completed.

Cross sections of the ^{56}Fe(n,α)^{53}Cr and Fe54(n,α)Cr51 reactions were measured in several experiments at E_n = 5.5 и 6.5 MeV and E_n = 4.0, 4.5, 5.5, и 6.5 MeV, respectively (**Fig. 9** and **10**). The results are in agreement with the calculations using the TALYS-1.6 code.

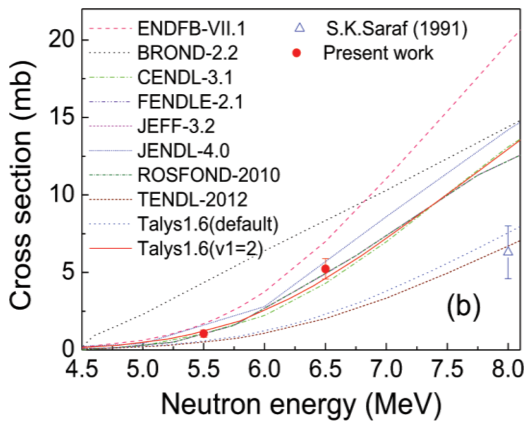


***Fig. 9**. Cross sections of the ^{56}Fe(n,α)^{53}Cr reaction in comparison with those from the existing experiments and estimations for neutron energies from 4.5 to 8.0 MeV.*

For the $^{56}Fe(n,\alpha)^{53}Cr$ reaction, there are only two measurements with large uncertainties, which are in significant disagreement with the estimates of the libraries. These experimental data are supported by such libraries as JENDL-4.0, JEFF-3.2, FENDLE-2.1 and CENDL-3.1. The obtained results are useful both for revision of nuclear data libraries and testing nuclear models and practical applications. Measurements of these reactions are planned to be performed at neutron energies above 7 MeV.

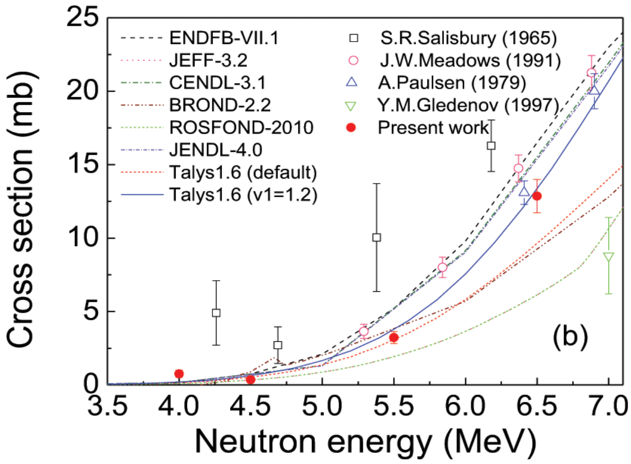


***Fig. 10**. Cross sections of the $^{54}Fe(n,\alpha)^{51}Cr$ reaction in comparison with those from the existing experiments and estimations for neutron energies from 3.5 to 7.0 MeV.*

The measurements of the (n,α) reaction on ^{144}Nd and ^{91}Zr isotopes at an energy of 5.0 - 6.5 MeV have been conducted, the data treatment is in progress.

The cross sections and angular distributions of the (n,α) reaction for the nuclei of medium atomic weights have been analyzed. Calculations using the TALYS-1.6 computer code have been done and compared with our data, other existing experimental data and estimates of various libraries for 11 isotopes from ^{39}K to ^{95}Mo.

The development of a PIXIE-4-based electronic system of acquisition and storage of multidimensional data from an alpha-spectrometer has been completed and tests have been carried out on a fast neutron beam.

Investigations of nuclear structure

An experimental study of the dynamics of the superfluid state of nuclear matter in excited nuclei requires the simultaneous determination of both the density levels and the partial widths of the emission of nuclear reaction products [3] in the entire range of excitation energies. In practice, this condition can be realized only in the measurement of the intensities of two-step cascades between compound states and several low-lying levels. The data are represented as the convolution of energy dependencies of the level density $\rho(E_{ex})$ and radiation widths $\Gamma(E_\gamma)$ (E_{ex} is the excitation energy, E_γ is the gamma-ray energy). In practice, ρ and Τ should be specified as functional dependencies with a minimum number of free parameters.

The intensities $I_{\gamma\gamma}(E_1)$ of two-step cascades were measured for 43 nuclei of different parities: even-odd nuclei ^{71}Ge, ^{125}Te, ^{137}Ba, ^{139}Ba, ^{163}Dy, ^{165}Dy, ^{181}Hf, ^{183}W, ^{185}W, ^{187}W, ^{191}Os, ^{193}Os, even-even nuclei ^{74}Ge, ^{114}Cd, ^{118}Sn, ^{124}Te, ^{138}Ba, ^{150}Sm, ^{156}Gd, ^{158}Gd, ^{164}Dy, ^{168}Er, ^{174}Yb, ^{184}W, ^{188}Os, ^{190}Os, ^{196}Pt, ^{200}Hg and odd-odd nuclei ^{28}Al, ^{40}K, ^{52}V, ^{60}Co, ^{64}Cu, ^{128}I, ^{140}La, ^{160}Tb, ^{166}Ho, ^{170}Tm, ^{176}Lu, ^{177}Lu, ^{182}Ta, ^{192}Ir, и ^{198}Au.

Figure 11 shows the relationships U_l/Δ_0 (l = 2, 3) and B_n/Δ_0. It can be seen that the points in the mass region 150<A<190 (region of deformed nuclei) are significantly lower than the others. The model parameters U_l are determined with an accuracy allowing one to notice the difference for nuclei with different parities of neutrons and protons. As can be seen from the figure, the threshold for the breaking of the third Cooper pairs of nucleons outside the specified mass range approximately corresponds to the neutron binding energy (for spherical nuclei it is the lower bound estimate of the U_3 parameter), and for deformed nuclei the U_3 parameter is half as much. Thus, the main result of the analysis is the statement that the thresholds for the breaking of Cooper pairs have larger values for spherical nuclei than for deformed ones.

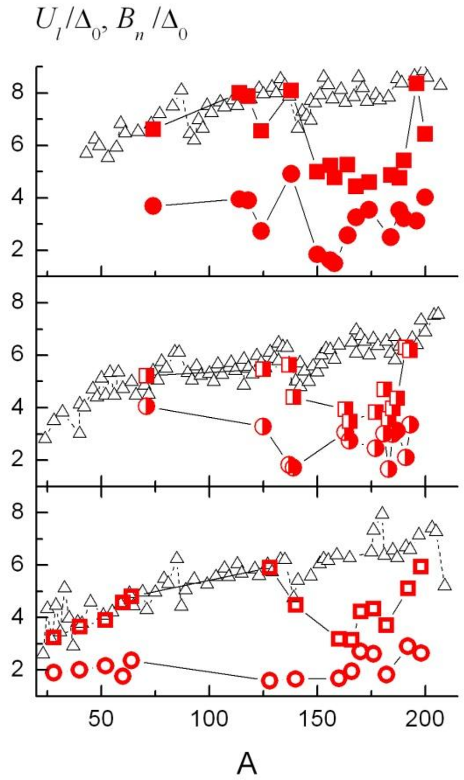


***Fig. 11**. The dependence of the threshold for the breaking of the second (circles) and third (squares) Cooper pairs U on the mass number A. Solid circles are even-even compound nuclei, half-open circles indicate even-odd ones and open circles represent odd-odd compound nuclei. Triangles stand for the mass dependence of the ratio B_n/Δ_0 of the neutron binding energy to the average value of the coupling energy of the last neutron in the nucleus with the same nucleon parity.*

Calibration of the "DEMON" neutron detector on a beam of the Nuclotron accelerator

A large neutron detector "Demon" based on liquid scintillator NE-213 (diameter – 16 cm, length – 20 cm) was used in the measurements of leakage neutron spectra on the "Quinta" setup in the framework of the "Energy+Transmutation" collaboration. The main feature of this detector is its ability to separate signals from neutrons (recoil protons produced as a result of the elastic scattering of neutrons by protons) and γ-rays by a pulse shape. In the experiments with "Quinta" instrumental spectra of leakage neutrons have been obtained, but to obtain the energy spectra, the calibration of the detector response function at different neutron energies is required. Experiments at the Nuclotron allow one to determine the response function with reasonable accuracy using the time-of-flight method to select neutrons of required energies. For this purpose it is necessary to have a start detector in the direct beam of the Nuclotron capable of detecting single signals from the beam particles, a neutron-producing target installed immediately after the start detector, "Demon" installed on the flight path which is sufficient to determine the neutron energy with reasonable accuracy (5-10 m) and a veto detector placed in front of it to eliminate charged particle events. **Figure 12** presents a schematic of the experimental setup.

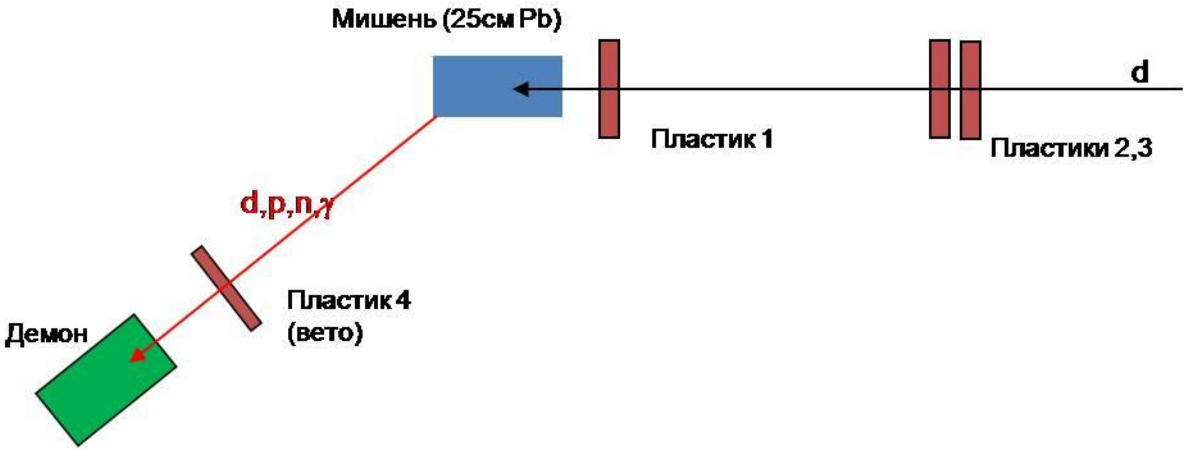


Fig. 12. A schematic of the experimental setup.

Plastic-1 served as the main start detector installed directly in front of the target (25-cm-thick lead). Plastics-2,3 were included in the coincedence circuit and served to eliminate background events in plastic-1. Plastic-4 was included in the anti-coincidence circuit as a veto detector. The distance from the target to the front wall of the "Demon"detector was 520 cm.

The signals in the "Demon" detector were separated by the time of release into two groups: light group containing mainly gamma-rays and light particles (electrons, muons) and heavy group containing signals from neutrons (recoil protons), as well as heavy charged particles (protons, deuterons) from the target. **Figure 13** shows the TOF spectra for these two components, as well as the second (neutron) component from the veto detector rejecting charged particles.

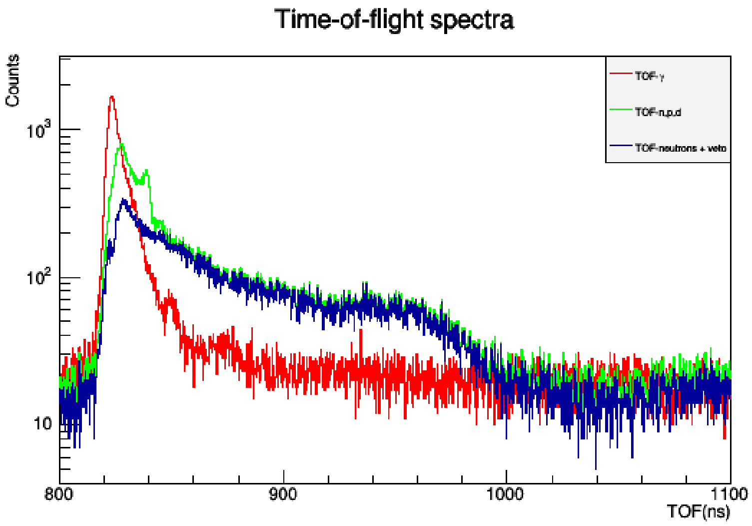


***Fig. 13**. TOF spectra of gamma-rays (red), neutrons and charged particles (green) and neutrons (blue). The zero (start) time corresponds to channel 806 ns.*

To obtain the response functions for neutrons of various energies, the TOF neutron spectrum (blue curve in **Fig. 14**) was divided into intervals corresponding to specified average neutron energies (see **Fig. 14**).

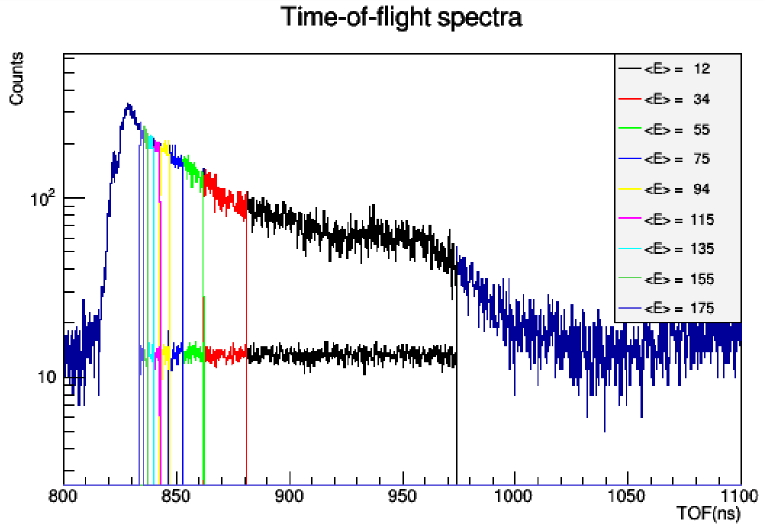


***Fig. 14**. Partition of the TOF neutron spectrum into energy intervals. Horizontal spectra below show the background level found to be at the level of random coincidences.*

For these intervals the obtained instrumental spectra of the "Demon" detector approximate to a certain degree the detector response functions for the neutrons of corresponding energies. A correction for the background of random coincidences was made by subtracting a "random" detector response function normalized to the contribution of the background of random coincidences in each energy interval. The resulting response functions for the indicated medium-energy neutrons are given in **Fig. 15**.

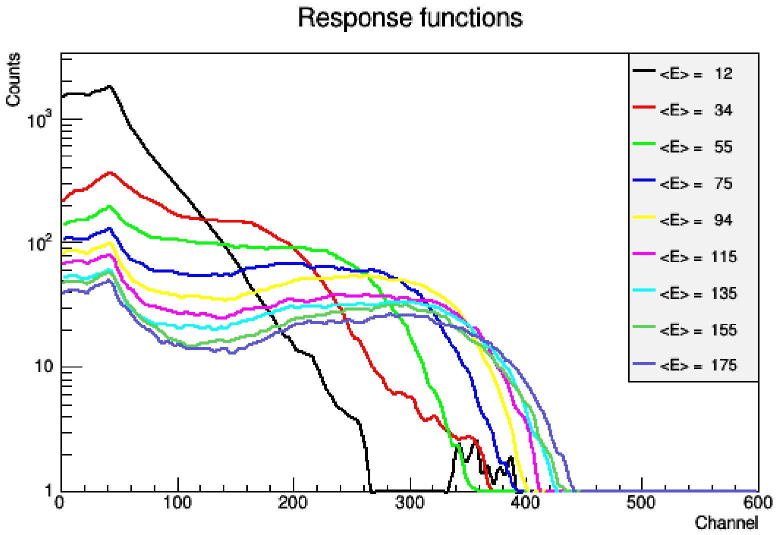


***Fig. 15**. Response functions of the "DEMON" detector for different neutron energies.*

On the whole, the experiment has shown a principal possibility for this type of calibration to be carried out on the Nuclotron beam. Despite the presence of overlaps in the start plastic detector they could be eliminated with a sufficiently high degree of reliability by analyzing the digitized signals from the plastic detector. The obtained response functions have poor statistical accuracy, yet they appear to be sufficient for qualitative analysis of the data obtained by "Quinta".

Measurement of P-odd asymmetry in the emission of α-particles in the reaction $^{10}B(n,\alpha)^{7}Li$ with cold polarized neutrons

An experiment to measure P-odd correlations of the ($\sigma_n p_\alpha$) type, where σ_n is the neutron spin, p_α is the momentum of the emitted α-particle in the $^{10}B(n,\alpha)^{7}Li$ reaction, has been started on a cold polarized neutron beam of the PF1B instrument at the ILL reactor (Grenoble, France). The experiment is carried out in the framework of the search for neutral currents in electroweak hadron interactions conserving strangeness. A 48-section ionization chamber is used as a neutron detector (**Fig. 16**). The events are detected using the current method with the compensation of reactor power fluctuations and false effects [4]. According to the theoretical estimates [5] the expected effect does not exceed several units of 10^{-8}. For 7.5 days of the experiment the value of $A_\alpha = (-4.0 \pm 5.6)\times10^{-8}$ has been obtained (**Fig. 17**) basing on the raw data treatment (without corrections for the background, degree of polarization and the average value of the cosine of the detection solid angle). The experiment will be continued in 2016.

__Fig. 16__. Multisection ionization chamber before final assembly and installation on the beam (left).

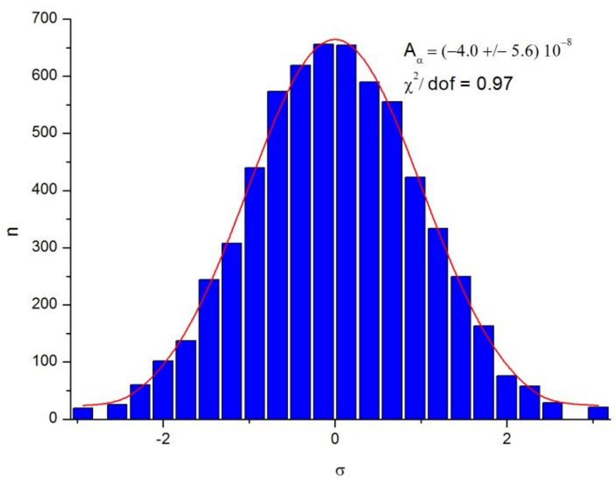
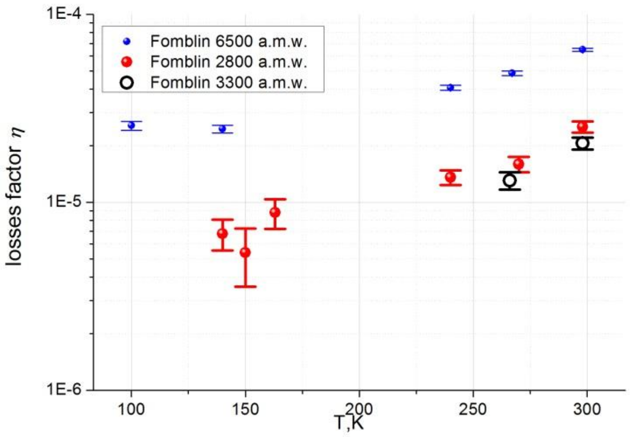


__Fig. 17__. Histogram of experimental values and a comparison with the normal distribution (right).

Investigations of UCN interaction with the surface of Fomblin oil

The interaction of UCN with the surface of hydrogen-free Fomblin oil has been experimentally studied. The experiments have been carried out on the GRANIT spectrometer, which allows simultaneous measurements of the UCN loss factor during the interaction with the surface of a substance (η), and the probability of quasi-elastic scattering of UCN (P_{VUCN}) at various temperatures. Measurements were carried out for three types of Fomblin oil with different molecular weights of 6500, 3300, 2800 amu. The results of the measurements are presented in **Fig. 18**.



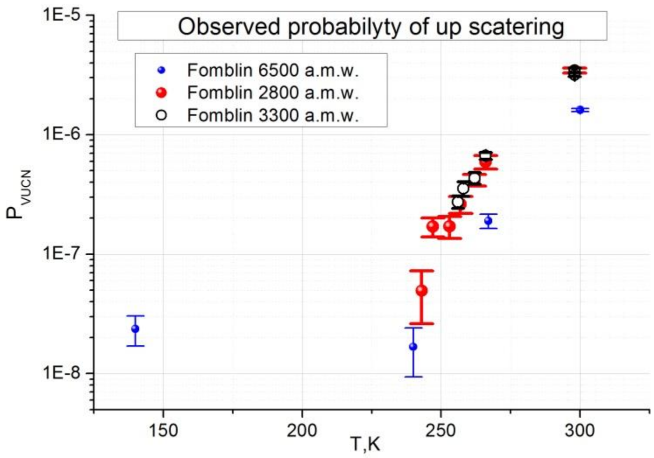


***Fig. 18**. Results of the measurements of the UCN loss factor (η) during the interaction with the surface of the substance, and the probability of quasi-elastic scattering of UCN (P_{VUCN}).*

These measurements had two objectives. One was to study the process of quasi-elastic scattering of UCN from the surface of hydrogen-free Fomblin oil. The results suggest that from the two existing hypotheses about the nature of quasi-elastic scattering of UCN — scattering from nanoparticles (nanodroplets) on the surface and scattering from surface capillary waves — the second hypothesis is apparently most reliable.

Another objective concerned the choice of material for the walls of the UCN storage volume in the framework of the preparation for an experiment on measuring the neutron lifetime. The required material should have the lowest η and P_{VUCN}.

The measurements have shown that for all the samples under study the probability of quasi-elastic scattering becomes less than the spectrometer sensitivity (10^{-8}) with decreasing temperature below the freezing point of the oil. At the same time, when the temperature is lowered below 150 K, there is a slight increase in P_{VUCN}, which is apparently due to the cracking of the hardened oil. Therefore, the optimum temperature of the UCN storage volume with the walls covered with Fomblin oil will be in the range of 150 - 200 K.

The smallest loss factor was obtained for the oil with a molecular weight of 3300 amu; therefore this oil is the best candidate for covering walls of the UCN storage volume.

Calculations of a UCN source of a new type at an external beam of thermal neutrons

A detailed calculation of the parameters of a UCN source of a new type has been conducted, which is based on a new method for production of ultracold neutrons in a helium source. The principal idea of the method presented for the first time in [6] consists in installing a helium UCN source into a thermal neutron beam and in surrounding it with a moderator/reflector, which is a source of cold neutrons needed to produce UCN. At the same time, the flux of cold neutrons in the source could be several times greater than the flux of incident neutrons due to their numerous reflections from the moderator/reflector.

The source of this type should be installed close to the reactor biological shielding. **Figure 19** presents the layout of the source on one of the beamlines of the PIK reactor.

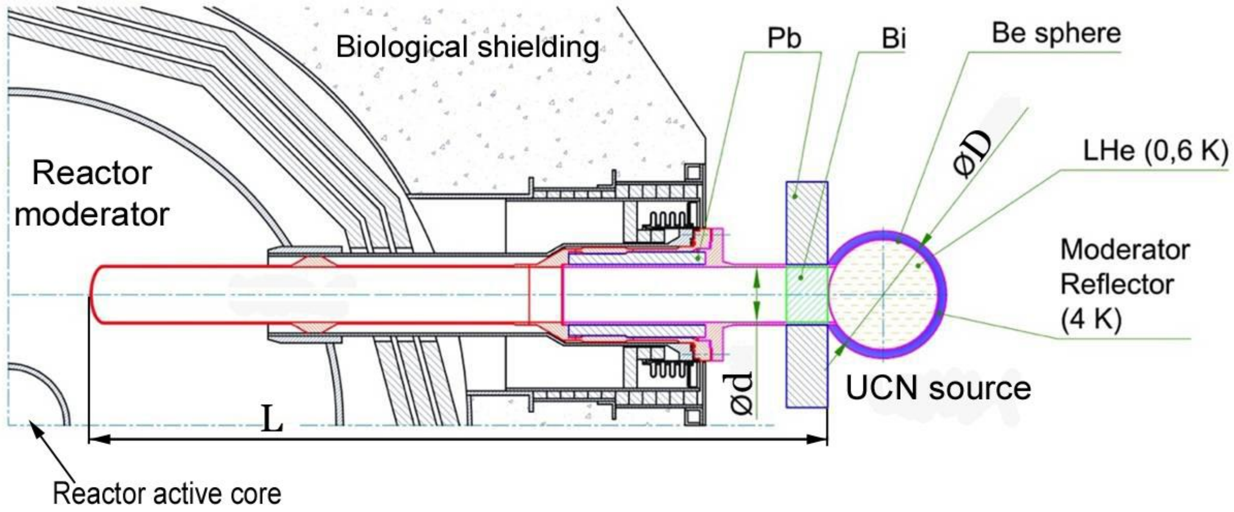


Fig. 19*. A possible layout of the UCN source on one of the thermal neutron beamlines of the PIK reactor.*

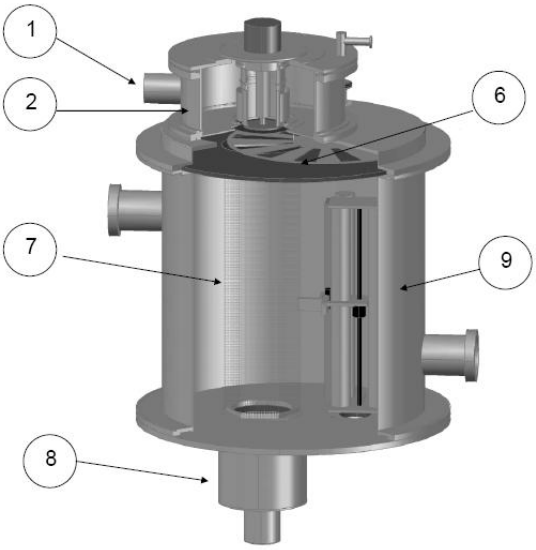
Calculations of the parameters of the source with a moderator/reflector of solid methane and liquid deuterium have been performed.

These calculations have shown that the installation of such a UCN source with a methane moderator on a thermal neutron beamline of the PIK reactor allows achieving the UCN density of $\sim 1{\cdot}10^{5}$ cm^{-3} in the source with the production rate of $\sim 2{\cdot}10^{7}$ s^{-1}, which is, respectively, a factor of 1000 and 20 higher than those that can be provided by the most intensive UCN source available today. At the same time the UCN density in the source with a deuterium moderator can be $\sim 2{\cdot}10^{5}$ cm^{-3} with the production rate of the source of $\sim 8{\cdot}10^{7}$ s^{-1}.

Calculations of the heat release in the UCN source have also been performed demonstrating that with achieving the above parameters, the heat release power will be in the range of 1-2 W, which makes it possible to realize the proposed concept of the source in practice.

Neutron diffraction from a moving grating

The results obtained in the experiment in 2014 (November-December) have been analyzed. In that experiment time-of-flight spectra of UCN that passed through a rotating phase diffraction grating were obtained using the Fourier spectroscopy method (**Fig. 20**). The method for the first time made it possible to carry out measurements for a wide range of the resulting neutron energy, 60÷250 neV, which allowed us to simultaneously observe the lines corresponding to five diffraction orders. The spectra were obtained for three velocities of the grating. The profile of the grating was analyzed using an atomic force microscope (**Fig. 21**).



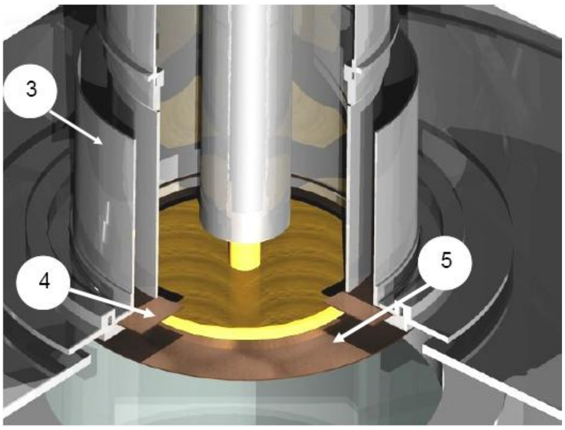
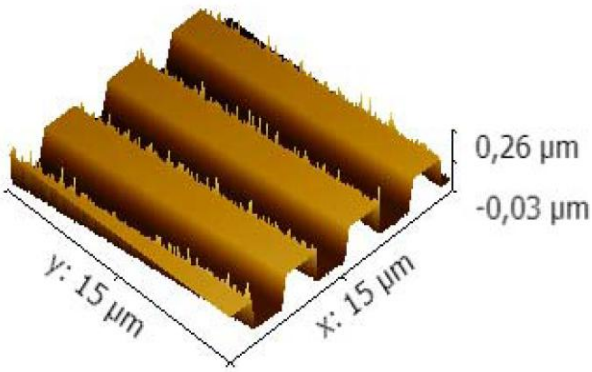
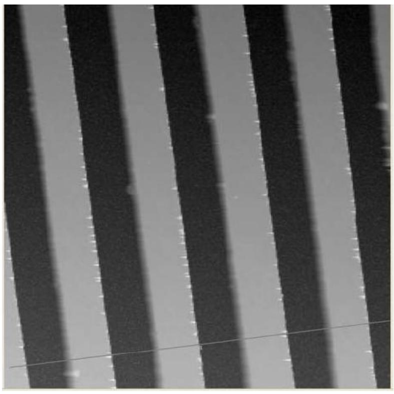


Fig. 20. *TOF Fourier spectrometer: general view (left) and its upper part (right): 1 – inlet neutron guide, 2 – inlet chamber, 3 – annular corridor, 4 – filter-monochromator, 5 – grating, 6 – rotor of Fourier chopper 7 – vertical glass neutron guide, 8 – detector, 9 – vacuum chamber.*





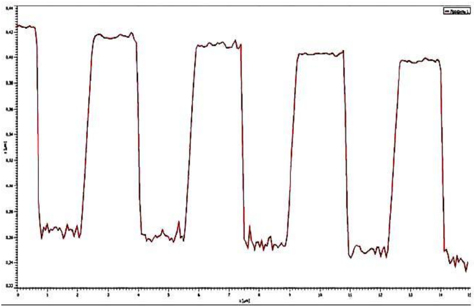


Fig. 21. *3D image of a fragment of the grating obtained using an atomic force microscope (top left), 2D image of a fragment of the grating (top right) and its profile (bottom).*

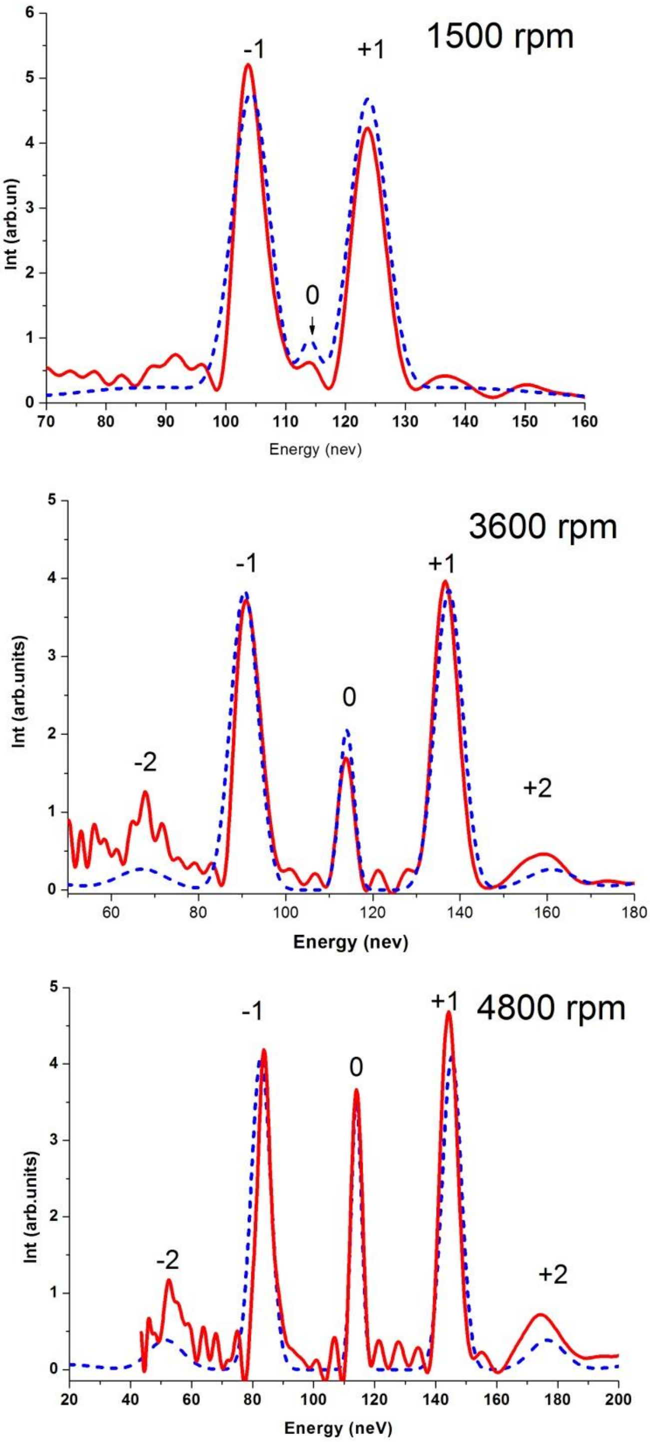
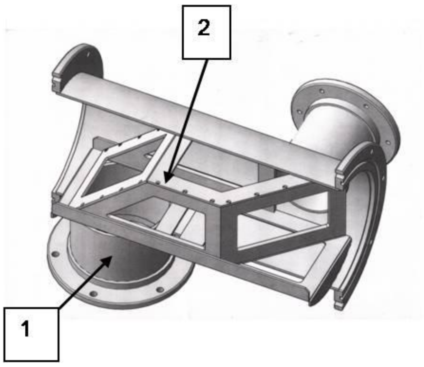


Fig. 22. *Experimental (red solid line) and theoretical (blue dotted line) spectra of neutrons resulting from the diffraction by a moving grating for three rotation frequencies of the latter.*

The theoretical calculation of the diffraction pattern for a specified initial neutron energy distribution, velocity of the grating and its measured profile was performed by numerically solving the system of equations obtained in the framework of the multi-wave theory of dynamical diffraction in the approximation of slowly varying amplitudes. The experimental TOF spectra were compared with the theory after conversion to the energy scale taking into account the transformation of the spectrum due to the Earth's gravity. The experimental and theoretical results are presented in **Fig. 22**. It can be seen that the data are in good agreement with the theoretical predictions.

Improvement of the TOF Fourier spectrometer of UCN

To increase the luminosity of the Fourier spectrometer, a search for other possibilities of forming the initial spectrum of UCN free of the very cold neutron background has been undertaken. As an alternative to the flow-type UCN storage chamber used previously, a system of two total reflection mirrors has been proposed. A preliminary study of the properties of this system was carried out by the MC simulation using the Geant4-UCN package. On the basis of the results of the calculation a full-scale prototype of a spectrum formation unit (**Fig. 23**) has been produced. Its efficiency was checked in a test experiment on a UCN beam at ILL in October 2015.



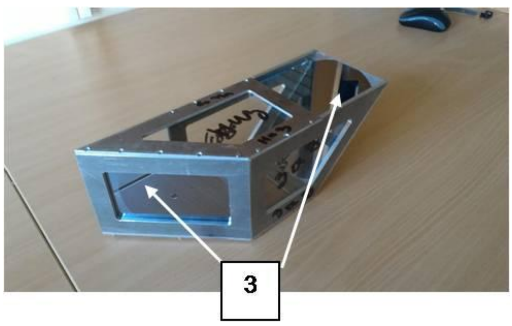


Fig. 23. *Sectional view of a spectrum formation unit of the spectrometer (left) and a frame with mirrors (right). 1 – vacuum chamber, 2 – frame with mirrors, 3 – mirrors 1 and 2.*

Measurements were performed with silicon, glass, and sapphire mirrors. The best results were obtained with glass mirrors. It has been shown that the use of the specified inlet chamber makes it possible to achieve a gain in the counting rate by a factor of 6-7 with a satisfactory effect/background ratio.

Preparation of an experiment on the observation of interaction of UCN with an oscillating barrier at giant accelerations

The purpose of the planned experiment is the verification of the validity of the effective potential model at giant accelerations of the sample. An important stage in the preparation of the experiment is a quantum calculation of the interaction of a neutron wave packet with a potential structure oscillating in the space for different values of the maximum acceleration of the object $w_{max} = A(2\pi f)^2$, where A and f are the amplitude and frequency of vibration, respectively. In the case of the oscillating potential barrier, the calculations have shown that for the values of interest $w_{max} \approx 10^8\ cm/s^2$ the observed non-stationary effects are rather small. In the case of the vibrating resonant structure defined as two barriers and a well in between, the calculations have shown that there is a noticeable oscillation in the count rate for a wide range of amplitudes and frequencies in the transmitted state. This geometry has been selected as the main one for further research. Possible approaches to carry out the experiment to test the effective potential model at giant accelerations of a sample have been considered.

A new approach to the experiment to test the weak equivalence principle for the neutron

A new approach to the experiment testing the weak equivalence principle for the neutron has been proposed. It is suggested that in an experiment on the observation of the neutron free fall a fall time is measured for several lines of the spectrum obtained by diffraction from a moving grating. This approach requires only the knowledge of the value for the quantum splitting of the spectrum $\Delta E = 2\pi\hbar\left(V/d\right)$, where V and d are the velocity and period of the grating, respectively. The knowledge of the absolute energy or geometric parameters of the setup is not necessary.

Theoretical investigations

Quantum mechanics

As a result of theoretical research in the field of quantum mechanics, it has been discovered that a continuous spectrum of singular bound states of electrons can exist in atoms. In these states, with a probability of ~ 10^{-6} the screening of the Coulomb field is possible at distances of the order of the nuclear radius. In case of hydrogen or deuterium, such screening leads to the formation of a neutral particle that can participate in nuclear fusion reactions with other nuclei at moderate temperatures. In particular, this allows one to explain the star ignition mechanism with increasing density due to the gravity. Another achievement is the formulation of a new Bell inequality in the field of the EPR paradox. New inequality makes it possible to check out the particle states in one measurement. Namely, the question is, if a source radiates a pair of similar particles, then whether individual particles are emitted or the particles are emitted in a mixed state, which transforms into individual particles only after measurements. Previous approaches to answer this question required minimum four measurements, and no indisputable result has yet been obtained.

Electroweak interactions

The effective lagrangian describing electroweak hadron transitions has been investigated [7]. On the basis of the general principles of global and local symmetries the effective pion-nucleon lagrangian, essentially non-linear in a pion field, has been developed to describe the low-energy electroweak hadron interactions with strangeness conservation. We encounter no divergence summarizing properly all the infinite power series in a pion field which occur in the course of the treatment. The used consistent approach can be applied to consider the pion-nucleon interactions with the spatial parity violation.

3. Methodological and applied research

Methodological investigations at the IREN facility

Since one of the possibilities to increase the neutron yield at the IREN facility is the replacement of a tungsten neutron production target with a target of natural uranium, measurements with a uranium target prototype and comparison of yields have been performed. The comparison has been made using the yield of the (n,γ) reaction in resonances of Ta in the energy range of ~ 4-1200 eV. The events have been detected by a large 6-section liquid scintillation detector [8] at a 60-m flight path. The detection mode for the multiplicity of γ-rays in the neutron capture (simultaneous response of the sections) was $m \geq 2$. The sample was a Ta-foil (thickness 0.11 mm, size 12.2 x 15.4 cm and weight 34.06 g). The results of the measurements and analysis are shown in **Fig. 24**. The spectra in the top figure are normalized to the acquisition time of 8 h 50 min (acquisition time for the tungsten target). The accelerator parameters were about the same for both measurements: electron current in a pulse – 1.2-1.5 A; repetition frequency – 20 Hz. The experimental data have also been normalized to the average values of the electron current. The bottom figure demonstrates the yield ratios in the resonances compared with the yields calculated using the GEANT and FLUKA programs. The experimental and calculated values are $R_{exp} = 2.57 \pm 0.12$; $R_{GEANT} = 3.05$; $R_{FLUKA} = 1.39$.

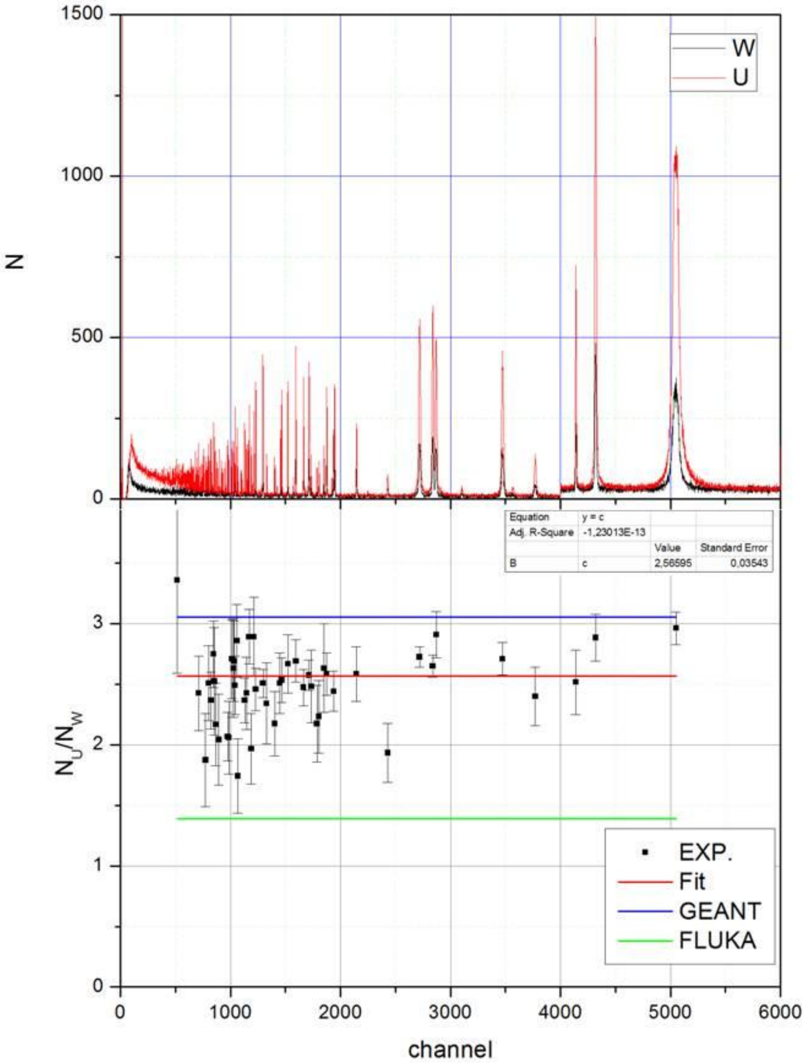


__Fig. 24__. At the top - TOF spectra of the Ta(n,γ) reaction normalized to the same acquisition time for tungsten (black line) and uranium (red line) targets. At the bottom – yield ratios: points – experimental data; red line – the average over the experimental data; blue line – calculations by GEANT; green line – calculations by FLUKA.

Analytical investigations on charged particle beams of the EG-5 accelerator

Experiments with the beams of charged particles employing analytical techniques of the Rutherford back scattering and recoil detection analysis were regularly carried out throughout the year. The elemental depth profiles in the samples used to study structural characteristics of epitaxial films have been measured. The effect of neutron and Xe-ion irradiation on the properties of SiC films synthesized by different technologies of the plasma-chemical vapor deposition has been investigated.

Also, the temperature-induced growth of oxide films on a steel surface and the effect of annealing on the structure and optical properties of TiO_2 films deposited on silicon substrates have been studied.

Using the recoil detection method the accumulation/redistribution of hydrogen and deuterium in an assembly of two (Ni, Ti and Zr) high-purity foils after exposure to pulsed fluxes of high-temperature deuterium plasma at the "Plasma Focus" (PF-4) setup has been studied. It has been found that when exposed to pulsed fluxes of high-temperature plasma the assemblies of the studied foils show the redistribution of the implanted deuterium and gas impurities of hydrogen to great depths far exceeding deuterium ion flight paths.

As a result of the studies of the effect of proton irradiation (energy 2.5 MeV) on the critical current and critical temperature of 2-G composite HTSC tapes, the radiation resistance values: $2x10^{16}$ rad/cm^2 for YBCO (123) and $6x10^{16}$ rad/cm^2 for GdBCO (123) have been obtained. These values have been determined from the analysis of the critical current degradation, which is accompanied only by slight decrease in the critical temperature. A strong influence of proton irradiation on the critical current at a temperature of 770 K in its own field has been revealed for conductive tapes of these two compositions.

In 2015, the EG-5 accelerator was in operation for experiments for 510 h.

Analytical investigations at the IBR-2 reactor

In 2015, at the REGATA facility a multielement instrumental neutron activation analysis of ~ 2600 ecological samples (vegetation, soil, air filters), as well as a number of technological, biological and archaeological specimens and samples of extraterrestrial origin has been performed in the framework of the programs and grants of JINR Member States and Protocols of Cooperation with JINR Non-Member States. Investigations of test samples have been conducted for an interlaboratory comparison of the results under the IAEA program.

Development of the NAA&AR Sector experimental base

In the reporting period in the NAA&AR Sector the development of a software package for complex automation of multielement neutron activation analysis (NAA) at the IBR-2 reactor [9] was continued; three automatic sample changers (SC) were installed and successfully operated to automate mass measurements of spectra of irradiated samples on three detectors. Two HPGe detectors (new and upgraded) have been put into operation. Work has started on the automation of sample irradiation procedure (replacement of sensors, electronics and software development). The activities on automation of NAA were conducted in the framework of the IAEA Coordinated Research Project «Development of an Integrated Approach to Routine Automation of Neutron Activation Analysis” (F1.20.25/CRP1888, Contract No. 17363).

A radiation monitoring system has been installed and put into service in the rooms of the REGATA facility.

The specialists from Intertech Corporation have completed the start-up and commissioning work on the iCE3500 atomic absorption spectrometer by Thermo Scientific and conducted personnel training.

Biomonitoring of air pollution

In 2015, the summing-up of the activities conducted in 2010-2011 in the framework of the international program "Heavy metal atmospheric deposition in Europe – estimations based on moss analysis" was done [10]. The long-term cooperation with the Slovak specialists in the field of biomonitoring atmospheric deposition of trace elements has found its reflection in the chapter of a book "Air Pollution" [11] as well as in the ISINN Proceedings [12, 13]. The analysis of moss-biomonitors from Belarus collected in 2014 on the territory of Minsk, Mogilev, Gomel and Vitebsk regions has been completed [14]. In the reporting period, two studies on data analysis of atmospheric deposition of heavy metals and other elements in Albania have been performed [15, 16]. In the framework of the Serbia-JINR Cooperation Program a comparative analysis of air pollution in the so-called "street canyons" in Moscow and Belgrade has been performed. The paper was submitted to the journal «*Environmental Monitoring and Assessment*». The NAA has been used to study the samples of mosses collected by teachers and pupils in the national parks of Poland in the framework of the Poland-JINR Cooperation Program. The preparation of a joint publication is in progress.

The study on the determination of concentrations of elements in mosses-biomonitors and soils collected in the area of the lead-zinc plant in Kardzhali (one of the most environmentally contaminated places in Bulgaria) has been completed [17, 18].

Biotechnologies

In 2014-2015, in collaboration with the biophysicists from the E.Andronikashvili Institute of Physics, I.Javakhishvili Tbilisi State University and I.Chavchavadze State ***University*** (***Tbilisi*****,** ***Georgia***) the studies were conducted on the development of methods for synthesis of silver and gold nanoparticles by new species of microorganisms – Archaea. The strain of thermo-acidophilic crenarchaeon *Sulfolobus islandicus* LAL14/1 provided by the Pasteur Institute (Paris, France) was used to obtain silver and gold nanoparticles at high temperatures (75 °C). In combination with a number of optical and analytical methods the neutron activation analysis at the IBR-2 reactor was used to characterize the processes of synthesis of gold and silver nanoparticles by the Archaea strain [19]. The interest in the ongoing studies is connected with both unique technological application possibilities of Archaea and almost complete lack of studies in this research area.

In collaboration with the A.N.Frumkin Institute of Physical Chemistry and Electrochemistry of RAS in the framework of the projects supported by RFBR (15-05-08919 and 15-33-20069) work has started to study the processes of accumulation and biosorption of metals (vanadium, chromium, uranium, lanthanum) from mono- and multicomponent systems by microalgae *Spirulina platensis* and bacteria *Pseudomonas putida*.

In cooperation with the University of Oulu, Finland, the application of NAA for analysis of pine sawdust used in wastewater treatment as a sorbent of metals has been studied [20].

In cooperation with the Institute of Microbiology and Biotechnology of ASM studies of biochemical changes in the main components of *Spirulina* biomass (proteins, carbohydrates, etc.) during the synthesis of silver nanoparticles by microalgae were conducted [21]. Work has started on the biosynthesis of selenium nanoparticles using *Spirulina platensis* and *Nostoc linckia* microalgae as a matrix. To understand the mechanisms of synthesis of metal nanoparticles and to determine their localization in the biomass, experiments have been performed to obtain silver nanoparticles on the fractions of proteins and polysaccharides extracted from the biomass of microalgae.

In 2015, the joint investigation carried out in cooperation with the biochemists from the Institute of Microbiology and Biotechnology of ASM was continued to study the process of removing toxic metals (chromium, nickel) from wastewater using microalgae *Spirulina platensis* [22].

Environmental assessment

In 2015, the NAA analysis of soils and bottom sediments from various regions of the Nile delta, along its riverbed and artificial canals performed in the framework of the joint JINR-Egypt project «Assessment of the environmental situation in the delta of the Nile River using nuclear and related analytical techniques» was completed. The obtained results have shown that the element composition of these samples is determined mainly by geochemical features of the region under study and is not affected by the anthropogenic load [23]. For the first time the NAA was applied to study the composition of the soil and sediment samples from the Siwa oasis in the Western Sahara desert, the obtained results have provided new information about this unique oasis [24].

In collaboration with the University in Stellenbosch, South Africa, complex investigations of air pollution using mosses and lichens were continued. In the framework of the project "Mollusks as Biomonitors of Water Ecosystems in the Republic of South Africa" the stage of the work on the analysis of soft tissues and shells of the Saldanha and Danger bays in the Atlantic Ocean, West Coast of South Africa has been completed [25].

In order to assess the state of the Crimea coastal ecosystem, the analysis of the samples of macroalgae-biomonitors (red, green and brown) collected in the coastal zone of the Black Sea has been completed in collaboration with the A.O.Kovalevsky Institute of Marine Biological Research (Sevastopol). The algae-concentrators of specific groups of elements including halogens were revealed and the cleanest water areas of the coastal zone of the Crimea were found [26]. The study of the seasonal variation of concentrations of 46 elements in the phytoplankton of the Black Sea has been completed. The effect of the elemental composition on the biophysical parameters of the functional activity of phytoplankton communities in the coastal areas has been assessed. The results have shown that phytoplankton can be successfully used as a biomonitor of water ecosystems [27].

In 2015, in cooperation with Moscow State University (Faculty of Biology) the investigation on the determination of the elemental composition of soil, bottom sediments, terrestrial and aquatic vegetation to assess the transport of pollutants in the strategically important areas of the Black Sea (coastal zone of Anapa, Novorossiysk and Tuapse) was completed [28] .

On the basis of the analysis of mosses-biomonitors and lichens, an important study has been performed on the impacts of an oil refinery and oil pipeline on the natural environment of the Yamal Peninsula. The assessment of the atmospheric deposition of toxic elements associated with the oil industry has shown no excess of the maximum allowable concentration of these elements [29].

Analysis of food products

The studies have been completed and a joint paper (in cooperation with the analytical center of the Geological Institute of RAS) on the application of nuclear-physical analytical methods for studying the intake of Cl, Br, I and Se in the human body with food, has been published in the leading American academic journal *Food and Nutrition Sciences* [30]. The results of a complex study using NAA, ICP-MS, AAS on the assessment of mercury content in diagnostic biomaterials of different population groups of urban areas in the Moscow region have been analyzed in cooperation with the analytical center of the Geological Institute of RAS and I.M.Sechenov First Moscow State Medical University [31].

Geology

The study performed in 2015 in the framework of the joint JINR-Romania project (University of Bucharest) on the geochemistry of loess samples of the Quaternary Period collected in the Dobrogea region (Romania) made it possible to obtain information about the climate of the Quaternary Period [32].

In cooperation with the Western Cape University (South Africa) the NAA study of new samples of coal fly ash from the Matla coal power station in the Mpumalanga province in South Africa was conducted. The data treatment is in progress.

Analysis of materials of extraterrestrial origin

In 2015, a study aimed at searching for cosmic dust in peat columns collected in Siberia in the area of the Tunguska meteorite fall was performed in cooperation with the Adam Mickiewicz University in Poznan, Poland. The age determination of peat column layers was carried out in Poland.

The data treatment has been completed; a paper is being prepared for publication. Using scanning electron microscopy and energy-dispersive X-ray spectroscopy (EDAX) moss samples collected in the Arctic (Northern Norway) and Antarctic (King George Island) have been analyzed. The particles detected by means of electron microscopy along with the results of the neutron activation analysis of samples allow us to make a conclusion about their origin, which will contribute to the development of criteria for identification of particles of extraterrestrial origin. A multielement analysis of meteorites of unknown nature received from Italy has been performed. The NAA results and the use of statistical methods of multielement analysis for their processing have made it possible to determine the type of the meteorite material: ferrous chondrites and carbonaceous chondrites. The results of the research were presented and discussed at the International Conference organized by LRB JINR "Modern Trends in Radiobiology and Astrobiology", October 28-30, 2015. Dubna [33].

Medicinal plants

In 2015, we continued investigations in a new promising line of research – determination of the elemental composition of plants used in medicine. These studies are conducted in cooperation with the specialists from Mongolia, Bulgaria, Poland [34] and starting from 2015 from China [35].

Materials science

In 2015, in the framework of the BRFBR-JINR joint grant and in cooperation with the Scientific and Practical ***Materials Research Center*** of the National Academy of Sciences of Belarus, the investigations of the crystallization processes and the characterization of artificial diamonds in the C-Mn-Ni-Fe system were conducted. In the course of the experiment diamond crystals were obtained in the Fe-Ni-C and Mn-Ni-C systems at a pressure of 5 GPa and a temperature of 1700 K. The use of NAA allowed us to study the impurity composition of the diamonds. Using electron microscopy the size and shape of the obtained crystals were determined. The results of the research were published [36, 37]. In 2014, a part of the experimental material was sent to the University of Galaţi, Romania, to perform X-ray diffraction and scanning electron microscopy analyses [38]. A joint project was continued aimed at studying phase formation processes and physical characteristics of the compounds in the Cu-Fe-S system at high pressures and temperatures. The NAA of 12 samples was performed and the results were forwarded to Minsk.

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