1. SCIENTIFIC RESEARCH

1.2. NEUTRON NUCLEAR PHYSICS

1.2.1 Experimental and instrument development activities.

1.2.1.1. Development and improvement of multi-detector systems for neutron cross-section easurements at the IREN facility

A mobile reconfigurable gamma-spectrometer system nGamma has been developed and tested. The system is intended for studying nuclear reactions with the emission of gamma-rays induced by neutrons of various energies. In the initial (minimum, test) configuration it consists of 24 NaI(Tl) gamma-ray detectors mounted on two rings (**Fig. 18**). The energy and time characteristics of individual sections of the system have been determined experimentally. Using the system, the energy dependence of neutron flux density has been measured at a distance of 60 m from a neutron-generating target of the IREN pulsed neutron source.
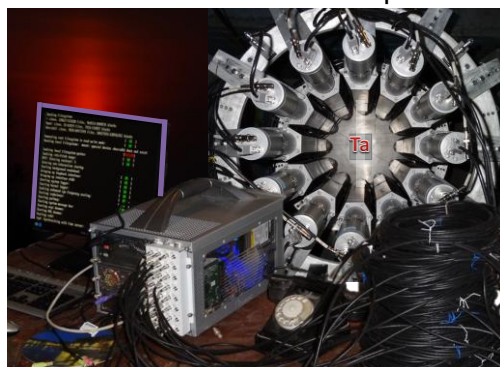
A 12-detector (2 modules of 6 NaI(Tl) crystals each) gamma-spectrometer system "Romashka" designed to study resonance radiative capture (and fission) of nuclei by

Fig.18. Multi-detector mobile reconfigurable gamma-spectrometer

neutrons has been assembled and tested on beam 4 of the IREN facility (**Fig. 19**). The energy characteristics of individual sections of the system have been measured using a computerized acquisition and analysis system of the nGamma instrument. A gamma-neutron beam collimator has been assembled and installed.

Fig. 19. 12-detector NaI(Tl) gamma-spectrometer system "Romashka" (INRNE-BAS) on beam 4 of the IREN pulsed neutron source.

1.2.1.2. Activities on the preparation of the (n,e) scattering experiment.

The adjustment of the experimental setup AURA for measuring the energy dependence of angular anisotropy of slow neutrons scattered by noble gases in order to determine the (n,e)-scattering length is in progress. At present, the AURA setup is placed on a 15-m flight path of beam 2 of the IREN facility. The layout of the AURA setup is presented in **Fig. 20**.

Four shielded ^{3}He-counters and a sample holder (a cylindrical aluminum chamber is provided for gaseous targets) are fixed on a rotating platform. The platform is rotated through ±180° by a PC-controlled stepper motor.
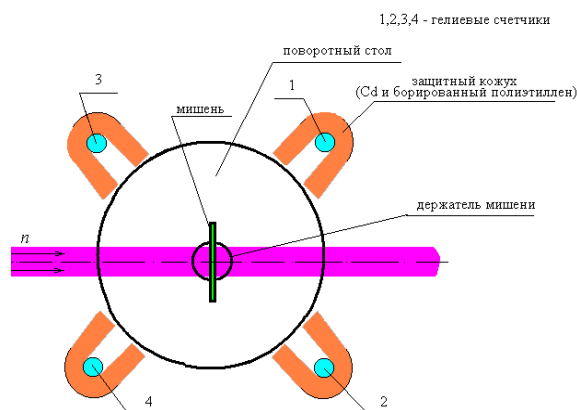

Fig.20. Layout of a detector module of the AURA setup for studying solid samples.

2013
Annual Report

An 8-channel time encoder is connected with a computer via a USB-2 port and receives signals from detectors and two monitor ^{3}He-counters. Changes in the detectors' position at specified parameters, in the exposure in each position and the accumulation of measured data in 8 spectra (for each counter in 2 positions) are handled by the experiment control software.

Test experiments on solid samples have been performed at a neutron beam intensity of IREN of ~2·10^{11} n/s. **Fig. 21 a** and **b** illustrate the time-of-flight spectra obtained by neutron scattering from a 0.5-mm-thick cadmium target and a 0.3-mm-thick tungsten target, and **Fig. 22** presents the time-of-flight spectra obtained with a plexiglass target. As is obvious from **Fig. 22** forward-scattering of neutrons is predominant as it should be on a hydrogen-containing target.
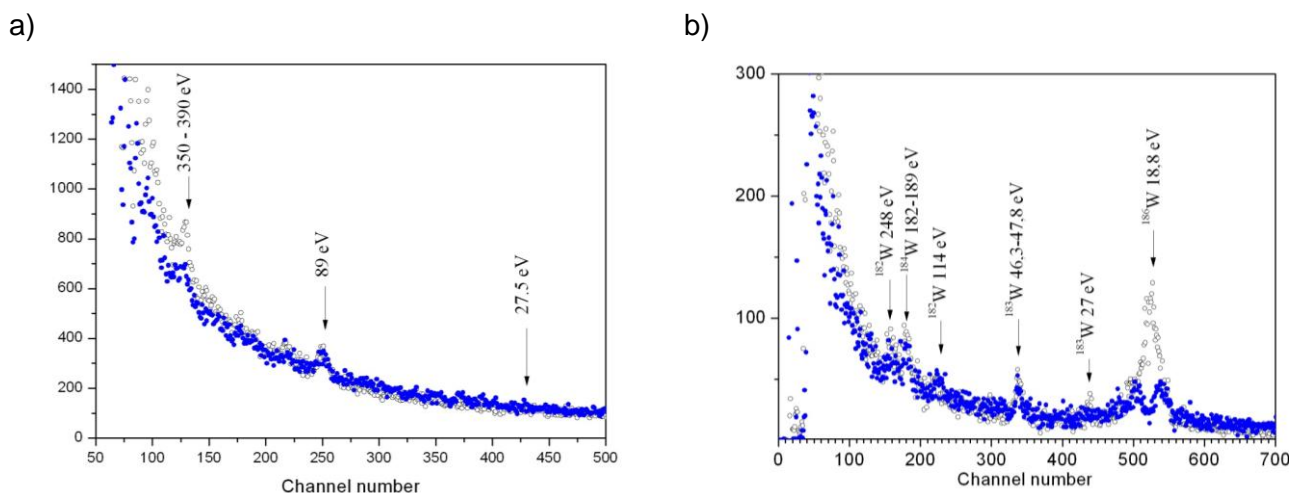
a)   b)

Fig. 21. a)Time-of-flight neutron scattering spectra of cadmium obtained by one of the detectors. Open circles – back-scattering, full circles – forward-scattering. Time channel width is 0.5 μs. b) Time-of-flight neutron scattering spectra of tungsten. Open circles – back-scattering, full circles – forward-scattering. Time channel width is 0.5 μs.

The inlets of the 2nd and 4th detectors were covered by silver plates, which resulted in a dip in the respective neutron forward-scattering spectra at an energy of ~ 10 eV. The dip is related to the fact that neutrons with this energy after scattering by hydrogen at 45° acquire an energy corresponding to a "silver resonance" at 5.15 eV.

The calculations aimed at refining the corrections for the experiment on the determination of the n,e-scattering length from the angular anisotropy of slow neutrons scattered by argon at normal pressure are in progress. To determine b_{ne} with a precision of 2-3%, the accuracy of all corrections should be no worse than 10^{-4}.

A kinematic correction — the ratio between the efficiencies of the detectors registering slow neutrons scattered forward or backward taking into account the thermal motion of gas atoms — is calculated by the Monte Carlo method in the real geometry (using LIT cluster). The accuracy of this correction required for a time-of-flight experiment has been obtained for measurements with argon. The corrections have been calculated for 20 energy points in the neutron energy range from 0.0065 to 0.8 eV. The calculated dependence of neutron scattering anisotropy on the initial neutron energy with regard to the thermal motion of argon atoms at bne = −1.32·10^{-3} fm and the anisotropy without considering n,e-scattering are presented in **Fig. 23**.
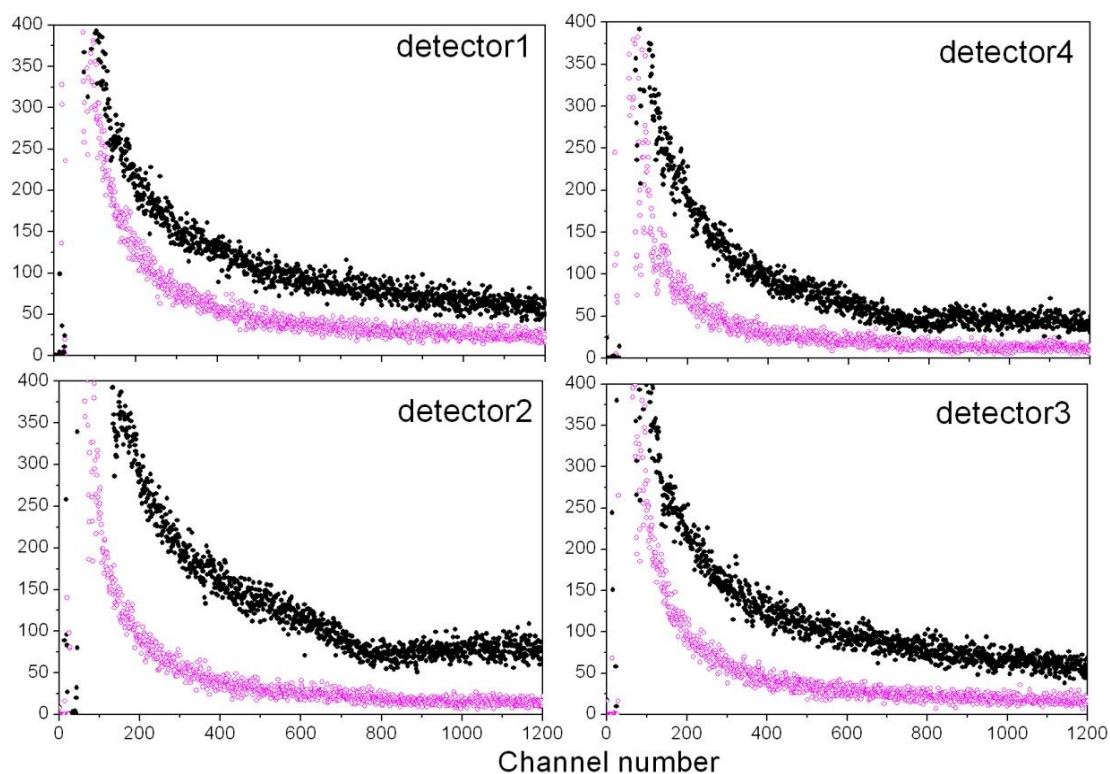
1. SCIENTIFIC RESEARCH

Fig. 22. Time-of-flight neutron scattering spectra of Plexiglas. Open circles – back-scattering, full circles – forward-scattering. Time channel width is 0.5 μs.
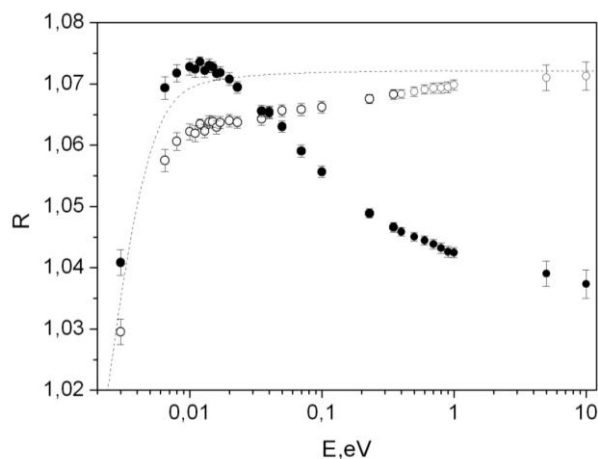

Fig. 23. Dependence of neutron scattering anisotropy on the initial neutron energy with regard to the thermal motion of Ar atoms at $b_{ne} = -1.32 \cdot 10^{-3}$ fm. Open circles – calculations corrected for efficiency, full circles – without corrections. The dotted curve is the anisotropy without considering n,e-scattering.

The correction $C(E)=\varepsilon(135^0)/\varepsilon(45^0)$ obtained from the Monte Carlo calculations for the differences in the intensities of neutrons scattered forward and backward by argon with regard to the thermal motion of its atoms along with the calculation of this correction without considering the thermal motion of gas atoms (dashed curve) are shown in **Fig. 24**. Similar calculations of this correction for krypton as a scatterer are in progress.

The estimates of neutron scattering by cadmium covering the walls of collimators have shown that at a neutron energy of 0.5 eV $0.6\cdot10^{-4}$ neutrons incident at various angles pass through 0.2 cm-thick cadmium and 10^{-4} neutrons are reflected. This uncertainty is acceptable in our experiment.
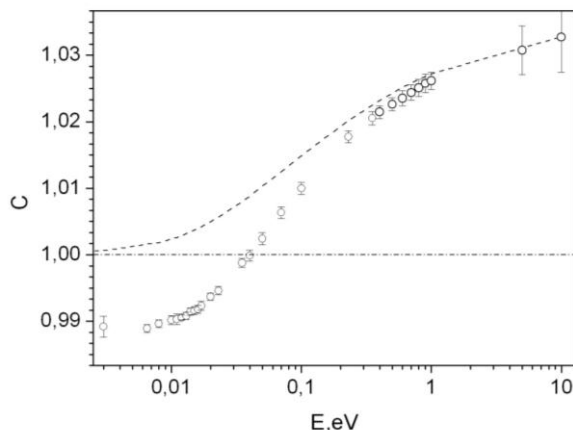

Fig. 24. The correction $C(E)=\varepsilon(135^0)/\varepsilon(45^0)$ obtained from the Monte Carlo calculations for intensities of neutrons scattered forward and backward by argon. The dashed curve is the correction $C(E)$ without regard to the thermal motion of gas atoms.

Upon completion of tests on IREN the AURA setup is proposed to be placed on beam 1 of the IBR-2 reactor for carrying out measurements with noble gases. To perform a final check of the AURA setup, it is planned to carry out measurements with a vanadium sample in order to obtain scattering anisotropy in the thermal neutron energy range. In this energy range in the experiment with vanadium performed earlier on IBR-2 the observed anisotropy of neutron forward- and back-scattering differed from a kinematic one. It would be of interest to confirm this result by carrying out measurements with the AURA setup on IREN.

The corrections for multiple neutron scattering from vanadium of different thicknesses have been estimated. The calculations have been made for neutron energies of 0.025 eV and 0.1 eV for three forward-scattering angles 30°±2.5°, 45°±2.5° and 60°±2.5° and for respective back-scattering angles 150°±2.5°, 135°±2.5° and 120°±2.5°. It can be seen from the calculations that the earlier negligence of multiple scattering for such thickness of vanadium was justified.

1.2.1.3. Development of methods for studying physics of fission

The activities carried out in cooperation with the Czech Technical University in Prague on the application of pixel silicon detectors for detecting charged particles emitted in fission are in progress. In earlier studies the possibility of measuring the energy of fission fragments using pixel detectors Medipix2 as well as the directions of fragment emission due to a high position resolution of these detectors has been demonstrated. A Medipix2 detector is a two-layer silicon detector with dimensions of 1.4×1.4 cm^2. The upper sensor layer is a conventional semiconductor detector (as a rule, a 300 μm-thick silicon layer is used). The lower layer (called a read-out layer) consists of 256×256 pixels (size of one pixel is 55×55 microns). Each pixel is an integrated chip, which makes it possible to register a signal in a pixel and to count events at specified differential (upper and lower) thresholds. The detection principle in the detectors of the Medipix family is based on the charge sharing effect, i.e. the charge created by the particle entering the detector sensitive area spreads over a rather wide

1. SCIENTIFIC RESEARCH

region during the charge collection process and can be finally collected by several adjacent pixels forming a cluster. The cluster size depends on the type and energy of the particle.

A new generation of pixel detectors – TimePix – also makes it possible to measure the arrival time of a particle to impinge on each pixel. In addition, the detector can operate in the time-over-threshold mode, in which the charge deposited by the incoming particle is determined by measuring the time during which the signal exceeds the detection threshold level. In 2013 the measurements of ternary spontaneous fission of ^{252}Cf using Timepix detectors were carried out in FLNP in collaboration with the Technical University in Prague. The ΔE-E technique, which allows charge identification of light charged particles, was used to identify ternary particles. A thin silicon detector (12 μm) was used as a ΔE-detector and a pixel detector TimePix with a 300 μm-thick sensor layer – as an E-detector.

The scheme of the experimental setup is shown in **Fig. 25**. A spontaneous fission source ^{252}Cf and the assembly of ΔE-E detectors are placed in a vacuum chamber. A 31-μm-thick aluminum foil is put between the source and detectors and provide full absorption of fission fragments and alpha-particles from spontaneous alpha-decay of californium (6.2 MeV). Thus, the detectors register only long-range light ch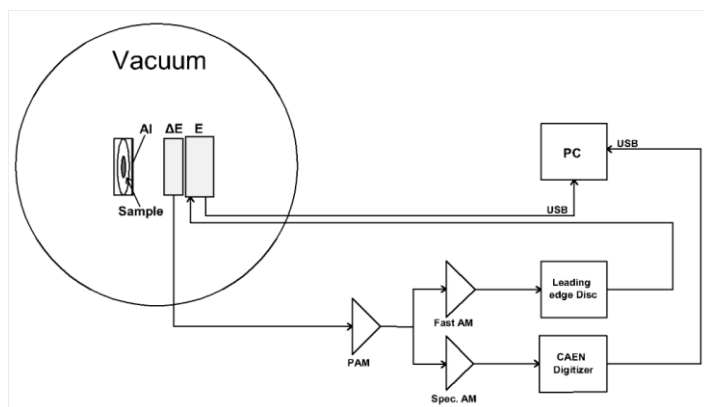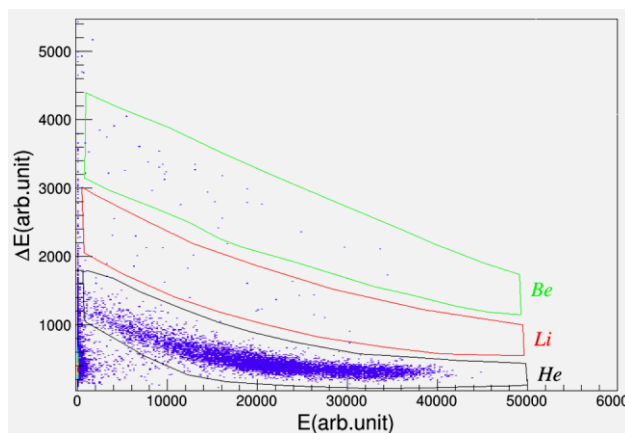arged particles from ternary fission. A signal from a ΔE detector is fed to a charge-sensitive preamplifier, then the amplified signal is divided and passed to the fast and spectroscopic tracts, respectively. The fast tract consists of a shaping amplifier and a discriminator with a fixed threshold; a shaped logic signal (+3.3 V CMOS-TTL) is fed to the external input (determining trigger) of the

Fig. 25. Scheme of the experimental setup.

Timepix detector.

The second part of the signal is fed to a spectrometric amplifier, which forms a signal for processing it in a digitizer CAEN DT5720. The digitized signals are saved in the computer memory through a standard USB port. Signals from a Timepix detector operating in a TOT mode are read through a USB FitPIX interface and also saved in the computer memory using a Pixelman program. The synchronization of two independent data flows (from ΔE and E detectors) is performed in the off-line mode by comparing the time stamps from the digitizer and FitPIX interface.

A 2D ΔE-E spectrum is presented in **Fig. 26**, where one can clearly see the separation of light charged particles by charge. Hydrogen isotopes cannot be observed because of a high threshold of the ΔE detector. Heavier particles have a significantly lower yield and are not observed when a weak source is used. The final objective of the experiment is to search for and study a quaternary fission with the simultaneous emission of two light charged particles.

Fig. 26. ΔE-E distribution of light charged particles from spontaneous fission source ^{252}Cf.
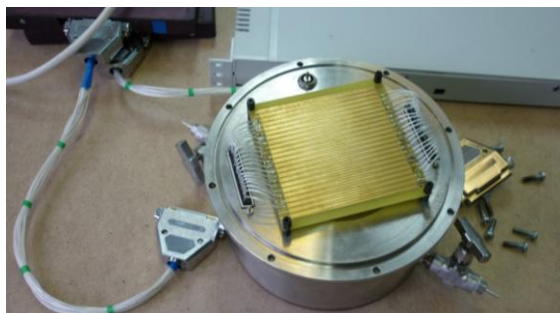
In 2013, a setup for precision measurements of prompt fission neutron multiplicity depending on the mass distributions of fission fragments and their total kinetic energy was designed and constructed. The detector is based on a position-sensitive double fission ionization chamber with the anode consisting of 48 strips (**Fig. 27**). According to calculations the spatial resolution in the anode plane does not exceed several hundredths of a millimeter. This setup makes it possible to perform not only high-quality measurements of prompt fission neutron distributions but also mass-energy characteristics. In addition, it has been suggested that the detector be used in neutron radiography experiments as a competitive

Fig.27. General view of the position-sensitive chamber.

alternative to the available present-day solutions. For this purpose a fully digital variant of electronics based on 128 parallel channels for discretization of signals of the double ionization chamber has been considered.

1.2.1.4 Investigations of space parity violation effects in nuclear reactions

Previously, the measurements of the P-odd asymmetry in the radiative cross-section on natural lead have been performed on the PF1B instrument of the ILL reactor (Grenoble, France). The experiment was conducted to obtain additional information to explain an anomalously high value of the neutron spin rotation in the measurements of transmission of transversely polarized neutrons through a sample. A constraint on the effect in the radiative capture $\alpha_\gamma \leq 8.1 \cdot 10^{-7}$ was obtained. A theoretical analysis was performed and calculations of P-odd effects in the interactions of polarized neutrons with natural lead were made. The calculations were done for two sets of resonance parameters. For further investigation of parity violation effects in lead two experiments may be suggested to be carried out: the measurement of the asymmetry in total cross section and in radiative capture cross section. Though these effects are much weaker than in the spin rotation experiments, but their realization is much easier methodologically.

The experimental coefficients of the left-right and P-odd asymmetry in the integral spectrum of γ-quanta in the interaction of nuclei with polarized thermal neutrons have been analyzed. From the results it follows that in all cases when a significant effect is observed in the measurements of the P-odd asymmetry, the coefficient of the left-right asymmetry is much less than the coefficient of the P-odd asymmetry, while according to the theoretical calculations one expects that they should be approximately the same for the integral spectrum of the thermal energy of neutrons from one and the same nucleus. No left-right asymmetry has been reliably observed in the nuclei under study except for bromide. Since the measured coefficients of the left-right asymmetry are significantly less for ^{nat}La, ^{nat}Cl, ^{nat}Br, than it follows from the calculations, these investigations should be continued at high-flux neutron sources to obtain, if possible, the reliable results on the coefficients of the left-right asymmetry and to clarify the reasons for the deviations between calculations and experiment.

1.2.1.5. Investigations of a possibility to search for space parity violation effects in neutron diffraction

Neutron diffraction investigations with a potassium bromide single crystal in the vicinity of p-wave resonance of ^{81}Br have been carried out on beam 1 of the IBR-2 reactor. Neutron diffraction spectra for three neutron angles of incidence on a single crystal are presented in **Fig. 28**. It can be seen that the rotation of the crystal through 100'' results in the splitting of the 1st order diffraction peak and in a shift of the 2nd order diffraction peak. The observed effect is most likely connected with three-wave neutron diffraction (multiple scatterin).
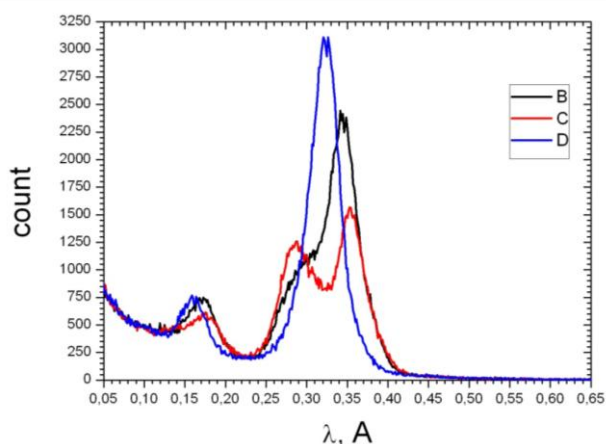
1. SCIENTIFIC RESEARCH

Fig. 28. Neutron diffraction spectra. The blue line is exact satisfaction of Bragg conditions, the black line – the crystal is rotated through 60'', the red line – the crystal is rotated through 100''.

In order to verify the multiple scattering effect in neutron diffraction, it has been decided to perform investigations with neutrons in the lower energy range. The results of the measurements are presented in **Fig. 29**. One can see that the 2nd order diffraction peak is larger than the 1st order diffraction peak and it can be explained only by three-wave neutron diffraction (multiple Bragg scattering).
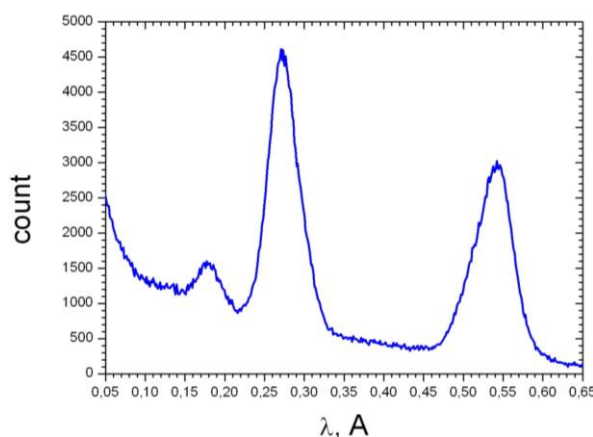

Fig. 29. Neutron diffraction spectra of single crystal KBr, 1st order diffraction peak corresponds to the neutron wavelength of ~ 0.55 Å.

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

The experimental and theoretical investigations of the (n,p), (n,α) reactions induced by fast neutrons continued. The experiments are carried out at the Van de Graaf accelerators EG-5 in FLNP JINR (Dubna, Russia) and EG-4.5 of the Institute of Heavy Ion Physics of Peking University (Beijing, China). 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. In addition, these data are of importance in choosing engineering materials and in performing calculations in the development of new facilities for nuclear power engineering.

At the end of 2013 the measurements of the $^{66}Zn(n,\alpha)^{63}Ni$ and $^{144}Sm(n,\alpha)^{141}Nd$ reactions at E_n=4 MeV were conducted, thus completing a series of measurements that started a year ago. The measurements of the $^{54}Fe(n,\alpha)^{51}Cr$ reaction were also carried out at E_n=5.5 and 6.5 MeV. The energy spectra of charged particles were obtained and the data treatment is in progress.

The data treatment for the measurements of the $^{57}Fe(n,\alpha)^{54}Cr$ and $^{63}Cu(n,\alpha)^{60}Co$ reactions at E_n~4.0-6.5 MeV has been completed. A comparison with the available library estimates and with the data obtained by other authors has been performed (**Fig. 30, 31**).

The analysis reveals a significant discrepancy between the estimates given by different nuclear data libraries, while no experimental data are available for ^{57}Fe isotope. The available data for ^{63}Cu from two rather old measurements in the range of several MeV show a considerable discrepancy.
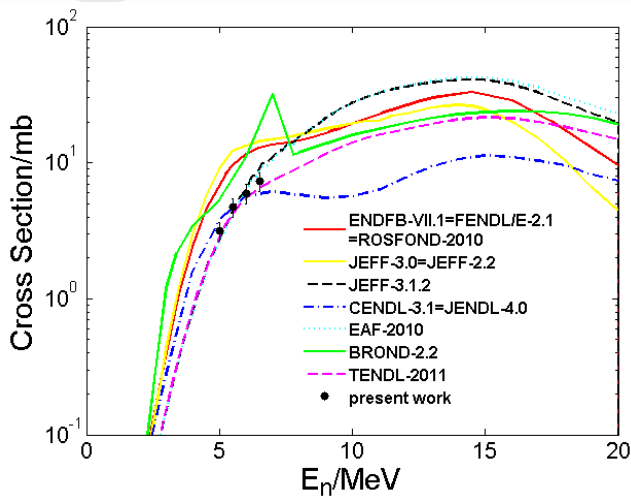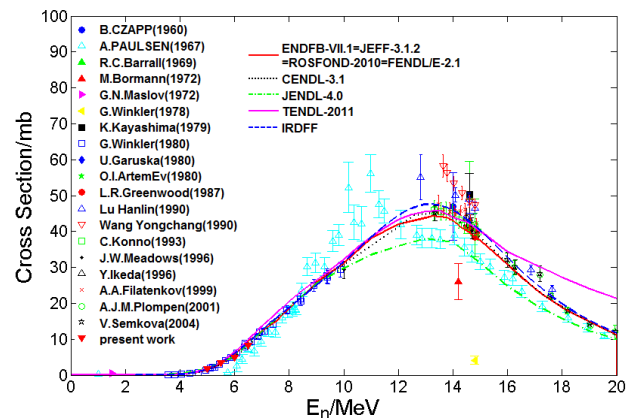
Fig. 30. The obtained cross sections of ^{57}Fe$(n,\alpha)^{54}$Cr in comparison with the available library estimates and with the data obtained by other authors (left).

Fig. 31. The obtained cross sections of ^{63}Cu$(n,\alpha)^{60}$Co in comparison with the available data and estimates(right).

A theoretical analysis of the cross-sections (averaged over the fission spectrum) of the (n,p), (n,α) reactions has been done in the framework of the statistical model. The cross-sections of the (n,p), (n,α) reactions induced by fast neutrons are of importance, on the one hand, for evaluating the production of hydrogen and helium, the nuclear heating and transmutations in constructional materials for nuclear power engineering; on the other hand, the systematic analysis of neutron cross-sections is required in studies of the mechanisms of nuclear reactions. Additionally, it is often necessary to estimate the neutron cross-sections for the nuclei, for which the experimental data are unavailable or may be difficult or impossible to be obtained. The statistical model based on the Weisskopf-Ewing theory was used for systematic analysis of the known experimental cross-sections of the (n,p), (n,α) reactions averaged over the fission neutron spectrum of ^{235}U. Since the main objective of the research was to obtain the averaged systematic behavior of the cross-sections of the (n,p), (n,α) reactions for intermediate and heavy nuclei in the energy range of the neutron fission spectrum, the detailed Hauser-Feshbach theory, which employs the optical potential depending on the specific properties of nuclei, was not considered. For the intermediate and heavy nuclei (Z >> 1) the following formulas were obtained:

$$\sigma(n,p) = C_p \pi (R + \lambda/2\pi)^2 e^{-K_p \frac{N-Z+1}{A}},$$

where $C_p = \exp\left(ZA^{1/6} \frac{2\gamma-1}{\sqrt{13.5(E_n+Q_{np})}} \right)$, $K_p = 4\xi \sqrt{\frac{A}{13.5(E_n+Q_{np})}}$

$$\sigma(n,\alpha) = C_\alpha \pi (R + \lambda/2\pi)^2 e^{-K_\alpha \frac{N-Z+0.5}{A}},$$

$$C_\alpha = 2\exp\sqrt{\frac{A}{13.5(E_n+Q_{n\alpha})}}\left(-3\alpha + \gamma\left(\frac{4Z}{A}\right) + \varepsilon_\alpha - 2.058\frac{Z}{A^{1/3}}\right), K_\alpha = 2\xi\sqrt{\frac{A}{13.5(E_n+Q_{n\alpha})}}.$$

1. SCIENTIFIC RESEARCH

Here Z, N, A are the neutron, proton and mass numbers of the target nuclei, respectively; α, γ, ξ are the Weizsäcker constants; ε_α is the binding energy of the α-particle. The parameters K_i and C_i (I = p or α) for each neutron energy can be obtained from the corresponding dependences in the available experimental data. In **Figs. 32 a** and **b** the values of the cross-sections for the mean neutron energy of 5 MeV (calculated in accordance with the above formulas with the parameters $K_p = 80$, $C_p = 2.8$, $K_\alpha = 65$, $C_\alpha = 0.04$) are compared with the experimental data.
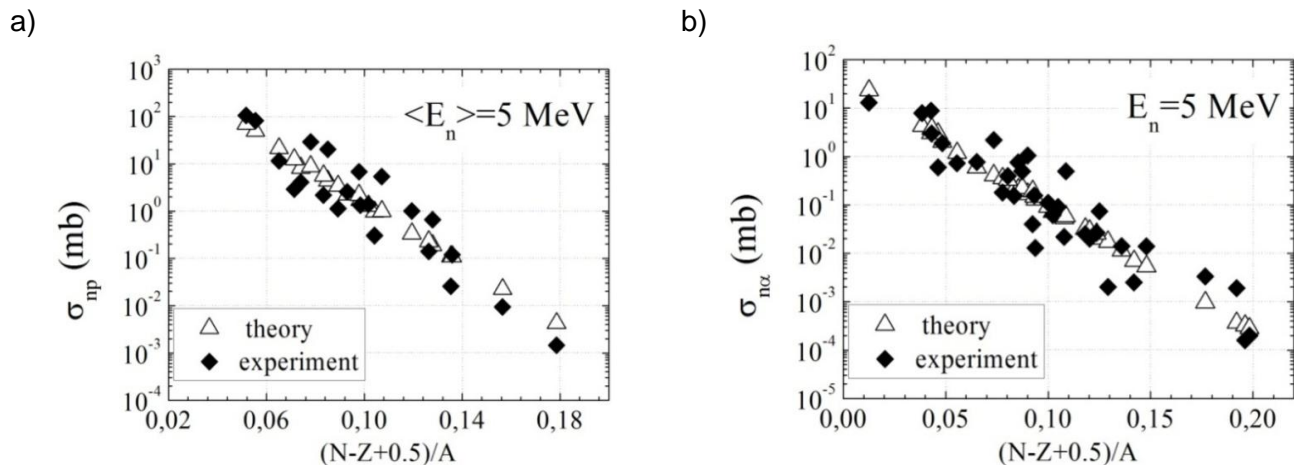
a)
b)

Fig. 32. a) Theoretical and experimental cross-sections of the (n,p) reactions. b) Theoretical and experimental cross-sections of the (n,α) reactions.

1.2.1.7. Investigations of nuclear structure

The first variant of a promising practical model of the cascade gamma-decay of the neutron resonance has been developed on the basis of the Strutinsky model for the density of n-quaziparticle levels and the Kadmensky-Markushev-Furman model for radiation widths of E1-transitions between highly excited levels using some phenomenological representations. The model is based on the results of the analysis performed in FLNP JINR of the experimental data obtained to date on the intensities $I_{\gamma\gamma}$ of two-quantum cascades between the neutron resonance and the group of its low-lying levels. The model suggests that the co-existence and interaction of fermion and boson components of nuclear matter can determine the properties of the latter in an excitation energy interval equal to or slightly larger than the binding energy of the neutron in the nucleus.

In the implemented variant the model has made it possible to describe the intensities of such cascades with a precision of the experiment for the available set of 40 compound nuclei in the mass region from ^{40}K to ^{200}Hg. The existing so far model descriptions of the nucleus as a purely fermion system repeat these data with an error from several tens to hundred percent (or even higher).

The investigations have demonstrated that neutron resonance gamma-decay spectra and probably neutron-nucleus interaction cross sections can be calculated with the precision of the present-day experiments when the breakup of maximum four Cooper pairs of neutrons (and/or protons) are taken into account. Thus, our model makes it possible to gain fundamental information (which cannot be obtained using other experimental techniques) about the properties of nuclear matter in an object of finite size containing charged and neutral fermions and others.

As an example, the results of the model approximation to the cascade intensities in three even-odd isotopes of tungsten are given below (**Fig. 33**). The experimental data were obtained in one and the same experiment. Correspondingly, small experimental errors are strongly correlated and cannot explain the difference between the experimental data and calculations, which use the model representation of the nucleus as a purely fermion system.
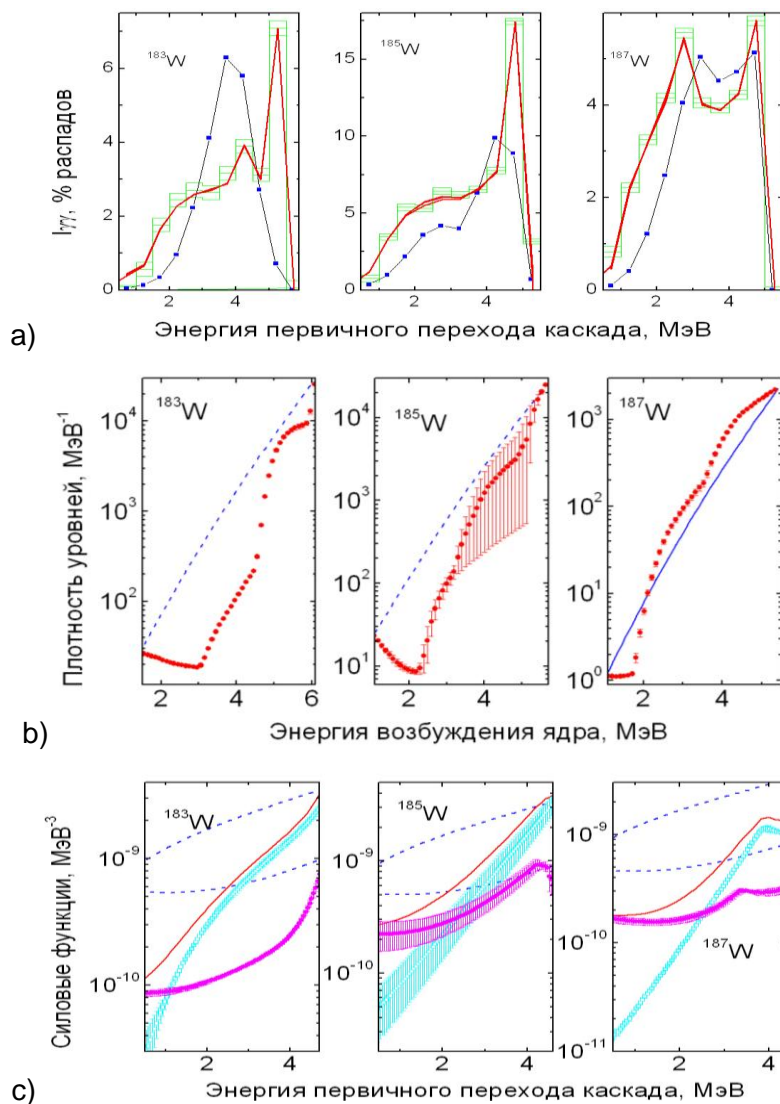
Fig. 33. **a**. Histograms comparing experimental cascade intensities (along with experimental errors) and calculations using the statistical representation of the nucleus and generally accepted models of the level density and radiation strength functions (blue points). The red lines denote a group of seven best approximations, which differ in the initial data of the proposed model and stochastic ways of the χ^2 minimization processes. A very narrow spread of these data shows that for the realized model there is only one minimum of the likelihood function. **b**. The red points with errors denote the mean value of the best approximated level density and their spread for the above seven variants of approximation. The blue line denotes the density of intermediate cascade levels for the Fermi-gas model. The break points are the most probable pair-breaking thresholds of the next Cooper pair of nucleons in the nucleus. **c**. The upper blue lines show the extrapolation of the tail of a giant dipole electric resonance; the lower lines show the KMF models summated with the constant strength functions of M1-transitions. The blue and magenta points with errors show the strength functions of E1- and M1-transitions and their spreads, respectively. The red lines denote the mean value of the sum of the strength functions of E1- and M1-transitions providing best approximation of $I_{\gamma\gamma}$ (without coefficients accounting for the ratio between the model and approximated level densities (**Fig. 33 b**)).

1. SCIENTIFIC RESEARCH

This is a direct consequence of the fact that the coefficients of the error recalculations from the errors of the level density and strength functions to the $I_{\gamma\gamma}$ errors increase sharply when the energy of the primary transition of the cascade decreases and can exceed the value of 10^2-10^3.

A step-like structure of the most probable level density can be explained only in the frame of the model which suggests that the number of unpaired neutrons and protons (quasiparticles in terms of the theoretical models of the nucleus) increases by two at threshold energies of Cooper pair breakup. The necessity to use in the experimental analysis the fully phenomenological representations of the boson excitation density and width of gamma-transitions at their decay/excitation causes inevitable systematic errors in the obtained data for both level density and strength functions. At the moment, there are no proper models for experimental analysis, which would account for the successive breaking of Cooper pairs and describe the corresponding parameters of the boson component of the nucleus.

A significant but finite spread of the data for the fixed multipolarities of gamma-transitions and its practical absence for their sum is indicative of a strong anticorrelation of the density of the levels with the given parity and the multipolarity of primary transitions exciting them. However, this correlation is significantly lower as compared to the data of other experiments performed so far.

1.2.1.8. Search for the singlet state of the deuteron

An experiment to search for the singlet deuteron in the reaction n + p → d + 2γ has been conducted on beam 11b of the IBR-2 reactor. Gamma-quantum spectra from a polyethylene target have been obtained using an HPGe detector. The peak corresponding to a direct transition with an energy of 2223 keV contains $2 \cdot 10^8$ counts. The upper boundary for the cross section of emitted gamma quanta with an energy in the range of 2100-2200 keV was found to be of the order of 15 μb (at the level of 3σ) which is half the value obtained by R.Hackenburg (BNL). It is planned to continue this experiment with an improved technique and new software. There is also a probability to carry out this experiment in Grenoble.

1.2.1.9. Modernization of the "Kolkhida" setup

The "Kolkhida" setup intended for studies of neutron optics phenomena in interactions of polarized neutrons with polarized nuclei has been constructed at the IBR-2 pulsed reactor. The "Kolkhida" instrument consists of the following components: polarized neutron spectrometer, polarized nuclear target, control system. The polarized neutron spectrometer is located on the tangential beam 1 of the IBR-2 pulsed reactor. The layout of the spectrometer is shown in **Fig. 34**.
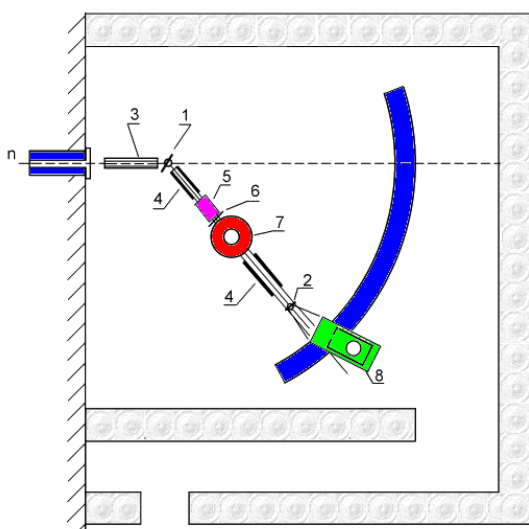

Fig. 34. The layout of the spectrometer: 1 – primary collimator; 2 – Soller collimator; 3 – polarizer crystal; 4 – guiding field electromagnets; 5 – Mezei flipper; 6 – shim; 7 – cryostat; 8 – analyzer crystal; 9 – detector.

Within the framework of the preparation of the "Kolkhida" setup for regular operation the modernization of control electronics of actuating mechanisms has been carried out. In particular, for the polarized neutron spectrometer the stepper motors FL57STH76-1006B for changing the angular position of the detector arm, platform, polarizer and analyzer have been installed. To determine the rotation angles, angle sensors OCD-SL00B-0016-C100 CRW have been set up. The rotation of various components of the setup is controlled by a computer program. The program uses the algorithm that accounts for the motor play. Thus, the angles can be specified with an accuracy of < 0.1°. Another computer program controls a power supply, which allows us to set the current in the superconducting solenoid to 110 A with an accuracy of 5 mA.

A polarized nuclear target has been modernized as well. The infrastructure of a ^{3}He-in-^{4}He dilution cryostat has been upgraded by replacing outdated vacuum devices with modern ones; a new dilution bath and a new component of the cryostat for neutron scattering studies of samples in a strong magnetic field and at room temperature have been developed (**Fig. 35**).
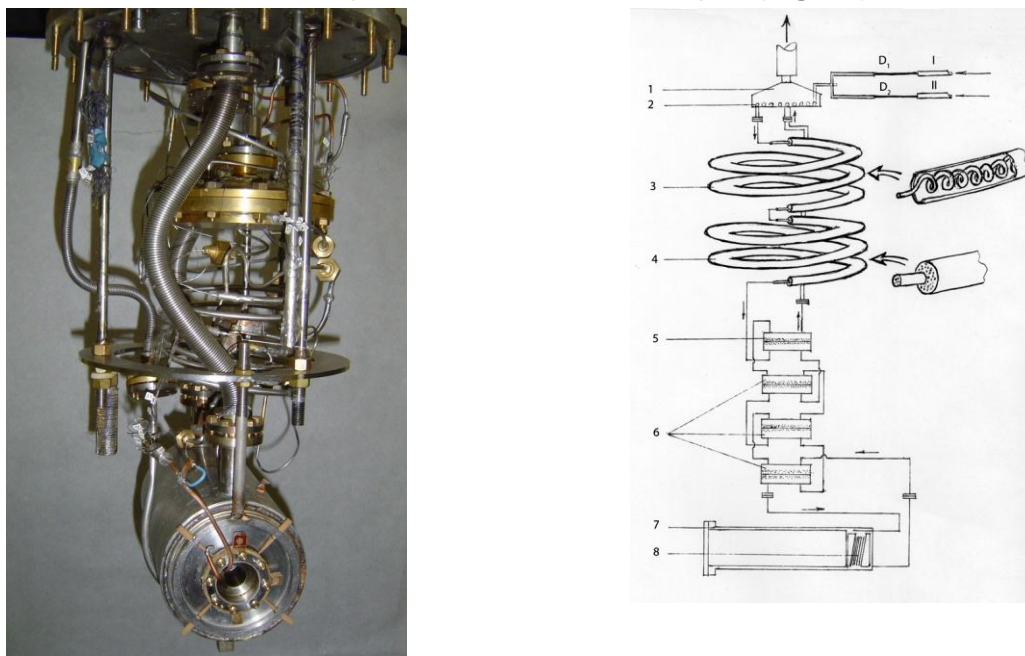

Fig. 35. General view and diagram of ^{3}He-^{4}He dilution stages: 1 – evaporation bath; 2 – evaporation bath heat exchanger; 3 – continuous heat exchanger; 4 – continuous sintered heat exchanger; 5 – discrete copper heat exchanger; 6 – discrete heat exchangers of sintered silver powder; 7 – dilution bath; 8 – ferromagnetic neutron resonator with polarized nuclear target.

1.2.1.10. Experimental study of the possibilities of cold neutron accumulation at the end of a thermal neutron beam line

Earlier we proposed a project of a new high-intensity UCN source capable of producing ~10^8 UCN/s with the UCN density in the storage volume reaching 10^5 n/cm^3, which is 3 orders of magnitude higher than that of the available sources. The idea consists in producing the flux of cold (wavelength of 9 Å) neutrons by using a helium UCN source in the cavity of the moderator/reflector placed at the end of a neutron guide with thermal neutrons. In this case the cavity itself is a source of cold neutrons. Solid methane was proposed to be used as a moderator/reflector. Thus, the source is a spherical vessel filled with liquid helium at a temperature of 0.6 K and surrounded by a solid methane moderator. This layout of the source makes it possible to position it on extracted thermal neutron beams, which reduces many fold the heat load on the source and, accordingly, its cost as

1. SCIENTIFIC RESEARCH

compared to the sources located near the reactor core. This allows the range of applications of UCN to be extended many times and to use them not only for scientific research but for applied and educational purposes as well.

Test measurements have been carried out to test the idea of using a cavity of solid methane for producing a cold neutron flux at the end of a neutron guide with thermal neutrons. For these measurements a special cryostat was designed and constructed in 2012-2013. The test measurements were done in 2013 on the DIN-2PI instrument on beam 2 of the IBR-2 reactor. The instrument is intended to measure the inelastic neutron energy transfer by the time-of-flight method. The preliminary results on the measurements of the neutron spectrum formed in the methane cavity under irradiation of neutrons with an energy of 25.0 eV (wavelength 1.8 Å) are presented in **Fig. 36**.

The Maxwellian neutron spectra corresponding to various temperatures are shown for comparison with the measured spectrum. One of them is the spectrum at which the maximum number of neutrons with the wavelength of 9 Å (T = 6 K) is achieved. The second one is the neutron spectrum in one of the neutron guides at the cold moderator of the ILL reactor (France) (T = 15 K). The integrals of all spectra are the same. On the basis of the results of the measurements, it has been estimated that methane albedo for the spectrum that is presented in **Fig. 36**, is ~ 65%, which is very close to the preliminary calculated estimates that follow from the energy dependence of the cross-sections.

Fig. 36. Spectrum of neutrons moderated in the methane cavity.

The results of the test measurements show that one can obtain the neutron spectrum close to that from the cold reactor source by using the thermal neutron beam inside the methane cavity. The albedo of solid methane for cold neutrons is close to the calculated value. Thus, the idea of a helium UCN source inside a cold cavity at the end of a neutron guide with thermal neutrons appears feasible. The next step in the development of the given idea is to construct a prototype of the source to test the solutions for a number of technical problems. Further optimization of the temperature of the moderator is possible at the prototype UCN source using the yield of cold neutrons, since the contribution of multi-phonon processes in the UCN production can be significant.

1.2.1.11. Investigations of UCN physics

In the framework of the UCN collaboration (LANSCE, Los Alamos) inelastic scattering (UCN upscattering) cross sections for vanadium, V, and polyethylene, $[C_2H_4]_n$. have been measured and published. Such measurements are of contemporary importance since these materials are widely used in UCN experiments, but the available data are conflicting and often do not agree with the theory. The measurements have been performed using a solid-deuterium ultracold neutron source driven by an 800-MeV proton beam. The performed measurements are based on the comparison between V and $[C_2H_4]_n$ ratios of count rates from a γ-detector and neutron scattering detector using the known values of radiative capture cross sections. The measurements with the γ-detector (high purity germanium detector HPGe) and neutron detector (^{3}He gas counter) were carried out simultaneously. For the UCN velocity spectrum with an average velocity of 4 m/s the upscattering cross section values of 1970 ± 130 b and 25 ± 9 b have been obtained for polyethylene and vanadium, respectively. The result for vanadium has been obtained for the first time, and it is in
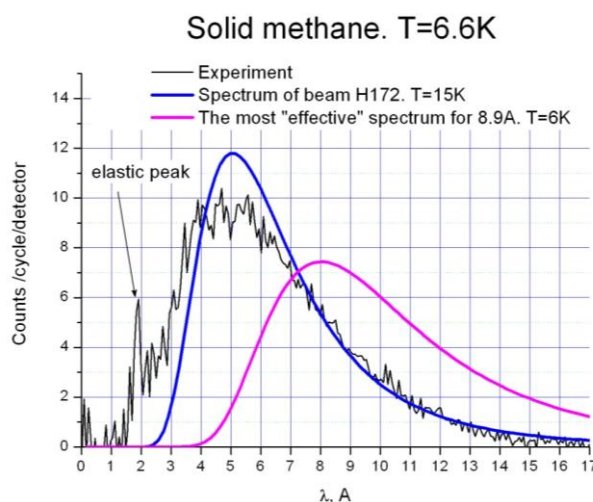
agreement with the theoretical value. A comparison with the data from other experiments has shown that the result for polyethylene agrees only with the value obtained by Yu.Pokotilovski in Grenoble, but it is much lower than the model value of 3500 b obtained from extrapolation to 4 m/s using MCNP calculations with the available thermal neutron data library.

Within the framework of the same collaboration a measurement of the average energy of the flux of upscattered neutrons after the interaction of UCN with hydrogen bound in polycrystalline polymer PMP, $[C_6H_{12}]_n$, has been performed. This study is of interest for comparison with the UCN upscattering in polyethylene, $[C_2H_4]_n$, and in the context of the as-yet-unresolved problem of UCN losses during storage. The measurement has been conducted at the Los Alamos National Laboratory solid-deuterium ultracold neutron source. The ratio of count rates of scattered neutrons for two detectors of different efficiencies has been measured and this ratio depends on the shape of the spectrum of the flux and its average energy. Gas ^{3}He detectors with a partial pressure of 180 kPa in one detector and 20 kPa in the other detector were used. To obtain the result, the measured ratio was compared to the calculations for different average energy values using the MCNP program in which the modeling of scattering is mainly based on one-phonon approximation and also takes some account of multiphonon processes of inelastic neutron scattering. This modeling has demonstrated that the energy spectrum of the neutron flux is clearly not Maxwellian. We obtained an average energy value of 26 ± 3 meV for polymer PMP (polymethylpentene), which is twice as much as the value of 10-13 meV for polyethylene that was obtained earlier in the analysis in the frame of Maxwellian approximation. Finally we adduce some arguments, which allow us to expect close average energy values for $[C_6H_{12}]_n$ and $[C_2H_4]_n$.

1.2.1.12. Cooperation in the framework of the GRANIT project in ILL (France)

FLNP JINR in cooperation with the P.N.Lebedev Physical Institute of RAS and Virginia State University (USA) are the members of the GRANIT collaboration. The GRANIT project aimed at designing and building a second-generation gravitational neutron spectrometer with ultra-high energy resolution GRANIT (**GRA**vitational **N**eutron **I**nduced **T**ransitions). This spectrometer will make it possible to observe resonance transitions between neutron quantum states in the Earth's gravitational field. It is planned for the first time to directly measure the energy of quantum states. The storage time of UCN in quantum states for this spectrometer is expected to reach values of the order of a second.

By the end of 2013 all the main units of the spectrometer have been put into operation and tested. The UCN source designed for the spectrometer operates reliably and neutrons from the source have been extracted into the spectrometer. The spectrum of the neutrons extracted into the spectrometer has been obtained and turned out to be a very soft one. In connection with the shutdown of the reactor in ILL (from August, 2013 to July, 2014) where the GRANIT spectrometer is located, the collaboration is conducting research activities on the improvement of parameters of the UCN source and neutron detection system.

1.2.1.13. Continuation of the experiment to test the equivalence principle for the neutron

The experiment to verify the equivalence principle for the neutron with the UCN spectrometer Epigraph designed and constructed in 2010-11 has continued. The operation of the instrument is based on the combined use of Fabry-Perot neutron interferometers and neutron flux modulator-chopper (see **Fig. 37**). A change in the energy of the neutron falling in the gravitational field is compared with the energy transferred to the neutron diffracted into the −1 order by a moving diffraction grating.

Fig. 37. Chopper-modulator.

1. SCIENTIFIC RESEARCH

A specific feature of the instrument is the possibility of using an original time-of-flight technique based on the measurement of the detector count rate oscillation phase. The detection of UCN is performed by a scintillation detector synchronized with a modulator. A high degree of beam monochromatization ($\Delta v/v < 2\%$) makes it possible to work with the times of flight, which many times exceed the modulation period, thus ensuring a unique energy resolution of the instrument.

A full-scale test experiment with new Fabry-Perot interferometers and new diffraction grating has been conducted on the UCN beam of the Institute Laue Langevin (Grenoble, France). A number of improvements have been made in the design of the instrument. As a result, the experimental conditions have been significantly improved (see **Fig. 38** and **39**).

The count rate and the effect/background ratio have increased considerably. An increase in the count rate oscillation amplitude has made it possible to increase the modulation frequency and hence to enhance the sensitivity of the experiment.

As a result, the statistics collection rate in the experiment increased three times (from 1.5×10^{-2} events per day in 2011 to 5×10^{-3} events per day) which reduces the statistics collection time by almost an order of magnitude.

At the same time, the experimental results are indicative of some systematic effects, which should be studied and eliminated in the next stage of the experiment.

f = 75Hz Amplitude of oscillation A= 0.223 $\pm$ 0.011

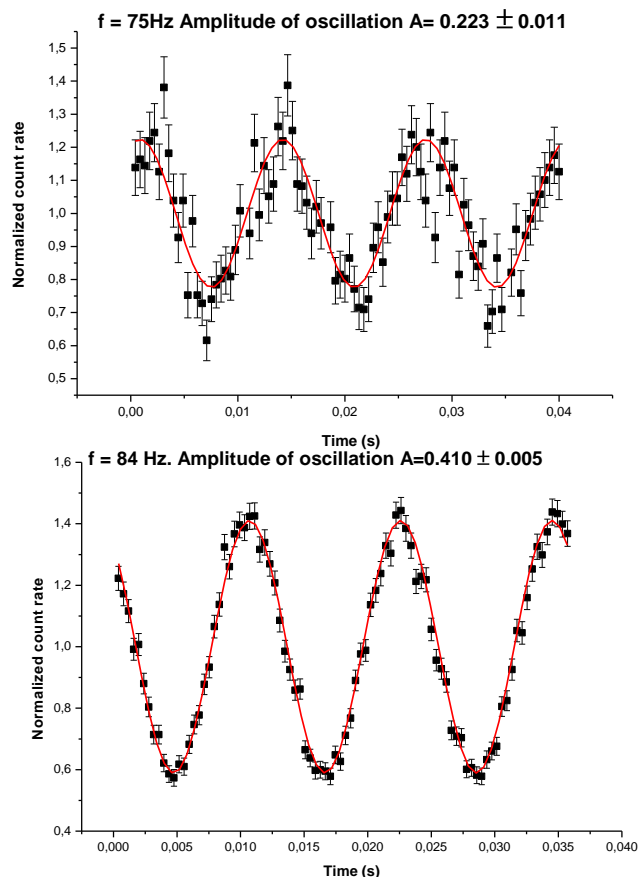**f = 84 Hz. Amplitude of oscillation A=0.410 $\pm$ 0.005**

Fig. 38. Count rate oscillation in the experiment in 2011 (top) and in the new experiment
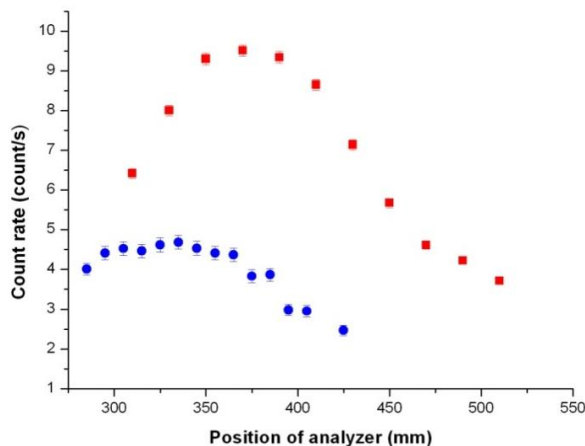
Fig. 39. Neutron scanning (spectrum) curve in the −1 order of diffraction from a moving grating in the experiment in 2011 (blue circles) and in the new experiment (red squares).

1.2.1.14. Search for new type interactions

The interferential method to search for new hypothetical interactions has been considered. At present, the chameleon scalar fields are considered to be a possible reason for the acceleration of the expansion of the Universe. The presence of a chameleon field results in a change in the particle's potential energy in the vicinity of a massive body. A neutron Lloyd's mirror interferometer has been proposed for a highly-sensitive search for effects of the chameleon field, where the interaction of neutrons with the reflecting mirror results in a phase shift of neutron waves.

Possible neutron interferometer experiments to search for new interactions, both spin-dependent (axion interaction) and spin-independent (short-range non-Newtonian gravity), have been analyzed.

1.2.2. Methodical and applied research
1.2.2.1. Activities in cooperation with the Space Research Institute of RAS

The activities to design equipment for studying the planets in the Solar system are in progress. In 2013, the calibration of the neutron detectors and gamma-spectrometer of the scientific instrument "Mercury Gamma-ray and Neutron Spectrometer" (MGNS) was done. MGNS will be placed on board *BepiColombo* European Space Agency interplanetary mission to be launched in 2015. The instrument is intended to search for water ice and to determine the elemental composition of the Mercury shallow subsurface.

The monitoring of the neutron yield of the pulsed neutron generator ING-10K is conducted. An identical generator is a part of the scientific instrument "Dynamic Albedo of Neutrons" (DAN) onboard NASA's Mars rover "Curiosity".

1.2.2.2. Analytical and methodical investigations at the IREN facility

The investigations aimed at detecting cosmic dust in the soil samples from a high-mountain glacier Aktru in Altai continued on a neutron beam of the IREN facility using neutron spectroscopy techniques. The treatment of the data from the neutron transmission measurements with the novel multifunctional materials prepared in the Belarussian State University (Minsk) continued. The research objective was to determine the boron content in the samples. The comparative investigations of ore samples provided by the Central Geological Laboratory of the Mongolian Ministry of Natural Resources and Energy were carried out to further develop the nondestructive testing method for determining the elemental/isotopic composition of samples using neutron spectroscopy techniques. In one case the measurements were performed using the neutron resonance capture analysis, and in the other, employing the activation technique. The results of both methods are in good agreement, but at a given intensity of the IREN facility the activation technique is more sensitive.

In 2013 the radiation tests of scintillators and megatile samples of the CMS setup (CERN) were performed. It was necessary for the optimization of the conditions for future experiments. The neutron spectrum at IREN is close to that at the CMS hadron calorimeter. The samples were irradiated by the total fluence of 10^{12} n/cm^2. Then during three weeks the induced activity was measured at two distances from the sample. The emitted gamma-radiation was measured by a Canberra HpGe-detector.

Several methods for direct measurements of the fast neutron spectrum of the IREN facility have been probed. The use of a fission chamber with ^{235}U target and current preamplifier for reading signals proved to be rather promising. The application of such equipment along with the high time resolution of the facility (100 ns) makes it possible to detect neutrons with an energy of up to 20 MeV (see **Fig. 40**) at a flight path of 60 m. However, in the energy range above 3 MeV there is some deviation between the measured and calculated (by the Monte-Carlo method) flux density. The investigations will continue.
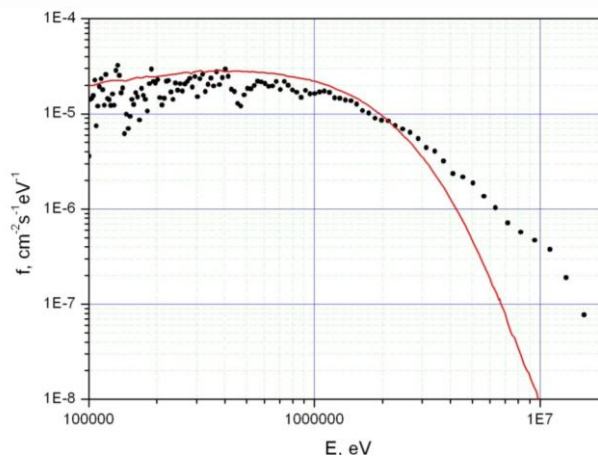
1. SCIENTIFIC RESEARCH

Fig. 40. Neutron flux density of the IREN facility at a 60 m flight path: points are the experimental values; the line is the calculation by the Monte-Carlo method.

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

Over the past year the EG-5 accelerator was in operation for various experiments for about 600 hours. The investigations of depth profiles of elements using nuclear analytical techniques: RBS (*Rutherford Backscattering Spectrometry*) and ERD (*Elastic Recoil Detection*) have been carried out in cooperation with the representatives from various research institutes of the JINR Member States. The specialists from FLNR, DLNP, Voronezh State University, Tomsk Polytechnic University, Marie Curie-Sklodowska University (Lublin, Poland) and Institute of Electrical Engineering of the Slovak Academy of Sciences (Bratislava, Slovak Republic) took part in the experiments. The samples of different elemental composition and prepared using various technologies have been analyzed. In particular, the depth profiles of elements in the samples of nanocrystalline silicon carbide films prepared using PECVD (plasma-enhanced chemical vapor deposition) technology have been investigated. A study of electrical and optical characteristics of films depending on their elemental composition has been carried out.

The depth profiles of hydrogen and deuterium in the samples prepared for studying the nuclear reaction $d(d,\gamma)^3He$ at low energies have been investigated also using nuclear analytical RBS and ERD techniques.

1.2.2.4. Analytical investigations at the IBR-2 reactor
Development of the NAA Sector experimental base

In the reported period the software package has been developed for complex automation of the neutron activation analysis on the IBR-2 reactor, which includes:
- database of samples under study and of all operations for performing NAA;
- software for automation of induced activity spectrum measurement using the Genie-2000 software for collection and analysis of spectra and the S561 Genie-2000 batch programming support package;
- software for automation of calculations of element concentrations on the basis of the results from the treatment of gamma-spectra by Genie-2000 software;
- set of service programs for automation and facilitation of database creation;
- set of assistance programs for ensuring convenience in performing some QC/QA procedures.

In the process of training the personnel to work with the program package, the software underwent development and upgrade. A partial modernization of the mechanical part of the

pneumatic transport facility has been carried out. Work to develop and construct automatic sample-changing devices on three detectors is in progress (devices for two-axial linear movement of samples have been purchased; other component devices have been designed and are being manufactured).

The devices that provide linear movement of samples have been tested at a test stand. The design of a control program for automatic sample-changing devices combined with the program for spectrum measurement automation is in progress.

The activities on automation of NAA at the IBR-2 reactor are 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).

Method development

New packing materials for sample irradiation and for production of transport containers have been tested to select a material with high radiation resistance and low induced radiation background after irradiation. The measurements of thermal and resonance neutron flux densities have been carried out on some neutron beams in new experimental conditions after the completion of the IBR-2 modernization.

Biomonitoring

In 2013, in the framework of the international program "Heavy metal atmospheric deposition in Europe – estimations based on moss analysis" the multielement analysis of 330 moss-samples from Romania (NAA in Dubna and atomic absorption spectroscopy (AAS) in Valahia University of Targoviste) was completed. The samples were collected by the participants of the JINR-Romania project from four Romanian universities in Targoviste, Galaţi, Baia Mare and Iaşi. A statistical analysis of the obtained data for 34 elements has been performed and the preparation for the publication of the Atlas of Atmospheric Deposition of Trace Elements in Romania has been conducted. The results of this work will be reported at the forthcoming 27th Task Force Meeting of UNECE ICP Vegetation (January 28-30, 2014, Paris). The contribution of the NAA Sector to the European Atlas of Heavy Metal Atmospheric Deposition is reflected in the publications of the Sector for Slovakia, Macedonia, Albania, Croatia. A student's degree thesis has been performed on the assessment of atmospheric deposition of trace elements near a thermal power plant in the territory of Ochakovo-Matveevskoe district of Moscow. The work on the active moss-transplant biomonitoring of airborne trace elements allowed us to study the air pollution in the center of Belgrad, Serbia, as well as in one of the most ecologically unsafe regions of Greece – Greater Thriasion Plain, Attica. The efficiency of using moss-biomonitor technique to study atmospheric depositions of radionuclides has been demonstrated in the joint projects carried out in collaboration with Slovakia, Belarus, South Africa, Serbia and Thailand.

Ecosystem condition assessment

In 2013, the multielement analysis of soils and bottom sediments from various regions of the Nile delta and its near-shore area continued 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». It has been 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.

Within the framework of the Cooperation Agreement with the Institute of Biology of the Southern Seas (Sevastopol, Ukraine) the analysis of macroalgae-biomonitor samples in the coastal zone of the Black Sea has been performed to assess the state of the coastal ecosystem of the Crimea. A technique of sampling and preparation of plankton for NAA on the IBR-2 reactor has been developed and the element composition of 30 samples has been determined. The obtained results have shown that plankton can be successfully used as a biomonitor of water ecosystems.

The results of complex investigations of air pollution using mosses and lichens as well as of water ecosystem using mollusks and oysters near a growing port in Cape Town (Saldanha Bay, the

1. SCIENTIFIC RESEARCH

Atlantic Ocean near the West coast of the Republic of South Africa) have aroused considerable interest among environmental specialists of the Republic of South Africa and *willingness to cooperate in this research area*. In collaboration with the University in Stellenbosch the international project proposal "Mollusks as Biomonitors of Water Ecosystems in the Republic of South Africa" has been submitted for the NFS-RFBR competition for 2014 (reg. number 14-05-93963).

Two joint papers of the NAA Sector and the Analytical Center of the Geological Institute of RAS concerning the application of nuclear physics analytical methods for studying the quality of food, in particular, of basidiomycetes (mushrooms) of the European part of Russia have been completed and accepted for publication in the leading American journal *Advances in Microbiology*, and the paper on the determination of Cl, Br, I and Se in human body – in *Environmental Geochemistry and Health*. The studies of agricultural plants subjected to bioenergy activation have been carried out in collaboration with I.Javakhishvili Tbilisi State University, Georgia (submitted to *Agricultural Chemistry*, 2013).

Geology

In the framework of the joint JINR-Romania project the analysis of bottom sediments and rocks of two semiclosed ecosystems of the glacial lake Balea (Fagaras mountains) and the crater lake St. Ana (Harghita mountains) have been performed to assess the level of anthropogenic pollution and to find the source of origin of bottom sediments. It has been shown that according to the Romanian standards the content of potentially toxic elements (Cr, Co, As, Sb, Se) is comparable to that of the natural environment. Further data treatment (R-mode, principle component analysis) separately for each lake has revealed that Sr, Cr, Co, on the one hand, and As, Sb, Br, Se, on the other, create two different clusters with different geochemical properties for these lakes.

In cooperation with the Western Cape University (South Africa) the NAA study of coal fly ash from the Matla coal power station in the Mpumalanga province in South Africa has been conducted. The analytical advantages of NAA using epithermal neutrons in determining the elemental composition of ash have been demonstrated over such methods as inductively coupled plasma atomic emission spectroscopy (ICP-AES), laser ablation inductively coupled plasma mass spectrometry (LA ICP-MS) and X-ray fluorescence (XRF).

Within the framework of the joint project of the NAA sector and the University in Bucharest the elemental analysis of therapeutic muds collected at different sites in Romania has been completed. Further investigations of the structure of the mineral matrix of the muds under study are essential for a better understanding of the significance of increased concentrations of some heavy metals as well as of the role of the organic compounds present in the muds.

Analysis of materials of extraterrestrial origin

In 2013, the intermediate stage of the search for cosmic dust in peat columns collected in Siberia and in the meltwater from the high-mountain glacier Aktru in Altai was completed. The age determination of peat column layers was carried out at the Adam Mickiewicz University in Poland. The particles detected by means of electron microscopy along with the results of the neutron activation analysis of peat column samples (judging from the iron/nickel concentration ratio) allow us to assume that these particles could be of extraterrestrial origin. The identification of the material collected using magnetic traps in the meltwater from the glacier in Altai is more controversial. The results of these studies were reported and discussed at a seminar in the Sternberg Astronomical Institute of the Moscow State University in October, 2013.

Anthropological research

In the framework of the RFBR project (№12-06-00096/13 due to be completed in 2013) in cooperation with the Moscow State University (*D.N.Anuchin Research Institute* and *Museum* of *Anthropology*) the NAA of hair samples of a representative group of children from the Ongudaysk District of the Altai Republic as well as soil and plant samples from the places of their residence has

been conducted to find possible correlations between their elemental composition and to reveal the endemic features of the effect of the geochemical environment on the human body.

Biotechnologies

In 2013, in collaboration with the E.Andronikashvili Institute of Physics, I.Javakhishvili Tbilisi State University and I.Chavchavadze State *University* (*Tbilisi, Georgia*) the studies continued on the development of methods for synthesis of silver and gold nanoparticles by certain new kinds of bacteria – extremophilic bacteria and blue-green algae *Spirulina platensis*. In combination with a number of optic and analytical methods the neutron activation analysis was used to develop the technology for the synthesis of nanoparticles by the bacteria under study. On the IBR-2 reactor using the NAA method the elemental composition of the microbiological samples containing gold and silver nanoparticles was investigated to assess the possibility of application of the obtained nanomaterials for medical and pharmaceutical purposes. The effect of the synthesis of nanoparticles on the distribution of matrix and trace elements in cells was studied as well.

A second major line of investigation carried out in cooperation with the Institute of Microbiology and Biotechnology of ASM is focused on the biosorption of zinc from wastewater by microalgae *Spirulina platensis*. The elemental composition of microbiological samples and the efficiency of accumulation of zinc and other metals by *Spirulina* biomass were determined using the NAA technique on the IBR-2 reactor. This study was awarded with a gold medal at the V European Exhibition of Creativity and Innovation EUROINVENT 2013, Iaşi, Romania in the category "PhD research project". On the basis of the research results in the field of biotechnologies a PhD dissertation was defended in October, 2013.

Materials science

In 2013, 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 and the specialists in x-ray diffraction and scanning electron microscopy from the University of Galaţi, Romania, the investigations of the changes of nitride characteristics in the Li-N system synthesized at different pressures continued. It has been shown that the increase in nitrogen pressure during the formation of nitrides results in the formation of structures with a higher nitrogen content in the bulk and a smaller crystallite size.

Educational activities.

In 2013, on the basis of the NAA&AR Sector the training courses were held for senior-year students of the University of Dubna and for students and school teachers of International Summer Schools (May-June, July and October, 2013) organized by the JINR University Center, as well as for attendees of the III All-Russian Summer Field Session of the Academic community "Ecos" together with the Summer School "Russian Reporter" (http://letnyayashkola.org/ecos) (July 20 - August 10, 2013).

During the reported period two term papers, four Bachelor's degree and two Master's degree theses have been completed in the NAA Sector. Five Ph.D. theses are being written.