NEUTRON NUCLEAR PHYSICS

In 2012, the instrument development activities on the preparation of experiments at the pulsed resonance neutron source IREN continued. The multi-detector system «ROMASHKA»-1 intended for neutron cross-section measurements and the AURA facility for (n,e)-scattering investigations were tested on the extracted neutron beams. The applied research activities using the neutron spectroscopy techniques were actively carried out.

The greater part of the fundamental investigations in the field of neutron nuclear physics was carried out on the neutron beams of nuclear research centers in Russia, Germany, Republic of Korea, China and France. The studies were conducted 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 electromagnetic properties of the neutron and of its beta-decay; 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.

I. Experimental and instrument development activities.

Development and improvement of multipurpose detector systems for neutron cross-section measurements at the IREN facility.

In the framework of cooperation between JINR and the Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences (BAS) the development and modernization of the NaI-crystal-based detector systems “Romashka-1” and “Romashka-2” are in progress. These systems are planned to be used in experiments on beams of the IREN facility.

“Romashka-1” is a movable, easy-adjustable, multidetector system for registering γ-rays, which consists of 24 scintillation cells (hexahedral NaI(Tl) crystals Amcrys + photomultiplier R1306 with a divider and high-voltage generator Hamamatsu) (**Fig. 17**).

Fig. 17. “Romashka-1” on channel №3 of the IREN facility.

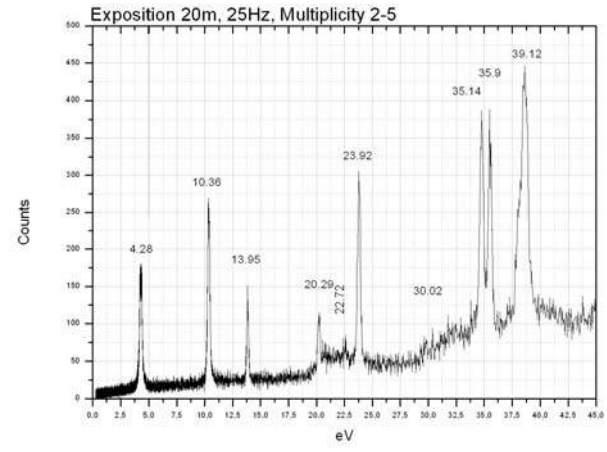

Рис. 18. **Зависимость выхода реакции Ta(n,γ) от энергии нейтронов, полученная в измерениях на пролетной базе 30 м.**

The energy and time calibration of the crystals has been made. The data acquisition system based on two 16-channel digitizers (AFI Electronics) combined in one 32-channel module has been produced. The system makes it possible to save on a hard disk all information registered by each of 24 crystals with the following analysis in the off-line mode. This allows one to register both time-of-flight and energy spectra, as well as to analyze overlappings, coincidence multiplicity, dead time and other parameters required for correct determination of neutron cross-sections and parameters of neutron resonances. At present, the system is being tested on beam №3 of the IREN facility (**Fig. 18**).

"Romashka-2" consists of two sets of 6 NaI(Tl) monocrystals of trapezoidal cross section (in the shape of a daisy) that are placed in metal cylindrical containers 30 cm in diameter. A photoelectronic multiplier PEM-110 is optically connected to the butt end of each crystal. The system is intended for the determination of the concentration of radioactive elements in the environment and for investigations of the radioactive neutron capture in experiments at the IREN facility by measuring gamma-ray multiplicity in the decay of radioactive nuclei.

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

The installation of the AURA instrument on beam 2 of IREN has been completed. The software of the measuring module with a new 8-channel time encoder has been adjusted. During the tests of the AURA instrument on beam 2 of IREN, the spectra of the neutron beam passing through an Ag filter have been obtained using a ^{3}He-counter (diameter 30 mm, pressure 8 at). The beam was formed by a paraffin-boron collimator with an aperture 80 mm in diameter. The counter was placed vertically along the beam axis. The neutron beam area at the counter was ~ 22 cm^2. The neutron beam spectrum is given in **Fig. 19**.

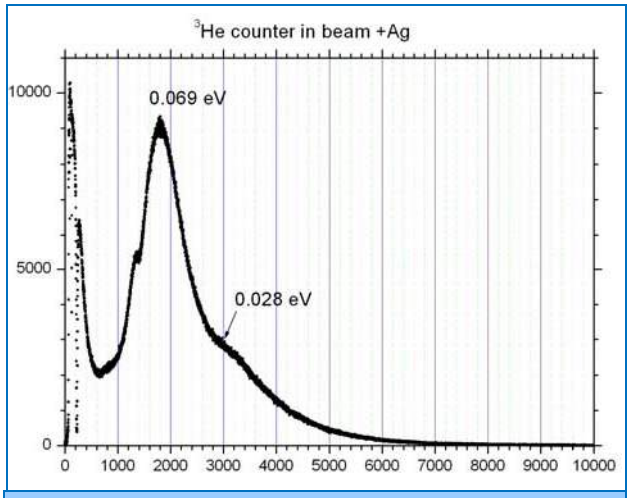

Fig. 19. Neutron spectrum on beam 2 of IREN, time channel width is 2 μs.

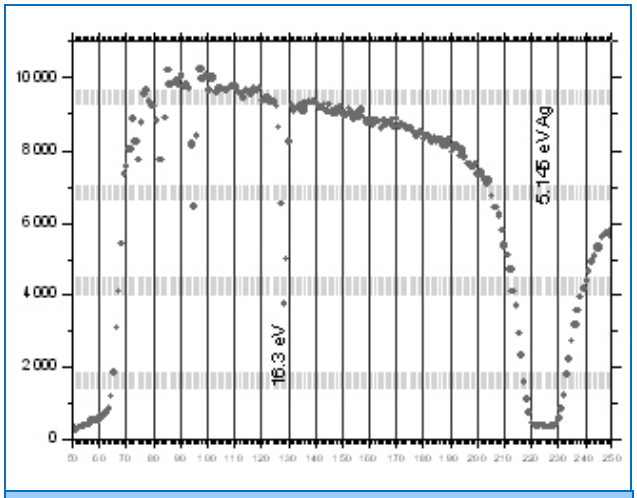

Fig. 20. Part of the neutron spectrum with resonance dips from Ag; time channel width is 2 μs.

Figure 20 shows a part of the spectrum with resonance dips from Ag, which was used for determining the flight path – distance between the IREN neutron source and the location of the helium counter.

The flight path was determined to be 13.75 m and the time between the start pulse and the burst – 7 μs. The estimated integrated neutron intensity of the IREN facility during its operation at a pulse repetition rate of 25 Hz was 1.2·10^{11} 1/s. 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 (accuracy of corrections should be no worse than 10^{-4}) are in progress. The corrections for efficiency variation of detectors registering slow neutrons scattered forward or backward taking into account the thermal motion of argon atoms are calculated in the real geometry (at the LIT cluster). The required accuracy has been already obtained for 20 energy points in the neutron energy range from 0.0065 to 0.8 eV. The estimates of neutron scattering and transmission by cadmium covering the walls of collimators have been made in order to take into account the corresponding errors associated with the reflection of neutrons into detectors from “their own” collimators and from the collimators opposite to them.

Measurement of angular correlation between the spins of fission fragments and the direction of prompt fission neutron emission.

It is well-known that in the laboratory coordinate system prompt fission neutrons are emitted with a strong anisotropy, which is mainly determined by neutron focusing with respect to the direction of fission fragment emission. However, various attempts to analyze the experimental data on the anisotropy of neutron radiation have led to the conclusion that the anisotropy cannot be fully described by kinematic focusing of neutrons emitted by a moving fragment. Possible reasons which could explain the observed deviations in the experimental data are either the existence of the so-called «scission» neutrons or the presence of an anisotropic component in the neutron emission in the center-of-mass system of the fragments. The latter hypothesis is tested in the present study.

The first exploratory experiment using the CODIS detector system for registering fission fragments and a set of neutron detectors DEMON was performed in 2003 in Strasbourg to check out the possibility of running such kind of experiments. The analysis of this test measurement has shown that the anisotropy of neutron emission relative to the fragment spin can be effectively measured using triple neutron-neutron-fragment correlations. However, no conclusions about the presence of this effect have been drawn because of the poor statistics in this experiment. The main experiments with sufficient statistics were carried out in Strasbourg in 2009-2011. In 2012, the analysis of the experiments were performed. The data treatment was based on the determination of emission angles of fission fragments forming the fission axis and on the following projection of the directions of emission of two or more fission neutrons on the plane perpendicular to the fission axis. The theoretical calculations predict that there should be an angular anisotropy in this plane described by the formula $W=1+a2*\cos(2\phi)$ (**see Fig. 21a**).

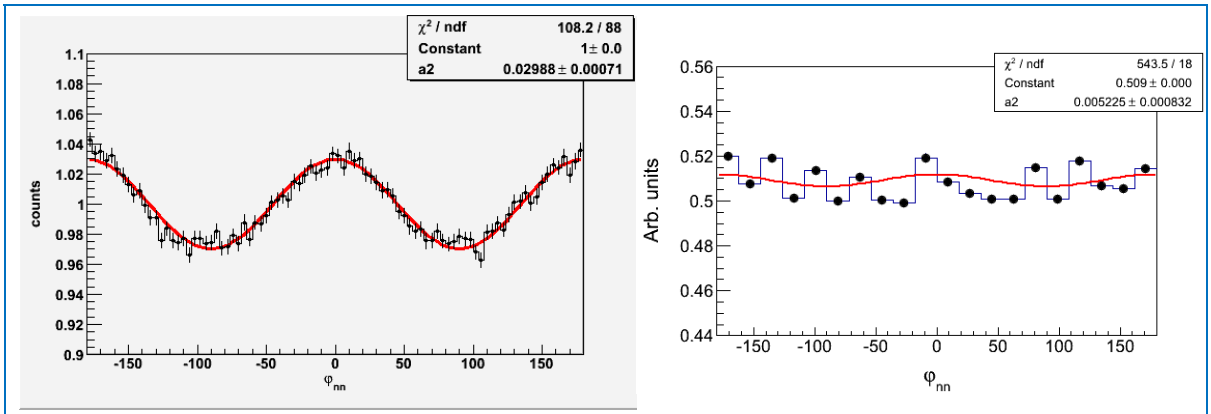

Fig. 21. a) calculated curve of the angular anisotropy of emission of two neutrons in a plane perpendicular to the fission axis; b) experimental curve demonstrating the sought-for anisotropy.

The experimental curve was obtained only for a part of the accumulated data, which is explained by the complexity of the technique used for the data treatment. The curve demonstrates the existence of some anisotropy of an analogous kind (see **Fig. 21b**) with the coefficient a2 characterizing the effect to be $(6\pm3)\times10^{-3}$, which is in qualitative agreement with the theoretical calculations.

Development of research methods in fission physics.

A new method of determination of prompt fission neutron energy that is applicable to single events with measured neutron time of flight has been developed and applied to study spontaneous fission of ^{252}Cf. The experimental data were obtained using a twin Frisch-grid ionization chamber and a liquid-scintillator-(NE213)-based fast neutron detector. The electronic equipment comprised the system of eight synchronized 12-bit waveform digitizers with 100 MHz sampling frequency. Prompt neutron multiplicity and energy distributions were determined with the help of the analysis of the kinematics of the fission process using the measured values of kinetic energies of fission fragments, the angle between the fission fragments and the neutron and the measured neutron time of flight along a given flight path. The idea of the determination of neutron energy distributions is based on the fact that the measured value of the neutron time of flight in a single fission event was considered as an average value of the known time-of-flight distribution. On this basis, a set of other realizations of the given value with the corresponding probabilities was determined and used further in the calculations of the required kinematic characteristics of the fission event. As a result of the averaging over the formed sampling, we obtained the data free of systematic errors associated with a non-linear dependence between the measured and calculated values. In the course of the analysis of experimental data a new method of separation of prompt neutrons and γ-quanta has been developed. The method is based on correlation functions whose parameters are used for separation of γ-quanta from prompt fission neutrons. The maximum of the correlation function (between a detector signal and exponent with a fall time constant close to the similar parameter of the detector signal) is realized when an exponential signal is delayed for a time equal to the time of flight of a neutron over a given flight path. The digital realization of the correlation algorithm made it possible to enhance the suppression factor for prompt fission γ-quanta by more than an order of magnitude. An important advantage of the method is that it has only one parameter for the event selection criterion.

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.

The measurements of the parameters of the ^{57}Fe(n,α)^{54}Cr and ^{63}Cu(n,α)^{60}Co reactions at E_n ~ 4.0-6.5 MeV have been carried out; the data processing has started. The data treatment for the measurements of the ^{35}Cl(n,α)^{32}P and ^{40}Ca(n,α)^{37}Ar reactions conducted in a neutron energy range of 4.5-6.5 MeV has been completed.

Within the framework of the statistical model the systematic analysis of the (n,α) reaction cross-sections in an energy range from 6 to 20 MeV has been performed. The α-particle clustering factor has been determined from the comparison of experimental and theoretical cross-section values. It has been shown that this factor depends on the energy of neutrons.

Investigations of nuclear structure.

The analysis of the experimental data on the intensities of two-quantum cascades in ~40 nuclei in a mass range of 39<A<201 is in progress. We have tested several well-known and proposed phenomenological energy dependences of level density and radiative strength functions of cascade gamma transitions and found the most appropriate to provide the maximally accurate approximation of experimental data.

The development of radically new models of level density and γ-quantum emission widths is necessary first of all to assess the need for new experimental data and to determine parameters of the superfluid phase of nuclear matter, the threshold for Cooper pair breakup with an accuracy of no worse than several tens of percent in the first place. This would make it possible to thoroughly study the process of changing superfluid properties of such specific object as a heated atomic nucleus.

The information available now is insufficient for a full-scale solution of this problem. But the development of further experimental investigations in this direction presents no major difficulties and may well be realized on the experimental basis used in the low-energy physics.

Investigations of a possibility to search for space parity violation effects in neutron diffraction at IBR-2.

A prototype of the instrument for experimental determination of spatial parity violation in neutron diffraction has been tested at a 30-m flight path of beam 1 of the IBR-2 reactor. Testing of the data acquisition and accumulation system has been performed. The parameters of the neutron beam have been determined. The tests have given some indication of a pendulum-like behavior of the reflected neutron beam in the diffraction experiment, which is evidence of a high quality of a potassium bromide single crystal and the neutron beam. On the basis of the obtained results an estimate of time necessary for detecting the spatial parity violation effect in diffraction with a statistical accuracy of $3 \cdot 10^{-4}$ has been made.

Investigations of the interaction of a relativistic deuteron beam with a massive multiplying target of natural uranium.

In March and December of 2012 in the framework of the research project «Energy and Transmutation of Radioactive Wastes» («E&T RAW») a massive (500 kg) natural uranium ($\varnothing$ 30 × 65 cm) target assembly QUINTA with a 10-cm lead blanket was irradiated at JINR NUCLOTRON by accelerated deuterons with energies from 1 to 8 GeV. The characteristics of energy spectra of prompt neutrons and time spectra of fission delayed neutrons (DN) between accelerator pulses have been obtained using the detectors DEMON and IZOMER-M. The optimization of the detector shielding has been successfully performed to reduce the background from various sources. The treatment of the results from the measurements conducted in December, 2012 is in progress. The dependence of the incident deuteron energy, E_d, on the relative total yield of DN, Y_{DN}, measured in March, 2012, is in agreement (up to $E_d = 8$ GeV) with the corresponding dependence of the total number of fission events, N_f, obtained by the integration of the spatial distributions of natural uranium fission rates over the QUINTA volume. The above-mentioned distributions were measured using solid-state track detectors and independently by the activation method. The values of Y_{DN} and N_f (normalized to one incident deuteron and one GeV) were found to be constant within the limits of experimental errors (10-15%) for the whole deuteron energy range under study. The group analysis of

DN time spectra indicates a growth of the average energy of the neutrons initiating fission of target nuclei with an increase in the energy of incident deuterons. The group analysis of DN time spectra indicates a growth in the average energy of the neutrons initiating fission of target nuclei from 15 to ~ 45 MeV with an increase in energy of the incident deuterons from 1 to 8 GeV. This result will be refined by further analysis of the data from the measurements of December 2012 conducted with minimum incident deuteron pulse duration.

Development of a facility to study the possibility of cold neutron accumulation at the end of a neutron beam line.

Earlier we have 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 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. This allows the range of application of UCN to be extended many times and to use them not only for scientific research but for applied and educational purposes as well.

In the framework of the study of the possibility to create a new helium UCN source, work has been conducted to develop and construct an experimental facility for carrying out test measurements. Test measurements should show what gain in cold neutron flux may be expected in a cavity at the end of a neutron guide surrounded by a solid methane moderator/reflector. The main parts of the facility have been developed and manufactured:

- cryostat for creating a methane cavity and cooling methane down to the helium temperature, which includes the system for feeding and evaporating methane from the cryostat (**Fig. 22**);
- neutron flux chopper (**Fig. 23**).

Fig. 22. Cryostat (exploded view).

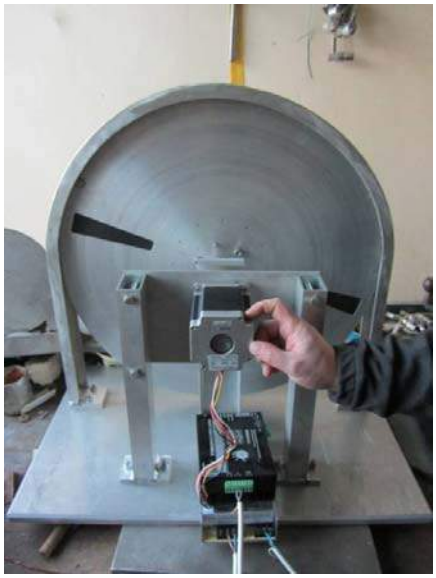

Fig. 23. Neutron flux chopper.

The measurements are scheduled for 2013. They can be performed on both the IBR-2 reactor (beam 2) and on the IR-8 reactor (KI, Moscow). In the first case the spectrum of neutrons leaving the cavity can be obtained for different energies ('monolines') of incident neutrons. In the latter case the time-of-flight method is used to get spectra at the inlet and outlet of the cavity. For these measurements a chopper has been designed and constructed.

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

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.

The GRANIT spectrometer will become a unique tool for carrying out a wide range of investigations in the field of physics of elementary particles and fundamental interactions, quantum mechanics, surface physics and applied research. In the framework of the GRANIT collaboration the FLNP specialists took part in the activities on the adjustment of detectors for the spectrometer and in the commissioning and adjustment of its UCN source.

In 2012 the collaboration was engaged in the commissioning of various parts of the GRANIT spectrometer. The first important step is to ensure reliable operation of the UCN source of the GRANIT facility and its effective interfacing with the spectrometer. Work on the optimization and adjustment of operation of a helium source was carried out.

Experiment on the direct measurement of the n-n scattering.

In cooperation with Gettysburg College (Gettysburg, Pennsylvania, USA) the final stage of the analysis of data from the first experiment on the direct measurement of the n-n scattering cross section at the YAGUAR pulsed reactor (Snezhinsk, Russia) aimed at studying the charge symmetry of nuclear forces has been performed. It has been shown that the observed abnormally strong effect of an increase in the scattering intensity with increasing JAGUAR pulse energy can be explained by radiation desorption of hydrogen from the surface of the aluminum channel of the facility induced by a powerful dose of gamma radiation during the reactor pulse. The obtained value of the desorption coefficient, $\eta(\gamma) = 0.02$, is in agreement with the data from other experiments. The performed analysis of literature on metal surface treatment methods suggests that $\eta(\gamma)$ can be reduced down to the value that would be acceptable for n-n scattering cross-section measurements.

Investigation of time variation of the fine structure constant.

In collaboration with the North Carolina State University (NCSU, Raleigh, North Carolina, USA) research work has been conducted on the application of isotope data from the Oklo natural nuclear reactor zones for studying time variation of the fine structure constant α. The results for α depend on the poorly-known temperature of active zones during reactor operation (10^9 years ago). It has been shown that the applied Lutetium thermometry based on a strong temperature dependence of the burn-up cross section of ^{176}Lu and, respectively, on the change in the concentration of ^{176}Lu and ^{175}Lu isotopes, suffers from insufficient accuracy of neutron capture cross sections of lutetium-175 forming lutetium-176 in the ground and isomeric states. The modeling of gamma-ray fluxes in the Oklo reactor has been performed leading to the result that they are insufficient to influence the burn-up of ^{176}Lu by means of gamma quanta as it occurs in stars producing powerful bursts of gamma radiation.

1. SCIENTIFIC RESEARCH

II. Theoretical investigations.

Investigations of neutron fluxes generated by linear electron accelerator-based neutron sources.

In 2012, the investigations of the production of neutrons and radioisotopes on E-linac-driven neutron sources continued. The basic physical characteristics of the production of neutrons from high-atomic-number materials irradiated by electron beams have been studied. The bremsstrahlung of incident electrons inducing photonuclear reactions has been considered. The experimental data on photonuclear reactions are used to describe the generation of neutrons caused by gamma radiation absorption by nuclei. The available theoretical approaches are applied to study the energy distribution of photo-neutrons. The neutrons statistically distributed over the energy are considered as the main part of all produced neutrons; the share of direct neutrons is taken into account as well. The neutron spectrum, mean neutron energy and total neutron yield are calculated in relation to the energy and current of the electron beam, as well as to the characteristics of irradiated samples. No numerical Monte-Carlo simulations were applied in the study. The results of the calculations are in satisfactory agreement with those of the experimental measurements.

On the possibility to increase the IREN neutron flux.

The neutron yields from tungsten and uranium targets of different configurations have been calculated using the FLUKA program. The results for a tungsten target have made it possible to compare them with the experimental data obtained on the IBR-30 booster using the EKON program. The possibility to increase the neutron yield by a factor of 2-4 without using the second section of the accelerator has been demonstrated provided a bremsstrahlung target of tungsten or plutonium is surrounded by two layers of 18 plutonium rods.

Wave optics research.

A new effective analytical approach to describe electromagnetic waves in anisotropic media has been proposed. An analytical description of the refraction and reflection at an interface between isotropic and anisotropic media has been demonstrated. Beam splitting upon reflection and refraction as well as surface wave generation have been studied. D'yakonov surface waves and methods of their observation are under discussion. Analytical and numerical calculations of the reflection and transmission of plane-parallel uniaxial plates have been demonstrated.

III. Methodical and applied research.

Investigations of properties of semiconductor detectors and scintillators.

In 2012, alpha and gamma detectors were manufactured from fast inorganic scintillators LFS based on micropixel avalanche photodiodes with high pixel density (15000 pixel/mm^2).

The registration of alpha particles has been investigated using fast inorganic scintillators LFS-3 ($2 \times 2 \times 10$ mm) based on micropixel avalanche photodiodes at room temperature. The energy resolution for 5.5 MeV alpha particles from radioactive ^{241}Am source was 9%. The amplitude spectrum is given in **Fig. 24** (at the left). The gamma-radiation was registered using scintillator LFS-8 ($3 \times 3 \times 0.5$ mm^3) based on micropixel avalanche photodiodes in a wide energy range (59.6-662 keV) at room temperature. The energy resolution is 11.5% for 662 keV gamma quanta from ^{137}Cs radioactive source. The amplitude spectrum is given in **Fig. 24** (at the right).

The results have demonstrated that these detectors can be used in positron emission scanners for controlling radioactive contamination in various media and public safety (Associated Particle Imaging for the detection of explosives and drugs).

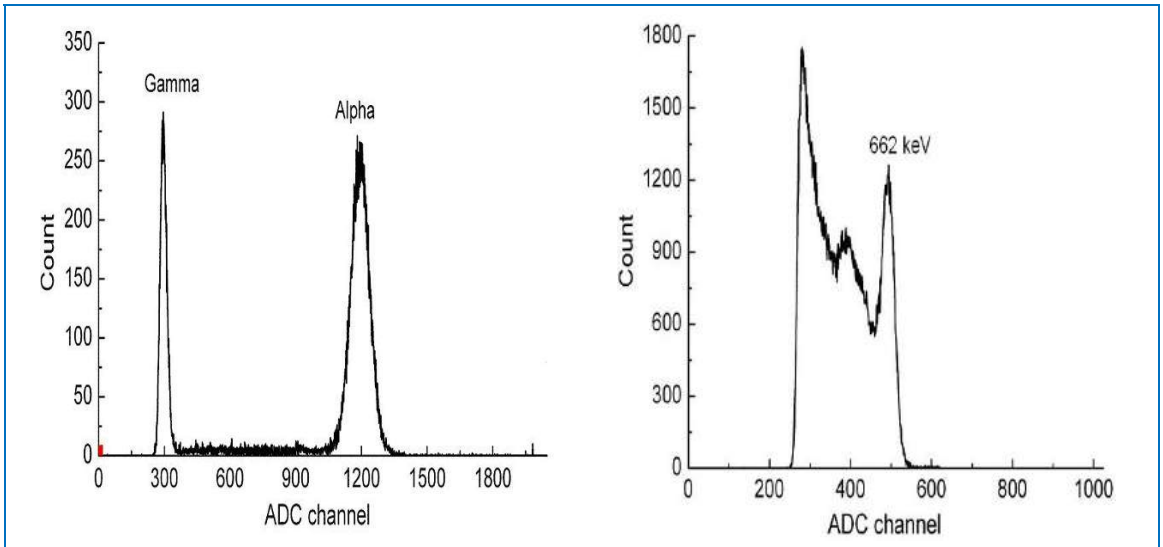

Fig. 24. Amplitude spectra of ^{241}Am alpha- (left) and ^{137}Cs gamma- (right) sources.

In addition, to detect fission fragments and light charged particles emitted in fission, a stand consisting of a thin silicon ΔE-detector about 12 μm thick and 600-μm silicon detector Timepix (E) with full absorption of the particle energy has been constructed (**Fig. 25**).

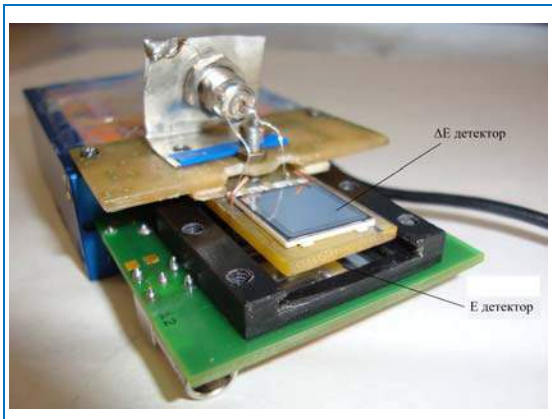

Fig. 25. Half-part of the stand.

This stand is intended for studying the possibility to apply the E-ΔE method in combination with a high-resolution position-sensitive detector Timepix for investigating the fission process. This method allows one to identify light charged particles by their charge and mass, as well as to separate them from background events related to the scattering of the fragments by the substrate. One of the most complicated problems in the design of the given stand was the organization of the coincidence scheme for simultaneous registration of ΔE and E signals. The detector E (Timepix) has its own readout system, which makes it possible to register the time of each event but does not allow the integration with external electronic modules. A signal from the ΔE detector is read out by a desk-top digitizer CAEN (12 bit, 250 MHz), which can also register the arrival time of events. At this stage the coincidences are organized by means of the analysis of the time labels of two event types saved on the computer in the off-line mode. The time resolution of this method is not enough for the efficient organization of coincidences. The development of a more efficient coincidence scheme is in progress.

1. SCIENTIFIC RESEARCH

Development of analytical techniques using neutron spectrometry.

At the IREN pulsed resonance neutron source the activities have been carried out on the development and application of the methods of elemental and isotope analysis using neutron spectrometry. The analysis of the boron content in ceramics of nanocomposite materials prepared in the Belorussian State University (Minsk) has been performed by measuring neutron transmission. These new multifunctional materials combine efficient neutron shielding properties with high heat resistance and mechanical strength.

In cooperation with the Sternberg Astronomical Institute, MSU, the investigations of the samples (presumably cosmic dust) from an Altai mountain glacier by means of the resonance spectrometry method continued.

At the request of the Central Geological Laboratory of the Mongolian Ministry of Natural Resources and Energy the analysis of the content of rare-earth elements in ore samples has been made.

Nuclear analytical techniques using charged particle beams.

Non-destructive nuclear analytical techniques based on low-energy charged particle beams are widely used for the analysis of elemental depth profiles in various kinds of technical and research problems. Their analytical possibilities have been investigated using specially selected samples. The method of Rutherford back-scattering of helium ions allows one to determine depth profiles of almost all elements with rather high depth resolution.

As one can see in **Table 1**, the treatment of one spectrum of the scattered helium ions gave the information about depth profiles of 7 elements from carbon to bismuth with atomic concentrations within an interval of 1-100 at.%. Two layers (140-nm-thick titanium oxide and 100-nm-thick cobalt on a silicon substrate) are observed in the sample. An intermediate 20-nm-thick layer consisting of all three elements is observed in-between.

Table 1.

Layer thickness 10^{15} at./cm^2	Depth, nm	Element concentration, at.%						
		C	O	Si	Ti	Co	Br	Bi
50	5,5	8,0				89,3	1,0	1,7
100	16,6	5,0				94	1,0	
760	101,2					100		
100	117,5		40		30	30		
650	255,3		70		30			
5000	10301,5			100				

A thin layer on the sample surface contains some amount of impurities including carbon (9×10^{15} at./cm^2), bromine (1.5×10^{15} at./cm^2) and bismuth (8.5×10^{14} at./cm^2). The analysis of this layer demonstrates both the advantages and disadvantages of the Rutherford back-scattering technique.

The amount of bismuth atoms observed in the experiment shows that the method is sensitive to the amount of atoms of a heavy element, which is below their amount in a monolayer. On the other hand, a rather significant amount (~10^{16} at./cm^2) of carbon atoms does not provide a noticeable yield of scattered helium ions.

The analytical possibilities of the Rutherford back-scattering technique can be improved by increasing the initial energy of helium ions. Thus, for example, the sensitivity to oxygen atoms can be enhanced by increasing the initial energy of helium ions up to above 3.045 MeV. The energy dependence of the scattering cross section shows a narrow resonance with the maximum cross section higher than the Rutherford scattering by a factor of 17. For the electrostatic generator EG-5 this energy is quite achievable. Measurements at several energies, which exceed the resonance one make it possible to investigate in details the oxygen depth profile in the near-surface layer of samples.

An oxygen depth profile of a TiO\Pt\Si sample has been studied by employing a resonance in the elastic scattering of helium ions with the energy of 3.045 MeV from oxygen atoms. Three 10-30 nm-thick layers with an oxygen content of 50-60-67 at. % and one layer with an oxygen concentration of 10 at. % were detected by scanning over the energy range near the resonance. The oxygen content was measured with an accuracy of 2 at. %.

A sequential analysis of samples using a proton and helium ion beam makes it possible to improve the precision in the determination of concentrations for light elements and to increase the covered depth. A sample composed of two layers (Ag and $LiNbO_3$ on silicon substrate) was used to demonstrate these possibilities. The mentioned analysis gave the information not only about the elemental composition of the two layers with the total thickness of 2.5 μm but also about the element distribution over the sample depth up to 20 μm. The treatment of two spectra showed the presence of a noticeable concentration of silicon in both Ag and $LiNbO_3$ layers. An in-between 100-nm-thick layer is of intermediate composition with Si inclusions.

The effect of irradiation with fast neutrons at a dose rate of $1.4 \cdot 10^{14}$ n/cm^2 on the properties of SiC and SiC(N) films has been studied using nuclear analytical RBS and ERD techniques. A 100-fold change in the conductivity of layers was found while the element content and layer thickness in the samples experienced no noticeable changes.

Deuterium concentration depth profiles in the samples intended for investigations of the astrophysical S-factor and the screened electron potential in the $d(d, n)^3$He reaction on targets of deuterides of titanium, tantalum and zirconium have been studied using nuclear analytical methods.

Analytical investigations at the IBR-2 reactor.

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 a database, database management programs, programs for registering the weight of samples, for obtaining spectra and for calculating the concentration of elements. While running the software, the programs underwent development and upgrade. Various nonstandard cases arising in the process of treating gamma-spectra by the Genie 2000 (Canberra) software were studied. The development of the mechanical part of a sample-changing device on the detectors started and the modernization of the pneumatic transport facility continued.

The measurements of thermal and resonance neutron flux densities have been carried out in the irradiation channels of the REGATA pneumatic transport facility and on some other neutron beams in new experimental conditions after the completion of the IBR-2 modernization.

1. SCIENTIFIC RESEARCH

In 2012, in the framework of the international program “Heavy metal atmospheric deposition in Europe – estimations based on moss analysis” the data analysis was completed and a number of papers, which reflect the contribution of the NAA Sector to the European Atlas of Heavy Metal Atmospheric Deposition for Macedonia, Bulgaria, Croatia and Serbia were published. The data on some regions of the Russian Federation (Tikhvin; Kostroma, Ivanova, Moscow) were submitted to the European Atlas as well.

In 2012, the mass multielement analysis of soils and bottom sediments from various regions of the Nile delta and its near-shore area was 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». The soil samples from the Siwa Oasis in the Sahara desert have been studied as well. The obtained results are of interest to the geologists and ecologists of Egypt from the viewpoint of new information on the elements whose concentrations have been determined for the first time.

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 from the Tarkhankut peninsula to the Kerch Peninsula has been performed to assess the state of the coastal ecosystem of the Crimea.

For the first time the results of the multielement analysis of moss-biomonitors and lichens from the area of Stellenbosch and Cape Town (South Africa) have been obtained for the evaluation of atmospheric pollution in this region. To assess the state of water ecosystem of this region, the analysis of samples of mollusks and oysters from two gulfs of the Indian Ocean has been made. The preliminary results have demonstrated the efficiency of the chosen objects for the development of the biomonitoring system under conditions of a growing port in Cape Town.

A review on the results of more than 20 years of cooperation between the Sector of Neutron Activation Analysis and Applied Research (SNAA&AR) and the Analytical Center of the Geological Institute RAS in the field of research of food quality by nuclear and related analytical techniques has been prepared and published. Similar studies have started in cooperation with I.Javakhishvili Tbilisi State University (Tbilisi, Georgia).

In cooperation with the specialists from the University of Bucharest, Romania, the samples of poorly studied loess deposits (up to 20 m deep) in the southeast Dobruja have been analyzed to assess the changes in the elemental composition of this kind of soils for the last 1.2 million years. The results of INAA performed on the IBR-2 reactor in 2012 along with the data of electron paramagnetic resonance (EPR), x-ray phase analysis (XPA), scanning electron microscopy (SEM), radiometric and thermoluminescence analysis have allowed us to make a number of conclusions reflected in *Duliu et al. 2012a*. It has been found that the samples from different time periods have similar elemental composition, which suggests that the wind-blown dust originated from the same most likely source – the Măcin Mountains located in the north of the Dobruja Massif.

The results of the study 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 presented at the International Seminar ISINN-20 (Duliu et al., 2012b).

In 2012 on the REGATA facility the neutron activation analysis was conducted to search for cosmic dust in two peat columns (natural slabs) collected in Western Siberia. These studies along with the results of scanning electron microscopy suggest the possible presence of particles of

extraterrestrial origin. The material collected using magnetic traps from a melting high-mountain glacier in Altai with traces of the substance of extraterrestrial origin has been analyzed as well.

In the framework of the RFBR project 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 Ongudaysky District of the Altai Republic as well as soil 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.

In 2012, 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 has been investigated to assess the possibility of application of the obtained nanomaterials for medical and pharmaceutical purposes.

The research work to study the changes in the characteristics of nitrides in the Li-N system at different pressures of synthesis has been carried out 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 Galați, Romania. It has been shown that an increase in the nitrogen pressure during the formation of nitrides results in the synthesis of structures with a higher nitrogen content in the bulk and a smaller crystallite size.