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NEUTRON NUCLEAR PHYSICS

In 2011, at the Frank Laboratory of Neutron Physics the applied research activities using the neutron spectroscopy techniques were actively carried out at the pulsed resonance neutron source IREN. A number of instrument development and analytical investigations were performed during the power start-up of the modernized IBR-2 reactor. Also, the instrument development activities on the preparation of experiments at the IREN facility were continued. 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.

3. Experimental and instrument development activities

3.1. Modernization of the detector system “Romashka-1”

In the framework of cooperation between the Institute for Nuclear Research and Nuclear Energy (INRNE) of the Bulgarian Academy of Sciences (BAS) and JINR in the field of investigation of neutron-nuclear interactions a low-background detector system “Romashka-1” for detecting gamma rays has been delivered from INRNE to FLNP JINR. A general view of the 12-section scintillation system is presented in **Fig. 15**.

The system is intended to determine the concentration of radioactive elements in the environment and to study the radiative neutron capture in the experiments conducted on the IREN facility in FLNP JINR by measuring gamma-ray multiplicity in the decay of radioactive nuclei. The gamma-ray spectrometry system consists of two sets of 6 NaI(Tl) monocrystals of trapezoidal cross section in the shape of a daisy that are placed in metal cylinders-containers about 30 cm in diameter (**Fig. 16**). A photoelectronic multiplier PEM-110 is optically connected to the butt end of each crystal.

The main characteristics of the gamma-spectrometry system “Romashka-1” are given in **Table 1**.

Table 1. The main characteristics of the gamma-spectrometry scintillation system “Romashka-1”.

Parameter	Value
Scintillation material	NaI(Tl)
Total volume of scintillators	~ 16.6 l
Length of individual scintillator elements	~ 200 mm
Detection efficiency 1.46 MeV □-rays of ^{40}K (10 Bq)	~ 97%
Minimum detected □-activity	~ 0.5 Bq
Energy resolution for detection of ^{60}Co□-rays of one section	~ 10 %
Energy resolution for detection of ^{60}Co□-rays of 12 sections	~ 15 %

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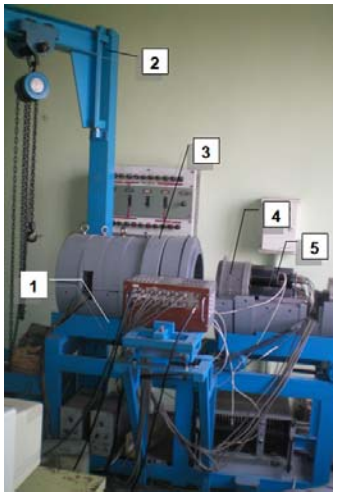

Fig. 15. 12-section gamma-spectrometry scintillation system "Romashka-1": **1** – iron support-holder, **2** – hoisting mechanism, **3** – segmental lead jacket, **4** – assembly of 6 NaI(Tl) scintillation crystals, **5** – photoelectronic multiplier.

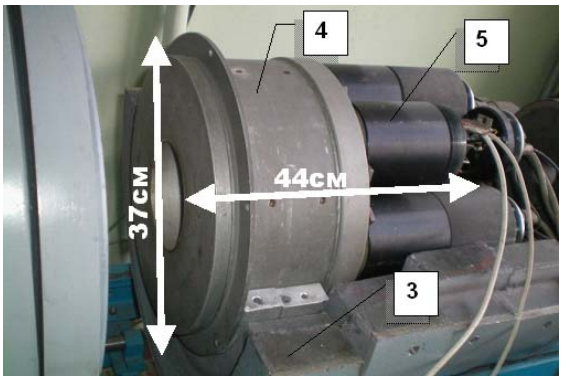

Fig. 16. An external view of one scintillation assembly: **3** – segmental lead jacket, **4** – six NaI(Tl) in the housing; **5** – electronic signal conversion-amplification modules PEM-110.

The modernization of the gamma-ray scintillation spectrometer includes the following activities:

– manufacturing of the 16-module photomultiplier high-voltage supply system by the firm "High-voltage systems" (Dubna) of the type shown in **Fig.17**;

- manufacturing of ADC of the board for 16 channels for simultaneous acquisition, digitization, accumulation and preliminary sorting of signals from all 12 sections of "Romashka" by the firm AFI Electronics-JINR (**Fig. 18**);

Fig.17. 6-channel high-voltage power supply source.

Fig. 18. ADC ADCM16-LTC 16-channel system.

- manufacturing of high-voltage and signal cables;

– development of software for processing experimental data.

The instrument will be located on beam 4 of IREN at a distance of about 31 m from a neutron-producing target.

3.2. Investigation of the fission process at low excitation energies

The fission fragment mass and kinetic energy characteristics play a key role in the description of the fission process. In the modern interpretation of the fission process the major role belongs to the shell effects, due to which the physicists have gained a better insight into the asymmetric mass fragmentation in the nuclear fission at low excitation energies. Owing to the possibilities of modern computers the calculation methods for the dynamic characteristics of nuclear fission (such as the nuclear surface potential energy dynamics at the nuclear surface fluctuations) are developing rapidly. As a result, higher requirements are imposed on the accuracy of experimental data, which characterize the fission process more comprehensively: mass and energy distributions of fission fragments, prompt neutron multiplicity and their dependence on the total kinetic energy and mass of fission fragments. In this connection, in FLNP the experimental methods for measuring the mentioned characteristics of nuclei in the resonance and mega-electron-volt energy range of neutrons inducing nuclear fission of transuranium elements are being developed. In the FLNP Nuclear Physics Department the techniques and equipment have been developed for carrying out nuclear fission investigations at the resonance neutron source IREN and the fast neutron source EG-5.

For the first time the technique of direct analysis of current pulses of a twin Frisch-gridded ionization chamber has been developed. The advantages of the method of direct processing of current pulses in comparison with the traditional conversion of current signals to step-function pulses by means of charge-sensitive converters have been demonstrated. The application of digital processing techniques has made it possible to get the best fission fragment mass and kinetic energy resolution in the investigations of spontaneous fission of Cf-252. A specialized software package has been developed for digital processing of signals for prompt fission neutron and fission fragment mass spectroscopy in low-energy fission experiments. The prompt fission neutron time-of-flight spectrum unfolding method that can be applied to single fission events and allows the determination of prompt neutron-induced fission energy has been developed.

A twin ionization chamber that allows along with the fission fragment mass spectroscopy the determination of fission axis orientation in space, has been constructed. The first results have been obtained that demonstrate reasonable angular ($\cos(\Delta x)$, $\cos(\Delta y)$, $\cos(\Delta z)$ ~0.05) and kinetic energy resolution for fission fragments (**Fig. 19**).

The signal formation in the Frisch-gridded ionization chamber has been studied using the finite difference method. The obtained solution of the Laplace equation has made it possible to find the relation between the geometric parameters of the chamber and the shape of pulses induced on the chamber electrodes in the process of the drift of ionization electrons. As a result, the formulae of dependence between the induced signals on the anode of the chamber and the direction of motion of a charged particle in the sensitive volume of the chamber have been derived. This has allowed us to resolve the ambiguities of interpretation of the grid inefficiency concept. The equipment and the software for digital signal processing that includes eight PC-built-in channels of fast analog-to-digital converters (8 bits, 250 MHz) have been developed, constructed and tested in the test data acquisition experiments with the twin ionization chamber (at EG-5) and the fast

neutron scintillation spectrometer (with a neutron source). The developed equipment of the time-of-flight analyzer together with the fast current amplifiers has been used in the experiments on the measurement of the IBR-2 thermal neutron beam intensity. The doubtless advantage of the current converter over the charge one has been demonstrated.

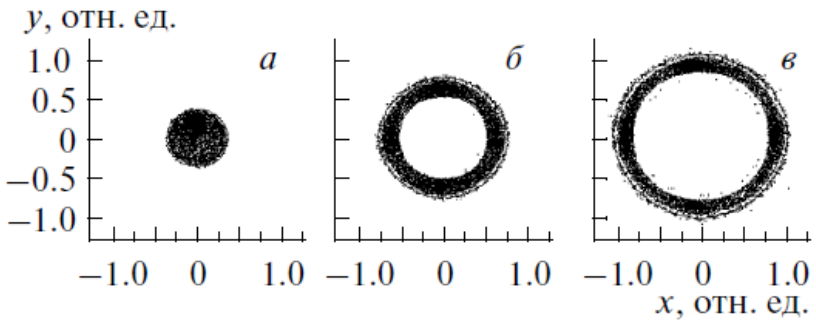

Fig. 19. Demonstration of fission fragment angular resolution using a position-sensitive twin Frisch-gridded ionization chamber.

3.3. Measurement of fission fragments using Medipix2 and Timepix detectors

In the framework of the collaboration between JINR and Czech Technical University in Prague a number of experiments have been conducted to study the properties of silicon pixel detectors of the Medipix family and the possibilities of their application for measuring heavy charged particles, specifically for searching and studying rare nuclear fission modes. The measurements of fission fragments and alpha-particles in the spontaneous fission of ^{252}Cf have been performed using several detectors Timepix and Medipix-2 included in the coincidence circuit, and in particular, using a start module specially developed for these measurements. A typical scheme of measurements is given in **Fig. 20**.

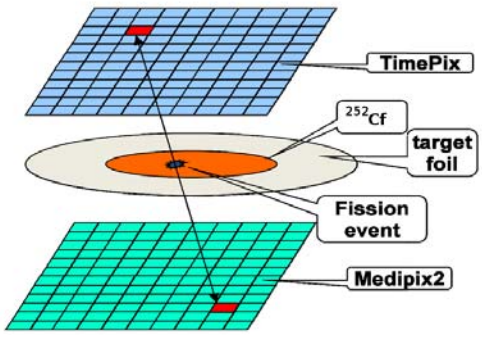

Fig. 20. Scheme of the measurement with Medipix2 and Timepix detectors.

The spontaneous fission source of ^{252}Cf was placed between two pixel detectors (in other measurements it was surrounded by four detectors) which allowed us to detect the arrival time and energy of fission fragments and alpha particles, as well as with a high accuracy the coordinates of the

particle's entry point in the detector. The possibility of measurement of fission fragments in coincidence with each other and with alpha particles has been demonstrated, which makes it possible to register ternary fission events with the help of pixel detectors. It has been shown that the Timepix detector exhibits the best characteristics for such investigations allowing one to work in two modes – measurement of the arrival time of a signal in each pixel and measurement of the energy transferred by a particle in the given pixel.

3.4. Activities on the preparation of a precision experiment for n,e-scattering length extraction

Fig. 21. An overall view of 8-channel time encoder.

The experimental installation AURA for measuring the angular anisotropy of slow neutrons scattered by noble gases in order to determine the (n,e)-scattering length has been assembled on beam №2 of the IREN facility. The development of the software for controlling the turn-table with neutron detectors has been completed, and the installation has been tested in the operating mode without a neutron beam. A new 8-channel fast time encoder (**Fig. 21**) has been developed and tested using the loading of noise pulses from the detectors (at low thresholds).

For a precise measurement of the angular anisotropy of neutrons scattered by inert gases in the energy region from a few MeV up to 1 eV it is necessary to know all corrections with an accuracy of no worse than 10^{-4}. Only in this case one can obtain the n,e-scattering length b_{ne} with the appropriate accuracy of 2-3 %. The corrections for efficiency variation of detectors registering slow neutrons scattered forward or backward taking into account the thermal motion of argon atoms have been calculated by the Monte Carlo method in the real geometry (**Fig. 22**).

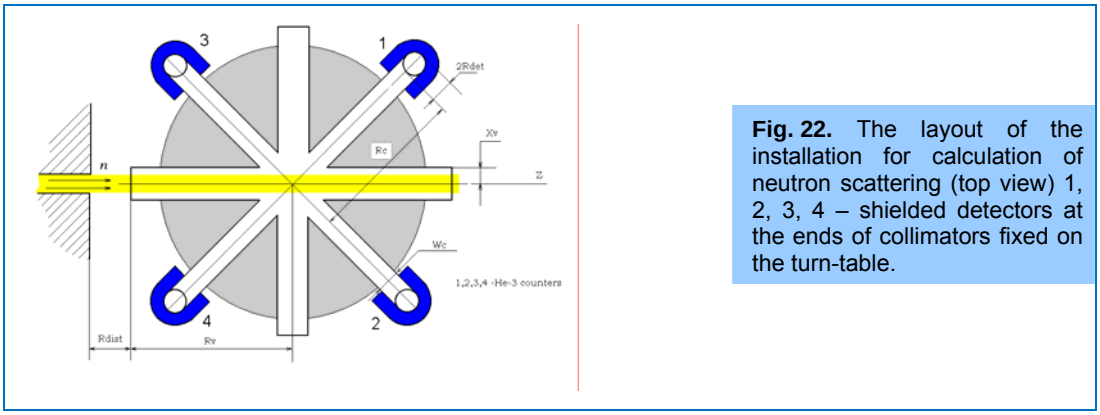

Fig. 22. The layout of the installation for calculation of neutron scattering (top view) 1, 2, 3, 4 – shielded detectors at the ends of collimators fixed on the turn-table.

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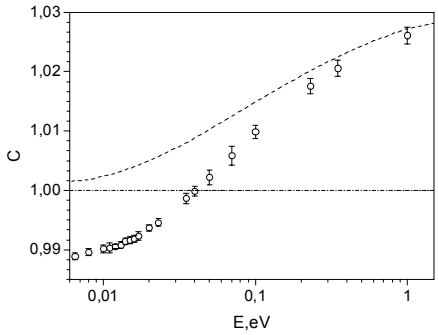
The ratio of efficiencies of counters detecting neutrons scattered forward and backward depends on the initial neutron energy and real angular distribution complicated by the thermal motion of gas atoms. This ratio should be accurately calculated for correction of the experimental results in each point of the energy region under study. For this purpose the Monte Carlo calculations have been performed for argon at a pressure of 10 atm and at initial neutron energies from 0.001 eV. (**Fig. 23**).

Fig. 23. The corrections $C(E)=\varepsilon(135^0)/\varepsilon(45^0)$ obtained from the Monte Carlo calculations for intensities of neutrons scattered forward and backward by argon. The dashed curve is a raw count of *C(E)* without taking into account the thermal motion of gas atoms.



The cumbersome calculations in the real geometry taking into account the thermal motion of gas atoms are necessary to reduce the uncertainty of the correction coefficient *C*(*E*) to the desired value. Only accurate account of this correction will make it possible to obtain the *R*(*E*) ratio in the neutron energy region of more than 0.1 eV.

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

In accordance with the Protocol on Cooperation between JINR and Peking *University* the experimental and theoretical investigations of the reactions (neutron, charged particle) induced by fast neutrons have been carried out. The experiments are conducted 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) in collaboration with the University of Lodz (Poland), the National University of Mongolia (Ulaanbaatar, Mongolia) and the Oak Ridge National Laboratory (USA). 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, atomic nuclear structure and for determining alpha-particle optical potential parameters. The latter is of much importance for calculations of various scenarios in astrophysics. In addition, these data are essential for choosing construction materials and for performing calculations in the development of new facilities for nuclear power engineering.

The data treatment for the measurements of the ^{149}Sm(n,α)^{146}Nd reaction conducted in the neutron energy range between 4.5 and 6.5 MeV has been completed. The data on the cross sections and angular distributions for this neutron energy range have been obtained for the first time; a comparison with the available estimates and theoretical models has been performed. They are of great importance because of significant discrepancies between the estimates given by different nuclear data libraries, which are based on theoretical predictions, and since only very scarce data are available for cross sections in the (n,α) channel, in particular, in the given mass range (**Fig. 24**).

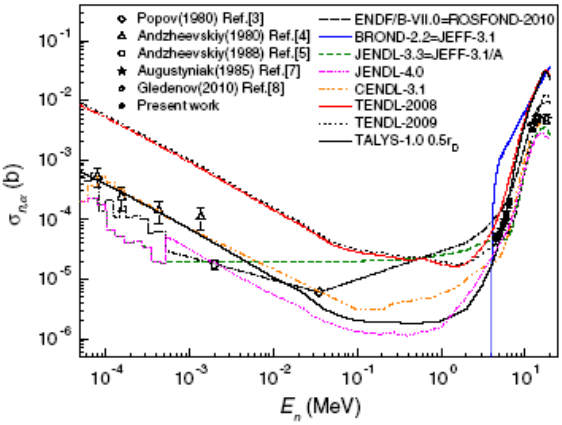


Fig. 24. Cross section of $^{149}Sm(n,\alpha)^{146}Nd$ in comparison with the estimates given by different nuclear data libraries and the calculations using the TALYS-1.0 software package.

The treatment and analysis of data from the measurements of the $^{35}Cl(n,\alpha)^{32}P$ and $^{40}Ca(n,\alpha)^{37}Ar$ reactions at a neutron energy E_n ~ 4.0 – 6.5 MeV have started. The measurements of the $^{nat}Mg(n,\alpha)$ reaction at E_n ~ 4.0-6.5 MeV have been performed. The samples of $^{54,57}Fe$ and ^{63}Cu have been prepared and in November, 2011, the measurements started on a neutron beam of EG-4.5.

3.6. Investigations of nuclear structure

By now the application of an original technique for determination of level density and radiative strength functions from the intensities of two-quanta cascades proceeding between neutron resonance and a group of its low-lying levels has made it possible to develop a radically new technique for determination of parameters of the phase transition of any nucleus from the superfluid to the normal state. The main result is that the breaking of the first four nucleon Cooper pairs occurs successively and the thresholds of the next pair breaking differ by the value comparable with the doubled nucleon pairing energy and decreasing with an increase in the nuclear excitation energy. Hence it follows that in the neutron resonance energy region their structure can differ to such a degree that this distinction can be revealed experimentally. For preliminary assessment of this possibility a technique for determination of distribution parameters of neutron and radiative resonance widths has been developed. It is based on the results of the analysis of the nuclear level density below the neutron binding energy obtained in Dubna and includes as a special case the Porter-Thomas distribution widely used for this purpose. The reanalysis of the distributions of the reduced neutron and total radiative widths of neutron resonances within the framework of the modified model of distributions of these quantities has been completed. The maximum approximation accuracy has been achieved on the assumption that the respective experimental data are the superposition of up to 4 distributions of amplitudes with different dispersions and mean values. This result corresponds to the obtained earlier conclusions on the dynamics of nuclear transition between Fermi- and Bose-states.

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

The JINR research project «Energy and Transmutation of Radioactive Wastes» («E&T RAW») is aimed at exploring possibilities of a new electro-nuclear scheme based on the use of deep subcritical multiplying systems of natural (depleted) uranium or thorium for energy production and utilization of spent nuclear fuel. The period of execution of the project first stage is 2010-2012. It is

carried out within the framework of a broad international collaboration on the basis of the JINR facilities.

In 2011, using a new subcritical assembly "QUINTA" consisting of 500 kg of natural metal uranium, the distributions of neutron fluxes, fission rates and ^{239}Pu recovery as well as the time dependence of the delayed neutron yield after irradiation of the assembly with a pulsed deutron beam of the JINR nuclotron were measured in the energy range of E_d = 2 – 6 GeV. The tendency of the average energy of neutrons $<E_n>$ inducing fission of ^{238}U inside the assembly to grow with an increase in the energy of incident deutrons (discovered in the experiments in 2010) has been confirmed. The value of $<En>$ ran as high as ~ 30 MeV at E_d = 6 GeV. It has been found (with an error of 10-15 %) that the integral number of fissions in the assembly grows, at least linearly with increasing E_d, whereas the relative total yield of delayed neutrons generated in the fission of the assembly nuclei increased approximately six times as the value of E_d grew from 2 to 6 GeV. In December, 2011, the measurements on the nuclotron continued in a wider deuteron energy range and using a more advanced technique (**Fig. 25**).

The long-term research objective is to obtain reliable data on the nuclear-physical characteristics of the QUINTA assembly as a central zone of a large (22 tons) uranium target BURAN (**Fig. 26**) available in JINR, and the complex development of the measurement techniques with this target.

Fig. 25. QUINTA assembly at the radiation position. March, 2011.

Fig. 26. Large uranium target BURAN.

In addition, the obtaining of the fullest possible set of experimental data on the QUINTA assembly is of independent fundamental importance for modification of the models of interaction of relativistic particles with extended multiplying media and for verification of the corresponding codes.

3.8. Experiment to study the quasi-elastic scattering of ultracold neutrons upon reflection from the surface of hydrogen-free Fomblin oil

An experiment has been carried out to measure the probability of quasi-elastic UCN scattering ("weak heating" of UCN) following their reflection from the surface of hydrogen-free Fomblin oil. The experiment has been performed in ILL (PF2 instrument) with the LGS spectrometer (developed in FLNP). Its external view is presented in **Fig. 27**.

Fig. 27. An external view of the LGS spectrometer.

The temperature dependence of the probability of UCN "weak heating" (**Fig. 28**) and spectra of heated neutrons have been obtained. The comparison of the obtained temperature dependence with the results of the work [A.P. Serebrov et al., Physics Letters A 309 (2003) 218–224] taking into account the difference in the performance of the experiments, allows us to draw a conclusion that the spectrum of scattered neutrons remains the same at all temperatures and only the total probability of weak heating undergoes a change.

Nowadays there are two hypotheses explaining this phenomenon – UCN scattering by capillary waves and UCN scattering by nanodrops formed near the liquid surface. The comparison of the Fomblin-heated neutron spectra with the spectra obtained with nanodispersed diamond samples and the comparison of the obtained temperature dependence with the dependence calculated in the work [S.K. Lamoreaux, R. Golub, Phys. Rev. C 66, 044309 (2002)] point to the fact that the second hypothesis is more credible. To reach an unambiguous conclusion, additional calculations of the temperature dependence of UCN scattering by capillary waves should be performed.

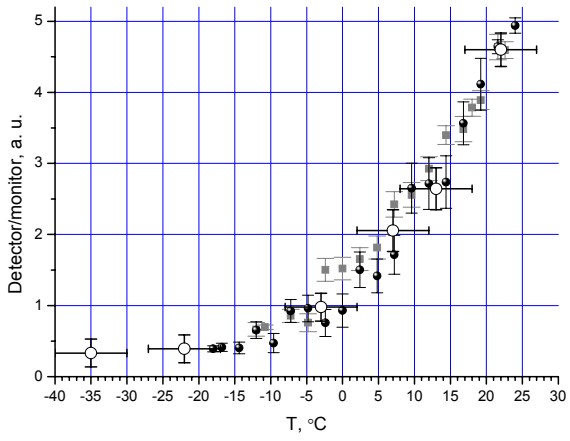


Fig. 28. The dependence of the ratio of heated neutrons counted for a cycle to the monitor count on the temperature of Fomblin oil (arbitrary units). Black circles – measurements with decreasing temperature. Grey squares – measurements with increasing temperature. White circles – data from [A.P. Serebrov et al., Physics Letters A 309 (2003) 218–224] reduced to our measurements at a temperature of 22 °C.

3.9. Status of a new experiment to test the equivalence principle for neutrons

A new UCN spectrometer EPIGRAV specially designed for the experiment to verify the equivalence principle for neutrons was constructed and tested in 2010 (**Fig. 29**).

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Fig. 29. The EPIGRAV spectrometer on the UCN source at ILL (Grenoble, France). December, 2011.

The operation of the instrument is based on the combined use of Fabry-Perot neutron interferometers and neutron flux modulator-chopper. The peculiarity of the instrument is the possibility of using the 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 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.

The analysis of the results of its first tests, however, pointed to the insufficient stability of its basic module: chopper-modulator. What is more, it was realized that under some conditions a failure in the operation of the modulator can lead to a serious breakdown. Therefore in 2011 a new chopper-modulator (**Fig. 30**) was designed and constructed, which demanded an essential change in the configuration of the spectrometer. Simultaneously, a mechanism for moving an interferential filter was improved and a new gas UCN detector with a thin converter layer of ^{10}B was manufactured. In cooperation with the group of the Institute of Nuclear Physics of the Johannes Gutenberg University of Mainz (Germany) new Fabry–Pérot interferometers (FPI) intended for use in the new spectrometer have been calculated, constructed and tested.

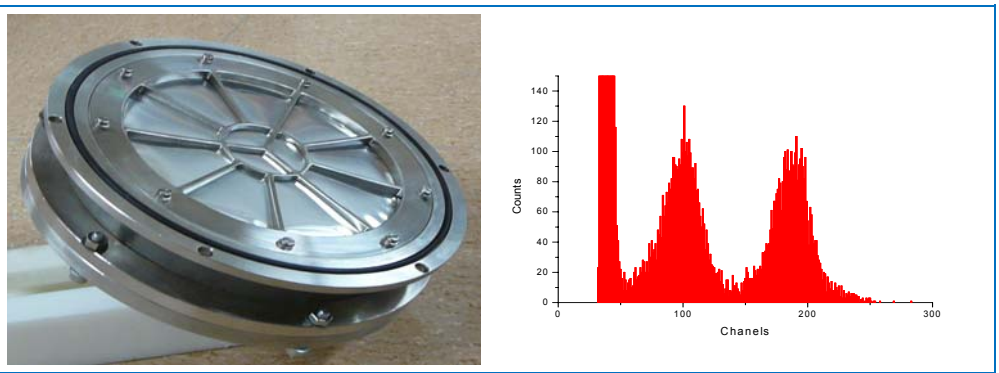

Fig. 30. A new detector with ^{10}B converter and its amplitude spectrum.

Comprehensive tests of the device have been conducted on the UCN beam of the Institute Laue Langevin (Grenoble, France). The new version of the chopper proved to be very good. During the tests it has worked without failures for about five hundred hours. The stability of frequency modulation was of the order of 2×10^{-4}. The spectrometer has rather high spectrometric qualities. The time resolution $\Delta t/t$ measured in the experiment was less than 2 % (**Fig. 31**). During the trials the spectrometer has been tested in all modes necessary for conducting a new gravitational experiment to verify the equivalence principle for neutrons. A number of test experiments to search for optimum conditions for the measurements have been carried out.

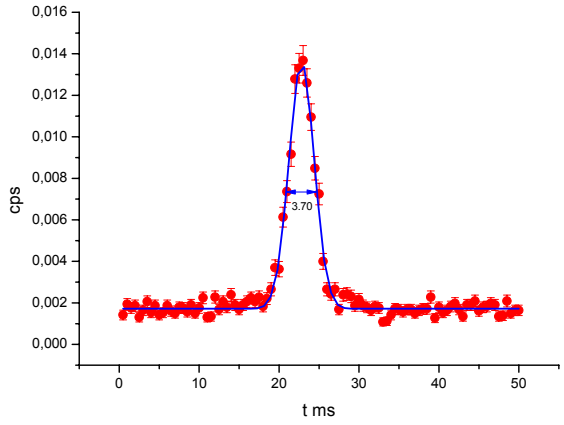

Fig. 31. A time-of-flight spectrum of ultracold neutrons monochromated by passing through a Fabry–Pérot interferometer.

3.10. Investigations of space parity violation effects

The measurements of the P-odd asymmetry in the radiative cross-section of natural lead have been performed at the PF1B cold polarized neutron beam facility in ILL (Grenoble, France). The experiment was conducted to obtain additional information to explain the anomalously high value of the neutron spin rotation in the measurements of transmission of transversely polarized neutrons through a sample.

The cold-neutron flux (average wavelength – 4.7 Å) was ~ 10^{10} 1/s. The neutron polarization was no worse than P_n = 92 %. A lead target (purity – 99.95 %) was positioned on the longitudinally polarized neutron beam between γ-quantum detectors. NaI (Tl) crystals 200 mm in diameter and 100 mm thick served as detectors. For absorption of scattered neutrons the target was placed in a box of lithium rubber (^{6}LiF) ~ 1.9 mm thick, open from the side of beam entrance to the target. In the "zero" experiment the measurements were carried out with the box without a sample. The neutron polarization was changed by an adiabatic flipper. To decrease the effect of the reactor power fluctuations, an integral method was used at neutron polarization switching frequencies (8.3 Hz) higher than the frequencies of the main spectrum of the neutron noise of the reactor. The measurements with the lead sample were carried out for 10 days. The measurement result corrected for the neutron polarization is $\alpha_\gamma^{\exp} = (3.3 \pm 2.9)\times10^{-7}$. The measurement result of the “zero” test on the beam without a lead target normalized to the usual components of the basic experiment and corrected for the neutron polarization is $\alpha_{0-test} = (1.0 \pm 2.0)\times10^{-7}$. The measurement time – 6.5 days. Taking the “zero-test” into account the asymmetry effect was found to be $a_\gamma(^{nat}Pb) = (2.3 \pm 3.5)\times10^{-7}$ or $\alpha_\gamma \le 8.1\times10^{-7}$ at the 90% *confidence level.* The achieved accuracy is still insufficient to perform the combined analysis of P-odd effects in lead.

3.11. Work in the framework of the project dedicated to the direct measurement of n-n scattering.

In cooperation with Gettysburg College (Gettysburg, Pennsylvania, USA) the results from the first experiments on the direct measurement of the n-n scattering cross section at the YAGUAR pulsed reactor (Snezhinsk, Russia) aimed at studying charge symmetry of nuclear forces have been prepared for publication. According to the preliminary data the background of unknown nature has been detected, which was assumed to be connected with the radiation-induced hydrogen desorption from the surface of the aluminum channel of the instrument under an extremely high dose of gamma radiation during the reactor pulse. The simulation of transport of photons and photon-generated electrons in the central metal tube of the n-n facility has demonstrated that the desorption with a coefficient $\eta(\gamma) = 0.01$ is induced by low-energy (15-200 eV) electrons. The paper titled "Direct measurement of nn-scattering: the gamma ray-outgassing complication" has been submitted for publication in "*Journal of Physics G: Nuclear and Particle Physics*".

3.12. Creation and development of UCN sources

In cooperation with the research team of the ultra-cold neutron source of the Los Alamos National Laboratory (Los Alamos, New Mexico, USA) the simulation and the measurement of the flux density of cold neutrons in the facility have been performed. This source utilizes fast neutrons generated by 800-MeV protons in a tungsten target of the accelerator. Using polyethylene, the source slows down neutrons to cold energies and in a special cryostat converts them to UCN in the open 1.5-liter volume of solid deuterium cooled by liquid helium. UCN are transported to the experimental hall through stainless steel pipes. The density of 30 UCN/cm^3 behind a biological shield has been achieved. This work has become a component part in the publication "Performance of the LANL spallation-neutron driven solid deuterium ultra-cold neutron source" submitted to "*Review of Scientific Instruments"*.

3.13. Search for new short-range spin-dependent interactions

Possible neutron experiments to search for new short-range spin-dependent forces have been considered. The spin-dependent nucleon-nucleon interaction between neutrons and nuclei may be responsible for various effects: phase shift of a neutron wave in neutron interferometers of different types, in particular of the Lloyd mirror configuration, neutron spin rotation in a pseudo-magnetic field, and transverse deflection of a polarized neutron beam by a layer of substance. The sensitivity assessment of these experiments has been made.

4. Theoretical investigations

4.1. Development of the IREN facility

The energy and angular distributions of neutrons produced under irradiation of various samples-radiators by electron beams of linear accelerators have been investigated. Neutron spectra have been obtained for radiators consisting of heavy elements (U, Ta, W, Pb) in relation to current, electron energy of the accelerator and parameters of the radiator, which is necessary for optimization of neutron sources that use modern electron linear accelerators. A consistent theoretical description of interaction of electrons and photons with nuclei makes it possible to describe successfully the production of neutrons without resorting to numerical simulations. The neutron distributions obtained thus far in the experimental measurements on various linear electron accelerators have been compared with the results of the calculations.

4.2. On the possibility to increase the IREN neutron flux

A neutron-generating target of IREN surrounded by a beryllium cylinder 11-41 cm in diameter is considered (**Fig. 32**). A considerable cross section of the (n, 2n) reaction for beryllium (of the order of 0.6 barn) at a neutron energy of 4-10 MeV may increase the IREN neutron flux if the real neutron spectrum from the source has a significant part of fast neutrons. The neutron yield and time distribution for a W-Be source have been estimated using the GEANT and FLUKA software packages (**Table. 2**).

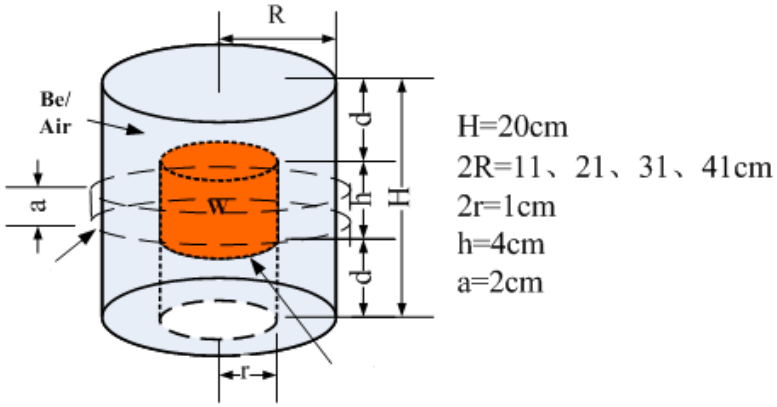

Fig. 32. The source design for the given calculations.

Table 2. Neutron yield per 1 electron (calculations using GEANT).

		Cylinder diameter			
		11 cm	**21 cm**	**31 cm**	**41 cm**
Electron energy of 30 MeV					
Yield in 4π	Air	0.00648	0.00642 0.0064*	0.00647 0.0063*	0.00640 0.0062*
	Be	0.00728	0.00760	0.00779	0.00767
	Be/Air ratio	1.12	1.18	1.20	1.20
Yield from cylinder lateral surface	Air	0.00575	0.00452	0.00362	0.00289
	Be	0.00662	0.00514	0.00343	0.00200
	Be/Air ratio	1.15	1.14	0.95	0.69
Electron energy of 50 MeV					
Yield in 4π	Air	0.0139	0.0139 0.0128*	0.0139	0.0139
	Be	0.0159	0.0166	0.0167	0.0167
	Be/Air ratio	1.14	1.19	1.20	1.20
Yield from cylinder lateral surface	Air	0.0123	0.00983	0.00776	0.00631
	Be	0.0145	0.0112	0.00738	0.00440
	Be/Air ratio	1.18	1.14	0.95	0.70

** - values obtained using FLUKA*

The effect of increasing number of neutrons after their passage through a beryllium layer of thickness L can be written as:

$$N = N_0 + N_0 \int_0^L [\exp(-n\sigma_t x) n\sigma_t dx] \frac{\sigma_{n,2n}}{\sigma_t} \quad \Rightarrow \quad N_0(1+\mu),$$

$$\mu = \frac{\sigma_{n,2n}}{\sigma_t}[1-\exp(-n\sigma_t L)]$$

In the case that $L > 10$ cm $\mu \approx \frac{\sigma_{n,2n}}{\sigma_t}$ and for neutron energies higher than 4 MeV $\mu \approx 1/2$.

The calculations presented in **Fig. 33**, have demonstrated the groundlessness of the idea about a possible time delay of neutrons due to their passage through beryllium (and, as a result, about possible neutron pulse widening). The estimated pulse widening was no more than 200 ns.

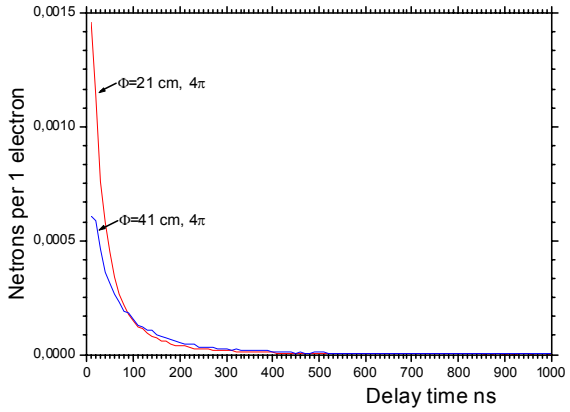

Fig. 33. Neutron time delay distribution when moving through beryllium (beryllium diameters – 21 and 41 cm).

4.3. Investigations of neutron-optical phenomena

The feasibility of experimental investigation of magnetic structures placed in an oscillating field is under discussion. It has been shown that the probabilities of reflection and transmission with and without spin flip have a resonance structure. The application of this phenomenon makes it possible to measure the magnetic field penetration profile, induction and magnetic susceptibility in alternating fields with a higher precision. It has been demonstrated that the refraction of neutrons in a magnetic prism under the action of an alternating field results in 8-fold splitting of an initially unpolarized beam. The intensity and polarization of each component depend on the magnitude and frequency of the alternating field. The possibility of measurement of magnetic permeability of films of angstrom-order thickness in alternating fields inside wave neutron resonators has been studied.

An experiment has been proposed on the amplification of an electromagnetic field under multiple total internal reflection from active media.

The Einstein-Podolsky-Rosen (EPR) paradox has been considered. The unavoidable redefinition of values of physical quantities has been shown to resolve the paradox. It has been demonstrated that according to the EPR logic the entangled states do not exist, and the measurement of violations of Bell's inequalities using downconversion photons does not mean a rejection of quantum mechanical locality. The consequences of the absence of the entangled states are under discussion.

1. SCIENTIFIC RESEARCH

5. Applied research

5.1. Nuclear-physical analytical techniques using charged particle beams

At the charged particle beams of the EG-5 accelerator (FLNP) the systematic studies of depth profiles of the elements in the near-surface layers of construction materials with the depth resolution of about 10 nm have been performed. In cooperation with IEE SAS (Bratislava, Slovakia) the content of light elements (including hydrogen) in layered structures produced on the silicon surface by means of PECVD (*plasma-enhanced chemical vapor deposition*) has been studied.

In cooperation with VSU (Voronezh) the studies of various layered structures for the technical use by means of the back-scattering of helium ions have continued.

In cooperation with MCSU (Lublin, Poland) the influence of the ion implantation on the optical properties of the natural oxide layer covering the silicon surface and A3B5-type compounds has been investigated.

The investigations of deuterium depth profiles have proved to be useful for studying the influence of the electronic screening effect on the $d(d,n)^3He$-reaction rate in the range of ultralow deuteron collision energies in ZrD_2 and TiD_2 targets. This work has been done by a large group of researchers from JINR, P.N.Lebedev Physical Institute of RAS (Moscow), National Research Tomsk Polytechnic University (Tomsk, Russia), Institute of Electrical Engineering of the Slovak Academy of Sciences (Bratislava, Slovak Republic), University of California (USA), University of Science and Technology (Krakow, Poland).

5.2. 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. In cooperation with the Sternberg Astronomical Institute MSU the objects of presumably extraterrestrial origin have been investigated by means of the resonance spectrometry method. In the samples from bottom sediments of a brook in an Altai mountain glacier a rather high iron content has been found. The work is in progress.

5.3. Analytical investigations at the IBR-2 reactor and IREN

Development of the NAA Sector experimental base.

IBR-2. In 2011, the rooms of the radioanalytical complex REGATA were repaired. The spectrometer equipment and software for processing gamma spectra were modernized, the software package was developed for automation of spectrum acquisition on the basis of Genie-2000 (Canberra) and for calculation of element concentrations determined by the neutron activation method. In the process of preparation of the NAA and Applied Research Sector for accreditation according to the ISO-17025 standard the universal database control system for NAA has been created in FLNP JINR.

IREN. In cooperation with «Development and Application Base in Physics (DAB-Physics)», Sofia, Bulgaria, the manufacturing of a pneumatic transport system for NAA studies at the IREN facility has been completed.

Method development. In October, 2011, during the first reactor cycle after the completion of modernization of IBR-2 the measurement of thermal, resonance and fast neutron flux densities was carried out in the irradiation channels of the REGATA pneumatic transport facility.

1. SCIENTIFIC RESEARCH

Biomonitoring. In 2011, in the framework of the international program "Heavy metal atmospheric deposition in Europe – estimations based on moss analysis" the studies on multielement atmospheric deposition in Croatia (Spiric et al., 2011) and in Serbia (Krmar et al., 2011) reflecting the contribution of the NAA Sector to the European Atlas were published. In cooperation with the Belgian Nuclear Research Centre SCK CEN a technique for the determination of depleted uranium in moss-biomonitors using k_0-method in NAA has been developed (P. Vermaercke et al., 2011). In October-December, 2011, NAA was performed for moss samples from three regions of the Russian Federation (Leningrad region, area near the city of Tikhvin; Kostroma region; Western Siberia, Iksinsky swamp), Belarus (Minsk and Gomel regions) and the ferrochrome production area in Norway.

Ecosystem condition assessment. A report for the Black Sea Economical Council and a publication in the international journal have been prepared on the results of the international project between Black See countries (BSEC-PDF) "Revitalization of urban ecosystems with the help of higher plants" with the participation of Russia (JINR), Bulgaria, Greece, Serbia, Romania and Turkey (2008-2010).

In December, 2011 within the framework of the project «The environmental assessment of the Nile delta area using nuclear-physical analytical methods» the neutron activation analysis of soils and bottom sediments from the territory under study was performed on the IBR-2 reactor in cooperation with the Egyptian specialists. Data treatment is in progress.

Radioecology. The program for investigation of distributions of ^{137}Cs and ^{210}Pb isotopes in mosses-biomonitors collected on the territory of Belarus and Slovakia 23 years after the Chernobyl accident has been completed. Gamma-spectrometry of the moss samples has been performed in the low-background laboratories at the Comenius University in Bratislava, Slovakia, and at the Nuclear Energy Corporation of South Africa (NECSA). In cooperation with the Slovakian and Norwegian scientists the data on the season variations of ^{137}Cs and ^{40}K isotopes in the ground air of Bratislava have been analyzed, which in the authors' opinion is the result of soil resuspension.

Geology. In cooperation with the Bucharest University, Romania, and the Geological Institute of RAS the multi-element 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) has been carried out at the reactor of MEPHI in Moscow. The obtained results are of great interest for practical geology. The analysis of geological samples (ore) from one of the most promising non-ferrous metal deposits in Mongolia has been made using the neutron activation technique. In cooperation with the Vietnamese specialists and employees of FLNR JINR the behavior of rare-earth elements in the plant-soil system of Northern Vietnam has been studied. In December, 2011 the analysis of soils and medicinal clays from Romania was carried out on the IBR-2 reactor.

Analysis of materials of extraterrestrial origin. In December, 2011 on the REGATA facility the test neutron activation analysis was conducted for the sample of presumably extraterrestrial origin, which had been collected from a melting high-mountain glacier in Altai. The analysis of the same sample was performed on the IREN facility. The continuation of this work is scheduled for 2012.

Human and animal health, herbs. The studies on biomonitoring of atmospheric deposition with the use of land plants and their relation with the epidemiological data carried out in the NAA and applied research sector have been presented at the ***All-Russian scientific*** and ***practical conference*** «Monitoring of the health state, quality and lifestyle patterns of the population in Russia. The effects of behavioral risk factors on the population health» (June 7-8, 2011, Moscow).

Unique data on the element composition of some herbs from Mongolia and India applied in Asian alternative medicine have been obtained for the first time.

Biotechnologies. In 2011, in collaboration with the E.Andronikashvili Institute of Physics, I.Javakhishvili Tbilisi State University and I.Chavchavadze State ***University*** (***Tbilisi***, ***Georgia***) the studies on the development of methods for synthesis of silver and gold nanoparticles by certain

kinds of Actinomycetes including *Arthrobacter* as well as by blue-green algae *Spirulina platensis* continued. The effect of time and dose dependences on the formation of nanoparticles was investigated. A complex of spectroscopic and analytical methods – ultra-violet spectroscopy (UV-vis), X-ray diffraction (XRD), transmission electron microscopy (TEM), scanning electron microscopy (SEM), as well as neutron activation analysis (NAA) and atomic absorption spectroscopy (AAC) techniques was used for testing the experimental samples. Within the framework of joint studies with the South African Nuclear Energy Corporation (NECSA) NAA of a biomass with gold nanoparticles has been performed on the SAFARI-1 reactor (Pretoria, South Africa).

Materials science. In cooperation with the Scientific and Practical Materials Research Center of the National Academy of Sciences of Belarus the studies of the role of trace impurities in the technology of crystallization of cubic boron nitride continued. Starting from 2011 within the framework of the joint grant (JINR-Romania, 2011) the Romanian specialists in x-ray diffraction and scanning electron microscopy under the direction of Prof. A.Ene (University of Galati, Romania) take part in these studies.