1.2. NUCLEAR PHYSICS WITH NEUTRONS

1. Introduction

In the reported period the program of investigations in neutron nuclear physics in FLNP covered traditional and relatively new research directions. The fundamental properties of neutrons, spatial parity violation in different nuclear reactions induced by neutrons, highly excited states of nuclei in reactions with resonance and fast neutrons, astrophysical aspects of neutron physics were experimentally investigated and experiments with ultracold neutrons were conducted. An extensive program of studies in resonance neutron induced fission completed.

Development of experimental approaches of investigations in the fundamental field of time-noninvariance effects in the interaction of resonance neutrons with nuclei was under way. At present, polarized neutron transmission through polarized targets seems to be the most convenient tool to conduct direct tests of time-reversal invariance.

Applied research in the field of neutron activation analysis (NAA) and methodological development of neutron and gamma detectors of different types was carried out.

These investigations were mainly done on seven neutron beams of the IBR-30 booster, beams 1 and 11 of the IBR-2 reactor and with the experimental facility «Regata» for neutron activation analysis at IBR-2. In addition, a number of works were conducted in collaboration with nuclear centers of Russia (RRC KI, ITEP, MEPI, PNPI, PEI, RSRIEP), Ukraine (INR NU, Kiev), Bulgaria (INRNE, Sofia), Poland (UL, Lodz; INP, Krakow), Czech (NPI, Řež near Prague), Germany (FZK, Karlsruhe; Tuebingen Univ.; THD, Darmstadt; FRM, Garching), Republic of Korea (PAL, Pohang; KAERI, Taejon), France (ILL, Grenoble; CEC CEA, Cadarache), Belgium (IRMM, Geel), USA (LANL, Los Alamos; ORNL, Oak-Ridge), China (Peking University) and Japan (Kyoto University; KEK, Tsukuba) at their neutron sources.

Interesting possibilities are opening in the framework of a wide international collaboration on the basis of the new n-TOF facility put into operation in CERN at the end of the year 2000, PS-213.

2. Experimental investigations

2.1. Parity violation and time reversal invariance in neutron transmission

2.1.1. Parity violation in compound nuclei. TRIPLE results

Frank Laboratory of Neutron Physics is a member-organization of the Time Reversal Invariance and Parity at Low Energy collaboration (TRIPLE) for the study of the effective weak interaction in nuclei by measuring parity-nonconserving (PNC) asymmetries of neutron p-wave resonance cross sections. The measured PNC asymmetry values lie in the range from 10^{-3} to 10^{-1} for the neutron energy from several eV to 300-2000 eV depending on the target. A high density of states results in the enhancement of the parity violation effect by a factor as large as 10^{6} compared to parity violation in the *pp*- scattering. Since compound states have contributions from many single-particle levels, it is possible to use statistical methods to determine the mean square root weak matrix element *M* of each nucleus. To date, the data-taking stage in the Los Alamos National Laboratory has completed and the data-analysis stage is approaching its final phase.

In 2000, analysis of the thorium data extended to the neutron energy above 250 eV where PNC effects of two signs are detected.

The new results show that ten positive-sign PNC effects observed earlier in ^{232}Th in the neutron energy interval below 250 eV can be interpreted as a local doorway state of the statistical nature. The results of the analysis are published by Sharapov et al.[1, 2]. A sizable parity violating off-resonance effect is not expected within contemporary theoretical models. It was experimentally proved by Mitchell et al [3], who analyzed the thorium data between resonances. The obtained value of the PNC asymmetry P_{off} = (0.5±1.6) ~ 10^{-6} establishes an upper limit for the off-resonance PNC effect that is four orders of magnitude smaller than a typical size of the order of one percent of the PNC-enhanced resonance effect. The indium PNC data were analyzed by Stephenson et al [4]. A total of 36 *p*-wave neutron resonances were studied in ^{115}In [4] to the neutron energy 316 eV and statistically significant asymmetries were observed for nine resonances.

The ***rms*** weak matrix element value $0.67^{+0.16}_{-012}$ meV obtained in the analysis is in agreement with theoretical predictions. A detailed description of the transmission technique of PNC studies at LANL is published by Yen et al. [5]

2.1.2. Current state of work on the project KaTRIn

The project KaTRIn is for the use of an optically polarized Rb – ^{3}He nuclear target as a neutron polarizer and an analyzer of neutron polarization [6, 7]. In the reported period the quality of the polarization ^{3}He cells was improved. A new system for the filling of the cells was developed, manufactured and tested *Fig. 1*. In addition, a prototype of the ^{3}He polarizer of neutrons was installed on beam 2 of the IBR-30 neutron source and trials started. The scheme of the experiment is presented in *Fig. 2*. In the course of the trials the following is done to study the characteristics of the polarizer and complete its design:

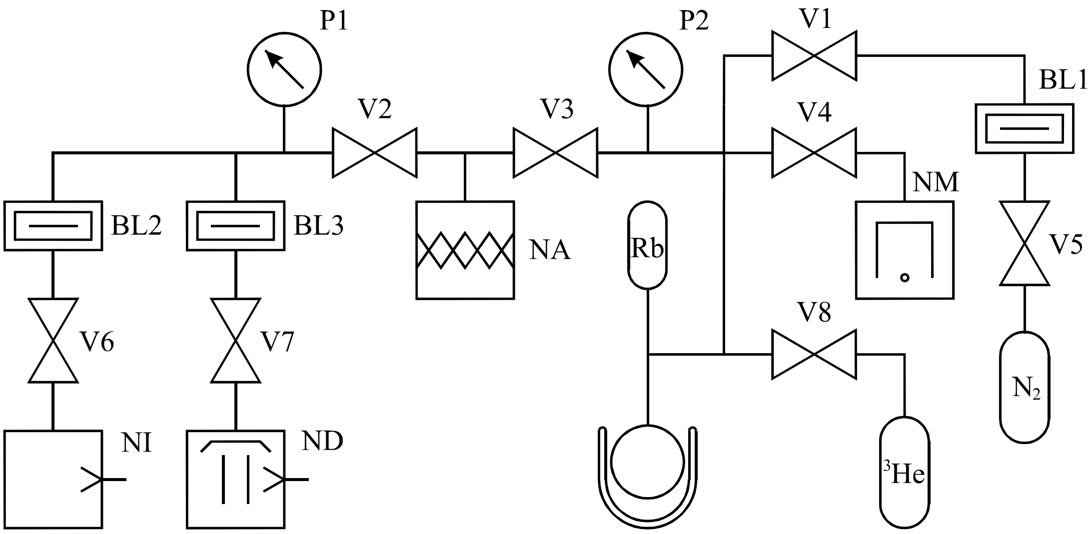

Fig. 1. *The pumping system for the ^{3}He cells. NI – forevacuum pump; ND – diffusion oil pump; NA – sorption pump; BL1, BL2, BL3 – nitrogen traps; P1, P2 – vacuum-meters.*

1. ^{3}He and correspondingly, neutrons are polarized in the absence of a leading magnetic field.
2. The possibility of measurements of P-odd effects at transmission of polarized neutrons through a ^{139}La target without reversing the neutron spin direction is verified.
3. The structure of the polarizer is optimized.

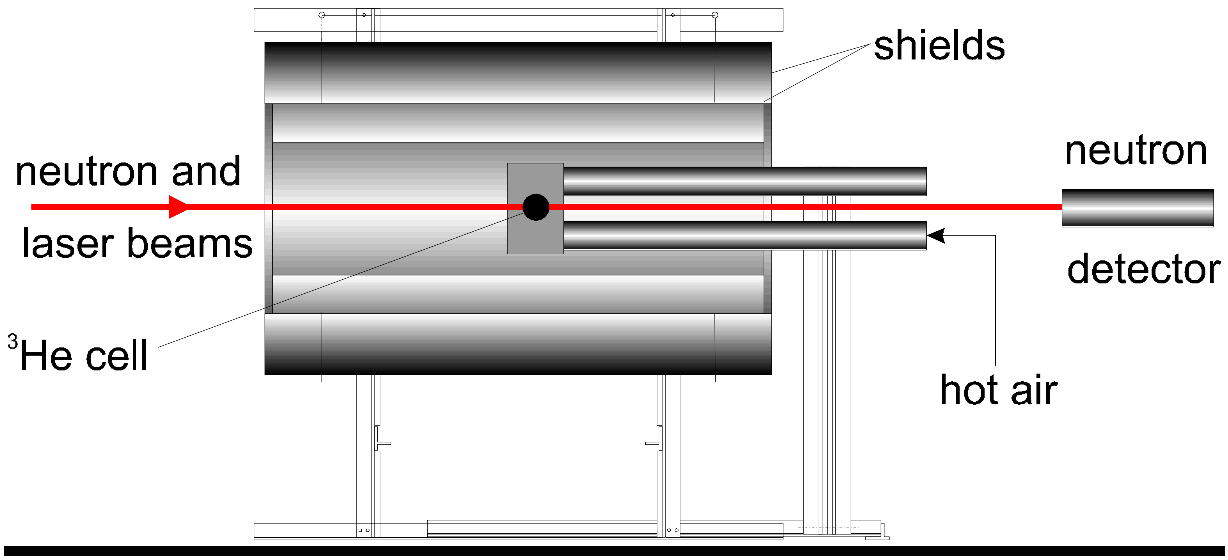

Fig. 2*. The neutron polarizer prototype*

Work on the second paragraph of the program completed at the end of the year 2000. The stage concerned with the ^{3}He cell and laser pumping of polarization will be executed in the first half of the year 2001.

2.2. Parity violation and interference effects in angular distributions of fission fragments

2.2.1. Investigation of interference effects in angular distributions of fission fragments of heavy nuclei

In 2000, investigations of spatial parity violation and interference effects in the angular distribution of fission fragments from the resonance neutron induced fission of heavy nuclei continued. The existing theories [8, 9] make it possible to describe the experimentally measured asymmetry coefficients as a function of the parameters of the s- and p- wave resonances and also, of the matrix elements of the weak interaction for the coefficient a_{pv} that characterizes parity violation. In recent years, experimental investigations of above effects in the resonance energy region were carried out by joint groups of PINP (Gatchina) and FLNP, JINR. Generalized results of all the investigated effects for ^{235}U are published in [10]. The experiments with ^{233}U that completed in 1999 are described in [11].

Measurements with ^{239}Pu that were initiated in 1999 continued through the year 2000. The advantage of ^{239}Pu over uranium isotopes is that it has a noticeably smaller density of levels. The average distance between resonances is 2.3 eV. This simplifies simultaneous processing of the obtained spectra because the contribution of neighboring resonances to the analyzed section decreases. At the same time, however, this leads to a decrease of the effect as soon as it depends on the distance between the mixing levels.

The ^{239}Pu measurements will continue till the end of June 2001 for which the decommissioning of IBR-30 is scheduled.

2.2.1. Investigation of the angular anisotropy of ^{235}U fission fragments from the aligned target

A set of investigations of the angular anisotropy of fragments from the fission of aligned ^{235}U nuclei induced by resonance neutrons completed providing unique information on the contribution of K-channels to the total and spin-separated fission cross sections and the effect of their interference on the structure of the cross sections. To refine further the obtained data, it is necessary to know more exactly the superfine electric quadruple interaction constant of the employed monocrystal uranyl rubidium nitrate targets that determines the alignment coefficient of spins in uranium nuclei. To do this, the temperature dependence of the angular anisotropy of alpha- particles on the radioactivity of the investigated samples was measured over the temperature interval $290-0.4K$, the experimental data processing is under way, and it is planned to conduct analogous measurements at lower temperatures.

2.3. High-excited states

2.3.1. Investigations of two-step gamma-cascades

In 2000, we continued acquisition, analysis and systematization of the experimental data on nuclear properties in the excitation energy interval corresponding to the nuclear transition from simple low-lying levels to compound states.

The goal is to identify the most general regularities of the process. The volume of the accumulated data allows the assumption that the properties of the excited states below the neutron binding energy, B_n, should be, to a large extent, due to transition from superfluid to usual phase of nuclear matter.

In 2000, the intensity distributions of two-step cascades following the α-decay of ^{40}K, ^{60}Co, ^{80}Br, and ^{185}W compound nuclei were measured. In addition, an analysis of the earlier data obtained for ^{191,193}Os was preformed.

It should be noted that high statistics in joint Dubna - Řež experiments makes it possible to determine the intensity of two-step cascades as a function of the energy of intermediate cascade levels for ^{185,187}W and ^{191,193}Os compound nuclei with an uncertainly not more than 10-20%. This allows one to verify the earlier conclusions based on data with a higher uncertainty and obtain a more detailed picture of processes occurring in nuclei.

Experiments were performed to systematize the phenomena observed earlier and extend the database on the density of levels with a given spin and parity and on the radiative strength functions as most informative parameters of the process under study. We developed and tested the new technique of data analysis to derive not only the total level density but also to determine separately the level density for positive and negative parities from the experimental data. This provided additional evidence in favor of an earlier conclusion about the possibility of rather abrupt changes in the properties of heavy nuclei in the vicinity of the excitation energy 3-4 MeV.

The obtained data are needed for the verification and further development of the level density models that take into account the coexistence and interaction of usual and superfluid phases of nuclear matter over the entire range of nuclear excitation energies below the neutron binding energy, B_n.

2.3.2. Investigations of radiative neutron capture, the nuclear data program

Three sets of measurements of gamma-ray multiplicities in the radiative capture of neutrons by ^{238}U and ^{232}Th nuclei were carried out using a 16-section liquid scintillation detector with a volume of 80 l and a HPGe detector on beam 3 of IBR-30 (123 m base, spectrometer PARUS) [12]. The measurements were conducted to determine the radiative capture cross section of ^{232}Th. Using it as a reference has made it possible to determine the group average radiative cross section and the cross sections in resolved resonance of ^{232}Th with an accuracy of 4-9%. Within the indicated errors, the experimental values are in good agreement with the values calculated with the libraries ENDBF/B-6, JENDL-3, and BROND (Table1, Table2). The measurements will continue in the year 2001 using ^{232}Th filter-samples of different thickness to determine the resonance self-shielding factors.

Table 1

The radiative cross sections in resolved ^{232}Th resonances at neutron energies from 21.5 to 215 eV*

E(eV)	RC(barn)	R_{ENDF}	R_{JENDL}	R_{BROND}
21.79	371.6 ± 12.5	1.05	1.03	1.04
23.46	572.7 ± 19.2	0.98	0.98	0.99
59.51	252.6 ± 10.1	1.13	1.11	1.11
69.19	877.8 ± 30.3	1.00	1.01	0.97
113.03	346.9 ± 16.0	1.14	1.17	1.12
120.85	407.9 ± 16.5	1.05	0.95	1.05
129.19	90.0 ± 8.1	1.00	0.95	0.97
170.39	398.2 ± 19.9	0.95	1.04	0.95
192.70	232.5 ± 18.8	1.17	1.14	1.11
199.40	152.1 ± 12.7	1.12	1.05	1.08

* R_{ENDF}, R_{JENDL}, R_{BROND} are the ratios of the results reported in [12] to the cross section values in the libraries ENDBF/B-6, JENDL-3, and BROND, respectively.

Table 2

The group average radiative capture cross-sections of ^{232}Th

E(eV)	RC(barn)	R_{ENDF}	R_{JENDL}	R_{BROND}
21.5 ÷ 46.5	37.9 ± 1.6	1.00	0.99	1.00
46:5 ÷ 100	21.1 ± 1.0	1.02	1.02	1.01
100 ÷ 215	13.8 ± 0.9	1.05	1.04	1.03

On beam 6 of IBR-3, measurements of the multiplicity spectra of gamma- rays at radiative neutron capture in ^{235}U in the neutron energy range 2 meV ÷ 2 eV completed.

On beam 6 of IBR-30 (500 m flight path, ROMASHKA spectrometer), three sets of measurements of ^{235}U radiative capture spectra of 15 multiplicities were conducted in the neutron range 20 eV to 10 keV, which made it possible to obtain the value of $\alpha = \sigma_\gamma / \sigma_f$, the radiative capture to fission cross section ratio, for over 200 resolved resonances up to the energy 300 eV and the averaged over energy values of α up to the energy 10 keV.

2.3.3. Partial capture cross- section determination by measuring energy shifts of primary gamma-transition

Development of the new neutron spectroscopy method consisting of the measurement of the energy shift of the primary γ-transition, which first allowed the determination of the energy dependence of the partial cross section of radiative neutron capture, continued. In the year 2000, the partial cross sections of ^{58}Ni for γ-transitions to the ground, first, and the second excited states of the daughter nucleus ^{59}Ni were conducted at neutron energies from 10 to 100 keV. This has become possible due to the development of a compact experimental geometry allowing a two times increase in the luminosity of the method in comparison with the time of flight method applied at a similar electrostatic generator operating in the pulsed mode.

The analysis of the results [13] contributed new information about the nature of γ-transitions and radiative strength functions of multipolarity M1 and made it possible to refine spin identification of a number of ð-wave resonance.

Distinct correlation between reduced neutron widths of s-wave neutron resonances and partial γ-widths of transitions to the ground state is discovered. This speaks for the single-particle nature of the investigated γ-transitions.

The partial cross section of γ-transitions to the first excited state is strongly suppressed for s-wave neutron resonances because for γ-transitions between the states with spins $1/2^+$ and $5/2^-$ the multipolarity can be either M2 or E3. For ð-wave neutron resonances with spin $3/2^-$, M1 transitions are possible and for resonances with spin $1/2^-$, E2 γ-transitions can take place. An analysis of the results of our measurements of $\sigma(n,\gamma_1)$ leads to the conclusion that spin identification of resonances in the last compilation by S.I. Sukhoruchkin [[14]] is not correct. Our results are described well if the compilation of the Oakridge group [[15]] is accepted.

To the cross section $\sigma(n,\gamma_2)$ there contribute γ-transitions of the same multipolarity as of transitions to the ground state. However, no correlation with reduced neutron widths is observed in this case.

The possibility of analysis of stationary neutron spectra over the energy interval 10 – 150 kev is experimentally verified [[16]].

2.3.4. Measurements of radiative capture spectra

On beam 5 of IBR-30, spectra of the radiative capture of neutrons with the energy up to 100 eV by the nuclei of the isotopes ^{181}Ta , ^{121}Sb, ^{123}Sb were measured in collaboration with the group of Prof. M Psitula (Lodz, Poland). For antimony isotopes, correlations between population of the excited states and spins of resonances are observed, which allows the use of precision gamma-spectroscopy to study the resonance structure of this nucleus.

2.4. Neutron reactions with emission of charged particles

2.4.1. Investigations of the (n,p), (n,α) reactions on resonance neutrons

On beam 1 of the IBR-30 pulsed source of FLNP JINR, the angular distribution of fission products from the reaction $^{35}Cl(n,p)^{35}S$ in the region of the resonance E_0=398 eV was measured. This was aimed at determination of the parameters of the angular distribution and extraction from them of partial neutron and proton widths, $\Gamma_{n,p}^{1/2,3/2}$, for the p-wave resonance of ^{35}Cl. A two-section ionization chamber with a grid and a system of acquisition and analysis of multidimensional data were employed in the experiment. Several runs of measurements were conducted. The obtained data are being processed.

2.4.2. Investigations of the (n, p), (n, α) reactions on fast neutrons

At the EG-5 accelerator of FLNP JINR, methodological measurements of the ^{6}Li(n,α)T and ^{235}U(n,f) reactions on neutrons with the energy 4.14, 4.79, 5.24, 5.76 MeV were carried out using a two-section ionization chamber with removable samples and a system of acquisition and analysis of multidimensional data. The goal was to test the created complex of equipment and method for the investigation of the (n,p), (n,α) reactions on fast neutrons. The neutron source was the D(d,n)^{3}He reaction. There was used a solid TiD-target without special cooling and the deuteron current 2-4 μa. The results helped assess the neutron flux and the background conditions of the experiment. Today, equipping of the special channel and the cooling system of neutron producing targets is completed, which will increase the deuteron current by an order of magnitude and as a result, raise the neutron yield.

In collaboration with Peking and Tsinghua Universities (Peking, China) experiments to measure the cross sections and angular distributions of the ^{6}Li(n,α)T, ^{10}B(n,α)^{7}Li, ^{58}Ni(n,α)^{55}Fe, ^{64}Zn(n,α)^{61}Ni reactions for a number of neutron energies in the interval 1-7 MeV were conducted. The experiments were carried out with the Van-de-Graaf accelerator of the Institute of Heavy Ions of Peking University and the two-section ionization chamber with removable samples constructed in FLNP JINR. The measurement of ^{6}Li and ^{10}B was made at E_n=1.8 and 2.6 MэB with neutrons from the T(p, n)^{3}He reaction. The objective of the experiment was to investigate the behavior of the angular distribution (differential cross section) of reaction products with changing energy of the incident neutron for light nuclei. The obtained experimental data are being processed. Measurements of ^{58}Ni and ^{64}Zn were made at E_n=6.8 MeV with neutrons from the D(d,n)^{3}He reaction. They were aimed at the study of contributions of the different mechanisms of the reaction (compound nucleus, pre-equilibrium and direct processes). The experimental data are being processed.

Processing of the experimental data on the ^{39}K(n,α)^{36}Cl and ^{40}Ca(n,α)^{37}Ar reactions for neutron energies in the interval 4.5-6.5 MeV completed. The total, partial (α_0, $\alpha_{1,2}$), and differential cross section values are obtained. The obtained data together with the data by other authors were used to analyze the parameters of the reactions in the framework of the spherical optical and dispersion optical model. The results of the analysis show that the two models describe well the parameters of the (n,α) reaction on ^{39}K and ^{40}Ca for the neutron energies below 7 MeV [17, 18, 19].

2.4.3. Program of (n, α) reaction measurements to study explosion nucleosynthesis

In 1999-2000 the procedure was developed and first successful measurements of the ^{147}Sm(n,α)^{144}Nd reaction were conducted on neutron beams of the accelerator ORELA in Oakridge USA. In 2000, the results of interest for astrophysics were obtained and prepared for publication.

The new data on this reaction at energies from 3 eV to 500 keV (***Fig. 3***) were used to verify nuclear statistical models employed to calculate the rapidity of the reactions (including those that are impossible to measure) involved in the scenarios of explosion nucleosynthesis [20].

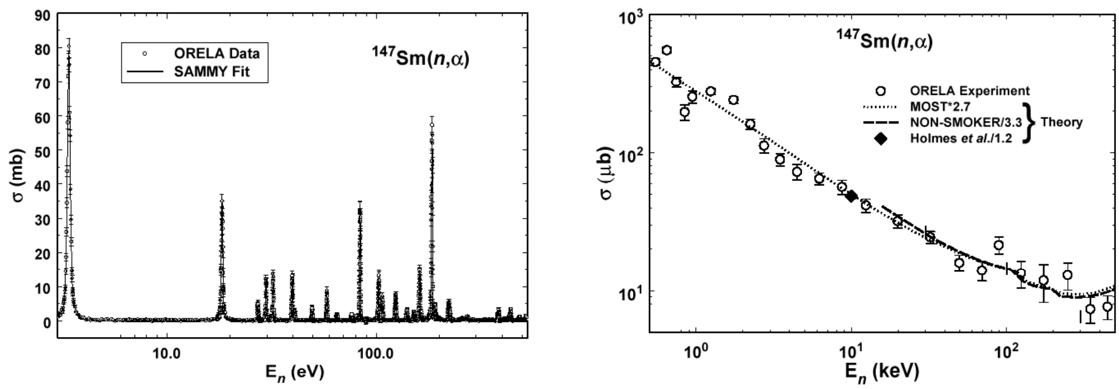

Fig. 3. *The cross section data from [20] for the ^{147}Sm(n,α)^{144}Nd reaction in the region of resolved resonances from 3 to 530 eV (left) and of unresolved resonances from 0.5 keV to 500 keV (right).*

2.5. Physics of ultracold neutrons (UCN), neutron optics

2.5.1. Investigations of “weak” UCN heating at their storage in traps

At the reactor of ILL studies of the mechanism of weak UCN heating continued. The temperature dependence of inelastic UCN scattering with a small energy transfer (~10^{-7} eV), weak heating, on the surface of beryllium or copper was observed. The intensity of scattering on the surface of these materials decreased 2.5 times as the temperature changed from room to liquid nitrogen temperature. The upper and lower limits of the probability of UCN heating with a small energy transfer were refined.

The experimental upper limit of subbarrier UCN transmission through a 14 um vacuum-tight beryllium foil was improved two orders of magnitude to be $(-1.2 \pm 1.0)\cdot 10^{-8}$ per bounce.

2.5.2. Neutron spin optics

The Larmor precession of spin was used as a clock to measure the difference between the speeds of the neutron in vacuum (**V**) and matter (**nV**), where **n** is the refraction index. The experiment was staged on the spin-echo spectrometer IN15 of the Laue-Langevin Institute. The change in the time of flight $\Delta \mathbf{t} = \mathbf{k}(1-\mathbf{n})\frac{\mathbf{d}}{\mathbf{V}}$ due to refraction in the sample of thickness **d** gives rise to an additional precession phase, $\Delta\varphi = \omega_L \Delta \mathbf{t}$, where $\omega_L = \frac{2\mu \mathbf{B}}{\hbar}$ - Larmor frequency, μ - neutron magnetic moment, **B** is the magnetic induction. It is the precession phase that is measured in the experiment. The effect was measured for a number of samples of silicon, beryllium, quartz, and pyrolytic graphite. The experimentally obtained values of the refraction index coincide, within several percent, with the theoretical values of $\mathbf{n} = \sqrt{1-\frac{4\pi\rho\mathbf{b}}{\mathbf{k}_0^2}}$, where b – coherent scattering length, ρ - nuclear density, $\mathbf{k}_0$ - is the wave number. The measuring accuracy of the delay in the time of flight was (3÷5)x10^{-10} sec. The sensitivity of the method is so high that even the effect of diamagnetism in the sample material (usually small) affects the results.

2.5.3. UCN diffraction on a moving grid

A quantum experiment to observe a discrete energy spectrum at diffraction of initially monochromatic (ultracold) neutrons on a moving grid was staged on the UCN spectrometer with interference filters in ILL. The quantum experiment is thus made with the help of an instrument based on quantum principles. The basic result is illustrated in *Fig. 4.*

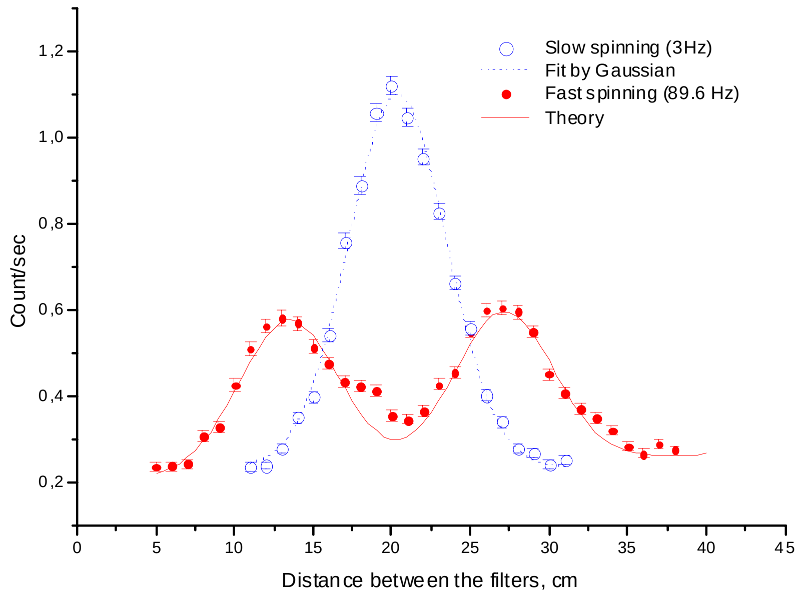

Fig. 4. *The dependence of the counting rate of the UCN detector on the distance between resonance filters.*

In the figure, the open points represent the measured spectrum of neutron transmission through a grid moving at a very small velocity and the corresponding curve is the fitting of the spectrum. The full points represent the measured spectrum of neutron transmission through a fast moving grid, the curve being theoretical.

The essence of the phenomenon can be explained in terms of frequency modulation of the primary beam occurring as the moving periodic structure traverses the neutron beam. The modulation frequency is $\Omega = \pi \mathbf{V}/\mathbf{a}$, where 2a is the period of the grid and V is its linear velocity. In the discussed case, it is a purely phase modulation, $\Omega \approx \mathbf{1.07} \times \mathbf{10^7}$ radian/s. (10 MHz).

2.5.4. Neutron scattering on optical inhomogeneities at resonance tunneling

An experiment to observe neutron scattering on optical inhomogeneities at resonance tunneling through an interference filter was performed in ILL. As calculations show, in the conditions of resonance tunneling the cross sections of all processes, including absorption and scattering, increase several orders of magnitude. This is due to a long stay of the neutron in the system. We assume that this fact may lead to the effect of resonance mode mixing in quantum systems comprising three barriers and two potential wells. In accordance with the general principles of quantum mechanics the splitting of quasibound state levels occurs in such systems. The experiment consisted in that the primary neutron spectrum irradiating the system corresponds basically to just one resonance. The scattering on inhomogeneities results in the appearance of neutrons with the energy corresponding to another resonance. The experiment confirmed qualitatively our assumption.

The prospects of the work consist of the development of a new, highly sensitive approach to investigations of the quality of inter-layer surfaces important for applied neutron optics. A better understanding of resonance scattering processes will allow a more reliable interpretation of the results obtained earlier in the experiment of verification of the UCN dispersion law.

3. Theoretical research

3.1. Structure of neutron-excess Λ - hypernuclei

Calculations of different hypernuclei in the 1ð shell ($^{12}Be, ^{9}He, ^{11}He, ^{11}Li, ^{16}C$) were performed by the Skirm-Hartri-Fock method. To obtain the experimental values of the separation energy of the neutron halo in the primary nucleus, fitting of the single-particle potential acting on the neutron was carried out. The halo system is considered to be a neutron in a pure single-particle state immediately outside the core whose ground state is excited both by the neutron and hyperon.

3.2. Correlation between the polarizations of two particles [21]

It is known that if a pair of spinor particles in the singlet state is born in the system in the process of reaction, the polarization of one is strictly determined by the polarization of the other. This means that having measured the polarization of one particle we can be sure that the spin of the other particle has an exactly opposite direction.

In [21] the $\pi^{+}+{}^{4}He=p+{}^{3}He$ reaction, where the first two primary particles are scalar and have a common spatial parity of –1 while each of the two final particles has the spin s=1/2, is investigated. Since this common parity must conserve, the final particles can be only born in the triplet spin state. Therefore, the spins of the particles correlate. If protons with a given spin projection are separated, the nuclei ^{3}Íå will mainly have the polarization in the same direction in these events. It is true, however, that this will not be a 100% polarization.

3.3. Aaronov-Bom effect [22]

As it is known, as electrons experience scattering on toroidal magnets, the interference of the electron waves that passed through and round the toroid magnet hole takes place. In this case, the interference pattern depends on the magnetic flux enclosed in the toroid. The interference even occurs when the toroid is covered with an electron absorbing material, i.e. the electrons diffracted from the toroid do not come into immediate touch with the magnetic field in its interior. The calculation of the integral cross section of inelastic scattering on a thin toroid covered with an absolutely black screen and having a hole of the area S gives

$$\sigma_{el} = \int \sigma_{el}(\Omega) d\Omega = 4S \sin^2(\pi e \Phi / hc),$$

where $\sigma_{el}(\Omega)$ is the differential cross section of elastic scattering as a function of the scattering angles Ω, Φ is the magnetic flux, å is the electron charge, h is the Planck constant, and ñ is the velocity of light. This expression is of a somewhat paradoxical character as it provides evidence of dependence on the flux although the flux produces no strength effect on the electron.

The authors show that the strength interaction between the electron and the magnetic field is characterized not by the elastic but transport scattering cross section equal to

$$\sigma_{tr} = \int \sigma_{el}(\Omega)[1 - \cos(\theta)] d\Omega.$$

The calculation of the transport cross section yields a quantity independent of the flux, if the toroid is screened from electrons, and to a quantity dependent on the direct strength interaction with the flux, if the toroid is not screened and electrons penetrate it and experience the action of the Lorentz force from the magnetic field. Thus, the Aaronov-Bom paradox is removed.

3.4. Multilayer systems [23]

Using an earlier developed analytical apparatus of waves multireflection it is possible to find resonances in multilayer systems in a simple analytical form, describe them with the Breit-Wigner formulas, and determine the total width of the resonance together with the partial widths related to the exiting of the multilayer system in one or another direction and also, to absorption.

A mathematical apparatus for the calculation of resonances in magnetic multilayer systems where the magnetization of neighboring levels is not collinear is also developed. In this case, for partial widths there is a possibility of exiting the system with or without spin-flip.

3.5. Coherent wavelength of the neutron [24]

As is known, the coherent neutron length can be defined as a parameter characterizing the preparation of the neutron beam, i.e. its collimation and monochromatization. However, it is also possible to determine the coherent length of the neutron itself that characterizes its own wave packet. The question of how it is possible to separate the neutron's own coherent wavelength then arises. In [24], an attempt to do it is made. The reflection curve of neutrons from thin films at a given angle is known to have an interference behavior depending on the neutron energy, i.e. it has a set of minimums whose position depends on the thickness of the sample and the wavelength of the neutron. The depth of the minimums is mainly determined by the parameters of the beam, scattering on roughness, incoherent scattering, and by absorption. After taking into account all these factors the description of the depth of the minimums is yet not sufficiently good. It turns into a more satisfactory description as soon as the neutron's own coherent length, that appears to be of the order of magnitude of the de Broil packet width found earlier from the description of the UCN storage anomaly, is introduced

3.6. Neutron holography [25]

Holography is described with the wave process. In the case of the neutron, however, we deal with a large number of wave processes. One of them is connected with the de Broil wavelength of the neutron itself. In [25], another wave process, i.e., the one related to spin precession in the magnetic field is investigated. For the given value of the field B and velocity v the wavelength of the neutron itself is $\lambda = vh / \mu B$, where μ is its magnetic moment. Making use of this wave process it is possible to record diagrams without the reference beam.

4. Methodological

4.1. Precision gamma-spectroscopy, the COCOS project

The development of combined correlation gamma-gamma spectroscopy of neutron-nuclear interactions was under way. The method was tested in the experiment of the spectroscopy of the gamma-radiation of fragments from the resonance neutron induced fission of ^{239}Pu carried out on one of the IBR-30 beams, which demonstrated its effectiveness.

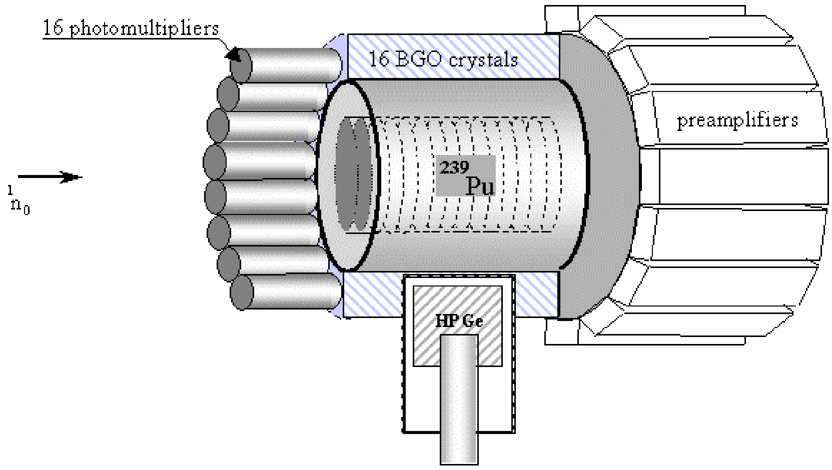

Fig. 5. *The schematic layout of the HPGe-BGO gamma-spectrometer.*

Work to create a 16-BGO-scintillation-block-multidetector for the HPGe-BGO gamma-spectrometer completed **(***Fig. 5***).**

4.2. Investigations with the electrostatic generator EG-5

4.2.1. Neutron spectrometry in gamma-spectrum form

Van de Graaf accelerator-aided experiments to finish off the new method of neutron spectrometry and obtain new data on partial cross sections of radiative neutron capture continued. The experiments were carried out with samples of nickel, copper, and manganese at proton energies higher than the $^{7}Li(p,n)$ reaction threshold by 100 keV. The energy dependence curves of the partial cross section of the $^{58}Ni(n,\gamma)^{59}Ni$ reaction are obtained. The results of measurements of copper and manganese samples are currently being processed.

In addition, the possibility of measuring the neutron energy spectra with the help of the $^{58}Ni(n,\gamma)^{59}Ni$ reaction was investigated. Measurements of the spectra of gamma-transitions populating the ground state of the daughter nucleus were carried out for different neutron spectra. It was studied how sensitive the form of the gamma-transition spectrum is to the energy distribution of incident neutrons. It is shown that the employed method makes it possible to study the energy distribution of incident neutrons by investigating the form of the spectrum of primary gamma-transitions from the (n,γ) reaction. Our findings are published in the proceedings of the ISINN-8 conference.

4.2.2. Obtaining of the neutron flux with a Maxwell velocity distribution

A set of experiments to study the possibility of obtaining the neutron flux with a Maxwell velocity distribution for the purposes of further measurements of the neutron capture cross section were carried out at the van de Graaf accelerator.

A graphite prism was used as a moderator. The average neutron flux in the points on the prism surface selected by the Monte-Carlo method was measured by the neutron activation method. Gold plates were used as an activated sample. The measurements yielded relative neutron flux values in different points on the surface of the prism. A comparison of the experimental and calculated data revealed the existence of an unaccounted contribution to the neutron flux. Additional measurements were conducted (FLNP) and new calculations are presently under way to uncover the reason of the discrepancy (INR).

4.2.3. Calibration of the fast neutron detector HEND

In the year 2000, calibration of the fast neutron detector HEND (High Energy Neutron Detector) designed to work on board the American research apparatus Mars Surveyor Orbiter 2001 as an element of the gamma-spectrometer complex was carried out in cooperation with specialists from DRRI. The work was done under a long-term agreement between the Institute of Space Research, RAS, and JINR specifying that JINR develops the physical concept of the instrument, performs physical and mathematical modeling of its characteristics, and does its efficiency calibration.

The spectrum and the flux of neutrons from the $^{7}Li(p,n)^{7}Be$ reaction over the neutron energy range from 200 to 1000 keV were measured with the help of a ^{3}He high pressure cell counter and a standard SNM-16 counter in a polyethylene jacket. The obtained data were used to determine an absolute efficiency of four detectors.

5. Analytical investigations at IBR-2: neutron activation analysis and radiation research

The instrumental neutron activation analysis method (INAA) at IBR-2 is mainly applied to solve environment protection problems under the auspices of the JINR first-priority project REGATA, IAEA coordination programs, JINR plenipotentiaries' grants, and individual projects. The analytical results of the multielement neutron activation analysis of moss-biomonitors reflecting the level of pollution by heavy-metal and other toxic elements of the investigated territories are sent to the Nordic Committee (Sweden). They are included in the atlas of «Atmospheric Heavy Metal Deposition in Europe» whose publication will be overtaken by the United Nations in 2001. The results of the work carried out in Dubna in the year 2000 were presented at 4 international conferences and are included in the IAEA reports. To prepare the results, GIS techniques (geology computer information systems) are widely used. The final results are presented as color geographical maps of the distribution of elements of high practical importance. A set of CD maps is being prepared.

Under the auspices of the international project (ISTC) studies of the ecological safety of building materials on the example of kinescope broken glass were conducted in cooperation with the Faculty of Safety of Nuclear Facilities of Moscow Construction University. Together with RODON (Sergiev Posad), investigations of the materials used in the solidification of liquid and solid radioactive wastes were carried out. An application for patenting the development and creation of a selenium-containing *Spirulina Platensis*-based pharmaceutical is being prepared together with the Andronikashvily Institute in Tbilisi [26]. The analytical part of work was done using epithermal neutron activation in Dubna in 2000.

The publication of *Tables for Identification of Nuclides Formed in Nuclear Reactors* [27] intensively used in INAA experiments at IBR-2 must be specifically emphasized. The Tables reflect the many-year experience of work with reactor neutrons acquired in the Neutron Activation Analysis and Radiation Research Sector.

On the basis of a radiochemical laboratory of the 3rd class (PTF Regata at IBR-2) practices for students of senior courses of the MSU Interfaculty Center and Dubna University doing a special course in Nuclear Physical Methods of Substance Analysis are organized. In the year 2000, two B.A. and two M.A. degrees in this theme were received and another three M.A. papers are in process and will be ready at the beginning of 2001. Five Candidate-of-Science papers are being written. Members of the AA and RR sector took active part in the preparation of the international conference *Radionuclides and Heavy Metals in Environment* (2-6 October, 2000, Dubna) held with the support of NATO.

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