1. SCIENTIFIC RESEARCH

1.2. NUCLEAR PHYSICS WITH NEUTRONS

Introduction

In the year 2002 the program for experimental research in neutron nuclear physics in the Frank Laboratory of Neutron Physics (FLNP) included the following FLNP-traditional research directions: studies of spatial and time parity violation at interaction of neutrons with nuclei, of quantum mechanical properties and the dynamics of the fission process, experimental and theoretical investigations of electromagnetic properties of the neutron and neutron beta-decay, gamma-spectroscopy of neutron-nucleus interactions, obtaining of new data for the purposes of reactor technology and nuclear astrophysics, and applied research.

The shut down of the IBR-30 reactor has shifted the focus of the experimental investigation to the IBR-2 and EG-5 machines in FLNP as well as to basic facilities in other nuclear centers in Russia, Bulgaria, Poland, Czech Republic, Germany, Republic of Korea, France, USA and Japan.

1. Experimental investigations

1.1. Spatial and time parity violation at interaction of neutrons with nuclei

1.1.1 Search and investigation of the structure of sub-threshold p-resonances of lead isotopes by combined correlation gamma-spectroscopy

To search for a sub-barrier neutron p-resonance of lead isotopes and to explain the parity violation effect **(**spin rotation of the neutron polarized perpendicularly to the momentum on going through a lead target), experiments were conducted on channel 1 of the IBR-2 reactor. The energy dependence of the neutron radiative capture cross section was studied. The expected deviation of the dependence from the law $1/\sqrt{E}$ due to the existence of such a resonance is shown in **Fig. 1.**

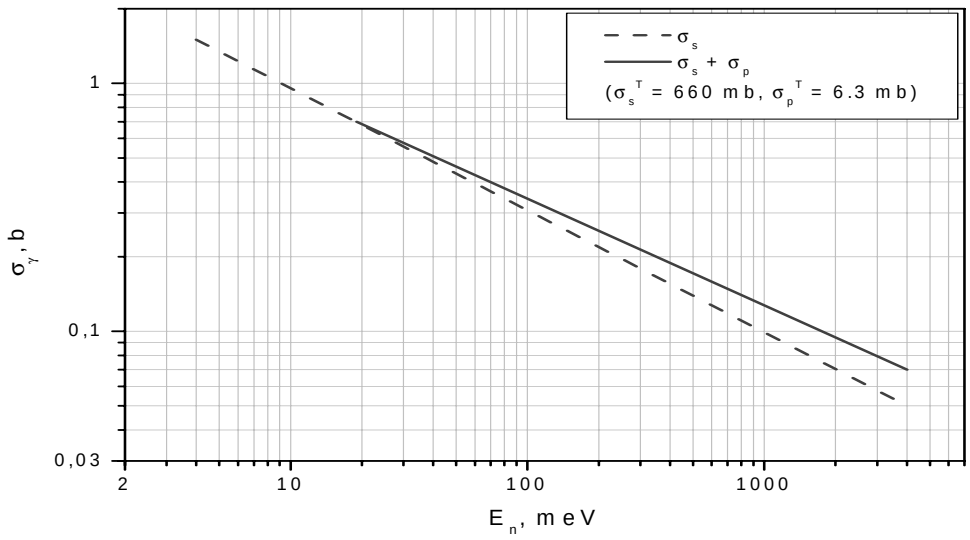

Fig. 1. *The energy dependence of the neutron radiative capture cross section for s- and s+p waves.*

At neutron energies from 80 meV to 3 eV there were measured the radiative capture gamma-spectra of a 4.7 g sample of lead enriched with a ^{204}Pb isotope on the spectrometer COCOS whose schematic is shown in **Fig. 2.**

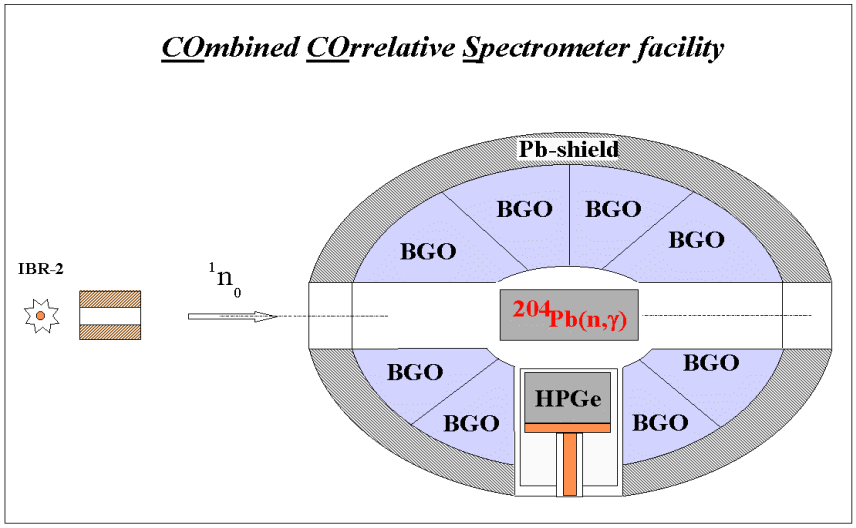

Fig. 2. *The schematic of the gamma-spectrometer COCOS.*

The fundamental possibility of the precision gamma-spectroscopy of small quantities of lead isotopes in unfavorable background conditions of a pulsed neutron source and the effectiveness of the chosen methodological approach were demonstrated. The preliminary results show no demonstration of the sought resonance of the isotope ^{204}Pb within a 15%-accuracy.

1.1.2 The measurement of the P-odd asymmetry of triton emission in the reaction ^{6}Li(n,α)^{3}H and recent results of the measurement of the P-odd asymmetry of γ-quanta emission in the reaction ^{10}B(n,α)^{7}Li*→γ→^{7}Li(o.c.)

Experiments to measure P-odd asymmetry of the type $\alpha_{PNC}(\mathbf{s_n},\mathbf{p_t})$ in the reaction ^{6}Li(n,α)^{3}H were performed on cold (<λ_n>=4.7 Å) polarized (94%) neutron beams of the reactor PF1B in ILL, Grenoble, France by a FLNP JINR-PINP-ILL collaboration. The details of the experiment are described in an article included in the special section of the present report. During the main measurements for 18 days α^t_{PNC} = -(8.1 ± 3.9)·10^{-8} was obtained. In addition, measurements to estimate the contribution of the P-even left-right asymmetry $\alpha_{LR} \le 8\cdot10^{-9}$ were carried out. Our results and those of similar measurements made in PINP, Gatchina, helped estimate the value of the weak meson constant corresponding to the neutral current - $f_\pi \le 1.2\cdot10^{-7}$. The measurements will be continued.

The first experiment to measure the P-odd asymmetry of γ-quanta emission in the reaction ^{10}B(n,α)^{7}Li*→γ→^{7}Li(o.c.) was made in 2001 in Grenoble using the polarized neutron beam of the reactor PF1B of ILL. The main measurement yielded the value of the P-odd asymmetry of the type $\alpha_{PNC}(\mathbf{s_n},\mathbf{p_\gamma})$ - α = + (8.8±4.6)·10^{-8} and a zero experiment revealed a considerable background effect, α_0 = -(14.8±3.3)·10^{-8}. In the 2002-year's experiment much attention was paid to the clarification of the nature of the background effect. Investigations to estimate possible contribution to the measured value from reactions with the construction materials of the facility and samples, such as lead, aluminum, lithium, and air, were carried out. It was established that the sample used in the first experiment for a zero test was locally contaminated, most likely, with chlorine (or bromine) and this largely affected the background. The basic results of the experiment (preliminary): measurements with a sample - ^{10}B - α = -(11.0 ± 6.6)·10^{-8}, 0-test - α_0 = (0.7 ± 3.7)·10^{-8}. The calculation of the investigated reaction in the framework of the cluster model using the "best" values of the weak meson constant gives α^{theor} = -7.24·10^{-8} for P-odd correlation. The achieved experimental precision does not allow the estimation of the weak meson constant f_π yet. The measurements will be

continued using the new supermirror polarizer that provides a many times higher intensity of polarized neutrons.

1.1.3 Parity violation in compound nuclei: TRIPLE's latest results

Under the collaboration Time Reversal Invariance and Parity at Low Energy (TRIPLE), analysis of measurements of parity-violating spin rotation in the region of the 0.75 eV neutron p-wave resonance of ^{139}La completed. The experiment was done at the Los Alamos pulsed source by measuring neutron transmission with two optically polarized ^{3}He cells used as a polarizer and analyzer of neutron spin. Analysis of the data yields the weak matrix element $xW=(1.71\pm0.25)$ meV in agreement with the earlier experimental data on lanthanum.

1.1.4 Current status of the KaTRIn project

Under the **KaTRIn** project for the preparation of the experiment to test time invariance in nuclear reactions, a program for the modeling of polarized epithermal neutron transmission through polarized targets has been developed. The program works with cross section libraries analogous to those incorporated in MCNP. Additional libraries to take into account spatial and time parity violation effects are calculated in the two-level approximation.

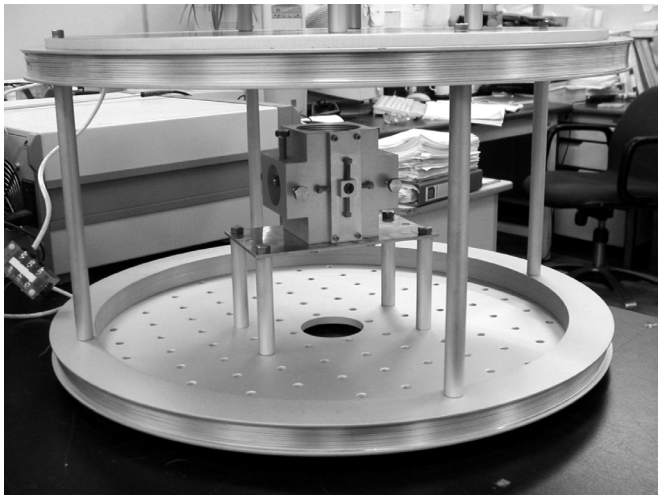

Fig. 3. *The system of Helmholtz rings assembled with a target heater.*

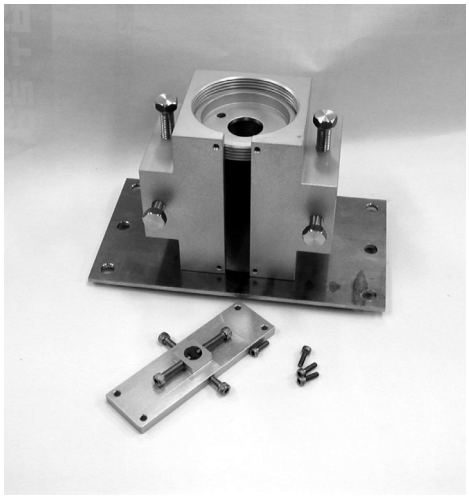

Fig. 4. *The target heater.*

Under a FLNP JINR – FIAN (Physical Institute of Academy of Sciences) collaboration aimed at improving the neutron polarizer on the basis of ^{3}He with optical pumping, the system for the filling of cuvettes with ^{3}He and rubidium using high purification filters of ^{3}He (getter) is being modernized.

In parallel, work to create a neutron polarizer on the basis of a ^{3}He gas target with laser pumping for PAL and the reactor «HANARO» (KAERI) is carried out. A system of 50 cm diameter Helmholtz rings with a power supply, a heater for the target, and the fastening elements are manufactured. The photographs of the rings and heater assembly are presented in **Fig. 3**. **Figure 4** shows the heater in the knock-down form. The measured magnetic field in the center is 23 Gauss, which is in full agreement with the calculation.

In the future, the system will be used in joint FLNP JINR – PAL – KEK experiments of testing time invariance in nuclear reactions.

1.1.5 Development of an aligned nuclear target for the search of T-invariance

To investigate T-noninvariance effects in the neutron-nuclei interaction by P-even T-odd five-fold correlation **c**[**pI**](**pI**) (where **c**, **p** and **I** are the neutron spin, neutron moment and the nucleus spin), it is necessary to have a sample with aligned nuclei. To align quadrupole nuclei in monocrystals, a dynamic method involving the saturation of NCR-transitions using a SHF electromagnetic field was suggested. In this connection, studies of the applicability of the nuclei dynamic alignment method (NDA) for the investigation of T-noninvariance effects were carried out in 2002:

- In cooperation with IONKh the NCR method was used to perform investigations with a monocrystal of lutetium niobate with a paramagnetic admixture of trivalent chromium. Three resonance lines corresponding to transitions between levels with the spins 7/2, 5/2, 3/2 and 1/2 are found. The transition frequencies differ slightly from those obtained previously with a ceramic sample.
- The relative position of the electric field gradient direction and the main C-axis of the crystal is determined.

1.2 Neutron-induced and spontaneous fission

1.2.1 Interference effects in the resonance-neutron induced fission of ^{239}Pu

In the framework of the new Barabanov-Furman theoretical approach to the description of fission, which employs the spiral representation of output fission channels and a conventional theory of nuclear reactions, there were obtained formulas for the partial and differential cross sections of fission. Making use of them, of the multilevel $R-$matrix formalism and of the minimization program FUMILI there was developed a program for analysis of the experimental

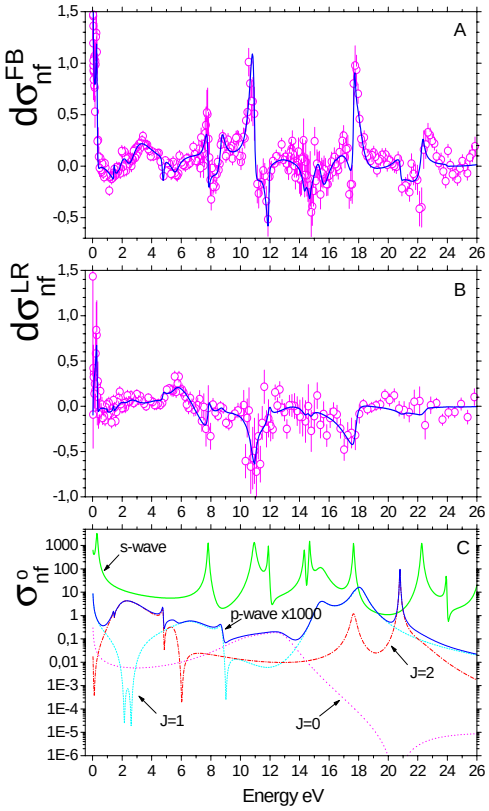

Fig. 5. *The results of fitting of the P-odd data on the angular asymmetry "forward-backward" (A) and "left-right" (B) of fission fragments from the reaction* $^{239}Pu(n,f)$ *in the region* $0.02-25\,eV$, *points – experiment, curves – fitting results. C – s- and p-wave cross sections (bearing indication of spin components for p-wave fission cross section). The fitting was done taking into account the resolution of the spectrometer.*

data with respect to angular anisotropy of the resonance neutron-induced fission of aligned nuclei and with respect to P-odd angular correlations “forward-backward” and “left-right” due to the interference of s- and p-wave resonances. The created program made it possible to do analysis of the experimental data on P-even angular correlations obtained for ^{239}Pu at the booster IBR-30+LUE-40. Earlier, analysis of such data was performed using a less strict approach suggested by Sushkov-Flambaum in 1982. The advantage of the new method and the new program is the possibility of joint analysis of the entire data set on total, partial and differential cross sections using a single set of resonance parameters. **Figure 5** illustrates the results of fitting of the experimental data on the angular correlations “forward-backward” and “left-right” for ^{239}Pu. Calculations have shown that the description of the experimental data with a satisfactory value of χ^2 is achieved for the different sets of p-resonances (in their number and spins) due to a low statistical accuracy of the experimental data, limited energy resolution and a large number of the introduced parameters of p-wave resonances. Therefore, the continuation of the experiments in the conditions of good statistics and resolution is of much interest.

1.2.2 Interference effects in the angular distribution of fission fragments

In the conducted cycle of investigations of the angular anisotropy of fission fragments from the resonance neutron-induced fission of ^{235}U (Phys. of Atom. Nucl., **62,** p.840 (1999)) there remained unsolved the problem of reliable normalization of the angular anisotropy coefficient $A_2(E)$ extracted from the experiment. Its absolute normalization depends on the correct assessment of the alignment of ^{235}U spins in the target, which is a monocrystal of uranyl-rubidium nitrate, which, in turn, depends on the precision of the superfine coupling constant P/k of the monocrystal. Measurements of the temperature dependence of the angular anisotropy of alpha particles in ^{233}U (basic activity of the sample) to refine the constant P/k for the investigated nucleus were undertaken. Cooling the sample to $0.2K$, an accuracy of 30 % was obtained. To achieve the goal set (an accuracy of $5-10\,\%$) it is necessary to continue the experiments at temperatures down to several mK.

1.2.3 Experiments to investigate triple fission

In cooperation with GSI and the Technical University (Darmstadt, Germany) an experiment to study the spontaneous fission of ^{252}Cf accompanied with emission of light charged particles was performed. In the experiment, a double ionization chamber allowing the registration of the energy and direction of two fission fragments with a high efficiency was used. To register light charged particles, a set of ΔE-E telescopes fixed at nearly 90° angles to the chamber axis was used. In addition, γ-quanta from the fission were registered with two large-volume segmented germanium detectors (GSI Super Clover detectors). The total angular resolution of the detecting systems makes it possible to obtain a resolution in gamma-quanta of ΔE / E =1% (after correcting for the Doppler effect), which allows speaking about the precision gamma-spectroscopy of moving fragments. Besides, of interest is the possibility of observation of gamma-emission from the excited states of triple particles. The probability of light charged particle formation is a very important parameter for the theory of triple fission as it may allow the assessment of the temperature of the nucleus at the moment of fission.

1.3 Gamma-spectroscopy of neutron-nucleus interactions

1.3.1 Investigation of two-step gamma-cascades

Processing and analysis of the to-date accumulated experimental data on two-step cascades in nuclei earlier not studied continue. Analysis of such data for the nuclei ^{60}Co and ^{184}W completed.

The scheme of excited levels of the isotope ^{184}W belongs to the class of those studied well in various nuclear reactions. Nevertheless, the information about 240 energy-resolved cascades allows one to extend the energy range of excited levels whose decay modes are determined over two times. Such information is necessary for the testing of today's models of the nucleus.

For the compound nuclei ^{185,187}W and ^{191,193}Os the intervals of the most probable densities of levels excited by primary dipole transitions on thermal neutron capture and their radiative strength functions are determined from the intensity of two-step cascades. For the tungsten isotopes the discussed parameters of the cascade gamma-decay of the neutron resonance are obtained with a less statistical and systematic error than the earlier results.

In all the nuclei a clearly expressed step-like structure is observed in the excitation energy in the interval from ~1 to ~2-2.5 MeV. In the framework of a generalized model of the superfluid nucleus this fact is evidence of the existence of appreciable influence of the coupling nucleon interaction on the observed properties of the nucleus at least below half neutron binding energy.

1.3.2 Spectroscopy of the nucleus ^{159}Gd

The nucleus ^{159}Gd lies in the middle of the rare-earth region, is strongly deformed and can be represented as an even-even ellipsoid with a neutron on the outermost shell. The low-lying levels group into rotational bands built on single quasiparticle states. The basic properties of such a system can be looked at as interaction of a single particle with the field of the nucleus ^{158}Gd whose properties are well known. The levels of ^{159}Gd were studied in the reaction ^{158}Gd(n,gamma) in FLNP JINR, in BNL (Brookhaven, USA) and in ILL (Grenoble) as well as in the transfer reactions ^{158}Gd(d,p) and ^{160}Gd(d,t) at the Van de Graaff accelerator in the Technical University (Munich). In 2002, the results of measurements of the transfer reactions ^{158}Gd(d,p) and ^{160}Gd(d,t) were analyzed. The charged particles from the reaction were separated in energy and type in the Q3D spectrograph shown schematically in **Fig. 6** and were registered with a position-sensitive detector.

The proton yield from the reaction ^{158}Gd(d,p) was measured at 10 angles. To describe theoretically the angular distributions of protons energy-related with definite final states of ^{159}Gd, the DWBA approximation was used. The reaction ^{160}Gd(d,t) was measured at an angle of 8, 40, 45 or 50 degrees with unpolarized deuterons and at an angle of 12, 16, 20, 25, 30 or 35 degrees with polarized deuterons. For a theoretical description of angular distributions there was also used the

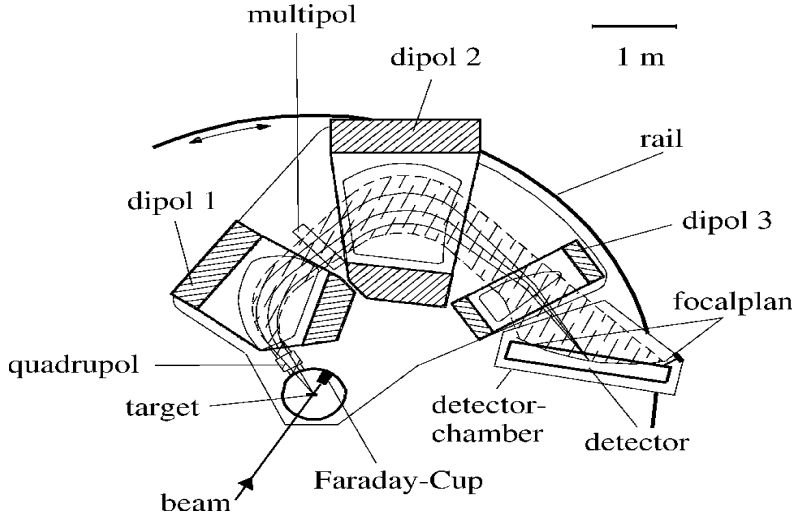

***Fig. 5**. The Q3D spectrograph at the Van de Graaff accelerator in the Technical University (Munich).*

DWBA approximation. An analysis of the results has made it possible to determine the spin and parity of levels in ^{159}Gd up to the excitation energy 2320keV. Basing on the results of measurements of all of the reactions rotational bands in the nucleus ^{159}Gd to the energy 1220 keV were built.

1.3.3 Investigation of level densities and radiative strength functions of Mo and Si isotopes

Work to investigate nuclear level densities and radiative strength functions continued in collaboration with the University of Oslo (Norway) and the Livermore National Laboratory (USA). A joint experiment was carried out at the cyclotron of the University of Oslo to study the nuclei ^{96}Mo and ^{97}Mo using the reactions (^{3}He,$\alpha\gamma$) and (^{3}He,^{3}Heγ). Collaborative processing of the results of the previous measurements of the nuclei ^{27}Si and ^{28}Si completed. For the nuclei, the level densities in the excitation energy interval down to the neutron binding energy as well as the energy dependence of radiative strength functions were obtained. Methodological work to demonstrate a method of the experimental investigation of the electromagnetic nature of the pigmy resonance in the radiative strength function by combined analysis of the data from the reactions (^{3}He,$\alpha\gamma$) and (n,2γ) in application to the same investigated nuclei was carried out. Processing of the results of the joint experiment to study the thermal neutron-induced reaction ^{171}Yb(n,2γ)^{172}Yb, which was conducted in the Los Alamos National Laboratory at the end of 2001, continued.

1.3.4 Measurement of gamma-spectra for separate resonances of tantalum

In cooperation with the University of Lodz (Poland) experiments aimed at finishing of the measuring technique of gamma-spectra for separate resonances of tantalum were performed. An original idea to use a very thick sample, which would suppress the background due to the spectrometer itself within the limits of the investigated resonance, has made it possible to reduce the background due to gamma-quanta from neutron capture in the Germanium detector by an order of magnitude and for the first time to measure gamma-spectra of radiative neutron capture for several resonance of Ta by measuring the slowing down time in lead with the help of a neutron spectrometer.

1.4 Astrophysical aspects of neutron physics

1.4.1 Measurement of the neutron capture cross section of the isotopes ^{22}Ne, ^{30}Si, ^{40}Ar, ^{78,80,84,86}Kr at astrophysical energies

Processing of the experimental data completed and analysis of the results of joint FLNP JINR - Forschungszentrum Karlsruhe experiments was carried out under the program of nuclear data for astrophysics. The experiments were conducted at the Van de Graaff accelerators in Karlsruhe and Tubingen, Germany. The reactions ^{7}Li(p,n) and T(p,n) were used as a source of neutrons. The capture cross sections of isotopes were determined by the activation method. The cross sections for the neutron energy interval 25 – 215 keV were obtained. On the basis of the obtained data and available data on resonance parameters the Maxwell spectrum average capture cross sections were obtained for the temperature range corresponding to kT = 1 – 250 keV. In a number of cases, the new values differ appreciably from those recommended for astrophysical calculations (see **Fig. 7**). A qualitative analysis of the possible influence of the new data on various astrophysical scenarios of the production of elements was performed.

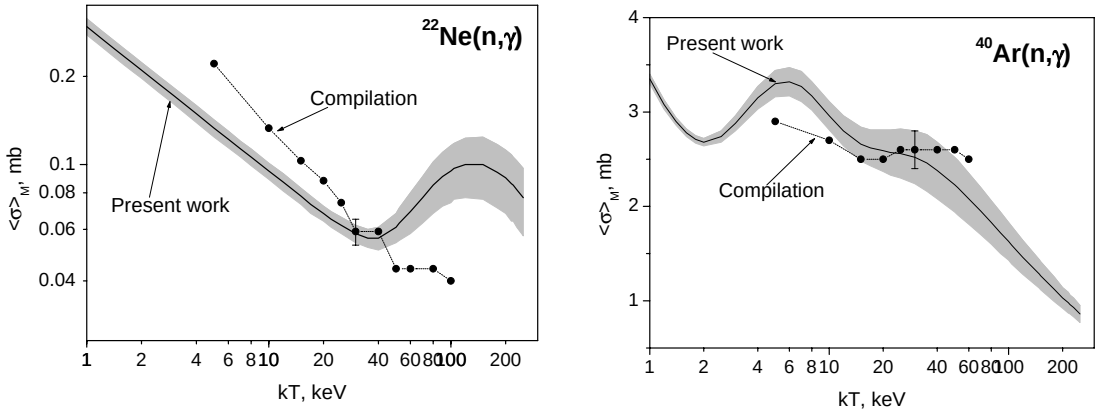

Fig. 6. *The Maxwell distribution average cross sections obtained in this work in comparison with the recommended data.*

1.4.2 Modeling of neutron nucleosynthesis in the region of sulphur and chlorine in the stage of hydrostatic burning of massive stars

Work to model different scenarios of nucleosynthesis continues in cooperation with members of the University of Lodz, Poland. The earlier developed program for the calculation of neutron nucleosynthesis in the stage of hydrostatic burning of helium in stars with a mass of 25 $M_{\odot}$ is extended to the next stage of hydrostatic burning of carbon. The program is complemented with the possibility of determination of integral fluxes of reactions, analysis of branching points and contributions of the branches to the production of isotopes. Analysis of the formation of elements in the region S-Cl-Ar was performed accounting for the new data on neutron cross sections obtained for a number of isotopes. The dependence of the concentration of elements from the discussed region in the stage of He- and C-burning on time is calculated.

1.5 Fast neutron-induced reactions accompanied with emission of charged particles

The modernization of the detectors, electronic equipment and fast neutron channels at EG-5 in FLNP JINR started. The characteristics of the fast neutron beam with neutron energies from 3.5 to 6.5 MeV from the reaction d-D were studied. Another deuterium gas target as well as a lithium and a tritium targets will be created.

Under development is a technique of measurements of light nuclei whose investigation has a number of peculiarities and thus, the problem cannot be solved using the methods that were successfully applied to study nuclei of middle mass.

Two more problems, an understanding and separation of the background and correct accounting for distortions in the energy spectrum of the neutron source, are being solved.

When the chamber is irradiated with a fast neutron flux, in addition to signals from the charged particles from the investigated reaction and background reactions on construction materials there are also registered signals from the charged particles arising in the working gas. For the preparation of the experiment and the following procession of the results it is necessary to know to which region of the two-dimensional amplitude spectrum ($P_{Ан} \times P_{Kam}$) signals from the charged particles from the reaction of interest will come. To serve the purpose, a complex of programs modeling the processes going in the chamber has been developed.

For the purpose of a detail comparison of spectra obtained in the measurement and identification of particles, the spreading of signals due to the resolution power of the detector and changes in the energy of α-particles due to transmission through a substance layer of finite length as well as neutron energy spreading in the initial spectrum were taken into account in the calculation.

To this end, a program, which models the emitted neutron spectrum for a van de Graaff accelerator-based source, was written. Changes in the neutron spectrum due to transmission through a substance were calculated by the program MCNP. The experimental data obtained for the reaction $^{64}Zn(n,\alpha_0)^{61}Ni$ at the neutron energy E_n=5 MeV and the gas pressure Kr+4.71% CH_4 1.2 atm are in good agreement with the model calculation. In the future, to test the correctness of the calculation, measurements of neutron spectra will be carried out at EG-4,5 in Peking University.

Work to build a measuring module for multiparameter measurements (with the prospect of using it at IREN) started in cooperation with physicists of the University of Lodz.

1.6 Nuclear data program

1.6.1 Investigation of the resonance structure of the neutron cross section of fission fragment and fissionable materials

In 2002 processing of the time-of-flight spectra of *Nb, Mo, Pb,* ^{235}U, ^{239}Pu sample-filters measured earlier on the flight paths 122 m, 501 m or 1006 m of IBR-30 using multi-section detectors of neutrons and gamma-rays continued. After subtracting the background total and partial neutron group cross sections, resonance blocking factors of the total cross section and the scattering cross section of *Nb, Mo* and *Pb* in the energy range 0.100 eV to200 keV were determined from the time-of-flight spectra. The experimental error of cross sections and blocking factors is 3-7% and 8-15%, respectively. Analogous values were calculated on the basis of the estimated data from various libraries by the program GRUKON. On the whole, the calculated and experimental data coincide but in some energy groups, discrepancies are outside the experimental error limits.

For uranium-235 and plutonium-239 alpha values ($\alpha=\sigma_\gamma/\sigma_f$) in resolved resonances for the energy interval 1-1200 eV and in energy groups 20 eV - 10 keV were determined from the time-of-flight spectra of different coincidence multiplicity gamma-rays after subtracting background components. In addition, the Doppler effect in the value of alpha was **first** studied for plutonium-239 at the temperature 293 K and 77 K. The experimental error of the alpha value is from 2 to 30% in dependence on its resonance peculiarities. Alpha values were also calculated on the basis of the estimated data from various libraries by the program GRUKON. The difference between the calculated and experimental values reaches 50% in some resonances and energy groups.

1.6.2 Total neutron cross section measurements

Under a FLNP JINR – PAL (Pohang Accelerator Laboratory) POSTECH (Pohang, Republic of Korea) collaboration the total neutron cross sections of Ag, Cu, Sm, In, Dy (natural mixture of isotopes) were measured. For Ag and Sm there were obtained the parameters of neutron s – wave resonances in the region 0.1 – 80 eV and for Sm and In similar parameters were obtained in the region up to 10 eV.

The measurements of the total neutron cross sections were performed on a vertical neutron channel in PAL by the time-of-flight method. The flight path was 10.8 m. In the experiments a mechanism for automatic replacement of samples developed and built in FLNP JINR (see **Fig. 8**) was used. The mechanism allows carrying out measurements of four samples, which are introduced in turn into the neutron beam. The inaccuracy of sample position fixing in the beam is less than 1 mm.

Neutrons were registered with the scintillation detector BC702/5 of Bicron Corp., (ZnS(Ag)) enriched with ^6Li. To separate neutrons from gamma-rays (see **Fig. 9**), a scheme of n - γ separation created in 2001 on the basis of standard blocks produced by the company EG&G ORTRC was used. The scheme allows almost complete separation of pulses due to neutrons from those due to gamma-quanta with respect to the back front duration loosing not more than 15% of neutrons.

The total cross section data for Sm and In was processed in KAERI (Korean Atomic Energy Research Institute). The data for Ag and Sm were first processed in PAL by the program SAMMY-M2 and then sent to KAERI for possible further processing and inclusion into the neutron cross section library.

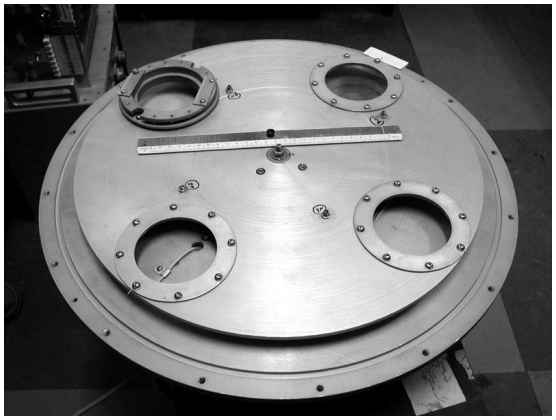

Fig. 7. *The mechanism for sample replacement, the hermetic jacket being removed.*

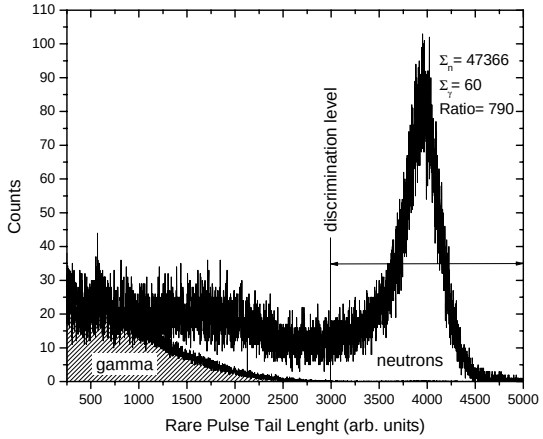

Fig. 8. *Separation of pulses due to neutrons from those due to gamma-quanta with respect to the form (duration) of the back front. The arrow shows the length interval of the back front pulses transmitted through the scheme to accumulate time spectra.*

1.7. Fundamental properties of the neutron

1.7.1 Investigation of the neutron charge radius

In the traditional research directions of the Scientific Experimental Division of Nuclear Physics (SEDNP) in FLNP investigating the electric polarizability and the mean square charge radius of the neutron in 2002 much attention was given to the study of the charge radius determined by the n,e-scattering length b_{ne}. Since the situation with the experimental values of b_{ne} is quite ambiguous (there exist several dozens of values within an accuracy of $(0.03 \div 0{,}05)\cdot 10^{-3}$ Fm that group around $\sim -1.3\cdot 10^{-3}$ Fm and $\sim -1.6\cdot 10^{-3}$ Fm), it is very important to improve measuring methods and seek errors in the applied techniques.

It is suggested that b_{ne} should be measured using the forward-backward scattering asymmetry of neutrons in argon determined by the time-of-flight method for different neutron energies. The total cross section of argon was determined for the neutron energy interval ~5 eV to 30 keV and all known cross sections of Ar and ^{36}Ar for the energies beginning from thermal energies were analyzed. This allowed obtaining of a record accuracy of the nuclear scattering coherent length to total nuclear scattering cross section ratio

$$a_{coh}^{N} / \sigma_{s}^{N} = (0.0287 \pm 0.0001)\ \text{Fm}^{-1}$$

for natural argon. It is necessary for a reliable extraction of b_{ne} from the results of future experiments.

A careful analysis of the results of the study of neutron scattering on noble gases by Krohn and Ringo, which has become a classical work, has revealed appreciable dependence of the observed scattering asymmetry on the pressure of krypton and xenon varied from 0.4 to 1.2 atm in [3]. This is very likely due to not accounting for the effect of neutron diffraction on a single-atom

gas. Krohn and Ringo's $b_{ne} = -(1.34 \pm 0.03) \cdot 10^{-3}$ Fm must be changed for $b_{ne} = -(1.24 \pm 0.06) \cdot 10^{-3}$ Fm if the discovered effect is taken into account. The question of neutron diffraction on a gas is thus of great importance and need to be studied carefully.

1.7.2 Experiments of direct measurements of the neutron-neutron scattering length at the pulsed reactor JAGUAR (Snezhinsk)

As part of the experiment preparation theoretical modeling of the processes of neutron-neutron collision in the central channel of the reactor, neutron scattering on a calibration gas and of neutron radiation propagation in the neutron channel continued.

The experimental data on the thermal neutron output from the different thickness moderators are in agreement with the modeling results. From the modeling it follows that the angular distribution parameters correspond to the isotropic source used in the analytical calculation of the number of collisions and the detector's counting rate.

The spatial distribution of thermal neutrons along the Z-axis of the channel is sensitive to the distribution of the reactor construction materials, which is also, though slightly, sensitive to the situation of the moderator relative to the center of the liquid active zone and changes as the level in the zone changes. The modeling of both reveals a distribution asymmetry similar to that observed in activation measurements.

The calculated energy spectrum of thermal and epithermal neutrons is in agreement with the conducted measurements. The model distribution of the flux density has a section of epithermal neutrons proportional to 1/E and a Maxwellian distribution of thermal neutrons with a most probable energy of 26 meV. The interrelation of the two parts of the spectrum corresponds to activation measurements.

Analytical calculation of the neutron field inside a through channel of the reactor was performed. The results on the neutron density agree with those of the modeling of the spatial neutron density distribution in the reactor by the Monte-Carlo method. The number of *nn*-collisions in the channel and the angular distribution of neutron scattering in the laboratory system of reference are calculated. The number of events of neutron scattering on the neutron and on calibration gases is calculated. The calculation is done for the Maxwell distribution of neutrons in velocity without taking into account possible contribution of epithermal neutrons and the effect of the nonstationary stage of neutron moderation.

Work to prepare the physical environment of the reactor necessary for carrying out the experiment started. An insert tunnel of 10 m to host the neutron channel and the detector was manufactured.

1.7.3 Neutron decay-related investigations (lifetime and correlation coefficient)

Several hydrogen-free fluoropolymers with a low melting temperature were investigated as to their possible use as a wall material of ultracold neutron traps with low neutron losses. Their viscosity at 150-300 K and neutron cross sections at 10-300 K for the neutron wavelengths 1-20 A were measured. Conclusions about their possible parameters as a material for ultracold neutron traps were made. The quasielastic reflection of neutrons from the surface of a viscid liquid is investigated in the framework of the Maxwell model and on the basis of PINP's published experimental results on UCN quasielastic scattering quantitative conclusions about the dynamical parameters of the liquid – rigidity and relaxation time – are made. This has formed a basis for joint experiments with the Univ. of Rhode Island, Harvard Univ., PINP, ILL, and Kyushu Univ. to investigate UCN quasielastic scattering on such liquids at low temperatures. Promising results were obtained giving hope to improve measurements of the neutron lifetime at their storage in traps.

The mechanisms of ultracold neutron depolarization in traps at their reflection from the walls are investigated. The first involves spin-flip at elastic or quasielastic scattering on hydrogen-bearing surface admixtures. A second says that appreciable neutron depolarization may occur even

at high adiabatic parameters in the process of neutron movement in an inhomogeneous magnetic field due to sharp changes in the neutron trajectory caused by neutron reflection from the walls.

1.8 Physics of ultracold neutrons, neutron optics

1.8.1 Investigation of supersmall energy transfer processes at interaction of ultracold neutrons (UCN) with solid body surfaces

Studies of the processes of small UCN energy transfer in the Large Gravitational Spectrometer (LGS) continued. LGS allows simultaneous observation of the stored UCN neutrons and the forming "excited" ultracold neutrons (EUCN) and enables the registration of EUCN over the energy range 50-150 neV with an effectiveness of ~50%.

In the reported year the differential spectra of EUCN and their dependence on the UCN spectrum for a stainless steel sample were obtained using the new facility. The temperature dependence of the probability of weak heating on samples from stainless steel, copper, and diamond nanopowder is obtained for the temperature range from 300K to 100K. The characteristic dependence of the weak heating probability on the surface of an A304 stainless steel sample on the temperature of preliminary degassing is obtained.

A pronounced process of weak UCN heating has been discovered for a sample of ultradisperse diamonds with a mean size of 50Å and no heating has been observed on the surface of a sapphire monocrystal within the sensitivity of the facility.

Additional investigations with a microscope of atomic forces showed changes in the nanostructure of the surface of the A304 stainless steel sample depending on the degassing temperature and the absence of surface nanoformations on the sapphire monocrystal.

The results obtained under the project point to the fact that the nature of weak UCN heating on solid body surfaces is connected with the interaction of UCN with surface nanoformations. The obtained results are an experimental indication of the possibility of building a fundamentally new high density UCN source based on the thermolization of cold neutrons due to nanostructures. It is the first time that the fundamental possibility of studies of the dynamics of nanostructures with the help of UCN was demonstrated using the built facility.

1.8.2 Development of high-resolution differential UCN spectrometry

Experiments to develop the differential spectrometry of superlow energy neutrons by the time of flight employing the mechanic and magnetic modulation of the neutron flux in the pseudorandom mode were prepared and conducted.

The geometry and method for the measuring of spectra of the quasielastically reflected neutrons at energy transfers in the interval up to 200 neV and small scattering probabilities were proposed. The method involves the use of a threshold detector displaceable in the gravitational field. The achievable energy resolution is 3-5 neV. The Monte-Carlo modeling of the spectrometer operation was carried out.

2 Theoretical investigations

2.1 Theoretical investigations in reflectometry of multilayer systems

There is jointly proposed the new method of the preparation of supermirrors that increases the total neutron reflection angle. The supermirror is designed as a combination of several periodical systems of bilayers with overlapping Bragg peaks. Such a system is analyzed analytically and the number of layer thickness chains and the number of periods in each chain are determined. The case when the critical angle increases 3.2 times is calculated. The calculation is done for an ideal system with and without accounting for losses in the layers. It is shown that to increase the critical angle 2 times, it suffices to have 12 chains and not more than 46 bilayers.

An analytical approach to the processing of the experimental data on thin film reflectometry taking into account smooth transitions at interfaces has been developed.

2.2 Problem of baryon charge nonconservation and search of neutron-antineutron oscillations with the help of ultracold neutrons

The influence of the neutron collision with the wall on the process of neutron to antineutron transition was investigated and a comparison of the search effectiveness of neutron-antineutron oscillations in beam experiments and in experiments with ultracold neutrons is performed. The conditions in which the effectiveness of ultracold experiments could be higher than that of beam experiments by 2 orders of magnitude are outlined.

2.3 Investigation of weak one-nucleon interaction to P-odd nucleon-nuclear potentials and of spin effects in nuclear reactions

Theoretical investigations of the weak one-nucleon Hartry-Fock potential V_W^{HF} constructed on the basis of the weak *P*-odd *NN*-interaction continued. It is shown that the corresponding Hartry terms and the Fock terms of a zero order have a pronounced surface character. The indicated surface terms of the potential V_W^{HF} were calculated for the nuclei ^{208}Pb and ^{40}Ca on the basis of a characteristic set of weak *NN*-forces.

The relationship between the cross section of the charge-exchange break-up of the deuteron $d + a \to (pp) + b$ and the differential cross section of the nucleon recharge reaction $n + a \to p + b$ was investigated. The dependence of the differential cross section of the process $d + p \to (pp) + n$ in the direction "forward" on the polarization parameters of the deuteron and proton was investigated. The influence of the *D*-wave state of the deuteron on the polarization effects and the spectrum of relative momentums of two protons were analyzed for the process $d + p \to (pp) + n$ in the direction "forward".

The transformations of the components of the correlation tensor in a system of two particles with spin 1/2 at transition of the pair of particles from the center of mass to laboratory system of reference were investigated taking into account the relativistic effect of spin rotation.

2.4 Theoretical investigations of neutron β-decay

In the framework of the Standard Model radiative corrections to the β-decay of the neutron were calculated. The electroweak interactions were consistently taken into account in accordance with the Weinberg-Salam theory. The effect of strong interactions is parametrized by introducing the quantities g_A, g_V, g_{WM} … as in the theory of β-decay by Fermi. The radiative corrections to the decay probability W and the distribution asymmetry coefficient of electrons A are $\delta W = 8\%$ and $\delta W \approx -2\%$, which is essential for the extraction from the experimental data of the weak theory characteristics, particularly of the element V_{nd} in the matrix CKM.

2.5 Calculation of hypernuclei formation cross sections

The calculation of the cross sections of the formation of the neutron-excess hypernuclei $^{12}_{\Lambda}$Be, $^{16}_{\Lambda}$C, and $^{10}_{\Lambda}$Li in the reactions (π^-,K^+) and (K^-,π^+) together with accounting for two possible formation mechanisms of such systems continued. The first is a two-step process with recharging (for example, $\pi^-p \to \pi^0 n$, $\pi^0 p \to K^+\Lambda$). The second is the one-step reaction of the formation of Σ^- admixtures ($\pi^-p \to K^+\Sigma^-$) taking place in Λ-hypernuclei due to ΛN-ΣN mixing. In the majority of cases the two-step process appears to be more productive. The differential cross section for a zero angle in the reaction $^{10}B(\pi^-,K^+)^{10}_{\Lambda}Li(2^-)$ is about 70 nb/sr for the pion pulse 1.05 GeV/c. The estimation was made in connection with the staging of the corresponding experiment in KEK

(Tsukuba, Japan) in October, 2002. A preliminary analysis of the experimental data has only yielded an estimate of 10 nb/sr.

3. Analytical investigations at the IBR-2 reactor

3.1 Ecology

In 2002 work to study atmospheric depositions of heavy metals by the biomonitoring technique, NAA and GIS technologies (REGATA project) over the territory of Central Russia (Tver, Yaroslavl and Northern Moscow regions) as well as a number of European countries (Bulgaria, Slovakia, Romania, Ukraine, Poland, Serbia, Bosnia) continued. The results of the investigations are contributed to the European Atlas published under UN. Analogous works are being carried out in South Korea, China, Macedonia and Turkey. In November 2002 the IEAE project for investigations in the Southern Ural region, whose goal was the assessment of the contamination of the Chelyabinsk region with heavy metals and radionuclides completed having analyzed over 1500 analyzed.

Work to investigate the contamination of soils with heavy metals and other toxic elements due to over-the-road transport (Minnesota, USA) completed having analyzed 200 samples. A total of 250 air filters were analyzed to study the air quality in the tube in London. The method of fluorine identification in air filters was tested at IBR-2 for the first time. In cooperation with the Geological Institute, RAS there was carried out a comparative analysis of the element composition of a number of food products grown in the condition of strong antropogenic influence in the deltas of the Volga and the Nile (Egypt) (300 samples).

In 2002 the first stage of the project «Monitoring of Workplaces and Health of Personnel Engaged in Phosphor Fertilizer Production at Plants in Russia, Uzbekistan, Poland, and Romania» (European Program 5 Copernicus) completed. The results of an analysis of ecological samples, including raw materials, soils, sediments, water, and filters, and of human biosubstrates like hair, nails, urine, and teeth, were discussed by the participants of the project at meetings in Dubna and Gdansk.

3.2 Materials science

The impurity elements content of 300 samples of diamonds artificially grown in the Institute of Solid State Physics and Semiconductors of the National Academy of Sciences of Belorussia in Minsk was studied. Also, samples of superpure silicon developed by the Institute of Crystallography in Moscow were irradiated. An analysis of 20 archeological ceramic samples from Romanian museums was carried out what will allow the determination of their origin.

3.3 Biotechnologies

The work carried out in cooperation with a group of biophysicists from the Institute of Biophysics of the Academy of Sciences in Georgia to develop pharmaceuticals based on the blue-green alga *Spirulina platensis* continued. The NAA method was applied to study the composition of the pharmaceuticals extracted from the spirulina biomass (DNA and C-phycocyanin). The peculiarities of the interaction of the microalga with Cr(III) and Cr(VI) and of a combined effect of chromium and selenium on the spirulina were studied.

In 2002 investigations of the composition and behavior of another microorganism – *Arthrobacter oxidants* – with the aim of studying the possibility of its application for the purposes of biotechnology started.

Together with Tbilisi Technical University we completed a cycle of works to substantiate the use of peat suspensions for bacterial leaching out of some metals from rocks, ores, and industrial wastes as well as the application of natural sorbents (tea, moss, etc.) for the extraction of metals from the leached solutions.