1.3. NEUTRON NUCLEAR PHYSICS

1.3.1. TECHNICAL PROJECTS

The decision to create a new pulsed source of resonance neutrons, IREN, and the startup of realization of this project, stimulated the active work of nuclear physicists to update the existing and to develope novel techniques for experiments in sectors traditional for FLNP.

After a prolonged delay due to insufficient financial support, full-scale realization of the UGRA project began for measurement of the neutron electric polarizability. Implementation of the UGRA project is under way in collaboration with the Institutes of Nuclear Research in Kiev (Ukraine) and Rez (Chekhia), and with the Technical University of Munich (FRG). A large-scale vacuum multidetector chamber is under construction for measurement of neutron angular distributions in elastic scattering. Two new types of neutron detectors have been created and tested for this chamber. At the same time a series of technical issues has been investigated with a prototype of the UGRA setup. For example, new data have been obtained on the contribution of p-wave neutron scattering on heavy nuclei. Assembly of the chamber in the experimental hall and its tests are scheduled for the end of 1994. The setup should be ready by the startup of the new pulsed neutron source, IREN.

Good facilities for studying short-lived fissioning isomers and delayed fission neutrons in the millisecond region are provided by a new device installed on beam N 11 of IBR-2, that was commissioned in 1992. Test experiments revealed the necessity of modifying the device, which was done in 1993. For instance a new chopper was constructed and installed on the neutron beam. On-beam adjustment of the device was performed. In 1994 measurements will be carried out with samples prepared at NIIAR.

Preparation has been started in collaboration with Physics-Power Engineering Institute (Obninsk) for measurements of the energy and angular dependences of emissions from fission fragments at resonances with an aligned ^{235}U nuclear target. The first version of the target was installed on beam N 5 of the IBR-30 booster. Tests of the target permitted the choice of the final target construction. In 1993 it was realized, and complex adjustment of the setup was performed. The first measurements were carried out for the (n, f)-reaction with the ^{235}U nucleus. The setup is ready for data taking in 1994.

An experimental setup is being created for measuring the p-odd asymmetry of γ-quanta emission from the reaction $^{10}B(n, \alpha)^{7}Li^{*} \rightarrow {}^{7}Li+\gamma$ in the high intensity beam of polarized thermal neutrons at the St.Petersburg Institute of Nuclear Physics (Gatchina). Measurements are scheduled for the second half of 1994.

The ROMASHKA setup has been updated for the investigation of γ-quanta multiplicities in decays of neutron resonances. It comprises neutron detectors with a 2π-geometry, which will permit significant improvement of the accuracy in extracting the parameters of neutron resonances.

Much work has been carried out for mathematical simulation of the experiment and of a series of parts of the setup intended for the first straightforward measurement of the neutron-neutron scattering amplitude at the BIGR reactor (All-Russian Research Institute of Experimental Physics, Arzamas).

1.3.2. EXPERIMENTAL STUDIES

During the period covered by the report, implementation continued of the program fixed earlier of experimental studies of the fundamental properties of the neutron, of parity violation in the interaction of slow neutrons with nuclei, neutron resonance decay channels, etc. Studies were performed at the FLNP JINR pulsed neutron sources, IBR-2 and IBR-30, and also at neutron sources of a number of other world nuclear centers (PINP, Gatchina; INR, Kiev; Oak Ridge and Los Alamos, USA; Garching, FRG; Beiging, China, Geel, Belgium).

The FLNP-PINP-VNIIEF-TU (Munich)-INR (Ukraine) collaboration continued, examining the issues of electric polarizability within the framework of the research program for investigating the electromagnetic properties of the neutron. Measurements were performed of the energy dependence of the total neutron interaction cross section with the nucleus of the lead isotope ^{208}Pb. Their analysis revealed that the neutron coefficient of electric polarizability strongly (up to a change in sign) depends on the neutron-electron interaction amplitude chosen for the calculations. Since the values of this amplitude derived from various experiments differ by several standard deviations, new approaches are necessary to this problem. One such approach involves precise measurement of the total cross section for the lead isotope indicated in filtered neutron beams. These measurements were initiated at the reactor of the INR of the Ukrainian Academy of Sciences in 1993. The first experiments demonstrated the feasibility of achieving the required precision. Great difficulties are encountered, unfortunately, in providing the resources required for operation of the reactor in Kiev.

Another fundamental characteristic of the neutron is its lifetime τ_n relative to β-decay. In the FLNP report covering 1991, joint measurements of τ_n at the KOVSH setup were announced by the Dubna-Gatchina collaboration. The precision achieved in measuring τ_n amounted to about 0.3%. Here an anomalous leakage of UCN was observed, which exceeded by a factor of over 100 the theoretical estimate derived from experimental data obtained with very cold neutrons (VCN). To investigate the reasons for such leakage, an activation technique was developed for measuring the spectra of neutrons produced in inelastic interactions of UCN with the surface material of the vessel. The technique was tested at the UCN channel in Gatchina with materials exhibiting record low absorption coefficients (10^{-5}-10^{-6} per collision). At the same time, modernization of the KOVSH-2 setup was completed. It was ready for the experiment, but it was not possible to start experiments in 1993, because of difficulties in putting the new UCN channel in operation at the VVR-M reactor in Gatchina.

Precise measurement of τ_n is one of the purposes of the new project that is being developed jointly by FLNP and VNIIEF (Arzamas). Design and construction have been completed of the ISPIN setup, which will permit realization of a new method for obtaining, extracting and utilization of superdense (about 10^5 cm^{-3}) UCN gas from the BIGR aperiodic pulsed reactor. Estimates show that when the expected parameters of the setup are achieved, it will be possible to measure τ_n with an accuracy higher than 0.3%. However, since the safety requirements at BIGR have become more stringent, the construction of the setup must be modified. This will result in a delay of the first experiments until 1995.

Essential development took place of the program for studying parity violation and time invariance in neutron induced reactions. New results have been obtained on violation of space parity. The Dubna monoisotopic ^{113}Cd sample was used in a joint Dubna-Geel experiment, in which measurements were performed of the spins of p-wave neutron resonances observed earlier by FLNP physicists. Then, the same sample was used for measuring p-odd effects in neutron transmission with the wide aperture spectrometer of resonance neutrons, LANSCE, at Los Alamos. A preliminary analysis of the first series of joint measurements, that relied heavily on data relevant to the spins of p-wave resonances, seems to indicate an absence of the sign coherence of p-odd effects observed earlier for thorium and uranium nuclei. Experiments with the ^{113}Cd sample will be continued considering the sign anomaly to be essential for understanding the nature of space parity violation in nuclei.

The obtained information turned out to be very useful in planning future experiments for studying the effects of p- and t-parity violation. A special monocrystalline ^{165}Ho sample was made at Duke University for investigating the violation of t-invariance. The depolarization of neutrons in the sample must be known with a high accuracy before the main measurements can be initiated. To this end the POLYANA spectrometer of polarized neutrons and nuclei has been modernized, and a new cryostat has been created for alligning the nuclei in the ^{165}Ho sample. The first stage of measurements were performed at the IBR-30 booster by the FLNP-Duke University-LANL collaboration. Analysis of the results points to a significant (up to 300%) angular dependence of the depolarization effect (Fig. 22), which requires correction of the technique for the planned measurement of the t-odd five-vector correlation between the spins of the neutron and nucleus and the neutron momentum.

Also with the POLYANA setup, and using a record-breaking (1.5 kg) polarized ^{139}La sample, a measurement was made of the transmission cross section for polarized neutrons (Fig. 23). The energy dependence, necessary for analyzing p- and t-odd effects to be studied at Dubna and Gatchina, was obtained for the polarization cross section.

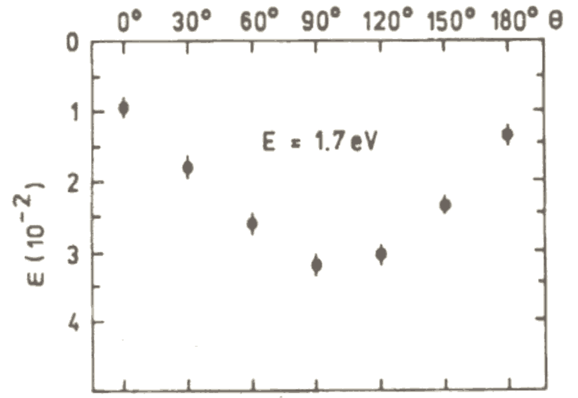

Fig. 22. Angular dependence of the transmission effect ε due to depolarization of neutrons in a holmium monocrystal for various orientations of its c- axis.

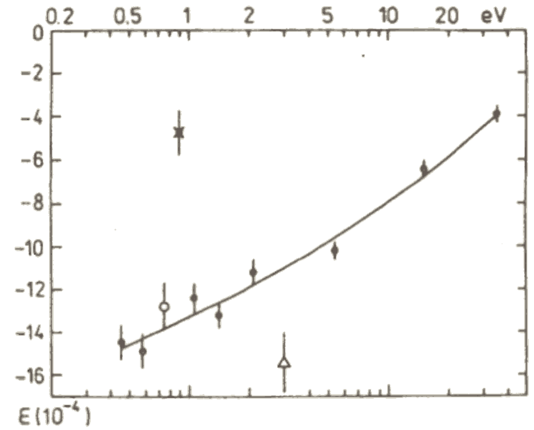

Fig. 23. Transmission effect ε of polarized neutrons through a polarized lanthanum target. The open circle represents the 0.74 eV resonance (^{139}La), the triangle - the 3.0 eV resonance (^{138}La), the cross - the 0.87 eV resonance (mixture of ^{149}Sm in La target), black dots indicate the region of smooth dependence of the ^{139}La cross section, due to a strong negative resonance.

Closely related to the above topic are the joint studies carried out by the Dubna-Gatchina collaboration at the PINP high-intensity beam of polarized thermal neutrons for observing parity violation in reactions involving emission of charged particles. The p-odd asymmetry a_{pnc} was measured in the $^{10}B(n, \alpha)^7Li$ reaction. The upper limit of the effect, significant from the point of view of theory, was derived from experimental data for α_0-lines - $a_{pnc} = (3.4 \pm 6.7) \cdot 10^{-7}$ and the α_1-line - $a_{pnc} = (-2.4 \pm 1.6) \cdot 10^{-7}$.

A series of interesting new results was obtained in traditional neutron spectroscopy. Studies of amplified (by factors of up to ten) electromagnetic transitions between highly excited states, which are most likely related to the fragmentation of single-particle 4S- and 4P-neutron shells into states participating in gamma transitions, were continued with a number of even-even nuclei in the vicinity of ^{158}Gd using the CASCAD setup. A joint analysis of experimental data on (n, γ)- and (n, 2γ)-reactions for the ^{187}W nucleus resulted in obtaining a record-breaking, from the point of view of completeness, scheme of levels including the 1.5-3.5 MeV excitation energy interval, not previously studied. The radiation strength functions of primary dipole γ-transitions of the discharge cascade of the capture state were obtained for $^{137,\,139}$Ba and ^{181}Hf nuclei. For these nuclei, like for the nuclei studied previously, the radiation strength function was established to depend on the temperature of the excited nucleus.

Measurements of the cascade γ-radiation were performed for the ^{170}Yb nucleus produced after the β-decay of ^{170}Lu. This allowed an essential correction of the known scheme of levels (Fig. 24) obtained by traditional methods of precision nuclear spectroscopy. This experiment revealed the existence of new possibilities in this field.

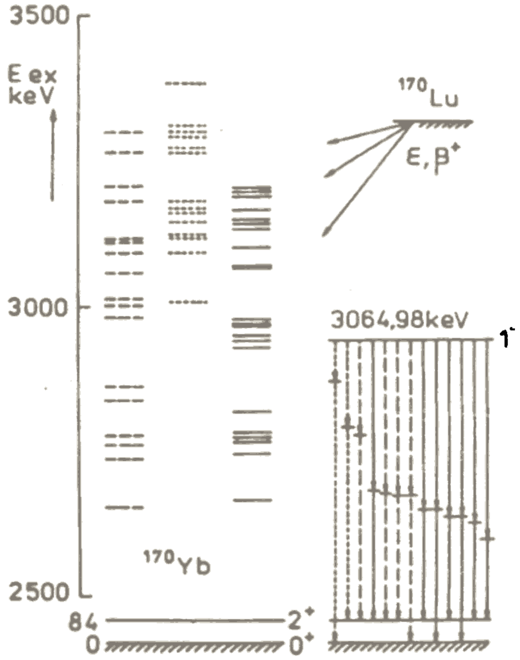

Fig. 24. Scheme of the levels of ^{170}Yb: ------ - previously known levels confirmed by this work; - - - - not confirmed levels; — — -- - newly discovered levels. At the right - example of analysis of two-quantum gamma-transitions from the 3064.98 keV level of the ^{170}Yb nucleus. The notation is the same.

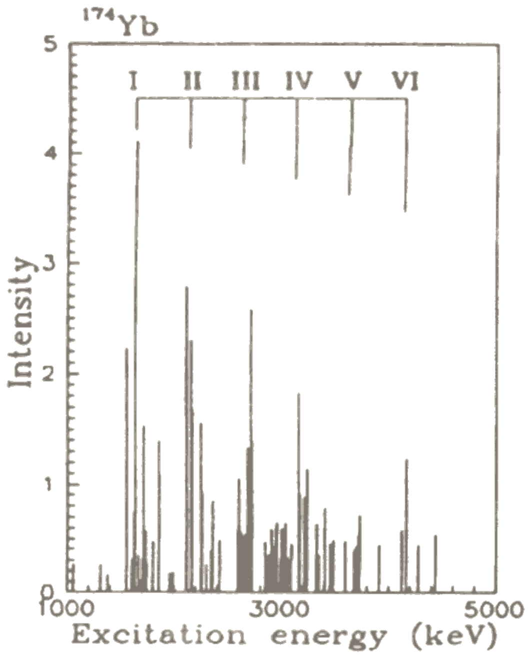

Fig. 25. Dependence of absolute intensity of two-quantum cascades to the first excited state of ^{174}Yb on excitation energy. The Roman numbers indicate probable groups of equidistant states.

The two-step γ-cascades measured earlier at FLNP for twenty target nuclei in the $114 < A < 187$ mass interval were analyzed with the aim of revealing intense γ-transitions between approximately equidistant excited levels (Fig. 25). A conclusion was made concerning the possible existence in heavy nuclei of groups of excitations of the vibrational type with a characteristic energy interval E = 500-800 MeV. For confirmation of this conclusion measurements must be performed at a number of neutron resonances, which requires a significant (and expensive) enhancement of the luminosity of the existing spectrometer. Certain progress is expected in 1994, should the new gamma spectrometers ordered in Krakow arrive.

Measurements of the multiplicity distribution of γ-quanta after radioactive capture of neutrons by $^{147,\,148,\,149}Sm$ nuclei, that were started earlier with the aid of the ROMASHKA setup (a 4π-detector based on NaJ(Tl) crystals), have been completed. New data have been obtained on resonance parameters. For example, a unique set of data on the total radioactive widths has been determined for ^{149}Sm (Fig. 26). Similar measurements have been carried out for the $^{176,\,177,\,178}Hf$ isotopes, but have not been processed yet.

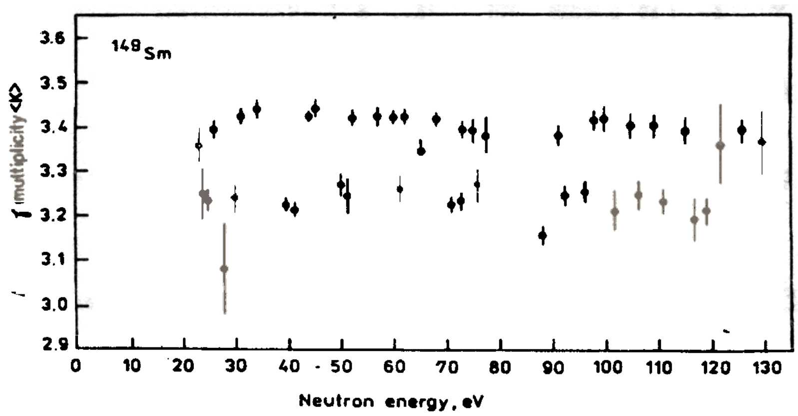

Fig. 26. Dependence of average multiplicity on neutron energyin the radiative capture of neutrons by ^{149}Sm

Studies have continued of reactions induced by neutrons on stable and radioactive isotopes and involving the emission of charged particles. Results were obtained in measurements of (n, p)-reactions on the radioactive target nuclei ^{36}Cl and ^{49}V, carried out by the Dubna-Gatchina group and by the Dubna-Los Alamos collaboration with the aid of the technique developed at FLNP.

Processing has been completed of measurements of the $^{36}Cl(n, p)^{36}S$ reaction that plays a key part in the production of the ^{36}S isotope, which, in turn, essentially affects the branching of the fast and slow processes of nucleosynthesis in stars. Analysis of the energy dependence of the cross section (Fig. 27) within a wide range of neutron energies (up to 800 keV) has required the application of multilevel multichannel formalism. The calculated ^{36}S production reaction rate turned out to be two times lower than the rate utilized previously in calculations, which permits significant difficulties in the theoretical description of the S-process of nucleosynthesis to be overcome.

Earlier, measurements were reported of the spectra of prompt γ-quanta from fragments produced in the fission of the ^{240}Pu compound nucleus. Processing of these measurements has been completed. Data have been obtained on the variation of independent yields of fragments produced at a level >-1% in the neutron resonances of ^{239}Pu, and the yields and lifetimes of the isomer fragments have been determined. Within a 5% precision, the conclusion has been made that fission from the compound state of spin 1^+ is single-channeled. Indications have been obtained that the integrated yield of fragments is dependent upon the fission resonance width. Multiplicity measurements have been carried out of prompt γ-quanta from ^{233}U, ^{235}U, ^{237}Np and ^{239}Pu fission resonances.

Measurements have been completed and analyzed of the neutron induced fission cross section for the ^{237}Np isotope, which is important in the problem of transmutation of the minor actinides. The results permitted the removal of a previous contradiction between the data of different groups (Fig. 28).

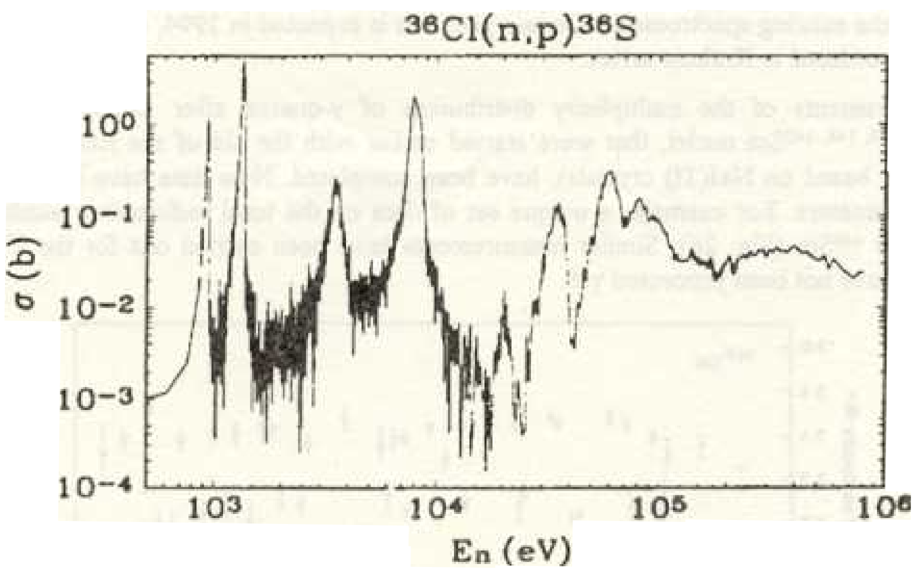

Fig. 27. Dependence of $^{36}Cl(n, p)^{36}S$ reaction cross section on neutron energy.

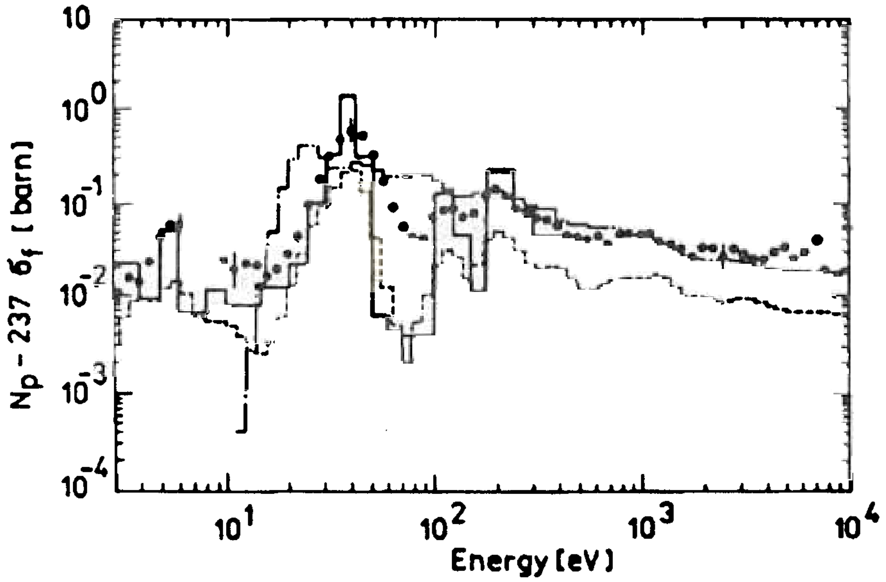

Fig. 28. Comparison of fission cross sections σ_f for ^{237}Np measured in Saclay (dashed line), for neutrons from an underground nuclear explosion (dot-dashed line), on the lead cube of the Kyoto university (black dots) and at FLNP (solid line)

Completion of the above indicated studies turned out to be possible due to RFFI grants, and to the contribution of collaborants from Poland, Chekhia, Slovakia, USA, and the Netherlands.

1.3.3. THEORETICAL INVESTIGATIONS

Theoretical work in fundamental nuclear physics continued in a number of sectors.

Calculations were performed of the electric polarizability α_n of a free neutron and of a neutron bound in nuclear matter. The resulting values of α_n are in quantitative agreement with existing experimental estimates. Meson (π, ρ and ω) degrees of freedom have been shown to be essential for describing nuclear matter, especially in the case of high densities and temperatures. Dense nuclear matter has been investigated at a temperature $T \sim (1\text{-}2)\ m_\pi$. The change in the pion spectrum of such a gas, as compared with the spectrum of free pions, consists in substitution of the effective mass $m_\pi(T)$, that increases with temperature for the mass m_π. The main thermodynamic quantities of the system decrease, as compared with an ideal pion gas.

An original method of solving the multiparticle problem has been applied in studying a system of three neutrons. The phenomenon of the appearance of artificial resonances has been observed and explained as non-physical solutions, as the area considered was limited. This gives rise to doubt concerning the previous conclusion on the existence of a three-neutron resonance.

An original microscopic method of describing cluster radioactivity has been applied in making detailed calculations of the probability of emission of carbon, oxygen and neon nuclei for the region of daughter nuclei in the vicinity of the doubly magic $^{100}Sn^{50}$ nucleus. The theoretical predictions differed from previous ones by six and more orders of magnitude and were confirmed by measurements performed at FLNR JINR. Theoretical investigation of effects due to the structure of the initial and final nuclei in cluster decay points to their being of a more complex nature than the similar mechanism of α-decay. Thus, for example, the hindrance factors of cluster radioactivity cannot be explained if only singlet nucleon-nucleon pairing is taken into account.

An experimental method for measuring UCN reflections from powders has been developed at FLNP for studies of anomalous losses of UCN. Owing to the diffusion of a neutron between grains and to multiple scattering from the surface of individual grains, the sensitivity to small losses of a single reflection increases. For interpreting the results of measurements, a model was proposed that takes into account the influence of the packing density of grains on the albedo. It turned out to be possible to achieve qualitative agreement with experimental data with the aid of this model.

The theory of multiple scattering of waves was analyzed in detail to establish the applicability of the optical potential in describing UCN reflection from a boundary surface. With its aid corrections were found to the reflection from the surface of a monocrystal with a precision up to $(d/\lambda)^2$, where d is the lattice parameter, and λ is the neutron wavelength.