# 1.2. NUCLEAR PHYSICS WITH NEUTRONS

In 1997, nuclear physics investigations with slow neutrons were carried out on seven beams of the IBR-30 + LUE-40 neutron source, on beam 11 of the IBR-2 reactor and on neutron beams of other sources in Russia, Germany, France, USA, and China. In the reported year, the research program at IBR-30 was formed accounting for the working schedule of creation of the new JINR neutron source for nuclear physics investigations, IREN. A very extensive program of studies in resonance neutron induced fission was, in the main, completed. At the same time traditional investigations of the properties of highly excited states of heavy nuclei, parity violation effects, and reactions with emission of charged particles were successfully carried out. Very interesting and promising results were obtained with UCN in ILL.

## *1.2.1. EXPERIMENTAL*

**Parity Violation and Time Non-Invariance Effects in the Interaction of Resonance Neutrons with Nuclei**

**TRIPLE collaboration. Recent results**

In the framework of a TRIPLE collaboration, the investigation of the mass dependence of the mean-square matrix element $M_W$ of the weak neutron-nucleus interaction continued on the polarised neutron beam of LANSCE, Los-Alamos. The $(\sigma_n k_n)$ correlation measurements were conducted by the transmission method for natural Pa and the capture gamma-ray registration method for the $^{106}Pa$ and $^{108}Pa$ isotope targets. For the neutron energies $E_n < 1000$ eV, there are observed 6 p-wave neutron resonances with meaningful *P*-odd effects. It was established that most of the resonances represent the compound states of $^{105}$Pa nuclei. Analysis of replicated experiments with $^{232}Th$ and $^{238}U$ targets in the energy region up to 300 eV is completed. The results for the mean-square matrix elements *M* are: $M(^{238}U)$ = 0.68+0.25-0.16 meV, $M(^{232}Th)$ = 1.28+0.33-0.24 meV. In them, the main uncertainty is due to the limited number of resonances. For uranium, 3 *P*-odd effects with a plus and 3 with a minus sign are found while for thorium, the existence of the so-called “sign effect” (all effects (10) have plus signs) is confirmed.

**Nuclear fission**

***Angular correlations of fission fragments in the resonance neutron induced fission of the $^{235}U$ nucleus***

Investigations of the angular anisotropy of fission fragments $A_2(E_n)$ with respect to the target spin orientation continued on beam 5 of IBR-30. The total measurement time at low sample temperature ($T \sim 0.1$ K) for measuring the angular anisotropy of fission fragments $A_2(E_n)$ with respect to the target spin orientation increased up to 1100 hours. Thus, the experimental data for $A_2(E_n)$ are now available in energy bins of 0.05 eV with an accuracy of 3 – 5 %, up to $E_n < 30$ eV. With the aid of an original code for multilevel, many-channel R-matrix analysis as well as a specially modified standard code SAMMY, the $A_2(E_n)$ data are fitted together with spin separated and total fission cross-sections, neutron capture and total cross-sections. It is established that to describe the experimental data adequately, one has to assume that fission channels with $K$=0, $K$=1 and $K$=2 are open for resonances with spin $J$=3 and channels with $K$=1, $K$=2 - for resonances with spin J=4. In this case, the relative contribution to $A_2(E_n)$ from different K-channels appears to be 18%, 63% and 19% for $K$=0, 1 and 2, respectively. It is also found that the interference of resonances with different spins appears to be significant and contributes approximately 16% to $A_2(E_n)$. It becomes evident that the old approach in which definite $A_2$ values were assigned to definite resonances does not work because of a high level density and strong interference between resonances.. Progress in the description of the fission process is achieved thanks to the new theoretical approach developed by Barabanov- Furman. The results of measurements and the theoretical description are presented in Figure 1.

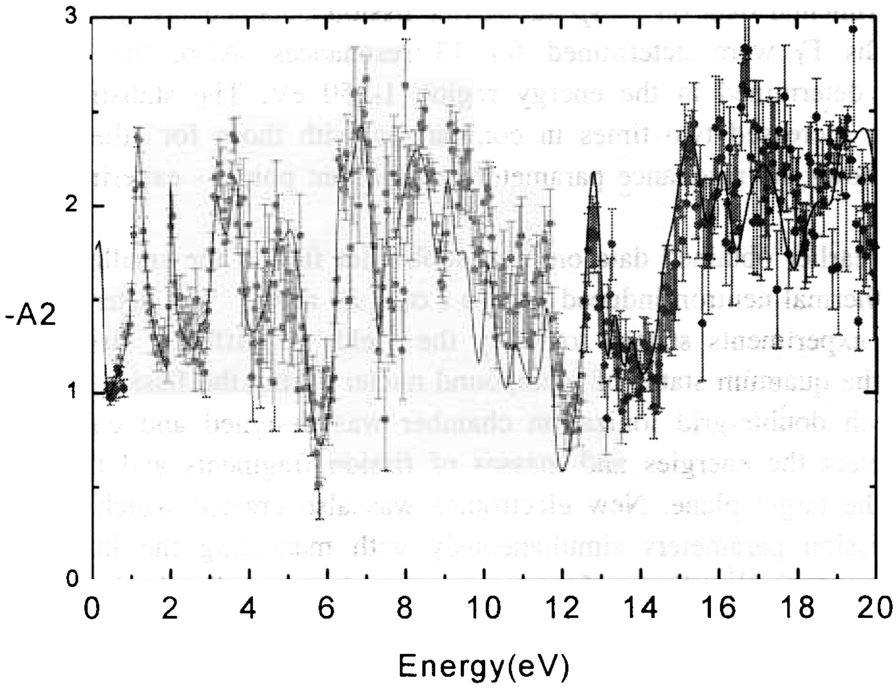


*Figure 1*

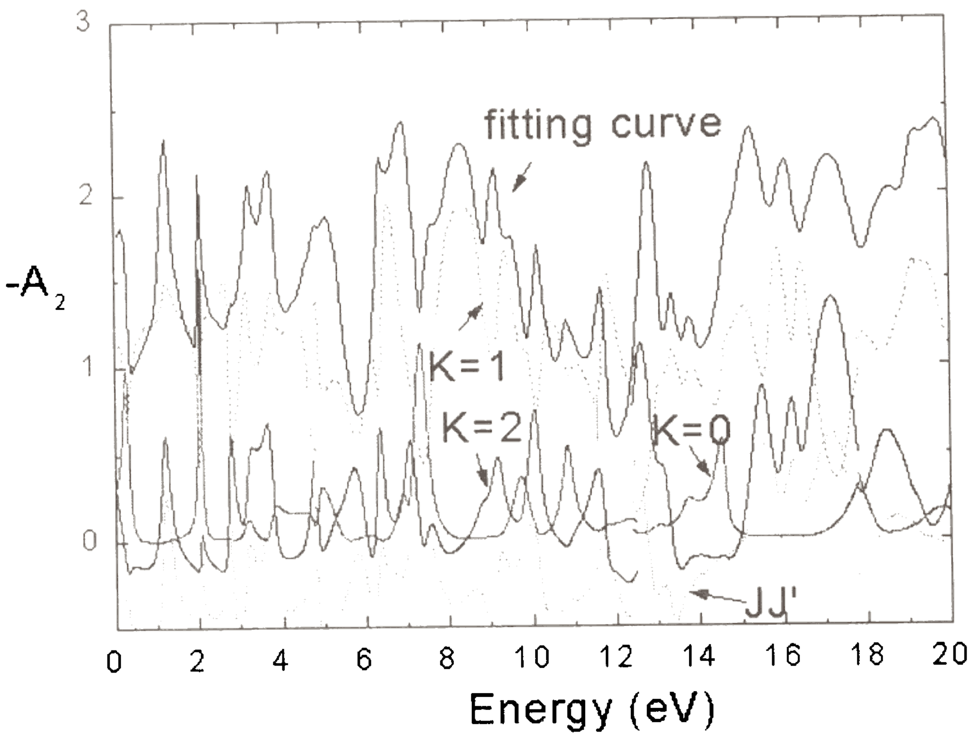


*Figure 2*

Solid points are the experimental data. The solid curve is the theoretical curve with parameters correlating well with total cross section and fission cross section data (total and spin separated). Figure 2 illustrates the influence of separate *K*-channels and spin interference.

***Subthreshold fission and delayed neutron yields***

The experimental data on $^{237}Np$ subbarrier fission obtained last year were improved and the fission widths $\Gamma_f$ were determined for 13 resonances. Also, the cross section energy dependence was determined in the energy region 1- 50 eV. The statistical accuracy and the energy resolution increased two times in comparison with those for the data set obtained in 1993. Figure 3 shows the resonance parameters evaluation: points - experimental data, solid line - fitting curve.

From the earlier obtained data on $^{234}U$ subbarrier fission the smallest upper limit for the cross-section of thermal neutron induced fission ( $\sigma_{nf} \leq$ 20 mbn ) was determined.

The first experiments started to study the yields of different fission modes and their correlation with the quantum states of compound nuclei during the fission induced by resonance neutrons. A Frisch double-grid ionization chamber was designed and constructed in 1997. It allows one to detect the energies and masses of fission fragments and the emission direction with respect to the target plane. New electronics was also created which makes it possible to measure these fission parameters simultaneously with measuring the initial neutron time of flight. Measurements of $^{235}U$ fission fragment mass and energy distributions were performed up to 25 eV. About 50 million fission events were registered and data analysis started.

For the first time neutron resonances in the $^{243}Am(n,f)$ reactions were measured using a fast ionization chamber which makes it possible to register fission fragments against a high background of α-particles ($N_f / N_\alpha \sim 10^{-10}$). This opens good possibilities for measuring earlier unknown fission cross-sections for minor actinides in the resonance region.

***High resolution prompt γ- spectroscopy of fission fragments***

To refine the earlier experimental data on independent fission fragment yields and obtain new information with the aid of fast γ-γ coincidences for two fission fragments, measurements of the γ-spectrum of $^{239}Pu$ fission fragments were performed on the 57 m flight path of beam 5 at IBR-30. There were registered $6 \cdot 10^8$ fission events. Data processing is in progress.

**Highly excited states of nuclei**

***Cascade gamma decay of compound states after thermal neutron capture***

Investigations of highly excited nuclear states in energy regions not properly studied so far, continued. To this end, coincidence gamma spectra of 2γ-cascades were studied for $^{140}La$ and $^{188,90}Os$ target nuclei. The energy of the final levels lies below 0.8 MeV. Analogously to the earlier studied spherical nuclei, the cascade γ-decay of their compound states demonstrates typical features. Namely, the probability of excitation and γ-decay of low lying ($E$<2-3 MeV) states enhances in comparison with model calculations based on standard assumptions concerning the level density and radiative strength functions. At the same time, these probabilities are relatively depressed at high excitation energies. So, the situation is quite opposite to that observed in deformed nuclei where most 2γ-cascades are connected with the excitation of levels lying above 3-4 MeV.

A combined analysis of experimental results for 40 nuclei studied up to now gives good reason to believe that the coupling nucleon interaction at excitation energies in the 1-5 Mev energy region produces much stronger influence on the levels structure than predicted by modern nuclear models.

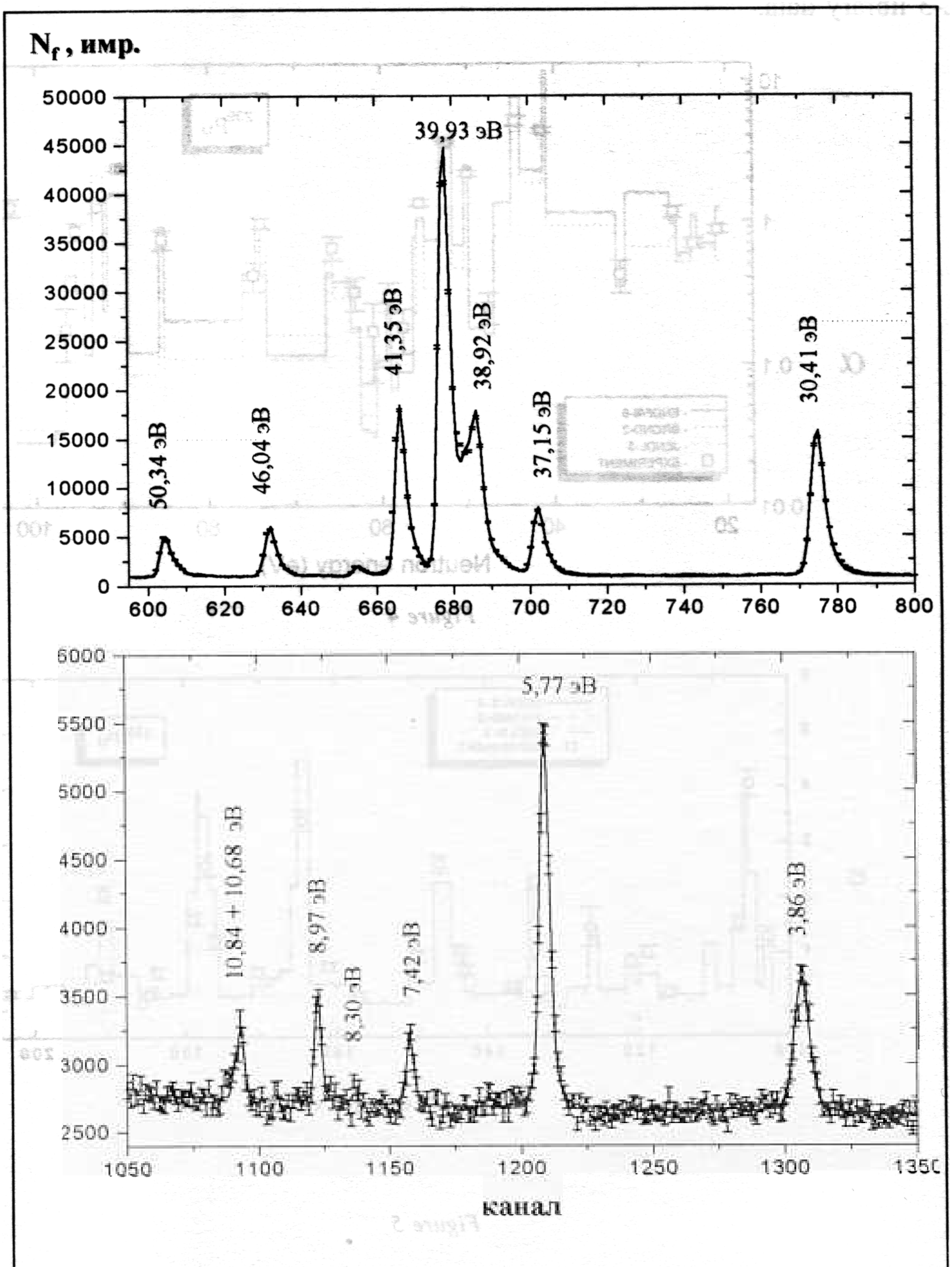


*Figure 3*

***Radiative resonance neutron capture. ROMASHKA & PARUS spectrometers***

Pioneering experiments to measure the effects of resonance self-shielding and the value of $\alpha = \sigma_\gamma / \sigma_f$ for $^{235}U$ target nuclei in the 20-2000 eV energy region were performed. Multiplicity spectra were also measured for the $^{239}$Pu target to refine the $\alpha$ value for $^{239}Pu$ in the 0.007-20 keV energy region. As a result, $\alpha$ values were obtained for 80 resonances and several energy groups.

Figure 4 and 5 show the experimental $\alpha$ values for $^{239}Pu$ (points) in comparison with the evaluated by the GRUCON computer program on the basis of BROND-2, ENDF/B-6, and JENDL-3 library data.

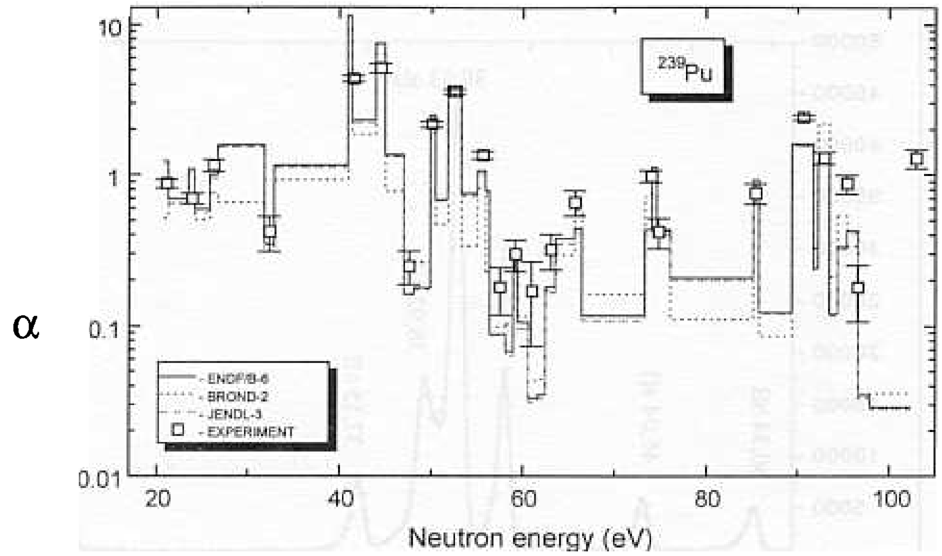


*Figure 4*

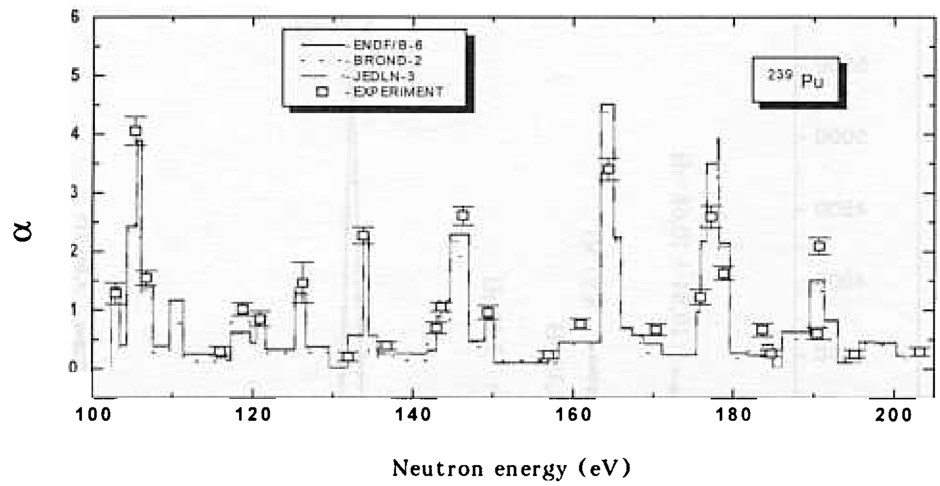


*Figure 5*

With the PARUS spectrometer (beam 3 of IBR-30, 122 m flight path) 80-litre volume multisectional detector multiplicity spectra were measured for $^{232}Th$, $^{235,\,238}U$, $^{239}Pu$ and *Pb* to determine $\alpha$ values and radiative capture cross sections.

**Neutron induced reactions with charged particle emission**

The $^{26}Al(n,\alpha)$ and $^{26}Al(n,p)$ nuclear reactions may form the basis of the main mechanism of *Al* destruction in nature. Precise measurements of their cross sections are important for the understanding of $\gamma$-spectra of "live" $^{26}Al$ in our Galaxy and " dead" $^{26}Al$ in meteorites.

In collaboration with Los-Alamos physicists investigations of the $^{26}Al(n,\ \alpha)^{23}Mg$ and $^{26}Al(n,\ p)^{26}Mg^*$ reactions in the energy region from thermal to 10 keV and 70 keV, respectively, were performed. The results are illustrated in Figure 6 and 7.

These very reactions are mainly responsible for *Al* destruction in the nucleosynthesis and the determination of their cross sections is therefore very important.

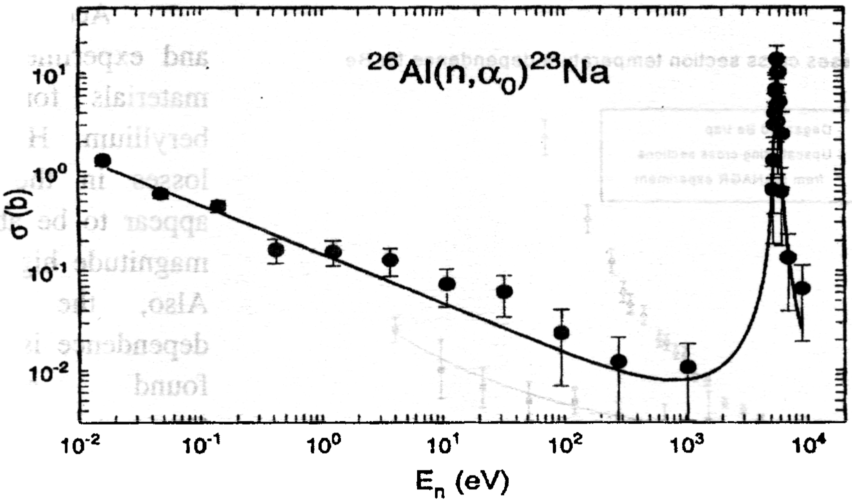


*Figure 6*

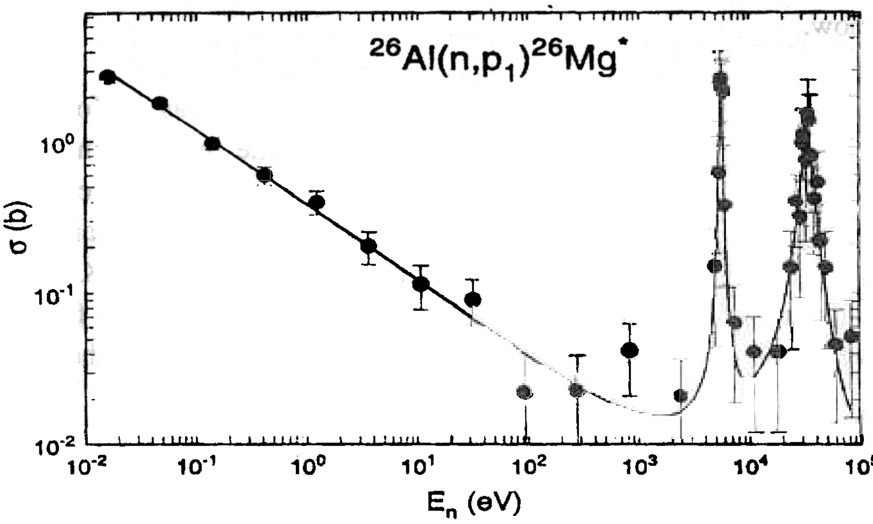


*Figure 7*

**(n, γ) reactions for astrophysics**

The investigation of the $^{48}Ca(n, \gamma)$ reaction completed in 1997. The results were obtained and processed for a Maxwellian neutron spectrum with $kT$ = 25 keV. The $^{50}Ti(n, \gamma)$ reaction was studied with neutrons from a Maxwellian spectrum with $kT$ = 25 keV as well as with 29 keV and 145 keV monoenergy neutrons. The results are being processed.

**Investigations with ultracold neutrons**

***Experiment to study the temperature dependence of the UCN upscattering on beryllium***

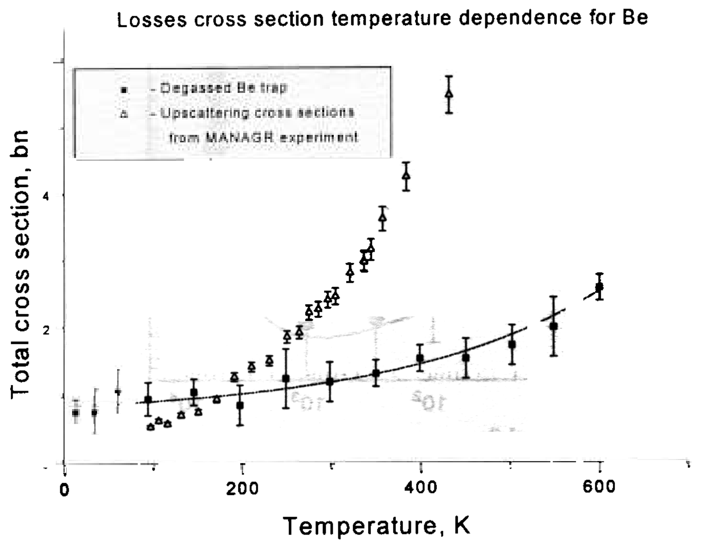


*Figure 8*

According to both theory and experiment, one of the best materials for UCN storage is beryllium. However, total UCN losses in the walls of a trap appear to be about two orders of magnitude higher than predicted. Also, the UCN temperature dependence is surprising: there is found some additional temperature-independent mechanism of losses with a high cross section of 0.9 bn corresponding to the loss probability $3 \cdot 10^{-5}$ per bounce (solid curve in Figure 8). Also, in the same experiment it was determined that no additional losses in the walls material take place. Thus, the losses can be attributed to the surface. This experiment has no reasonable explanation up to now.

An experiment to study the upscattering of UCN on Be was performed in May-April 1997 on the High Flux Reactor in Grenoble, France. The experimental count rates of upscattered neutrons were transformed into upscattering cross-sections. One can see the results in Figure (uppper triangles). Introducing capture cross-sections obtained in different experiments one can explain the anomaly of UCN losses for temperatures down to 90 K. It should be noted that further investigations of UCN upscattering in the temperature interval from 90 K to liquid helium temperatures are essential for the verification of the hypothesis of anomalous upscattering.

**Precise experimental test of the UCN dispersion law**

In the frame of a FLNP-Kurchatov Institute-ILL-Melbourne University collaboration, a precision experiment to verify the neutron wave dispersion law was performed using an original method. It is based on a search for the resonance line shift in an interference filter, the Fabri-Perrot interferometer, accompanied with a change in the neutron velocity component parallel to the filter surface. It is found that when the filter moves parallel to its surface with the velocity 35 m/s, the effective neutron spectrum goes through the resonance shifted by +0.100±0.016 neV for the initial UCN energy 107 neV. In the test experiment it was shown that when the initial spectrum is narrow and the transmission line of the filter broadens, monochromatic neutrons do not change their energy during tunnelling through the moving filter. The observed effect may be interpreted as a very serious evidence of the fact that some deviation from the commonly accepted dispersion law really exists.

*1.2.2. THEORETICAL*

The effect of electromagnetic interactions on the strangeness-conserving β-decay of baryons, neutron (**n**) and Σ-hyperon (Σ), is demonstrated. The modifications of the total decay probability, $\delta W_n \approx 8\%$ , $\delta W_\Sigma \approx 0.5\%$, the $e^{\pm}$ spectrum and the angular distribution with respect to the polarization vector $\xi$ of the initial baryon, $\delta A_n \approx -1.9\%$ , $\delta A_\Sigma \approx 1.8\%$, were obtained. The dependence of the results on the value of the ultraviolet cut-off parameter $\Lambda$ is elucidated. The spectrum and the yield of γ-radiation accompanying β-decay are calculated and special attention is paid to infrared (soft-photon) radiation. The photon radiation of pions constituting the baryon's ``pion cloud" is investigated. Radiative corrections to the total β-decay probability, the electron energy and the angular distributions found in this work prove to be of pivotal importance for obtaining the main characteristics of weak interaction by experimental data processing.

It is shown that applying the multiple wave scattering technique to the problem of the interaction of slow neutrons with a substance with simple crystalline structure does not reveal any anomalies in the slow neutron dispersion law and cannot explain excessive UCN losses during storage in material traps.

A possible alternative explanation of anomalous UCN losses is investigated theoretically. The ground for this hypothesis is the de Broglie description of the wave function. The results of experiments are analyzed under this assumption.

Due to high densities, some intermediate products of the *pp*-cycle in stars can emerge not only from two-body but also three-body initial states. Their role is not properly estimated yet. Moreover, three-body states have different selection rules and may significantly change the entire picture of the nucleosynthesis. We performed (for the first time) a microscopic analysis of several nuclear reactions not included in the standard model of the *pp*-chain. The fate of $^7Be$ in this chain is of special interest. The fact is that a combined analysis of all experiments measuring the neutrino flux from the sun leads to a paradox conclusion: the production of $^7Be$ nuclei (more precisely, the flux of neutrinos due to $^7$Be) must be strongly suppressed or even negative. This means that something is wrong either in the standard model or in the experimental data.

The problem of possible *T*-invariance violation in the "backward" elastic scattering of neutrons by a spinless nucleus was investigated. It is shown that under *T*-invariance the amplitude and the cross-section of "backward" scattering do not depend on the neutron spin. An observation of such dependence will unambigously point to T-invariance violation. However, the fulfilled estimates of the possible spin asymmetry of "backward" scattering demonstrate that the corresponding effect is very weak (about $10^{-8}$ - $10^{-7}$) and can hardly be observed experimentally in the nearest future.

*1.2.3. METHODOLOGY*

**KaTRIn project status**

In the frame of the KaTRIn project (see a separate article below) aimed at studying time–non invariant (*T*-odd) effects in resonance neutron induced reactions, work to create a $^3$He based neutron polarizer - analyzer was carried out during 1997 in collaboration with Lebedev institute (Moscow).

A $^3He$ based neutron polarizer with laser pumping is attractive for many tasks in neutron physics. It does not require cooling and strong magnetic fields. The polarization that can be achieved for 1 eV neutrons is about 75% with the transmission about 20%. This allows such a polarizer to be compact with a small weight.

During 1997, the prototype of the $Rb$ - $^3He$ polarizer, a two-chamber aligned aluminosilicate glass cell filled with $^3He$ at 10 atm, was created. Two Helmholtz ∅ 1400 mm coils to produce the leading field about 20 G with the homogeneity not worse than $5\times10^{-4}$ in the center and a pair of RF ∅ 600 mm coils perpendicular to the leading one were built and will operate at 80 kHz. The pick - up coils are incorporated with a cell holding platform. The setup is a multifunctional stand for the investigation and adjustment of the design and working regime of the cell.

**Neutron induced reactions with emission of charged particles**

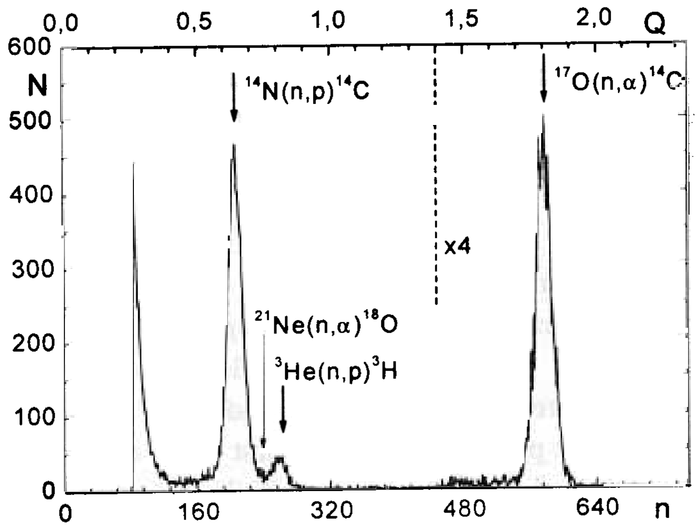


*Figure 9*

Using the created unique ionization chamber (IC) with a gas target a number of reactions were measured, including: $^{17}O(n,\ \alpha)^{14}C$, $^{36}Ar(n,\ \alpha)^{33}S$ and $^{21}Ne(n,\ \alpha)^{18}O$. The new method for measuring $(n,\ \alpha)$ and $(n,\ p)$ was developed and tested on the thermal neutron beam at the IBR-2 reactor. Figure 9 shows the pulse-height spectra form the IC collector.

The thermal neutron cross sections obtained from these measurements are in good agreement with earlier ones for $^{17}O$ and $^{36}Ar$ while for $^{21}Ne$, our result is significantly smaller.

Further development of this technique will make it possible to use resonance neutrons in the investigation, particularly, of $(n,\ \alpha)$ reactions using $^{37}Ar$ and $^{39}Ar$ targets. These processes are of crucial importance for the understanding of the origin of $^{36}S$ rare isotopes.

**Modernization of the ISOMER installation**

The new system for automatic alternating the background and physical measurements was created.

The new fast electronics was created to decrease sufficiently the dead time in the whole delayed neutron registration module.

After the modernization rather precise data on delayed neutron yields from the $^{237}Np$ fission induced by thermal neutrons were obtained.

**Neutron spectra analysis in the 2-100 keV region with the aid of a (n, γ) converter.**

The new method of neutron spectrometry based on shape analysis of γ lines was tested at the electrostatic generator EG-5. The preliminary results show high efficiency of the method for the purposes of spectrometry with stationary and pulsed neutron sources.

**The anticompton gamma spectrometer HPGe-BGO for nuclear physics experiments at pulsed neutron sources**

The HPGe detector with the efficiency 9% and the resolution 2.0 keV at the energy 1332.5 keV is used as the main part of the spectrometer. The detector is 78 mm in diameter and 120 mm in length. The choice of the design is determined by its simplicity and cost as well as the results of computer modelling. The schematic view of the spectrometer including the passive shielding is presented in Figure 10. The BGO surrounding consists of 32 rectangular crystals with maximum dimensions 40 mm × 40 mm × 80 mm and the total volume 3 litres. A simplified system with 10 photomultipliers is used for photon registration. The employed module scheme of the design allows the transformation of the shielding to make the spectrometer suitable for studying γ-ray multiplicities in neutron-nuclear interactions. Figure 11 demonstrates the unsuppressed (1) and suppressed (2) experimental spectra together with the experimental (3) and calculated (4) suppression coefficients for the standard $^{60}Co$ source. The use of the CSS for the investigation of the peculiarities of the resonance neutron induced fission of $^{239}Pu$ has reduced the background of the measured prompt γ-spectra 2 - 3 times and improved the accuracy of fission fragment yields by a factor of 1.5.

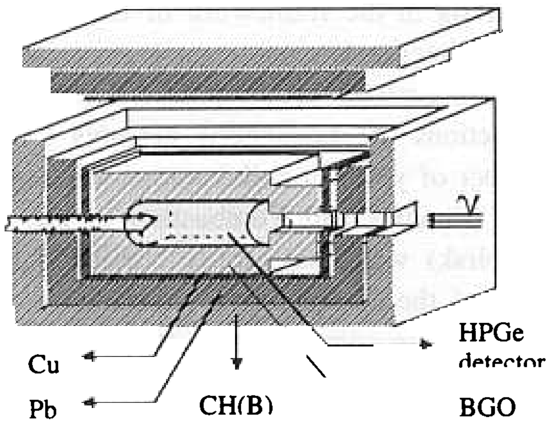

*Figure 10*

**Test of the UGRA installation**

The first test of the UGRA instrument shows that it is necessary to modernize old neutron detectors to adjust them for operation in vacuum conditions. This work was carried out at the end of 1997. However, without IBR-30 neutron beams it turned out to be impossible to test the new detectors.

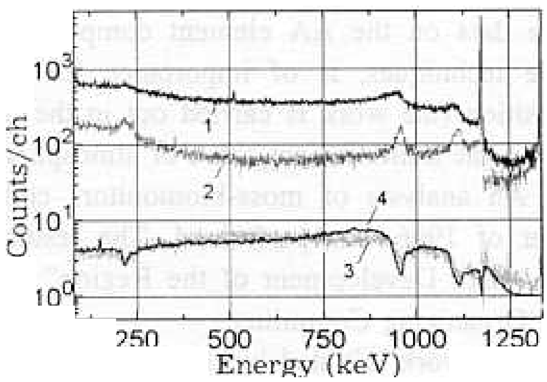

*Figure 11*

**Construction of the KOLHIDA instrument**

The new set-up KOLHIDA shipped from Georgia in 1996 is and mounted and adjusted on beam 1 of the IBR-2. This installation allows one to use the intense beam of polarized neutrons to study nuclear pseudomagnetism and some new parity violating effects in neutron optics.