FISSION PHYSICS IN PNPI OF RAS FOR 30 YEARS

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I. Introduction

Neutron induced fission reaction of atomic nuclei represents a very specific field of nuclear physics and is in existence for more than 60 years. In PNPI of RAS the experimental investigations in this field perform mainly with the use of the WWR-M reactor and, since 1971, with the use of the neutron spectrometer GNEIS at the synchrocyclotron with the energy 1 GeV.

A natural question arises here, what is the reason for such a long and intensive interest to such an old branch of science in spite of the huge number of experimental and theoretical works performed for more than half a century? The most expressive peculiarities of this nuclear process are connected with a crucial role of the collective effects, with theexistence only a few transition states (so called O.Bohr's channels) under the availability of the huge number (up to 10^{10}) of formal channels at the reaction exit. And, at last, one more peculiarity, non-existent in any other nuclear reaction at low energy, lies in the rupture of a large strongly deformed nuclear bulk into two or more pieces. If one adds to all aforesaid, that a wide variety of the exotic neutron-rich nucleus fragments come into existence as a result of fission reaction, it can be considered as an exceptionally rich nuclear laboratory, incorporating practically all types of radioactive transformations and decays.

Today the prevailing view is that the main nuclear energetic requirements were largely provided in the first 30 years of fission physics history. In this connection one important question goes back a long way: is it worthwhile to continue the new experimental data collecting, and if yes, in what direction? To answer this question first and foremost, it is useful to take into account that the rich experimental information, accumulated during the first 30 years, deals with only average characteristics of fission process, which very often does not allow to choose between quite different theoretical models. That is why the tendency of the present experimental investigations consists in performance the multiparameter experiments, when, with the aim of special selection of the events, the number of simultaneously measuring parameters is continuously increased to minimize the averaging effect of the fission process investigated. The other tendency involves the search and use of the new non-traditional directions of fission investigations, which can bring into existence the principal new information.

In the course of the recent 20 – 30 years some very interesting and unexpected discoveries were made in the field of fission physics , such as deformed shells, subbarrier structures in fission cross sections, shape isomers, Brosa's valleys on potential surfaces, PNC effect in low energy fission process, and, at last, so called T-odd asymmetry of the light charged particle (LCP) emission in ternary fission. The most important and interesting question of the modern physics of fission becomes undoubtedly the fission dynamics.

All these tendencies and the most important items of possible investigations were took into account in working out scientific programs in fission physics over 30 years of the Institute existence. Fission Physics Group (later Fission Physics Laboratory (FPL)) is of the same age as the WWR-M reactor. The first scientific program of investigations had been proposed by Professor L.I. Rusinov even in 1956. The main aim of that program was to study angular and energy distributions of the fast and delayed γ-quanta accompanying thermal neutron induced fission of $^{233,\,235}$U and ^{239}Pu. After ten years of FPL's activity this program was successfully performed, and first three Candidates of Sciense appeared as a result.

The first half of the seventies was connected with development of the neutron time-of-flight spectrometer GNEIS at the 1 GeV proton synchrocyclotron. The new scientific program was directed toward the (n,γf) process study. By the idea of the FPL the first measurements had been carried out in collaboration with JINR at the pulsed neutron reactor IBR-30. Subsequent experiments were performed at neutron spectrometer GNEIS at Gatchina. The whole search met with success and the fourth Candidate of Sciences became a member of the highly trained personnel of FPL.

In the late seventies the part of FPL closely connected with the WWR-M reactor was bound up with the search experiments in the field of spontaneous fission isomerism and multi-parameters studies of the prompt gamma, x-ray and electron emission in fission process.

Since 1978 the main part of the FPL had switched its attention to the investigation of a new comprehensive effect of parity nonconservation (PNC) effect in the heavy actinide fission induced by slow polarized neutrons. Distinctive features of such investigations at Gatchina consisted in use of spectroscopic methods of fission fragment registration, in the first use of crystal diffraction monochromator of polarized neutrons for the PNC effect study in fission, and in simultaneous study of neutron energy dependence of the PNC effect together with P-even interference effects in fission fragment angular correlation. The most important stages of this new program realization were the first study of the fragment mass and the total kinetic energy dependence of the PNC effect, the new search measurements of the PNC effects in ^{229}Th, ^{237}Np, ^{241}Pu, ^{241}Am, ^{245}Cm, and ^{249}Cf fission, and the first observation of the resonance behavior of the PNC and P-even interference effects as a function of polarized neutron energy. Over the last ten years a part of these investigations were carried out in the broad collaboration both with Russian institutions (JINR, Khlopin Radium Institute, and ITEP), ILL (France), and Universities of Tuebingen and Darmstadt (Germany). As a part of an exploration program more than 40 scientific articles had been published. The results of these investigations together with the first pioneering work of ITEP have made an integral part of the modern concept of the PNC effect in fission induced by slow polarized neutrons. In addition, the PNC effect studies in PNPI provided the subject of matter for two Candidate and one Doctor theses.

In 1998 the FPL of PNPI in collaboration with ITEP, RI, ILL, and Universities of Tuebingen, Darmstadt (Germany) and Finland took part in the first observation of so-called T-odd triple correlation in ternary fission induced by the cold longitudinally polarized neutrons. The investigations of this very interesting effect are continueing in the FPL up to date at the High flux reactor of ILL. Nowadays, it is considered by us as evident that this effect is closely determined by the specific properties of fission dynamics and its further investigation promises to give a new information about ternary fission process at low excitation energy.

But during its whole forty-year history the FPL was never involved only into fission physics field affairs. As an examples, one can mention such works as the first observation the thermal neutron acceleration in the CO_2 gas discharge, neutron polarizability in the strong Coulomb field of heavy nucleus, the PNC neutron spin rotation in the vicinity of the La p-wave resonance of 0.78 eV and etc.

Scientific activity and the level of the works performed by the FPL gained wide acceptance that is confirmed by numerous National and International Grants such as RFBR (8), IFR (3), INTAS (3), ISTC 2).

The main directions of scientific investigations of the FPL and the most important results obtained for the last thirty years of its existence are presented in the subsequent chapters of this article.

II. Physical investigations at the neutron time-of-flight spectrometer GNEIS

1. Neutron Time-of-Flight Spectrometer GNEIS at the 1 GeV Proton Synchrocyclotron of PNPI of RAS

The Gatchina neutron spectrometer GNEIS [1] is intended for neutron-nucleus interaction studies utilizing the time-of-flight technique over wide range of neutron energy from $\approx 10^{-2}$ eV up to hundreds of MeV. The spectrometer is based on the 1 GeV PNPI proton synchrocyclotron and is used for physics experiments from 1975. The hight quality of the GNEIS neutron source (high neutron intensity and short pulse) makes experimental capabilities of GNEIS comparable with that of the TOF-facilities at electron Linacs, e.g. ORELA (Oak-Ridge), GELINA (Geel), LUE-40/IBR-30 (Dubna), FAKEL (KI, Moscow), as well as high intensity proton accelerators, e.g. LANSCE (Los Alamos).

The main parameters of accelerator and spectrometer GNEIS are as follows:

Pulsed neutron source:

– average fast neutron intensity	$\approx 3 \cdot 10^{14}$ n/s
– duration of the fast neutron pulse	$\approx$ 10 ns
– repetition rate	< 50 Hz
– internal water-cooled rectangular lead target	40 cm × 20 cm × 5 cm
– rectangular polyethylene moderator	30 cm × 10 cm × 5 cm

Spectrometer:

– number of evacuated flight paths (No 5 beam looking at the target and No 1-4 beams looking at the moderator)	5
– length of flight paths	35 – 50 m
– experimental area (GNEIS building)	45 × 30 m^2

Physical equipment:

– neutron detectors	^{6}Li-glass, ^{3}He-chamber,
4π-liquid scintillator tanks	
– γ-ray detectors	NaI(Tl), C_6D_6-liquid scintillators
– fission fragment detectors	multiplate ionization chambers

Fig.1 shows the general layout of the GNEIS facility. Also shown are the inserts with short titles of experiments performed at the GNEIS facility. Some recent experiments have been carried out under support of Russian Foundation for Basic Research and International Science and Technology Centre, in collaboration with V.G. Khlopin Radium Institute (St.-Petersburg), A.F. Ioffe Physical-Technical Institute (St.-Petersburg), I.M. Frank Laboratory of the Joint Institute for Nuclear Research (Dubna), Radiation Physics and Chemistry Problems Institute (Minsk-Sosny), Institute of Theoretical and Experimental Physics (Moscow), Institute of Reference Materials and Measurements (Geel, Belgium), Kyoto University Research Reactor Institute (Kumatori-Osaka, Japan), Nucle-ar Data Centre/Japan Atomic Energy Research Institute (Tokai, Japan).

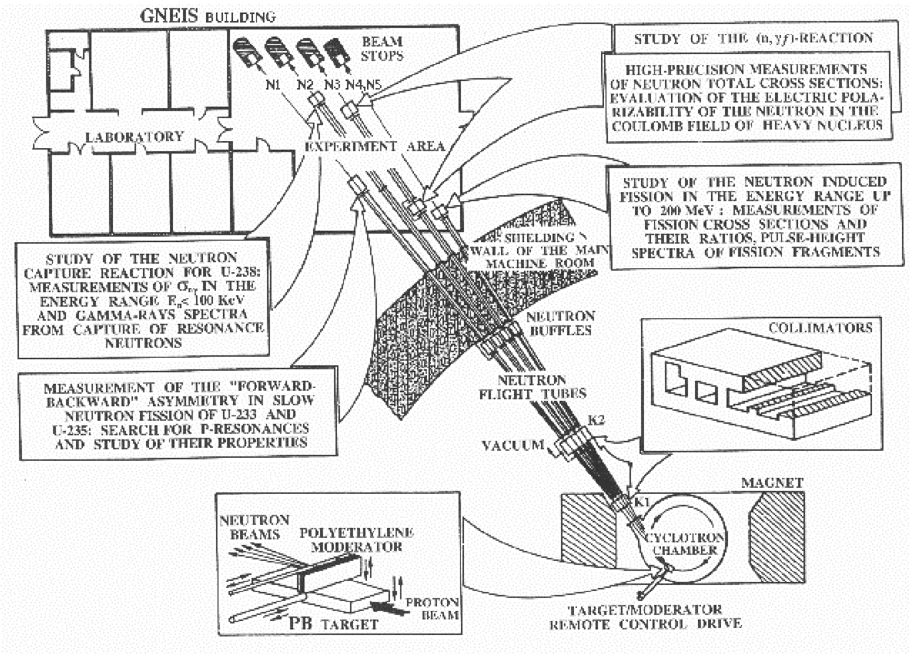


Fig.1. General layout of the Gatchina neutron time-of-flight spectrometer GNEIS

2. Study of the (n,γf) reaction in neutron resonances of ^{235}U and ^{239}Pu

Experimental studies on the two-step (n,γf) reaction give unique information not only about fission process itself, but also about the structure of highly excited compound states in heavy nuclei and radiative transitions between them, both in the 1st and 2nd wells of the fission barrier. The fission γ-ray multiplicity has been measured in neutron resonances of ^{235}U and ^{239}Pu [2,3,4]. The experimental prefission widths $\Gamma_{\gamma f}$ have been obtained from the observed correlations between the multiplicity of fission γ-rays and reciprocal fission width Γ_f^{-1} of resonances:

^{235}U: $\Gamma_{\gamma f}(4^-) = 0.32$ meV ± 0.13 meV	^{239}Pu: $\Gamma_{\gamma f}(1^+) = 1.9$ meV ± 0.8 meV
$\Gamma_{\gamma f}(3^-) = 0.87$ meV ± 0.89 meV	$\Gamma_{\gamma f}(0^+) = 2.8$ meV ± 9.2 meV.

The experimental and calculated prefission width $\Gamma_{\gamma f}$ is shown in Fig. 2 for the 4^--resonances of ^{235}U and 1^+-resonances of ^{239}Pu as a function of the ratio of E1 and M1 components in the prefission γ-ray spectrum. The comparison of the experimental and calculated $\Gamma_{\gamma f}$-widths shows predominance of the M1 radiation in

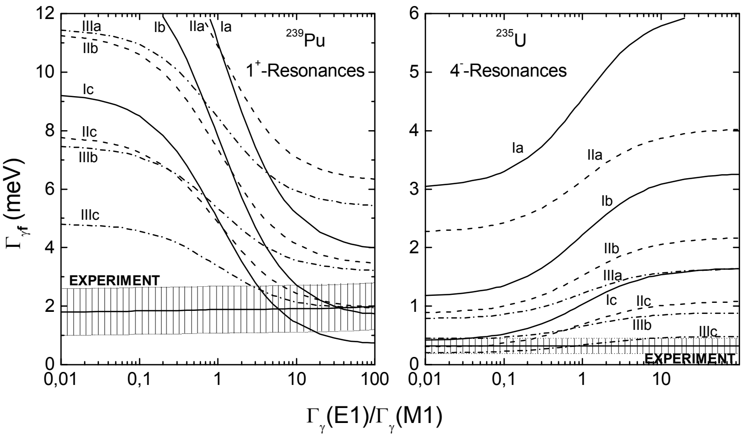


Fig. 2. Experimental and calculated widths $\Gamma_{\gamma f}$ for 1$^+$-resonances of ^{239}Pu and 4$^-$-resonances of ^{235}U. Calculation model: *I* is single-humped fission barrier, *II*, *III* is double-humped barrier (complete and intermediate damping of the vibrational states in the second well, respectively); *a* is single-particle model (Weisskopf) for probabilities of γ-transitions; *b*, *c* is GDR model (Axel-Brink, Lorentzian-shaped probability of partial γ-transitions proportionate to E_γ^4 and E_γ^5, respectively)

compound nucleus ^{236}U and that of E1 radiation in the prefission spectra of γ transitions between the highly excited states in compound nucleus ^{240}Pu. It was also found that the best agreement between experiment and calculations is obtained by using the model of intermediate damping of the vibrational states in the second well and the Giant Dipole Resonance model.

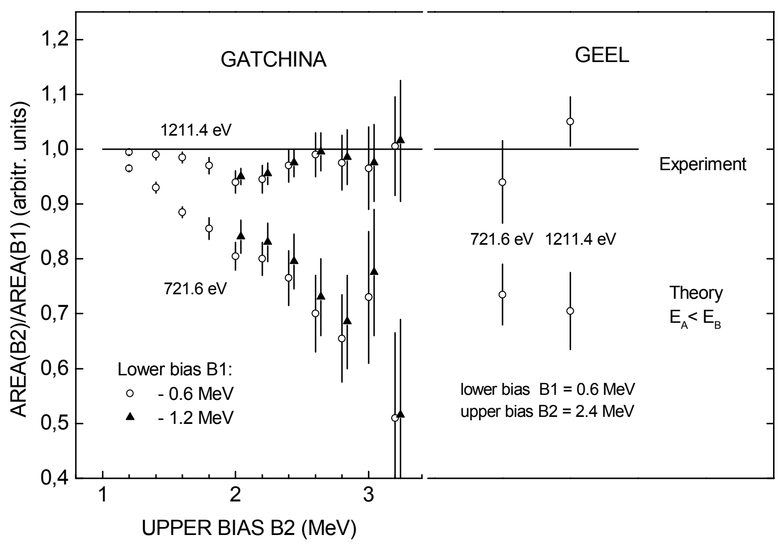
In another experiment at the GNEIS, the pulse-height spectra of fission gamma-rays have been measured in isolated resonances of ^{239}Pu in the energy range from 10 eV to 91 eV [5]. The difference pulse-height spectra for weak (Γ_f <10 meV) and strong (Γ_f >10 meV) 1$^+$-resonances show a few structures that could be interpreted as prefission γ transitions between the levels at excitation energy 1–3 MeV below the neutron binding energy B_n.

3. Measurements of the capture cross section of ^{238}U in energy range E_n<100 keV and gamma-ray spectra from the capture of resonance neutrons: study of the nature of the 721.6 eV resonance

Due to high intensity and small pulse width of the pulsed neutron source, it is possible to study with the GNEIS facility the very rare processes induced in heavy nuclei by resonance neutrons, such as a subthreshold fission. In the course of neutron capture cross-section measurements of ^{238}**U**, a special experiment [6] has been carried out with the aim to clarify a nature of the 721.6 eV resonance of this nucleus.

Two the lowest energy resonance clusters in the subthreshold fission cross-section of ^{238}**U** are dominated by the 721.6 eV and 1211.4 eV resonances. Anomalously small capture width of the 721.6 eV resonance (≈ 4.7 meV) is a strong evidence that this resonance is not usual (i.e., class-I, corresponding to the first well of fission barrier) compound state. If the 721.6 eV resonance is predominantly class-II (corresponding to the second well) in character, then not only its radiative width Γ_γ should be small, but the capture γ-ray spectrum of this resonance should be softer than that of other s-wave resonances (class-I). Prior to the present measurements, J.C. Browne (LLNL, Livermore) observed a much softer γ-ray spectrum for the 721.6 eV resonance than for neighbouring resonances, whereas H. Weigmann et al. (IRMM, Geel) found no difference. To resolve this contradiction, the capture γ-ray spectra in isolated neutron resonances of ^{238}U in the energy range from 400 eV to 1300 eV have been measured at the GNEIS. The data obtained have been processed by the slightly modified method of Weigmann et al. The idea was to detect a γ-decay branch within the second well using two different pulse height bias values for the γ ray registration: lower B1 and upper B2. Then, for value of B2 larger than B_n- E_{II} (2 MeV, height of the second minimum of fission barrier), the ratio of resonance area A_γ measured with two biases B1 and B2: R = A_γ(bias B2)/A_γ(bias B1) should be smaller for the resonance having major class-II fraction than for ordinary class-I resonances because the softer class-II component will be under the upper bias B2 for this resonance.

The results of the present measurements and those of Weigmann et al. are shown in Fig. 3. As seen from our data, the capture γ-ray spectrum of the 721.6 eV resonance is much softer than that of the neighboring s-wave resonances. Our data enable to make a conclusion that the 721.6 eV resonance is predominantly



class-II by nature. As for the 1211.4 eV resonance, both our data and the results of Weigmann et al. show that there are no solid arguments to consider this resonance as a class-II state.

Fig. 3. Results of the capture γ-ray measurements for resonances of ^{238}U

4. Measurement of the neutron total cross sections of ^{209}Bi and ^{208}Pb: estimate of the electric polarizability of the neutron

The electric polarizability α_n is one of the characteristics of the neutron as an elementary particle and determines the induced electric dipole moment in an external electric field: $D = \alpha_n E$. The information about polarizability of the neutron can be obtained from the neutron total cross section measurements for heavy nuclei. In Coulomb field, an addendum

$V = - 1/2 \cdot DE = - 1/2 \cdot \alpha_n Z^2 e^2 / r^4$

caused by polarizability is added to the neutron-nucleus interaction potential, which leads to several additional terms in the total scattering cross section, main of them, σ_p, being linear bydepended on k, where k is the wave number (or, the same, on $\sqrt{E_n}$, here E_n is neutron energy). The contribution of σ_p to the total cross section of heavy nuclei such as ^{209}Bi or ^{208}Pb can be written approximately as

$$\sigma_p \approx 10^{-4} \cdot \alpha_n \cdot \sqrt{E_n} \text{ b.}$$

Here α_n is in units of $10^{-3} Fm^3$ and E_n is in eV. So far as with an increase of neutron energy, a contribution of this term in total cross section increases in proportion to the wave number k, then, from the principal standpoint, a measurement of polarizability could be reduced to comparison of total cross sections measured at different energies.

The total cross section of ^{209}Bi in the energy range from 1 eV to 100 eV and that of ^{208}Pb from 1 eV to 20 keV have been measured at the GNEIS. Simultaneously, the total cross section measurements for silicon and carbon were carried out as a zero-test of the experiment. For silicon and carbon, the polarizability influence should be negligibly small in comparison with that of bismuth and ^{208}Pb because the polarizability contribution to the cross section is proportional to the square of nuclear charge Z^2.

The ionization ^3He-chamber was used as neutron detector at the 40 m flight path. Resonance filters of Co(132 eV, 4.3 keV, 5.0 keV), W(18.8 and 4.16 eV), In(1.46 eV) and Al(34 keV) were placed in the beam for permanent background monitoring. In order to suppress the overlap neutrons, cadmium filter was placed in the beam. The measured total cross sections of ^{209}Bi and Si are shown in Fig. 4 and that of ^{208}Pb and C in Fig. 5. Only the energy dependence of cross section is used for estimation of α_n. For this purpose, it is necessary to make corrections to the total cross section for Schwinger and (n,e) interactions, solid state effects, absorption cross section and neutron resonances contributions.

Bismuth

Analysis of the data for Bi using the method with simultaneous variation of two parameters - polarizability and resonances contribution leads to $\alpha_n = (25 \pm 11) \cdot 10^{-3}$ Fm^3 [7,8]. One can not obtain better precision

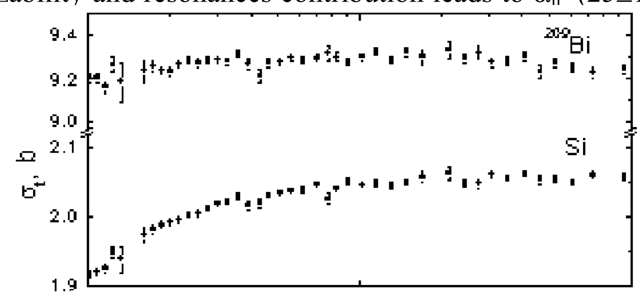


Fig. 4. Measured total cross sections of ^{209}Bi and Si.

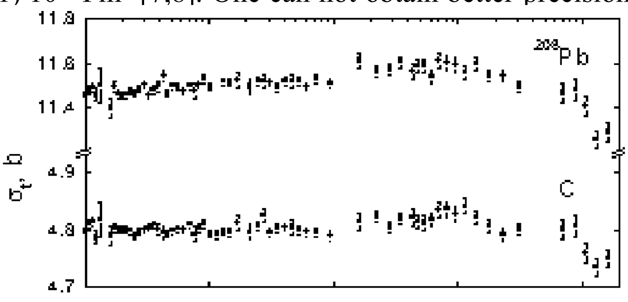


Fig. 5. Measured total cross sections of ^{208}Pb and C.

Lead-208

Applied method of evaluation of α_n-value for ^{208}Pb has been developed in ref. [9]. In accordance with this method, the total cross section of ^{208}Pb in the investigated energy range can be written under two very common assumptions, optical theorem and first Born approximation, as:

$$\sigma_t/4\pi = (1/4\cdot\Sigma_2 + 1/4\cdot\Sigma_3 - 1/2k^2)\cos(2\delta_0 + 2\eta_0 + 2\zeta_0) -- 1/2k\cdot\Sigma_1\cdot\sin(2\delta_0 + 2\eta_0 + 2\zeta_0) + 1/2k^2\cdot\cos(2\eta_0 + 2\zeta_0)\ .$$

Here $(\delta_0 + \eta_0 + \zeta_0)$ is a sum phase of s-scattering:

$\delta_0 = -\,k\,R_0'$ describes pure nuclear interaction (R_0' is radius of potential s-scattering),

$\eta_0 = k\,a_{ne}\,F$ - due to (n,e) interaction (F is integrated electron form-factor),

$\zeta_0 = f_\alpha\,k\,(6/5 - \pi/3\cdot kR - 5/7\cdot(kR)^2)$ is additional part of phase of s-scattering caused by neutron polarizability, $f_\alpha = m\alpha_n/R\cdot(Ze/h)^2$, R is radius of nucleus.

Terms Σ_1, Σ_2 and Σ_3 are due to resonances. Thus, there are three parameters, R_0', a_{ne} and α_n, for the least square fitting procedure in investigated energy range. An accuracy of α_n estimation is strongly dependent on the number of fitting parameters. And in case of ^{208}Pb an estimated value of the neutron electric polarizability is found to be $\alpha_n = (2.4\pm1.1)\cdot10^{-3}\,\mathrm{Fm}^3$ [8,10]. This estimated value of α_n is compatible with zero value. A further progress in increasing the precision of α_n-measurements could be related to substitution of the utilised neutron detector for more effective one in conjunction with a detailed background analysis, therefore increasing the high-energy boundary of measured cross section.

5. Estimation of the Neutron Polarizability from Joint Analysis of the Total Cross Sections of Lead-208 and Carbon

A lot of the neutron total cross section measurements for heavy nuclei have been performed to evaluate α_n. Investigators approach closely the upper limit of polarizability about $1\cdot10^{-3}\,\mathrm{Fm}^3$. The sole exception is the result $\alpha_n = (1.20\pm0.15\pm0.20)\cdot10^{-3}\,\mathrm{Fm}^3$ obtained by J. Schmiedmayer et al in Oak Ridge. But in spite of a non-zero value of α_n, many investigators think that error of this result is very underestimated because it takes no account for additional parameters necessary to fit the total cross section with the aim to evaluate α_n.

An analysis of the experimental data obtained at the GNEIS [7,8,10] showed that the main problem was systematical errors of the total cross sections due to uncertainties of experimental backgrounds. In this work the neutron total cross sections has been measured at GNEIS with an accuracy of $\Delta\sigma/\sigma \approx 10^{-3}$ for ^{208}Pb and C in the energy range from 1 eV to 20 keV. The results of these measurements are shown in Fig. 5.

The method employed for evaluation of α_n for ^{208}Pb is described in ref. [9]. The results of fitting for ^{208}Pb are presented in Fig. 6. Points are experimental total cross section after the Schwinger and solid-state corrections and contribution of radiative absorption have been subtracted. The neutron polarizability obtained is $\alpha_n = (2.4\pm1.1)\cdot10^{-3}\,\mathrm{Fm}^3$ and the amplitude of neutron-electron interaction is $a_{ne} = -\,(1.78\pm0.25)\cdot10^{-3}$ Fm . Fitting results for carbon are presented in Fig. 7. From Fig. 6,7 one can see that group of points in vicinity of energy about 1 keV lies systematically higher than fitting curve. This energy region corresponds to the case, when the experimental background changes sharply its energy behaviour. Therefore, the experimental background in this energy range can not be satisfactory described using conventional black-resonance filter method.

The total cross section measurements for ^{208}Pb and C were carried out in similar experimental conditions [7,8,10]. At the same time, the thickness of samples was chosen for their transmissions to be approximately equal in energy range of interest. As the result, the experimental background, were equal in cases of ^{208}Pb and C in these measurements and, therefore, distortions caused by uncertainties of experimental background should influence on the measured total cross sections of ^{208}Pb and C in the same manner. Thus, to eliminate influence of the distortions caused by uncertainties of experimental background, the difference

$$\sigma(^{208}\mathrm{Pb}) = const\cdot\sigma(\mathrm{C})$$

has been used for the neutron polarizability estimation [10,11]. Here a value of *const* = 2.42 was chosen, so that the average value of the difference to be about equal to zero in the energy range under investigation. Fitting results for this difference are shown in Fig. 8. Using this method, the polarizability was obtained near the same value $\alpha_n = (2.44\pm1.32)\cdot10^{-3}$ Fm^3 . The value obtained for amplitude of neutron-electron interaction is a_{ne} = - (1.75±0.27)·10^{-3}Fm.

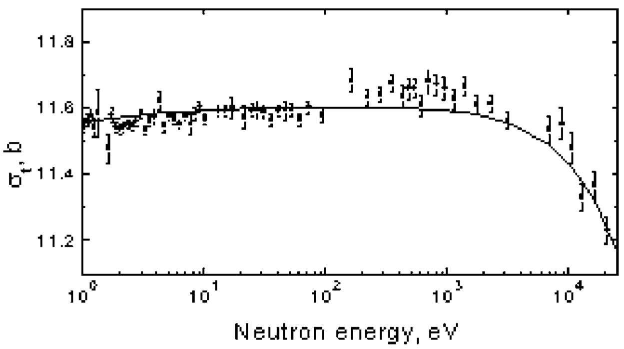


Fig. 6. Fitting results for ^{208}Pb

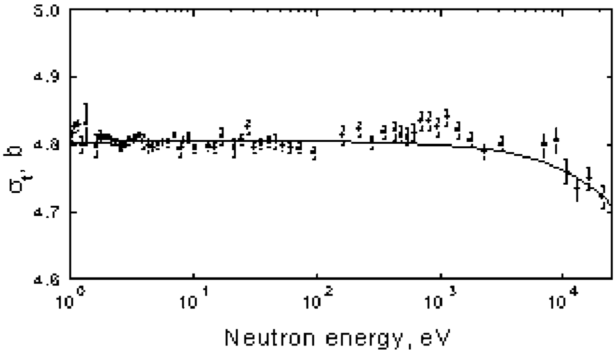


Fig. 7. Fitting results for C

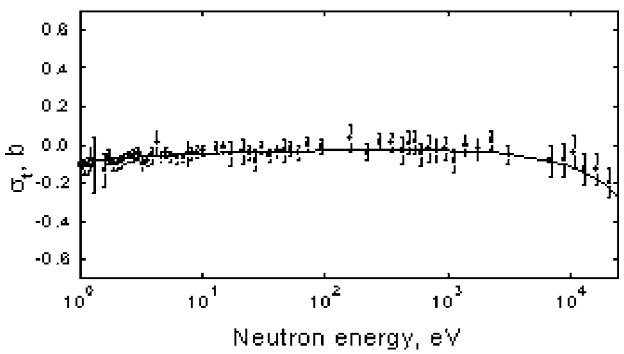


Fig. 8. Fitting results for difference $\sigma(^{208}Pb)$ - 2.42 · σ(C)

This method of joint analysis of the experimental data is effective in a sense of obtaining reliable result for α_n independent of experimental background. This is very important in a case when experimentalists achieve a level of accuracy when systematical errors of measured cross section due to experimental background are comparable with the statistical ones.

6. Measurement of the forward-backward asymmetry of fission fragment emission

Parameters and decay properties of low energy **p**-resonances in heavy fissile nuclei are in practice unknown because of the difficulties existing when generally accepted methods are used. The new method to obtain such an nformation is a study of the neutron energy dependence of the forward-backward asymmetry of angular distribution of fission fragments which is the result of **s**- and **p**-wave interference in neutron capture process:

$$W(\Theta) = 1 + \alpha_{fb}\cdot(p_n\cdot p_f)$$

where p_n and p_f are the neutron and light fragment momenta respectively. The principal advantage of this method if compared with the other asymmetry-measurements is that a non-polarised neutron beam can be used. The first measurements of the forward-backward asymmetry coefficient α_{fb} for ^{235}U and ^{233}U from 1 eV to 136 eV have been performed at the GNEIS facility [12]. The results obtained for ^{235}U in the energy range from 1 eV to 21 eV are shown in Fig. 9.

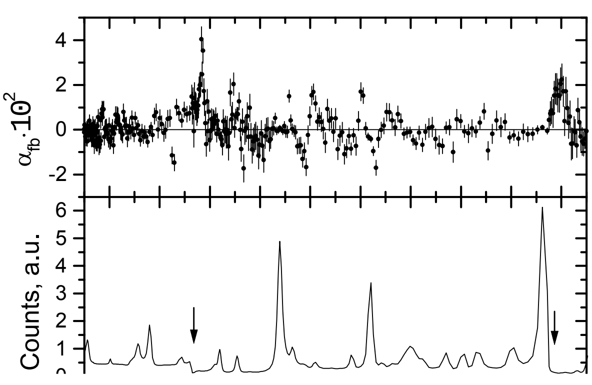


Fig. 9. Energy dependence of the asymmetry coefficient α_{fb} and fission yield for ^{235}U

Several irregularities caused by p-resonances have been observed in energy dependence of the coefficient α_{fb}. The estimation of parameters of the largest p-resonance has been made. Fitting analysis of the data showed that the average total width of the p-resonances is rather greater than that of s-resonances. For example, in a case of ^{235}U $<\Gamma_{fp}> = (200 \pm 50)$ meV and $<\Gamma_{fs}> = (140 \pm 10)$ meV. On the basis of analysis of these data, the evaluation of fast direct fission (without compound nucleus stage) contribution to the total fission cross section was obtained. It was found to be lower than $5 \cdot 10^{-2}$ at 95 % confidence level. The information obtained in these measurements is very important for the fundamental investigations of the P- and T-parity violation effects that are expected to be resonancely enhanced in the vicinity of p-resonances.

The investigations initiated at the GNEIS at Gatchina for ^{235}U have been continued for ^{233}U and ^{239}Pu at Dubna in the course of joint research with the Frank Laboratory of JINR.

7. Neutron induced fission cross-sections of ^{233}U, ^{238}U, ^{232}Th, ^{237}Np and ^{239}Pu relative to ^{235}U in the energy range 1 – 200 MeV

There is a long-standing need in information about fission of heavy nuclei induced by the particles at intermediate energies of 100 MeV – 1 GeV. The regular experimental studies of fission in this energy region started comparatively recently, mainly due to the increased capabilities of modern neutron sources and experimental techniques. In nuclear physics, the fission reaction at excitation energies above 20 MeV is studied mainly in heavy ion experiments. However, a separation of fission channel in such reactions is complicated by interference of internal (thermal) excitation with other collective excitation modes related with compression and rapid rotation of the compound nucleus formed. Investigation of the fission of "hot" nuclei with the use of intermediate energy nucleons is free of this drawback and therefore is of great interest.

Among new applications of the fission data above 20 MeV, the most important are an accelerator-driven transmutation of waste nuclear reactor materials and energy production, a peaceful use of weapon plutonium, accelerator and spaceship shielding, radiation therapy, etc. During the last 10 – 15 years, the measurements of neutron-induced fission cross sections for some long-lived actinides in the energy above 20 MeV with continuous spectrum neutrons have been systematically performed only at the WNR/LANSCE facility in Los Alamos and at the GNEIS at Gatchina. The experiments at GNEIS have been carried out as collaborative research of PNPI, V.G. Khlopin Radium Institute (KRI) and Japan Atomic Energy Research Institute (JAERI). Also, the participants from A.F. Ioffe Physical-Technical Institute (St.-Petersburg) and Radiation Physics and Chemistry Problems Institute (Minsk) took part in experiments.

Fission cross-section ratios for ^{233}U, ^{238}U, ^{232}Th, ^{239}Pu and ^{237}Np relative to ^{235}U have been measured [13-18] using a 50 m flight path of GNEIS. The results of these measurements are shown in Fig.10,11,12. To obtain fission cross sections from the measured ratios, the recommended data for fission cross-section of ^{235}U have been used. The solid lines show JENDL-3.2 data in the energy below 20 MeV. Also shown are the data of measurements carried out in Los Alamos by P.W. Lisowski et al., Staples and Morley, as well as some approximations and theoretical calculations.

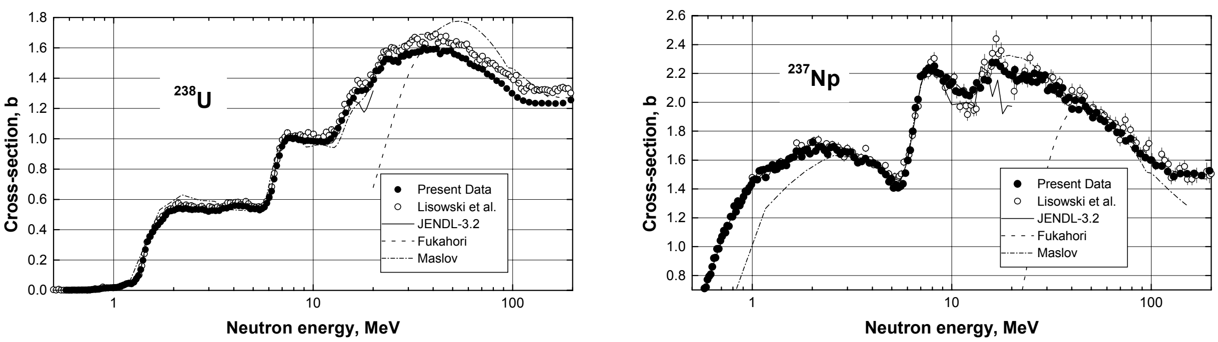


Fig. 10. Fission cross-section for ^{238}**U** and ^{237}**Np** in the energy range up to 200 MeV

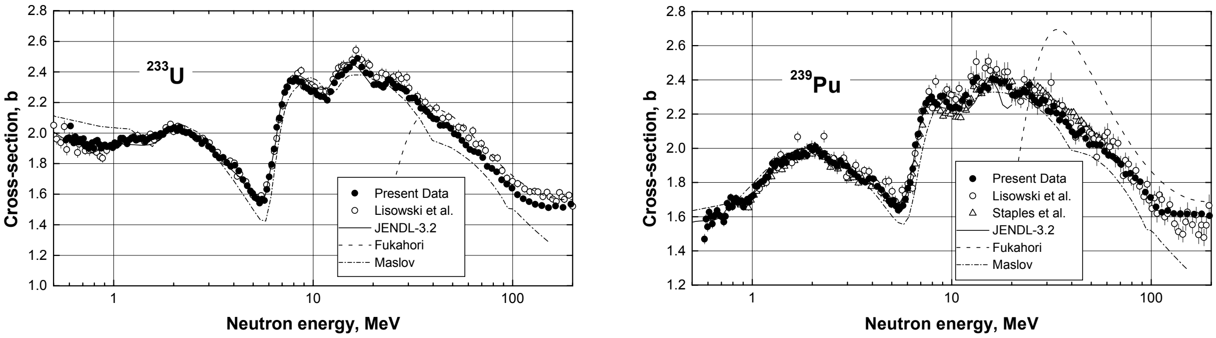


Fig. 11. Fission cross-section for ^{233}**U** and ^{239}**Pu** in the energy range up to 200 MeV

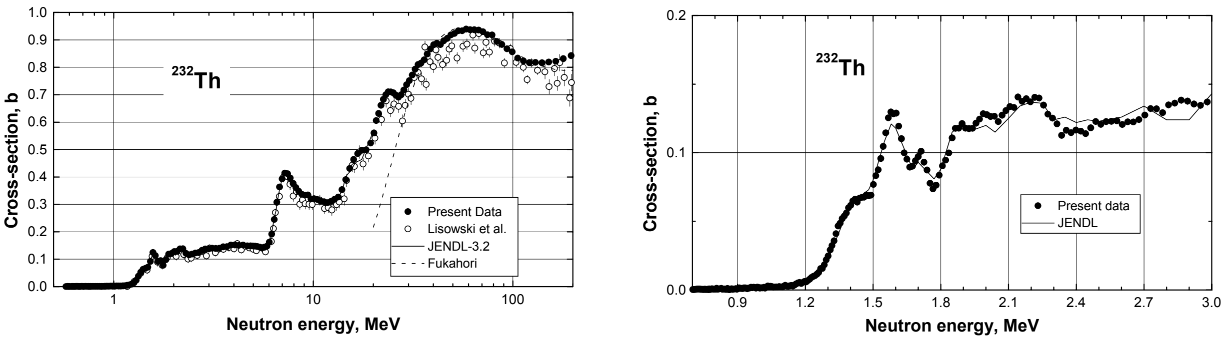


Fig. 12. Fission cross-section for ^{232}**Th** in the energy range up to 200 MeV

8. Neutron-induced fission cross-sections of lead and bismuth relative to ^{235}U in the energy range 30 - 200 MeV

During the last years, a need in information about neutron and proton-induced fission of lead and bismuth at intermediate energies increased significantly, mainly due to probable use of these metals as structural materials in the neutron-producing targets of high-current proton accelerators of new generation. Besides, the neutron-induced fission cross-sections of ^{208}Pb and ^{209}Bi are very convenient as standards in the intermediate energy range because they have thresholds at 25 – 40 MeV, which eliminates the influence of low energy neutrons. The existing experimental data are very scarce mainly due to the lack of intense neutron sources suitable to carry out the measurements in this energy range for nuclei having very small neutron partial cross sections.

The fission cross-section ratios for ^{nat}Pb and ^{209}Bi relative to ^{235}U have been measured [19] at the GNEIS simultaneously with those of actinide nuclei, using a fast multiplate ionisation chamber. An absolute normalization of the measured cross section ratios has been done using the thickness values of the targets and detection efficiencies. Finally, the cross-section ratios have been converted to cross-sections using the recommended reference fission cross section of ^{235}U. The results of the present measurements are shown in Fig. 13 as fission cross sections of ^{nat}Pb and ^{209}Bi for the neutron energies from threshold up to 200 MeV together with the experimental data of other authors and with some parameterisations.

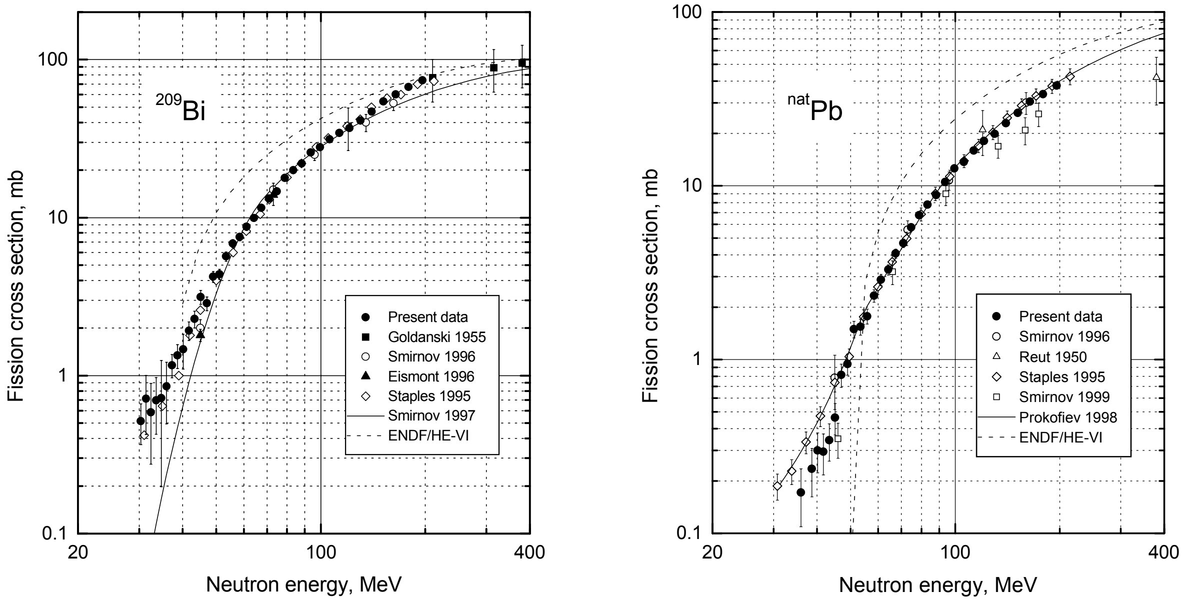


Fig. 13. Fission cross-section of ^{nat}**Pb** and ^{209}**Bi** in the energy range up to 200 MeV

9. Multiplicity distributions for fission neutrons emitted from complementary fragments in spontaneous fission of ^{244}Cm, ^{248}Cm and ^{252}Cf

The most direct information about the shape of nascent fission fragments at scission point can be obtained from the number of prompt neutrons emitted from each of two complementary fission fragments. The first neutron multiplicity measurement of this type combined with the direction–sensitive spectroscopy of fission fragments for spontaneous fission of ^{252}Cf has been done at KRI more than decade ago, followed by the analogous measurements carried out by the TUD-HMI collaboration (Germany). These experiments revealed some unusual effects, such as shape-asymmetric cold fission. A new series of such measurements for ^{244}Cm, ^{248}Cm and ^{252}Cf [20-24] has been carried out by the KRI-PNPI-IRMM collaboration within the framework of the ISTC Project 554.

The fission source was placed between two large 200 litre Gd-loaded liquid scintillator tanks which were used for neutron detection in a $2 \times 2\pi$-geometry to separate contributions from complementary fragments. An efficiency of the neutron registration was about 55% for each detector. A thick iron shielding inserted between the tanks was used to decrease both fission neutrons and capture gamma scattering from one tank into another (cross talks). The fission fragments were collimated toward neutron detectors by means of a pin-hole collimator combined with a common cathode of the twin parallel plate flow-gas ionization chamber with Frish grids.

To deduce mass and kinetic energy distributions of fission fragments, the pulse height data have been corrected for the grid inefficiency, the pulse height defect, energy losses in the sample, backing and pinholes. On the basis of reference values of themost probable mass and energies of the fission fragments, the provisional distributions have been constructed which then were corrected for mean neutron multiplicities. Neutron multiplicity measurements have been corrected for pile-up effects, background and detector efficiency, including cross talk effects. Detector efficiency have been calculated using Monte-Carlo method and known moments of the prompt neutron multiplicity distribution.

The average neutron multiplicity $\langle\nu\rangle$, the total neutron multiplicity ν_t , variance of ν, covariance $cov(\nu_l,\nu_h)$ as a function of the total kinetic energy (TKE) and the energy distribution are shown in Fig.14 (left). The same values except covariance as a function of fragment mass are shown in Fig.14 (right). The minimum in $\nu(m)$, as well as in variance is observed around m = 128 − 129 amu for all the nuclides due to the presence of a Z, N magic shells. The average level of variance for ^{252}Cf is less than in the data of Signar bieux et al. but in a good agreement with the results of Alkhazov et al. (KRI). For total neutron multiplicity the increased neutron yield is observed in symmetric fission region for ^{248}Cm and ^{252}Cf unlike to ^{244}Cm.

The average value of the cov(ν_l,ν_h) for ^{244}Cm is approximately one half as much than for ^{248}Cm and ^{252}Cf. Variances show rather flat energy dependence except the weak decrease at the lowest and the highest values of TKE, that is in a reasonable agreement with the results of Alkhazov et al. for ^{252}Cf.

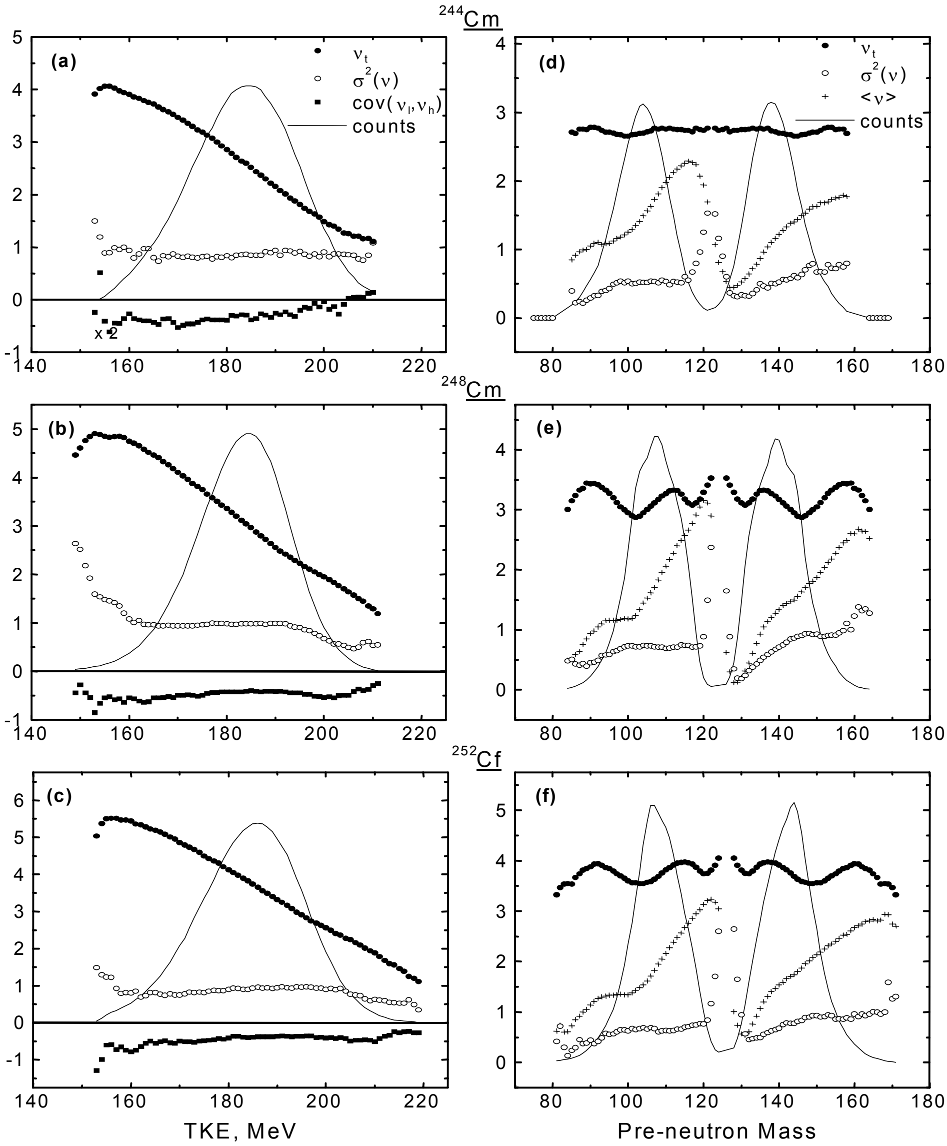


Рис. Энергетическая и массовая зависимость средней множественности нейтронов $<\nu>$, дисперсии σ^2 и ковариантности ($\nu1$,$\nu2$) вместе с массовым и энергетическим распределением

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III. Investigations of the space parity nonconservation (PNC) in the slow neutron induced fission of heavy actinides

The first observation in 1977/78 of the light (heavy) fragment emission asymmetry relative to transversally polarization of thermal neutrons initiating the $^{233,\,235}$U and ^{239}Pu fission had demonstrated that space parity is violated in this very complicated quasiclassical process [1]. The PNC asymmetry coefficients in the fragment angular distribution turned out to have the same value as the ones in more simple (n,γ) reaction.This point brought up some very important questions as follows:

– what is the manner in which universal two-body weak interaction comes into existence the P-odd asymmetry of heavy fragment emission observed in experiments,

– why the PNC effect is found to be enhanced 10^3 times to be compared with initial weak interaction,

– why the PNC effect does not disappear after averaging over huge the number of formal exit channels of the reaction,

– which stages of the strongly deformed fissioning nucleus play crucial role in the mechanism of arising PNC effect,

– which is the PNC effect dependence on the entrance and exit channel characteristics.

By the early 1980 two different theoretical approaches had been forwarded to explain the PNC effect in nuclear fission [2,3].. In spite of some differences in these two approaches, their main conclusions were in practice the same:

– starting point of the PNC effect arising is in the mixing compound states with the same spins but opposite parities by the weak N-N interaction,

– similar to the (n,γ) reaction the PNC effect enhancement is connected with the complicated structure and high level density of compound states,

– the P-odd level mixture is transferring without losses to the cold stage of strongly deformed nucleus where the PNC asymmetry of fragment emission is formed,

– the averaging of the PNC effect does not in practice come because of very the small number of the quasi steady quantum states near the top of external potential barrier that just play the role of real exit channels of fission reaction,

– according to the theory average PNC effect values are expected to be the same for different fragment kinetic energies and masses.

It was supposed in the both theoretical approaches that collective movement of deforming excited compound system over fission barriers to the rupture point has to be adiabatic with respect to the single particle excitations. The theories advocate in addition that well known in nuclear physics P-even interference effects of left-right and forward-backward asymmetry of reaction product (fragments) emission have to have very similar mechanism of arising in fission as the PNC effect. The only difference exists between them: P-even interference effects have their origin in overlapping of all the neighbouring compound states excited after s- and p-wave neutron capture as compared with the compound states mixing by the weak N-N interaction in the PNC effect mechanism.

Thus, the total angular distribution of fragments in fission induced by low energy polarized neutrons in general case has the following view:

$$W(\phi,\varphi,\theta) = 1 + \alpha_{nf}\cdot(\boldsymbol{\sigma}_\mathbf{n}\cdot\mathbf{p}_\mathbf{f}) + \alpha_{lr}\boldsymbol{\sigma}_\mathbf{n}\cdot[\mathbf{p}_\mathbf{n}\ \mathbf{x}\ \mathbf{p}_\mathbf{f}] + \alpha_{fb}(\mathbf{p}_\mathbf{n}\cdot\mathbf{p}_\mathbf{f})\cdot$$

where $\mathbf{p_f}$ and $\mathbf{p_n}$ are linear momenta of the light (heavy) fission fragment and neutron, σ_n **is** neutron polarization, α_{nf} , α_{lr} and α_{fb} **are** PNC, left-right, and forward-backward asymmetry coefficients respectively. It is very simple to see that all the types of these angular distributions contain only odd spherical harmonics. For the simplest case of mixing only two isolated compound states with opposite parities the theory presents the following equations for the asymmetry coefficients [2,3]:

$$\overline{\alpha}_{nf}(E_n) = Q'_{sp}\cdot\sqrt{\frac{\Gamma_p^f}{\Gamma_s^f}}\cdot\mathrm{Re}\left\{\frac{\langle\ \mathrm{P}|V_{sp}|S\ \rangle}{(E-E_p)+i\Gamma_p/2}\cdot\exp(i\Delta'_{sp})\right\},$$

$$\overline{\alpha}_{lr}(E_n) = Q_{sp}\cdot\sqrt{\frac{\Gamma_p^f\Gamma_p^n}{\Gamma_s^f\Gamma_s^n}}\cdot\mathrm{Im}\left\{\frac{(E-E_s)+i\Gamma_s/2}{(E-E_p)+i\Gamma_p/2}\cdot\exp(i\Delta\varphi_{sp})\right\},$$

$$\overline{\alpha}_{fb}(E_n) = Q_{sp}\cdot\sqrt{\frac{\Gamma_p^f\Gamma_p^n}{\Gamma_s^f\Gamma_s^n}}\cdot\mathrm{Re}\left\{\frac{(E-E_s)+i\Gamma_s/2}{(E-E_p)+i\Gamma_p/2}\cdot\exp(i\Delta\varphi_{sp})\right\},$$

where Γ_s^n and Γ_s^f are s-wave neutron and fission widths, Γ_p^n and Γ_p^f are p-wave neutron and fission widths, Γ_s and Γ_p are total s-wave and p-wave widths, E_s and E_p are energies of s- and p-resonances mixed. Q_{sp} is spin factors of mixing s- and p-resonances, $\Delta\varphi_{sp}$ is phase difference of mixing s- and p-resonances.

In the real case of heavy fissile nucleus the equations look considerably more complicated as the level spacing in such nuclei is ofthe same order of magnitude as the total level widths. But from these simplified expressions one can easily see the main similarities of all three asymmetry effects and understand the fact that joined investigation of these effects can give very rich information about parameters of s- and p-wave neutron resonances and matrix elements of weak interaction.

1. Average values of the PNC asymmetry effect of fission fragment emission

These systematic investigations were begun in 1978 at the polarized neutron guide of the WWR-M reactor and were continued and completed at the High Flux reactor of the Laue-Langevin Institute in Grenoble (France). At the first stage of investigations the aim consisted in verification of the first results [1] of ITEP group. Hereafter the investigations were directed to measurements of signs and magnitudes of the PNC effect in ^{229}Th, ^{237}Np, ^{241}Pu, ^{241}Am, ^{245}Cm , and ^{249}Cf fission. Our principal concern was the subbarrier fission of ^{237}Np and ^{241}Am because of theoretical prediction of Vladimirsky [4] concerning the possible existence of so-called barrier enhancement of the PNC effect in spontaneous fission. In some cases the P-even effect of left-right asymmetry were measured in the same experimental runs. The results of all these investigations together with some important characteristics of fissioning systems are shown in the Table I [5,6,7,8]. In the first column of the Table I the following parameters are shown: I is fissile target spin, $(B_n–E_A^f)$ and (B_n-E_B) are excitation energies of compound system above the tops of internal and external fission barriers, <D> and $<\Gamma_f>$ are average compound level spacing and fission width, S_0 and S_1 are s- and p-wave neutron strength functions, α_{nf} and α_{lr} are PNC and left-right asymmetry coefficients, $<D_{trip}>$ is average value of T-odd asymmetry coefficient in ternary fission (see chapter III).

***Table* 1**

The PNC and P-even left-right asymmetry coefficients together with some important parameters of fissile nuclei studied (all coefficient are reduced to the neutron wavelength of 4Å)

value\target	^{229}Th	^{233}U	^{235}U	^{237}Np	^{239}Pu	^{241}Pu	^{241}Am	^{245}Cm	^{249}Cf
J	5/2+	5/2+	7/2-	5/2+	1/2+	5/2-	5/2-	7/2+	9/2+
σ_f, b	30	529	583	0.0215	748	1011	3.2	2145	1642
$(B_n–E_A^f)$, MeV	1.2	1.2	0.9	-0.1	0.9	0.7	-1.0	0.76	0.9
$(B_n–E_B^f)$, MeV	0.1	1.3	1.0	0.4	1.4	1.2	0.1	2.26	2.6
ΔE_{sc}	15	20	19	20	22	21	26	26	28
<D>, eV	0.53	0.55	0.44	0.52	2.3	1.34	0.55	1.14	1.07
$<\Gamma_f>$		0.37	0.15	10^{-6}	1.13	0.35	1.5×10^{-4}		
$S_0\times10^4$	0.62	1.04	1.0	1.02	1.3	1.1	0.9	1.2	1.0
$S_1\times10^4$	(~2)	(~2)	1.8	2.3.	(~2)	(~2)	(~2)	(~2)	(~2)
$\alpha_{nf}\times10^4$	-5.6(2)	3.67(6)	0.84(6)	0.9(4)	-5.0(1)	-0.89(4)	-1.0(2)	-0.26(6)	0.13(13)
$\alpha_{lr}\times10^4$	2.1(3)	-2.3(2)	1.6(1)	–	1.3(3)	–	–	0.1(1)	–
$<D_{trip}>\times10^4$	–	24(1)	4(1)	–	1(2)	–	–	13(6)	–

Analysis of the data presented in the Table I leads to the following conclusions:

– the PNC asymmetry effect is observed in all the cases investigated except ^{249}Cf, where statistical accuracy is not high enough,

– in spite of evident fluctuations, the general tendency of decreasing of the PNC effect magnitudes is observed when going from ^{229}Th to ^{249}Cf. Similar tendency, but more evident expressed, is observed for the P-even left-right asymmetry effect magnitudes.

– such a tendency may be explained by partial depolarization of compound system spin caused by progressive violation of adiabatic movement of the deforming system over potential barrier to the rupture point,

– any essential specific barrier enhancement (or reduction) of the PNC effect value, predicted by Vladimirsky [4], is not observed in experiment.

2. The PNC effect dependence on the fission fragment masses and on total kinetic energies

These experimental investigations were carried out in three steps. In the first experiments, performed at the WWR-M reactor in 1979/81, it was shown that the PNC asymmetry effect in ^{233}U fission does not depend on the intervals of fragment masses and on the total kinetic energies within the limits of experimental errors [7,8]. This experiment was performed with rather poor resolution for masses (about 6 a.m.u) and fragment kinetic energies (about 2 MeV), see Fig. 1.

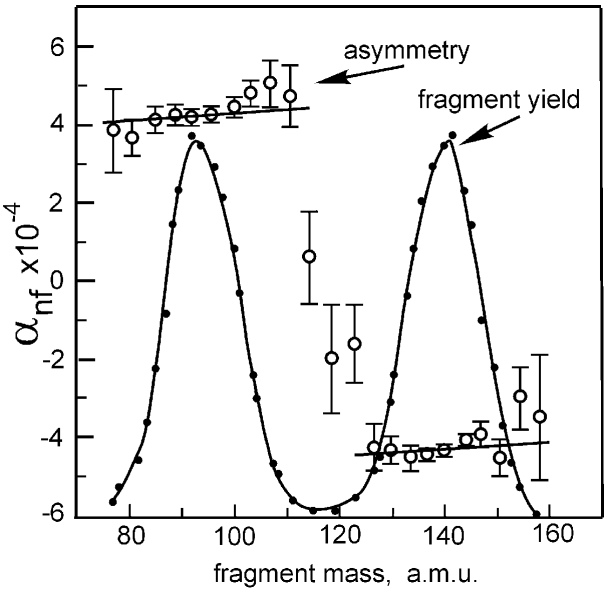

Fig. 1. P-odd asymmetry as a function of fragment mass

For presentation of two parameter experimental data we used the linear expansion of the PNC asymmetry coefficient

$$\alpha_{nf}\left(M, E_{kin}^{t}\right) = \alpha_0 + \alpha_1\left(M - M_0\right) + \alpha_2\left(E - E_0\right) + \ldots$$

The expansion coefficients are turned out to be equal to: $\alpha_0 = (4.43 \pm 0.10)\cdot10^{-4}$, $\alpha_1 = (0.03 \pm 0.02)\cdot10^{-4}$ and $\alpha_2 = (0.01 \pm 0.01)\cdot10^{-4}$.

At the second stage of investigations the average values of the PNC asymmetry coefficients were measured in the ^{229}Th, ^{233}U, ^{241}Pu and ^{241}Am for three selected intervals of the heavy fragment kinetic energies typical for so-called Brosa's valleys [5]. These data presented in the Table 2 do not demonstrate any essential difference in the PNC-effect values for selected energy interval as well.

***Table* 2**

P-odd asymmetry coefficients for different intervals of the heavy-fission-fragment kinetic energies

α_{nf}^{i}	^{229}Th	^{233}U	^{241}Pu	^{241}Am
$\alpha_1\ 10^4$	(5.5 ± 0.3)	$-(3.6 \pm 0.1)$	(0.96 ± 0.05)	(0.9 ± 0.4)
$\alpha_2\ 10^4$	(5.7 ± 0.3)	$-(3.6 \pm 0.1)$	(0.83 ± 0.05)	(0.9 ± 0.4)
$\alpha_3\ 10^4$	(5.6 ± 0.3)	$-(3.8 \pm 0.1)$	(0.86 ± 0.05)	(1.1 ± 0.4)

In 1998 these experimental data and all the conclusions made from the data analysis were completely confirmed in the experiment carried out in ILL in collaboration with Tuebingen University with very good fragment mass and kinetic energy resolution /6/. In such a manner it was fully strengthened the theoretical prediction about the PNC effect independence on the main fission product properties such as their masses and total kinetic energies (average fragment excitation energies).

3. Joint investigations of neutron energy dependence of the PNC and P-even left-right and forward-backward asymmetry effects

The first attempt to study neutron energy dependence of the PNC asymmetry effect value in the ^{239}Pu fission was made by the ITEP – JINR collaboration at the pulsed reactor IBR-30. But because of small amount of fissile material and relatively low intensity of polarized neutron beam, it was only demonstrated the PNC effect increases in the vicinity of the strong s-resonance of 0.3 eV as compared with thermal neu tron point. The first systematic investigations of the PNC and left-right asymmetry effects at different neutron energies became possible in LNPI with the use of crystal diffraction monochromator of polarized neutrons placed on the radial channel of the WWR-M reactor [9,10].

Systematic investigations of another P-even interference effect of forward-backward asymmetry of fission fragment emission were started at the time-of –flight spectrometer GNEIS after development of special method to damp false asymmetry effects. In the course of measurements, the geometrical axis of the many section ionisation chamber had two possible orientations along the neutron beam and was changed periodically by the computer-controlled mechanical driver [11].

For the fragment energy registration and rough separation of light and heavy fragment groups the fast many sectioned ionization and scintillation chambers of different types had been developed. In such a manner it had been made possible to use a large amount of fissile isotopes (up to 100 mg in the first experiments and about 1 – 2 g. in the experiments at the IBR-30).

The main measurements of the PNC and P-odd asymmetry coefficients as functions of the resonance neutron energies in the ^{233}U, ^{235}U, and ^{239}Pu fission were carried out by LFP in collaboration with the Laboratory of Neutron Physics (JINR) in Dubna. Measurements of the left-right asymmetry and parity violation effects require the beam of polarized resonance neutrons. They are available from the IBR-30, where the POLYANA facility for neutron polarization is located at 9 m. from the reactor moderator. The forward-backward asymmetry measurements were carried out on nonpolarized neutron beam of the IBR-30 with the 33 m flight path.

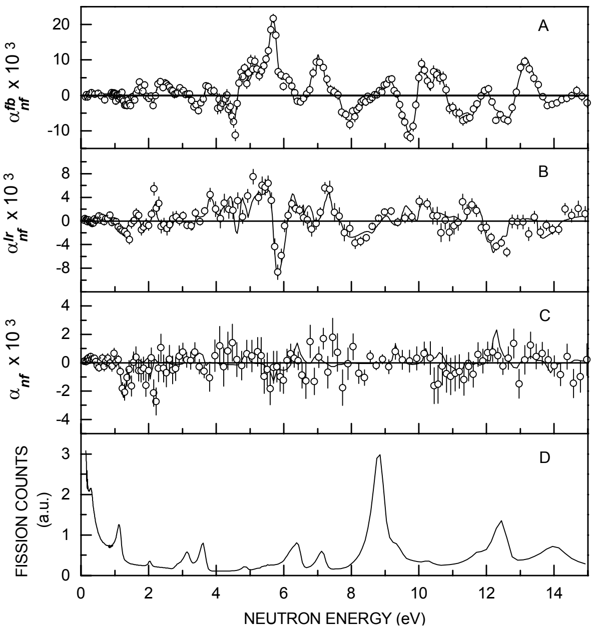

Fig. 2. PC forward-backward (A), PC left-right (B) and PNC (C) interference effects in the fission fragment emission of ^{235}U as a function of neutron energy over the range 0.02 – 1) eV; the curves are the result of the theoretical fit. D is the experimental fission count spectrum

The measurements with different targets were carried out consecutively beginning with ^{235}U, then we had changed it on ^{233}U, and finished with ^{239}Pu (the measurements for the last nucleus are in progress for the moment). The energy range investigated was up to 100 eV [12,13,14,15].

As an illustration of the information obtained in such experiments, the neutron energy dependence of the P-even and PNC asymmetry coefficients in the ^{235}U fission for two low-energy regions is shown in Figs. 2, 3 (parts A, B, and C, respectively) and in Table 3. The curves shown in the figures are the result of theoretical fittings. It is interesting to point out some general characteristics of the asymmetry coefficients as the functions of the neutron energy presented in Figs. 2, 3.

First, the neutron energy dependence of the FB and LR asymmetry coefficients have well-marked irregularities over the whole investigated energy of range ^{235}U according to the modern theory.

Second, in some cases the widths of the observed irregularities exceed the average widths of s- and p-resonances. The number of such irregularities is found to be well below the average s- and p-resonance density expected from the known data. Such strong irregularities may arise as the result of accidental overlapping of some neighbouring resonances with the same sign of the interference effects.

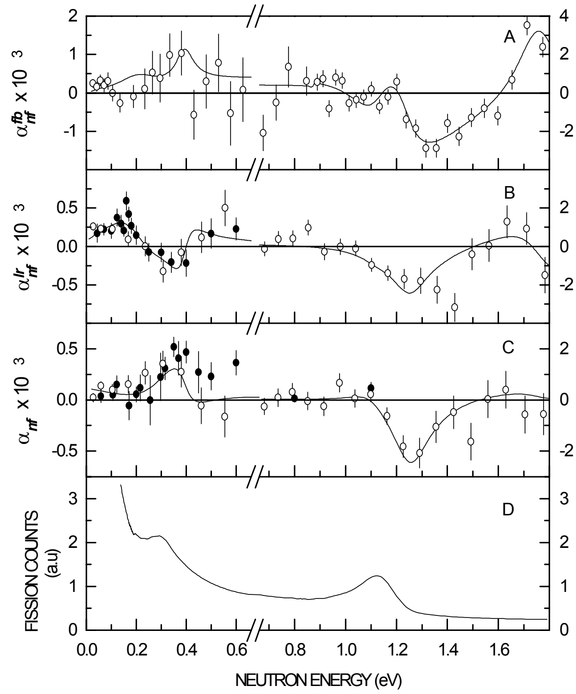

Fig. 3. PC forward-backward (A), PC left-right (B) and PNC (C) interference effects in the ^{235}U fission fragment emission as a function of the neutron energy over the range 0.02 – 1.8 eV. Open circles are the results of the measurements at the IBR-30 reactor, solid circles are the data obtained at the WWR-M reactor ; the curves are the result of the theoretical fit. D is the experimental fission count spectrum

Third, in contrast to FB and LR asymmetry effects the statistical accuracy of the PNC effect measurements achieved in our investigations is not high enough to examine the behaviour of the α_{nf} coefficient as a function of the neutron energy over the whole available interval. For example, in the case of ^{235}U fission the resonance behaviour of the PNC asymmetry coefficients was reliably observed only in the region of low neutron energies: E_n=0.3 eV and E_n=1.2 eV (and, possibly, 2.0 eV). The effects have different signs and magnitudes in the maxima.

As a result the low energy range presents a special interest for the theoretical analysis. Results of the combined analysis of the PC and PNC asymmetry coefficients from 20 meV up to ≈2 eV are presented in Fig. 3. The closed points show our early results of the PC LR and PNC asymmetry studies obtained with polarizing crystal-diffraction monochromator of the WWR-M reactor. One can see a good agreement between the experimental points obtained with the use of two quite different methods.

As it follows from the theoretical equations presented above, the values of both PC interference effects are determined with the same set of s- and p-resonances.

Having the experimental data on neutron energy dependence of the α^{lr}_{nf} and α^{fb}_{nf} asymmetry coefficients and using well-known parameters of s-resonances inside the energy interval of interest, one can obtain the most probable values of p-wave resonance energies, its angular momentum, and neutron and fission widths.

As this takes place, the PNC asymmetry coefficients $\alpha_{nf}(E)$ can be used to determine the weak interaction matrix elements. The only parameters that can be changed in the last fitting procedure are the matrix elements playing, in fact, the role of scale factors and has no effect on the shape of the PNC effect peculiarities in neutron energy dependence. To obtain p-resonance parameters by the least-squares method, we used the standard FUMILI code. P-wave resonance parameters for all the investigated nuclei are presented in Table 3.

Systematic errors may appear because of a limited knowledge of some s-resonance parameters like, for example, partial fission widths for different *K*-value. It is common knowledge that for heavy fissile actinides under low excitation energies ($E^*\approx B_n$) there may be following values for this parameter: *K*=0; 1; 2.

In the absence of reliably determined *K*-values, usually we used in our fitting procedure *K*=1 as the most probable parameter for all the resonances.

The energies and total widths of p-resonances may be considered as the most stable fitted parameters, because they are determined mainly by the peculiarity positions and widths under the condition that the numbers and spins of p-resonances involved in the analysis are determined correctly.

There is no preliminary definite information about phase difference factor $\Delta\varphi^f_{sp}$. Bunakov and Gudkov [3] proposed the value $\Delta\varphi^f_{sp} = 0$ for all the cases of low energy fission. In contrast to these authors, Flambaum and Sushkov [2] used indeterminate factor $\Delta\varphi^f_{sp}$ that has to be determined from the experiment.

So, we retain $\Delta\varphi^{f}_{sp}$ as a fitting parameter too. As a result of the fit it was obtained that $\Delta\varphi^{f}_{sp}$ is changeable and is situated in the range from -π to π. Moreover, as usual phase factors include all the inaccuracies of the main simplified assumptions and the fitting procedure as well.

***Table* 3**

Main p-resonance parameters obtained in a combined fit of the PC (forward-backward and left-right) asymmetry effects in the range 0.02 – 15 eV in ^{235}U fission

	E_p, eV	J_p	Γ^{n1}_p, meV **	Γ^{f}_p, meV	$\Gamma^{n}_{p,1/2}/\Gamma^{n}_p$	$\Delta\varphi^{f}_{sp}, rad$
1.	0.19±0.03	3	0.3±0.1	180±60	0.99±0.01	2.4±0.3
2.	0.39±0.02	(3)	0.02±0.01	60±50	0.50 *	2.9±0.3
3.	1.21±0.02	4	0.23±0.09	210±25	0.66±0.09	1.2±0.2
4.	1.76±0.01	4	0.10±0.02	190±45	0.71±0.03	0.00±0.01
5.	2.17±0.01	3	18 *	70±35	0.99±0.01	0.0 *
6.	2.54±0.02	4	0.4±0.1	440±75	0.22±0.01	0.01±0.02
7.	319±0.02	3	0.08±0.02	330±150	0.22±0.01	2.5±0.5
8.	3.35±0.05	4	2.3 *	20 *	0.98±0.02	0.0±0.1
9.	3.70±0.01	4	0.05±0.02	80±60	0.11±0.02	0.0±0.4
10.	3.97±0.02	4	0.05±0.02	160±90	0.87±0.04	0.0±0.1
11.	4.57±0.02	(3)	1.4±0.4	70±30	0.01±0.01	0.17±0.01
12.	5.29±0.02	4	1.4±0.3	470±80	0.21±0.02	0.00±0.01
13.	5.40±0.09	3	3.9±0.7	1640±240	0.97±0.01	-0.05±0.15
14.	5.74±0.02	4	3.5±0.3	150±20	0.80±0.06	-0.1±0.1
15.	6.95±0.03	4	0.7±0.2	190±60	0.76±0.14	-2.2±0.2
16.	7.37±0.04	3	0.8±0.3	250±130	0.99±0.01	0.1±0.2
17.	7.78±0.19	(4)	1.6±0.2	1370±220	0.16±0.08	0.5±0.1
18.	9.28±0.08	4	1.6±0.4	120±30	0.37±0.05	0.15±0.05
19.	9.77±0.02	(3)	0.7±0.2	90±60	0.01±0.01	1.0±0.2
20.	10.16±0.03	4	4.5±2.3	50±20	0.23±0.03	0.05±0.05
21.	10.65±0.05	4	1.5±0.3	220±90	0.44±0.19	0.00±0.15
22.	11.28±0.05	(3)	1.6±0.5	190±90	0.14±0.12	2.1±0.2
23.	11.66±0.14	3	2,0±1.3	200±150	0.97±0.07	0.05±0.40
24.	12.00±0.02	4	0.5 *	180 *	0.99±0.01	0.00±0.01
25.	12.23±0.03	3	0.8±0.3	80 *	0.99±0.01	2.5±0.5
26.	12.38±0.12	4	1.2±0.8	70±50	0.99±0.01	-2.3±0.3
27.	12.85±0.03	(4)	4.5±1.2	290±150	0.30±0.20	-3.1±0.3
28.	13.23±0.05	4	0.6±0.2	450±150	0.30±0.15	0.3±0.3
29.	13.90±0.04	4	0.5±0.2	150±100	0.99±0.01	3.15±0.25

*) The estimates of these parameters are not reliable.

**) Γ^{n1}_p is the total reduced neutron width.

All the pointed errors are fitting procedure ones only (see text).

Finally, it can be seen from Figs. (2,3) that a satisfactory, on the whole, joint description of the PC and PNC interference effects has been achieved for the ^{235}U.

Values of the weak interaction matrix elements for the low energy p-resonances in ^{235}U fission obtained by fitting procedure are presented below:

E_p, eV	0.19	0.39	1.21
$\langle p\|H_W\|s\rangle$	$1\cdot10^{-4}$	$7\cdot10^{-4}$	$5.5\cdot10^{-4}$

The estimated errors are about 30%. For the resonance with E_p = 2.17 eV in ^{235}U fission we could obtain only a preliminary estimate for the matrix element value of about $3\cdot10^{-3}$ eV. For all other p-resonances involved in the forming of the PNC-effect, and invisible in the neutron energy dependence of $\sigma_{nf}(E_n)$ coeffi cients because of a low statistical accuracy, we can give only the upper limit of the weak interaction matrix element equal to about 10^{-3}.

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IV. Investigations of the triple correlation in the ternary fission induced by the cold polarized neutrons

In 1998 collaboration of ITEP, PNPI of RAS and Tuebingen and Darmstadt Universities have observed for the first time so called T-odd triple correlation in the ^{233}U ternary fission of the following type:

$$W(\theta,\varphi) = 1 + \langle D\rangle\cdot\sigma_{\mathbf{n}}\cdot[\mathbf{p_f} \times \mathbf{p}_\alpha],$$

where σ_n, $\mathbf{p}_f$, and $\mathbf{p}_\alpha$ being unit vectors of longitudinal polarization of cold neutrons and linear momenta of the separated fission fragments and the light charged ternary particles respectively. The average asymmetry <D> coefficient value was turned out to be equal to $(2.40 \pm 0.08)\cdot 10^{-3}$ [1]. The next two years the collaboration continued the triple correlation investigations on the powerful polarized neutron beam of the High Flux Reactor of the Laue-Langevin Institute using modernized experimental set-up constructed by two German Universities [2,3]. As a result T-odd effect was observed in the ^{235}U ternary fission as well and was measured separately for the α-particles and tritons in both fissile isotopes. In addition rather strong dependence of the <D>coefficient values on the light particle kinetic energies was observed. At the same time in parallel with the main experiment the new experimental set-up, designed in PNPI of RAS, was used for the first search investigations of the triple correlation in the ^{239}Pu and ^{245}Cm ternary fission [4].

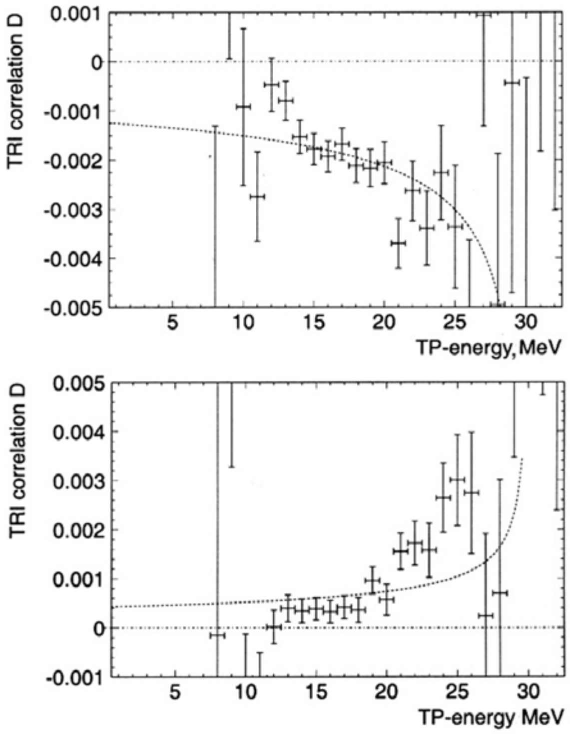
All the experimental information about triple correlation in ternary fission together with the values of P-odd and P-even interference effects in ternary and binary fission obtained in the same investigations are presented in the Table 1 and Fig.1.

***Table* 1**

T-odd, P-odd, and P-even asymmetry coefficient values in ternary and binary fission of heavy actinides induced by the cold polarized neutrons [1,2,3]

Target coefficient	^{233}U	^{235}U	^{239}Pu	^{245}Cm
$<D_\alpha>\cdot 10^3$	- (2.52 ± 0.14)	+(0.83 ± 0.11)	- (0.08 ± 0.23)	+(1.30 ± 0.48)
$<D_t>\cdot 10^3$	- (1.99 ± 0.63)	+(0.60 ± 0.41)	—	—
$<\alpha_\alpha>^{LR}\cdot\cdot 10^4$	- (0.8 ± 0.8)	—	—	—
$<\alpha_\alpha>^{PNC}\cdot 10^4$	- (0.6 ± 0.4)	—	—	—
$<\alpha_{ft}>^{PNC}\cdot 10^4$	+ (3.7 ± 0.10)	—	—	—
$<\alpha_{fb}>^{PNC}\cdot 10^{4\,(*)}$	+ (3.65 ± 0.06)	+ (0.80 ± 0.06)	- (5.1 ± 0.1)	- (0.26 ± 0.06)
$<\alpha_{fb}>^{LR}\cdot 10^{4\,(*)}$	- (2.33 ± 0.25)	+ (0.91 ± 0.07)	+ (0.47 ± 0.11)	+ (0.2 ± 0.2)
$<\alpha_{ft}>^{LR}\cdot 10^4$	- (5.7 ± 1.3)	—	—	—

(*) Experimental values of asymmetry coefficients for binary fission was taken from the Table 2 (chapter III).



Even preliminary analysis of the experimental data obtained up to now has lead us to a conclusion that the new effect in ternary fission is closely connected with fission dynamics. It seems to be evident that detailed theoretical and experimental investigations of the triple correlation present a new way to obtain very interesting and important information about this complicated nuclear process. On the other hand so called T-odd asymmetry effect observed probably has no connection with the problem of time reversal invariance as it was proposed before, but it is a result of outgoing particles interaction at the exit of the ternary fission reaction.

Fig.1. Dependence of the T-odd asymmetry coefficients <D> on the kinetic energies of the light charged particles in the ^{233}U (top panel) and ^{235}U (bottom panel) ternary fission induced by the cold polarized neutrons. Dotted curves present the fit of theoretical equations from the works Bunakov et al [5,6]

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V. First measurements of the PNC neutron spin rotation in the vicinity of p-wave resonance of ^{139}La with the energy of 0.734 eV

At the first sight these investigations are situated aside of the main field of the PFL interests. But on the other hand the crystal diffraction method of the PNC effect investigations in fission developed in the FPL presented very tempting possibility to study this PNC effect in neutron optics never experimentally observed before. As it is well known, the universal weak interaction makes into existence the PNC neutron optics phenomena under polarized neutron passing through the matter. These effects consist in neutron spin rotation about its linear momentum:

$$\phi^{PNC} = - 4\pi/k\cdot n\cdot L\cdot Re\ (\ f(0)_+ - f(0)_-\ )$$

and so-called neutron optical dichroism:

$$\Delta\sigma^{PNC} = 4\pi/k\cdot Im\cdot(\ f(0)_+ - f(0)_-\ ),$$

where k is neutron wave number, n is nuclear density, L is target thickness, and $f(0)_\pm$ are neutron scattering amplitudes for two opposite neutron helicities. These effects were observed before for the thermal neutrons, but only PNC effect of neutron dichroism had been investigated for the resonance neutrons. Using specially designed in the FPL original neutron polarimeter and polarizing crystal diffraction monohromator, placed on the horizontal radial channel of the WWR-M reactor, both these effects were measured for the first time in the vicinity of the ^{139}La p-wave resonance with the energy of 0.734 eV [1]. The results of these measurements are presented in Fig.

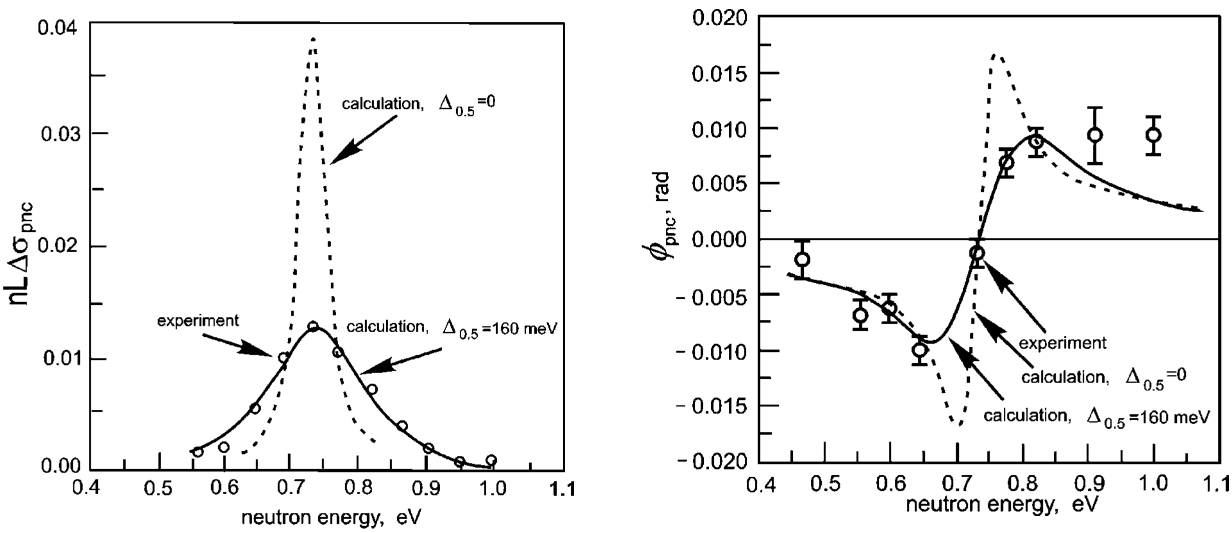

Fig. Main experimental results (points) in comparison with theoretical predictions (solid curves): PNC neutron dichroism (left) and PNC effect of neutron spin rotation (right). Dotted curves are the same effects but with ideal energy resolution

Three years later the same measurements had been carried out with a new polarimeter at the High Flux reactor in the Laue-Langevin Institute in Grenoble [2]. The third version of neutron polarimeter had been prepared for the new measurements of the PNC neutron spin rotation in bromine [3].

Apart from the new important physical information receipt, these experiments brought into existence essential improvement of experimental methods of a neutron spin rotation effects measurements what is extremely important for the future search experiments on the possible time reversal invariance violation.

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V. Conclusion and a short sketch of scientific program for the new reactor PIK

Taking into account forty-years experience of FPL in the field of fission physics and twenty years of investigations in the field of fundamental law in the complicated nuclear reactions with neutrons, we plan to continue our scientific activity in these both directions after putting into operation the new powerful reactor PIK as well. We start from the point that the success may be achieved only with new and original experimental techniques of investigations of high efficiency. That is why we are directing our efforts on design and development of such techniques and new experimental methods. In particular, one of the problem of great importance consists in creation of powerful beams of polarized and unpolarized resonance neutrons of low energies (up to 10 eV). As a result of very fruitful collaboration with ITEP the mechanical chopper-monochromator of high transparency was developed and tested at the reactor WWR-M. The monochromator consists of four synchronized metallic rotors hanging up in magnetic field and rotating in vacuum. The results of tests and calculations had shown that this device being placed at the radial channel of the PIK reactor will be able to give the intensity of low energy neutrons comparable with modernized pulsed reactor IBR-30 or spallation source LAMP (USA).

Another installation, directed to the creation of powerful polarized neutron beam of resonance neutrons up to 2 eV, is planned to be placed on the radial channel of PIK reactor as well. It will be based at polarizing crystal (Heisler alloy of FeCo) or at polarized ^{3}He target + crystal with high reflectivity. A full scale model of such an instrument with magnetized Heisler alloy crystal, being developed about 20 years ago, was very successfully used for fundamental investigations.

The main directions of fission physics investigations will be connected with fission dynamics. Basically instruments for the investigations in this field are double arms fission fragment spectrometer with the internal target placed near the reactor core and the 4π-crystal-ball detector of fission neutrons and gamma rays. The modeling of the instruments of such types had been already performed partly at the through channel of the WWR-M reactor. In collaboration with MEPhI double-arms time-of-flight spectrometer of fission fragments with the internal target was successfully tested at the WWR-M reactor as well. Owing to the magnet "JOSEF", done by Jülich Institute, we have very important part of our future magnetic spectrometer of unslowed fission fragments which is very similar to the famous spectrometer "LOHENGRIN" of the Laue-Langevin Institute in Grenoble. The prototype of 4π-crystal-ball detector does successfully operate already in the measurements of fast fission neutron multiplicity.

In conclusion we would like to express a hope that our plans and program will be favorably accepted by scientific authority and will get all the necessary support.