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

O.A. Shcherbakov, A.B. Laptev, G.A. Petrov
A.S. Vorobyev

Petersburg Nuclear Physics Institute, Gatchina
Leningrad district, 188355, Russia
shcherba@hep486.pnpi.spb.ru

B.P. Konstantinov Petersburg Nuclear Physics Institute
Russian Academy of Sciences

RESEARCH AREAS:

- **elementary particle physics**
- **nuclear and atomic physics**
- **physics of the condensed matter**
- **molecular and radiation biophysics**

MAIN RESEARCH FACILITIES:

- **1 GeV proton synchrocyclotron**
- **18 MWt reactor WWR-M**
- **100 MWt high flux reactor PIK (under construction)**

Internet URL http://www.pnpi.spb.ru

PNPI SYNCHROCYCLOTRON
general information

Diameter of the magnet pole pieces	685 cm
Width of the gap between poles	50 cm
Magnet weight	8,000 t
Electric power supplied	1 MWt
Frequency range	30 – 13 MHz
Accelerating voltage	10 kV
Repetition rate	40-60 Hz
Internal beam intensity	< 3 μA
Extraction coefficient	30 %
Duty cycle coefficient	50 %

proton beam characteristics

particle	E (GeV)	ΔE/E (%)	Intensity (s^{-1})	channel number	comment
proton	1	1	$6 \cdot 10^{12}$	P1,P2,P3,P4	
proton	1	1	10^8	P2	medical small size beam 3 mm x 5 mm
proton	1	0.03	10^{10}	P2	spectrometry beam, time gate extraction

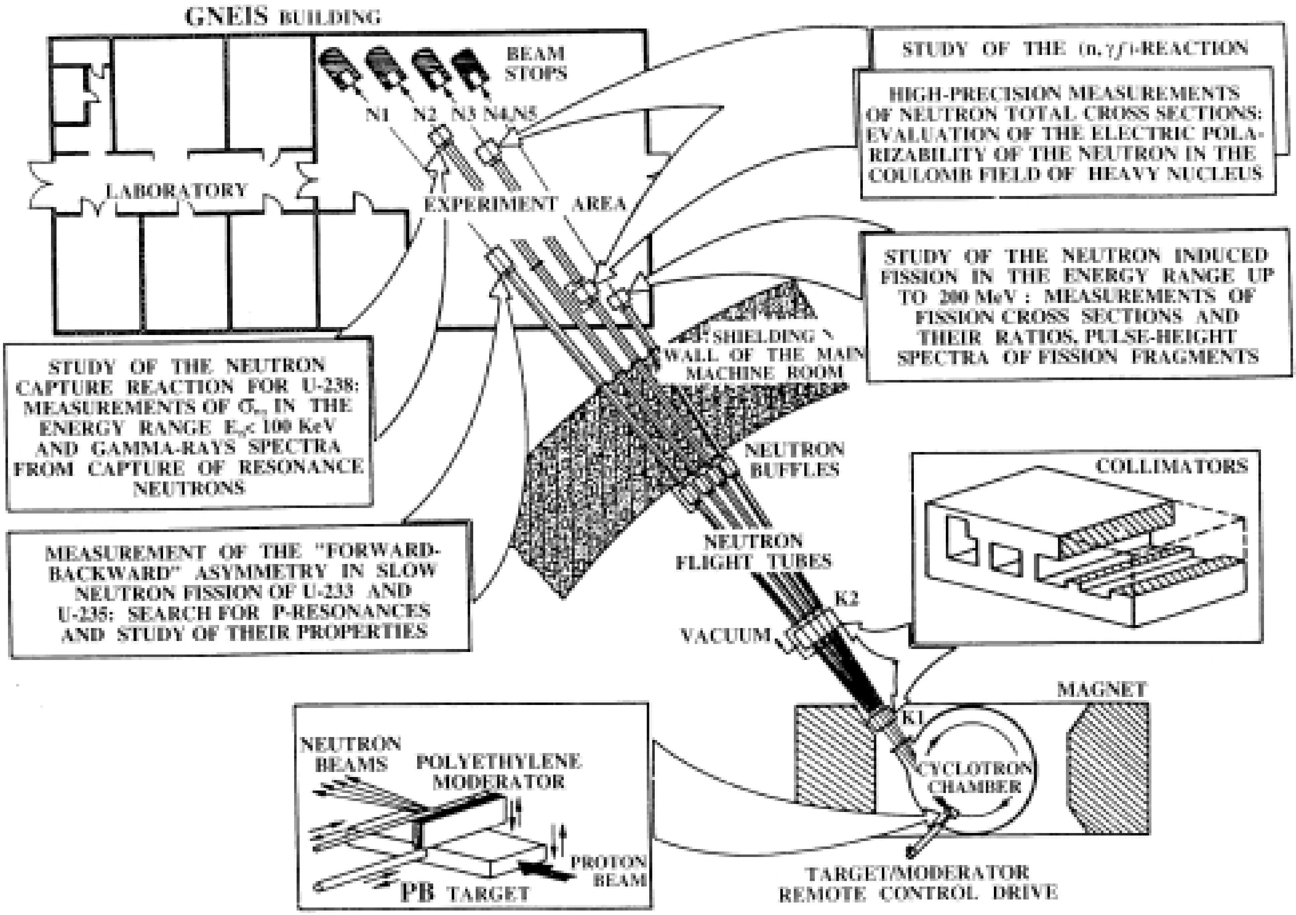


Fig.1. General layout of the Gatchina neutron time-of-flight spectrometer GNEIS

Pulsed neutron source:

- internal water-cooled rectangular lead target	**40 cm x 20 cm x 5 cm**
- rectangular polyethylene moderator	**30 cm x 10 cm x 5 cm**
- duration of the fast neutron pulse	**~ 10 ns**
- repetition rate	**< 50 Hz**
- average fast neutron intensity	**~ $3\cdot10^{14}$ n/s**

Spectrometer:

- number of evacuated flight paths (one beam N5 axis looking at the target and others N1-4 looking at the moderator)	**5**
- length of flight paths	**35 – 50 m**
- experimental area (GNEIS building)	**45 x 30 m^2**

Reference: N.K. Abrosimov et al., Nucl.Inst.Meth., A242 (1985)121

Study of the (n,γf)-reaction in Neutron Resonances of U235 and Pu239.

O.A. Shcherbakov, A.B. Laptev, G.A. Petrov

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 states in heavy nuclei, both in 1-st and 2-nd wells of the fission barrier, and radiative transitions between them. The fission γ-ray multiplicity has been measured in neutron resonances of $^{235}\mathbf{U}$ and $^{239}\mathbf{Pu}$. 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. The experimental and calculated prefission width $\Gamma_{\gamma f}$ is shown in Fig.2 for the 4^--resonances of $^{235}\mathbf{U}$ and 1^+-resonances of $^{239}\mathbf{Pu}$ as function of the ratio of the **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 compound nucleus $^{236}\mathbf{U}$ and that of **E1** radiation in the prefission spectra of γ-transitions between the highly excited states. 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 GDR model.

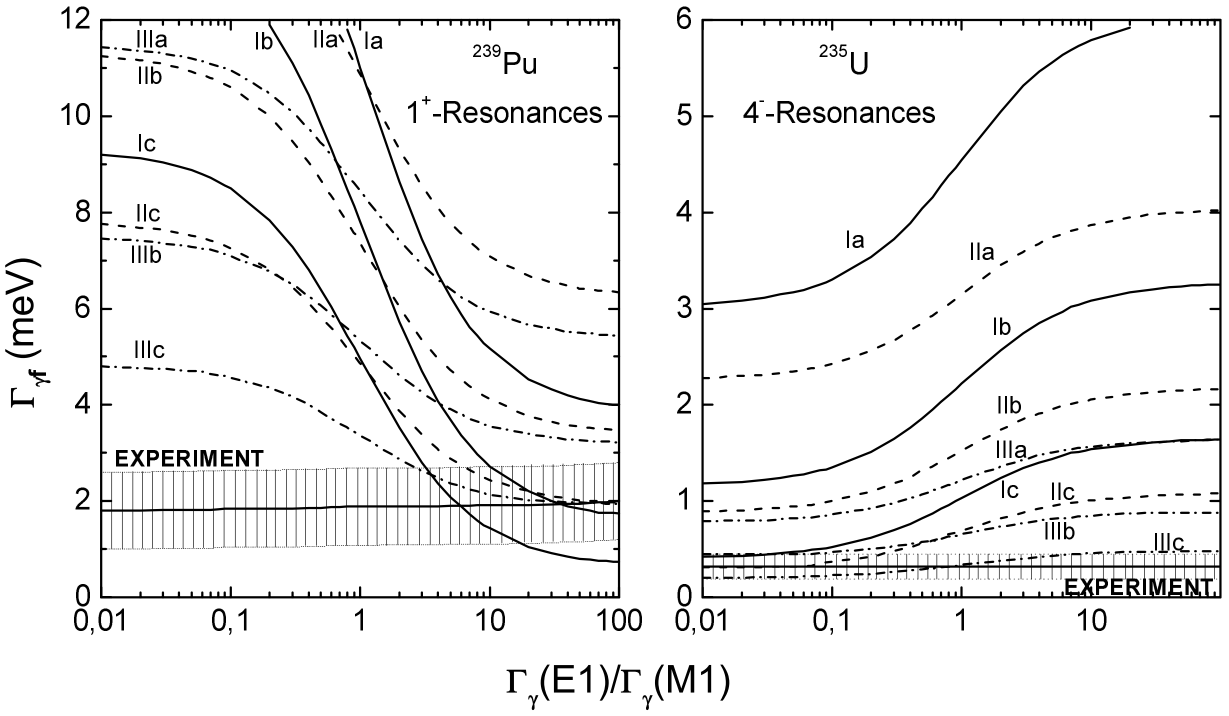


Fig.2. Experimental and calculated widths $\Gamma_{\gamma f}$ for 1^+-resonances of $^{239}\mathbf{Pu}$ and 4^--resonances of $^{235}\mathbf{U}$. Calculation model: **I-** single-humped fission barrier, **II,III-** double-humped barrier (complete and intermediate damping of the vibrational states in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

In another experiment at the GNEIS, the pulse-height spectra of fission gamma-rays have been measured in isolated resonances of $^{239}\mathbf{Pu}$ in the energy range from 10 eV to 91 eV. 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 gamma-transitions between the levels at excitation energy 1-3 MeV below the neutron binding energy $\mathbf{B_n}$. .

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

O.A. Shcherbakov and A.B. Laptev

Two 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 (class-I, corresponding 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 present measurements, J.C. Browne (1976) observed a much softer γ-ray spectrum for the 721.6 eV resonance than for neighboring resonances, whereas H. Weigmann et al. (1975) 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 after the slightly modified method of Weigmann et al. The idea was to detect a γ-decay branch within the second well using two different bias values for the γ-ray registration: lower **B1** and upper **B2**. Then, for value of **B2** larger than $\mathbf{B_n- E_{II}}$ (2 MeV, height of the second minimum), the ratio of resonance area $\mathbf{A_\gamma}$ measured with two biases **B1** and **B2**: $\mathbf{R = A_\gamma(bias\ B2)/A_\gamma(bias\ B1)}$ 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 (Geel) are shown in Fig. 3. As it is 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.

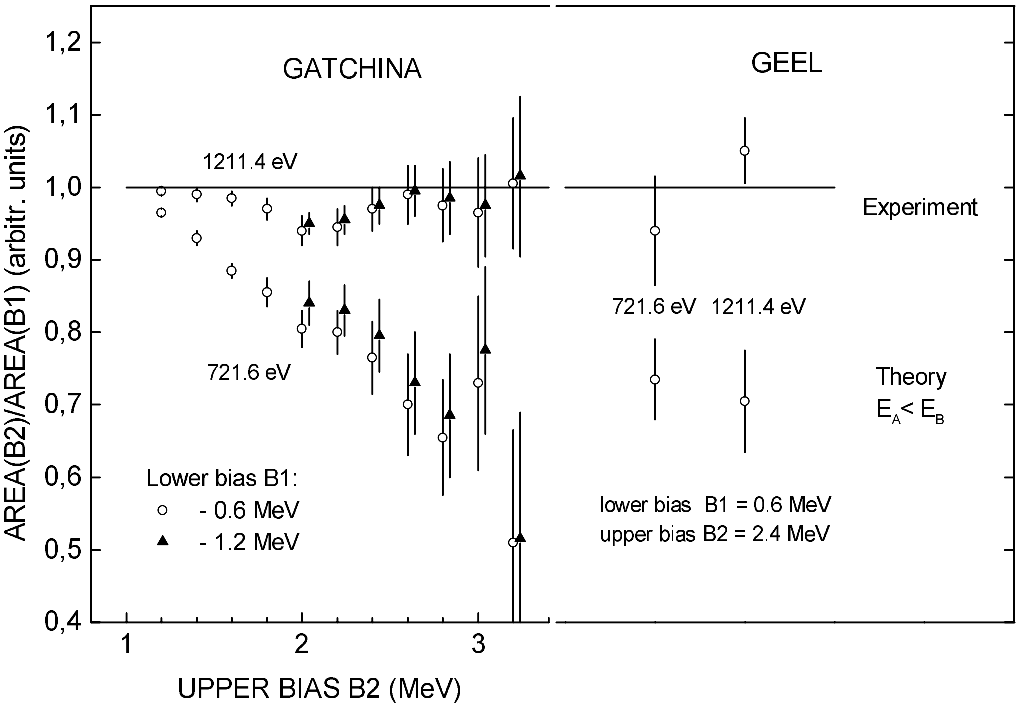


Fig. 3. Results of the capture γ-ray measurements for resonances of U238.

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

I.S. Guseva, A.B. Laptev, G.A. Petrov and O.A. Shcherbakov

The results of the total cross section measurements for **^{208}Pb** and **C** from 1 eV to 20 keV performed at the GNEIS facility for the purpose of estimating α_n are given in this report and shown in Fig. 4, the given errors are statistical ones.

The method employed for evaluation of α_n for **^{208}Pb** is described in detail in ref. Guseva, I. S., Preprint 1969, PNPI, Gatchina, 1994. Fitting results for **^{208}Pb** are presented in fig. 5. Points are experimental total cross section after the Schwinger and solid-state corrections and contribution of radiative absorption having been subtracted. The reduced χ^2 is equal 2.5 . The neutron polarizability obtained is $\alpha_n = (2.4\pm1.1)\cdot10^{-3}$ 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. 6, the value of reduced χ^2 is equal 1.7 .

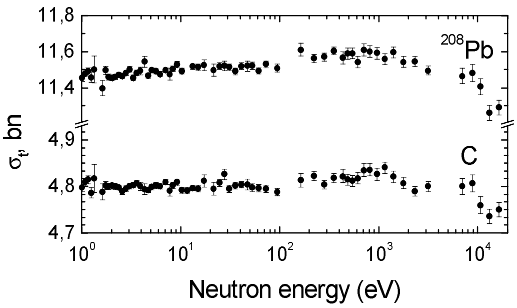


Fig. 4. Measured total cross sections of ^{208}Pb and C.

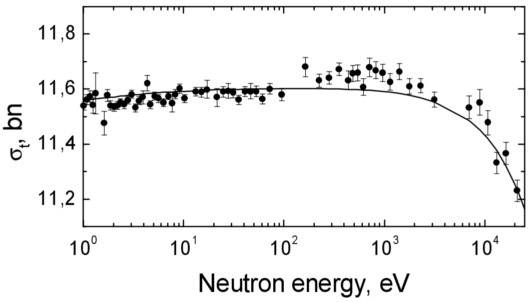


Fig. 5. Fitting results for ^{208}Pb.

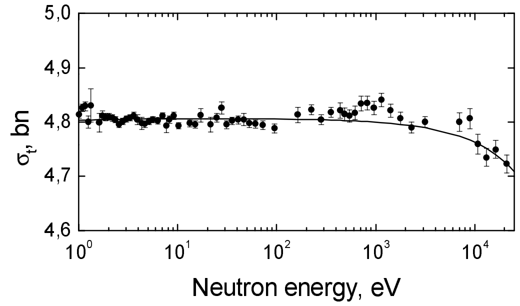


Fig. 6. Fitting results for C.

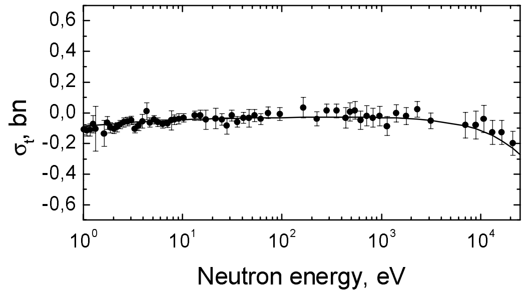


Fig. 7. Fitting results for difference $\sigma(^{208}\text{Pb}) - 2.42\cdot\sigma(\text{C})$.

To eliminate influence of the distortions caused by uncertainties of experimental background the difference **$\sigma(^{208}\text{Pb}) - 2.42\cdot\sigma(\text{C})$** used for the neutron polarizability estimation. Fitting results for this difference are shown in fig. 7. 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 $a_{ne} = -(1.75\pm0.27)\cdot10^{-3}$ fm , the value of reduced χ^2 is equal 0.7 .

Measurement of the forward-backward asymmetry in slow neutron fission

A.M. Gagarsky, S.P. Golosovskaja, A.B. Laptev, A.K. Petukhov, G.A. Petrov, V.E. Sokolov and O.A. Shcherbakov

Parameters and decay properties of low energy **p**-resonances in heavy fissile nuclei are practically unknown because of the difficulties existing when generally accepted method are used. The new method to obtain such information is the 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

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

where $\mathbf{p_n}$ and $\mathbf{p_f}$ are the neutron and light fragment momenta. The principal advantage of this method if compared with the other asymmetry-measurements: a non-polarized neutron beam can be used. The 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. The results obtained for ^{235}**U** in the energy range from 1 eV to 21 eV are shown in Fig. 8.

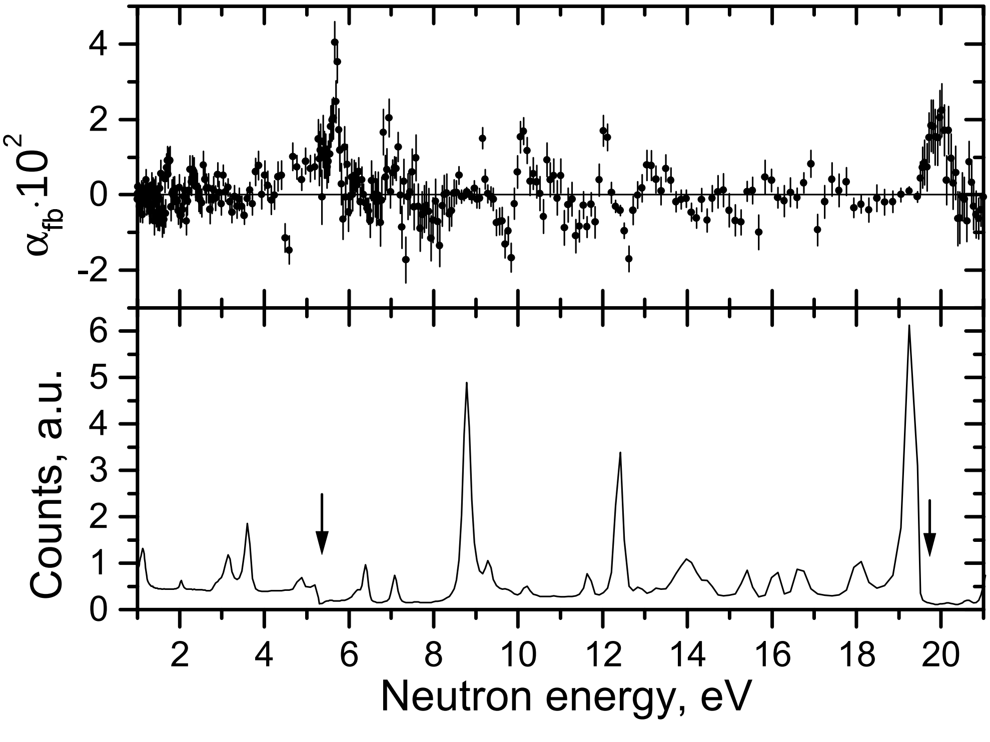


Fig. 8. Energy dependence of the asymmetry coefficient α_{fb} and fission yield for ^{235}**U**.

Several irregularities caused by **p**-resonances have been observed in energy dependence of the coefficient α_{fb}. Estimations of the main **p**-resonance parameters have been made. Fitting analysis of the data gives that the average total width of the **p**-resonances is some greater than that of **s**-resonances. For example in case of ^{235}**U** $\langle\Gamma_{fp}\rangle = (200 \pm 50)$ meV and $\langle\Gamma_{fs}\rangle = (140 \pm 10)$ meV. On the base of analysis of this 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 $5\cdot10^{-2}$ at 95 % - level of reliability.

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 a vicinity of **p**-resonances.

Neutron induced fission cross-sections of U233, U238, Th232, Np237 and Pu239 relative to U235 from 1 MeV to 200 MeV

O.A. Shcherbakov, A.B. Laptev, G.A. Petrov, A.S. Vorobyev, A.Yu. Donets, A.V. Fomichev and Yu.V. Tuboltsev

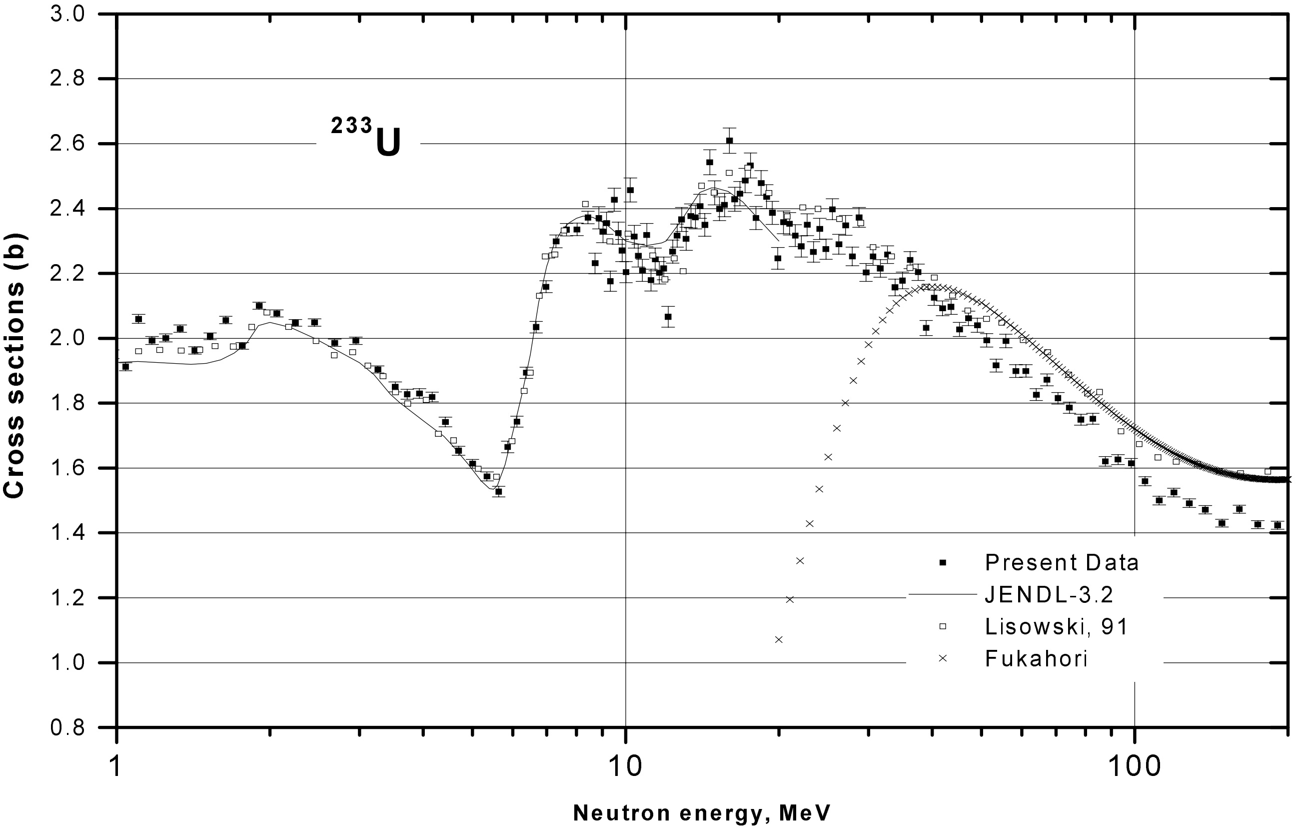
There is a long standing need in information about fission of heavy nuclei induced by the particles at intermediate energies. Regular experimental studies of fission in this energy region started comparatively recently, mainly due to the increased capabilities of modern neutron sources and experimental techniques. Among new applications of the fission data above 20 MeV, the most important are accelerator-driven transmutation of waste reactor materials and energy production, peaceful use of weapon plutonium, accelerator and spaceship shielding, radiation therapy.

During the last decade, the measurements of neutron-induced fission cross-sections for some long-lived actinides in the energy range above 20 MeV with continuous spectrum neutrons have been systematically performed only at the WNR/LANSCE facility in Los Alamos and the GNEIS facility in Gatchina. Analysis of the experimental data available in the energy range 20-200 MeV, as well as experience in producing evaluated fission cross-sections below 20 MeV, shows that new independent measurements aimed to improve fission cross-section data base in the energy range above 20 MeV are necessary. At the same time, calculation methods for the fission cross-sections of actinide nuclei at intermediate energies are still under development, except some codes such as ALICE and HETC. In such situation, the semi-empirical formulae based on the few known experimental data are used to estimate the fission cross-sections. These formulae can give not only the systematics for fission cross-section at a certain energy point but also its energy dependence.

Fission cross-section ratios for U233, U238, Th232, Pu239 and Np237 relative to U235 have been measured using a 50-m flight path. A system of few iron, brass and lead collimators gives the beam diameter of 18 cm at the fission chamber location. The last series of the measurements were carried out with the use of “clearing” magnet placed at 30 m from the source-target. This magnet removes charged particles produced in the collimators and filters from the neutron beam.

The fission reaction rate was measured using a fast parallel plate ionization chamber with electrode spacing 7 mm and filled with methane working gas. The fission chamber contained 6 foils of oxide fissile material 200 $\mu g/cm^2$ thick and 18 cm in diameter deposited onto 0.015 cm thick aluminum backings. Also, a weak Cf252 deposit was applied on each fissile foil to match the gains of electronics. The distances between the neutron production target and each fissile foil were determined using C^{12} neutron transmission resonances. For each isotope under investigation, the time-of-flight and pulse height spectra were accumulated.

The results of present measurements are shown in Fig.9,10,11. To obtain fission cross-sections from the measured ratios, the recommended data for fission cross-section of U235 (INDC-368, IAEA, 1997) have been used.The error bars represent the statistical errors only (one standard deviation). The solid lines show JENDL-3.2 data in the energy range below 20 MeV. Also shown are the data of measurements carried out at the WNR/LAMPF facility in Los-Alamos by P.W. Lisowski et al. (1992) and the data of systematiscs (T. Fukahori, 1998).



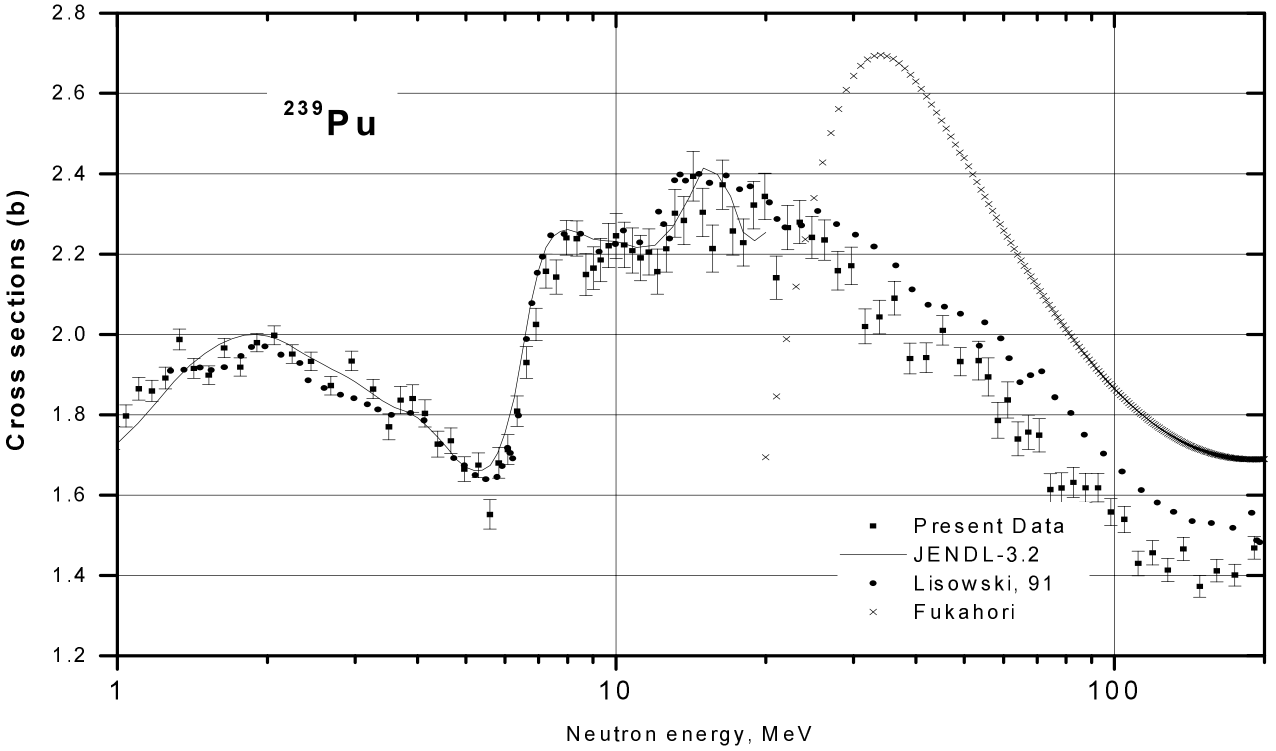
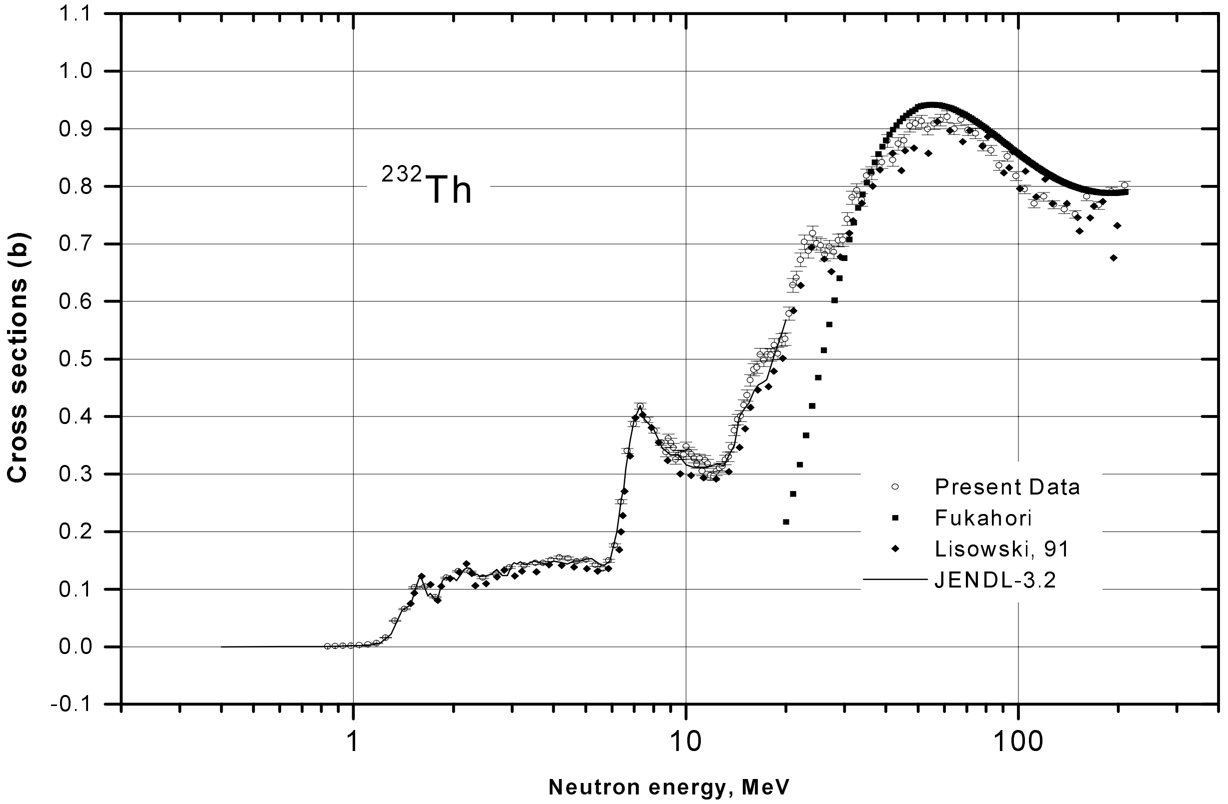


Fig.9. Fission cross sections of U233 and Pu239 in the energy range from 1 to 200 MeV



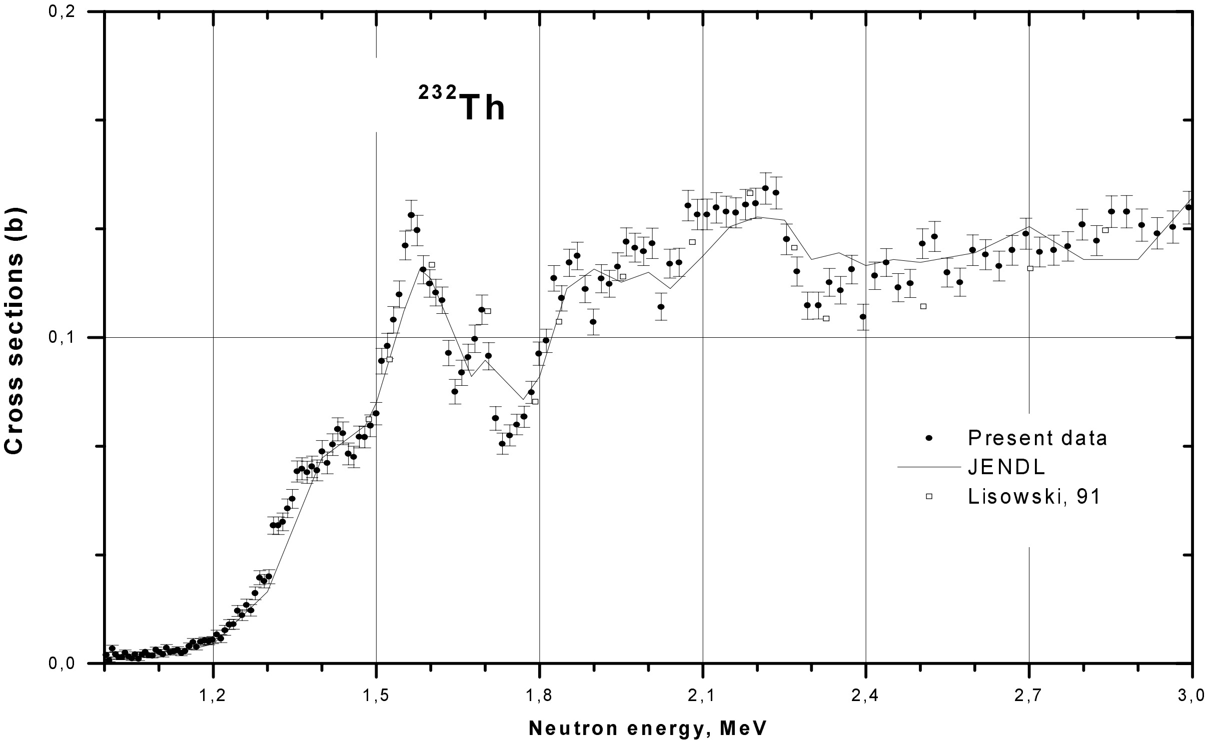
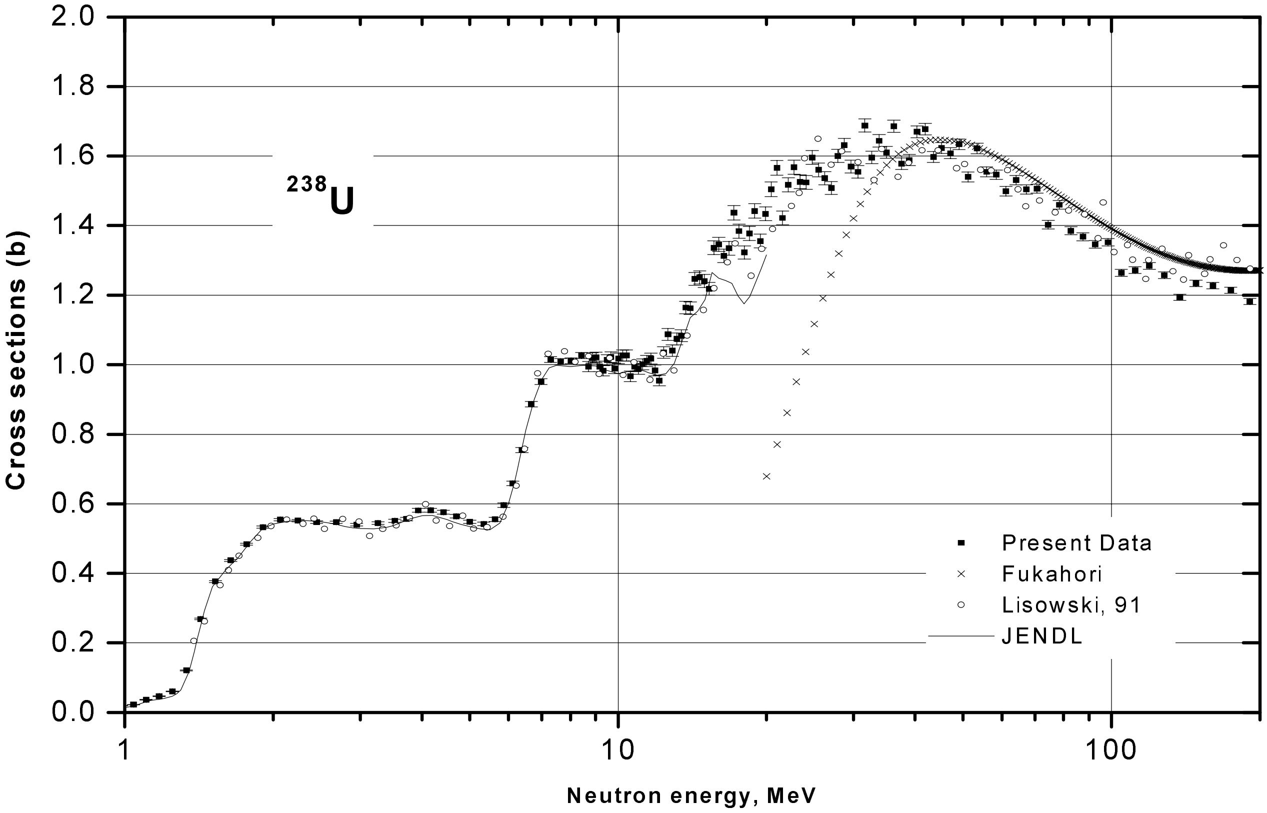


Fig. 10. Fission cross section of Th232 in the energy range from 1 to 200 MeV



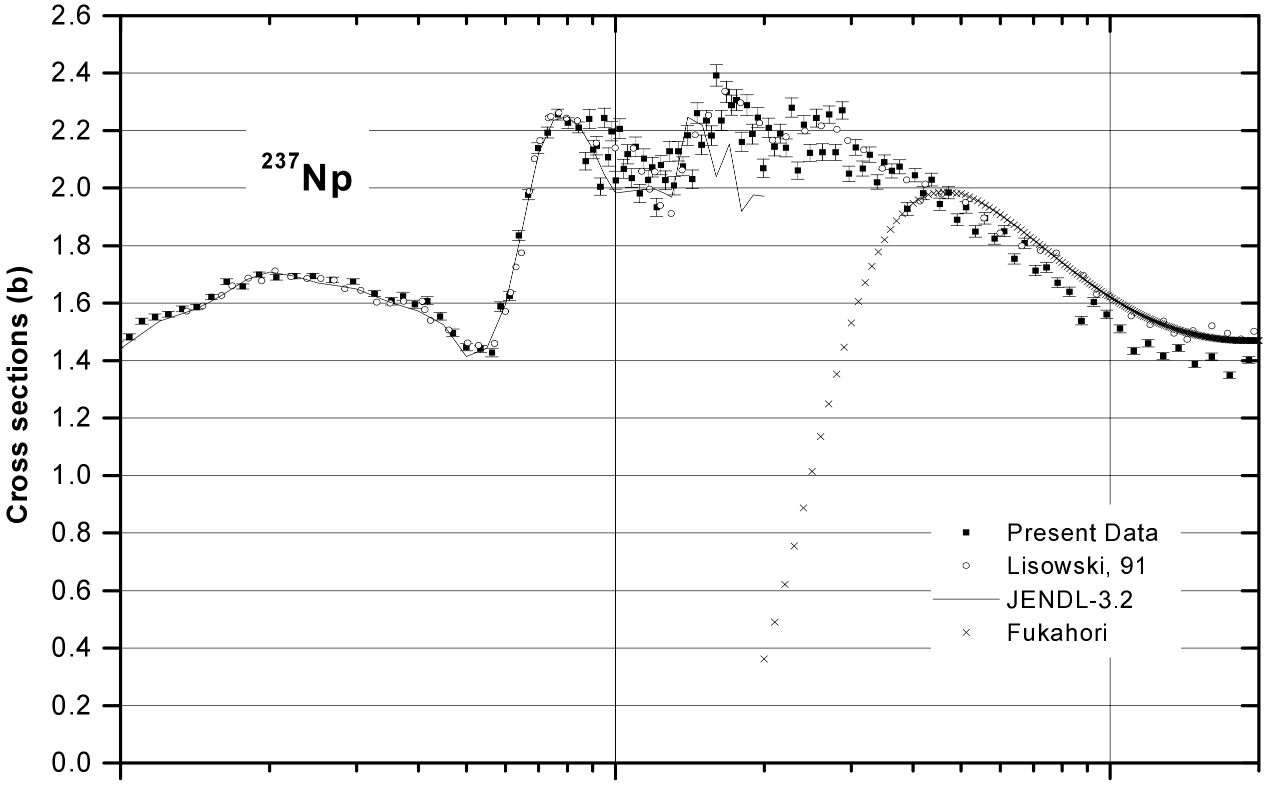


Fig. 11. Fission cross sections of U238 and Np237 in the energy range from 1 to 200 MeV