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EXPERIMENTS AT THE TIME-OF-FLIGHT NEUTRON SPECTROMETER GNEIS IN GATCHINA

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ЭКСПЕРИМЕНТЫ НА НЕЙТРОННОМ ВРЕМЯПРОЛЕТНОМ СПЕКТРОМЕТРЕ ГНЕЙС В ГАТЧИНЕ

О.А.Щербаков

Аннотация

Даны основные характеристики и краткое описание нейтронного времяпролетного спектрометра ГНЕЙС в Гатчине на базе синхроциклотрона на энергию протонов 1 ГэВ. Приведены некоторые результаты экспериментов по физике деления ядер и измерениям нейтронных сечений, демонстрирующие не только работу установки, но и основные направления проводимых на ней исследований.

Abstract

A brief description of the Gatchina neutron time-of-flight spectrometer GNEIS at the 1 GeV proton synchrocyclotron and its main characteristics are given. Some results of the nuclear fission experiments and neutron cross section measurements are presented not only to illustrate the facility's performance but to outline the basic directions of the research as well.

1. Description of the TCF-spectrometer

The Gatchina neutron spectrometer GNEIS is intended for neutron-nucleus interaction studies utilizing the time-of-flight technique over a wide range of neutron energy from $\sim 10^{-2}$ eV up to $\sim$100 MeV. The spectrometer is based on the 1 GeV LNPI proton synchrocyclotron [1] which is the most powerful cyclotron of this type in the world. The machine has come into operation on physics research since 1970. It is used mainly for high energy (meson) physics, some specific applications including proton radiotherapy and isotope production, and for neutron spectroscopy. About thirty experiments are carried out per year with running time of the accelerator for experiments $\sim$5,000 hours.

The detailed information about GNEIS can be found elsewhere [2-4]. The main parameters of the facility are as follows:

- proton beam energy	1 GeV
- average proton beam current	2.3 μA
- pulse width	10 ns
- average neutron production rate	$3\cdot10^{14}$ n/s
- repetition rate	$\leqslant$ 50 Hz
- number of flight paths	5

Fig.1 shows the general layout of the GNEIS facility. The titles of the experiments which are performed at GNEIS are displayed in the insets.

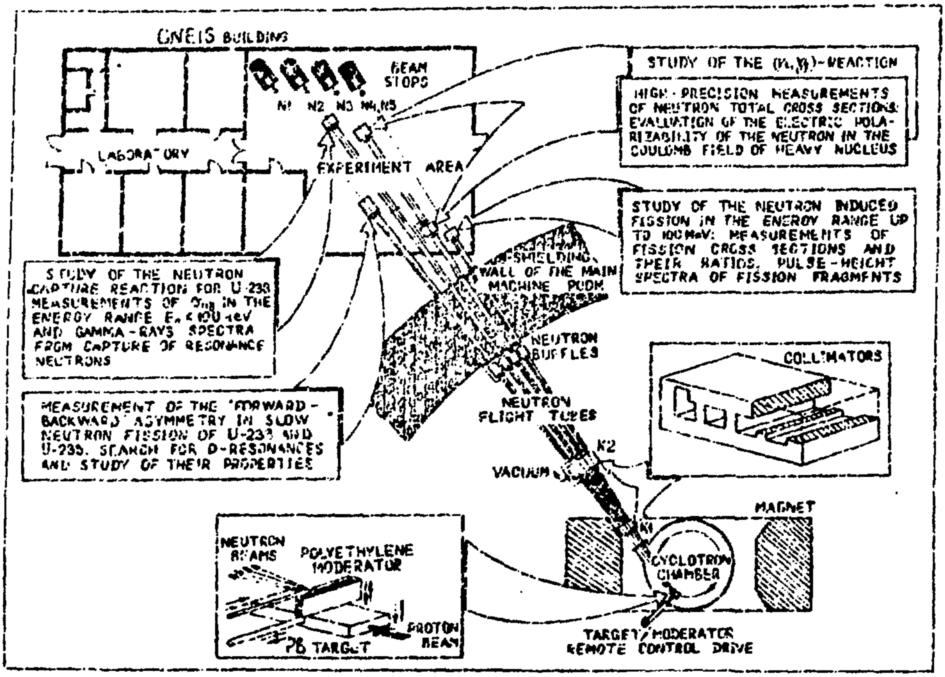

Fig.1. General layout of the GNEIS facility.

The water-cooled lead target and polyethylene moderator(s) are placed inside the vacuum chamber of the accelerator. Five neutron beams are transported outside through the shielding wall of the machine main room, in the laboratory building. The 35-50 m flight path lengths are determined by dimensions of the experimental area. The spectrometer is equipped with a radial data acquisition system based on a CM 1420 computer intended to control a few CAMAC autonomous measuring stations [5].

The comparison of the energy resolution and neutron intensity of GNEIS with the analogous parameters of the other well known TOF-facilities (e.g. ORELA, GELINA and LAMPF/WNR) shows that GNEIS competes successfully mainly in the energy region <100 KeV.

2. Investigations of the (n,γf)-reaction

(G.Z.Borukhovich, A.B.Laptev, G.A.Petrov, O.A.Scherbakov, T.K.Zvezdkina)

During the first few years of the spectrometer operation, a number of experiments [6-9] have been made within the framework of the (n,γf)-reaction research. Measurements of the fission γ-ray multiplicities have been carried out in the energy range from 4 eV to 130 eV for ^{235}U [6] and for ^{239}Pu [7] in the range

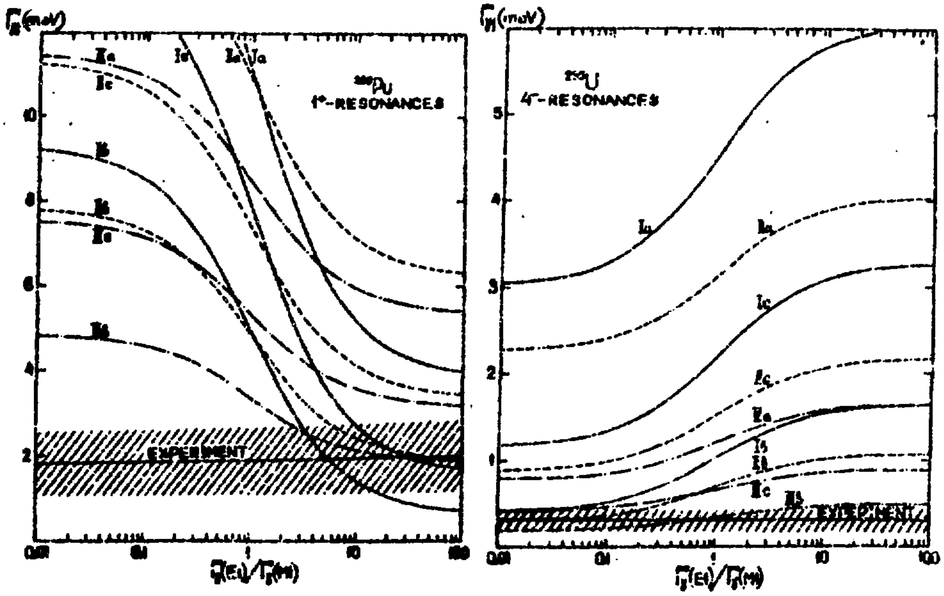

Fig.2. Experimental and calculated $\overline{\Gamma}_{\gamma f}$-widths for 1^+-resonances of ^{239}Pu and 4^--resonances of ^{235}U. Calculation models: I-single-humped fission barrier; II-double-humped barrier (complete damping of the class II states); III-double-humped barrier (intermediate damping); a-single-particle model(Weisskopf) of γ-transitions; b,c- giant dipole model (Lorentz line shape).

from 14 eV to 205 eV. The $\overline{\Gamma}_{\gamma f}$-widths obtained in these experiments are shown in fig.2 as a function of the ratio of E1- and M1-transition intensities in the prefission γ-rays. It was shown that the best agreement between the experimental results and model calculations is reached using the giant dipole resonance model (Lorentz relationship for γ-transition probabilities) and the modified doorway state model [10] with a moderate damping of the states in the second well of the fission barrier. A comparison of the experiment with calculations shows the predominance of M1-transitions in ^{236}U and that of E1-transitions in ^{240}Pu in the spectra of radiative transitions between the highly excited states just beneath the neutron binding energy. It ought to mention that analogous conclusion for ^{236}U was made by Dlouhy *et al.*

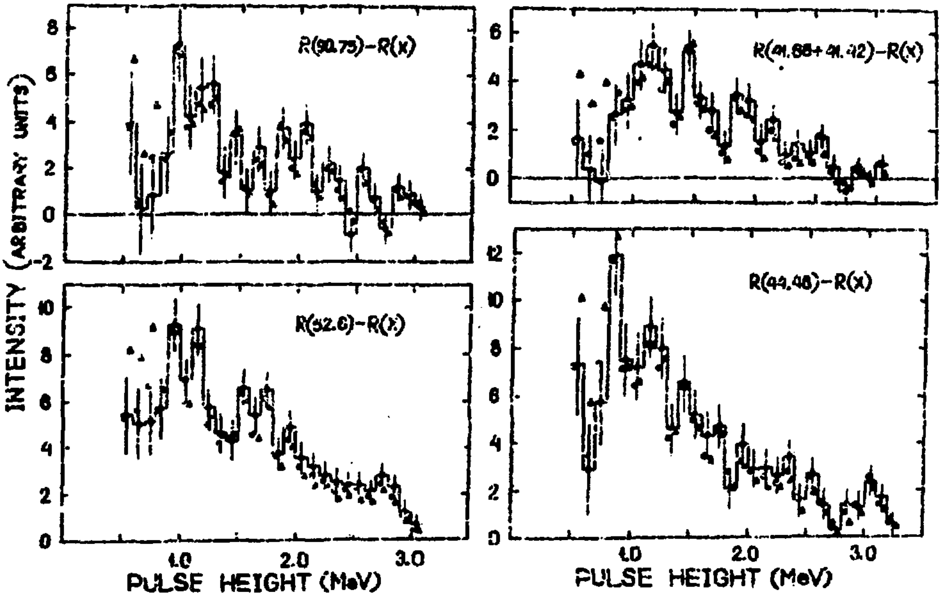

Fig.3. Difference pulse-height spectra of fission γ-rays of the resonances of ^{239}Pu. Resonance energies.
⸸ R(x)=R(10.93 eV), ○ R(x)=R(17.66 eV),
▲ R(x)=R(22.29 eV).

[11] at Dubna from the analysis of the fluctuations of X-ray yield in slow neutron fission resonances of ^{235}U.

In the next experiment [8] the pulse-height spectra of fission γ-rays have been measured for 8 resonances of ^{239}Pu in the energy range from 10 eV to 91 eV. The aim of these measurements was to obtain the prefission γ-ray spectrum as a result of direct comparison of the very weak 1^+-resonances where the (n,γf)-reaction is expected to be dominant, with the strong 1^+-resonances where direct fission is the main de-excitation mechanism. Fig.3 shows the obtained difference pulse-height spec-

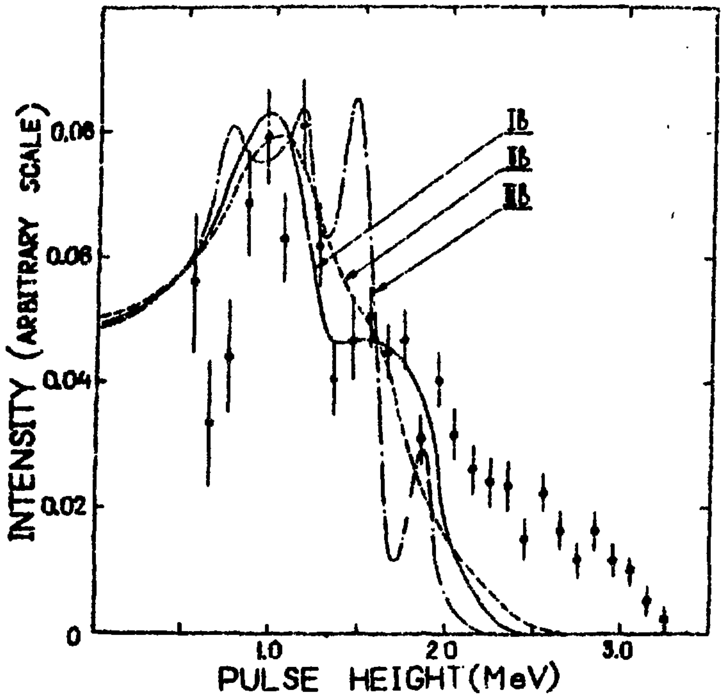

Fig.4. ^{239}Pu: calculated prefission γ-ray spectra and the experimental (⫯) difference pulse-height spectrum averaged over 1^+-resonances R(90.75 eV), R(52.6 eV), R(44.48 eV) and R(41.42 eV + 41.48 eV). Calculation model notations are the same as in fig.2.

tra of fission γ-rays for weak (Γ_f<10 meV) and strong (Γ_f>40 meV) resonances of ^{239}Pu. Besides the known maximum at E_γ≈2 MeV first observed by Trochon *et al.* [12] at Saclay, these spectra display some more structures which could correspond to prefission γ-transitions to the levels at the excitation energies 1 MeV- 3 MeV below the neutron binding energy. After that, the fission from these levels could go via moderately damped states in the second well of ^{240}Pu.

A comparison of the calculated prefission γ-ray spectra with the measured difference fission γ-ray spectra (averaged over a few weak 1^+-resonances) shows the presence of a hard component at E_γ > 2 MeV (see fig.4). This one could be considered as a manifestation of the transition states which are not observed in the ^{239}Pu(d,pf)-reaction, so far as experimental data about transition states from this reaction were used in the calculations.

An ongoing interest in (n,γf)-investigations is stimulated by the known fluctuations of the fission fragments <TKE> observed for some nuclei [13] in the nearthreshold region. The information about all components of the energy balance in fission, including ν_n and $\bar{E}_\gamma$, is needed to determine the nature of these variations. The present energy range is of some more interest, because according to theoretical evaluations [14] the anisotropy of prefission γ-rays by more than order exceeds that of prompt γ-rays from fission fragments for even-even nuclei in the nearthreshold range. The observation of the high anisotropy lines in the fission γ-ray spectra measured in the vicinity of vibrational resonances gives one more method to study the (n,γf)-reaction. At last, recent experimental data on the variations of <TKE> for neutron resonances of ^{235}U [15] give the grounds to carry out new investigations of the (n,γf)-reaction in the slow neutron resonance region.

3. 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, Yu.S.Pleva, V.E.Sokolov, O.A.Scherbakov)

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

$$W(\theta) = 1 + \alpha_{nf}^{fb} \cdot (\vec{p}_n \cdot \vec{p}_f)$$

where $\vec{p}_n$ and $\vec{p}_f$ are the neutron and (light) fragment momenta.

The investigations of the energy dependence of the asymmetry coefficient α_{nf}^{fb} have been done for ^{235}U and nowadays are continued for ^{233}U at the GNEIS neutron beam No1. The large volume (~70 l) fast multiplate ionization chamber [16] containing ~2 g of ^{235}U was used in these measurements (see fig.5). The light group of the fission fragments is separated from the fragment kinetic energy spectra.

To minimize a false instrumental effect the mutual orientation of ionization chamber and neutron beam axes is changed periodically.

Fig.6 shows the energy behavior of the coefficient α_{nf}^{fb} for ^{235}U in the energy range from 1 eV to 21 eV. At least four irregularities can be observed at 5.73 eV, 9.91 eV, 12.6 eV and 20 eV. The preliminary analysis of the data shows that the average total width of the probable p-resonances is a few times greater than that of the s-resonances.

The distribution of α_{nf}^{fb} around its mean value (over the whole investigated energy interval 1 eV - 135 eV for ^{235}U) is characterized by:

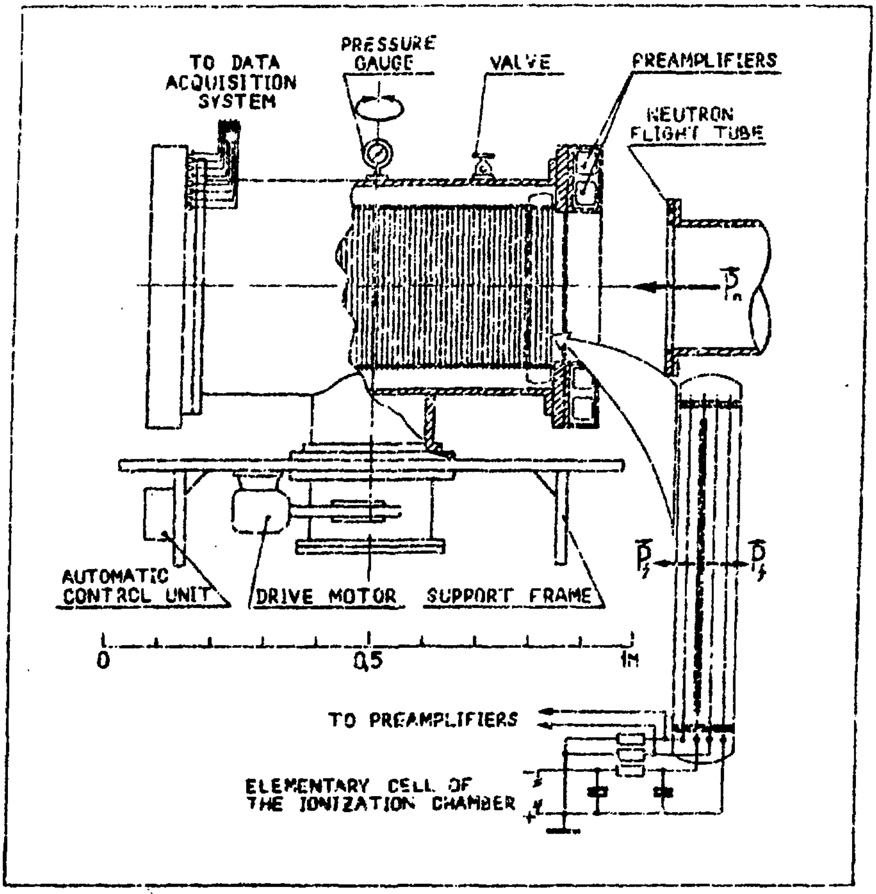

Fig.5. Experimental set-up for the forward-backward asymmetry measurements.

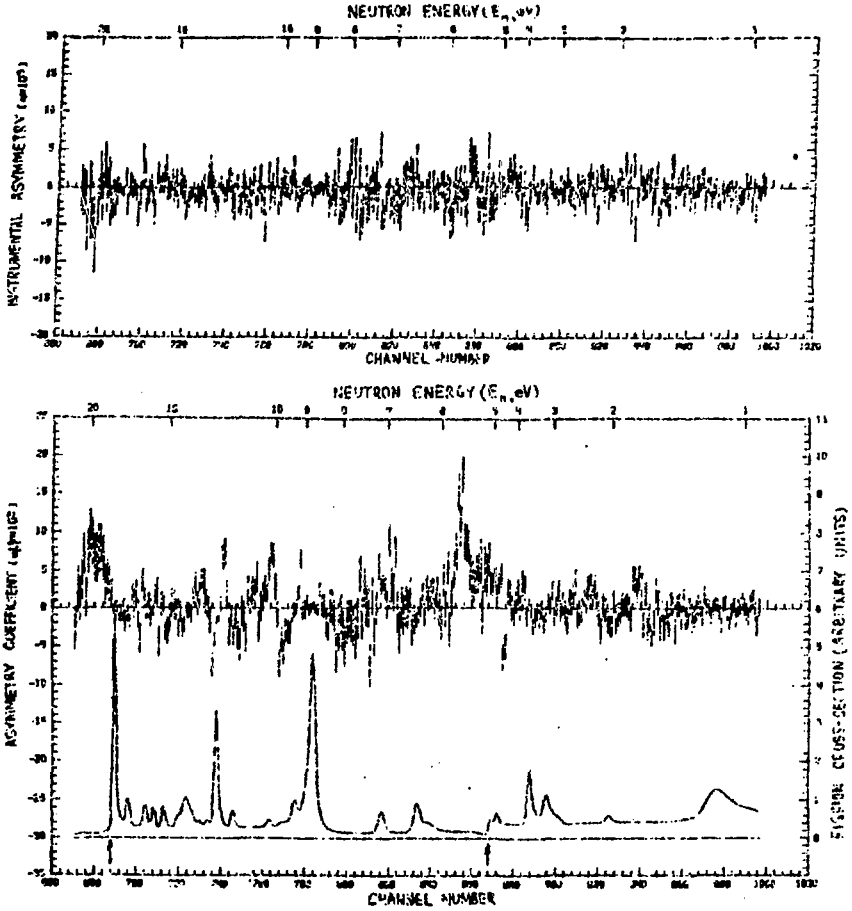

Fig.6. Energy dependence of the forward-backward asymmetry coefficient α_{nf}^{fb} and instrument asymmetry α_{instr} for ^{235}U in the energy range 1 eV < E_n < 21 eV.

$$\overline{\alpha}_{nf}^{fb} = -(0.29 \pm 0.83)\cdot 10^{-3} \qquad \chi^2_{red} = 1.9 \pm 0.05$$

while for instrumental asymmetry the analogous quantities are

$$\overline{\alpha}_{instr} = -(1.31 \pm 0.83)\cdot 10^{-3} \qquad \chi^2_{red} = 1.05 \pm 0.05$$

The information obtained in these measurements is very important for the fundamental investigations of P- and T-parity violation effects which are expected to be resonancely intensified in a vicinity of p-wave resonances [17,18].

4. Study of the neutron capture reaction for ^{238}U

(A.B.Laptev, O.A.Scherbakov)

Another example of the spectrometer performance is the neutron capture measurement for ^{238}U [4]. In this experiment capture γ-rays are detected by a pair of C_6D_6-liquid scintillators and NaI(Tl)-scitillator (fig.7). The first two detectors are used in conjunction with a pulse-weighting technique for the capture cross section measurements in the energy range from thermal up to 100 KeV. According to WRENDA [19], this cross section is needed for the fast neutron reactor calculations with an accuracy 1-3 %.

For the implementation of the weighting procedure, the response functions of the detectors were calculated using the Monte Carlo code BRAND [20].

The NaI(Tl)-detector is used for measurements of the capture γ-ray spectra from the separate resonances of ^{238}U. The most interesting are those at 721.6 eV and 1211.4 eV. It was concluded from the results of fission [21] and capture [22] cross section measurements made at ORELA that resonances in question are pre-

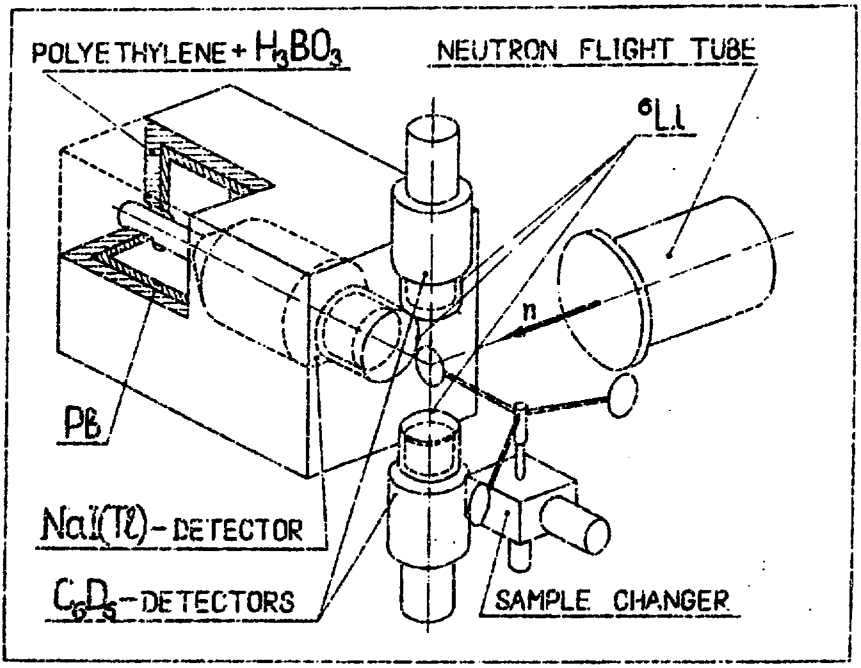

Fig.7. Experimental arrangement for the neutron capture measurements.

dominantly class II levels. Besides the anomalously small capture widths, the observation of a much softer (than for the neighboring resonances) capture γ-ray spectrum could help to understand the nature of these resonances.

Furthermore, the type of the coupling between class II and class I states in ^{239}U could be determined unambiguously. To date, the situation is contradictory because Browne [23] observed a much softer γ-ray spectrum for 721.6 eV resonance, whereas Seigmann *et al.* [24] observed no difference.

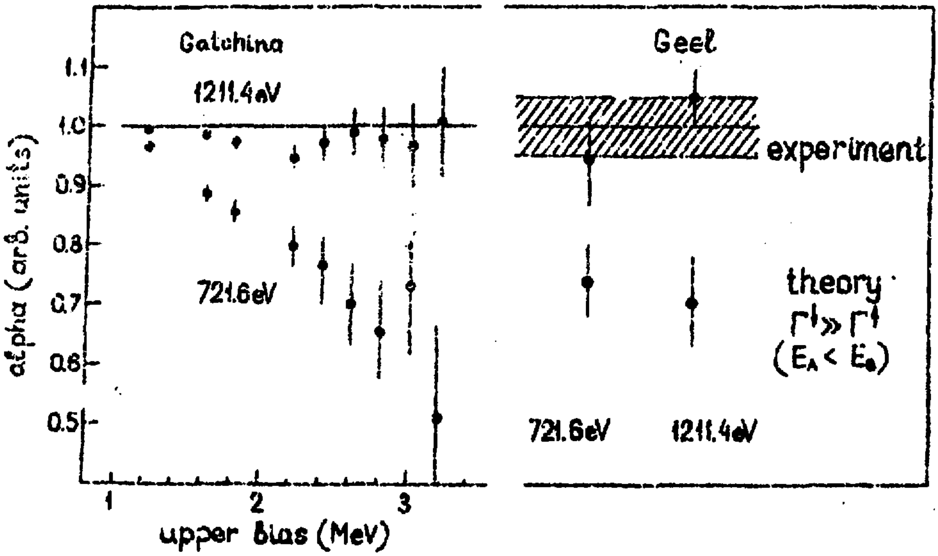

Fig.8. Results of the capture γ-ray measurements for 721.6 eV and 1211.4 eV resonances of ^{238}U.

The capture γ-ray spectra measurements were carried out at GNEIS after the manner of Weigmann. Preliminary results for 721.6 eV and 1211.4 eV are shown in fig.8, where the ratio of resonance area for low bias B1 and upper bias B2 is plotted as a function of B2. Also shown are the results of Weigmann *et al.* [24]. For B1 = 0.6 MeV and B2 varying from 1 MeV to 3 MeV, it can be concluded that 721.6 eV resonance is essentially class II state, whereas 1211.4 eV one is pure class I state. Furthermore, it means that the relations between the fission barrier parameters E_A and E_B are different for 721.6 eV and 1211.4 eV resonances. Consequently, it could manifest the existence of the different fission modes for neighboring sub-barrier clusters.

5. High precision measurements of neutron total cross sections

(Yu.A.Alexandrov,[*] I.S.Guseva, A.B.Laptev, V.G.Nikolenko,[*] G.A.Petrov, O.A.Scherbakov)

One of the characteristics of the neutron as an elementary particle is its electric polarizability α_n which determines the induced dipole moment of the neutron in an external electric field: $D = \alpha_n E$. It is known [25] that information about α_n can be obtained from the high precision ($\Delta\sigma/\sigma < 10^{-3}$) neutron total cross section measurements for heavy nuclei using different energy dependence of the components that compose σ_{tot}.

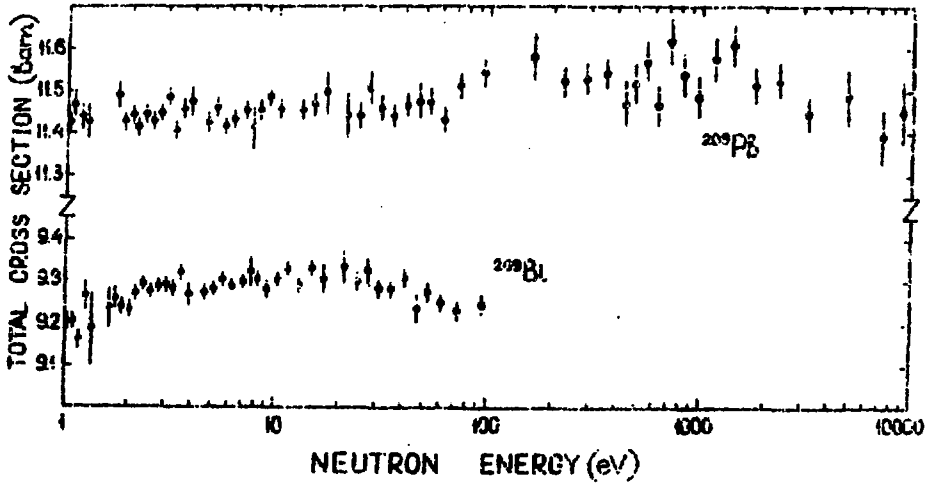

Fig.9. Total cross sections of ^{209}Bi and ^{208}Pb.

With a view to evaluate the electric polarizability α_n, the neutron cross sections have been measured accurately at GNEIS for ^{209}Bi in the energy range from 1 eV to 100 eV and for ^{208}Pb - from 1 eV up to 10 KeV. The utilization of the ^{3}He - ionization chamber (designed and manufactured by A.V.Strelkov, JINR)

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[*] Joint Institute for Nuclear Research, Dubna

as a neutron detector enabled to have the reduced (< 0.5 %) neutron background nearly constant in the explored energy region. The results of σ_{tot}-measurements for ^{209}Bi and ^{208}Pb (preliminary) are shown in fig.9. Simultaneously with ^{209}Bi (^{208}Pb), the total cross section measurements for Si (C) were carried out as a test of the experimental technique. For silicon and carbon the polarizability influence should be negligible in comparison with that for bismuth and lead because α_n-contribution in cross section is nearly proportional to Z^2.

Having corrected measured cross sections for resonance scattering and capture, neutron-electron interaction, Schwinger scattering and condensed matter effects, α_n-values have been obtained:

^{209}Bi: $\alpha_n = (25 \pm 11)\cdot 10^{-3}$ fm^3

^{208}Pb: $\alpha_n = (2.3 \pm 2.1)\cdot 10^{-3}$ fm^3, supposing $a_{ne} = -1.55\cdot 10^{-3}$ fm

$\alpha_n = (2.7 \pm 2.0)\cdot 10^{-3}$ fm^3, $a_{ne} = -1.32\cdot 10^{-3}$ fm

It should be underlined that given values of α_n are preliminary. Analysis of the available experimental results and the data treatment methods used by other authors [26-28] shows that nowadays, in order to obtain reliable value of α_n and its uncertainty, we need both precise cross section data and improved adequate methods of data processing.

6. Study of the fast neutron induced fission in the energy range up to 100 MeV

(A.V.Fomichev*), A.B.Laptev, G.A.Petrov, O.A.Scherbakov)

Within the framework of this direction, the fission cross section ratios measurements for ^{235,238}U and ^{232}Th have been carried out from 1.3 MeV to 42 MeV. The first results of this experiment are presented here.

Measurements were performed using a 38 m flight path No5 which is the only one viewed the bare lead target of the GNEIS neutron source. The fission ionization chamber contained the layers of uranium and thorium in a form of oxide material deposited on thin aluminum backing using a painting technique. An additional ^{252}Cf layer was included in the chamber to calibrate the pulse-height spectra of fission fragments which were stored simultaneously with the TOF-spectra. Flight path length was obtained using the low energy neutron resonances of ^{235}U.

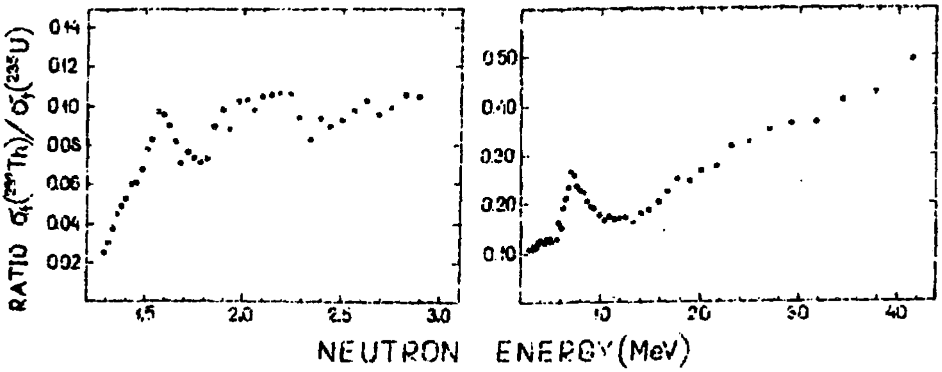

Fig.10. Fission cross section ratio of ^{232}Th/^{235}U from 1.3 MeV to 42 MeV.

Fig.10 displays the preliminary results of the fission cross section measurements of ^{232}Th/^{235}U in the energy range up to 42 MeV.

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*)V.G.Khlopin Radium Institute, Leningrad

7. Conclusion and acknowledgement

The neutron spectrometer GNEIS is a powerful time-of-flight facility, suitable for high-level investigations in nuclear physics and applied purposes. Nowadays, number of experiments are performed mainly in the field of neutron induced fission. Some new experimental evidences, such as forward-backward asymmetry in slow neutron fission of ^{235}U and anomaly in neutron capture γ-rays of the 721.5 eV resonance of ^{238}U, show that so far many interesting problems still exist which could be solved by means of the modern neutron time-of-flight spectroscopy.

The author would like to acknowledge the essential contributions of his colleagues, whose names are given immediately after the title of every experiment.

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