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JOINT INSTITUTE FOR NUCLEAR RESEARCH
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NUCLEAR RESEARCH CARRIED OUT AT IBR

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The pulsed fast reactor is a neutron source over a wide energy range permitting to solve a wide variety of scientific problems associated with neutron spectra measurements. At present it is used in two modes of operation, namely, as a reactor a as a multiplier together with a microtron. The main characteristics that are essential for measurements by the time-of-flight technique are as follows: an average power is 6 kW , the total neutron yield is 3×10^{14} neutrons/sec., the width of fast neutron burst is 55 μsec[x)], the repetition rate 5 sec^{-1}, the best resolution (for a flight path of 1000 m) is 55 nsec/m . The corresponding characteristics for multiplier operation mode a 1 kW, 5×10^{13} neutron/sec, 3 μsec , 50 sec^{-1} and 3 nsec/m respectively. Some other characteristics and a more detailed description of the reactor can be found in ref.[2/]

There are two major lines in which research at the reactor is being made, in particular :

1) studies of neutron interactions with atomic nuclei and the properties of nuclear levels excited by resonant neutrons;
2) studies of the structure and dynamics of solids and liquids using thermal and cold neutron scattering. The present report give a review of . experiments on the subjects listed in item 1.

The high intensity,low background and resolution adequate for solving a lot of scientific tasks, permit to carry out a detailed study of a wider range of nuclear level properties. For this purpose, a Measuring Centre[3/] and a set of detectors re -

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[x)] At the reactor disc rotation speed of 3,000 rev/min; at the speed of 5,000 rev/min the burst width is 36 μ sec.

cording neutrons and their interactions with atomic nuclei, have been designed in the Laboratory of Neutron Physics.

Presently the Measuring Centre comprises four 4096-channel analyzers capable of measuring time, amplitude and multidimensional spectra, three 2048-channel time analyzers, and a multidimensional magnetic-tape memory analyzer with a number of channels up to 2^{20}. The data from the analyzers can be fed via cable into a computer for subsequent treatment.

The major information about the detectors is given in table I. Physical research has been carried out at IBR since 1961. Table II lists the investigated nuclei and some conditions of measurements on the neutron spectrometer, the results of which were published by the middle of 1966.

Since the time of the Geneva Conference on Peaceful Uses of Atomic Energy where the IBR operation was reported$^{24/}$, a number of ne new experiments has been completed. Some of these experiments have widened a traditional scope of investigations in neutron spectroscopy. First, we mean here experiments using the polarized beam of resonant neutrons, and, second, the investigations of the previously unstudied alpha decay after resonance neutron capture. Below follows a short description of these and some other experiments carried out during the recent years.

POLARIZED NEUTRON EXPERIMENTS

In principle, the interaction of polarized neutrons with polarized nuclei siggests a lot of possibilities for determining resonance spins with the aim of clarifying the spin dependence of level parameters. The scheme of the experimental set-up$^{25/}$ is shown in fig.1. The arrangement contains a proton target $32 cm^3$($5.0 \times 3.4 \times 1.9\ cm^3$) in volume operating at a temperature of 0.95° K with a magnetic field of 17 kOe and r.f.field of 69 GHz, which provides neutron polarization f_n=75%; a spin rotator permitting to vary neutron polarization direction; a device to provide sample polarization in the magnetic field of about 15 kOe that operates at 0.3°K; and lastly, a liquid scintillation boron detector 500cm^2 in area similar to that described in ref.[4/] The polarized neutron beam of energy up to a few tens keV is produced by transmission o neutrons through the polarized proton target as a result of stron spin dependence of n-p scattering. The resultant weakening of the intensity by a factor of the order of 10 is a rather cheap cost o a 75% polarization beam. This arrangement has been used to complete the experiment on resonance spin determination for Ho^{165} in the region below 50 eV[20/]. The present year the measurements have been in progress using the microtron which permitted to determine the spins of a number of levels in the region up to 150 eV. The work is currently under way on the construction of other rare earth polarized targets.

Recently measurements have been made here of polarized neutron transmission through polarized deuterium in the energy interval 0.01 - 5 eV[27/]. Both the deuterium and proton targets have been polarized using the dynamical method[26/]. Two series of measurements have been made for two directions of deuterium polarization. Light and black dots in Fig. 2 show the relevant experimental results. In both cases the value $\mathcal{E}$ has been measured which represents relative transmission variation with varying neutron spin orientation with respect to the deuterium magnetic field. The experiment permitted to choose one of the known alternative sets of n-d scattering lengths, and the right one was the set where the quartet scattering length exceeded the doublet.

α - DECAY AFTER RESONANCE NEUTRON CAPTURE

The study of the (n,α) reaction in medium-weight and heavy nuclei by resonance neutrons which has been initiated at IBR is a new trend in neutron spectroscopy not developed earlier apparently due to the difficulties associated with a low reaction cross section at a high γ -ray background: $\sigma(n,\alpha)/\sigma(n,\gamma)=10^{-6} \div 10^{-5}$. This imposes rather strict requirements to measuring equipment. The general scheme of the detector employed in ref.[7] is presented in fig. 3. A gas-filled xenon scintillation chamber has been chosen in which layers of the studied substance deposited on parallel aluminium plates have been placed. The total area of the sample was 7,000 cm^2.

At the layer thickness of $4 \div 5$ mg/cm^2, the detector recorded the reaction (n,α) with an efficiency of about 50%, the efficiency of γ -ray detection being less than 10^{-6}%. The intrinsic detector background was 20 pulse/min.

The good discrimination of γ- rays and the reduction of the intrinsic background of the detector were achieved by application of the electric field of about 700 V/cm that caused a considerable increase in xenon light output. Electric field application results in an appreciable extension of light burst with a front of about 1.5 μsec. However, in the case of the IBR-microtron mode of operation at about 4 μ sec burst duration, this did not essentially influence the resolution.

Using this detector, measurements have been carried out of the α-decay after the resonance neutron capture by ^{147}Sm, ^{149}Sm, ^{143}Nd and ^{145}Nd nuclei. The measurements have been made at IBR used in conjunction with the microtron at resolutions 0.10 and 0.03μsec/m.

Fig.4 shows the curve of α - detector counts as a function of neutron energy, obtained from a 56-hour experiment with samarium sample. The same figure presents the analogous curve obtained using the (n, γ) detector. By comparison of these curves, the ratios $\Gamma_\alpha/\Gamma_\gamma$ have been derived for 25 levels of the isotopes under consideration. The α -widths averaged over resonances have been compared with the statistical theory predictions. It has turned out that for ^{143}Nd and ^{149}Sm agreement is observed within the limits of 20% whereas for ^{145}Nd and ^{147}Sm disagreement reaches a factor of 8 ÷ 3. Further development of these experiments is supposed to involve measurements on enriched isotopes of rare earths as well as a search for the reaction (n, α) in other regions of the periodic table.

NEUTRON CROSS SECTIONS

Neutron spectroscopy research at IBR includes the measurement of the total and partial cross sections for both fissionable and non-fissionable nuclei. During the two last years, non-fissionable nuclei experiments have been carried out in the rare earth region and for nuclei with A $\lesssim$ 100. The information presently available for rare earths has been obtained long ago using samples from natural mixtures of elements at a poor resolution. In this connection a research program has been initiated and is in progress at IBR for neutron resonances in this mass number region. In addition to the previously studied Pr and Tb nuclei, measurements have been made with ^{165}Ho and Yb separated isotopes. Transmission, self-indication and radiative capture have been measured. The parameters of a large number of resonances have been obtained. In the measurements, there have been employed a neutron liquid scintillation detector with an efficiency of the order of 50%, a (n,γ) scintillation liquid detector of about 30% efficiency operating in coincidence with pulses from two big tanks, and a (n,γ)-detector with two Na I 100 x 100 mm crystals. Measurements on separated Er and Nb isotopes are currently in progress at IBR with the microtron. The remainder of the studied nuclei are related to the region $60 < A < 100$, in which the information about resonances especially concerning radiation widths has been up to recently poor and inexact. The total and partial cross sections have been measured and the level parameters for seven elements have been deduced. In addition to the mentioned detectors, in the measurements use has been made of a neutron lithium-glass and scattered-neutron scintillation detectors. The advantage of the latter detector is a relatively high efficiency (about 10% in the 4π geometry) weakly dependent upon energy. The gain in efficiency is achieved at the expense of an increase in life time ($5 \div 15$ μ sec. depending on detector type). Therefore, such a detector can be employed on long-burst spectrometers.

The microtron brought into operation has made it possible to extend the research on medium-weight nuclei to a higher energy region. Presently measurements are under way with germanium isotopes in the neutron energy region up to 40 keV. For illustration, one of the experimental curves for radiative capture of natural germanium, resultant from the 20-hour operation of the reactor at the power 300 W, is shown in fig. 5.

For fission and radiative capture studies for fissionable nuclei, a liquid scintillation detector with cadmium propionate is used capable of detecting both fission events and radiative capture with efficiency ~ 50% and 25% respectively. The detector permits to work with fissionable element samples weighing up to several hundred grams. The fission and radiative capture cross sections have been measured for ^{239}Pu and ^{235}U with a resolution of 40-60 nsec/m in the energy regions up to 15 and 30 keV respectively. Fig. 6 presents the apparatus curves for radiative capture and fission in ^{239}Pu, obtained from using a 8.8 x 10^{20} nucl./cm^2 sample for 30-hour reactor operation at a power 2 KW. The constant background of 600 counts has been subtracted from both curves. With the aid of the other detector (gas-filled xenon chamber) , ternary resonance fission of ^{235}U has been studied for energies up to 50 eV. A ternary fission event was identified by coincidences of one of the fission fragments with a long-range alpha.

LEAKAGE NEUTRON SPECTRUM

The neutron spectrum occurring in depleted uranium and some reactor materials (nickel, iron, stainless steel) is of considerable interest for reactor calculations. Such investigations have been usually made by the resonance indicator method with a loss an appreciable fraction of neutron spectrum information. The construction of IBR made it possible to use the time-of-flight method, since at the reactor burst duration 40÷ 60 μ sec. the time of neutron delay in heavy elements is of no importance now and the high pulse intensity has permitted to use the flight path of 1000 meters and to provide a sufficiently good resolution.

The measurements have been made using the 50 ÷ 70cm thick prisms from nickel, iron and stainless steel disposed just near the reactor core[29/]. Fig.7 shows one of the characteristic leakage spectra for the nickel prism. One can clearly see the resonant structure of the cross section. The obtained experimental data have permitted to make more precise the system of constants employed in many-group calculations.

γ- RAY SPECTRA IN RESONANCES

The pulsed fast reactor IBR has been also used for spectroscopy of neutron capture γ-rays in resonances. For the previous years, these measurements were carried out on a 100 x 100 mm NaI(Tl) crystal single-channel scintillation spectrometer, with information recorded by means of a multi-dimensional magnetic-tape memory analyzer. There have been studied praseodymium and barium resonances. For a more detailed study of this anomaly, present day measurements are made with semiconducting Ge(Li) detectors with effective volumes 7cm^3 and 5cm^3 and resolutions 6.5 keV and 4.3 keV respectively. The first soft ground-state transition measurements for ^{135}Ba resonances have been undertaken using the flat Ge(Li) detector 3.5cm^2 x 4mm in size, the results published in ref.[9/]

Now the measurements are completed for the γ-ray energy region from 0.4 to 10 MeV. For the sake of illustration, fig.8 shows the hard γ-ray amplitude spectra in 24.5 eV and 82÷88 eV resonances and for the neutron energy region 15 ÷ 1000 eV. The spectra are obtained from a 100-hour operation of the reactor in conjunction with microtron. The mentioned above anomaly is distinctly seen for the lines of 8.385 and 9.210 MeV.

NEUTRON POLARIZABILITY

The investigation of the angular distributions of neutrons with energy up to 25 KeV [30/]scattered by heavy nuclei can be considered as an instance of a very hard experiment associated with the observation of the effect of the order of a percent. In this experiment, neutrons were detected by 180 $B^{10}F_3$ counters distributed to nine scattering angles. The measurements were made in the reactor mode of operation at a 250 m flight path. Statistics was accumulated during 200 hours. These experiments yielded in a few times more precise estimate of the previously known neutron polarizability α. The value has been found to lie within the limits of $-4.5 \times 10^{-42} < \alpha < 6.1 \times 10^{-42}$ cm^3. Fig.9 presents the experimental points for coefficients ω at cos θ in the angular distributions of different energy neutron scattering. The solid curves are plotted for the α values indicated in the figure.

CONCLUSION

The five-year operation of IBR revealed good experimental opportunities both of the pulsed reactor (IR) and the reactor used in conjunction with an injector (IRI) for nuclear investigations even at the present very low average power (6kW and 1 kW respectively). In technical respect it is quite practicable to construct a more powerful pulsed reactor, the optimum magnitude of the average power is a few megawatts at a burst duration $T=50 \div 75\,\mu$sec[2/]. The reduction of the burst duration advantageous from the viewpoint of the known θ/τ^2 criterion can be achieved by using either mechanical choppers synchronized with the pulsed reactor, or electron injector. At the neutron pulse duration τ the effective power will be equal to $Q_{eff} \simeq \frac{1}{2} Q \frac{\tau}{T}$ for the pulsed reactor with chopper (factor 1/2 takes account of chopper transmission), and $Q_{eff} \simeq 5 I \tau^2$ for the pulsed reactor with injector (I is electron current per pulse in amperes, the fast neutron life time in IRI is accepted to be equal to $2 \times 10^{-2}\,\mu$ sec., and the repetition rate is 100 Hz). At Q= 4 MW, T= 75 μsec. the utilization of the injector turns out to be more advantageous at $I\tau > 5$ amp. μ sec. or 5a at $\tau \simeq 1\,\mu$sec. When comparing power IR and IRI with other neutron sources, one should necessarily take into consideration the following research areas:

1) Traditional time-of-flight neutron spectrometry aiming at measuring the major parameters of individual resonances (E_0, Γ_n, Γ_γ, J, π) in the neutron energy range as wide as possible to establish the laws of these parameters distribution and to find their mean values.

2) Detailed study of the properties of individual resonances and the nuclear excited states resultant from their decay. For example, we can mention the spectrometry of resonant capture γ-rays: measurement of the electric quadrupole and magnetic dipole momenta of compound nucleus resonant states[32/] and levels produced after γ-ray emission; rare reaction studies, e.g. (n , α); investigation of fission products in resonances; investigation of the resonant line shape from the viewpoint of crystal coupling, etc. The work in these directions is presently in its very initial stage For a few following years it will be restricted to the region of relatively low energies (say $\lesssim$ 100 eV) since the neutron flux in the given energy interval ΔE , as well as resonance strength and the intensity at the given ΔE increase with energy decrease (as a result, the effect counting rate is $E^{-4} \div E^{-4.5}$). Since at E=100eV the neutron time-of-flight is about 0.07 μsec/cm, the time spread of delay (equivalent to $\Delta \ell$ = 2cm) and neutron detection makes it unreasonable to use neutron bursts shorter than 0.5 - 1 μsec.

3) Nuclear studies with thermal neutrons which require the energy separation of neutrons, large pulsed fluxes or low backgrounds. The examples are n-e interaction, n-n scattering, and use of thermal neutron gas for a target for the studied isotope ion beam.[31/] In the last experiment, neutron capture by nucleus is detected by the mass separator at the beam exit or by induced activity.

With varying ion velocity, one can find the energy dependence for the neutron capture cross section. An advantage of this method is a possibility to make measurements with a very small quantity of substance, which is of importance in radioactive nuclei cross section studies.

4) Studies of neutron spectra occurring in reactor materials or multiplying assemblies. The spectrum occurrence time is a few microseconds (depending on the substance mass number and energy region), therefore such experiments do not require very short bursts.

5) Condensed medii studies with thermal and cold neutron scattering.

6) Non-stationary effect studies at the neutron influence upon solids.

A. STEADY REACTORS.

A comparison of experimental data obtained using steady reactors and IBR leads to the conclusion that the opportunities of the latter in respect of the research trends 1,2,4 and 5 are not worse or even better than those of a steady reactor with a power higher by 3 orders. Apparently the gain will decrease up to 2 orders with a power pulsed reactor used (in view of the fact that a sample or detector will be unable to "see" the entire active zone of the reactor) and as compared to the more reasonably designed reactor, for instance HFBR type[33]. Difficulties associated with heat removal and fast fuel burnup complicate the construction of the HFBR-Type reactor of 500 megawatts with a flux of the order of 10^{16} neutron /cm^{2}sec. An equivalent pulsed reactor with a power of several megawatts may be constructed using the present day experience with liquid-metal coolant fast reactors. This kind of reactor could be employed to carry out research mentioned in items 1-5 above.

B. LINEAR ELECTRON ACCELERATORS

Since the electron beam energy release per neutron is about 30 times larger than that in fission reaction, for all studies that do not require bursts essentially shorter than 1 sec. it is more advantageous to use an electron accelerator as a pulsed reactor injector. For the first item studies, electron accelerator operation without multiplier is more suitable at a burst duration less or comparable to the fast-neutron life time which is about $2x\ 10^{-2}$ μsec. in the large IRI. The time spread due to the moderator becomes equal to 20 nsec. for neutrons with energy E= 10 keV. Thus, only for spectrometry in the energy region above 10 keV, the multiplier has negative influence upon the work. To carry out research in this direction, it may appear reasonable to envisage a possibility to use electron beam without multiplication.

C.PROTON ACCELERATORS FOR ENERGY ABOUT 1 GeV seem, in principle, to be more promising[34/], however at present such devices are more expensive and complicated to construct.

In conclusion we can say that the pulsed reactor of average power of several megawatts used in conjunction with choppers or electron injecting accelerator is a more flexible and universe device to carry out pulsed neutron research compared with other neutron sources.

TABLE I

CHARACTERISTICS OF THE LABORATORY OF NEUTRON PHYSICS DETECTORS

Detector type	Efficiency	Detector or sample area cm^2	Time uncertainty (μsec)	Reference
Liquid scintillation natural-boron neutron detector	50% for 100eV 25% for 10keV	800	1.5	4/
Liquid scintillation boron-10 neutron detector	70% for 100eV 35% for 10keV	500	0.4	4/
Liquid scintillation (n,γ) detector	30 %	250	0.2	5/
Scattered neutron detector	10%	250	15	6/
Gas scintillation (n, α) detector	50%	7000	1.5	7/
Liquid scintillation fission detector	50%	250	0.2	8/
Ge (Li) detectors		volume up to 7 cm^3		9/

TABLE II

Target nucleus	Experiment type	Resolution μsec/m	Energy interval eV	Reference
Cl	Transmission Self-indication	0,05 0,08	< 500	/10/
Zn*	Transmission Radiative capture Self-indication	0,05 0,08 0,08	< 600	/11/
Br.	Transmission Radiative capture Self-indication Scattering	0,05 0,05 0.08	< 400	/12/ /13/
Rb*	Transmission Radiative capture Self-indication	0.05 0.05	< 1200	/14/
b	Transmission Radiative capture Self-indication Scattering	0.04 0,05 0,08	< 400	/14/
o	Transmission Radiative capture Self-indication	0.05 0,05	< 200	/11/
u	Transmission Radiative capture Self-indication Scattering	0,06 0.06 0.08	< 150	/13/
h	Transmission Radiative capture Self-indication Scattering	0,04 0,05 0,08	< 330	/15/
a	Transmission Radiative capture Self-indication Scattering γ-ray spectrum	0.08 0.08 0,08 0.12 **	< 300	/16/ /9/

TABLE II (continued)

Target nucleus	Experiment type	Resolution μsec/m	Energy interval ev	Reference
Pr	Transmission	0.04	< 1000	/17/
	Radiative capture	0.03		
	Self-indication			
	Scattering	0.08		
	γ-ray spectrum			
Nd*	(n, α)	0.03 **	< 600	/18/
Sm*	(n, α)	0.10 **	< 200	/18/
Tb	Transmission	0.04	< 100	/17/
	Radiative capture	0.05		
	Self-indication			
	Scattering	0.08		
Ho	Transmission	0.06		
	Self-indication	0.08	< 100	
	Radiative capture	0.006	< 600	/19/
	Scattering	0.50	< 60	/20/
Yb*	Transmission	0.04	< 150	/21/
	Radiative capture	0.06		
^{233}U	Ternary fission	2,0	1 - 10	/21/
^{235}U	Transmission	0.04	2-30000	/22/
	Radiative capture			
	Self-indication			
	Fission			
	Ternary fission	0.6	0.1 - 50	/28/
^{239}Pu	Fission	0.06	6-15000	/23/
	Radiative capture			
	Ternary fission	7,0	0,05 - 0,7	/35/

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* Measurements were made on enriched isotopes.

** Measurements were made using the reactor in

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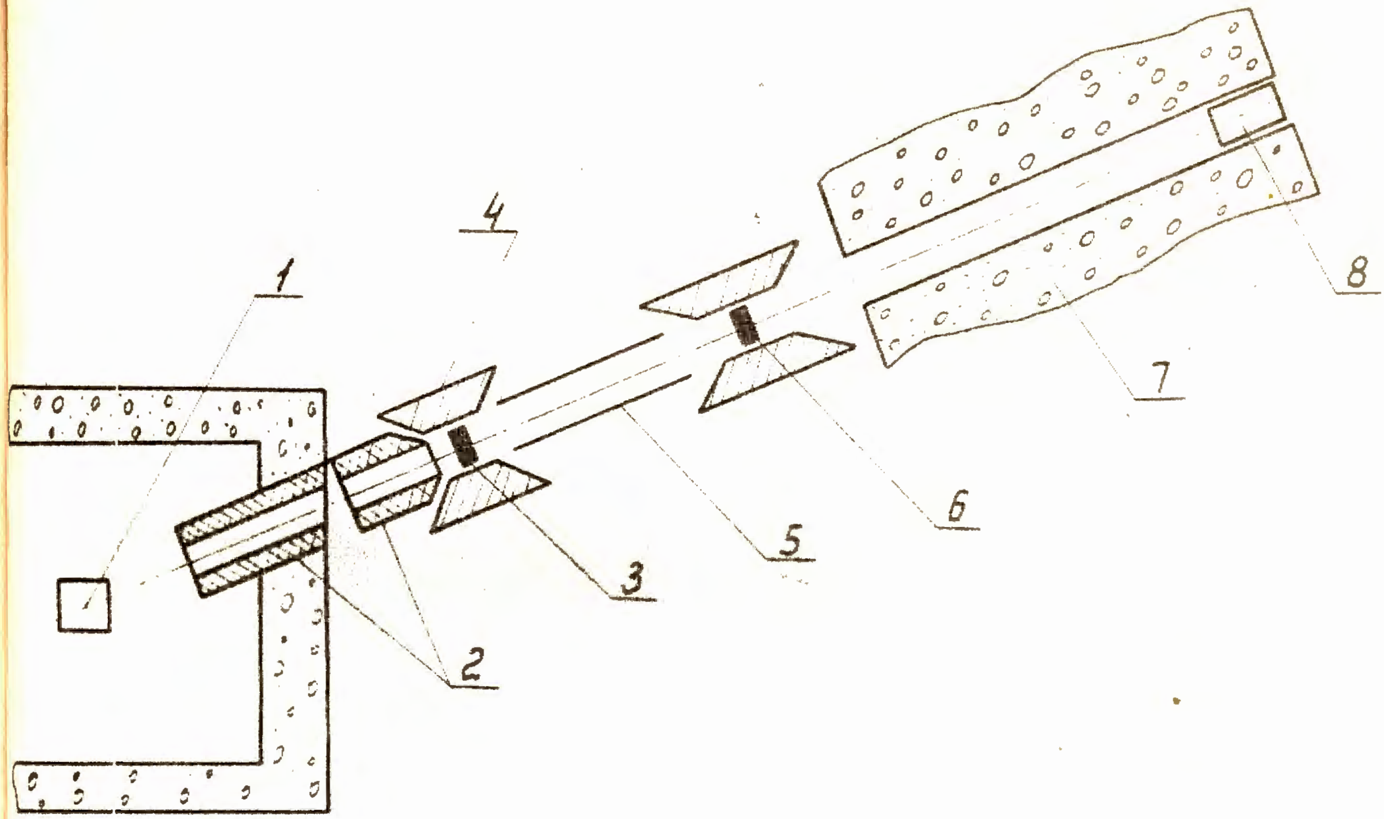

Fig.1. The lay-out of the experiment with polarized neutrons:

1 = the reactor active zone, 2 = collimators,

3 = polarized proton target, 4 = magnets, 5 = spin rotator,

6 = polarized sample under investigation, 7 = shielding,

8 = detector.

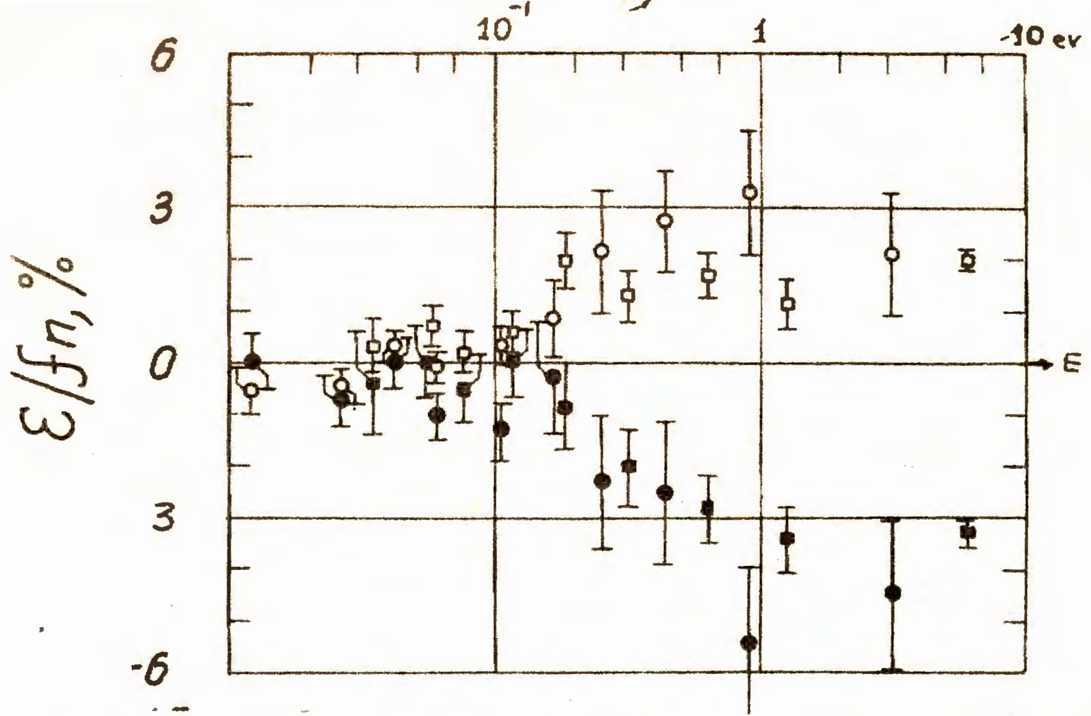

Fig.2. Experimental results of polarized neutron transmission through polarized deuterium. Indications are given in the text.

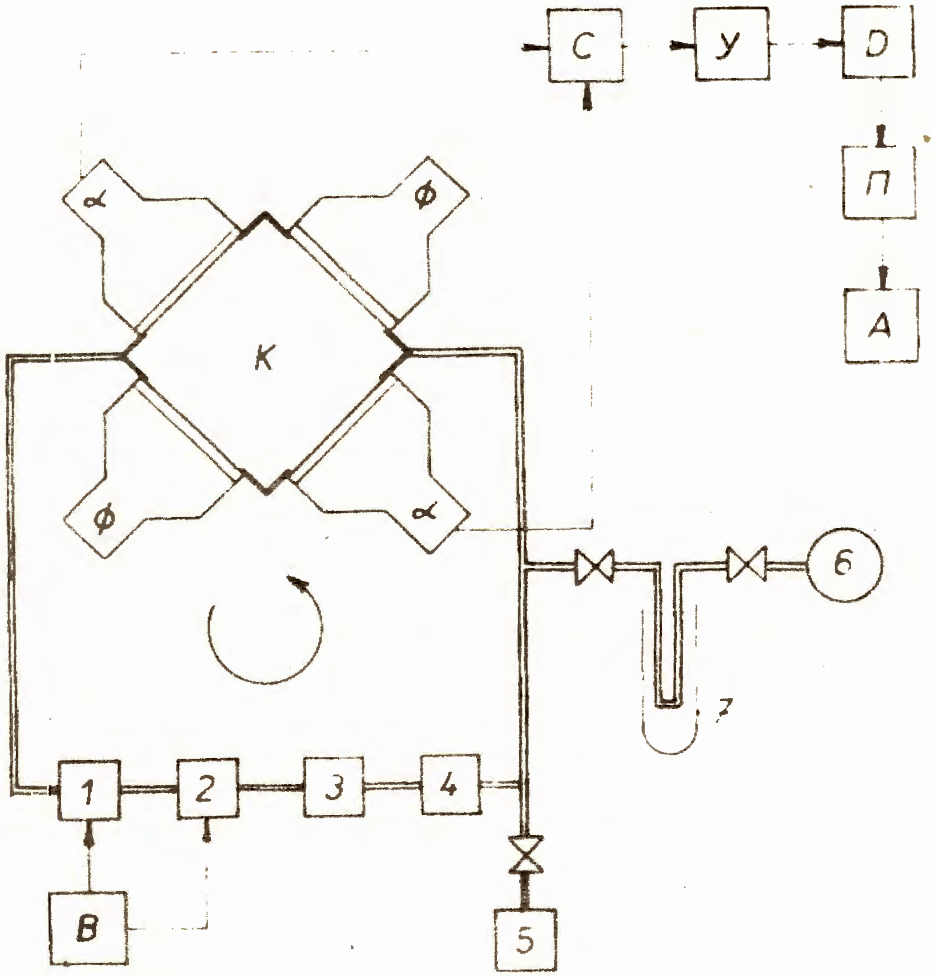

Fig.3. The general scheme of the (n, α) detector.

K = xenon chamber, 1+ 7 = the detector vacuum part (pumps and the xenon purification system). C+ A = detector electron par

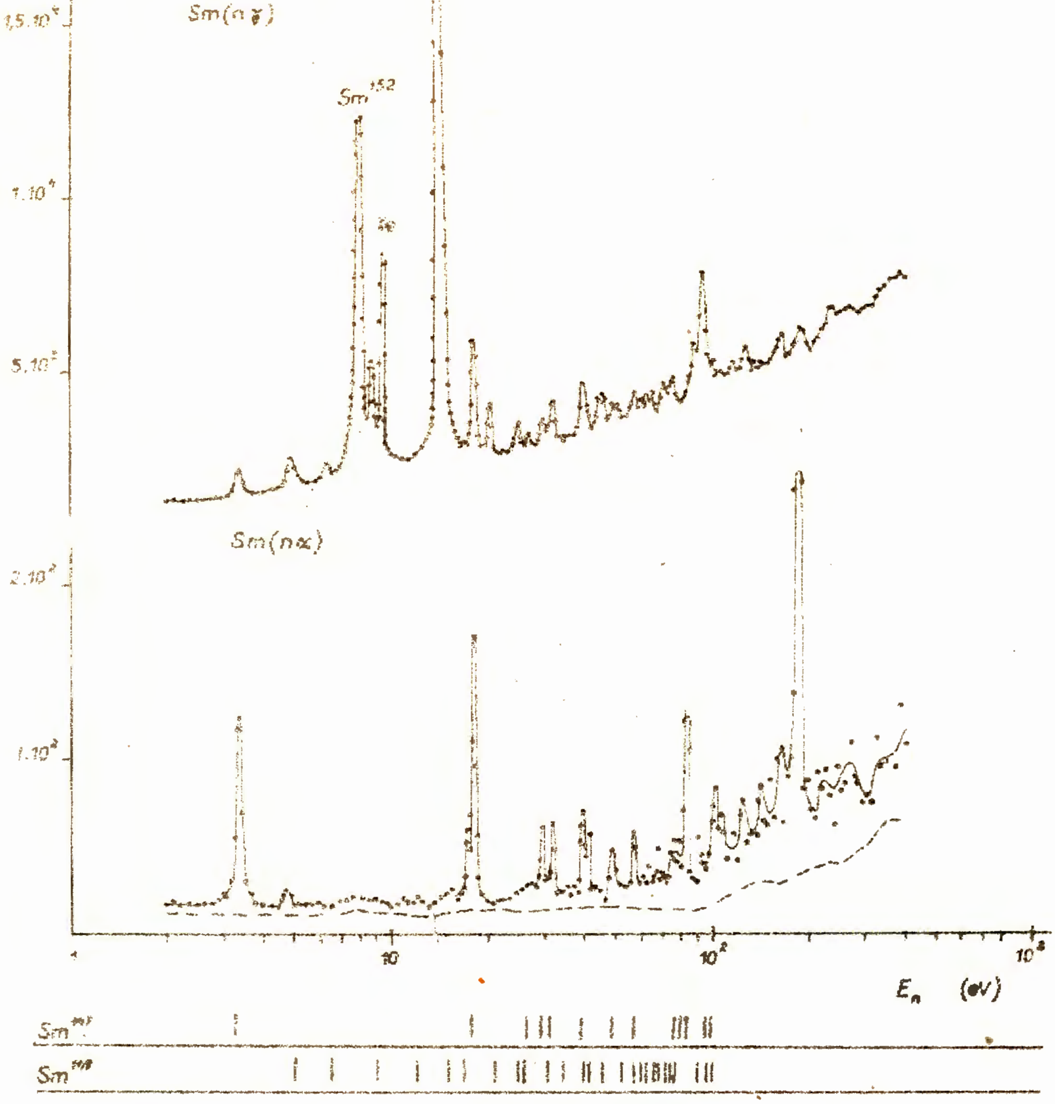

Fig.4. The apparatus time spectrum for the reactions (n, α) and (n, γ) on Sm.

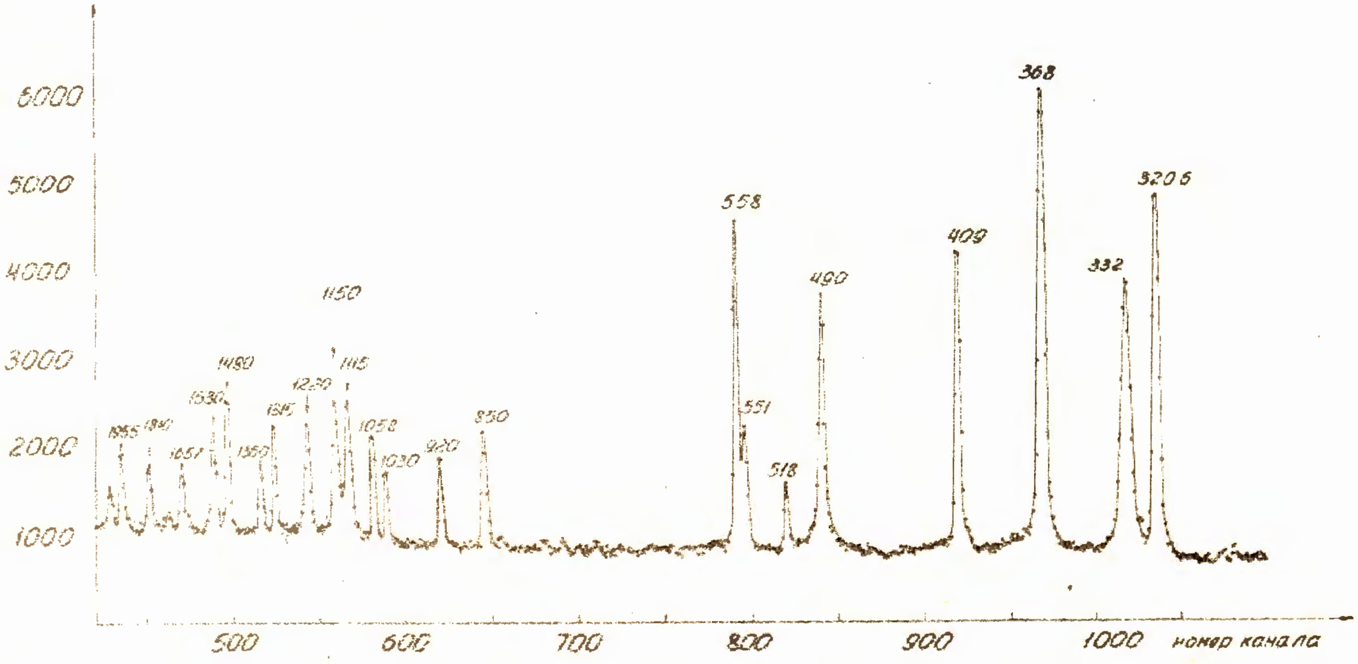

Fig.5. The radiative capture vs. time-of-flight apparatus curve for Ge.

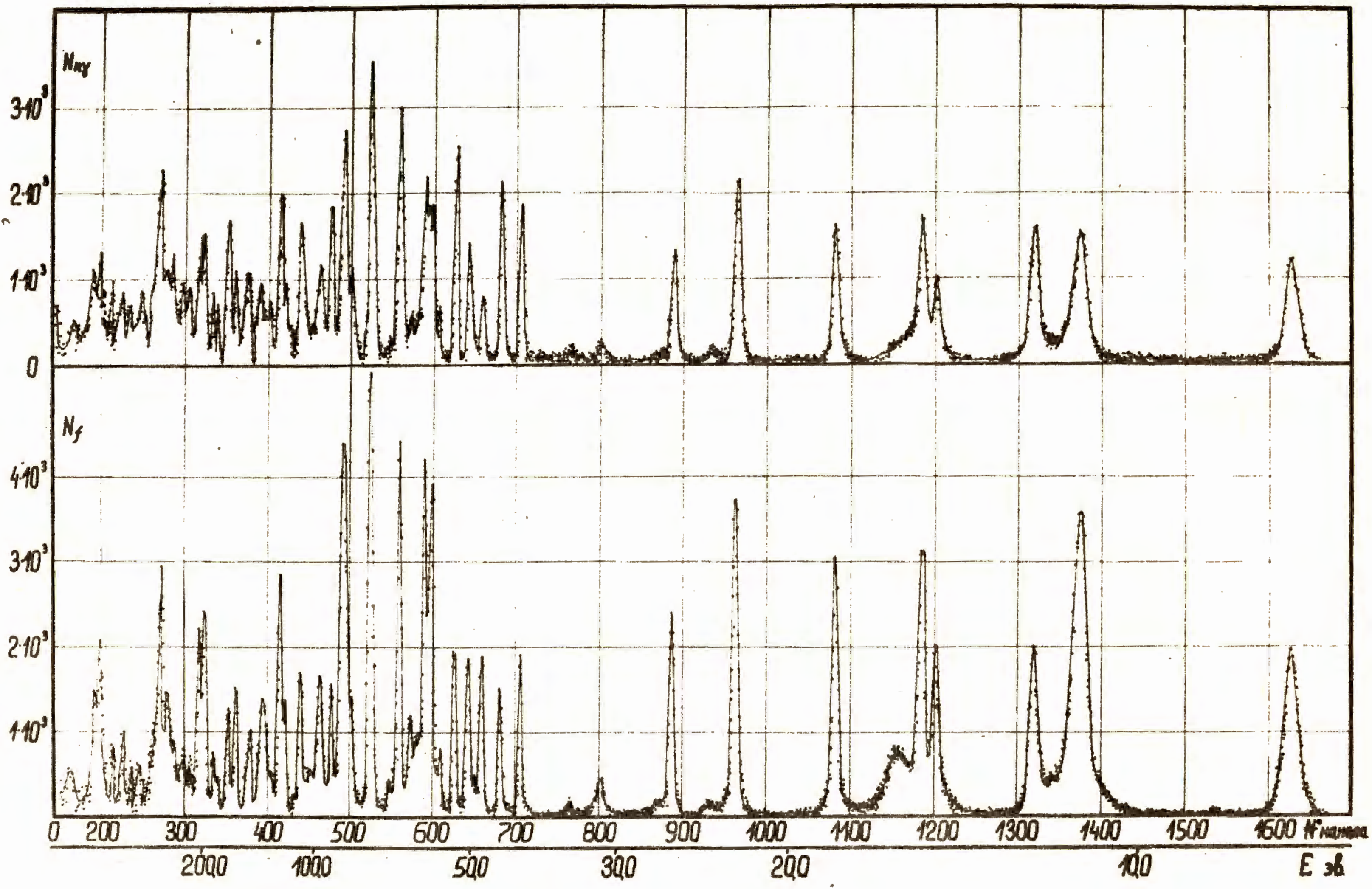

Fig.6. The radiative capture and fission vs. time-of-flight apparatus curves for ^{239}Pu. From both curves 600 constant background counts are subtracted.

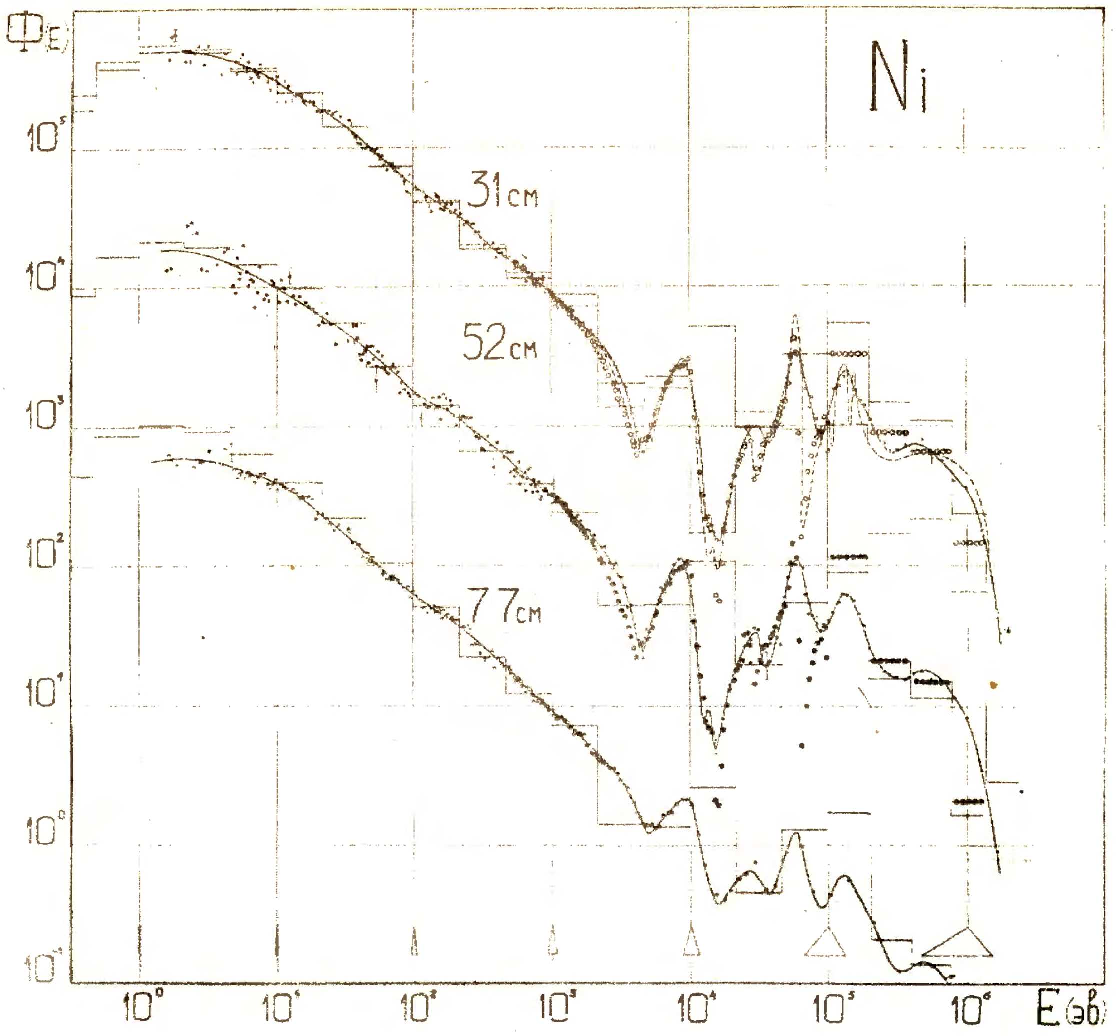

Fig.7. The experimental spectrum of neutrons transmitted through various thickness Ni prisms.

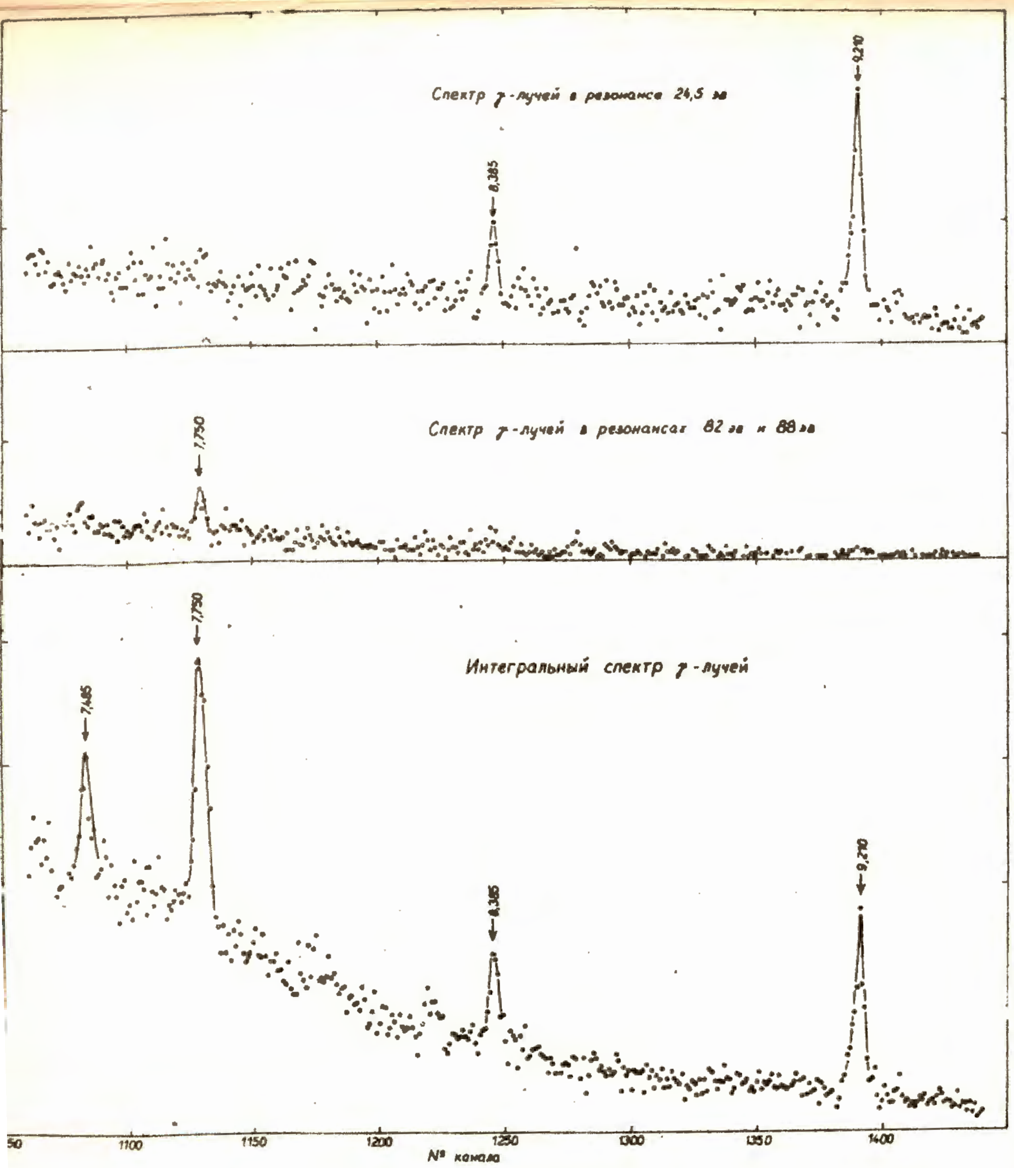

Fig.8. The amplitude spectra of hard γ -rays in Ba
sonances obtained with the aid of Ge (Li) detectors.

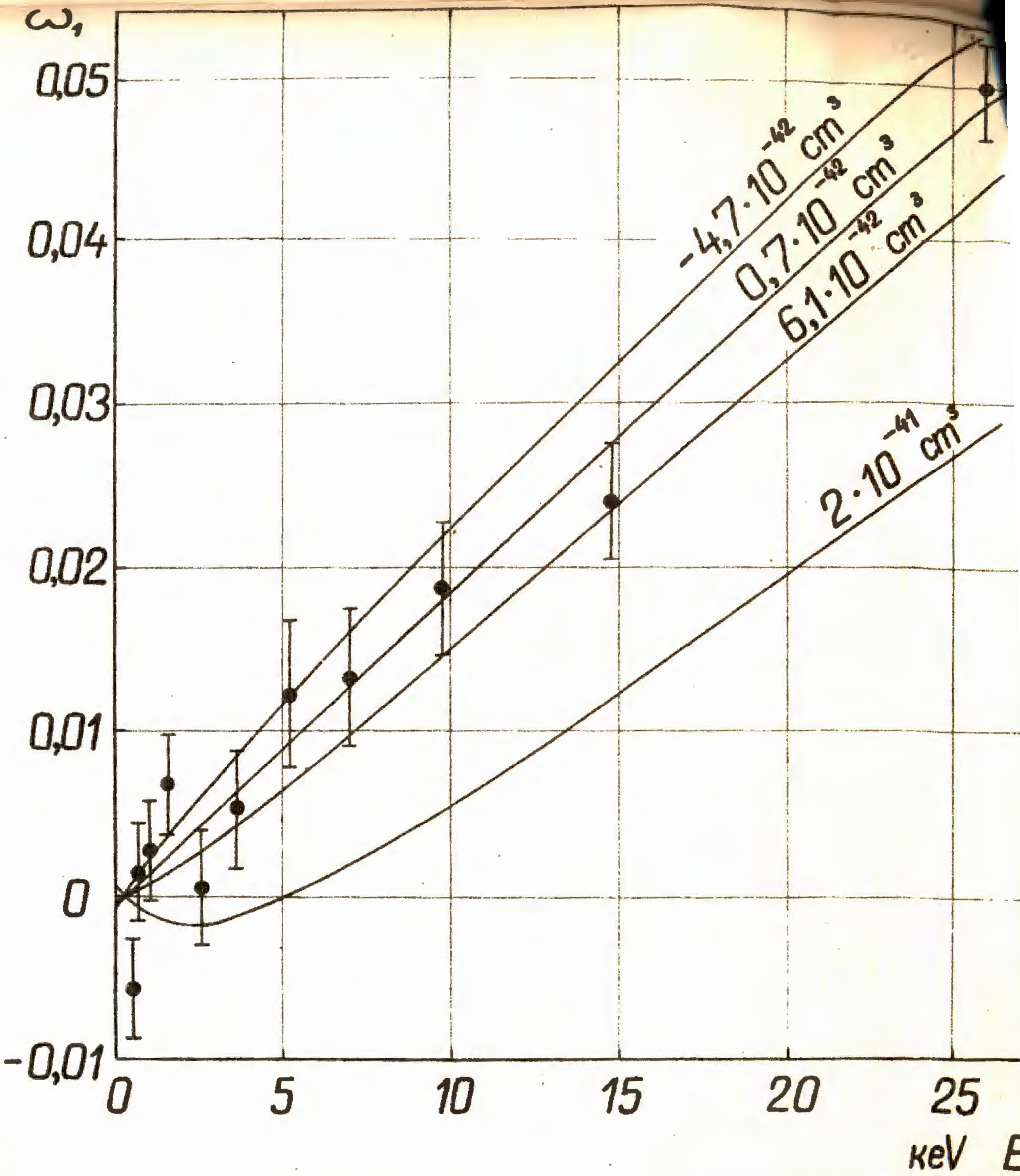

Fig.9.

The experimantal results of neutron polarizability stud
Indications are given in the text.