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Abstract

Translation of eleven papers, selected for their nuclear data interest, which were published in "Topics in Atomic Science and Technology", Series Nuclear Constants, Volume 1 (40), Moscow (1981). The original report was distributed as INDC(CCP)-167/G, and has also the report number YK-40.

April 1982

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EVALUATION OF EXCITATION FUNCTIONS FOR (n,2n) AND (n,3n) REACTIONS INVOLVING FISSILE NUCLEI

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Institute of Physics and Power Engineering

Interest in the cross-sections for the (n,2n) and (n,3n) reactions involving transactinium nuclei has recently begun to increase in connection with the specific problems of reprocessing nuclear fuel in the external fuel cycle of fast-neutron reactors.

Experimental determination of the cross-sections for these reactions in fissile nuclei is difficult in that the neutrons are emitted in the (n,2n) and (n,3n) reactions against a background of nuclear fission. It is therefore useful to investigate the possibility of evaluating the cross-sections for these reactions by theoretical methods.

Recently a number of papers [1-5] have been published suggesting various approaches to the evaluation of excitation functions for the (n,2n) and (n,3n) reactions involving fissile nuclei. The problem of theoretically describing these reactions may be briefly summarized as follows: the basic difficulty is the determination of the neutron/fission width ratio Γ_n/Γ_f in terms of statistical theory. The usual methods of calculating this value do not yield satisfactory results, so all these papers ultimately introduce normalization to some experimental data or other. In addition, most of the papers do not take into account non-equilibrium effects in the neutron channel. This question was discussed in detail in Refs [6, 7], where it was shown that the relative contribution by non-equilibrium emission of neutrons increases for fissile nuclei. This is because fission takes place after the compound nucleus has reached the equilibrium state and cannot therefore compete with the non-equilibrium processes. The contribution of the latter varies slightly from nucleus to nucleus; as a result the neutron emission spectra (leaving aside fission neutrons) will be harder for fissile nuclei. The influence of pre-equilibrium emission of neutrons on the energy dependence of the excitation function for the $^{238}U(n,2n)^{237}U$ reaction was also discussed in Refs [3, 8].

In the present paper we suggest a method of calculating the cross-sections for the (n,2n) and (n,3n) reactions based on the use of simplified versions of the statistical model and the exciton model. The basic relationships obtained for these models in the absence of a fission channel are given in Ref. [9].

The competition of fission was taken into account using a system of experimental data on the neutron/fission width ratio Γ_n/Γ_f on the assumption that this ratio depends weakly on the excitation energy of the nucleus. The dependence of Γ_n/Γ_f on the parameter $x = Z^2/A$ is approximated by the expression (Fig. 1)

$$\Gamma_n/\Gamma_f = \exp\left\{-\alpha(x-\beta)\right\},$$

where α and β are certain constant coefficients for a given Z.

Figure 2 compares fission cross-sections calculated by means of this system for the isotopes ^{232}Th, ^{238}U and ^{239}Pu with data recommended by the ENDF/B-IV data file.

Figures 3 and 4 show a comparison of the (n,2n) and (n,3n) cross-sections calculated for this paper with experimental data on the ^{239}Pu and ^{238}U nuclei. Figure 4 also shows a version of the calculation that does not take non-equilibrium processes into account. The neutron emission spectra for these reactions are calculated in the same way as the data of Ref. [6].

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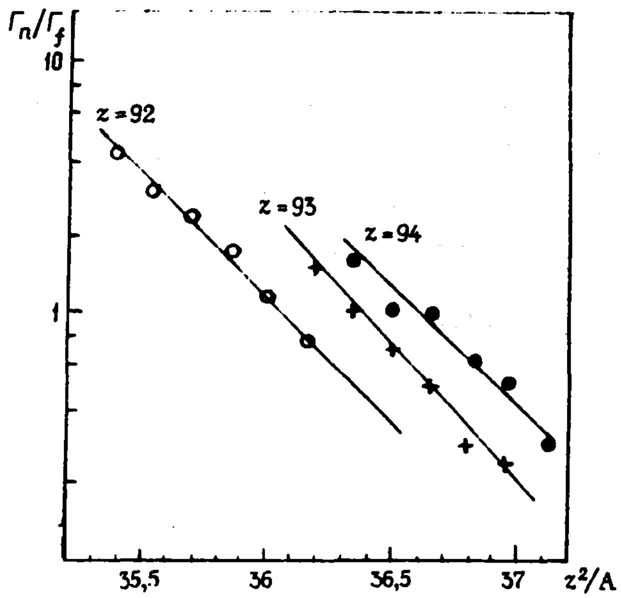

Fig. 1. Dependence of Γ_n/Γ_f on the parameter Z^2/A.

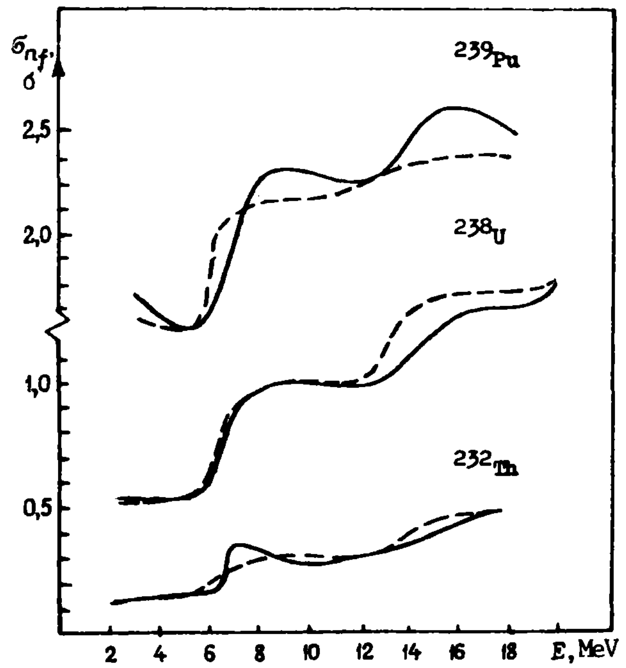

Fig. 2. Fission cross-sections for ^{232}Th, ^{238}U, ^{239}Pu: ——ENDF/B-IV data; - - - - calculations for present paper.

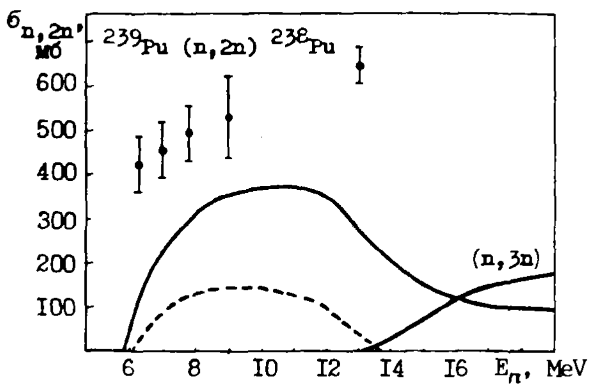

Fig. 3. Cross-sections for the (n,2n) and (n,3n) reactions in ^{239}Pu: experimental data from Ref. [10]; - - - evaluation from Ref. [1]; —— calculations for present paper.

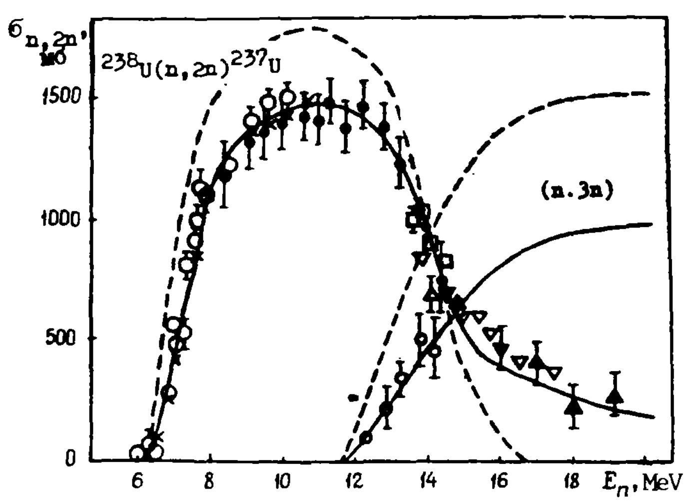

Fig. 4. Cross-sections for the (n,2n) and (n,3n) reactions in ^{238}U: —— calculations for present paper; - - - calculation not taking into account non-equilibrium processes; points - data from various authors.

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INVESTIGATION OF AVERAGED CROSS-SECTIONS FOR (n,α) REACTIONS INVOLVING ^{123}Te, ^{143}Nd, ^{147}Sm AND ^{149}Sm NUCLEI

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The research on (n,α) reaction cross-sections averaged over resonances, which was recently started in the Neutron Physics Laboratory of the Joint Institute for Nuclear Research, has made it possible substantially to broaden the neutron energy range in comparison with earlier work on the (n,α) reaction in various resonances [1]. Averaging over a large number of resonances enables us to improve the accuracy with which mean α-widths are determined and to study their dependence on neutron energy.

The authors of the present paper have tested the following methods of measuring averaged cross-sections for the (n,α) reaction:

- Use of the $^{7}Li(p,n)^{7}Be$ reaction as a neutron source [2];
- Use of filtered beams from a stationary reactor [3, 4];
- Time-of-flight method [5, 6].

The third method yields the most information, as it allows measurements to be made simultaneously in a continuous sequence of ranges, which leads to a smaller error in the determination of the relative behaviour of the cross-section and makes it possible to find its local changes, due, for instance, to the occurrence of α-cluster states in the compound nucleus.

Measurements for all nuclei were made by the time-of-flight method in a booster regime of the IBR-30 reactor at a mean power of 7 kW and a time resolution of 48 ns/m.

The measurement time was generally about 200 h. A cylindrical grid ionization chamber [7] was used as an alpha-spectrometer. The data from the chamber were coded and collected in two-dimensional form (signal amplitude - time-of-flight) in a minicomputer memory and then recorded on magnetic tape. On completion of the measurements the data were sorted in time windows in order to obtain amplitude spectra.

Typical $^{147}Sm(n,\alpha)^{144}Nd$ reaction spectra averaged over resonances are shown in the figure.

The background was excluded by smooth extrapolation from low energies. The cross-sections were normalized to low-lying resonances of the nuclei under consideration by means of the expression

$$\langle \sigma_{n,\alpha_f} \rangle = \frac{N_{\alpha_f} \Phi(E_0^k) \lambda_k^2 g_J^k \pi \Gamma_n^k \Gamma_\alpha^k}{N_{\alpha_k} 2\Gamma^k \int\limits_{\Delta E_n} \Phi(E_n)\, dE_n},$$

where N_{α_f} is the α-particle count for the transition to the final state f;

$\Phi(E_n) = \Phi_o E_n^{-0.9}$ is the dependence of the neutron flux on energy [8];

λ is the neutron wavelength; and

Γ, Γ_n, Γ_α are the total, neutron and alpha widths of the resonance.

The index k refers to the support resonance. The support resonance parameters were taken from Refs [1, 9-12].

The measured total cross-sections for the (n,α) reaction and the α-widths obtained on the basis of these data are given in Tables 1 and 2. The mean total α-widths of the isotopes ^{123}Te and ^{143}Nd (see Table 1) are actually partial widths of α-transitions to the ground state of the daughter nuclei, since transitions to the excited states are diminished by a factor of about 100 by the drop in penetrability of the barrier for α-particles (in the daughter nuclei the distance between the ground state and the first excited state is large). The errors in the mean cross-sections given in the tables contain the statistical error and the calibration error in the error of the mean α-widths. In addition, the errors due to the finite number of α-decay channels in the resonance and the finite number of resonances in the averaging interval are taken into account. Details of the relation between the mean cross-sections and the α-widths and their errors are given in Ref. [5].

For the total α-widths of the isotopes ^{143}Nd and ^{147}Sm, which were measured with the greatest precision and over the widest range of neutron energies, an attempt was made to verify the accuracy of the assumption of the statistical theory that the mean α-width is independent of the neutron energy. The χ^2 test showed that this assumption is consistent with the data obtained; e.g. for ^{147}Sm the confidence level $P(\chi^2)$ was 60%. At the same time, the possibility cannot be ruled out, on the basis of the data obtained, that the mean α-width might vary; for ^{147}Sm, for instance, it can double over the range 0.5-8 keV. For ^{143}Nd the small value of the cross-section in the range 1.6-2.4 keV should be noted; this corresponds to the transmission band of the scandium filter, where $\langle \sigma_{n,\alpha} \rangle$ (2 $\pm$ 0.4 keV = 55 $\pm$ 20 μb) and hence $\langle \frac{\Gamma_\alpha}{D} \rangle_J = (4 \pm 2.5) \times 10^{-8}$, which is less by a factor of three than the mean value in the range 0-13 keV. The cross-sections for the (n,α) reaction in ^{123}Te and ^{149}Sm nuclei are appreciably smaller, so it was possible to obtain the value of the cross-section only up to an energy of the order of 2 keV. As Tables 1 and 2 show, the results obtained are also consistent with statistical theory.

For ^{147}Sm it was possible to distinguish the cross-sections for α-transition to the ground state and to the first excited state (Table 3). Although the error in the values obtained for the reduced α-width ratios is large, the entire set of data does not exclude the possibility of amplification of the α-transition to the first excited state, as predicted in Ref. [15] (see Table 3). However, if such an amplification exists at all, its value does not exceed 2.

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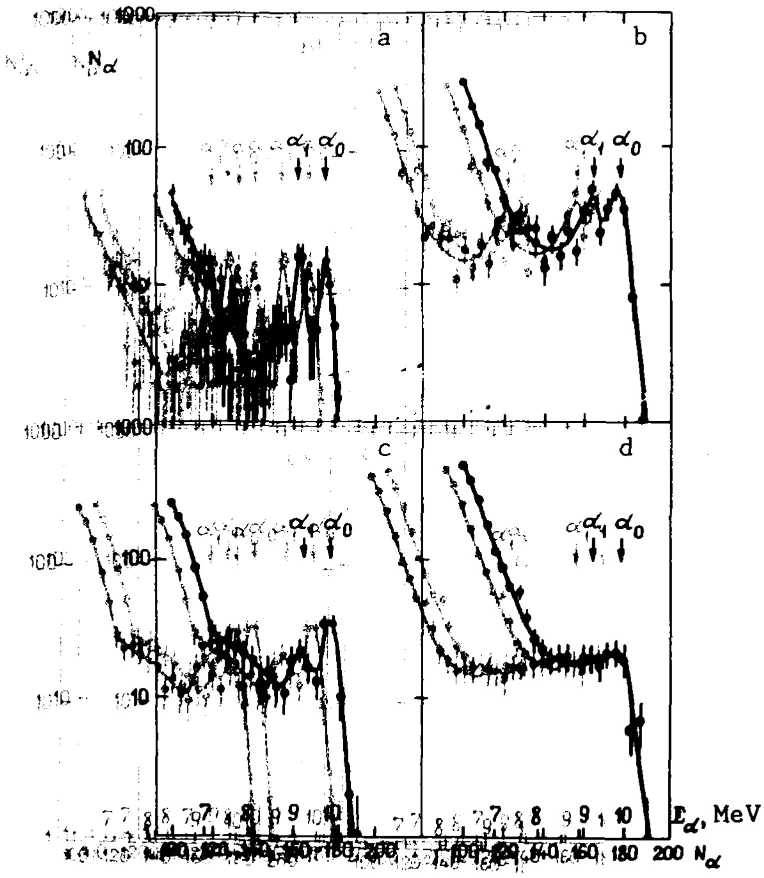

Spectra for the reaction $^{147}Sm(n,\alpha)^{144}Nd$ averaged over resonances for neutron energies (keV): 0.25-0.5(a); 0.7-1.5; 1.5-3.3(c) and 3.3-8.5(d).

Table 1

Total cross-section for the (n,α) reaction and α-widths for two isotopes

Target nucleus	Ref.	ΔE_n, keV	μ_0	N_{α_0}	$\langle \sigma_{n,\alpha_0} \rangle$, μb	$\left\langle \frac{\Gamma_{\alpha_0}}{D} \right\rangle_J$, xI0^{-8}	$\langle \Gamma_{\alpha_0} \rangle$, μeV
^{123}Te	/I0/	0–0,62	6	-	-	I,8±0,9	7,5±4,5
	Present paper	0,5–I,25	22	I50±50	80±30	3,I±I,5	I3±6
	"	I,25–2,5	40	65±20	40±I5	3,5±I,5	I4±6
	"	2,5–5,0	80	< 70	< 45	< 7	< 30
	"	5,0–I0	I65	< 45	< 30	< 8	< 35
	"	I0–20	330	< 60	< 30	< I4	< 60
^{143}Nd	"	0–I,2	I5	-	-	I3±5	22±8
	"	I,2–2,9	I9	I45±30	I50±35	II±5	I8±7
	"	2,9–5,0	27	72±II	I05±24	I4±5	23±8
	"	5,0–8,5	44	44±I0	65±2I	I3±6	2I±9
	"	8,5–I3,7	66	28±I5	45±24	I4±9	23±I4
	/4/	22–27	27	-	I5±4	II±4 (6±2)	I9±7 (9±3)
	/I3/	8–70	200	-	20±3	-	I4±2

Note: Values after deduction of the p-neutron contribution are given in brackets.

Table 2

Total cross-section for the (n,α) reaction and α-widths for samarium isotopes

Target nucleus	Ref.	ΔE_n, keV	μ_t	N_{α_t}	$\langle \sigma_{n,\alpha_t} \rangle$, μb	$\left\langle \frac{\Gamma_{\alpha_t}}{D} \right\rangle_J$, xI0^{-8}
^{147}Sm	Present paper	0,25–0,5	23	I27±I2	590±90	I4±4
	"	0,7–I,5	I3I	280±25	390±60	I8±4
	/3/	I,7–2,3	I56	-	I55±30	I3±3
	Present paper	I,5–3,3	300	I70±20	230±35	2I±4
	"	3,3–8,5	790	I50±30	I60±50	28±9
	"	I0–20	2400	< 20	< I00	< 50
	/2/	8–70	3000	-	32±8	23±6
	/4/	22–27	450	-	24±6	I4±4
^{149}Sm	/I/	0–0,09	28	-	-	2,3±I,0
	Present paper	0,06–0,I	25	53±I2	530±I80	5,I±2,2
	"	0,I–0,2I	62	4I±I2	240±I00	3,7±I,6
	"	0,2I–0,65	I98	39±I2	I40±55	4,0±I,6
	"	0,65–2,09	655	36±I2	II0±45	7,8±3,3

Table 3

Mean α-widths and reduced α-width ratio for ^{147}Sm

Ref.	ΔE_n, keV	$\langle \sigma_{n,\alpha_0} \rangle$, μb	$\langle \sigma_{n,\alpha_1} \rangle$, μb	$\left\langle \frac{\Gamma_{\alpha_0}}{D} \right\rangle_J$, x10^{-8}	$\left\langle \frac{\Gamma_{\alpha_1}}{D} \right\rangle_J$, x10^{-8}	$\frac{\langle \gamma^2_{\alpha_1} \rangle}{\langle \gamma^2_{\alpha_0} \rangle}$
[14]	0-0,2	-	-	6,5±4	2,5±1,5	1,5±2
Present paper	0,25-0,5	260±50	220±50	6±3	5,5±2	1,8±1,2
"	0,7-1,5	180±40	160±35	9±3	7±2	1,6±0,6
[3]	1,7-2,3	70±20	55±15	6±2,2	4,5±1,4	1,5±0,45
Present paper	1,5-3,3	110±25	90±20	10±3	7±1,8	1,48±0,45
"	3,3-8,5	70±20	55±15	12,5±4	10±2,8	1,6±0,45
[4]	22-27	13±3	8±2	7±1,7	5±1,2	1,23±0,32

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A STUDY OF THE FLUCTUATIONS IN CROSS-SECTIONS AND TOTAL α-WIDTHS IN THE $^{147}Sm(n,\alpha)^{144}Nd$ and $^{67}Zn(n,\alpha)^{64}Ni$ REACTIONS

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The properties of such complex states as neutron resonances are usually described on the basis of statistical theory, within the context of which their neutron, radiation and alpha widths are studied. Against the overall background of statistical patterns, indications of possible deviations are found (see, for example, Ref. [1]). In particular, in a study of the $^{147}Sm(n,\alpha)^{144}Nd$ reaction an anomaly in the characteristics of a resonance with E_o = 185 eV and a marked difference between the values of $<\Gamma_\alpha>$ for the ranges E_n < 100 eV and 100 < E_n > 200 eV have been found [2]. Accordingly, it would be interesting to determine what the situation is over a broader energy range: this question is not an arbitrary one, since it has a bearing on the laws of alpha-cluster-level force fragmentation in compound states. For this purpose measurements were made on a neutron beam from the "Fakel" device at the I.V. Kurchatov Institute of Atomic Energy [3]. The layout of the experiment is shown in Fig. 1, and data on the targets and other experimental conditions are given in Table 1. For detecting alpha particles a multi-section detector developed by the authors, consisting of paired proportional chambers operating on the coincidence principle, was used [4].

Time spectra of the alpha particle yield were measured. For the $^{147}Sm(n,\alpha)^{144}Nd$ reaction, calibration was based on the ^{147}Sm resonance with E_o = 83.4 eV, and for ^{67}Zn on the ^{67}Zn resonance with E_o = 1548 eV, which have alpha widths of $2.5 \pm 0.3\,\mu eV$ [5] and $680 \pm 300\,\mu eV$ [6] respectively. Values or upper limits were obtained for Γ_α for all known resonances of ^{147}Sm up to 700 eV and of ^{67}Zn up to 4 keV, which agree well with the data already available [5, 6].

Table 2 gives values for the quantities $R_n = 2g\Gamma_n^o/<2g\Gamma_n^o>$ and $R_\alpha = \Gamma_\alpha/<\Gamma_\alpha>_{J=3^-}$: these are relative probabilities of a given decay mode or, in I.M. Frank's terminology [7], affinities for a given decay mode. It will be seen that, up to 700 eV, of the two resonances with high Γ_α values, only one (185 eV) exhibits specific properties in the neutron decay channel as well. At higher energies the ^{147}Sm time spectrum is seen to have several peaks (Fig. 2), which may correspond to resonances with large alpha widths. Since the resonance parameters in the neutron energy region 1.1-3.2. keV are unknown, our estimates of the alpha widths for them were made on the assumption of a thin sample and large neutron width ($\Gamma_n >> \Gamma_\gamma$) and lie in the range (30-50 $\pm$ 40%) μeV. It appears that the experimental probabilities of resonances with large Γ_α existing are in agreement with those calculated in statistical theory on the assumption that the total alpha widths obey a χ^2 distribution with $\nu_{ef} = 2$ degrees of freedom; thus in terms of this parameter they are not anomalous.

For ^{67}Zn, in the range up to 30 keV the experimental results suggest that there are no resonances with anomalous alpha widths.

The time-of-flight method can be used to obtain information about average cross-sections in particular energy ranges. The absolute value of a cross-section averaged over the energy range ΔE_n was determined from the formula

$$\langle \sigma(n,\alpha) \rangle = \frac{N_\alpha}{(N_\alpha)_k} \; \frac{\Phi(E_0^k)\lambda_k^2 (g\Gamma_n)_k (\Gamma_\alpha)_k}{2\Gamma_k \int_{\Delta E_n} \Phi(E_n) dE_n},$$

where N_α is the number of alpha particles counted in the range ΔE_n; λ is the wavelength of the neutron; Φ is the neutron flux; and the subscript k signifies pertinence to the calibration resonance. The resonances used for reference values were the same as those used for the determination of the alpha widths. The dependence of the background on the time of flight was obtained by counting between resonances and in resonances of manganese (E_o = 0.377, 1.098 and 2.375 keV). The background varied little with the energy E_n; thus, in the measurement on ^{147}Sm in the range $0.1 < E_n < 3$ keV the background was 0.7-0.8 pulses per channel.

Figure 3 shows the cross-sections $<\sigma(n,\alpha)>$ averaged over the energy ranges ΔE_n. The uncertainties include only the experimental errors. The solid line is the result of fitting to the statistical model, while the dotted lines show the error band which corresponds to σ and 2σ. It will be seen that there is a considerable fluctuation in the cross-sections when they are averaged over ranges including 10-15 resonances (ΔE_n = 100 eV for ^{147}Sm and 5 keV for ^{67}Zn). We did not succeed, using a single fitting parameter $<\Gamma_\alpha>$, in obtaining good agreement between the experimental cross-section and that calculated by the usual formula for averaged cross-sections [8] (the result of fitting over 14 ^{147}Sm data points gives $\chi^2_{min} = 60$ for $<\Gamma_\alpha>_{J=3^-} = 25$ μeV, and over 6 ^{67}Zn data points $\chi^2_{min} = 11$ for $<\Gamma_\alpha>_{J=3^-} = 268$ μeV).

Whether the marked differences in $<\sigma(n,\alpha)>_{\Delta E_n}$ observed are connected with random deviations (on the assumption that the statistical model is followed) or have specific physical causes remains an open question. A first step towards answering it might be verification of the existence of correlations with other channels. It would also be interesting to extend the range of energies investigated.

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Table 1

Target nucleus	Enrichment	Foil thickness, mg/cm^2	Area cm^2	No. of foils	Time resolution ns/m	Measurement time, h
^{147}Sm	95.3	5.00	625	2	4	180
^{67}Zn	91.8	2.97	625	4	2.5	100
^{6}Li	90.5	0.023	620	1	-	-

Table 2

E_o, eV	$2g\Gamma_n^o$, meV	$\Gamma_\alpha \times 10^7$, eV	R_n	R_α
185.0 ± 0.4	24.1 ± 1.7	196 ± 18	4.0	4.5
663 ± 1	3.0 ± 1.5	173 ± 80	0.5	4.0

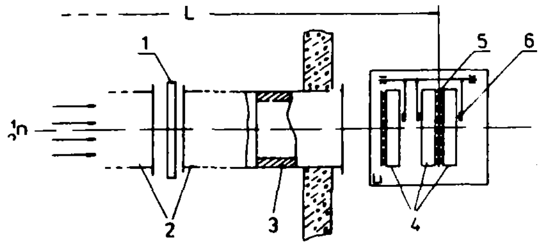

Fig. 1.

Experimental layout: 1 - boron filter;

2 - neutron guide;

3 - collimator;

4 - paired proportional chambers;

5 - targets;

6 - alpha reference sources.

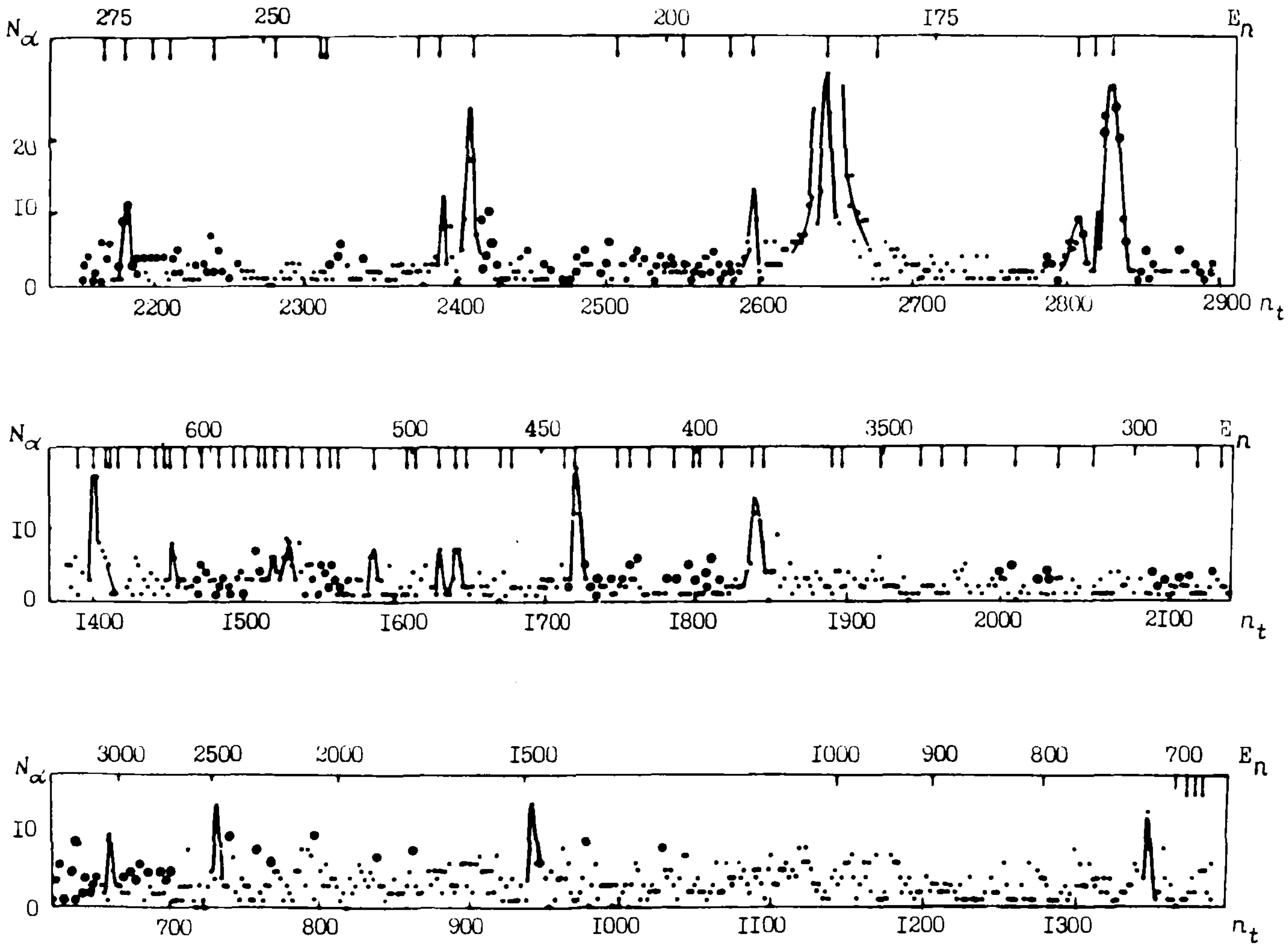

Fig. 2. Time spectrum of alpha particles from the $^{147}Sm(n,\alpha)^{144}Nb$ reaction.

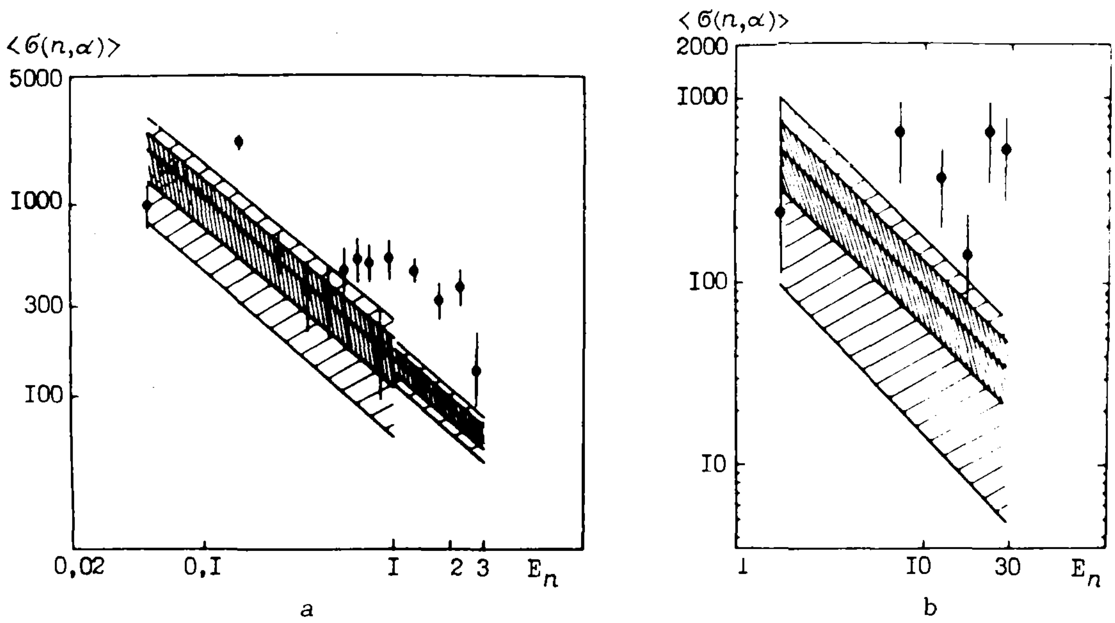

Fig. 3. Cross-sections $\langle\sigma(n,\alpha)\rangle$ averaged over intervals ΔE_n:
a – for ^{147}Sm; b – for ^{67}Zn.

UDC 539.172.4

STUDY OF THE POSSIBILITY OF EXCITATION OF ISOBARIC ANALOGUE STATES IN THE ^{207}Pb(np) REACTION

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It is important to study the excitation of isobaric analogue states (IAS) in isospin-forbidden reactions with neutrons in order not only to understand the reaction mechanism but also to elucidate the mechanism of the loss of isospin symmetry.

Venetskij and co-workers [1] were the first to observe two resonances at E_n = 16.6 and 17.2 MeV in the ^{208}Pb compound nucleus in the ^{207}Pb(nn) reaction. While the total resonance width of Γ = 200 keV is characteristic of IAS, the elastic neutron width was found to be unusually large (Γ_n = 120 keV). In the ^{208}Pb(np) reaction [2] no IAS excitation was observed, whereas both ^{90}Zr(nn) and (np) [3] showed excitation of several IAS with typical widths, Γ = 50 keV and Γ_n = 1.0 keV.

Earlier, IAS were observed in the ^{207}Pb compound nucleus in the ^{206}Pb(np) reaction at neutron energies of 14.0 and 14.4 MeV [4]; the widths obtained were Γ = 150 keV and $\Gamma_n^{\uparrow}$ = 0.06 keV.

In the experiments described in this paper we studied neutron-induced excitation of IAS in the ^{208}Pb compound nucleus in the ^{207}Pb(np) reaction (E_n = 15.3-19.0 MeV). The neutron energy needed for excitation of the isobaric analogue of the ground state of the parent ^{208}Tl nucleus is 15.6 MeV. The level scheme of the ^{208}Tl nucleus for excitation energies above 1 MeV is not known [5], and it is therefore not possible to calculate E_n for the corresponding analogues. From the experimental data on the neighbouring n-n nuclei it follows that the total number of levels of the parent nucleus in the energy range studied is more than 60. Most of them have a simple particle-hole structure.

The ^{207}Pb(np)^{207}Tl reaction with Q = -0.7 MeV was identified from the induced β-activity. The residual ^{207}Tl nucleus is a pure β-emitter with $E_{\beta\,max}$ = 1.4 MeV and $T_{\frac{1}{2}}$ = 4.77 min. The ^{207}Pb(n,pn+nd)^{206}Tl reactions are also possible. The ^{206}Tl isotope is a pure β-emitter with a half-life of $T_{\frac{1}{2}}$ = 4.3 min. These reactions cannot be separated from the main reaction by the activation method, but it follows from Ref. [6] that they do not hinder observation of IAS.

The (nd) reaction is doubly isospin-forbidden. The enriched ^{207}Pb samples contained 79% ^{207}Pb, 18% ^{208}Pb and 3% ^{206}Pb, so that the total activity associated with the reactions $^{207}Pb(np+n,pn+nd)+{}^{208}Pb(np+n,pn+n\alpha)$ was measured. Neutrons with energies of 15-19 MeV were obtained from the T(dn) reaction in an EhG-5 electrostatic generator by changing the deuteron energy from 0.8 to 3 MeV and arranging the samples at angles of 10 and 50^o to the deuteron beam. Ti-T targets with a thickness of 0.6-0.8 mg/cm^2 were used. The accelerator calibration and the target thickness were checked on the basis of the (pn) reaction threshold. The energy spread of the neutron beam was about 200 keV and the energy step during the measurements 50-150 keV.

The ^{207}Pb samples, 30 x 50 mm plates with a thickness of 0.4 mm, were placed at a distance of 5 cm from the target with their narrow side facing the neutron source. The irradiation time was 6 min. The activity of the samples was measured by a system of two SBT-10 counters having a working area of 30 cm^2 with their windows facing each other (4π geometry); to reduce the background, these were placed inside a 5-cm-thick lead cylinder surrounded by an array of MS-6 counters connected to the anticoincidence circuit. The counters operated in the Geiger regime.

The primary neutron beam was monitored by activating one of the samples (^{28}Si, ^{27}Al and ^{138}Ba) arranged at an angle of 120^o to the deuteron beam. For this angle the energy of the neutrons (E_n = 13.4 MeV) is not dependent on the energy of the deuterons. The monitoring samples had half-lives close to 5 min and a large reaction cross-section. In the case of the ^{138}Ba monitor (99.8% enriched), the reaction $^{138}Ba(n,2n)^{137}Ba^m$ with Q = -8.61 MeV was used. The activity of the $^{137}Ba^m$ isomer emitting gamma quanta with E_γ = 0.66 MeV was measured with a Ge(Li) spectrometer. The aluminium and silicon monitors were found to be more convenient. The $^{27}Al(np)$ and $^{28}Si(np)$ reactions were used, their β-activity being measured on the same apparatus used for the ^{207}Pb. They had the added advantage of ensuring high statistical accuracy. There was good agreement between the results obtained with different monitors.

The ^{207}Pb samples contain ^{208}Pb as an impurity, so we measured the energy behaviour of the activities in ^{208}Pb (98% enriched) for 16.4-17.7 MeV neutrons. The deviations from a smooth dependence lie within the experimental errors and the contribution of ^{208}Pb to the ^{207}Pb activity did not exceed 25%.

We carried out several series of measurements on the excitation function of the $^{207}Pb(np)$ reaction. The measurement results are shown in Fig. 1 (which also gives the χ^2 distributions of the average components).

The total experimental error for a confidence probability of 0.7 is about 5%. A curve was drawn through the experimental points by the least squares method and the deviations of the experimental points from the curve were calculated by the χ^2 method (see Fig. 1). In connection with the data given in Ref. [1], particular attention was paid to the E_n = 16.4-17.2 MeV region. Treatment in all the series gives χ^2 = 0.8-1.4 and does not indicate any anomalies. The plots of the χ^2 components averaged over a sliding interval of three points in all series show spikes with a quadratic amplitude from 1 to 3, so that no conclusion can be drawn about the presence of resonances in the whole neutron energy region studied.

We can only evaluate the upper value of the resonance cross-section $\sigma^R_{np} = 0.1\sigma_b$ (two errors), where σ_b is the background cross-section. Taking the data from Ref. [7] and our present measurements, with allowance for the contribution from ^{208}Pb activity, we obtain σ_b = 6 mb, and $\sigma^R_{np} \lesssim 0.6$ mb. Using the Breit-Wigner formula for a single resonance and the value interval $0.1 < \Gamma_p/\Gamma < 0.7$ for IAS in the neighbourhood of lead [6], we obtain the elastic neutron width $\Gamma^{\uparrow}_n < 10$ keV. The calculation performed in Ref. [8] gives $\Gamma^{\uparrow}_n$ = 0.002 keV. The value obtained in Ref. [1] is $\Gamma^{\uparrow}_n$ = 120 keV. This value is an order of magnitude higher than ours obtained in the present experiments, and is also larger than the values of $\Gamma^{\uparrow}_n$ obtained in other experiments [9].

The results of the present experiments and the experiments described in Ref. [1], where the same compound nucleus exhibited resonances with σ^R_t = 150 mb in the total and differential cross-sections for 16.6 and 17.2 MeV neutrons (excitation energy 24.0 and 24.6 MeV), can be correlated if $\sigma^R_{np} = \sigma^R_t \Gamma_p/\Gamma$, so that $\Gamma_p/\Gamma < 3 \times 10^{-3}$; or $\Gamma_n/\Gamma_p > 3 \times 10^2$.

Reference [6] notes that IAS ($J^\pi = 1^-$) has been observed in the reactions $^{208}Pb(\gamma p + \gamma_1 pn)$ and $^{208}Pb(e,e'p)$ for E_* = 25 MeV. These resonances are not seen in the $^{207}Pb(np)$ reaction, possibly because the effect is of smaller magnitude and because in the (np) reaction, in contrast to (γp), many IAS may be excited which cannot be observed owing to their overlapping.

Let us now compare the results of the above three experiments with σ_γ - the total absorption cross-section for gamma quanta in ^{208}Pb [10]. Let us assume that the resonances observed in reactions with neutrons [1] and gamma quanta are identical. The resonance cross-section for IAS excitation in the (γp) reaction is $\sigma^R_{\gamma p} = 3$ mb [6]. Using $\Gamma_n/\Gamma_p > 3 \times 10^2$, obtained from the first two experiments, we can calculate the resonance cross-section for the reaction ^{208}Pb(γ,n): $\sigma^R_{\gamma n} = 3 \times 3 \times 10^2 = 900$ mb. As follows from Ref. [10], in this gamma energy region no resonances were observed in σ_γ, although $\sigma_\gamma < 50$ mb and is constant over a very wide range of E_γ.

It is highly probable that the resonances observed in experiments with neutrons and gamma quanta belong to different highly-excited states of the ^{208}Pb nucleus. Further confirmation of this is to be found in the 700 keV resonance-energy shift observed in both experiments. The foregoing and also the unusually high $\Gamma_n^\uparrow$ suggest that the resonances observed in Ref. [1] are possibly associated with the formation of other input states at high excitation energies.

In conclusion, it should be pointed out that the neutron resonance energies quoted in Ref. [1] are close to the proton energies characteristic of IAS $d_{5/2}$ and $S_{1/2}$ excitation, which are excited most strongly in the (pp) reaction in lead isotopes [11].

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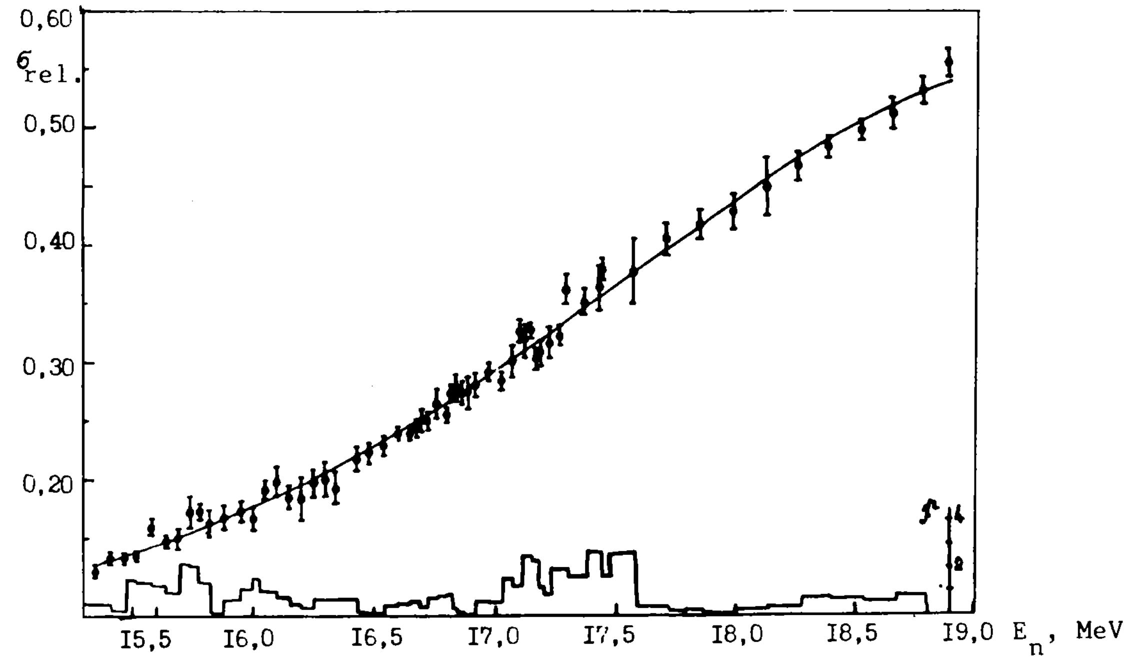

Fig. 1. Excitation functions for the $^{207}Pb(np)$ reaction.

UDC 539.172.162.2

THE ENERGY DEPENDENCE OF THE TOTAL CROSS-SECTION FOR INTERACTION BETWEEN NEUTRONS AND ^{3}He NUCLEI IN THE RANGE 0.025-250 eV

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The cross-section for interaction between neutrons and ^{3}He nuclei is one of the standard cross-sections [1], i.e. one of those which vary evenly over a wide range of energies and are known to a high degree of accuracy. However, this last requirement is met by measurements of the total cross-section [2] and the scattering cross-section [3] only in the thermal region. Until recently there were very few data on cross-sections in the energy range 10 eV-10 keV. The only experimental result for the absorption cross-section [the ^{3}He(n,p) reaction] was found from the cross-section ratio for the ^{3}He(n,p) and ^{6}Li(n,α) reactions [4].

The authors of this paper report measurements of the total cross-section for interaction between neutrons and ^{3}He nuclei in the energy range 0.025-250 eV. The measurements were made using the time-of-flight method on the IBR-30 pulsed reactor. The drift space to the detector was 115.51 $\pm$ 0.05 m for measurements in the thermal energy region (reactor operating mode), and 57.72 $\pm$ 0.03 m in the resonance region (booster operating mode of the reactor together with the LUEh-40 electron accelerator). The targets used were gaseous samples in cylindrical stainless steel containers 50 mm in diameter and 590.3 $\pm$ 0.05 mm long. The operating pressures at a temperature of 22°C were 100.59 $\pm$ 0.02 torr and 49.86 $\pm$ 0.05 torr (1 torr = 133.322 Pa) in samples for the thermal region, and 751 $\pm$ 0.2 torr in the sample for the resonance region. The containers were pumped out to produce a high vacuum when heated to 150°C; the inleakage amounted to not more than 4 x 10^{-6} torr/h. The ^{3}He for the targets was purified using cryogenic sorbtion traps. The amount of ^{4}He in the ^{3}He samples used was (1.7 $\pm$ 0.1)%, and this was measured by mass analysis on the EhG-5 electrostatic accelerator. The gaseous sample thicknesses measured with this fact taken into account were 1.906 x 10^{20}, 0.945 x 10^{20}, 0.970 x 10^{20} and 1.421 x 10^{21} ^{3}He nuclei per cm^2.

After ten minutes of measurement with and without a gaseous sample the samples were changed automatically. During measurement without a sample a vacuum container with transmission characteristics the same (to within 0.02%) as those of the sample container was introduced into the beam. The experimental spectra obtained in the resonance energy region for measurements with and without a sample are shown in Fig. 1. The lower scale corresponds to the time of flight of neutrons t (channel width 2 μs) and the upper scale to the neutron energy E in electron-volts. The statistical collection time for each spectrum was 29 h. In these measurements there were always background resonance filters of manganese (337 eV), rhodium (1.26 eV) and cadmium (0.178 eV) in the beam. The energy dependence of the background curve was determined by a separate measurement using additional filters of bromine (35.8 eV), silver (5.2 eV) and cobalt (132 eV). When transmission measurements were made the total cross-section σ_t was found. The accuracy of the experimental points of σ_t was 0.5% at the beginning of the energy range (at $E \simeq 2$ eV) and approximately 2% at the end of it.

Measurements with thermal neutrons covered the energy region 0.02-0.17 eV. The background was determined by extrapolation of detector readings in the time channels between neutron bursts to the region being studied, where it did not exceed 2% of the maximum experimental spectrum. The least-squares method was applied to the data for individual energy sectors of the spectrum in order to find $(\sigma_a\sqrt{E})_T$. The average result over three samples (with σ_n being disregarded) was

$$(\sigma_a\sqrt{E})_T = 848,6 \pm 1,2 \text{ b}\cdot\text{eV}^{1/2}.$$

This value corresponds to the cross-section at the thermal point, which is equal to

$$\sigma_a(2200 \text{ м/с}) = 5337 \pm 8 \text{ b},$$

this is in agreement with the value of 5327 ± 10 b found earlier [2].

The total cross-sections found are shown in Fig. 2 in the form of a dependence of $\sigma\sqrt{E}$ (the point) on energy. The broken line represents the case in which only the absorption cross-section σ_a has been taken into account; the deviation of σ_a from the 1/V law in the energy range studied may, as is shown in Ref. [4], be given in the form

$$\sigma_a\sqrt{E} = (1+4,6.10^{-2}\sqrt{E\ \text{keV}})^{-1}(\sigma_a\sqrt{E})_T . \qquad (1)$$

This deviation already becomes marked (approximately 2%) at 200 eV. Unfortunately, it was not taken into account in Ref. [5], the authors of which measured the ratio of the $BF_3(n,\alpha)$ and $^3He(n,p)$ cross-sections and concluded that the molecular link between atoms influences the neutron cross-section.

Deviation in the experimental points of Ref. [2] from the broken line is a systematic one. It can be explained in terms of an increase in the relative contribution of the scattering cross-section σ_n to the total cross-section σ_t in accordance with the expression

$$\sigma_t\sqrt{E} = \sigma_n\sqrt{E} + \sigma_a\sqrt{E} . \qquad (2)$$

The scattering cross-section can thus be found from the energy dependence of the total cross-section by using the deviations of the cross-section σ_a from the 1/V law. The presentation of the experimental points in Fig. 2 by means of Eq. (2), in which $\sigma_a\sqrt{E}$ is determined by Eq. (1), takes the form of a solid line, the parameters of which have been found to be equal to

$$(\sigma_a\sqrt{E})_T = 848,0\pm0,4\ \text{b}\cdot\text{eV}^{1/2};$$

$$\sigma_n = 3,3\pm0,2\ \text{b}.$$

These values are in good agreement with the measurements of σ_t [2] and σ_n [3] in the thermal energy region. It would be of interest to extend the neutron energy region studied up to some hundreds of kiloelectron-volts.

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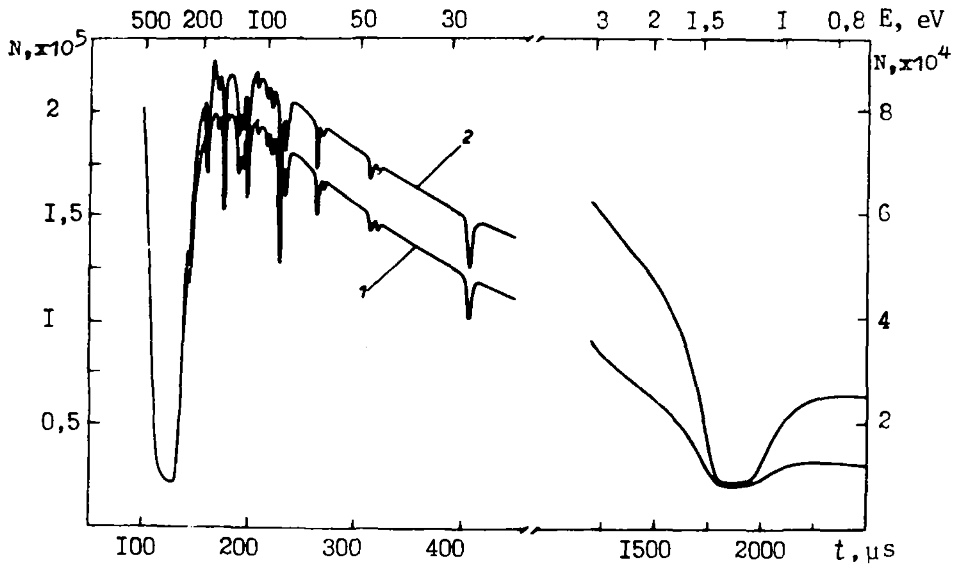

Fig. 1. Experimental spectra with sample (curve 1) and without (curve 2) obtained by transmission of ^{3}He in the resonance neutron energy region.

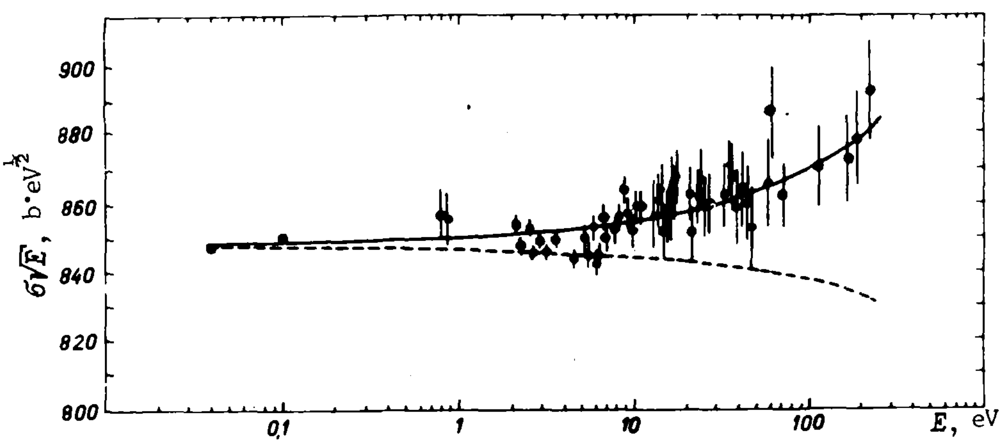

Fig. 2. Values of $\sigma\sqrt{E}$ as a function of neutron energy.

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A NEUTRON DATA LIBRARY FOR THERMAL REACTOR CALCULATIONS

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The main virtue of the evaluated neutron data files that have now been distributed is the completeness of the information on characteristics of neutron interaction with nuclei. However, this completeness naturally causes libraries to be very large, which renders their direct use for reactor calculations difficult if not impossible. At the same time, for thermal reactor calculations only a small part of the information in the files is actually used in practice. It should also be mentioned that existing libraries are severely lacking in values used in standard reactor calculation schemes (for example, resonance integrals).

These considerations have led to the establishment of an evaluated data library designed to be used for thermal reactor calculations and other applications of low-energy neutron physics. The library has been called the "KORT" (thermal reactor constant) library.

The KORT library contains the following data:

- General characteristics of nuclei: mass, capture and fission reaction energies, radioactive disintegration parameters;
- Partial cross-sections of thermal-energy neutrons and numbers of secondary fission neutrons, evaluated errors in these values;
- Factors determining the deviations of the capture and fission cross-sections from the 1/V law in the Maxwellian spectrum;
- Resonance integrals of capture and fission and evaluated errors in these values;
- Detailed energy dependence of cross-sections in the region 10^{-4}-5 eV;

- Resolved neutron resonance parameters. This part of the library is linked with the resonance parameter cross-section calculation program taking into account Doppler broadening and interference between resonances and resonance and potential scattering cross-sections [1];
- Oscillation frequency spectra of moderator atoms. This part of the library is linked with the slow-neutron differential scattering cross-section program taking into account the thermal motion of and chemical bonds between atoms [2]. The fast operation of this program has made it unnecessary to store scattering laws, as is done in the ENDF/B library.

The data on thermal cross-sections, resonance integrals and resonance parameters are the result of an evaluation performed on experimental results [3] and of a critical analysis of evaluations of results (Refs [4-6] and others).

The nuclear masses and radioactive disintegration parameters are taken from the handbook Ref. [7]. The fission energy is evaluated in Ref. [8], the capture energy is calculated from the mass balance and the oscillation frequency spectra of moderator atoms are taken from the recommendations in Ref. [9].

The elements and isotopes for which data are recorded in the KORT library are divided into three groups:

- Basic fissionable and raw-material isotopes, structural materials, absorbers, slow-neutron detectors and highly absorbent fission fragments (74 nuclides in all). When evaluating data for these isotopes use was made of references published up to August 1978;
- Eight basic reactor moderators;
- Actinides formed in the process of a thermal reactor run as a result of the (n,γ) reaction and radioactive disintegration (a total of 68 isotopes from ^{228}Th to ^{256}Fm). For the evaluation, data published up to August 1979 were used.

Some data on actinides from the KORT library are given in the table.

The KORT library has been recorded on magnetic tape in a format similar to that of the SOKRATOR [10] and UKNDL [11] libraries and can be used both directly in calculation programs and as reference material.

For the KORT library to be used effectively, all the features of the TEKDA library service program complex [12] may be called into play.

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Some characteristics of actinides from the KORT library

Isotope	σ_c^T, б	g_c	IR_c, б	σ_f^T, б	g_f	IR_f, б	E_R^{max}, eV
^{228}Th	I23±I5	-	>I000	-	-	-	-
^{229}Th	54±6	I,043	I000±I80	30,5±3,0	I,025	464±70	9,I5
^{230}Th	23,2±0,6	I,0I3	I0I0±30	-	-	-	294
^{232}Th	7,40±0,08	0,995	85±3	-	-	-	3994
^{231}Pa	20I±20	I,020	470±I00	-	-	-	99
^{232}Pa	760±I00	-	-	700±I00	-	-	I7
^{233}Pa	4I±6	0,980	895±30	-	-	-	-
^{232}U	73,I±I,5	0,973	280±I5	75,2±4,7	0,973	350±I00	74,2
^{233}U	40,6±2,0	0,999	I40±6	533,2±3,0	0,997	764±I3	64,3
^{234}U	I00±I,5	0,989	645±70	-	-	-	I486
^{235}U	9I,9±2,3	0,98I	I44±6	588,I±I,9	0,98I	275±5	I0I
^{236}U	5,2±0,3	I,002	365±20	-	-	-	3967
^{237}U	380±I00	-	I200±200	-	-	-	-
^{238}U	2,7I±0,02	I,002	278±5	-	-	-	5756
^{239}U	22±5	-	-	I4±3	-	-	-
^{237}Np	I69±3	0,952	660±50	-	-	-	I50
^{236}Pu	-	-	-	I62±30	-	-	-
^{237}Pu	-	-	-	2200±400	-	-	-
^{238}Pu	547±20	0,956	I62±I5	I6,5±0,5	0,956	23±5	496
^{239}Pu	265,9±4,I	I,063	I90±20	748,I±2,8	I,065	3I0±I0	647
^{240}Pu	287±I,4	I,028	8260±250	-	-	-	5692
^{241}Pu	355±8	I,040	I62±8	I023±II	I,046	570±I7	I00
^{242}Pu	I8,5±0,4	I,0I0	I280±50	<0,2	-	4,7±4,7	3836
^{243}Pu	87±I3	-	265±60	I80±30	-	540±I40	-
^{241}Am	836±20	0,994	I400±90	3,I4±0,I	I,0I4	22±2	49,3
	752±20(g)	-	II90±80(g)	-	-	-	-
	83,6±2,6(m)	-	220±I5(m)	-	-	-	-
^{242g}Am	-	-	<300	2I00±I200	-	-	-
^{242m}Am	II00±II00	I,I04	230±I00	6900±400	I,I00	I900±300	3,3
^{243}Am	79±4	I,0I3	2050±I00	0,20±0,II	-	I0±6	250
^{242}Cm	20±I0	0,927	I50±40	-	-	-	265
^{243}Cm	I3I±I0	-	2I5±20	609±25	-	I550±200	25,8
^{244}Cm	I3,5±2,0	I,00I	625±50	I,0±0,2	0,998	I9±2	972
^{245}Cm	350±30	0,936	I04±8	2030±60	0,942	790±40	60
^{246}Cm	I,3±0,3	I,005	II7±8	0,I5±0,07	I,006	I2±2	3I3
^{247}Cm	59±6	I,002	500±75	80±7	0,995	750±I00	38
^{248}Cm	2,9±0,3	I,002	265±25	0,37±0,07	-	I4±2	239I
^{249}Bk	I800±I00	-	I400±700	-	-	-	-
^{250}Bk	-	-	-	960±I50	-	-	-
^{249}Cf	500±300	-	660±I20	I660±50	-	I900±I00	-
^{250}Cf	I750±250	-	8300±4000	<350	-	-	-
^{251}Cf	2850±290	-	I590±70	4800±480	-	5400±800	-
^{252}Cf	20,4±I,5	-	43±4	32±4	-	II0±20	-
^{253}Cf	I2±2	-	I2±2	II00±220	-	2000±500	-
^{254}Cf	σ_α=90±30	-	-	-	-	-	-

UDC 539.173.4

0.4-1.3 MeV NEUTRON-INDUCED FISSION CROSS-SECTION FOR ^{244}Cm

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At present, we have measurements of the monoenergetic-neutron-induced fission cross-section of ^{244}Cm only at certain points in the above-threshold region of neutron energies E_n [1,2], together with more systematic measurements over a wide range of E_n, which used underground nuclear explosions as the neutron source [3-5]. In their experiments, the authors employed the method of measuring $\sigma_f(E_n)$ of transuranic elements with a pulsed electrostatic accelerator using nanogram quantities (an amount smaller by a factor of ~ 10^4 than was required earlier) of the substance; this method had been developed earlier and described in Ref. [6]. The purpose of the present work is not only to derive the dependence $\sigma_f(E_n)$ for ^{244}Cm, but also to verify this method under the actual conditions of a physical experiment.

The neutron source was a TiT target bombarded with protons from a pulsed electrostatic accelerator [7]. The proton beam on the target had a diameter of about 1 mm; the current pulse frequency was 2 MHz, the pulse duration about 5 ns and the average current ~ 6 μA. A layer with a diameter of about 1.5 mm and containing ~ 5 ng of ^{244}Cm was placed at an angle of 0^o to the proton beam. The distance between the centres of the target and the layer was about 3 mm during relative measurements of $\sigma_f(E_n)$ and 6 mm during absolute measurements of σ_f for E_n = 1100 keV. The fragments were recorded by means of a scintillation chamber 2 cm in diameter and 1 cm in thickness, which was filled with xenon to a pressure of 1.5 atm and connected to a photoelectric multiplier. The neutron flux was monitored by "long" detectors graduated with the help of reference PuBe sources. A time-of-flight spectrometer circuit developed earlier was used to record the fragment time spectra [7]. Part of the instrument spectra obtained for E_n = 480 and 950 keV is shown in Fig. 1. As will be seen from the figure, the neutron-induced fission events are clearly separated from the background of uniformly distributed spontaneous fissions, although the total number of induced fissions N_{ind} is much lower than that of spontaneous fissions N_{sp}. From the relationships

$$N_{sp} = \frac{2.2 \cdot 10^{-8} N_{at} \varepsilon t_{meas.}}{T_{f\ year}} \qquad (1)$$

$$N_{ind} = N_{at} N_n \sigma_{fcm^2} \varepsilon \qquad (2)$$

where N_{at} is the number of atoms in the layer, N_n the number of neutrons incident on 1 cm^2, ε the fragment recording efficiency, T_f the half-life for spontaneous fission and $t_{meas.}$ the measurement time in seconds, follows

$$\sigma_f = \frac{2.2\cdot10^{16} N_{ind} t_{meas.}}{N_{sp} T_{f\ year} N_n} b. \qquad (3)$$

Thus, the expression for the fission cross-section does not include N_{at} and ε, which usually introduce large errors into the measurement results. In absolute measurements of the cross-section, account was taken of the experimentally measured correction for the scattering of neutrons by the chamber which are recorded by the long counters, and of the calculated corrections associated with the comparability of the target-layer distance with the target and layer diameters, possible layer and target inhomogeneities and the anisotropy of neutron yield from the target. The main errors are due to the absolute measurement of the neutron flux ($\pm$6%) and to the uncertainty of the isotopic composition of the layer. The proportion of the different isotopes was calculated from the curves of isotope accumulation during irradiation in the reactor [8], normalized with respect to the γ-yields of ^{243}Am, ^{244}Cm + ^{246}Cm and ^{245}Cm measured by the Ge(Li) spectrometer. Thus, the following composition of the layer (%) was obtained: ^{241}Am 0.12 $\pm$ 0.08, ^{243}Am 4.1 $\pm$ 1.0, ^{243}Cm 0.08 $\pm$ 0.08, ^{244}Cm 76 $\pm$ 3.5, ^{245}Cm 1.3 $\pm$ 0.4, ^{246}Cm 18 $\pm$ 3, ^{247}Cm 0.4 $\pm$ 0.1, ^{248}Cm 0.4 $\pm$ 0.1.

The measurements of σ_f are given in Table 1. They agree satisfactorily with the data obtained by Moore [4] during a nuclear explosion and, like the latter, for $E_n < 800$ keV are ~40% higher than the results in Ref. [5]. On the basis of the data obtained in the experiment described here, with allowance for increase in the effective number of channels of the competing neutron emission process $N_n(E^*) = 2\pi\Gamma_n(E^*)/\rho_{comp}(E^*)$ and neutron binding energy $B_n = 5.52$ MeV, the fission barrier height for ^{245}Cm was calculated as $B_f^{245} = 6.17 \pm 0.03$ MeV and its curvature as $\hbar\omega_f = 2\pi dE^*/d\ln N_f = 0.70 \pm 0.04$ MeV.

The present paper thus gives the measurements of the 400-1300 keV monoenergetic-neutron-induced fission cross-section for ^{244}Cm and shows that the method developed is suitable for fission cross-section measurements with nanogram quantities of isotopes with high spontaneous fission activity.

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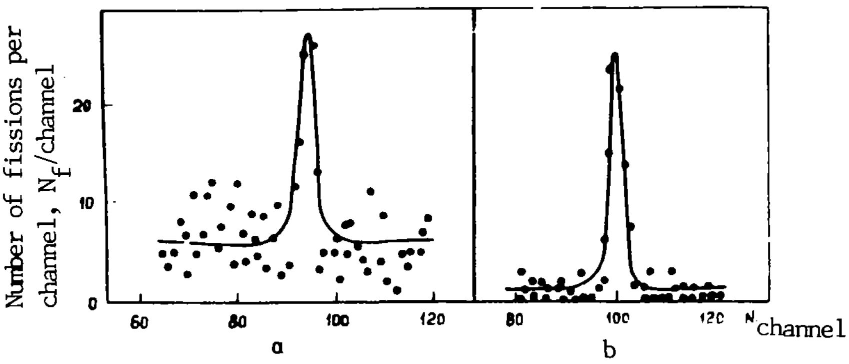

Fig. 1. The time spectra for fissions obtained at E_n = 480 keV for 10 h (a) and at E_n = 950 keV for 2 h (b) of measurement.

$E_n \pm \Delta E_n$, keV	σ_f , b	$\delta\sigma_{f\,stat}$,%	$\delta\sigma_{f\,is.comp}$,%	$\delta\sigma_{f\,tot.}$,%
390±70	0,I8	22	I5	28
480±90	0,44	I4	8	I9
580±90	0,65	I4	5,3	I8
690±90	I,06	I5	3,2	I8
790±I00	I,72	II	2,7	I5
950±95	I,77	9	2,2	I4
I080±90	I,63	I0	I,8	I4
I200±80	I,[illegible]	I5	I,7	I8

Table 1

UDC 539.173.84

MEASUREMENTS OF THE ENERGY DEPENDENCE OF THE MEAN NUMBER OF PROMPT NEUTRONS IN NEUTRON-INDUCED FISSION OF ^{237}Np NUCLEI

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Measurements of the mean number of prompt neutrons $\bar{\nu}_p$ in neutron-induced fission of ^{237}Np nuclei in the energy range 1-6 MeV were carried out relative to the value $\bar{\nu}_p$ = 3.733 [1] for spontaneous fission of ^{252}Cf. Ionization chambers with layers of ^{237}Np and ^{252}Cf were placed in the secondary-neutron detector in the path of a collimated beam of mono-energetic neutrons inducing nuclear fission. The neutron detector was an assembly of 16 ^{3}He-filled counters in a polyethylene cylinder. The chamber with the ^{237}Np layers was divided into six sections in order to reduce overlapping of pulses from α-particles. An electronic circuit, based on an LP-4840 pulse analyser, permitted concurrent measurements of the number of fission neutrons for ^{237}Np and ^{252}Cf and measurements of the corresponding backgrounds.

As a result of the experiment, corrections were introduced (Table 1) to deal with the following effects:

- The difference between the fission neutron energy spectra for ^{237}Np and ^{252}Cf (δ_1);
- The dependence of the fission neutron counting efficiency on the location of the source on the detector axis (δ_2);
- The difference between the ^{237}Np and ^{252}Cf layer diameters (δ_3);
- Counting errors due to coincidence, within the "dead" time period, of two pulses from fission neutrons (δ_4) or of a fission neutron pulse with a background pulse (δ_5);
- The fission fragment counting efficiency (δ_6);
- The difference between the ^{237}Np and ^{252}Cf layer thicknesses (δ_7);
- The α-particle pulse overlap count in the fission fragment channel (δ_8);
- The difference between the angular distributions of fragments in ^{237}Np fission induced by neutrons of various energies (δ_9);
- The low-energy neutron contribution when the (d,d) reaction is used (δ_{10}).

The statistical error of the measurements was about 0.4%. The measurement results and the total errors are given in Table 2.

The figure compares results of measuring the number $\bar{\nu}_p$ in ^{237}Np fission obtained for the present paper with data from Ref. [2]. The difference between the results does not exceed the limits of the measurement error. Only at a neutron energy $E_n = 1$ MeV do the results disagree. In a first approximation the energy dependence of $\bar{\nu}_p$ in the neutron energy range studied (1-6 MeV) can be described by the linear function $\bar{\nu}_p(E_n) = (2.620 \pm 0.012) + (0.146 \pm 0.005)E_n$. However, the results of measuring the kinetic energy of the fragments in neutron-induced fission of ^{237}Np [3] show that a physical mechanism reducing the kinetic energy is set in action at neutron energies above 3 MeV. For this reason the change in the energy of the fission-inducing neutrons cannot be used as a full measure of the change in excitation energy of the fragments.

The reduction in the kinetic energy of the fragments must cause an increase in the growth rate of $\bar{\nu}_p$. In order to bring out this effect a separate analysis was made of the energy dependence of $\bar{\nu}_p$ and E_k for the neutron energy regions below and above 3 MeV. The results of this analysis are presented in Table 3. The growth rates of $\bar{\nu}_p$ as a function of the excitation energy E* lie within the limits of error in both neutron energy ranges. This result shows the usefulness of the assumption that the change in the kinetic energy of the fragments is not a consequence of a change in the charge distribution among the fragments, or of other effects leading to a change in fission energy, but is a result of a change in the fission energy distribution between the excitation energy and the kinetic energy of the fragments.

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TABLE 1

Values of the corrections and their contribution to the total error in measurements of $\bar{\nu}_p$

Correction, %	Error
δ_1 =-(0,7-I,3)	±0,3
δ_2 =+4,4	±0,3
δ_3 =-0,3	±0,2
δ_4 =-(I,0-I,5)	±0,3
δ_5 =+(0,I-0,4)	±0,05
δ_6 =+4,7	±0,9
δ_7 =+0,I	±0,3
δ_8 =+(0,2-0,9)	±0,3
δ_9 = <0,I	±0,I
δ_{10} =+I,0	±0,I

TABLE 2

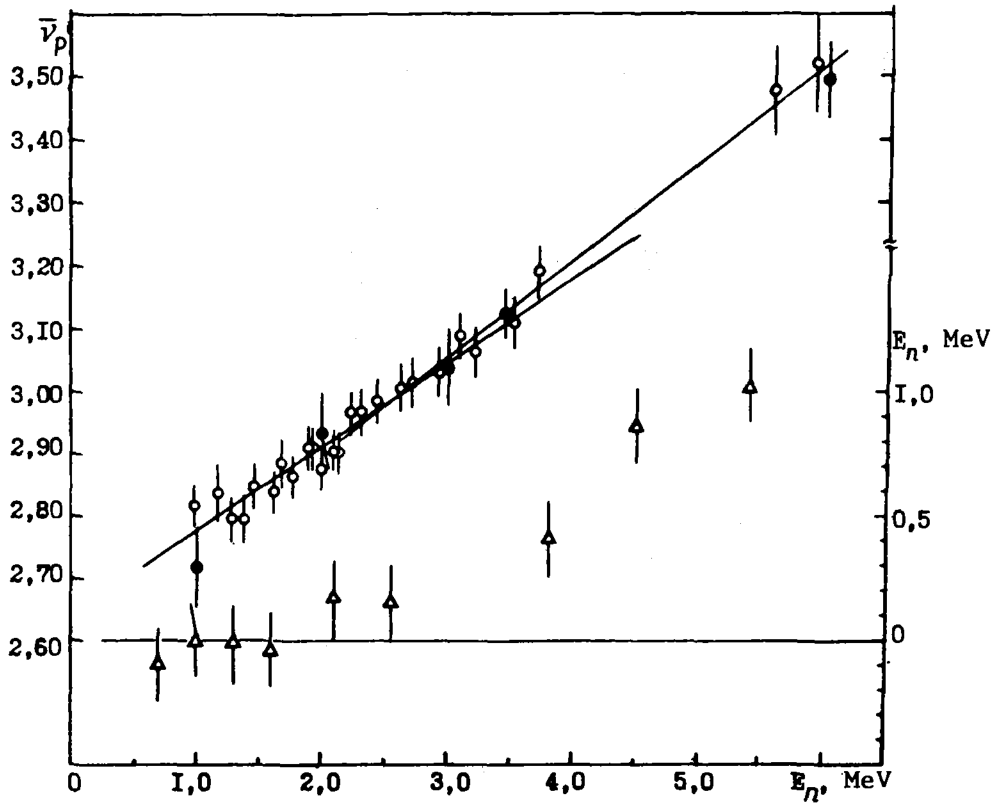
Results of measuring the energy dependence of $\bar{\nu}_p$

E_n, MeV	$\pm\Delta E_n$, MeV	$\bar{\nu}_p$	$\pm\Delta\bar{\nu}_p$	E_n, MeV	$\pm\Delta E_n$, MeV	$\bar{\nu}_p$	$\pm\Delta\bar{\nu}_p$
0,98	0,04	2,8I6	0,034	2,23	0,03	2,966	0,034
I,I7	0,04	2,836	0,047	2,3I	0,03	2,966	0,038
I,28	0,04	2,795	0,035	2,43	0,03	2,983	0,036
I,38	0,04	2,793	0,039	2,62	0,04	3,004	0,037
I,46	0,04	2,846	0,036	2,7I	0,03	3,0I3	0,039
I,62	0,04	2,838	0,035	2,92	0,03	3,029	0,039
I,68	0,04	2,904	0,040	3,09	0,03	3,088	0,037
I,77	0,04	2,863	0,034	3,2I	0,03	3,063	0,039
I,89	0,04	2,909	0,037	3,45	0,03	3,I34	0,040
I,92	0,04	2,908	0,035	3,52	0,03	3,I08	0,042
2,00	0,04	2,875	0,034	3,7I	0,02	3,I90	0,042
2,09	0,04	2,902	0,036	5,58	0,08	3,47I	0,07I
2,I3	0,04	2,900	0,033	5,90	0,08	3,520	0,079

TABLE 3

Growth rates of the values of $\bar{\nu}_p$ and $\bar{E}_k$

E_n, MeV	$d\bar{\nu}/dE_n$, MeV^{-1}	dE_κ/dE_n	$d\bar{\nu}/dE^*$, MeV^{-1}
I-3	0,I34±0,0I0	0	0,I34±0,0I0
3-6	0,I54±0,009	-0,32±0,07	0,II7±0,0I5



Dependence of the mean number of prompt neutrons $\bar{\nu}_p$ on the energy of neutrons inducing fission of ^{237}Np nuclei (● - Ref. [2]; o - present paper), and Δ - changes in the mean kinetic energy of fragments $\Delta\bar{E}_k = \bar{E}_k\ (1\ \text{MeV}) - E_k(E_n)$ [3].

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ANALYSIS OF THE ENERGY DEPENDENCE OF THE AVERAGE NUMBER OF PROMPT NEUTRONS FOR NEUTRON-INDUCED FISSION OF ^{238}U

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The average number of prompt neutrons, $\bar{\nu}_p$, for neutron-induced fission of ^{238}U was measured relative to $\bar{\nu}_p = 3.733$ for spontaneous fission of ^{252}Cf. A detailed description of the measurement method is given in other papers. Here we shall merely mention some of its special features concerning ^{238}U measurements. The ionization chamber, containing uranium-238 layers with a total mass of 0.76 g, consisted of six sections. For this work ^{238}U with an enrichment of 99.999% was used. The layer thickness was approximately 1 $mg \cdot cm^{-2}$. The efficiency of fission fragment detection was in the region of 90%. The possibility of increasing it further is limited because of the counting of alpha-particles in the fission fragment detection channel. Monoenergetic neutrons were obtained in the T(p,n) and D(d,n) reactions. The neutron background arising out of the interaction of neutrons with the target backing material and with implanted deuterons was taken into account by performing measurements with a blank target without an adsorbed deuterium layer. The number of ^{238}U fission events induced by background neutrons did not exceed 10% when using a fresh target for 12 hours.

The corrections shown in Table 1 took into account the following effects: δ_1 - the difference in the fission neutron energy spectra; δ_2 - the dependence of the neutron recording efficiency on the position on the detector axis; δ_3 - the difference in the diameters of ^{238}U and ^{252}Cf layers; δ_4 - miscalculations as a result of coincidence within dead-time limits of pulses from fission neutrons; δ_5 - miscalculations through the coincidence, within dead-time limits, of a fission neutron pulse and a background pulse; δ_6 - discrimination in the fission fragment channel; δ_7 - the difference in the layer thicknesses of ^{238}U and ^{252}Cf; δ_8 - spontaneous fission of ^{238}U and alpha-particle pulse pile-up count; δ_9 - angular anisotropy of fission fragments; δ_{10} - background neutrons where the (d,d) reaction is used.

The statistical error in the measurements was approximately 0.5%. The measurement results are given in Table 2.

Detailed measurements of the energy dependence of $\bar{\nu}_p$ for neutron-induced fission of ^{238}U in the 1.2-6.0 MeV energy range were performed earlier by the authors of Refs [2-4]. The figure compares the data given in these papers with those of the present paper. Satisfactory agreement is observed between the measurement results of the four research groups, all of which used independent methods. In addition to the $\bar{\nu}_p$ measurement results, the figure also shows measurement results for the average fragment kinetic energy for the neutron-induced fission of ^{238}U [5]. At neutron energies above 2.7 MeV, the average fragment kinetic energy decreases as E_n increases. To explain the effect of this phenomenon on the size of $\bar{\nu}_p$, the rate of increase of $\bar{\nu}_p$ in the 1.0-2.7 and 2.7-6.0 MeV neutron energy ranges was examined. The values obtained by the least squares method from all the data available for $\bar{\nu}_p$ and from the data in the present paper are given in Table 3.

If we assume that the variations in the value $\bar{E}_k$ are not due to a variation in the fission energy, then the reduction in this value must be attributed to the corresponding increase in the fission fragment excitation energy E*. It follows from both the results of this paper and the set of results shown in the figure that the difference in the rates of increase $d\bar{\nu}_p/dE^*$ in the 1.0-2.7 and 2.7-6.0 MeV neutron energy ranges does not exceed the measurement error limits. Because of this, the reduction in the fragment kinetic energy and the greater rate of increase $d\bar{\nu}_p/dE_n$ in the 2.7-6.0 MeV neutron energy range can be regarded as the result of a redistribution of fission energy between the kinetic energy and excitation energy of the fragments. In our opinion, careful measurement of the fragment kinetic energy in ^{238}U fission induced by neutrons with an energy greater than 3 MeV will make it possible to increase the reliability of the results of such an analysis.

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Table 1

Corrections and their contributions to the $\bar{\nu}_p$ total measurement error

Correction,%	Error	Correction, %	Error
δ_1 =-(0,6-I,9)	±0,4	δ_6 =+0,2	±0,I
δ_2 =+4,6	±0,3	δ_7 =+0,I	±0,3
δ_3 =-0,3	±0,2	δ_8 =+(0,2-0,5)	±0,2
δ_4 =+(0,9-I,8)	±0,2	δ_9 =0,I	±0,I
δ_5 =+0,I	±0,I	δ_{10} =+(I,0-I,2)	±0,I

Table 2

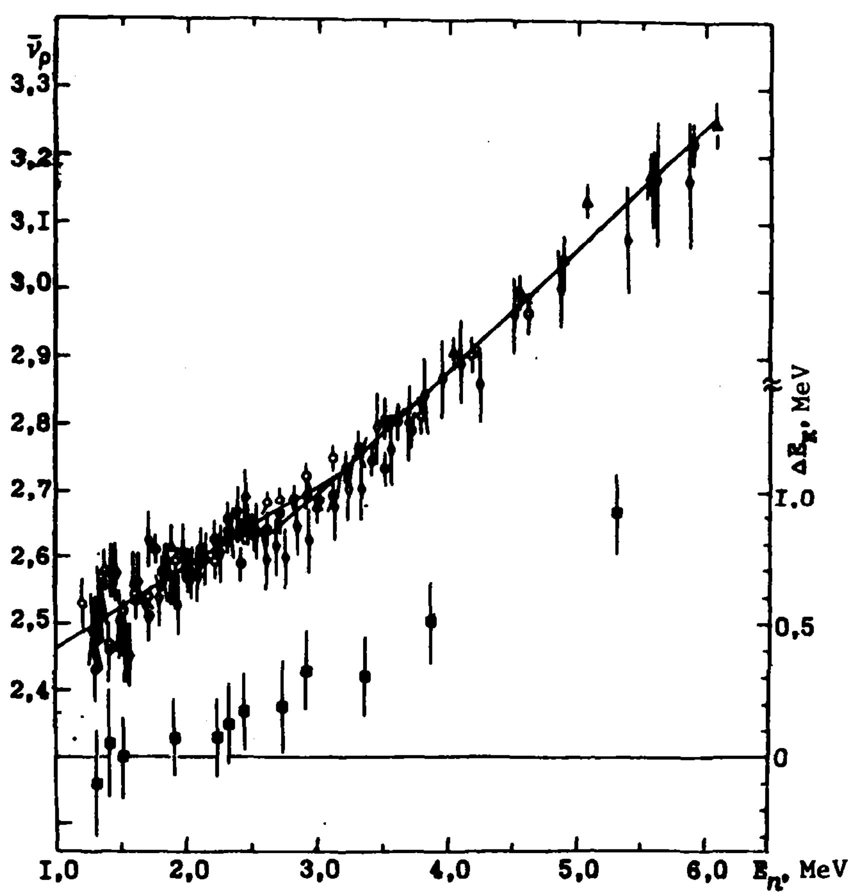
Measurement results of energy dependence of $\bar{\nu}_p$

E_n, MeV	$\pm\Delta E_n$, MeV	$\bar{\nu}_p$	$\pm\Delta\bar{\nu}_p$	E_n, MeV	$\pm\Delta E_n$, MeV	$\bar{\nu}_p$	$\pm\Delta\bar{\nu}_p$
I,30	0,05	2,43I	0,048	2,60	0,03	2,638	0,025
I,40	0,05	2,458	0,045	2,70	0,03	2,66I	0,028
I,50	0,04	2,473	0,027	2,80	0,03	2,687	0,020
I,60	0,04	2,533	0,026	2,90	0,04	2,693	0,023
I,70	0,04	2,5I0	0,035	3,00	0,04	2,683	0,023
I,75	0,06	2,6I0	0,023	3,I0	0,04	2,693	0,028
I,80	0,04	2,537	0,026	3,20	0,04	2,735	0,023
I,90	0,04	2,547	0,025	3,30	0,04	2,765	0,023
2,00	0,04	2,565	0,022	3,40	0,03	2,745	0,026
2,I0	0,04	2,6I3	0,03I	3,50	0,03	2,735	0,023
2,20	0,03	2,625	0,025	3,60	0,03	2,803	0,029
2,30	0,03	2,655	0,022	3,70	0,03	2,790	0,026
2,40	0,03	2,587	0,022	5,58	0,08	3,I5I	0,058
2,50	0,03	2,632	0,022	5,89	0,07	3,2I9	0,03I

Table 3

Rate of increase of $\bar{\nu}_p$ and $\bar{E}_k$

E_n, MeV	$d\bar{\nu}_p/dE_n$, MeV^{-1}	dE_k/dE_n	$d\bar{\nu}_p/dE^*$, MeV^{-1}	Remarks
1,0–2,7	0,121±0,009	0	0,121±0,009	For all data
	0,131±0,017	0	0,131±0,017	Present paper
2,7–6,0	0,182±0,005	0,30±0,07	0,140±0,011	For all data
	0,174±0,010	0,30±0,07	0,134±0,015	Present paper



Measurement results for the average number of prompt neutrons, $\bar{\nu}_p$, for the neutron-induced fission of ^{238}U (Δ - [2]; ◇ - [3]; o - [4]; • - present paper) and ■ is the variation in the fragment kinetic energy ΔE_k in the neutron-induced fission of ^{238}U [5].

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ENERGY AND ANGULAR DISTRIBUTIONS OF NEUTRONS FROM ^{252}Cf SPONTANEOUS FISSION

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It is interesting to study the energy and angular distributions of fission neutrons because the neutrons seem to be emitted partly during the early stages of fission, before the fragments are fully accelerated by the Coulomb forces. A study of the characteristics of these neutrons may yield information on the state of the nuclei in the interval close to the moment when the fissionable nucleus separates into fragments. Since the first detailed papers [1, 2] were published in the early sixties, several theoretical and experimental studies (e.g. Refs [3, 4]) have been performed, but progress towards an understanding of the nature of the "separating" neutrons has been limited by the difficulties of setting up multiparameter experiments and the poor efficiency of the neutron spectrometers used.

In Ref. [4] we presented some results from a first series of measurements of energy and angular distributions of neutrons from ^{252}Cf spontaneous fission using a spectrometer with high neutron detection efficiency, i.e. a 4π neutron time-of-flight spectrometer [5]. Subsequently, a second series of measurements was performed using a more sophisticated technique. For this second series, we used a more intense ^{252}Cf layer (25 000 spontaneous fissions per second). The angular resolution was improved by a factor of 2-3 by combining the hexahedral counter modules, placed at the same angle with respect to the direction of motion of the fragments, in new panoramic counters. The neutron counters were calibrated against the average ^{252}Cf neutron spectrum at several positions of the axis of the fragment detector with respect to the neutron counters. In the spectrum measurements and calibration work, the scattered neutron background was not determined theoretically, as in the first series of measurements, but experimentally using four extra scintillation counters with scatter cones; the counters were set up at 60°, 80°, 100° and 120° to the direction of separation of the fragments.

During the second series of measurements, approximately 1.5×10^6 fissions and 1.2×10^6 neutrons were detected. During the counter calibration exercises, $\sim 2.5 \times 10^6$ fissions were recorded.

The time-of-flight distributions of the fragments and neutrons were mainly processed in the same manner as for the first series. The neutron distributions were sorted into eight ranges of heavy fragment mass M_H and total fragment kinetic energy $E_{t.k.}$; the number of fissions and the $\bar{M}_H$ and $\bar{E}_{t.k.}$ values for each range are shown in the table. For the counters at $\bar{\theta} \approx 90^o$, there were 20-30 full corrections and statistical errors of 5-8% in the neutron distributions. For the counters placed in the direction of motion of the fragments, the corrections and errors were several factors less. The neutron spectra were calculated separately for all the panoramic counters and then averaged over groups of four counters. As a result, neutron spectra were obtained at twelve $\bar{\theta}^o$ angles to the direction of motion of the light fragments in all eight M_H and $E_{t.k.}$ ranges.

The figure shows the experimental spectra for range 5 (R5) and the results predicted according to the theory of isotropic neutron evaporation from all the accelerated fragments. At $\bar{\theta} = 26^o$ and 154^o, the spectra coincide since at these angles the experimental spectra were used to calculate the parameters of the neutron spectra in the fragments' centre-of-mass system; at other $\bar{\theta}$ angles, the experimental spectra are more intense than the theoretical spectra. There are more "separating" neutrons at high $E_{t.k.}$ values, i.e. in R2, 4-5 and 7 compared to R1, 3 and 6, respectively. This result agrees with the data presented in Refs [3, 4]. It turned out, however, that at several $\bar{\theta}$ angles in the ranges with low $E_{t.k.}$ values (R3 and particularly R1 and 6), the experimental spectra were less intense than the theoretical spectra. This result may be due to the anisotropic angular distribution of the neutrons in the fragment system. We have begun to prepare calculations based on more complex fission neutron emission models.

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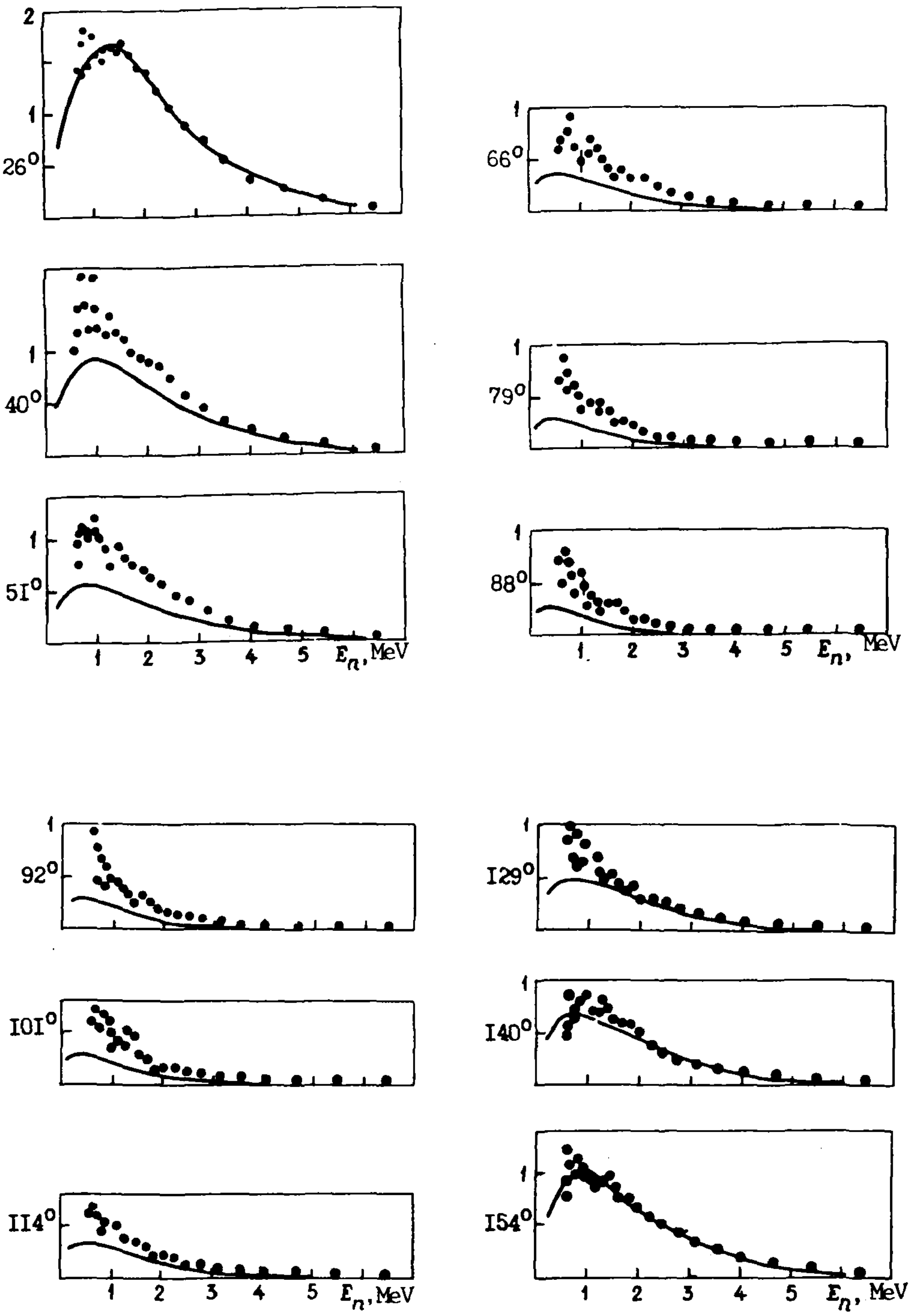
Table.

Range No.	No. of fissions	$\overline{M}_H$ amu*	$\overline{E}_{t.k.}$ MeV
1	78 852	132.6	181.6
2	111 244	132.6	200.3
3	294 260	144.2	173.9
4	646 539	142.8	189.8
5	87 383	140.8	204.9
6	120 635	154.2	172.0
7	73 678	153.3	186.9
8	1 414 251	143.1	186.1

* 1 amu ≈ 1.66057×10^{-27} kg.



Neutron spectra at $\bar{\theta}^{o}$ to the direction of motion of light fragments (range 5); $\bar{M}_H$ = 140.8 amu; $\bar{E}_{t.k.}$ = 204.9 MeV; ϕ = experiment; the solid curves represent the results predicted according to the theory of isotropic neutron evaporation from all the accelerated fragments.

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STUDY OF THE INFLUENCE OF SCATTERING EFFECTS ON THE SHAPE OF THE FISSION NEUTRON SPECTRUM

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Precision neutron spectrometry is based essentially on the time-of-flight technique, since it gives one a high energy resolution. However, fission spectrum measurements by this technique show a substantially greater spread of experimental data than might be expected from the errors cited by the authors, especially in the low-energy region. The discounting of effects such as neutron scattering in particle detectors, on structural parts and in the environment, can lead to a noticeable distortion of the neutron spectrum [1-3] and is possibly the major reason for the discrepancy observed in the experimental results.

For the study and consideration of these neutron scattering effects both experimental and theoretical methods can be applied usefully, since they supplement each other and increase the reliability of the results. In our study we have used for the first time a calculation algorithm which takes into account the process of multiple scattering in time. This is a much more complex problem than calculations not involving time. Mathematically, we are solving the inverse problem of the theory of radiation transfer [4], i.e. on the basis of a known experimental spectrum we reconstruct the energy spectrum of the neutron source. This, in effect, amounts to solving Fredholm's equation of the first kind:

$$\int A(E,t)\varphi(E)dE = \Phi(t), \tag{1}$$

which directly connects the neutron spectrum being sought $\varphi(E)$ with the experimental time spectrum $\Phi(t)$. The kernel of the integral equation $A(E,t)$ is the time spectrum for neutrons from a monoenergetic source with energy E recorded by the experimental apparatus, and is a generalized multidimensional analogue of the commonly used concept of neutron detector efficiency. We note that the above equation has no property of error stability on the right-hand side and is therefore incorrect, hence regularization methods must be used for its solution. The Monte Carlo method was used at the stage of calculation of matrix A(E,t), and the calculations were performed on a BEhSM-6 computer.

The influence of the effects associated with neutron scattering was determined for a specific case - measurement of the spectrum for neutrons from spontaneous fission of ^{252}Cf by the time-of-flight technique. The experimental conditions were as follows: the neutron detector was a $^{7}LiI(Eu)$ crystal (diameter 17 mm, thickness 4 mm; thickness of the aluminium packing 0.5-1 mm and that of glass 0.5 mm); the fission fragment detector was a scintillation gas counter (steel cylinder 18 mm in diameter and 70 mm in height with a wall thickness of 0.15 mm). Both detectors were connected to a FEhU-71 photoelectric multiplier. The spectrum was measured for four path lengths: 6.25, 12.5, 25.0 and 50.0 cm. The shortest distance from the walls of the room and remote objects was about 2 m.

By the method described we calculated multiple neutron scattering in the crystal with allowance for the packing and the adjacent photomultiplier glass. The elements of matrices A(E,t) obtained for three neutron energies and two crystal thicknesses are given in Fig. 1. It will be seen that the process of neutron recording in time for the 4 mm thick crystal differs appreciably from that for the 8 mm crystal. The corrections for multiple scattering, obtained by calculation for three path lengths are given in Fig. 2 (with allowance for the spectrometer time resolution). In the 300-400 keV region we observe a neutron excess of about 5%, corresponding to the contribution of neutrons scattered by the nuclei of oxygen in the composition of the packing and photomultiplier glass at a resonance energy of 440 keV. The shift of the resonance energy to the lower-energy region is due to delay in neutron recording. For $E_n = \sim 240$ keV (see Fig. 2) the curves have approximately 5% minima, owing to neutrons of this energy leaving the beam during elastic resonance scattering by lithium and aluminium nuclei.

Analysing the influence of neutron scattering on the photomultiplier and the structural parts of the detectors, we note that in order to reduce distortions in the low-energy region, some authors have tried to move the neutron source away from scattering parts and to reduce, as far as possible, the scattering parts of the neutron detector. It should be borne in mind, however, that by moving the scattering parts of detectors away from the source and neutron detector scintillator one cannot expect to eliminate spectrum distortion. Firstly, with increase in distance the scattered neutron flux decreases and, secondly, these neutrons begin to attain ever lower energies, i.e. there is lower intensity of the fission neutron spectrum. The scattering by the detectors was evaluated experimentally by doubling their scattering parts, while approximately retaining the same geometry for each path length. The experimental results obtained showed satisfactory agreement with the theoretical evaluations. Figure 3 gives the energy dependence of the correction for scattering from the photomultiplier and the structural parts of the neutron detector for a path length of 6.25 cm. The correction is irregular in shape. If we had used FEhU-36, FEhU-30 and KhR-1021 devices, the corrections would have been considerably larger (by a factor of 5-10), owing to substantially bigger scattering parts of these photomultipliers. We may assume that it is neutron scattering with which the detection of fine structure in fission neutron spectra is associated, or this is at least partially the case [5].

As regards neutron scattering by the surrounding air, we note that this effect is disregarded in most studies although air represents a significant scattering medium. It is shown in Refs [2, 3] that during measurement of fission neutron spectra for large path lengths neutron scattering by the air between the source and the detector leads to slight spectrum distortions in the form of fine structure. In the case described, neutron scattering by the surrounding air was calculated for path lengths of 6.25-50 cm in a single-interaction approximation. The obtained energy dependence of the correction for neutron scattering by the surrounding air for a path length of 6.25 cm is shown in Fig. 3. According to the data of Ref. [2], the correction increases monotonically with decrease in energy.

The dimensions of the measurement room often are such that high-energy neutrons scattered from the walls may be recorded over the time interval studied. The magnitude of this effect can be evaluated experimentally by means of measurements with a shielding cone. In the present work we used a wax cone with a length of 50 cm. Since the sum of the distances from the source and the neutron detector to the walls was much greater than the path lengths used, the measured effect was independent of path length, provided the contribution of neutrons scattered by the surrounding air is subtracted. The correction thus obtained for the path length of 6.25 cm, which is given in Fig. 3, shows that the size of the correction grows rapidly with decrease in energy and, for $E_n \approx 1$ keV, is 100% of the intensity of the direct neutron spectrum.

It follows from the data given here that during precision measurements of fission neutron spectra correct account should be taken in every way of the contribution made by scattered neutrons.

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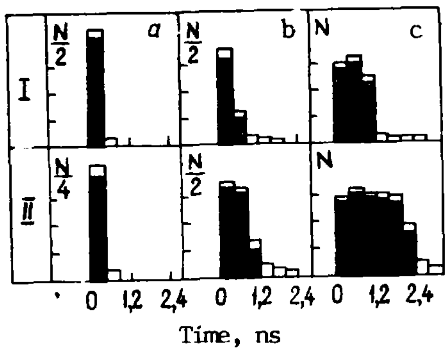

Fig. 1. Elements of A(E,t) for crystals with a thickness of 4 mm (I) and 8 mm (II) and for three neutron energies, keV: (a) 2970; (b) 470; (c) 89.

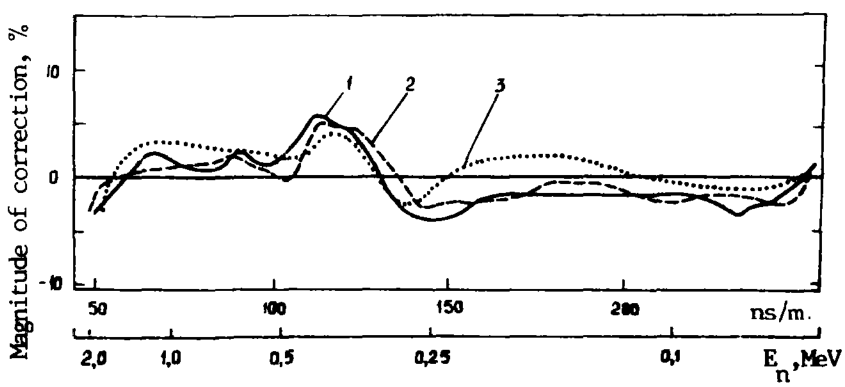

Fig. 2. Corrections for multiple neutron scattering in the case of path lengths, cm: (1) 50; (2) 25; (3) 12.5.

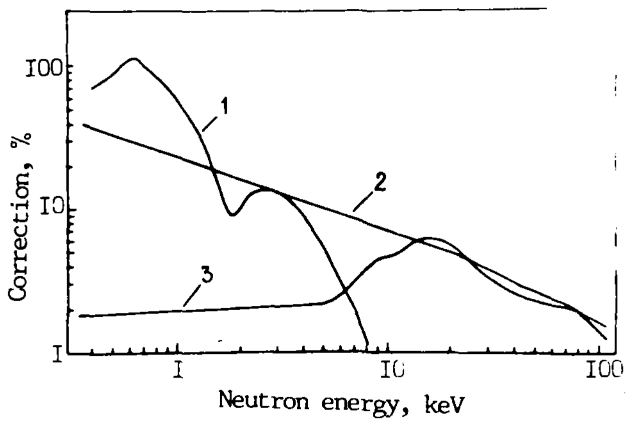

Fig. 3. Corrections in the case of a path length of 6.25 cm for neutron scattering by walls (curve 1), surrounding air (curve 2) and neutron detector (curve 3).