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Experiment

Cross Section for the Subthreshold Fission of ^{236}U

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Abstract—The cross section for ^{236}U fission in the neutron-energy range $E_n = 0.001–20$ keV was measured by using the INR RAS (Institute of Nuclear Research, Russian Academy of Sciences, Moscow) LSDS-100 neutron spectrometer of the lead slowing-down spectrometer type. The resonance fission areas of the resonances at 5.45 eV and 1.28 keV were found, and the fission widths of these resonances were evaluated. The cross section for the ^{238}U(n, f) fission process was measured, and the threshold sensitivity of the LSDS-100 to small values of fission cross sections was estimated. The well-known intermediate structure in the cross section for the neutron-induced subbarrier fission of ^{236}U was confirmed.

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INTRODUCTION

Interest in studying cross sections for neutron-induced fission in the region of neutron energies below the fission threshold is associated with searches for the gross structure of fission widths for neutron resonances. These structures were explained within the model of a two-humped barrier [1, 2], where fission is a multistep process that proceeds through beta-vibrational states of a strongly deformed nucleus in the second potential well. Because of residual interaction with other degrees of freedom, a vibrational state acquires a damping width with respects to decay to states of more intricate nature—intermediate levels of class II. The latter are related to compound states (levels of class I), which are excited upon neutron absorption in the first potential well corresponding to the equilibrium shell of the nucleus being considered.

The level-coupling strength $\langle\lambda_{\rm II}|\, H_c\, |\lambda_{\rm I}\rangle$ is determined by the interaction potential H_c and is dependent on the potential barrier V_A separating levels $|\lambda_{\rm II}\rangle$ of class II from the phase space of levels $|\lambda_{\rm I}\rangle$ belonging to class I. In the case of a deep well, the damping width of a vibrational resonance is large, so that intermediate structures are determined by states of class II. This pattern was observed in the fission cross section $\sigma(E_n)$ for the ^{234}U, ^{238}U and ^{240}Pu nuclei in the neutron-energy range $E_n = 0.1–20$ keV. A characteristic period of structures is $D_{\rm II} = 0.7–3$ keV or $D_{\rm II} = (50–200)\, D_{\rm I}$, where $D_{\rm I}$ is the spacing between the levels of a compound nucleus. An analysis of the above structures within R-matrix theory [2] makes it possible to deduce information about the average matrix element $|\langle\lambda_{\rm II}|\, H_c\, |\lambda_{\rm I}\rangle|$, the decay width $(\Gamma_{\rm II}, \Gamma_{{\rm II}(f)})$, and barrier parameters.

Previously, the cross section for the neutron-induced fission of ^{236}U in the resonance region of neutron energies was measured by the time-of-flight method in [3–6], but there is a sharp discrepancy between the results of those studies. The intermediate structure in question was observed in some studies [3, 5], but it was not found in other studies [4, 6]. The fission-cross-section estimate recommended in ENDF/B7 (2006) [7] is based on data obtained in [4] and confirmed in [6]. In order to resolve the existing contradictions, we performed an independent experiment, employing a neutron spectrometer of the lead slowing-down (LSD) type. The first LSD spectrometer was designed and created at the Lebedev Institute of Physics (Russian Academy of Sciences, Moscow) [8]; the theory of LSD spectrometers, basic results of experiments performed with them thus far, and prospects of future investigations with such spectrometers were considered elsewhere [9, 10].

Second-generation LSD spectrometers of energy resolution $\Delta E/E \cong 0.3$ were successfully used in measuring (n,γ) and $(n,\ f)$ cross sections for nuclides that can hardly be studied by other methods. High neutron fluxes into such spectrometers (RINS spectrometer [11]) made it possible to single out

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reliably intermediate resonances in the subthreshold-fission cross section for targets of mass equal to a few micrograms; to record the p-vibrational resonance at an energy of 5 keV for ^{232}Th; and to measure ultrasmall cross-section values at a level below 1 μb [12], which is presently inaccessible to time-of-flight spectrometers.

Available data (which were borrowed from the EXFOR library [13]) on the cross section for the subthreshold neutron-induced fission of ^{236}U(n, f) are presented in Fig. 1. In order to compare these data with the results obtained from measurements with the LSD-100 spectrometer, the former were averaged with the Gaussian function characterized by the spreading-parameter value of $\Delta E/E = 0.35$. Upon correcting experimental data from [3] with allowance for the background from the ^{235}U$(n,\ f)$ fission process (this was not done previously), there appears a sharp discrepancy between the data obtained by a Los Alamos group [3, 5] and the data reported in [4, 6]. In the Los Alamos studies, fission events were recorded by fission-fragment detectors, while, in the other studies, fission neutrons [4] and fission gamma rays [6] were recorded by means of scintillation detectors.

The discrepancy is the strongest for the resonance at 5.45 eV. The Γ_f value measured in [5] (1.3 ± 0.1 μeV) proved to be smaller than its counterpart in [4] by a factor of about 200. Moreover, no fission events were observed in [4] for other resonances up to an energy of 1 keV. Data from [4] reveal weak fluctuations of the widths Γ_f and their explicit correlation with the radiative widths Γ_γ, this being indicative of the sensitivity of the fission detector to capture gamma rays ($\Gamma_\gamma \gg \Gamma_f$). An insufficient discrimination of capture gamma rays may be a reason for the large value obtained in [6] for the fission cross section.

1. METHOD OF MEASUREMENTS

Our experiment was performed with the INR (Institute for Nuclear Research, Russian Academy of Sciences, Moscow) LSD-100 neutron spectrometer [14] installed in the MMF (Moscow meson factory) proton beam. The energy of the proton beam was 209 MeV, the current-pulse duration was 1 μs, the pulse-repetition frequency was 50 Hz, and the current in a pulse was 8 to 10 mA. An air-cooled lead target was used to generate neutrons.

The LSD-100 third-generation spectrometer was assembled in the form of an elongated prism formed by blocks of high-purity lead (99.996%), their total mass being 100 t. The length of the assembly was 3.3 m, its width was 1.62 m, and its height was 1.79 m. The assembly was arranged within a steel frame at a height of 66 cm from the concrete floor. The measurements were performed within the working channel of diameter 65 mm, its axis being at a distance of 120 cm from the neutron-generation center.

Fission events were recorded by a fast ionization fission chamber containing fissile layers of ^{236}U, ^{235}U, ^{238}U, and ^{239}Pu. Similar fission chambers were previously applied in experiments devoted to measuring cross sections for fission induced by fast neutrons [15].

The ^{236}U layer (the uranium mass was $m =$ 1.30 mg, and the composition of the layer was U_3O_8) was of high purity: $(99.845 \pm 0.005)\%$ ^{236}U, $(0.047 \pm 0.002)\%$ ^{235}U, $(0.107 \pm 0.002)\%$ ^{238}U, and 0.001% ^{234}U (similar targets were used in [6], but, in [4], the admixture of ^{235}U was 0.3%). The layers of ^{235}U ($m = 1.07$ mg) and ^{239}Pu ($m = 0.55$ mg, and the composition of the layer was PuO_2) were applied as neutron-flux monitors. The ^{238}U layer (99.999% ^{238}U, $3 \times 10^{-4}\%$ ^{234}U, $3 \times 10^{-4}\%$ ^{235}U, and $3 \times 10^{-4}\%$ ^{236}U; the uranium mass was $m =$ 1.60 mg; and the composition of the layer was U_3O_8) was used to determine the sensitivity threshold of the LSD-100 spectrometer with respect to small values of the fission cross section.

The fission chamber consisted of two sections, each being a flat cylindrical fission chamber. The sections had a common cathode, on the two sides of which layers of fissile matter were arranged. The sections were screened by a grounded electrode. The cathode potential with respect to the earth was −500 V. The current signals (of duration 20 to 25 ns) were read out from two other electrodes (anodes), which had a zero potential. The anode and cathode radii were identical and were equal to 40 mm, the distance between the electrodes was 1.5 mm, and the diameter of the fissile layer was 18 mm. The chamber was filled with an $Ar + 10\%$ CO_2 gas mixture at a pressure of 1.5 atm. The negative-polarity signal from the fission-chamber anode was transferred to the input of a charge-sensitive preamplifier (Canberra model 2003BT), was amplified, and was shaped (Polon 1501 model; the shaping time was 20 ns). The shaped analogous signal was transferred along an RK-50 cable (of length 100 m) to the input of the system for fission-event detection in order to perform an amplitude and a time analysis. The electronic modules of the data-acquisition system were performed within the CAMAC standard and were controlled within the LINUX environment.

The detection and analysis of signals were based on recasting the pulse shape into a digital form and on determining both their time and their amplitude

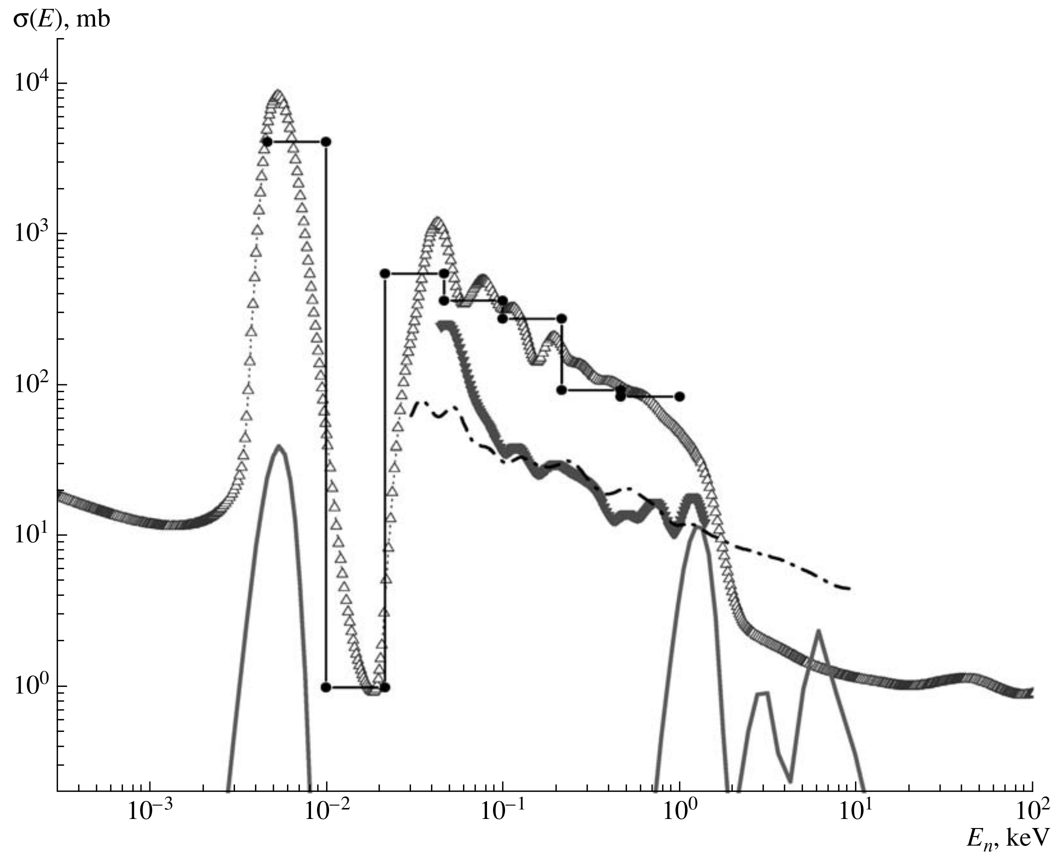

Fig. 1. Result of averaging, with the Gaussian function characterized by the parameter $\Delta E/E = 0.353$, the cross section for the $^{236}\mathrm{U}(n,\ f)$ fission process: (line connecting open triangles) ENDF/B7 estimate [7], (line connecting closed triangles) data from [3], (solid line) data from [5], (line connecting closed circles) data from [6], and (dash-dotted line) contribution of the $^{235}\mathrm{U}(n,\ f)$ fission reaction to experimental data [3].

features. The channels for digitizing signals from detectors employed the same scheme involving a controlled band-filter amplifier and an analog-to-digital converter (ADS) whose interval of measurements was 10 ns. A digital code corresponding to each ADC was fed to an FPGA (field-programmable gate array) logic scheme, where the instant of signal arrival from the detector was determined in a digital form (to a precision of 10 ns) and where histogramming was performed in a preset time interval (directly in the data-acquisition system). The readout and the recording of data for transferring them with the aim of an ultimate data treatment and the visualization of the results were performed upon the completion of direct data accumulation.

For a first approximation, the time spectrum of fission events recorded by the detector, $N(t)$, is related to the measured fission cross section $\sigma(E)$ by the equation

$$N(t) = Cw(t)\left\langle \sqrt{E}\sigma(E)\right\rangle_{\overline{E}(t)}, \qquad (1)$$

where C is a constant that takes into account the thickness of the target used (which must be rather thin for blocking effects to be negligible); $w(t)$ is the neutron density at the sample surface for the slowing-down time t; and the symbol $\langle\ \rangle$ means averaging over the spectrometer energy resolution in the vicinity of the average energy of the neutron spectrum, $\overline{E}(t) = K(t)/(t+\tau)^2$ with $\tau = 0.3$ μs. Usually, the function $K(t)$ is assumed to be constant. For various spectrometers, its values fall within the range 160–183 keV $(\mu\mathrm{s})^2$, depending on the dimensions of the LSD spectrometer, the presence of admixtures in lead, the primary neutron spectrum, and the presence of voids.

2. DESCRIPTION OF THE EXPERIMENT

2.1. Measurement of the Properties of the LSD-100 Spectrometer

The energy calibration of the LSD spectrometer—that is, a determination of the function $K(t)$ relating the neutron energy to the slowing-down time—was

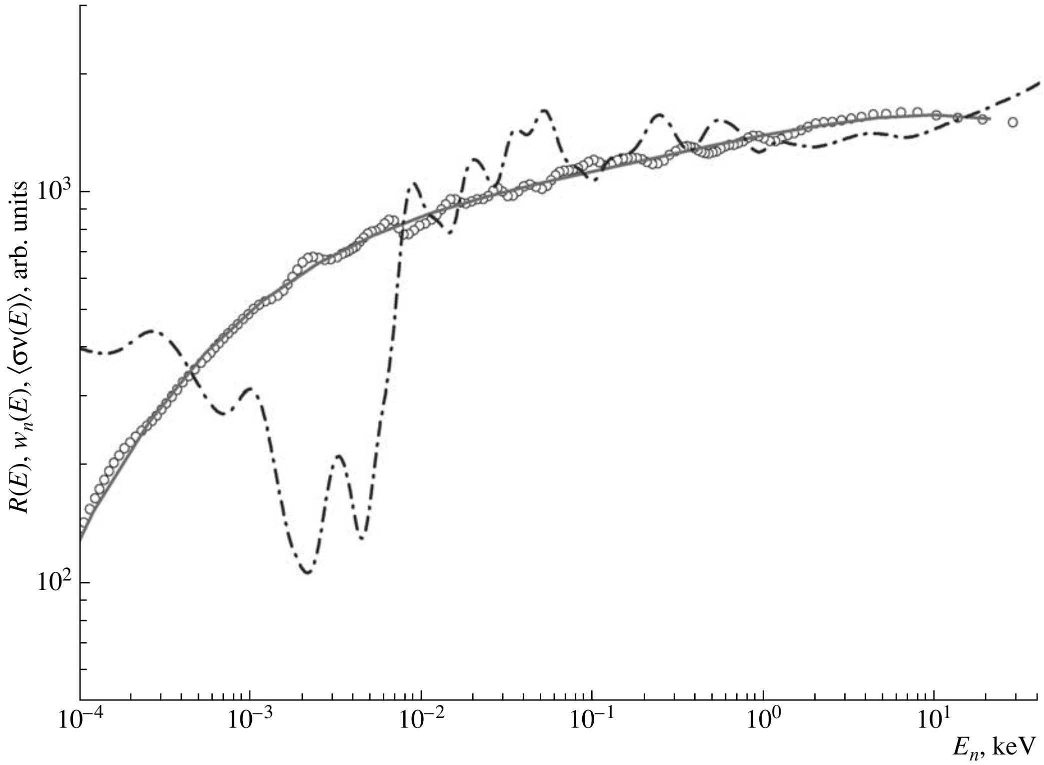

Fig. 2. Reduced experimental spectrum $R(E) = N(E)/\langle\sigma v\rangle$ (open circles), neutron density $w_n(E)$ (solid curve), and average $\langle\sigma v\rangle$ of the cross section for the $^{235}\mathrm{U}(n,\ f)$ fission process over the spectrometer resolution function (dash-dotted curve) versus the neutron energy.

performed by using known neutron resonances in the cross sections for ^{235}U and ^{239}Pu fission (22 calibration points). The cross sections for these nuclei are known to a high degree of precision (0.5–2%) and belong to the class of reference cross sections with respect to which the cross sections for neutron-induced reactions on other nuclei are measured. It turned out that the resulting values of $K\,(t)$ fit in the time dependence $K\,(t) = 165 - 15.2\exp{(-t/27.7)}$ keV $(\mu\mathrm{s})^2$. The accuracy of the calibration is 2 keV $(\mu\mathrm{s})^2$. This dependence is confirmed by the results of a simulation of the LSD detector, which are also indicative of a decrease in the function $K\,(t)$ with decreasing time for $t < 30$ μs.

In the calibration procedure, we employed the quantities $\langle\sigma v\rangle = \langle\sqrt{E}\sigma(E)\rangle$ for the ^{235}U and ^{239}Pu nuclei in the neutron-energy region $E_n > 0.1$ eV from the ENDF/B7 library (Fig. 2), where averaging was performed with a Gaussian function. In evaluating the average $\langle\sigma v\rangle$, the energy dependence of the resolution was taken to be $\Delta E/E = \left(a^2 + bE + c/E\right)^{1/2}$, where $E \equiv \overline{E}\,(t)$ [12]. In the ideal case, the resolution has the form [9]

$$\Delta E/E = \left[a_0^2 + (kT/E)\right]^{1/2},$$

where $a_0 = 0.274$ and $kT = 0.0253$ eV is the thermal energy of the moderator—that is, the parameter c takes into account neutron-thermalization effects. In the region $t < 10$ μs, the resolution becomes poorer because of the effect of the primary spectrum of neutrons, a finite proton-pulse spread, and the width of the time-analyzer channel. For a first approximation, this contribution to the variance is in direct proportion to energy. Comparing the experimental spectra $N\,(E)$ with the averaged data from the libraries, $\langle\sigma v\rangle$, by means of relation (1) and varying the parameters a, b, and c, we can obtain optimum values for the parameters of the LSD resolution function and for the neutron density in the measurement channel, $w_n\,(t)$. The optimum values of the parameters proved to be $a = 0.30$, $b = 3 \times 10^{-5}$ eV^{-1}, and $c = 0.025$ eV. The spectrometer has the highest resolution, which is 31%, in the energy range 40–120 eV.

It is rather difficult to attain a perfect description (that is, to eliminate statistical errors) of the resonance structure in the experimental spectra of the LSD spertrometer [10]. There are nonstatistical fluctuations in $R = N\,(E)/\langle\sigma v\rangle$ values calculated at the optimum values of the parameters in the resolution function. Since the function $w_n\,(E)$ must be a smooth function of energy [8–10], it was found by smoothing the resulting values of R by means of a fourth-degree polynomial in the coordinates $\log(w_n)$ and $\log(E)$. The function $w_n(E)$ and the values of $R(E)$ for ^{235}U in the energy range 10^{-4}–20 keV are given in Fig. 2.

In order to estimate the sensitivity threshold of the LSD-100 spectrometer with respect to small cross-section values, we measured the cross section for the neutron-induced fission of ^{238}U and compared this cross section with data obtained by means of the RINS spectrometer [11] with the fission chamber containing $m = 0.80$ g of uranium. In the present study, we employed a ^{238}U layer of mass 1/500 times as large as that. The largest cross-section value corresponds to a resonance of class II at 0.72 keV and is equal to 1.45 mb.

Fission events were recorded within two time windows: the first (main) had a width of 2 ms and a channel value of 0.5 μs, while the second (background) had a width of 2 to 18 ms and a channel value of 4 μs. The time spectra of detected events of the neutron-induced fission of ^{238}U and ^{235}U in the main window are displayed in Fig. 3. The total time of accumulation of the spectrum was about 11 h. In the spectrum for ^{238}U, signals from the neutron-induced fission of ^{235}U constituted a significant fraction, this admixture being dominant in the region $t \geqslant 17$ μs. A theoretical estimate of the ^{235}U$(n,\ f)$ contribution is 4.5×10^{-6}, while the observed contribution is 2.5×10^{-4}. The reason for this discrepancy is that some electronic signals from the ^{235}U channel occurred in the ^{238}U channel. The number of recorded useful events proved to be sufficient for revealing the resonance structure in the cross section for the neutron-induced fission of ^{238}U in the vicinity of 1 keV.

The cross section for the neutron-induced fission of ^{238} was determined with respect to the cross section for ^{235}U fission as

$$\sigma_x(E) = (N_x/N_5)_{E=E(t)}(n_5/n_x)(\varepsilon_5/\varepsilon_x)\sigma_5(E), \tag{2}$$

where x is the index of the measured nuclide, N_x is the number of counts in the chamber containing layer x for a slowing-down time t (neutron energy E), n_x is the number of nuclei in layer x, ε_x is the detection efficiency for fission fragments in the chamber containing layer x, and $\sigma_5(E)$ is the average of the cross section for ^{235}U fission (ENDF/B7 estimate) over the spectrometer resolution function ($\Delta E/E = 0.424$). The detection efficiencies for fission events in the two fission chambers agreed to within 5%. The measured cross sections for the neutron-induced fission of ^{238}U are presented in Fig. 4. The value obtained for the averaged cross section at the maximum of the resonance at $E_n = 0.72$ keV is 1.78 ± 0.24 mb (the respective value in [11] was 1.446 mb, the statistical and systematic errors there being, respectively, 0.012 mb and 5 to 10%). The existing statistical accuracy is insufficient for observing the resonance structure in the energy region around 20.4 eV (the cross section there is about 0.4 mb) and in the energy region around 11.1 keV (according to data from [11], the cross section there is about 0.106 mb). The achieved sensitivity threshold of the LSD-100 spectrometer at the above parameters of the accelerator beam (within the irradiation time of 11 h) is $m\sigma_f \cong 1$ mg mb, which is close to the values obtained with the RINS spectrometer [11, 12].

2.2. Results of Measurement of the Cross Section for the Neutron-Induced Fission of ^{236}U

The time spectra of detected events of the neutron-induced fission of ^{236}U and ^{235}U are displayed in Fig. 5. The total time of the accumulation of the spectrum was about 17.5 h. The spectrum for ^{236}U receives a significant contribution from the ^{235}U$(n,\ f)$ fission process, this admixture being dominant in the region $t \geqslant 250$ μs. We concurrently measured the spectrum for ^{235}U and determined its fraction in the spectrum for ^{236}U, and this fraction proved to be $\alpha = 0.00082 \pm 0.00001$. If the detection efficiency for fission events in the chambers containing ^{236}U and ^{235}U were identical, α would assume a value of 0.00057 ± 0.00003 upon taking into account the isotopic composition and thickness of the layers. The difference in the estimates of α is associated with the transition of electronic signals from the ^{235}U channel to the ^{236}U channel. For the ^{238}U channel, this effect is 0.00024 ± 0.00001, which can explain the difference in the estimates.

Upon the subtraction of the background, the spectrum of events of the neutron-induced fission of ^{236}U exhibits distinct resonance structures in the region around 5.45 eV and in the range 1–10 keV. At the peaks, the statistical accuracy of the measurements was 13 and 5%, respectively. In the remaining regions of the neutron energy, the possible effects are smaller than the measurement errors.

The cross section for the neutron-induced fission of ^{236}U was determined with respect to the cross section for ^{235}U fission by formula (2). The enhancement factors and the discrimination thresholds in spectrometric channels for the chambers containing ^{235}U and ^{236}U layers were chosen in such a way that the amplitude spectra of fission fragments were nearly identical. Therefore, the detection efficiencies for fission fragments agree to within 3%. The error in the measured cross section is determined by the statistical error in N_6 and by the normalization error (6%). The results obtained by measuring the cross

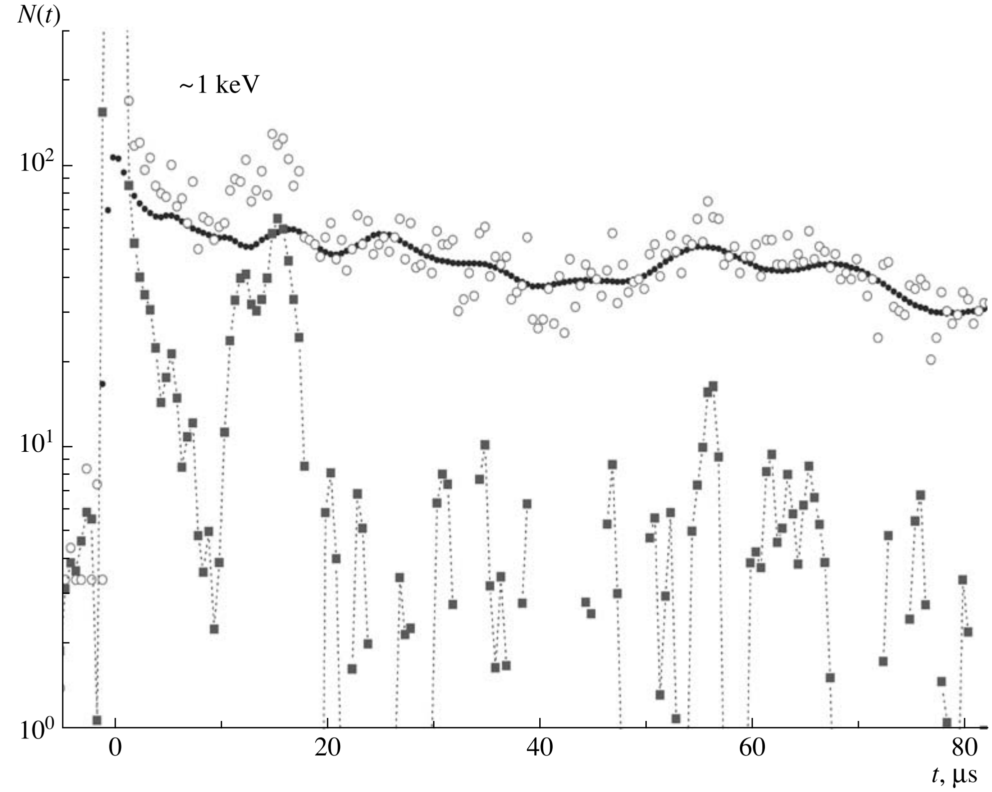

Fig. 3. Time spectra of detected events of the neutron-induced fission of (closed boxes connected by a dotted line) $^{238}\mathrm{U}(n, f)$ and (line formed by closed circles) $^{235}\mathrm{U}(n, f)$ nuclei and (open circles) time spectrum of all events in the main time window.

section for the neutron-induced fission of ^{236}U are given in Figs. 6 and 7. These figures also show the averages of the cross sections from the ENDF/B7 library over the LSD-spectrometer resolution function and the average cross sections calculated on the basis of data on resonance integrals from [5].

Our data in the region $E_n < 100$ eV (Fig. 6) are in a sharp contradiction with data from [4] but agree with the conclusions drawn by Parker et al. [5], who observed only one resonance occurring at 5.45 eV and having a very small fission width Γ_f, but who did not observe a strong resonance structure in the region around 40 eV. Table 1 presents values of the resonance integral $A_f = (\pi/2)\,\sigma_0\Gamma_f$, where $\sigma_0 = 4\pi\lambda\!\!\!^{-}{}_0^2 g\Gamma_n/\Gamma$, and the calculated widths Γ_f, which proved to be somewhat less than in [5]. In calculating σ_0, we used the resonance-parameter values from the ENDF/B7 estimate—$\Gamma_n = 2.24$ meV and $\Gamma_\gamma = 24.5$ meV—which are identical to those in [4].

A similar situation is observed in the energy region above 100 eV as well (see Fig. 7). Data in [4] are sharply at odds with the ENDF/B7 estimate. Only

Table 1. Parameters of the resonance at an energy of 5.45 eV

Experiment	Resonance parameters		
	Γ_f, μeV	A_f, mb eV	σ_0, b
Teobald et al. [4]	290 ± 7	18 200	39 870
Parker et al. [5]	1.3 ± 0.1	82 ± 8	40 300
INR + IPPE	1.05 ± 0.1	66 ± 6	39 870

Note: The notation INR + IPPE stands for a joint experiment performed by research groups from the Institute for Nuclear Research (INR, Moscow) and the Institute of Physics and Power Engineering (Obninsk).

Table 2. Parameters of class-II states excited in subthreshold neutron-induced fission of ^{236}U

	$\Gamma_{\mathrm{II}(c)}$, eV	$\langle H_c\rangle^2$, eV^2	$\Gamma_{\mathrm{II}(f)}$, meV
$V_{A,B}$	10.8	31.6	35.9
$V^+_{A,B}$	4.9	14.3	10.7
$V^-_{A,B}$	23.4	68.5	120
[5]	5	12	9.5

Note: $V^{+,-}_{A,B} = V_{A,B} \pm 0.1$ MeV.

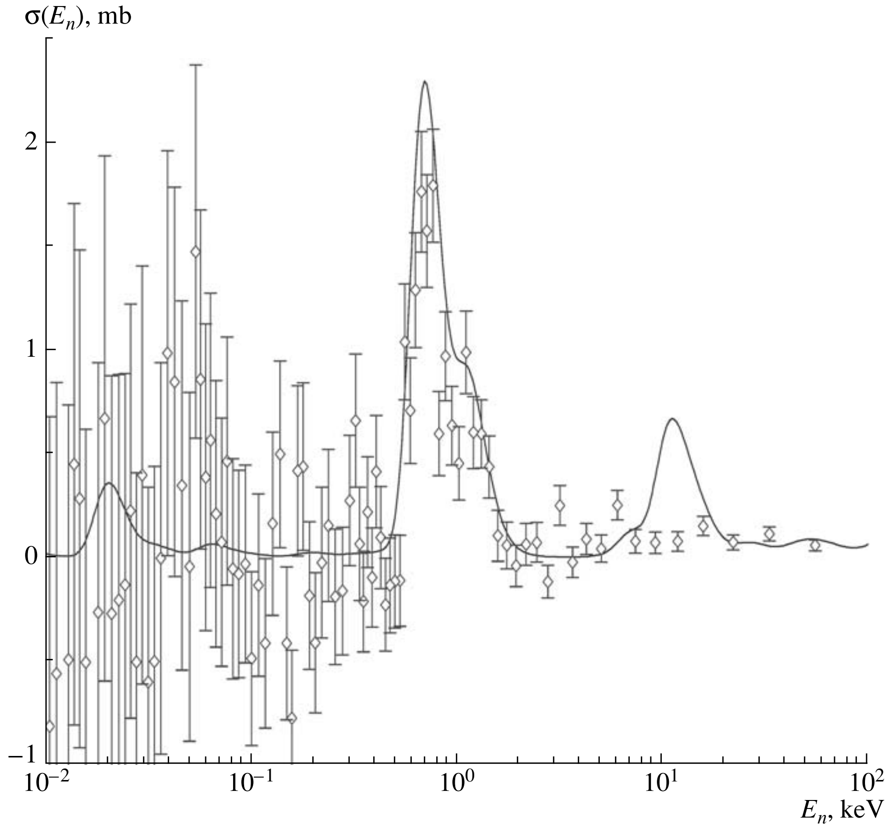

Fig. 4. Cross section for the neutron-induced fission of ^{238}U: (points) our present data and (solid curve) averaged data from the ENDF/B7 library.

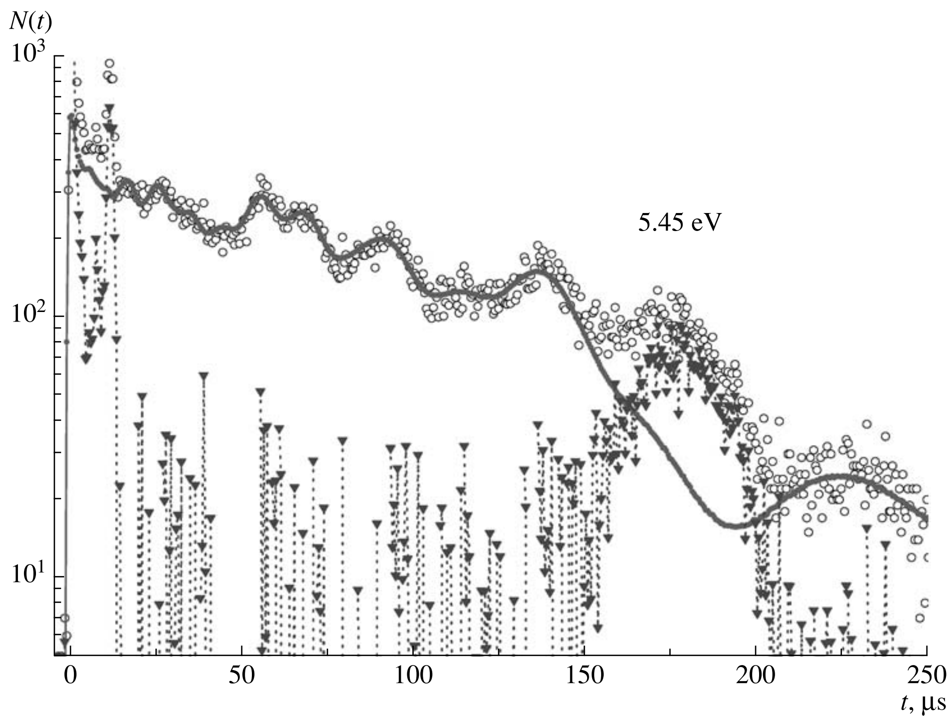

Fig. 5. Time spectra of fission events for the ^{236}U target: (open circles) total spectrum, (closed triangles connected by dotted lines) contribution of the neutron-induced fission of ^{236}U, and (solid curve) contribution of the neutron-induced fission of ^{235}U.

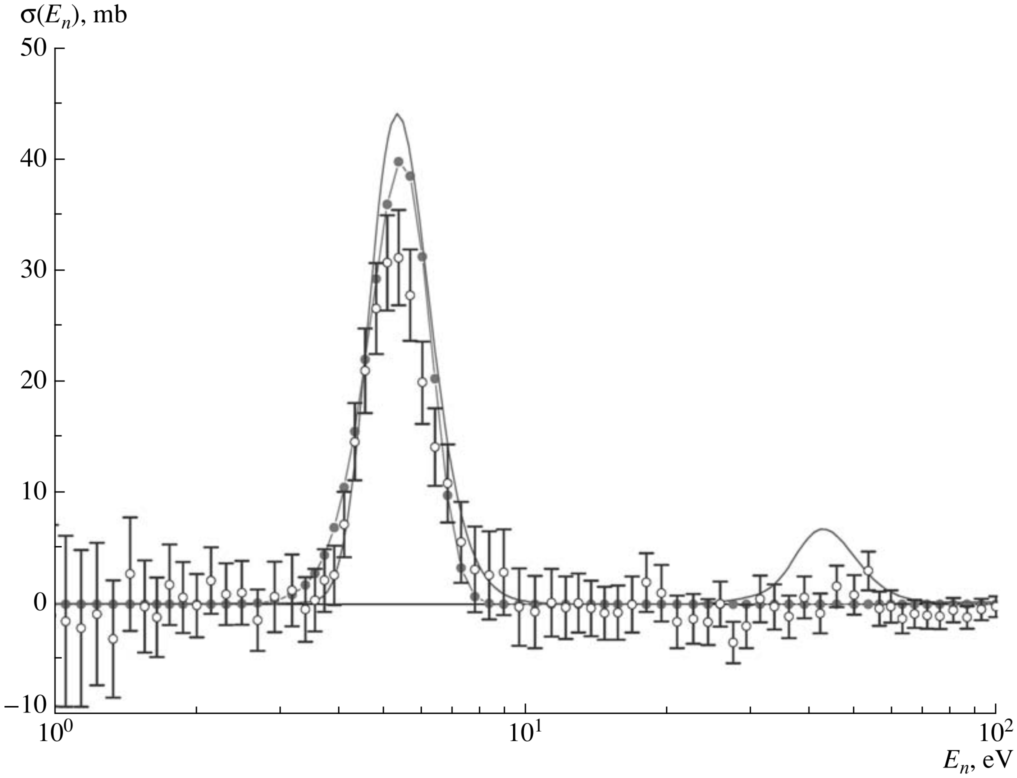

Fig. 6. Cross section for the neutron-induced fission of ^{236}U in the neutron-energy region below 100 eV: (circles) our present data, (curve connecting closed circles) results of averaging data over resonance integrals [5], and (solid curve) estimate from the ENDF/B7 library (it is reduced by a factor of 200).

a triplet at an energy of 1282 eV ($A_f = 5.8$ b eV) and resonances at energies of 2959 ($A_f = 1.1$ b eV), 6300 ($A_f = 5.7$ b eV), and 10 400 eV ($A_f = 1.5$ b eV) are observed. In [5], all of these resonances were associated with states of class II. The resolution of the LSD-100 spectrometer makes it possible to detect only the resonances at $E_n = 1.28$ and 2.96 keV. For the first resonance, A_f was estimated at 4.9 ± 0.6 b eV, which is 14% below the data from [5]. If σ_0 is calculated on the basis of the ENDF/B7 resonance parameters ($\Gamma_n^0 = 0.00197(23)$ eV$^{1/2}$, $\overline{\Gamma}_\gamma = 0.01983(44)$ eV, and $\Gamma_n = 70.5(82)$ meV), then a value of $\Gamma_f = 2.0 \pm 0.32$ meV is obtained for the average fission width. This value is one-fourth as large as that in [5], and the reason is that different basic estimates are used for Γ_n. It should be noted that this resonance was first observed in the "bomb" experiment [3], its resonance integral being $A_f \approx 2$ b eV.

3. ANALYSIS OF THE RESULTS AND DISCUSSION

Using the results obtained here and some new data on the ^{236}U$(n,\ f)$ fission process, we can refine theoretical estimates deduced in [5]. Figure 8 shows the cross section for ^{236}U fission induced by fast neutrons. The information on display there includes experimental data, the ENDF/B7 estimate, and the results of a theoretical analysis from [17] within statistical fission theory.

A description of the chance structure of cross sections for neutron-induced emissive fission for the entire chain of nuclei from ^{233}U to ^{238}U within a unified approach is a feature peculiar to the analysis in [17]. In order to describe the level density of excited nuclei, realistic spectra of single-particle states in the superfluid model of the nucleus were used there. The neutron channel was described on the basis of the nonspherical optical model. For the heights $V_{A,B}$ of humps A and B of the fission barrier in ^{236}U, the analysis yielded the values of $V_A = 5.7$ MeV and $V_B = 5.9$ MeV. For the sake of comparison, it should be indicated that the estimates $V_A = 6.1$ MeV and $V_B = 5.9$ MeV from [2] were used in [5].

Knowing V_A and the curvature $\hbar\omega_A$ of barrier A, we can calculate the strength function for the mixing of class II states as

$$2\pi\left(\Gamma_{\mathrm{II}(c)}/D_{\mathrm{II}}\right) = N_{\mathrm{eff}}T_A$$
$$= N_{\mathrm{eff}}\left[1 + \exp\left(2\pi\Delta V_A/\hbar\omega_A\right)\right]^{-1},$$

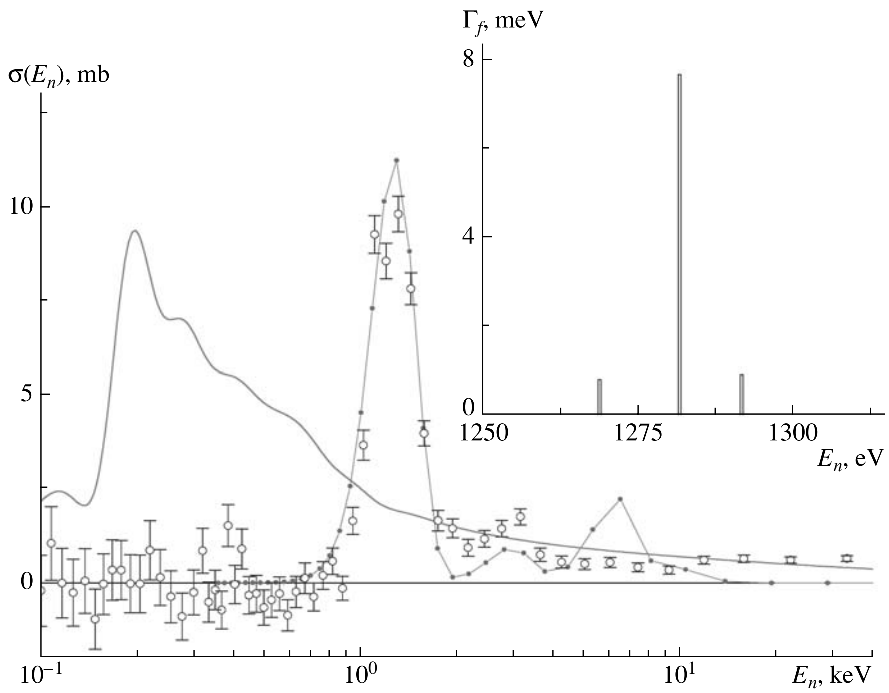

Fig. 7. Cross section for the neutron-induced fission of ^{236}U$(n,\ f)$ in the neutron-energy region above 100 eV: (open circles) our present data, (curve connecting closed circles) results of averaging data over the resonance integrals from [5], and (solid curve) estimate from the ENDF/B7 library (it is reduced by a factor of 20). The inset shows the distribution of Γ_f values for the resonance at 1282 eV [5].

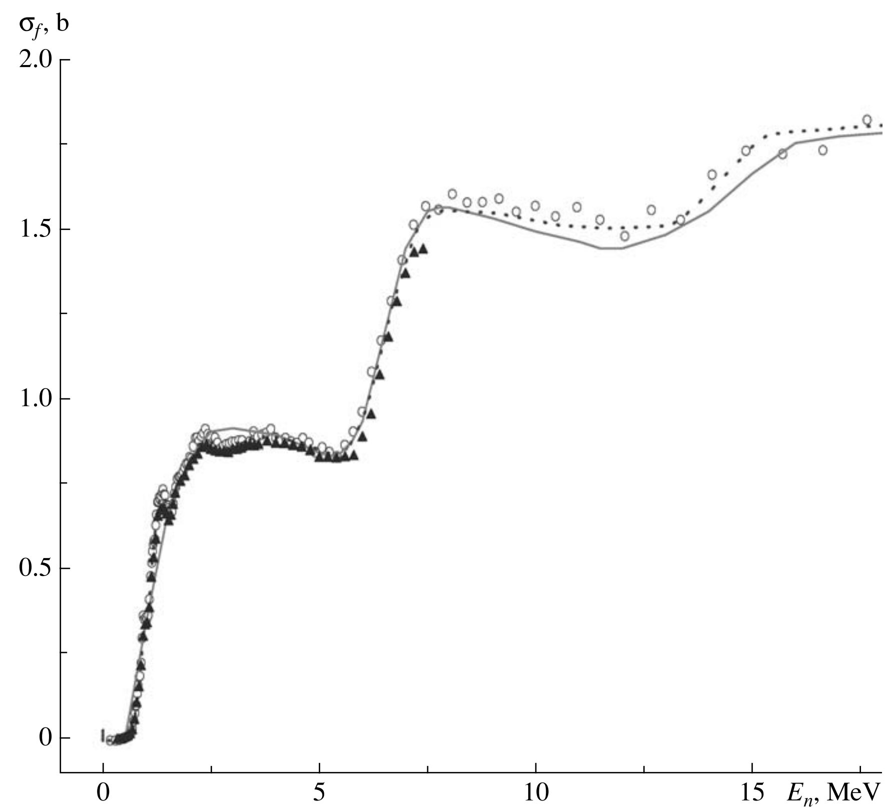

Fig. 8. Cross section for ^{236}U fission induced by fast neutrons: (closed triangles) experimental data from [15], (open circles) experimental data from [16], (solid curve) result of a theoretical analysis of [17], and (dotted curve) ENDF/B7 data [7].

where $\Gamma_{\mathrm{II}(c)}$ is the mixing width; T_A is the penetrability of barrier A; N_{eff} is the effective number of fission channels; and $\Delta V_A = V_A - B_n$, B_n being the neutron binding energy in the compound nucleus (5.126 MeV). The quantity $\Gamma_{\mathrm{II}(c)}$ is directly related to the matrix element of channel coupling as

$$\Gamma_{\mathrm{II}(c)} = \Gamma_{\mathrm{II}} - \Gamma_{\mathrm{II}(f)} = 2\pi \left[\langle \lambda_{\mathrm{I}} | H_c | \lambda_{\mathrm{II}} \rangle^2 / D_{\mathrm{I}} \right].$$

The penetrability T_B of barrier B determines the fission strength function for class-II states as

$$2\pi \left(\Gamma_{\mathrm{II}(f)} / D_{\mathrm{II}} \right) = T_B = \left[1 + \exp\left(2\pi \Delta V_B / \hbar\omega_B \right) \right]^{-1}.$$

Table 2 gives new estimates of the parameters $\Gamma_{\mathrm{II}(c)}$, $\langle H_c \rangle^2$, and $\Gamma_{\mathrm{II}(f)}$ with allowance for the uncertainties in $V_{A,B}$ (0.1 MeV).

The results obtained in [5] from an analysis of the fragmentation of the class-II resonance at an energy of 1280 eV agree with our estimates at the parameter values of $V_A = 5.8$ MeV and $V_B = 6.0$ MeV ($\hbar\omega_A = 0.8$ MeV, $\hbar\omega_B = 0.52$ MeV, $D_{\mathrm{II}} = 2.6$ keV, and $D_{\mathrm{I}} = 18.4$ eV). A high sensitivity of the properties of class-II states to variations in the barrier-parameter values is noteworthy. At the same time, the analysis involves difficulties in determining the average values of the parameters of class-II states since the number of such states observed experimentally is not large and since $\Gamma_{\mathrm{II}(f)}$, $\langle H_c \rangle^2$, and D_{II} are strongly fluctuating random variables.

In conclusion, we note that not only has the present study made it possible to obtain new data on the cross section for the neutron-induced fission of ^{236}U on the basis of an alternative experimental procedure but it has also clarified the reason behind existing discrepancies in the behavior of this cross section. It is the direct method used in the present study and in [3, 5] to detect fission events by recording fission fragments rather than the method of recording accompanying neutrons or gamma rays, as in [4, 6], that made it possible to measure small values of the cross section for ^{236}U fission and to reveal an intermediate structure in the cross section.

The recommended data on the neutron-induced fission of ^{236}U in the resonance energy region (from the ENDF/B7 library) are obviously unsatisfactory and call for revision.

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