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Neutron–Induced Fission Cross Section of Uranium, Americium and Curium Isotopes

Progress report - Research Contract 14485
Coordinated Research Project on Minor Actinide Neutron Reaction Data (MANREAD)

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ABSTRACT

This report contains brief description of the Lead Slowing Down Spectrometer and results of measurements of neutron-induced fission cross sections for ^{236}U, ^{242m}Am, ^{243}Cm, ^{244}Cm, ^{245}Cm and ^{246}Cm done at this spectrometer. The work was partially supported through the IAEA research contract RC-14485-RD in the framework of the IAEA Coordinated Research Project "Minor Actinide Neutron Reaction Data (MANREAD)". The detailed description of the experimental set up, measurements procedure and data treatment can be found in the JIA-1182 (2007) and JIA-1212 (2009) reports from the Institute of Nuclear Research of the Russian Academy of Science published in Russian. Part 1 contains the first year report of the research contract and part 2 the second year report.

December 2009

CONTENTS

1. Part 1: 1st Year Report RC-14485-RD 7
   1.1. Neutron–Induced Fission Cross Section of ^{236}U, ^{242m}Am and ^{245}Cm.......... 7
   1.2. References 10
   1.3. Figures 11

2. Part 2: 2nd Year Report RC-14485-RD.......... 15
   2.1. Neutron–Induced Fission Cross Section of ^{243}Cm, ^{244}Cm and ^{246}Cm.......... 15
   2.2. References 19
   2.3. Figures 20

Part 1: 1st Year Report RC-14485-RD

1.1 Neutron–Induced Fission Cross Section of ^{236}U, ^{242m}Am and ^{245}Cm

A.A. Alekseev, A.A. Bergman, A.I. Berlev, E.A. Koptelov,
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Neutron induced fission cross sections of ^{242m}Am and ^{245}Cm were measured from 0.03 eV to about 20 keV at INR RAS Lead Slowing Down Spectrometer LSDS-100. Using a computer model of LSDS spectrometer and Monte Carlo calculations for experimental data processing it was possible to extend the operational range of LSDS up to thermal neutrons. ^{236}U(n,f) cross section has been measured from 1 to 20 keV. The fission resonance areas at 5.45 and 1.28 keV resonances were obtained and their fission widths were evaluated. The well known intermediate structure in the neutron-induced fission cross section of ^{236}U has been confirmed.

Most of the minor actinides (Np, Am, Cm) are the high radioactivity nuclides. Because of this, the fresh radiochemically separated small samples of actinides and intensive neutron fluxes are needed to measure the fission cross sections of these nuclides. In this work, the fission cross sections of ^{242m}Am and ^{245}Cm and sub-barrier fission cross section of ^{236}U were measured at the Lead Slowing Down Spectrometer (LSDS-100) installed at the INR RAS proton Linac ("Moscow Meson Factory"). Such spectrometers can be successfully used for cross section measurements of the nuclides that cannot be investigated by other methods.

The experimental method has been described in the papers [1-3]. The proton beam parameters are following: the primary energy is equal to 209 MeV, the current pulse width is 1 μs, the repetition rate is 50 Hz, and the peak current is 8÷10 mA. The electronics used allow a time and an amplitude analysis of fission events during the time interval up to 18 ms. Detector system was multi-sectional fast fission chamber being placed into the operating channels of the LSDS-100 at the distance 140 cm from neutron source centre.

The targets were prepared using the separated isotopes of high purity: ^{236}U (mass m = 1.30 mg, 0.047% impurity of ^{235}U), ^{245}Cm (m = 3.06±0.09 μg, impurities: 1.11% of ^{244}Cm and 0.405% of ^{246}Cm), ^{242m}Am (m = 3.44±0.11 μg, impurities: 13.77% of ^{241}Am and 5.34% of ^{243}Am). The chambers with fissile layers of ^{235}U (m = 1.07 mg) and ^{239}Pu (m = 0.55 mg) were used as flux neutron monitors. The layer of ^{238}U (m = 1.60 mg, impurities: ^{234}U – 3 ppm, ^{235}U – 3 ppm,) were used for estimating the threshold sensitivity of the LSDS-100 to the low values of fission cross sections. The targets of ^{242m}Am, ^{245}Cm and ^{239}Pu were prepared just before irradiation. The mass of the fissile material was determined on its α-activity using semiconductor spectrometer.

The average reduced cross section values $\langle \sigma \sqrt{E} \rangle$ can be calculated from the measured time spectra of fission events $N(t)$ using the relation

$$\langle \sigma(E)\sqrt{E} \rangle = N(t)/(C_0 \cdot w(t)), \quad (1)$$

where $\langle \ \rangle -$ is a sign of averaging on the actual neutron energy E in the vicinity of the mean neutron energy $\overline{E}(t)$ at the moment t of the slowing down time; $w(t) -$ is the neutron density at the sample surface.

In this work the functions $w(t)$ and $\overline{E}(t)$ were calculated in the framework of the LSDS computer model (using the Monte-Carlo method). The model parameters have been deduced from the condition of the optimal fitting of the measured time spectra by simulated time spectra calculated using standard cross sections for ^{235}U(n,f) and ^{239}Pu(n,f) from the ENDF/B-VII.0 library [7].

Sphere with the equivalent radius $R_0 = 150$ cm has been taken as the model of the spectrometer. The sphere had a void spherical sub-layer to take into account the effects of the LSDS operating channels. The thermalization of the neutrons was calculated in the approximation of the heavy gas moderator. The model had four free parameters: the void layer width, the medium temperature kT, the normalizing parameter C_0 and the percentage of hydrogen impurity. With the last parameter the approximate influence of the light elements impurities was taken into account. By adjusting the parameters in the fitting procedure, it was possible to reproduce all observed structures in the fission cross sections up to epithermal neutron energies ($t \le 6000$ μs), both for ^{235}U(*n,f*) and ^{239}Pu(*n,f*). This approach allowed substantial reducing of the LSDS lower energy boundary in the measurements (usually ~1 eV due to neutron thermalization effect on the LSDS resolution).

The model calculations show that in the range $t > 300$ μs the mean neutron energy $\overline{E}(t)$ depends on the slowing down time t as

$$\overline{E}(t) = K/(t + t_0)^2 + e_T , \qquad (2)$$

where the parameter e_T is varied from 20 meV to kT as a function of t. The slowing down constants K equals 167.6 keV·μs^2 and t_0= 0.85 μs.

The function $w(t)$ follows the predictions of the elementary theory of slowing down for determination of neutrons age. At large slowing down times, it depends on t as $\exp(-t/t_D)$ where the constant t_D is equal to 766.7±2 μs for adjusted model. This is confirmed by the experimental results obtained for ^{235}U, ^{239}Pu, ^{242m}Am and ^{245}Cm samples; the mean experimental value is t_D=763 μs.

For ^{242m}Am and ^{245}Cm the parameter C_0 (Eq. 1) was determined through the normalization using ENDF/B-VII.0 values [4] in the neutron energy range 30 meV – 1 eV. The relative statistical uncertainty of the resulting cross sections values (total operating time is 55 h) is less than 2% in the main time window ($t <$ 2000 μs) but it goes up to 10% at the range edge (~5000 μs). The systematic uncertainty due to possible uncertainties in the time behavior of the neutron density $w(t)$ is not over 5%.

The main part of the ^{236}U time spectrum (total operating time is 17.5 h) consists of the signals from ^{235}U(*n,f*) reaction and this admixture is dominant at $17 < t < 150$ μs and at $t >$ 200 μs. The statistical uncertainty of the ^{236}U(*n,f*) registered events (after subtracting the background) is equal to 13% at 5.45 eV resonance and 5% in the range 1–10 keV. At other neutron energies the contribution from ^{235}U impurity is below the measurement uncertainties. The ^{236}U fission cross section was measured relatively to ^{235}U(*n,f*) cross section. The uncertainty of the resulting cross section values includes the statistical uncertainty and the uncertainty of the normalization (6%).

The threshold sensitivity of the LSDS-100 was estimated from the measurement of the ^{238}U fission cross sections (total operating time is 11 h) in the maximum of the 0.72 keV resonance (σ_m = 1.78±0.24 mb). The measured value ($m\sigma_f \cong 1$ mg·mb) is close to the library one.

A. ^{242m}Am. The results of the fission cross section measurements in the epithermal neutron energy range are shown in Fig. 1. The averaged value weighted on all data at 25.3 meV [5] is equal to 6408±212 b that agrees with the ENDF/B-VII.0-VII.0 recommended value (6416 b) and is close to the time-of-flight (TOF) data of Los Alamos 6329±320 b [6]. The averaged value for $\sigma_T \sqrt{E_T}$ is 1020±34 b·eV$^{1/2}$. In the energy range 30 – 50 meV the LSDS–100 data are in a good agreement with the data of the Japan group [7] (where LSDS-40, thermal neutron facility and TOF method were used) and the TOF data of Oak Ridge [8]. The extrapolation of the LSDS–100 data to the thermal point gives the value 1087 b·eV$^{1/2}$ with statistical uncertainty 9 b·eV$^{1/2}$.

Available data on the ^{242m}Am fission cross section in the resonance energy range are shown in Fig. 2. The ENDF/B-VII.0 evaluation is based on the TOF data of Los Alamos [6]. There is a systematical discrepancy (~20%) between these data and the TOF data of Oak Ridge [8]. For comparison with the LSDS-100 results these data were averaged with LSDS-100 resolution function [2]. The Japanese data (LSDS–40) [7] are in agreement with TOF data [8] at $E >$ 80 eV but at $E <$ 1 eV they are closer to the Los Alamos data [6].

The LSDS-100 results are between the data [6] and [8] at $E = 20$ eV–1 keV. At $E > 8$ keV our data follow the data [6]. There is a visible peak at 4.5 keV in the results of Japanese measurements but it is not displayed in the other data. It is needed to mention that the LSDS–40 energy resolution is lower than LSDS–100 one.

B. ^{245}Cm. The results for epithermal neutrons are shown in Fig. 1. The value of the thermal cross section recommended in ENDF/B-VII.0 (σ_T=2149 b) is based on the TOF data (2143±58 b) from Livermore [9]. The weighted average value at 25.3 meV for reactor data [5] is equal to $<\sigma_T>$=1971 ±33 b which is 8% less than ENDF/B-VII.0 value. The ENDF/B-VII.0 value for $\sigma_T \sqrt{E_T}$ is 342±9 b·eV$^{1/2}$ at the energy 25.3 meV. The extrapolation of the LSDS–100 data to the thermal point gives the value 344±8 b·eV$^{1/2}$.

Available data for the ^{245}Cm fission cross section in resonance energy range are shown in Fig. 3. The ENDF/B-VII.0 evaluation is based on the TOF data of Livermore ($E < 63$ eV) [9, 10]. For neutrons with $E > 20$ eV, the Physics 8 bomb shot experiment [11] resulted with some remarkable data. To compare with the LSDS-100 result, all the former data [4, 9 – 11] were averaged with the LSDS-100 spectrometer resolution function [2]. For neutrons with energy below 200 eV the LSDS-100 data agrees well with other data as on absolute values of the cross sections as well as on its energy dependence. The good agreement between our data, the bomb shot data and LSDS-44 KIAE data [12] demonstrates the drawback of the ENDF/B-VII.0 evaluation which does not reproduce the intermediate structure in the cross section observed at 100– 200 eV energy range and near 8 eV. Our data are also 12–17% higher than the ENDF/B-VII.0 values in the energy range $E_n = 2$– 20 keV.

C. ^{236}U. Previously the sub-barrier fission cross section of ^{236}U has been measured in the resonance energy range only by TOF method [13 – 16]. Most available data are shown in Fig. 4. For comparison with the LSDS-100 results, the former data were averaged with the Gaussian function with a characteristic width close to the energy resolution $\Delta E = 0.35E$. There is a strong discrepancy between the Geel data [13] (not shown in thefigure) and the Los Alamos data [16]. The ENDF/B-VII.0 [4] evaluation is based on the results of Los Alamos measurements [16] confirmed by the data [14]. The Pommard bomb shot experimental data [15] (after some correction of the contribution from the ^{235}U(*n,f*) reaction) confirm the data [16] where the measured value of Γ_f for 5.45 eV resonance is about 200 times lower than data from [13]. Moreover, for other resonances no fission events were observed [16] up to 1 keV energy. An insufficient discrimination of capture gamma rays in the fission detectors [13, 14] may be a reason for such discrepancy.

Our data in the region $E_n < 100$ eV are in strong contradiction with the Geel data [13] but agree with the Los Alamos results [16], so only the resonance at 5.45 eV is observed and there is no strong resonance structure in the region around 40 eV. Table 1 shows the values of the measured resonance areas $A_f = (\pi/2) \cdot \sigma_0 \cdot \Gamma_f$ and fission widths Γ_f calculated using σ_0 total peak cross section value from the ENDF/B-VII.0 file. Our values are about 25% below the Los Alamos data [16].

Table 1. Parameters of resonance at 5.45 eV

Experiment	Parameters		
	Γ_f, μeV	A_f, mb·eV	σ_0, b
Teobald *et al.* [13]	290 ± 7	18200	39870
Parker *et al.* [16]	1.3 ± 0.1	82 ± 8	40300
Present work	1.05 ± 0.1	66 ±6	39870

Above 100 eV, the ENDF/B-VII.0 data does not agree with the LANL data [16]. Only a triplet of resonances at the energy 1282 eV (A_f = 5.8 b·eV) and resonances at the energies of 2959 eV (A_f = 1.1 b·eV), 6.3 keV (A_f = 5.7 b·eV) and 10.4 keV (A_f = 1.5 b·eV) are observed. For 1.28 keV resonance only an estimation of A_f value can be given (4.9 ±0.6 b·eV), and is 14% less than the LANL value. The average value of fission width calculated from the resonance parameters of the ENDF/B-VII.0 file is equal to Γ_f = 2.0±0.32 meV, which is 4 times less than value given in [16].

Using a Lead Slowing Down Spectrometer LSDS-100 INR RAS we were able to obtain new data on the fission cross section of ^{242m}Am and ^{245}Cm in the neutron energy range E_n = 0.03 eV–20 keV. For the first time the operating energy range of the LSDS spectrometer has been extended to the epithermal neutrons. The results obtained show the need in the revision of the ENDF/B-VII.0 fission cross sections for ^{242m}Am, ^{245}Cm and especially for ^{236}U.

1.2 References

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1.3 Figures

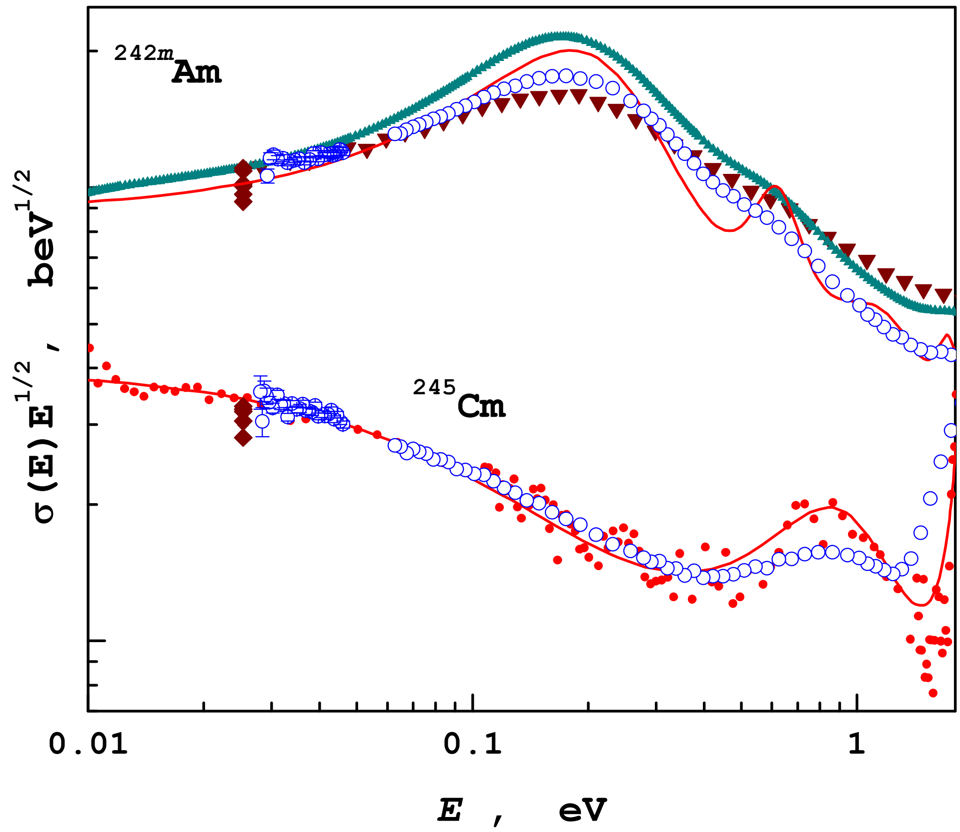

Fig. 1. The reduced fission cross section $\left\langle \sigma(E)\sqrt{E} \right\rangle$ of ^{242m}Am and ^{245}Cm from 10 meV to 1 eV. Designations: ○ - LSDS-100 data [3]; solid line — -ENDF/B-VII.0 data [4]; ▲– [8]; ▼ – [7]; ◆– 25.3 meV data [5]; ● – [9].

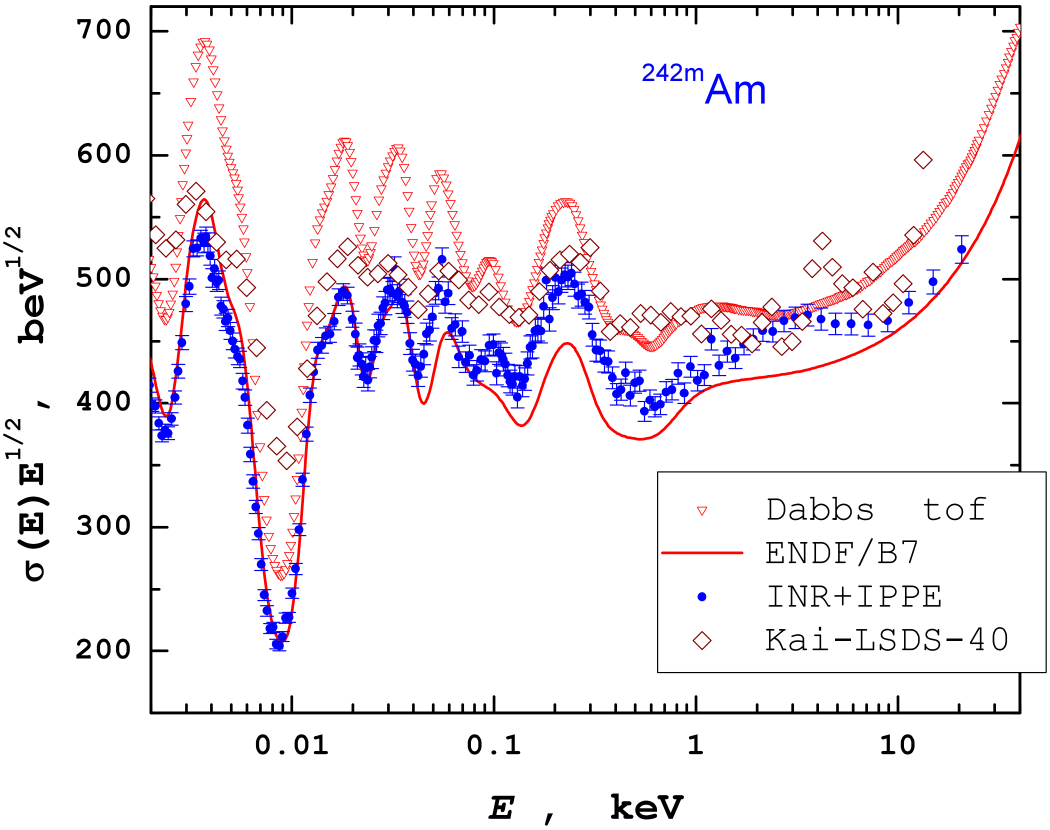

Fig. 2. The reduced fission cross section $\left\langle \sigma(E)\sqrt{E} \right\rangle$ of ^{242m}Am from 0.8 eV to 30 keV. Designations: ● – LSDS-100 data [3]; solid line — – [4]; ▽– [8]; ◊ – [7]. The data [4, 8] are averaged with account of LSDS–100 energy resolution.

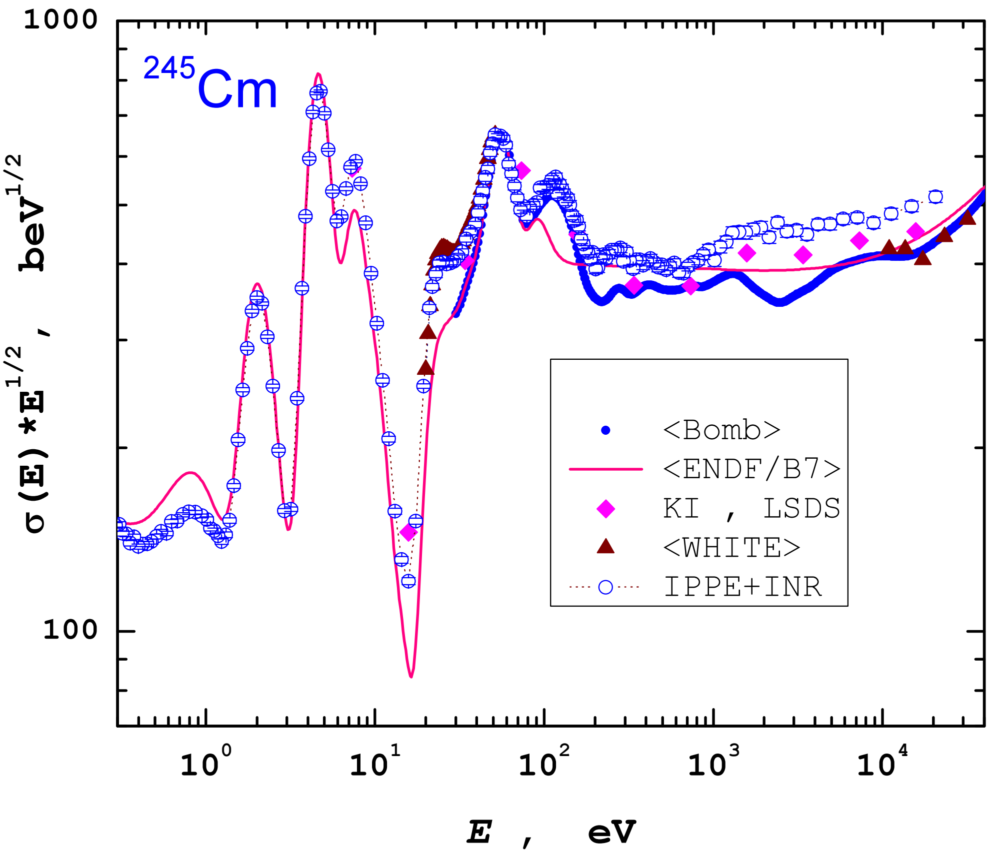

Fig. 3. The reduced fission cross section $\left\langle \sigma(E)\sqrt{E} \right\rangle$ of ^{245}Cm from 0.5 eV to 20 keV. Designations: ○ – LSDS-100 data [3]; solid line — – ENDF/B-VII.0 [4]; ◆ – LSDS-44 [12]; ▲ – [10]; • – [11]. The data [4, 10, 11] are averaged with account of LSDS-100 energy resolution.

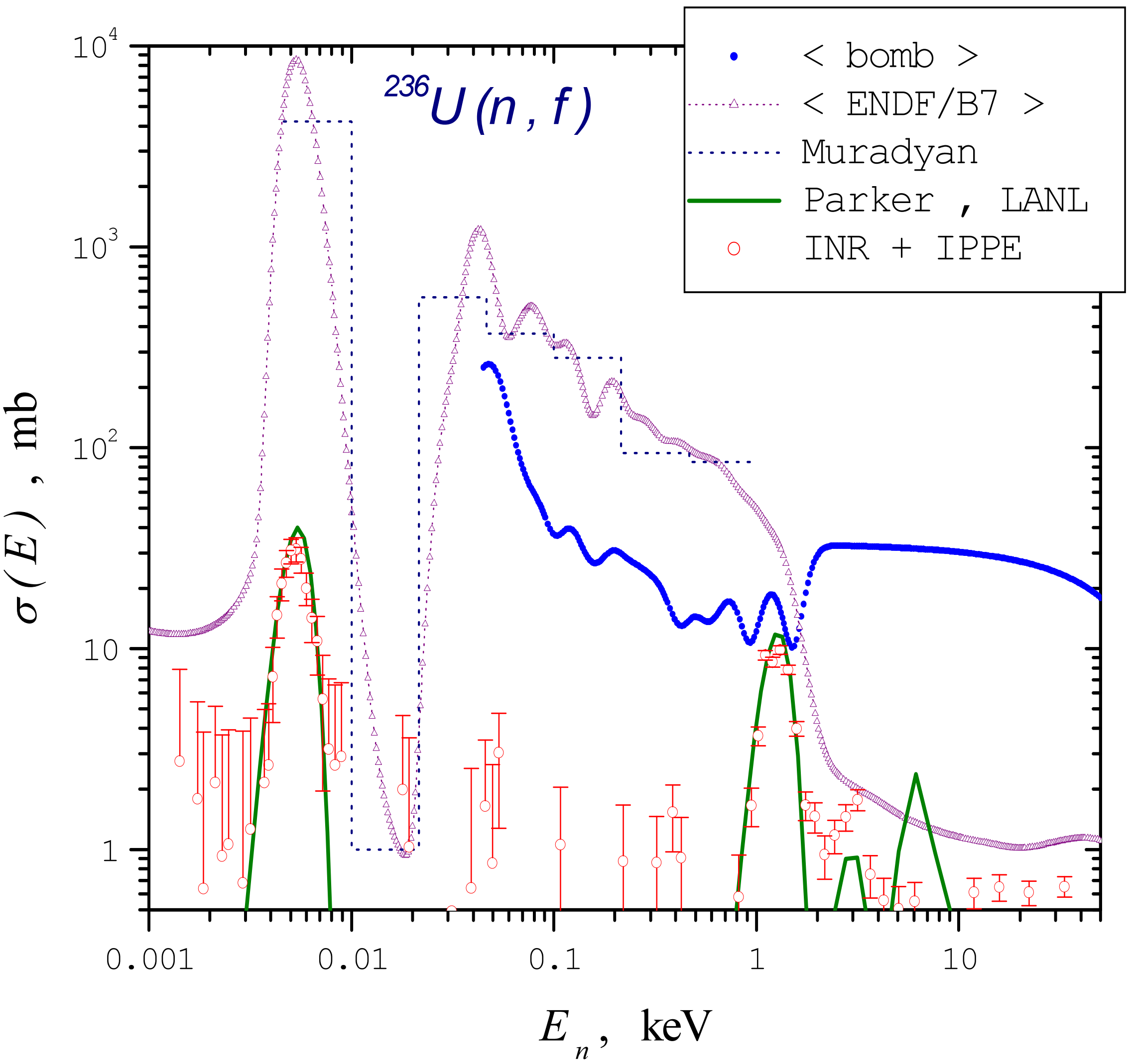

Fig. 4. Comparison of the averaged ^{236}U(n,f) fission cross section. Designations: △ – ENDF/B-VII.0 data [4]; ○ – present work [1, 2]; • –[15], - - - – [14], — – [16].

2.1 Neutron–induced Fission Cross Section of $^{243, 244, 246}$Cm

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Using INR RAS Lead Slowing Down Spectrometer LSDS-100, the neutron induced fission cross section of ^{243}Cm, ^{244}Cm and ^{246}Cm were measured for neutron energies below 20 keV. For ^{243}Cm the operational range of LSDS spectrometer was extended to thermal neutrons (0.03 eV). The fission resonance integrals were evaluated by using the obtained cross section data. The results have been compared with the available experimental and evaluated data.

Most of the minor actinides (Np, Am, Cm) are highly radioactivity nuclides. Therefore, the minute samples of actinides and intensive neutron fluxes are needed to measure the fission cross sections of these nuclides. In this work, the fission cross sections of the curium isotopes ^{243}Cm, ^{244}Cm and ^{246}Cm were measured with a Lead Slowing Down Spectrometer (LSDS-100) installed at the INR RAS proton Linac (Moscow Meson Factory - MMF). Such spectrometers are successfully used for cross section measurements of the nuclides that can not be investigated by other methods.

The experimental method has been described in the papers [1-4]. The proton beam parameters are following: the primary energy is equal to 209 MeV, the current pulse width is 2 μs, the repetition rate is 50 Hz, and the current in the peak is ~ 8 mA. The electronics made allow time analysis and amplitude one of fission events during the time interval up to 18 ms. The fission events were detected by the multi-sectional fast fission ionization chambers being placed into the operating channels of the LSDS-100 at the distance of 82 cm ($^{244, 246}$Cm) and 120 cm (^{243}Cm) from centre of the neutron source.

The fissile samples were prepared using the separated isotopes of high purity just before the measurements. The isotopic composition of the samples is listed in Table 1. The mass of the fissile material was determined on its α-activity using semiconductor spectrometer. The Cm fission cross sections were measured relatively to the ^{239}Pu(*n,f*) cross section. A mass of the high purity (99.9966%) ^{239}Pu sample was 17.3 μg. The ratio of the Cm α-activity to the ^{239}Pu one was determined with 1% uncertainty.

Table 1. The masses of Cm samples (*m*) and the isotopic contents

Sample	*m* μg	Content, % at.				
		^{243}Cm	^{244}Cm	^{245}Cm	^{246}Cm	^{247}Cm
^{243}Cm	4.26	**95.65**	3.79	0.057	0.48	0.100
^{244}Cm	4.51	0.018	**99.32**	0.09	0.56	0.007
^{246}Cm	8.44	---	0.207	0.0165	**99.53**	0.137

The average reduced cross section values $\langle \sigma \sqrt{E} \rangle$ of the curium isotope x are obtained from the measured time spectra $N(t)$ of fission events using the relation

$$\langle \sigma_x(E)\sqrt{E} \rangle = (N_x/N_9)_{E=\bar{E}(t)} \cdot (n_9/n_x) \cdot (\varepsilon_9/\varepsilon_x) \cdot \langle \sigma_9(E)\sqrt{E} \rangle, \qquad (1)$$

where $\langle\ \rangle -$ an averaging sign on the actual neutron energy E in the vicinity of the mean neutron energy $\bar{E}(t)$ at the moment t of the slowing down time; index $x = 9$ is corresponding to the ^{239}Pu standard sample; n_x is the number of atoms in the sample x; ε_x is the detection efficiency for fission fragments in sample x; $\langle \sigma_9(E)\sqrt{E} \rangle$ is the average reduced cross section of ^{239}Pu from the ENDF/B-VII.0 evaluation [5]. The ratio $N_x(t)/N_9(t)$ is calculated from the measured time spectra, the value (n_9/n_x) is determined in the α-activity experiment, and $(\varepsilon_9/\varepsilon_x)$ is found from the analysis of the measured amplitude spectra with taking into account corrections on the fission fragments losses in the fissile layers.

In this work, the determination of the functions $\overline{E}(t)$ and $\langle \sigma_9(E)\sqrt{E} \rangle$ was done in the framework of the LSDS computer model (based on Monte-Carlo calculations). The model parameters have been deduced from the condition of the optimal fitting of the measured time spectra for ^{235}U and ^{239}Pu with the simulated time spectra calculated using the ENDF/B-VII.0 files [5]. The model allowed reproducing all observed structures in ^{239}Pu fission cross section up to epithermal neutron energies ($t \leq 6000$ µs).

The model calculations show that the mean neutron energy $\overline{E}(t)$ depends on the slowing down time t as

$$\overline{E}(t) = K / (t + t_0)^2 + e_T , \tag{2}$$

where the parameter e_T is varied from 20 meV to kT as a function of t. In the case of $^{244, 246}Cm$ the slowing down constant K is equal to 169.2 keV·µs^2 and t_0 = 0.35 µs; for ^{243}Cm case $K =$ 168.8 keV·µs^2, $t_0 =$ 0.85 µs.

A. ^{243}Cm [4]. The time spectrum $N(t)$ has been measured for the neutrons with corresponding energies in the range $E = 0.03$ eV to 20 keV. The total operating time of measurements is 45 h. Due to low detection efficiency (about 60%) the absolute value of the fission cross section $\langle \sigma(E)\sqrt{E} \rangle$ was determined by the normalization to the ENDF/B-VII.0 data [5] at the neutron energies 29 – 62 meV. The correction was applied at 11% admixture of ^{239}Pu daughter atoms formed due to α-decay of ^{243}Cm. No corrections have been made for negligible contributions from ^{244}Cm and ^{246}Cm isotopes presented in the ^{243}Cm sample.

Analysis of the fission cross section shape in the epithermal energy range allowed estimating Westcott factor as $g(T) = 0.985$ for the temperature $T = 293.6 K$. The ENDF/B-VII.0 evaluation for $\sigma(E_T)\sqrt{E_T}$ is based on the experimental value at the thermal point E_T with $g(T)$=1. After corresponding correction, the new ENDF/B-VII.0 value $\sigma(E_T)\sqrt{E_T}$ obtained was 102.1±4.6 b·eV$^{1/2}$, comparing with 98.7 b·eV$^{1/2}$ - old ENDF/B-VII.0 value.

The final ^{243}Cm cross section data after their renormalization are shown in Fig. 1. Their systematic uncertainty due to the normalization procedure and 2% uncertainty in the $\langle \sigma_9(E)\sqrt{E} \rangle$ values is less than 5%. The relative statistical uncertainty depends on the neutron energy and is equal to 2.2 – 1% in the range 14 keV – 1.5 eV, 2 – 6.8% in the range 1 – 0.29 eV, 2.3 – 9.8% in the range 0.28 eV– 43 meV and it goes up to 55% at $E = 30$ meV.

In order to compare LSDS-100 results with the available experimental data of the Los Alamos group [6] and the ENDF/B-VII.0, these data were averaged with the Gaussian resolution function having a half-width of distribution $\Delta E = 0.35E$. As seen in Fig. 1, the LSDS-100 data match to the expanded Los Alamos data, especially in the range 20 -50 eV, and it confirmed the known resonance structure. The resonance peak at 72 eV in our data has less strength than resonance in the bomb shot data [6] and in the evaluated data. The JEFF - 3.1 data show strong resonance at $E \cong 16$ eV but it has not been seen practically in the ENDF/B-VII.0 data. The peak in our data has an intermediate strength. JEFF - 3.1 data does not point out the presence of any resonance at $E \cong 27$ eV as seen in other works.

In the range $E < 10$ eV, where the experimental fission data are absent, the LSDS-100 data are ~25% below ENDF/B-VII.0 data but the cross sections shape is the same. Remarkable peaks at E~7 eV (due to two resonances at 6.15 eV and at 7.21 eV), E~2.31 eV and E~0.67 eV were observed.

The LSDS-100 data allow calculation of the fission resonance integral I_f

$$I_f = \int_{E_C}^{E_2} \sigma_f(E)\, dE/E, \tag{3}$$

where E_C is the cadmium filter cut-off energy, and E_2 is the upper limit of the neutron energy spectrum. The results of calculations are presented in Table 2. It was found that $I_f = 1180 \pm 60$ b what is ~1.3 times below ENDF/B-VII.0 value.

B. ^{244}Cm [3]. The time spectrum was measured in the neutron energy range from $E = 0.1$ eV to 20 keV. The total operating time is 45 h. The absolute values of the fission cross section $\langle \sigma(E)\sqrt{E} \rangle$ have been calculated by using Eq.1 with the normalization constant $(n_9/n_4)\cdot(\varepsilon_9/\varepsilon_4) = 4.11 \pm 0.17$. The ratio $(\varepsilon_9/\varepsilon_4)$ found was 1.07±0.04. It is a result of analysis of the measured amplitude spectra and calculation of the detection efficiency ($\varepsilon_4 = 0.91 \pm 0.03$). The systematic uncertainty due to the normalization is equal to 4.1%. The cross section values have been corrected for contribution from daughter nuclei of ^{240}Pu formed in the α-decay of ^{244}Cm, and for impurities of the principal isotopes ^{243}Cm and ^{245}Cm in the ^{244}Cm sample.

Table 2. Fission resonance integrals I_f for curium isotopes

Isotope	Data	I_f b	E_c eV	E_2 keV
^{243}Cm	LSDS-100	**1180±60**	0.5	20
	ENDF/B-VII.0	1531	0.5	20
^{244}Cm	LSDS-100	**6.32±0.26**	0.5	20
	ENDF/B-VII.0	5.864	0.5	20
^{246}Cm	LSDS-100	**1.80 ±0.22**	0.5	27.4
	ENDF/B-VII.0	4.862	0.5	27.75

The results of the fission cross section measurement are shown in Fig. 2. The statistical accuracy of the data is 4.12% for $E \geq$ 5.6 eV in the average (the best is 1.90%, the worst 11.43%). The relative uncertainty increased from 12% and 40% to low energies.

Our data have confirmed all the known resonance structures at $E > 5$ eV and are in good agreement with the LANL data [7]. The LANL data were obtained by using time-of-flight method (TOF) and neutrons produced in underground nuclear explosion (Physics 8). For comparison with LSDS-100 data, the LANL data were reduced to the LSDS–100 energy resolution. Excluding the range 5–20 eV, the LSDS–100 values are well below the values obtained with the LSDS–75 assembly RINS [8]. The ENDF/B-VII.0 evaluation is based on the RINS data in the range $E > 1$ keV. The discrepancy between the RINS results and the ENDF/B-VII.0 data in $E < 5$ eV region is explained by the isotopic impurities of ^{245}Cm and ^{243}Cm.

The resonance analysis allowed to determine the fission area of the resonance $A_f = (\pi/2)\sigma_0 \Gamma_f$, where σ_0 is the total peak cross section in the resonance, Γ_f is the fission width. Our results for the resolved low-energy resonances at 7.67 eV and 16.8 eV are in good agreement with RINS data and ENDF/B-VII.0 evaluation. The results for 35 eV, 86 eV and 96 eV resonances match the LANL data [7]. For 22.85 eV resonance our value exceeds the bomb shot result almost 1.5 times but this resonance is at lower limit of the energy range for the bomb shot measurements.

The resonance integral calculated from the LSDS-100 data in the energy range from 0.5 eV up to 20 keV is $I_f = 6.32 \pm 0.26$ b (Table 2). This value exceeds the ENDF/B-VII.0 one at 2σ uncertainty.

C. ^{246}Cm. The total operating time of measurements was 47 h. The time spectrum contains a constant background component due to spontaneous fission, which dominates in the range $t > 450$ µs. In this range the statistical uncertainty exceeds 50 %. The statistical accuracy is ~6% for $t < 50$ µs in the average (the best is 3.0%, the worst is 7.7%). In the range $t = 50 - 200$ µs the relative uncertainty is changed between 5% for resonance peaks and 36% for cross section valleys.

The absolute values of the fission cross section $\langle \sigma(E)\sqrt{E} \rangle$ have been calculated using Eq. 1 with the normalization constant $(n_9/n_6) \cdot (\varepsilon_9/\varepsilon_6) = 2.25 \pm 0.08$. The ratio $(\varepsilon_9/\varepsilon_6)$ has been found equal to 1.07±0.04 and the detection efficiencies are $\varepsilon_6 = 0.91 \pm 0.03$ and $\varepsilon_9 = 0.97 \pm 0.02$. The systematic uncertainty due to the normalization is equal to 4.0%. The cross sections $\langle \sigma\sqrt{E} \rangle$ are plotted in Fig. 3. The data have been corrected at the contribution from high fissile isotopes ^{243}Cm and especially ^{247}Cm [8] (Table 1) in the ^{246}Cm sample. The contribution from ^{247}Cm dominates in the range $E < 3$ eV.

In the range $E = 0.71 - 2.63$ eV the data have been combined into a single group. The accuracy of the cross section value in this energy group is ~50% and is determined by a separation of dominant contribution of ^{247}Cm resonance at 1.24 eV. In the range $E = 0.0615 - 0.68$ eV the measured average cross section is negative. The upper limit of the 95% confidence interval for this range is equal to 0.038 b·eV$^{1/2}$ what is most probably the sensitivity threshold for these measurements.

As it can be seen in Fig. 3, the LSDS–100 data are between the RINS data [7, 8] and the bomb shot results of LANL group [6]. All known resonance structures have been confirmed. The ENDF/B-VII.0 evaluation is based on the RINS data in the range above 3 eV. Our data in the range $E > 200$ eV are about 1.4 times lower than the RINS data. Above 3 eV the average accuracy of the RINS values is ~10% and the best one is ~7%. At lower energies the uncertainties are between 30 and 50%. The best accuracy of the LANL data [6] is equal to 11% and in the average is less than 20%.

Table 3. Fission resonance areas A_f (b·eV) for ^{246}Cm

Energy E_0 eV	LSDS-100	RINS	LANL
4.315	**3.57±0.17**	2.14±**0.12**	18.2±**0.9**
15.33	**4.1±0.5**	**1.6±0.3**	14.5±**2.5**
84.43 91.84			15.1±**0.6**

The fission resonance areas A_f are shown in Table 3. Our results for the resolved low-energy resonances at 4.32 eV and 15.33 eV do not contradict the RINS data. The difference between the data is less than 2σ uncertainty. The resonances at 84.4 eV and 91.8 eV are not resolved in this experiment, but their total area was found to be equal 18.2±0.9 b·eV. This value agrees with the LANL [7] and RINS data within the limits of the 2σ uncertainty.

Unlike the RINS data, our data show fully resolved resonances below 85 eV. It seems that the existence of resonances at 33 eV and 47 eV assumed in the ENDF/B-VII.0 evaluation can not be justified. Our data do not contradict to the ENDF/B 7 data in the energy range below 3 eV. The resonance integral calculated with the LSDS-100 data for the energy limits 0.5 eV–27 keV was $I_f = 1.80 \pm 0.22$ b (Table 2). The ENDF/B-VII.0 value is ~2.7 times larger than our result. The accounted contribution of ^{247}Cm isotope based on the data [8] is 1.193(±10%) b.

The LSDS-100 fission cross section data of curium isotopes obtained in the neutron energy range $E_n = 0.03$ eV–20 keV will allow the testing of the ENDF/B-VII.0 evaluation. The obtained data and their uncertainties also demonstrate the level of our knowledge of the fission cross sections for higher acitnides.

2.2 References

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2.3 Figures

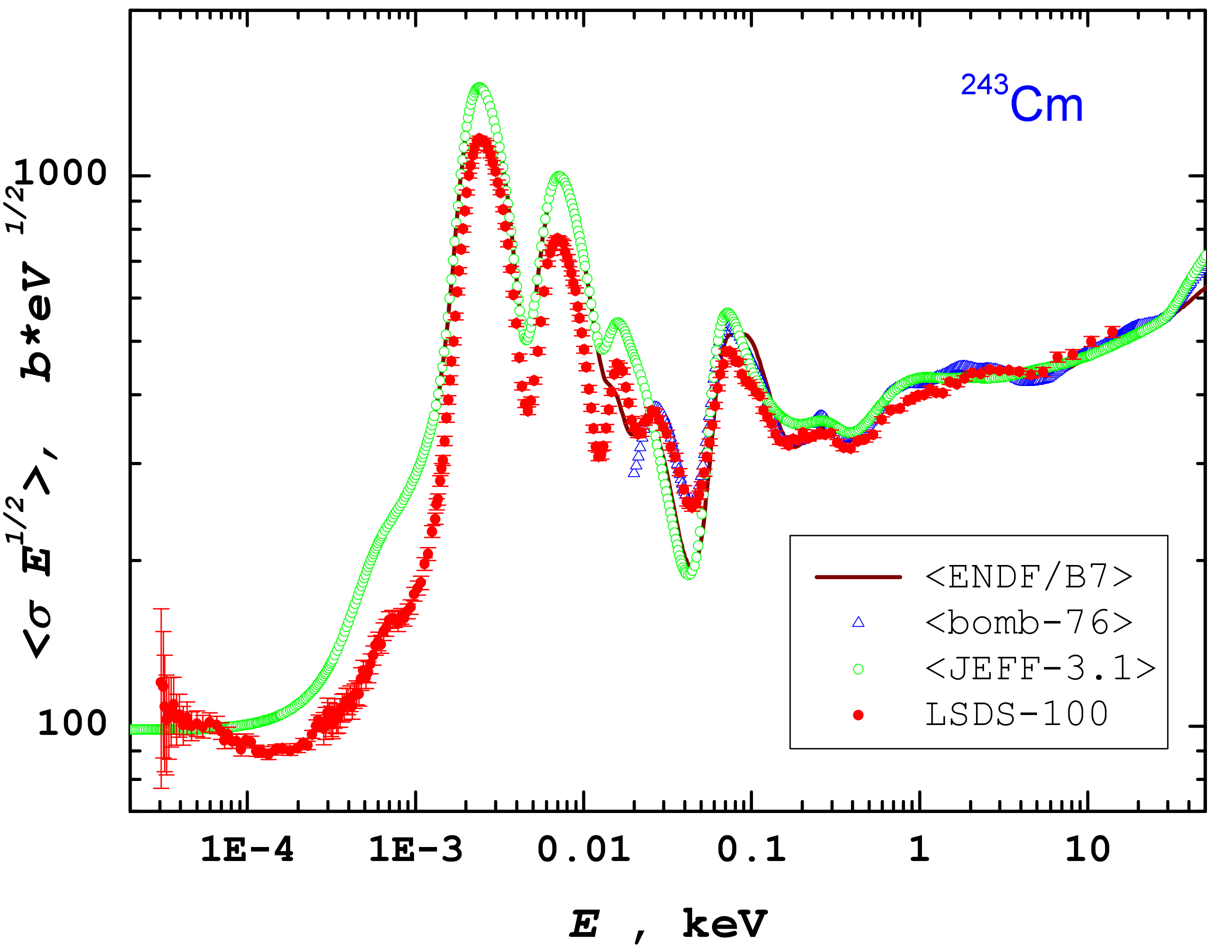

Fig. 1. Reduced fission cross section $\left\langle \sigma(E)\sqrt{E} \right\rangle$ of ^{243}Cm vs. neutron energy E. Designations:

● – LSDS-100 data [4]; (△) – "bomb" data [6]; solid line– ENDF/B-VII.0 data; (○) − JEFF–3.1 data. The "bomb" data and the recommended data are averaged on the LSDS-100 resolution function.

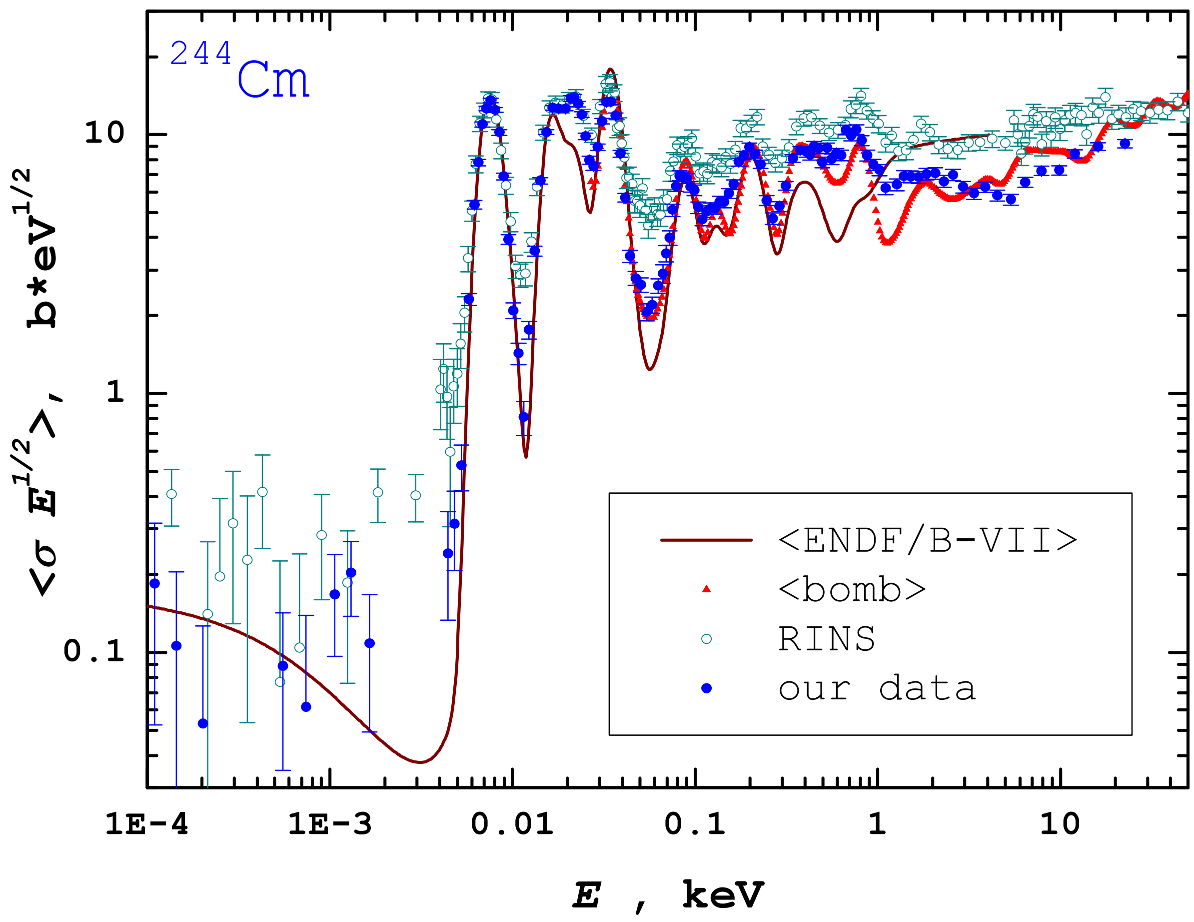

Fig. 2. Reduced fission cross section $\left\langle \sigma(E)\sqrt{E} \right\rangle$ of ^{244}Cm vs. neutron energy E. Designations:

● – LSDS-100 data [3]; ▲ – LANL data [7], ○ – RINS data [8]; solid line — – ENDF/B-VII.0 data. The LANL and the ENDF/B-VII.0 data are averaged on the LSDS-100 resolution function.

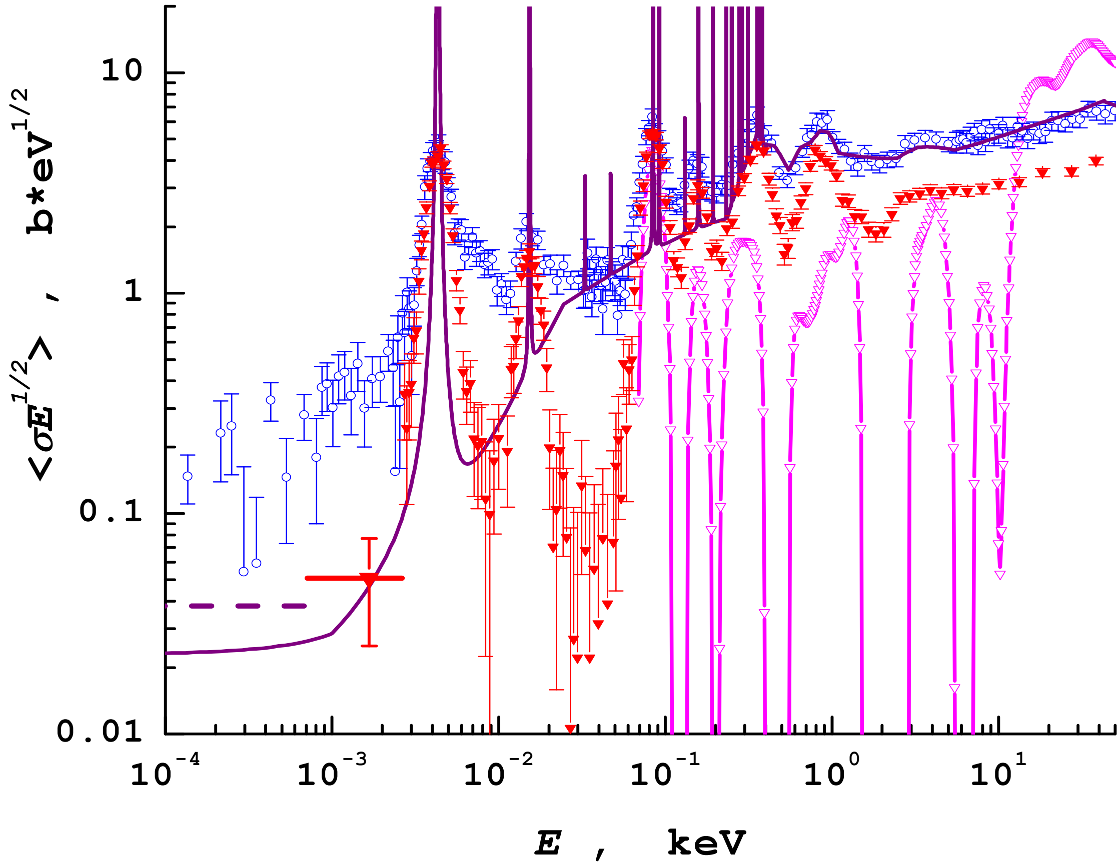

Fig. 3. Reduced fission cross section $\left\langle \sigma(E)\sqrt{E} \right\rangle$ of ^{246}Cm vs. neutron energy E. Designations: (▼) – LSDS-100 data; dash line (- -) – top 95% confidence level for our data; (○) – RINS data [8, 9]; solid line (--) – ENDF/B-VII.0 data; (▽) –LANL data [7], averaged on the Gaussian with a width *△E=0.28E*

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