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THE ABSOLUTE TOTAL DELAYED NEUTRON YIELDS, RELATIVE ABUNDANCES AND HALF-LIVES OF DELAYED NEUTRON GROUPS FROM NEUTRON INDUCED FISSION OF ^{232}Th, ^{233}U, ^{236}U, ^{239}Pu AND ^{241}Am

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ABSTRACT

The absolute total yield, relative yields and half-lives of individual delayed neutron groups produced from fast neutron-induced fission of ^{232}Th, ^{233}U, ^{236}U, ^{239}Pu and ^{241}Am are measured by performing cyclic irradiations of the sample and subsequently measuring the time dependence of the delayed neutron activity decay. The data are analysed using an iterative least-squares fitting procedure to estimate the temporary delayed neutron parameters both for the 6- and 8-group models at each incident neutron energy. The improved data contribute to the continuing effort to meet the data requirements emerging from the current trends in reactor technologies, including the growing interest in fuel recycling strategies and new concepts of actinide burners.

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The absolute total delayed neutron yields, relative abundances and half-lives of delayed neutron groups in 6- and 8-group model format from neutron induced fission of ^{232}Th, ^{233}U, ^{236}U, ^{239}Pu, and ^{241}Am in the energy range from 0.35 MeV (or threshold energy) to 5 MeV

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1. Introduction

The latest evaluation of delayed neutron constants was made for main fuel nuclides (^{235}U, ^{238}U, ^{239}Pu) within an working group under the auspices of the Nuclear Energy Agency's (NEA) Working Party on International Evaluation Cooperation (WPEC), Subgroup 6 (SG6) in 1999 [1]. As a result of this work the total delayed yields for the above nuclides were essentially corrected as compared with Tuttle's recommended data set [2]. For the total delayed yields from ^{238}U correction is +5.6%, for thermal induced fission of ^{239}Pu - +3.4%, and for fast neutron induced fission of ^{239}Pu - +3.2%. This is a direct indication that there is a need for a continuing effort on delayed neutron data improving. From now, this will be mainly directed at satisfying new requirements emerging from the current trends in reactor technology, such as: the use of high burn-up fuel, the burning of plutonium stocks and the general growing interest in fuel recycling strategies, and new concept of actinide burners.

The main objective of the present work is the measurements of absolute total yield, relative yields and half-lives of individual delayed neutron groups at fast neutrons fission of ^{232}Th, ^{233}U, ^{236}U, ^{239}Pu, and ^{241}Am. The measurements were carried out by a method based on the cyclic irradiation of the sample under study followed by the measurement of the time dependence of delayed neutron activity decay. The neutron detector represents a assembly of 30 counters SNM-11 distributed in the polyethylene moderator block possessing an external shield from the neutron background in the experimental room of accelerator. The sample is transferred from the irradiation position to the neutron detector through a pneumatic system. The time of sample transfer is about 150 ms that allows obtaining information on the most short-lived delayed neutron groups. Neutron flux was measured by ^{237}Np and ^{239}Pu fission ionization chambers. Analysis of delayed neutron decay curves for each isotope were performed using an iterative least-squares fitting procedure to estimate the temporary delayed neutron parameters both for the 6- and 8-group models at each incident-neutron energy. Measurements were performed on the proton and deuteron beam of CG-2.5 cascade generator (SSC RF–IPPE). Flux of mono-energetic neutrons was obtained from T(p,n) and D(d,n) reactions.

2. Method and experimental techniques

Experimental set-up employed in the present work was installed on the beam line of electrostatic accelerators CG-2.5 of the IPPE [3]. The main components of the set-up are shown in Fig. 1.

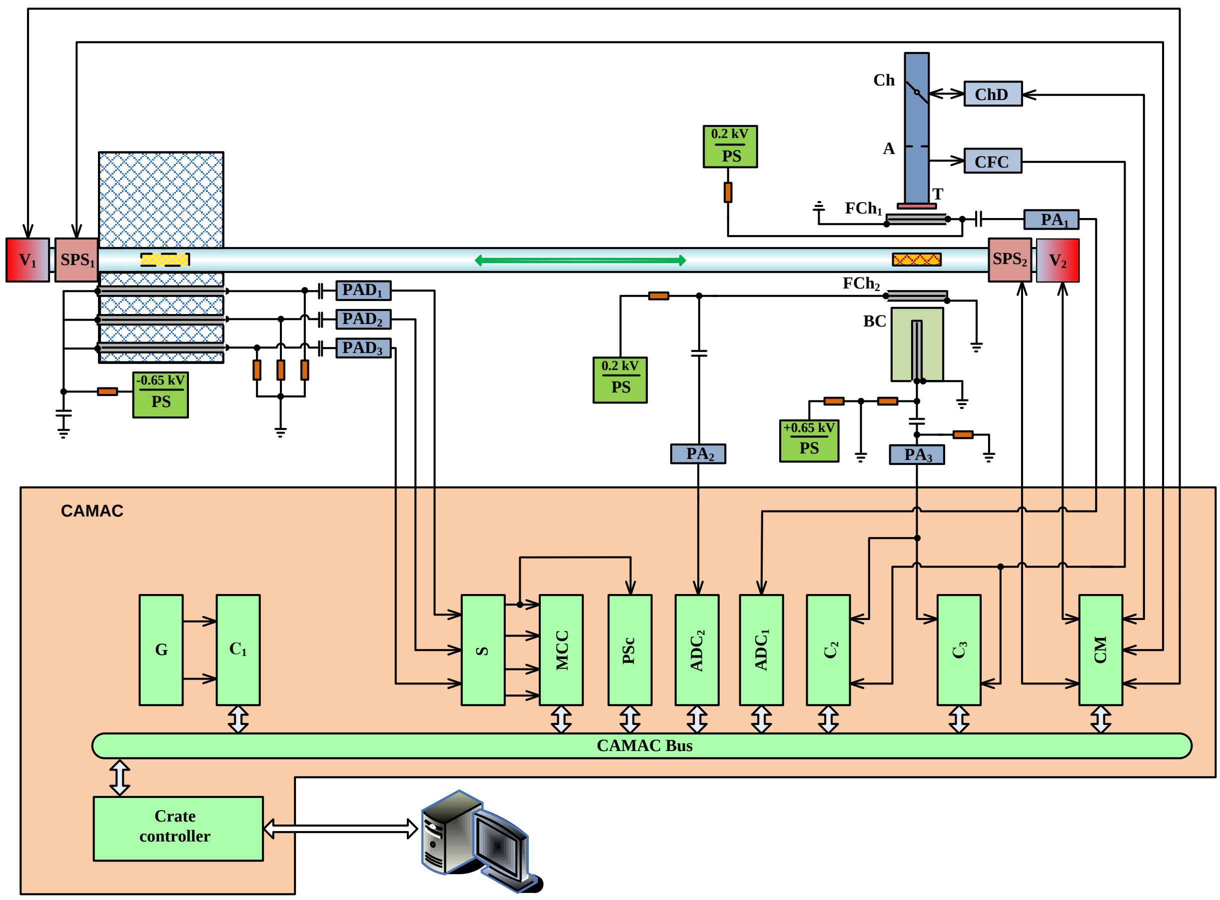

FIG. 1. Block diagram of the experimental setup: (PAD) preamplifier, amplifier, and discriminator; (S) summator; (PA) preamplifier and amplifier; (V) electromagnetic valve; (SPS) sample position sensor; (CM) controlled unit; (CFC) current-to-frequency converter; (ADC) analog-to-digital converter; (PSc) preset-scaler ; (MCC) multichannel counter; (G) quartz generator of pulses; (PS) power source; (Ch) chopper; (ChD) magnetic chopper drive; (A) ion guide aperture; (T) accelerator target; (FCh) fission chamber; (BC) boron counter of neutrons; (C1) counter with a preset exposure time; (C2) counter of total counts from the CFC and BC; and (C3) counter of the CFC and BC counts within present time intervals.

The boron counter of SNM-11 type at the operational potential of 650 V in the proportional mode of operation was chosen as the main detector counting unit. The manufactured detector is an assembly of 30 boron counters distributed in polyethylene moderator along three concentric circles with diameters of 106, 160 and 220 mm. The outer diameter of moderator is 400 mm, its length is 300 mm. In the centre of the detector there is a through hole with diameter of 36 mm to install the sample flight tube. The detector is shielded against the neutron background by borated polyethylene, boron carbide powder and cadmium sheets. The construction details of the delayed neutron detector used in the present experiment are shown in Fig. 2.

The output signals from amplifiers and pulse discriminators are fed to a mixing module. The test of the neutron detector showed that the detector is insensitive to gamma rays from ^{237}Np sample of 2 grams. The neutron detector dead time measured with a ^{252}Cf spontaneous fission neutron source is 2.3±0.2 μs. The neutron detector has a smooth efficiency response function for the energy range which is typical for the delayed neutrons. The above mentioned parameters of the detector meet the requirements in measuring the delayed neutron yields and half-lives of their precursors. Stability of neutron detector parameters and appropriate electronic modules was controlled with the help of isotopic neutron sources - Am(Li) and Pu(Li).

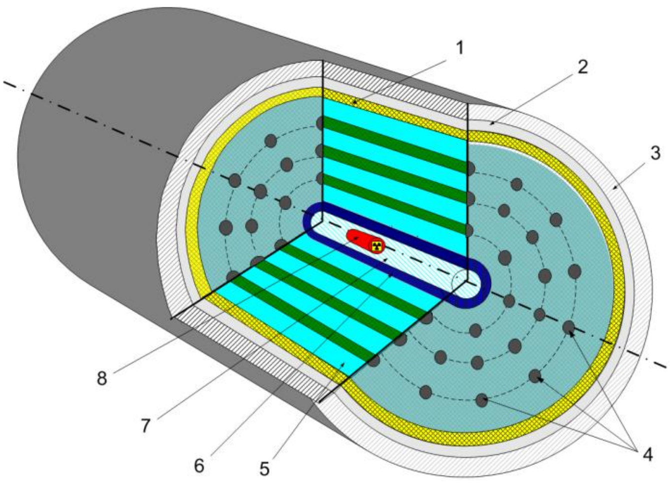

FIG. 2. 4π- neutron detector. (1- cadmium sheet, 2- boron carbide powder, 3- polyethylene contained boron carbide powder, 4- boron counters (SNM-11-type), 5- polyethylene, 6- Pb shield, 7- hole for the sample transporting system, 8- fissionable sample.)

The pneumatic transfer system is capable to transport the sample for the time short enough to measure the delayed neutron yields with the shortest half-lives. Two electromagnetic valves are responsible for the sample transportation route. The stainless steel tube with diameter of 10 mm and wall thickness of 0.3 mm serves as a pneumatic flight guide. The final position of the sample in the neutron detector is fixed by the plug with adjustable central hole which provides the excessive pressure in front of the moving sample and smooths the contact between the sample and the plug. The information on the sample location is obtained from two photodiodes and light sources installed on a flight tube at the sample irradiation position and the central point of the neutron detector. The times of sample transportation from the irradiation position to the neutron detector were from 150 to 200 ms depending on gas pressure and the weight of the samples under investigation.

The basic experimental method employed in these experiments is based on periodic irradiations of the fissionable samples in a well-defined neutron flux followed by the measurement of the time dependence of delayed neutron activity. For this purpose a tube of sample transfer system with samples under investigation was placed between two fission chambers close to tritium or deuterium accelerator targets on the beam line of the CG-2.5 accelerator (see Fig. 3).

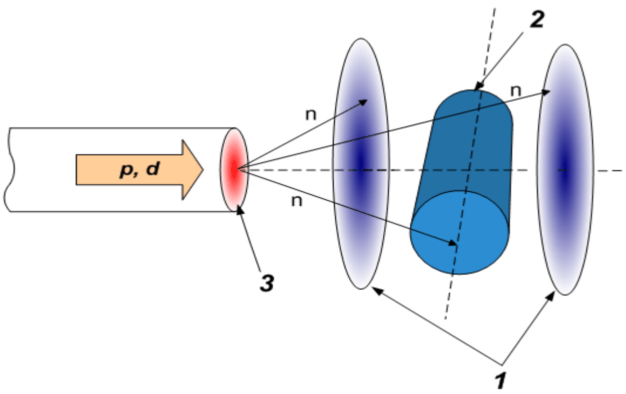

FIG. 3. The scheme of layout of an investigated sample and fissionable layers of fission chambers relatively to accelerator target. 1- ^{237}Np or ^{239}Pu fissionable layers of fission chambers, 2- fissionable sample, accelerator target on the beam line of the CG-2.5 accelerator.

The measurements included two different types of experiments. The first one consists of the measurements of the delayed neutron abundances and periods. In this type of experiments the measurements with different irradiation and delayed neutron counting time intervals were foreseen to enhance the contribution of certain delayed neutron groups in the composite delayed neutron decay curve. In the second type of experiments intended for measurements of the total delayed neutron yields the irradiation time of fissionable samples was several times longer as compared with the longest half-life of delayed neutron precursors. In both types of experiments the measurements of delayed neutron activity of a fissionable sample were made by the neutron detector placed at 3 m aside from accelerator target. The irradiation time intervals were 15, 180 and 300 s. Depending on background conditions the delayed neutron counting intervals were 424.5 and 724.5 s with the time channel sequence after the end of sample irradiation: 0.01 s (150 channels), 0.02 s (150 channels), 0.1 s (200 channels), 1 s (200 channels) and 10 s (30 or 50 channels).

The PC computer serves as a central processor controlling the irradiation and counting time, the number and width of the time channels for the delayed neutron activity measurements. The system makes it possible to measure the following parameters: pulse height distributions from two fission chambers located in front of and behind the sample at the irradiation position, time dependence of the neutron flux from the target, time dependence of the ion current on the target, the time dependence of the delayed neutron activity from the irradiated sample, pulse height distribution from ^{3}He-spectrometer, number of counts from each row of neutron detector, time delay of the sample on the irradiation position, transportation time of the sample. The personal computer controls also the operation of the pneumatic transport system and the accelerator mode switches.

2.1 Background condition of experiments

In Fig. 4 one can see the delayed neutron decay curves for all investigated nuclides accumulated in one cycle run of appropriate experiments. It can be seen from the Fig. 4 that background condition of experiments are considerably different. It worth to note that the ^{241}Am experiment was extremely difficult due to very high neutron background ~130 counts/s (three orders value higher than in common case) caused by the (α,n) reaction on oxygen which was present in the americium sample. Special experimental and computational arrangements were done to overcome these difficulties.

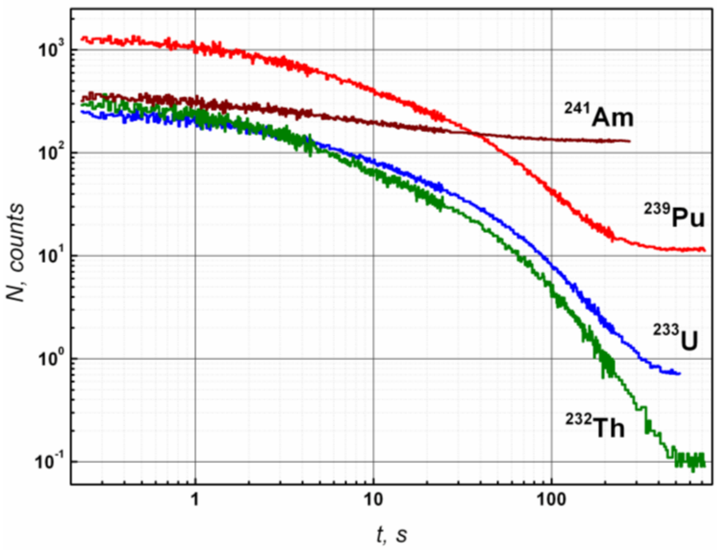

FIG. 4. Delayed neutron activity measured after the end of one cycle of irradiation of ^{233}U, ^{239}Pu, ^{232}Th and ^{241}Am samples by fast neutrons.

Experimental arrangements included the choice of optimal time intervals for irradiation and delayed neutron counting. Special attention was paid to make precise measurements of neutron background associated with neutrons from (α,n) reaction occurring in the americium sample. An example of the decay curve measured in a ^{241}Am experiment is shown in Fig. 5 and 6. In the first one the data are presented in counts per channel units. In the second one the data are transformed in counts per time units.

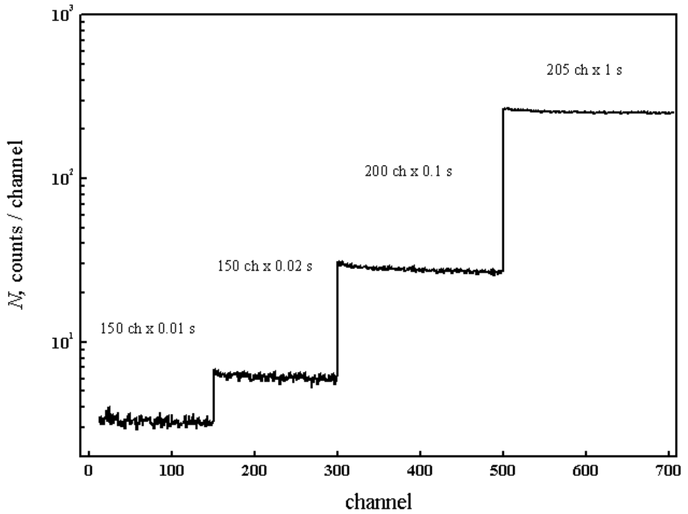

FIG. 5. Delayed neutron activity measured after irradiation of samples of ^{241}Am presented in the counts per time channel.

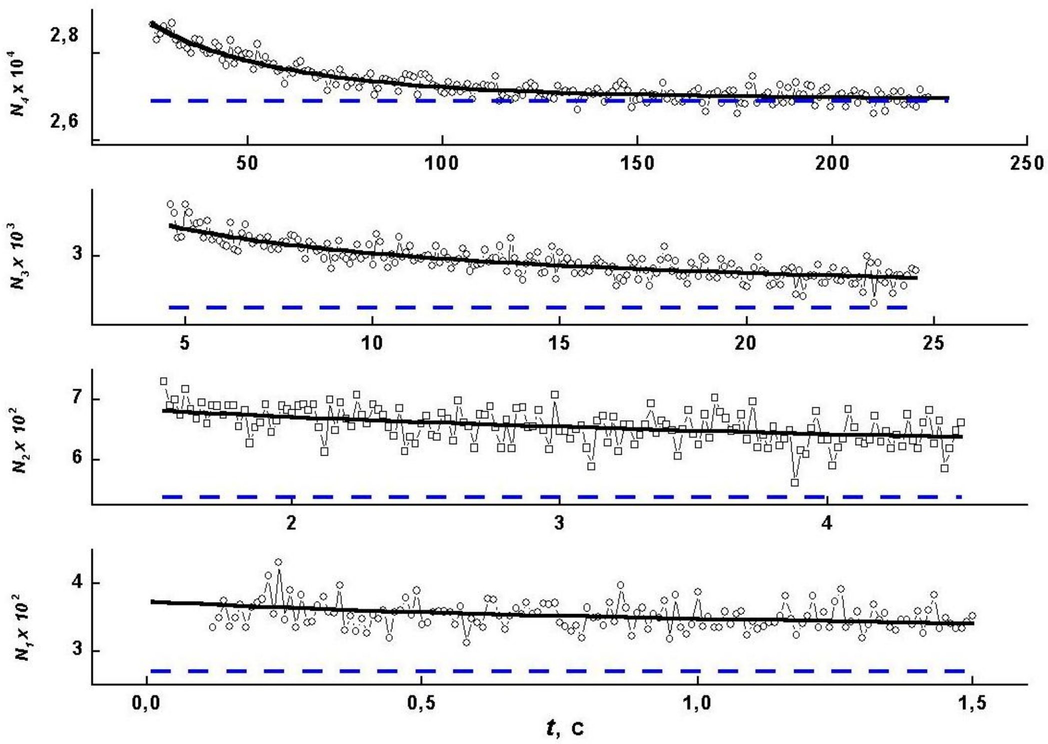

FIG. 6. Delayed neutron activity measured after irradiation of ^{241}Am samples presented in the counts per time unit. The dotted line represents the neutron background, and solid line represents the result of estimation of delayed neutron parameters.

The values of neutron background during delayed neutron counting after irradiation by neutrons from the $D(d,n)^3He$ and $T(p,n)^3He$ neutron sources are presented in Table I. Table shows that the magnitude of neutron background was different depending on the samples under investigation and parameters of specific experiment.

TABLE I. BACKGROUND CONDITIONS OF EXPERIMENTS.

	^{232}Th		^{233}U		^{239}Pu		^{241}Am		
t, s	724.5	224.5	724.5	224.5	724.5	224.5	229.5	224.5	100
$\Sigma(b) / \Sigma(N_d)$, %	1.10 - 1.84	0.35 - 0.58	5.95	2.69	30	12	95.2	95.1	41.5
b, 1 / s	0.16		0.73		11.58		129.9		

t – delayed neutron counting interval (s), b – intensity of neutron background (neutron / s), $\Sigma(N_d)$ – number of counts in appropriate time interval (724.5, 224.5 or 100 s).

2.2 Experimental results

2.2.1 Experimental results on the relative abundances and periods of delayed neutrons from fission of ^{232}Th, ^{233}U, ^{236}U, ^{239}Pu, and ^{241}Am

The general equation for the determination of the total delayed neutron yields and temporary delayed neutron characteristics (a_i, λ_i) on the basis of measured values can be represented by the following expression

$$N(t_k) = A \cdot \sum_{i=1}^{m} T_i \cdot \frac{a_i}{\lambda_i} \cdot (1 - e^{-\lambda_i \cdot \Delta t_k}) \cdot e^{-\lambda_i \cdot t_k} + B \cdot \Delta t_k \, ,$$

$$T_i = (1 - e^{-\lambda_i \cdot t_{irr}}) \cdot \left(\frac{n}{1 - e^{-\lambda_i \cdot T}} - e^{-\lambda_i \cdot T} \cdot \left(\frac{1 - e^{-n \cdot \lambda_i \cdot T}}{((1 - e^{-\lambda_i \cdot T})^2} \right) \right),$$

$$A = \varepsilon_n \, \sigma_f \, \varphi \, N_f \, \nu_d \, ,$$

where $N(t_k)$ - the number of counts registered by the neutron detector in the time-channel t_k with time-channel width Δt_k, ν_d - the total delayed neutron yield per one fission, B- the intensity of neutron background, λ_i and a_i - the decay constant and relative abundance of i -th group of DN, n - the number of cycles, m- the number of delayed neutron groups, T - the duration of one cycle of measurements, which includes the irradiation and the delayed neutron counting time, t_{irr} - irradiation time, ε_n - efficiency of neutron detector, φ - the neutron flux, σ_f - fission cross section, N_f - the number of atoms in fissionable nuclide under investigation.

After introduction of some corrections the decay curves were analysed in a 6-group approximation with the help of the iterative least-squares method [4]. Group periods and relative abundances were obtained on the basis of experimental data which were measured with different irradiation times. In the analysis of the delayed neutron time-dependence the data with long irradiation time were used to obtain the group constants for the first and second group of delayed neutrons. These data were analysed with help of the iterative least squares program for the time interval 3.0 - 721 s after the end of irradiation. Group constants for the third to the sixth groups have been obtained from the data measured in the experiment with the short irradiation time. The group constants obtained from the long-time irradiation data were fixed in the analysis of short time irradiation data.

The numerical data on the energy dependence of the relative abundances and half-lives of their precursors from fission of ^{232}Th, ^{233}U, ^{236}U, ^{239}Pu and ^{241}Am are presented in the 6-groups and 8-groups models presentation. The 6-groups data are listed in the tables below. The 8-groups model data are presented in Appendix. Data obtained in separate runs and related to definite energy of primary neutrons were averaged taking into account the matrix of correlation coefficients available for each run.

Comparison of the obtained data with corresponding data of other authors was made in terms of the average half-life of delayed neutron precursors. The average half-life of delayed neutron precursors was obtained on the basis of relative abundances and half-lives of their precursors according to formula

$$< T >= \sum_{j=1}^{6} T_j \cdot a_j$$

Dispersion of the average half-life of delayed neutron precursors was calculated taking into account the correlation properties of the group parameters as follows

$$\begin{aligned} D(< T >) = \sum_{i=1}^{6} \left[T_i^2 \cdot D(a_i) + a_i^2 \cdot D(T_i) \right] + 2 \cdot \sum_{i=1}^{5} \sum_{j=i+1}^{6} \mathrm{cov}(a_i, a_j) \cdot T_i \cdot T_j + \\ +2 \cdot \sum_{i=1}^{5} \sum_{j=i+1}^{6} \mathrm{cov}(T_i, T_j) \cdot a_i \cdot a_j + 2 \cdot \sum_{i=1}^{6} \sum_{j=1}^{6} \mathrm{cov}(a_i, T_j) \cdot T_i \cdot a_j \end{aligned},$$

where T_j – half-life value of delayed neutron precursors of *j*-th DN group averaged over separate experimental runs, a_j – relative abundance of *j*-th DN group averaged over separate experimental runs, $D(T_j)$, $D(a_j)$- dispersion of DN parameters of *j*-th DN group related to the averaged set of the data, *cov(x, y)*- covariation of *x* and *y* DN parameters.

The 8-group data for ^{233}U, ^{238}U and ^{239}Pu were obtained by the method described in [5]. The 8-group data for ^{232}Th, ^{236}U and ^{241}Am were obtained as estimation parameters in analyses of experimental decay curves by iteration least squares method [4]. Appropriate the 6-group data measured by other authors can be taken from compilation [6].

The energy dependence of the relative abundances of delayed neutrons and periods of delayed neutrons from fission of ^{232}Th by neutrons in the energy range 3.2-5.1 MeV

The energy dependence of the relative abundances and periods of delayed neutrons from fission of ^{232}Th has been obtained for the first time. Numerical data on the relative abundances and periods of delayed neutrons from fission of ^{232}Th in the energy range 3.2–5.1 MeV are presented in Table II. Relative abundances of delayed neutrons and periods of their precursors from fission of ^{232}Th analysed in terms of the average half-life of delayed neutron precursors in Fig. 7. Appropriate data in 8-group model are presented in Appendix.

TABLE II. THE ENERGY DEPENDENCE OF THE RELATIVE ABUNDANCES AND PERIODS OF DELAYED NEUTRONS FROM FISSION OF ^{232}TH IN 6-GROUPS MODEL PRESENTATION.

E_n, MeV	Group number							<*T*>, s
	i	1	2	3	4	5	6	
3.2 ± 0.2	a_i	0.0309 ± 0.0011	0.145 ± 0.005	0.147 ± 0.007	0.459 ± 0.011	0.178 ± 0.009	0.0399 ± 0.0020	6.66 ± 0.12
	T_i	55.24 ± 0.64	21.05 ± 0.34	5.51 ± 0.16	2.161 ± 0.053	0.547 ± 0.027	0.2155 ± 0.0108	
3.8 ± 0.1	a_i	0.0310 ± 0.0005	0.149 ± 0.002	0.151 ± 0.003	0.456 ± 0.005	0.174 ± 0.003	0.0393 ± 0.0008	6.78 ± 0.06
	T_i	55.19 ± 0.27	20.63 ± 0.14	5.81 ± 0.07	2.211 ± 0.022	0.592 ± 0.011	0.2143 ± 0.0043	
4.2 ± 0.2	a_i	0.0307 ± 0.0005	0.145 ± 0.002	0.153 ± 0.003	0.457 ± 0.005	0.175 ± 0.003	0.0399 ± 0.0008	6.73 ± 0.06
	T_i	54.22 ± 0.27	20.86 ± 0.15	5.952 ± 0.068	2.218 ± 0.022	0.598 ± 0.011	0.215 ± 0.004	
4.5 ± 0.2	a_i	0.0323 ± 0.0006	0.144 ± 0.003	0.149 ± 0.003	0.466 ± 0.006	0.167 ± 0.004	0.0409 ± 0.0010	6.57 ± 0.08
	T_i	53.77 ± 0.34	20.29 ± 0.19	5.539 ± 0.093	2.085 ± 0.030	0.582 ± 0.014	0.213 ± 0.005	
4.7 ± 0.2	a_i	0.0318 ± 0.0005	0.145 ± 0.003	0.157 ± 0.003	0.460 ± 0.005	0.163 ± 0.004	0.0418 ± 0.0009	6.63 ± 0.07
	T_i	54.29 ± 0.30	20.46 ± 0.16	5.53 ± 0.07	2.07 ± 0.02	.58308 .01231	0.213 ± 0.005	
4.9 ± 0.2	a_i	0.0327 ± 0.0007	0.149 ± 0.003	0.147 ± 0.004	0.471 ± 0.007	0.158 ± 0.005	0.0411 ± 0.0012	6.65 ± 0.09
	T_i	54.07 ± 0.38	19.95 ± 0.19	5.49 ± 0.09	2.09 ± 0.03	0.566 ± 0.016	0.213 ± 0.006	
5.1 ± 0.2	a_i	0.0319 ± 0.0011	0.141 ± 0.005	0.159 ± 0.007	0.446 ± 0.009	0.181 ± 0.008	0.0413 ± 0.0021	6.51 ± 0.11
	T_i	53.86 ± 0.53	20.26 ± 0.31	5.62 ± 0.13	2.10 ± 0.05	0.559 ± 0.027	0.214 ± 0.011	

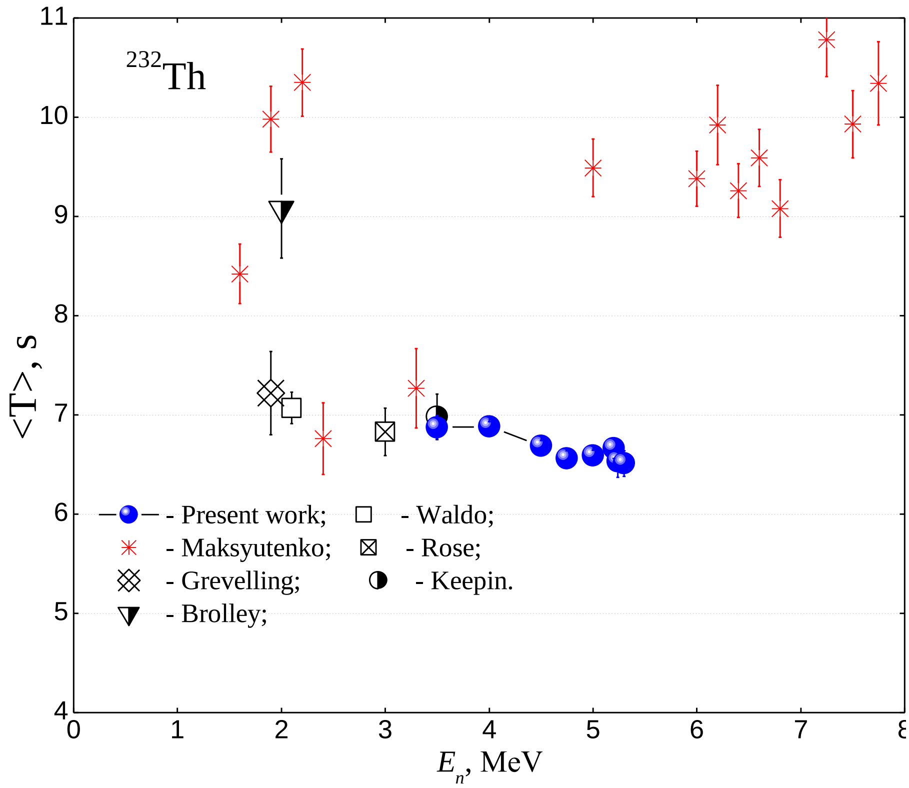

FIG. 7. The energy dependence of the average half-life of delayed neutron precursors from fission of ^{232}Th.

The analysis of the data shows that the general trend in the behaviour of the average half-life of delayed neutron precursors for ^{232}Th is similar to other studied nuclides. Namely, the average half-life of delayed neutron precursors in general decreases as the energy of primary neutrons increases.

The energy dependence of the relative abundances and periods of delayed neutrons from fission of ^{233}U by neutrons in the energy range from thermal to 4.72 MeV

Numerical data on the relative abundances and periods of delayed neutrons in 6-group model presentation from fission of ^{233}U in the energy range from thermal to 4.72 MeV are presented in Table II. Appropriate data in 8-group model are presented in Appendix. Comparison of the present data with data available from literature is made in terms of the average half-life of delayed neutron precursors in Fig. 8.

TABLE II. THE ENERGY DEPENDENCE OF RELATIVE ABUNDANCES AND PERIODS OF DELAYED NEUTRONS FROM FISSION OF ^{233}U BY NEUTRONS IN 6-GROUPS MODEL PRESENTATION.

E_n, MeV	Group number							$\langle T \rangle$, s
	i	1	2	3	4	5	6	
$2.85 \cdot 10^{-6}$	a_i	0.085 ±0.001	0.291 ±0.004	0.254 ±0.004	0.285 ±0.003	0.051 ±0.001	0.034 ±0.001	12.69 ±0.11
	T_i	54.64 ±0.20	20.77 ±0.13	5.25 ±0.05	2.143 ±0.025	0.611 ±0.013	0.276 ±0.006	
0.34 ±0.07	a_i	0.085 ±0.002	0.280 ±0.005	0.230 ±0.005	0.310 ±0.006	0.072 ±0.002	0.023 ±0.001	12.64 ±0.16
	T_i	54.62 ±0.32	21.09 ±0.19	5.58 ±0.09	2.397 ±0.050	0.543 ±0.016	0.221 ±0.006	
0.59 ±0.08	a_i	0.086 ±0.002	0.275 ±0.006	0.233 ±0.006	0.310 ±0.007	0.073 ±0.003	0.023 ±0.001	12.50 ±0.20
	T_i	54.55 ±0.39	20.92 ±0.23	5.66 ±0.10	2.308 ±0.058	0.539 ±0.019	0.221 ±0.008	
0.81 ±0.09	a_i	0.086 ±0.002	0.272 ±0.005	0.234 ±0.005	0.311 ±0.006	0.074 ±0.002	0.023 ±0.001	12.50 ±0.20
	T_i	54.84 ±0.34	21.10 ±0.19	5.62 ±0.09	2.266 ±0.048	0.542 ±0.016	0.222 ±0.006	
1.01 ±0.10	a_i	0.086 ±0.002	0.270 ±0.006	0.231 ±0.006	0.318 ±0.008	0.072 ±0.003	0.023 ±0.001	12.34 ±0.19
	T_i	54.70 ±0.38	20.88 ±0.23	5.44 ±0.10	2.253 ±0.057	0.543 ±0.019	0.222 ±0.008	
3.23 ±0.15	a_i	0.086 ±0.002	0.265 ±0.007	0.233 ±0.006	0.320 ±0.008	0.073 ±0.002	0.023 ±0.001	12.48 ±0.22
	T_i	56.50 ±0.83	21.02 ±0.29	5.33 ±0.12	2.378 ±0.060	0.546 ±0.016	0.221 ±0.006	
3.75 ±0.14	a_i	0.087 ±0.002	0.235 ±0.006	0.246 ±0.006	0.335 ±0.007	0.074 ±0.003	0.023 ±0.001	11.95 ±0.19
	T_i	55.31 ±0.46	21.15 ±0.25	5.79 ±0.09	2.181 ±0.050	0.559 ±0.029	0.222 ±0.008	
4.20 ±0.17	a_i	0.087 ±0.001	0.256 ±0.005	0.234 ±0.006	0.329 ±0.008	0.072 ±0.003	0.022 ±0.001	12.24 ±0.17
	T_i	57.36 ±0.87	20.25 ±0.29	5.16 ±0.10	2.478 ±0.063	0.550 ±0.019	0.220 ±0.008	
4.72 ±0.21	a_i	0.087 ±0.003	0.255 ±0.007	0.236 ±0.007	0.327 ±0.009	0.073 ±0.003	0.022 ±0.001	12.33 ±0.25
	T_i	56.68 ±0.90	21.05 ±0.33	5.13 ±0.14	2.470 ±0.073	0.546 ±0.019	0.221 ±0.008	

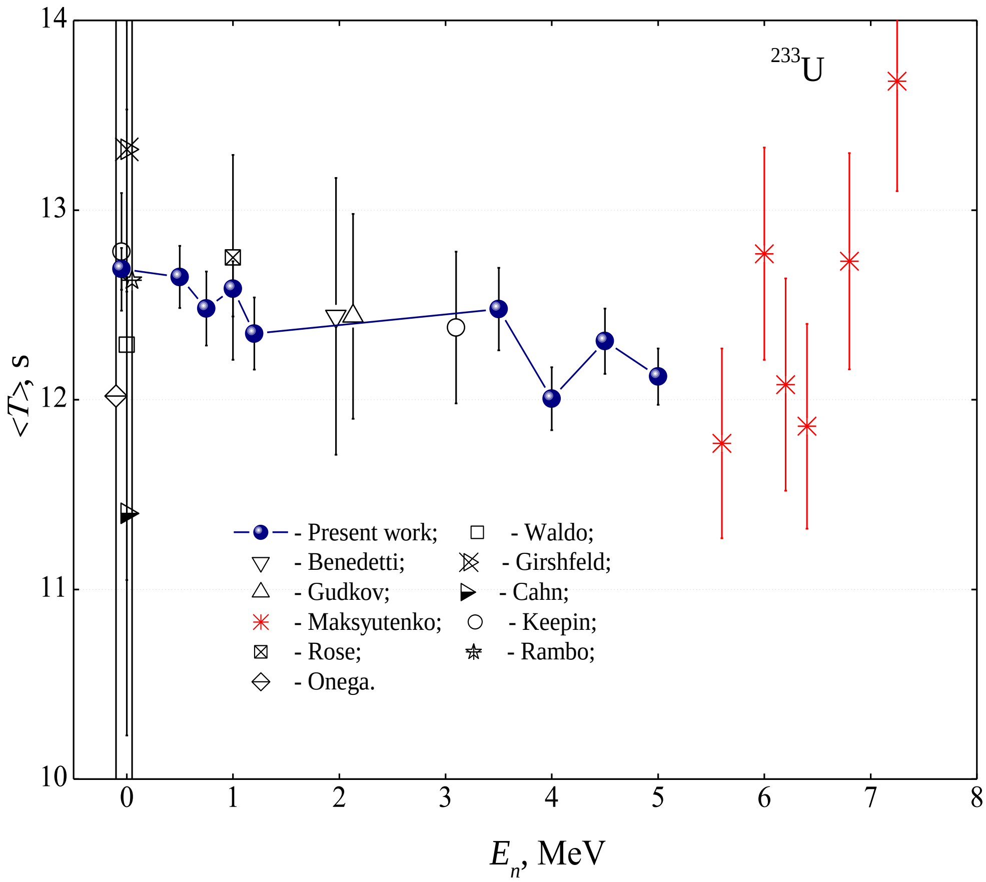

FIG. 8. The energy dependence of the average half-life of delayed neutron precursors from fission of ^{233}U.

Fig. 8 shows that the present data at thermal and fast neutrons agree within uncertainties with corresponding data by Keepin, *et al*. [7] clearly showing the general trend that the average half-life of delayed neutron precursors decreases as the excitation energy of compound nucleus increases. The decrease of the average half-life of delayed neutron precursors for ^{233}U in the energy range from $2.53 \cdot 10^{-8}$ to 4.72 MэВ is 4.5% per MeV.

The energy dependence of the relative abundances and periods of delayed neutrons from fission of ^{236}U by neutrons in the energy range 1–4.72 MeV

The energy dependence of temporary characteristics of DN from fission of ^{236}U has been obtained for the first time. Numerical data on the relative abundances and periods of delayed neutrons from fission of ^{236}U in the energy range 1-4.72 MeV in 6-group model format are presented in Table III. Comparison of the present data with data available from literature is made in terms of the average half-life of delayed neutron precursors in Fig. 9. Appropriate data in 8-group model are presented in Appendix.

TABLE III. THE ENERGY DEPENDENCE OF RELATIVE ABUNDANCES AND PERIODS OF DELAYED NEUTRONS FROM FISSION OF ^{236}U BY NEUTRONS IN 6-GROUPS MODEL PRESENTATION.

E_n, MeV	Group number							<T>, s
	i	1	2	3	4	5	6	
1.01 ±0.10	a_i	0.0249 ±0.0005	0.214 ±0.004	0.337 ±0.006	0.314 ±0.007	0.098 ±0.003	0.0121 ±0.0004	7.93 ±0.10
	T_i	54.58 ±0.37	21.68 ±0.13	4.29 ±0.05	1.425 ±0.033	0.479 ±0.014	0.214 ±0.006	
3.23 ±0.15	a_i	0.0246 ±0.0006	0.195 ±0.005	0.353 ±0.008	0.317 ±0.009	0.098 ±0.003	0.0124 ±0.0004	7.76 ±0.13
	T_i	55.43 ±0.55	22.33 ±0.22	4.29 ±0.07	1.477 ±0.045	0.477 ±0.017	0.214 ±0.008	
3.75 ±0.14	a_i	0.0255 ±0.0006	0.195 ±0.004	0.322 ±0.006	0.347 ±0.008	0.098 ±0.003	0.0125 ±0.0005	7.72 ±0.11
	T_i	55.81 ±0.38	21.92 ±0.14	4.50 ±0.05	1.495 ±0.036	0.484 ±0.017	0.214 ±0.008	
4.20 ±0.17*)	a_i	0.025 ±0.001	0.197 ±0.007	0.329 ±0.010	0.337 ±0.013	0.099 ±0.005	0.0130 ±0.0006	7.58 ±0.39
	T_i	56.68 ±0.70	21.68 ±0.29	4.22 ±0.10	1.352 ±0.056	0.484 ±0.024	0.214 ±0.011	
4.72 ±0.21	a_i	0.0260 ±0.0006	0.191 ±0.004	0.332 ±0.006	0.332 ±0.008	0.106 ±0.004	0.0130 ±0.0005	7.51 ±0.11
	T_i	55.38 ±0.42	21.60 ±0.15	4.32 ±0.05	1.404 ±0.036	0.456 ±0.016	0.215 ±0.008	

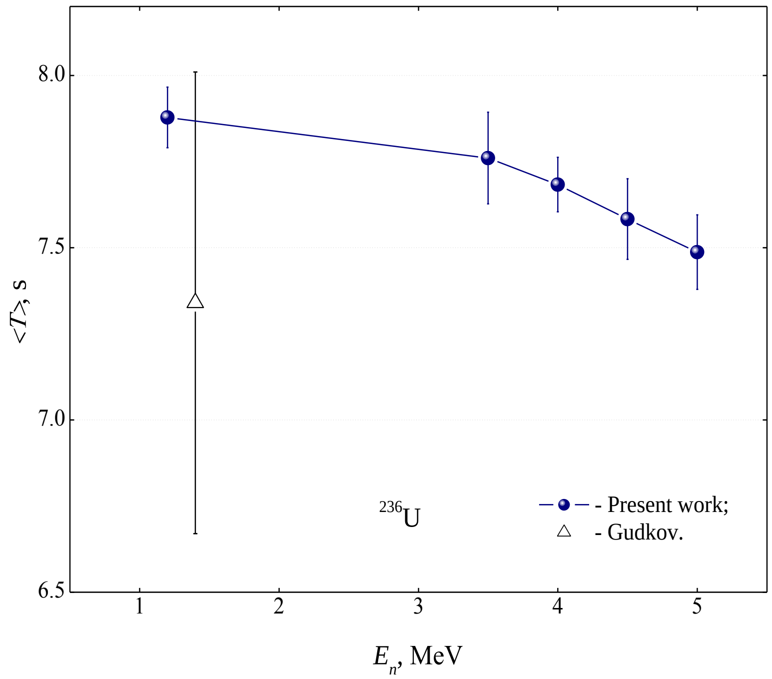

FIG. 9. The energy dependence of the average half-life of delayed neutron precursors from fission of ^{236}U.

The present <T> value agrees with appropriate data obtained by Gudkov, *et al*. (1989) [8] within quoted uncertainties. It is seen from Fig. 9 that the average half-life of delayed neutron precursors from fission ^{236}U decreases as the excitation energy of compound nucleus increases.

The energy dependence of the relative abundances and periods of delayed neutrons from fission of ^{239}Pu by neutrons in the energy range from thermal to 5 MeV

Numerical data on the relative abundances and periods of delayed neutrons in 6-groups model presentation from fission of ^{239}Pu in the energy range from thermal to 4.97 MeV are presented in Table IV. Comparison of the present data with data available from literature is made in terms of the average half-life of delayed neutron precursors in Fig. 10. Appropriate data in 8-group model format are presented in Appendix.

TABLE IV. THE ENERGY DEPENDENCE OF RELATIVE ABUNDANCES AND PERIODS OF DELAYED NEUTRONS FROM FISSION OF ^{239}PU BY NEUTRONS IN 6-GROUPS MODEL PRESENTATION.

E_n, MeV	Group number							$<T>$, s
	i	1	2	3	4	5	6	
$2.85 \cdot 10^{-6}$	a_i	0.035 ±0.001	0.302 ±0.007	0.204 ±0.005	0.332 0.006	0.084 ±0.003	0.043 ±0.002	10.59±0.17
	T_i	53.19 ±0.46	22.61 ±0.11	5.59 ±0.08	2.17 ±0.04	0.621 ±0.022	0.256 ±0.009	
0.37±0.06	a_i	0.037 ±0.001	0.295 ±0.006	0.212 ±0.005	0.319 ±0.005	0.103 ±0.003	0.034 ±0.001	10.36 ± 0.15
	T_i	52.09 ±0.41	22.34 ±0.11	5.26 ±0.07	2.06 ±0.04	0.543 ±0.015	0.218 ±0.006	
0.62±0.06	a_i	0.037 ±0.001	0.295 ±0.007	0.217 ±0.006	0.321 ±0.007	0.096 ±0.003	0.034 ±0.001	10.47 ± 0.17
	T_i	53.19 ±0.49	22.44 ±0.12	5.30 ±0.08	2.09 ±0.04	0.568 ±0.019	0.214 ±0.008	
0.86±0.06	a_i	0.037 ±0.001	0.289 ±0.005	0.216 ±0.005	0.322 ±0.005	0.102 ±0.003	0.034 ±0.001	10.27 ± 0.13
	T_i	53.81 ±0.41	22.19 ±0.10	5.25 ±0.07	2.06 ±0.03	0.547 ±0.016	0.217 ±0.006	
1.06±0.06	a_i	0.038 ±0.001	0.292 ±0.004	0.214 ±0.004	0.320 ±0.004	0.101 ±0.002	0.035 ±0.001	10.37 ± 0.11
	T_i	53.51 ±0.33	22.23 ±0.09	5.11 ±0.05	2.15 ±0.03	0.555 ±0.012	0.215 ±0.005	
3.27±0.14	a_i	0.038 ±0.001	0.271 ±0.007	0.220 ±0.006	0.332 ±0.008	0.104 ±0.003	0.035 ±0.001	10.06 ± 0.19
	T_i	55.29 ±1.45	22.23 ±0.29	5.11 ±0.13	2.16 ±0.06	0.547 ±0.016	0.216 ±0.006	
3.81±0.11	a_i	0.038 ±0.001	0.247 ±0.004	0.227 ±0.004	0.348 ±0.005	0.105 ±0.002	0.035 ±0.001	9.68 ± 0.11
	T_i	56.19 ±0.53	22.51 ±0.14	5.22 ±0.07	2.09 ±0.03	0.552 ±0.012	0.217 ±0.005	
4.27±0.11	a_i	0.038 ±0.001	0.243 ±0.005	0.230 ±0.005	0.348 ±0.006	0.106 ±0.003	0.035 ±0.001	9.65 ± 0.14
	T_i	56.68 ±0.65	22.49 ±0.18	5.31 ±0.08	2.10 ±0.04	0.554 ±0.016	0.217 ±0.006	
4.81±0.13	a_i	0.039 ±0.001	0.238 ±0.004	0.228 ±0.004	0.355 ±0.005	0.105 ±0.003	0.035 ±0.001	9.62 ± 0.11
	T_i	57.49 ±0.49	22.54 ±0.14	5.32 ±0.07	2.10 ±0.03	0.554 ±0.014	0.217 ±0.005	
4.97±0.13	a_i	0.039 ±0.001	0.243 ±0.006	0.232 ±0.006	0.341 ±0.008	0.109 ±0.004	0.036 ±0.001	9.59 ± 0.16
	T_i	58.17 ±0.65	22.04 ±0.19	4.92 ±0.09	2.17 ±0.05	0.553 ±0.019	0.217 ±0.008	

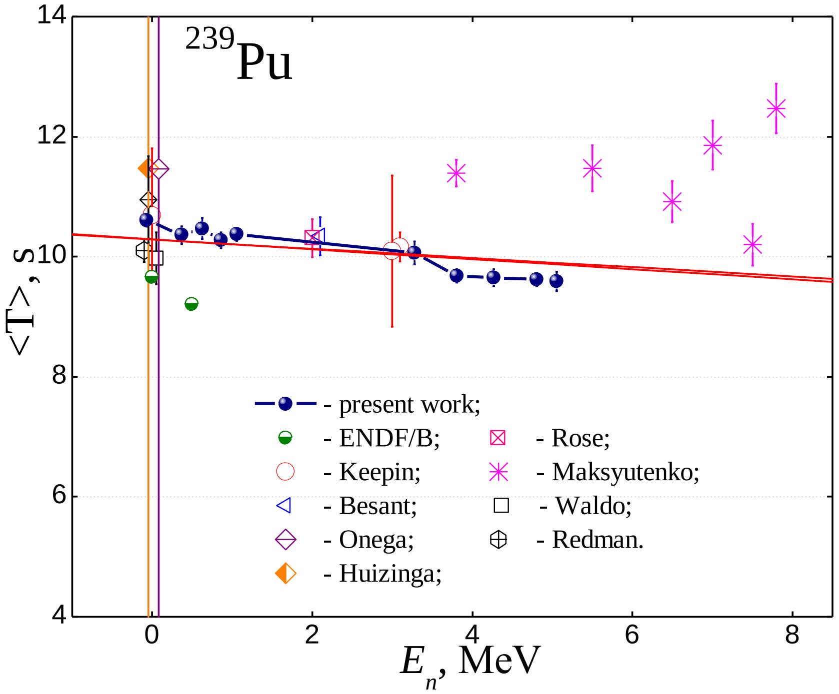

FIG. 10. The energy dependence of the average half-life of delayed neutron precursors from fission of ^{239}Pu in the energy range from thermal to 4.97 MeV.

Fig. 10 shows that the present low energy results on temporary DN characteristics of ^{239}Pu agree with the experimental data by Keepin, *et al*. [7]. However it should be noted that present data have the smaller uncertainties than that given in [7]. In the neutron energy higher than 3 MeV there is large disagreement between the present data and the data by Maksyutenko, *et al*. [9] (the only available data in this energy range). The overall decrease of the average half-life of delayed neutron precursors for ^{239}Pu in the energy range $2.53 \cdot 10^{-8}$–4.97 MэВ is 10.6 %. As an example in the Table V a correlation matrix is shown for the neutron energy 0.37 MeV.

TABLE V. CORRELATIONS MATRIX OF DELAYED NEUTRON GROUP PARAMETERS RELATED TO 0.37 MEV NEUTRON INDUCED FISSION OF ^{239}PU.

	a_1	T_1	a_2	T_2	a_3	T_3	a_4	T_4	a_5	T_5	a_6	T_6
a_1	1,0											
T_1	0,0	1,0										
a_2	0,0	0,77	1,0									
T_2	0,0	-0,18	0,09	1,0								
a_3	0,0	0,26	0,41	0,33	1,0							
T_3	0,0	-0,13	-0,16	0,65	-0,22	1,0						
a_4	0,0	0,43	0,6	0,45	-0,07	0,51	1,0					
T_4	0,0	0,08	0,14	0,01	-0,46	0,0	0,12	1,0				
a_5	0,0	0,08	0,11	0,06	0,02	0,03	-0,05	0,19	1,0			
T_5	0,0	0,04	0,06	0,05	0,01	0,05	-0,07	0,09	0,0	1,0		
a_6	0,0	0,01	0,02	0,01	0,0	0,0	0,0	0,03	-0,01	0,0	1,0	
T_6	0,0	0,01	0,02	0,01	0,0	0,0	0,0	0,04	-0,01	0,0	0,0	1,0

The energy dependence of the relative abundances and periods of delayed neutrons from fission of ^{241}Am by neutrons in the energy range 0.62–4.97 MeV

The energy dependence of DN relative abundances and periods of their precursors from fission of ^{241}Am has been obtained for the first time. Numerical data on the relative abundances and periods of delayed neutrons from fission of ^{241}Am are presented in Table VI. Comparison of the present data with data available from literature is made in terms of the average half-life of delayed neutron precursors in Fig. 11.

TABLE VI. THE ENERGY DEPENDENCE OF RELATIVE ABUNDANCES AND PERIODS OF DELAYED NEUTRONS FROM FISSION OF ^{241}AM IN 6-GROUPS MODEL PRESENTATION.

E_n, MeV	Group number							$<T>$, s
	i	1	2	3	4	5	6	
0.62 ± 0.06	a_i	0.0434±0.001	0.264 ±0.008	0.201 ±0.006	0.317 ±0.009	0.152 ±0.005	0.0229 ±0.0007	10.2 ± 0.6
	T_i	54.3±1.6	21.94 ±0.66	6.08 ±0.18	2.24 ±0.07	0.496 ±0.015	0.179 ±0.005	
0.86 ± 0.06	a_i	0.0432±0.0005	0.271±0.003	0.199±0.002	0.314±0.004	0.151±0.002	0.0228±0.0003	10.4 ± 0.1
	T_i	53.97±0.61	22.61±0.25	6.08±0.07	2.24±0.03	0.498±0.006	0.179±0.002	
0.96 ± 0.06	a_i	0.0436±0.0007	0.284±0.005	0.199±0.003	0.302±0.005	0.148±0.003	0.0229±0.0004	11.1 ± 0.2
	T_i	53.99±0.93	23.51±0.39	6.27±0.11	2.279±0.039	0.494±0.009	0.179±0.003	
1.06 ± 0.06	a_i	0.0436±0.0009	0.276±0.006	0.202±0.004	0.308±0.006	0.148±0.003	0.0228±0.0005	10.9 ± 0.2
	T_i	54.0±1.1	23.92±0.45	6.13±0.12	2.31±0.05	0.49±0.01	0.179±0.004	
3.27 ± 0.14	a_i	0.0434±0.0009	0.272±0.006	0.199±0.004	0.312±0.007	0.150±0.003	0.0229±0.0005	10.8 ± 0.2
	T_i	54.5±1.1	23.47±0.49	6.10±0.13	2.26±0.05	0.496±0.011	0.179±0.004	
3.81 ± 0.11	a_i	0.0433±0.0007	0.251±0.004	0.201±0.003	0.329±0.005	0.153±0.003	0.0228±0.0004	9.7 ± 0.1
	T_i	54.47±0.93	21.28±0.31	5.85±0.09	2.23±0.04	0.503±0.009	0.179±0.003	
4.27 ± 0.11	a_i	0.0433±0.0009	0.266±0.006	0.202±0.004	0.317±0.006	0.149±0.003	0.0228±0.0005	10.2 ± 0.2
	T_i	54.4±1.2	21.75±0.41	5.99±0.12	2.30±0.05	0.49±0.01	0.179±0.004	
4.97 ± 0.13	a_i	0.043±0.001	0.237±0.007	0.202±0.006	0.336±0.008	0.159±0.005	0.0229±0.0007	9.7 ± 0.5
	T_i	56.5±1.7	22.19±0.39	5.69±0.15	2.18±0.05	0.502±0.015	0.180±0.005	

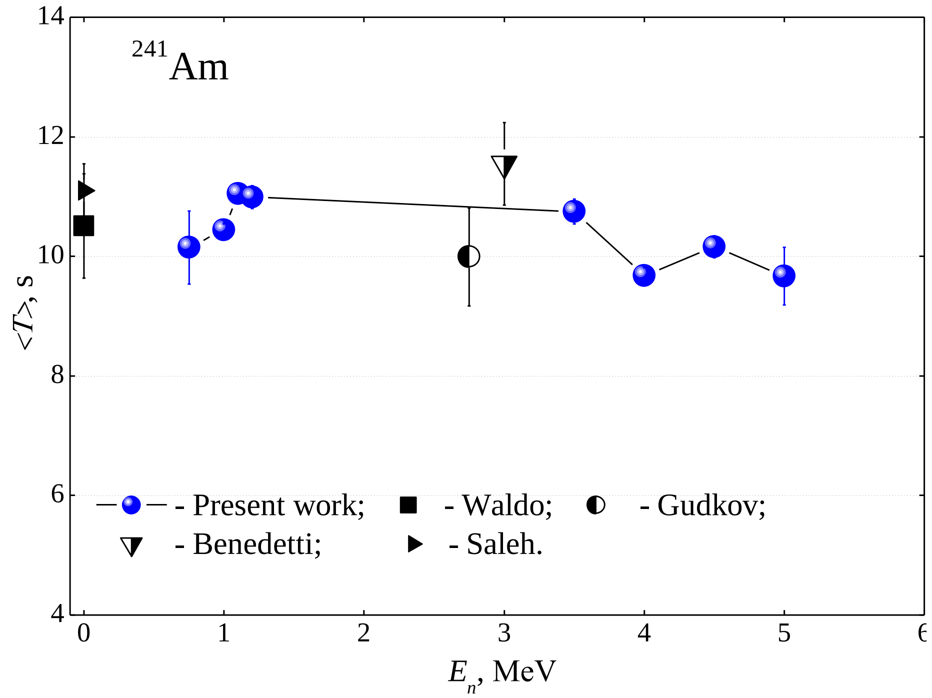

FIG. 11. The energy dependence of the average half-life of delayed neutron precursors from fission of ^{241}Am.

Comparison of delayed neutron parameters (a_i, T_i) obtained in this work with the relevant data from other authors was carried out in terms of the average half-life of delayed neutron precursors. Fig. 11 shows that the behavior of the average half-life of delayed neutron precursors in fission ^{241}Am in the range of 1-5 MeV is similar to the behavior of this quantity in fission of other nuclei (^{238}U, ^{239}Pu, ^{233}U, etc.) – the average half-life $<T>$ decreases with increasing excitation energy of fissioning nucleus. A specific feature of the energy dependence of the temporal parameters of delayed neutrons in fission ^{241}Am is a sharp increase in the average half-life of delayed neutron precursors near the threshold of fission reaction (0.5-1 MeV) up to a maximum value at the first plateau of fission cross-section. The effect of increasing $<T>$ at the threshold of fission cross section found in fission ^{241}Am is not observed in case of other threshold nuclides. Moreover, in case of ^{237}Np one can observe the opposite effect - the increase of the average half-life of delayed neutron precursors with decreasing excitation energy of compound nucleus [10].

2.2.2 Results on the energy dependence of the total delayed neutron yield from fission of ^{232}Th, ^{233}U, ^{236}U, ^{239}Pu, ^{241}Am

In the present work two methods for calculation of the total delayed yields were used both based on the main expression used for modelling the time dependent intensity of delayed neutrons from a sample after its irradiation in a well-defined flux of mono-energetic neutrons. In the first method the sum of delayed neutron counts registered in the time interval (t_1 - t_2) and temporary parameters (a_i, T_i) of delayed neutrons obtained during the analysis of delayed neutron curves were used

$$\nu_d = \frac{\left[\sum_{t_1}^{t_2} N(t_k) - B(t_2 - t_1)\right]}{<\varepsilon_n> \cdot R_s \cdot \sum_{i=1}^{6}\left[T_i \cdot \frac{a_i}{\lambda_i} \cdot \left(e^{-\lambda_i \cdot t_1} - e^{-\lambda_i \cdot t_2}\right)\right]},$$

$$T_i = (1 - e^{-\lambda_i \cdot t_{irr}}) \cdot \left(\frac{n}{1 - e^{-\lambda_i \cdot T}} - e^{-\lambda_i \cdot T} \cdot \left(\frac{1 - e^{-n \cdot \lambda_i \cdot T}}{((1 - e^{-\lambda_i \cdot T})^2}\right)\right),$$

where $N(t_k)$ - the number of counts registered by the neutron detector in the time-channel t_k with time-channel width Δt_k, ν_d - the total delayed neutron yield per one fission, $B(t_k)$ - the intensity of neutron background in the time channel t_k, λ_i and a_i - the decay constant and relative abundance of i -th group of delayed neutron, n - the number of cycles, T - the duration of one cycle of measurements, which includes the irradiation and delayed neutron counting time, t_{ir} - irradiation time, $<\varepsilon_n>$ - efficiency of neutron detector, φ - the neutron flux, σ_f - fission cross section, N_s - the number of atoms in fissionable nuclide under investigation, N_{ch}- the number of atoms in fissile layer of the fission chamber, N_c - number of counts per channel of the pulse height distribution registered by fission chamber monitor.

In the second method (known as "extrapolation to zero") the information on the saturation activity A of delayed neutrons obtained during analysis of the appropriate delayed neutron curves is used

$$\nu_d = \frac{A}{<\varepsilon_n> \cdot R_s},$$

It was expected that the concurrent utilization of the two methods for obtaining the total delayed yields will serve as a test for consistency of experimental data that in one's turn should improve reliability of the final data on delayed neutron yields. Uncertainties of the relative total delayed neutron yields include the uncertainties of delayed neutron abundance and period values, error of the sample under investigation and fission chamber positions relatively to the neutron target in the run to run measurements, uncertainties of fission rate calculations, and statistical uncertainties. It was assumed that there was no energy dependent systematic error in the calculation of fission rate ratio value for the sample and fission layer. Main contribution to the total uncertainties is from the uncertainties of abundances and periods of delayed neutrons (1.8-2%).

As can be seen from the above expression in both methods one needs to have information on the efficiency of neutron detector $<\varepsilon_n>$ and fission rates $R_s(E_n)= N_s<\sigma\varphi>_s$ in the sample under investigation. The $<\varepsilon_n>$ value has been measured in a special experiment and it is the characteristic of the neutron detector only, whereas the value $R_s(E_n)$ characterizes experiment as a whole and depends on many factors (geometry of experiment, mass of a sample and its sizes and configuration, features of a neutron source etc.). Therefore from the methodical point of view the most complicated task is to determine the value of $R_s(E_n)$ at different energies of incident neutrons.

The fission rate in the sample R_s can be represented in simplified form by the following expression

$$R_s = N_s \int\int \varphi_s(E_n,\theta,\phi) \cdot \sigma_s(E_n) dE_n dV_s \ ,$$

where N_s - number of atoms in the fissionable sample, $\varphi_s(E_n,\theta,\phi)$ - absolute neutron flux from the target, dV_s - elemental volume of the sample, E_n – energy of neutrons emitted in direction of radius vector $\boldsymbol{r}(\theta,\phi)$.

Information about absolute value of the neutron flux $\varphi_s(E_n,\theta,\phi)$ was obtained on the basis of the number of counts in the fission chamber monitors ΣN_c registered during irradiation time interval t_{irr} in all cycles of measurement

$$\frac{\sum N_c}{t_{irr}} = N_{ch} \int\int \varphi_{ch}(E_n,\theta,\phi) \cdot \sigma(E_n) dE_n dV_{ch},$$

where N_{ch} - the number of ^{237}Np or ^{239}Pu atoms in the fission chamber deposits, dV_{ch} – an elemental volume of the fission chamber deposit. The final expression for the fission rate in the sample can be written in the following simplified form

$$R_s = \frac{N_s \cdot \sum N_c \int\int \varphi_s(E_n,\theta,\phi)\sigma(E_n) dE_n dV_s}{N_{ch} \cdot t_{irr} \int\int \phi_r(E_n,\theta,\varphi)\sigma(E_n) dE_n dV_{ch}} = \frac{\sum N_c \cdot N_s \cdot <\sigma\varphi>_s}{N_{ch} \cdot t_{irr} \cdot <\sigma\varphi>_{ch}}.$$

Fission rate ratio $<\sigma\varphi>_s/<\sigma\varphi>_{ch}$ calculated per one nuclide has been obtained with the help of the Monte Carlo method. Detailed approach used in the determination of fission rates in the fissionable samples is described in [11].

The energy dependence of the total delayed neutron yield from fission of ^{232}Th by neutrons in the energy range 3.2–5.1 MeV

The energy dependence of the total delayed neutron yields from fission of ^{232}Th by neutrons in the energy range 3.2–5.1 MeV was obtained for the first time. Obtained results in numerical form are presented in Table VII. In Fig. 12 these data are compared with appropriate data which are available from literature. In addition in Fig. 12 there is the energy dependence of the total delayed neutron yield obtained on the basis of the systematic relation $\ln[\nu_d(E_n)] = a + b(\ln\langle T(E_n)\rangle)$ [12]. It is seen from Fig. 12 that ν_d in the energy range 3.2–5.1 MeV has no energy dependence within quoted uncertainties.

TABLE VII. THE TOTAL DELAYED NEUTRON YIELD FROM FISSION OF ^{232}TH BY NEUTRONS IN THE ENERGY RANGE 3.2–5.1 MEV.

E_n, MeV	Total DN yields ν_d, neutron/fission	References
1,45	0.054 ± 0,0041	Cox (1970) –experiment (Averaged value)
2,4	0,0571 ± 0,0051 2)	Maksyutenko (1959)
3,0	0,0568 ± 0,0145 2)	Brunson et al..(1955)
3,0	0,0375 ± 0,0090 2)	Rose (1957)
3,1	0,0566 ± 0,0042 2)	Masters (1969)
3,2	0,0579 ± 0,0023	Present work
3,3	0,0534 ± 0,0048	Maksyutenko (1959)
3,5	0,0505 ± 0,0052 2) 0,0496 ± 0,0020 1)	Keepin (1957)
3,8	0,0572 ± 0,0024	Present work
4,2	0,0550 ± 0,0042	Present work
4,5	0,0557 ± 0,0063	Present work
4,7	0,0543 ± 0,0031	Present work
4,9	0,0568 ± 0,0032	Present work
Fast neutrons	0,0527 ± 0,004	Waldo (1981)
3,1	0,0531 ± 0,0023	Tuttle (1979)-evaluation
Fast neutrons	0,0564 ± 0,0041	Brady (1989)-summation
Fast neutrons	0,0607 ± 0,0035	Blashot (1997)-summation
Fast neutrons	0,06321	Wilson (2002)-summation
Fast neutrons	0,0561	Mills (1991)-summation
Fast neutrons	0.0515±0.0031	Manevich (1988)-summation
0 – 4	0,0547	ENDF/B-VII
0 – 4	0,0527	JEFF-3.1
0 – 3	0,0531	JENDL3.3

1)- original value ν_d; 2) – adjusted value (recalibration).

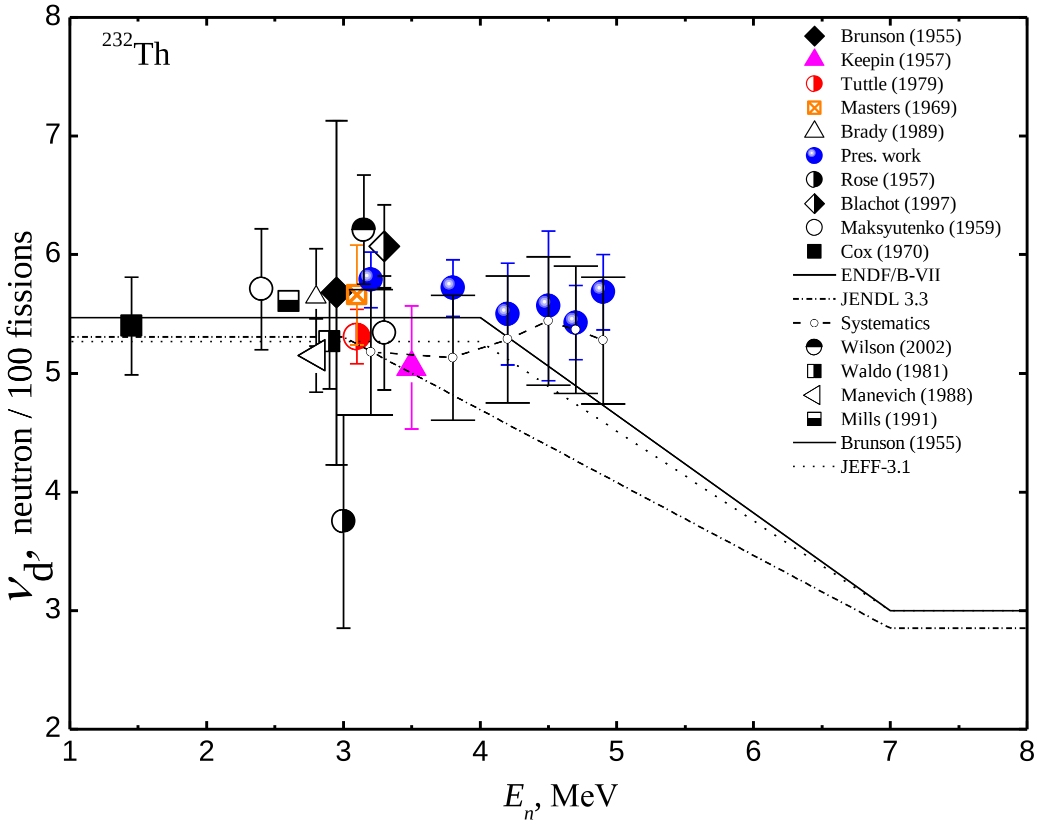

Fig. 12. The energy dependence of the total delayed neutron yield from fission of ^{232}Th by neutrons in the energy range 3.2–5.1 MeV. Dash line –systematics ln[$\nu_d(E_n)$]= a + b(ln<T(E_n)>) [12].

According to the present data in the energy range 3.2–5.1 MeV there is no evidence for the energy dependence of the total delayed neutron yields within the data uncertainties.

The energy dependence of the total delayed neutron yield from fission of ^{233}U by neutrons in the energy range 0.34–4.90 MeV

Numerical data on the total delayed neutron yield from fission of ^{233}U by neutrons in the energy range 0.34–4.9 MeV are presented in Table VIII. The energy dependence of the total delayed neutron yield from fission of ^{233}U is presented in Fig. 13 together with appropriate data available from literature and systematic ln[$\nu_d(E_n)$]= a + b(ln<T(E_n)>).

TABLE VIII. THE TOTAL DELAYED NEUTRON YIELDS FROM FISSION OF ^{233}U BY NEUTRONS IN THE ENERGY RANGE 0.34–4.9 MEV.

E_n, MeV	Total DN yields, neutron/100 fissions.
0.34 ± 0.07	0.746 ± 0.037
0.59 ± 0.08	0.748 ± 0.037
0.81 ± 0.09	0.746 ± 0.035
1.01 ± 0.10	0.744 ± 0.037
3.23 ± 0.15	0.794 ± 0.039
3.75 ± 0.14	0.804 ± 0.040
4.20 ± 0.17	0.760 ± 0.038
4.72 ± 0.21	0.69 ± 0.03
4.90 ± 0.21	0.668 ± 0.033

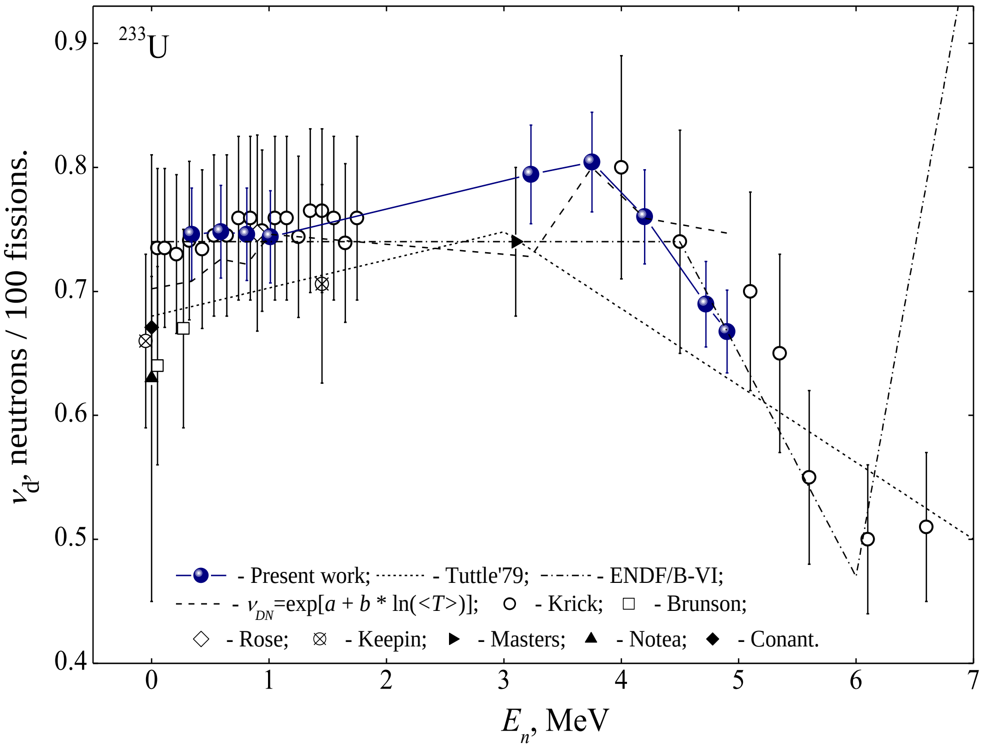

Fig. 13. The energy dependence of the total delayed neutron yield from fission of ^{233}U.

Fig. 13 shows that the obtained data on the energy dependence of the total delayed neutron yields are in agreement with corresponding data by Krick (1972) [13], measured by an independent method. In the energy range 0.34–1.01 MeV ν_d is constant within uncertainties. In the energy range 1.01–3.75 MeV there is an increase of 8% ($d\nu_d/\nu_d$) in ν_d. Above 3.75 MeV there is a decrease in ν_d. Thus the obtained results clearly confirm that the decrease of the total delayed neutron yield from fission ^{233}U starts at the neutron energy below the threshold of the (n, n′f) reaction.

The energy dependence of the total delayed neutron yield from fission of ^{236}U by neutrons in the energy range 1.01–4.72 MeV

The energy dependence of the total delayed neutron yield from fission of ^{236}U by neutrons has been measured for the first time. Numerical data are presented in Table VIII. The energy dependence of the total delayed neutron yield from fission of ^{236}U is presented in Fig. 14 together with appropriate data available from literature and systematic.

TABLE IX. THE TOTAL DELAYED NEUTRON YIELDS FROM FISSION OF ^{236}U BY NEUTRONS IN THE ENERGY RANGE 1.01–4.72 MEV.

E_n, MeV	Total DN yields, neutron/100 fissions.
1.01 ± 0.10	2.18 ± 0.22
3.23 ± 0.15	2.33 ± 0.12
3.75 ± 0.14	2.32 ± 0.12
4.20 ± 0.17	2.18 ± 0.11
4.72 ± 0.21	2.20 ± 0.11

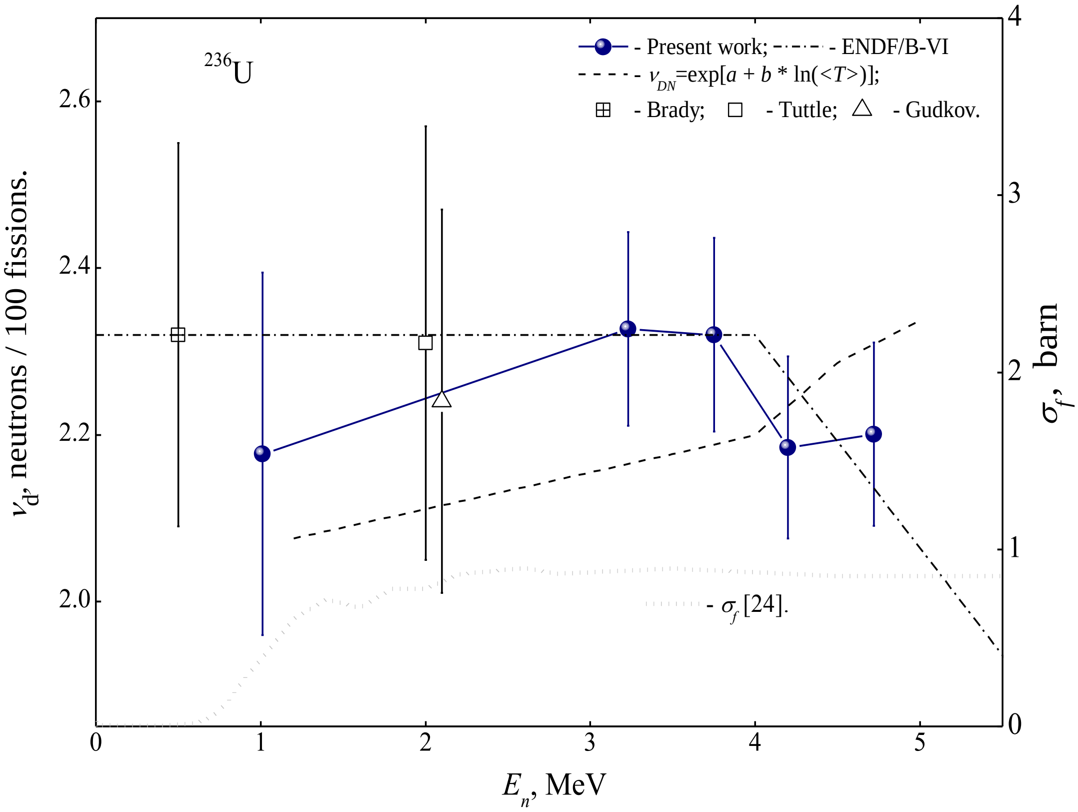

Fig. 14. The energy dependence of the total delayed neutron yield from fission of ^{236}U (dotted line - the fission cross section of ^{236}U, dash line – systematics $ln[\nu_d(E_n)] = a + b(ln<T(E_n)>$ [12]).

The energy dependence of the total delayed neutron yield from fission of ^{239}Pu by neutrons in the energy range 0.34–4.9 MeV

The energy dependence of the total delayed neutron yield from fission of ^{239}Pu by neutrons is presented in Table IX and Fig. 15 together with appropriate data available from literature and systematic results.

TABLE IX. THE TOTAL DELAYED NEUTRON YIELDS FROM FISSION OF ^{239}PU BY NEUTRONS IN THE ENERGY RANGE 0.34–4.72 MEV.

E_n, MeV	Total DN yields, neutron/100 fissions.
0.34 ± 0.07	0.651 ± 0.020
0.59 ± 0.08	0.645 ± 0.009
0.81 ± 0.09	0.643 ± 0.001
1.01 ± 0.10	0.656 ± 0.014
3.23 ± 0.15	0.712 ± 0.033
3.75 ± 0.14	0.704 ± 0.017
4.20 ± 0.17	0.689 ± 0.017
4.72 ± 0.21	0.668 ± 0.019
4.90 ± 0.21	0.608 ± 0.009

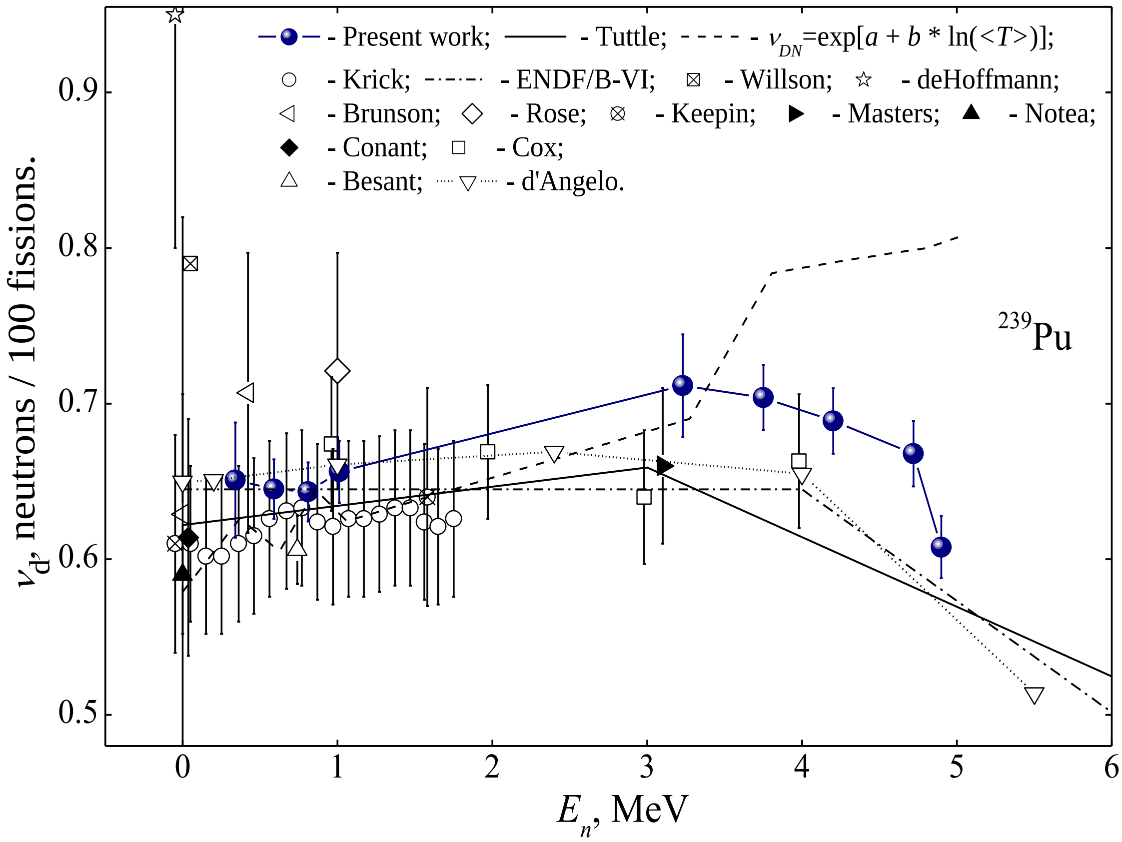

Fig. 15. The energy dependence of the total delayed neutron yield from fission of ^{239}Pu.
Dash line –systematics $ln[\nu_d(E_n)] = a + b(ln<T(E_n)>)$ [12].

According to the present data in the energy range 0.34–1.01 MeV there is no evidence for the energy dependence of the total delayed neutron yields within the data uncertainties. This observation can be considered as a confirmation of the latest evaluation results. In the energy range 1.1–3.2 MeV the total delayed neutron yield increases as neutron energy of primary neutrons increases. Above 3.5 MeV point the total delayed neutron yield steadily decreases. The rate of increase of ν_d in the energy range from 1 up to 3.2 MeV is 2.43 x 10^{-4} neutrons/MeV ($d\nu_d/\nu_d$ ~8%).

The energy dependence of the total delayed neutron yield from fission of ^{241}Am in the energy range 0.86–4.85 MeV

The energy dependence of the total delayed neutron yield from fission of ^{241}Am by neutrons has been measured for the first time. Preliminary numerical data are presented in Table X. The energy dependence of the total delayed neutron yield from fission of ^{241}Am is presented in Fig. 16 together with appropriate data available from literature and systematics.

TABLE X. THE TOTAL DELAYED NEUTRON YIELDS FROM FISSION OF ^{241}AM BY NEUTRONS IN THE ENERGY RANGE 0.86– 4.85 MEV.

E_n, MeV	Total DN yields, neutron/100 fissions.
0.86	0.330 ± 0.050
0.96	0.360± 0.054
1.01	0.460 ± 0.069
3.85	0.490 ± 0.074
4.85	0.540 ± 0.082

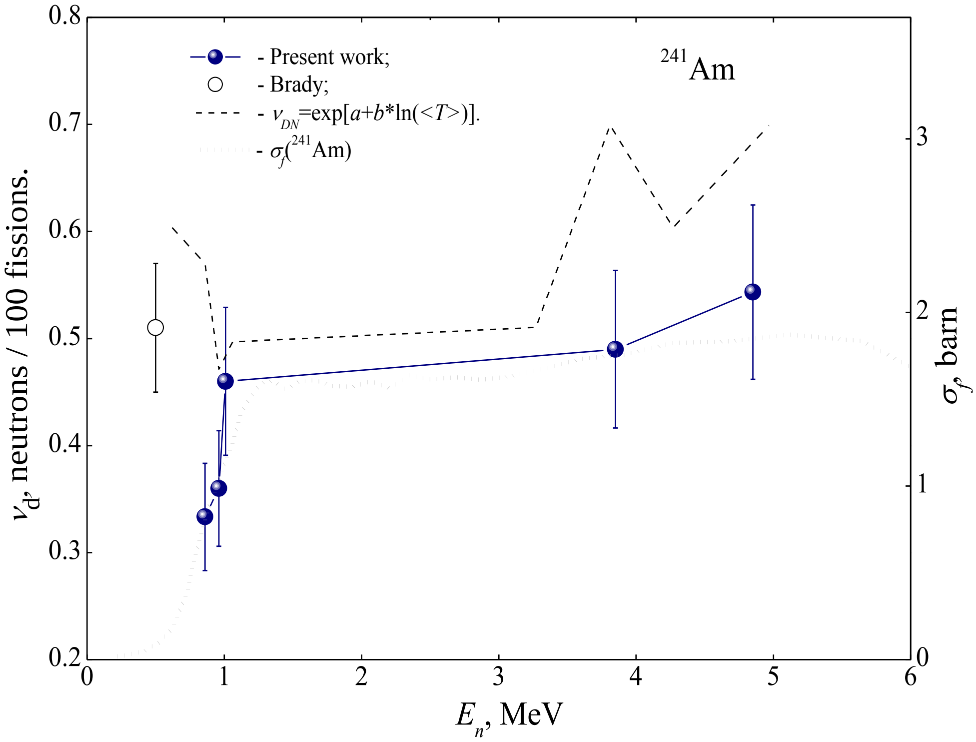

Fig. 16. The energy dependence of the total delayed neutron yield from fission of ^{241}Am. Dash line –systematics $ln[\nu_d(E_n)] = a + b(ln\langle T(E_n)\rangle)$ [12].

From analysis of the data made in terms of average half-life of delayed precursors it should be noted that the behaviour of the average half-life of delayed neutron precursors have irregularities in the vicinity of the fission reaction threshold. In contrast to other nuclide studied the average half-life of delayed neutron precursors of ^{241}Am (n,f) reaction is increases as the energy of primary neutrons increases at the threshold of the reaction and then, above the threshold, one can see a common behaviour of the <T> value - decrease of the average half-life up to 5 MeV energy point.

Conclusion

As a result of the work made on the processing of the experimental information gathered in the above experiments the following characteristics of delayed neutron have been obtained:

- the energy dependence of the relative abundances and periods of delayed neutrons in 6-groups model presentation from fission of ^{232}Th in the energy range 3.2-5.1 MeV;
- the energy dependences of the relative abundances and periods of delayed neutrons in 6- and 8- groups model presentation from fission of ^{233}U in the energy range from thermal to 4.72 MeV;
- the energy dependence of the relative abundances and periods of delayed neutrons in 6- and 8- groups model presentation from fission of ^{236}U in the energy range 1.01-4.72 MeV;
- the energy dependences of the relative abundances and periods of delayed neutrons in 6- and 8- group model presentation from fission of ^{239}Pu in the energy range from thermal to 4.97 MeV;
- the energy dependence of the relative abundances and periods of delayed neutrons in 6-model presentation from fission of ^{241}Am in the energy range 0.62-4.97 MeV;
- the energy dependence of the total delayed neutron yields from fission of ^{232}Th in the energy range 3.2–5.1 MeV;
- the energy dependence of the total delayed neutron yields from fission of ^{233}U in the energy range 0.34–4.90 MeV.

- the energy dependence of the total delayed neutron yields from fission of ^{236}U in the energy range 1.01–4.72 MeV;
- the energy dependence of the total delayed neutron yields from fission of ^{239}Pu in the energy range 0.34–4.90 MeV;
- preliminary data on the energy dependence of the total delayed neutron yields from fission of ^{241}Am in the energy range 0.86–4.85 MeV.

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TABLE I. THE ENERGY DEPENDENCE OF RELATIVE ABUNDANCES AND PERIODS OF DELAYED NEUTRONS FROM FISSION OF ^{239}PU IN 8-GROUPS MODEL PRESENTATION.

$\langle E_n \rangle$, MэВ	Half-life,s								$\langle T \rangle$, s.
	55.6	24.3	16.3	5.21	2.37	1.04	0.424	0.195	
	Group number								
	1	2	3	4	5	6	7	8	
2.85□10^{-6}	0.029 ± 0.001	0.240 ± 0.008	0.083 ± 0.004	0.188 ± 0.007	0.289 ± 0.010	0.089 ± 0.004	0.059 ± 0.003	0.023 ± 0.001	10.63 ± 0.22
0.37 ± 0.06	0.028 ± 0.001	0.236 ± 0.008	0.078 ± 0.003	0.182 ± 0.007	0.284 ± 0.010	0.097 ± 0.005	0.071 ± 0.004	0.024 ± 0.001	10.37 ± 0.21
0.62 ± 0.06	0.030 ± 0.001	0.231 ± 0.008	0.083 ± 0.004	0.184 ± 0.007	0.294 ± 0.010	0.088 ± 0.004	0.068 ± 0.003	0.022 ± 0.001	10.46 ± 0.22
0.86 ± 0.06	0.032 ± 0.001	0.212 ± 0.007	0.097 ± 0.004	0.173 ± 0.007	0.300 ± 0.010	0.088 ± 0.004	0.076 ± 0.004	0.022 ± 0.001	10.29 ± 0.20
1.06 ± 0.06	0.032 ± 0.001	0.220 ± 0.008	0.089 ± 0.004	0.172 ± 0.007	0.322 ± 0.010	0.061 ± 0.003	0.084 ± 0.004	0.020 ± 0.001	10.38 ± 0.22
3.27 ± 0.14	0.036 ± 0.001	0.190 ± 0.007	0.099 ± 0.004	0.167 ± 0.007	0.346 ± 0.011	0.051 ± 0.003	0.093 ± 0.005	0.018 ± 0.001	10.06 ± 0.20
3.81 ± 0.11	0.038 ± 0.001	0.173 ± 0.006	0.090 ± 0.004	0.175 ± 0.007	0.339 ± 0.010	0.082 ± 0.004	0.078 ± 0.004	0.025 ± 0.001	9.66 ± 0.18
4.27 ± 0.11	0.039 ± 0.001	0.164 ± 0.006	0.097 ± 0.004	0.179 ± 0.007	0.336 ± 0.010	0.080 ± 0.004	0.082 ± 0.004	0.023 ± 0.001	9.62 ± 0.18
4.81 ± 0.13	0.042 ± 0.002	0.154 ± 0.006	0.102 ± 0.004	0.172 ± 0.007	0.348 ± 0.011	0.078 ± 0.004	0.083 ± 0.004	0.021 ± 0.001	9.61 ± 0.20
4.97 ± 0.13	0.043 ± 0.002	0.138 ± 0.005	0.122 ± 0.004	0.146 ± 0.006	0.399 ± 0.011	0.030 ± 0.002	0.110 ± 0.005	0.012 ± 0.001	9.55 ± 0.18

TABLE II. THE ENERGY DEPENDENCE OF RELATIVE ABUNDANCES OF DELAYED NEUTRONS FROM FISSION OF ^{236}U IN 8-GROUPS MODEL PRESENTATION.

$<E_n>$, MeV	Half-life, s								$<T>$, s.
	55.6	24.3	16.3	5.21	2.37	1.04	0.424	0.195	
	Group number								
	1	2	3	4	5	6	7	8	
1.01 ± 0.10	0.0218 ±0.0009	0.143 ±0.006	0.079 ± 0.003	0.196 ± 0.007	0.287 ± 0.009	0.200 ± 0.009	0.049 ± 0.002	0.023 ± 0.001	7.94 ± 0.16
3.23 ± 0.15	0.0229 ± 0.0009	0.144 ± 0.005	0.055 ± 0.003	0.209 ± 0.007	0.309 ± 0.010	0.185 ± 0.008	0.049 ± 0.002	0.024 ± 0.001	7.75 ± 0.15
3.75 ± 0.14	0.0244 ± 0.0009	0.12872 ± 0.005	0.075 ± 0.003	0.201 ± 0.007	0.291 ± 0.009	0.215 ± 0.009	0.042 ± 0.002	0.023 ± 0.001	7.72 ± 0.15
4.20 ± 0.17	0.0249 ± 0.0009	0.120 ± 0.005	0.083 ± 0.003	0.175 ± 0.007	0.291 ± 0.009	0.223 ± 0.009	0.058 ± 0.003	0.025 ± 0.001	7.56 ± 0.15
4.72 ± 0.21	0.0242 ± 0.0009	0.122 ± 0.005	0.077 ± 0.003	0.191 ± 0.007	0.295 ± 0.009	0.195 ± 0.009	0.080 ± 0.004	0.0173 ± 0.0009	7.50 ± 0.15

TABLE III. THE ENERGY DEPENDENCE OF RELATIVE ABUNDANCES OF DELAYED NEUTRONS FROM FISSION OF ^{233}U IN 8-GROUPS MODEL PRESENTATION.

$<E_n>$, MeV	Half-life, s								$<T>$, s.
	55.6	24.3	16.3	5.21	2.37	1.04	0.424	0.195	
	Group number								
	1	2	3	4	5	6	7	8	
2.85×10^{-6}	0.078 ± 0.003	0.164 ±0.006	0.150 ±0.005	0.209 ±0.008	0.287 ±0.009	0.046 ±0.002	0.048 ±0.002	0.0173 ± 0.0009	12.65 ± 0.23
0.34 ± 0.07	0.078 ± 0.003	0.169 ± 0.006	0.135 ± 0.005	0.224 ± 0.008	0.296 ± 0.009	0.0176 ± 0.0009	0.070 ±0.003	0.0101 ± 0.0005	12.62 ± 0.23
0.59 ± 0.08	0.079 ± 0.003	0.159 ± 0.006	0.143 ± 0.005	0.219 ± 0.008	0.291 ± 0.009	0.026 ± 0.001	0.073 ± 0.004	0.0092 ± 0.0005	12.52 ± 0.23
0.81 ± 0.09	0.081 ± 0.003	0.159 ± 0.006	0.139 ± 0.005	0.214 ± 0.008	0.293 ± 0.009	0.034 ± 0.002	0.071 ± 0.004	0.0089 ±0.0005	12.52 ± 0.23
1.01 ± 0.10	0.079 ± 0.003	0.155 ± 0.006	0.139 ± 0.005	0.205 ± 0.007	0.310 ± 0.009	0.035 ± 0.002	0.068 ± 0.003	0.0088 ± 0.0004	12.37 ± 0.23
3.23 ± 0.15	0.088 ± 0.003	0.127 ± 0.005	0.158 ± 0.005	0.199 ± 0.007	0.330 ± 0.010	0.019 ± 0.001	0.064 ± 0.003	0.0104 ±0.0005	12.48 ± 0.25
3.75 ± 0.14	0.084 ± 0.003	0.128 ± 0.005	0.135 ± 0.005	0.223 ± 0.008	0.298 ± 0.009	0.057 ± 0.003	0.066 ± 0.003	0.0085 ±0.0004	11.98 ± 0.23
4.20 ± 0.17	0.093 ± 0.004	0.085 ± 0.004	0.188 ± 0.005	0.196 ± 0.007	0.357 ± 0.010	0.0125 ± 0.0006	0.05± 0.003	0.0118 ±0.0006	12.24 ± 0.27
4.72 ± 0.21	0.090 ± 0.004	0.122 ± 0.005	0.149 ± 0.005	0.202 ± 0.008	0.356 ± 0.010	0.0117 ±0.0006	0.056 ± 0.003	0.0116 ±0.0006	12.39 ± 0.25

TABLE IV. THE ENERGY DEPENDENCE OF RELATIVE ABUNDANCES OF DELAYED NEUTRONS FROM FISSION OF ^{232}TH IN 8-GROUPS MODEL PRESENTATION.

E_n, *MeV*	Group number and half-life, s								Average half-life,s	
	1 55.6	2 24.5	3 16.3	4 5.21	5 2.37	6 1.04	7 0.424	8 0.195	8 group	6 group
3.2 ±0.2	0.029 ±0.001	0.078 ±0.003	0.081 ±0.003	0.121 ±0.005	0.406 ±0.010	0.133 ±0.006	0.115 ±0.005	0.036 ±0.002	6.65 ±0.12	6.66 ±0.12
3.8 ±0.1	0.029 ±0.001	0.713 ±0.003	0.095 ±0.003	0.136 ±0.006	0.394 ±0.010	0.142 ±0.007	0.099 ±0.005	0.033 ±0.001	6.77 ±0.12	6.78 ±0.06
4.2 ±0.2	0.027 ±0.001	0.079 ±0.003	0.085 ±0.003	0.148 ±0.006	0.382 ±0.010	0.150 ±0.007	0.097 ±0.004	0.032 ±0.001	6.72 ±0.12	6.73 ±0.06
4.5 ±0.2	0.028 ±0.001	0.073 ±0.003	0.087 ±0.003	0.123 ±0.005	0.390 ±0.010	0.177 ±0.008	0.090 ±0.004	0.031 ±0.001	6.58 ±0.12	6.57 ±0.08
4.7 ±0.2	0.029 ±0.001	0.073 ±0.003	0.089 ±0.003	0.128 ±0.005	0.384 ±0.010	0.178 ±0.008	0.087 ±0.004	0.031 ±0.001	6.64 ±0.12	6.63 ±0.07
4.9 ±0.2	0.029 ±0.001	0.068 ±0.003	0.098 ±0.003	0.118 ±0.005	0.404 ±0.010	0.161 ±0.007	0.089 ±0.004	0.033 ±0.001	6.66 ±0.12	6.65 ±0.11

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