QUASI-EQUILIBRIUM ENERGY SPECTRA OF DELAYED NEUTRONS FOR EPITHERMAL NEUTRON-INDUCED FISSION OF ^{235}U

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Abstract

In this work, delayed neutron spectra from epithermal neutron induced fission of ^{235}U was measured in different time intervals 0.12-1, 1-2, 2-3, 3-4, 4-44 s with irradiation time 20 s. The comparison of the composite delayed neutron spectra obtained in present work with relative abundances of the 8-group model for ^{235}U shows, that composite spectra obtained in the in the first time window (0.12-1 s) after the end of irradiation is the most close to equilibrium spectrum and can be considered as near-equilibrium or quasi-equilibrium.

Introduction

The phenomenon of emission of delayed neutrons (DN) that accompanies the process of fission of heavy nuclei is of considerable interest from the point of view of many fundamental aspects of nuclear physics, astrophysics, and the process of nuclear fission. The energy spectrum of delayed neutrons from fission of heavy nuclei is of great importance for calculation of the effective delayed neutron fractions. At present, there are two sources of information on the delayed neutron spectra – experimental data on the aggregate delayed neutron spectrum and experimental and theoretical data on delayed neutron spectra from individual precursors. In frame of so-called “microscopic approach” the delayed neutron spectra from individual precursors are used for calculating the group and composite spectra by summing the contributions from individual precursors. Some of the delayed neutron spectra for important precursors are not available and therefore experimental data should be supplemented by nuclear model calculations.

The purpose of this work is measurements of composite delayed neutron spectra in different time intervals after the end of irradiation of ^{235}U sample by epithermal neutron.

Experimental technique

Measurements of the energy spectra of delayed neutrons in the fission of ^{235}U nuclei by epithermal neutrons were carried out at the facility, established on the basis of electrostatic accelerator KG-2.5 IPPE. The main components of the set-up are shown in Fig. 1.

Measurements have been performed by the method of cyclic irradiation of ^{235}U sample by epithermal neutrons followed by delayed neutron counting with ^{3}He-spectrometer. Neutron source was based on utilization of the T(p,n)^{3}He reaction on the solid tritium target of the IPPE electrostatic accelerator CG-2.5. For production of epithermal neutron flux the accelerator target was surrounded by a polyethylene cube of 27 cm. The ^{235}U metallic sample was placed in the horizontal hole of the cube. During irradiation, the sample was located about 3.2 cm from the neutron target. Transport of the sample from the irradiation position to the ^{3}He-spectrometer was accomplished by a fast pneumatic system.

Sample transport tube is a thin-walled stainless steel tube with an outer diameter 10 and a wall thickness of 0.3 mm. Two solenoid valve controls the supply of compressed air in the guide tube. The position of the sample in the neutron detector was fixed with a plug with a hole in the center for controlling the discharge of excess pressure in front of a moving sample and mitigate the impact of the sample.

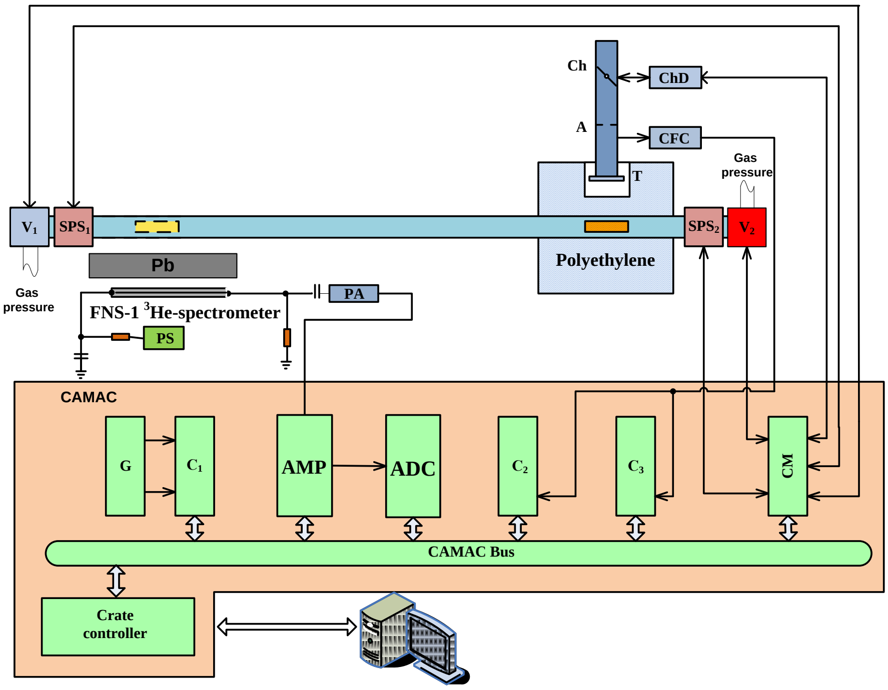


Fig. 1. Block diagram of the experimental setup: (PAD) preamplifier, amplifier, and discriminator; (S) summator; (PA) preamplifier; (V) electromagnetic valve; (SPS) sample position sensor; (CM) control unit; (CFC) current-to-frequency converter; (ADC) analog-to-digital converter; (PSc) preset-scaler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

Information on the status of the sample was obtained from the two photodiodes and light sources mounted on the guide tube in position in the center of irradiation and neutron spectrometer. On the average, the sample delivery time was 120 ms that is short enough to get information related to the shortest precursors groups.

Measurements of delayed neutron spectra were made in the time intervals 0.12-1, 1-2, 2-3, 3-4, and 4-44 s with irradiation time 20 s. Measured spectra are presented in fig. 2.

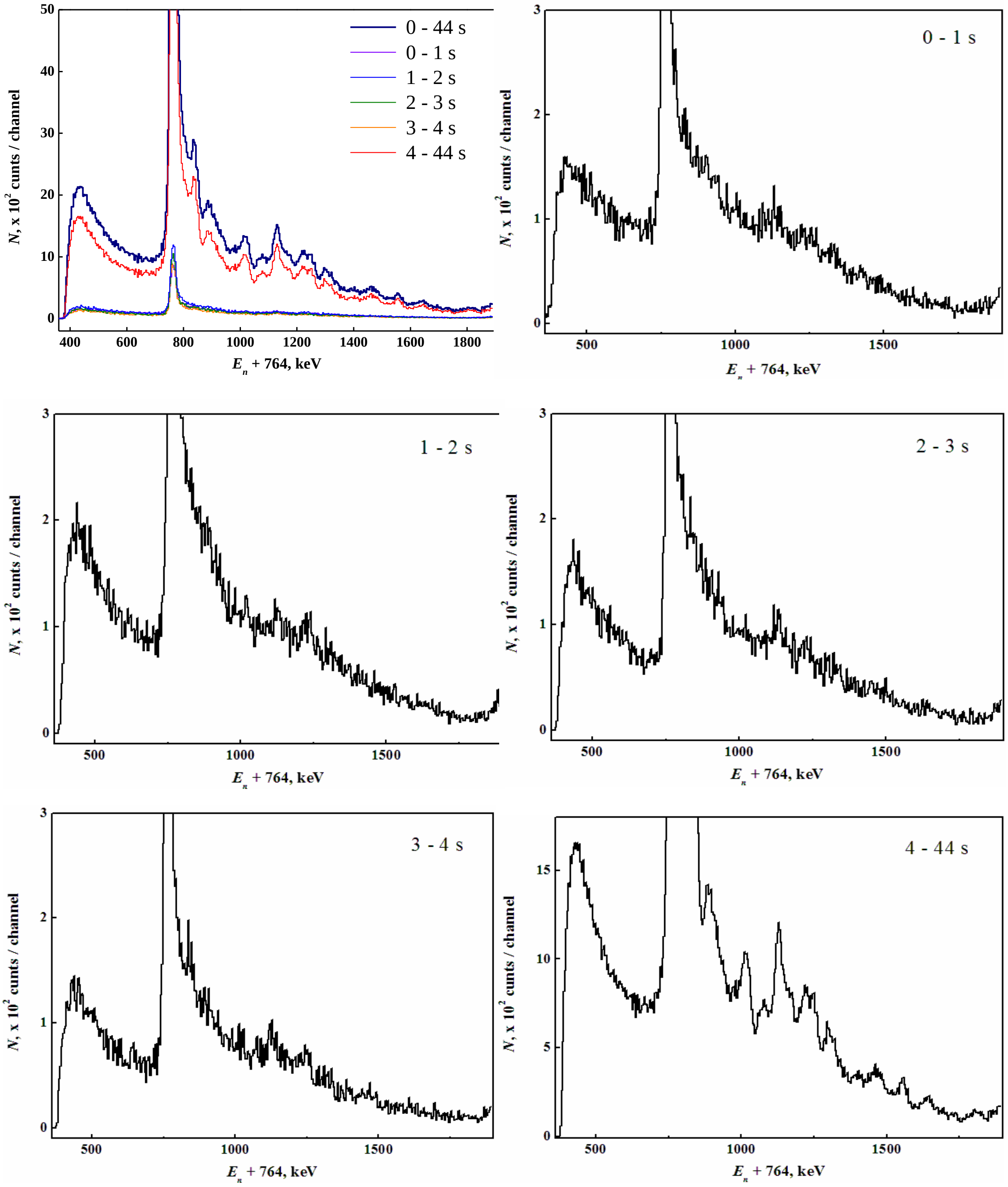


Fig. 2. The pulse height distribution of delayed neutrons from epithermal neutron induced fission of ^{235}U registered by FNS type ^{3}He-spectrometer. The irradiation time is 20 s. Measurements of delayed neutron spectra were made in the following sequence of time intervals after the end of irradiation: 0-1 s, 1-2 s, 2-3 s, 3-4 s, and 4-44 s (see inserts in figures).

Quasi-equilibrium spectra can be represented by following formula:

$$dN(E_n)dE = A\sum_{i=1}^{N}\left[\left(\frac{a_i}{\lambda_i}\right)\left(1-e^{-\lambda_i t_{irr}}\right)\left(e^{-\lambda_i t_d}\right)\left(1-e^{-\lambda_i \Delta t_c}\right)\right]T_i\chi_i(E_n)dE_n \qquad (1)$$

wherea_i –relative abundance of i-th delayed neutron group. $a_i$in 8 group approximation have the values presented in table 1.

$$T_i = \left[\frac{M}{1-e^{-\lambda_i T}} - e^{-\lambda_i T} \frac{1-e^{-M\lambda_i T}}{(1-e^{-\lambda_i T})^2} \right],$$

where T_i term describes dependence of sample activation on number of irradiation cycles, A – saturation activity; $\chi_i(E_n)$ – energy spectrum associated with i-th delayed neutron group; λ_i – decay constant of i-th delayed neutron group; t_{irr} – irradiation time, s; t_d – delay time, s; Δt_c – delayed neutron counting, s; M – number of cycles; T – period of one irradiation cycle (irradiation-cooling-counting).

Table 1. Relative abundances and periods of DN for epithermal neutron induced fission of ^{235}U in 8-group approximation

Nucleus	Group number, half-life, s							
	1	2	3	4	5	6	7	8
	55.6	24.5	16.3	5.21	2.37	1.04	0.424	0.195
^{235}U	0.034 ±0.001	0.153 ±0.006	0.086 ±0.004	0.212 ±0.007	0.298 ±0.009	0.105 ±0.005	0.073 ±0.004	0.039 ±0.002

Proximity to equilibrium spectra is determined by the term in square brackets, we calculate it and obtain its value. Results of calculation are presented in the table 2.

Table 2. Percentage contribution of each DN group for the time interval 0.12-1 s (t_{irr}=20 s)

Group number	Half-life, s	Abundance, %					
		0.12-1 s	1-2 s	2-3 s	3-4 s	4-44 s	Equilibrium spectra[1]
1	55.6	1.85	2.34	2.83	3.32	9.40	3.30
2	24.5	11.15	13.90	16.54	19.11	40.80	15.40
3	16.3	7.78	9.57	11.22	12.78	21.75	9.10
4	5.21	24.34	27.49	29.46	30.65	19.38	19.70
5	2.37	40.18	39.08	35.72	31.68	8.43	33.10
6	1.04	8.99	6.17	3.88	2.37	0.23	9.00
7	0.424	5.05	1.42	0.34	0.08	1.73E-03	8.10
8	0.195	0.66	0.03	1.00E-03	3.91E-05	1.04E-07	2.30

In the table 2, from one time interval to other greater abundance shifts from 2.37 s group to the 24.5 s. So 8-group data in conditions: irradiation time – 20 s, delay time – 0.12 s and counting time 0.88 s is the closest to equilibrium spectra and can be considered as quasi-equilibrium spectrum.

Processing of experimental data

It is well known that the spectral data obtained with the help of neutron spectrometer on the basis of ^{3}He(n,p)^{3}H reaction are mainly distorted by recoil nuclei and the edge effect which create a continuum below full-energy peak. To account for these distortions we used procedures described by Ohm et al. [2].

The relative efficiency of ^{3}He-spectrometer was presented by the formula from [3] which was obtained for the FNS-1 type spectrometer in the energy range $0.019 \le E_n \le 2.77$ MeV by Franz et al. [4]

$$\begin{aligned}\varepsilon = {} & \exp\left[3.75 - 0.629 \cdot \ln E_n\right] - 0.15 \cdot \exp\left[-1/2 \cdot \left(\frac{E_n - 120}{21}\right)^2\right] - 0.39 \cdot \exp\left[-1/2 \cdot \left(\frac{E_n - 250}{89}\right)^2\right] \\ & - 0.13 \cdot \exp\left[-1/2 \cdot \left(\frac{E_n - 440}{127}\right)^2\right] + 0.057 - 3.06 \cdot 10^{-5} E_n\end{aligned} \qquad (2)$$

The dependence described by formula (2) is shown on fig. 3.

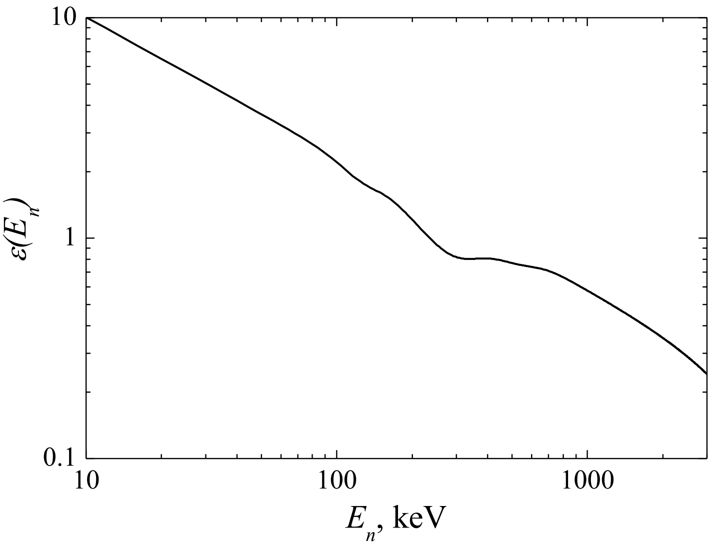


Fig. 3. Relative efficiency of FNS-1 type ^{3}He-spectrometer.

The correction was applied for the neutron flux attenuation effect in the Pb gamma-shield (6 cm thick) of the neutron spectrometer. The transmission correction was made on the basis of Monte-Carlo calculations and appropriate measurements which were made with the help of mono-energetic neutrons.

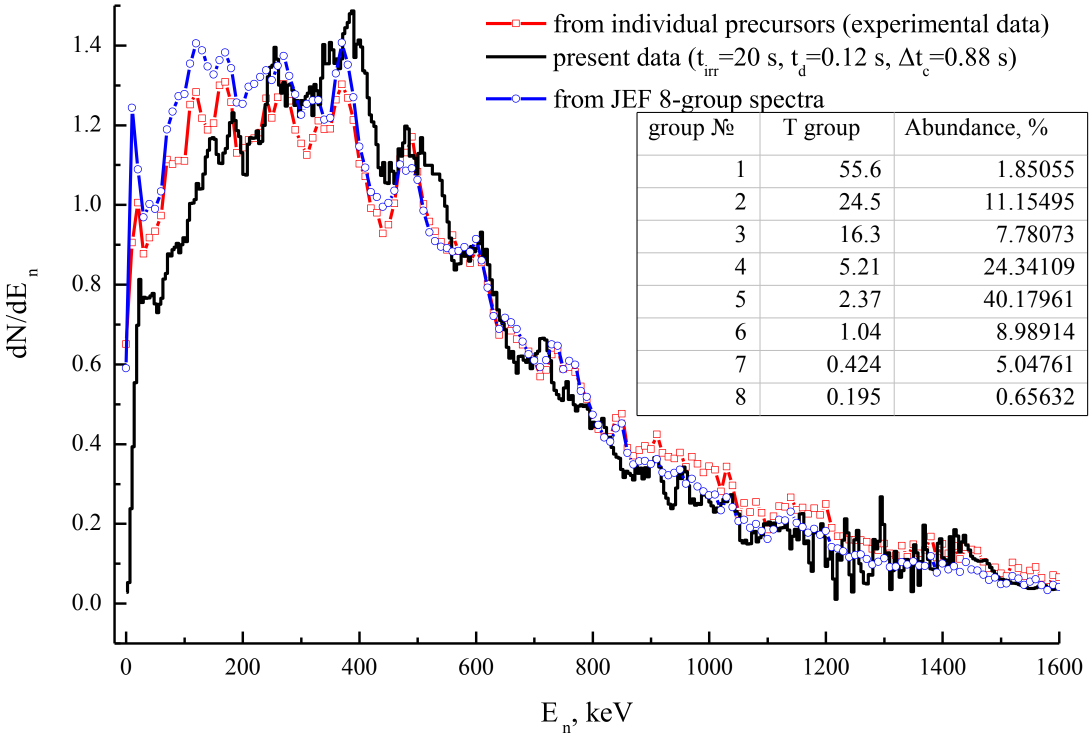
Results

As a result of processing of experimental data there was obtained aggregate delayed neutron spectra measured in the time intervals 0.12-1, 1-2, 2-3, 3-4, and 4-44 s after the end of

20 s - irradiation. On the figure 4, we show quasi-equilibrium aggregate DN spectra measured in time interval 0.12-1 s.

For the comparison on the figure 4 shows data calculated on the basis of the 8-group delayed neutron spectra presented in the JEF 2.2 library using the formula (1), which in turn was derived by the summation technique.

Alsoon the figure 4 shown data calculated on the basis of spectra from individual precursors of delayed neutrons by summation technique using the formula (1), where $a_i = P_{ni} \cdot CY_i$, P_{ni} – probability of delayed neutron emission of i-th precursor, CY_i – cumulative yield of i-th precursor.



group №	T group	Abundance, %
1	55.6	1.85055
2	24.5	11.15495
3	16.3	7.78073
4	5.21	24.34109
5	2.37	40.17961
6	1.04	8.98914
7	0.424	5.04761
8	0.195	0.65632

Fig. 4. Composite spectrum of delayed neutron in the time interval 0.12-1 s from neutron induced fission of ^{235}U (irradiation time – 20 s).

It should be noted that spectra obtained from experimental data of individual precursors is closer to the measured data than spectra obtained on the basis of 8-group data. As a rule the spectra based on the group data overestimate the intensity of delayed neutrons in the region below 200 keV especially in the case of data measured after short delay after the end of irradiation. The reason may be that theoretical model used for estimation of non-measured spectra of possible short-lived precursors cannot reproduce real spectra.

For chosen quasi-equilibrium spectra, it was made comparison with experimental spectra measured by other authors, which were calculated with the help of the group spectra obtained by decomposition of aggregate spectra.

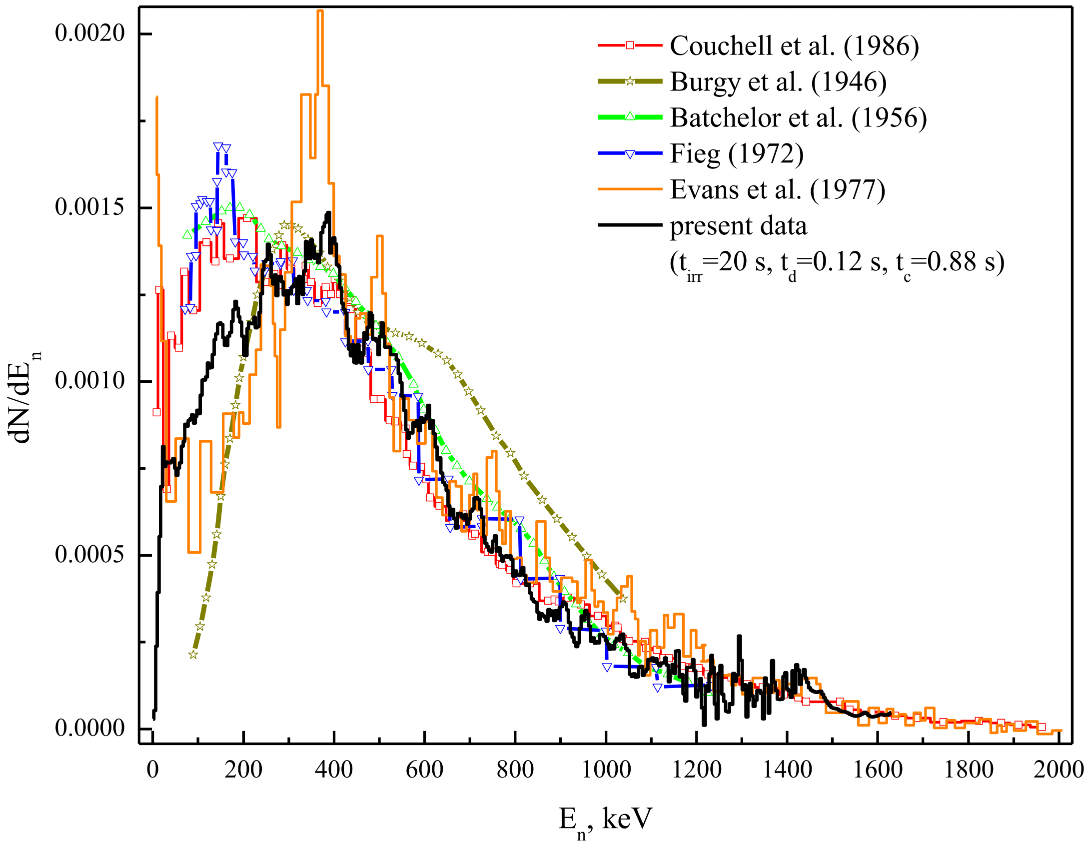


Fig. 5. Equilibrium spectrum of delayed neutrons from fission of ^{235}U by thermal neutrons. The present spectra measured in the range of 0.12-1 s after irradiation of 20 s can be considered as a quasi-equilibrium spectrum. Equilibrium spectra by other authors were calculated with the help of the group spectra obtained by decomposition of appropriate aggregate spectra. Couchell et al.(1986) – [5], Burgy et al. (1946) – [6], Batchelor et al. (1956) – [7], Fieg (1972) – [8], Evans et al. (1977) – [9].

Comparison shows that our quasi-equilibrium spectrum has more pronounced peak structure as compared with appropriate experimental data obtained by other authors. Peak structure presented in Evans et al. data [9] is very close to the peak structure of present data but the overall form of spectrum is strongly deformed that can be explained by possible errors in the determining efficiency of ^{3}He-specrometer. Another important feature of the present quasi-equilibrium spectrum is lower intensity of delayed neutron below 200 keV as compared with early made experiments except Evans et al. data [9]. It is interesting to analyze equilibrium spectrum data obtained by the summation techniques and presented in fig.6.

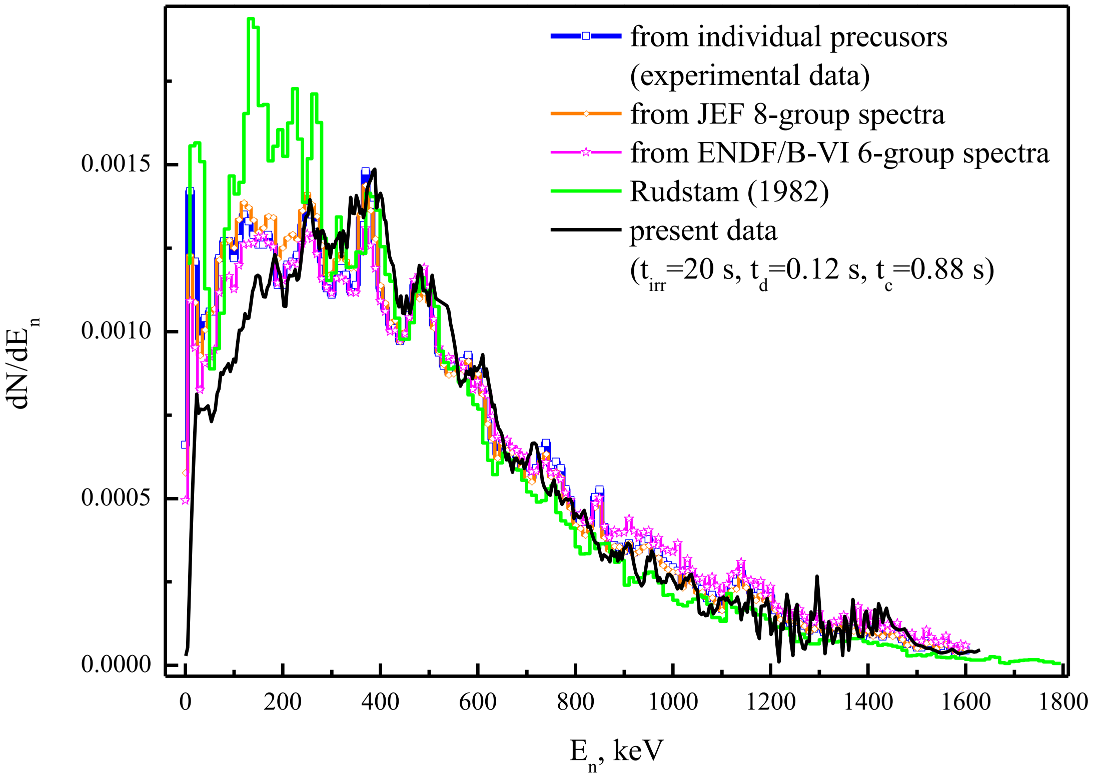


Fig. 6. Equilibrium spectrum of delayed neutrons from fission of ^{235}U by thermal neutrons. The present spectra measured in the range of 0.12-1 s after irradiation of 20 s can be considered as a quasi-equilibrium spectrum. Also shown the spectra calculated with the help of the group spectra from JEF 2.2 and ENDF/B-VI library, and experimental delayed neutron spectra from individual precursors. Rudstam's spectra are based on early measured P_n and $\chi_i(E_n)$ data. Rudstam (1982) – [10].

It is seen from Fig.6 that equilibrium spectrum of delayed neutrons presented in JEF 2.2 and ENDF/B-VI libraries as well as spectrum based on experimental data for individual precursors are in reasonable agreement with present data especially in the energy range about 200-1600 keV. However the calculated spectra do not reproduce the peaks at 350 and 550 keV and have more narrow peak at energy 380 keV. Most likely that there are unresolved peak or group of peaks on the right side of this peak in the present data. Below 200 keV the present spectrum has the same peak structure as calculated one but intensity of delayed neutron in our spectrum in this energy region is lower. It worth to note that equilibrium spectrum calculated on the basis only experimental precursor data is closer to our spectrum in the energy region below 200 keV than spectra calculated with both experimental and theory based data.

Conclusions

Composite delayed neutron spectra from epithermal neutron induced fission of ^{235}U was measured in time intervals 0.12-1, 1-2, 2-3, 3-4, 4-44 s at 20 s irradiation time. There was made comparison of measured spectra with equilibrium spectrum obtained on the base of 8-group recommended data [1]. Comparison shows that the spectrum measured in time interval

0.12-1 s (irradiation time 20 s) is the closest to the equilibrium spectrum and can be considered quasi-equilibrium.

Obtained in present work the quasi-equilibrium spectrum of delayed neutrons in contrast to early experiments has definitely established peak structure, which agrees with results obtained on the basis of individual precursor data. However, the present equilibrium spectrum displays less structure and intensity of delayed neutrons in the energy range below 200 keV. Besides that, some of the energy peaks are not reproduced in the equilibrium spectra based on the individual precursor data.

It was found that both equilibrium spectrum and composite spectra in different time windows calculated on the basis only experimental precursor data is closer to our measured spectra in the energy region below 200 keV than spectra calculated with both experimental and theory based precursor data.

References

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