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THE ENERGY DEPENDENCE OF THE AVERAGE NUMBER OF PROMPT NEUTRONS RESULTING FROM THE NEUTRON FISSION OF ^{236}U

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ABSTRACT

The paper gives the numerical results of measurements of the average number of prompt neutrons per fission, $\bar{\nu}_p$, from neutron-induced fission of ^{236}U in the 0.8 - 6.0 MeV range. An analysis of corrections and errors is given and a curve is recommended for $\bar{\nu}_p$ as a function of neutron energy. The estimated measurement accuracy is approximately 1%.

During reactor operation, the nuclear transformations which accompany neutron capture or emission by nuclei generate new transactinide nuclei, some of which are heavier and some lighter than the original nuclei of the fuel or raw materials. A considerable build-up of transactinide nuclei occurs with the large-scale exploitation of nuclear power. These nuclei play a number of different roles throughout the nuclear fuel cycle, contributing to the chain reaction during operation as well as to fuel heat emission and radioactivity during transport and reprocessing. There is, therefore, a need for detailed research into the nuclear properties of the transactinide nuclei: we want a quantitative analysis of their role in the nuclear power reactor fuel cycle and an evaluation of the possibility of utilizing them as fuel or in connection with the development of special combustion techniques.

One important characteristic of fissile nuclei is the average number of prompt neutrons per fission - $\bar{\nu}_p$.

This paper is concerned with a study of the energy dependence of $\bar{\nu}_p$ in ^{236}U neutron fission. Conde and Holmberg [1] describe measurements of $\bar{\nu}_p$ for ^{236}U fission but do not give a sufficiently detailed account of the measurement method to enable us to judge whether the energy dependence of $\bar{\nu}_p$ deviated from linear. Measurements by an independent method are therefore needed and have the additional advantage of enabling us to determine absolute values of $\bar{\nu}_p$ for ^{236}U nuclei with good reliability.

Preliminary and incomplete measurements of $\bar{\nu}_p$ for ^{236}U neutron fission were presented by the authors of the present paper at the Kiev Conference on Neutron Physics [2].

Measurements of $\bar{\nu}_p$ for ^{236}U fission induced by neutrons of various energies were performed on the EG-1 electrostatic accelerator of the Institute of Physics and Power Engineering. The Li(p,n), T(p,n) and D(d,n) reactions were used to obtain the neutrons. The neutron energy resolution with solid lithium and tritium targets was 30 keV, and 80 keV when a deuterium target was used. In order to take into account the background neutrons generated by the deuterium trapped in the target holder and the deuteron interaction with the nuclei of the target holder, special measurements were made with a dummy target identical with the actual target but containing no deuterium. The $\bar{\nu}_p$ measurement method and the design of the experimental device have already been described in detail [3].

The neutron detector was shielded from virgin neutrons by a 2-m-thick concrete wall. A monoenergetic neutron beam was formed using a channel 38 mm in diameter driven through the concrete wall and a special insert of lithium hydride in paraffin at the channel exit. After passing through the measuring system, the neutron beam entered a trap made of borated polyethylene. A neutron flux monitor was located inside the trap.

The measurements of $\bar{\nu}_p$ for ^{236}U neutron fission were made in relation to $\bar{\nu}_p^o$, the value for spontaneous ^{252}Cf fission. Ionization chambers with layers of ^{236}U and ^{252}Cf were placed inside the secondary neutron detector in the path of the fission-inducing monoenergetic neutron beam.

The neutron detector consisted of a set of 16 counters filled with ^{3}He and placed in a cylindrical polyethylene unit. The operational characteristics of the detector have already been described in detail [3].

Ionization chambers were used as fission fragment detectors. The californium chamber contained an assembly with two plates 3 mm apart. The ^{252}Cf layer (8 fissions) was applied to a 1-mm-thick aluminium foil and covered with a layer of gold dust ($30\,\mu g \cdot cm^{-2}$). The diameter of the ^{252}Cf layer was 7 mm. The uranium chamber comprised ten plates 3 mm apart. Layers of uranous-uranic oxide ($1\ mg \cdot cm^{-2}$) were placed on both sides of a 0.1-mm aluminium foil. The diameter of the layer was 30 mm. The ^{236}U isotope content was more than 99%. The operational assembly consisted of six uranium chambers and one californium chamber positioned in the mdidle of the assembly. The whole assembly was placed in a container filled with argon with a 10% admixture of carbon dioxide at an overpressure of 0.6 atm.

The pulses from each of the six uranium fission chambers were accumulated following discrimination of α-particle pulses. In order to eliminate pulses from electrical interference, anticoincidence circuits controlled by a majority (more than two) coincidence circuit were introduced in the signal channels from the ^{236}U and ^{252}Cf fission chambers. When signals occurred simultaneously in two (or more) channels, no signal reached the output. In earlier work [3], because of the high α-activity of ^{237}Np, the current regime used in the fission chamber employed fast current amplifiers and shapers at the tunnel diodes. Slower apparatus was used in the $\bar{\nu}_p$ measurements for ^{236}U. The electron channel of each fission chamber consisted of a charge-sensitive preamplifier, a spectrometric amplifier and an integral discriminator, thus giving the entire circuit greater stability against interference. Figure 1 shows a typical amplitude spectrum of pulses generated by fragments and α-particles in one of the ^{236}U fission chambers as well as the pulse spectrum from the ^{252}Cf chamber. At the discrimination thresholds used during operation, the ^{236}U and ^{252}Cf fission fragment recording efficiency was estimated at 80% and 96% respectively.

Time analysis was used to determine the number of prompt neutrons. A pulse from the fission chamber activated the neutron counting channel. The time interval of the measurement cycle after each activation was considerably greater than the average lifetime of the prompt fission neutrons in the detector, so that both the effect and the background could be recorded. The use of several storage units made it possible to measure simultaneously the number of neutrons generated by induced ^{236}U fission and spontaneous ^{252}Cf fission and at the same time to record the number of fission events. A typical spectrogram is shown in Fig. 2. The fission neturon counting time after each fission fragment recording event was taken as 500 μs, which is ten times greater than the average neutron lifetime in the detector. An increase in this time did not affect the $\bar{\nu}_p$ measurement results but significantly enlarged the error associated with the background determination.

The value of $\bar{\nu}_p$ for ^{236}U neutron fission was determined from the relationship

$$\bar{\nu}_p = \bar{\nu}_p^o \beta K,$$

where $\bar{\nu}_p^o = 3.733$ is the average number of prompt neutrons from spontaneous fission of ^{252}Cf, β is the experimental value of the ratio between the average numbers of prompt neutrons in ^{236}U neutron fission and ^{252}Cf spontaneous fission, $K = (I + \delta_1)(I + \delta_2) \ldots\ldots (I + \delta_i)$, and δ_i are correction factors allowing for: the difference between the energy spectra of the ^{236}U and ^{252}Cf fission neutrons (δ_1), the dependence of the fission neutron recording efficiency on the position of the ^{236}U layers on the axis of the neutron detector (δ_2), the difference between the diameters of the ^{236}U and ^{252}Cf layers (δ_3), counting errors (δ_4, δ_5), the dependence of the number of recorded neutrons on the fission fragment recording efficiency (δ_6), the difference between the probabilities of total stopping in the layer of fissile material for fission fragments with differing kinetic energies (δ_7), the difference between the angular distributions of fragments from ^{236}U and ^{252}Cf fission (δ_8), and the presence of background neutrons when using the D(d,n) reaction (δ_9). The determination of these δ_i corrections has already been described in detail [3]. The correction δ_6, which takes into account the dependence of the number of recorded neutrons on the fission fragment recording efficiency, was determined experimentally. Figure 3 shows the corresponding dependence.

The correction factor δ_7 was also determined experimentally. By contrast with Refs [4, 5], we used uranium layers of different thicknesses in which the ^{252}Cf isotope, with a spontaneous fission intensity of about 20 fissions $\cdot s^{-1}$, was evenly distributed.

Table 1 gives the values of the δ_i corrections not dependent on the energy of the fission-inducing neutrons.

Table 2 shows the $\bar{\nu}_p$ measurement results and measurement errors.

Figure 4 compares our results with those of Conde and Holmberg [1]. In general, the differences between the results of the two papers do not exceed the measurement error limits, with the exception of the 4-6 MeV neutron energy region.

All the experimental results from the two papers in the neutron energy region below the (n,n'f) reaction threshold were described using the least squares method by a straight line:

$$\bar{\nu}_p = (2.297 \pm 0.009) + (0.1363 \pm 0.0034)E_n.$$

The statistical weight of the points was taken in accordance with the total errors given in the papers.

It is well known, however, that above a certain neutron energy the average kinetic energy of the fission fragments begins to decrease [6]. If we assume that this decrease is not due to a change in total fission energy, then a corresponding increase in the rate of growth of $\bar{\nu}_p$ above this neutron energy should be expected.

A discontinuity in the energy dependence of $\bar{\nu}_p$ has been observed for a number of other nuclei [7, 8]. The experimental data were therefore described using the least squares method by two straight lines, the intersection point of the lines being selected in accordsnce with the χ^2 minimum criterion. This method of presenting the energy dependence is considerably better than describing the data with one line.

For practical purposes, therefore, the following energy dependence of $\bar{\nu}_p$ for ^{236}U neutron-induced fission is recommended:

$$\bar{\nu}_p = \begin{cases} (2.346 \pm 0.012) + (0.1072 \pm 0.0071)E_n & \text{for } E_n \leq 2.35 \text{ MeV} \\ (2.236 \pm 0.024) + (0.1539 \pm 0.0068)E_n & \text{for } 2.35 \text{ MeV} \leq E_n \leq 5.9 \text{ MeV} \end{cases}$$

The errors in the line coefficients do not include the error in the average number of prompt neutrons from the ^{252}Cf standard used. The value of $\bar{\nu}_p^o$ for this evaluation was taken as 3.733.

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Measurements of energy dependence of $\bar{\nu}_p$ for neutron-induced fission of ^{237}Np

The energy dependence analysis of $\bar{\nu}_p$ for neutron induced fission of ^{238}U

Table I

Correction factors not dependent on neutron energy

Symbol	Correction value and its error	Symbol	Correction value and its error
δ_2	0,048 ± 0,002	δ_7	0,003 ± 0,00I
δ_3	-0.003 ± 0.002	δ_8	0.000 ± 0.00I
δ_6	0.0I5 ± 0.003		

Table II

Measured values of $\overline{\nu}_P$ for ^{236}U neutron-induced fission

E_n MeV	Correction values and their errors				$\overline{\nu}_P$	Statistical error*/	Total error
	δ_I	δ_4	δ_5	δ_9			
I	2	3	4	5	6	7	8
0,80	-0,0I9±0,005	0,002±0,00I	-0,0I9±0,002		2,45I	0,029	0,034
0,85	- " -	0,003±0,00I	- " -		2,446	0,027	0,033
0,90	- " -	0,003±0,00I	- " -		2,434	0,022	0,034
0,95	- " -	0,004±0,00I	- " -		2,430	0,023	0,035
I,00	- " -	0,004±0,00I	- " -		2,465	0,033	0,038
I,I0	- " -	0,002±0,00I	- " -		2,472	0,022	0,029
I,20	-0,0I8±0,005	0,005±0,00I	-0,0I7±0,002		2,50I	0,0I7	0,025
I,30	- " -	0,002±0,00I	- " -		2,469	0,030	0,035
I,35	- " -	0,00I±0,00I	- " -		2,476	0,03I	0,036
I,40	- " -	0,002±0,00I	- " -		2,480	0,0I5	0,024
I,50	- " -	0,002±0,00I	- " -		2,5I4	0,020	0,030
I,60	- " -	0,002±0,00I	- " -		2,5I5	0,0I7	0,025
I,70	- " -	0,003±0,00I	- " -		2,5I8	0,023	0,030
I,80	- " -	0,00I±0,00I	- " -		2,556	0,026	0,032
I,90	-0,0I7±0,004	0,003±0,00I	-0,0I7±0,002		2,549	0,0I2	0,02I
2,00	- " -	0,003±0,00I	- " -		2,545	0,035	0,039
2,I0	-0,0I6±0,004	0,00I±0,00I	-0,0I7±0,002		2,575	0,033	0,037
2,20	- " -	0,002±0,00I	- " -		2,558	0,024	0,030
2,25	-0,0I5±0,00I	0,004±0,00I	-0,0I7±0,002		2,6II	0,0I6	0,024

I	2	3	4	5	6	7	8
2,30	-0,0I5±0,004	0,002±0,00I	-0,0I7±0,002		2,604	0,0I5	0,023
2,40	- " -	0,005±0,00I	- " -		2,588	0,0I5	0,023
2,50	- " -	0,005±0,00I	- " -		2,626	0,029	0,034
2,60	-0,0I4±0,004	0,00I±0,00I	-0,0I6±0,002		2,684	0,028	0,034
2,70	- " -	0,009±0,00I	- " -		2,667	0,023	0,029
2,80	- " -	0,003±0,00I	- " -		2,669	0,032	0,037
2,90	- " -	0,004±0,00I	- " -		2,678	0,024	0,030
3,00	-0,0I4 ±0,004	0,003±0,00I	-0,0I6±0,002		2,690	0,0I3	0,023
3,I0	- " -	0,002±0,00I	- " -		2,704	0,023	0,030
3,20	- " -	0,004±0,00I	- " -		2,727	0,0I6	0,025
3,30	- " -	0,002±0,00I	- " -		2,732	0,02I	0,029
3,40	-0,0I2±0,003	0,004±0,00I	-0,0I5±0,002		2,780	0,022	0,029
3,50	- " -	0,003±0,00I	- " -		2,772	0,0I5	0,023
3,60	- " -	0,005±0,00I	- " -		2,775	0,022	0,029
3,70	- " -	0,005±0,00I	- " -		2,8I9	0,0I9	0,026
5,05	-0,009±0,003	0,005±0,00I	-0,0I3±0,002	-0,002±0,003	3,007	0,0I6	0,030
5,60	-0,007±0,002	0,002±0,00I	-0,0I0±0,002	0,008±0,003	3,I67	0,026	0,034
5,90	-0,007±0,002	0,002±0,00I	-0,0I0±0,002	0,0II±0,003	3,I54	0,042	0,046

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*/ The error given is that calculated from the spread of measurement results in individual series, if it exceeded the statistical error.

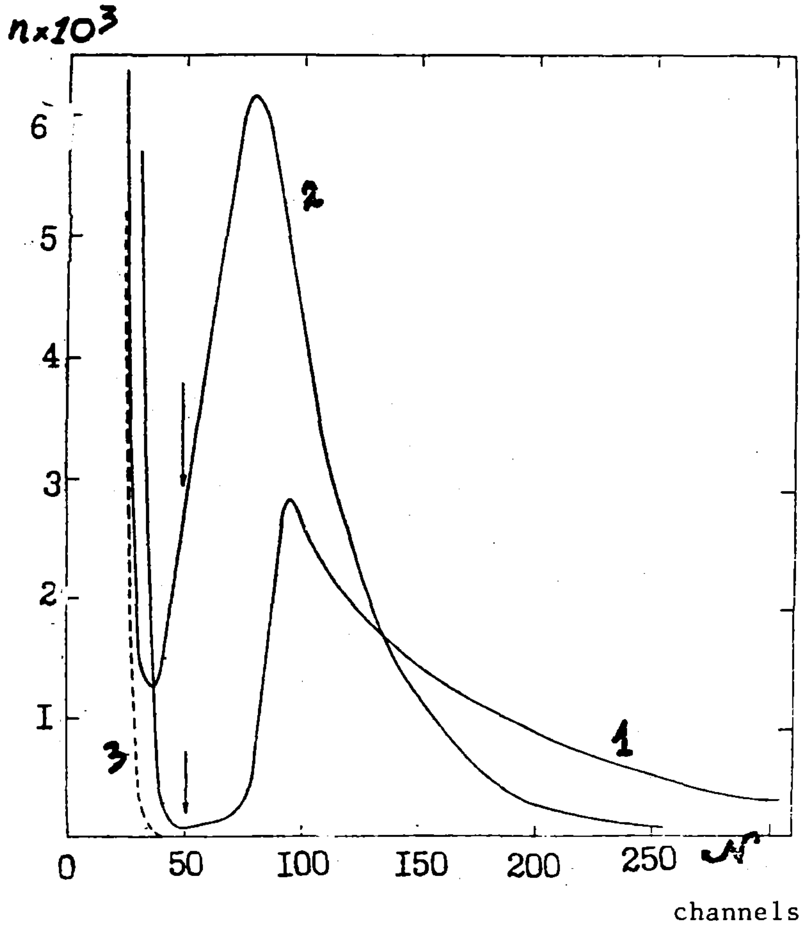
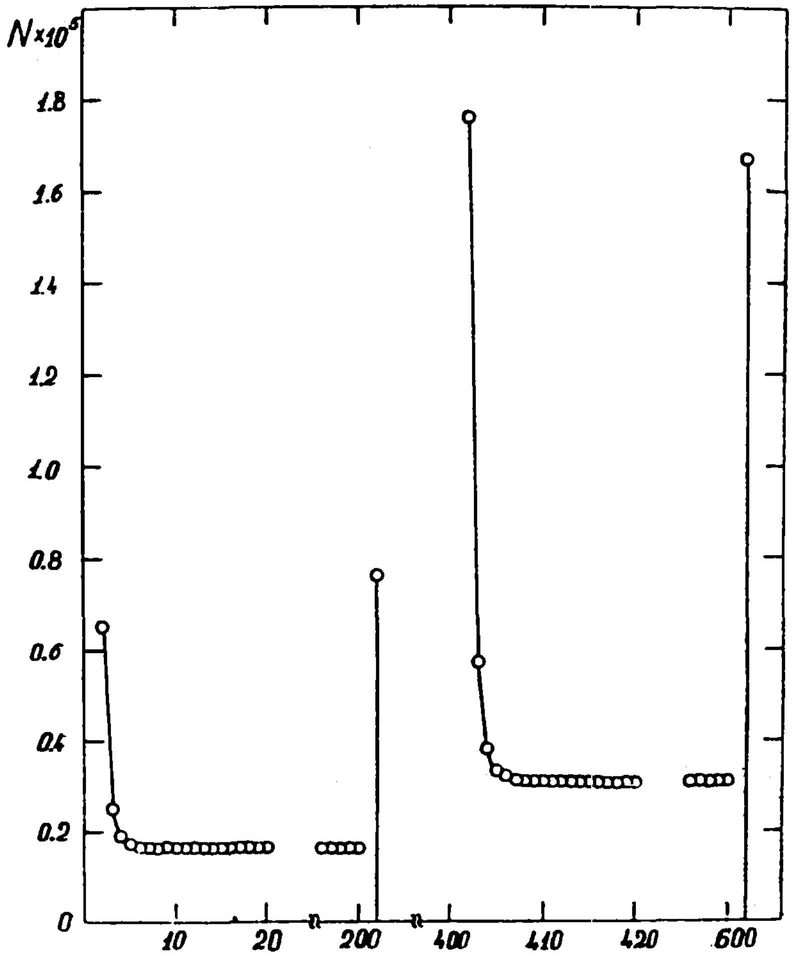


Fig. 1. Spectrum of pulses generated in the fission chamber by fragments and α-particles: 1 - ^{252}Cf spontaneous fission; 2 - ^{236}U neutron-induced fission; 3 - α-particles. The dotted line shows the level of discrimination.



Channel number

Fig. 2. Typical pulse time spectrogram. The number of ^{236}U and ^{252}Cf fission events is fixed at channels 202 and 602 respectively.

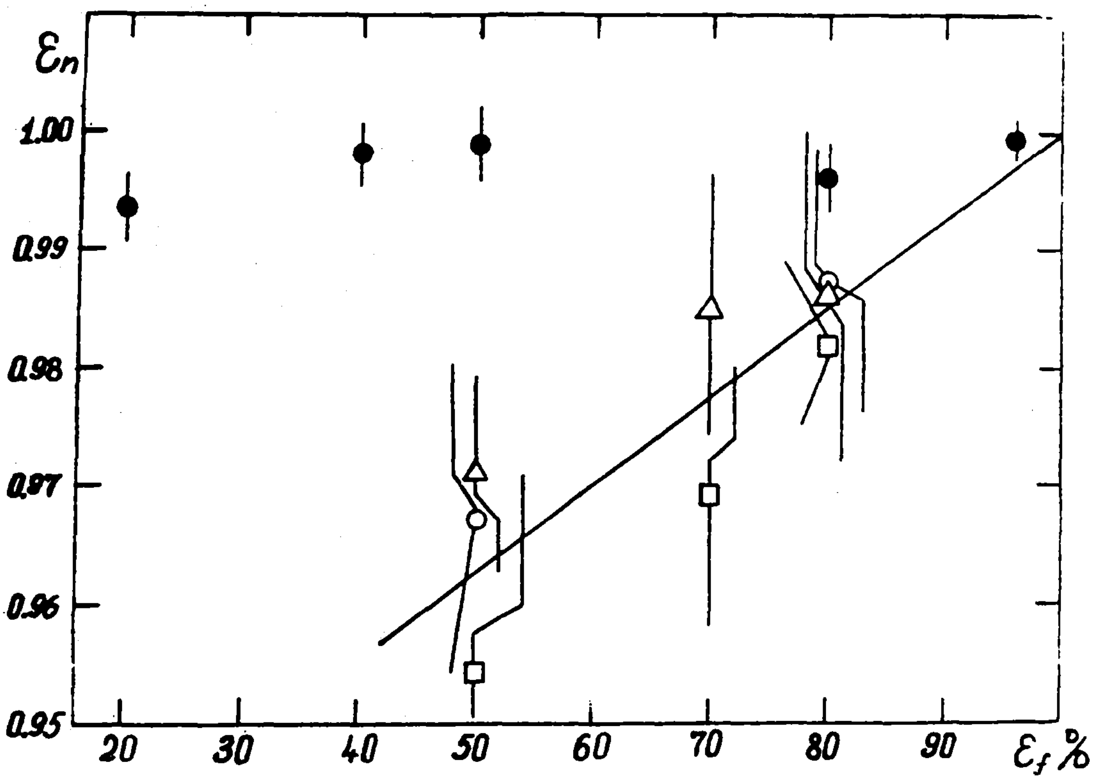


Fig. 3. Dependence of the number of neutrons recorded (relative units) on the fission fragment recording efficiency. Solid points - ^{252}Cf, open symbols - ^{236}U. (o - 2 MeV, △ - 2.5 MeV, □ - 3 MeV)

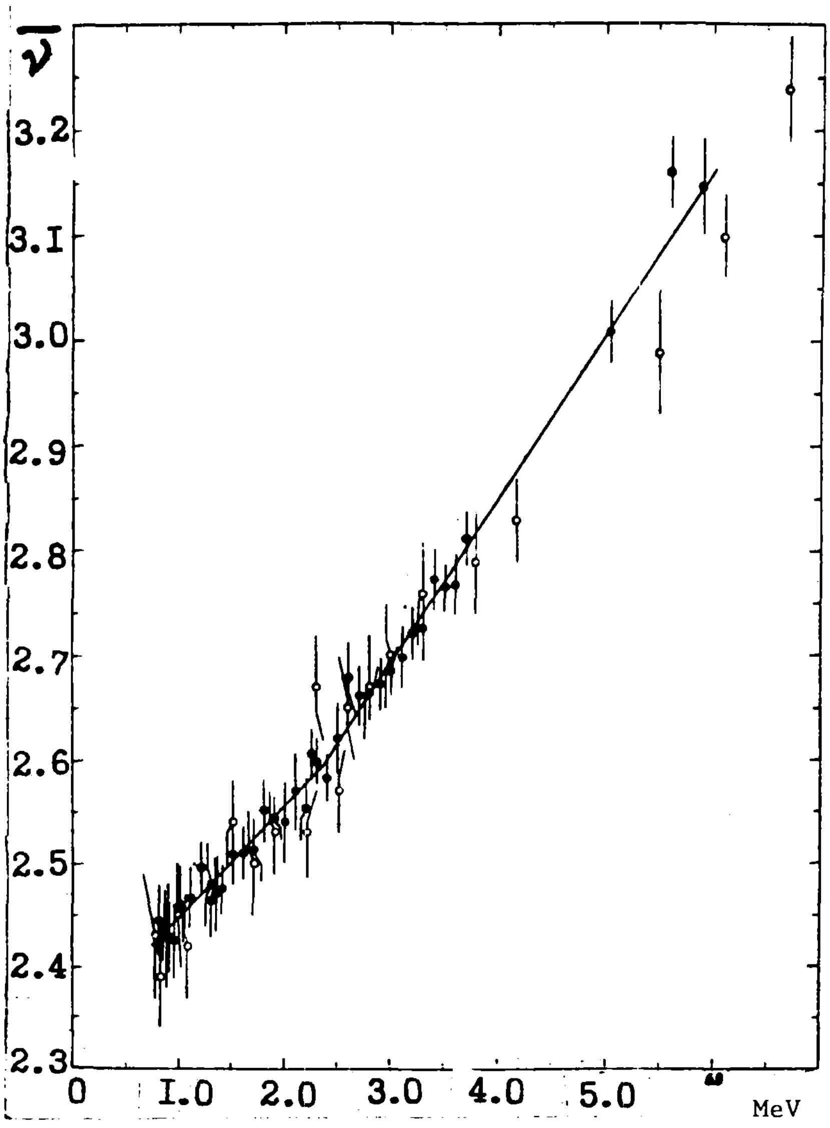


Fig. 4. Energy dependence of $\bar{\nu}_p$ for ^{236}U neutron fission. O – [1]; ● – present paper; line – recommended dependence.