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COHERENT EVALUATION OF $\bar{\nu}_p$ FOR ^{235}U, ^{238}U, AND ^{239}Pu

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ABSTRACT

The average number of prompt neutrons emitted per fission, $\bar{\nu}p$, has been evaluated for the neutron induced fission of ^{235}U, ^{238}U and ^{239}Pu in the energy range from 10^{-5} eV to 30 MeV. A particular attention has been paid to the thermal and resonance energy region for ^{230}Pu where the fluctuations due to the $(n,\gamma f)$ reaction have been taken into account.

RESUME

Le nombre moyen $\bar{\nu}p$ de neutrons prompts de fission a été évalué pour la fission de ^{235}U, ^{238}U et ^{239}Pu induite par des neutrons d'énergie comprise entre 10^{-5} eV et 30 MeV. On a porté un effort particulier sur le ^{239}Pu dans le domaine thermique et la région des résonances où les fluctuations introduites par la réaction $(n,\gamma f)$ ont été prises en compte.

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INTRODUCTION

The average number of prompt neutrons emitted per fission, $\bar{\nu}_p$, is generally measured relative to $\bar{\nu}_p$ for the spontaneous fission of ^{252}Cf used as a standard. The first stage of a coherent evaluation consists therefore in determining the "best value" for the standard.

Axton [1] has recently performed a simultaneous evaluation of the thermal neutron constants of the major fissile isotopes and of $\bar{\nu}_p$ for ^{252}Cf, with a covariance matrix for the input data. The $\bar{\nu}_p$ values of this evaluation are taken as a basis for the present work :

^{252}Cf : $\bar{\nu}_p$: 3.757 ± 0.0048

thermal $\bar{\nu}_p$ values :

^{235}U : $\bar{\nu}_p = 2.4150 \pm 0.0039$

^{239}Pu : $\bar{\nu}_p = 2.8736 \pm 0.0053$

The small discrepancies observed between the different sets of published $\bar{\nu}_p$ data have been discussed in a recent paper [2]. They reflect the present state of the experimental techniques involved in $\bar{\nu}_p$ measurements.

The present evaluation is mainly based on data obtained at BRC which have been obtained on a wide energy range (~ 1 eV to 30 MeV) using essentially a same apparatus.

II - $\bar{\nu}_p$ for ^{235}U

II.1. - Thermal and resonance energy region

Careful measurements of $\bar{\nu}_p$ for ^{235}U have been performed between 0.005 eV and 10 eV at ORELA [3], and in the resolved resonances at Saclay [4]. No fluctuations of $\bar{\nu}_p$ have been observed within the experimental uncertainties. Therefore $\bar{\nu}_p$ has been assumed constant in that energy range and equal to 2.4150, the thermal value.

II.2. - Energy range below 1 MeV

The most accurate data sets [5,6] are plotted in figure 1. They are in overall good agreement within 0.5 %. A least square fit to the data gives a zero energy value which is about 1 % lower than thermal value. This result can be correlated with a measured average fragment kinetic energy $\bar{E}_K$ about 200 keV larger in this energy range than the value for thermal fission [7]. However the $\bar{\nu}_p$ and $\bar{E}_K$ data between thermal energy and 50 keV are very scarce and do not permit to determine accurately the $\bar{\nu}_p$ shape in that region. Therefore, we have choosen to impose the thermal $\bar{\nu}_p$ value as the zero energy value in the least square fit. Under these conditions the data are correctly fitted up to 2.25 MeV with a single line :

$$\bar{\nu}_p = 2.4150 + 0.0945\ En$$

This line remains a very good representation of the data below 1 MeV (figure 1).

II.3. - Energy range above 1 MeV (figures 2, 3)

In this energy range, the existing data [6,8,9] are well fitted by 4 lines :

$$2.25\ \text{MeV} \leqslant E_n \leqslant 3.90\ \text{MeV} \quad : \quad \bar{\nu}_p = 2.3544 + 0.1214\ E_n$$

$$3.90\ \text{MeV} \leqslant E_n \leqslant 7\ \text{MeV} \quad : \quad \bar{\nu}_p = 2.1324 + 0.1785\ E_n$$

$$7\ \text{MeV} \leqslant E_n \leqslant 17\ \text{MeV} \quad : \quad \bar{\nu}_p = 2.3399 + 0.1483\ E_n$$

$$17\ \text{MeV} \leqslant E_n \leqslant 30\ \text{MeV} \quad : \quad \bar{\nu}_p = 3.0928 + 0.1038\ E_n$$

The change in slope arounds 4 MeV is clearly correlated to the energy dependence of $\bar{E}_K$ [7].

III - $\bar{\nu}_p$ for ^{238}U

The existing data [9, 10, 11] below 6 MeV are plotted in figure 4. The low russian values near threshold might be due to an angular anisotropy effect [2]. Fragment kinetic energy measurements for ^{238}U [12] show a change in slope around 3 MeV, similar to the change observed for ^{235}U around 4 MeV.

The corresponding change in the $\bar{\nu}_p$ slope is clearly seen in BRC data ; it is less apparent in russian measurements, perhaps masked by the low values measured near threshold.

The existing data above 5 MeV [9] are plotted in figure 5.

The evaluated $\bar{\nu}_p$ values are represented by 4 lines :

$E \leqslant 2.9$ MeV	$\bar{\nu}_p = 2.4412 + 0.0712\ E_n$
$2.9 \text{ MeV} \leqslant E_n \leqslant 5.05$ MeV	$\bar{\nu}_p = 2.0950 + 0.1903\ E_n$
$5.05 \text{ MeV} \leqslant E_n \leqslant 15.85$ MeV	$\bar{\nu}_p = 2.2949 + 0.1516\ E_n$
$15.85 \text{ MeV} \leqslant E_n \leqslant 30$ MeV	$\bar{\nu}_p = 2.9039 + 0.1132\ E_n$

IV - $\bar{\nu}_p$ for ^{239}Pu

IV.1. - Thermal and Resonance Energy Region

Our $\bar{\nu}_p$ measurements in the resonance energy region [4] clearly show fluctuations for the $J^\pi = 1^+$ resonances which have been interpreted as an effect of the (n,γf) reaction. This effect is practically negligible for the $J^\pi = 0^+$ resonances. However, because we were only interested in the variations of $\bar{\nu}_p$ from resonance to resonance, the experimental data were not accurately corrected to deduce the best "absolute" values. Small corrections due to the detection dead time or the relative position of the sample in the detector, for example, have been omitted. Because of the procedure used in data reduction, it does not seem realistic to try to correct the data a posteriori. For these reasons, we have choosen to normalize our data on the measurements of GWIN et al [6] in the energy range between 7 and 20 eV. A normalization factor of 1.006 was deduced.

The experimental data below 10 eV [3,4] are plotted in fig. 6. The measurement of GWIN et al [3] is in very good agreement with the accepted thermal value $\bar{\nu}_p = 2.8736$. The influence of the (n,γf) reaction in the 0.3 eV $J^\pi = 1^+$ resonance is clearly seen. Using the renormalized data from ref.[4], one can deduce a value of $\bar{\nu}_p = 2.859$ for that resonance, to be compared to the value $\bar{\nu}_p = 2.855 \pm 0.005$ measured at 0,3 eV [3]

The data for the resolved resonance energy region are plotted in figures 7 and 8. For the evaluation procedure, the correlated information on the prompt fission gamma ray energy [4] has been used in order to reduce the statistical fluctuations in the experimental $\bar{\nu}_p$ data.

Assuming that the $\bar{\nu}_p$ variations result from the relative influence of the (n,γf) reaction [4], the evaluated data appear to be very consistent with the variations as a function of energy of the average fission widths [14]. We have therefore used the data of [14] to extrapolate the evaluation up to 660 eV. Fluctuations of $\bar{\nu}_p$ comparable to these observed for α certainly exist at higher energies. Evaluation of $\bar{\nu}_p$ requires however the previous determination of the variation as a function of energy of the average fission width and relative contribution of the $J^\pi = 1^+$ resonances, which is beyond the scope of the present evaluation.

IV.2. - $\bar{\nu}_p$ below 1.5 MeV

The $\bar{\nu}_p$ data between 0.1 and 1.5 MeV [5, 6, 10] are plotted in figure 9. They are in overall good agreement. A good representation of the data below 1 MeV is given by the line of equation :

$$\bar{\nu}_p = 2.8736 + 0.1183\ E_n$$

This line is also fitting the data of GWIN et al [6] between 1 keV and 100 keV.

IV.3. - $\bar{\nu}_p$ above 1 MeV

The $\bar{\nu}_p$ data between 1 and 10 MeV [9, 10, 6, 13] are plotted in figure 10, and the data above 10 MeV [9] are plotted in figure 11.

An overall good fit to the data is obtained with 4 lines of equation :

$1\ \text{MeV} \leqslant E_n \leqslant 4.2\ \text{MeV}$	$\bar{\nu}_p = 2.8490 + 0.1429\ E_n$
$4.2\ \text{MeV} \leqslant E_n \leqslant 10.6\ \text{MeV}$	$\bar{\nu}_p = 2.7684 + 0.1621\ E_n$
$10.6\ \text{MeV} \leqslant E_n \leqslant 19.6\ \text{MeV}$	$\bar{\nu}_p = 3.1107 + 0.1298\ E_n$
$19.6\ \text{MeV} \leqslant E_n \leqslant 30\ \text{MeV}$	$\bar{\nu}_p = 3.8838 + 0.0903\ E_n$

CONCLUSION

The $\bar{\nu}_p$ data for ^{235}U, ^{238}U and ^{239}Pu have been evaluated in the energy range from thermal up to 30 MeV. The evaluated values are given in ENDF format (linear-linear interpolation) in tables I, II and III, respectively.

The present evaluation is totally consitent with the thermal $\bar{\nu}_p$ values deduced from a simultaneous evaluation of the thermal neutron constants and of $\bar{\nu}_p$ for ^{252}Cf [1].

A particular attention has been paid to the thermal and resonance energy region for ^{239}Pu. The measured fluctuations of $\bar{\nu}_p$ from resonance to resonance [4] have been taken into account, as well as the dip observed for the 0,3 eV resonance [3], as shown in fig. 6-8. The resulting evaluated values are consistent with experimental data as well as with what can be predicted from the underlying (n,γf) process at the origin of the fluctuations. In this energy range, the present evaluation shows a real improvement compared to other existing evaluations, in particular ENDF/BV (fig. 6).

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TABLE I

Evaluated $\bar{\nu}_p$ values for ^{235}U

1.00000 - 05	2.41500 + 00	2.53000 - 02	2.41500 + 00	2.25000 + 06
2.62760 + 00	3.90000 + 06	2.82820 + 00	7.00000 + 06	3.38000 + 00
1.70000 + 07	4.85920 + 00	3.00000 + 07	6.20680 + 00	

TABLE II

Evaluated $\bar{\nu}_p$ values for ^{238}U

1.00000 - 05	2.44120 + 00	2.90000 + 06	2.64730 + 00	5.15000 + 06
3.07530 + 00	1.58500 + 07	4.69730 + 00	3.00000 + 07	6.29990 + 00

TABLE III

Evaluated $\bar{\nu}_p$ values for ^{239}Pu

1.00000 - 05	2.87360 + 00	2.53000 - 02	2.87360 + 00	5.00000 - 02
2.87250 + 00	1.00000 - 01	2.86600 + 00	2.00000 - 01	2.85550 + 00
4.00000 - 01	2.85550 + 00	1.00000 + 00	2.87500 + 00	6.00000 + 00
2.87500 + 00	7.00000 + 00	2.85600 + 00	2.00000 + 01	2.85600 + 00
4.00000 + 01	2.81950 + 00	4.80000 + 01	2.82200 + 00	5.80000 + 01
2.87400 + 00	9.60000 + 01	2.85600 + 00	1.05000 + 02	2.81100 + 00
1.25000 + 02	2.87100 + 00	2.00000 + 02	2.87100 + 00	3.20000 + 02
2.84200 + 00	4.50000 + 02	2.87200 + 00	5.70000 + 02	2.87200 + 00
5.80000 + 02	2.85400 + 00	6.50000 + 02	2.85400 + 00	6.60000 + 02
2.87350 + 00	1.00000 + 06	2.99190 + 00	4.20000 + 06	3.44920 + 00
1.06000 + 07	4.48660 + 00	1.96000 + 07	5.6542 + 00	3.00000 + 07
6.59280 + 00				

FIGURE CAPTIONS

Note

Data of fig. 6, 7 and 8 normalized to $\bar{\nu}_p$ = 3.757 for the spontaneous fission of ^{252}Cf. Data of all other figures normalized to $\bar{\nu}_p$ = 3.732 for the spontaneous fission of ^{252}Cf. The lines through the data correspond to the present evaluation.

Figure 1 $\bar{\nu}_p$ below 1 MeV for ^{235}U

Δ : Ref.[6] , x : Ref.[5] (Boldeman), 0 : Ref.[5] (BRC)

Figure 2 $\bar{\nu}_p$ between 1 and 10 MeV for ^{235}U

0 : Ref.[6] , + Ref.[8]

Figure 3 $\bar{\nu}_p$ between 10 and 30 MeV for ^{235}U

+ : Ref.[8] and [9]

Figure 4 $\bar{\nu}_p$ between 1 and 6 MeV for ^{238}U

Δ : Ref.[9] , x : Ref.[10] , 0 : Ref.[11]

Figure 5 $\bar{\nu}_p$ between 10 and 30 MeV for ^{238}U

+ : Ref.[9]

Figure 6 $\bar{\nu}_p$ for ^{239}Pu below 10 eV

histogram : Ref.[3] , 0 : Ref.[4]
* : evaluated thermal $\bar{\nu}_p$ [1]
.... present evaluation
..——.. ENDF/BV evaluation

Figures 7 and 8

$\bar{\nu}_p$ for ^{239}Pu in the resolved resonance energy region.
All data from ref. [4] and multiplied by 1.006 (see text)

Figure 9 $\bar{\nu}_p$ for ^{239}Pu between 0.1 and 1.5 MeV

Δ : Ref.[15] , ◘ : Ref.[6] , 0 : Ref.[13], x : Ref [10]

FIGURE 10 $\bar{\nu}_p$ for ^{239}Pu between 1 and 10 MeV

Δ : Ref.[9] , x : Ref.[10], 0 : Ref.[6], ● : Ref.[13]

Figure 11 $\bar{\nu}_p$ for ^{239}Pu between 10 and 30 MeV

All data from ref. [9]

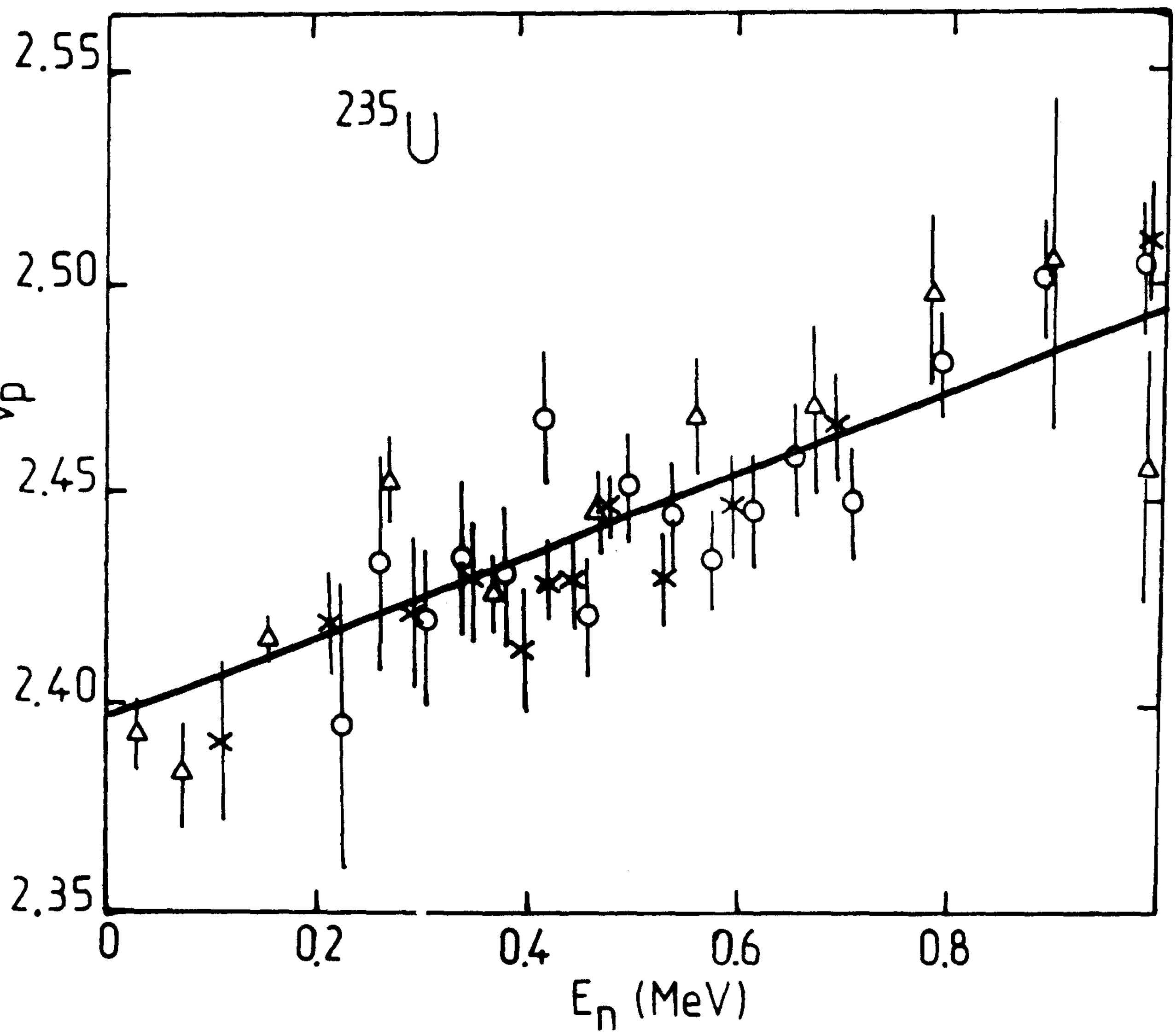


FIGURE 1

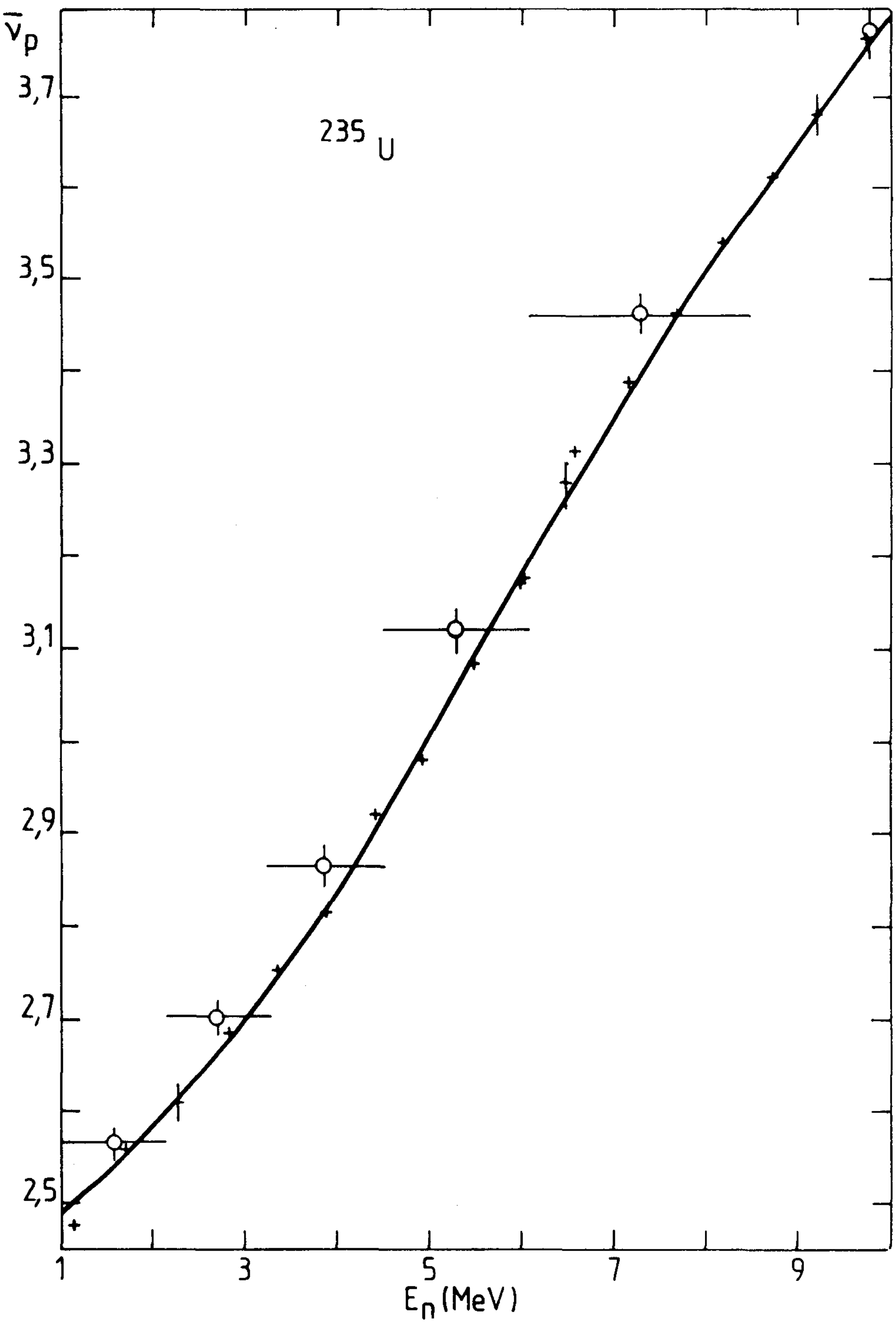


FIGURE 2

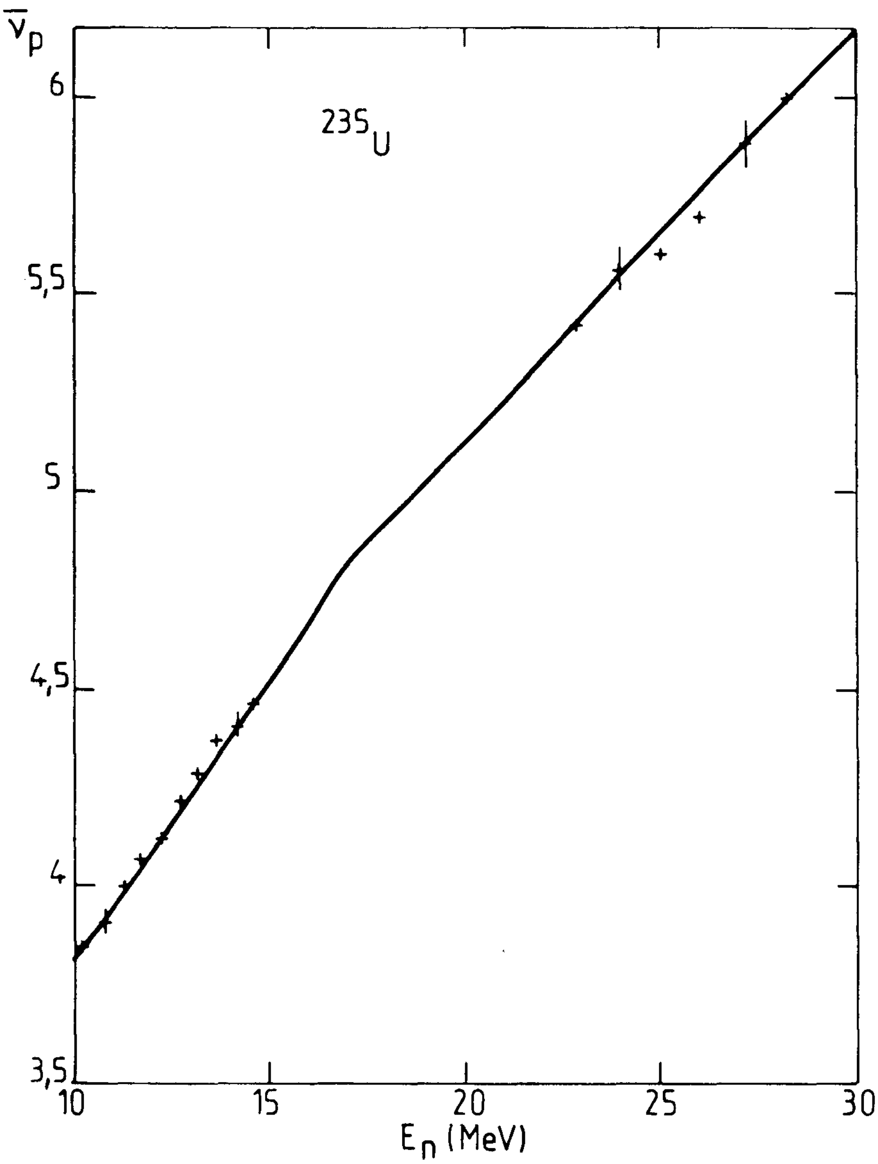


FIGURE 3

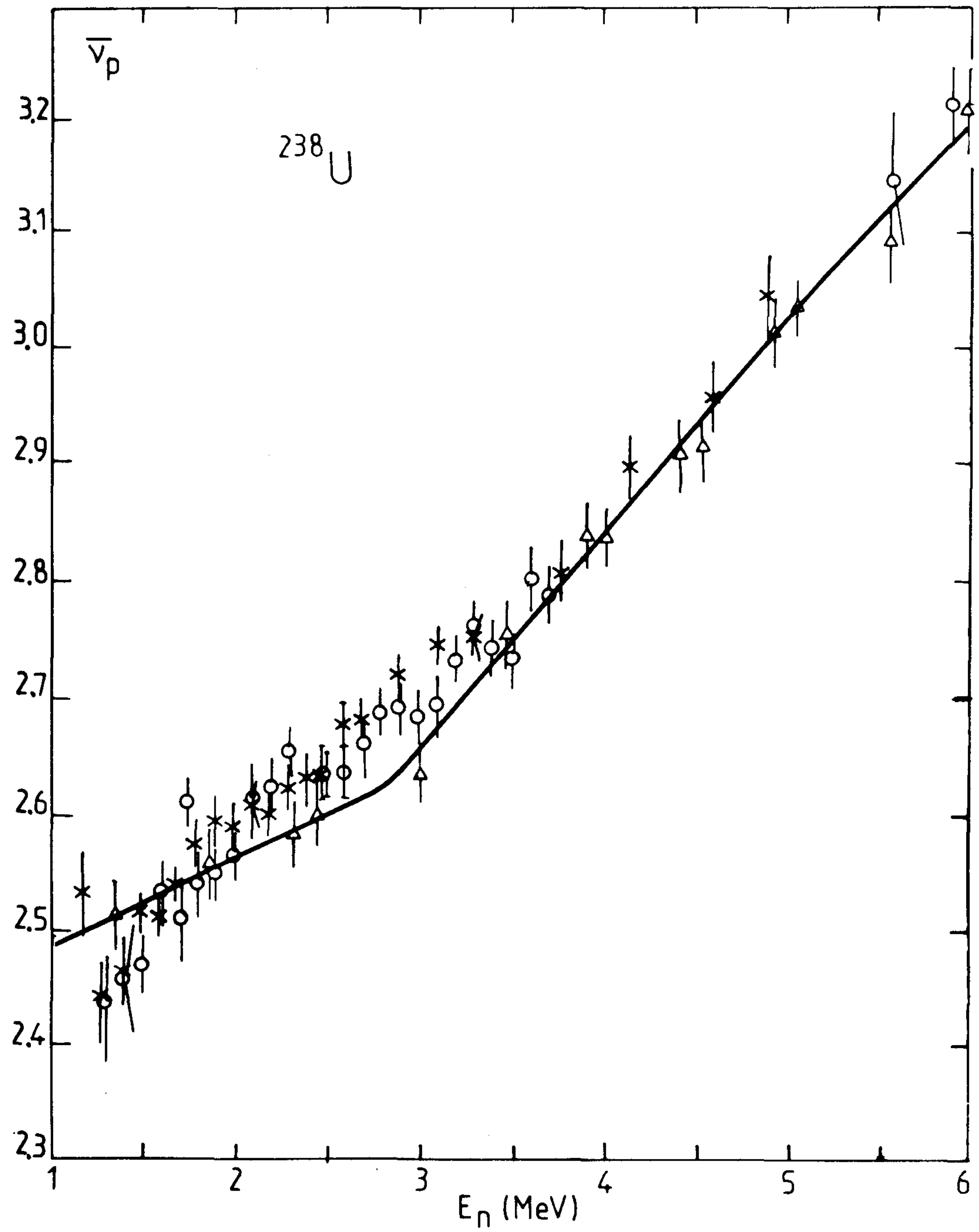
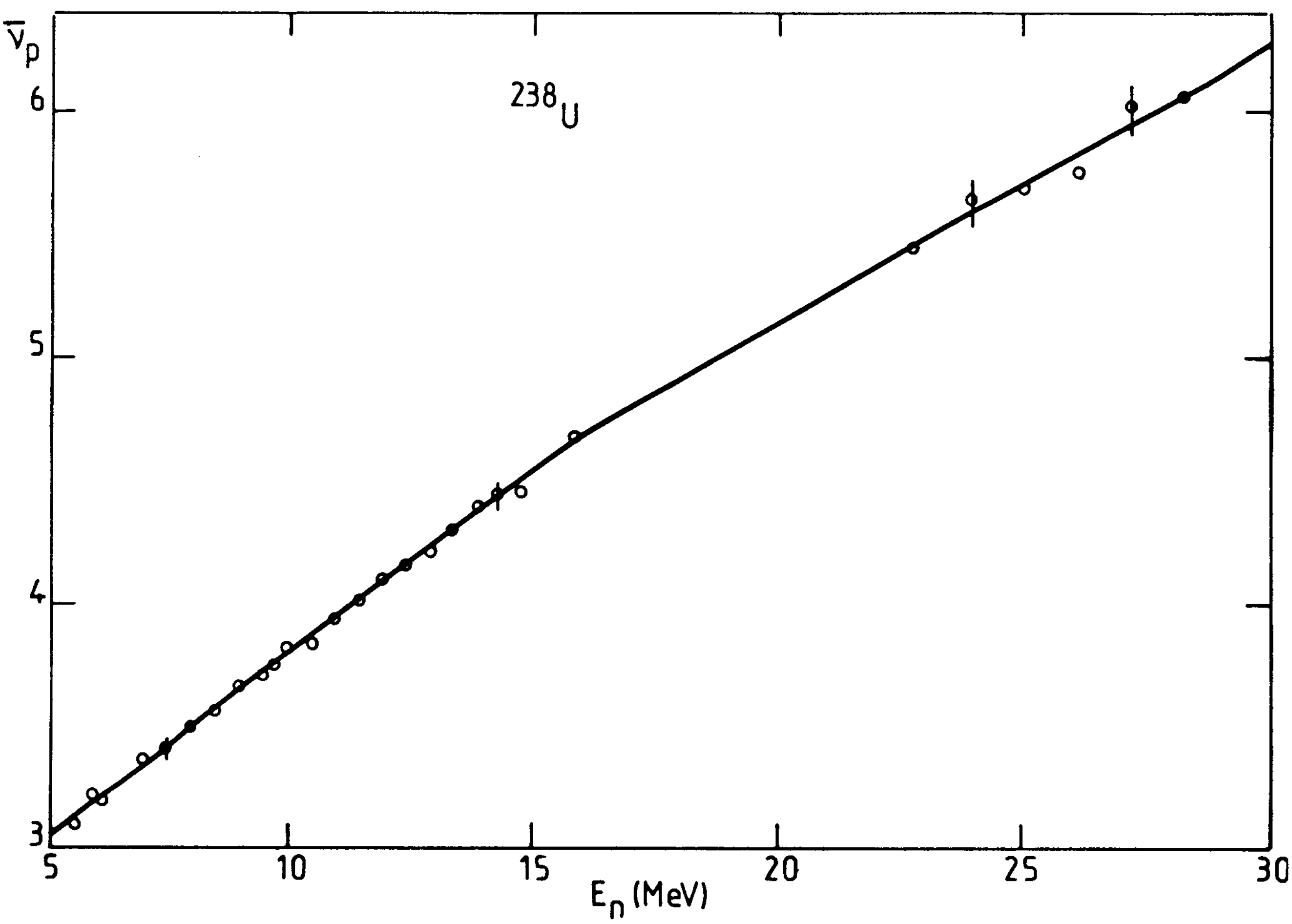


FIGURE 4



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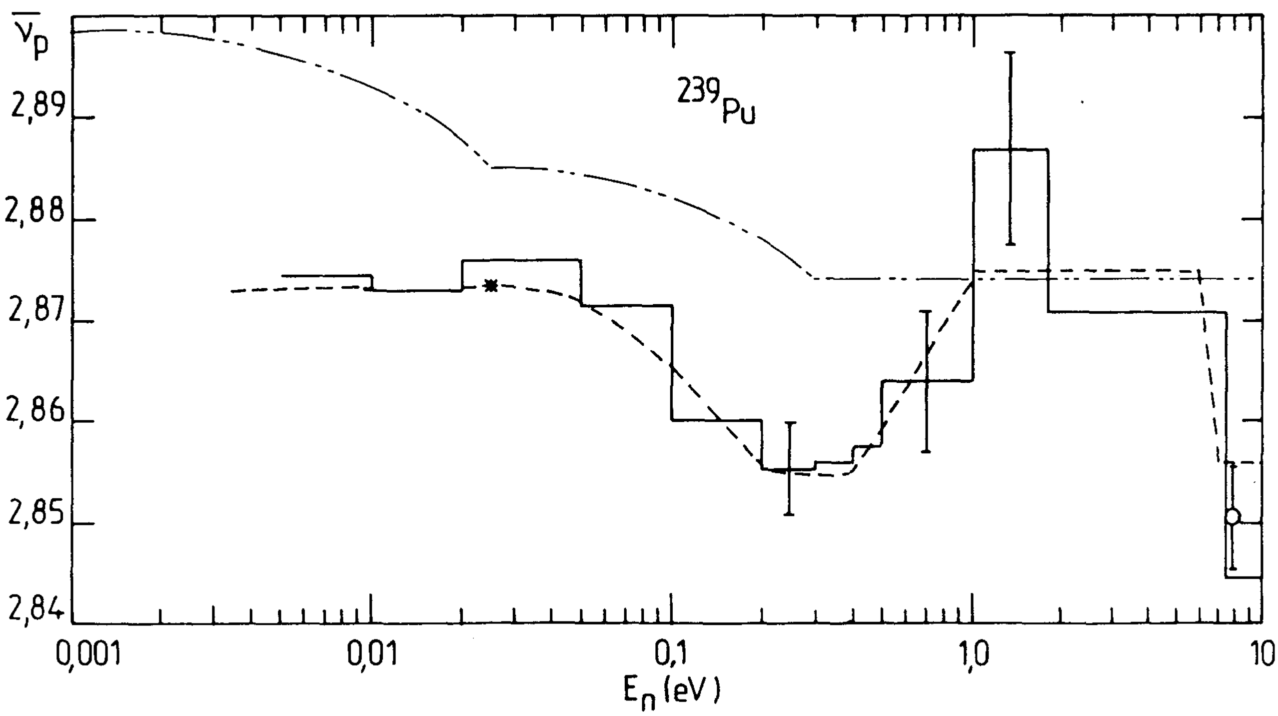

$\overline{\nu}_p$
^{239}Pu
2,89
2,88
2,87
2,86
2,85
2,84
0,001
0,01
0,1
1,0
10
E_n (eV)

FIGURE 6

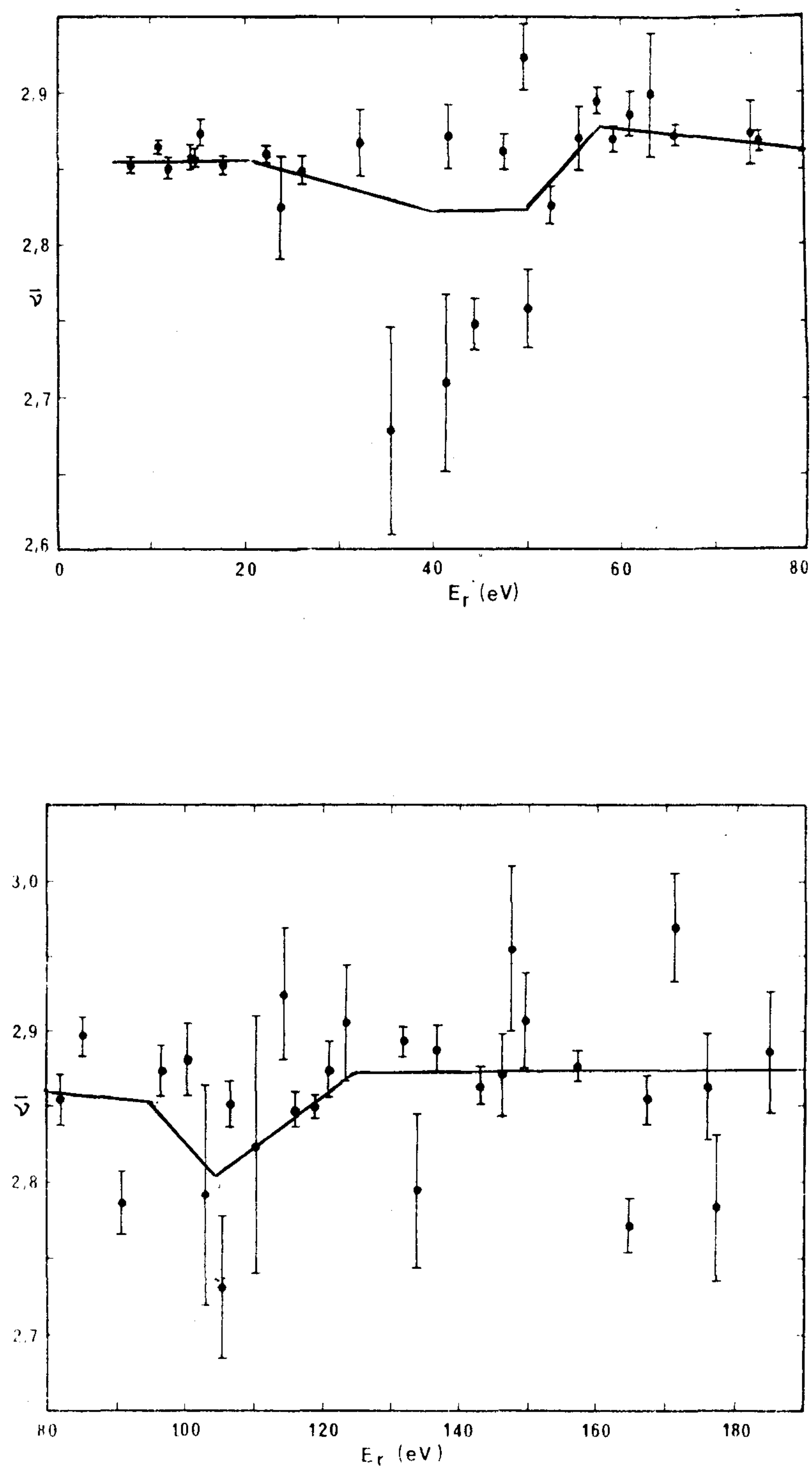
2,9
2,8
ν̄
2,7
2,6
0
20
40
60
80
E_r (eV)
3,0
2,9
ν̄
2,8
2,7
80
100
120
140
160
180
E_r (eV)

FIGURE 7

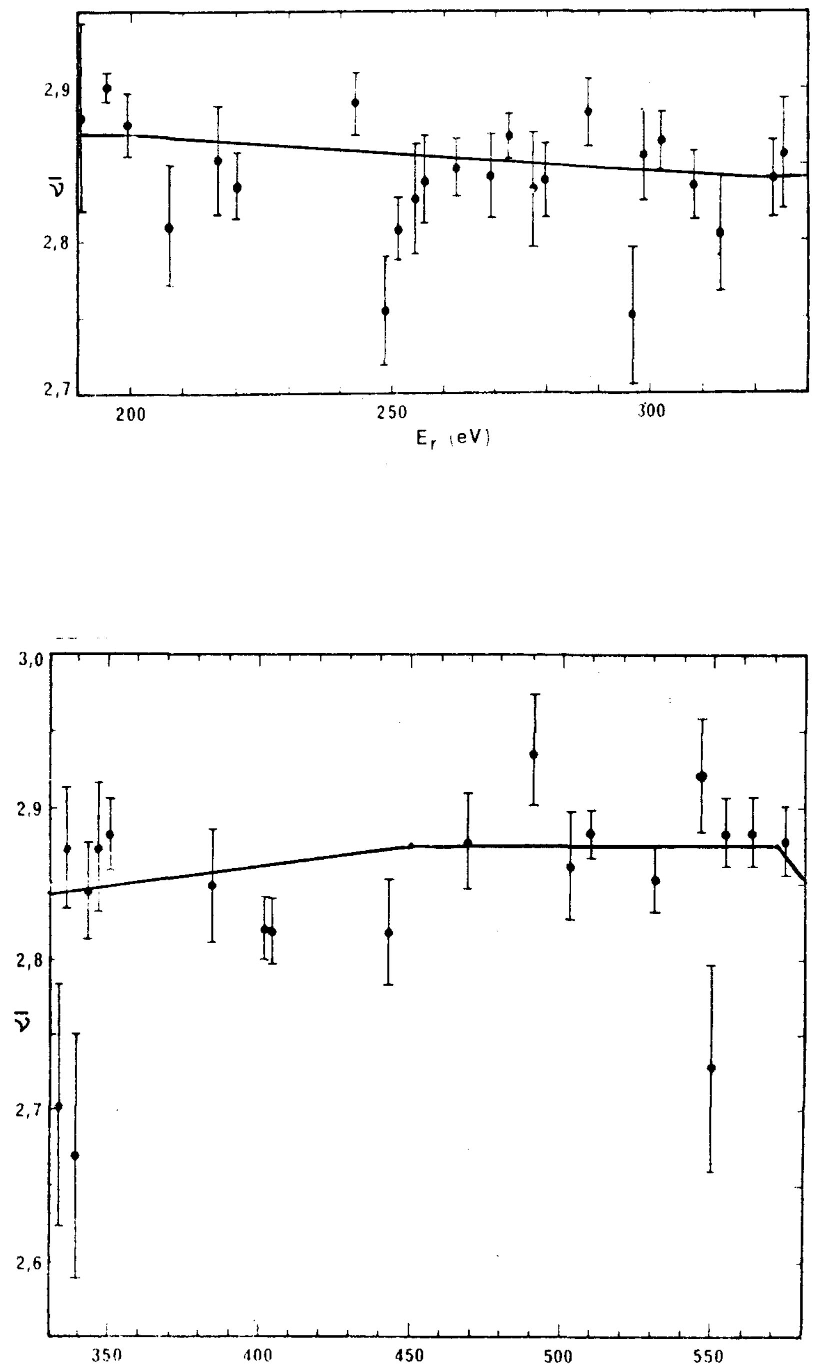
2,9
2,8
2,7
200
250
300
E_r (eV)
$\bar{\nu}$
3,0
2,9
2,8
2,7
2,6
350
400
450
500
550
E_r (eV)
$\bar{\nu}$

FIGURE 8

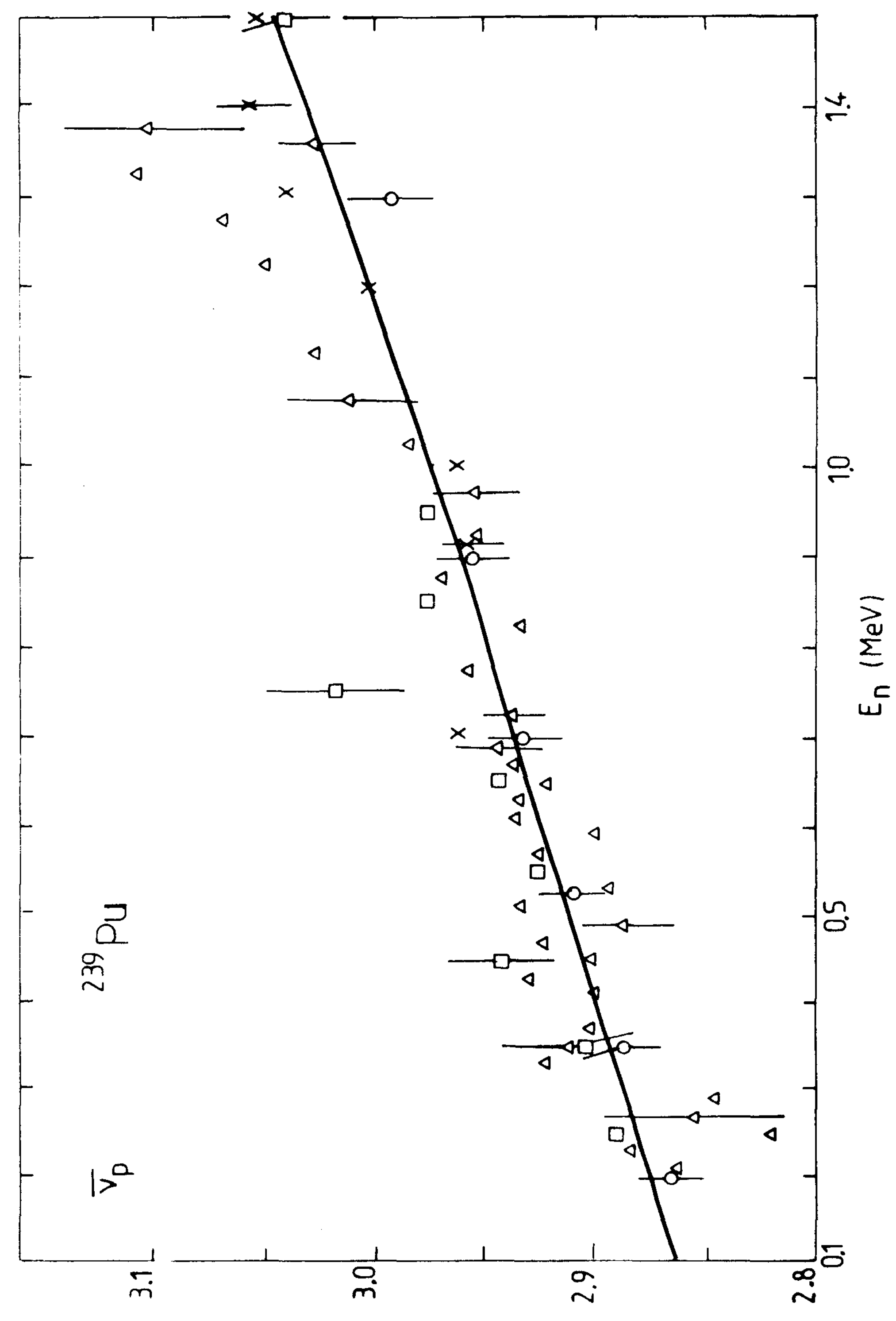

FIGURE 9

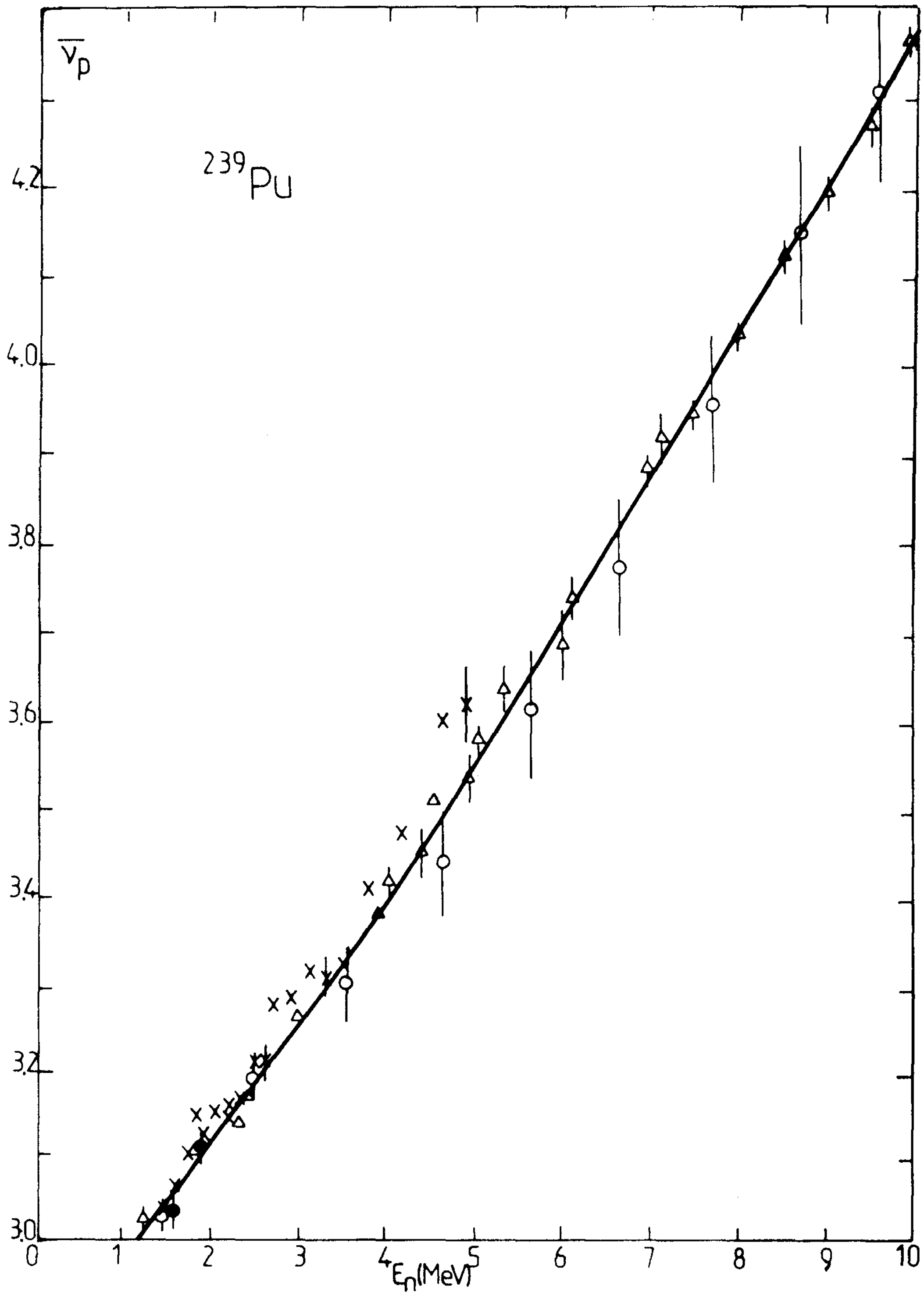

FIGURE 10

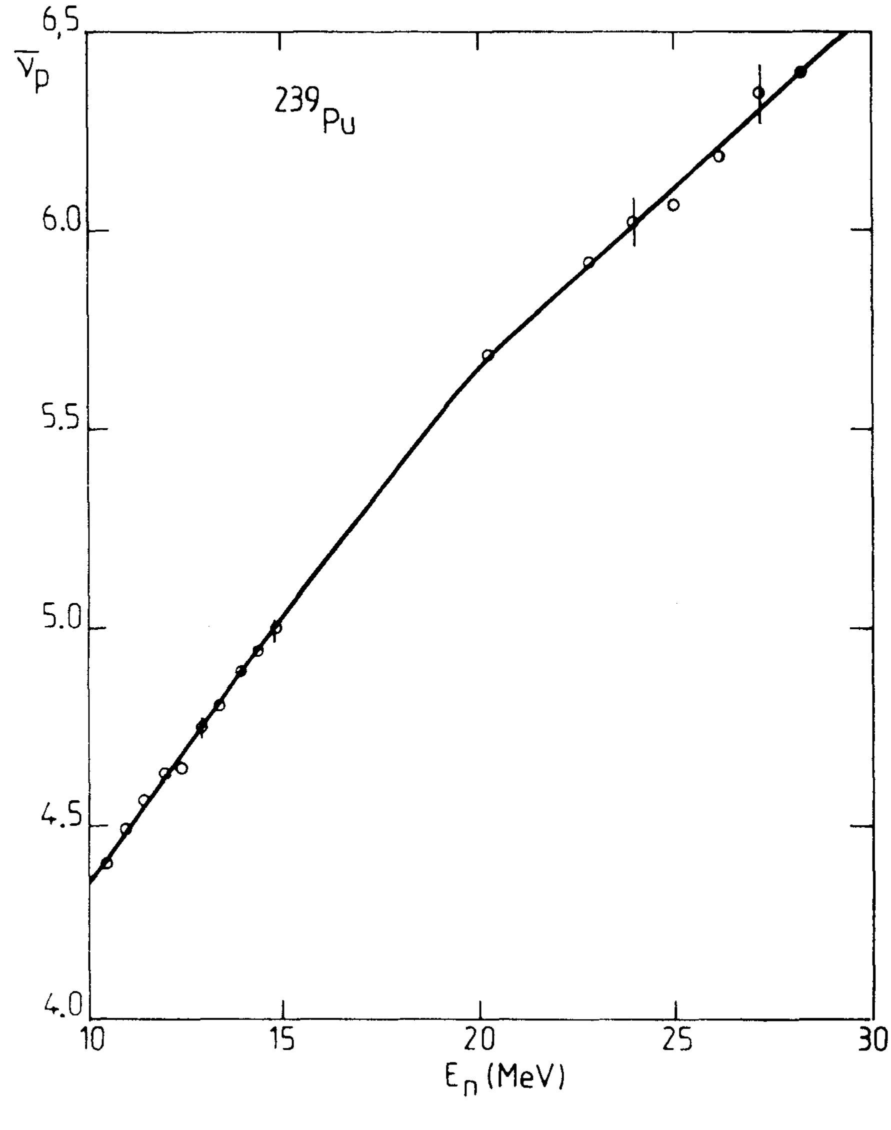

FIGURE 11