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SYSTEMATICS AND EVALUATION OF (n,2n) AND (n,3n) CROSS-SECTIONS

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SYSTEMATICS OF THE (n,2n) AND (n,3n) EXCITATION FUNCTIONS

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ABSTRACT

In this paper systematics of the (n,2n) and (n,3n) excitation functions and maximum cross-section values for these reactions are proposed. The systematics were approximated by simple expressions and can be used for nuclear data evaluations in the neutron energy region from threshold up to 20 MeV.

Systematics of the (n,2n) excitation function

The evaluation of threshold reaction cross-sections is based to a great extent on the use of systematics of cross-sections in the neutron energy range ~ 14-15 MeV. For evaluating the (n,2n) and (n,3n) reaction cross-sections, the author suggests using the maximum cross-section systematics of these reactions in relation to the mass number A obtained on the basis of existing experimental data.

Analysis of the experimental data shows that the (n,2n) reaction excitation functions have a similar form in the incident neutron energy range from the reaction threshold to the energy at which the cross-section reaches its maximum value. In order to validate this assumption the experimental (n,2n) reaction cross-sections on the neutron energy (mainly from Refs [1, 2]) were normalized to the maximum cross-sections and the corresponding neutron energies measured from the reaction threshold[*]. In those cases where there was

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[*] A similar normalization was carried out by Prof. H. Vonach in 1989 [6].

a wide spread of data at the maximum, the maximum cross-sections were evaluated within the limits of experimental error.

In order to illustrate the basis of the suggested systematics, Fig. 1 shows a schematic of the (n,2n) and (n,3n) excitation functions and indicates the notation used in the paper. Figure 2 shows the result of normalizing 30 experimental excitation functions for the (n,2n) reaction to $\sigma^{max}_{n,2n}$ and $E^{n,2n}_{max}$, where $E^{n,2n}_{max}$ is the neutron energy measured from the reaction threshold at which the reaction cross-section achieves a maximum ($\sigma^{max}_{n,2n}$). The broken lines indicate the boundaries of the spread of the normalized curves, and the points indicate 15 excitation functions at 1 MeV intervals. The other 15 functions lie within the same limits. As can be seen, the (n,2n) excitation functions in this energy range have a similar form. Variations in the shape of the normalized excitation functions are within the limits of experimental error. There are some indications that within the spread of the curves, the shape of the excitation functions is slightly dependent on E_{max}. However, owing to the errors in the existing experimental data, this assumption cannot be reliably confirmed.

The dependence plotted in Fig. 2 may be taken to represent the systematics of the shape of the excitation functions and can be approximated by the following expression:

$$\frac{\sigma_{n,2n}}{\sigma^{max}_{n,2n}} = \left(\frac{E}{E^{n,2n}_{max}}\right)^{1.35} \cdot \exp\left[1.40\left(1 - \frac{E}{E^{n,2n}_{max}}\right)\right]. \qquad (1)$$

If the contribution of competing reactions (apart from the (n,3n) reaction) is insignificant, then $E^{n,2n}_{max} = E^{n,3n}_{th} - E^{n,2n}_{th}$, provided that the quantity $E^{n,3n}_{th} - E^{n,2n}_{th} \leq 7\text{-}7.5$ MeV.

This limitation on the magnitude of the difference in the (n,3n) and (n,2n) reaction thresholds is due to the fact that when the difference is large (more than $\sim$ 7.5 MeV) the (n,2n) reaction cross-section, as shown by the experimental dependences, achieves a maximum in the majority of cases at energies of less than $E_{th}^{n,3n}$ (approximately in the range 6.5-7.5 MeV above the (n,2n) reaction threshold).

Accordingly, for evaluating such excitation functions, E_{max} should be assumed equal to 6.5-7.5 MeV in expression (1). When sufficiently reliable experimental data are available, a more exact determination of E_{max} will result from matching of the functional dependence with the experimental data.

It should however be noted that calculation using expression (1) slightly overestimates the reaction cross-section in the energy range from the threshold to ~ 1 MeV above the threshold for excitation functions with a high value ($Q_{n,3n}$- $Q_{n,2n}$) (above 7.5-8.5 MeV). In this case, for neutron energies up to ~ 1 MeV above the threshold it is preferable to use the experimental dependence indicated in Fig. 2 by the broken lines.

Analysis of all the available data and the practical application of expression (1) have shown that the similarity of (n,2n) excitation functions exists over the whole range of mass numbers.

Systematics of the (n,3n) excitation function

Very little experimental data is available in the neutron energy range 20-30 MeV, where the (n,3n) reaction cross-section achieves a maximum. However, analysis of the few available (n,3n) excitation functions leads to the quite definite conclusion that in this case too there is similarity in the shape of the reaction cross-section energy dependence in the neutron energy range from the threshold to energy $E_{max}^{n,3n}$, at which the cross-section reaches a maximum $\sigma_{n,3n}^{max}$. Figure 2 shows the (n,3n) cross-sections from Refs [3, 4] normalized to $\sigma_{n,3n}^{max}$ and $E_{max}^{n,3n}$. The broken lines indicate the range of spread of the experimental curves. This dependence can be approximated by the formula:

$$\frac{\sigma_{n,3n}}{\sigma_{n,3n}^{\max}} = \left(\frac{E}{E_{\max}^{n,3n}}\right)^{3.3} \cdot \exp\left[3.3\left(1 - \frac{E}{E_{\max}^{n,3n}}\right)\right], \qquad (2)$$

where E is measured from the threshold $E_{th}^{n,3n}$. These systematics enable the competition of the (n,3n) reaction to be taken into account when evaluating the (n,2n) reaction cross-sections over the whole range of incident neutron energies from the threshold to 20 MeV.

Systematics of ($\sigma_{n,2n}^{max}$) and ($\sigma_{n,3n}^{max}$) in relation to A

$\sigma_{n,2n}^{max}$ was evaluated on the basis of experimental data for approximately 60 isotopes and the dependence on the mass number A was plotted. The result is shown in Fig. 3. Within the error limits indicated, this dependence is approximated well within the range $50 \leqslant A \leqslant 210$ by the simple relationship:

$$\sigma_{n,2n}^{max} = 65.4 \cdot A^{2/3} \qquad (3)$$

The results of analysis of the (n,2n) reaction from Ref. [5] were also used in plotting the dependence.

The appreciable deviation of $\sigma_{n,2n}^{max}$ of the (n,2n) reaction for a given isotope from the systematics may be due to experimental error or to a large contribution from another competing reaction apart from the (n,3n) reaction, in particular the reaction (n,np). Possible competition from the (n,np) reaction can be determined by comparing the dependence of the (n,2n), (n,3n) and (n,np) reaction thresholds on the atomic weight of the isotopes of a given element. Figure 4 shows two examples of such a comparison. A lower threshold of the (n,np) reaction compared to that of the (n,2n) reaction is a necessary but insufficient condition for the presence of a significant contribution from the (n,np) reaction. Analysis has shown, for example, that for isotopes with even A a high value of ($E_{th}^{n,3n}$ - $E_{th}^{n,2n}$) (higher than ~ 9 MeV) may be a sufficient condition. Figure 4 shows that such conditions are obtained for ^{58}Ni and ^{92}Mo. In this case the (n,np) reaction is dominant for ^{58}Ni and significant for ^{92}Mo.

The amount of experimental data for the (n,3n) reaction is adequate for constructing reliable systematics of the maximum value of the cross-section for this reaction. The data shown in Fig. 4 give an approximate evaluation of $\sigma^{max}_{n,3n} = 10 \cdot A$ within the error limits and assuming a linear dependence.

The use of the systematics presented here for evaluation of (n,2n) reaction cross-sections in conditions where reliable experimental data are available enable the (n,2n) excitation functions to be approximated with an acceptable degree of error in the energy range from the threshold to 20 MeV. Figure 5 shows by way of example calculations of the (n,2n) reaction cross-sections for ^{96}Zr, ^{127}I, ^{100}Mo and ^{197}Au, performed using the systematics. No additional correction was made to obtain better agreement with experimental data. Evaluated data from other libraries are given for comparison. The results indicate that sufficiently reliable evaluations may be obtained for reaction excitation functions where only few or contradictory data are available.

Although the proposed systematics give fully satisfactory results for the current status of experimental data and their error levels, as new experiments appear, more thorough analysis is performed and wider use is made of the systematics, and it is likely that the latter, along with the coefficients adopted, will undergo refinement.

The author wishes to express his gratitude to Mr. A.I. Blokhin and A.V. Ignatyuk for their useful comments.

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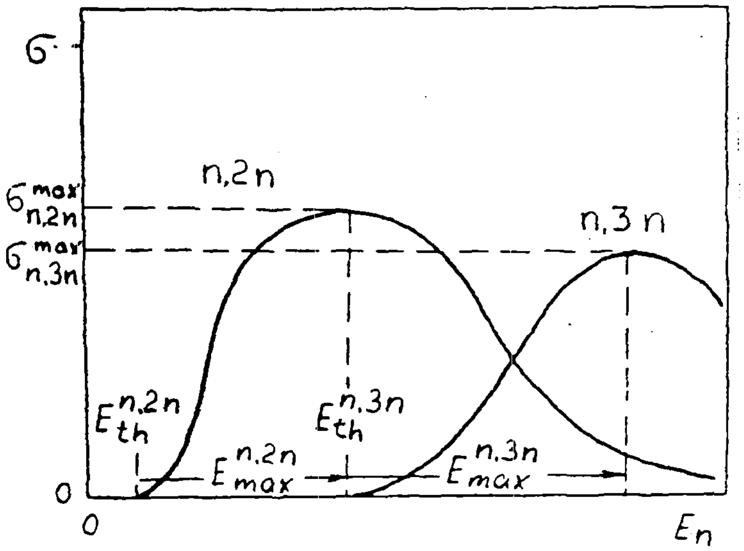

FIG. 1. *Parameter notation for (n,2n) and (n,3n) reactions.*

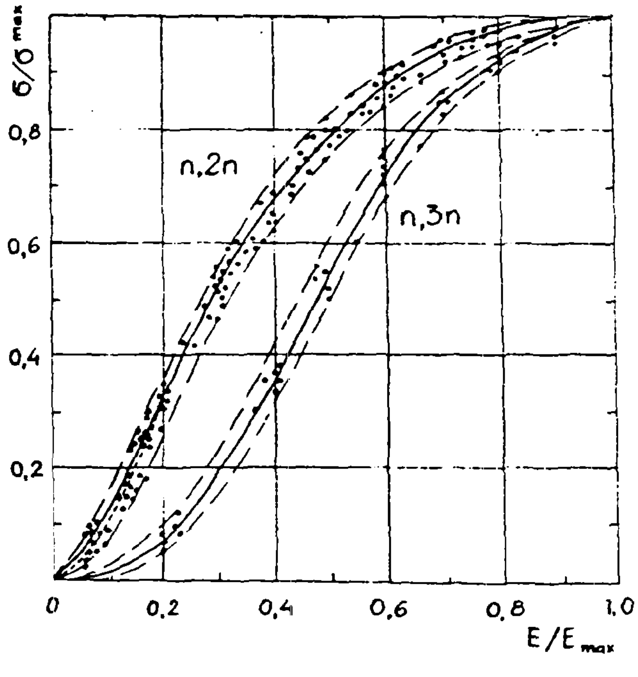

FIG. 2. *Normalized excitation functions for (n,2n) and (n,3n) reactions.*

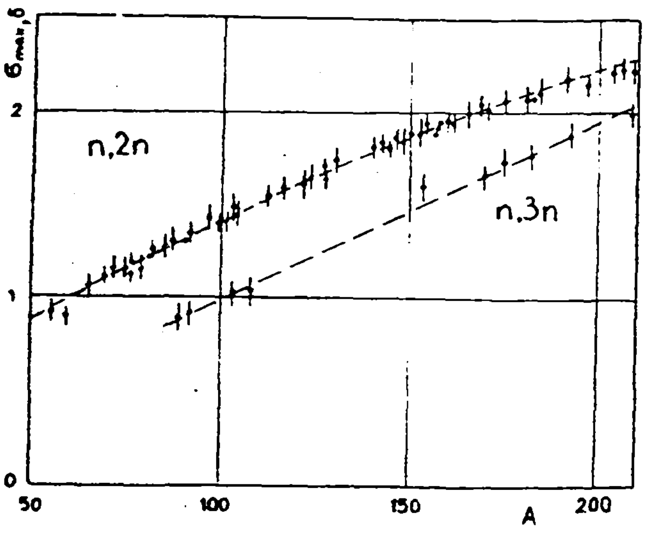

FIG. 3. *Dependence of maximum cross-sections of (n,2n) and (n,3n) reactions on A.*

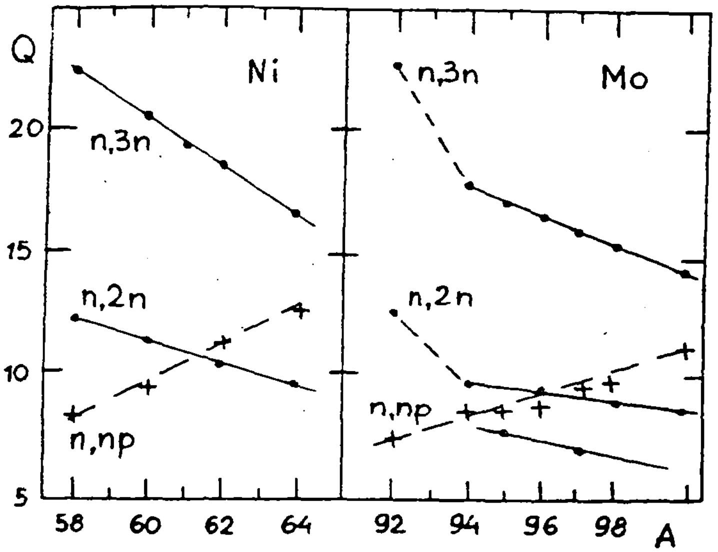

FIG. 4. *Dependence of the thresholds of (n,2n), (n,3n) and (n,np) reactions on A.*

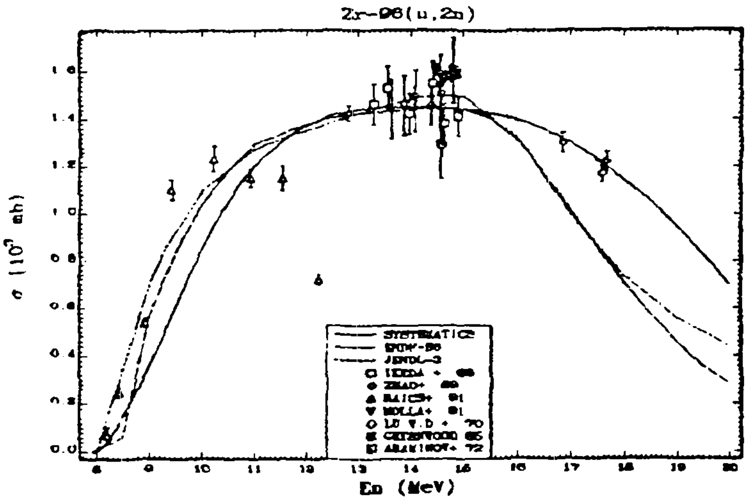

FIG. 5. *Excitation function of (n,2n) reaction on ^{96}Zr.*

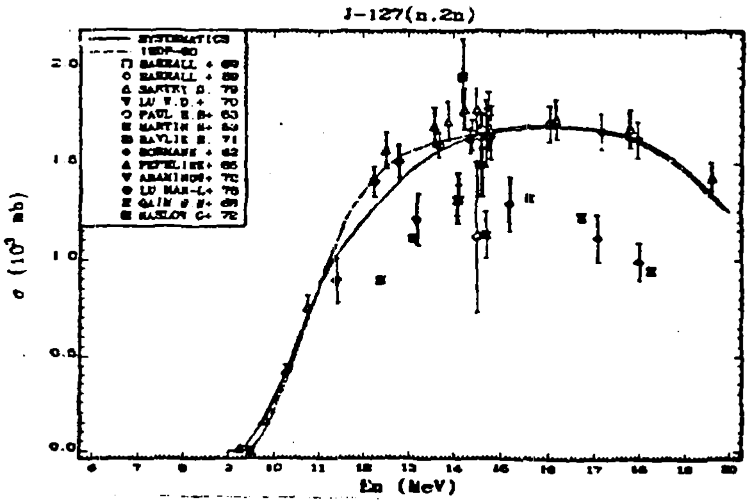

FIG. 6. *Excitation function of (n,2n) reaction on ^{127}I.*

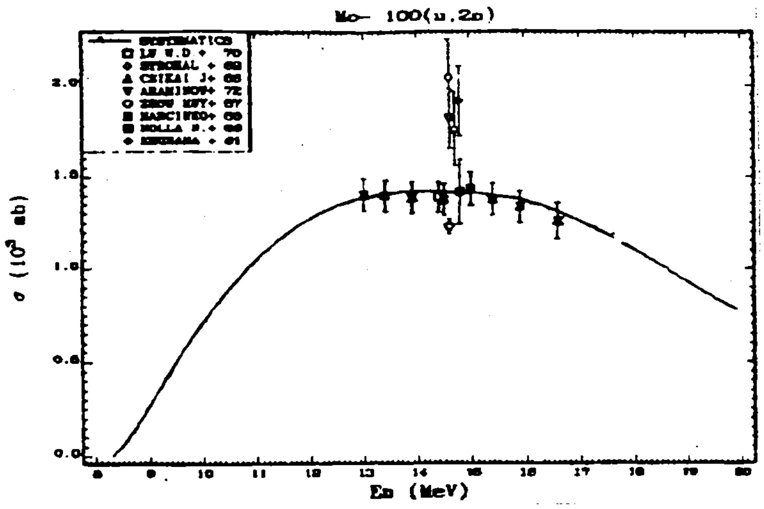

FIG. 7. *Excitation function of (n,2n) reaction on* ^{100}*Mo.*

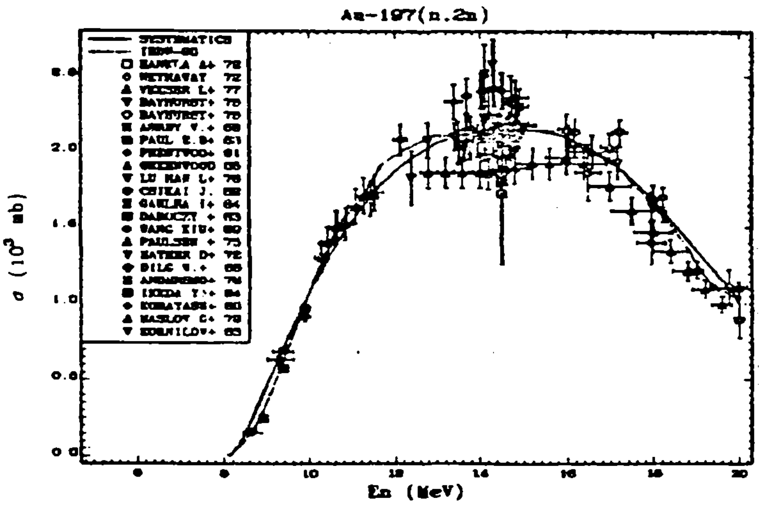

FIG. 8. *Excitation function of (n,2n) reaction on* ^{197}*Au.*

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EVALUATION OF THE (n,2n) REACTION CROSS-SECTIONS FOR SCANDIUM

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ABSTRACT

Using excitation function systematics, a consistent evaluation was performed of the cross-sections of the ^{45}Sc(n,2n) reaction leading to production of ^{44}Sc^{m}, ^{44}Sc^{g} and ^{44}Sc^{m+g} in the neutron energy region from the threshold to 20 MeV.

The scandium (n,2n) reaction is used in reactor dosimetry. As a result of this reaction, a radioactive nucleus in a ground and isomeric state is formed. Table 1 gives the main parameters of the reaction.

TABLE 1

Reaction	$Q_{n,2n}$	$E_{th}^{n,2n}$ threshold	$T_{1/2}$	Spin
^{45}Sc (n,2n) ^{44}Sc^{m}	-11.595	-11.855	58.6 h	6+
^{45}Sc (n,2n) ^{44}Sc^{g}	-11.324	-11.575	3.927 h	2+

The isomer ratio was evaluated in Ref. [1] as 0.45 ± 0.06. The experimental data on the reaction cross-sections are given in Refs [3-25]. With the aid of the excitation function systematics proposed in Ref. [2], a consistent parametrization was performed of the sum cross-section and the cross-sections of the (n,2n) reaction with formation of a residual nucleus in the ground and isomeric states, assuming a constant isomer ratio over the whole energy range examined. The initial parameters used to calculate the cross-sections were varied within the limits of experimental error, so as to obtain good agreement with the measurements in Refs [3, 5, 6], and the data from Ref. [5] were multiplied by 1.078, in accordance with the recommendations of Ref. [26].

Consistent parametrization was obtained for the condition $\sigma_m/\sigma_m + \sigma_g = 0.40 \pm 0.02$.

The results of the evaluation are listed in Table 2 and illustrated in Figs 1-3. The errors in the evaluated data were determined from the errors in the systematics used for the parametrization. These errors include the systematic error involved in normalizing the data to the maximum cross-section, and an indeterminacy in the form of a dependence of the excitation functions on neutron energy.

In Figs. 1-3 the data from the evaluations performed in Ref. [3] are shown for comparison. Significant divergences in the evaluations may be observed. The main difference is that in the present work the isomer ratio was assumed to be constant, whereas in Ref. [3], as analysis of the evaluated data given shows, the isomer ratio decreases from 0.45 to ~ 0.36 as neutron energy rises.

The evaluation performed here was used to create a data file in ENDF format which it is proposed to include in the Russian Dosimetric File (RDF-93) currently being established at the Nuclear Data Centre of the Power Physics Institute.

TABLE 2

Neutron energy, MeV	^{45}Sc (n,2n) ^{44}Sc	^{45}Sc (n,2n) ^{44}Sc^{g}	^{45}Sc (n,2n) ^{44}Sc^{m}
11.6	0	0	
12.0	10 ± 2	10 ± 2	0
12.5	45 ± 6	28 ± 5	17 ± 3
13.0	108 ± 10	65 ± 6	43 ± 4
13.5	178 ± 18	106 ± 11	72 ± 7
14.0	248 ± 15	148 ± 8	100 ± 5
14.5	304 ± 15	184 ± 9	120 ± 6
15.0	338 ± 17	205 ± 11	134 ± 7
16.0	395 ± 20	257 ± 13	156 ± 8
17.0	425 ± 22	266 ± 13	168 ± 9
18.0	441 ± 22	266 ± 13	175 ± 9
19.0	446 ± 23	268 ± 14	178 ± 9
20.0	450 ± 23	270 ± 14	180 ± 9

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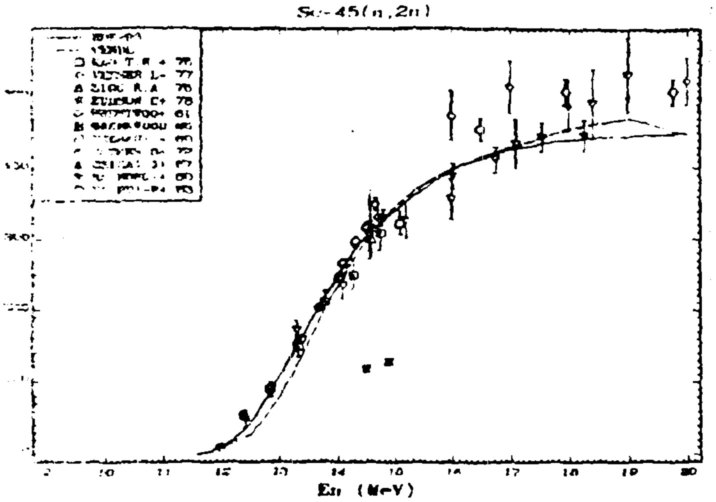

FIG. 1. Excitation function for the reaction $^{45}Sc(n,2n)^{44}Sc$.

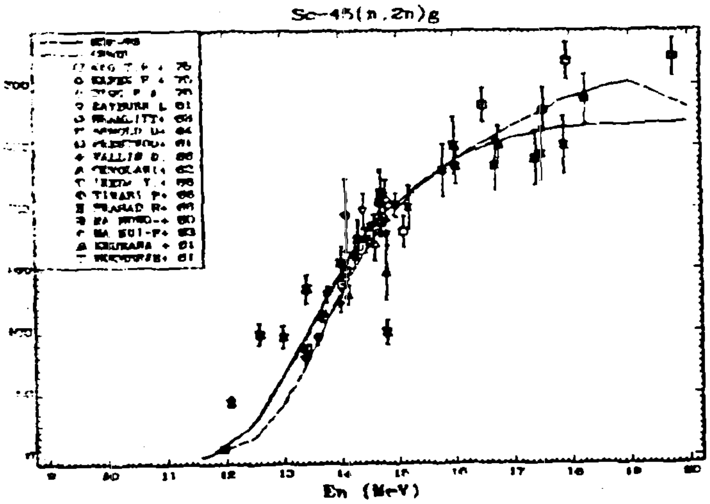

FIG. 2. Excitation function for the reaction $^{45}Sc(n,2n)^{44}Sc^{g}$.

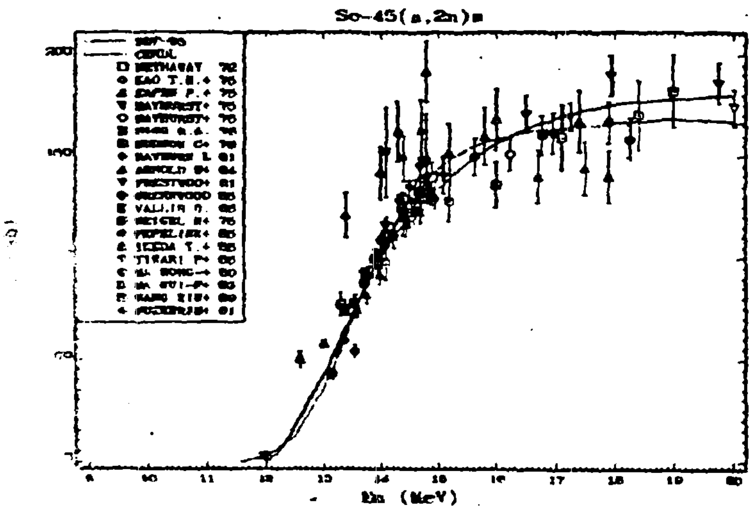

FIG. 3. Excitation function for the reaction $^{45}Sc(n,2n)^{44}Sc^{m}$.

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