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Evaluation of Some Fast Neutron Cross Section Data*

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Abstract

Presented here are cross section evaluations for $^{27}\text{Al}(n, \alpha)$, $^{56}\text{Fe}(n, p)$, $^{63}\text{Cu}(n, 2n)$ and $^{65}\text{Cu}(n, 2n)$ reactions which are often adopted as standards in fast neutron experiments. Data from some fifty papers reporting excitation functions and individual experimental points are averaged by a computer procedure. Information on input values is summarized in a table. Output values are displayed in a table and on graphs which also contain experimental points for comparison. The neutron energy range is from threshold to $\simeq 20$ MeV. The literature is covered to the end of 1967. Values reported in 1968 and 1969 are discussed in a note.

* Work performed as one of the projects of the Japanese Nuclear Data Committee.

二、三の高速中性子断面積の評価*

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要 旨

高速中性子断面積を測定する際に、しばしば標準断面積として使われる4種類の反応を選んで評価した。入射中性子のエネルギーが、反応しきい値から約20 MeVまでの評価の結果、採択された断面積の値、およびそれらと実験値との比較を、表とグラフの形で整理してある。評価の方法については、序論でかなり詳しく述べてある。実験データはかなり多いにもかかわらず、たとえば $^{63}\text{Cu}(n, 2n)$ 反応の場合にみられるような若干の問題点を残しているものもあるので、今後さらに測定が行なわれることが強く望まれる。

* この仕事はシグマ研究委員会の計画の一つとして行なわれた。

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1. Introduction

Critical review of reaction cross sections for fast neutrons is needed for investigation of nuclear reaction theory as well as in connection with standards for neutron flux measurements. Although extensive experimental work has been reported on (n, α) , (n, p) and $(n, 2n)$ reactions for a number of targets in the energy region from threshold to 20 MeV, the experimental cross sections reported by different workers are so scattered that it is not easy to find reliable values. Evaluation of results for four reactions by an objective, computerized technique is reported here. The four reactions chosen, $^{27}\text{Al}(n, \alpha)$, $^{56}\text{Fe}(n, p)$, $^{63}\text{Cu}(n, 2n)$, and $^{65}\text{Cu}(n, 2n)$, are especially useful as standards in cross section measurements by means of the activation method, since the cross sections are large for 14 MeV neutrons and fabrications of the targets required is easy.

2. Compilation of Existing Data

The papers we surveyed are mainly those listed in CINDA and found in journals dated up to December 1967. Since in the present work we are not interested in the fine structure of the excitation function, articles concerning cross-section fluctuations were not considered. In some original papers the spread of the neutron energy was not mentioned. For such cases the spread was estimated by checking the experimental condition if possible, otherwise ± 0.5 MeV was assigned arbitrarily*. So far as we could see, there are no systematic deviations due to differences in experimental method.

All data points are classified in two categories in our evaluation process: (A) data obtained by absolute measurement, and (R) data obtained by measurements relative to other cross sections. Category (A) contains only data from experiments in which the neutron flux is measured by the number of associated alpha particles from $T(d, n)^4\text{He}$ and the residual activity is counted by means of calibrated detectors. TABLE I indicates all papers reviewed and shows whether the measurements were absolute (A) or relative (R). This table also lists standards used, method of detecting emitted particle or activity of the product, number of values determined and neutron energy range covered. In cases where the measurements were relative, the standards used are given.

3. Determination of the Shape of the Excitation Function

Using the data on excitation function, mainly category (R), we first determine the most probable shape of the excitation function. Looking at all available data, we divide the whole energy range into a few sub-regions with slight overlaps. In a sub-region, the data covering at least five data points are selected in order to use a least-squares fitting procedure with a quadratic function of energy. Assigned weights are based on the reported errors in the cross section and

* This does not mean that the experiments without any description of energy spread are not reliable. Our choice of ± 0.5 MeV is merely for calculational convenience.

spread of neutron energy. Details of this procedure are given in the Appendix. The curve thus obtained for each sub-region is connected to the neighboring one by moving up (or down) along the ordinate with logarithmic scale. In the present case, the discontinuity arising from possible difference in the curvature at the connecting point was not so serious that it was smoothed out by hand. Thus we find the most probable shape of the excitation function for the whole energy range.

4. Determination of an Absolute Value of the Cross Section

Since almost all absolute measurements have been made at energies between 14 and 15 MeV, we choose 14.5 MeV as the energy point at which to determine the absolute value of the cross section. The data at other energy points of category (A) are shifted to 14.5 MeV along the most probable shape of the excitation function determined in the previous sub-section or along the experimenter's excitation curve determined by absolute measurement. Absolute value of the cross sections at 14.5 MeV are then calculated as weighted means. TABLE 2 shows the individual values obtained in this way (with references) and the weighted averages.

By normalizing the most probable excitation function determined previously to the absolute value of the cross section at 14.5 MeV, we obtain the adopted cross sections in the whole energy range. These are tabulated in TABLE 3 with 0.5 MeV steps. Here, $\Delta\sigma$ corresponds to a band with confidence coefficient of 95% in t-distribution.

The adopted curves are presented in Figs. 2-5 which also contain the experimental points as originally reported in the literature. The renormalizing factor $(1+\delta)$ required to bring any author's results into least squares conformity with the adopted curve can be found from TABLE 1 where δ is given in per cent. If these renormalization values are used, the fit shown in Figs. 6-9 is found.

5. Discussion

For the $^{27}\text{Al}(n, \alpha)$ and $^{56}\text{Fe}(n, p)$ reactions, as shown in Figs. 2 and 3, the cross-section behavior near threshold agrees with theoretical prediction for charged-particle-emitting reactions¹⁾, namely cross-section curve rises exponentially. For two-particle-emitting reactions, no theoretical prediction on the cross-section behavior near threshold has been made. The curves in Figs. 4 and 5, however, suggest that the cross-section behavior near threshold for $(n, 2n)$ reactions is similar to that for single charged-particle-emitting reactions, if account is taken of the Q-values of $^{63}\text{Cu}(n, 2n)$ and $^{65}\text{Cu}(n, 2n)$ reactions, 10.84 and 9.91 MeV, respectively.

In Fig. 10, our adopted excitation functions are compared with those presented in BNL-325³⁾ and in Nagel's report⁴⁾. The $(n, 2n)$ cross sections calculated by PEARLSTEIN⁵⁾ are also shown. Around 13 MeV our result for the $^{27}\text{Al}(n, \alpha)$ excitation function disagrees with the curve of BNL-325³⁾ which probably has been drawn intuitively. Nagel's curve at 12 MeV for $^{27}\text{Al}(n, \alpha)$ reaction seems to be considerably lower than ours. Our result in this energy region is affected mainly by the experimental data by BUTLER and SANTRY⁶⁾ which are fairly well reproduced by calculation⁷⁾ based on statistical theory.

Above 15 MeV, our adopted curve for $^{63}\text{Cu}(n, 2n)$ reaction falls below the curves of BNL-

325³⁾ and NAGEL⁴⁾. This is due to different methods of evaluating the experimental data in this energy region where the data points seem to lie, as seen in **Fig. 4**, on two separated curves. Since the most of these data points have been obtained by relative measurements and so belong to category (R) according to our classification, they are used to determine only the shape of the excitation function in our case. However, the number of data points in upper group is larger than in lower one, so that it might be possible to draw a curve close to the upper group if the least squares method were applied in another way.

In evaluating the data on $^{65}\text{Cu}(n, 2n)^{64}\text{Cu}$ reaction, the recently evaluated branching ratio for ^{64}Cu -decay⁸⁾ was used for revision of measured values. However, this correction does not affect our final result very much (<0.6%).

The authors wish to thank Dr. S. IGARASI for his advice on computer program, and members of the Japanese Nuclear Data Committee for many discussions. We are also grateful to Dr. K. WAY for valuable discussions and comments.

Note

Long time was taken to prepare this manuscript since we have discussed with Dr. K. WAY about our preliminary discussions published in the Proceedings of the Conference on Neutron Cross Sections and Technology⁹⁾. New data appeared in the meantime. The pertinent references until December 1969 have been added at the end of **TABLE I**. If these values reported are plotted on **Figs. 2-5**, it is found that the new data points are in fairly good agreement with the adopted cross-section values for these reactions except for the case of $^{63}\text{Cu}(n, 2n)$ reaction. In the case of $^{63}\text{Cu}(n, 2n)$ reaction, the new data points by 69Bol and 69Cr are found to be considerably high in the energy range of 13 to 18 MeV.

References

- 1) BLATT J. M. and WEISSKOPF V. F.: *Theoretical Nuclear Physics*, John Wiley and Sons (1952) p. 394.
- 2) MAPLES C., GOTH G. W. and CERNY J.: *Nucl. Data A2*, 429 (1966).
- 3) BNL-325, Second Edition, Supplement No. 2, Vol. I (1964) and Vol. IIA (1966).
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- 5) PEARLSTEIN S.: *Nucl. Data A3*, 327 (1967).
- 6) BUTLER J. P. and SANTRY D. C.: *Can. J. Phys.* **41**, 372 (1963).
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Appendix

Procedure for determining shape of excitation function

The procedure for determining the shape of the most probable excitation function in each sub-region ($E_i \leq E \leq E_f$) is shown schematically in **Fig. 1**. The explanation of this figure is following: One data set is chosen as the first reference data D_R and the least squares method used to fit it with a quadratic functional form F_R , marked as ① in the figure. A different functional form F_O , ② in the figure, is obtained from other data D_O . The values of F_R and F_O at energy

of E_N are used in normalizing D_0 to D_R , and the normalized D_0 is specified by D_{ON} . Again the least squares method is applied to both D_R and D_{ON} , and the standard deviation is calculated. By changing the normalization point E_N in step of 0.5 MeV, we look for the best normalization point \tilde{E}_N at which the standard deviation is minimum. Thus we find combined data of $D_R(E)$ and $D_{ON}(E, \tilde{E}_N)$, and use this as the second reference data. The least squares fit to the second reference data is shown in the figure as ③. Repetition of the least squares fit and the normalization operations leads to a weighted average excitation curve in each sub-region of neutron energy. A typical example of the curve obtained by these operations is also illustrated in Fig. 1. It should be pointed out that the choice of the first reference data, $D_R(E)$ in Fig. 1, does not affect the final shape of the excitation function. Thus we find the most probable shape of the excitation function for whole energy range by connecting each curve.

Figures and Tables

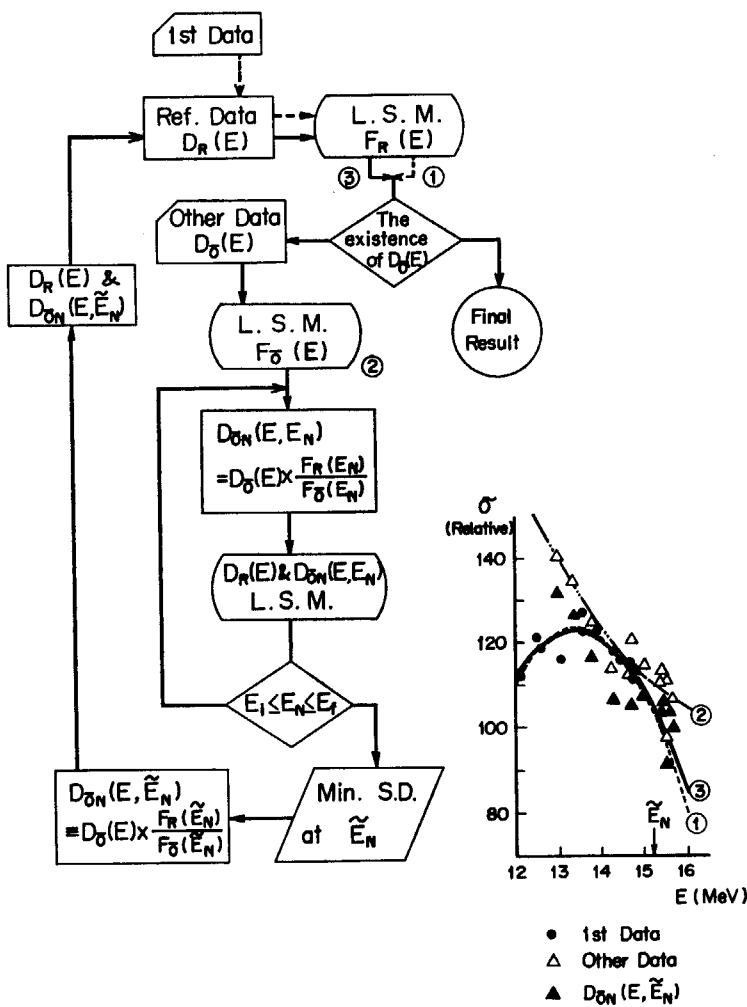
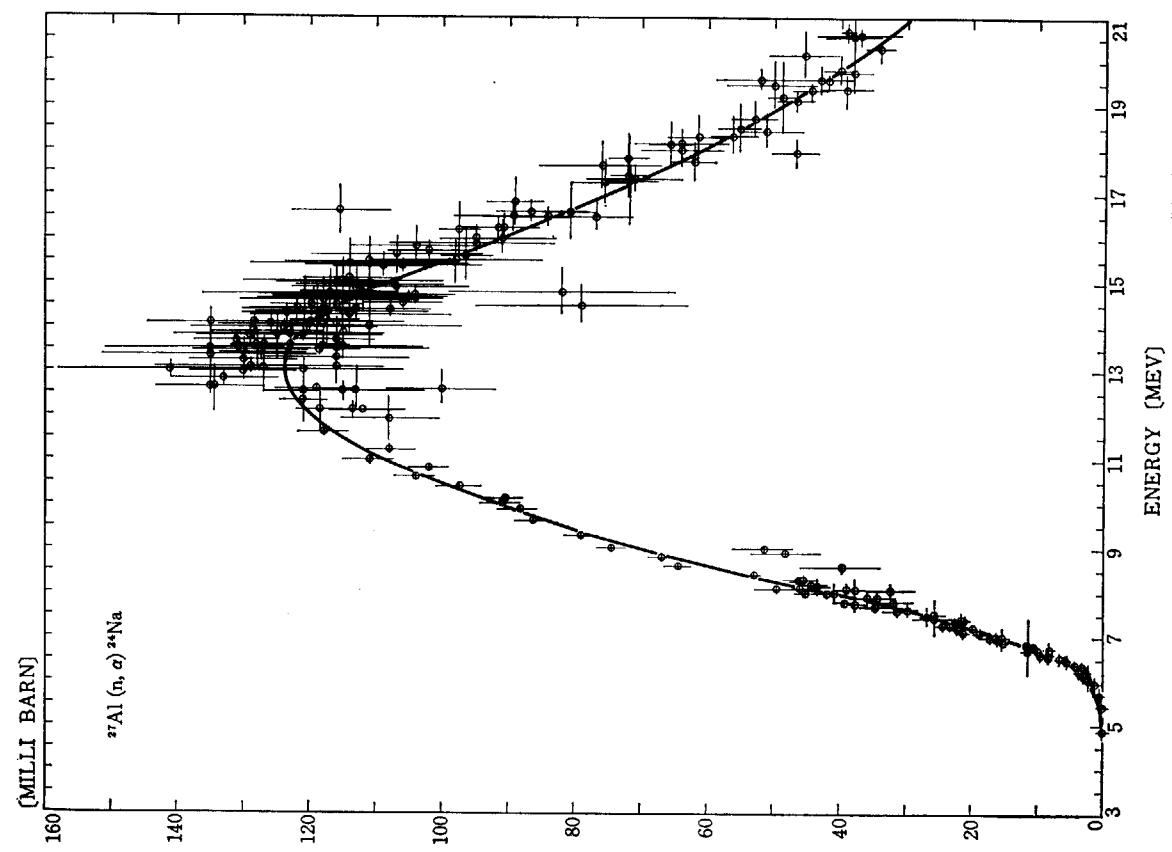
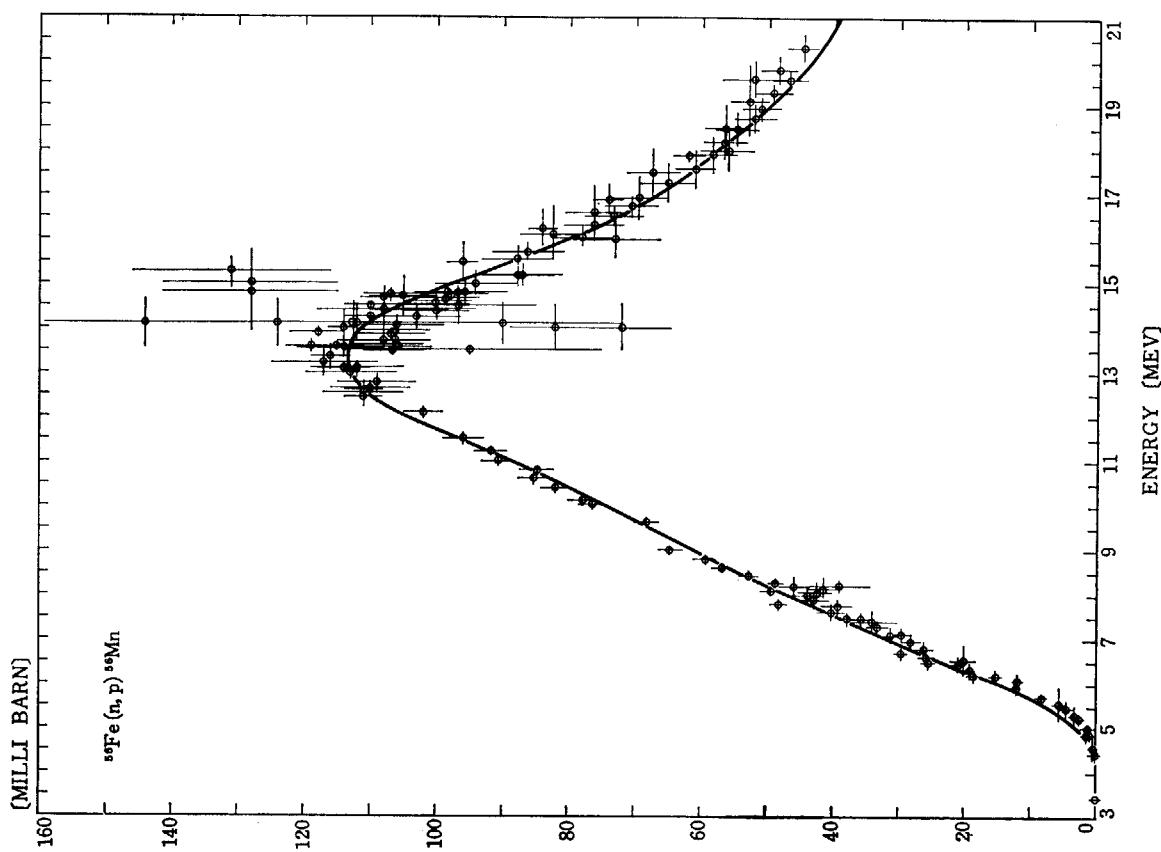


Fig. 1 Schematic representation of steps in procedure for determination of shape of excitation functions.

Fig. 2 Experimental points and the adopted cross-section curve for $^{27}\text{Al}(\text{n}, \alpha)$.Fig. 3 Experimental points and the adopted cross-section curve for $^{56}\text{Fe}(\text{n}, \text{p})$.

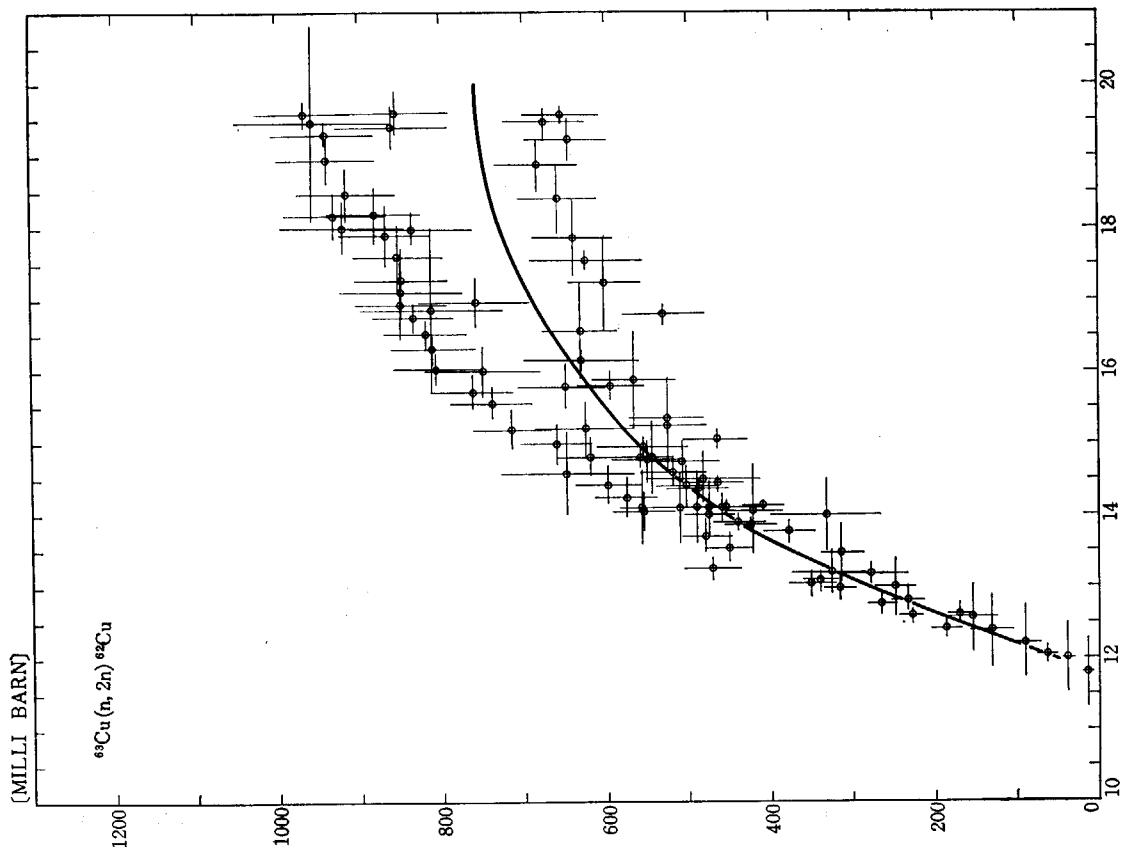


Fig. 4 Experimental points and the adopted cross-section curve for $^{63}\text{Cu}(n, 2n)$.

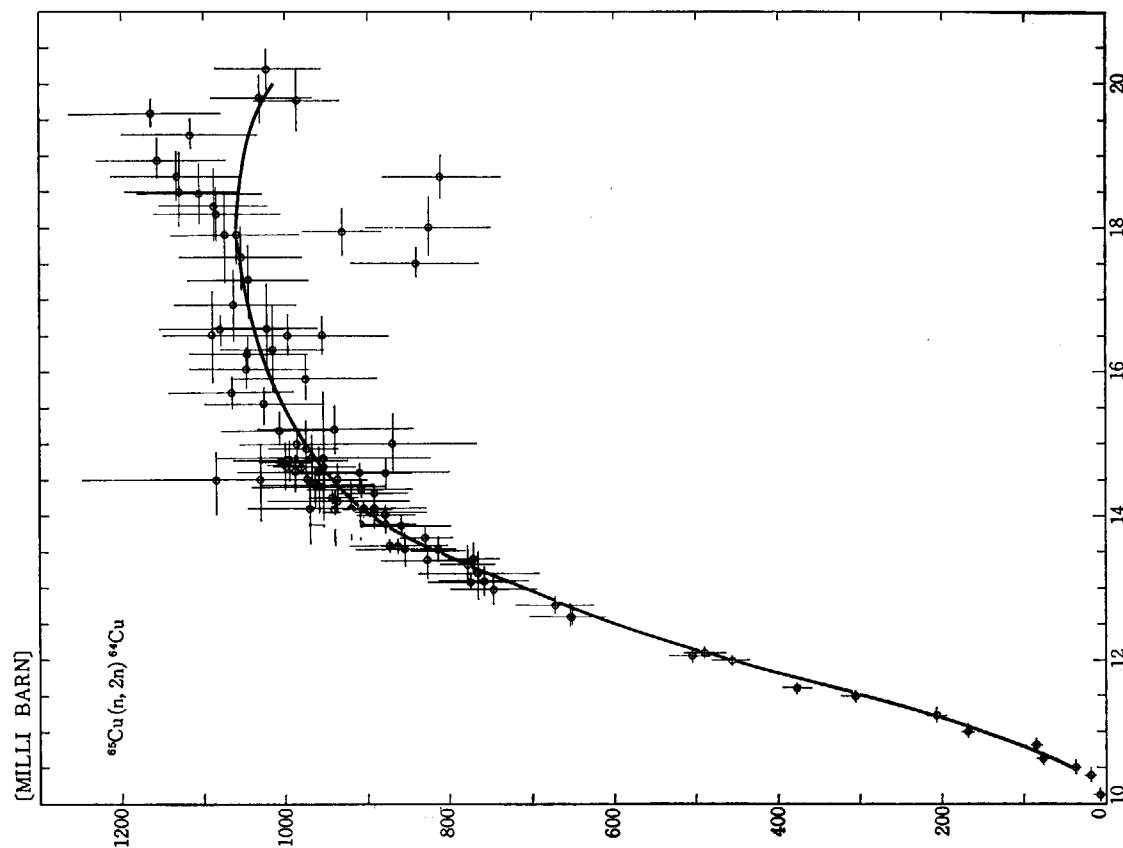


Fig. 5 Experimental points and the adopted cross-section curve for $^{65}\text{Cu}(n, 2n)$.

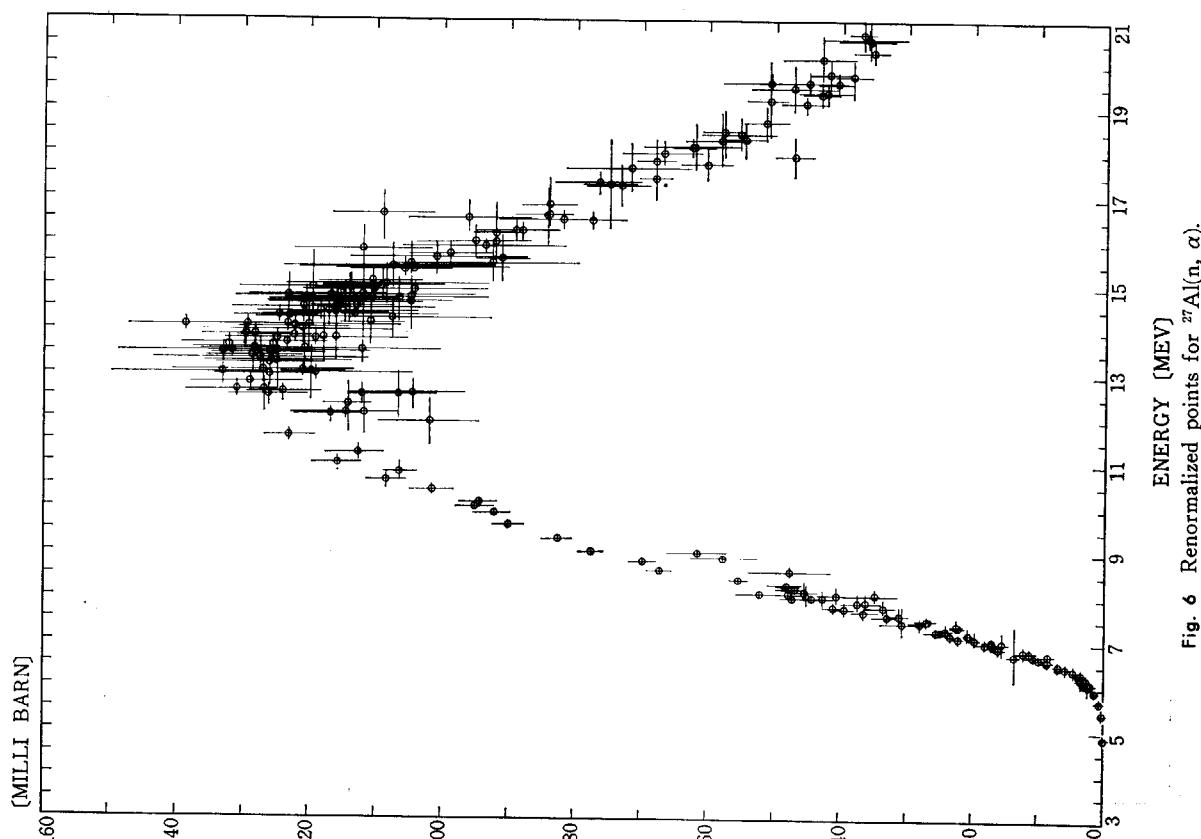


Fig. 6 Renormalized points for $^{27}\text{Al}(\text{n}, \alpha)$.

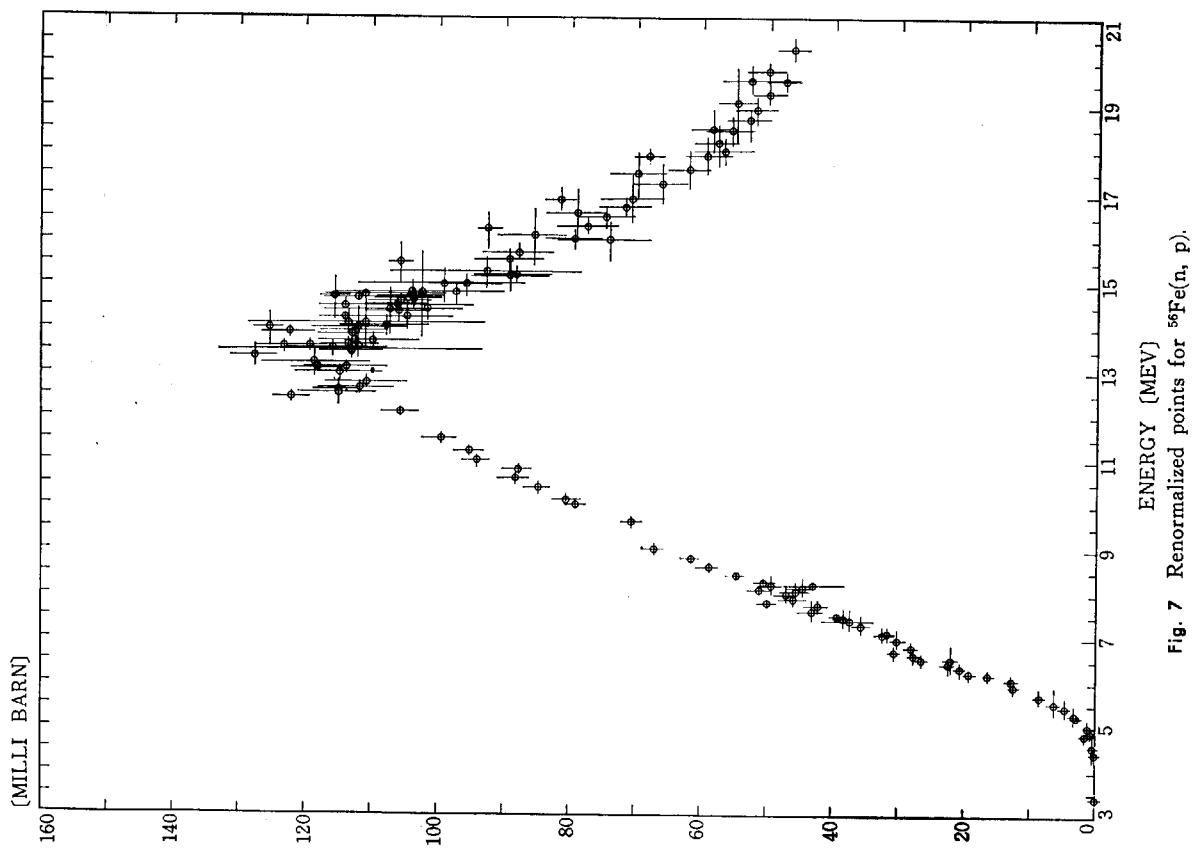


Fig. 7 Renormalized points for $^{56}\text{Fe}(\text{n}, \text{p})$.

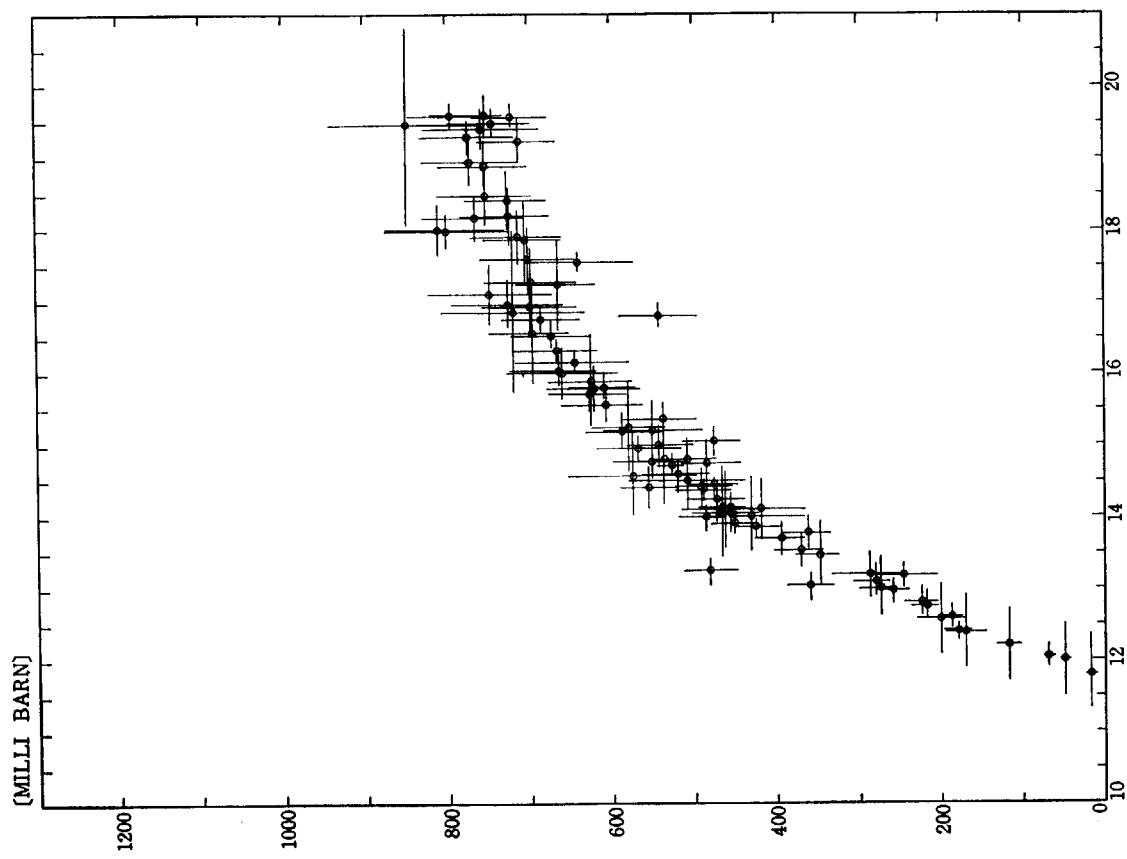


Fig. 8 Renormalized points for ${}^{63}\text{Cu}(n, 2n)$.

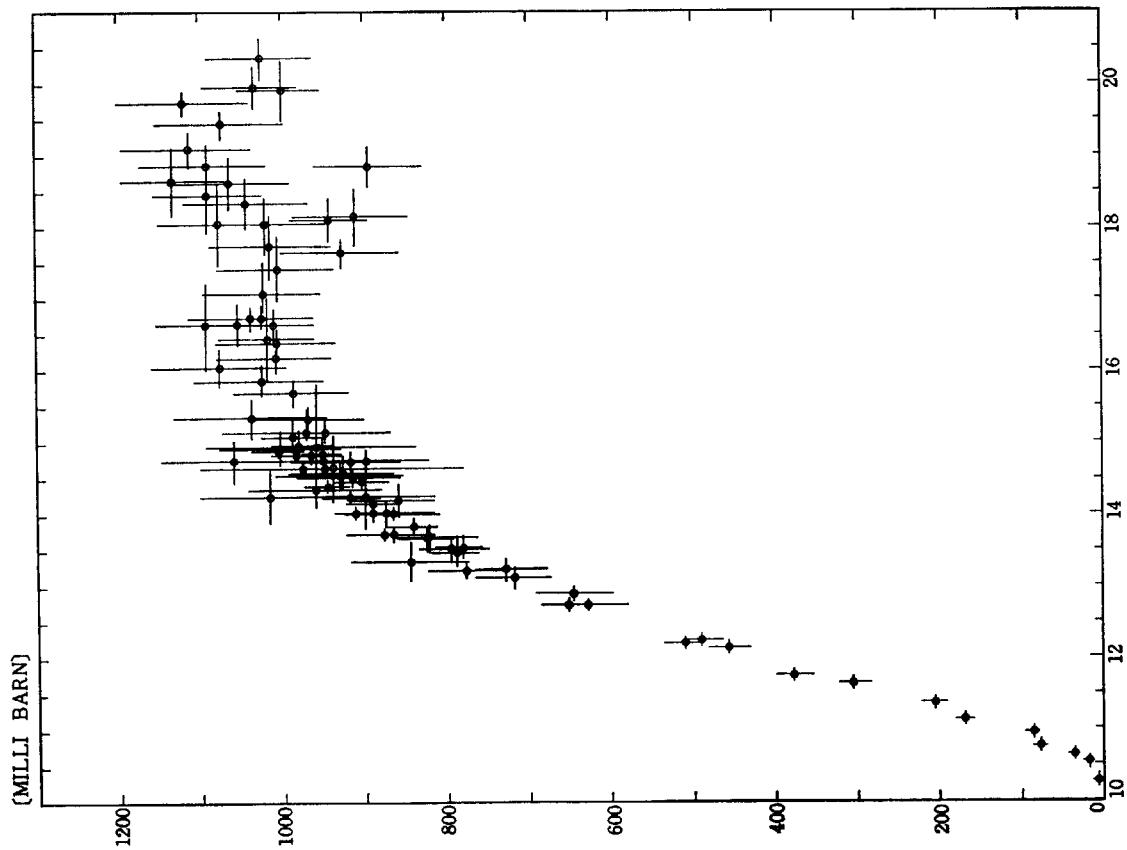


Fig. 9 Renormalized points for ${}^{63}\text{Cu}(n, 2n)$.

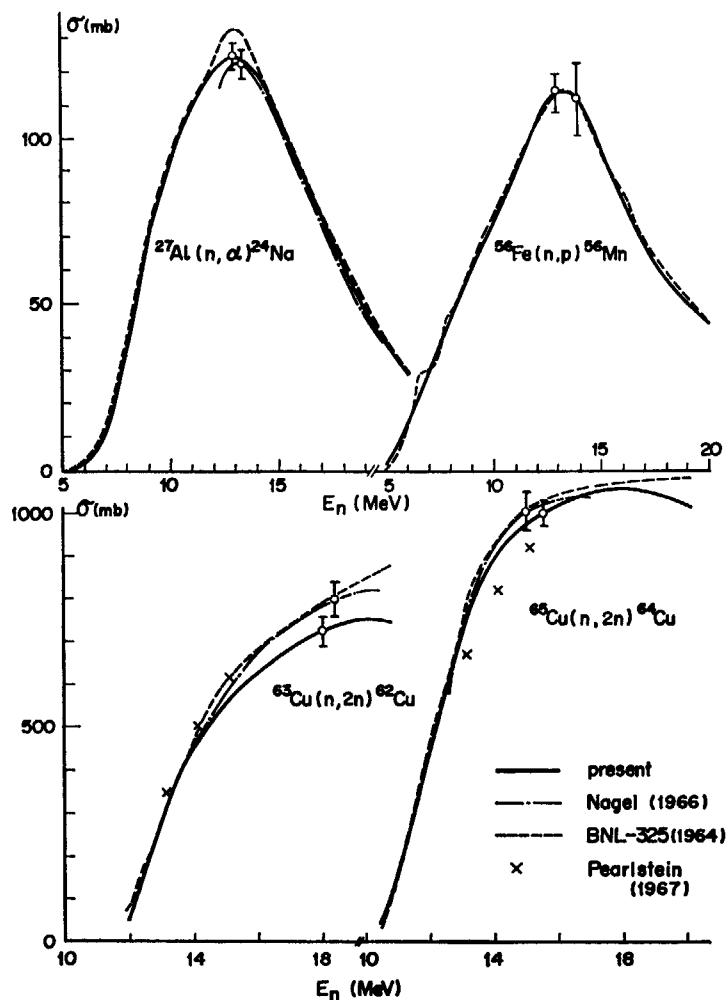


Fig. 10 Comparison of adopted curves (—) with those of Nagel⁴⁾ (---), BNL-325³⁾ (- - -) and Pearlstein⁵⁾ (×).

TABLE 1 Summary of papers reviewed
(See end of table for explanation of abbreviations.)

Ref.	Target nuclei	A/R	Neutron-flux measurement	Methods and instruments	No. of data	E_n range (MeV) comment	^{27}Al	^{56}Fe	δ (%)	^{63}Cu	^{65}Cu
50Fo	^{63}Cu	R	$^{65}\text{Cu}(\text{n}, \gamma)$ $^{65}\text{Cu}(\text{n}, \gamma)$	560 mb (E_{th})	β G-M	6	11. 8-14. 0	+29. 8			
52Br	^{63}Cu	R	$^{65}\text{Cu}(\text{n}, \gamma)$	560 mb (E_{th})	β G-M	6	13. 2-27. 1	-11. 3			
52Fo	^{27}Al , ^{56}Fe	A	α	pc	β G-M	1	14. 1	-11. 0	-10. 6	- 9. 37,	- 7. 35
53Pa	^{27}Al , ^{56}Fe , ^{63}Cu , ^{65}Cu	A	α	pc	β G-M	1	14. 5	+46. 8	+ 9. 62	+ 5. 60,	-13. 6
55Mc	^{56}Co	-	α	scin	?	1	No information				(55. 6)
56Al	^{56}Fe	R	$^{63}\text{Cu}(\text{n}, 2\text{n})$	482 mb (14. 1 MeV)	β G-M	12	13. 1-17. 6				+ 2. 40
57Br	^{56}Fe	-			p ppl		Only $\sigma(90^\circ)$				
57Ku	^{27}Al	-	α	pc	p ppl		No σ given				
57Ya	^{27}Al , ^{56}Fe , ^{63}Cu	A	α	scin ZnS(Ag)	α ppl		Superseded by 58Ku				
58Gr	^{27}Al	R	$^{238}\text{U}(\text{n}, \text{f})$	fc	β 4 π pc	7	6. 7-14. 1	+ 0. 13	-23. 0	- 16. 9	
58Ku	^{27}Al	A	α	pc	β gas-flow pc			+19. 6			
58Ma	^{56}Fe	R	$\text{H}(\text{n}, \text{p})$	ppl	α ppl	1	14. 8	+36. 6			
58Te	^{56}Fe	R	$^{56}\text{Fe}(\text{n}, \text{p})$	110 mb (14. 3 MeV)	β G-M	18	3. 4-17. 9	+19. 0			
59Ke	^{27}Al , ^{56}Fe	A	α	scin	γ NaI(Tl)	12	13. 0-15. 6	+10. 0			
59Kh	^{27}Al	R	$^{56}\text{Fe}(\text{n}, \text{p})$	110 mb (14. 3 MeV)	β G-M	1	14	- 5. 69	-29. 3		
59Po	^{27}Al	^{65}Cu	R	$^{63}\text{Cu}(\text{n}, 2\text{n})$	556 mb (14. 1 MeV)	1	14. 8	+ 9. 01			
60De	^{27}Al , ^{56}Fe	^{65}Cu	R	$^{63}\text{Cu}(\text{n}, 2\text{n})$	556 mb (14. 1 MeV)	β pc	1	- 1. 72,	+ 0. 44		
60Fe	^{63}Cu	R	$^{61}\text{Li}(\text{n}, \text{t})$	scin	β end-window c	1	15	- 6. 03,	-22. 6,	+11. 62	
60Ma	^{27}Al	R	$^{27}\text{Al}(\text{n}, \alpha)$	125 mb (14. 1 MeV)	γ^* coin NaI(Tl)	7	12. 4-18. 0	- 4. 22			
60St	^{56}Fe	R	$\text{H}(\text{n}, \text{p})$	scin	γ NaI(Tl)	24	11. 9-20. 7	- 5. 65	+23. 2		
60We	^{65}Cu	R	$^{63}\text{Cu}(\text{n}, 2\text{n})$	522 mb	γ NaI(Tl)	1	14. 1			- 8. 93	
61Al	^{56}Fe	R	$^{54}\text{Fe}(\text{n}, \text{p})$	scin	p ppl	1	14	+36. 6			
61Ba	^{27}Al	A	α	c	β pc	10	13. 4-14. 9				
61Bo	^{27}Al	^{56}Fe	R	$^{238}\text{U}(\text{n}, \text{f})$	γ NaI(Tl)	5	7. 0-19. 8			-20. 0	
61Ch			$^{61}\text{Li}(\text{n}, \text{t})$	scin	β pc	1	14. 8	+ 4. 49			
61Po	^{56}Fe , ^{63}Cu , ^{65}Cu	R	$^{63}\text{Cu}(\text{n}, 2\text{n})$	556 mb (14. 1 MeV)	γ NaI(Tl)	5	12. 6-19. 6				
61Pr		^{65}Cu	$^{27}\text{Al}(\text{n}, \alpha)$	114 mb (14. 8 MeV)	β pc	1	14. 8				
61Ra		^{65}Cu	$^{61}\text{Li}(\text{n}, \text{t})$	scin	γ NaI(Tl)	1	14. 1	- 1. 45,	- 5. 67,	- 4. 39	
			$^{238}\text{U}(\text{n}, \text{f})$	scin	β pc	12	13. 3-14. 9	+ 1. 28			
			$^{63}\text{Cu}(\text{n}, 2\text{n})$	503 mb (14. 4 MeV)	γ^* coin	4	12. 1-19. 8				
						1	14. 4	- 3. 09			

61Sa	^{27}Al	^{63}Cu	α	$^{238}\text{U}(\text{n}, \text{f})$	1.24 b (14.8 MeV)	β scin	1	14.1	6.1-14.8	+ 0.92
61Sc	^{56}Fe , ^{63}Cu	^{63}Cu	R	$^{56}\text{Fe}(\text{n}, \text{p})$	112.5 mb (14 MeV)	γ NaI(Tl)	28	13.2-19.6	+ 5.33	+ 1.35, -11.9
62Bo	^{27}Al , ^{56}Fe	^{63}Cu	R	A	semi	γ NaI(Tl)	8	14.1	+ 14.0	- 1.51, - 0.67
62Ce	^{27}Al , ^{56}Fe	^{63}Cu , ^{65}Cu	A	A	scin	γ^{\pm} coin NaI(Tl)	1	13.8-15.9	+ 0.27, + 0.78	+ 0.26
62Ga	^{27}Al	^{63}Cu	A	A	scin	γ^{\pm} coin NaI(Tl)	11	13.9-14.8	No σ given	No σ given
62Gl	^{27}Al	^{63}Cu	A	A	scin	α ppl	5	14.6	- 0.21	- 0.21
62Pa	^{27}Al	^{63}Cu	—	$^{56}\text{Fe}(\text{n}, \text{p})$	110 mb (14 MeV)	β G-M	1	14.6	+ 10.4	+ 10.4
62St	^{27}Al	^{63}Cu	R	$^{27}\text{Al}(\text{n}, \alpha)$	118 mb (14.1 MeV)	γ NaI(Tl)	1	13.2-18.7	+ 4.30	+ 4.30
63Bo	^{27}Al	^{65}Cu	R	$^{32}\text{S}(\text{n}, \text{p})$	250 mb (4.9 MeV)	γ NaI(Tl)	9	13.9-20.3	+ 2.51	- 2.75
63Bu	^{27}Al	^{65}Cu	R	$^{10}\text{B}(\text{n}, \alpha)$	226 mb (14.5 MeV)	β 2 π -flow pc	46	12.6-21.0	+ 8.26	+ 8.26
63Cs	^{27}Al	^{65}Cu	R	$H(\text{n}, \text{p})$	long c	β G-M	1	14.6	+ 1.29, - 1.21,	- 4.82
63Ir	^{27}Al	^{65}Cu	R	$^{63}\text{Cu}(\text{n}, 2\text{n})$	503 mb (14.4 MeV)	α pc+CsI(Tl)	1	No σ given	+ 3.64	+ 3.64
63Je	^{27}Al	^{65}Cu	R	A	scin	γ NaI(Tl)	8	12.1-19.6	- 4.82	- 4.82
63Ra	^{27}Al	^{65}Cu	R	A	semi	β end-window c	1	14.6	+ 1.29, - 1.21,	- 4.82
64Ar	^{27}Al , ^{56}Fe	^{65}Cu	A	A	semi	β G-M	1	14.7	+ 3.64	+ 3.64
64Bo	^{27}Al , ^{56}Fe	^{65}Cu	R	$^{32}\text{S}(\text{n}, \text{p})$	263 mb (4.6 MeV)	β pc	47	4.6-20.3	No σ given	No σ given
64Sa	^{27}Al	^{65}Cu	—	—	226 mb (14.5 MeV)	γ NaI(Tl)	Fluctuation	Fluctuation	Fluctuation	Fluctuation
64St	^{27}Al	^{65}Cu	—	—	—	γ^{\pm} coin NaI(Tl)	14.8	12.6-19.6	+ 1.65, -17.8	+ 2.36
65Ba	$^{63}\text{Cu}_{11}$	^{63}Cu	R	A	semi	γ Well NaI(Tl)	1	14.2-14.6	- 3.80	- 3.80
65Cs	$^{63}\text{Cu}_{11}$	^{63}Cu	R	A	semi	β scin	1	12.6-19.6	+ 0.97	+ 0.97
65Gr	$^{63}\text{Cu}_{11}$	^{63}Cu	R	H(n, p)	c telescope	γ NaI(Tl)	28	12.6-19.6	- 3.06	- 3.06
65Li	^{56}Fe , $^{63}\text{Cu}_{11}$	^{63}Cu	R	$^{56}\text{Fe}(\text{n}, \text{p})$	118 mb (14.2 MeV)	β G-M	2	12.6-19.6	+ 0.65, + 5.85	+ 0.65, + 5.85
65Na	$^{63}\text{Cu}_{11}$	^{63}Cu	R	H(n, p)	112 mb (14.6 MeV)	γ NaI(Tl)	27	12.6-19.6	+ 4.50, + 7.45	+ 4.50, + 7.45
65Pa1	^{27}Al	^{65}Cu	R	H(n, p)	c telescope	γ^{\pm} coin NaI(Tl)	23	12.6-19.6	226 mb (14.5 MeV)	226 mb (14.5 MeV)
65Pa2	^{27}Al	^{65}Cu	R	H(n, p)	scin	α CsI(Tl)	1	14.1	10.1-20.2	10.1-20.2
65Se	^{27}Al	^{65}Cu	R	H(n, p)	scin	γ^{\pm} coin NaI(Tl)	1	14.8	- 1.32	- 1.32
66Ch	^{27}Al , ^{56}Fe	^{65}Cu	A	He gas	accumulation	liquid c	4	13.5	+ 0.65, + 5.85	+ 0.65, + 5.85
66He	^{27}Al , ^{56}Fe	^{65}Cu	R	H(n, p)	c telescope	γ NaI(Tl)	7	13.5-14.8	+ 0.26	+ 0.26
66Li	^{27}Al , ^{56}Fe	^{65}Cu	R	$^{32}\text{S}(\text{n}, \text{p})$	393 mb (10.1 MeV)	γ^{\pm} coin NaI(Tl)	17	6.1-8.2	No σ given	No σ given
66Sa	^{27}Al , ^{56}Fe	^{65}Cu	R	$^{32}\text{S}(\text{n}, \text{p})$	226 mb (14.5 MeV)	γ NaI(Tl)	28	10.1-20.2	No σ given	No σ given

Ref.	Target nuc'ei	A/R	Neutron-flux measurement	Methods and instruments	No. of data	E_n range (MeV) comment	^{27}Al	^{56}Fe (%)	^{63}Cu	^{65}Cu
67Fe 67Me	^{27}Al ^{27}Al	—	$^{238}\text{U}(\text{n}, \text{f})$ R	1. 3 b (6. 1 MeV)- 2. 1 b (19. 4 MeV) semi $^{56}\text{Fe}(\text{n}, \text{p})$ 100 mb	γ NaI(Tl) γ NaI(Tl)	10	Fluctuation 6. 1-19. 4	+ 7. 6		
67Pa 67Wo	^{27}Al	^{63}Cu	A R	α $^{56}\text{Fe}(\text{n}, \text{p})$	β G-M γ Ge(Li)	1	14. 7 14. 4	+ 3. 30		
66Na 67Bo	^{27}Al	^{63}Cu	R R	$^{56}\text{Fe}(\text{n}, \text{p})$ 118 mb (14. 2 MeV)	— γ NaI(Tl) γ NaI(Tl)	1	14. 2 Fluctuation	+ 3. 68		
67Co 67Gr	^{27}Al , ^{56}Fe ^{27}Al , ^{56}Fe ,	^{63}Cu , ^{65}Cu ^{63}Cu , ^{65}Cu	A R	α $^{238}\text{U}(\text{n}, \text{f})$ $^{63}\text{Cu}(\text{n}, 2\text{n})$ $^{65}\text{Cu}(\text{n}, 2\text{n})$ $^{65}\text{Cu}(\text{n}, 2\text{n})$	925 mb (6. 97 MeV) 469 mb (14. 1 MeV) 919 mb (14. 1 MeV) 1000mb (14. 8 MeV)	β pc β pc	9	3. 95-14. 1 Fluctuation		
68Cu 68Le	^{56}Fe	^{63}Cu	R	$^{27}\text{Al}(\text{n}, \alpha)$	111.5mb (14.5 MeV)	β G-M	1	14. 8		
68Ti 68Vo	^{27}Al , ^{56}Fe	^{65}Cu	R	$^{27}\text{Al}(\text{n}, \alpha)$	111.5mb (14.5 MeV)	γ NaI(Tl)	1	14. 2		
69Bo1 69Bo2	^{27}Al ^{27}Al	^{63}Cu , ^{65}Cu	A A A	α α α	γ^{\pm} coin NaI(Tl)	γ NaI(Tl)	8	14. 7 and fluctuation 13-18		
69Cr	^{27}Al	^{63}Cu , ^{65}Cu	A	α	γ NaI(Tl)	2	14. 2 and fluctuation 14. 7-14. 8			

Abbreviations

- A : absolute measurement
 c : coincidence
 coin : coin coincidence
 fc : fission chamber
 G-M : Geiger-Müller counter
 pc : proportional counter
 ppl : photoplate or emulsion
 R : relative measurement
 semi : semiconductor detector
 scin : scintillation counter
 γ^{\pm} : annihilation radiation
 δ : value appeared in renormalization factor

TABLE 2 Absolute values of the cross-sections

Ref.	Original data			Cross sections shifted to 14.5 MeV	
	$E_n + E_{\alpha}$ (MeV)	$\sigma \pm \Delta\sigma$ (mb)			
$^{27}\text{Al}(n, \alpha)$					
52Fo	14.1 (0.5)	135	9.5	130.7	9.5
53Pa	14.5 (0.5)			79	16
57Ya	14.1 (0.5)	120	14	116.2	13.6
58Ku	14.8 (0.5)	82.0	17	84.8	17.6
64Bo	14.7 0.3	112.0	4.0	114.5	4.4
64Ar	14.6 0.15	106.0	5.0	107.1	5.3
59Ke*	13.02—15.64			117.1	15.9
61Ba*	13.80—14.90			121.9	6.7
62Ga*	13.08—15.89			116.2	12.2
66He*	13.47—13.56			106.8	5.5
Weighted mean				116	4†
$^{56}\text{Fe}(n, p)$					
52Fo	14.1 (0.5)	124.0	12.4	119.8	13.4
53Pa	14.5 (0.5)			96.8	13.4
57Ya	14.1 (0.5)	144.0	19.0	139.1	19.6
59Ke	15.27 0.33	131	15	147.2	19.7
62Ga	14.4 (0.5)	108	10	106.9	11.9
64Bo	14.7 0.3	105	5	107.4	7.2
66He	13.5 0.1	106.7	4.7	100.4	4.6
Weighted mean				106	12†
$^{63}\text{Cu}(n, 2n)$					
52Fo	14.1 (0.5)	510	35.7	562	117
53Pa	14.5 (0.5)			482	98
57Ya	14.1 (0.5)	556	28	612	122
61Sa	14.1 0.2	458	45.8	504	64
62Ce	14.13 0.1	409	25	450	36
62Gl	14.77 0.25	570	40	527	51
65Gr	14.8 0.1	558	30	529	46
67Pa	14.7 0.1	511	15	492	23
Weighted mean				509	12†
$^{65}\text{Cu}(n, 2n)$					
52Fo	14.1 (0.5)	890	71	1015	122
53Pa	14.5 (0.5)	1060	162	1085	186
62Gl	14.77 0.25	975	69	929	100
64Bo	14.7 0.3	970	24	984	43
61Pr*	13.33—14.93			936	37
Weighted mean				938	15†

* The excitation function by absolute measurements is given. The second and third columns show the energy range and the weighted mean cross-section value, respectively.

† Standard deviation (Not same as $\Delta\sigma$ in TABLE 1).

TABLE 3 Adopted cross-section values

E_n (MeV)	$^{27}\text{Al}(n, \alpha)^{24}\text{Na}$ σ (mb)	$\pm \Delta\sigma$	$^{56}\text{Fe}(n, p)^{56}\text{Mn}$ σ (mb)	$\pm \Delta\sigma$	$^{63}\text{Cu}(n, 2n)^{62}\text{Cu}$ σ (mb)	$\pm \Delta\sigma$	$^{65}\text{Cu}(n, 2n)^{64}\text{Cu}$ σ (mb)	$\pm \Delta\sigma$
5.0	0.1	0.6	2.5	0.4				
.5	0.8	0.6	7.3	1.1				
6.0	1.7	0.5	14.4	2.2				
.5	6.9	0.5	22.5	2.4				
7.0	15.0	0.6	30.4	3.4				
.5	26.2	1.1	38.1	4.2				
8.0	40.2	1.6	45.6	5.0				
.5	57.3	2.5	52.8	5.9				
9.0	70.4	2.8	59.8	6.6				
.5	81.7	3.3	66.6	7.4				
10.0	91.4	3.7	73.2	8.1				
.5	99.3	4.0	80.4	8.9			50	10
11.0	108	4	88.2	9.8			155	7
.5	115	4	96.0	10.6			291	12
12.0	120	4	104	12	50	25	457	14
.5	123	4	109	12	173	14	597	14
13.0	124	4	113	13	281	18	715	16
.5	123	4	113	13	372	19	812	17
14.0	121	4	112	12	449	24	887	18
.5	116	4	106	12	509	26	938	19
15.0	109	4	97.5	10.5	554	28	970	20
.5	100	4	88.1	9.7	592	30	994	20
16.0	91.6	3.7	81.0	9.0	627	32	1014	20
.5	83.7	3.4	73.4	8.1	658	33	1032	20
17.0	76.1	3.0	67.9	7.5	684	34	1045	21
.5	68.9	2.8	62.8	6.9	705	35	1053	22
18.0	62.0	2.8	58.2	6.4	723	35	1052	24
.5	55.6	2.8	54.0	6.0	736	35	1050	24
19.0	49.6	2.8	50.3	5.0	745	36	1043	23
.5	44.0	2.7	47.0	5.1	750	36	1032	23
20.0	38.7	2.7	44.2	4.9	750	36	1015	23
.5	33.9	3.4	41.8	4.6				
21.0	29.4	4.5	39.8	3.4				

$\pm \Delta\sigma$ =Limits of 95% confidence band.

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