International Atomic Energy Agency

INDC(NDS)-47/L

INDC INTERNATIONAL NUCLEAR DATA COMMITTEE

STATUS OF NEUTRON CROSS SECTION DATA FOR REACTOR RADIATION MEASUREMENTS

Part I.

Reactions of high priority.

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Contents

INTRODUCTION

This is a report on the status of neutron cross section data for reactor radiation measurements being prepared at the request of the International Working Group on Reactor Radiation Measurements (IWGRRM) for its November 1972 meeting. This is to be considered as a first step towards the later establishment of internationally accepted standard values for these reactions. The eighteen reactions considered most important in the list of reactions suggested by the members of IWGRRM, W. Zijp and P. Mas, in a letter to the Nuclear Data Section in 1971 have been surveyed. The other reactions on that list will be included in Part II, which will be published in the near future.

A brief description of the status of the data for each of these reactions is given including in most cases displays of the latest evaluations and of any data measured subsequent to these evaluations. The final sections of the report summarize the requested accuracies as given in RENDA-72(1), the accuracies presently attained and remarks concerning requirements for improving the present accuracies.

A draft of this report was discussed at the 32nd Meeting of the EURATOM Working Group on Reactor Dosimetry in Rome in September 1972. Comments received from this Working Group are included in this report.

The authors would welcome any comments and suggestions of IWGRRM on this report, particularly on the observations and recommendations as contained in chapters XIX and XX of this report.

THERMAL AND INTERMEDIATE CROSS SECTIONS

II. $Li^6(n,\alpha)$ +)

The $Li^6(n,\alpha)$ reaction is used as a standard for high accuracy measurements of partial neutron cross sections(particularly capture and fission), especially in the keV region of neutron energies. At higher energies it is important as a standard for in-pile reactor neutron spectrum measurements.

The following table taken from reference [2] gives the Q-values and thresholds of the possible reactions produced by neutron interaction with the Li^6 nucleus.

Reaction	Q-value MeV	Threshold energy, MeV
$Li^6 + n \rightarrow \alpha + t$	4.785	Exothermic
" $\rightarrow Li^7 + \gamma$	7.253	Exothermic
" $\rightarrow \alpha + d + n$	- 1.472	1.719
" $\rightarrow He^5 + d$	- 2.430	2.838
" $\rightarrow He^6 + p$	- 2.727	3.185
" $\rightarrow Li^{6*} + n'$		2.184

It is seen that below 1.719 MeV only three reactions are possible, viz. elastic scattering, (n,α) and (n,γ). The cross section for the (n,γ) reaction is very small (at thermal about 40 mb compared to 940 barn for the (n,α) reaction). The cross sections for absorption and for the (n,α) reaction are thus essentially identical and can also be obtained as the difference of the total and the scattering cross sections. The existence of significant competing reactions above 1.718 MeV makes Li^6 rather unsuitable as a standard for cross section measurements at higher energies.

The main evaluated data sets for $Li^6(n,\alpha)$ available at present and discussed in the paragraphs below are the following:

(i) DFN 214 D of the UK nuclear data library (UKNDL) [3], which now is only of historical value, but forms the basis for the ENDF/B file mentioned under (ii) above about 2 MeV;

+) Fast Cross Section for this reaction is included in this chapter also.

(ii) MAT.1115 of the ENDF/B-III library [4];

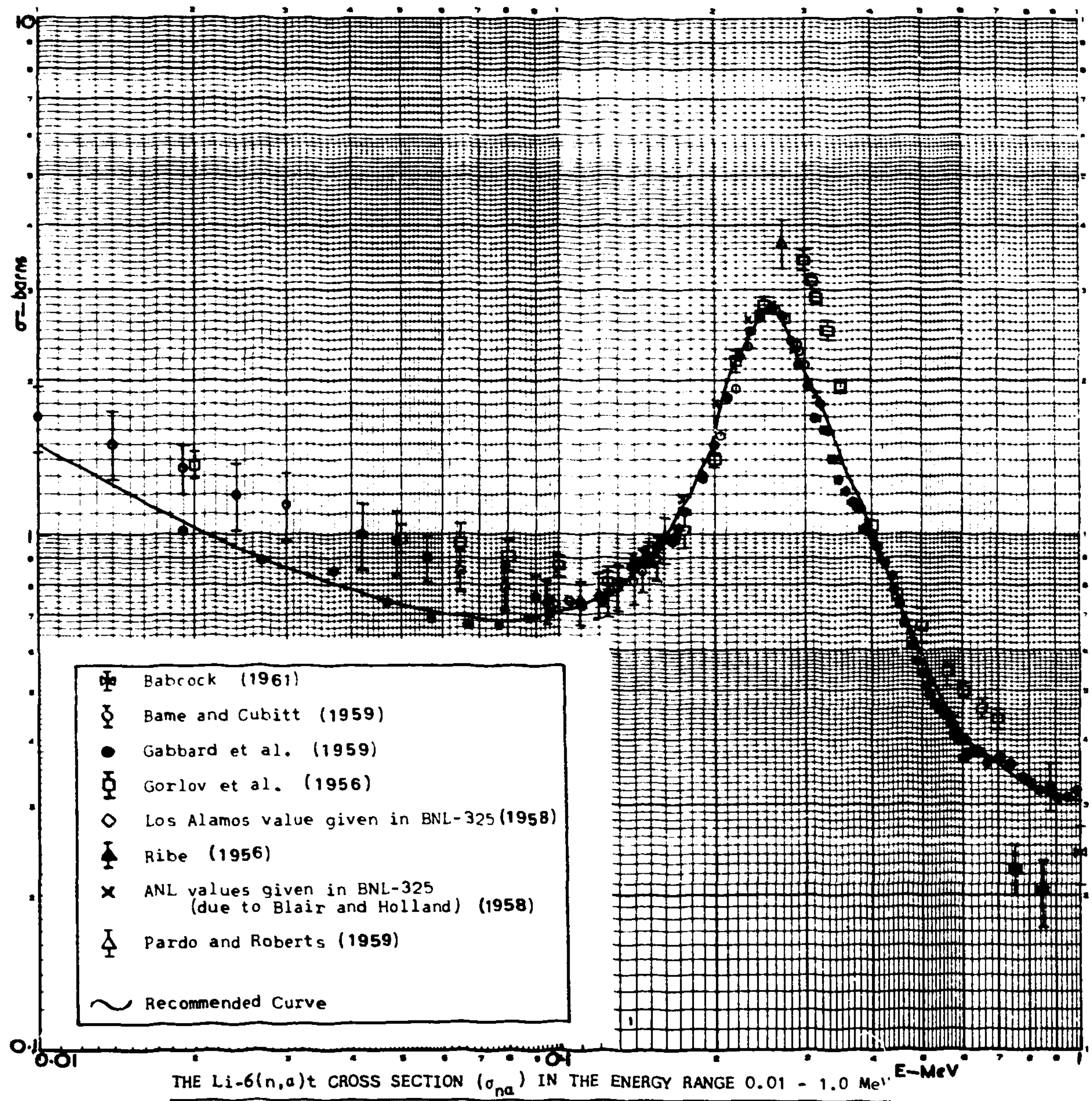
(iii) DFN 914 of the UKNDL which supersedes DFN 214 D.
This file is still not available to IAEA/NDS, but comments on and plots of the data are contained in reference [5].

Figures 1 and 2 taken from [3] display the DFN 214 D data [3] together with all experimental results available before 1964. The (n,α) data contained in MAT.1115 are based on the evaluations by Uttley et al. [2] from thermal to 1.7 MeV and by Pendlebury [3] above 1.7 MeV. They are displayed by the solid curve in figures 3 and 4 together with some more recent experimental data. DFN 914 is based on Uttley's older evaluation [2] below 0.5 MeV and on Uttley's more recent evaluation [5] above 0.5 MeV. Figure 4 shows all three evaluated data sets above 0.5 MeV; note that DFN 914 is much lower than the two other evaluations between 0.5 and about 6 MeV due to data by Clements and Rickard [6] used in DFN 914.

In the following the status of the data is discussed by order of energy.

Thermal

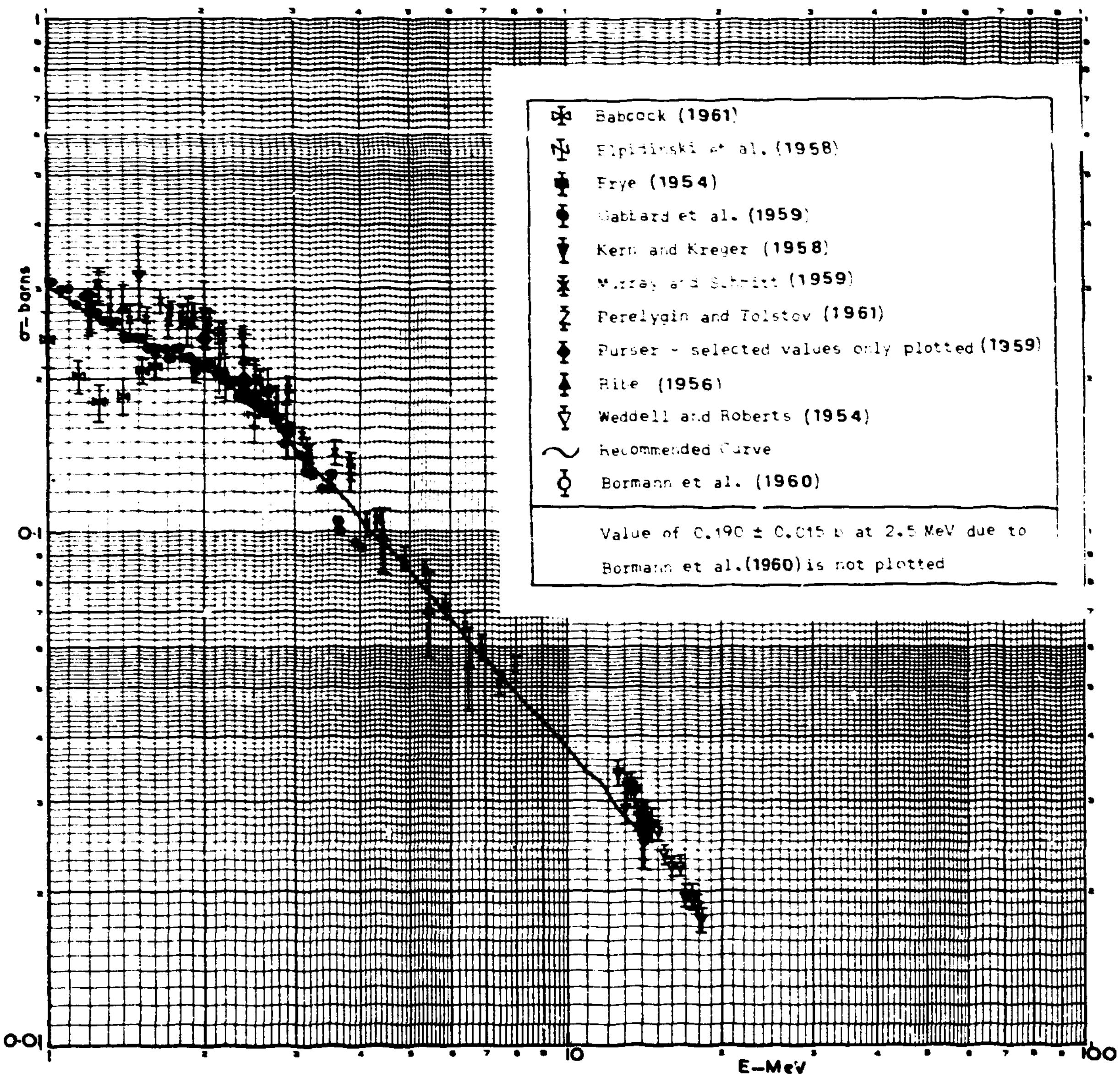
The 2200 m/sec cross section value is established to about 0.5%. The most recent very careful measurements on 96 and 99% enriched Li^6 samples by Meadows and Whalen [7] yield 938 ± 6 barn in excellent agreement with a value of 940 ± 6 b deduced by Uttley and Diment [8] by extrapolation of their fit to the total cross section and in good agreement with a more recent still unpublished value of 943.8 ± 2.8 barn obtained by Silk and Wade [9]. The present "best" value (weighted mean of the above three) is 942.4 b [10] with a confidence level 0.5%. For comparison: the value used in MAT.1115 is 940.25 b and in DFN 914 940 ± 5 b. No further work is needed.



THE Li-6(n,α)t CROSS SECTION ($\sigma_{n\alpha}$) IN THE ENERGY RANGE 0.01 - 1.0 MeV

(reproduced from /3/)

Fig. 1



THE Li-6(n,α)t CROSS SECTION ($\sigma_{n\alpha}$) IN THE ENERGY RANGE 1.0 - 15.0 MeV

(reproduced from /3/)

Fig. 2

Thermal energies to 10 keV

Below 10 keV σ_α follows the 1/v law to within 1% [2]. The 1/v expressions corresponding to the aforementioned 2200 m/sec values are:

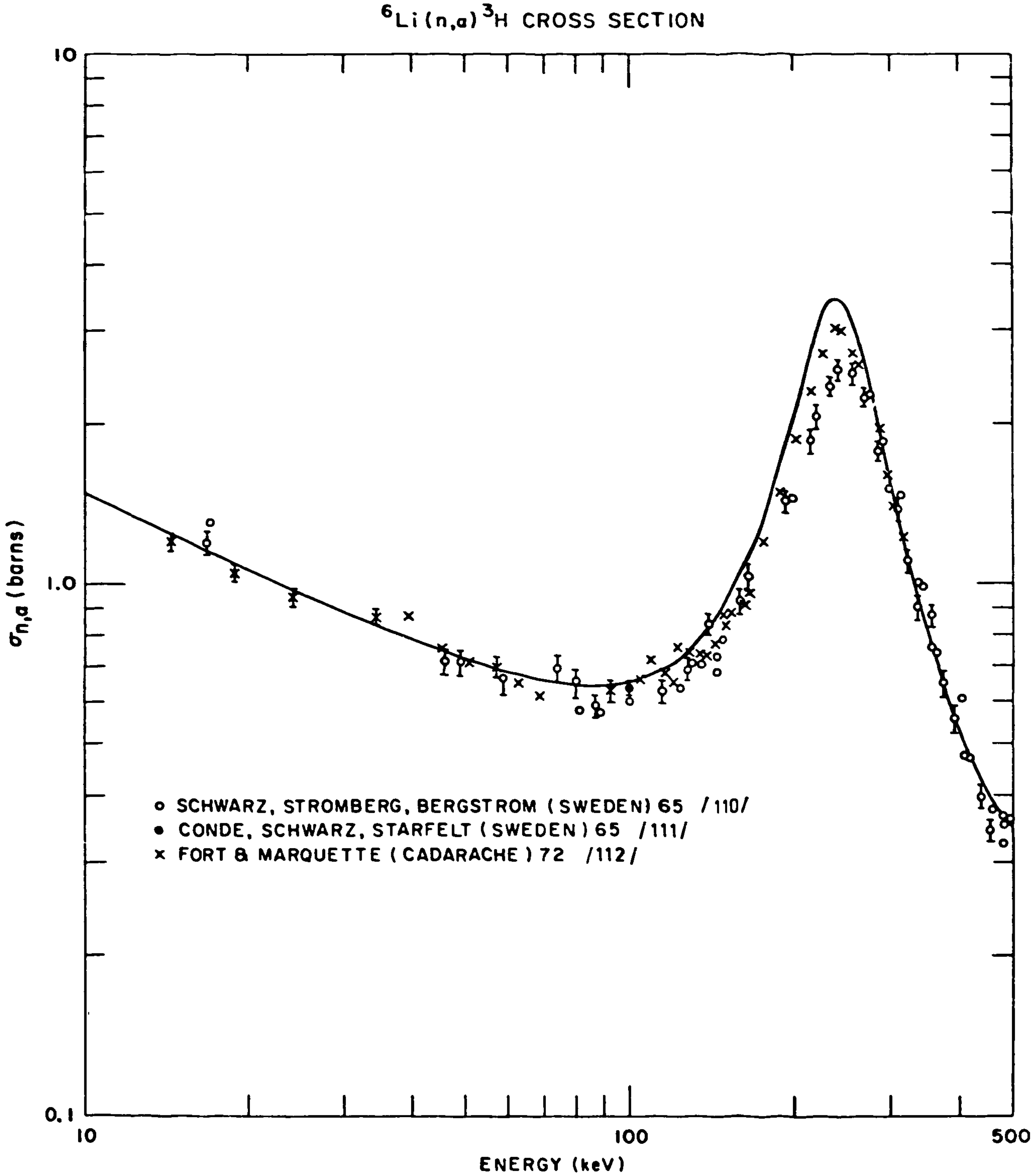
σ_α	=	$149.9b/\sqrt{E/ev}$	present "best" value [10]
"	=	$149.56b/\sqrt{E/ev}$	MAT.1115 [4]
"	=	$149.5b/\sqrt{E/ev}$	DFN 914 [5]

No further work is needed.

10 - 500 KeV

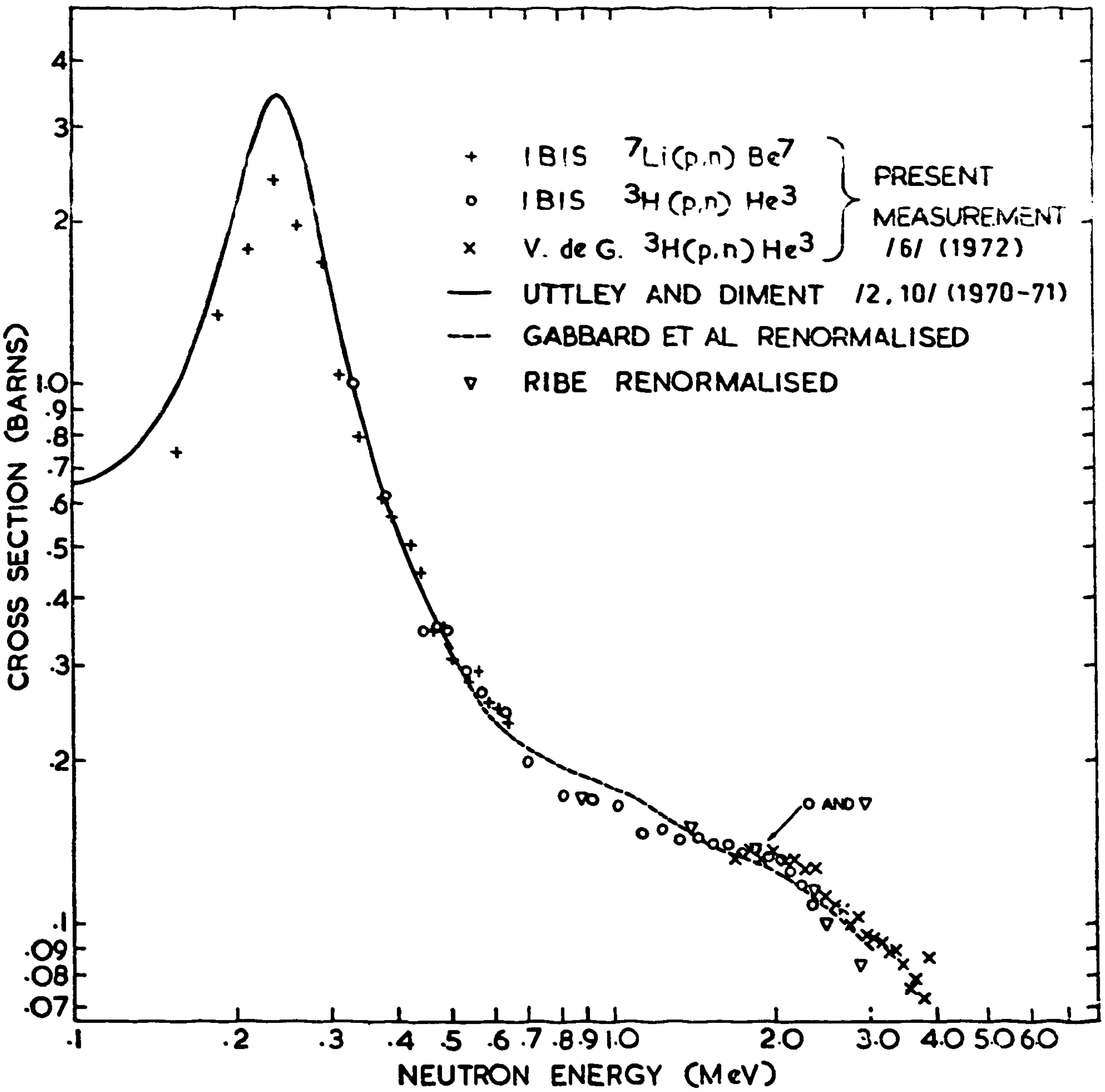
The available experimental data and the curve calculated by Uttley et al. [2,8] as the difference $\sigma_T - \sigma_n$ are displayed in figures 3 and 5 taken from references [4] and [10] respectively. It is believed that at present Uttley's calculations give the best description of σ_α in the vicinity of the 247 KeV resonance. They are very well confirmed particularly by the recent direct σ_α measurements of Coates et al. [11] (see figure 6 taken from reference [11]). The recent discrepancy observed between the Coates' data (Harwell) and the lower results obtained recently by Fort and Marquette [12] (Cadarache) which were essentially due to the use of different Li glass thicknesses and different multiple scattering corrections is approaching resolution more in favour of the higher Coates data [13]. Most of the other data displayed in figures 3 and 5 are much older and are discrepant to the recent data sets mainly because of probably doubtful multiple scattering and other corrections.

Uttley et al. [2] conclude that the present accuracy of the σ_α data ($\pm$ 1 standard deviation) is about 2% at 100 KeV rising to 5% between 150 and 300 KeV and increasing to 10% at 500 KeV. We concur particularly with their recommendations for new σ_T measurements to confirm the results of Uttley and Diment [8] and a remeasurement of the elastic scattering cross section to confirm the data of Lane et al. [14] over the 247 KeV resonance used in Uttley's derivation.



(reproduced from /4/)

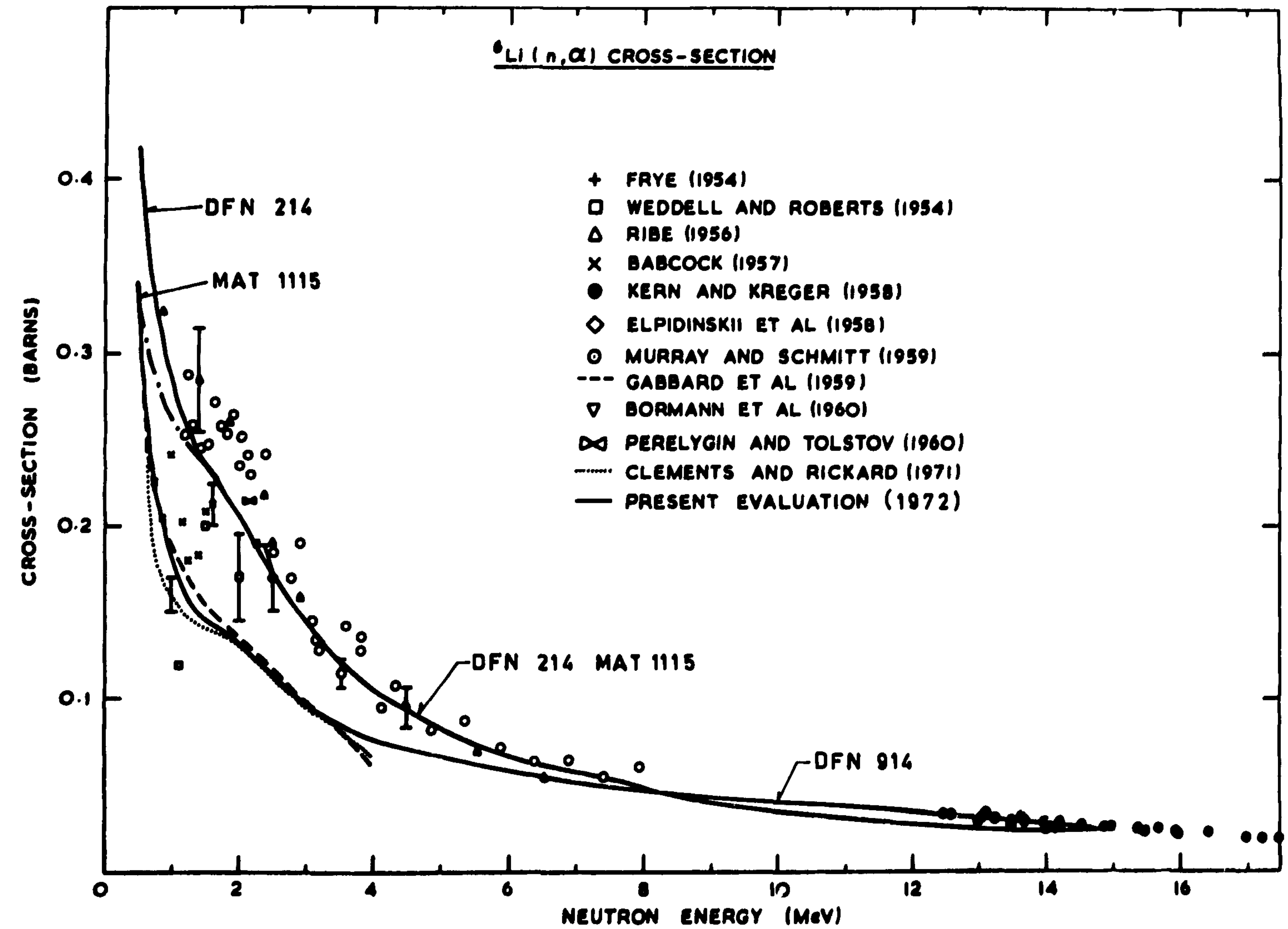
Fig. 3



THE RESULTS OF MEASUREMENTS OF THE Li(n,α)t CROSS SECTION
A.E.R.E. R.7075

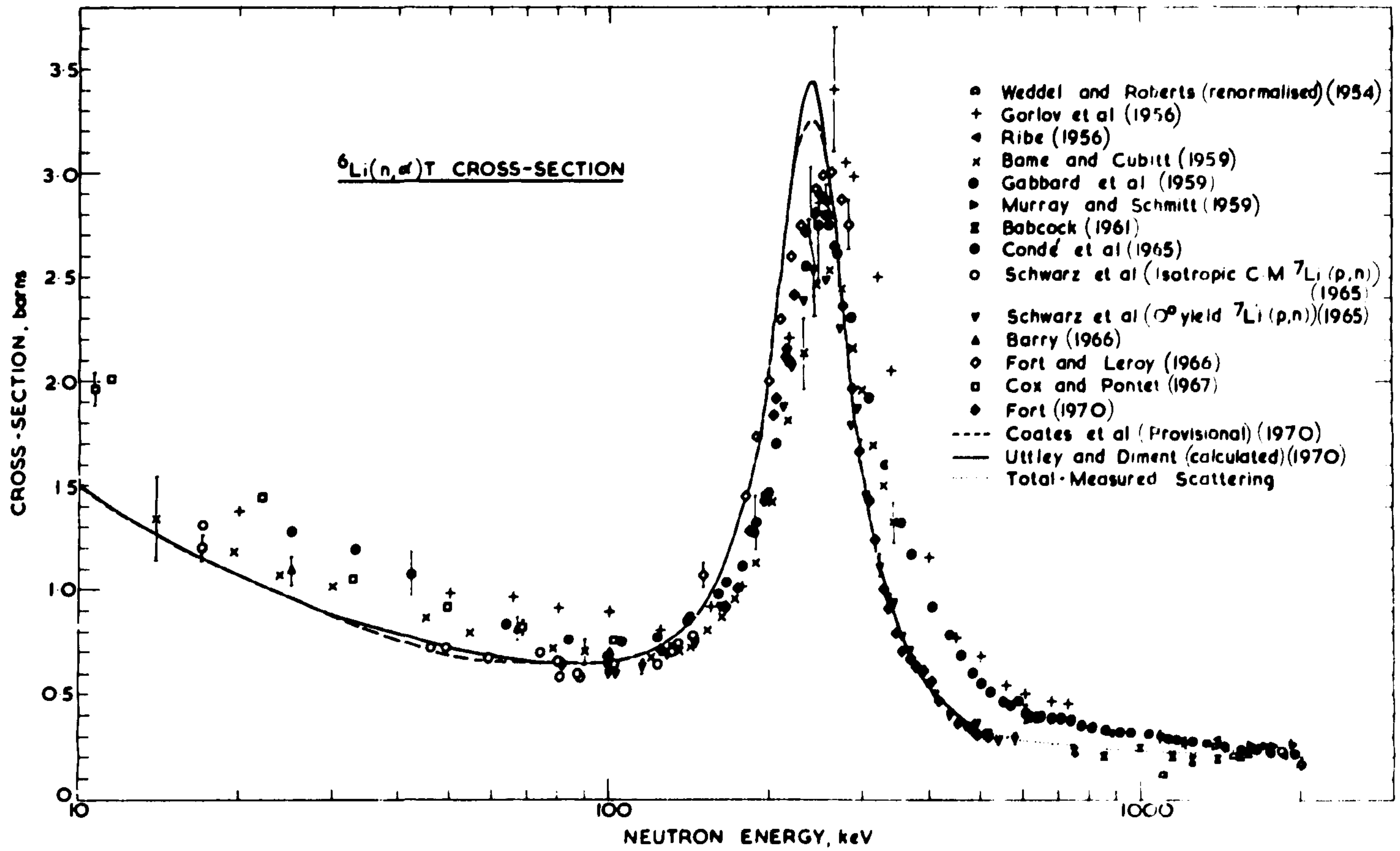
(reproduced from /6/)

Fig. 3a



The evaluated $^{6}Li(n,\alpha)$ cross-section above 0.5 MeV
(reproduced from /5/; MAT 1115 and DFN 214 added)

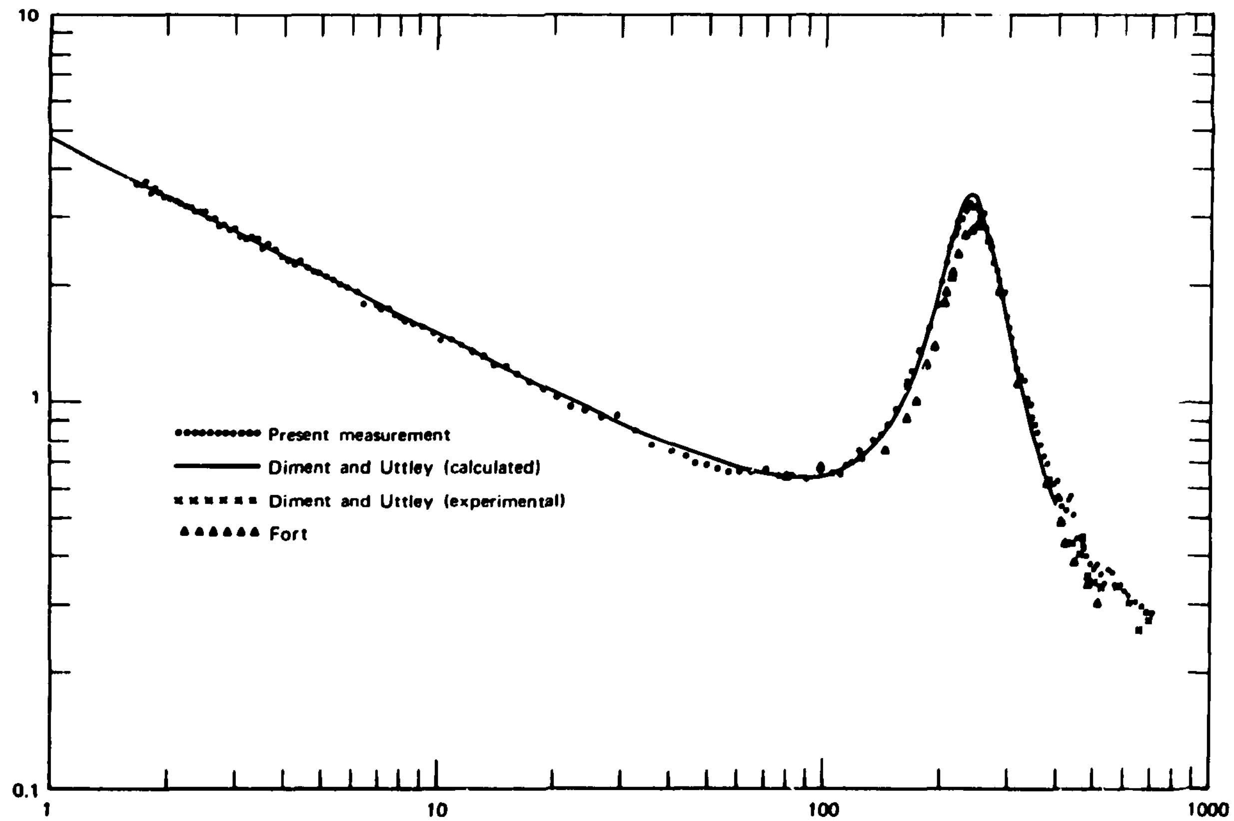
Fig. 4



THE ^{6}Li (n, α) CROSS-SECTION

(reproduced from /10/)

Fig. 5



(reproduced from /11/)

Fig. 6

500 keV - 15 MeV

The available data displayed in figure 4 show a large discrepancy in the range 0.5 to 4 MeV between essentially all older measurements done before 1960, on which DFN 214 and MAT.1115 (above 1.7 MeV) are based, and the DFN 914 data. Trusting more the σ_α data derived from σ_T and σ_n Uttley et al. [5] obtained the DFN 914 σ_α data by normalizing the relative measurements below 4 MeV by Gabbard et al. [15] (1959) and by Clements and Rickards [6] (1972, particularly accurate) to their derived σ_α value at 500 KeV and interpolating smoothly to the experimental data available above 12 MeV [16]. According to Uttley et al. [5] these data are reasonably consistent with the inaccurate values obtained from the difference between the nearly identical total and elastic scattering cross sections below 1.7 MeV.

In conclusion further σ_α measurements are urgently needed below 4 MeV to confirm the data by Clements and Rickards [6]. Between 4 and 12 MeV measurements are needed to consolidate knowledge (4 - 8 MeV) and to close gap (8 - 12 MeV). Until solution of the mentioned discrepancy the DFN 914 data are recommended for use.

III. $Co^{59}(n,\gamma)Co^{60}$

The production of Co^{60} from neutrons interacting with a Co^{59} target is used as a fluence monitor in the thermal and intermediate energy region. Most of the experimental information available consists of thermal capture cross sections and resonance integrals.

A complete review of thermal data before 1968 was performed by Story [17] who recommends a value of 37.5 ± .13 barns at .0253 eV. A review in 1969 by Silk & Wade [18] including their own new measurement recommends 37.34 ± 0.09 barns. Finally in 1971 there is a recommendation of 37.3 ± .2 barns from Köhler and Vaninbroukx [19]. If only data since 1963 are used [18] then 37.34 ± 0.09 is the weighted mean. It would appear that a value of 37.34 barns for the thermal capture cross section of Co^{59} with an uncertainty of .5% should be used.

There exist three compilations of Co^{59} infinite dilute capture resonance integrals by Drake [20], Zijp [21] and R. Barrall and McElroy [115]. Drake recommends a value for $RI_\gamma(Co^{59})$ of 75 barns. The reported resonance integrals [21] range from 38.3 to 81. barns. Köhler and Vaninbroukx [19] recommend 70 ± 6 barns. Recent (1972) recommendation by Holden [116] is 75 b. These two values represent the realistic limits of this integral. Recent measurements indicate that the value is between these extremes (see Table XIXA).

The thermal capture cross section obeys a 1/v law in the thermal region up to about 5. ev. Figure 7 gives the recommended curve of Simons and McElroy [22] giving three prominent resonances below 10 kev. The reference does not give the source of this line shape but it is probably a reconstruction from various published resonance parameters. This curve gives 70.0 b for the resonance integral and 36.9 b for the thermal cross section. Zijp [21] also gives a recommended curve from 1 eV to 1 keV but this curve appears to be the total cross section from the 2nd Edition of BNL-325 [23] and not the capture cross section for Co^{59}. This total cross section shows considerable structure above 10 kev which is not present in the Simons evaluation. There are two values for the capture cross section reported by Macklin [24] which are shown on Figure 7. The agreement is not very good with the Simons evaluation, maybe because of the missing structure in the evaluation. Finally,

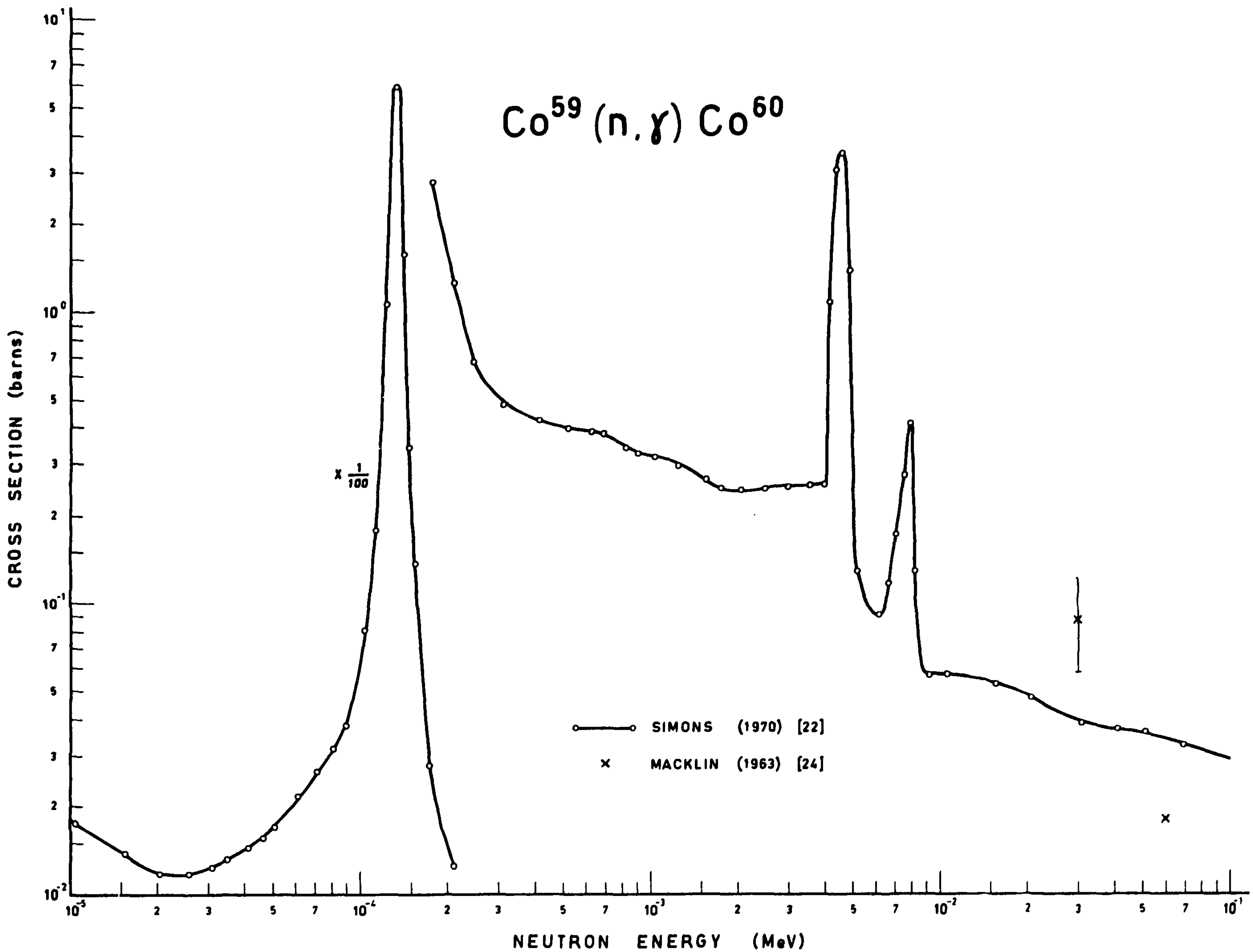

Co^59 (n,γ) Co^60
CROSS SECTION (barns)
NEUTRON ENERGY (MeV)
x 1/100
SIMONS (1970) [22]
MACKLIN (1963) [24]
10^1
10^0
10^-1
10^-2
10^-5
10^-4
10^-3
10^-2
10^-1

Fig. 7

one unpublished 2 keV value from INC is in excellent agreement with the Simons evaluated curve.

From the foregoing, it would appear that the Simons and McElroy are the best data currently available for the capture cross section of Co^{59} and that the thermal cross section is known to about 5% and the resonance integral to about 10%.

IV. $Au^{197}(n,\gamma)Au^{198}$

The gold capture cross section is displayed in Figure 8 in two regions 1) from .1 eV to 10 eV including the resonance at 4.9 eV. 2) from 1 keV to 100 keV. The values from 10 to 100 keV are those recommended by Vaughn and Grench (25) and used in the ENDF/B library as a cross section standard. From 1 to 10 keV the Simons (22) evaluation is displayed. Between 10 eV and 1 keV no data has been plotted but the resonance parameters of Julien et al. (26) are recommended as they are the most extensive measurements available and form the basis for all evaluations. The region below 10 eV is obtained from resonance parameters and with an additional 1/v component required, due to negative resonances to reproduce the recommended 2200 meter/second value obtained from thermal measurements. The parameters for the 4.9 eV resonance are taken as "best" from Wood (27). The curve as plotted is due to Simons and McElroy (22). The region below .1 eV is assumed to be 1/v.

The infinite dilute capture resonance integral given by this data (22) is 1585 barns and the thermal cross section is 99 barns. R. Beaugé as reported by Zijp (21) recommends a resonance integral of 1551 $\pm$ 20 barns. It would appear that the uncertainty in the resonance integral is about 2% but the spread of the resonance integral measurements approaches 15%. The thermal value most often recommended is 98.8 barns and is good to about 1/3%. See Table XIXA.

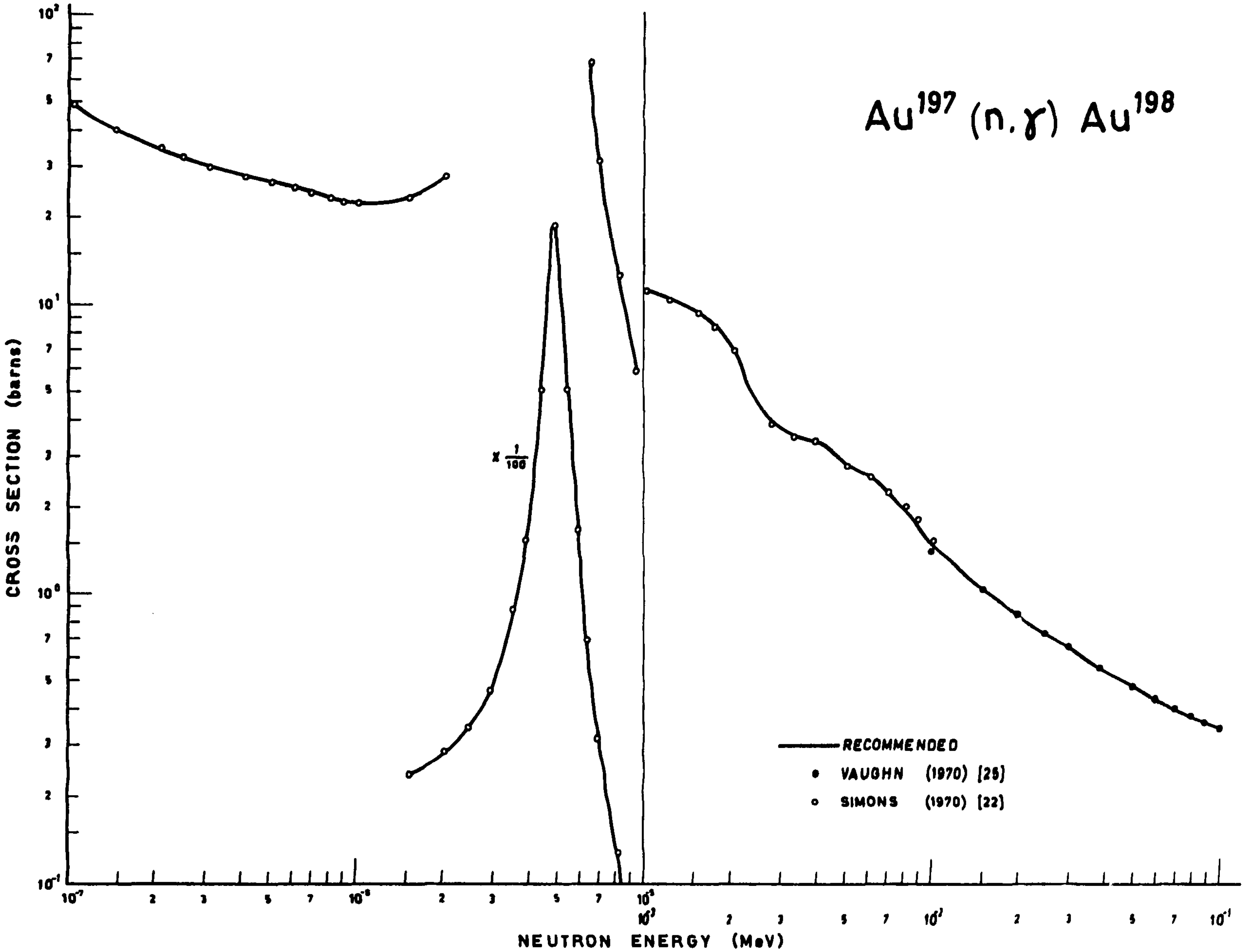

Au197 (n,γ) Au198
CROSS SECTION (barns)
NEUTRON ENERGY (MeV)
x 1/100
RECOMMENDED
VAUGHN (1970) [25]
SIMONS (1970) [22]

Fig. 8

V. U-235(n,f) and Pu-239(n,f) Thermal Region

The thermal and Maxwellian average cross-sections of U-235 and Pu-239 have been evaluated, simultaneously with U-233, Pu-241 and $\bar{\nu}$(Cf-252), by the IAEA consultants group of G.C. Hanna et al in 1969 [28]. The recommended values are given in the table below.

		U-235	Pu-239
absorption cross-section	σ_a	678.5 ± 1.9	1012.9 ± 4.1
fission cross-section	σ_f	580.2 ± 1.8	741.6 ± 3.1
capture cross-section	σ_γ	98.3 ± 1.1	271.3 ± 2.6
bound-atom scattering cross-section	σ_s	17.6 ± 1.5	8.5 ± 2.0
capture/fission cross-section ratio	α	0.1694 ± 0.0021	0.3659 ± 0.0039
total neutron-yield per absorption	η	2.0719 ± 0.0060	2.1085 ± 0.0066
total neutron-yield per fission	$\bar{\nu}_t$	2.4229 ± 0.0066	2.8799 ± 0.0090
g-factor for absorption	g_a	0.9787 ± 0.0010	1.0752 ± 0.0030
g-factor for fission	g_f	0.9766 ± 0.0016	1.0548 ± 0.0030
g-factor for neutron-yield per absorption	g_η	0.9979 ± 0.0018	0.9810 ± 0.0027

The tabulated cross-sections in barns are meant for monoenergetic neutrons of 0.0253 eV or 2200 m/s. The quoted errors are meant as standard deviations, not as confidence limits. Maxwellian average cross-sections for a spectrum-temperature of 20.4°C can be obtained by multiplication with the corresponding g-factor [29] : $\hat{\sigma}_f = g_f\ \sigma_f$. For other spectrum-temperatures the g-factors from Westcott [29] should be reduced to the 20.4°C values contained in the table.

The shape of $\sigma(E)$ in the thermal energy-range is implied in the g-factors. The evaluation by G.C. Hanna et al does not give recommended $\sigma(E)$ curves; but the corresponding curves in the ENDF/B library have been adjusted such that they agree with the cross-sections and g-factors given in the table.

Since the time of this evaluation (1969) some new experiments have been performed which will increase the fission cross-sections and decrease the neutron-yields per fission.

Based on a new value of the U-234 α half-life, Deruytter and Becker [30] obtained σ_f (U-235) = 587.9 ± 3.4 barns, a value which is 1.3% higher than the previously recommended value. Their result of σ_f (Pu-239) = 742.5 ± 3.7 barns confirms Hanna's value, but it may require revision to 752 barns, if one believes the new value of the Pu-239 half-life found by Oetting [31].

The previously existing discrepancy in experimental values of $\bar{\nu}_t(C_f\text{-}252)$ seems to be resolved at a value of about 3.73 [32] compared to the value of 3.765 ± 0.012 recommended by Hanna et al [28]. This would reduce the $\bar{\nu}_t$-values of U-235 and Pu-239 in the same proportion, if this would not be in conflict with the established values of η.

These problems are being evaluated right now by a new IAEA consultants group which will establish a new set of recommended values in 1973. Until the new evaluation is complete, it is recommended to use the 1969 values tabulated above, which are consistent with ENDF/B-3.

VI. $U^{235}(n,f)$ and $Pu^{239}(n,f)$ Resonance Integrals

Recent evaluations and experiments on U-235 and Pu-239 resonance-integrals have been compiled in the table below. This table is not meant to be complete but to give an impression about the scatter of existing values.

All data areinfinite dilute resonance-integrals of the form

$$\int_{E_{min}}^{\infty} \sigma(E)\,\frac{dE}{E}$$

In the table the upper boundary of the integral varies between 1. MeV or 15. MeV; this should make little difference for the data. Note, however, that the data cannot easily be compared when E_{min} is different.

Although the paper [28] by Hanna et al did not aim at evaluating resonance-integral data, the values used in this paper and listed in the second line of the table seem to represent fairly well the average and can therefore be recommended.

Resonance-Integrals (barns)
for U-235 and Pu-239

Energy range	U-235 fission	U-235 capture	Pu-239 fission	Pu-239 capture	Reference
E v a l u a t i o n s					
0.55 eV up			279.51	171.33	DFN 65A 1970 [37]
0.5 eV - 1. MeV	270. ± 10.	140. ± 7.	300. ± 10.	181. ± 15.	Hanna 1969 [28]
0.5 eV - 15. MeV	281.4	140.7	309.1	181.3	ENDF/B-1 1969 [36]
3.0 eV - 15. MeV	205.4	124.9	227.9	148.2	
0.45 eV - 0.5 eV	9.2	1.1			Hennies 1967 [33]
0.45 eV - 10. KeV	274.	139.			
10. KeV - 1. MeV	8.0	2.7			
4.65 eV - 10. KeV			202.1	147.6	
0.45 eV up	277. ± 5.	144. ± 5.	324. ± 9.	195. ± 12.	Cabell 1965 [38]
E x p e r i m e n t s					
0.5 eV up	292. ± 14.	150. ± 6.	312. ± 14.*		Eiland 1970 [34]
ca. 0.5 eV up	274. ± 11.		330. ± 30.		Bak 1969 [35]
0.5 eV up	263. to 291. with errors of ± 8. to ± 16.	136. to 144. with errors of ± 5. to ± 8.	301. to 385. with errors of ± 9. to ± 26.		previous experiments+ quoted by [34]

+ For U-235 experimental data were corrected by Eiland [34] to E_{min} = 0.5 eV. For Pu-239 E_{min} varies between 0.45 and 0.55 eV.

* Experimental result is 231. ± 14. for E_{min} = 3.0 eV. The energy-range from 0.5 to 3.0 eV was added using ENDF/B data quoted in [34].

VII. $U^{238}(n,\gamma)U^{239}$

Very little work has been done on the thermal cross sections for U-238 capture in the past ten years. The review by J.J. Schmidt [39] gives all measurements of the U-238 thermal capture cross section occurring before 1966. The weighted mean value is 2.73 ± .02 barns. Data values range from 2.53 to 3.05 barns, both extremes occurring before 1952. There are three more measurements by Stavisskii[40], Bigham[113] and Hunt[114] and an evaluation of all data by Leonard[117] who recommends 2.720 barns at thermal.

Approximately 88% of the thermal cross section is due to the known positive energy resonances, the remainder being due to unknown bound levels. The thermal cross section obeys a 1/v law up to about .1 ev and then begins to deviate due to the first resonance at 6.67 eV. The Schmidt [39] review also tabulates measured values of the U-238 capture resonance integral (< 1966). When all corrections for 1/v contribution (~1.2 barns) and common Cd-cutoff of 0.5 ev are made the recommended value is very close to 280 barns. Except for one measurement, all measured values fall between 277 and 286 barns. The resonance parameters recommended by Schmidt yield 278.2 barns for the resonance integral. Since the Schmidt evaluation, extensive resonance measurements have been made at Columbia and Oak Ridge. If detailed line shape representations are required the results of such work should be used but there would be no important improvement in agreement between measured and calculated resonance integrals. In summary, no further work seems needed on this reaction.

VIII. $Al^{27}(n,p)Mg^{27}$

This threshold reaction is important for short irradiations. In the region threshold - 6 MeV data are available from Henkel et al. [41], Calvi et al. [42] and Grundl [43]. All these are Van de Graaff measurements using the activation technique. They are displayed in figure 9. Large discrepancies are seen between Henkel's and Calvi's data, particularly in the vicinity of the threshold. Only the overall trend of the measurements shows some similarity.

In the range 6 - 10 MeV there is only one systematic measurement available due to Bass et al. [44] and three selected data points obtained by Grundl [43]. The Bass data are fully displayed in figure 10 and selectively in figure 11. Figure 11 shows that the Bass data are up to 30% higher than Grundl's.

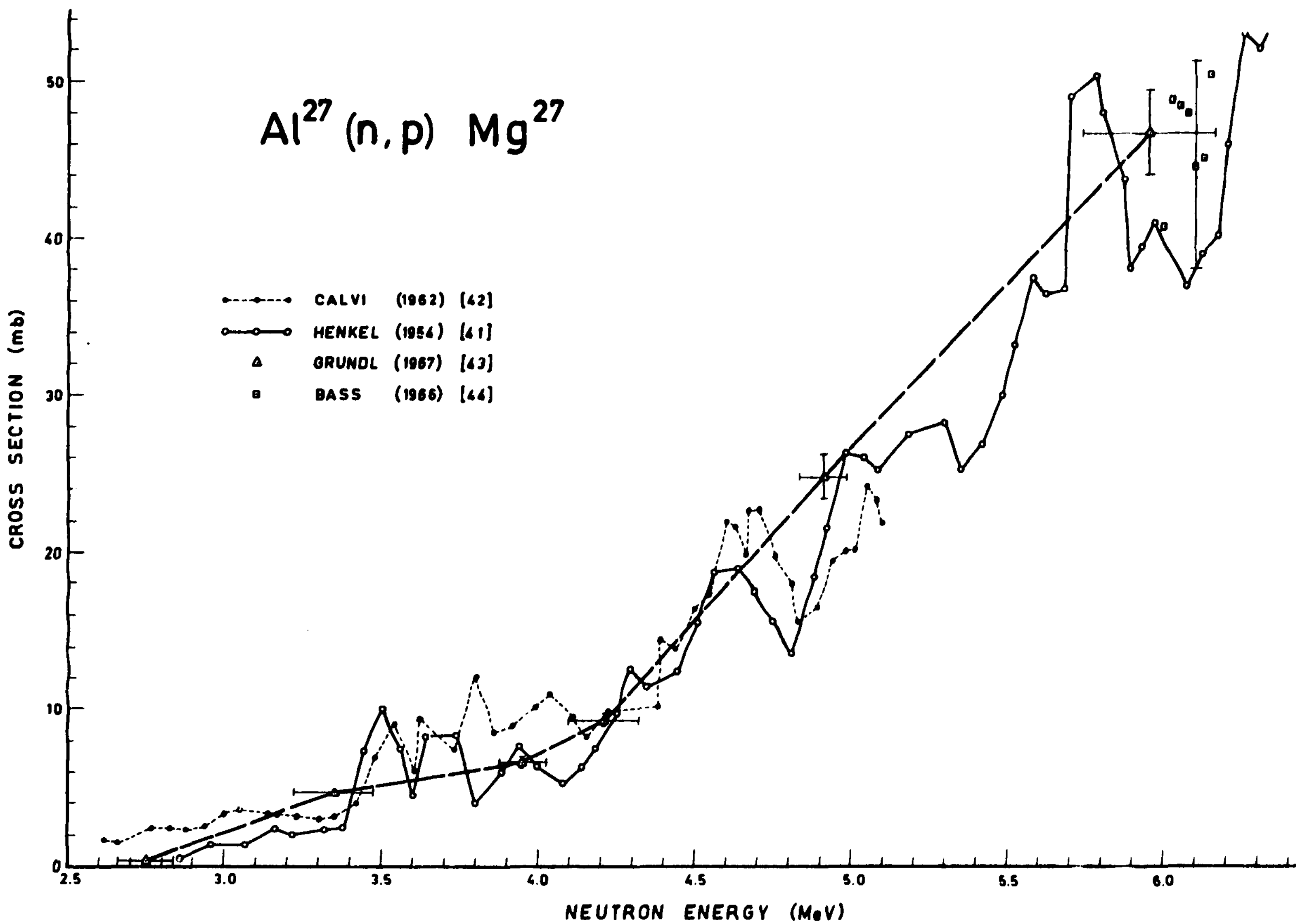
In the range 10 - 12 MeV there is a gap in experimental data.

In the range 12 - 15 MeV a number of experiments are available, particularly one-point-measurements around 14 MeV. Figure 12 shows the large scatter in the data amounting to up to about ± 30%, which is partly due to different normalizations. (Note: only representative data are plotted.) Considering all presently available one-point-measurements between 14 and 15 MeV it is interesting to note that values obtained by β-counting (84-97 mb, average 90 ± 7 mb) seem to be systematically higher than those obtained by γ-ray counting (72-82 mb, average 74 ± 7 mb).

The following evaluations are of interest:

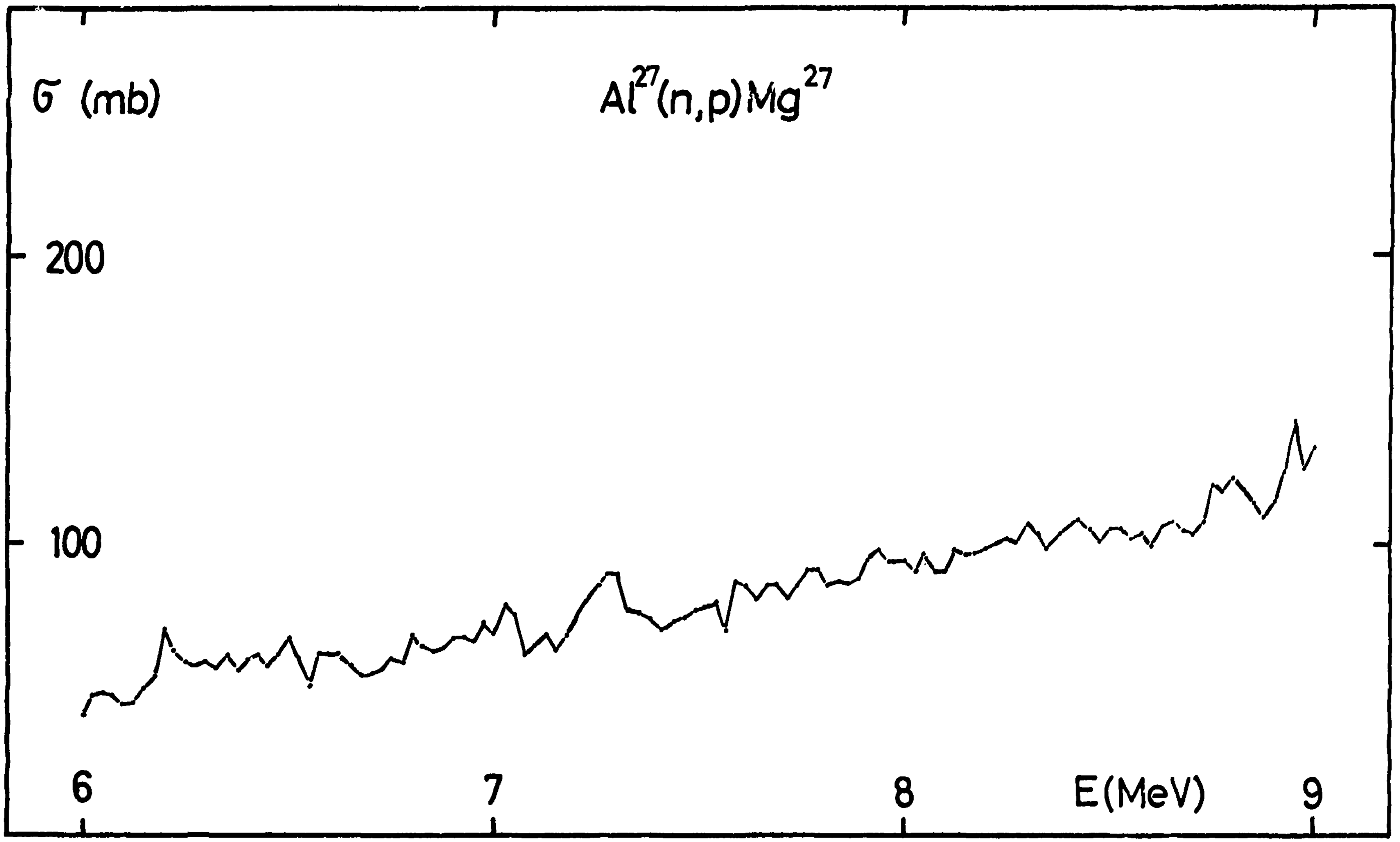
a. L. Forsberg [59] from 1963; this evaluation was incorporated into UKNDL as DFN 35 (see AEEW-M-445, January 1964) and later into the KEDAK library;

b. H. Alter [60] from 1965; based essentially on data contained in BNL-325 and BNL-325, Suppl.2;



Al^{27} (n, p) Mg^{27}
CALVI (1962) [42]
HENKEL (1954) [41]
GRUNDL (1967) [43]
BASS (1966) [44]
CROSS SECTION (mb)
NEUTRON ENERGY (MeV)
0
10
20
30
40
50
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0

Fig. 9



(Results of R. Bass et al., reproduced from /44/)

Fig. 10

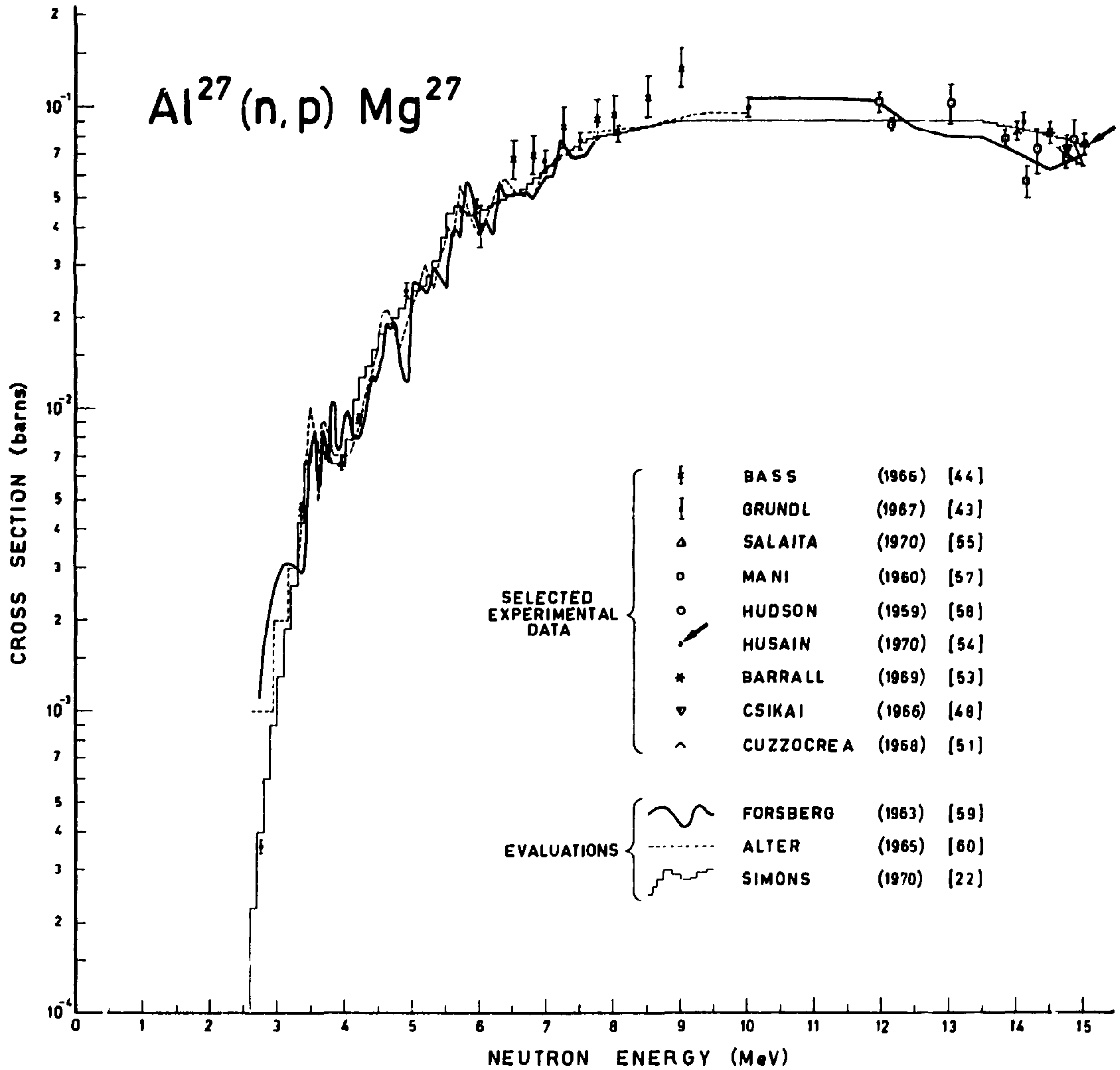
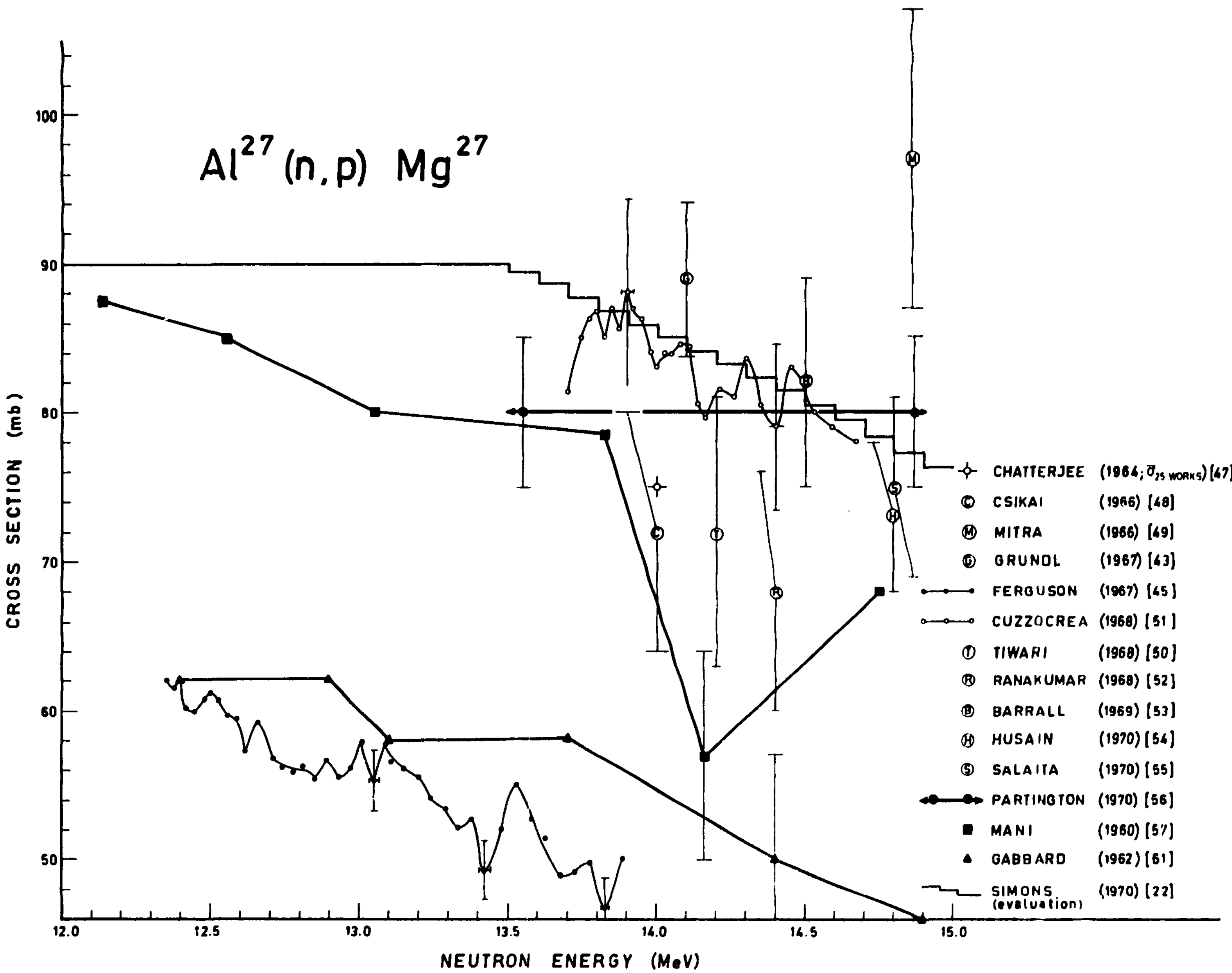

Al27 (n, p) Mg27
CROSS SECTION (barns)
NEUTRON ENERGY (MeV)
SELECTED EXPERIMENTAL DATA
BASS (1966) [44]
GRUNDL (1967) [43]
SALAITA (1970) [55]
MANI (1960) [57]
HUDSON (1959) [58]
HUSAIN (1970) [54]
BARRALL (1969) [53]
CSIKAI (1966) [48]
CUZZOCREA (1968) [51]
EVALUATIONS
FORSBERG (1963) [59]
ALTER (1965) [60]
SIMONS (1970) [22]

Fig. 11



$Al^{27}(n,p)\ Mg^{27}$
CROSS SECTION (mb)
NEUTRON ENERGY (MeV)
100
90
80
70
60
50
12.0
12.5
13.0
13.5
14.0
14.5
15.0
CHATTERJEE (1964; $\bar{\sigma}_{25}$ WORKS) [47]
CSIKAI (1966) [48]
MITRA (1966) [49]
GRUNDL (1967) [43]
FERGUSON (1967) [45]
CUZZOCREA (1968) [51]
TIWARI (1968) [50]
RANAKUMAR (1968) [52]
BARRALL (1969) [53]
HUSAIN (1970) [54]
SALAITA (1970) [55]
PARTINGTON (1970) [56]
MANI (1960) [57]
GABBARD (1962) [61]
SIMONS (evaluation) (1970) [22]

Fig. 12

c. Simons et al. [22] from 1965; this evaluation was incorporated into UKNDL as DFN 226;

d. Foster and Young from LA in 1972; this evaluation is incorporated in ENDF/B-III, the data are not yet available to the Agency.

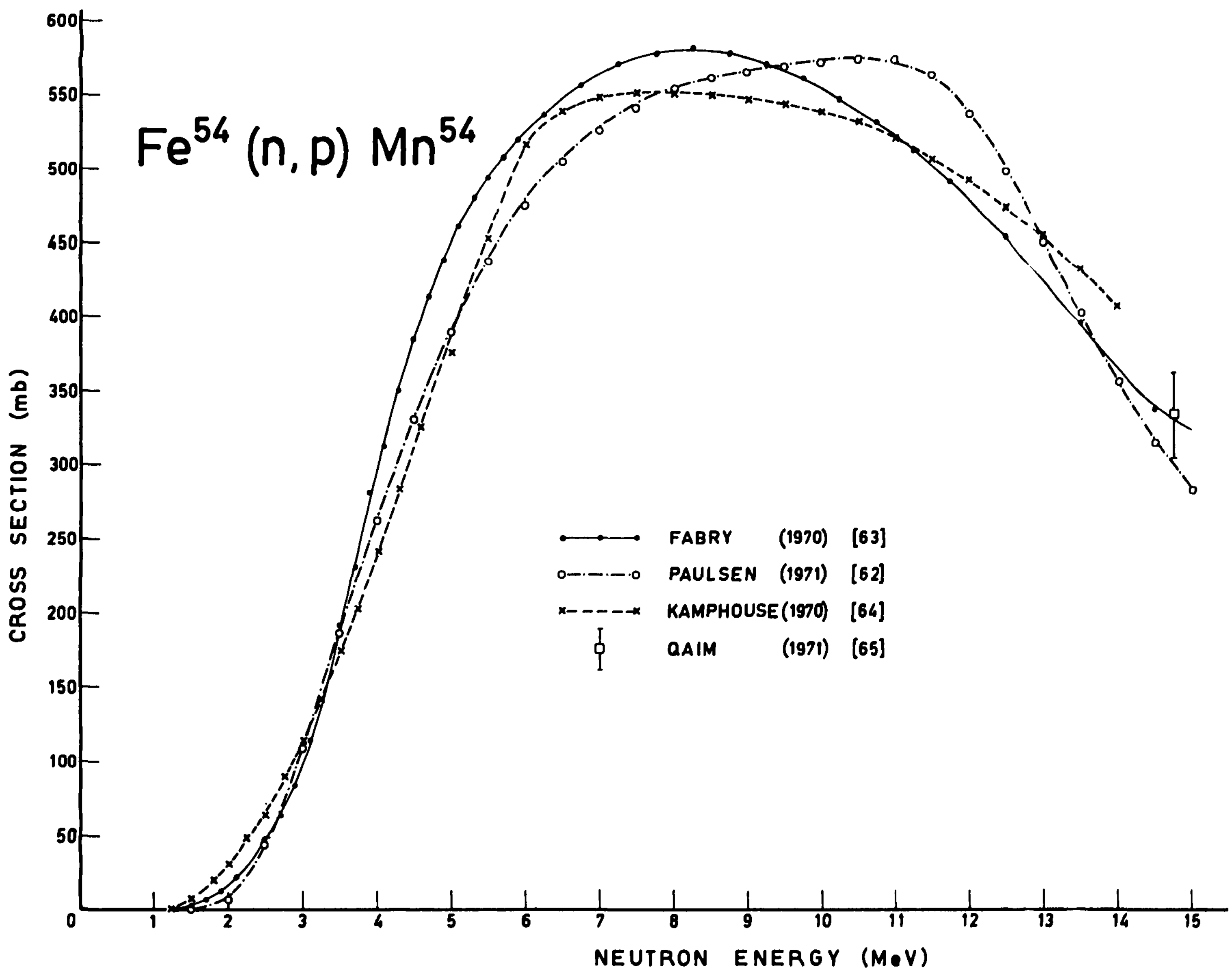
Forsberg's evaluation below 5 MeV is based essentially on Calvi's data [42]. The later more accurate Grundl measurements [43] are in better average agreement with Henkel's data [41]. Simons et al. [22] base their evaluation on Grundl. A new consistent measurement in fine energy detail is needed to confirm Grundl's data.

There are data gaps between 5 and 6 MeV and between 9 and 12 MeV which should be closed by new measurements.

Between 6 and 9 MeV Simons et al. [22] follow Grundl; the 1965 data of Alter [60] agree essentially with Simons. There is an urgent need to resolve the large discrepancy between Bass [44] and Grundl in this energy range.

In the range 12 - 15 MeV Forsberg follows the lower pattern suggested by experiments available before 1963, whereas Simons gives higher data due to more recent experiments. A careful study of the different normalizations and a thorough comparison of different measurement techniques is recommended in this range in order to resolve the existing discrepancies of the order of 10 - 30%.

At the present time we recommend the use of the Simons and McElroy evaluation [22], shown in Fig. 11.
This recommended curve yields a fission spectrum averaged cross section 3.73 mb in a Cranberg spectrum, which is apparently consistent with Fabry [89] and our recommended value of 3.88 mb in a Watt spectrum.
The best value obtained from several integral measurements is given by Fabry [46] as 4.0 ± 0.4 mb.



Fe^{54} (n, p) Mn^{54}
CROSS SECTION (mb)
NEUTRON ENERGY (MeV)
FABRY (1970) [63]
PAULSEN (1971) [62]
KAMPHOUSE (1970) [64]
QAIM (1971) [65]
0
50
100
150
200
250
300
350
400
450
500
550
600
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

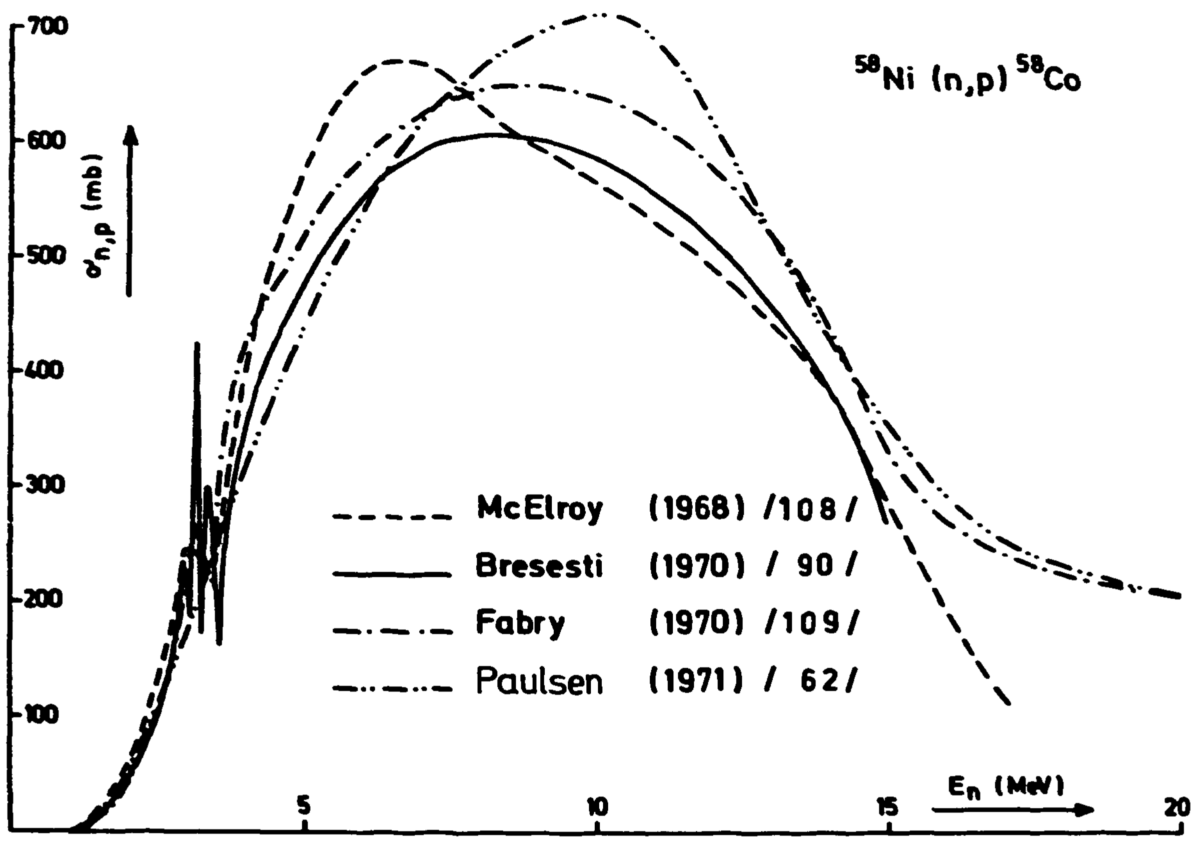
Fig. 13

IX. $Fe^{54}(n,p)Mn^{54}$

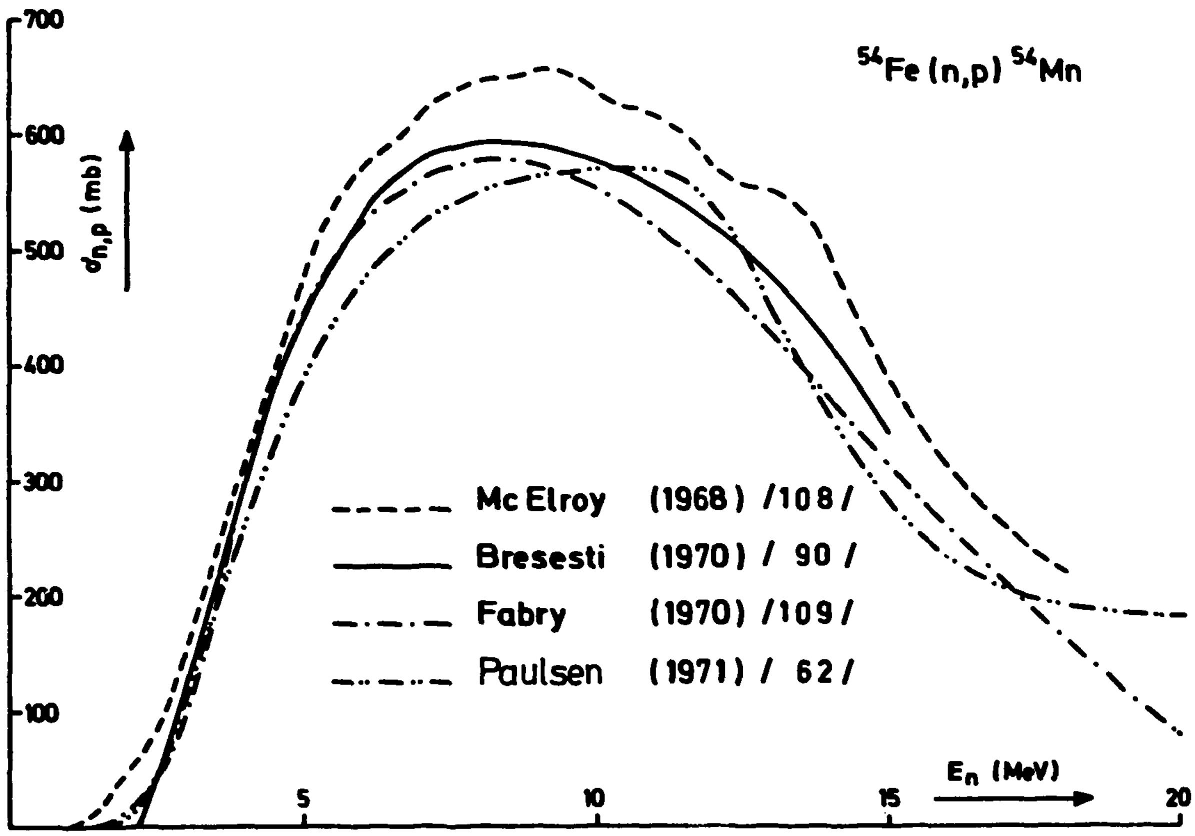
The production of Mn^{54} from neutrons incident on Fe^{54} has widespread application as a fluence monitor. A rather complete review of the status of the cross sections for this reaction was given in 1971 by Paulsen and Widera [62]. Figure 13 gives their least squares fit to the existing data as well as evaluations by Fabry [63] and Kamphouse [64]. One later data point by Qaim et al. [65] at 14.7 MeV has also been plotted. A second figure (Figure 14) has been taken from the Paulsen review to show two other recent evaluations.

The Fabry evaluation which we recommend at present favours the low measured values at threshold and higher values above 3.5 MeV. No data exist between 6 and 13 MeV so the large discrepancies between the different evaluations are understandable and due to different interpolations in that region. The most serious discrepancies for fluence measurements exist in the threshold region ranging up to 50%. In general there is about a 20% uncertainty above the threshold region.

The measurements of the fission averaged cross section have a large spread. Fabry[46], after extensive renormalization of available measurements, recommends an average of 82.5 $\pm$ 2 mb from measurements and 76.5 mb from his recommended differential data. The Paulsen[62] least squares fit gives 74.1 mb and the Kamphouse[64] data 73.8 mb. It would appear that the Fabry value of 76.5 should be used with an uncertainty of 10%.



Comparison of the latest best curves for the 58-Ni(n,p)58-Co cross section



Comparison of the latest best curves for the 54-Fe(n,p)54-Mn cross section

Fig. 14 **(reproduced from /62/)**

X. $Ni^{58}(n,p)Co^{58}$

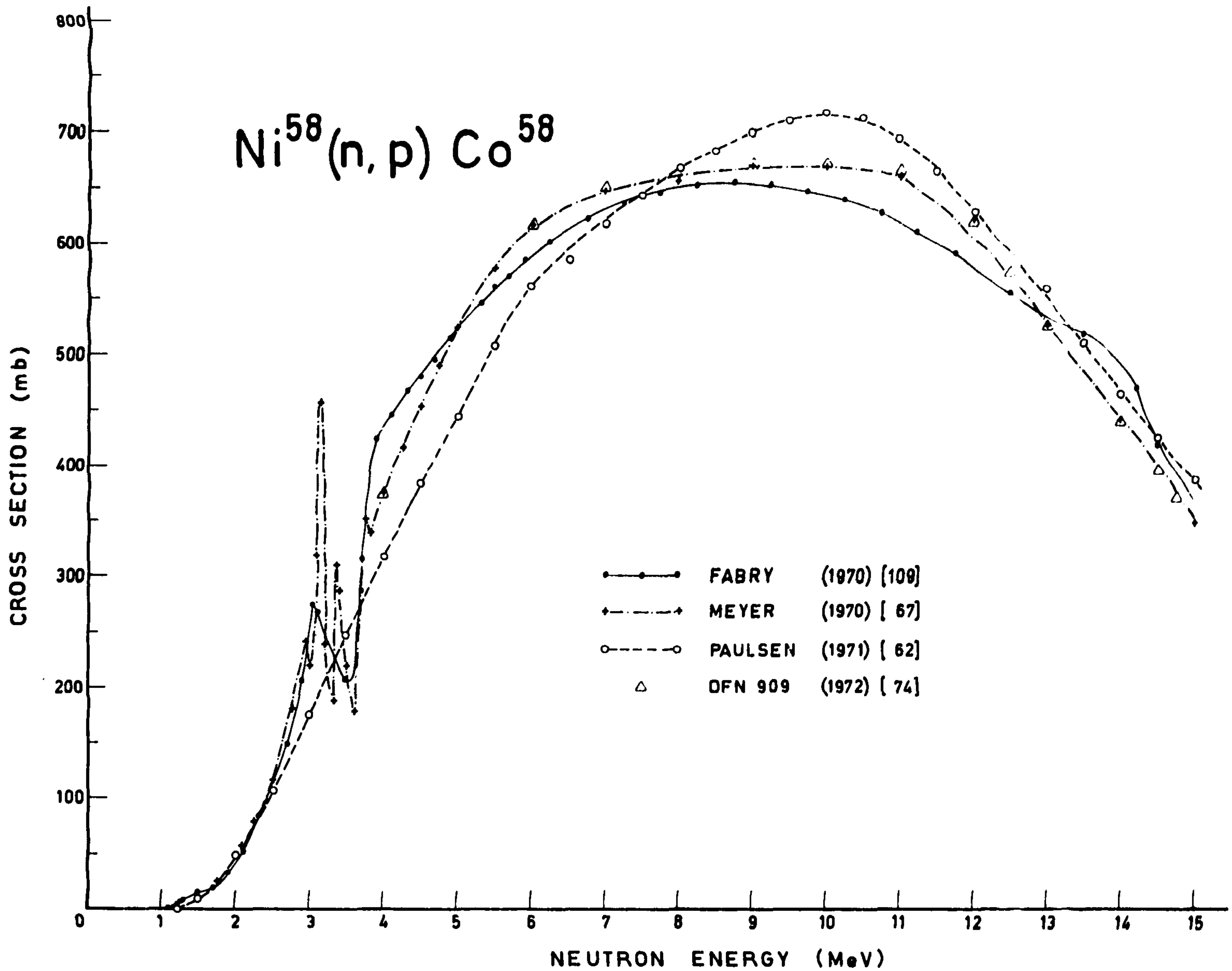
The three most recent evaluations for the $Ni^{58}(n,p)$ cross section are shown in Figure 15. These evaluations are due to Paulsen and Widera [62], Fabry and Schepers [63] and Meyer [67]. The available experimental data upon which these evaluations are based show considerable scatter, particularly from 2 to 4 MeV and 12.5 to 15. MeV. Unlike $Fe^{54}(n,p)$ there is only a small gap in the experimental data in the region 9 to 12.5 MeV.

In Figure 15 are plotted also some data points from DFN 909 UKAEA[74] nuclear data library. The data points of this file follow closely the Meyer data and repeat the structure in the energy range between 3 and 4 MeV.

This file was received by the Agency in September 1972, but the data was evaluated in January 1972. The evaluation is still undocumented, but we believe it is taken from the earlier Meyer evaluation. Figure 14 from the work of Paulsen[62] displays two other evaluations.

There is little difference between the evaluations for energies below 2.5 MeV. There is evidence for structure between 3 and 4 MeV which is given in some detail by Meyer [67], and not at all by Paulsen's [62] least squares fit. The Fabry evaluation gives some coarse structure which is probably adequate for application purposes.

The fission spectrum average of the $Ni^{58}(n,p)$ cross section has been measured and values reported range from 90 to 120 mb. Köhler [66] gives an average value of 98.4 mb but Fabry [63] after corrections recommends 113 mb. The Paulsen differential curve yields a fission spectrum average cross section of 103.3 mb, Meyer 105 mb and Fabry 111 mb. The differential $Ni^{58}(n,p)$ cross section recommended is that of Fabry and it seems to be known to about 20% above 2.5 MeV and 10-15% below that energy. The fission integral recommended is 111 mb with a 10 to 15 % accuracy. The Meyer evaluation gives more detailed structure and represents a best fit to the data in a least squares sense but gives too low a fission averaged cross section.


Ni^{58}(n, p) Co^{58}
CROSS SECTION (mb)
800
700
600
500
400
300
200
100
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
NEUTRON ENERGY (MeV)
FABRY (1970) [109]
MEYER (1970) [67]
PAULSEN (1971) [62]
DFN 909 (1972) [74]
Fig. 15

XI. $Ni^{58}(n,\alpha)Fe^{55}$

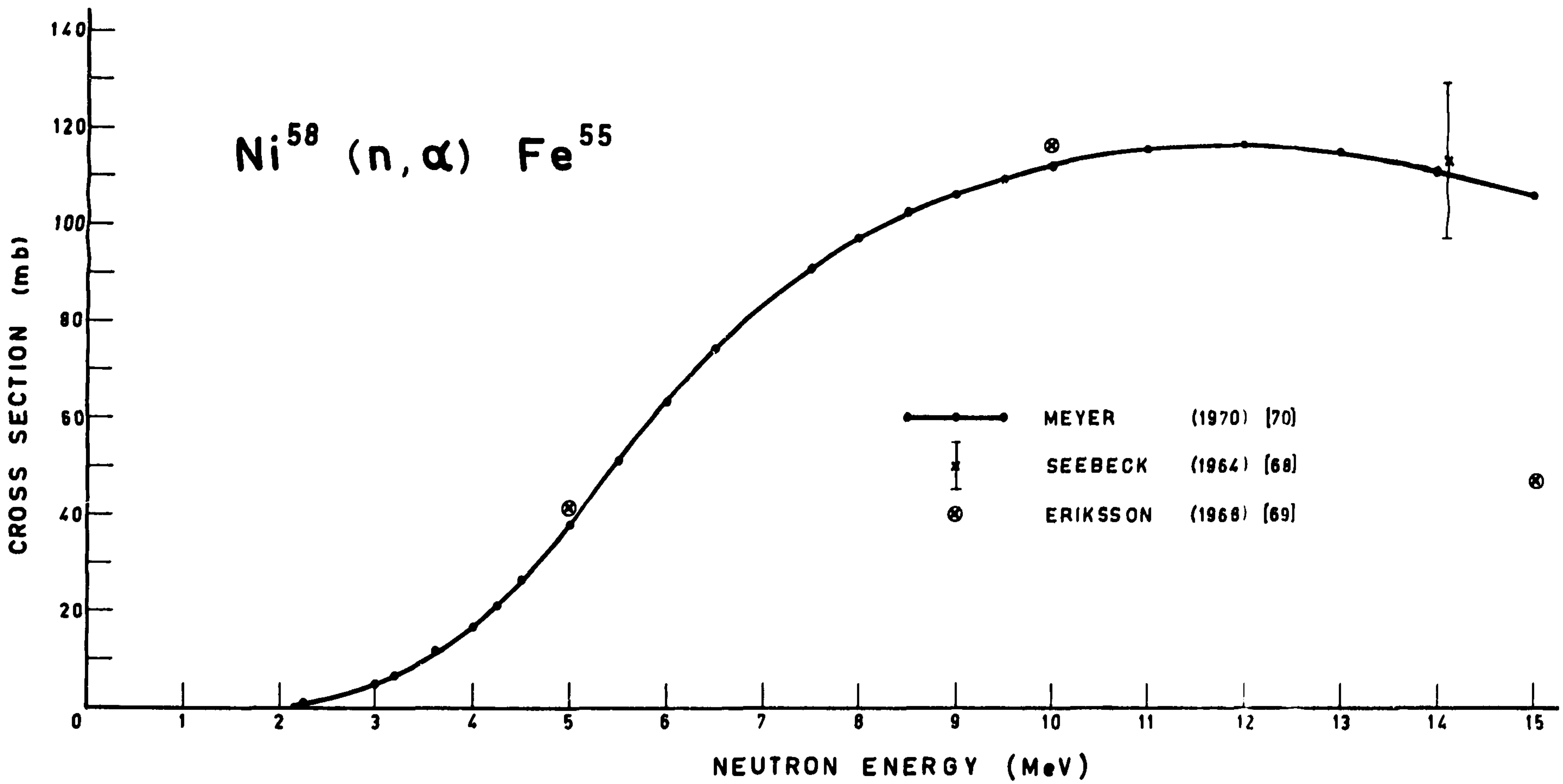
Only one measurement of the $Ni^{58}(n,\alpha)$ differential cross section exists[68]. This value is for 14.1 MeV incident neutrons. At this energy the measurement includes $Ni^{58}(n,n'\alpha)Fe^{54}$ and $Ni^{58}(n,\alpha n')Fe^{54}$ reactions ($Q = -6.41$ MeV) as well as the reaction of interest for fluence measurements. The data point was corrected for these two additional contributions by the author as is shown in Figure 16.

In addition there is a statistical theory calculation by Eriksson [69] giving points at 5, 10 and 15 MeV. These two pieces of information form the basis of the Meyer evaluation [70] shown in Figure 16. The Eriksson point as plotted and used by Meyer differs by a factor of 10 from that given apparently erronously in the original Eriksson paper. And Eriksson's 15 MeV point is in complete disagreement with the one measured value at 14.1 MeV.

A search of the literature gives only one integral measurement for this reaction from 1957 by Schuman et al[118] yielding 0.15 mb. This is in complete variance with measurements of this fission average integral for natural nickel which give a value about 4.8 mb (see Table XX). Ni^{58} is about 2/3 of natural nickel and the thresholds for the other components are larger, therefore the contributions from the other isotopes will be smaller than from Ni^{58}. The Meyer curve when averaged over fission spectrum gives 6.2 mb.

If we assume that all other isotopes give no contributions, then the spectrum averaged cross section for natural nickel would be about 4 mb. In fact, there will be contributions from the other isotopes of nickel, so that one would expect the fission average (n,α) cross section of natural nickel to be at least 10-20% higher than this minium value, which is in very good agreement with measured values for natural nickel.

In summary, the present data are apparently completely inadequate for reliable use of the $Ni^{58}(n,\alpha)Fe^{55}$ reaction for fluence measurements. Considerable work is necessary to provide adequate experimental and/or theoretical data to improve the situation.



Ni58 (n, α) Fe55
CROSS SECTION (mb)
NEUTRON ENERGY (MeV)
MEYER (1970) [70]
SEEBECK (1964) [68]
ERIKSSON (1968) [69]
0
20
40
60
80
100
120
140
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

Fig. 16

XII. $Cu^{63}(n,\alpha)Co^{60}$

The production of Co^{60} by neutron bombardment of Cu^{63} is the quantity of interest for dosimetry measurements. Only one set of experimental data is available covering the energy region from 5.5 to 15 MeV[71]. The cross section from threshold (-1.72 MeV) to 5.5 MeV is negligibly small due to the Coulomb barrier. Paulsen gives a fission spectrum averaged cross section for his data of .34 ± .04 mb[71].

The data serves as the basis for the Simons and McElroy[22] evaluation with some increase in the threshold region to obtain a fission spectrum average of .356 millibarns. This evaluation is shown in Figure 17. There are several measurements of the fission spectrum averaged cross section ranging from .45 to .62 mb. See Table XXA. As a result of his survey of these measurements Fabry[46] recommends a value of 0.50 ± 0.05 mb.

A further recommended curve is given by Fabry and Schepers[63]. They have renormalized the Paulsen data[71] by 56.4% in order to give a higher fission spectrum averaged cross section of .535 mb (see Figure 17). Possible support for this renormalization is a value of 5.65 mb/steradian at 55° for 15 MeV neutrons by Irfan and Jacks[75]. However, the angular distribution is highly anisotropic in this energy region and in fact has a maximum near 55°[76]. Thus the multiplication of the 55° value by 4π probably overestimates the true value integrated over all exit angles.

At the recent Euratom WGRD meeting[72] Liskien reported results of a measurement of the ratio $\sigma_{n,\alpha Cu^{63}}/\sigma_{n,\alpha Al^{27}}$ at the maximum of the response function /8 MeV/. The results of this measurement are in good agreement with the ratio of differential measurements, but contradict the ratio of results of integral measurements. He concludes that serious errors exist in integral measurements.

Because there is no data to support the Fabry renormalization and, because the fission average cross section is most sensitive to the threshold region cross section for reactions with such high threshold energies, one cannot justify the Fabry renormalization and so the Simons-McElroy evaluation is recommended.

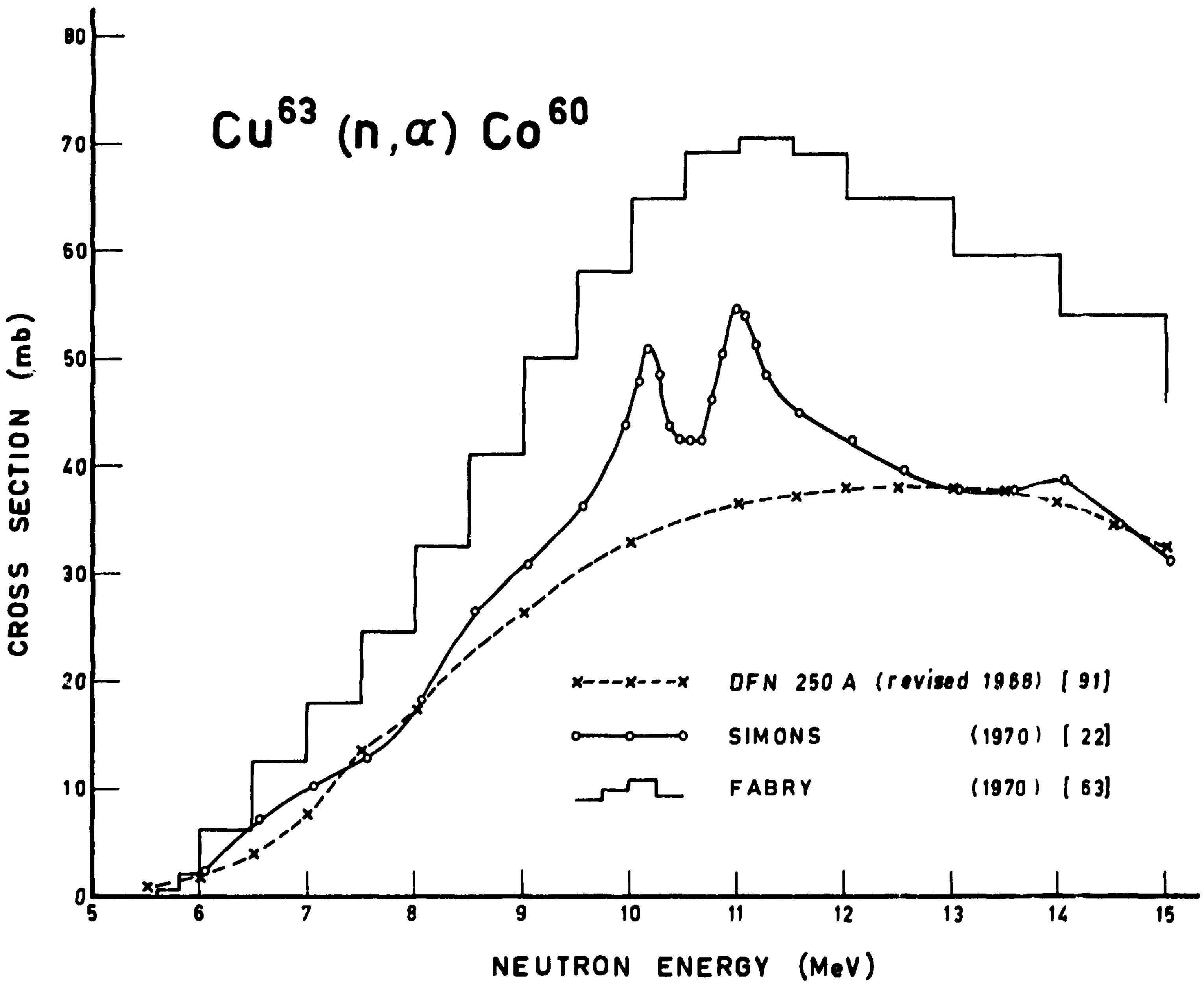

Cu63 (n,α) Co60
CROSS SECTION (mb)
NEUTRON ENERGY (MeV)
DFN 250 A (revised 1968) [91]
SIMONS (1970) [22]
FABRY (1970) [63]
0
10
20
30
40
50
60
70
80
5
6
7
8
9
10
11
12
13
14
15

Fig. 17

XIII. $Nb^{93}(n,n')Nb^{93M}$

The quantity required for flux measurement purposes is the cross section for production of the Nb^{93} isomeric state at 28 keV by inelastic scattering of neutrons. There are no direct measurements of this quantity at any energy. The data presented in Figure 18 represent derived data of two types which we shall discuss briefly.

The data points in Figure 18 are all based on the measurement of gamma ray spectra from inelastic neutron scattering by Nb. In order to interpret this kind of measurement, one must know the level structure of Nb^{93} and the gamma ray decay scheme for Nb^{93}. Until recently there was considerable doubt as to the location and spin of many important low lying levels. Much of the disagreement has been resolved in level structure implications of the γ-spectrum measurements by Rogers et al.[(77)] and Göbel et al. [(78)] although some details are still in doubt. However, the isomeric state of Nb^{93} at 28 keV $(1/2^+)$ can be populated in only two ways, either by direct neutron excitation or by a gamma ray cascade during deexcitation of higher levels. The last gamma ray in this cascade can only be the 780 kev transition from a level at about 808 kev.

Measurements of the production cross section for 780 kev gamma rays have been taken from several references (78-82).In all cases it was necessary for us to add the cross section from the direct production of the isomer state. This correction curve was taken from Hauser-Feshbach calculations reported by Rogers [(79)] and extrapolated as shown in Figure 18. It is clear that there are large discrepancies in the region of reported data mostly between .9 and 2.2 Mev. The Rogers and Nath data lie low, the TNC (1971) and Göbel data are high and the older Texas Nuclear Corp. (TNC) 1967 data fall in the middle. The TNC (1971) data were given at 55° only. Isotropy was assumed in order to get the integral cross section thus neglecting any possible but unknown anisotropy.

The histogram curve covering the entire energy range to 15 Mev was taken from work of Hegedüs [(83)]. The basis of his method is the measurement of the activation of Nb in several different fast neutron spectra which are known. The unknown cross section can then be "unfolded". This

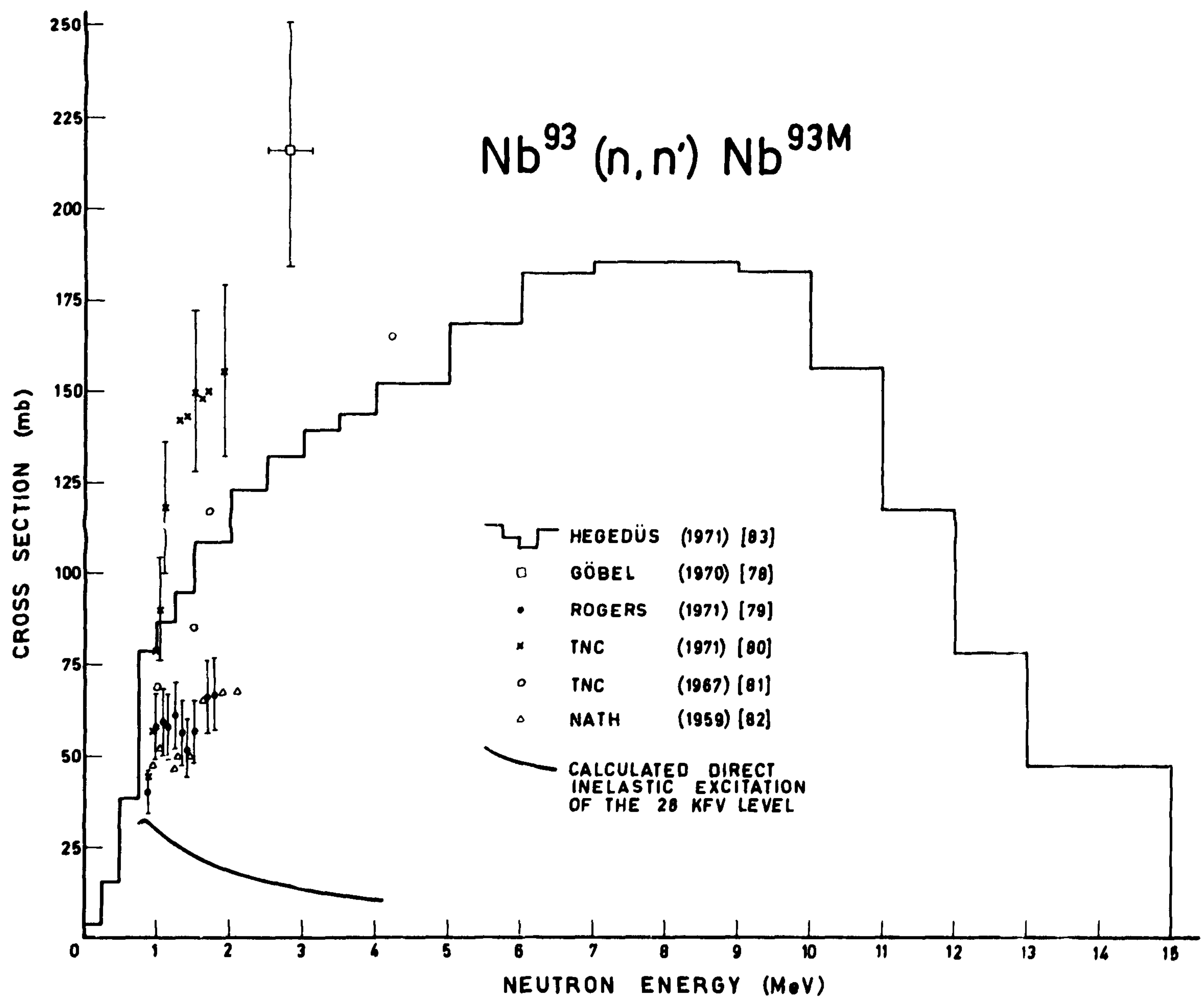

Nb93 (n, n') Nb93M
CROSS SECTION (mb)
NEUTRON ENERGY (MeV)
0
25
50
75
100
125
150
175
200
225
250
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
HEGEDÜS (1971) [83]
GÖBEL (1970) [78]
ROGERS (1971) [79]
TNC (1971) [80]
TNC (1967) [81]
NATH (1959) [82]
CALCULATED DIRECT
INELASTIC EXCITATION
OF THE 28 KEV LEVEL

Fig. 18

technique is the logical inverse of that normally used in neutron fluence measurements. It is interesting to note that in the region 1 to 3 MeV, this method yields values for the Nb isomer generation cross section which fall between those two conflicting groups, of data derived from gamma ray spectrum measurements. Hegedüs also gives a fission spectrum average value of 97 millibarns for this cross section.

One other difficulty with the use of this reaction as a fluence monitor is the discrepancy in experimental determinations of the half-life of the isomeric state. Measurements before 1954 give about 4 years for the half life and later measurements about 12 years. Hegedüs[83] recommends 11.4 ± 0.9 years.

Improvements in the situation pictured in Figure 18 will require more accurate determination of the 780 kev gamma ray production from inelastic scattering over a larger energy range. Direct excitation of the 28 kev level is most important just above threshold and can probably be obtained from Hauser-Feshbach theory with sufficient accuracy using the present knowledge of level structure estimates. Alternatively, calculations using Hauser-Feshbach theory and presently known level structures, densities, and branching ratios could be used over the entire energy region to provide additional information.

At the present time, the multigroup cross sections of Hegedüs should be used as they are the only values which span the entire energy region and they are not in disagreement with the other measurements below 3 MeV. However, the group data need confirmation before the reliability of the data can be assured.

XIV. $Rh^{103}(n,n')Rh^{103M}$

The quantity of interest for reactor fluence measurements is the cross section for excitation of the 40 kev isomeric level $(7/2^{+})$ by inelastic neutron scattering. In contrast to the $Nb^{93}(n,n')Nb^{93M}$ reaction, this reaction has a much larger cross section, because the majority of the levels of Rh^{103} decay through this level rather than to the ground state. The half-life of this isomeric state is 57 minutes with no large discrepancies (about 1%) in reported values.

All the reported data have been obtained by the activation technique. One set of data from Butler and Santry[84] covers the entire energy range from 0 to 15 Mev. Another set of data from Kimura et al[85] covers the energy range to 4.6 Mev. There is also one point from Aten and Nagel[86] at 14.2 Mev. These results are given in Figure 19.

Below 600 kev there are no great discrepancies between the two sets of avail··le data. Above that energy, the data of Kimura are consistently lower. ·ie energy dependent shape of the Butler data between 600 kev and 4 Mev can be easily understood with the present knowledge of the level structure and decay scheme of Rh^{103}. However the "hump" in the Butler data between 5.5 and 11 Mev has no explanation from level structure systematics. In this context it is interesting to note that the neutron source reaction used in the measurement changes at 5 MeV. On the other hand, the Kimura data do not cover the range above 4 MeV well (only one point). The one point of Kimura only suggests that the cross section is not increasing in that energy range. The point of Nagel and Aten at 14.2 MeV is higher than Butler and would appear to be in error, as the Butler data are particularly accurate in this range.

Because a large fraction of the excited levels of Rh^{103} decay to the isomeric state one would expect that the isomeric production cross section would be less than but close to the total inelastic cross section of Rh^{103}. A relative curve of the Rh^{103} inelastic cross section has been measured by Trebilcock.[87] If we normalize that curve to 150 mb at 500 kev then we find that it lies above the Butler and Santry data up to 5 Mev and below that data above 5 Mev.

There are also wide discrepancies in measured fission spectrum averaged activation cross sections for Rh^{103}. Very old values are near 1100 mb which cannot be supported by the differential measurements. Butler and Santry[84]

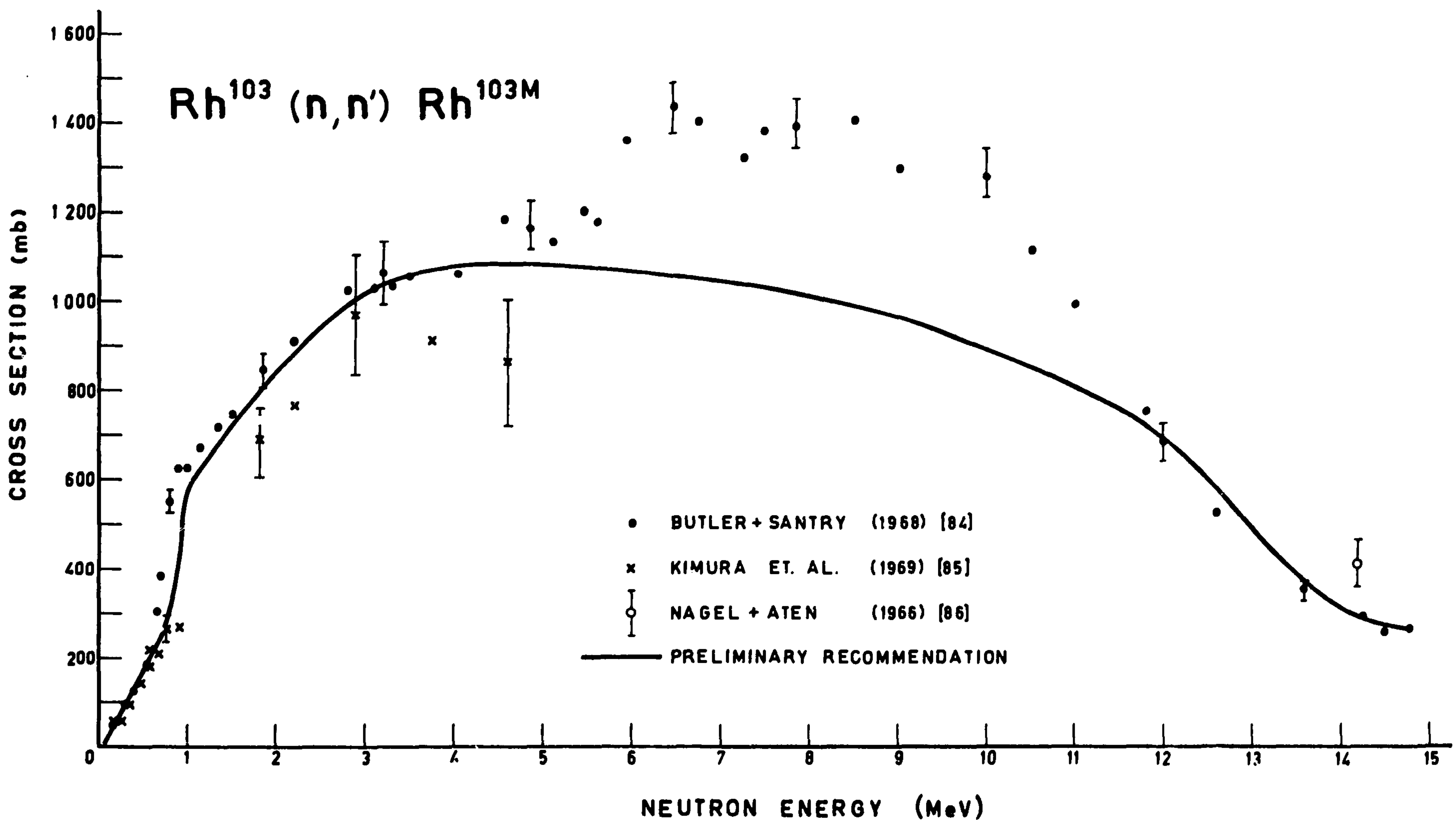

Rh103 (n,n') Rh103M
CROSS SECTION (mb)
NEUTRON ENERGY (MeV)
BUTLER + SANTRY (1968) [84]
KIMURA ET. AL. (1969) [85]
NAGEL + ATEN (1966) [86]
PRELIMINARY RECOMMENDATION

Fig. 19

give 716 ± 40 mb, Kimura[85] on the other hand calculates from his measured differential data 558 ± 32 mb. Of course, the fission spectrum averaged cross section is most sensitive to the differential cross section below 2.5 Mev. One value of the fission average cross section from an integral experiment has been reported by Köhler(and Knepf)[88]. This value is 403 ± 40 mb. However, he gives a value of 60 ± 5 mb for Ni^{58} (n,p) average, which is almost a factor of two too small, indicating a softer than fission spectrum. He has performed some corrections, but this correction procedure is extremely difficult and unreliable.

It is apparent that a curve following the Butler shape and lying a little lower in magnitude should be used up to 4.5 MeV due to the large uncertainties (lower weight) of the Kimura data. Above 13.5 MeV Butler uses a third neutron source and this data may be adequate for practical purposes. In the intervening energy region a smooth connecting curve should be used. Confirmation of such a recommended curve should be sought through further activation measurements above 5.5 MeV and Hauser-Feshbach calculations. Additional data would be needed and/or statistical theory calculations to confirm Butler's cross section shape between about 700 keV and 5.5 MeV The uncertainty of between 20-40% in the differential data make this reaction unsuitable for use at this time.

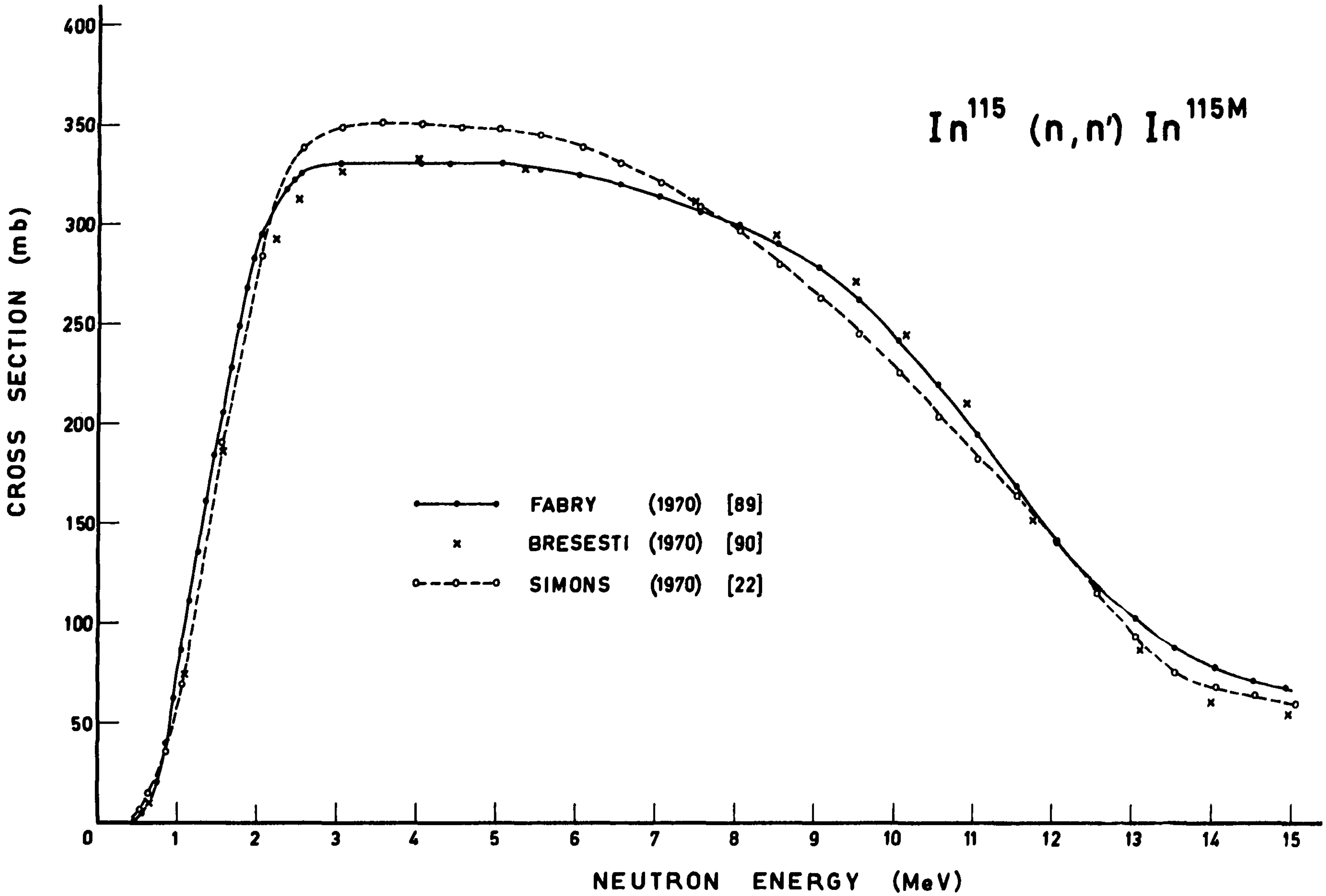
XV. $In^{115}(n,n')I^{115M}$

The neutron fluence measurements utilizing Indium make use of the inelastic excitation of the isomeric level at 335 keV ($7/2^-$) which has a half life of 4.5 hours. For this reaction there are presently three evaluations generally available to us using essentially the same experimental data[22,89-90]. These evaluations are plotted in Figure 20.

The evaluations of Fabry[89] and Bresesti[90] are essentially identical. The evaluation of Simons is lower in the threshold region (< 2 MeV) and higher over the plateau region (2 to 8 MeV). Once again, the Simons evaluation drops below the other evaluations up to 13 MeV. It would appear that, in contrast to Fabry or Bresesti, the Simons evaluation had not used data renormalized to account for later evaluations of the gold capture and uranium-235 fission standard cross sections than those used by the original authors.

There is a measured value of the fission spectrum averaged activation cross section given by Fabry of 187 $\pm$ 6 mb[46]. The recommended data of Fabry yield a spectrum average cross section of 187.5 mb, and that of Bresesti yields a value of around 178 mb. Additional studies of the activation of In with several neutron sources by Pauw and Aten[92] indicate that the cross sections recommended by Fabry and Bresesti are 13% too low. However, there is no indication from available microscopic data that the recommended cross sections can be increased by that large a percentage.

Until such time as this discrepancy is resolved, the recommended data of Fabry[89] are preferred with a confidence of about 10%; Bresesti's evaluation is close to Fabry's, but gives a somewhat smaller fission spectrum average.

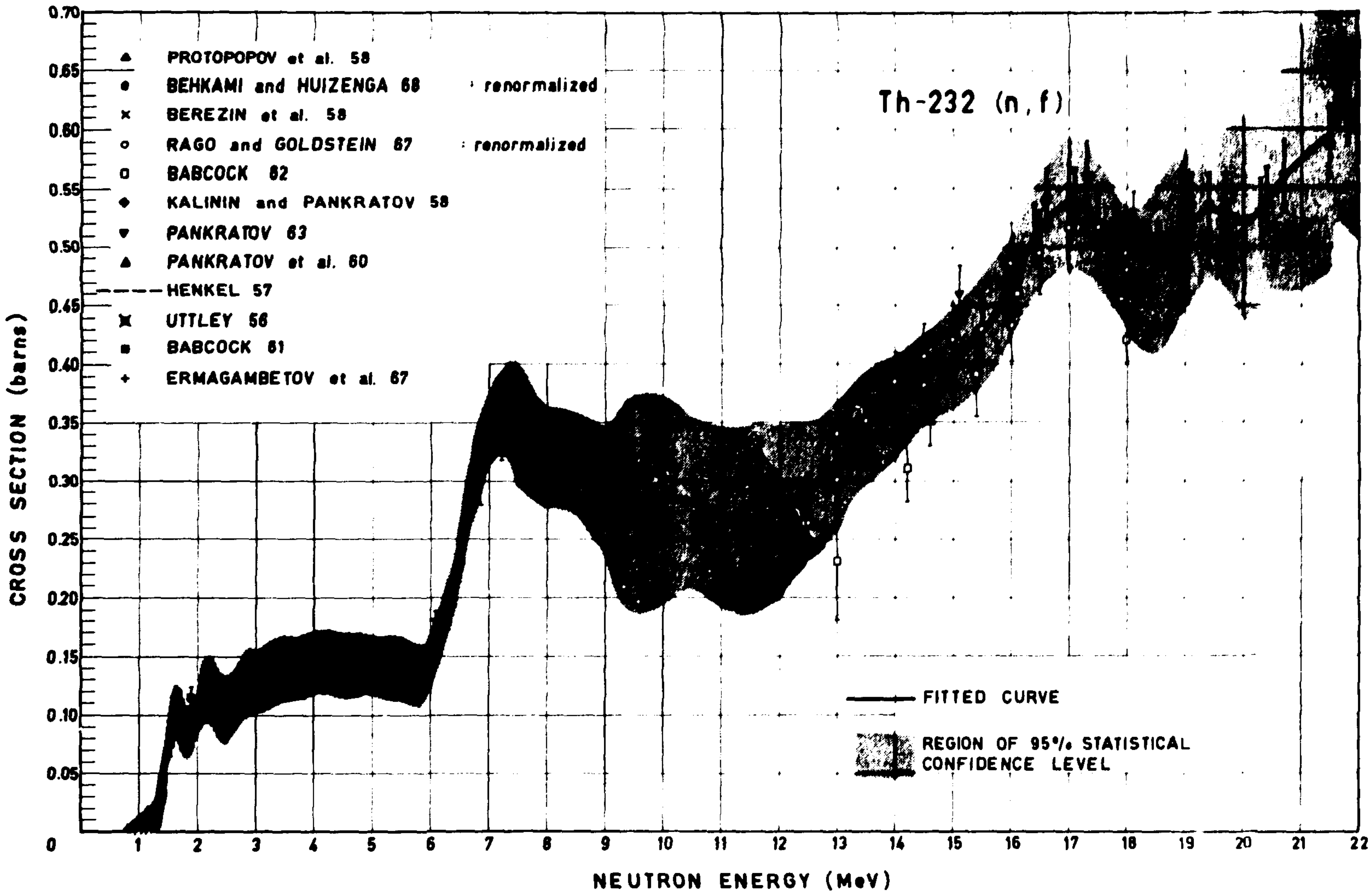


In^{115} (n,n') In^{115M}
FABRY (1970) [89]
BRESESTI (1970) [90]
SIMONS (1970) [22]
CROSS SECTION (mb)
NEUTRON ENERGY (MeV)
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
50
100
150
200
250
300
350
400

Fig. 20

XVI. $Th^{232}(n,f)F.P.$

A complete review of available experimental data on Thorium-232 fission has been made recently by Bak and Lorenz [93]. All data were normalized to the same standard cross section where necessary and fitted with a least squares polynomial. The results are shown in Figure 21 taken from their report. The shaded area represents the 95% confidence level. One additional set of experimental data from Muir and Veeser [94] became available after this review. The data cover the energy range to 3 Mev and are in good agreement with the evaluation in this region. Only one measured value of 82 $\pm$ 3 mb has been reported by Fabry [46] for the fission spectrum averaged cross section of $Th^{232}(n,f)$. The Bak and Lorenz evaluation gives 70.2 $\pm$ 13.5 mb, which is close to results obtained from evaluations by Davey[104], Bresesti[90] and Wittkopf[73]. (See Table XXA). These two values are in strong disagreement and until this discrepancy is resolved this reaction cannot be used with the desired accuracy for neutron fluence measurements.



Th-232 (n, f) EXCITATION CURVE

(reproduced from /93/)

Fig. 21

XVII. U^{238}(n,f)

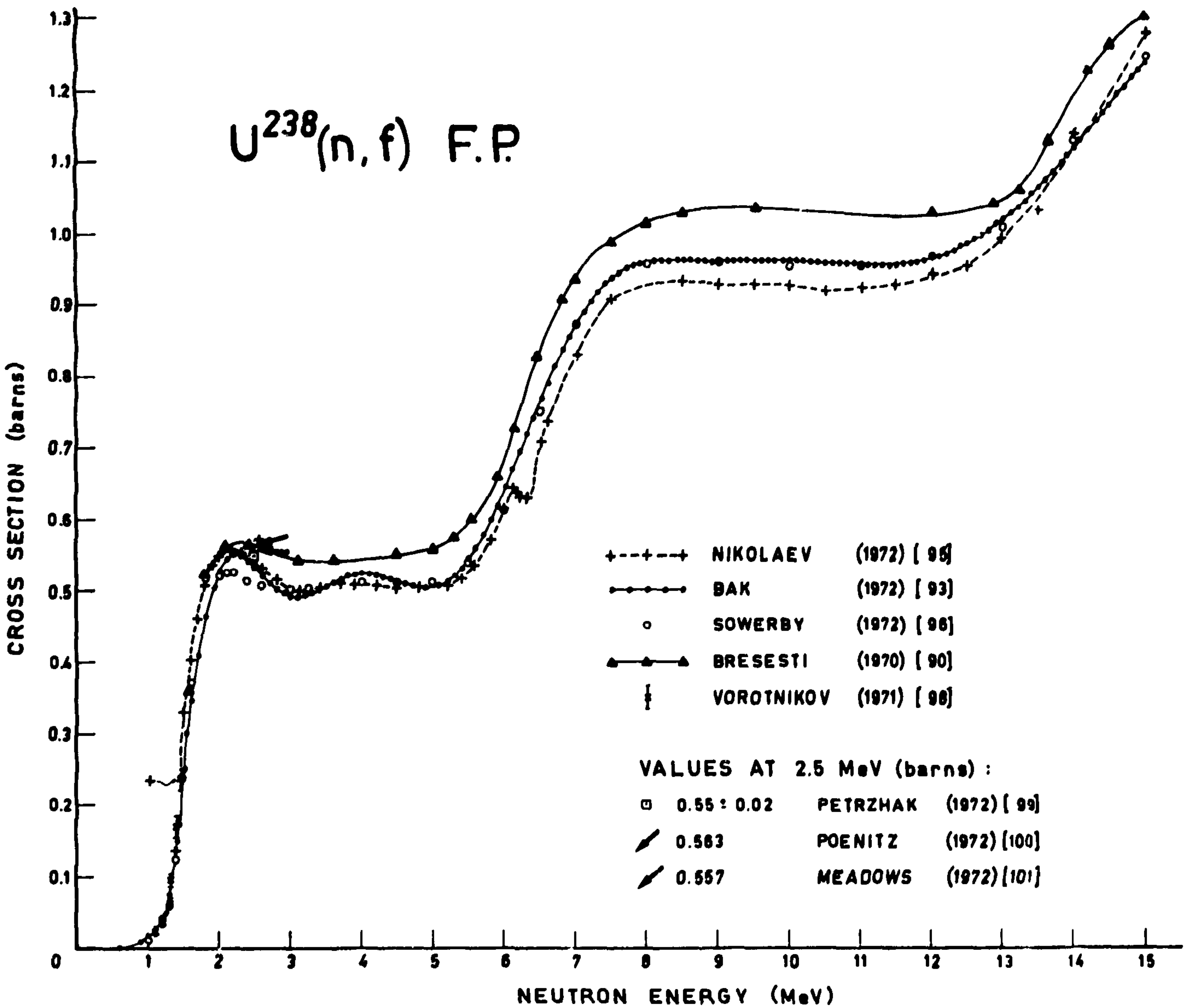
The data situation with regard to the fission reaction on U^{238} has recently been thoroughly reviewed by Bak and Lorenz [93]. Their final recommended curve is displayed in figure 23 together with the significant experimental data available before 1970.

Many other evaluations for this reaction are available. Three were done around 1970 and are due to Simons and McElroy [22], Bresesti et al. [90] and Fabry [89]. Three other evaluations were done after Bak and Lorenz by Nikolaev and Bazazjanz [95] (USSR evaluated data library DFN 2001), Sowerby et al. [96] (UKNDL DFN 272) and Pitterle and Durston [97] (ENDF/B-III, MAT-1158, still not available to IAEA). The 1972 evaluations except Pitterle's and Bresesti's evaluation, are displayed in figure 22 together with Bak's curve and the recent experimental data by Vorotnikov [98] which became available after Bak's evaluation. The Vorotnikov data cover essentially the threshold region and support former experimental work.

Except for small local deviations there is good agreement between Bak and Sowerby and Nikolaev, whereas Bresesti's curve is consistently higher by about 5 - 10% and Nikolaev's slightly lower in the second plateau region. Bresesti's data are higher because he renormalized to get a higher (about 0.308 b) fission neutron spectrum average. Not plotted are Fabry's and McElroy's evaluations. McElroy follows very closely the Bak curve with exception of the range 8-12 MeV, where it is about halfway between Bak and Bresesti, i.e. about 5% higher than Bak. Except for small local deviations Fabry agrees with Bak.

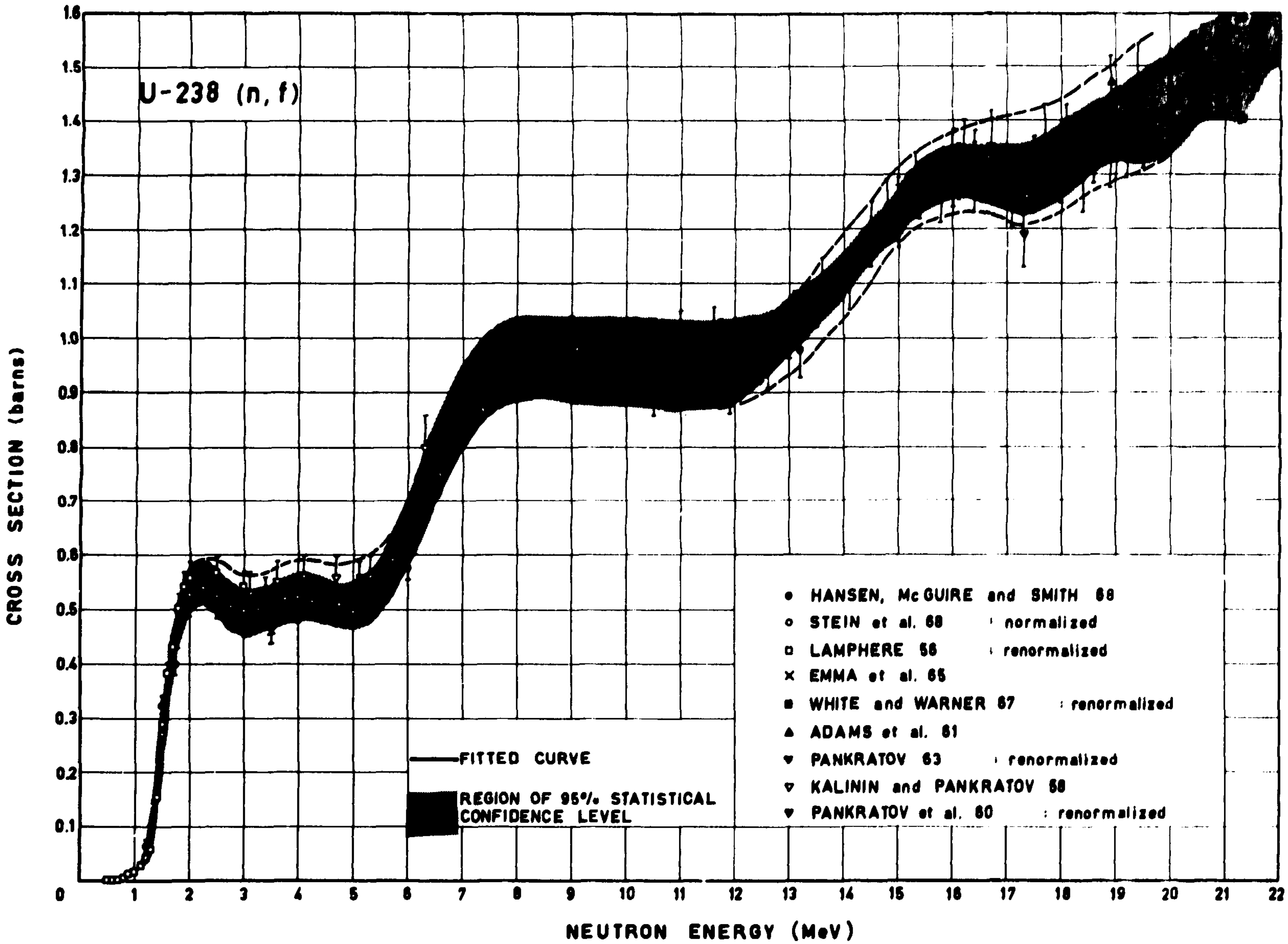
At 2.5 MeV three very recent independent precision measurements by Petrzhak et al. [99], Poenitz [100] and Meadows [101] are seen to be in excellent agreement with each other and with the mentioned evaluations within a few % (see Figure 22.

The 95% statistical confidence level of Bak's and Lorenz's recommended curve is about 5 - 10% and embraces practically all available measurements and evaluations. In order to improve the data to the confidence levels of 1 - 5 % requested in RENDA 72 [1], detailed very accurate remeasurements (few points absolute and/or detailed ratios to U^{235} fission) covering



U238(n, f) F.P.
CROSS SECTION (barns)
NEUTRON ENERGY (MeV)
NIKOLAEV (1972) [95]
BAK (1972) [93]
SOWERBY (1972) [96]
BRESESTI (1970) [90]
VOROTNIKOV (1971) [98]
VALUES AT 2.5 MeV (barns) :
0.55 ± 0.02 PETRZHAK (1972) [99]
0.563 POENITZ (1972) [100]
0.557 MEADOWS (1972) [101]

Fig. 22



U-238 (n, f) EXCITATION CURVE

Fig. 23 (reproduced from /93/)

preferably the whole interesting energy range between threshold and 15 MeV (and higher) would be desirable. More specifically it is recommended to have further accurate measurements in fine energy detail in the threshold region below 2 MeV, to confirm the older Smith and Henkel and the recent Vorotnikov data and to allow resolution of the inconsistencies in the evaluated data sets. New measurements would also be desirable above 6 MeV where only old experimental data (< 1963) exist and where there is some disagreement in the evaluated data sets.

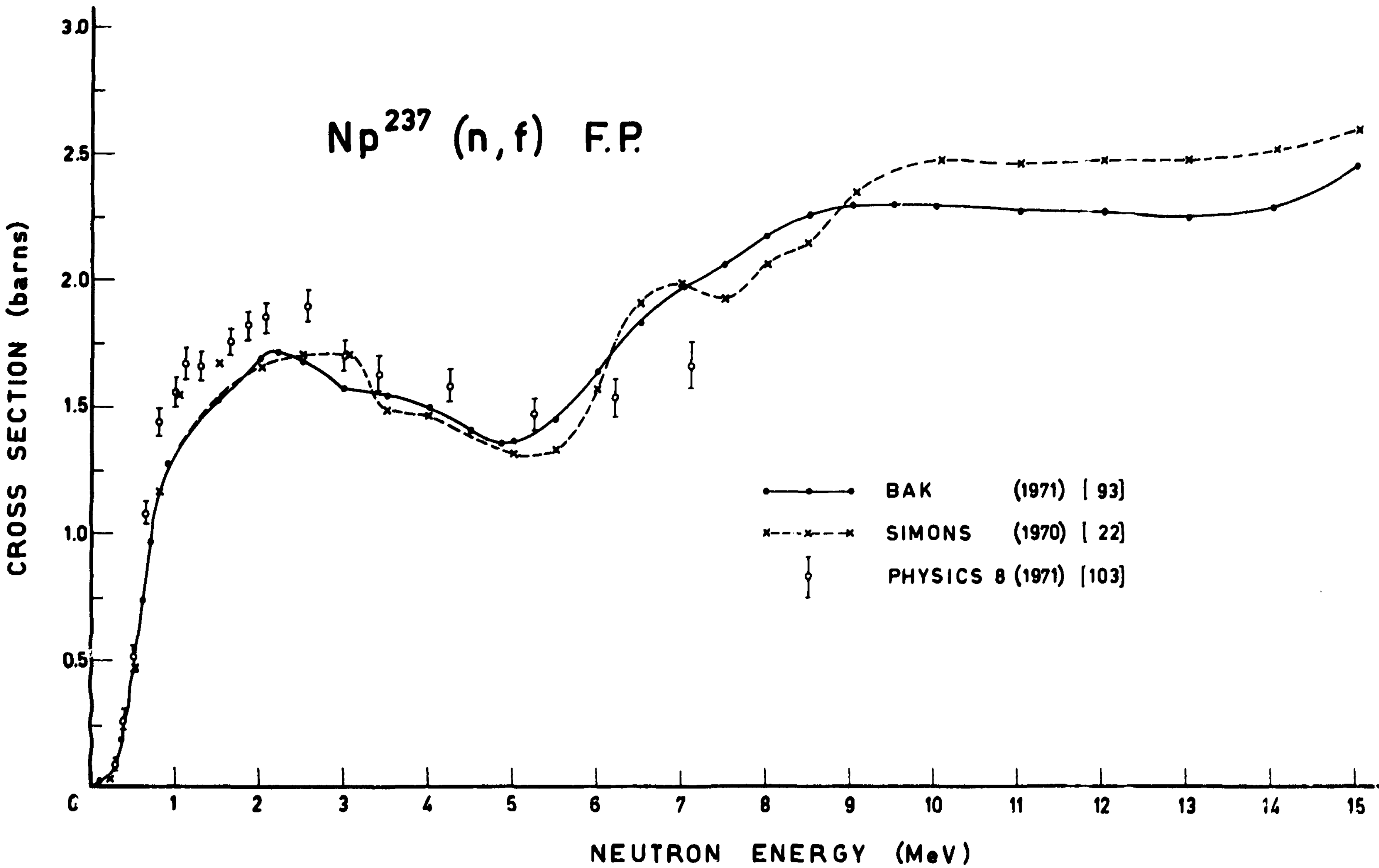
Until these recommendations are fulfilled it is recommended to use the Bak and Lorenz curve as reference data. The fission spectrum average (Cranberg spectrum) of Bak's data gives 285 ± 27 b which seems to be about 10% too low compared to direct measurements of this quantity (see extensive listing and review of these data in the Bak and Lorenz review article [93]). This well-known discrepancy needs urgent resolution. The Experts Meeting on the Status of Fission Neutron Spectra [102] convened by the IAEA in August 1971 discussed this matter thoroughly and felt strongly that this discrepancy was not due to inaccurate knowledge of the fission neutron spectrum.

XVIII. $Np^{237}(n,f)F.P.$

The fast fission cross section of Np^{237} has been recently reviewed by Bak and Lorenz.[93] Their display of the experimental data, the recommended curve and the confidence limits are shown in Figure 25. Since this review only one additional set of experimental data has been made available from the Physics-8 underground explosion.[103] These data are plotted in Figure 24 along with the Bak and Lorenz evaluation and the Simons and McElroy [22] evaluation. The Simons evaluation above 750 kev is taken from an earlier evaluation by Davey.[104] There also exists a separate evaluation by Smith and Grimesey[105] which is used in ENDF/B-III, but only data curves are generally available.

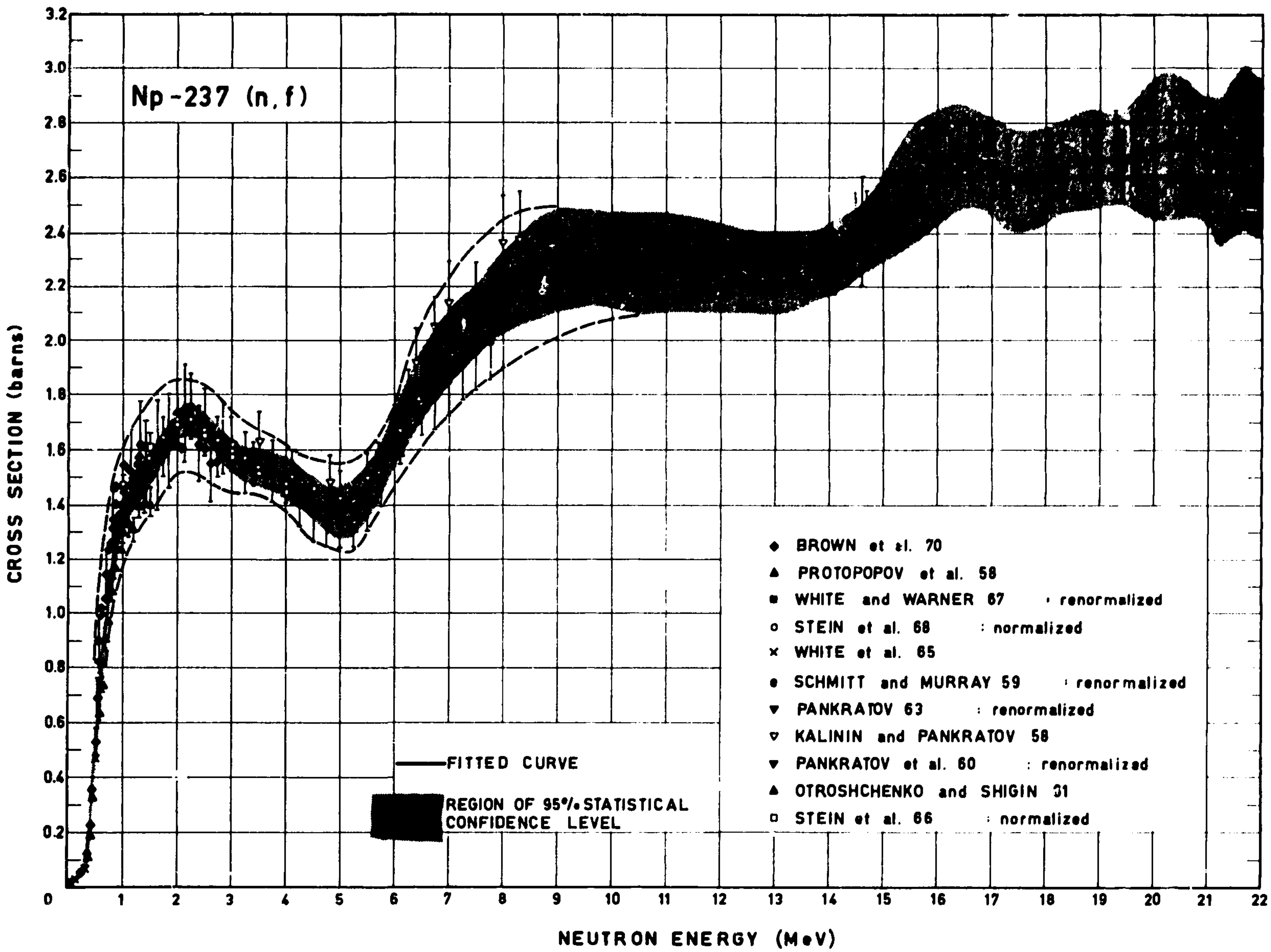
The confidence limits derived by Bak and Lorenz show that this cross section is not adequately known for accurate fluence measurements. In fact, the data from Physics-8 tend toward the extremes of the Bak and Lorenz curve and so have not improved the reliability of the microscopic data.

Two separate measurements of the fission averaged cross section are reported by Grundl[106,107] giving values of 1355 and 1365 $\pm$ 95 mb. The Bak and Lorenz curve yields 1289 $\pm$ 87 mb and the Simons and McElroy curve, 1293 mb. The use of the Physics-8 data would raise the evaluated cross sections near the peak of the fission spectrum and so increase the fission averaged cross section, suggesting that the Grundl values may be more accurate but the error is still about 7%.



Np^{237} (n, f) F.P.
CROSS SECTION (barns)
3.0
2.5
2.0
1.5
1.0
0.5
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
NEUTRON ENERGY (MeV)
BAK (1971) [93]
SIMONS (1970) [22]
PHYSICS 8 (1971) [103]

Fig. 24



Np-237 (n, f) EXCITATION CURVE

Fig. 25 (reproduced from /93/)

XIXA. Summary for Thermal and Intermediate Cross Sections (< 100 keV)

σ_0 : the 2200 m/sec cross section.

E_{Cd}: the cut-off energy, lower energy limit of I_{tot}.

I_{tot}: the total infinite dilution resonance integral (1/v contribution included); measured and recommended values only.

Reaction	σ_0 (in b)	Error (in ±b)	Ref.	E_{Cd} (in eV)	I_{tot} (in b)	Error (in ±b)	Ref.
$^{6}Li(n,a)^{3}H$	938	6	Meadows 70 [1]m				
	940	6	Uttley 69 [2]m				
	943.8	2.8	Silk 71 [3]m				
	942.4	2.4	Uttley 71 [4]R				
	940.25		Labauve 72 [5]r MAT.1115				
	940	5	Uttley 72 [6]r DFN 914				
$^{59}Co(n,\gamma)^{60}Co$	37.34	0.09	Silk 70 [7]r r		75		Holden 72 [15]r
$T_{1/2}$ = 5.272 ± 0.001	37.55	0.13	Story 68 [8] abs.		70	6	Köhler 71 [9]r
years	37.50	0.13	Story 68 [8]r act.	0.55	71.9	3.5	Gaggero 69 [16]m
[14]	37.3	0.2	Köhler 71 [9]R act.	0.5	74.6	3.0	Schuman 69 [17]m
	37.24	0.11	Silk 70 [7]m abs.		75.3	0.76	Kim 68 [11]m
	37.14	0.27	Merritt 68 [10]m act.	0.5	67.4	4.0	Vidal 65 [18]m
	36.6	0.5	Kim 68 [11]m act.	0.52	67.	12.	Beauge 63 [19]r
	37.75	0.40	Deworm 67 [12]m	0.5	69.9	3.5	Eastwood 63 [20]m
	37.35	0.30	Vaninbr.66 [13]m	0.49	72.3	5.0	Dahlberg 61 [21]m

Reaction	σ_0 (in b)	Error (in ± b)	Ref.	E_{Cd} (in eV)	I_{tot} (in b)	Error (in ± b)	Ref.
^{I97}Au(n,γ)^{I98}Au	98.8	0.3	Goldberg 66 [23]R		I560		Holden 72 [15]r
$T_{I/2}$ = 2.6946 ±	98.7	0.2	Westcott 65 [24]r	0.5	I550		Drake 66 [30]r
0.00I0 days	98.5	2.0	Friesenhahn 68 [25]m	0.52	I55I	20	Beauge 63 [19]r
[22]	98.6	0.2	Als-Nielsen 64 [26]m		I592	80	Wall 68 [31]m
	98.9	0.3	Teutsch 62 [27]m		I558	60	Fastrup 62 [49]m
	98.2	0.5	Meadows 6I [28]m	0.5	I535	40	Jirlow 60 [32]m
	98.8	0.3	Gould 60 [29]m		I534	40	Johnston 60 [33]m
					I558	77.9	Macklin 56 [34]m
^{238}U(n,γ)^{239}U	2.73	0.02	Schmidt 66 [35]r		280	I2	Stehn 65 [36]r
0.0253 ev"g" factor	2.73	0.04	Stehn 65 [36]r		282	II	Barrall 65 [43]r
for capture is	2.72I	0.0I6	Bigham 69 [37]m		278.2		Schmidt 66 [35]r
1.0021 [39]	2.69	0.03	Hunt 69 [38]m		278.2	I0	Baumann 64 [44]m*
	2.720		Leonard 7I [39]r		28I.2	I0	Isakoff 62 [45]m*
	2.74	0.06	Stavisskii 65 [40]m		283.2	8	Hardy 62 [46]m*
	2.73	0.07	Palevsky 55 [41]m		286.2	25	Tattersall 60 [47]m*
	2.76	0.06	Small 55 [42]m				
^{235}U(n,f)F.P.	580.2	I.8	Hanna 69 [48]R		270	I0	Hanna 69 [48]R
	577.I	0.9	Stehn 65 [36]r		274	I0	Stehn 65 [36]r
More details and Westcott"g" factors see in Ch.V,p.I8-20.							
^{239}Pu(n,f)F.P.	74I.6	3.I	Hanna 69 [48]R		300	I0	Hanna 69 [48]R
More details and Westcott"g" factors see in Ch.V,p.I8-20.	740.6	3.5	Stehn 65 [36]r		333	I5	Stehn 65 [36]r

Footnotes to the Table XIX A: r - recommended value, R - preferable recommended value,

m - measurement,

m^* - I.2 b added to original data to obtain I_{tot} from I' [35] .

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XIXB. Summary for Thermal and Intermediate Cross Sections (≤ 100 KeV)

Reaction	Accuracy (±%) Requested (RENDA 72 [1])	Accuracy (±%) Attained	Remarks
$Li^6(n,\alpha)$	1 - 10 (average:4) (none for thermal)	0.5 at thermal 1-2 below 100 KeV	No more work needed
$Co^{59}(n,\gamma)$	1 - 10	0.5 at thermal 10 in RI	Low priority work needed to improve resonance integral
$Au^{197}(n,\gamma)$	2 - 5	0.33 at thermal 2 in RI	Low priority work needed to remove discrepancy between resonance parameters and resonance integral
$U^{235}(n,f)$	1 - 5	~ 0.5 at thermal 5 in RI	No more work needed in addition to planned IAEA 1972/73 update
$U^{238}(n,\gamma)$	NONE	~ 1 at thermal 1-2 in RI	No more work needed
$Pu^{239}(n,f)$	2 - 5	~ 5 at thermal ~ 10 in RI	More experimental and evaluation work needed

XX A. Summary for Fast Cross Sections (> I00 keV)

Cross Sections Averaged Over The Uranium - 235 Thermal Fission Neutron Spectrum (mbarns)

Reaction	integral measurements Ref.	σ (mb)	Error (±mb)	renormalized* σ (mb)	Error (±mb)	calculated from differential data Ref.	σ (mb)	Error (±mb)
$^{6}Li(n,a)\ H^{3}$						Alter 65 [42]	516	
$^{27}Al(n,p)^{27}Mg$	Boldeman 64 [2]	2.9	0.5	3.4	0.6	Grundl 67 [7]	3.8	
$T_{I/2}$ = 9.46 min	Najzer 70 [3]	2.9	0.3	3.5	0.35	Fabry 70 [4]	3.88	
/ I /	Fabry 70 [4]	4.35	0.20	4.07	0.I5	Barrall 65 [8]	4.I5	
	Richmond 57 [5]	3.4		4.0I		McElroy 72 [9]	3.73^{Cr}	
	Fabry 72 [6]	recomm.	value:	4.0	0.4			
$^{54}Fe(n,p)^{54}Mn$	Boldeman 64 [2]	66	3.5	77	4	McElroy 70 [I5]	76.3	
$T_{I/2}$ = 312 ± 0.5 d	Bresesti 67,70 [II]	76.5	3.0	81.5	3.2	Bresesti 70 [II]	76.5	3.0
/I0/	Fabry 70 [I2]	89	5	83.5	2.5	Fabry 70 [I2]	76.5	+I9 -I3
	Martin 64 [I3]	76	3	83	3.3	Paulsen 7I [I6]	74	
	Nasyrov 68 [I4]	67	9	84.7	I0.5	Kamphouse 7I [I7]	73.8	
	Fabry 72 [6]	recomm.	value:	82.5	2			
$^{58}Ni(n,p)^{58}Co$	Boldeman 64 [2]	I05	5	I22.5	6	Fabry 70 [4]	III	8.5
$T_{I/2}$ = 7I.3 ± 0.2 day	Bresesti 67,70 [II]	I04.5	4	III.3	4.3	Bresesti 70 [II]	I09	3
/ I0 /	Fabry 70 [I2]	I20	6	II2.5	3.5	Meyer 70 [I9]	I05	
	Schuman 69 [I8]	II4	7	II0.5	7	Paulsen 7I [I6]	I03	
	Martin 64 [I3]	I07		II3		Kamphouse 7I [I7]	I09	
	Nasyrov 68 [I4]	96	I3	II3	I5	McElroy 70 [I5]	I02	

Reaction	integral measurements Ref	σ (mb)	Error (±mb)	renormalized* σ (mb)	Error (±mb)	calculated from differential data Ref	σ (mb)	Error (±mb)
^{58}Ni(n,a)^{55}Fe	Shuman 57 [20]	0.15		0.5		Roy & Hawton 60 [25]	3.4	semiempirical estim.
$T_{1/2}$ = 2.60 y [1]	For natural nickel:					Meyer 70 [26]	6.2	
	Weitman 68 [21]	4.2		4.95	renorm[22]			
	Freeman 69 [22]	4.7	0.6					
	Weitman 70 [23]	4.8						
	McElroy 71 [24]	4.0						
^{63}Cu(n,a)^{60}Co	Nilsson 63 [28]	0.54	0.07	0.594	0.07	McElroy 70 [15]	0.356	
$T_{1/2}$ = 5.272 ± 0.001 y	Clare 64 [29]	0.45	0.05	0.475	0.05	Paulsen 67 [30]	0.34	0.04
[27]	Nasyrov 68 [14]	0.382	0.036	0.449	0.042	McElroy 71 [24]	0.47[a]	
	Fabry 70 [12]	0.66	0.06	0.62	0.04	a : this value was obtained with artificially introduced thermal cross section.		
	McElroy 71 [24]	0.46	mass spectrometry					
	" " 71 [24]	0.53	radiochemistry					
	Fabry 72 [6]	recommended values		0.50	0.05			
^{93}Nb(n,n')^{93m}Nb $T_{1/2}$ = 11.4 ± 0.9y [31]						Hegedus 71 [31]	97	35
^{103}Rh(n,n')^{103m}Rh	Köhler 67 [33]	403	40			Butler 68 [34]	716[Cr]	40
$T_{1/2}$ = 56.116 ± 0.009 min [32]						Kimura 69 [35]	558[Cr]	32
						Hegedus 71 [31]	595	150

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	integral measurements			renormalized*		calculated from differential data		
Reaction	Ref	$\bar{\sigma}$ (mb)	Error (± mb)	$\bar{\sigma}$ (mb)	Error (± mb)	Ref	$\bar{\sigma}$ (mb)	Error (± mb)
$^{115}In(n,n')^{115m}In$	Bresesti 67,70 [11]	177.0	0.6	188.5	6.4	Kimura 69 [35]	177	10
$T_{1/2}$= 4.50 h	Najzer 70 [3]	156	5	188	6	Fabry 70 [4]	187.5	
[I]	Fabry 70 [4]	200	8	187.5	6	McElroy70 as given by		
	Fabry 72 [6]	recomm.	value:	188	4	Zijp 72 [36]	184.6	
						McElroy72 [9]	180^{Cr}	
						Bresesti 70 [11]	178	
$^{232}Th(n,f)$F.P.	Fabry 70 [4]	87.5	3.5	82	3	Bresesti 63 [37]	71.9	
	Fabry 72 [6],					Bak 71 [38]	70.2^{Cr}	13.5
	from McElroy72 [9]	85.2	7.7			Zijp 72 [36]#	71.31	
	Fabry 72 [6]	recomm.	value:	83	3.5	Zijp 72 [36]##	69.81	
$^{238}U(n,f)$F.P.	Bresesti 67,70 [11]	308.0	15.0	328	16	Bak 71 [38]	$\underline{285}^{Cr}$	27
	Grundl 68 [39]			328	14.6	McElroy 70 [15]	287.0	
	Fabry 70 [4]	353	30	330.5	15.7	Zijp 72 [36]###	300.1	
	Nikolaev 58 [40]	310	10			Fabry 70 [4]	300.4	
	Leachman 57 [41]	310	4.0					
$^{237}Np(n,f)$ F.P.	Fabry 70 [4]	1295				Fabry 72 [6]		
	Grundl 68 [39]	1367				from Grundl 68 [39]	1359	
						McElroy 70 [15]	1293	
						Zijp 72 [36]####	1360	
						Bak 71 [38]	$\underline{1289}^{Cr}$	87

Remarks to the Table XXA: * - all renormalized data, if not specially indicated, taken from Fabry 72 /6/.

Cr - Cranberg Spectrum; in all other cases Watt spectrum used.

Watt spectrum:

$$\chi^{W}(E) = 0.48395 \exp(-E) \sinh \sqrt{2E} \qquad /1/$$

Cranberg spectrum:

$$\chi^{Cr}(E) = 0.45274 \exp(-E/0.965) \sinh \sqrt{2.29E} \qquad /2/$$

where E is neutron energy in MeV.

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[36#] The same as [36]; data from ENDF/B-III. Mat. 1117 (evaluation of Wittkopf, 1967) used.

[36##] The same as [36]; data of W. Davey (Nucl. Sci. Eng. 26(1966), p. 149) used.

[36###] The same as [36]. Data from DFN 401D (evaluation of J. Ravier, PNR/SETR R025, 1968) used.

[36####] The same as [36]; data from Mat. 1048 (evaluation of J.Smith and R. Grimesey, IN 1182, 1969) used.

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XXB. Summary for Fast Cross Sections (> 100 KeV)

Reaction	Accuracy (±%) Requested	Attained	Remarks
$Li^6(n,\alpha)$ (fast)	5 - 10	5-10: 150 - 500 KeV discrepancy up to factor 2: 0.5-4 MeV 10-20: 4-12 MeV 10 : 12 MeV	More σ_T and σ_n measurements needed over 247 KeV resonance for confirmation. σ_α measurements badly needed below 4 MeV to confirm derived σ_α data, 4-8 MeV to consolidate knowledge and 8-12 MeV to close gap.
$Al^{27}(n,p)$	4 - 8	10-20: thresh.-5 MeV 30: 6-9 MeV 10-30: 12-15 MeV $\bar{\sigma}$ to 10 $\bar{\sigma}(\chi_f)$ to 10	Confirming measurements needed threshold - 5 MeV. No measurements 5 - 6 MeV and 9 - 12 MeV. 6 - 9 MeV discrepancy to be resolved by measurement and/or evaluation, careful reevaluation needed 12 - 15 MeV.
$Fe^{54}(n,p)$	4 - 10	50 at threshold 20 above $\bar{\sigma}(\chi_f)$ to 10	Another accurate measurement in threshold region plus theoretical analysis needed. Two measurements in the 6-13 MeV region needed to define shape.
$Ni^{58}(n,p)$	4	10-15 below 2.5 MeV 20 above 25 MeV $\bar{\sigma}(\chi_f)$ to 10-15	Theoretical analysis plus measurements from 4 to 15 MeV required.
$Ni^{58}(n,\alpha)$	NONE	Unknown	Several measurements over entire energy range needed as well as theoretical analysis.
$Cu^{63}(n,\alpha)$	4 - 10	15 $\bar{\sigma}(\chi_f)$ to 75	Big problem is the fission spectrum average discrepancy.
$Nb^{93}(n,n')$	10	40 below 4 MeV Unknown Above $\bar{\sigma}(\chi_f)$ to 40	Careful measurements of the 780 KeV γ-ray production cross section would be useful. Hegedüs "unfolded" shape above 4 MeV requires confirmation. Theory could help.

Reaction	Accuracy (±%) Requested	Attained	Remarks
$Rh^{103}(n,n')$	5 - 10	20 below 1 MeV 40 above 1 MeV $\bar{\sigma}(\chi_f)$ to 50	A set of measurements between 4 and 12 MeV needed as well as 2 more $\bar{\sigma}(\chi_f)$ values.
$In^{115}(n,n')$	3	10 $\bar{\sigma}(\chi_f)$ to 10	It will be difficult to get 3% accuracy. Low priority work needed on $\bar{\sigma}(\chi_f)$ discrepancy.
$Th^{232}(n,f)$	5	15 $\bar{\sigma}(\chi_f)$ to 25	Work on $\bar{\sigma}(\chi_f)$, both theory and experiment required.
$U^{238}(n,f)$	1 - 5	5-10 $\bar{\sigma}(\chi_f)$to 10	A few accurate absolute points and/or detailed ratio to U-235 fission measurements needed covering whole energy range threshold to at least 15 MeV. Discrepancies between microscopic and integral fission spectrum averages need urgently resolution.
$Np^{237}(n,f)$	5	12 $\sigma(\chi_f)$ to 7	Careful evaluation necessary to resolve discrepancies or recommend action.

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