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INDC INTERNATIONAL NUCLEAR DATA COMMITTEE

"INDC Discrepancy File 1979"

Compiled by F. Fröhner

Chairman
of the
INDC Subcommittee on Discrepancies
in Important Nuclear Data and Evaluations

June 1980

IAEA NUCLEAR DATA SECTION, WAGRAMERSTRASSE 5, A-1400 VIENNA

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This working document of the Discrepancy Subcommittee of the INDC contains a number of recent reviews of important discrepancies in nuclear data. They were written and compiled under the auspices of INDC for the Discrepancy File which is updated periodically by the INDC and, in a parallel and alternating effort, by the NEANDC. The present update consists of the following contributions.

- ^{235}U, ^{238}U and ^{239}Pu Resonance Parameters
  H. Derrien, Cadarache
- Inelastic Neutron Scattering from ^{238}U
  A.B. Smith, ANL
- Fast Neutron Capture in Cr, Fe and Ni
  F.H. Froehner, KfK
- Thorium-232 Capture and Fission Cross Sections
  M.K. Mehta and H.M. Jain, BARC
- ^{241}Am Fission Cross Section
  A. Michaudon, H. Derrien and G. Grenier,
  Bruyeres-le-Chatel and Cadarache
- Comments on the Excitation Function for the ^{93}Nb(n,n')^{93m}Nb Reaction
  J.J. Schmidt, IAEA/NDS
- Comments on the Excitation Function for the ^{63}Cu(n,α)^{60}Co Reaction
  R. Paviotti Corcuera, C.S.A. da Silva, H. Lemmel
  IAEA/NDS

In addition to these the following items are at present on the INDC list of outstanding discrepancies.

- Delayed Neutron Emitters
- Capture-to-Fission Ratio (alpha) of ^{235}U and ^{239}Pu above 100 eV
- Resonance Parameters of the 2.85 keV Resonance of Sodium
- ^{59}Ni(n,α)

As there are no recent experimental data for the last two items there are no new entries. The remaining two items could not be included due to various reasons, among them distraction of the editor by other urgent work and the Swedish strike in May 1980.

THORIUM-232 CAPTURE AND FISSION CROSS SECTIONS

A. Requirements

The thorium-uranium fuel cycle, in spite of some drawbacks, has sufficiently attractive features to command serious attention. Th-232 is the basic fertile isotope on which the technology of the whole fuel cycle rests. Apart from the total cross section the most important cross sections are those for the (n,γ), (n,f) and (n,2n) reactions. In the fast energy region there are

- 2 requests for (n,γ) cross sections with requested accuracies ranging from 3 to 10% and priority 1,
- 4 requests for (n,f) cross sections with 3 to 5% accuracy and priority 2 (ratio to U-235 fission preferred),
- 1 request for (n,2n) cross sections with 10% accuracy and priority 2.

In addition there is one request each for total, elastic and inelastic cross sections with 5 to 10% accuracy and priority 2.

B. Status

The most recent total cross section measurement is that of Whalen and Smith [WHALEN 1978] performed with a statistical accuracy of about 2% in the range from 0.1 to 5.0 MeV. The recent evaluation by Meadows et al. [MEADOWS 1978] includes these together with older experimental data. An independent evaluation of the data on Th-232 is being carried out at BARC and a preliminary technical report on the evaluation of the total cross section has been prepared [GARG 1979]. As the point data of WHALEN 1978 were not yet available from NDS at the time of preparation of this report they could not be included in the evaluation.

On the status of the fission cross section there are three recent reviews [MEADOWS 1978, PATRICK 1978 and MEHTA 1978]. Between them they give a good account of all the reported measurements which are summarised in Table 1. The most recent measurements by Poenitz [POENITZ 1978] and NORDBORG 1978 are not included in the evaluation by Meadows et al. Only preliminary data are reported for the more recent measurements by PLATTARD 1978 and SYME 1978. Most of the data measured from 1956 onwards are shown in Fig. 1 which is a copyof the curve shown by PATRICK 1978 that includes the NORDBORG 1978 data but not those of POENITZ 1978.

Most of the measurements have used U-235(n,f), U-238(n,f) or Pu-239(n,f) as reference while Poenitz' measurement is based on the reaction U-233(n,f). The cross sections derived from the ratios Th-232/U-238 and Th-232/U-235 agree reasonably well when evaluated values from ENDF/B-V are used for the two reference cross sections [MEADOWS 1978]. However, the measured absolute data are lower by about 15% than the ratio data thus normalised. Behrens et al.[BEHRENS 1977] quote the smallest errors and cover the widest energy range, viz. 0.7 to 32 MeV. Their measurement can be considered a very good shape determination. The NORDBORG 1978 data agree well with BEHRENS 1977 in the region of mutual overlap. The MEADOWS 1978 evaluation quotes accuracies varying from 4 to 10% between threshold and 20 MeV.

Fine structure in the cross section below and across the threshold has been observed by a number of workers. New measurements [BLONS 1978] have confirmed the details of this structure and removed ambiguities. These data have been interpreted in terms of a triple-humped fission barrier [CARUANA 1977, BLONS 1978 and JARY 1979]. As the cross section is very low, the details of the fine structure have little practical impact from the reactor physics point of view, but such investigations extend our knowledge of the basic nuclear physics which will enable fission cross sections for nearby nuclides to be calculated with improved accuracy.

The fission-spectrum-averaged cross section has been measured byKOBAYASHI [1976, 1977] and FABRY 1972. The results agree within quoted errors. However, MEADOWS 1978 calculated this average cross section with their own evaluated values and a Maxwellian fission neutron spectrum (T = 1.32 MeV) and obtained a value which is lower by about 10% than the measured averages.

The neutron capture cross section of Th-232 is of primary importance in the Th-U fuel cycle and determines the feasibility of a breeder reactor, and yet it has been rather poorly known. Table 2 summarises the information on available data. The MEADOWS 1978 evaluation does not include the data of KOBAYASHI 1978. As can be seen from the table, three different techniques are used for the capture measurements.[BELANOVA 1958, 1960, 1965] used spherical shell transmission. The difference between the 1958 and 1965 values exceeds six times the errors quoted. There are no other measurements utilising this technique and thus no comparative values are available to discriminate between the two sets. Therefore the shell transmission data were considered uncorroborated and need not be included in an evaluation.

The other two techniques rely on measurements of induced activation and of prompt capture gamma rays, both using suitable standards as reference. Standards used include U-235(n,f), U-238(n,γ), B-10(n,α), Li-6(n,α) and I-127(n,γ). Most of the older measurements before 1970 were based on beta counting and radiochemical separation and the standards used were poorly known. These data are very much discrepant with each other in the energy range 0.1 to 1.0 MeV. The ENDF/B-IV evaluation which was based on these standards is considerably higher compared to the recent measurements LINDNER 1976, MACKLIN 1977 and POENITZ 1978. Out of the earlier measurements only MISKEL 1962 and CHELNOKOV 1972 are in agreement with these recent data. Data from LINENBERGER 1946, STAVISSKII 1961, STUPEGIA 1963 and TOLSTIKOV 1963 are much higher, and the data of HANNA 1959 deviate too much from these recent measurements to be considered.

MACKLIN 1977 and POENITZ 1978 are the only two published measurements based on observation of capture gamma rays. Preliminary results of KOBAYASHI 1978 are also obtained with this technique. LINDNER 1976 and MACKLIN 1977 differ by 10-20%. The POENITZ 1978 measurement, performed to settle this discrepancy, agrees with LINDNER 1976 and is higher than MACKLIN 1977 by about 10% and also higher than the MEADOWS 1978 evaluation. The data of JAIN 1978 agree with MACKLIN 1977 at three energies within the quoted errors but differ from LINDNER 1976 and POENITZ 1978 at 460 and 680 keV. The preliminary values of KOBAYASHI 1978 are also lower than those of POENITZ 1978. In Fig. 2 these recent data are shown for the energy range from 100 keV to 4 MeV.

Between 1 and 4 MeV there are three sets of measurements with accuracies better than 10% which agree within quoted errors. Thus the requested accuracies are satisfied in this energy range. However, no measurements exist between 4 and 14 MeV and only one measurement at 14.5 MeV [PERKIN 1958]. The MEADOWS 1978 evaluation consists just in an "arbitrary interpolation" between 2.5 and 14 MeV.

The POENITZ 1978 measurement extends down to 30 keV. CHAUBEY 1965 and YAMAMURO 1978 have measured the cross section at 24 keV using a Sb-Be photoneutron source and an iron-filtered beam, respectively. Their results agree with the trend of the POENITZ 1978 results. The measurement of CHELNOKOV 1972 includes the 24 and 34.5 keV data points, that of KOBAYASHI the 55 keV data point. These are lower by 8 to 13% than the POENITZ 1978 data. The useful data below 100 keV are shown in the insert to Fig. 2. All other measurements in this energy region are not reliable enough to be included in the graph. The main source of discrepancy in these earlier measurements could be attributed to uncertain standards.

C. Conclusions and Recommendations

Measured total cross sections exist up to 15 MeV and evaluated data have accuracies between 2 and 5%. Thus present requirements for total cross sections are met. However, the presently specified target accuracies may not be adequate for detailed optimisation calculations for an actual reactor, in which case more accurate measurements may become necessary in specific energy ranges. Above 15 MeV deformed and spherical optical model predictions are available [MEADOWS 1978 and GARG 1979].

For the fission cross section between threshold and 20 MeV the MEADOWS 1978 evaluation gives accuracies varying between 4 and 10%. Thus for this region the WRENDA 76/77 requirements are not fully met in view of the requested accuracies of 3-5%. The 14 MeV data are used for normalisation between various sets which thus determine the shape over the whole energy range. There is some ground for more accurate measurements around this energy as the existing data exhibit large scatter.

Concerning the capture cross section between 400 keV and 1 MeV the scatter of the data is slightly more than the quoted errors on recent measurements. One concludes that the 3-5% accuracy requirement is not fulfilled and that more measurements are needed. Between 1 and 4 MeV the three existing data sets agree reasonably well and the requested accuracies seem to be reached. However, between 4 and 14 MeV no data exist and measurements are needed to permit a more reliable evaluation up to 15 MeV. At lower energies below 400 keV the errors of POENITZ 1978 are given as 3% which would meet the requirements. However, the discrepancies with CHELNOKOV 1972 and KOBAYASHI 1978 indicate a need for more corroborating measurements in this energy region.

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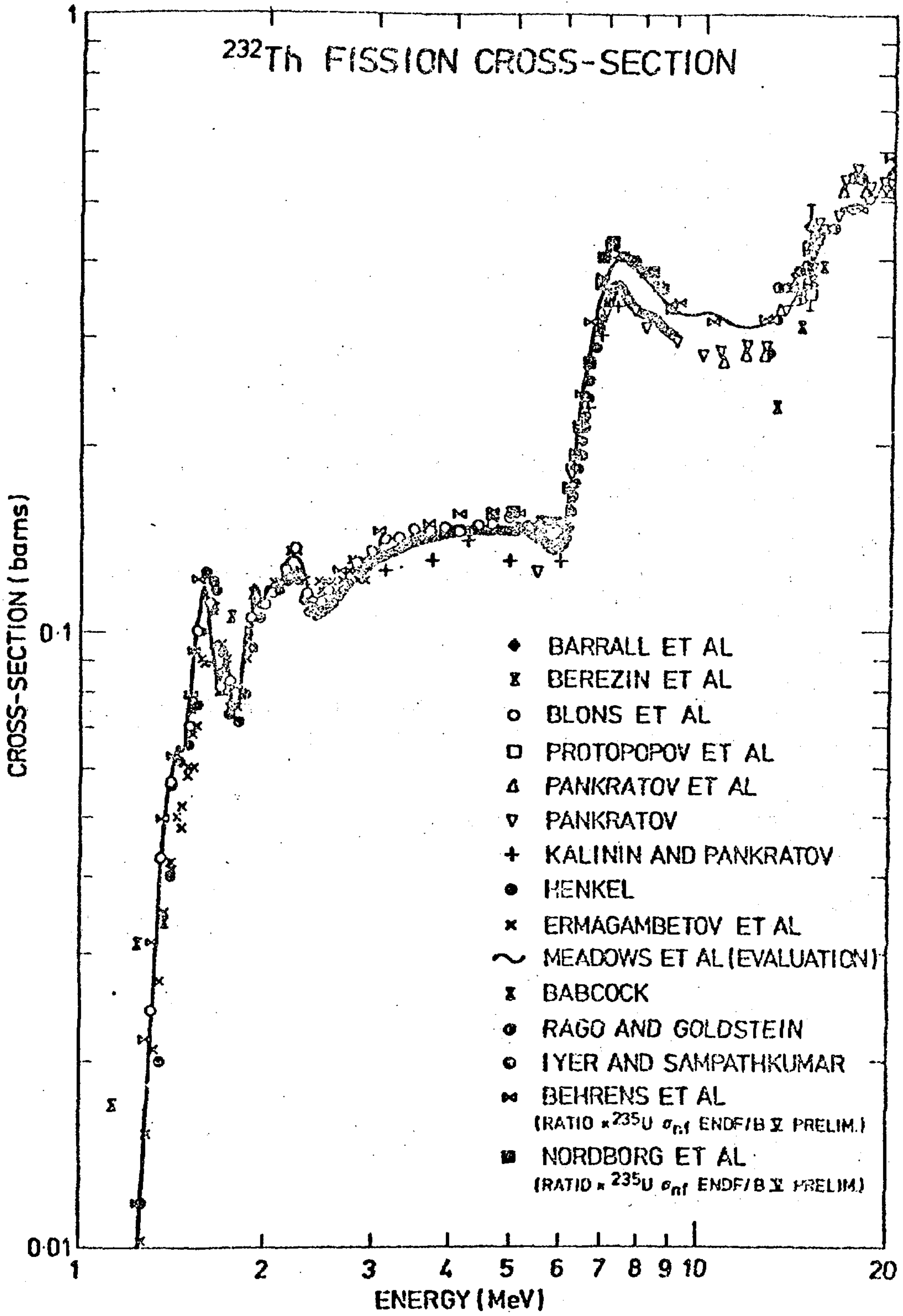

232Th FISSION CROSS-SECTION
CROSS-SECTION (barns)
ENERGY (MeV)
1
0·1
0·01
1
2
3
4
5
6
7
8
9
10
20
BARRALL ET AL
BEREZIN ET AL
BLONS ET AL
PROTOPOPOV ET AL
PANKRATOV ET AL
PANKRATOV
KALININ AND PANKRATOV
HENKEL
ERMAGAMBETOV ET AL
MEADOWS ET AL (EVALUATION)
BABCOCK
RAGO AND GOLDSTEIN
IYER AND SAMPATHKUMAR
BEHRENS ET AL
(RATIO × 235U σnf ENDF/B V PRELIM.)
NORDBORG ET AL
(RATIO × 235U σnf ENDF/B V PRELIM.)

Fig. 1

Fig. 2.2-2 Capture cross section for ^{232}Th

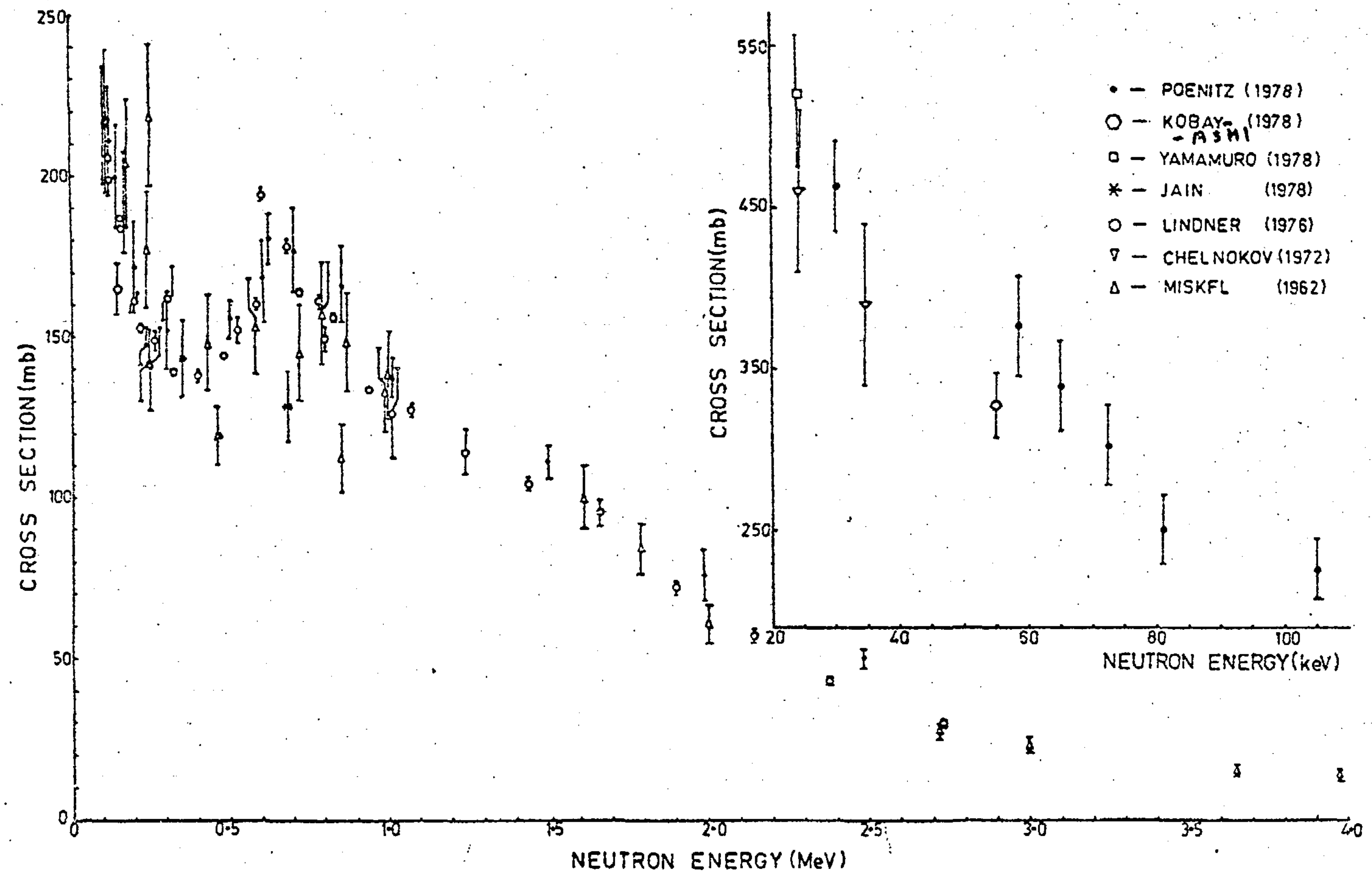

Fig. 2

Table 1 - Summary of ^{232}Th fission cross section measurements

Author Reference	Energy range (MeV) Number of points	Type of measurements	Error reported	Technique
Williams (1944) LA-520, 4603	3·4 - 5·85 3	Ratio	-	Charge particle reaction ^{232}Th(n,f); ^{235}U(n,f)
Phillips (1948) LAMS-774, 4809	14 1	Ratio	8%	(D-T) reaction Photographic plates ^{232}Th(n,f); ^{238}U(n,f)
Nyer (1950) LAMS-938, 50	14 1	Ratio	3%	(D-T) reaction Ionization chamber ^{238}U(n,f)=1·12±0·03b standard
Uttley (1956) AERE-Np/R 1996	14·1 1	Ratio	5·2%	Back to back fission counter ^{238}U(n,f) = 1·14±0·078b standard
Henkel (1957) LA-2122, 5703	1·15-9 158 1·2-9·47 209	Ratio	-	Spiral fission chamber ^{235}U(n,f) standard
Berezin (1958) AE, 5, 659	14·6 1	Absolute	5·4%	^{3}H(d,n)^{4}He reaction Ionization chamber-fission Associated α-counting-neutron Mass of deposition-α, counting
PROTOPOPOV (1958) AE, 4, 190	14.6 1	Absolute	5.7 %	Same as Berezin (1958)
KALININ (1958) 58 GENEVA, 16/36	3.1 - 7.2 9 3 - 10.9 23	Absolute		Ionization chamber Long counter
PANKRATOV (1960) AE, 9, 399	10.7 - 21.5 16	Absolute	3 %	D(d,n)^{3}He reaction and TOF Gas filled scintillation fission counter Long counter and telescope
BABCOCK (1961) BABCOCK (6110)	1.14 - 1.88 7 13 - 18 5	Ratio	8.35 % 5 - 22 %	Charge particle reaction ^{238}U (n,f), BNL-325 (1958)

Table 1 – Contd. Summary of ^{232}Th fission cross section measurements

Author / Reference	Energy range (MeV) Number of points	Type of measurement	Error reported	Technique
KATASE (1961) W. KATASE (6109)	13.5 - 14.8 3	Absolute	10 %	$^{3}H(d,n)\,^{4}He$ reaction Nuclear emulsion Associated α-counting
PANKRATOV (1963) AE, 14, 177	5.4 - 36.5 39	Absolute	5%, 5 - 27 MeV 10% >27 MeV	Same as Pankratov (1960)
ERMAGAMBETOV (1963) AE, 23, 20	0.5 - 3.0	Ratio	15 % at 0.6 MeV 3 %	$^{3}H(p,n)\,^{3}He$ reaction Ionization chamber $^{235}U(n,f)$ standard <840 keV $^{238}U(n,f)$ " >840 keV
RAGO (1967) HP, 13, 654	12.5 - 18 16	Ratio	5 %	$^{3}H(d,n)\,^{4}He$ reaction LAXAN, tracks, optical micro. $^{232}Th(n,f):^{238}U(n,f)$
BEHKAMI (1968) ND / A118, 65	1.2 - 1.6 3	Ratio	6 - 8 %	$^{7}Li(p,n)\,^{7}Be$ reaction MAKROFOL - tracks $^{236}U(n,f)$ standard
IYER (1969) Roorke conf. 2 (1969) 289	14.1 1	Ratio	9 %	(D - T) reaction LEXAN - tracks $^{238}U(n,f)$=1.20 b Mass of deposition, α- counting
BARRALL (1969) AFWL-TR-68-134	14.6 1	Absolute	8.9 %	(D - T) reaction LEXAN - tracks Na I(Tl) - ^{99}Mo (f.f.) $^{27}Al(n,\alpha)$: 0.1207 b, standard
MUIR (1971) Knoxvill conf. 1 (1971) 292	0.598 - 2.96 104	Ratio	15 %	EXPLOSION Solid state detector $^{239}Pu(n,f)$, NSE, 32, (1968) 35 standard

Table 1 – contd.- Summary of ^{232}Th fission cross section measurements

Author / Reference	Energy range (MeV) Number of points	Type of measurement	Error reported	Technique
SHPAK (1972) ZEP. 15, 323	13.5 – 14.8 10	Ratio	2 – 3 %	(D-T) reaction Glass detectors ^{238}Pu (n,f) standard
KONECNY (1972) ZP, 251, 400	1.1 – 1.9	Ratio	—	^{7}Li (p,n)^{7} Be reaction ^{235}U (n,f) standard 8 keV resolution
BLONS (1975) PRL, 35, 1749	1.21 – 5.01 638	Ratio	1 – 2	LINAC + TOF Gas scintillator ^{235}U (n,f), ENDF B/IV 3 keV resolution at 1.6 MeV
BEHRENS (1977) UCID – 17442	0.697 – 32.6 14.5	Ratio	1 – 2 % above 1.4 MeV	LINAC + TOF Back to Back Ionization chamber ^{232}Th (n,f): ^{235}U(n,f) data Mass of deposition –threshold method
NORDBORG (1978) Harwell conf.(1978)	4.6 – 8.8	Ratio	5 %	Charge particle reaction + TOF Back to Back fission chamber ^{232}Th (n,f): ^{235}U(n,f) data Mass of deposition-Weighing
BLONS (1978) PRL, 41, 1289	~1.6	Ratio	—	LINAC + TOF Gas scinillator ^{235}U (n,f) standard 2.3 keV resolution at 1.6 MeV
BLONS. Priv. comn.	9	Ratio	—	Same as BLONS (1978)
PLATTERED (1978) Priv. comn.		Ratio		LINAC + TOF Gas scintillator ^{235}U (n,f) ENDF/B IV standard
SYME (1978) Priv. comn.	1.2 – 2.0	Absolute	—	Fission neutron detection
POENITZ (1978) Ref. MEADOWS (1978)	1.2 – 8.5	Ratio	—	^{233}U (n,f) standard

Table 2 Summary of ^{232}Th capture cross section measurements

Author Reference	Energy range (keV) Number of points	Type of measurements	Error reported	Technique
Linenberger (1946) LA - 467	3 - 390 7	Ratio	10 %	Activation Charge particle reaction $^{7}Li(p,n)$, $D(d,n)$ $^{235}U(n,f)$ standard
Macklin (1957) PR,107, 504	24 1	Ratio	20%	Activation Sb-Be source Chemical separation of ^{233}Pa, 310 keV γ-ray from ^{233}Pa by NaI $^{127}I_{53}(n,\gamma) = 0{\cdot}820$ b standard
Belanova (1958) Fiz, 34, 574	25-830 3	Absolute	1-2%	Spherical shell transmission
Leipunskij (1958) Geneva 1958	200 1	Ratio	5%	Activation $^{127}I_{53}(n,\gamma)$ standard
Perkin (1958) PPS, 72, 505	14·5 Mev 1	Ratio	15 %	Activation $^{27}Al_{13}(n,\gamma)$ standard
Barry (1959) PPS, 74, 685	300-1200 10	Ratio (600keV) Absolute	8 %	Activation Charge particle reaction $T(p,n)$ β-counting of ^{233}Th and ^{239}U with end window GM counter $^{238}U(n,\gamma)$ at 600keV standard Long counter $^{10}B(n,\alpha)$ Neutron monitor
Hanna (1959 JNE, 8, 197	100-1230 13	Absolute	8-10%	Activation β-counting of ^{233}Th with end window GM counter Fast flux monitored by proton recoil $H(n,n')$-standard
Belanova (1961) AE, 8, 549	220 1	Absolute	2%	Spherical shell transmission
Stavisskii (1961) AE, 10, 508	30-964 25 1·0-5·85 MeV 9	Ratio	3-10% -	Activation $^{127}I_{53}(n,\gamma)$ standard $^{235}U(n,f)$ standard

Table 2 . Contd. Summary of ^{232}Th capture cross section measurements

Author Reference	Energy range(MeV) Number of points	Type of measurements	Error reported	Technique
Miskel (1962) PR,128,2717	0·032-3·970MeV 26	Ratio	±10%	Activation Charge particle reaction $^{7}Li(p,n)$ β-Counting of ^{233}Pa with calibrated end window proportional counter chemical separation of ^{233}Pa $^{235}U(n,f)$ from LA-2124(1957)-standard
Tolstikov (1963) AE,15,414	5·5-102 10	Absolute	15-20%	Activation Charge particle reaction $^{7}Li(p,n)$ β-Counting of ^{233}Th with end window GM counter Long counter $^{10}B(n,\alpha)$ flux monitor
Moxon (1963) TRDWP/P-8	3 -143 keV 98	Absolute		Prompt gamma ray Time-of-flight .LINAC Moxon-Rae Detector for gamma ray $^{10}B(n,\alpha)$ neutron monitor
Stupegia (1963) JIN,25,627	191-1170 22	Ratio	7%	Activation β-Counting of ^{233}Th with end window proporional counter $^{235}U(n,f)$,BNL-325(1964) standard
Chaubey (1965) NP 66,267	24 1	Ratio	10 %	Activation Sb-Be source β-Counting with end window GM counter $^{127}I_{53}(n,\gamma)$=0·820b standard
Belanova (1965) AE,19,3	24 1	Absolute	4%	Spherical shell transmission Sb-Be source Four long counter to detect neutron
Koroleva (1966) AE,20,431	24 1	Absolute	7%	Spherical shell transmission Sb-Be source Neutron detector through $^{127}I_{53}(n,\gamma)$ gamma detected with NaI
Forman (1971) CONF 710301,735	20ev-30keV 28	Absolute	±15%	Prompt gamma ray Underground nuclear explosion with time-of-flight Moxon-Rae detector for gamma ray $^{6}Li(n,\alpha)$ neutron monitor

Table 2 Contd. Summary of ^{232}Th capture cross section measurements

Author Reference	Energy range Number of points	Type of Measurements	Error Reported	Technique
Chelnokov (1972) YFI-13, 6	0·2 - 34·6 keV	Ratio	8-12%	Prompt gamma ray Lead-slowing down spectrometer -(D-T) reaction Gamma ray measurements with proportional counter ^{235}U(n,f) standard
Lindner (1976) NSE,59,384	0·121 - 2·73 MeV	Ratio	0·6-5·7%	Activation Charge particle reaction ^{3}H(P,n)^{3}He Radiochemical separation of ^{233}Pa. β-counting by 4 π proportional counter caliberated with ^{237}Np(α) ^{233}Pa source ^{235}U(n,f) from ENDF/B-IV, standard, silicon surface barrier detector
Macklin (1977) NSE,64,849	2·6 - 800 keV	Ratio	2% up to 100 keV 2·5%, 100-450 keV 5-10% above 450 keV	Prompt gamma ray Time-of-flight, LINAC Liquid scintillator for γ-ray ^{6}Li(n,α) neutron monitor Isotopically purified thorium
Yamamuro (1978) NST,15,637	24 keV 1	Absolute	9%	Prompt gamma ray Fe-filtered beam Liquid scintillator for gamma ray ^{10}B(n,α) , standard
Kobayashi (1978) PRELIMINARY	1 keV-450 keV 24, 55, 146 keV 3	Ratio	3-5%	Prompt gamma ray Time-of-flight, LINAC Fe-Si filtered beam Liquid scintillator for γ-ray ^{10}B(n,α) standard
Jain (1978) HARWELL Conf(1978)	350, 460, 680 keV 3	Ratio	8%	Activation Charge particle reaction ^{7}Li(p,n) ^{7}Be Ge(Li) detector, γ-rays from ^{233}Th decay ^{197}Au(n,γ) standard
Poenitz (1978) ANL/NDM-42	30 keV-2·5 MeV 23	Ratio	3% 0·4-10·5% 4·7%	Prompt gamma ray, 58-850 keV Charge particle reaction, 500 keV-2 MeV White neutron source, 50-300 keV Liquid scintillator for γ-ray ^{197}Au(n,γ) standard. Activation above 240 keV Ge(Li) detector, γ-rays from ^{233}Pa decay ^{235}U(n,f) standard ^{197}Au(n,γ) standard, 30 keV

SOME REMARKS AND RECOMMANDATIONS ABOUT THE U235, U238 and Pu 239 resonance parameters*

Hervé DERRIEN
CEN CADARACHE

- oOo -

The status of neutron cross-section measurements and evaluated data of U 235, U238, Pu 239 in the resolved resonance region has been reviewed recently by G.A KEYWORTH and M.S MOORE (1) in an invited paper given at "the international conference on Neutron Physics and Nuclear Data for reactors and other applied purposes". This paper contains the references to the main works connected with these actinides. The authors have examined the results of the recent experiments and evaluations and have proposed some important extensions due to their own works ; they have concluded about the future experiments which should be undertaken to obtain some improvements in the existing set of data. Since nothing new had been obtained after the HARWELL conference, it does not seem necessary to return to an other review of the available data. The author of this note will only give his own opinion on the conclusions of KEYWORTH et al. and will, if possible, bring some new conclusions firstly concerning each isotopes and secondly about some general problems.

U 235

When evaluating the resonance parameters of U 235, two sets of data should be reasonably used as the starting point of the evaluation. These data are the following :

1°) The results of the old total cross-section measurements of MICHAUDON et al.(2) performed at liquid nitrogen temperature with a very high quality of resolution ; these data still remain the most important set of 2g Γ^o_n values available up to 150 ev neutron energy ;

2°) The results of the fission measurements of KEYWORTH et al with polarized neutron beam and polarized target recently published by MOORE, KEYWORTH et al. (3).

A simple examination of these two sets of data shows immediatly what improvements can be obtained when using polarized neutron beam and polarized target. The spin-separated fission cross-sections show off a large number of small resonances (14 in the 0 - 50 ev energy range) and about the same number of relatively large resonances, which are not apparent in the total cross-section. The former correspond to the 20 % of missed weak levels (small value of 2gΓ^o_n) foreseen by MICHAUDON et al. ; the later were not expected from the examination of the total cross-section of Saclay, and correspond to doublets in the non spin-separated data. As a consequence, the corrected mean level spacing of 0.54 ev obtained by MICHAUDON et al. is much larger than the value of 0.44 ev proposed by MOORE et al. Nevertheless, the 20 % of missed levels resulting from the Saclay analysis were confirmed by a Monte-Carlo simulation of the cross-sections. But the average fission width used to calculate the cross-sections was too small (44 mev) compared to the values of 196 mev (spin 3) and 91 mev (spin 4) obtained by MOORE et al. from the spin-separated fission cross-sections. Consequently the effect of the resonance overlapping was reduced and a large number of unresolved doublets was not observed in the Saclay simulated cross-sections.

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The existence of this large number of doublets explains why the average Γ_γ value obtained at Saclay is 25 % larger than the one used by MOORE et al. It is now possible to identify the few well isolated resonances in the total cross-section for which the Saclay shape analysis should give an accurate value of Γ_γ There are only six resonances of this type :

ENERGY (ev)	Γ_γ (mev) of MICHAUDON et al.
2.03	36
4.84	37
7.07	36
10.18	37
11.66	36
16.09	37

These values are in excellent agreement with the value of (35 $\pm$ 2) mev choosen by MOORE (4) from a systematic study of s and p wave capture widths.

The set of resonance parameters recommended by MOORE et al does not contain the entire accuracy that should be expected from the analysis of the spin-separated fission cross-sections. Two recommandations should be made :

1°) A new shape analysis of the Saclay total data should be undertaken by using as starting point the new informations obtained from the spin-separated data, i.e the exact position of the resonances and more accurate values of Γ_f and Γ_γ . This new analysis should lead to very accurate values of $2g\Gamma_n^{\circ}$ which could then be used to analyse KEYWORTH et al. data ;

2°) A multi-level analysis could be done easily on the spin-separated fission cross-sections, at least on the spin 3 cross-section. For this spin state the fission widths are larger and the number of fission channels smaller ; consequently the level-level interferences are more important than in the spin 2 state ; that is clearly seen on the spin-separated fission cross-sections. Such a multi-level analysis (using two fission channels

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for the spin 3 state) should lead to more accurate fission widths and should give more confidence in the identification of some very weak resonances.

U 238

Concerning the resonance parameters of U 238, the situation seems to be seriously improved since the evaluation presented by MOXON at the 1974 specialist meeting of Saclay (5).

New data are available and the very recent evaluation of DE SAUSSURE et al (6)complemented by some remarks of KEYWORTH et al. seems to provide a definitive answer to several questions. The method used by DE SAUSSURE et al. shows how it is possible to conciliate several large sets of experimenal data apparently conflicting by a careful study of the possible systématic errors.

Pu 239

This nucleus has always been considered as a nice exemple for the study of the nuclear properties in the resonance region especially for the spin assignments and the fission widths. However the review by KEYWORTH et al. brings in some new problems which need to be solved ; these new problems concern the mean level spacing and the spin assignments. KEYWORTH et al. have used the method of moments to compare against the Porter-Thomas distribution for neutron widths of the levels assumed to be 1^+. They suggest that the 1^+average spacing is (2.62 $\pm$ 0.24) ev instead of (3.2 $\pm$ 0.20) ev as given by the Saclay group (7). That means that one must admit 25 % of missed levels in the total cross-section measured at Saclay with a very high quality of resolution, while these experimentators predict only 5 %. KEYWORTH and al. have the feeling that 20 % of weak 1^+ levels could be missed and that a large part of the levels assigned 0^+ should be 1^+ levels. Indeed, it is likely that some of the resonance spins are not assigned correctly, but the existence of 20 % of missed weak levels is questionnable. On the other hand, it is hard to believe that the problem concerning the resonance identification for Pu 239 is as *difficult as that for U 235. It would therefore seem that the problem is still far from being completely solved. It is also obvious, that a better answer should be obtained by undertaking a fission or a total cross-section measurement of Pu 239 by using polarized neutrons and polarized target.*

Some general recommendations

1°) One of the main problems arising from the study of the resonance parameters of the actinides is the exact determination of the s-wave level spacing. It is obvious that it is impossible to identify all the resonances in the experimental cross-section, even if the resolution is excellent. A correction needs to be applied to the observed level spacing to obtain a value as close as possible to the unknown value. The methods used to obtain the corrected value are numerous : least square fitting or maximum of likelihood on the Porter-Thomas distribution, Δ 3 statistics, examination of the Wigner distribution, simulation of cross-sections by Monte-Carlo method etc... But, having regard to the disparity of the results obtained by the different methods applied to the same data, it is urgent to consider the following points:

a) Should the level spacings and the reduced neutron widths follow strictly the Wigner and the Porter-Thomas law. If not, what deviation should be expected or accepted ?

b) Is it possible to "standardize" the methods used in the investigation of the missed levels ? One should establish some rigorous conditions of utilisation of these methods. For instance, it appears that one method works well when applied to a particular case and give inconsistent results when applied to another case. To avoid misunderstanding in the interpretation of the results, a maximum of details of the analysis should be given.

2°) The data obtained from a good transmission measurement should be the obligatory starting point for the evaluation of the resonance parameters of a fissile nucleus. Now, in the resonance

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region, thereare few transmission measurements available whith very good quality of resolution. It is regrettable that some U 235 or Pu 239 transmission measurements similar to those performed at Saclay 15 years ago have not been undertaken on ORELA or GELINA.

3°) As pointed out by DE SAUSSURE et al. one should avoid to recommend a set of resonance parameters obtained by averaging all the data available in the litterature. This type of evaluation leads to a set of data which does not represent the reality and which is not representative of a particular experiment. In such a data set it is impossible to preserve the correlations which exist in a serie of mesurements or in several series of measurements, unless all the data sets are consistent. In the last case, averaging the data or choosing a particular data set will lead to about the same results. In the case of large discrepancies, one must try to show off the systematic errors which are the cause of the discrepancies ; it is then possible to "adjust" the data and to obtain a consistent serie of values on which the average procedure could be applied. This method has been used by DE SAUSSURE et al. for the evaluation of U 238 on the large sets of data from Oak-Ridge, Columbia and Geel. KEYWORTH et al. have also "adjusted" the Columbia Th 232 data to the Saclay data by correcting the Columbia data. One must point out that this kind of "adjustment" has been already suggested in 1970 by RIBON et al. (8) who have shown, by applying the least square shape analysis method to the Columbia data, that the discrepancies between Columbia and Saclay were mainly due to an underestimation of the background in the Columbia experiment. One should also mention that the results of KEYWORTH et al. Th 232 evaluation are consistent with the evaluation performed at Saclay in 1973 (9) and based on the Saclay transmission data.

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INELASTIC NEUTRON SCATTERING FROM ^{238}U*

Experimental knowledge of the energy-averaged neutron total and elastic scattering cross sections of ^{238}U has considerably improved in the last few years [1,2]. This, aided by improved model calculations[3], has resulted in a better understanding of the non-elastic cross section. The result, known to ~7%, is shown in Fig. 1 and indicates an increase in the non-elastic cross section from that implied by ENDF/B-IV. Version-V is consistent with the higher values. Below the onset of the (n;2n') cross section the non-elastic cross section, corrected for the relatively small fission component, is essentially the neutron inelastic scattering cross section. Thus the latter follows to within ~10% over the energy range of primary interest.

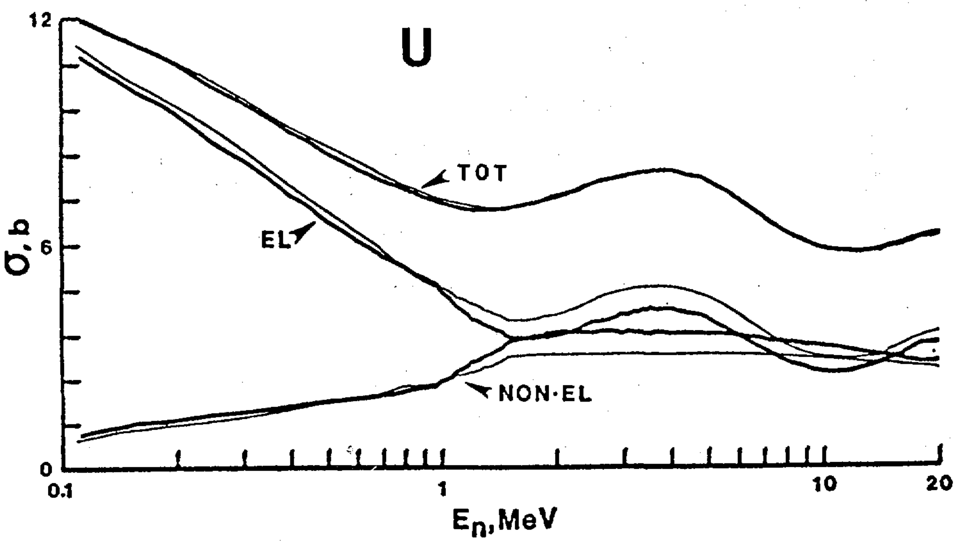

Fig. 1. Neutron total, elastic and non-elastic cross sections of ^{238}U. The light curves denote ENDF/B-IV values, the heavy curves ENDF/B-V results.

ENDF/B-V treats neutron inelastic scattering processes as; the excitation of discrete states, the excitation of composite contributions from a number of poorly resolved states and as the excitation of a continuum of unresolved states. The cross sections for excitations to energies of ~1.0 MeV are reasonably known and are individually treated in the Version-V evaluation. The contributions from states at excitation energies of $\gtrsim$1.0 MeV are more complex and uncertain. The Version-V groups such excitations into 10 groups to energies of 2.5 MeV. States with excitations in the range 2.5-4.0 MeV are represented by a simple ladder model with level-density increasing with energy. This representation is physically reasonable and blends smoothly into the continuum distribution starting at excitations of 2.5 MeV. The initial inelastic scattering cross sections were slightly adjusted to obtain improved agreement between measured and calculated integral benchmarks with such adjustments confined to reasonable uncertainties in the microscopic values and consistency with the measured non-elastic cross section.

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*Detailed discussion of this process is found in the Argonne National Laboratory Report, ANL/NDM-32, W. P. Poenitz et al., (1977).

The low-energy inelastic scattering cross section is dominated by the ground-state rotational band consisting of 45, 148 and 308 keV states. The latter contribution is small thus higher order states of this band were ignored in the Version-V evaluation. The Version-V evaluation is based upon a correlated application of measurement results and calculation as outlined in the footnote. The experimental results are reasonably consistent as illustrated in Fig. 2.

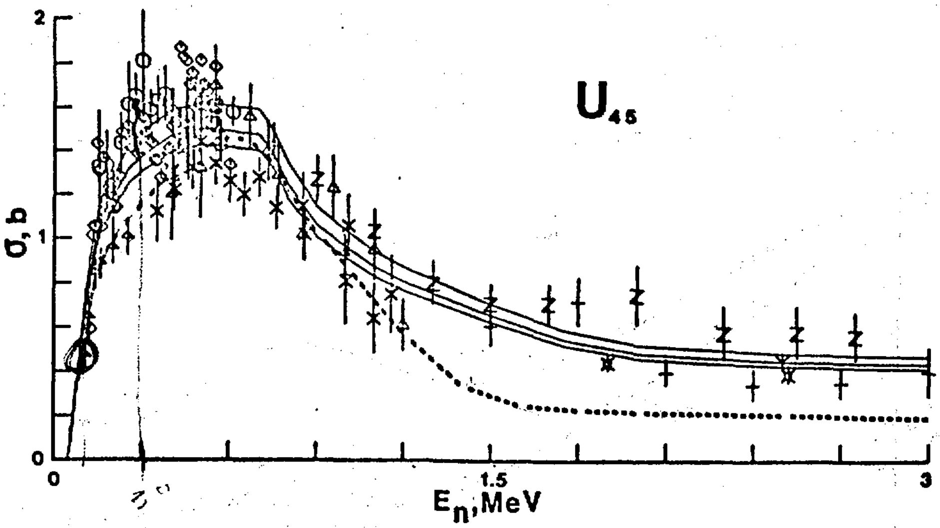

Fig. 2. Cross sections for the excitation of the 45 keV (2+) state. Measured values are indicated by symbols. The solid curve denotes the ENDF/B-V result with respective ± uncertainties. The dotted curve is from Version-IV.

Generally, the uncertainty in the evaluation of the prominent components is 5-10%. The most significant uncertainties are at low energies where the evaluation relied primarily on calculational extrapolation. Measured values at an incident energy of 85 keV are to be reported by Winters et al.[4] and should help resolve the low energy uncertainties. The ground-state-excitations of Version-V are much larger than those of Version-IV in the few MeV range in accord with measurements and calculations[2,3]. This results in a sharply larger total inelastic scattering cross section but has little impact on the typical fast-reactor multi-group transfer matrix.

The significant contributions from the K=0 band consist of 680, 732 and 827 keV states. The respective cross sections have been deduced from both direct neutron detection measurements and (n;n',gamma) measurements. The first two of these states make the major contribution to the cross section and the experimental results are reasonably consistent. The Version-V evaluation is primarily based upon the direct neutron measurements. The respective evaluation uncertainties are ~10%.

At excitations above ~1.0 MeV the Version-V evaluation combines discrete excitations into composite groups made up of the contributions from a number of states. The groups structure is a compromise between the resolutions available from the experiments and the definition needed for applications. The uncertainty associated with any one excitation function in this region can be large but the non-elastic cross section limits the cumulative uncertainty to 10-15%.

Recent (n;n',gamma) measurements by Olsen et al.[5] have improved the definition of the excitation of states at energies of ~0.7-1.5 MeV. A white source was used providing very good energy detail that makes possible the quantitative determination of the inelastic scattering cross sections in this energy range. Illustrative results for the 680 keV (1-) state are shown in Fig. 3.

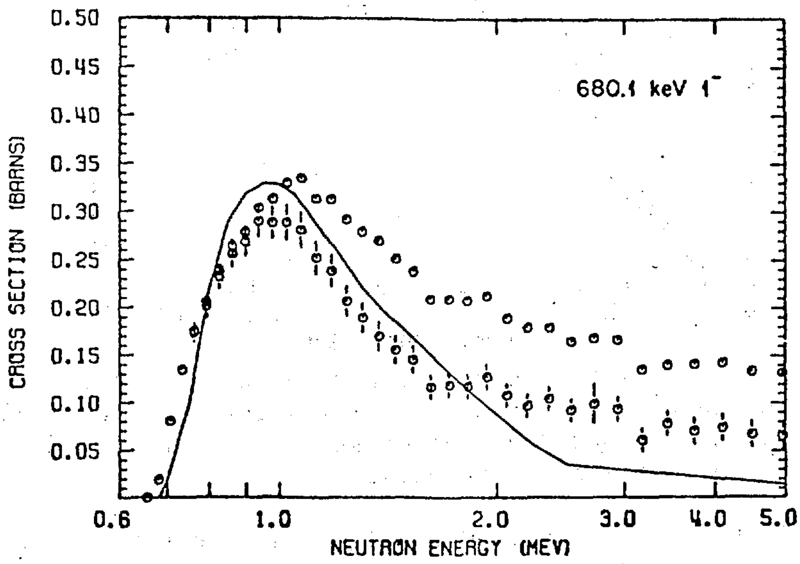

Fig. 3. ENDF/B-V (solid curve) compared with measured values of Ref. 5 for the excitation of the 680 keV state. The data points with bars are corrected for feeding from higher-energy levels and are to be compared with the evaluated cross section.

Similar comparisons can be made in a broader energy-average as illustrated in Fig. 4. Generally, the Olsen et al. results tend to be slightly smaller than the evaluation in this region but the difference is well within the respective uncertainties. Similar (n;n',gamma) measurements have recently been reported by Mittler et al.[6] A monoenergetic source was used in an energy range comparable to that of Ref. 5. Again, inelastic cross section values were deduced from the measurements. The results tend to be somewhat larger than given in Ref. 5 and in the Version-V evaluation. Thus the Version-V evaluation remains a reasonable representation of present experimental data base over the energy range of these most recent measurements.

The magnitude of the continuum inelastic cross section in Version-V is defined by the non-elastic component and the remaining independently-defined contributions. In addition, the evaluation was guided by macroscopic "benchmark" trials at energies above ~10 MeV. The resulting continuum contribution is considerably smaller in Version-V than Version-IV.

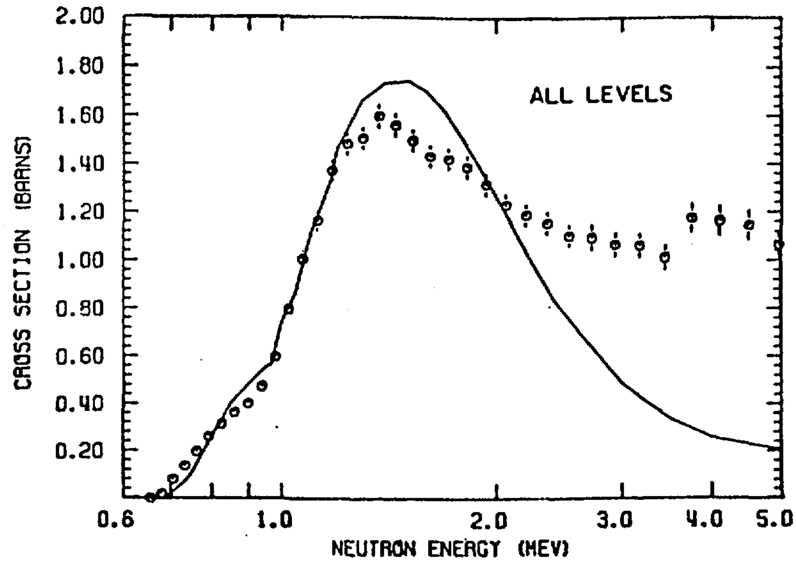

Fig. 4. ENDF/B-V compared with the corresponding GS-transition gamma-ray production and E0 cross sections for all levels from 680-1169 keV of excitation. Measured values of Ref. 5 are indicated by data points, the evaluation by the curve.

The Version-V evaluation is summarized in Fig. 5 and compared with the total inelastic scattering cross section as given in Version-IV. Over wide energy ranges Version-V total inelastic scattering cross sections are much larger than those given in Version-IV. This difference can be deceptive as the transfer matrix involved in many applications insignificantly changed. Indeed, in some applications the newer evaluation may even lead to reduced energy transfer in the inelastic scattering process due to the re-arrangement of the higher-energy excitations.

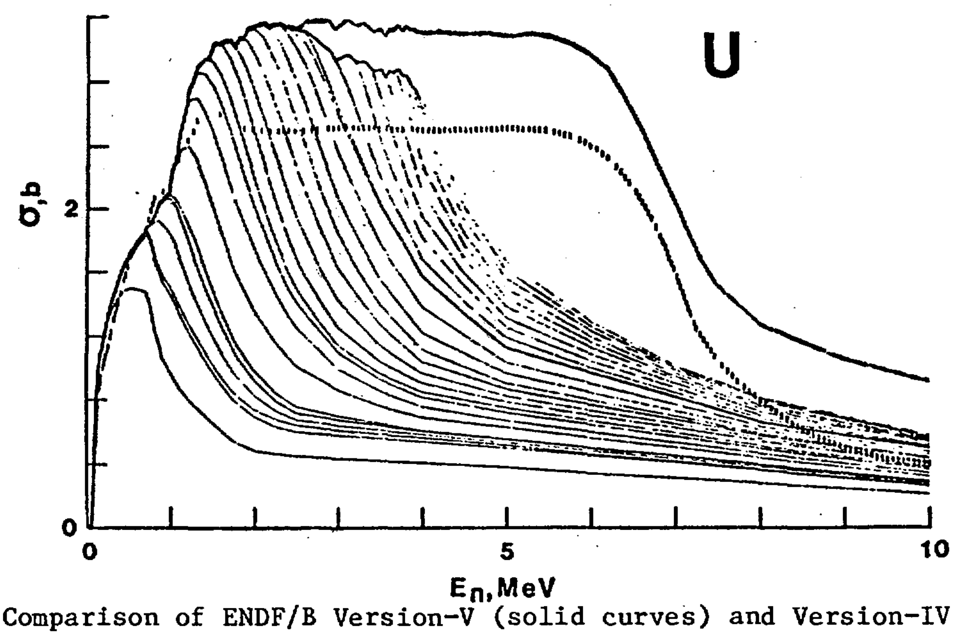

Fig. 5. Comparison of ENDF/B Version-V (solid curves) and Version-IV (dashed curves). The Version-V individual excitation functions are cumulatively summed to obtain the total inelastic scattering cross section. The corresponding total inelastic scattering cross section from Version-IV is shown.

Future work could well emphasize the following areas.

1. Experimental determination of the cross section at ~500 keV to ± 3% or better. Necessary for normalizing other measured and calculated shapes.

2. Resolution of question of fluctuations at energies of less than 500 keV.

3. Several measured values in the range 100-300 keV to accuracies of 10%.

4. Precision measurements of the differential-elastic-scattering cross section such that the non-elastic cross section is determined to ~5% from 1-20 MeV.

5. Relatively broad group excitations (e.g. ΔE_x ~250 keV) to accuracies of 10% for incident neutron energies in the range 1-5 MeV.

6. Several detailed measurements of the emission spectrum at incident neutron energies in the range 5-15 MeV with particular attention to pre-compound "tails".

7. Theoretical study of the excitation of the ground-state band particularly as relevant to the magnitude of enhancement factors. Present models generally underestimate the cross section at energies below 500-1000 keV.

A. B. Smith
Argonne, April 1980.

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FAST NEUTRON CAPTURE IN Cr, Fe AND Ni

A. Requirements

The importance of Cr, Fe and Ni in nuclear technology is due mainly to the large amount of steel in fuel claddings and support structures of reactors, but also to the use of nickel as a neutron reflector and to the problems of activation, swelling and embrittlement of steel components. For core neutronics one needs primarily the capture cross sections up to about 500 keV with accuracies of 5% for Fe, 8% for Ni and 12% for Cr [1]. Furthermore, the sharp p- and d-wave resonances of the structural materials contribute significantly to the Doppler coefficient of fast reactors, hence their resonance parameters, including radiation widths and level spins, are needed for the calculation of temperature-dependent self-shielding factors.

B. Status

The status of structural-material capture cross sections was reviewed in [2] and [3]. The status in 1978 can be briefly summarised as follows. Capture measurements at Harwell [4], RPI [5], KfK [6] and ORNL [7] with liquid scintillator tanks and Moxon-Rae detectors have reasonably well established the p- and d-wave resonance capture cross sections, with an accuracy of about 10-20%. The main sources of systematic errors are the flux normalisation and the sensitivity of the capture detectors to gamma spectrum fluctuations and, of course, their absolute values. Multiple scattering is less of a problem for p- and d-wave levels and well-tested codes are available to calculate the necessary corrections. The s-wave capture cross sections, however, are still quite uncertain due to the difficulty to determine the background caused by quasi-prompt capture of resonance-scattered neutrons in the vicinity of the sample. With practical sample thicknesses this effect is quite large because of the large scattering-to-capture ratios in the s-wave resonances of structural materials which typically have $\Gamma_n/\Gamma_\gamma \sim 100 - 1000$. The situation is illustrated by the scatter of the radiation widths obtained for the broad 27.7 keV resonance of ^{56}Fe by various groups, see Table 1. One concludes that there is an uncertainty of perhaps 50% for s-wave capture which means 20-30% for total capture on the average.

Recent improvements to experimental techniques include utilisation of C_6D_6 detectors at ORNL and Geel and especially the radically new technique demonstrated by Wisshak and Kaeppeler at KfK [8]. These authors exploit the capability of Van de Graaf accelerators to produce quasi-monoenergetic neutrons.

They produced neutrons just in the vicinity of the 27.7 keV resonance of ^{56}Fe and used a fast (Moxon-Rae) gamma ray detector located about twice as far from the sample as the sample is separated from the neutron source, viz. by 8 cm. This delayed the unwanted events caused by capture of resonance-scattered neutrons outside the sample so much that the 27.7 keV capture peak was practically unaffected. Furthermore, the short primary flight path permitted much thinner samples than in prior experiments, and the samples themselves were metal discs of practically pure ^{56}Fe. This kept multiple-scattering corrections low and reduced systematic errors to about 6%. Three quite different samples gave the same radiation width within ±1%, see Table 1. These results form a reliable base for the correction of older KfK (and perhaps other) data on ^{56}Fe with respect to quasi-prompt capture of scattered neutrons so that the same accuracy can be achieved for both s- and p- or d-wave capture cross sections, i. e. 10% in favourable cases.

Recent high-resolution total and scattering measurements at KfK [9] and ORNL [10] have led to the assignment of more than half the p- and d-wave level spins of ^{56}Fe below 825 keV. This permits a more reliable calculation of temperature-dependent self-shielding factors than before. The lack of good high-resolution total cross section data for ^{58}Ni and ^{60}Ni, which for years held up the analysis of capture data, has been removed by recent measurements at ORNL [11] and Harwell [12].

C. Conclusions and Recommendations

The required accuracies for capture cross sections of structural materials have not been attained yet. Now that a new technique for discrimination against quasi-prompt capture of resonance-scattered neutrons has been successfully demonstrated [8] it is recommended that the broadest Ni and Cr resonances are remeasured at Van de Graaff accelerators with this method. Larger energy ranges must, however, be covered by linac measurements which should be further developped so as to reproduce the Van de Graaff results. High-resolution scattering measurements on nickel and chromium isotopes should also be pursued in order to establish p- and d-wave level spins for application to temperature effect calculation.

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Table 1 - Radiation Widths Reported for the 27.7 keV Level of ^{56}Fe+n

Authors	Sample Thickness (at./b)	Radiation Width (eV)
Hockenbury et al. 1969	5.4 10^{-2} 6.3 10^{-2} 6.8 10^{-3}	1.44 ± .14
Ernst et al. 1975	9.9 10^{-3}	1.25 ± .20
Allen et al. 1977	8.2 10^{-3}	1.6 ± .3
Allen et al. 1979		0.6 ± .2
Gayther et al. 1977 (preliminary)	5.1 10^{-2} 1.7 10^{-2} 4.1 10^{-3}	0.94 ± .02 [a] 1.05 ± .02 [a] 0.73 ± .06 [a]
(final)		0.85 ± .09
Brusegan et al. 1979	1.5 10^{-2}	0.8 ± .2
Wisshak+ Kaeppeler 1979	5.3 10^{-3} 2.7 10^{-3} 1.4 10^{-3}	0.99 ± .05 1.01 ± .05 1.00 ± .06

[a] statistical error only

INDC Discrepancy File

Comments on the Excitation Function for the $^{93}Nb(n,n')^{93m}Nb$ Reaction

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Introduction

^{93}Nb has an isomeric level slightly above 30 kev [1] which can be excited by inelastic neutron scattering. The decay of this level to the ^{93}Nb ground state proceeds almost exclusively via internal conversion whereby orbital electrons are emitted followed by x-rays or Auger electrons. The most easily detected and investigated x-rays are the K_α and K_β-lines of 16.6 and 18.7 kev respectively [2-5]. The intensity of the direct γ-ray decay to the ^{93}Nb ground state is very small and has recently been determined by Bambynek et al. [4, 5] to be $I_\gamma=(4.5 \pm 1.0)\cdot 10^{-6}$ for a γ-ray energy of (30.75 ± 0.10) kev. Half life determinations for this isomeric level range from 11.4 to 16.4 years.

The fairly long half life of the induced ^{93m}Nb activity, the low effective threshold close to 30 kev combined with the coverage by this reaction of the large energy range between 30 kev and about 15 Mev, and the expected similarity of its neutron energy dependence with that of the appropriate damage function [3], make the $^{93}Nb(n,n')^{93m}Nb$ reaction particularly suitable for the long-term determination of fast neutron fluence, especially for the investigation and surveillance of radiation damage in power reactor pressure vessels [3-6]. Because of its increasing importance this reaction has been proposed, at the recent IAEA Advisory Group Meeting on Nuclear Data for Reactor Dosimetry held in Vienna in November 1978, to be included in the International Nuclear Data File for Reactor Dosimetry, briefly called the International Reactor Dosimetry File (IRDF) [7].

While methods are being developed for the absolute determination of the ^{93m}Nb activity induced by neutron inelastic scattering in Nb foils, e.g. at Winfrith [3], and, while a few first irradiations of Nb foils for fluence measurements are being performed in several power and research reactors [5], the more systematic and widespread application of Nb dosimetry is being held up particularly by the lack of accurate knowledge of the half life of ^{93m}Nb and the energy dependence of the cross section for the $^{93}Nb(n,n')^{93m}Nb$ reaction. In the sections below the status of the data is briefly reviewed, followed by a few recommendations for further clarifications or measurements required.

Review of data

1. Half life

1.1. Status

The following table lists the more recent literature values for the half life of the ^{93}Nb isomeric level. The most recent data are two preliminary values obtained by Bambynek et al. after measurement periods of one year [4] and two years [5] respectively.

Half life (years)	Author/year	Reference
13.6 ± 0.3	Flynn et al. 1965	[8]
11.4 ± 0.9	Hegedüs 1971	[9]
16.4 ± 0.4	Lloret 1975	[10]
13.9 ± 1.5 (preliminary)	Bambynek 1978 et al.	[4]
15.3 ± 1.2 (preliminary)	Bambynek 1979 et al.	[5]

The overall large spread between these values is apparent and certainly unsatisfactory.

1.2. Recommendation

It would be useful to have one or two additional independent measurements of the half life, as checks to the expected final result of the still ongoing Geel measurements [4, 5].

2. Inelastic scattering cross section

2.1. Status

Since there have been no more data recently, this review is heavily based on the previous review by Vlasov et al. [11] in 1972.

The appended figure taken from reference [11] shows the available data. Note that there are no direct measurements of the inelastic scattering cross section. All data points in the figure correspond to measured cross sections for the production of 780 kev γ-rays from the γ-decay of a level at 810 kev to the isomeric state at 30 kev, to which the cross sections for the direct production of the isomer state as estimated from Hauser-Feshbach calculations have been added. These sum cross sections should be identical to the neutron inelastic excitation cross section for the isomeric level, since the isomeric state can only be populated either by direct neutron excitation or by gamma ray cascades during the deexcitation of higher levels, where the last γ-ray in this cascade leading to the isomeric state at 30 kev can only be the 780 kev γ-ray mentioned above.

It is seen that there are large discrepancies in the region of reported data mostly between 0.9 and 2.2 Mev. The data by Rogers et al. [13] and Nath et al. [16] lie low, the 1971 TNC [14] and Göbel et al. [12] data are high and the (older) 1967 TNC [15] data fall in the middle. Note that the 1971 TNC data [14] were given at 55° only and that isotropy was assumed to convert these data to integral cross sections, thus neglecting any possible but unknown anisotropy.

The histogram curve covering the entire energy range from threshold to 15 Mev was taken from work of Hegedüs [9]. From measurements of the activation of Nb in several different known fast neutron spectra he deduced the unknown (n,n') cross section by unfolding. In the region 1 to 3 Mev, this method yields cross section values which lie essentially between the two conflicting groups of data derived from γ-ray spectrum measurements; only the 1967 TNC data [15] are closer to the Hegedüs data within the range of uncertainties. Hegedüs also gives a fission spectrum average value of (97 ± 35) mb, which agrees within uncertainties with the value (87 ± 14) mb quoted by Erdtmann [17]. Recent preliminary measurements of the space dependence of ^{93}Nb(n,n')^{93m}Nb and ^{103}Rh(n,n')^{103m}Rh reaction rates performed by Taylor [3] in the core and axial breeder zones of the British Prototype Fast Reactor (PFR) show a similar shape thus confirming the earlier work and assumptions of Hegedüs [9].

2.2. Recommendations

(i) Improvements of the situation pictured in the appended figure will require more accurate determinations of the 780 kev γ-ray production cross section below about 3 Mev neutron energy and extension to higher energies up to 15 Mev, where no measurements exist. Direct excitation of the 30 kev level is most important just above threshold and could be obtained from Hauser-Feshbach theory with sufficient accuracy using the present knowledge of the ^{93}Nb nuclear level structure. Alternatively, calculations using Hauser-Feshbach theory and presently known nuclear level structures, level densities, and branching ratios could be used over the entire energy region to provide additional information.

(ii) At the present time, the histogram cross sections of Hegedüs [9] should still be used as being the only values available which cover the entire energy region. However, they would need confirmation by microscopic measurements and more testing by integral measurements before their reliability can be fully assured.

3. Note on planned work

(i) Vonach and Tagesen from the Radiumphysik-Institut in Vienna plan to do evaluations and theoretical calculations of the ^{93}Nb(n,n')^{93m}Nb cross sections during 1979. The results will be incorporated in IRDF.

(ii) At Birmingham, UK, differential cross section measurements seem to be planned with the Dynamitron [5].

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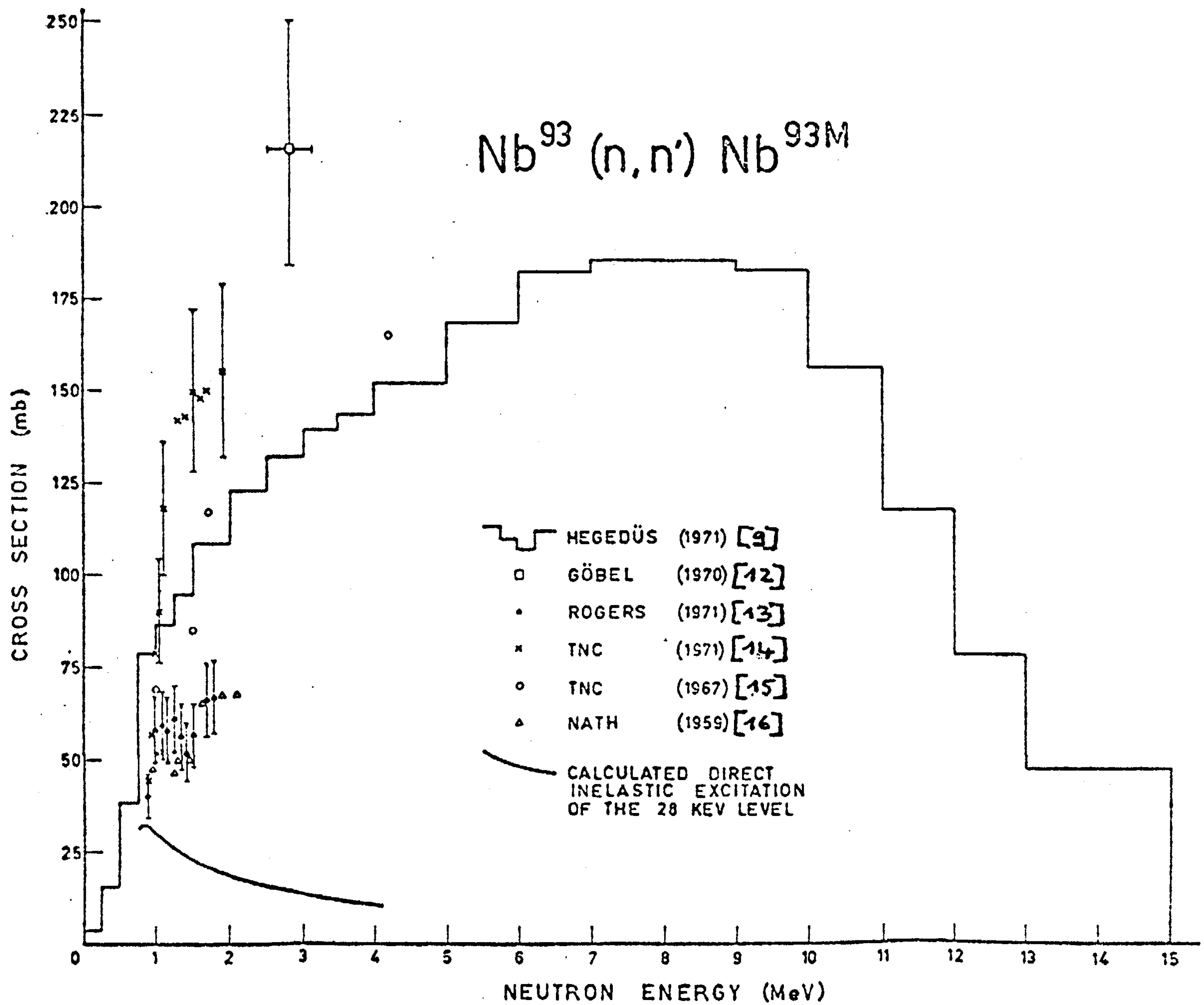

Nb93 (n, n') Nb93M
CROSS SECTION (mb)
NEUTRON ENERGY (MeV)
HEGEDÜS (1971) [9]
GÖBEL (1970) [12]
ROGERS (1971) [13]
TNC (1971) [14]
TNC (1967) [15]
NATH (1959) [16]
CALCULATED DIRECT INELASTIC EXCITATION OF THE 28 KEV LEVEL

^{241}Am FISSION CROSS SECTION

A. MICHAUDON, H. DERRIEN, G. GRENIER

I - RESONANCE REGION

I.1 - Measurements

The fission cross section measurements for ^{241}Am considered in this report are the following ones :

LRL - BOWMAN et al. (1965 [1]

Spark chamber data normalized at 3.13 barns at E_n = 0.0253 eV

KUR - GERASIMOV et al. (1966) [2]

Spark chamber data normalized at 3.13 barns at E_n = 0.0253 eV

SAC - DERRIEN et al. (1975) [3]

Data normalized on BOWMAN results

HAR - GAYTHER et al. (1977) [4]

Prompt fission neutron detection with pulse shape discrimination.
Measurement made relative to that of ^{235}U fission cross section

$$\left(\int_{1\ \text{keV}}^{2\ \text{keV}} \sigma_f \, dE_n = 7.167 \text{ b. keV for } {}^{235}U \right) .$$

GEEL - KNITTER et al. (1978) [5]

Special fission fragment chamber
Data normalized to the ^{235}U fission cross section

$$\int_{7.9\ \text{eV}}^{11\ \text{eV}} \sigma_f \, dE_n = 240. \text{ b. eV}$$

The values obtained for the fission widths from these measurements for the resonances with energies below 10 eV are given in Table 1 .

Above 10 eV, up to 40 eV, fission widths can be obtained from the Saclay data only .

The fission width values derived from these data, are given in Table II.

I.2 - Evaluation

An evaluation of the parameters for the ^{241}Am+n neutron resonances was presented in [6] .

Below 10 eV, the recommended fission width values are given in Table I . The following average fission width value is obtained

$$\langle \Gamma_f \rangle = 0.28 \text{ meV} \quad \text{for} \quad 0 < E_n < 10 \text{ eV}$$

Above 10 eV and up to 40 eV, only the Saclay results given in Table II are available and are taken as the recommended values .

The combined recommended values from 0 to 40 eV yield the following average fission width

$$\langle \Gamma_f \rangle = 0.24 \text{ meV} \quad \text{for} \quad 0 < E_n < 40 \text{ eV}$$

II - INTERMEDIATE AND FAST NEUTRON REGION

II.1 - Recent work

II.1.1 - Measurements

The recent measurements are reported below :

- Behrens and Browne, 1976 from 0.2 to 30 MeV [8]
- Gayther and Thomas, 1977 from 0.05 to 10 keV [4]
- Cancé et al., 1977 from 0.5 to 3 MeV [9]
- Knitter and Budtz-Jørgensen, 1978 from 0.1 to 5300 keV [5]
- Hage, Käppeler and Wisshak, 1978 from 10 to 1030 keV [10]

Some details (neutron source, method, accuracy) about these measurements are summarized in Table III .

The results given by Behrens and Browne [8] are still preliminary (see Table IV) .

The results given by Hage et al. [10] are also preliminary since corrections must be made for the various isotopes other than ^{241}Am present in the sample (there might be large amounts of ^{240}Pu and/or ^{242}Pu impurities in this sample) .

The data obtained in [5] and [10] are given in tabulated form in Tables V and VI respectively .

II.1.2 - Evaluations

A Japanese evaluation has been done by Igarasi [11] , based essentially on the data obtained by Seeger et al. [12] below the fission threshold .

A recent evaluation carried out by Mann and Schenter [13] is based on the data of Shpak and Smirenkin [15] for the low energy region, and especially on the data of Behrens and Browne above 400 keV .

The experimental data and the evaluations are plotted in Figs. 1 and 2 .

Patrick has also presented a review of the subject at the Meeting on Nuclear Data of Higher Pu and Am isotopes for reactor applications [14] . A compilation of ^{241}Am fission cross sections, as presented by Patrick, is shown in Fig.3 .

II.2 - Present status of the data

II.2.1 - Measurements

Below 400 keV, most of the data are now in good agreement taking into account their error bars . There are nevertheless two exceptions .

- The data reported by Seeger et al. are definitely too high because of the important uncertainty associated with a large background .
- From 2 to 10 keV, the data obtained by Gayther and Thomas are about twice as high as those reported by Knitter et al. [5] and by Shapk and Smirenkin [15]

Between 400 keV and 6 MeV, the recent measured data are in agreement within 15 %(very old measurements are excluded from the comparison) . The values of Behrens and Browne are approximately 6 % higher than those of Knitter et al.

From 6 MeV to 14 MeV, only the data obtained by Behrens and Browne should be considered .

Around 14 MeV, the measurements are fairly old and exhibit large differences up to 20 % . Therefore a new absolute measurement is needed at this energy .

II.2.2 - Evaluations

Below 400 keV, the evaluation made by Mann and Schenter [13] gives a good description of the recently measured data .

Above 400 keV, a new evaluation would be necessary, taking into account the recent results of Knitter et al. and Hage et al. However, at present, an approximate uncertainty of ± 15 % can be assigned to the σ_f values in this energy range .

TABLE I

FISSION WIDTHS OF ^{241}Am NEUTRON RESONANCES BELOW 10 eV

E_n (eV)	KUR	LRL	Γ_f (meV) SAC	HAR	GEEL	Recommended [6]
0.31	.33	.31				.32 ± .02
0.58	.15	.23				.19 ± .04
1.28	.35	.36	.37	.40	.37	.37 ± .04
1.93	.07	.08	.08	.06		.07 ± .02
2.37	.19	.17	.18	.16	.19	.18 ± .02
2.60	.15	.16	.17	.14	.15	.15 ± .02
3.97	.16	.16 **	.16	.13	.13	.15 ± .03
4.97	.24*	.42 **	.44	.48	.35	.42 ± .03
5.42	.45	.60	.63	.55	.64	.57 ± .04
6.12	.22*	.36 **	.42	.34	.34	.37 ± .05
6.74			.22	.08		.15 ± .07
7.66			.10			.10 ± .05
8.17			.15	.19		.17 ± .02
9.11	.26*	.17 **	.18	.17	.17	.17 ± .01
9.85	1.41*	.87	.95	.75	.75	.86 ± .08

* Very uncertain value (50 % error)

** Revised values

N.B. The fission data from KUR, SAC and GEEL are correlated .

TABLE II

FISSION WIDTHS OF ^{241}Am NEUTRON RESONANCES FROM 10 eV TO 40 eV (AS GIVEN IN [3] MODIFIED BY [7])

E_n (eV)	Γ_f (MeV)
10.12	0.16[a]
10.40	0.06[a]
10.99	0.13[a]
11.58	0.24[*b]
12.137	0.24[*b]
12.88	0.06[a]
14.68	0.27[a]
15.69	0.10[a]
16.39	0.11[a]
16.85	0.32[a]
17.73	0.30[a]
19.44	0.03[a]
21.74	0.27[a]
22.75	0.24[*b]
23.08	0.27[a]
23.34	0.17[a]
24.19	0.14[a]
25.63	0.29[a]
26.50	0.05[a]
26.67	0.19[a]
27.57	0.51[b]
27.73	0.19[b]
28.36	0.16[a]
28.90	0.16[a]
29.50	0.10[a]
30.82	0.27[b]
31.02	0.37[b]
31.25	0.22[a]
32.03	0.28[a]
34.03	very small[b]
34.46	0.85[b]
34.93	0.16[b]
35.48	0.10[b]
36.25	< 0.24[b]
36.98	0.51[a]
38.37	0.30[a]
39.62	0.23[a]

a) Values extracted from [3]

b) Values given in [7]

* Values taken equal to $<\Gamma_f> = 0.24$ meV

N.B. Several resonances between 36 eV and 40 eV have such a small neutron width that their fission width cannot be determined.

TABLE III - RECENT MEASUREMENTS OF THE ^{241}Am FISSION CROSS SECTION

Authors	Laboratory	Accelerator	Neutron energy range	Neutron source	Method	Comments
Behrens and Browne [8]	Livermore	Linac 100 MeV	0.2 - 30 MeV	White spectrum Pulsed source	$\sigma_{nf}(^{241}Am)/\sigma_{nf}(^{235}U)$ Ionisation chamber	Preliminary values Accuracy of ratio 38 - 8 % for 0.2-0.5 MeV 3 - 10 % for 0.5-20 MeV
Gayther and Thomas [4]	Harwell	Linac 45 MeV	0.05 - 10 keV	White spectrum Pulsed source	Detection of prompt fission neutrons	Accuracy of $\sigma_{nf}(^{241}Am)$ $\sim$ 25 %
Cancé et al. [9]	Bruyères-le-Châtel	Van de Graaff 4 MV	0.93 , 1.66 and 2.66 MeV	Monoenergetic neutrons Pulsed source	$\sigma_{nf}(^{241}Am)$ Gazeous scintillator	Accuracy of $\sigma_{nf}(^{242}Am)$ $\sim$ 15 %
Knitter and Budtz Jørgensen [5]	Geel	Van de Graaff 7 MV Linac 100 MeV	6 - 300 keV 0.150 - 5.3 MeV 100 eV-2.65 MeV	White spectrum Pulsed source Monoenergetic neutrons Pulsed source White spectrum Pulsed source	$\sigma_{nf}(^{241}Am)/\sigma_{nf}(^{235}U)$ Special ionisation chamber (α backround is suppressed)	(Accuracy of ratio) 11 - 3 % 50 - 8 % 8 - 12 %
Hage, Käppeler and Wisshak [10]	Karlsruhe	Van de Graaff 3 MV	10 - 120 keV 120 - 1030 keV	White spectrum Pulsed source Monoenergetic neutrons Pulsed source	Detection of prompt fission neutrons	Preliminary values Accuracy of $\sigma_{nf}(^{241}Am)$ 8 - 13 % 8 - 6 %

T A B L E   I V

THE $\bar{\sigma}_f$ VALUES OF ^{241}Am RELATIVE TO THOSE OF ^{235}U FROM 0.2 TO 30 MeV, AS GIVEN BY BEHRENS AND BROWNE [8]

Neutron energy (MeV)	Ratio	Statistical uncertainty[a] (%)	Neutron energy (MeV)	Ratio	Statistical uncertainty[a] (%)
0.2189	0.018	38	1.788	1.545	1.2
0.2438	0.018	31	1.930	1.542	1.2
0.2732	0.023	23	2.069	1.573	1.5
0.3084	0.031	15	2.200	1.533	1.5
0.3507	0.037	12	2.345	1.605	1.6
0.3885	0.044	12	2.504	1.583	1.6
0.4172	0.049	11	2.679	1.596	1.8
0.4492	0.0666	8.5	2.874	1.581	1.9
0.4850	0.0825	6.4	3.092	1.602	1.9
0.5200	0.0930	6.8	3.334	1.643	2.0
0.5530	0.1284	5.2	3.607	1.699	2.0
0.5894	0.1469	4.6	3.915	1.722	2.0
0.6294	0.1985	3.8	4.263	1.788	2.0
0.6660	0.2649	3.6	4.661	1.795	2.1
0.6976	0.3305	3.1	5.117	1.834	2.0
0.7315	0.3858	2.7	5.644	1.799	1.9
0.7679	0.5320	2.3	6.148	1.594	2.2
0.8072	0.6386	2.0	6.601	1.480	2.1
0.8495	0.7677	1.9	7.107	1.475	2.0
0.8952	0.8845	1.6	7.674	1.429	2.0
0.9447	0.9783	1.5	8.311	1.536	2.1
0.9985	1.108	1.4	9.032	1.544	2.3
1.057	1.218	1.3	9.851	1.537	2.6
1.121	1.395	1.2	10.79	1.547	2.9
1.191	1.483	1.2	11.87	1.475	3.3
1.267	1.563	1.1	13.11	1.334	3.6
1.351	1.574	1.1	14.57	1.285	4.0
1.444	1.526	1.1	16.29	1.343	4.5
1.546	1.571	1.1	18.34	1.256	5.2
1.660	1.579	1.2	20.80	1.254	6.0
			23.80	1.270	7.1
			27.50	1.455	7.6

[a]This indicates a counting error expressed as one standard deviation. Total errors may be estimated by combining the normalization error of 2.6% and the estimated overall systematic error of 2% with the counting errors in the table.

TABLE V A Neutron energy in MeV, ratios of the neutron induced ^{241}Am and ^{235}U fission cross sections and the errors of the ratios. Data were obtained by using monoenergetic neutrons from the Van de Graaff accelerator [5] .

ENERGY	RATIO	ERROR	ENERGY	RATIO	ERROR
1.53E-01	1.648E-02	2.46E-03	1.19E+00	1.272E+00	4.51E-02
1.63E-01	1.548E-02	3.92E-03	1.21E+00	1.397E+00	4.71E-02
1.90E-01	1.566E-02	3.73E-03	1.21E+00	1.325E+00	4.51E-02
2.16E-01	2.205E-02	2.68E-03	1.27E+00	1.370E+00	3.48E-02
2.45E-01	2.363E-02	5.04E-03	1.31E+00	1.433E+00	3.38E-02
2.70E-01	2.859E-02	4.24E-03	1.41E+00	1.443E+00	3.18E-02
3.39E-01	4.135E-02	5.16E-03	1.51E+00	1.500E+00	3.07E-02
3.90E-01	4.140E-02	4.28E-03	1.62E+00	1.485E+00	2.87E-02
4.25E-01	5.838E-02	4.28E-03	1.71E+00	1.468E+00	1.54E-02
4.58E-01	6.388E-02	3.70E-03	1.82E+00	1.453E+00	2.15E-02
4.90E-01	8.548E-02	4.78E-03	1.92E+00	1.424E+00	2.56E-02
5.19E-01	9.532E-02	5.98E-03	2.02E+00	1.452E+00	2.36E-02
5.48E-01	1.080E-01	6.59E-03	2.11E+00	1.435E+00	2.05E-02
5.74E-01	1.300E-01	5.99E-03	2.22E+00	1.454E+00	2.36E-02
6.00E-01	1.691E-01	8.71E-03	2.43E+00	1.504E+00	2.46E-02
6.28E-01	1.892E-01	6.60E-03	2.53E+00	1.499E+00	2.46E-02
6.55E-01	2.485E-01	1.64E-02	2.63E+00	1.522E+00	2.67E-02
6.80E-01	2.679E-01	1.13E-02	2.73E+00	1.500E+00	2.77E-02
7.05E-01	3.273E-01	1.54E-02	2.82E+00	1.512E+00	1.54E-02
7.33E-01	3.898E-01	1.95E-02	2.93E+00	1.523E+00	2.87E-02
7.60E-01	4.727E-01	2.15E-02	3.02E+00	1.552E+00	2.87E-02
7.80E-01	5.496E-01	2.36E-02	3.11E+00	1.550E+00	2.97E-02
8.01E-01	6.172E-01	2.26E-02	3.21E+00	1.594E+00	3.38E-02
8.16E-01	6.070E-01	2.67E-02	3.30E+00	1.570E+00	3.69E-02
8.31E-01	6.840E-01	2.77E-02	3.41E+00	1.603E+00	2.87E-02
8.60E-01	7.334E-01	2.15E-02	3.52E+00	1.539E+00	2.87E-02
8.62E-01	7.036E-01	2.46E-02	3.61E+00	1.545E+00	2.97E-02
8.74E-01	7.355E-01	2.67E-02	3.71E+00	1.611E+00	4.82E-02
8.86E-01	8.719E-01	3.28E-02	3.82E+00	1.612E+00	3.48E-02
8.86E-01	8.022E-01	2.66E-02	3.86E+00	1.572E+00	3.48E-02
8.98E-01	8.699E-01	2.46E-02	4.03E+00	1.622E+00	3.48E-02
9.10E-01	9.622E-01	5.23E-02	4.11E+00	1.664E+00	3.59E-02
9.37E-01	8.936E-01	3.59E-02	4.24E+00	1.630E+00	3.69E-02
9.63E-01	9.419E-01	4.20E-02	4.36E+00	1.605E+00	3.79E-02
9.92E-01	1.022E+00	3.59E-02	4.45E+00	1.656E+00	4.10E-02
1.02E+00	1.079E+00	4.20E-02	4.52E+00	1.563E+00	2.05E-02
1.05E+00	1.147E+00	4.10E-02	4.75E+00	1.557E+00	4.41E-02
1.08E+00	1.148E+00	4.00E-02	5.02E+00	1.607E+00	5.33E-02
1.11E+00	1.235E+00	5.12E-02	5.34E+00	1.686E+00	6.87E-02
1.16E+00	1.279E+00	4.10E-02			

TABLE V B Neutron energy in MeV, width of the energy interval in MeV, ratios of the neutron induced fission cross sections of ^{241}Am and ^{235}U and the errors of the ratios. The data were obtained by the time-of-flight method at the Van de Graaff accelerator [5].

ENERGY	WIDTH	RATIO	ERROR
6.00E-03	2.0E-03	1.787E-02	8.74E-03
8.50E-03	3.0E-03	7.708E-03	5.16E-03
1.25E-02	5.0E-03	8.718E-03	3.03E-03
1.75E-02	5.0E-03	9.075E-03	2.35E-03
2.50E-02	1.0E-02	1.203E-02	1.59E-03
3.50E-02	1.0E-02	1.107E-02	1.53E-03
4.50E-02	1.0E-02	1.273E-02	1.55E-03
5.50E-02	1.0E-02	1.177E-02	1.65E-03
6.50E-02	1.0E-02	1.445E-02	1.75E-03
7.50E-02	1.0E-02	1.592E-02	1.85E-03
8.50E-02	1.0E-02	1.412E-02	1.87E-03
9.50E-02	1.0E-02	1.552E-02	1.97E-03
1.10E-01	2.0E-02	1.540E-02	1.64E-03
1.35E-01	3.0E-02	1.731E-02	1.57E-03
1.755-01	5.0E-02	2.194E-02	1.67E-03
2.25E-01	5.0E-02	2.610E-02	2.13E-03
2.75E-01	5.0E-02	3.256E-02	2.60E-03

TABLE V C Neutron energy in MeV, width of energy interval in MeV, ratios of the neutron induced fission cross sections of ^{241}Am and ^{235}U and the errors of the ratios. The data were obtained by time-of-flight measurements at the linac [5].

ENERGY	WIDTH	RATIO	ERROR
1.49E-04	4.98E-05	1.639E-02	1.24E-03
2.49E-04	4.99E-05	1.062E-02	1.24E-03
3.49E-04	4.97E-05	2.056E-02	1.70E-03
4.48E-04	4.98E-05	1.232E-02	1.55E-03
5.48E-04	4.97E-05	9.238E-03	1.75E-03
6.98E-04	9.99E-05	1.254E-02	1.28E-03
8.98E-04	1.00E-04	1.111E-02	1.87E-03
1.07E-03	8.10E-05	1.718E-02	2.34E-03
1.25E-03	9.89E-05	1.190E-02	1.91E-03
1.46E-03	1.08E-04	9.879E-03	1.97E-03
1.70E-03	1.31E-04	7.419E-03	1.80E-03
1.99E-03	1.54E-04	6.241E-03	1.75E-03
2.32E-03	1.78E-04	1.095E-02	2.10E-03
2.71E-03	2.05E-04	1.146E-02	2.24E-03
3.16E-03	2.46E-04	1.128E-02	2.25E-03
3.68E-03	2.78E-04	8.625E-03	1.99E-03
4.29E-03	3.31E-04	9.142E-03	2.08E-03
5.01E-03	3.87E-04	1.184E-02	2.41E-03
5.85E-03	4.49E-04	1.253E-02	2.65E-03
6.81E-03	5.16E-04	9.709E-03	2.28E-03
7.94E-03	6.12E-04	1.669E-02	2.92E-03
9.27E-03	7.10E-04	1.196E-02	2.52E-03
1.08E-02	8.37E-04	1.097E-02	2.41E-03
1.26E-02	9.55E-04	1.462E-02	2.83E-03
1.46E-02	1.10E-03	1.571E-02	3.01E-03
1.70E-02	1.31E-03	1.156E-02	2.61E-03
1.99E-02	1.56E-03	1.290E-02	2.68E-03
2.33E-02	1.78E-03	1.396E-02	2.69E-03
2.71E-02	2.00E-03	1.028E-02	2.61E-03
3.15E-02	2.42E-03	7.329E-03	2.08E-03
3.67E-02	2.80E-03	1.373E-02	2.83E-03
4.29E-02	3.39E-03	1.050E-02	2.31E-03
5.00E-02	3.68E-03	1.650E-02	3.00E-03
5.83E-02	4.63E-03	1.696E-02	2.90E-03
6.82E-02	5.24E-03	1.226E-02	2.45E-03
7.93E-02	5.79E-03	1.568E-02	2.94E-03
9.23E-02	7.28E-03	1.642E-02	2.88E-03
1.07E-01	7.94E-03	1.289E-02	2.70E-03
1.25E-01	1.00E-02	1.662E-02	2.80E-03
1.46E-01	1.06E-02	2.119E-02	3.27E-03

TABLE V Continued :

1.70E-01	1.33E-02	2.324E-02	3.41E-03
1.98E-01	1.53E-02	2.293E-02	3.39E-03
2.31E-01	1.73E-02	2.982E-02	4.02E-03
2.68E-01	1.92E-02	2.654E-02	3.87E-03
3.11E-01	2.40E-02	3.773E-02	4.69E-03
3.66E-01	3.06E-02	5.105E-02	5.25E-03
4.25E-01	2.88E-02	7.176E-02	7.94E-03
4.97E-01	4.24E-02	8.862E-02	6.81E-03
5.77E-01	3.80E-02	1.547E-01	1.21E-02
6.72E-01	5.72E-02	3.504E-01	2.35E-02
7.90E-01	6.08E-02	6.320E-01	4.27E-02
9.12E-01	6.03E-02	1.065E+00	6.95E-02
1.06E+00	9.53E-02	1.119E+00	6.11E-02
1.26E+00	9.79E-02	1.406E+00	8.48E-02
1.44E+00	9.07E-02	1.494E+00	1.09E-01
1.69E+00	1.52E-01	1.499E+00	9.72E-02
1.99E+00	1.45E-01	1.378E+00	1.04E-01
2.31E+00	1.83E-01	1.658E+00	1.54E-01
2.65E+00	1.49E-01	1.312E+00	1.51E-01

TABLE VI

^{241}Am FISSION CROSS SECTION VALUES OBTAINED IN MEASUREMENTS DESCRIBED IN [10].

A

WITH A WHITE NEUTRON SOURCE

$\bar{E}$ keV	$\Delta\bar{E}$ keV	σ_f (mb)	$\Delta\sigma_f$ (mb)
11.3	5.8	42.6	3.2
22.2	5.9	19.5	1.5
32.3	5.8	20.2	1.1
44.7	10.2	19.0	1.0
58.3	8.2	15.9	1.2
72.0	11.3	17.5	1.7
91.4	16.1	16.6	2.0
120.3	24.8	18.5	2.4

B

WITH MONOENERGETIC NEUTRONS

$\bar{E}$ (keV)	$\Delta\bar{E}$ (keV)	σ_f (mb)	$\Delta\sigma_f$ (mb)
119.6	14.8	18.3	1.5
125.0	24.6	19.1	2.3
155.0	13.7	20.5	1.5
160.3	17.8	22.4	1.8
193.1	15.5	24.4	1.7
208.0	19.2	25.9	1.7
246.3	36.7	33.2	3.9
296.9	29.4	39.7	3.4
341.8	30.1	46.1	3.0
382.8	34.4	63.2	3.8
440.6	28.0	90.2	6.1
484.0	26.3	115.6	6.8
531.4	29.8	158.7	9.5
583.0	29.0	209.8	12.4
645.0	20.0	298.2	17.7
678.0	26.0	457.0	27.0
739.0	25.0	657.6	39.5
832.0	19.	904.4	54.0
929.0	22.	1090.	64.6
1029.	28.	1483.	88.7

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FIGURE CAPTIONS

Fig. 1 The experimental data and the evaluations of σ_{nf} ^{241}Am (below 400 keV) [13]

Fig. 2 The experimental data and the evaluations of $\sigma_{nf}(^{241}Am)$ (above 400 keV) [13]

Fig. 3 The compilation of ^{241}Am fission cross sections [14].

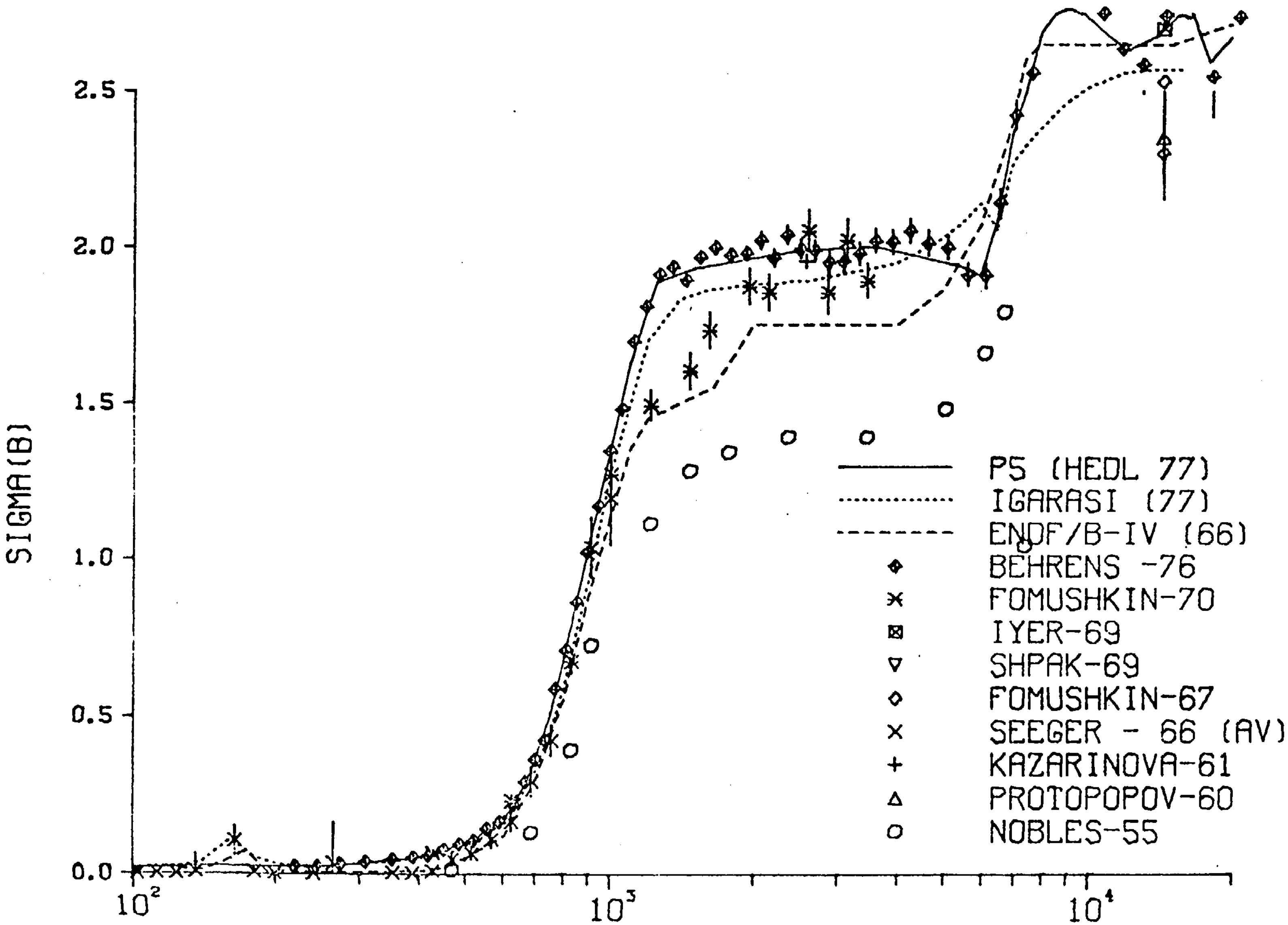
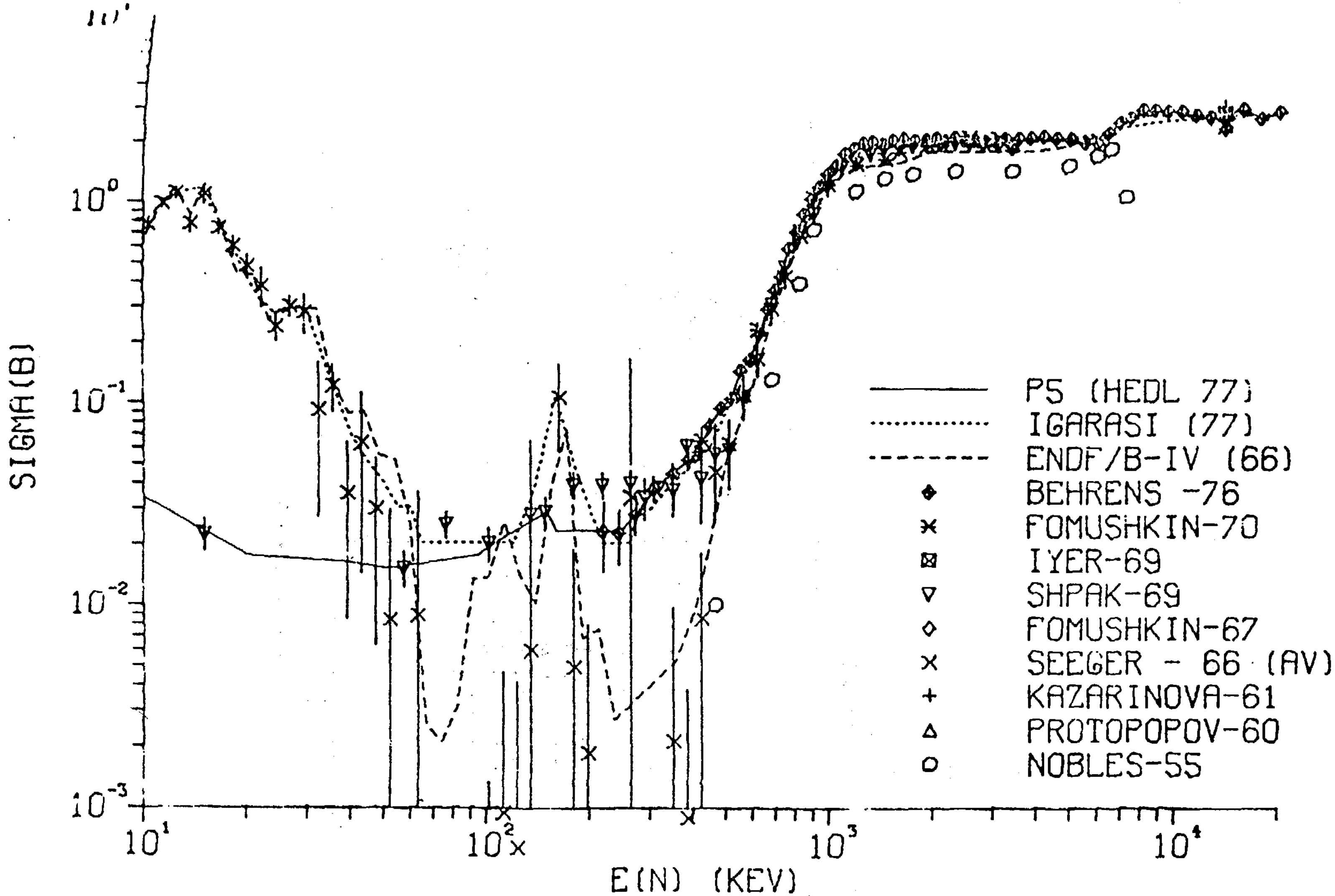
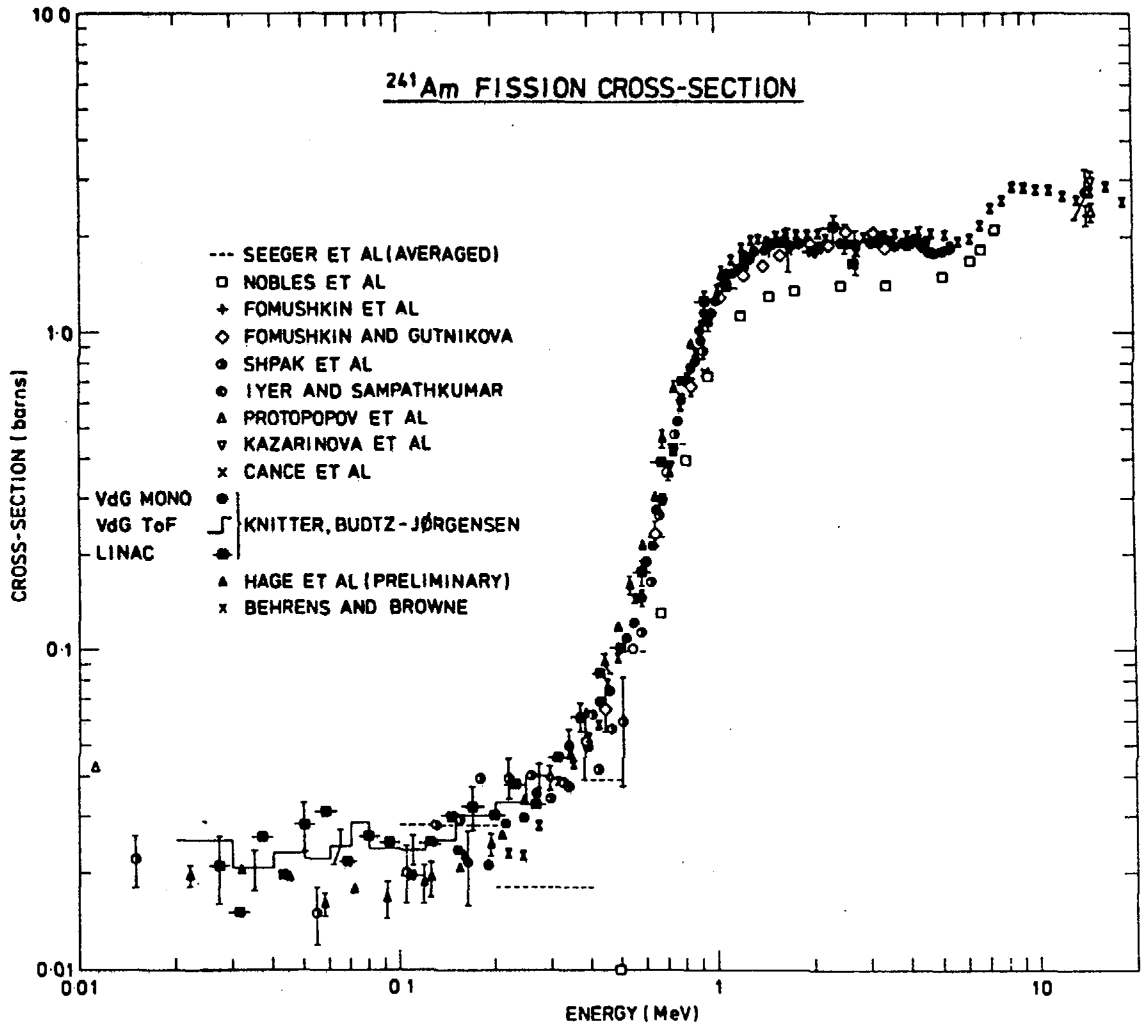

SIGMA(B)
2.5
2.0
1.5
1.0
0.5
0.0
10^2
10^3
10^4
E(N) (KEV)
PS (HEDL 77)
IGARASI (77)
ENDF/B-IV (66)
BEHRENS -76
FOMUSHKIN-70
IYER-69
SHPAK-69
FOMUSHKIN-67
SEEGER - 66 (AV)
KAZARINOVA-61
PROTOPOPOV-60
NOBLES-55

Fig. 1



SIGMA(B)
E(N) (KEV)
P5 (HEDL 77)
IGARASI (77)
ENDF/B-IV (66)
BEHRENS -76
FOMUSHKIN-70
IYER-69
SHPAK-69
FOMUSHKIN-67
SEEGER - 66 (AV)
KAZARINOVA-61
PROTOPOPOV-60
NOBLES-55

Fig. 2



241Am FISSION CROSS-SECTION
SEEGER ET AL (AVERAGED)
NOBLES ET AL
FOMUSHKIN ET AL
FOMUSHKIN AND GUTNIKOVA
SHPAK ET AL
IYER AND SAMPATHKUMAR
PROTOPOPOV ET AL
KAZARINOVA ET AL
CANCE ET AL
VdG MONO
VdG ToF
LINAC
KNITTER, BUDTZ-JØRGENSEN
HAGE ET AL (PRELIMINARY)
BEHRENS AND BROWNE
CROSS-SECTION (barns)
ENERGY (MeV)
10·0
1·0
0·1
0·01
0·01
0·1
1
10

Fig. 3

IAEA Nuclear Data Section

Comments on the Excitation Function for the Cu-63(n,α)Co-60 Reaction

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Vienna, 1 March 1979

Abstract

The status of the Cu-63(n,α)Co-60 threshold reaction which is of importance in the field of reactor dosimetry is reviewed. Recent available experimental data are compared showing a 30% discrepancy between integral and differential data, and 20% discrepancy among differential data.

Introduction

The threshold reaction Cu-63(n,α)Co-60 is of special importance in reactor dosimetry as a long-term fast flux integrator. The IAEA Advisory Group Meeting on Nuclear Data for Reactor Dosimetry (Nov. 1978, Summary Report to be published as INDC(NDS)-100) considered this reaction to be included in the International Reactor Dosimetry File. However, it represents a typical example for discrepancies existing between differential and integral measurements.

Review of data

1) Integral data

Table I gives a summary of integral cross-sections measured in a fission-neutron spectrum. The 9 experimental values (Ref. 1-9) are in reasonable agreement around a mean value of

$$0.47 \pm 0.07 \text{ mb}$$

however with extreme values of

0.66 and 0.36 mb respectively

The differential cross-section (excitation function) is determined by only one set of measurements (Paulsen and Liskien, Ref. 10-13) and the corresponding integrated value calculated from a Watt-spectrum (Ref. 14) is

$$0.34 \pm 0.04 \text{ mb}$$

which is 38% lower than the average of the experimental integral value quoted above. This discrepancy exceeds the quoted errors, though the lowest experimental integral value (Ref. 3) agrees with the value calculated from the differential data. A discussion of the possible reasons for these differential-integral discrepancies can be found in Ref. 15-17.

Table I - Available results for the average Cu-63(n,α)Co-60 cross-section measured in a fission neutron spectrum

	⟨σ⟩ mb	Reference
Experimental	0.54 ± 0.07	R. Nilsson (1963) Ref. 1
	0.42	C.H. Hogg et al (1963) Ref. 2
	0.36 ± 0.04	R.L. Ritzman et al (1963) Ref. 3
	0.45 ± 0.05	D.M. Clare (1964) Ref. 4
	0.52 ± 0.04	A. Fabry (1965) Ref. 5
	0.44	Lloret (1965) Ref. 6
	0.382	Nasyrov (1968) Ref. 7
	0.66	A. Fabry (1970) Ref. 8
	0.484 ± 0.034	K. Kobayashi (1975) Ref. 9
Mean	0.47 ± 0.07	unweighted mean value
Value calculated from differential measurement using Watt spectrum	0.34 ± 0.04	Liskien and Paulsen (1965) (1966) Ref. 10, 11 Spaepen (1967) Ref. 12 Paulsen (1967) Ref. 13
Evaluated values over Watt spectrum	0.49	SAND-I Ref. 25
	0.356	ENDF/B-IV Ref. 25

2) Differential data

In addition to the single existing measurement of the excitation function in the whole range from 5 to 20 MeV (Paulsen and Liskien, Ref. 10-13), there exist seven measurements (Ref. 18-24) made with neutrons between 14 and 15 MeV. These measurements are given in Table II.

Since the cross-section variation in the energy range from 14 to 15 MeV is small compared to the discrepancies, all these values can be considered together.

The three measurements by α-counting are quite discrepant between 26.1 and 67 mb. Their weighted mean of 35 ± 20 mb is rather meaningless.

We should point out that the last α-counting measurement (Ref. 22), which gives the high value of 56 ± 10 mb, was made by an improved technique using a magnetic quadrupole lens which permitted better measurements of signal-to-background ratios.

The four measurements by activation are in fair agreement around 47 ± 7 mb. Since the lowest result claims by far the highest accuracy, the weighted mean is 41 ± 8 mb.

Compared to this experimental value, the excitation function by Paulsen and Liskien, (Ref. 25) which has a value of 35 mb at 14.5 MeV, appears to be 17% too low.

3) Evaluated data

The data of SAND-1, having a Watt-spectrum average value of 0.49 mb, were apparently adjusted to integral data.

The ENDF/B-4 curve follows Paulsen's experimental excitation function. Thus the Watt-spectrum average value of ENDF/B-4 (0.356 mb as quoted in Ref. 25) is close to that obtained by Paulsen (0.34) from his own experimental data.

Paulsen's experimental data, however, leave some room for interpretation. Paulsen preferred a smooth curve through his points, and the same preference was applied for ENDF/B-4.

As can be seen in fig. 1 (= fig. 16 taken from Ref. 26) Paulsen's experimental points can be interpreted to show significant structure in the excitation function. This structure was adopted for the SAND-2 data. The corresponding Watt-spectrum average value, which is presently not available to us, would be somewhat larger than that obtained from ENDF/B-4, but the discrepancy with integral data would be reduced only slightly. The structure seen in Paulsen's points, however, can as well be interpreted as statistical fluctuations unless the structure is confirmed by another experiment.

The high curve by Fabry shown in fig. 1 was apparently designed to match his high integral value (see Table I). It can therefore not be considered as an evaluation of all available data.

Table II - Experimental differential cross-sections near 15 MeV

Cross-Section	Neutron Energy	Reference	Method
47.0 ± 9.4	14	Czapp and Vonach (1960) Ref. 18	Act.
67 ± 16	14	" " "	α
49.5 ± 10	14.6 ± 0.2	Barral et al (1968) Ref. 19	Act.
53.5 ± 6	14.6 ± 0.2	Maslov et al (1974) Ref. 20	Act.
26.1 ± 5	14.2	Borman et al Ref. 21	α
56 ± 10	15	Grimes et al Ref. 22	α
40 ± 1.2	14.8 ± 0.3	G. Winkler Ref. 23	Act.
35 ± 20	~14.5	weighted mean from α-counting	
47 ± 7	~14.5	unweighted mean from activation	
41 ± 8	~14.5	weighted mean from activation	
35	14.5	Paulsen (1967) Ref. 24	Act.

4) Conclusion

The excitation function derived by Paulsen from his own experimental data is

- 38% low compared to the mean of the integral data;
- 17% low compared to the mean of the 14-15 MeV activation data; (the same data measured by α-counting cannot be considered as reliable)
- and furthermore low compared to theoretical considerations (Ref. 27) which predict higher values near threshold.

This gives evidence that Paulsen's data are systematically too low, and it should be investigated whether a renormalization (ca 15-20% up) could be justified.

Investigations about possible error sources in existing experimental data are advisable.

New accurate measurements are required

- for the entire excitation function, with energy points dense enough to demonstrate whether there is a structure or not;
- in the 14-15 MeV range by different methods; the only existing precision measurement by Winkler (Ref. 23, 1978) at 14.8 MeV is not yet sufficient.

Although integral data are more consistent than the 14-15 MeV data, a further integral accurate measurement may be advisable, too.

As an interim solution it could be recommended to use Paulsen's excitation function increased by 17% with an uncertainty of ± 17%.

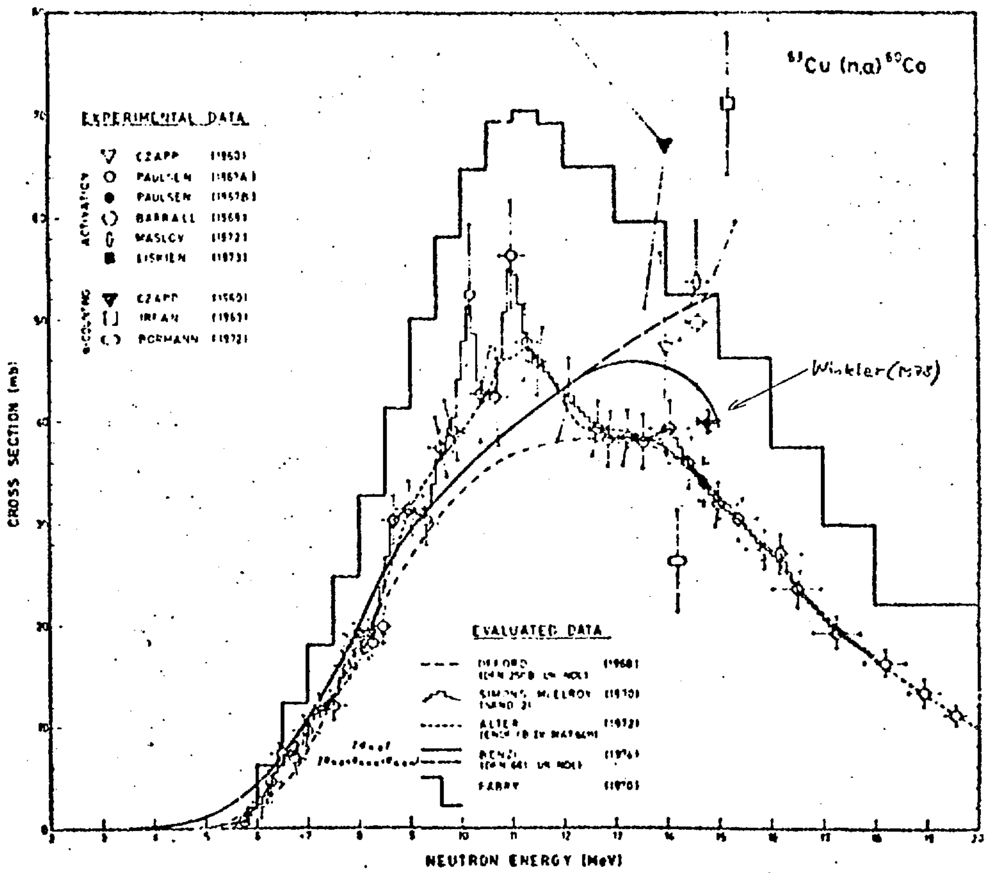
63Cu (n,α) 60Co
EXPERIMENTAL DATA
ACTIVATION
CZAPP
PAULSEN
PAULSEN
BARRALL
MASLOV
LISKIEN
CZAPP
IRFAN
BORMANN
Winkler (1978)
EVALUATED DATA
DELFORD
SIMONS, McELROY
ALTER
FABRY
CROSS SECTION (mb)
NEUTRON ENERGY (MeV)

Figure 1

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