

International Atomic Energy Agency

INDC(AUS)-014
Distr.: L

IN DC

INTERNATIONAL NUCLEAR DATA COMMITTEE

UPDATE OF THE EVALUATION OF THE CROSS SECTIONS FOR THE
NEUTRON-DOSIMETRY REACTIONS $^{19}\text{F}(n,2n)^{18}\text{F}$ AND $^{93}\text{Nb}(n,2n)^{92\text{m}}\text{Nb}$

M. Wagner
Institut für Radiumforschung und Kernphysik
der Universität Wien

October 1991

UPDATE OF THE EVALUATION OF THE CROSS SECTIONS FOR THE
NEUTRON-DOSIMETRY REACTIONS $^{19}\text{F}(\text{n},2\text{n})^{18}\text{F}$ AND $^{93}\text{Nb}(\text{n},2\text{n})^{92m}\text{Nb}$

M. Wagner
Institut für Radiumforschung und Kernphysik
der Universität Wien

October 1991

**Reproduced by the IAEA in Austria
October 1991**

91-05857

**Update of the evaluation of the cross sections for the neutron-dosimetry reactions
 $^{19}\text{F}(\text{n},2\text{n})^{18}\text{F}$ and $^{93}\text{Nb}(\text{n},2\text{n})^{92\text{m}}\text{Nb}$.**

M. Wagner

Institut für Radiumforschung und Kernphysik der Universität Wien

Abstract: The excitation functions for the reactions $^{19}\text{F}(\text{n},2\text{n})^{18}\text{F}$ and $^{93}\text{Nb}(\text{n},2\text{n})^{92\text{m}}\text{Nb}$, which are included in the International Reactor Dosimetry File (IRDF-90), were re-evaluated taking into account very recent experimental data. In the case of the reaction $^{19}\text{F}(\text{n},2\text{n})^{18}\text{F}$ the new measurements served to extend the neutron energy range beyond 20 MeV; for the $^{93}\text{Nb}(\text{n},2\text{n})^{92\text{m}}\text{Nb}$ reaction the new information concerning the energy region just above the threshold (9.0 - 10.6 MeV) substantially modified the results of the evaluation and thus the recommended cross sections in this energy region. The cross sections and their uncertainties were evaluated in energy groups with widths of 0.2 MeV to 2.0 MeV, and relative correlation matrices of the evaluated cross sections at the different energies were calculated. The results of the evaluation are compared with those given in the IRDF-90 and, in the case of $^{93}\text{Nb}(\text{n},2\text{n})^{92\text{m}}\text{Nb}$, with a model calculation carried out by Strohmaier. The results of this work are intended to replace the corresponding data given in Physics Data 13-5 and the recommended cross sections for these two reactions in the IRDF-90.

1. Introduction

The cross sections for the neutron-dosimetry reactions $^{19}\text{F}(\text{n},2\text{n})^{18}\text{F}$ and $^{93}\text{Nb}(\text{n},2\text{n})^{92\text{m}}\text{Nb}$ were evaluated at the Institut für Radiumforschung und Kernphysik (IRK) in the energy region from the respective thresholds up to 20 MeV [1, 2] and are included in the International Reactor Dosimetry File (IRDF-90) [3] as recommended values. In the case of the reaction $^{19}\text{F}(\text{n},2\text{n})^{18}\text{F}$ the results of the previous evaluation [2] were accepted unchanged (see Ref. 1, Section 4), because new measurements carried out in the 14 MeV energy range [4, 5, 6] did not alter the status of this cross section. Recently, however, Hartmann and De Luca reported a new experiment covering the 18 - 27 MeV region [7], which proved valuable for extending the energy range of our evaluation beyond 20 MeV. Besides, all additional measurements not yet included in the former evaluation, especially in the 14 MeV region, were taken into account for the revised version.

The evaluation of the excitation function for the reaction $^{93}\text{Nb}(\text{n},2\text{n})^{92\text{m}}\text{Nb}$ as published in Physics Data 13-5 [1] proved that the status of the recommended cross section close to the threshold (from 9.0 to \approx 10.6 MeV) was quite unsatisfactory, since large discrepancies existed between the few data sets reported for this energy region; moreover, recent model calculations [8] which were part of a consistent theoretical description of the main

neutron-induced reactions on ^{93}Nb , considerably disagreed with most experimental data in the energy range in question. Meanwhile, important new investigations carried out in different laboratories (*Santry* 90 at Chalk River, Canada; *Mannhart* 91 at the Physikalisch - Technische Bundesanstalt, Braunschweig, Germany; *Smith* 91 at the Argonne National Laboratory, United States) provided a consistent answer to the open problems and served to establish the $^{93}\text{Nb}(n,2n)^{92m}\text{Nb}$ excitation function more reliably particularly in the energy region from threshold to 12 MeV. Therefore, the re-evaluation of this cross section for neutron-dosimetry purposes was considered to be an urgent issue in order to replace the results incorporated in the IRDF-90 [3] by the new and more accurate ones.

In the present work, the procedures used in the previous IRK evaluation [9, 2, 1] were applied with some minor modifications. The updated evaluations are described in Section 2; in Section 3 the correlation matrices for the evaluated cross sections are given.

2. Updated evaluations

2.1. The reaction $^{19}\text{F}(n,2n)^{18}\text{F}$

2.1.1. Experimental data base

The data base already referred to in Ref. 2 was supplemented by carrying out a literature search in two steps:

- a. The very comprehensive compilations CINDA-A [10] and CINDA 90 [11] and, additionally, the data file EXFOR [12] were used as an index to experimental works.
- b. The most recent editions of some journals most likely to contain relevant information were also searched. The deadline for the data retrieval was June 1991.

The most important information on nine additional papers together with those quoted already in Ref. 2 is summarized in Table 2.1.1. There, in the columns 1 through 4 the lower and upper limit of the energy range covered in the respective experiments, the number of cross-section measurements within this range and the average uncertainty of the results are listed; the columns 5 and 6 indicate the method used to measure the induced ^{18}F activity or the particles produced in the considered reaction and the method applied for the neutron-fluence measurement; in column 7 the name of the first author and the year of the publication of the paper are given, and column 8, finally, informs on the reference number used furtheron in this compilation. If a reference cross section had been taken from an earlier absolute measurement carried out by the authors of the respective work, the $^{19}\text{F}(n,2n)^{18}\text{F}$ cross-section measurement then was also considered to be an absolute one, as discussed in Ref. 9, Section II.1.

In several cases different methods of neutron fluence measurement were applied for different parts of the excitation function or for a number of data points, or both the measurement of absolute values of the cross section at certain energies and of a relative excitation function were reported in one paper. Then the respective paper was split into two parts for further processing and two reference numbers were assigned to it. This

applies to the works *Bormann 65*, *Csikai 65*, *Nagel 66*, *Bormann 67*, *Vonach 68*, *Victorov 83* and *Hartmann 91*.

A detailed and critical examination of the experiments reported in the literature led to the rejection of the results of seven works which are either obsolete or obviously erroneous. This decision was based on the following facts:

The papers *Williamson 61* and *Picard 63* are identical with *Picard 65*, and *Nagel 65* was superseded by *Nagel 66*.

Strohal 64: The shape of the excitation function deviates markedly from all other data.

Csikai 65 (Ref. no. 177): The relative excitation function shows considerable fluctuations which could not be reproduced by the experiments *Bormann 67* and *Vonach 68*.

Picard 65: The relative excitation function given in this work did not permit an adequate renormalization due to its strongly deviating shape.

Shiokawa 68: The results of this experiment disagree with the average values by more than 6 standard deviations.

The cross sections reported in the papers *McCrary 60* and *Brill 61* were treated as relative data since the authors did not provide sufficient information on the method used to measure the neutron fluence. The absolute cross sections given in both works are too high in comparison to the mutually consistent results of other experiments, yet the shape of the measured $^{19}\text{F}(\text{n},2\text{n})^{18}\text{F}$ excitation function allowed a normalization of the results to the main body of the data in both cases.

A number of original values given for the cross sections and their uncertainties had to be renormalized according to the general procedures outlined in Ref. 9, Section II. For this purpose the following standards were taken:

- a. The decay data as given in the *Tables of Isotopes* [13]; since these data have not been changed significantly for many years, no corrections had to be applied in this respect.
- b. The cross sections measured relative to the cross sections for the dosimetry reactions $^{27}\text{Al}(\text{n},\alpha)^{24}\text{Na}$, $^{63}\text{Cu}(\text{n},2\text{n})^{62}\text{Cu}$ and $^{197}\text{Au}(\text{n},2\text{n})^{196}\text{Au}$ were renormalized using the results evaluated at the IRK and published in Ref. 1. For the intermediate energies linear interpolation of the recommended cross sections given for the centers of the respective energy groups was used. This renormalization was applied to the results of the works *Rayburn 61*, *Csikai 65* (Ref. no. 454), *Csikai 67*, *Menlove 67* in the energy range below 13 MeV, *Vonach 68* (Ref. no. 319), *Barrell 69A*, *Chatterjee 69*, *Mogharrab 72*, *Araminowicz 73*, *Sigg 76*, *Victorov 83* (Ref. no. 330) and *Hartmann 91* (Ref. no. 331).

For the cross section value published by Kobayashi et al. (1988) no renormalization was required, as the $^{27}\text{Al}(\text{n},\alpha)^{24}\text{Na}$ cross section used in their work corresponds to the evaluated reference cross section averaged over the spectrum of their neutron source, a $^6\text{Li}-\text{D}$ converter.

- c. In the 14 MeV range the reference cross sections for the reactions $^{56}\text{Fe}(\text{n},\text{p})^{56}\text{Mn}$, $^{65}\text{Cu}(\text{n},2\text{n})^{64}\text{Cu}$ and $^{93}\text{Nb}(\text{n},2\text{n})^{92m}\text{Nb}$ were taken from a recent careful evaluation performed by Ryves [14] at a neutron energy of 14.7 MeV. Ryves also gives the factors f_E (and their uncertainties) which account for the slope of the excitation function of the respective dosimetry reactions from 14.0 to 15.0 MeV neutron energy in steps of 0.1 MeV. In the case of the $^{93}\text{Nb}(\text{n},2\text{n})^{92m}\text{Nb}$ reaction the cross section remains constant

within 0.4% in the 13.4 - 15 MeV energy range [15]. The corresponding renormalizations were applied to the results reported by Nagel (1966) and Ikeda et al. (1988).

d. The data measured by Menlove et al. (1967) relative to the ^{235}U fission cross section at neutron energies between 13.28 MeV and 19.39 MeV were renormalized to the cross sections and uncertainties of this reference reaction recommended in the ENDF/B-VI file [16].

In three cases special corrections had to be applied instead of or in addition to the procedures specified above.

Pasquarelli 67: The systematic errors due to self-absorption and scattering in absolute beta-counting using fixed solid angle and rather thick samples are probably at least 5%; therefore the total error given in the paper appears to be unrealistic and was increased to 6%.

Bormann 67: Bormann reports mutually inconsistent results for measurements with two teflon-sample thicknesses. Only the results of the measurements with the thin sample which suffer less from scattering effects were used. In addition, the uncertainties given in that paper (only statistical) were increased by adding quadratically an assumed 3% error for scattering effects from the rather bulky target construction.

Araminowicz 73: In this work only statistical uncertainties are given. In order to obtain the total uncertainty an estimated 3% systematic error and the uncertainty of the reference cross section ($\pm 1\%$) were added quadratically.

Besides, seven relative excitation functions were renormalized by fitting the cross-section values to a preliminary evaluated excitation function for which only the absolute measurements were used, as described in detail in Ref. 9, Section II. The renormalization factors R and their uncertainties are listed in Table 2.1.2.

Table 2.1.2: Normalization factors R and their uncertainties ΔR used for the relative excitation functions.

	Reference	R	ΔR (%)
157	McCrory 60	0.693	2.00
318	Brill 61	0.573	4.82
304	Rayburn 62	0.749	2.88
306	Bormann 65	0.896	1.90
311	Bormann 67	0.407	0.78
325	Bormann 67	0.770	2.31
321	Vonach 68	49.765	1.54

The cross-section data from all accepted measurements, including those on which the former evaluation [2] was based, are listed in Table 2.1.3. For each data point the following quantities are given:

- the average neutron energy and the energy spread (half-width at half maximum) of the neutrons incident on the sample;
- the uncertainty of the average neutron energy;
- the cross-section values and uncertainties as given by the authors;
- an indication which renormalization procedures were applied to both the cross sections and their uncertainties according to the general rules stated in Ref. 9, Section II, and, finally,
- the renormalized cross sections and their errors.

For the experiments for which the energy spread and/or the uncertainty of the mean energy of the incident neutrons were not specified, these values were estimated according to the experimental conditions as described in the respective papers.

Figure 2.1.1. displays the renormalized cross sections of the works added to the previously existing data base together with the renormalized cross sections from the paper *Brill 61*. In the figure, these new values are compared with the cross sections obtained in the former evaluation [2].

In the energy region from the threshold to 12.6 MeV only one experimental data point is available. Therefore, the gap was filled by extrapolating the low-energy end of the evaluated excitation function according to theoretical considerations which indicate that the general shape of the ($n,2n$) excitation function near the threshold can be described very well by equation (1) (see Ref. 2):

$$\sigma(E) = \text{const} * (E - E_{\text{thresh}})^2 \quad (1)$$

By using this formula six additional data points, referenced Vonach 79, were added to the experimental data base, paying attention to a smooth continuation of the errors.

2.1.2. Evaluation and results thereof

The $^{19}\text{F}(n,2n)^{18}\text{F}$ excitation function was divided into 24 energy groups. From the threshold to 20 MeV the group structure given in Ref. 2 has been retained. As no strong cross-section fluctuations are evident for this reaction, the choice of the energy-group widths was governed mainly by the density of the available data points. Up to 12.4 MeV the sequence of the theoretically extrapolated data defines the group structure; in the 12.4 to 14.0 MeV region a width of 0.4 MeV was decided upon in order to ensure that each group contains the results of at least two independent measurements. Between 14.0 and 15.0 MeV sufficient data were reported so that a minimum width of 0.2 MeV could be chosen according to the neutron-energy spread given for the different experiments. Up to 20 MeV a group width of 1.0 MeV is considered to be adequate in view of the smooth course of the excitation function and the few data in some of the groups. The recent work by Hartmann and De Luca [7], finally, permitted to extend the range of this evaluation up to 28 MeV; yet the scarcity of the experimental data in that region established a group width of 2.0 MeV.

The results of the evaluation, i.e., the cross-section averages over the individual energy groups and their uncertainties, are listed in Table 2.1.4. The last column of the table gives the ratio of the external to the internal uncertainties of the recommended cross sections. This ratio is applicable for those groups only which contain data points from more than one experiment. The values $\Delta_{\text{ext}}/\Delta_{\text{int}}$ indicate an overall good consistency among different measurements; except for the energy group 13.20 - 13.60 MeV, where a ratio of 1.94 points to a scatter of the measured cross sections exceeding distinctly the uncertainties given in the individual works.

The evaluated cross sections can also be regarded as point cross sections at the centers of the single energy groups. Linear - linear interpolation is recommended to obtain the cross sections at intermediate energies.

In Figure 2.1.2 the results of the updated evaluation are compared with the previous ones. As evident from the figure, in the energy region from threshold to 20 MeV the new experimental data did not alter the status of the $^{19}\text{F}(\text{n},2\text{n})^{18}\text{F}$ cross section appreciably with regard to the absolute values; in some energy groups the uncertainties have been reduced so that an uncertainty of < 2.5% can be claimed in the 14 MeV region (from 13.60 to 15.0 MeV). In the 16 - 20 MeV range the small uncertainty of the evaluated cross sections (< 2%) is mainly due to the precision measurement carried out by Ryves (Ryves 78). The chief modification with respect to the former version concerns the extension of the evaluation beyond 20 MeV. Yet, additional measurements in that high-energy range would be desirable in order to confirm the cross sections recommended for this region.

In order to check the evaluated excitation function in the range from the threshold to 20 MeV, a fission-spectrum average, $\langle \sigma \rangle$, in the neutron spectrum of ^{252}Cf was calculated. For this purpose, the Cf neutron spectrum evaluated by Mannhart [17] was used. The calculated spectrum-averaged cross section $\langle \sigma \rangle_{\text{calc}}$ is $(1.728 \pm 0.086) \times 10^{-2}$ mb; the uncertainty comprises the uncertainties both of the ^{252}Cf spectrum and of the evaluated cross sections taking into account the relative correlations between the data for the different energy groups as given in the following section. The comparison to a recommended experimental $\langle \sigma \rangle$ value, $\langle \sigma \rangle = (1.628 \pm 0.054) \times 10^{-2}$ mb [18], shows that the calculated result, though being higher than the experimental one, still agrees with it within the combined uncertainty limits.

Table 2.1.1: Summary of experiments for the reaction $^{19}\text{F}(\text{n},2\text{n})^{18}\text{F}$.

ENERGY-RANGE [MEV]	NR.OF DATA POINTS	AVERAGE ACCUR %	METHOD	FLUX, REF CROSS SECTION	REF	NR.
14.50	14.50	1	30. ACT, PROP.C., BETA+	LONG C., CAL.BY ASSOC.ALPH.PART.	PAUL 53	12
14.10	14.10	1	15. DETECT.OF NEUTRON COINCID.		ASHBY 58	302
13.20	15.34	8	10. ACT, NAI-WELL, GAM	NO INF., TREATED AS RELATIVE	MC CRARY 60	157
11.60	34.00	11	6-35 ACT, GM, BETA+	NO INF., TREATED AS RELATIVE	BRILL 61	318
14.40	14.40	1	7.5 ACT-511 KEV GAM. COINCID.	63CU(N,2N):503 MB +- 7.3%	RAYBURN 61	112
12.25	21.00	8	ACT, NAI, GAM	PROTON RECOIL TELESCOPE	WILLIAMSON 61	327
14.10	14.10	1	6. ACT, 2*NAI, GAM. COINCID.	ASSOC. ALPHA PART.	CEVOLANI 62	169
12.60	17.90	10	9.5 ACT, 511 KEV GAM.COINCID.	REL. EXCIT. FUNCTION	RAYBURN 62	304
12.25	21.00	15	ACT, NAI, 511 KEV GAM.	PROTON RECOIL TELESCOPE	PICARD 63	322
13.90	14.80	27	ACT, NAI, 511 KEV GAM.	REL. EXCIT. FUNCTION	STROHAL 64	308
12.60	19.60	9	8.6 ACT, NAI-WELL, GAM	REL. EXCIT. FUNCTION	BORMANN 65	306
14.10	14.10	1	2.7 ACT, NAI-WELL, GAM	N-P SCATT., STILBENE CRYSTAL	BORMANN 65	301
13.56	14.71	24	ACT, NAI-WELL, GAM	REL. EXCIT. FUNCTION	CSIKAI 65	177
14.60	14.60	1	7.7 ACT, NAI-WELL, GAM	63CU(N,2N)62CU: 541 MB	CSIKAI 65	454
14.20	14.20	1	ACT, NAI, GAM	65CU(N,2N)920MB AND 56FE(N,P)118MB	NAGEL 65	309
12.30	20.90	15	ACT, NAI, GAM	REL. EXCIT. FUNCTION	PICARD 65	307
14.20	14.40	2	14 ACT. NAI, GAM	65CU(N,2N):945 MB AT 14.2 MEV	NAGEL 66	324
14.20	14.40	2	15 ACT, NAI, GAM	56FE(N,P):109 MB AT 14.2 MEV	NAGEL 66	323
16.70	17.80	38	3.2 ACT, NAI, GAM	REL. EXCIT. FUNCTION	BORMANN 67	325
13.50	15.00	21	3.2 ACT, NAI, GAM	REL. EXCIT. FUNCTION	BORMANN 67	311
13.99	13.99	1	15 ACT, NAI, GAM	63CU(N,2N):488 MB AT 14.1 MEV	CSIKAI 67	176

Table 2.1.1: Summary of experiments for the reaction $^{19}\text{F}(\text{n},2\text{n})^{18}\text{F}$ (continued).

ENERGY-RANGE [MEV]	NR. OF DATA POINTS	AVERAGE ACCUR %	METHOD	FLUX, REF CROSS SECTION	REF	NR.	
12.70	19.40	10	7.5	ACT, NAI, GAM	235U(N,FISS) AND 27AL(N,A)	MENLOVE 67	312
14.70	14.70	1	6	ACT, GM, BETA+	ASSOC. ALPHA PART.	PASQUARELLI 67	15
13.50	14.80	5		ACT, NAI-WELL,GAM	63CU(N,2N) FROM REF. 181	SHIOKAWA 68	313
14.70	14.70	1	2.2	ACT, NAI-WELL, GAM	27AL(N,A)24NA: 111.5 MB	VONACH 68	319
13.60	14.60	6	1.6	ACT, NAI-WELL, GAM	REL. EXCIT. FUNCTION	VONACH 68	321
14.60	14.60	1	8.5	ACT, NAI, GAM	27AL(N,A)24NA: 120.7 MB	BARRALL 69A	13
14.20	14.78	3	10	ACT, NAI, GAM. COINCID.	63CU(N,2N)62CU	CHATTERJEE 69	317
14.70	14.70	1	4.5	ACT, NAI, GAM	ASSOC. ALPHA PART.	CRUMPTON 69	167
14.10	14.10	1	2.2	ACT, PROP. COUNT., BETA+	27AL(N,A)24NA:120.4 MB	MOGHARRAB 72	159
14.60	14.60	1	9	ACT, NAI, GAM	63CU(N,2N)62CU:538 MB	ARAMINOWICZ 73	123
14.80	14.80	1	1.5	ACT, 4PI BETA-GAM COINCID.	56FE(N,P), OWN ABS. MEASUREMENT	ROBERTSON 73	16
14.60	14.60	1	6.5	ACT, GE(LI), GAM	27AL(N,A): 114.2 MB +-1.2%	SIGG 76	461
14.65	19.00	6	1.7	ACT, BETA-GAM. COINCID.	56FE(N,P) OWN ABS. MEASUREMENT	RYVES 78	326
11.20	12.30	6		THEORET. EXTRAPOL.	NOT APPLICABLE	VONACH 79	328
14.70	14.70	1	4.0	ACT, 19F IN PLASTIC SCINT.	ASSOC. ALPHA PART.	VICTOROV 83	329
14.70	14.70	1	7.5	ACT, 19F IN PLASTIC SCINT.	63CU(N,2N)62CU: 558 MB	VICTOROV 83	330
13.36	14.96	8	5	ACT, GE, GAM	93NB(N,2N)92MNB: 464 MB	IKEDA 88	137
14.05	14.05	1	4.1	ACT, GE(LI), GAM	27AL(N,A)24NA	KOBAYASHI 88	24
18.10	21.00	2	6-10	ACT, GE(LI), GAM	197AU(N,2N)196AU	HARTMANN 91	331
18.10	27.00	5	5 - 9	ACT, GE(LI), GAM	NAT.ZR(N,XN)89ZR	HARTMANN 91	332

Table 2.1.3: Cross section data for the reaction $^{19}\text{F}(\text{n},2\text{n})^{18}\text{F}$.

NR.	E-NEUTR	WIDTH	ERR.CENTR.	X-SECT(ORIG)	ERR(ORIG)	CORR.APPL.	X-SECT(FIN)	ERR(FIN)	REF
	[MEV]	[MEV]	[MEV]	[MB]	[MB]		[MB]	[MB]	
1	11.20	0.010	0.010	0.198	0.024	8)	0.198	0.024	VONACH 79
2	11.50	0.010	0.010	1.256	0.150	8)	1.256	0.150	VONACH 79
3	11.60	0.300	0.100	1.000	2.000	7)	0.573	1.147	BRILL 61
4	11.70	0.010	0.010	2.465	0.292	8)	2.465	0.292	VONACH 79
5	11.90	0.010	0.010	4.076	0.490	8)	4.076	0.490	VONACH 79
6	12.10	0.010	0.010	6.091	0.727	8)	6.091	0.727	VONACH 79
7	12.30	0.010	0.010	8.500	1.019	8)	8.500	1.019	VONACH 79
8	12.60	0.150	0.020	18.000	2.000	3)7)	13.333	1.546	RAYBURN 62
9	12.60	0.200	0.020	13.400	1.200	5)7)	12.007	0.503	BORMANN 65
10	12.70	0.360	0.040	16.300	1.600	6)	15.600	1.563	MENLOVE 67
11	12.94	0.680	0.070	22.800	2.300	6)	21.960	2.282	MENLOVE 67
12	13.00	0.150	0.020	25.000	3.000	3)7)	18.576	2.310	RAYBURN 62
13	13.20	0.200	0.020	25.700	2.200	5)7)	23.028	0.878	BORMANN 65
14	13.20	0.300	0.060	38.700	3.900	7)	26.819	2.755	MC CRARY 60
15	13.28	0.610	0.060	26.400	2.600	6)	26.300	1.837	MENLOVE 67
16	13.36	0.180	0.020	25.500	1.400	6)	25.200	1.200	IKEDA 88
17	13.40	0.150	0.020	37.000	4.000	3)7)	27.414	3.098	RAYBURN 62
18	13.50	0.470	0.050	30.500	3.700	6)	30.350	3.022	MENLOVE 67
19	13.52	0.075	0.010	81.300	0.800	6)7)	33.120	1.078	BORMANN 67
20	13.58	0.075	0.010	85.000	0.900	6)7)	34.628	1.129	BORMANN 67
21	13.58	0.150	0.015	27.000	1.400	6)	26.730	1.170	IKEDA 88
22	13.59	0.300	0.060	46.000	4.600	7)	31.878	3.251	MC CRARY 60
23	13.60	0.075	0.010	0.613	0.006	5)7)	30.657	0.495	VONACH 68
24	13.66	0.075	0.010	87.800	0.900	6)7)	35.768	1.162	BORMANN 67
25	13.74	0.075	0.010	87.500	0.900	6)7)	35.646	1.162	BORMANN 67
26	13.76	0.150	0.015	33.300	1.800	6)	32.980	1.527	IKEDA 88
27	13.80	0.075	0.010	0.683	0.007	5)7)	34.140	0.562	VONACH 68
28	13.82	0.075	0.010	90.300	0.900	6)7)	36.787	1.196	BORMANN 67
29	13.85	0.300	0.060	49.800	5.000	7)	34.511	3.533	MC CRARY 60
30	13.91	0.075	0.010	92.200	0.900	6)7)	37.561	1.221	BORMANN 67
31	13.99	0.100	0.015	35.800	1.900	6)	35.480	1.602	IKEDA 88
32	14.00	0.300	0.030	63.000	9.400	9)	58.840	8.870	CSIKAI 67
33	14.00	0.150	0.020	56.000	5.000	3)7)	41.496	3.931	RAYBURN 62
34	14.00	0.075	0.010	0.754	0.008	5)7)	37.674	0.613	VONACH 68
35	14.00	0.075	0.010	95.200	1.000	6)7)	38.783	1.263	BORMANN 67
36	14.05	0.800	0.070	41.590	1.700	NONE	41.590	1.700	KOBAYASHI 88
37	14.09	0.075	0.010	99.800	1.000	6)7)	40.657	1.322	BORMANN 67
38	14.10	0.300	0.030	41.200	2.200	5)	41.200	1.100	BORMANN 65
39	14.10	0.070	0.010	62.000	9.000	NONE	62.000	9.000	ASHBY 58
40	14.10	0.100	0.020	38.900	2.300	NONE	38.900	2.300	CEVOLANI 62
41	14.10	0.200	0.020	41.800	0.900	9)	42.340	0.930	MOGHARRAB 72
42	14.14	0.300	0.060	56.400	5.600	7)	39.085	3.959	MC CRARY 60
43	14.18	0.075	0.010	101.700	1.000	6)7)	41.431	1.347	BORMANN 67
44	14.20	0.200	0.020	40.100	5.300	6)	41.892	5.205	NAGEL 66
45	14.20	0.200	0.020	46.500	5.900	6)	45.020	5.413	NAGEL 66
46	14.20	0.100	0.020	52.000	5.200	9)	44.800	4.500	CHATTERJEE 69
47	14.20	0.300	0.100	72.000	4.000	7)	41.263	3.037	BRILL 61
48	14.20	0.075	0.010	0.824	0.008	5)7)	41.207	0.665	VONACH 68
49	14.23	0.180	0.018	40.200	2.200	6)	39.850	1.876	IKEDA 88
50	14.25	0.150	0.020	66.000	6.000	3)7)	48.912	4.710	RAYBURN 62
51	14.28	0.075	0.010	105.600	1.100	6)7)	43.020	1.401	BORMANN 67
52	14.37	0.075	0.010	108.700	1.100	6)7)	44.283	1.439	BORMANN 67
53	14.40	0.200	0.020	44.000	7.500	6)	45.966	7.552	NAGEL 66

Table 2.1.3: Cross section data for the reaction $^{19}\text{F}(\text{n},2\text{n})^{18}\text{F}$ (continued).

NR.	E-NEUTR	WIDTH	ERR.CENTR	X-SECT(ORIG)	ERR(ORIG)	CORR.APPL.	X-SECT(FIN)	ERR(FIN)	REF
	[MEV]	[MEV]	[MEV]	[MB]	[MB]		[MB]	[MB]	
54	14.40	0.200	0.020	50.000	7.800	6)	48.410	7.288	NAGEL 66
55	14.40	0.075	0.010	0.894	0.009	5)7)	44.691	0.732	VONACH 68
56	14.40	0.300	0.030	51.900	3.840	9)	51.250	3.850	RAYBURN 61
57	14.43	0.300	0.060	61.300	6.100	7)	42.481	4.312	MC CRARY 60
58	14.45	0.200	0.020	45.300	2.400	6)	44.910	2.020	IKEDA 88
59	14.46	0.075	0.010	111.200	1.100	6)7)	45.301	1.473	BORMANN 67
60	14.50	0.350	0.035	60.600	18.200	NONE	60.600	18.200	PAUL 53
61	14.50	0.100	0.020	55.500	5.500	9)	50.600	5.100	CHATTERJEE 69
62	14.54	0.075	0.010	113.000	1.100	6)7)	46.034	1.498	BORMANN 67
63	14.60	0.075	0.010	0.965	0.010	5)7)	48.225	0.783	VONACH 68
64	14.60	0.100	0.020	53.000	4.000	2)9)	51.730	3.950	CSIKAI 65
65	14.60	0.200	0.020	47.000	4.000	2)9)	44.434	3.788	BARRALL 69A
66	14.60	0.380	0.040	40.700	3.500	6)9)	39.943	3.661	ARAMINOWICZ 73
67	14.60	0.200	0.020	48.200	3.200	9)	48.160	3.200	SIGG 76
68	14.63	0.075	0.010	115.600	1.200	6)7)	47.094	1.532	BORMANN 67
69	14.65	0.100	0.040	46.900	1.600	5)	46.900	0.800	RYVES 78
70	14.69	0.220	0.022	50.400	2.700	6)	49.970	2.285	IKEDA 88
71	14.70	0.300	0.100	41.000	1.500	6)	41.000	2.500	PASQUARELLI 67
72	14.70	0.200	0.020	55.000	2.500	NONE	55.000	2.500	CRUMPTON 69
73	14.70	0.075	0.010	45.400	2.200	5)9)	45.807	1.110	VONACH 68
74	14.70	0.075	0.010	118.100	1.200	6)7)	48.112	1.565	BORMANN 67
75	14.70	0.100	0.020	50.400	2.000	NONE	50.400	2.000	VICTOROV 83
76	14.70	0.100	0.020	52.450	4.010	9)	51.000	3.802	VICTOROV 83
77	14.71	0.300	0.060	68.400	6.800	7)	47.401	4.807	MC CRARY 60
78	14.77	0.075	0.010	118.300	1.200	6)7)	48.193	1.569	BORMANN 67
79	14.78	0.100	0.010	47.900	1.400	5)	47.900	0.700	ROBERTSON 73
80	14.80	0.100	0.020	55.500	5.500	9)	53.600	5.400	CHATTERJEE 69
81	14.83	0.075	0.010	119.500	1.200	6)7)	48.682	1.586	BORMANN 67
82	14.88	0.075	0.010	122.300	1.200	6)7)	49.823	1.620	BORMANN 67
83	14.92	0.075	0.010	122.000	1.200	6)7)	49.701	1.620	BORMANN 67
84	14.95	0.075	0.010	122.000	1.200	6)7)	49.701	1.620	BORMANN 67
85	14.95	0.300	0.060	75.100	7.500	7)	52.044	5.301	MC CRARY 60
86	14.96	0.870	0.090	60.800	6.000	6)	56.420	3.965	MENLOVE 67
87	14.96	0.250	0.025	51.800	2.800	6)	51.350	2.380	IKEDA 88
88	14.99	0.075	0.010	121.800	1.200	6)7)	49.619	1.615	BORMANN 67
89	15.15	0.150	0.020	73.000	6.000	3)7)	54.155	4.757	RAYBURN 62
90	15.20	0.300	0.030	60.200	5.200	5)7)	53.940	2.064	BORMANN 65
91	15.34	0.300	0.060	82.900	8.300	7)	57.450	5.866	MC CRARY 60
92	15.82	0.450	0.050	71.400	7.000	6)	64.015	4.450	MENLOVE 67
93	15.90	0.150	0.020	89.000	7.000	3)7)	65.989	5.577	RAYBURN 62
94	16.00	0.300	0.100	113.000	7.000	7)	64.760	5.084	BRILL 61
95	16.00	0.300	0.030	68.700	5.900	5)7)	61.556	2.370	BORMANN 65
96	16.06	0.300	0.050	64.600	2.100	5)	64.600	1.050	RYVES 78
97	16.51	0.250	0.050	69.200	2.200	5)	69.200	1.100	RYVES 78
98	16.52	0.350	0.040	78.900	7.700	6)	69.298	4.785	MENLOVE 67
99	16.67	0.025	0.010	92.700	0.900	6)7)	71.286	2.791	BORMANN 67
100	16.70	0.150	0.020	98.000	8.000	3)7)	72.656	6.347	RAYBURN 62
101	16.71	0.025	0.010	94.500	0.900	6)7)	72.671	2.847	BORMANN 67
102	16.74	0.025	0.010	97.200	1.000	6)7)	74.747	2.925	BORMANN 67
103	16.77	0.025	0.010	95.500	1.000	6)7)	73.440	2.876	BORMANN 67
104	16.80	0.025	0.010	94.200	0.900	6)7)	72.440	2.838	BORMANN 67
105	16.84	0.025	0.010	95.200	1.000	6)7)	73.209	2.867	BORMANN 67

Table 2.1.3: Cross section data for the reaction $^{19}\text{F}(\text{n},2\text{n})^{18}\text{F}$ (continued).

NR.	E-NEUTR [MEV]	WIDTH [MEV]	ERR.CENTR [MEV]	X-SECT(ORIG) [MB]	ERR(ORIG) [MB]	CORR.APPL. 6)7)	X-SECT(FIN) [MB]	ERR(FIN) [MB]	REF
106	16.87	0.025	0.010	96.100	1.000	6)7)	73.901	2.895	BORMANN 67
107	16.91	0.025	0.010	95.800	1.000	6)7)	73.670	2.885	BORMANN 67
108	16.94	0.025	0.010	96.300	1.000	6)7)	74.055	2.897	BORMANN 67
109	16.97	0.025	0.010	97.200	1.000	6)7)	74.747	2.925	BORMANN 67
110	17.00	0.025	0.010	94.800	1.000	6)7)	72.901	2.856	BORMANN 67
111	17.03	0.025	0.010	95.200	1.000	6)7)	73.209	2.867	BORMANN 67
112	17.06	0.025	0.010	96.000	1.000	6)7)	73.824	2.887	BORMANN 67
113	17.09	0.025	0.010	97.700	1.000	6)7)	75.131	2.943	BORMANN 67
114	17.10	0.300	0.030	78.800	6.800	5)7)	70.606	2.766	BORMANN 65
115	17.12	0.025	0.010	98.600	1.000	6)7)	75.823	2.971	BORMANN 67
116	17.15	0.025	0.010	96.300	1.000	6)7)	74.055	2.897	BORMANN 67
117	17.18	0.025	0.010	97.000	1.000	6)7)	74.593	2.923	BORMANN 67
118	17.21	0.025	0.010	97.700	1.000	6)7)	75.131	2.943	BORMANN 67
119	17.24	0.025	0.010	98.000	1.000	6)7)	75.362	2.952	BORMANN 67
120	17.25	0.150	0.020	92.000	8.000	3)7)	68.237	6.306	RAYBURN 62
121	17.27	0.025	0.010	97.000	1.000	6)7)	74.593	2.923	BORMANN 67
122	17.30	0.025	0.010	97.000	1.000	6)7)	74.593	2.923	BORMANN 67
123	17.32	0.025	0.010	96.700	1.000	6)7)	74.362	2.913	BORMANN 67
124	17.35	0.200	0.050	76.000	2.500	5)	76.000	1.250	RYVES 78
125	17.35	0.320	0.040	90.500	9.500	6)	79.404	6.297	MENLOVE 67
126	17.35	0.025	0.010	96.500	1.000	6)7)	74.209	2.905	BORMANN 67
127	17.37	0.025	0.010	97.800	1.000	6)7)	75.208	2.944	BORMANN 67
128	17.43	0.025	0.010	97.500	1.000	6)7)	74.978	2.934	BORMANN 67
129	17.46	0.025	0.010	99.700	1.000	6)7)	76.669	3.001	BORMANN 67
130	17.49	0.025	0.010	98.600	1.000	6)7)	75.823	2.971	BORMANN 67
131	17.51	0.025	0.010	98.500	1.000	6)7)	75.747	2.963	BORMANN 67
132	17.54	0.025	0.010	99.700	1.000	6)7)	76.669	3.001	BORMANN 67
133	17.56	0.025	0.010	99.000	1.000	6)7)	76.131	2.981	BORMANN 67
134	17.59	0.025	0.010	97.700	1.000	6)7)	75.130	2.940	BORMANN 67
135	17.61	0.025	0.010	98.900	1.000	6)7)	76.054	2.980	BORMANN 67
136	17.63	0.025	0.010	99.500	1.000	6)7)	76.516	2.992	BORMANN 67
137	17.65	0.025	0.010	100.200	1.000	6)7)	77.054	3.018	BORMANN 67
138	17.68	0.025	0.010	99.800	1.000	6)7)	76.746	3.002	BORMANN 67
139	17.70	0.025	0.010	97.000	1.000	6)7)	74.593	2.923	BORMANN 67
140	17.72	0.025	0.010	96.300	1.000	6)7)	74.055	2.897	BORMANN 67
141	17.75	0.025	0.010	98.700	1.000	6)7)	75.900	2.972	BORMANN 67
142	17.80	0.300	0.100	145.000	15.000	7)	83.100	9.481	BRILL 61
143	17.80	0.300	0.030	86.500	7.400	5)7)	77.505	2.987	BORMANN 65
144	17.90	0.150	0.020	102.000	9.000	3)7)	75.652	7.085	RAYBURN 62
145	18.06	0.190	0.050	81.500	2.500	5)	81.500	1.250	RYVES 78
146	18.10	0.200	0.025	85.500	4.400	9)	80.580	4.600	HARTMANN 91
147	18.10	0.200	0.025	80.800	4.200	NONE	80.800	4.200	HARTMANN 91
148	18.44	0.330	0.040	90.200	9.000	6)	80.940	5.843	MENLOVE 67
149	18.50	0.300	0.030	94.500	8.100	5)7)	84.673	3.288	BORMANN 65
150	19.00	0.190	0.050	82.800	4.000	5)	82.800	2.000	RYVES 78
151	19.10	0.200	0.030	97.700	8.400	5)7)	87.540	3.471	BORMANN 65
152	19.39	0.350	0.040	85.400	8.400	6)	78.244	5.533	MENLOVE 67
153	19.60	0.100	0.030	91.900	7.900	5)7)	82.344	3.188	BORMANN 65
154	19.70	0.300	0.100	148.000	9.000	7)	84.819	6.581	BRILL 61
155	21.00	0.100	0.020	88.700	9.300	9)	82.500	8.300	HARTMANN 91
156	21.00	0.100	0.020	82.600	4.500	NONE	82.600	4.500	HARTMANN 91
157	21.40	0.300	0.100	119.000	9.000	7)	68.199	6.115	BRILL 61
158	22.00	0.300	0.100	130.000	25.000	7)	74.503	14.771	BRILL 61

Table 2.1.3: Cross section data for the reaction $^{19}\text{F}(\text{n},2\text{n})^{18}\text{F}$ (continued).

NR.	E-NEUTR [MEV]	WIDTH [MEV]	ERR.CENTR [MEV]	X-SECT(ORIG) [MB]	ERR(ORIG) [MB]	CORR.APPL.	X-SECT(FIN) [MB]	ERR(FIN) [MB]	REF
159	23.00	0.100	0.020	72.700	4.200	NONE	72.700	4.200	HARTMANN 91
160	25.00	0.300	0.100	112.000	15.000	7)	64.187	9.135	BRILL 61
161	25.00	0.100	0.020	57.200	2.900	NONE	57.200	2.900	HARTMANN 91
162	27.00	0.100	0.020	51.400	4.700	NONE	51.400	4.700	HARTMANN 91
163	27.60	0.300	0.100	84.000	31.000	7)	48.140	17.916	BRILL 61
164	30.50	0.300	0.100	80.000	24.000	7)	45.848	13.931	BRILL 61

CORRECTION CODES:

- 1) CROSS-SECTION RENORMALIZED TO PRESENT DECAY DATA (HALF-LIFE, BRANCHING RATIOS ETC.)
- 2) ERROR GIVEN IN PUBLICATION DID NOT INCLUDE ERROR OF REFERENCE CROSS-SECTION.
- 3) CROSS-SECTION RENORMALIZED TO ENDF/B-V VALUES OF REFERENCE CROSS-SECTION USED IN MEASUREMENT.
ERRORS TAKEN FROM THE ASSOCIATED FILE 33 INCLUDED IN FINAL ERROR.
- 4) CROSS-SECTION RENORMALIZED TO ANGULAR DISTRIBUTION OF SOURCE NEUTRONS OF LISKIEN AND PAULSEN.
- 5) ERROR HAS BEEN REDUCED BY A FACTOR TWO OR THREE IN ORDER TO REPRESENT 1 STANDARD DEVIATION.
- 6) SPECIAL CORRECTION. SEE TEXT FOR DETAILS.
- 7) CROSS-SECTION FROM MEASURED RELATIVE EXCIT. FN., NORMALIZED TO PRESENT EVALUATION.
- 8) CROSS-SECTION FROM THEORETICAL CALCULATION, NORMALIZED TO PRESENT EVALUATION.
- 9) RENORMALIZATION USING REF.CROSS-SECTION EVALUATED AT IRK, SEE PHYSICS DATA 13-5.

Table 2.1.4: Evaluated group cross sections for the reaction $^{19}\text{F}(\text{n},2\text{n})^{18}\text{F}$.

Energy Group [MeV] to [MeV]	Cross Section [mb]	Error [mb]	Error [%]	Ratio $\Delta_{\text{ext}}/\Delta_{\text{int}}$
11.00	11.40	0.20	0.04	21.5
11.40	11.60	1.26	0.16	12.7
11.60	11.80	2.41	0.30	12.6
11.80	12.00	4.08	0.50	12.3
12.00	12.20	6.09	0.74	12.1
12.20	12.40	8.50	1.03	12.1
12.40	12.80	12.30	0.50	4.1
12.80	13.20	20.47	2.33	11.4
13.20	13.60	27.59	1.16	4.2
13.60	14.00	34.59	0.65	1.9
14.00	14.20	40.75	0.64	1.6
14.20	14.40	42.67	0.57	1.3
14.40	14.60	46.28	0.63	1.4
14.60	14.80	47.76	0.57	1.2
14.80	15.00	50.72	1.20	2.4
15.00	16.00	58.01	1.75	3.0
16.00	17.00	68.55	0.95	1.4
17.00	18.00	77.05	1.17	1.5
18.00	19.00	82.99	1.12	1.4
19.00	20.00	82.93	1.59	1.9
20.00	22.00	78.71	4.29	5.4
22.00	24.00	72.61	4.03	5.5
24.00	26.00	57.84	2.76	4.8
26.00	28.00	51.20	4.55	8.9
				0.172

*) not applicable (see text)

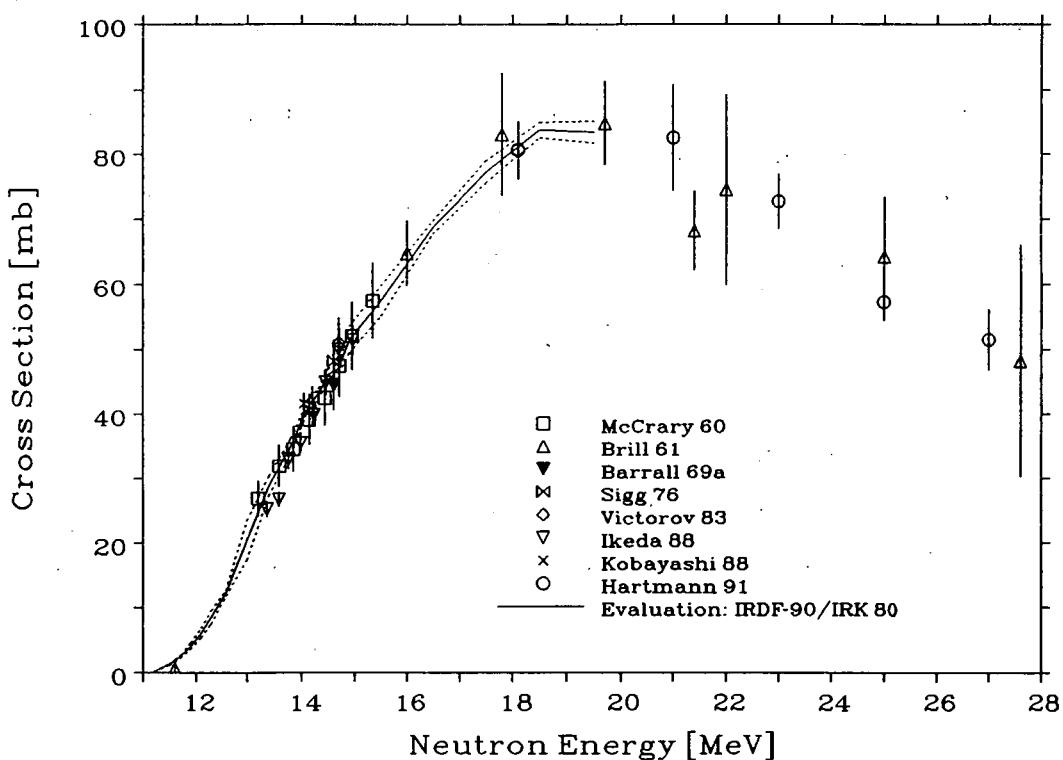


Figure 2.1.1: Recent experimental cross-section data for the reaction $^{19}\text{F}(\text{n},2\text{n})^{18}\text{F}$ compared with the results of the previous evaluation carried out at the IRK [1, 2]. (The figure displays the renormalized cross sections and their effective 1σ uncertainties. This applies also to the experimental data shown in all the following figures.)

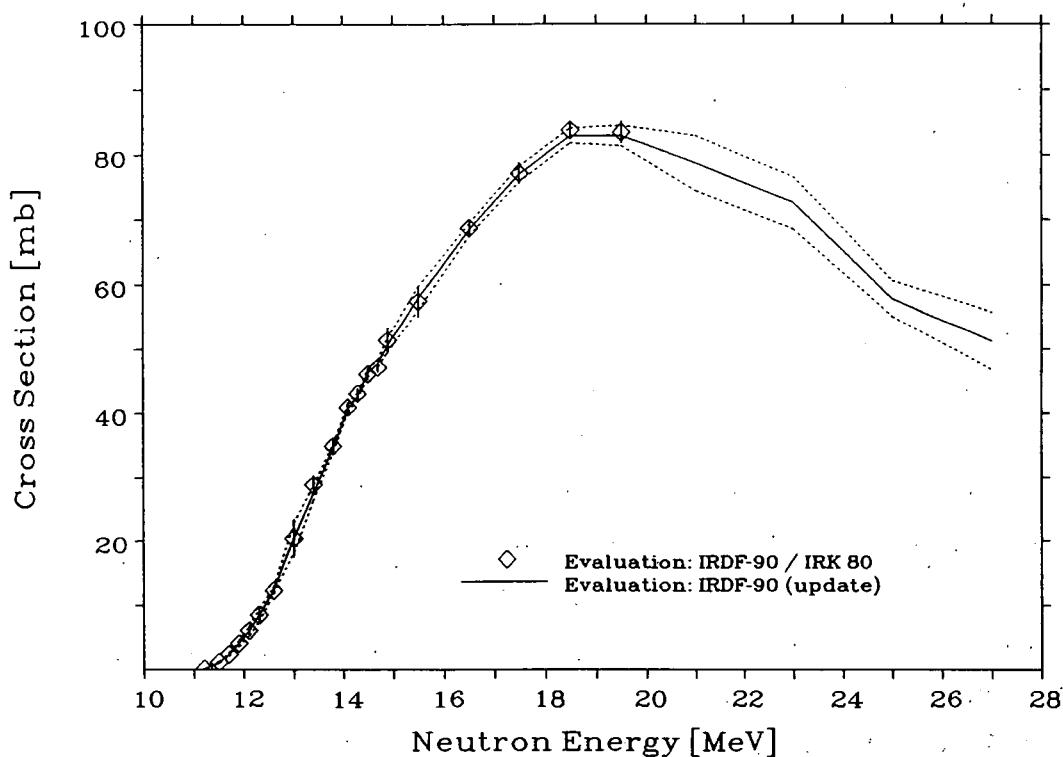


Figure 2.1.2: Results of the present evaluation of the cross section for the $^{19}\text{F}(\text{n},2\text{n})^{18}\text{F}$ reaction compared to the former evaluation reported in Ref. 2.

References of the experimental data base for the reaction $^{19}\text{F}(\text{n},2\text{n})^{18}\text{F}$

- Araminowicz* 73: J. Araminowicz and J. Dresler, Report INR-1464/I/A, 14, Institute of Nuclear Research, Warsaw (1973).
- Ashby* 58: V.J. Ashby, H.C. Catron and L.L. Newkirk, Phys. Rev. **111**, 616 (1958).
- Barrall* 69A: R.C. Barrall, J.A. Holmes and M. Silbergeld, Report AFWL-TR-68, 134, Air Force Weapons Lab., Kirtland (1969).
- Brill* 61: O.D. Brill et al., Soviet Phys. Doklady **6**, 24 (1961).
- Bormann* 65: M. Bormann et al., Nucl. Phys. **63**, 438 (1965).
- Bormann* 67: M. Bormann and I. Riehle, Z. Physik **207**, 64 (1967).
- Cevolani* 62: M. Cevolani and S. Petralia, Nuovo Cim. **26**, 1328 (1962).
- Chatterjee* 69: A. Chatterjee, A. Nath and A.M. Ghose, Nucl. Phys. and Solid State Phys. Symposium, Roorke (India), 1969, vol. 2, p. 117 (1969).
- Crumpton* 69: D. Crumpton, J. Inorg. Nucl. Chem. **31**, 3727 (1969), and D. Crumpton et al., J. Inorg. Nucl. Chem. **31**, 1 (1969).
- Csikai* 65: J. Csikai, Report EANDC-50 S, 2 (1965), and Atomki Közlemenek **8**, 79 (1966).
- Csikai* 67: J. Csikai and G. Petö, Acta Phys. Hungarica **23**, 87 (1967).
- Hartmann* 91: C.L. Hartmann and P.M. De Luca Jr., Nucl. Sci. Eng. (1991), in press.
- Ikeda* 88: Y. Ikeda et al., Report JAERI-1312, Japan Atomic Energy Research Institute, Tokai-mura (1988).
- Kobayashi* 88: K. Kobayashi and I. Kimura, *Nuclear Data for Science and Technology*, Proc. Int. Conf. Mito, Japan, May 30 - June 3, 1988, 261; S. Igarasi ed., Saikon Publ. Comp., Tokyo (1988).
- McCravy* 60: J.H. McCrary and I.L. Morgan, Bull. Amer. Phys. Soc. **5**, 246 (1960), and Report AFSWC-TR-30, (1960).
- Menlove* 67: H.O. Menlove et al., Phys. Rev. **163**, 1308 (1967).
- Mogharab* 72: R. Mogharab and H. Neuert, Atomkernenergie **19**, 107 (1972).
- Nagel* 65: W. Nagel and A.H.W. Aten jr., Physica **31**, 1091 (1965).
- Nagel* 66: W. Nagel, Thesis, Univ. of Amsterdam (1966).
- Pasquarelli* 67: A. Pasquarelli, Nucl. Phys. **A93**, 218 (1967).
- Paul* 53: E.B. Paul and R.L. Clarke, Can. J. Phys. **31**, 267 (1953).
- Picard* 63: J. Picard and C. Williamson, J. Phys. Rad. **24**, 813 (1963).
- Picard* 65: J. Picard and C.F. Williamson, Nucl. Phys. **63**, 673 (1965).
- Rayburn* 61: L.A. Rayburn, Phys. Rev. **122**, 168 (1961).
- Rayburn* 62: L.A. Rayburn, Proc. Conf. on Direct Interactions and Nuclear Reaction Mechanisms, Padua 1962, p.322 (1962).
- Robertson* 73: J.C. Robertson, B. Audric and P. Kolkowski, J. Nucl. Energy **27**, 531 (1973).
- Ryves* 78: T.B. Ryves, P. Kolkowski and J. Zieba, J. Phys. G (Nucl. Phys.) **4**, 1783 (1978).

- Shiokawa 68:* T. Shiokawa et al., J. Inorg. Nucl. Chem. **30**, 1 (1968).
- Sigg 76:* R.A. Sigg, Thesis, Univ. of Arkansas (1976), (Diss. Abstracts B, **37**, 2237).
- Strohal 64:* P. Strohal et al., Phys. Lett **10**, 104 (1964).
- Victorov 83:* D.V. Victorov et al., Atomnaya Energiya **54**, 58 (1983).
- Vonach 68:* H.K. Vonach et al., Proc. Conf. on Neutron Cross Sections and Technology, Washington, March 1968, NBS Special Publication 299, vol. 2, p. 885 (1968).
- Vonach 79:* H. Vonach in: Physics Data **13-2**, 12, Fachinformationszentrum Karlsruhe (1980).
- Williamson 61:* C. Williamson and J. Picard, J. Phys. Rad. **22**, 651 (1961).

2.2. The reaction $^{93}\text{Nb}(\text{n},2\text{n})^{92\text{m}}\text{Nb}$

2.2.1. Experimental data base

In the evaluation of the excitation function for this reaction the concept adopted already for the previous version, as presented in Ref. 1, Sections 3.3.1. and 3.3.2., was retained, i.e., the evaluated cross section reported at 14.7 MeV by Ryves [14] was accepted as the weighted average of all absolute measurements in the 13.4 to 15.0 MeV energy region. The precise relative measurement carried out by Csikai (*Csikai 87*) was then used to define the shape of the excitation function in this energy range. Accordingly, apart from the two references mentioned, the data base was restricted to measurements outside this energy region. In addition to the experiments quoted in Ref. 1 the measurements reported by Santry and Werner (*Santry 90*), by Ikeda et al. (*Ikeda 91*) and by the NEANDC Working Group on Activation Cross Sections (*Mannhart 91* and *Smith 91*) were considered. The deadline for the data retrieval was June 1991.

The most important information on these four recent experiments together with a short representation of the 12 papers quoted already for the previous evaluation [1] is summarized in Table 2.2.1, as described in the preceding section. In column 7 either the name of the first author or - in the case of the NEANDC Working Group - the leader of the experimental team is given. The relevant decay data for $^{92\text{m}}\text{Nb}$ were taken from Ref. 19.

The work *Santry 90* was split into two parts since the authors applied two different methods of neutron fluence measurement for different portions of the $^{93}\text{Nb}(\text{n},2\text{n})^{92\text{m}}\text{Nb}$ excitation function: In the energy range 9.02 MeV to 13.89 MeV they employed the $\text{D}(\text{d},\text{n})^3\text{He}$ source reaction and measured the neutron fluence at the position of the Nb sample by means of the ^{32}P activity induced in a sulphur sample via the reaction $^{32}\text{S}(\text{n},\text{p})^{32}\text{P}$; its cross section was taken from Ref. 20. Rather than referring to the $^{32}\text{S}(\text{n},\text{p})^{32}\text{P}$ reaction cross sections as recommended in the ENDF/B-V dosimetry file [21] for neutron energies from 9 MeV to 13.89 MeV, the values given by Santry and Butler [20] were retained for the reasons discussed in Ref. 1, Section 2.1.1. Since the uncertainty of the reference cross section is not included in the errors given, an uncertainty of $\pm 5\%$

was added quadratically in order to obtain the total error. In the energy region 12.54 MeV to 19.80 MeV neutrons were produced via the $T(d,n)^4He$ reaction; the Nb samples were positioned at various angles relative to the incident d^+ -beam. The neutron flux incident on each sample was determined by using the well-known angular distributions of the emitted neutrons and by normalizing the relative cross section data at 14.5 MeV with aid of the $^{32}S(n,p)^{32}P$ reference reaction. Additionally, the irradiation conditions were checked by a simultaneous measurement of the $^{27}Al(n,\alpha)^{24}Na$ cross section at the respective neutron energies. The $^{32}S(n,p)^{32}P$ reference cross section used by Santry and Werner at 14.5 MeV (226 mb) excellently agrees with the cross section recommended by Ryves [14] as a result of his evaluation, provided that the prescription for the extrapolation from 14.7 MeV to 14.5 MeV, as expressed by the correction factor f_E [14], is taken into account. The uncertainty for the relative angular neutron-intensity values ($\pm 3.5\%$) and for the reference cross section ($\pm 1.6\%$) were added quadratically to the errors given in *Santry 90*.

This experiment had been performed completely independently from the measurements initiated by the NEANDC Working Group on Activation Cross Sections [22]. The results reported by all three groups (Santry and Werner, Smith and Meadows, Mannhart) agree well with each other in the common energy region. Moreover, they support the outcome of the model calculation carried out by Strohmaier [8] in 1989, well in advance of the experimental verification.

Thus, it became evident that the results published in *Mannan 88* were obviously erroneous and had to be excluded.

Besides, the data measured by Ikeda et al. (*Ikeda 91*) were disregarded since the shape of the excitation function obtained in their work in the 9.5 to 11 MeV energy region markedly deviates from the mutually consistent results reported in the papers *Santry 90* and *Mannhart 91*.

Special corrections were applied to the following data sets:

Paulsen 70: The data published by Paulsen were renormalized to the evaluated cross-section value given by Ryves [14] at 14.7 MeV, the renormalization factor being $1.092 \pm 1.1\%$.

Csikai 87: In this work only relative values $\sigma(E_n)/\sigma(14.7 \text{ MeV})$ are reported. These data were multiplied by the cross section-value at 14.7 MeV evaluated by Ryves [14]. The uncertainties of the resulting cross sections were obtained by adding the uncertainty ($\pm 1.1\%$) of the evaluated cross section at 14.7 MeV quadratically to the estimated 1% uncertainty of the relative cross sections.

Smith 91: The uncertainties given for the results of this work comprise already an estimated 5% contribution from the uncertainty δE_n of the average neutron energy. Owing to the fact that most authors did not include this component into the final errors of their data, our evaluation code takes it into account according to the slope of the excitation function in the energy region in question. Therefore, in this case, this component had to be subtracted from the total uncertainty.

The cross sections reported in *Prestwood 61* were treated as relative data as the shape of the $^{93}Nb(n,2n)^{92m}Nb$ excitation function measured in that work agrees well with the main

body of the data, the absolute values, however, differ appreciably from the mutually consistent results of other experiments. The renormalization factor for the data given in *Prestwood 61* is $2.657 \pm 2.34\%$; it was obtained by fitting their cross-section values to a preliminary evaluated excitation function for which only the absolute measurements were used.

All accepted data points are listed in Table 2.2.2. The neutron energy spread and the uncertainty of the mean neutron energy, which were not reported in several papers, were estimated according to the experimental details published.

2.2.2. Evaluation and results thereof

The general evaluation procedure as outlined in Section II of Ref. 9 was slightly modified in this case in order to use the exact evaluation performed by Ryves [14] at a neutron energy of 14.7 MeV rather than repeating his work. Therefore, in the energy range from 13.4 to 15.0 MeV the absolute value of 460 ± 5 mb at 14.7 MeV obtained in Ref. 14 was adopted and combined with the accurate shape measurement given in *Csikai 87* in order to describe this energy range. No other data points in this region were included in the evaluation process; in the energy group from 14.5 MeV to 15.0 MeV only the evaluated data point determined by Ryves was considered, and in the energy region 13.4 - 14.5 MeV the cross-section values from the measurement *Csikai 87* were used.

The excitation function from 9.0 MeV to 20.0 MeV was divided into 18 energy groups ranging in width from 0.25 MeV in the first MeV above the threshold to 1.0 MeV in the 15 - 20 MeV region. The results of the evaluation, i.e., the cross-section averages over the individual energy groups and their uncertainties, are listed in Table 2.2.3. The last column of the table gives the ratio of the external to the internal errors, indicating a good consistency among the experimental data. This ratio is applicable for such energy groups only which contain data from different experiments.

The figures 2.2.1 to 2.2.3 show the evaluated group cross sections together with the input data, i.e., the renormalized experimental cross sections used in the evaluation. The result of this evaluation is very satisfactory above a neutron energy of 10 MeV, the uncertainties of the group cross sections range from 1.5% in the 14 MeV region to 3.8% in the 11.5 - 12.0 MeV energy group. Since several independent measurements provided consistent results in the 9 - 10 MeV energy range, the discrepancies pointed out in Ref. 1 have been resolved, and thus much improved and more reliable results could be obtained. In Figs. 2.2.4 and 2.2.5 the updated results are compared to the previous ones reported in Ref. 1 and to the model calculation carried out by Strohmaier [8], respectively. Significant modifications with regard to the absolute cross-section values and their uncertainties pertain to the neutron energy regions 9.5 - 10.5 MeV and 11.5 - 12.5 MeV. In the remaining regions the outcome of the updated version agrees with the original one within the limits of the uncertainties; no change at all occurred in the 13.4 - 15.0 MeV range. In the 10.5 - 11.0 MeV energy group the recommended cross section value has not been modified, yet its uncertainty is reduced considerably. Equally, the model calculations reported in Ref. 8 no longer disagree with the evaluation of the experimental data; in the

energy region below ≈ 12 MeV there appears to be an energy shift of ≈ 100 keV between the theoretical and the experimental curve.

The evaluated excitation function was checked by calculating a fission-spectrum average $\langle\sigma\rangle$ in the neutron spectrum of ^{252}Cf . Again, the Cf neutron spectrum evaluated by Mannhart [17] was used. The calculated averaged cross section $\langle\sigma\rangle_{\text{calc}}$ is 0.7846 ± 0.0269 mb; it agrees with the result of a recent experiment by Mannhart [23] ($\langle\sigma\rangle_{\text{exp}} = 0.749 \pm 0.038$ mb) within the limits of the uncertainties given.

Table 2.2.1: Summary of experiments for the reaction $^{93}\text{Nb}(\text{n},2\text{n})^{92\text{m}}\text{Nb}$.

ENERGY-RANGE [MEV]	NR.OF DATA POINTS	AVERAGE ACCUR %	METHOD	FLUX, REF CROSS-SECTION	REF	NR.
9.35 15.10	12	20.	ACTIV.	PROTON RECOIL TELESCOPE	TEWES 60	3
12.20 19.76	10	8.	ACTIV. GAM	238U(N,F)SMITH,B.AM.PH.SO.2,196(57)	PRESTWOOD 61	100
12.66 17.96	6	6.	ACTIV. NAI-WELL, GAM	1H(N,EL):689+-5 MB AT 14.1 MEV	BORMANN 70	553
10.26 19.59	32	5.- 8.0	ACTIV. GE(LI), GAM	PROTON RECOIL TELESCOPE	PAULSEN 70	552
13.30 19.00	7	9.5	ACTIV.	27AL(N,A)24NA	HUDSON 78	463
13.90 19.06	16	10.	ACTIV. GE(LI), GAM	27AL(N,A) + PROTON RECOIL TELESCOPE	NETHAWAY 78	558
12.79 18.24	13	4.	ACTIV. GE(LI),NAI, GAM	27AL(N,A)24NA: 117.5 MB AT 14.61 MEV	LU 82	466
9.39 9.90	2	12.	ACTIV. GE(LI), GAM	27AL(N,A) 238U(N,2N) 238U(N,F)	DAROCZY 83	608
13.43 14.77	18	1.	ACTIV. GE(LI),NAI, GAM	27AL(N,A) AT 14.1 MEV EVAL.TAGESEN	CSIKAI 87	609
9.09 10.61	4	9.	ACTIV. GE(LI), GAM	58NI(N,P) + 56FE(N,P)	MANNAN 88	560
12.55 19.58	15	5.	ACTIV. GE(LI), GAM	27AL(N,A) + PROTON RECOIL TELESCOPE	WOELFLE 88	554
14.70 14.70	1	1.1	EVAL.		RYVES 89	615
9.02 13.89	18	5.	ACTIV. NAI, GAM	32S(N,P)32P: EXCIT. FCT.	SANTRY 90	561
12.54 19.80	12	4.6	ACTIV. NAI, GAM	REL.TO 32S(N,P):226 MB AT 14.5 MEV	SANTRY 90	562
9.38 9.87	2	6.	ACTIV. GE, GAM	238U(N,FISS): ENDF/B-6	SMITH 91	563
9.14 13.47	14	3.8	ACTIV. GE, GAM	238U(N,FISS): ENDF/B-6	MANNHART 91	564
9.50 13.20	4	4 - 12	ACTIV. GE, GAM	197AU(N,2N)196AU: JENDL-3	IKEDA 91	565

Table 2.2.2: Cross section data for the reaction $^{93}\text{Nb}(\text{n},2\text{n})^{92\text{m}}\text{Nb}$.

NR.	E-NEUTR	WIDTH	ERR.CENTR	X-SECT(ORIG)	ERR(ORIG)	CORR.APPL.	X-SECT(FIN)	ERR(FIN)	REF
	[MEV]	[MEV]	[MEV]	[MB]	[MB]		[MB]	[MB]	
1	9.02	0.090	0.020	0.000	2.000	2)	0.000	2.000	SANTRY 90
2	9.14	0.110	0.020	1.165	0.217	NONE	1.165	0.217	MANNHART 91
3	9.25	0.085	0.020	10.000	2.000	2)	10.000	2.062	SANTRY 90
4	9.30	0.085	0.020	14.000	1.000	2)	14.000	1.221	SANTRY 90
5	9.35	0.200	0.040	8.000	1.600	NONE	8.000	1.600	TEWES 60
6	9.37	0.108	0.020	13.270	0.520	NONE	13.270	0.520	MANNHART 91
7	9.38	0.170	0.040	23.200	1.400	6)	23.200	0.780	SMITH 91
8	9.39	0.120	0.024	20.000	3.000	NONE	20.000	3.000	DAROCZY 83
9	9.50	0.106	0.020	29.000	1.090	NONE	29.000	1.090	MANNHART 91
10	9.63	0.085	0.020	54.000	3.000	2)	54.000	4.036	SANTRY 90
11	9.66	0.106	0.020	64.800	2.290	NONE	64.800	2.290	MANNHART 91
12	9.80	0.200	0.040	46.000	9.200	NONE	46.000	9.200	TEWES 60
13	9.80	0.085	0.020	87.000	4.000	2)	87.000	5.910	SANTRY 90
14	9.86	0.103	0.020	97.070	3.410	NONE	97.070	3.410	MANNHART 91
15	9.87	0.200	0.040	97.000	6.100	6)	97.000	3.700	SMITH 91
16	9.90	0.120	0.024	89.000	8.000	NONE	89.000	8.000	DAROCZY 83
17	10.00	0.085	0.020	137.000	7.000	2)	137.000	9.794	SANTRY 90
18	10.22	0.099	0.020	157.800	5.500	NONE	157.800	5.500	MANNHART 91
19	10.25	0.085	0.020	162.000	8.000	2)	162.000	11.385	SANTRY 90
20	10.26	0.250	0.050	167.000	13.360	6)	182.360	14.730	PAULSEN 70
21	10.35	0.200	0.040	160.000	32.000	NONE	160.000	32.000	TEWES 60
22	10.43	0.250	0.050	195.000	15.600	6)	212.935	17.195	PAULSEN 70
23	10.50	0.085	0.020	202.000	10.000	2)	202.000	14.213	SANTRY 90
24	10.56	0.096	0.020	215.900	7.700	NONE	215.900	7.700	MANNHART 91
25	10.63	0.240	0.048	229.000	18.320	6)	250.062	20.193	PAULSEN 70
26	10.74	0.096	0.020	241.900	8.600	NONE	241.900	8.600	MANNHART 91
27	10.75	0.085	0.020	233.000	11.000	2)	233.000	16.023	SANTRY 90
28	10.85	0.240	0.048	270.000	21.600	6)	294.833	23.810	PAULSEN 70
29	10.99	0.096	0.020	266.700	9.800	NONE	266.700	9.800	MANNHART 91
30	11.00	0.200	0.040	259.000	51.800	NONE	259.000	51.800	TEWES 60
31	11.00	0.085	0.020	279.000	14.000	2)	279.000	19.764	SANTRY 90
32	11.08	0.230	0.046	291.000	23.280	6)	317.765	25.660	PAULSEN 70
33	11.22	0.085	0.020	300.000	15.000	2)	300.000	21.213	SANTRY 90
34	11.28	0.200	0.040	357.000	28.560	6)	389.835	31.480	PAULSEN 70
35	11.39	0.094	0.020	334.300	12.500	NONE	334.300	12.500	MANNHART 91
36	11.44	0.180	0.036	350.000	28.000	6)	382.191	30.860	PAULSEN 70
37	11.50	0.200	0.040	309.000	61.800	NONE	309.000	61.800	TEWES 60
38	11.53	0.180	0.036	370.000	29.600	6)	404.031	32.630	PAULSEN 70
39	11.61	0.085	0.020	337.000	17.000	2)	337.000	23.936	SANTRY 90
40	11.80	0.085	0.020	335.000	17.000	2)	335.000	23.866	SANTRY 90
41	11.96	0.092	0.020	388.000	14.700	NONE	388.000	14.700	MANNHART 91
42	12.00	0.085	0.020	361.000	18.000	2)	361.000	25.491	SANTRY 90
43	12.10	0.200	0.040	331.000	66.200	NONE	331.000	66.200	TEWES 60
44	12.10	0.085	0.020	370.000	18.000	2)	370.000	25.812	SANTRY 90
45	12.20	0.180	0.036	156.200	7.800	7)	415.039	22.890	PRESTWOOD 61
46	12.30	0.200	0.040	377.000	75.400	NONE	377.000	75.400	TEWES 60
47	12.49	0.089	0.020	422.400	16.700	NONE	422.400	16.700	MANNHART 91
48	12.54	0.400	0.030	422.000	21.000	2)6)	422.000	26.547	SANTRY 90
49	12.55	0.270	0.054	457.000	23.000	NONE	457.000	23.000	WOELFLE 88
50	12.60	0.085	0.020	416.000	20.000	2)	416.000	28.856	SANTRY 90
51	12.63	0.110	0.022	415.000	20.750	6)	453.170	23.200	PAULSEN 70
52	12.66	0.100	0.020	556.000	34.400	NONE	556.000	34.400	BORMANN 70
53	12.69	0.290	0.058	471.000	24.000	NONE	471.000	24.000	WOELFLE 88

Table 2.2.2: Cross section data for the reaction $^{93}\text{Nb}(\text{n},2\text{n})^{92\text{m}}\text{Nb}$ (continued).

NR.	E-NEUTR [MEV]	WIDTH [MEV]	ERR.CENTR [MEV]	X-SECT(ORIG) [MB]	ERR(ORIG) [MB]	CORR.APPL.	X-SECT(FIN) [MB]	ERR(FIN) [MB]	REF
54	12.79	0.160	0.032	434.000	17.000	9)	420.893	12.968	LU 82
55	12.81	0.150	0.030	420.000	21.000	6)	458.629	23.480	PAULSEN 70
56	12.87	0.100	0.020	448.000	18.000	9)	434.470	13.939	LU 82
57	12.93	0.087	0.020	435.200	17.600	NONE	435.200	17.600	MANNHART 91
58	12.98	0.170	0.034	425.000	21.250	6)	464.089	23.760	PAULSEN 70
59	13.00	0.200	0.040	417.000	83.400	NONE	417.000	83.400	TEWES 60
60	13.24	0.200	0.040	428.000	21.400	6)	467.365	23.930	PAULSEN 70
61	13.30	0.140	0.028	562.000	49.000	9)	549.030	48.880	HUDSON 78
62	13.35	0.380	0.076	490.000	23.000	NONE	490.000	23.000	WOELFLE 88
63	13.39	0.130	0.026	524.000	31.400	NONE	524.000	31.400	BORMANN 70
64	13.43	0.115	0.030	458.850	0.000	6)7)	458.391	6.815	CSIKAI 87
65	13.48	0.108	0.030	458.896	0.000	6)7)	458.437	6.815	CSIKAI 87
66	13.52	0.102	0.030	459.080	0.000	6)7)	458.621	6.818	CSIKAI 87
67	13.60	0.091	0.030	459.310	0.000	6)7)	458.851	6.822	CSIKAI 87
68	13.68	0.080	0.030	459.494	0.000	6)7)	459.035	6.824	CSIKAI 87
69	13.70	0.000	0.000	457.930	5.000	NONE	457.930	5.000	RYVES 89
70	13.75	0.061	0.030	459.540	0.000	6)7)	459.080	6.825	CSIKAI 87
71	13.85	0.057	0.030	459.770	0.000	6)7)	459.310	6.828	CSIKAI 87
72	13.98	0.040	0.030	459.862	0.000	6)7)	459.402	6.829	CSIKAI 87
73	14.10	0.042	0.030	460.000	0.000	6)7)	459.540	6.831	CSIKAI 87
74	14.20	0.060	0.030	460.138	0.000	6)7)	459.678	6.834	CSIKAI 87
75	14.25	0.000	0.000	459.790	5.000	NONE	459.790	5.000	RYVES 89
76	14.30	0.088	0.030	460.460	0.000	6)7)	460.000	6.838	CSIKAI 87
77	14.40	0.119	0.030	460.230	0.000	6)7)	459.770	6.835	CSIKAI 87
78	14.70	0.000	0.000	460.000	5.000	NONE	460.000	5.000	RYVES 89
79	14.75	0.000	0.000	459.560	5.000	NONE	459.560	5.000	RYVES 89
80	15.09	0.260	0.052	420.000	21.000	6)	458.629	23.480	PAULSEN 70
81	15.10	0.200	0.040	485.000	97.000	NONE	485.000	97.000	TEWES 60
82	15.20	0.240	0.048	515.000	41.000	9)	485.270	39.230	HUDSON 78
83	15.37	0.250	0.050	412.000	20.600	6)	449.894	23.030	PAULSEN 70
84	15.45	0.250	0.050	411.000	41.100	9)	420.770	42.080	NETHAWAY 78
85	15.64	0.130	0.030	468.000	28.100	NONE	468.000	28.100	BORMANN 70
86	15.69	0.330	0.066	439.000	18.000	9)	425.742	14.095	LU 82
87	15.72	0.230	0.046	413.000	20.650	6)	450.986	23.090	PAULSEN 70
88	15.80	0.590	0.118	465.000	24.000	NONE	465.000	24.000	WOELFLE 88
89	15.86	0.580	0.116	464.000	23.000	NONE	464.000	23.000	WOELFLE 88
90	15.99	0.210	0.042	406.000	20.300	6)	443.342	22.700	PAULSEN 70
91	16.00	0.150	0.030	503.000	40.000	9)	500.560	41.050	HUDSON 78
92	16.05	0.310	0.062	429.000	17.000	9)	416.044	13.059	LU 82
93	16.21	0.200	0.040	417.000	41.700	9)	432.827	43.283	NETHAWAY 78
94	16.22	0.600	0.030	423.000	21.000	2)6)	423.000	26.571	SANTRY 90
95	16.25	0.200	0.040	403.000	20.150	6)	440.066	22.530	PAULSEN 70
96	16.30	0.600	0.030	420.000	21.000	2)6)	420.000	26.500	SANTRY 90
97	16.42	0.190	0.038	395.000	19.750	6)	431.330	22.080	PAULSEN 70
98	16.50	0.300	0.060	158.200	16.000	7)	420.353	43.637	PRESTWOOD 61
99	16.61	0.200	0.040	396.000	19.800	6)	432.422	22.140	PAULSEN 70
100	16.65	0.340	0.068	420.000	17.000	9)	407.316	13.219	LU 82
101	16.75	0.200	0.040	399.000	19.950	6)	435.698	22.306	PAULSEN 70
102	16.86	0.600	0.120	432.000	22.000	NONE	432.000	22.000	WOELFLE 88
103	16.95	0.140	0.028	428.000	25.700	NONE	428.000	25.700	BORMANN 70
104	16.97	0.300	0.060	438.000	43.800	9)	439.310	43.930	NETHAWAY 78
105	17.00	0.600	0.120	436.000	22.000	NONE	436.000	22.000	WOELFLE 88
106	17.10	0.100	0.020	496.000	50.000	9)	469.440	48.240	HUDSON 78

Table 2.2.2: Cross section data for the reaction $^{93}\text{Nb}(\text{n},2\text{n})^{92\text{m}}\text{Nb}$ (continued).

NR.	E-NEUTR [MEV]	WIDTH [MEV]	ERR.CENTR [MEV]	X-SECT(ORIG) [MB]	ERR(ORIG) [MB]	CORR.APPL.	X-SECT(FIN) [MB]	ERR(FIN) [MB]	REF
107	17.18	0.300	0.060	413.000	16.000	9)	400.527	12.121	LU 82
108	17.27	0.460	0.092	386.000	19.300	6)	421.502	21.580	PAULSEN 70
109	17.31	0.310	0.062	408.000	16.000	9)	395.678	12.214	LU 82
110	17.55	0.210	0.042	405.000	16.000	9)	392.769	12.268	LU 82
111	17.75	0.430	0.086	385.000	19.250	6)	420.410	21.520	PAULSEN 70
112	17.86	0.600	0.120	430.000	22.000	NONE	430.000	22.000	WOELFLE 88
113	17.90	0.500	0.030	410.000	20.000	2)6)	410.000	25.475	SANTRY 90
114	17.95	0.320	0.064	139.100	14.000	7)	369.603	38.192	PRESTWOOD 61
115	17.96	0.150	0.026	402.000	24.100	NONE	402.000	24.100	BORMANN 70
116	17.97	0.240	0.048	395.000	16.000	9)	383.071	12.446	LU 82
117	18.06	0.570	0.114	419.000	21.000	NONE	419.000	21.000	WOELFLE 88
118	18.24	0.160	0.032	388.000	16.000	9)	376.282	12.567	LU 82
119	18.33	0.380	0.076	365.000	18.250	6)	398.571	20.410	PAULSEN 70
120	18.40	0.240	0.048	483.000	48.000	9)	500.000	51.120	HUDSON 78
121	18.43	0.370	0.074	396.000	39.600	9)	407.739	40.770	NETHAWAY 78
122	18.71	0.330	0.066	357.000	17.850	6)	389.835	19.960	PAULSEN 70
123	18.75	0.510	0.102	398.000	20.000	NONE	398.000	20.000	WOELFLE 88
124	18.94	0.490	0.098	385.000	19.000	NONE	385.000	19.000	WOELFLE 88
125	19.00	0.130	0.026	391.000	39.000	9)	399.340	41.370	HUDSON 78
126	19.00	0.300	0.030	376.000	19.000	2)6)	376.000	23.883	SANTRY 90
127	19.06	0.200	0.040	370.000	37.000	9)	371.660	37.170	NETHAWAY 78
128	19.13	0.200	0.040	329.000	16.450	6)	359.260	18.390	PAULSEN 70
129	19.36	0.180	0.036	318.000	15.900	6)	347.248	17.780	PAULSEN 70
130	19.50	0.300	0.030	348.000	17.000	2)6)	348.000	21.642	SANTRY 90
131	19.58	0.250	0.050	343.000	18.000	NONE	343.000	18.000	WOELFLE 88
132	19.59	0.190	0.038	310.000	15.500	6)	338.512	17.330	PAULSEN 70
133	19.76	0.430	0.086	120.600	12.000	7)	320.446	32.755	PRESTWOOD 61
134	19.80	0.300	0.030	293.000	14.000	2)6)	293.000	17.976	SANTRY 90

CORRECTION CODES:

- 1) CROSS-SECTION RENORMALIZED TO PRESENT DECAY DATA (HALF-LIFE, BRANCHING RATIOS ETC.)
- 2) ERROR GIVEN IN PUBLICATION DID NOT INCLUDE ERROR OF REFERENCE CROSS-SECTION.
- 3) CROSS-SECTION RENORMALIZED TO ENDF/B-V VALUES OF REFERENCE CROSS-SECTION USED IN MEASUREMENT.
ERRORS TAKEN FROM THE ASSOCIATED FILE 33 INCLUDED IN FINAL ERROR.
- 4) CROSS-SECTION RENORMALIZED TO ANGULAR DISTRIBUTION OF SOURCE NEUTRONS OF LISKIEN AND PAULSEN.
- 5) ERROR HAS BEEN REDUCED BY A FACTOR TWO OR THREE IN ORDER TO REPRESENT 1 STANDARD DEVIATION.
- 6) SPECIAL CORRECTION. SEE TEXT FOR DETAILS.
- 7) CROSS-SECTION FROM MEASURED RELATIVE EXCIT. FN., NORMALIZED TO PRESENT EVALUATION.
- 8) CROSS-SECTION FROM THEORETICAL CALCULATION, NORMALIZED TO PRESENT EVALUATION.
- 9) RENORMALIZATION USING REF.CROSS-SECTION EVALUATED AT IRK, SEE PHYSICS DATA 13-5.

Table 2.2.3: Evaluated group cross sections for the reaction $^{93}\text{Nb}(\text{n},2\text{n})^{92\text{m}}\text{Nb}$.

Energy Group [MeV] to [MeV]		Cross Section [mb]	Error [mb]	Error [%]	Ratio $\Delta_{\text{ext}}/\Delta_{\text{int}}$
9.00	9.25	0.99	1.02	102.6	0.148
9.25	9.50	15.94	2.01	12.6	1.595
9.50	9.75	51.24	5.00	9.8	0.509
9.75	10.00	95.32	5.79	6.1	1.623
10.00	10.50	164.49	5.57	3.4	0.803
10.50	11.00	241.48	8.08	3.3	1.013
11.00	11.50	322.79	9.90	3.1	0.898
11.50	12.00	370.53	14.25	3.8	1.251
12.00	12.50	403.52	11.71	2.9	0.792
12.50	13.40	449.24	10.59	2.4	1.327
13.40	14.00	458.65	6.79	1.5	---
14.00	14.50	459.82	6.79	1.5	---
14.50	15.00	459.54	5.00	1.1	---
15.00	16.00	447.50	9.49	2.1	0.868
16.00	17.00	424.86	8.33	2.0	0.848
17.00	18.00	408.27	8.16	2.0	0.915
18.00	19.00	387.00	12.90	3.3	1.430
19.00	20.00	344.16	10.33	3.0	0.604

*) not applicable (see text).

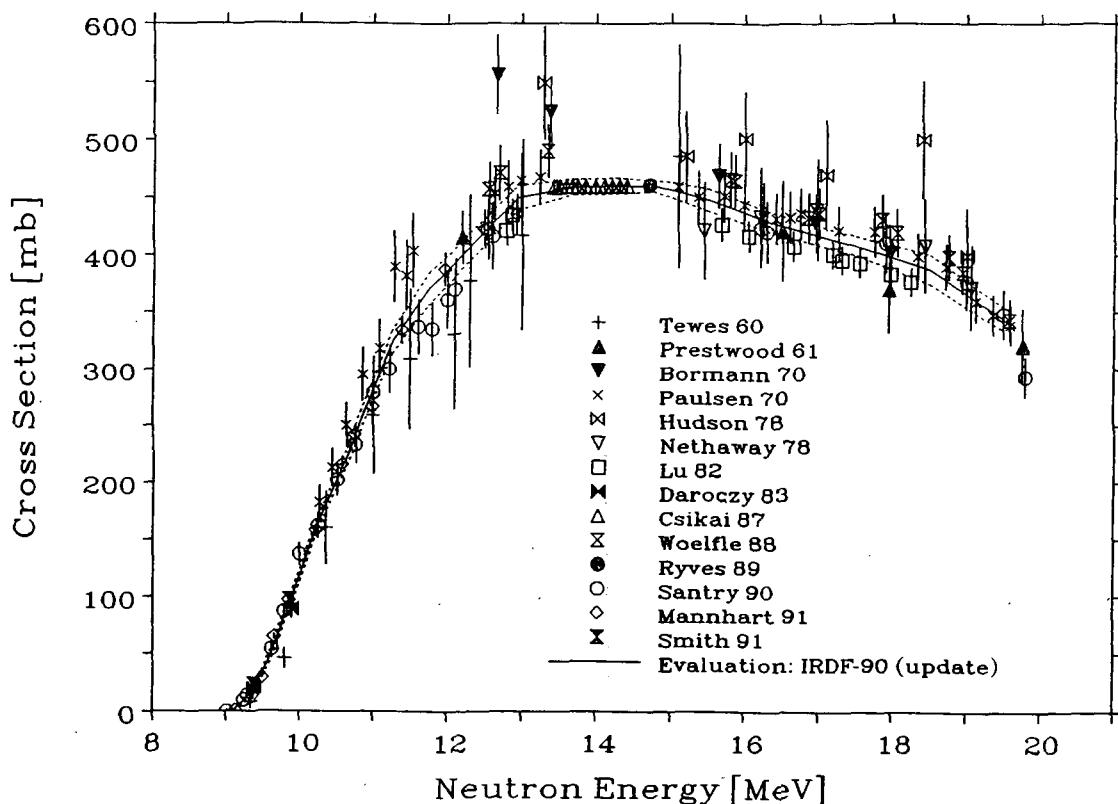


Figure 2.2.1: Experimental cross sections (renormalized and corrected) for the reaction $^{93}\text{Nb}(\text{n},2\text{n})^{92\text{m}}\text{Nb}$ together with the evaluated cross sections.

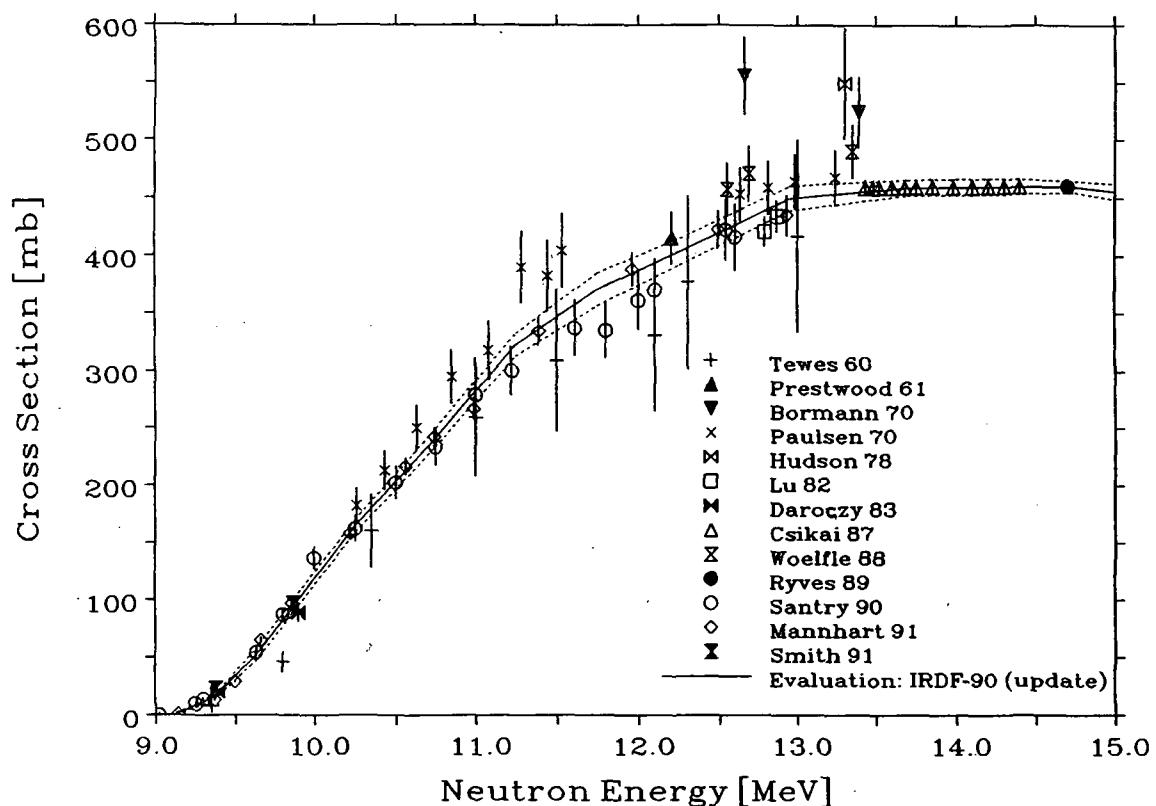


Figure 2.2.2: Experimental cross sections (renormalized and corrected) for the reaction $^{93}\text{Nb}(n,2n)^{92\text{m}}\text{Nb}$ together with the evaluated cross sections: expanded display of the energy range 9.0 - 15.0 MeV.

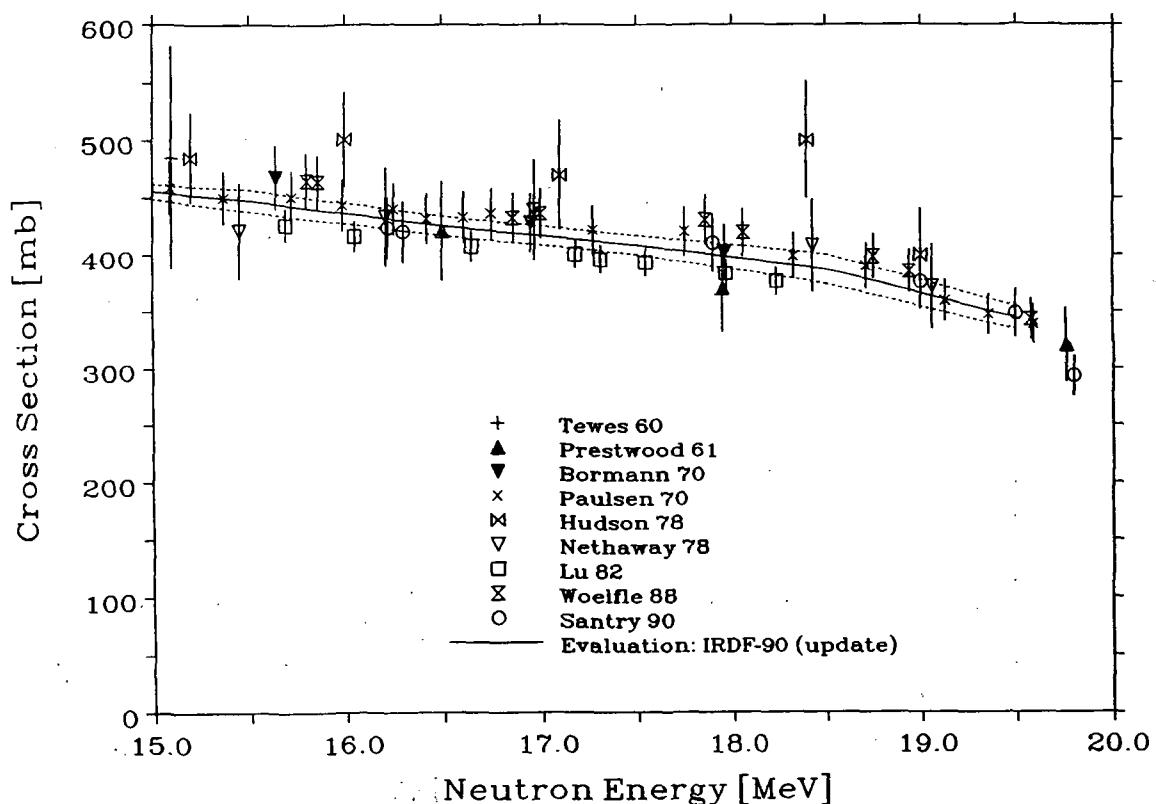


Figure 2.2.3: Experimental cross sections (renormalized and corrected) for the reaction $^{93}\text{Nb}(n,2n)^{92\text{m}}\text{Nb}$ together with the evaluated cross sections: expanded display of the energy range 15.0 - 20.0 MeV.

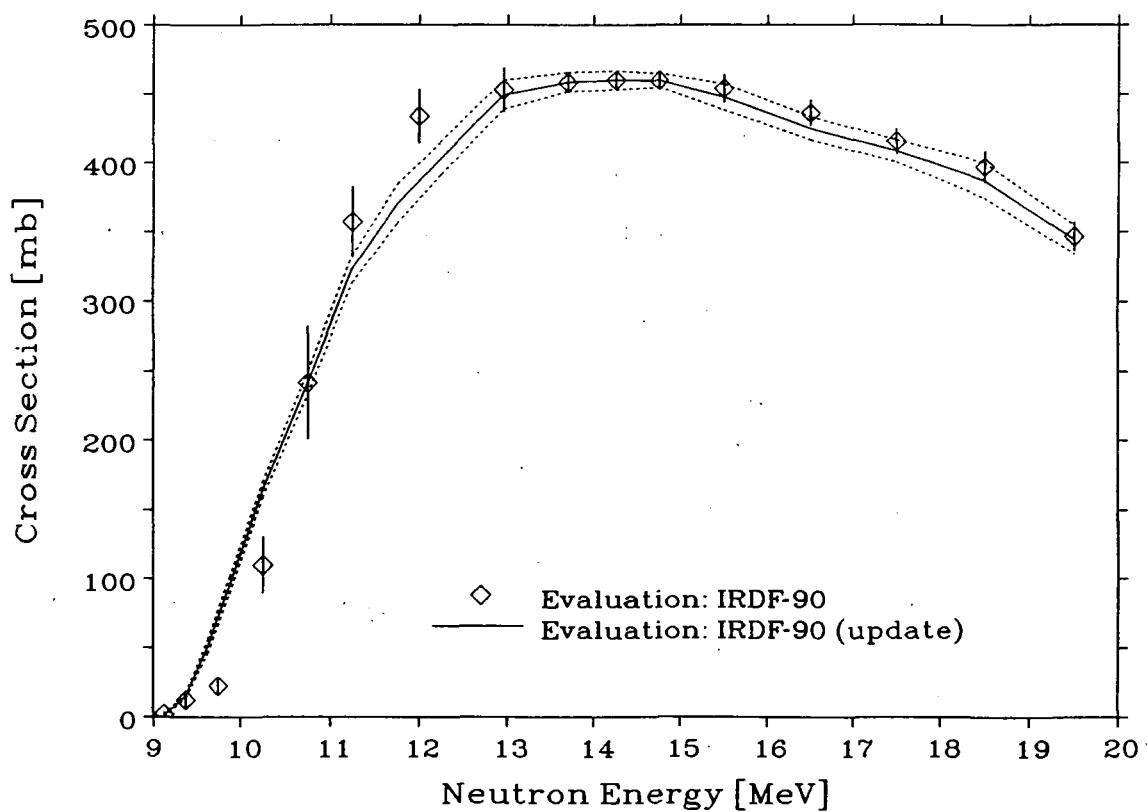


Figure 2.2.4: The evaluated cross section for the reaction $^{93}\text{Nb}(\text{n},2\text{n})^{92\text{m}}\text{Nb}$: updated version compared to the results of the previous evaluation reported in Ref. 1.

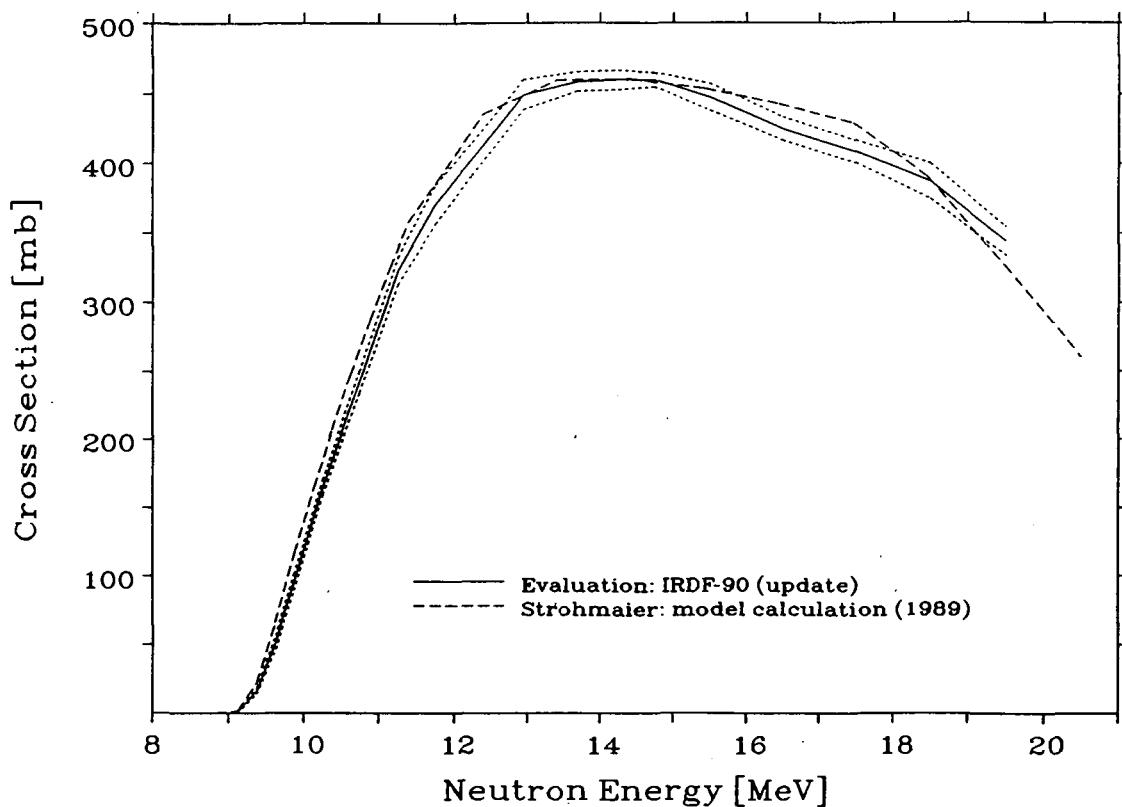


Figure 2.2.5: The evaluated cross section for the reaction $^{93}\text{Nb}(\text{n},2\text{n})^{92\text{m}}\text{Nb}$ compared to the results of model calculations [8].

References of the experimental data base for the reaction $^{93}\text{Nb}(\text{n},2\text{n})^{92\text{m}}\text{Nb}$

- Bormann 70*: M. Bormann et al., Nucl. Phys. **A157**, 481 (1970), and M. Bormann et al., Prog. Rept. EANDC(E)-127, 38 (1970).
- Csikai 87*: J. Csikai, Zs. Lantos and Cs.M. Buczko, Proc. LAEA Advisory Group Meeting on Properties of Neutron Sources, Leningrad, USSR, June 9 - 13, 1986, Report IAEA-TECDOC-410, 296, IAEA, Vienna (1987).
- Daroczy 83*: S. Daroczy et al., Proc. 6th All Union Conference on Neutron Physics, Kiev. Oct. 2 - 6, 1983, vol. 3, p.191 (1983).
- Hudson 78*: C.G. Hudson, W.L. Alford and S.K. Ghorai, Ann. Nucl. Energy **5**, 589 (1978).
- Ikeda 91*: Y. Ikeda et al., Nuclear Data for Science and Technology, Proc. Int. Conf. Jülich, May 13 - 17, 1991 (Paper O 21) (to be published).
- Lu 82*: Lu Hanlin et al., Nuclear Data for Science and Technology, Proc. Int. Conf. Antwerp, Sept. 6 - 10, 1982, 411; K.H. Böckhoff, ed., Reidel Publ. Comp., Dordrecht (1983).
- Mannan 88*: A. Mannan and S.M. Qaim, Phys. Rev. **C38**, 630 (1988).
- Mannhart 91*: W. Mannhart, "NEANDC Working Group on Activation Cross Sections", in: Nuclear Data for Science and Technology, Proc. Int. Conf. Jülich, May 13 - 17, 1991 (Paper O 18) (to be published).
- Nethaway 78*: D.R. Nethaway, J. Inorg. Nucl. Chem. **40**, 1285 (1978).
- Paulsen 70*: A. Paulsen and R. Widera, Z. Physik **238**, 23 (1970).
- Prestwood 61*: R.J. Prestwood and B.P. Bayhurst, Phys. Rev. **121**, 1438 (1961).
- Ryves 89*: T.B. Ryves, European Appl. Res. Rept. - Nucl. Sci. Eng., Vol.7, 1241 (1989), and Letter to the Editor of Ann. Nucl. Energy **16**, 307 (1989).
- Santry 90*: D.C. Santry and R.D. Werner, Can. J. Phys. **68**, 582 (1990).
- Smith 91*: D.L. Smith and J.W. Meadows, "NEANDC Working Group on Activation Cross Sections", in: Nuclear Data for Science and Technology, Proc. Int. Conf. Jülich, May 13 - 17, 1991 (Paper O 18) (to be published).
- Tewes 60*: H.A. Tewes et al., Report UCRL-6028-T, Lawrence Livermore Laboratory (1960).
- Woelfle 88*: R. Wölfle et al., Appl. Radiat. Isotopes (Int. J. Radiat. Appl. Instrum. Part A) **39**, 407 (1988).

3. Relative covariance matrices

Relative correlation coefficients and covariances between the evaluated group cross sections were calculated within the excitation function of the two reactions considered. For those parts of the excitation functions which are based on experimental data, the correlation coefficients were calculated from the quantities B_{nnk} , the average correlation coefficients within each data set k included in the respective evaluation, according to the

Table 3.1: Average relative correlation coefficients B_{nnk} assumed for the various experimental data sets (for definition see Ref. 9, equ. 1).

Reaction	Ref. No.	Reference	B_{nnk}
$^{19}\text{F}(\text{n},2\text{n})^{18}\text{F}$:			
	157	McCrary 60	0.05
	318	Brill 61	0.50
	304	Rayburn 62	0.10
	306	Bormann 65	0.40
	323	Nagel 66	0.90
	324	Nagel 66	0.90
	311	Bormann 67	0.10
	325	Bormann 67	0.40
	312	Menlove 67	0.13
	321	Vonach 68	0.90
	317	Chatterjee 69	0.50
	326	Ryves 78	0.50
	137	Ikeda 88	0.37
	331	Hartmann 91	0.35
	332	Hartmann 91	0.57
$^{93}\text{Nb}(\text{n},2\text{n})^{92m}\text{Nb}$:	3	Tewes 60	0.90
	100	Prestwood 61	0.80
	553	Bormann 70	0.70
	552	Paulsen 70	0.10
	463	Hudson 78	0.80
	558	Nethaway 78	0.50
	466	Lu 82	0.60
	608	Daroczy 83	0.80
	609	Csikai 87	0.55
	554	Woelfle 88	0.60
	561	Santry 90	0.65
	562	Santry 90	0.62
	563	Smith 91	0.57
	564	Mannhart 91	0.68

procedure described in Section II.2 of Ref. 9. These B_{nnk} values were estimated from the uncertainty information given in the experimental papers; they are listed in Table 3.1. for all measurements considered at more than one neutron energy. In the case of $^{19}\text{F}(\text{n},2\text{n})^{18}\text{F}$ the experimental data were supplemented by a phenomenological extrapolation between 11 and 12.4 MeV (see Chapter 2.2.1 and Ref.2). These calculated cross sections in different energy groups were considered to be fully correlated.

For the $^{93}\text{Nb}(\text{n},2\text{n})^{92m}\text{Nb}$ reaction the evaluation was carried out according to the standard procedure except for the 13.4 - 15.0 MeV energy region where the absolute value of the cross section at 14.7 MeV was taken from the evaluation performed by Ryves [14] and combined with the precise measurement of the relative excitation function by Csikai [15]. The uncertainties $\Delta\sigma(E_n)$ for the cross sections in the different energy groups in the 14 MeV range were obtained by quadratic addition of the uncertainty of the 14.7 MeV cross section (correlated part $\Delta\sigma_{corr}$) and the uncertainties of the relative cross

Table 3.2: Relative covariance matrix for the reaction $^{19}\text{F}(\text{n},2\text{n})^{18}\text{F}$.

Correlations given in %

GROUP NUMBER	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	ENERGY GROUP [MeV] to [MeV]															
1	100	100	98	100	100	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11.00	11.40														
2		100	98	100	100	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11.40	11.60														
3			100	98	98	0	0	0	0	0	2	0	0	0	2	1	0	2	5	3	3	2			11.60	11.80														
4				100	100	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11.80	12.00														
5					100	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12.00	12.20														
6						100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12.20	12.40													
7							100	5	22	0	0	0	0	0	1	31	15	15	13	18	0	0	0	0	0	0	0	12.40	12.80											
8								100	3	0	1	1	0	0	2	6	3	3	2	2	0	0	0	0	0	0	0	12.80	13.20											
9									100	9	2	7	8	4	14	21	10	10	9	12	0	0	0	0	0	0	0	13.20	13.60											
10									100	50	67	67	38	10	0	0	0	0	0	0	0	0	0	0	0	0	0	13.60	14.00											
11										100	49	49	28	3	1	0	0	0	0	0	0	0	0	0	0	0	0	0	14.00	14.20										
12											100	67	37	10	0	2	1	0	2	5	2	3	2					14.20	14.40											
13												100	37	10	0	0	0	0	0	0	0	0	0	0					14.40	14.60										
14													100	5	0	16	16	17	16	0	0	0	0	0	0					14.60	14.80									
15														100	2	1	1	1	1	0	0	0	0	0	0					14.80	15.00									
16															100	13	14	12	17	0	0	0	0	0	0	0					15.00	16.00								
17																100	45	40	42	5	2	3	2									16.00	17.00							
18																	100	39	41	3	2	2	2										17.00	18.00						
19																		100	41	15	14	14	15											18.00	19.00					
20																			100	6	3	4	3												19.00	20.00				
21																				100	48	49	48													20.00	22.00			
22																					100	57	57														22.00	24.00		
23																						100	57															24.00	26.00	
24																							100																26.00	28.00

Table 3.3: Relative covariance matrix for the reaction $^{93}\text{Nb}(\text{n},2\text{n})^{92m}\text{Nb}$.

Correlations given in %

GROUP NUMBER	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	ENERGY GROUP [MeV] to [MeV]	
1	100	51	42	49	62	59	59	58	53	33	0	0	0	0	0	0	0	0	9.00	9.25
2		100	45	69	54	50	54	54	50	31	0	0	0	3	0	0	0	0	9.25	9.50
3			100	46	46	54	53	54	49	30	0	0	0	0	0	0	0	0	9.50	9.75
4				100	51	49	52	53	48	30	0	0	0	2	0	0	0	0	9.75	10.00
5					100	58	61	61	54	35	0	0	0	3	1	1	2	2	10.00	10.50
6						100	60	60	54	34	0	0	0	1	1	1	2	2	10.50	11.00
7							100	62	55	35	0	0	0	3	1	1	1	2	11.00	11.50
8								100	55	35	0	0	0	3	1	1	1	2	11.50	12.00
9									100	31	0	0	0	1	8	8	0	13	12.00	12.50
10										100	0	0	0	41	44	44	38	22	12.50	13.40
11											100	54	73	0	0	0	0	0	13.40	14.00
12												100	73	0	0	0	0	0	14.00	14.50
13													100	0	0	0	0	0	14.50	15.00
14														100	49	48	47	24	15.00	16.00
15															100	55	44	32	16.00	17.00
16																100	43	29	17.00	18.00
17																	100	24	18.00	19.00
18																		100	19.00	20.00

sections (uncorrelated part). Accordingly, the correlation coefficients between different energy groups in the 14 MeV range were calculated as

$$\frac{\langle \Delta\sigma(E_i) \times \Delta\sigma(E_j) \rangle}{\langle \Delta\sigma(E_i) \rangle \langle \Delta\sigma(E_j) \rangle} = \frac{\Delta\sigma_{corr}^2}{\Delta\sigma(E_i) \times \Delta\sigma(E_j)}$$

The relative correlation matrices for the two reactions considered are given in Tables 3.2. and 3.3., respectively.

References

- [1] M. Wagner et al., Physics Data **13-5**, Fachinformationszentrum Karlsruhe (1990).
- [2] B. Strohmaier, S. Tagesen and H. Vonach, Physics Data **13-2**, 12, Fachinformationszentrum Karlsruhe (1980).
- [3] N.P. Kocherov and H. Vonach, Proc. of the 7th ASTM-EURATOM Symposium on Reactor Dosimetry, Strasbourg, France, 27-31 Aug. 1990 (to be published)
- [4] D.V. Victorov et al., Atomnaya Energiya **54**, 58 (1983).
- [5] Y. Ikeda et al., Rept. JAERI-1312, Japan Atomic Energy Research Institute, Tokai-mura (1988).
- [6] K. Kobayashi and I. Kimura, *Nuclear Data for Science and Technology*, Proc. Int. Conf. Mito, Japan, May 30 - June 3, 1988, p. 261; S. Igarasi, ed., Saikou Publ. Comp., Tokyo (1988).
- [7] C.L. Hartmann and P.M. De Luca, Jr., Nucl. Sci. Eng. (in press).
- [8] B. Strohmaier, Ann. Nucl. Energy **16**, 461 (1989).
- [9] S. Tagesen, H. Vonach and B. Strohmaier, Physics Data **13-1**, Fachinformationszentrum Karlsruhe (1979).
- [10] CINDA-A (1935 - 1987), The Index to Literature and Computer Files on Microscopic Neutron Data, IAEA, Vienna (1990).
- [11] CINDA 90 (1988 - 1990), The Index to Literature and Computer Files on Microscopic Neutron Data, IAEA, Vienna (1990).
- [12] EXFOR, File of Experimental Nuclear Reaction Data, as received from the IAEA, Nuclear Data Section, Vienna.
- [13] C.M. Lederer and V.S. Shirley, Eds., *Table of Isotopes*, 7th ed., Wiley Interscience Publ., New York (1978).
- [14] T.B. Ryves, European Appl. Res. Rept. - Nucl. Sci. Technol., Vol. 7, 1241 (1989) and Letter to the editor of Ann. Nucl. Energy **16**, 307 (1989).
- [15] J. Csikai, *Handbook of Fast Neutron Generators*, vol. 1, 16; CRC Press, Inc., Boca Raton (1987).

- [16] P. Rose, ed., ENDF/B-VI Summary Documentation, Report ENDF - 201, 4th ed., Brookhaven National Laboratory (in press).
- [17] W. Mannhart, *Proc. IAEA Advisory Group Meeting on Properties of Neutron Sources*, Leningrad, USSR, June 9 - 13, 1986, Report IAEA-TECDOC-410, IAEA, Vienna (1986).
- [18] W. Mannhart in: *Handbook on Nuclear Activation Data*, IAEA Technical Report Series 273, 413, IAEA, Vienna (1987).
- [19] P. Luksch (Editor), Nucl. Data Sheets 30, 573 (1980).
- [20] D.C. Santry and J.P. Butler, Can. J. Chem. 41, 123 (1963).
- [21] ENDF/B-V, Evaluated Nuclear Data File, National Nuclear Data Center, Brookhaven Nat. Laboratory (1979).
- [22] D.L. Smith et al., "NEANDC Working Group on Activation Cross Sections", in: *Nuclear Data for Science and Technology*, Proc. Int. Conf. Jülich, May 13 - 17, 1991 (Paper O 18) (to be published).
- [23] W. Mannhart, private communication (1990).