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COMPILATION AND EVALUATION OF 14-MeV NEUTRON-ACTIVATION CROSS SECTIONS FOR NUCLEAR TECHNOLOGY APPLICATIONS: SET I*

by

Bernard P. Evain**, Donald L. Smith and Paul Lucchese***

April 1985

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NUCLEAR REACTIONS. Compiled and evaluated selected experimental activation σ data. $E_n \approx$ 14-15 MeV. Adjusted original values for revised nuclear constants and standards. Transformed all values to equivalent 14.7-MeV σ. Least-squares evaluation procedure.

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COMPILATION AND EVALUATION OF 14-MeV NEUTRON ACTIVATION CROSS SECTIONS FOR NUCLEAR TECHNOLOGY APPLICATIONS: SET I*

by

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ABSTRACT

Available 14-MeV experimental neutron activation cross sections are compiled and evaluated for the following reactions of interest for nuclear-energy technology applications: $^{27}Al(n,p)^{27}Mg$, $Si(n,X)^{28}Al$, $Ti(n,X)^{46}Sc$, $Ti(n,X)^{47}Sc$, $Ti(n,X)^{48}Sc$, $^{51}V(n,p)^{51}Ti$, $^{51}V(n,\alpha)^{48}Sc$, $Cr(n,X)^{52}V$, $^{55}Mn(n,\alpha)^{52}V$, $^{55}Mn(n,2n)^{54}Mn$, $Fe(n,X)^{54}Mn$, $^{54}Fe(n,\alpha)^{51}Cr$, $^{59}Co(n,p)^{59}Fe$, $^{59}Co(n,\alpha)^{56}Mn$, $^{59}Co(n,2n)^{58}Co$, $^{65}Cu(n,p)^{65}Ni$, $Zn(n,X)^{64}Cu$, $^{64}Zn(n,2n)^{63}Zn$, $^{113}In(n,n')^{113m}In$, $^{115}In(n,n')^{115m}In$. The compiled values are listed and plotted for reference without adjustments. From these collected results those values for which adequate supplementary information on nuclear constants, standards and experimental errors is provided are selected for use in reaction-by-reaction evaluations. These data are adjusted as needed to account for recent revisions in the nuclear constants and cross section standards. The adjusted results are subsequently transformed to equivalent cross sections at 14.7 MeV for the evaluation process. The evaluations are performed utilizing a least-squares method which considers correlations between the experimental data.

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I. INTRODUCTION

In recent years there has been a resurgence of interest in 14-MeV neutron cross sections for fusion-energy technology applications. Very good progress has been made in understanding the Physics of high-temperature plasmas, and engineering breakthroughs have led to the achievement of much higher temperatures and longer containment times than were possible just a few years ago. Program schedules at several laboratories now project demonstration of "breakeven" for magnetic-fusion energy within the next decade. Thus, the resolution of a number of technological problems associated with 14-MeV neutrons from $T(d,n)^4He$ reactions in confined plasmas of deuterium and tritium is a matter which must be given attention.

One of the more pressing needs for 14-MeV data is for dosimetry applications. Neutron production from plasmas is now a reality, and accurate knowledge of several neutron activation cross sections is needed in order to monitor plasma temperatures and to assess D-T fuel "burn" rates during the containment intervals. Of concern for blanket design purposes are tritium-breeding cross sections and neutron-multiplier cross sections for energies of $\approx$ 14 MeV and below. Of longer-range concern are such matters as radiation damage by energetic neutrons and long-lived activation of fusion reactor structures. These are important matters which will affect the longevity and service of facilities and decommissioning procedures. Extensive nuclear data requirements are anticipated for all of these categories (e.g., see Ref. 1). The 14-MeV region is an especially important one since most neutrons are produced at around this energy and only suffer energy degradation after subsequent interactions with reactor components. The assessment of critical nuclear data needs for magnetic fusion energy has been sponsored by the U. S. Department of Energy (e.g., Refs. 2-3), and resulting data requests are serving to define the scope of several nuclear data research programs sponsored under DOE auspices (e.g., Ref. 4). The present set of reactions comes from a list of processes identified as being of specific interest for fusion applications (Refs. 2-3). However, the need for 14-MeV activation data is certainly not confined to fusion-energy development. There are specific nuclear-data needs in this category for other more conventional applications such as neutron activation analysis, medical technology, oil well logging [5], and mineral exploration in a broader sense [6]. The data needs are often not as clearly defined in these other areas as for fusion, but the demands for improved knowledge of certain cross sections still stem from the rapid advancements made in the respective application methodologies.

It is clear that extensive neutron cross section data are already available in the vicinity of 14 MeV (e.g., Ref. 7). In fact, the impression which a casual observer is likely to glean from a brief survey of the situation is that these cross sections are, in a sense, "over determined", and that it is difficult to justify further measurement effort. On closer inspection, one is likely to be rather disturbed, possibly even alarmed, by the extent of the discrepancies in various data sets which purport to correspond to the same basic physical quantities (e.g., see Ref. 8). There are many reasons why these discrepancies exist. The data base has been accumulating over a period of several decades. In fact, much of the work was done in the 1950's and 1960's, with somewhat lesser activity in evidence during the 1970's. Experimental techniques have changed quite a bit during this period. Improvement in the knowledge of nuclear constants and standard cross sections used in the measurements is also an important factor. Finally, it should be realized that many of the cross section values in the data files resulted from experiments which were designed to investigate certain physical principles in a qualitative fashion, not to provide quantitative results with state-of-the art accuracy. Undoubtedly, new measurements will have to be performed in order to resolve some of these discrepancies and to improve accuracies. However, this work should not be indiscriminant, since some apparent problems may be eliminated by careful examination and evaluation of existing data. A review of the existing data is a prudent first step toward improving the knowledge of cross sections in the 14-MeV energy region. It is in this spirit that the present investigation was undertaken.

Earlier compilations (e.g., Refs. 9-10) and evaluations (e.g., Refs. 11-12) of selected data have been reported. Compilations by themselves are of limited value since no attempt is made to deal with the discrepancies. The data user is faced with the inevitable problem of deciding which values to use. Therefore, there is an essential need to examine the reported experimental data and to adjust the values so that they correspond to current knowledge of applicable nuclear constants and standards. The adjusted data may then be averaged, utilizing weighting factors based on the relative accuracies of the results. Experimental results which cannot be thus assessed, owing to inadequate documentation, generally should be rejected. An alternative to rejecting poorly documented data is to weight them very little by assigning large fictitious errors. However, such a process involves considerably more subjectivity than merely rejecting them. For this reason we have chosen the the latter approach. Methods for performing "evaluations" of this nature have recently been discussed extensively in the literature (e.g., see Ref. 13). No matter which method is chosen, evaluators always face the same basic problem: inadequate and inconsistent documentation of the experimental procedures. It is uncommon to find an experimental work which is reported in such a way that all the essential ingredients required for rigorous evaluation of the results are explicitly at hand. Usually the evaluator must infer or estimate missing information. In short, regardless of the intrinsic rigor of the evaluation procedures used, all evaluations ultimately involve considerable subjectivity. In spite of these shortcomings, the process is a useful one. Also, experimenters are becoming more sophisticated in regard to reporting new results. The prognosis for future improvements is therefore good.

This particular endeavor is limited to twenty activation processes which have been explicitly identified as being of interest for magnetic-fusion-energy applications (Ref. 2-3). These are reactions not generally used as standards, and in several instances the data bases are not extensive. They are also reactions which we are interested in investigating experimentally in our laboratory. The compilation and evaluation procedures which we employ here involve compromises stemming primarily from time and information limitations, but also from our judgement concerning the degree of statistical rigor which is practical for this exercise. These methods are described in Section II and in the Appendix. For example, in our evaluation process we attempt to consider correlations between various reported data for a given reaction type whenever such correlations are apparent. Furthermore, we include estimated correlations for the standard cross sections. However, we have chosen not to perform a simultaneous evaluation of all these reactions, tracing common correlations in the manner of Poenitz [14]. Our evaluated results no doubt are affected somewhat by the various imperfections in our method. Nevertheless, we believe this approach is adequate to meet our primary intended objectives which are to assess the general status of the reactions we consider and to decide whether new measurements are warranted in order to meet the identified needs for nuclear-energy applications.

At 14-MeV energies, several reaction channels may lead to the same activity for elements having several isotopic components. This state of affairs is usually indicated by "(n,X)", e.g., $Ti(n,X)^{46}Sc$ collectively represents several open channels for activation of ^{46}Sc, involving ^{46}Ti, ^{47}Ti and ^{48}Ti. Often in the literature activation data of this nature are identified by the dominant reaction, e.g., $^{46}Ti(n,p)^{46}Sc$ in the preceding example. Table 1 elaborates on this issue for the present set of reactions. In this work we are not concerned with the relative contributions from the various channels. In many applications such knowledge is irrelevant; however, we are cognizant of the fact that it is a matter of concern in some special cases.

In Section II we describe the general methods used to deal with the individual reactions treated in Section III. Also, the matter of standards is discussed because of their communal nature. Section III contains twenty distinct subsections, one for each activation process considered. In Section IV we present some conclusions from the present exercise. The Appendix describes the weighted least-squares method employed in the present evaluations. We have attempted to make each (sub)section essentially self-contained. Each includes its own reference list, tables and plots, where applicable. References within the text to the literature, tables or plots automatically are intra-(sub)sectional unless otherwise explicitly stated. References relevant to various experimental works often appear on computer-generated lists, sometimes using reference notation compatible with CINDA [7]. Occasionally multiple references relevant to a given work are presented when these are cited in CINDA[7]. Our selection of symbols for plotting data is arbitrary, but is entirely consistent within each subsection of Section III. However, there is no correlation of the symbol choices between subsections. A catalogue of available symbols is presented at the beginning of Section III.

Table 1: Activation Reactions Treated in the Present Work

Element	Activity	Reaction[a]	Isotopic Abundance[b]	Q (MeV)	E_{th} (MeV)[c]
Aluminum	^{27}Mg	$^{27}Al(n,p)^{27}Mg$	100%	- 1.827	1.895
Silicon	^{28}Al	[$^{28}Si(n,p)^{28}Al$]	92.23%	- 3.861	4.000
		$^{29}Si(n,d)^{28}Al$	4.67%	-10.111	10.463
		$^{29}Si(n,np)^{28}Al$	4.67%	-12.335	12.764
Titanium	^{46}Sc	[$^{46}Ti(n,p)^{46}Sc$]	8.2%	- 1.585	1.620
		$^{47}Ti(n,d)^{46}Sc$	7.4%	- 8.240	8.417
		$^{47}Ti(n,np)^{46}Sc$	7.4%	-10.464	10.689
		$^{48}Ti(n,t)^{46}Sc$	73.7%	-13.611	13.897
	^{47}Sc	[$^{47}Ti(n,p)^{47}Sc$]	7.4%	+ 0.181	N
		$^{48}Ti(n,d)^{47}Sc$	73.7%	- 9.223	9.417
		$^{48}Ti(n,np)^{47}Sc$	73.7%	-11.447	11.688
		$^{49}Ti(n,t)^{47}Sc$	5.4%	-11.108	11.337
	^{48}Sc	[$^{48}Ti(n,p)^{48}Sc$]	73.7%	- 3.208	3.275
		$^{49}Ti(n,d)^{48}Sc$	5.4%	- 9.126	9.314
		$^{49}Ti(n,np)^{48}Sc$	5.4%	-11.350	11.584
		$^{50}Ti(n,t)^{48}Sc$	5.2%	-13.813	14.092
Vanadium	^{51}Ti	$^{51}V(n,p)^{51}Ti$	99.750%	- 1.684	1.717
	^{48}Sc	$^{51}V(n,\alpha)^{48}Sc$	99.750%	- 2.055	2.096
Chromium	^{52}V	[$^{52}Cr(n,p)^{52}V$]	83.79%	- 3.194	3.256
		$^{53}Cr(n,d)^{52}V$	9.50%	- 8.910	9.080
		$^{53}Cr(n,np)^{52}V$	9.50%	-11.134	11.346
		$^{54}Cr(n,t)^{52}V$	2.35%	-12.371	12.602

Table 1: Activation Reactions Treated in the Present Work (Continued)

Element	Activity	Reaction[a]	Isotopic Abundance[b]	Q (MeV)	E_{th} (MeV)[c]
Manganese	^{52}V	$^{55}Mn(n,\alpha)^{52}V$	100%	- 0.625	0.636
	^{54}Mn	$^{55}Mn(n,2n)^{54}Mn$	100%	-10.227	10.415
Iron	^{54}Mn	$[^{54}Fe(n,p)^{54}Mn]$	5.8%	+ 0.085	N
		$^{56}Fe(n,t)^{54}Mn$	91.8%	-11.929	12.144
	^{51}Cr	$^{54}Fe(n,\alpha)^{51}Cr$	5.8%	+ 0.843	N
Cobalt	^{59}Fe	$^{59}Co(n,p)^{59}Fe$	100%	- 0.783	0.796
	^{56}Mn	$^{59}Co(n,\alpha)^{56}Mn$	100%	- 4.535	4.613
	^{58}Co	$^{59}Co(n,2n)^{58}Co$	100%	-10.453	10.632
Copper	^{65}Ni	$^{65}Cu(n,p)^{65}Ni$	30.8%	- 1.356	1.377
Zinc	^{64}Cu	$[^{64}Zn(n,p)^{64}Cu]$	48.6%	+ 0.204	N
		$^{66}Zn(n,t)^{64}Cu$	27.9%	-10.354	10.512
	^{63}Zn	$^{64}Zn(n,2n)^{63}Zn$	48.6%	-11.861	12.048
Indium	^{113m}In	$^{113}In(n,n')^{113m}In$	4.3%	- 0.392	0.396
	^{115m}In	$115In(n,n')115^{m}In$	95.7%	- 0.336	0.339

[a] [...] indicates dominant reaction of series (i.e., "generic" reaction).
[b] Isotopic abundances in natural elements from Ref. 15.
[c] Threshold energy. N = Exothermic reaction with no threshold.

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II. PROCEDURE

The present investigation is comprised of two parts, data compilation and data evaluation, carried out independently for the twenty reactions considered.

We employed CINDA [1] as our principal guide to literature on the available data. Furthermore, we obtained the contents of the CSISRS [2] cross section data files for the reactions in question. In most instances, data sets appearing in the CSISRS [2] files were cited in CINDA [1], although there were some exceptions. The converse, however, was not true so we sought the original papers for entries in CINDA [1] which were not in CSISRS [2]. Other leads to existing data came from two previous compilations [3,4], and from citations found in accumulated references. This compilation procedure no doubt missed several possible references. CINDA [1] has limitations, and furthermore we were not able to obtain some of the references cited in CINDA [1] (or elsewhere) at the Argonne National Laboratory library and report archives. In the interest of expediency, we made no further attempt to acquire these "elusive" references, and proceeded with information which proved to be readily available. Our data compilation effort was confined to the 14-15 MeV energy range, except for a few values at energies very nearly in this range. It is this range which is normally designated "14 MeV". Data acquired by methods other than activation, or results which were not explicitly monoenergetic cross-section or cross-section ratio information were also excluded from the compilation process in order to avoid difficulties associated with trying to establish the equivalency of very diverse data.

The data gathered by this procedure are presented in Section III. Also included are results from selected evaluations. Listings of values and plots are provided. These compiled results are "untouched" in the sense that no adjustments were made to compensate for disparities in nuclear-constant and standard values. The plots are similar to those found in such compilations as BNL-325 [5], except the data exhibited are limited to a narrow energy range.

Prior to evaluation, these data were examined much more closely, and were adjusted as required so that the different results could be properly intercompared. Changes were made to modify the cross sections to be consistent with recent values for nuclear-decay constants and for standard-reaction cross sections, where applicable. Other adjustments deemed necessary were applied as needed. Details are discussed in the various subsections of Section III.

Information on errors was required for the present evaluation. For each reaction, specific error categories were defined, e.g., uncorrelated, systematic decay properties and systematic standards. The uncorrelated category included not only statistical errors, but also other identifiable errors which could be isolated to individual data sets. In all of the evaluations here we ignore possible errors due to isotopic abundances since we judged these to be neglibible compared with most other error sources. Covariance matrices were constructed from this information, following closely the method described on pp. 10-12 of Ref. 6 which need not be repeated here. The actual preparation of these covariance matrices was accomplished using a digital computer to speed up the process and avoid mistakes.

This data adjustment and evaluation procedure established stringent demands for detailed information and documentation from the authors. When such information was provided, we accepted the values given. In some situations, especially those regarding errors, the information provided seemed questionable, but we chose the consistent policy of accepting the word of the authors. The demands for information could not be met for many of the reported data sets. In some instances we were able to supplement missing information by relying on our general knowledge of the measurement procedures. Often, however, it was decided simply to reject certain data for lack of documentation.

Measurements could be categorized as either "absolute" (where neutron fluence was measured) or "relative" (where some other reaction served as a standard). The absolute measurements were most often of the associated-particle type, where the emitted α particles from the $T(d,n)\alpha$ neutron-source reaction are detected, or they involved calibrated detectors, e.g., a long counter. Ratio data involving several standards were encountered. We chose to limit the number of standards included in this analysis as much as possible, sometimes rejecting data involving so-called "standards" which we judged to be unorthodox or of substandard quality insofar as accuracy is concerned.

Our evaluation procedure (see Appendix) requires the averaging of entirely equivalent quantities. Consequently we removed energy dependencies (reported data roughly span the 14-15 MeV region) by converting all results to "equivalent" 14.7-MeV cross sections. The adjustment factors were calculated using shapes derived from various origins. Details are discussed in the individual subsections of Section III. Generally, no added error was assumed for this adjustment factor, though in a truly rigorous evaluation an uncertainty covariance matrix for the a priori assumed cross section would be considered. In some instances, when the shape needed for conversion to 14.7 MeV was barely more than a guess, and where the energy dependence was considerable, an additional error component was added to account for this obvious uncertainty. Whenever an author provided more than one value for the 14-15 MeV range, we calculated a weighted average after making all adjustments. This average was then used in the evaluation.

The accepted, adjusted data were analyzed using the computer code AVERG which is described in the Appendix. Generally the evaluation process required two passes. On the first pass all adequately-documented values were included. The analysis yielded a preliminary average, a standard deviation and a normalized chi-square. If the normalized chi-square exceeded unity (indicating data inconsistencies), then the calculated deviation was "enhanced" by multiplying it by the square root of the normalized chi-square. Then, all input values which significantly exceeded the initial average by three or more "enhanced" standard deviations were rejected and the analysis was repeated with a reduced data input. The second-pass average was accepted as the final average value. A new normalized chi-square was produced, of course, and if it also exceeded unity, the new standard deviation was also "enhanced" as described above. No further iterations were pursued. The concept of enhancing standard deviations when normalized standard deviations exceeding unity are encountered is discussed in Ref. 6, p. 34. Note, however, that for cases where the normalized chi-square amounted to less than unity, we did not reduce the standard deviation. We believe this approach is a suitably conservative one for present purposes. The reader should also realize that all the quoted errors in Section III are to be interpreted as one-standard deviation (1σ) errors.

In the previous paragraph we have clearly indicated two conditions under which we have rejected data. Since the matter of rejection of data is a very sensitive one in the community of nuclear data evaluators [A.4-A.7] (probably with good reason), some defense of our approach is clearly warranted. First, we will re-emphasized the point previously made that the present procedure stresses the analysis of "like" quantities. Thus we took the trouble to check standards and decay data, renormalizing reported results as required. Likewise, we adjusted to equivalent values at the same energy, 14.7 MeV, accounting for energy dependence as best we could. These are widely accepted practices. If, however, we are to properly ascertain whether the data being compared are equivalent, it is absolutely necessary to have adequate documentation available. The alternative, guesswork, is rather arbitrary and beset with risk. The data reviewed here chronologically span several decades, and in some cases where formal documentation was never prepared or was not accessible in a practical way, we felt no alternative but to simply ignore the results. We undertook such seemingly unavoidable action with considerable regret, but we remain of the opinion that evaluation is still partially an art in view of the imperfections of the existing procedures for measuring and reporting nuclear parameters. The rejection of data which appear "inconsistent" with the respect to the main body of available results (the 3σ test) is probably less defensible. Doing this amounts to making the assumption that most experiments deviate from each other due to random processes which can be analyzed by conventional statistical methods, while the few apparently "discrepant" values must have "hidden" systematic errors which made them somehow "wrong". We are certainly aware of exceptions to this philosophy that the "majority must be right". Many breakthroughs in science have resulted just this way. However, nuclear data research is an established field in which most of the techniques and methods are relatively conventional. Therefore, while exceptions may very well exist, and we must be on the lookout for them, more often than not apparently discrepant values probably are really discrepant. As indicated previously, an alternative exists to the rejection of apparently discrepant data [A.6]. It involves enhancement of the error for an offending point to the level where the observation of such a deviation is no less probable than say the 2σ level. Such an approach is, in fact, a way to finesse the problem since the influence of such a point will be downgraded to the negligible level without having to bear the responsiblity for total rejection. In most instances, the end consequence will be the same. In the final analysis, it is our belief that there is no entirely satisfactory way to handle systematic errors and discrepant data within the framework of a statistical analysis. Until a better method becomes established and widely accepted, a variety of partially biased methods, such as our present one, will continue to be used.

An inventory was made of the standards used for all the reported relative measurements considered in this work. It was found that most often these experiments utilized one or more of the following six reactions:

Symbol	Reaction
S1	$^{1}H(n,n)^{1}H$
S2	$^{27}Al(n,\alpha)^{24}Na$
S3	$^{32}S(n,p)^{32}P$
S4	$^{56}Fe(n,p)^{56}Mn$
S5	$^{63}Cu(n,2n)^{62}Cu$
S6	$^{65}Cu(n,2n)^{64}Cu$

Furthermore, these reactions were included in a recent evaluation effort of data at 14.7 MeV [7,8]. This investigation by Ryves and coworkers was a simultaneous evaluation which yielded not only a set of recommended values with corresponding uncertainties but also a correlation matrix relating the various reactions. The errors in the evaluated values were $\leq$ 2% in each case, so this set of standards was judged to be ideal for the present purposes. In all instances, independent evaluations were available which could be compared with the work of Ryves et al. [7,8]. We finally chose to select the recommended values of Ryves et al. [7,8] for all reactions other than hydrogen scattering. For hydrogen scattering we decided to employ ENDF/B-V [9] since most of the data for hydrogen is absolutely measured and we are inclined to believe that this primary standard should be independent and not be derived from a multi-reaction adjustment procedure such as that of Ryves et al. [7,8]. Consequently, the hydrogen scattering standard is treated here as uncorrelated to the other five reactions. For completeness we designate absolute measurements by "A".

Values for the standard cross sections were required at energies other than 14.7 MeV since the data renormalizations were usually carried out at the reported energies. In order to meet this requirement, we employed selected other reported evaluations for shape information, normalizing the results to 14.7 MeV. In each instance, we assumed that the uncertainty for the 14-15 MeV range (in percent) was constant and identical to that for the 14.7-MeV value. The correlations were also assumed to apply to the entire region, not just at 14.7 MeV. The selection of the shape evaluations merits additional discussion: For the $^{1}H(n,n)^{1}H$, the ENDF/B-V [9] evaluation yielded both the shape and final 14.7-MeV value. For $^{27}Al(n,\alpha)^{24}Na$, two recent evaluations were considered besides that of Ryves et al. [7,8]. These are ENDF/B-V [9] and the evaluation of Vonach and coworkers (e.g., see Refs. 10 and 11). The ENDF/B-V [9] evaluation for this reaction is a carryover from an earlier ENDF/B evaluation, with errors ~ 5% at 14 MeV. The predicted 14.7-MeV value differs from that of Ryves et al. [7,8] by ~ 3%. The evaluation of Vonach et al. [10,11] is of high quality and is in excellent agreement with the Ryves et al. [7,8] result at 14.7 MeV. Therefore we used the Vonach et al. [10,11] results for the shape, but normalized this to the Ryves et al. [7,8] 14.7-MeV value. For $^{32}S(n,p)^{32}P$, we employed the ENDF/B-V [9] evaluation for the shape and normalized this to the Ryves et al. [7,8] value at 14.7 MeV. The ENDF/B-V [9] 14.7-MeV value agreed very well with that of Ryves et al. [7,8]. For $^{56}Fe(n,p)^{56}Mn$, we employed the ENDF/B-V [9] shape, and normalized it to Ryves et al. [7,8] at 14.7 MeV. The error quoted ~ 14 MeV for ENDF/B-V [9] was only ~ 2%, but the predicted 14.7-MeV value differed by ~ 4% from that of Ryves et al. [7,8]. For $^{63}Cu(n,2n)^{62}Cu$, we employed the shape from the evaluation by Tagesen et al. [12], normalized to the result of Ryves et al. [7,8] at 14.7 MeV. The errors quoted for the evaluation of Tagesen et al. [12] are large (5-7% for the 14-15 MeV range), but the predicted 14.7 MeV value differs by only ~ 1% from that of Ryves et al. [7,8]. For $^{65}Cu(n,2n)^{64}Cu$ we employed the ENDF/B-V [9] evaluation for the shape and normalized this to the 14.7 MeV value of Ryves et al. [7,8]. ENDF/B-V [9] differed by $\gtrsim$ 4% from the result of Ryves et al. [7,8], but the latter includes new improved information on the decay scheme for ^{64}Cu, as discussed below.

Table 1 indicates the standard-reaction cross sections employed in the present investigation. Values, given at 100-keV increments between 14-15 MeV, were deduced by linear interpolation whenever they were not explicitly found in the original evaluations. Table 2 provides the assumed errors in these standards and correlations between them, based entirely on the work of Ryves et al. [7,8].

Unambiguous specification of the nuclear decay constants for the standard reactions is just as important as it is for the particular reactions being evaluated. For hydrogen scattering this issue is irrelevant. For all the other reactions, except $^{65}Cu(n,2n)^{64}Cu$, the nuclear decay constants suggested in Ref. 13 are consistent with the work of Ryves et al. [7,8] and were accepted for the present work. For ^{64}Cu decay, we relied on the results of Christmas et al. [14] which are the basis for the work of Ryves et al. [7,8]. This recent, careful investigation of the decay of ^{64}Cu provides improved information relative to that compiled earlier by Lederer et al. [13]. Table 3 summarizes the important nuclear decay constants for the standards used in the present work. Uncertainties attributed to the decay branching were assumed to be 100% correlated between the various reported values. Uncertainties due specifically to half-life are difficult to trace and are generally quite small. Only occasionally did we attempt to examine this issue. Generally we assumed that each individual author had included this among the errors of his experiment.

We observed, from numerous references to the literature, that authors are seldom inclined to provide much information about the standard reactions used, other than to give the cross section. Thus, we were faced with the inevitable problem of having inadequate information for the evaluations, in this particular context. Rather than trying to estimate what the uncertainty might be in each instance, we chose to overlook this matter. There are several reasons why this oversight is not as serious as it might appear. In general, since the measurements involve six standards as well as absolute data, no one standard has an exclusive impact. In this regard it is worthwhile to examine the frequency of citations to the various reference standards. Based on the content of Section III, we have compiled this information in Table 4. It is seen that the $^{27}Al(n,\alpha)^{24}Na$ (S2) reaction is the most common reference standard, with $^{56}Fe(n,p)^{56}Mn$ (S4) a distant second. Absolute measurements (A) and measurements involving $^{63}Cu(n,2n)^{62}Cu$ (S5) are also fairly numerous. If we refer to Table 3, we see that the decay properties of all the activation standards are relatively unambiguous, with the exception of $^{65}Cu(n,2n)^{64}Cu$ (S6). There are no ambiguities for hydrogen scattering (S1) or absolute measurements. Thus, our problem reduced to estimating what the effect of neglecting uncertainties in the decay of ^{64}Cu might be on our evaluation effort. First, we note from Table 1 that only six out of the twenty included evaluations are affected. Forty percent of the values included in the $Zn(n,X)^{64}Cu$ evaluation use this reference, but because ^{64}Cu is involved in both the standard and unknown, the uncertainties largely cancel. Among the others, we chose to examine this issue in more detail for $^{59}Co(n,2n)^{58}Co$, since it is typical of the others, with 25% of the included data referenced to $^{65}Cu(n,2n)^{64}Cu$. The results appear in Section III.O. We found that addition of a rather large (~ 8%) extra uncertainty to each data point involving the $^{65}Cu(n,2n)^{64}Cu$ standard changed the final evaluation by less than 1%, and had little effect on the standard deviation of the evaluated value, which exceeded 1% substantially.

A final consideration is the matter of internal conversion information. This issue is of particular importance for the isomer excitations of ^{113}In and ^{115}In. In order to estimate uncertainties due to this effect we referred to the calculations of Rose [15] and of Hager and Seltzer [16]. To trace the evolution of the accepted values for the internal conversion parameters we also compared values from an older version of Table of the Isotopes [17] with the latest version [13]. Some more recent decay information for certain of the reaction of present concern is also summarized in Table V of Ref. 18.

Table 1: Standard Cross-Section Values for the Present Investigation[a]

Reaction	Neutron Energy (MeV) 14.0	14.1	14.2	14.3	14.4	14.5	14.6	14.7	14.8	14.9	15.0
S1: $^{1}H(n,n)^{1}H$	692.9	688.3	683.7	679.0	674.4	669.8	665.4	661.1	656.7	652.4	648.0
S2: $^{27}Al(n,\alpha)^{24}Na$	122.8	122.5	122.6	120.6	118.1	116.6	115.1	113.7	112.9	111.9	110.9
S3: $^{32}S(n,p)^{32}P$	247.6	242.2	236.9	231.5	226.1	220.8	217.9	215.0	212.2	209.2	206.2
S4: $^{56}Fe(n,p)^{56}Mn$	114.6	113.9	113.2	112.3	111.2	110.3	109.3	107.8	106.3	104.9	103.4
S5: $^{63}Cu(n,2n)^{62}Cu$	438.0	451.8	465.6	479.8	494.4	509.0	523.4	538.0	551.2	563.2	575.2
S6: $^{65}Cu(n,2n)^{64}Cu$	888.0	899.5	910.9	922.4	933.8	945.3	954.6	964.0	973.4	982.7	992.1

[a]Cross-section values in mb.

Table 2: Standard Cross-section Errors and Correlations

Reaction	Error (%)	S_1	S_2	S_3	S_4	S_5	S_6
		Correlation Matrix					
S1: $^{1}H(n,n)^{1}H$	1.0	1					
S2: $^{27}Al(n,\alpha)^{24}Na$	0.6	0	1			(Symmetric)	
S3: $^{32}S(n,p)^{32}P$	1.5	0	0.26	1			
S4: $^{56}Fe(n,p)^{56}Mn$	0.6	0	0.58	0.31	1		
S5: $^{63}Cu(n,2n)^{62}Cu$	1.3	0	0.28	0.17	0.30	1	
S6: $^{65}Cu(n,2n)^{64}Cu$	1.2	0	0.45	0.21	0.44	0.45	1

Table 3: Nuclear Decay Constants for the Standard Reactions

^{24}Na Decay

$t_{1/2}$ = 15.030 ± 0.003 h

β^- emission: 100%

γ emission: 1.369 MeV (100%)
2.754 MeV (100%)
Others not important

^{32}P Decay

$t_{1/2}$ = 14.282 ± 0.005 d

β^- emission: 100%

γ emission: None

^{56}Mn Decay

$t_{1/2}$ = 2.5785 ± 0.0006 d

β^- emission: 100%

γ emission: 0.847 MeV (98.87 ± 0.04%)
Others not important

^{62}Cu Decay

$t_{1/2}$ = 9.73 ± 0.02 m

β^+ emission: 97.8%

Electron capture: 2.2%

γ emission: 0.511 annihilation
(1.956 γ rays per decay)
Others not important

Table 3: Nuclear Decay Constants for the Standard Reactions (Continued)

^{64}Cu Decay:

$t_{1/2}$ = 12.699 ± 0.008 h

β^+ emission: 17.86 ± 0.14%

Electron capture: 43.10 ± 0.47%

β^- emission: 39.04 ± 0.33%

γ emission: 0.511 annihilation
(0.3572 γ-rays per decay)
Others not important

Table 4: Utilization Frequency for Neutron Fluence Standards Considered in the Present Evaluation.

Number of Citations[a]

Activation Reaction	S1	S2	S3	S4	S5	S6	A
$^{27}Al(n,p)^{27}Mg$	1	11	0	5	3	0	5
$Si(n,X)^{28}Al$	0	1	0	4	1	0	1
$Ti(n,X)^{46}Sc$	1	5	0	1	0	0	0
$Ti(n,X)^{47}Sc$	0	4	0	1	0	0	1
$Ti(n,X)^{48}Sc$	0	10	0	2	1	0	2
$^{51}V(n,p)^{51}Ti$	0	4	0	3	2	0	4
$^{51}V(n,\alpha)^{48}Sc$	1	6	0	2	0	0	2
$Cr(n,X)^{52}V$	0	2	0	1	1	0	1
$^{55}Mn(n,\alpha)^{52}V$	1	2	0	1	2	0	1
$^{55}Mn(n,2n)^{54}Mn$	2	4	0	0	0	2	0
$Fe(n,X)^{54}Mn$	3	4	0	1	0	0	1
$^{54}Fe(n,\alpha)^{51}Cr$	1	3	0	1	0	1	0
$^{59}Co(n,p)^{59}Fe$	2	0	0	1	0	3	0
$^{59}Co(n,\alpha)^{56}Mn$	0	4	1	6	2	0	1
$^{59}Co(n,2n)^{58}Co$	2	5	0	0	2	3	0
$^{65}Cu(n,p)^{65}Ni$	0	2	1	5	2	1	2
$Zn(n,X)^{64}Cu$	1	3	1	1	0	4	0
$^{64}Zn(n,2n)^{63}Zn$	1	5	0	0	4	0	3
$^{113}In(n,n')^{113m}In$	0	1	0	2	0	0	1
$^{115}In(n,n')^{115m}In$	0	4	1	3	0	0	1
Totals:	16	80	4	40	20	14	26

[a]Only references which were actually used in the final stages of these evaluations (not rejected for one reason or another) are counted here. Standards are: S1: $^{1}H(n,n)^{1}H$, S2: $^{27}Al(n,\alpha)^{24}Na$, S3: $^{32}S(n,p)^{32}P$, S4: $^{56}Fe(n,p)^{56}Mn$, S5: $^{63}Cu(n,2n)^{62}Cu$, S6: $^{65}Cu(n,2n)^{64}Cu$ and A: Absolute.

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III. INDIVIDUAL REACTIONS

In this section we present the results of our compilation and evaluation effort for the reactions selected in the present study. Each reaction is treated in a separate, self-contained subsection as described in Section I. We have attempted to maintain as much symmetry as possible in presenting the material contained in these subsections. Various details related to each reaction appear in the text. The compiled data (unaltered) are presented in a first table, where the references and symbols used are also identified. Throughout this work symbols were selected from the available set in Table 1. The application of each compiled data set is also indicated in the first table by a capital letter which follows the reference number: "E" indicates data retained in the final evaluation, "D" designates data rejected for either inadequate documentation or because of use of an unorthodox standard, and "I" designates data which were rejected because of inconsistency with the general body of available values, as tested by the chi-square criterion discussed in Section II. Unavailable information is designated by "NA". All original compiled results are included in a plot which follows the first table. A selected evaluated curve is usually also shown in this plot for reference. In a second table we provide additional information for those values retained in the evaluation. The standard used (where applicable) is designated by the symbol Si (i=1,6) according to the convention of Section II. If a measurement is absolute it is so indicated by the symbol "A". The various adjustment factors applied to the reported cross sections prior to evaluation are listed, and the final adjusted cross sections are presented. Next, the various error components and the total errors, in percent, are given. Following the table, the final results of the evaluation are summarized. The evaluated value, normalized chi-square and selected standard deviation are provided. It is also indicated whether the standard deviation is "enhanced", as discussed in Section II and in the Appendix. Finally, a plot showing the relationship of all adjusted values designated by "E" to the evaluated value is presented. One-standard-deviation bands around the evaluated value are plotted. Each subsection ends with a list of compiled references applicable to the reaction in question.

Table 1: Catalogue of Symbols Available for the Present Study[a]

Symbol Identification	Symbol	Symbol Identification	Symbol	Symbol Identification	Symbol
1	X	3E	⬗	6E	⊠
2	□	3F	◈	6F	⊠
2A	■	3G	◇	7	⍓
2B	◧	4	△	7A	⍓
2C	◨	4A	▲	7B	⍓
2D	⬒	4B	◭	7C	⍓
2E	⬓	4C	◮	7D	⍓
2F	◪	4D	△	8	○
2G	◩	5	⧖	8A	●
2H	◩	5A	⧗	8B	◓
2I	◪	5B	⧗	8C	◒
2J	⊞	5C	⧗	8D	◑
3	◇	6	⊠	8E	◐
3A	◆	6A	⊠	8F	⊕
3B	⬘	6B	⊠	8G	⊙
3C	⬙	6C	⊠	8H	⊗
3D	⬖	6D	⊠	8I	⊖

[a]Not all available symbols are used in this work.

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

Aluminum is monoisotopic so only one neutron-induced reaction leads to the production of ^{27}Mg. The half life of ^{27}Mg given in Ref. II.13 is 9.462 ± 0.012 m. Normally this uncertainty of ~ 0.1% could be treated as negligible. However, for the measurements on this reaction several values of the half life have been used. Even when the values used were reported by the authors, it was usually impossible to correct for this effect since there were insufficient details given in the references. Often the half life values used were not even given. This situation added to the uncertainty of the evaluation process. ^{27}Mg decays entirely by β^- emission to levels in ^{27}Al. According to Ref. II.13, 72% of these decays go to the 0.844-MeV first-excited state while 28% go to the 1.014-MeV second excited state. There are three characteristic gamma rays emitted: 0.844 MeV (73 ± 1%), 1.014 MeV (29.1%) and 0.171 MeV (0.8%). An earlier reference on decay properties of nuclei (Ref. II.17) gives 70%, 30% and 0.7% for the branching factors of these gamma rays, respectively. Both β^- counting and gamma-ray counting methods have been used in measuring this cross section. Documentation ranges from relatively complete to essentially nonexistent in regard to the assumed decay properties. Adjustments for changing decay constants were made wherever possible. It was decided to assign a random error of $\lesssim$ 3% to each data set, in addition to the indicated 1.4% fully-correlated decay branch error, to account for uncertainty associated with half life and decay branching.

Forty-nine relevant references were compiled from the literature. From these, the 76 individual data points listed in Table 1 and plotted in Fig. 1 were derived. The data which were adequately documented were adjusted for changes in standard cross sections, and for decay branch changes. All values were converted to equivalent 14.7-MeV results. Multiple data sets were averaged to produce single values, and the random error was reduced accordingly. However, the minimum random error attributed to any data point was 5%. Owing to the obvious scatter in the adjusted values, and the uncertainties alluded to above, it was felt that any value of the error smaller than this was likely to be too optimistic. Data points carrying too-small errors, especially those with low cross section values, tended to upset the least squares averaging process, leading to anomalous low results.

Six data sets [15,16,18,20,22 and 48] were rejected at the outset owing to inadequate documentation for these results. Thus, only forty-two data values were initially considered in the analysis. Five other values [5,8,23, 32 and 37] were subsequently rejected because they were obviously inconsistent with the remaining values and their inclusion would have distorted the analysis performed by code AVERG (see Appendix). The first-pass analysis led to the rejection of twelve more values (see Table 1 for details). Thus, the present evaluation is based on twenty-five individual values.

The results of this analysis appear in Table 2 and in Fig. 2. The data used for the final evaluation are clearly consistent, as indicated by a normalized chi-square smaller than unity. The final evaluated cross section is 70.464 mb with a standard deviation of 1.397 mb (± 2%). This value is only 2.6% smaller than the 72.38 mb value given by ENDF-V [II.9].

Table 1: Compiled Data for $^{27}Al(n,p)^{27}Mg$

Ref. No.	Symbol	Application	Neutron Energy (MeV)	Energy Resolution (MeV)	Reported Cross Section (mb)	Reported Cross Section Error (mb)
1	1	E	14.1	NA	79.0	5.53
2	2F	I	14.5	NA	52.4	9.43
3	2D	I	14.1	0.15	70.0	14.0
4	2B	I	14.1	0.1	87.2	7.0
5	2C	I	14.0	NA	34.0	6.0
6	2J	D	15.0	0.12	80.0	20.0
7	2A	I	14.8	0.9	53.0	5.0
8	8H	I	14.0	NA	115.0	10.0
9	2E	E	15.0	0.4	59.0	6.0
10	2I	I	14.16	NA	57.0	7.0
			14.75	NA	68.0	5.0
11	2G	I	14.1	0.1	90.0	18.0
12	2	I	14.1	NA	85.0	2.8
13	2H	E	14.8	NA	77.0	7.7
14	3A	E	14.1	NA	80.8	4.4
15	3B	D	14.1	NA	53.0	NA
16	3C	D	14.1	0.1	62.0	8.7
17	3E	I	14.4	0.2	93.0	10.0
18	3D	D	14.4	NA	50.0	7.0
19	3	I	14.7	0.15	82.0	10.0
20	4	D	14.6	NA	72.0	NA
21	4A	E	14.7	0.3	66.0	2.0
22	4B	D	14.7	NA	78.0	NA
23	4D	I	14.8	0.1	97.0	10.0
24	4C	E	14.1	0.1	89.0	5.34
25	5	E	13.92	0.04	87.0	6.1
			13.95	0.04	86.3	6.0
			13.975	0.04	84.0	5.9
			14.0	0.04	83.0	5.8
			14.025	0.04	84.0	5.9
			14.055	0.04	84.0	5.9
			14.08	0.04	84.6	5.9
			14.11	0.04	84.4	5.9
			14.135	0.04	80.5	5.6
			14.16	0.04	79.6	5.6
			14.21	0.04	81.5	5.7
			14.26	0.04	81.0	5.7
			14.30	0.04	83.6	5.8

Table 1: Compiled Data for $^{27}Al(n,p)^{27}Mg$ (Continued)

Ref. No.	Symbol	Application	Neutron Energy (MeV)	Energy Resolution (MeV)	Reported Cross Section (mb)	Reported Cross Section Error (mb)
25	5	E	14.36	0.045	80.5	5.6
			14.40	0.05	79.0	5.5
			14.445	0.055	83.0	5.8
			14.525	0.06	78.0	5.5
			14.585	0.065	79.0	5.5
			14.67	0.09	78.0	5.5
26	5C	E	14.2	0.2	71.0	9.0
27	5A	E	14.4	0.15	68.0	8.0
28	5B	E	14.2	0.1	74.0	7.0
29	3F	E	14.8	NA	80.0	5.0
30	6	E	14.8	0.2	73.0	5.0
31	6B	E	14.7	0.15	75.0	2.0
32	6A	I	14.8	0.5	38.0	5.0
33	6D	E	14.8	NA	75.0	6.0
34	6E	E	14.1	0.1	68.6	1.4
35	6C	E	14.6	NA	74.47	4.2
36	6F	E	14.78	0.1	68.0	2.3
37[a]	-	I	14.1	NA	190.0	40.0
38	7B	E	14.6	NA	69.9	4.6
39	7C	E	14.9	NA	71.0	5.0
40	7D	E	14.9	0.1	68.0	4.0
41	8G	E	14.2	0.2	72.0	5.0
42	7	I	14.0	0.05	99.6	5.0
			14.23	0.05	98.9	4.7
			14.49	0.14	94.5	4.9
			14.61	0.14	92.1	5.2
			14.81	0.21	93.1	4.9
			14.92	0.25	90.4	4.4
43	8C	E	14.65	0.1	67.3	2.0
44	8B	I	14.7	0.4	82.0	8.0
45	8D	E	14.6	0.1	73.5	4.5
46	8F	E	14.2	0.1	68.0	6.0
47	8A	I	15.0	NA	48.91	2.5
48	8E	D	14.83	NA	64.17	3.9
49	8	E	14.10	NA	88.0	4.8
			14.39	NA	84.0	4.6
			14.66	NA	76.0	4.2
			14.78	NA	73.0	4.0

[a]Not plotted.

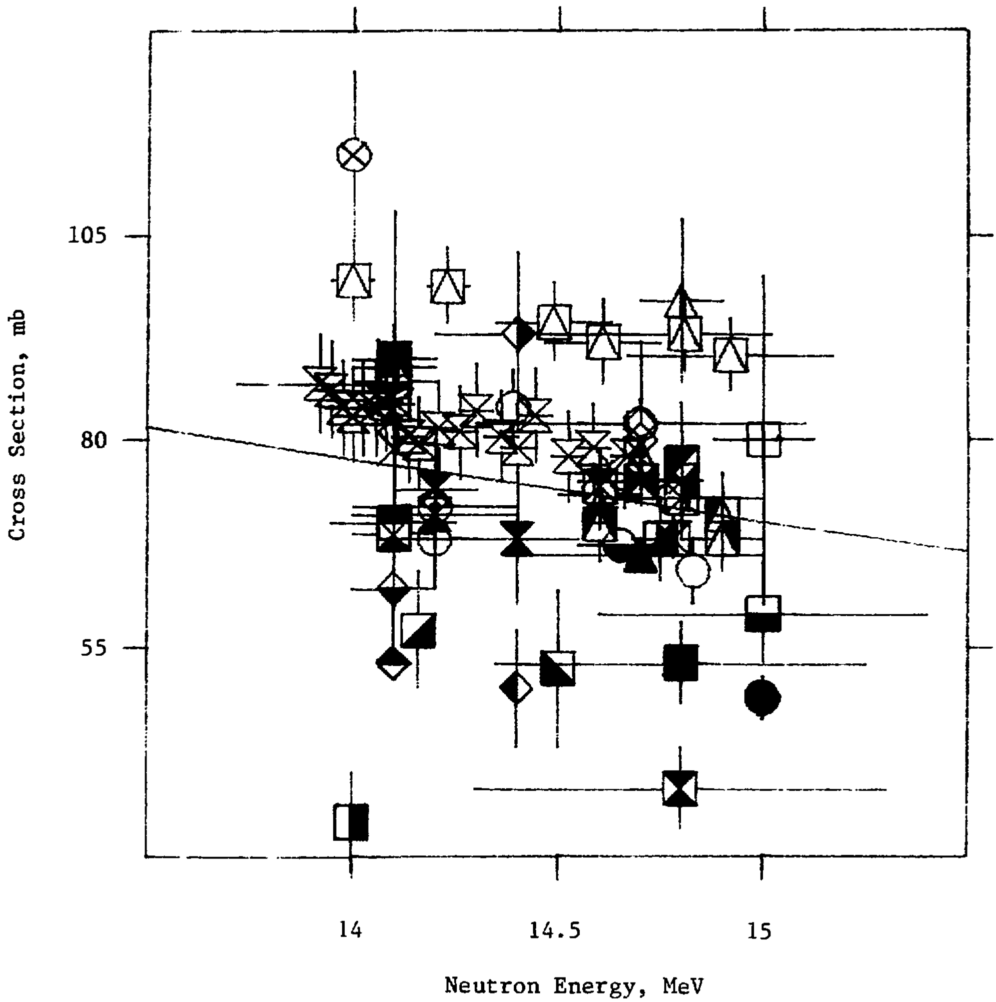


Figure 1: Compiled experimental data for Al-27(n,p)Mg-27

Table 2: Additional Information for the $^{27}Al(n,p)^{27}Mg$ Evaluation

Ref. No.	Standard	Standard Adjustment Factor	Energy Adjustment Factor	Decay Branch Adjustment Factor	Adjusted Cross Section (mb)		Errors (%) Uncorrelated	Standard	Total[a]
1	A	1.0	0.9406	1.0		74.31	7.7	0.0	7.8
9	S5	1.0354	1.0341	1.0		63.17	9.4	1.3	9.6
13	S2	0.9650	1.0111	1.0		75.13	10.4	0.6	10.6
14	A	1.0	0.9406	1.0		75.81	6.2	0.0	6.3
21	S1	1.0	1.0	1.0		66.0	5.0	1.0	5.3
24	S2	0.9074	0.9406	1.0		75.96	6.7	0.6	6.9
25	S5	0.9663	0.9242	1.0	77.69	75.55	5.9	1.3	6.2
			0.9270		77.30				
			0.9293		75.43				
			0.9316		74.71				
			0.9338		75.79				
			0.9365		76.01				
			0.9388		76.74				
			0.9415		76.78				
			0.9438		73.41				
			0.9498		73.05				
			0.9507		74.87				
			0.9554		74.78				
			0.9592		77.48				
			0.9644		75.02				
			0.9688		73.95				
			0.9731		78.04				
			0.9811		73.94				
			0.9875		75.38				
			0.9967		75.12				
26	S2	1.0661	0.9498	1.0		71.89	12.3	0.6	12.4
27	S4	1.1120	0.9688	0.9534		69.84	10.6	0.6	10.7
28	S2	1.0661	0.9498	0.9452		68.91	8.9	0.6	9.0
29	S5	0.9586	1.0111	0.9452		73.29	6.9	1.3	7.2
30	S4	1.0124	1.0111	0.9589		71.65	7.2	0.6	7.4
31	S2	1.0174	1.0	1.0		76.31	5.0	0.6	5.2
33	A	1.0	1.0111	1.0		75.83	8.7	0.0	8.8
34	S2	1.0174	0.9406	1.0		65.65	5.0	0.6	5.2
35	S4	1.0410	0.9891	1.0		76.67	6.5	0.6	6.6

Table 2: Additional Information for the $^{27}Al(n,p)^{27}Mg$ Evaluation (Continued)

Ref. No.	Standard	Standard Adjustment Factor	Energy Adjustment Factor	Decay Branch Adjustment Factor	Adjusted Cross Section (mb)	Errors (%) Uncorrelated	Errors (%) Standard	Total[a]
36	S4	0.9709	1.0089	1.0	66.61	5.0	0.6	5.2
38	S2	1.0079	0.9891	0.9863	68.73	7.2	0.6	7.4
39	S2	1.0081	1.0225	1.0	73.19	6.9	0.6	7.1
40	A	1.0	1.0225	0.9836	68.39	6.6	0.0	6.7
41	S2	1.0615	0.9498	1.0	72.59	7.2	0.6	7.3
43	S4	1.0032	0.9945	1.0	67.15	5.0	0.6	5.2
45	S2	1.0	0.9891	0.9863	71.70	7.1	0.6	7.3
46	A	1.0	0.9498	0.9959	64.32	9.3	0.0	9.4
49	S2	1.0041	0.9406	0.9863	81.97 } 77.59	5.3	0.6	5.5
			0.9678		80.51			
			0.9956		74.93			
			1.0089		72.94			

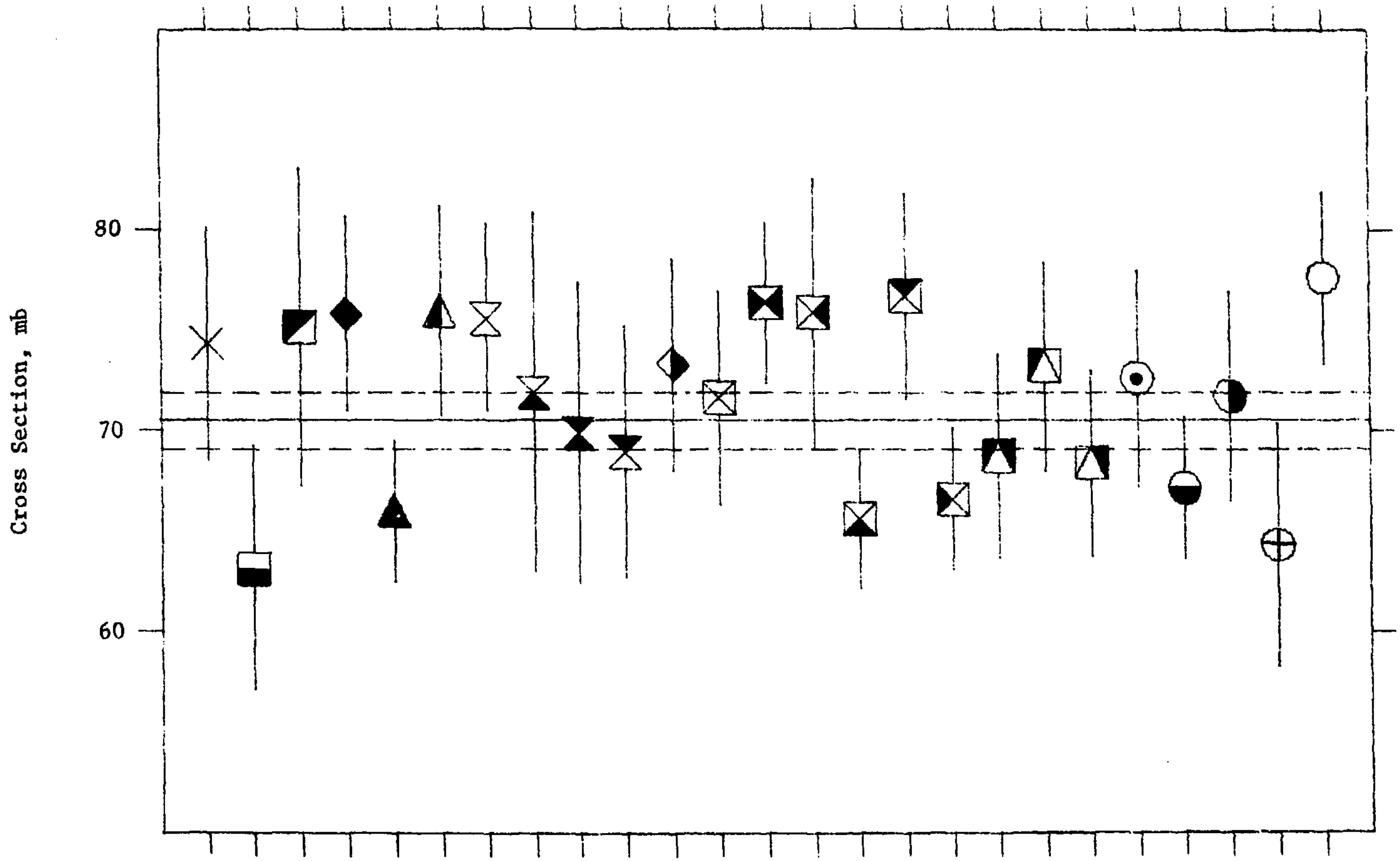
Evaluation Summary:

Evaluated cross section: 70.464 mb

Normalized chi-square: 0.912

Standard deviation: 1.397 mb (~2%)

[a] A fully-correlated error of 1.4% for activity decay branching uncertainty is included.



<u>Figure 2</u>: Evaluation of 14.7-MeV cross sections for Al-27(n,p)Mg-27

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(B) $Si(n,X)^{28}Al$

Elemental silicon has three stable isotopes: ^{28}Si(92.23%), ^{29}Si(4.67%) and ^{30}Si(3.10%) [II.13]. The reactions $^{28}Si(n,p)$, $^{29}Si(n,d)$ and $^{29}Si(n,np)$ need be considered for ^{28}Al production. $^{28}Si(n,p)$ is dominant because of the low threshold and a high abundance for ^{28}Si. Normally, what we call $Si(n,X)^{28}Al$ is referred to in the literature as $^{28}Si(n,p)^{28}Al$, and the isotopic cross section is given. We will adhere to this convention and consider the other two channels as small additive contributors. More details on these reactions . ar in Table I.1.

The decay of ^{28}Al is favorable for activation measurements in most respects. The half life is now well known (2.2405 ± 0.0003 m [II.13]). However, in cross section investigations many other values (both smaller and larger) have been used (ranging from 2.0-2.5 m). In some instances the half life values used were not reported. Since the cross section results depend upon the decay half life, this variation in half lives was a source of noticeable uncertainty for most of the reported data. Accordingly, we added additional random error ranging from 0-5% (in quadrature) to the reported random errors in order to account for this uncertainty. ^{28}Al decays entirely by β^- emission to the 2^+ first-excited of ^{28}Si. This level promptly decays 100% of the time to the ground state by 1.779-MeV gamma-ray emission [II.13]. Thus, regardless of whether beta detection or gamma-ray detection is used, there is no uncertainty due to branching effects in the cross section.

Our survey of the literature produced twenty relevant references, for a total of 46 cross-section values. These data are compiled in Table 1 and are plotted in Fig. 1. We have also plotted the (n,p) cross section for elemental silicon from ENDF/B-V [II.9] for comparison. The shape of this cross section, as well as the normalization, is dominated by $^{28}Si(n,p)^{28}Al$, thus it can be used to calculate energy adjustment factors for conversion of the available data to 14.7-MeV-equivalent values. Five data sets were rejected. The values of Cohen and White [2] were normalized to the result of Paul and Clarke [1] and thus provided no information other than the shape of the cross section from 13.85-15.45 MeV. The data of Kern et al. [3] were normalized to the $^6Li(n,t)^4He$ reaction which is unorthodox in the present context, therefore, we discarded these results. No error information was provided for the experiment of Strain and Ross [6] so it was of little value for our evaluation. The result of Khurana and Govil [7] was rejected because of uncertain documentation. Finally, the value of Ngoc et al. was rejected because of confusion regarding the use of standards [20].

The remaining fifteen data sets were adjusted for revised standards, and equivalent 14.7-MeV results were deduced. Multiple data sets were averaged to single values. The fifteen cross sections were plotted for comparison.

Wide discrepancies were apparent. In order to avoid unreasonable bias in the AVERG calculations, the four lowest cross section values (all < 200 mb) were rejected a priori since they are clearly inconsistent with the remaining data [4,5, 14 and 17]. The remaining eleven values were analyzed using code AVERG. The normalized chi-square obtained in this analysis was 3.14, indicating rather poor consistency for the input data. On the basis of a three-standard-deviation test, four more values were rejected [1,9,11 and 13]. A reanalysis using AVERG with only seven input values yielded an improved normalized chi-square of 2.43, but clearly inconsistency problems for the input data were still very much in evidence. The results of this second analysis were accepted for the final evaluation. This is summarized in Table 2. The value we obtain is 257.25 mb with an enhanced standard deviation of 2.5%.

Table 1: Compiled Data for $Si(n,X)^{28}Al$

Ref. No.	Symbol	Application	Neutron Energy (MeV)	Energy Resolution (MeV)	Reported Cross Section (mb)	Reported Cross Section Error (mb)
1	1	I	14.5	NA	220.0	50.6
2	2	D	13.85	0.3	259.0	14.0
			13.90	0.3	258.0	12.0
			14.0	0.3	261.0	17.0
			14.4	0.3	190.0	12.0
			14.6	0.3	192.0	12.0
			14.9	0.3	192.0	21.0
			15.05	0.4	202.0	12.0
			15.35	0.3	167.0	12.0
			15.45	0.7	181.0	12.0
3	2A	D	13.50	NA	381.6	45.0
			13.59	NA	388.8	46.7
			13.73	NA	348.5	35.0
			13.73	NA	326.4	33.0
			13.84	NA	415.0	46.0
			14.01	NA	441.3	53.0
			14.28	NA	350.5	39.0
			14.28	NA	376.6	47.0
			14.74	NA	340.3	37.0
			14.99	NA	306.2	40.0
			14.99	NA	344.6	45.0
			14.99	NA	260.1	31.0
			15.06	NA	301.0	33.0
			15.44	NA	298.5	33.0
4	2B	I	14.0	NA	157.0	17.27
5	2D	I	13.55	NA	189.0	25.0
			14.90	NA	181.0	20.0
6	3	D	14.7	NA	221.0	NA
7	3A	D	14.8	NA	180.0	18.0
8	3B	E	14.8	0.2	222.0	12.0
9	4	I	14.7	0.2	222.0	12.0
10	4A	E	14.4	0.6	252.0	15.0
11	4B	I	14.7	0.4	297.0	14.0
12	5	E	14.7	0.3	260.0	7.0
13	5A	I	14.5	NA	213.2	18.3
14	5B	I	14.8	1.0	170.0	15.0
15	6	E	14.6	NA	262.1	22.0
16	6A	E	14.78	0.2	265.0	7.5
17	6B	I	14.1	0.6	38.0	12.0
18	7	E	14.8	0.2	272.0	9.9
			14.8	0.2	268.1	6.8

Table I: Compiled Data for $Si(n,X)^{28}Al$ (Continued)

Ref. No.	Symbol	Application	Neutron Energy (MeV)	Energy Resolution (MeV)	Reported Cross Section (mb)	Reported Cross Section Error (mb)
19	8	E	13.9	0.6	285.0	19.0
			14.5	0.6	242.0	16.0
			15.0	0.6	219.0	14.0
			15.4	0.4	196.0	16.0
20	8A	D	14.6	0.4	234.0	15.0

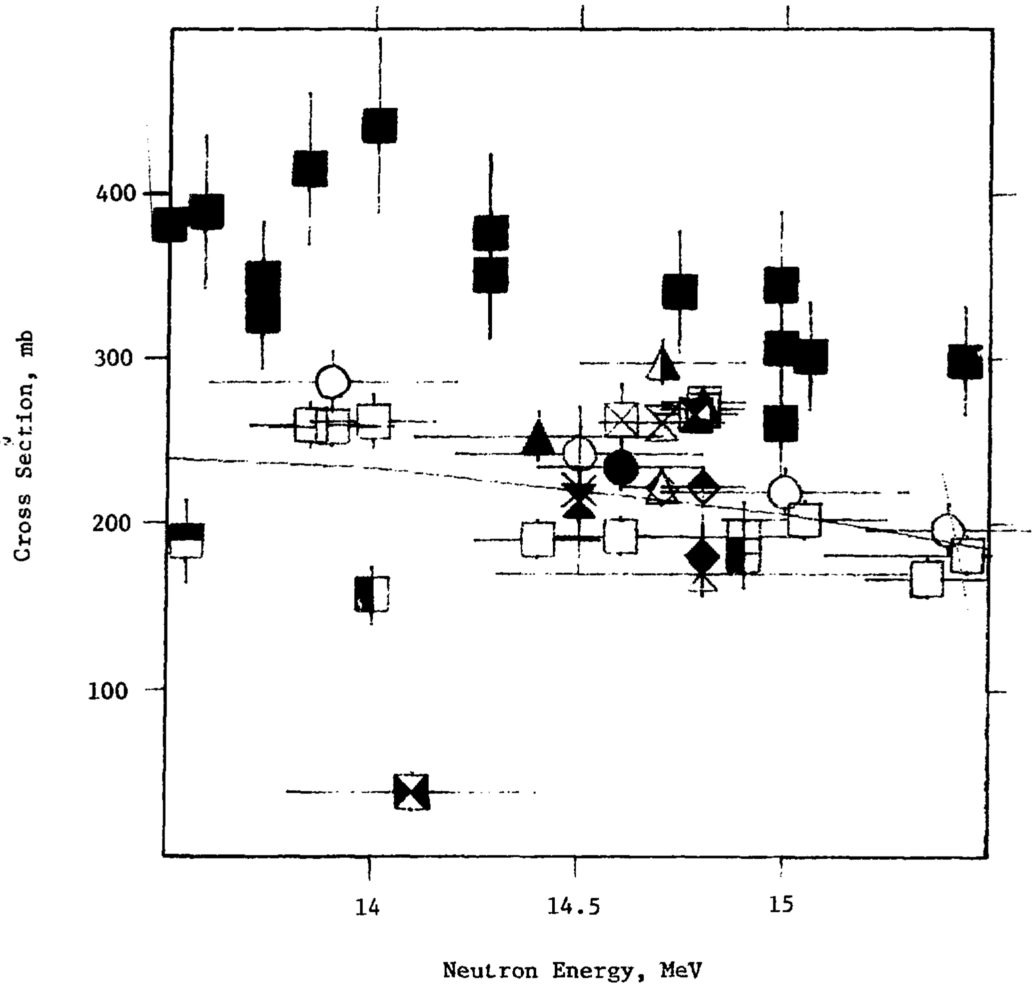

Figure 1: Compiled Experimental Data for Si(n,X)Al-28

Table 2: Additional Information for the Si(n,X)^{28}Al Evaluation

Ref. No.	Standard	Standard Adjustment Factor	Energy Adjustment Factor	Adjusted Cross Section (mb)		Errors (%) Uncorrelated	Standard	Total
8	S5	1.040	1.0135	234.0		3.6	1.3	3.8
10	S4	1.112	0.9615	269.4		6.0	0.6	6.0
12	S2	1.0151	1.0	263.9		5.7	0.6	5.7
15	S4	1.041	0.9863	269.2		8.7	0.6	8.7
16	S4	0.9709	1.0108	260.1		3	0.6	3.1
18	A	1.0	1.0135	275.67	273.0	2.9	0	2.9
				271.72				
19	S4	0.9771	0.9095	253.3	233.8	6.1	0.6	6.1
		1.0027	0.9740	236.3				
		0.9592	1.0417	218.8				
		1.023	1.1304	226.7				

Evaluation Summary:

Evaluated cross section: 257.25 mb

Normalized chi-square: 2.43

Standard deviation: 6.54 mb (2.5%) enhanced

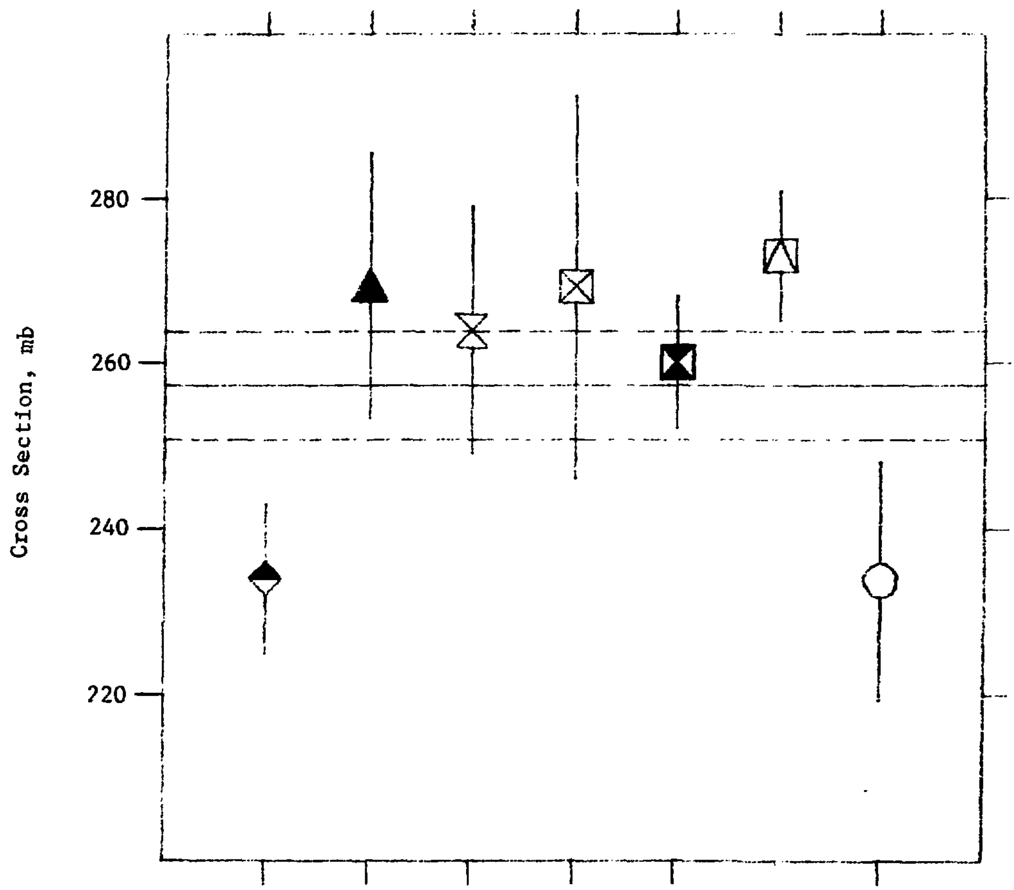

Figure 2: Evaluation of 14.7-MeV Cross Sections for Si(n,X)Al-28

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PRELIM.RESULTS F.ALL REACT.0/REPORT,ZFK-410,190,8001 (1980)

(C) $Ti(n,X)^{46}Sc$

The compilation and evaluation of data for this activation reaction is complicated by two factors: First, there is a short-lived isomer, ^{46m}Sc, and some authors have distinguished between the cross section for exciting this isomer and that for exciting only the ground state, ^{46g}Sc. In this work we designate ^{46}Sc as $^{46g}Sc+^{46m}Sc$; namely, we are interested in the total production of ^{46}Sc. According to Ref. II.13, ^{46m}Sc has a half life of 18.72±0.06 s while ^{46g}Sc has an 83.80±0.03 d half life. For dosimetry applications, where this reaction is of greatest practical interest, activity measurements are likely to be made long after the ^{46m}Sc activity has died away. Furthermore, ^{46m}Sc decays entirely to ^{46g}Sc via an E3 isomeric transition (IT), so measurement of the activities of samples made a few minutes after irradiation will involve the total (g+m) cross section [II.13]. The decay of the ground state, which we will henceforth designate as ^{46}Sc, with the qualifications indicated above, proceeds entirely via β^- emission. Ultimately, a 0.889-MeV gamma-ray, corresponding to the transition from the first-excited state in ^{46}Ti to its ground state, is emitted in 100% of the decays of ^{46}Sc [II.13]. Thus, no decay gamma-ray branch uncertainties need to be included. The second factor to be considered is that natural Ti has several isotopes, and thus several reactions contribute to ^{46}Sc production, as indicated in Table 1 of Section I. Of these, only the (n,p) reaction for ^{46}Ti and (n,np)+(n,d) reactions for ^{47}Ti are significant. In the present work, we have adopted the viewpoint that the ^{46}Sc production cross section for natural Ti is the process of practical interest. On the other hand, many investigators have been concerned with calculating and attempting to measure the individual components. Inevitably there has been a confusion of terms over the years, e.g., as is evident in Ref. 13. An important aspect of the present investigation has been to try and properly interpret the reported data so as to insure that comparable quantities are intercompared. In some instances data had to be rejected because the available information was not adequate to permit this distinction to be made.

In order to minimize the possibility for confusion, the cross section for this reaction should be treated as an elemental cross section. Instead, we have compiled and evaluated values equivalent to the elemental cross section divided by the ^{46}Ti isotopic abundance (8.2% [II.13]), in keeping with normal dosimetry practice. The data therefore represent the $^{46}Ti(n,p)^{46}Sc$ cross section plus an additional component for contributions from the other ^{46}Sc-producing reactions.

Twelve relevant data sets were found in the literature, corresponding to twenty-four distinct cross sections. These values are listed in Table 1 and are plotted in Fig. 1. We have not made a comparison of these values with ENDF/B-V [II.9] because no comparable evaluated results could be obtained from this source (the Dosimetry File gives the $^{46}Ti(n,p)^{46}Sc$ reaction cross sections only). From Ref. 13 it is evident that the cross section for the $Ti(n,X)^{46}Sc$ process, as defined here, varies quite slowly with neutron energy in the 14-15 MeV range, so we have treated all values considered here as comparable to 14.7-MeV values without adjustment of energy scale.

The data of Koehler and Alford [3] were not included in the present evaluation because the standard they used is not part of our basic set, as discussed in Section II. The work of Poularikas and Fink [1] and Qaim and Molla [7] involved the use of isotopically-enriched samples, in part, but an inspection of the details from these experiments indicated to us that not enough information was available to determine how the reported values could be compared to what we were attempting to evaluate. Therefore, these data were not included. The multiple-data-point sets of Liskien and Paulsen [4] and of Viennot et al. [10,11] were averaged to yield a single value per experiment, as described in Section II. No value was given for the standard cross section in the work of Kayashima et al. [8]; however, since $^{27}Al(n,\alpha)^{24}Na$ was used, and this work was relatively recent, we assumed that the standard value was identical to that in Table 1 of Section II and merely increased the uncorrelated error by 2%. Pai [5] and Ribansky and Gmuca [12] provide detailed information on their measurements, including data acquired using an enriched sample. For comparison with the present work, we added the (n,p) results for ^{46}Ti to the (n,np)+(n,d) data reported for ^{47}Ti, using the known isotopic abundances, to obtain a value comparable with the present cross section.

The first-pass evaluation involved 9 values and yielded a normalized chi-square a bit smaller than 2, which indicates fair consistency for the evaluated data. However, two of the values significantly exceeded the three-standard-deviation limit, and each of these bore a large error bar. They were rejected and a second-pass analysis was performed. The resultant normalized chi-square was slightly larger than the first pass, but still near to 2. The increase is not surprising since the data base for the evaluation was reduced by ~ 20% by rejecting two values having large errors and little influence on the chi-square. The net change in the evaluated cross section was negligible. Although the first-and second-pass analyses were thus shown to be nearly equivalent, we chose to report the results of the second pass. The final evaluated cross section is 294.83±6.73 mb. This standard deviation of ~ 2.3% is enhanced, as defined in Section II. The evaluation is summarized in Table 2. Fig. 2 provides a comparison between the evaluated value and the data from which it is derived.

Table 1: Compiled Data for Ti(n,X)^{46}Sc

Ref. No.	Symbol	Application	Neutron Energy (MeV)	Energy Resolution (MeV)	Reported Cross Section (mb)	Reported Cross Section Error (mb)
1	7	D	14.8	0.9	520.0	NA
2	2	E	14.5	NA	268.0	30.0
3	2H	D	14.7	0.35	324.0	97.2
4	3	E	14.05	0.25	299.0	21.0
			14.42	0.26	295.0	21.0
			14.61	0.26	293.0	21.0
			14.99	0.27	285.0	20.0
			15.18	0.26	290.0	20.0
5	8	E	14.8	0.1	291.83	24.51
6	8C	I	14.8	NA	230.0	50.0
7	5	D	14.7	0.15	166.0	15.0
8	6A	I	14.6	NA	230.0	50.0
9	6	E	14.6	0.21	291.4	14.0
10	4	E	14.11	NA	261.0	NA
			14.31	NA	268.0	NA
			14.49	NA	242.0	NA
			14.76	NA	271.0	NA
			14.86	NA	267.0	NA
11	1	E	14.11	NA	310.0	33.0
			14.30	NA	306.0	37.0
			14.47	NA	242.0	33.0
			14.73	NA	306.0	34.0
			14.83	NA	275.0	39.0
12	4A	E	14.8	0.125	323.41	8.87

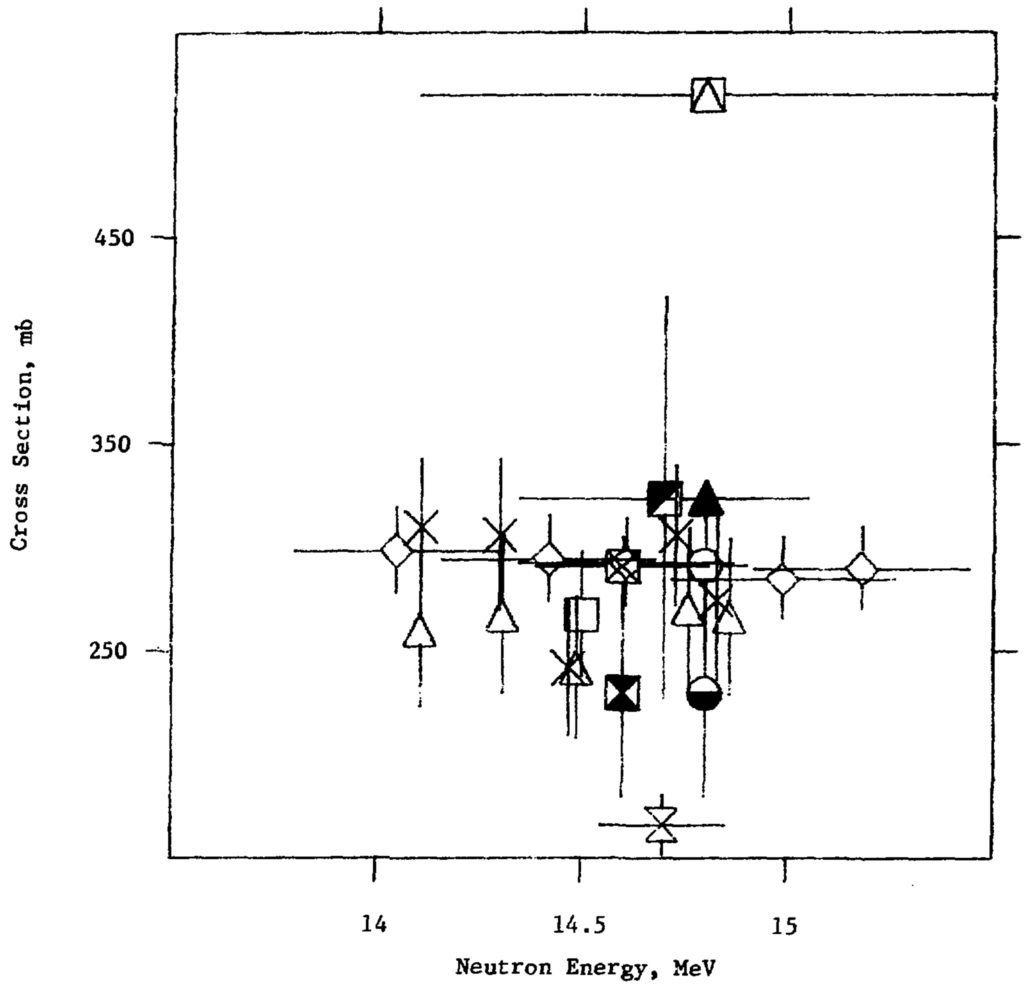


Figure 1: Compiled experimental data for Ti(n,X)Sc-46

Table 2: Additional Information for the Ti(n,X)^{46}Sc Evaluation

Ref. No.	Standard	Standard Adjustment Factor	Adjusted Cross Section (mb)[a]		Errors (%) Uncorrelated	Standard	Total
2	S2	1.0139	271.72		11.2	0.6	11.2
4	S1	1.0	299.0	292.40	3.2	1.0	3.3
			295.0				
			293.0				
			285.0				
			290.0				
5	S2	1.0095	294.60		7.1	0.6	7.1
9	S2	0.9784	285.11		4.1	0.6	4.1
10	S2	1.0049	262.28	260.60	6.4	0.6	6.4
		1.0178	272.77				
		1.0155	242.75				
		1.0073	272.98				
		1.0090	249.22				
11	S2	1.0048	311.49	290.75	5.5	0.6	5.5
		1.0310	315.69				
		1.0085	244.06				
		1.0032	306.98				
		1.0027	275.74				
12	S4	0.9734	314.81		2.7	0.6	2.8

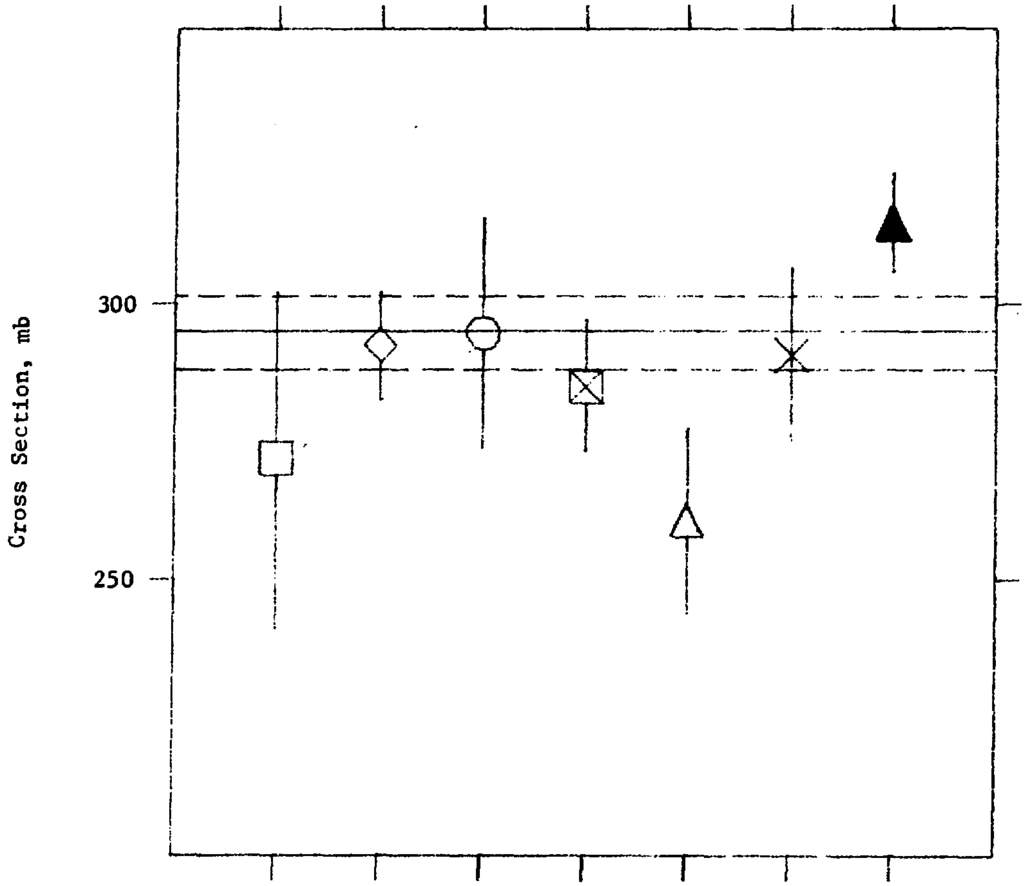
Evaluation Summary:

Evaluated cross section: 294.83 mb

Normalized chi-square: 1.81

Standard deviation: 6.73 mb (2.3%) enhanced.

[a]The energy correction factor is assumed to be 1.0 for all references [13].



<u>Figure 2</u>: Evaluation of 14.7-MeV cross sections for Ti(n,X)Sc-46

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SEE PP.353-360 , 375-426 (1978)

(D) $Ti(n,X)^{47}Sc$

^{47}Sc has a half life of 3.422±0.004 d [II.13], and it decays entirely via β^- emission to levels in ^{47}Ti. Of these decays, 68.5% proceed to the 0.159-MeV first-excited state which then decays with a 0.21 ns half life to the ground state via an electromagnetic transition. All other β^- decays of ^{47}Sc proceed directly to the ground state of ^{47}Ti. Thus, a 0.159-MeV gamma ray is observed in 68.5±2.7% of the ^{47}Sc decays [II.13]. Since the reported measurements of this cross section all involve observation of this gamma-ray, the available results are a priori uncertain by at least 3.9% due to the uncertainty in the gamma-ray branching factor. In an earlier evaluation of the decay parameters for ^{47}Sc (Ref. II.17) it was determined that the gamma-ray branching factor was 73%. In assessing the available data for this reaction we made the following assumptions when the value of the decay branch used was not stated by the authors: for references predating 1968 we assumed 73%, for references after 1978 we assumed 68.5%, and for references in the intervening period we assumed the average, 70.75% and then added an extra 3.3% uncertainty to the cross section error. Also, calibration of gamma-ray detectors for measurement of this gamma ray is somewhat more difficult than normal because of the relatively low gamma-ray energy. Larger-than-average photon absorption corrections are also likely to add to the overall measurement error to an above-average extent. So, it is seen that the activity measurement alone introduces substantial error in this cross section determination.

This, however, was not the major problem we encountered for this reaction. As discussed in some detail in Section III.C (for $Ti(n,X)^{46}Sc$) we are interested here in the cross section per atom of ^{47}Ti for producing ^{47}Sc by fast-neutron bombardment of elemental Ti. According to Table 1 of Section I, four reaction channels are open, involving three isotopes of Ti. Of these, the (n,p) reaction for ^{47}Ti and the indistinguishable (n,np) and (n,d) reactions for ^{48}Ti are dominant. The contribution from ^{48}Ti is substantial here, even though its isotopic cross sections are smaller for (n,np) and (n,d) than (n,p) is for ^{47}Ti, because of the large relative abundance of ^{48}Ti. Referring to Table 1 of Section I, we note that ^{48}Ti is 73.7% abundant while ^{47}Ti is only 7.4% abundant. This fact is the origin of our major difficulty with this reaction, namely that in several instances it was either not explicitly clear from the authors as to which process was measured or, even when the documentation seemed to be adequate, the final results nevertheless appeared to be suspicious. We found eleven references in the literature, for a total of 15 cross section values. These are identified in Table 1 and are also plotted in Fig. 1. The identity problem we faced is very evident in Fig. 1, and it also shows up in Fig. 11 on page 392 of Ref. 12. The reported values tend to cluster into two groups: one group lies < 150 mb and seems to indicate no pronounced energy dependence, while the second group of values is > 150 mb and indicates a pronounced rise in the cross section with neutron energy. It was our suspicion at the outset that the lower values probably represented the cross section for the (n,p) reaction for ^{47}Ti. They are generally consistent with the trend of this cross section as evidenced from the model calculations upon which ENDF/B-V [II.9] is based, and from the extensive data base available for lower energies (e.g., see Fig. 11 on page 392 of Ref. 12). The upper set of values seems to exhibit the correct magnitude and energy dependence for the Ti(n,X)^{47}Sc process we have chosen to investigate. However, our judgement as to which values to include or reject is based on a more careful examination of each reported data set, as discussed below.

The data of Viennot et al. [10] is the most extensive, and they span the 14-15 MeV energy range of interest for the present investigation. The documentation on this work is sufficiently detailed to convince us that the reported cross sections represent the process we are investigating. Furthermore, these data exhibit a well-defined energy dependence (see Fig. 1) which is consistent with a priori expectation, namely that the cross section increases due to the rapid growth in the contribution from ^{48}Ti(n,np) + (n,d) with neutron energy. This energy dependence appears to be nearly linear over the 14-15 MeV range, so we fitted a straight line to the data of Viennot et al. [10] by the least-squares method (see Fig. 2). Then we used this fit in order to adjust all the considered data to equivalent 14.7 MeV values. Three reported works, namely those of Poularikas and Fink [1], Cross and Pai [3] and Qaim and Molla [8] involved the use of isotopically enriched Ti samples. However, in each instance there was either insufficient documentation available, or some of the isotopic cross section values required to derive the Ti(n,X)^{47}Sc cross section were missing. Therefore, the data from these three works were not included in the present evaluation. On the other hand, Pai [4] and Ribansky and Gmuca [11] not only utilized enriched samples but also obtained values for all the necessary isotopic cross-section components of the Ti(n,X)^{47}Sc process. Thus, we were able to utilize these results in the present analysis.

The remaining values from our compilation ostensibily represent ^{47}Sc activation measurements for elemental Ti, and none could be rejected for inadequate documentation. However, the values of Tikku et al. [6] and of Hillman [2] are obviously quite low relative to the rest of the data under consideration. Our first attempt at a least-squares evaluation with AVERG involved inclusion of 8 values, including those of Tikku et al. [6] and Hillman [2]. This analysis produced an evaluated value of 97.5 mb, with a huge normalized chi-square of 41.5. Further consideration of this anomalous result convinced us that, in fact, the least-squares method we used essentially "breaks down" in the face of such an inconsistent data base. Since this point is of fundamental concern for our entire evaluation process, we explored the problem in more detail using hypothetical examples, and indeed we convinced ourselves that the least-squares method encounters serious difficulty when the data are very inconsistent. To illustrate this point we consider an extreme case where only two values are available, each with a comparable error of ~ 10%. However, one value is 1.0 (unity) while the second is 10.0. Clearly a data set consisting of 1.0 $\pm$ 0.1 and 10.0 $\pm$ 1.0 is highly inconsistent. Instinctively we would suspect that the best value is the average, 5.5, with a large error (perhaps ~ 4.5). We would be inclined to treat the stated 10% errors as unrealistic. However, rigorous application of the least-squares method, accepting the quoted errors, yields 1.089 as the best value (assuming no correlations)! So, we see a tendency for an evaluation to be strongly biased toward the low values of the set when the low-value errors are comparable percentagewise to errors of other members of the set, and when the data base is very inconsistent. This, then, is the crux of the main analytic problem we faced in evaluating the Ti(n,X)^{47}Sc reaction.

We subsequently attempted an evaluation in which the value of Tikku et al. [6], which carries a relatively small reported error, was excluded. The result was 205.1 mb with a normalized chi-square of 16.2. The rejection of this single data point led to a significant improvement. When the value of Tikku et al. [6] was retained but that of Hillman [2] excluded, the result of the evaluation was 99.6 mb with a normalized chi-square of 47.9. Exclusion of both the Tikku et al. [6] and Hillman [2] values produced the result 223.1 mb with a normalized chi-square of 13.2. Clearly a rational evaluation could not be performed without making a decision regarding these two apparently low values, especially that of Tikku et al. [6]. The choices available to us were to either reject these data (certainly that of Tikku et al. [6] and possibly the Hillman value [2] as well) or to increase the errors in order to mitigate their impact upon the evaluation. Rejection of both of these values appeared to us to be the least arbitrary of the available pragmatic options. In Table 1 we have indicated rejection on the basis incompatability with the general available body of information on this reaction. In fact, it seems to be quite reasonable to reject these values on the grounds that they appear to be consistent with the general knowledge of the isotopic ^{47}Ti(n,p)^{47}Sc cross section, based on lower-energy data and nuclear-model systematics, and so are very unlikely to represent the Ti(n,X)^{47}Sc process we are currently considering, since it has a considerably larger cross section.

The final results of our evaluation are summarized in Table 2 and Fig. 3. Our evaluated cross section is 223.11±38.33 mb. The indicated error is enhanced, as discussed in Section II, in accordance with the normalized chi-square of 13.23. Thus, the data we finally included in this evaluation are still quite inconsistent, and the error of 17.2% in the evaluation is, therefore, realistic.

Table 1: Compiled Data for Ti(n,X)^{47}Sc

Ref. No.	Symbol	Application	Neutron Energy (MeV)	Energy Resolution (MeV)	Reported Cross Section (mb)	Reported Cross Section Error (mb)
1	1	D	14.8	0.9	230.0	40.0
2	2	I	14.5	0.25	99.0	20.0
3	2A	D	14.5	NA	120.0	12.0
4	3	E	14.8	0.05	272.28	21.0
5	3A	E	14.8	NA	170.0	40.0
6	4	I	14.7	0.15	85.0	7.0
7	5	E	14.1	NA	121.0	11.0
8	6	D	14.7	0.15	116.0	14.0
9	6A	E	14.1	NA	220.0	5.0
10	7	E	14.11	NA	186.0	26.4
			14.31	NA	192.0	27.3
			14.44	NA	218.0	31.0
			14.76	NA	256.0	36.3
			14.86	NA	271.0	38.5
11	8	E	14.8	NA	284.39	8.6

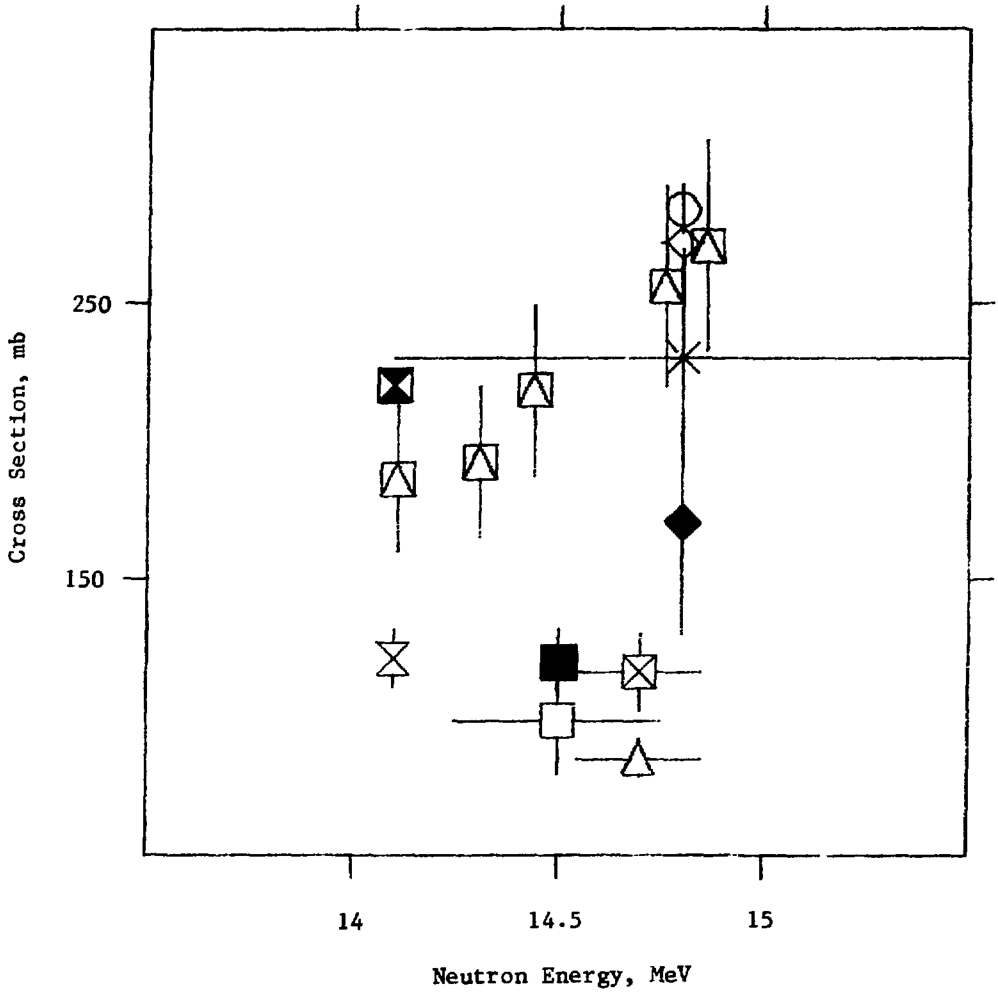

Figure 1: Compiled experimental data for Ti(n,X)Sc-47

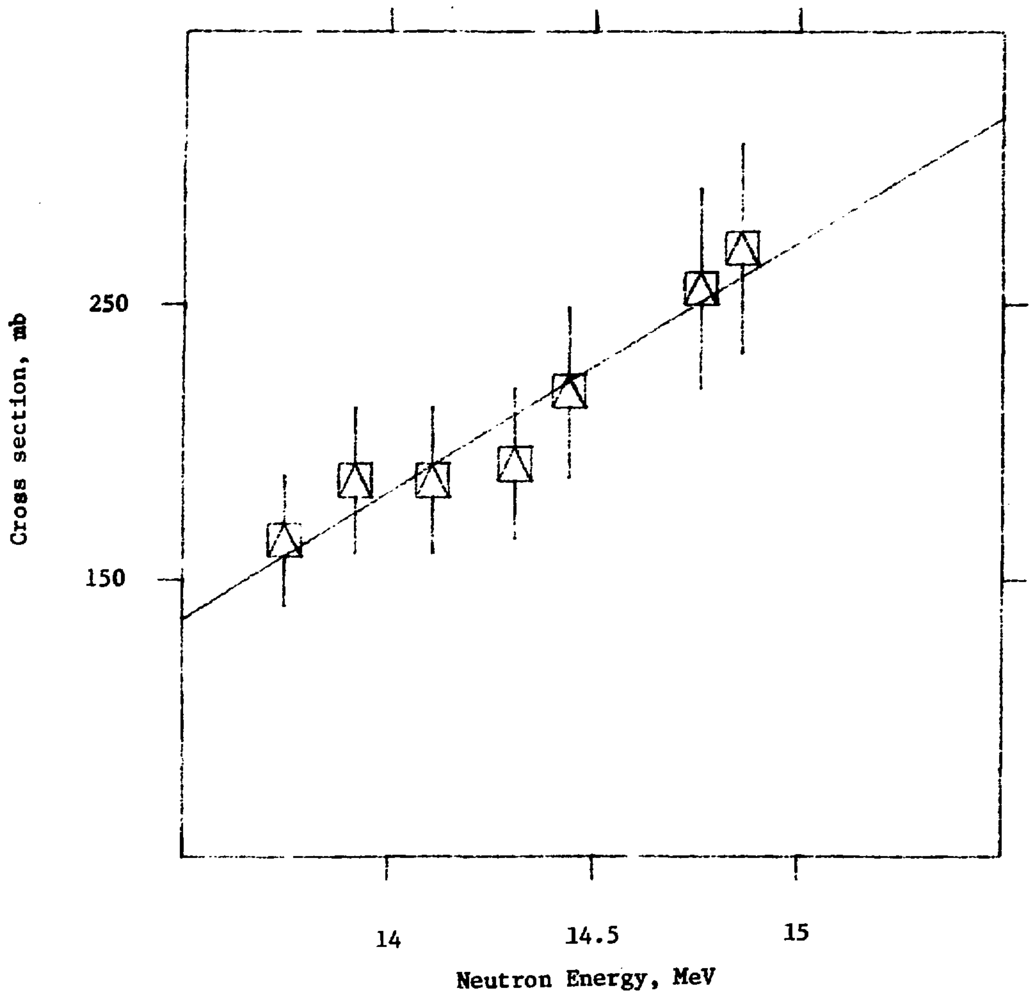

Figure 2: Least-squares fit of a straight line to the data of Viennot et al. (Ref. 10) for use in estimating energy correction factor for Ti(n,X)Sc-47 data.

Table 2: Additonal Information for the Ti(n,X)^{47}Sc Evaluation

Ref. No.	Standard	Standard Adjustment Factor	Energy Adjustment Factor	Decay Branch Correlation Factor	Adjusted Cross Section (mb)		Errors (%) Uncorrelated	Errors (%) Standard	Total[a]
4	S2	1.0095	0.9640	1.0657	282.38		6.3	0.6	7.4
5	A	1.0	0.9640	1.0657	174.65		23.5	0.0	23.9
7	S2	1.0652	1.2882	1.0657	176.94		5.9	0.6	7.1
9	S2	1.004	1.2882	1.0328	293.87		4.0	0.6	5.6
10	S2	1.0049	1.2821		239.64	243.76	6.4	0.6	7.5
		1.0178	1.1702		228.68				
		1.0155	1.0850	1.0	240.20				
		1.0073	0.9781		252.22				
		1.0090	0.9437		258.00				
11	S4	0.9734	.96400	1.0	266.86		3.0	0.6	5.0

Evaluation Summary:

Evaluated cross section: 223.11 mb

Normalized chi-square: 13.23

Standard deviation: 38.33 mb (17.2%) enhanced

[a]Includes a decay error of 3.9% which is 100% correlated.

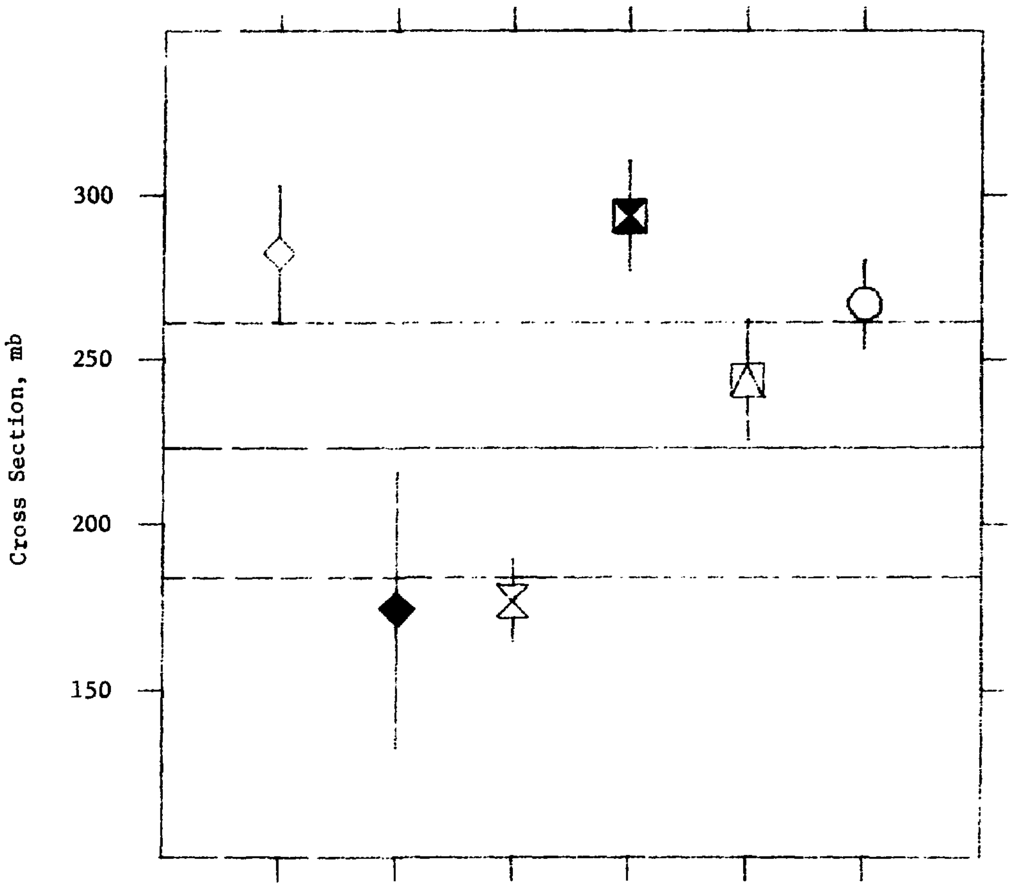

Figure 3: Evaluation of 14.7-MeV cross sections for Ti(n,X)Sc-47

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(E) $Ti(n,X)^{48}Sc$

The compilation and evaluation of data for this reaction presents relatively fewer problems than do the ^{46}Sc and ^{47}Sc production reactions for Ti, discussed in Sections III.C and III.D, respectively. First, the decay properties of ^{48}Sc are not complex. The half life is a convenient 43.67±0.09 h [II.13]. Uncertainties related to the half life can be neglected for practical purposes. ^{48}Sc decays to levels in ^{48}Ti by β^- emission, and prompt gamma rays are produced with the following branching factors: 0.984 MeV (100.0±0.2%), 1.312 MeV (97.5±0.3%) and 1.311 (100.0±0.3%). The only possible concern in gamma-ray counting is for experimental losses due to coincidence-summing effects. These corrections are very sensitive to the counting geometries and detectors involved, so we assume that the experimenters have taken this matter into consideration in their work. Natural Ti has several isotopes which lead to ^{48}Sc production (as indicated in Table 1 of Section I), among these only the (n,p) reaction for ^{48}Ti and (n,np) + (n,d) reactions for ^{49}Ti are important, and ~ 14 MeV the contribution attributed to ^{49}Ti is relatively small (less than 1%).

Twenty-two references were found in the literature, corresponding to fifty-one distinct cross sections. These values are listed in Table 1 and are plotted in Fig. 1. Three data sets were rejected: one because of a lack of documentation [15], a second because an unorthodox standard was used [3], and the third because no error information was provided in the documentation [6]. Thus, nineteen sets were initially taken into account for this evaluation. For the multiple-data sets [7,13,18,19 and 20] the available values were averaged in order to provide a single equivalent value for each set, after applying adjustments for revised standard cross sections and for neutron-energy effects. The neutron-energy adjustment factors were calculated using the ENDF/B-V evaluated curve shown in Fig. 1 [II.9]. For the multiple data sets of Mannhart and Vonach [13], Lu Han-Lin et al. [18] and Viennot et al. [19,20], it was not clear what portions of the errors in the measurements were correlated among the various points within each particular set and which were entirely random. Thus we assumed that ~ 50% of the quoted error was correlated within each set. This assumption assured that the averaging process did not produce too small an error (< 2%) for any one of the data sets.

The normalized chi-square obtained this way was 4.4, which indicates significant inconsistency in the input values. Four of these values exceeded the three-standard-deviation limit by considerable amounts so they were rejected and the analysis was repeated. The results of the second analysis, based upon fifteen values, appear in Table 2. For these the normalized chi-square is 2.54 which represents a considerable improvement. The fifteen values chosen for this final evaluation are only moderately inconsistent, as indicated by the calculated chi-square. For the final evaluation we obtain 60.61±1.43 mb. This standard deviation is 2.4%, including an enhancement factor of ~ 1.6 as defined in Section II. Fig. 2 provides a comparison between the evaluated value and the data upon which is it based. ENDF/B-V [II.9] predicts the value 62.8 mb at 14.6 MeV which is 3.6% larger than the present result.

Table 1: Compiled Data for $Ti(n,X)^{48}Sc$

Ref. No.	Symbol	Application	Neutron Energy (MeV)	Energy Resolution (MeV)	Reported Cross Section (mb)	Reported Cross Section Error (mb)
1	6A	I	14.5	NA	92.7	32.6
2	2F	E	14.8	0.9	58.0	8.0
3	3A	D	13.95	NA	66.0	3.0
			14.5	NA	67.0	3.0
			15.0	NA	66.0	3.0
4	2C	E	14.5	0.5	55.0	11.0
5	4B	E	14.5	NA	62.0	7.0
6	4A	D	14.7	NA	132.0	NA
7	5B	E	14.1	0.3	62.8	4.8
			15.0	0.3	64.0	6.7
8	1	E	14.8	0.1	63.7	4.0
9	2	E	14.8	NA	63.0	6.0
10	7C	I	14.7	0.2	80.0	4.0
11	7	E	14.8	0.5	70.0	6.0
12	7D	I	14.7	0.3	44.0	8.0
13	8A	E	13.6	0.16	57.1	0.7
			13.7	0.16	58.0	0.7
			13.8	0.16	58.8	0.7
			13.9	0.16	59.5	0.7
			13.95	0.16	59.8	0.7
			14.0	0.16	60.0	0.7
			14.1	0.16	60.5	0.7
			14.2	0.16	60.8	0.7
			14.3	0.16	61.1	0.7
			14.4	0.16	61.2	0.7
			14.5	0.16	61.2	0.7
			14.6	0.16	61.1	0.7
			14.7	0.16	60.9	0.7
14	8B	E	14.1	NA	66.0	7.0
15	8F	D	14.7	0.3	53.0	6.0
16	2B	E	14.1	NA	63.0	2.0
17	6	E	14.6	NA	55.0	5.0
18	3	E	13.68	0.35	59.6	3.1
			14.36	0.15	62.9	3.4
			14.61	0.21	63.7	3.2
			14.77	0.25	64.3	3.7
19	4	E	13.75	NA	49.0	NA
			13.92	NA	53.0	NA
			14.11	NA	54.0	NA
			14.31	NA	53.4	NA
			14.49	NA	55.2	NA
			14.76	NA	57.0	NA
			14.86	NA	57.4	NA
20	5	E	13.77	NA	51.0	3.0

Table 1: Compiled Data for Ti(n,X)^{48}Sc (Continued)

Ref. No.	Symbol	Application	Neutron Energy (MeV)	Energy Resolution (MeV)	Reported Cross Section (mb)	Reported Cross Section Error (mb)
20	5	E	13.93	NA	53.0	3.0
			14.11	NA	55.0	3.0
			14.30	NA	53.0	3.0
			14.47	NA	55.0	3.0
			14.73	NA	61.0	3.0
			14.83	NA	56.0	3.0
21	6B	I	14.8	0.3	38.0	7.7
22	8	E	14.8	0.25	72.2	2.6

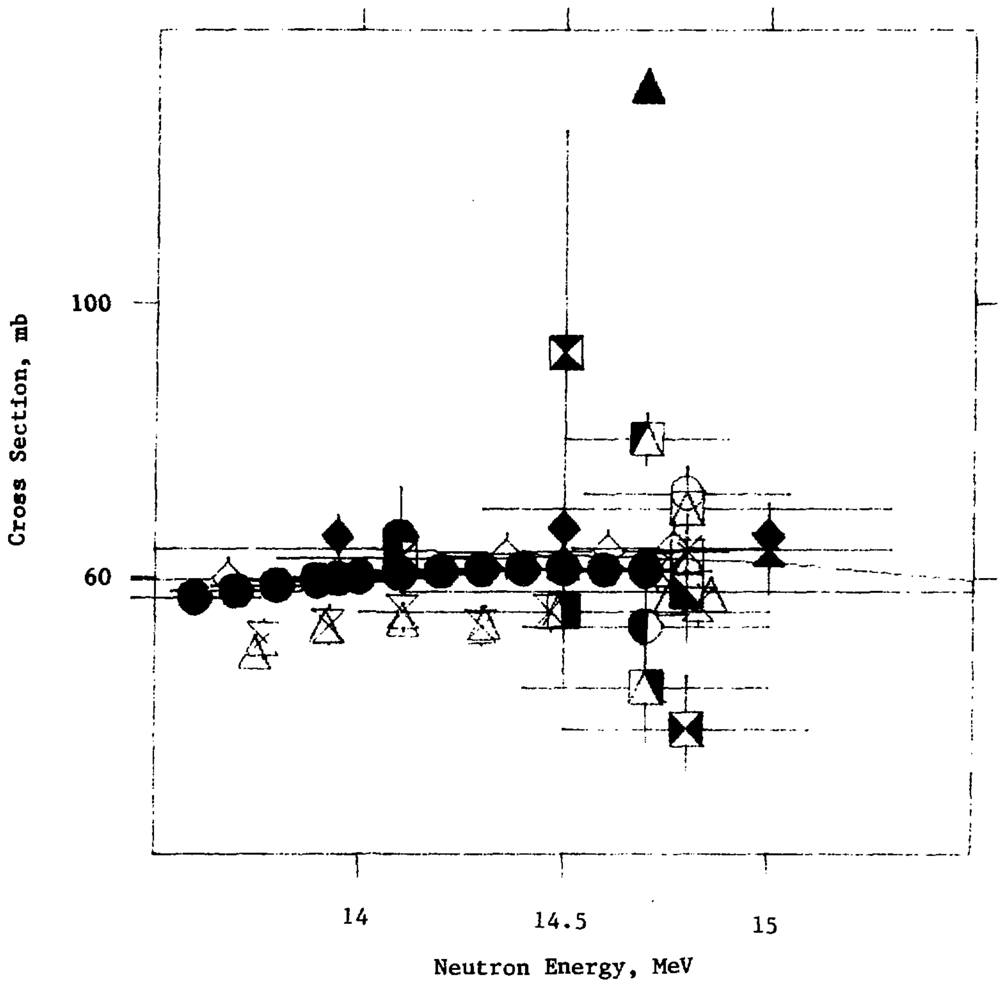

Figure 1: Compiled experimental data for Ti(n,X)Sc-48

Table 2: Additional Information for the Ti(n,X)^{48}Sc Evaluation

Ref. No.	Standard	Standard Adjustment Factor	Energy Adjustment Factor	Adjusted Cross Section (mb)		Errors(%) Uncorrelated	Errors(%) Standard	Errors(%) Total
2	S5	0.9914	1.0032	57.68		12.8	1.3	12.9
4	S2	1.014	0.9936	55.41		19.7	0.6	19.7
5	S2	1.014	0.9936	62.47		11.3	0.6	11.3
7	A	1.0	0.9812	61.62		6.4	0.0	6.4
8	S2	1.0095	1.0032	64.47		6.4	0.6	6.4
9	A	1.0	1.0032	63.20		9.5	0.0	9.5
11	S4	0.8436	1.0032	59.24		8.6	0.6	8.6
13	S2	1.0174	0.9750	59.17	59.97	3.5	0.6	3.8
			0.9750	56.50				
			0.9750	57.39				
			0.9750	58.18				
			0.9750	58.88				
			0.9750	59.37				
			0.9780	59.57				
			0.9811	60.06				
			0.9842	61.18				
			0.9873	61.48				
			0.9904	61.67				
			0.9936	61.77				
			1.0	61.96				
14	S2	1.056	0.9812	68.39		8.1	0.6	8.1
16	S2	1.0041	0.9812	62.07		3.5	0.6	3.5
17	S2	1.0	0.9968	54.82		9.3	0.6	9.3

Table 2: Additional Information for the Ti(n,X)^{48}Sc Evaluation (Continued)

Ref. No.	Standard	Standard Adjustment Factor	Energy Adjustment Factor	Adjusted Cross Section (mb)		Errors(%) Uncorrelated	Errors(%) Standard	Errors(%) Total
18	S2	0.9784	0.9781	56.94	60.75	4.2	0.6	4.2
			0.9892	60.88				
			0.9971	62.14				
			1.0022	63.05				
19	S2	1.0049	0.9871	48.16	53.88	4.5	0.6	4.5
		1.0049	0.9781	52.09				
		1.0049	0.9815	53.26				
		0.9875	0.9877	52.08				
		1.015	0.9940	55.72				
		1.0082	1.0019	57.58				
		1.0090	1.0058	58.25				
20	S2	1.0049	0.9781	50.13	54.59	4.5	0.6	4.5
		1.0049	0.9781	52.09				
		1.0049	0.9815	54.25				
		1.0052	0.9874	52.61				
		1.0094	0.9927	55.11				
		1.0032	1.0009	61.25				
		1.0079	1.0042	56.68				
22	S4	0.9734	1.0032	70.51		3.0	0.6	3.1

Evaluation Summary:

Evaluated cross section: 60.61 mb

Normalized chi-square: 2.54

Standard deviation: 1.43 mb (~ 2.4%) enhanced

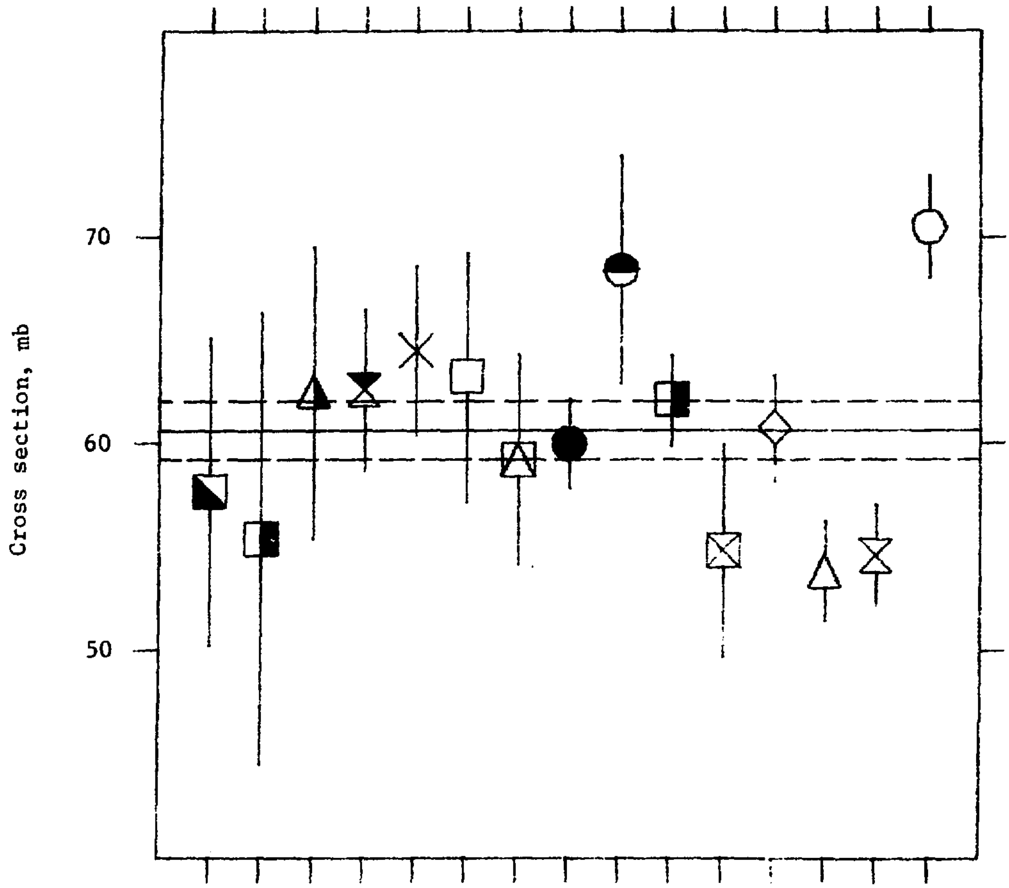

Figure 2: Evaluation of 14.7-MeV cross sections for Ti(n,X)Sc-48

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(F) $^{51}V(n,p)^{51}Ti$

^{51}V is 99.750% abundant and the only other isotope of vanadium is ^{50}V. Consequently, the production of ^{51}Ti activity proceeds exclusively via the single indicated reaction. ^{51}Ti decays by β^- emission, with a half life of 5.80±0.03 m, to levels in ^{51}V, and a 0.320-MeV gamma ray is emitted in 93.4±0.9% of these decays [II.13]. We assume that the half life is a source of ~ 0.5% error while the gamma decay branch contributes ~ 1% error for a net systematic error of ~ 1.1%. The currently accepted half life does not differ by more than 1% from most other values reported in the literature for the past two decades (e.g., Refs. 23, II.13 and II.17). We examined the sensitivity of the measurement process to the assumed half life and chose to increase the uncorrelated error accordingly for data where the authors quote half lives differing from 5.80 m, or where no value was provided for the half life. These error enhancements amounted to less than 2% in all cases. Likewise, we made estimates of the gamma-ray decay branching factor when it was not provided. In several instances β^- counting was performed, and sometimes it was not entirely clear what method was used to calibrate the beta counters. In these instances we also enhanced the uncorrelated errors, but never by more than 2%.

Twenty-three data points were compiled from the literature, corresponding to twenty one distinct experiments [1-21]. These data are listed in Table 1 and plotted in Fig. 1. Four of these sets [2,5,18 and 21] were rejected, in each case due to the absence of adequate details as needed for proper evaluation. Sets with multiple data were averaged to produce an equivalent single data point. All data were adjusted for standards revisions, neutron energy and decay constants, as described in Section II. This procedure yielded seventeen values for the initial evaluation using code AVERG. Taken together, these data exhibit a high degree of inconsistency, with a normalized chi-square of 26.94. Four data points were rejected as inconsistent with the ensemble based on the three-standard deviation test [4,8,13 and 15]. Conservatively, we rejected only those values which not only fell more than three standard deviations from the average but also had errors which failed to overlap this region. Included among the rejected values was that of Dressler et al. [13] which was not only discrepant but also carried a small quoted error, thus tending to distort the evaluation process with a resultant large normalized chi-square. A second evaluation calculation was performed with the thirteen remaining data points. This analysis yielded a normalized chi-square of 4.81. This result implies significant inconsistency in the data, but to a much lesser degree than initially obtained for the entire ensemble. Consequently, we base our evaluation on this second calculation. The results appear in Table 2 and are represented graphically in Fig. 2. Our evaluated cross section is 31.873±1.394 mb. The indicated 4.4% uncertainty includes an enhancement factor, as discussed in Section II. The cross section predicted by ENDF/B-V [II.9] is 36.1 mb, which is 13% larger than the present evaluated result.

Table 1: Compiled Data for $^{51}V(n,p)^{51}Ti$

Ref. No.	Symbol	Application	Neutron Energy (MeV)	Energy Resolution (MeV)	Reported Cross Section (mb)	Reported Cross Section Error (mb)
1	1	E	14.5	NA	27.0	4.05
2	2	D	14.8	NA	53.0	5.0
3	2A	E	14.1 15.2	0.4 0.8	36.5 36.0	3.0 3.0
4	2B	I	14.7	0.4	55.0	12.0
5	2D	D	14.7	NA	48.0	NA
6	3	E	14.0 14.8	NA NA	22.0 25.0	2.86 3.0
7	3A	E	14.8	0.2	24.7	2.2
8	3B	I	14.7	0.2	55.0	5.0
9	4	E	14.8	NA	38.0	8.0
10	4A	E	14.7	0.4	35.2	1.6
11	4B	E	14.8	1.0	37.0	4.0
12	5	E	14.7	0.6	24.9	2.7
13	5A	I	14.6	NA	14.6	0.7
14	5B	E	14.78	0.2	31.0	1.3
15	6	I	14.1	NA	42.0	4.0

Table 1: Compiled Data for $^{51}V(n,p)^{51}Ti$ (Continued)

Ref. No.	Symbol	Application	Neutron Energy (MeV)	Energy Resolution (MeV)	Reported Cross Section (mb)	Reported Cross Section Error (mb)
16	6A	E	14.6	0.4	35.0	4.0
17	6B	E	14.7	0.6	33.0	3.0
18	7	D	14.6	0.4	31.0	2.0
19	8	E	14.7	0.6	37.55	3.9
20	8A	E	14.2	0.4	32.3	2.6
21	8B	D	14.6	0.4	28.0	1.5

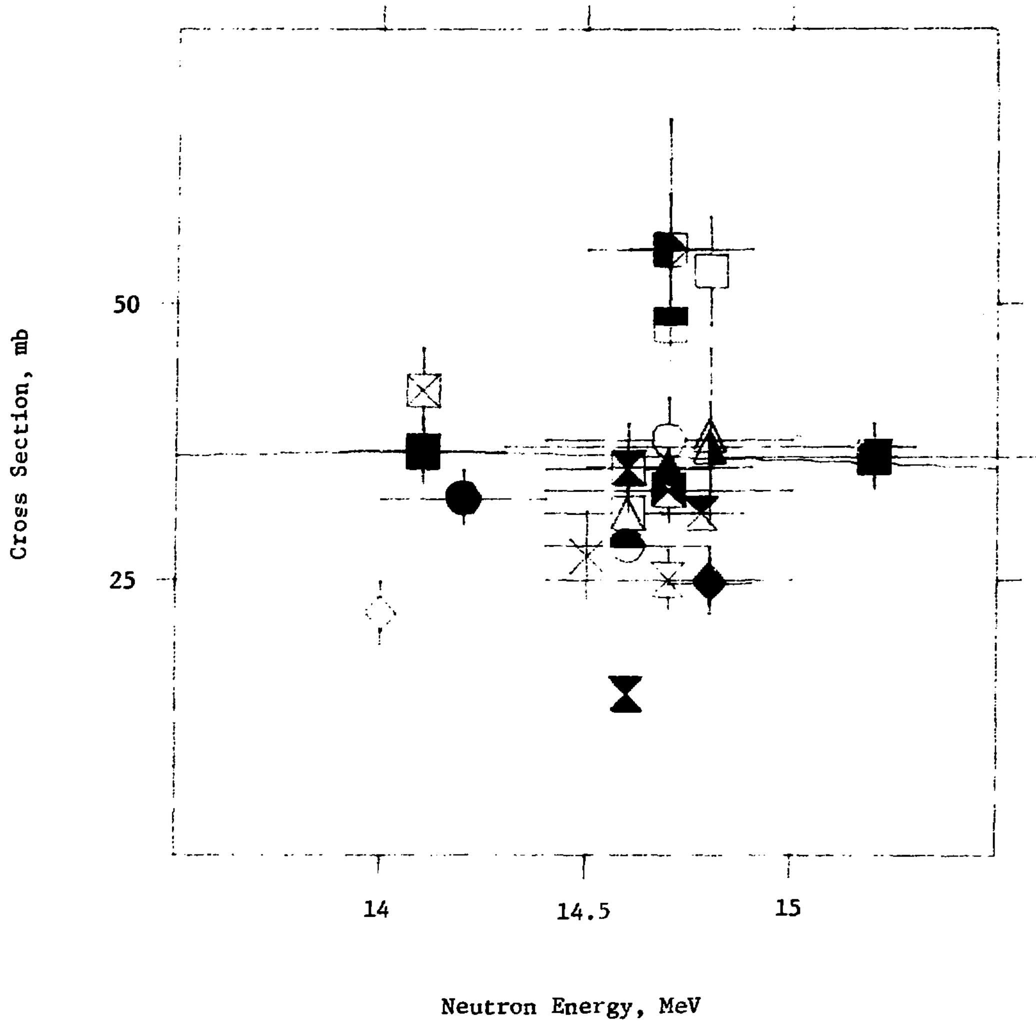

Figure 1: Compiled experimental data for V-51(n,p)Ti-51

Table 2: Additional Information for the $^{51}V(n,p)^{51}Ti$ Evaluation

Ref. No.	Standard	Standard Adjustment Factor	Energy Adjustment Factor	Decay Branch Adjustment Factor	Adjusted Cross Section (mb)		Errors(%) Uncorrelated	Errors(%) Standard	Errors(%) Totals[a]
1	A	1.000	0.9950	1.000	26.865		15.1	0	15.1
3	S5	0.9452	0.9852 1.017	1.017	34.567 35.194	34.881	1.9	1.3	2.6
6	S4	1.042	0.9828 1.003	1.000	22.53 26.13	24.33	9.2	0.6	9.3
7	S5	1.040	1.003	1.000	25.77		7.6	1.3	7.8
9	A	1.000	1.003	1.017	38.76		21.1	0	21.1
10	A	1.000	1.000	1.017	35.80		5.0	0	5.1
11	S4	0.8460	1.003	1.000	31.40		12.4	0.6	12.5
12	S2	0.9974	1.000	1.006	24.98		9.0	0.6	9.1
14	S4	0.9681	1.003	1.000	30.10		3.9	0.6	4.1
16	S2	1.008	0.9975	1.006	35.40		11.6	0.6	11.7
17	S2	0.9397	1.000	1.000	31.82		7.9	0.6	8.0
19	S2	0.9887	1.000	0.9636	35.77		9.8	0.6	9.9
20	A	1.000	0.9877	1.000	31.90		8.0	0	8.1

Evaluation Summary:

Evaluated cross section: 31.873 mb

Normalized chi-square: 4.81

Standard deviation: 1.394 mb (4.4%) enhanced

[a] A 100% correlated error of 1.1% is included for each of these data points to account for half life and decay uncertainties.

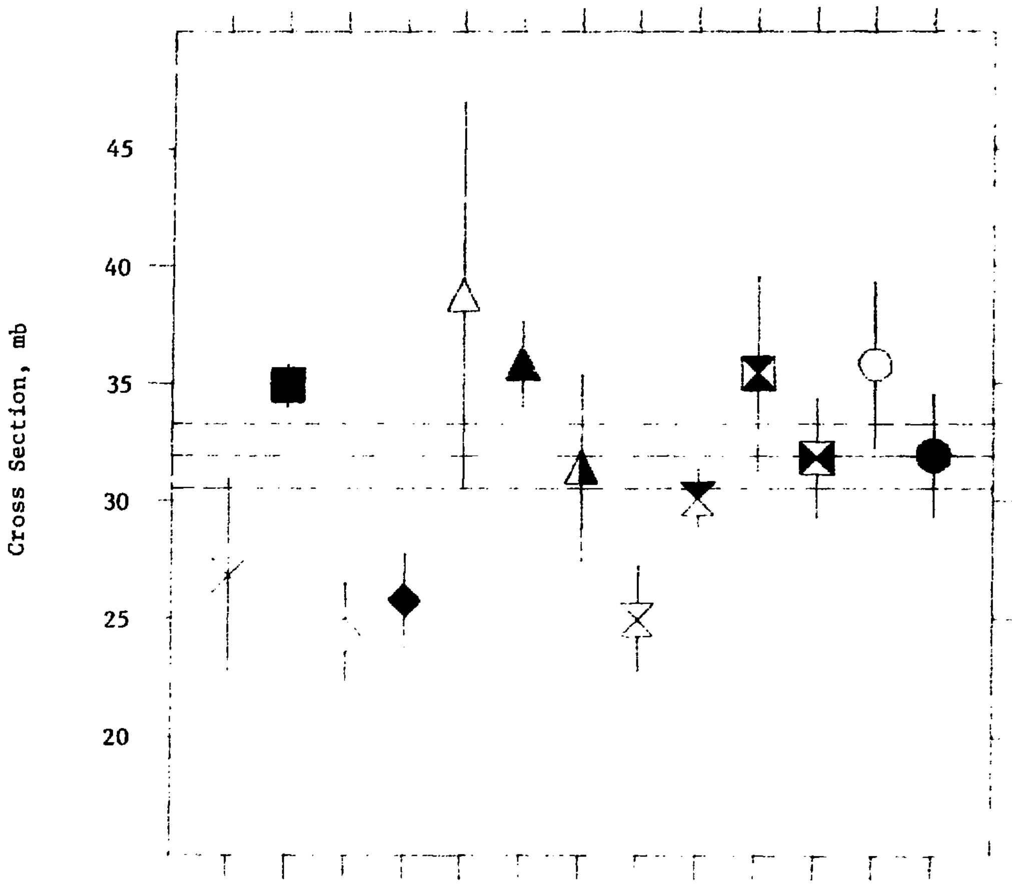

Figure 2: Evaluation of 14.7-MeV cross sections for V-51(n,p)Ti-51

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(G) $^{51}V(n,\alpha)^{48}Sc$

The isotope ^{51}V is 99.750% abundant in elemental vanadium so the distinction between the elemental and isotopic cross section is inconsequential [II.13]. Furthermore, no reactions other that $^{51}V(n,\alpha)^{48}Sc$ contribute to ^{48}Sc production when vanadium is bombarded with fast neutrons. ^{48}Sc decays entirely by β^- emission to levels in ^{48}Ti, and prompt gamma rays are produced. The dominant gamma-ray branches are 0.984 MeV (100.0 ± 0.3%), 1.037 MeV (97.5 ± 0.3%) and 1.312 MeV (100.0 ± 0.3%), with all other gamma-ray yields being much less important [II.13]. Therefore, gamma-ray counting provides a convenient means for measuring ^{48}Sc activity provided that corrections are applied for sum-coincidence effects in detector arrangements which are sensitive to this phenomenon. All data sets ultimately utilized were derived from gamma-ray counting measurements. We assume a 0.3% uncertainty in the decay branch in assessing the experimental errors.

In view of the above considerations, all the measured activation data can be viewed as being comparable. Our survey of the literature produced nineteen experimental data sets. Five of these sets involved more than one data point, so a total of 39 cross section values were considered. These data are listed in Table 1 and are plotted in Fig. 1. In addition, we have plotted the JENDL-2 evaluated cross section curve [20] for comparison. In a recent study from our laboratory (Ref. 21), we pointed out that this Japanese evaluation appears to better represent the available data ~ 14 MeV then does ENDF/B-V [II.9]. We employed the JENDL-2 [20] curve to estimate adjustment factors required to transform the reported values to equivalent 14.7-MeV cross sections.

Three data sets were rejected a priori because we could not obtain the original papers with details of the work (Refs. 2,3 and 17). A fourth (Ref. 7) was also rejected because the original paper contained no error information. Thus, fifteen sets were considered for the evaluation. For multiple data sets, the available values were averaged to produce single values, after applying adjustments for revised standard cross sections and for neutron-energy effects. The corresponding random errors were reduced as deemed appropriate. The fifteen values available for the evaluation were analyzed using code AVERC. The normalized chi-square was ~ 7.8 which indicates considerable inconsistency in the input values. Four of these values were obviously quite inconsistent with the weighted average of the entire collection so they were rejected. The remaining values either fell within the three-enhanced-standard deviation limit or were quite near, considering the error bars, so they were retained for the final evaluation.

The results of this evaluation, based on eleven values, appear in Table 2 and Fig. 2. The normalized chi-square was ~ 7.3 which indicates that rather little benefit accrued from rejecting four of the original fifteen values. The large normalized chi-square comes about mainly because some of the values (especially the two values originating from the work of Vonach et al. [8] and Mannhart and Vonach [13]) carry very small errors, while scatter in excess of the errors is evident from Fig. 2. The evaluated value we obtain is 15.888 ± 0.388 mb. The standard deviation of 2.4% includes an enhancement factor of ~ 2.7 to accommodate the large chi-square.

The present evaluated value and the 16.22-mb value predicted by JENDL-2 [20] for 14.7 MeV differ by only ~ 2%. However, ENDF/B-V [II.9] predicts a cross section of 17.54 mb which is ~ 10.4% larger than our result. It appears that the data indeed favor values lower than ENDF/B-V [II.9] in this energy region.

Table 1: Compiled Data for $^{51}V(n,\alpha)^{48}Sc$

Ref. No.	Symbol	Application	Neutron Energy (MeV)	Energy Resolution (MeV)	Reported Cross Section (mb)	Reported Cross Section Error (mb)
1	1	I	14.5	NA	28.6	12.0
2	2	D	14.1	NA	13.5	1.4
3	2A	D	14.8	NA	30.5	0.4
4	2B	I	14.1	0.4	20.6	4.3
			15.2	0.4	28.2	5.9
5	2D	E	14.5	0.5	18.0	3.0
6	3	I	14.7	0.2	23.0	4.0
7	3A	D	14.7	NA	34.0	NA
8	3B	E	13.6	0.075	12.1	0.46
			13.7	0.075	12.3	0.47
			13.8	0.075	12.5	0.47
			13.9	0.075	12.7	0.48
			14.0	0.075	13.0	0.49
			14.1	0.075	13.3	0.50
			14.2	0.075	13.5	0.51
			14.3	0.075	13.7	0.51
			14.4	0.075	14.0	0.53
			14.5	0.075	14.2	0.54
			14.6	0.075	14.5	0.55
			14.7	0.075	16.4	0.60
9	4	E	14.8	NA	16.0	3.0
10	4A	I	14.7	0.2	21.0	1.0
11	4B	E	14.78	0.1	19.5	1.2
12	5	E	13.60	0.23	13.8	0.7
			14.00	0.26	14.8	0.9
			14.40	0.44	16.3	0.9
			14.80	0.34	16.1	0.9
			15.20	0.39	17.9	1.0
13	5A	E	14.19	0.18	14.99	0.22
14	5B	E	14.6	0.2	17.3	1.4
15	6	E	14.7	0.3	16.0	1.0
16	6A	E	13.68	0.35	14.1	0.7
			14.36	0.15	16.0	0.8
			14.77	0.25	17.4	0.9
17	6B	D	14.6	NA	20.0	3.0
18	7	E	13.9	0.2	14.9	0.9
			14.5	0.2	14.8	0.9
			15.1	0.2	15.5	1.0
19	8	E	14.2	0.2	18.1	1.5

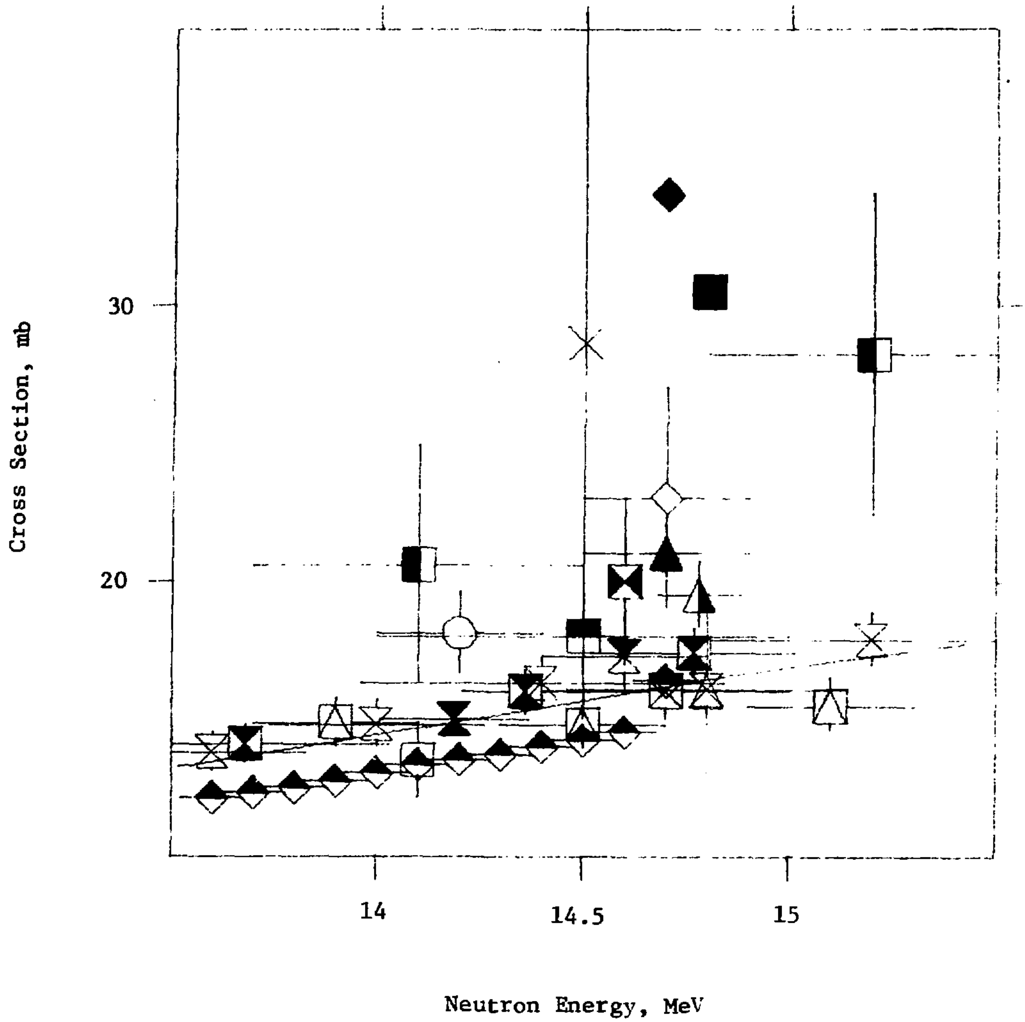

Figure 1: Compiled experimental data for V-51(n,alpha)Sc-48

Table 2: Additional Information for the $^{51}V(n,\alpha)^{48}Sc$ Evaluation

Ref. No.	Standard	Standard Adjustment Factor	Energy Adjustment Factor	Adjusted Cross Section (mb)		Errors (%) Uncorrelated	Errors (%) Standard	Errors (%) Total[a]
5	S2	1.014	1.032	18.84		14.6	0.6	14.6
8	S2	1.020	1.203	14.85	15.05	1.0	0.6	1.2
			1.181	14.82				
			1.160	14.79				
			1.140	14.77				
			1.121	14.86				
			1.102	14.95				
			1.084	14.94				
			1.066	14.90				
			1.048	14.97				
			1.032	14.95				
			1.016	15.03				
			1.000	16.73				
9	A	1.000	0.9848	15.76		18.8	0	18.8
11	S4	0.9709	0.9878	18.70		5.6	0.6	5.7
12	S1	1.000	1.203	16.60	16.59	4.7	1.0	4.8
			1.121	16.59				
			1.048	17.08				
			0.9848	15.86				
			0.9387	16.80				
13	S2	1.018	1.084	16.54		0.9	0.6	1.1
14	S2	1.008	1.016	17.72		8.0	0.6	8.0
15	S2	0.9397	1.000	15.04		3.8	0.6	3.9
16	S2	0.9796	1.185	16.37	16.68	4.0	0.6	4.1
			1.072	16.80				
			0.9894	16.86				
18	S4	1.078	1.140	18.31	17.30	4.3	0.6	4.4
		1.107	1.032	16.91				
		1.133	0.9496	16.68				
19	A	1.000	1.084	19.62		8.1	0	8.1

Evaluation Summary

Evaluated cross section: 15.888 mb

Normalized chi-square: 7.34

Standard deviation: 0.388 mb (2.4%) enchanced

[a]A decay error of 0.3% which is 100% correlated for all the references is included.

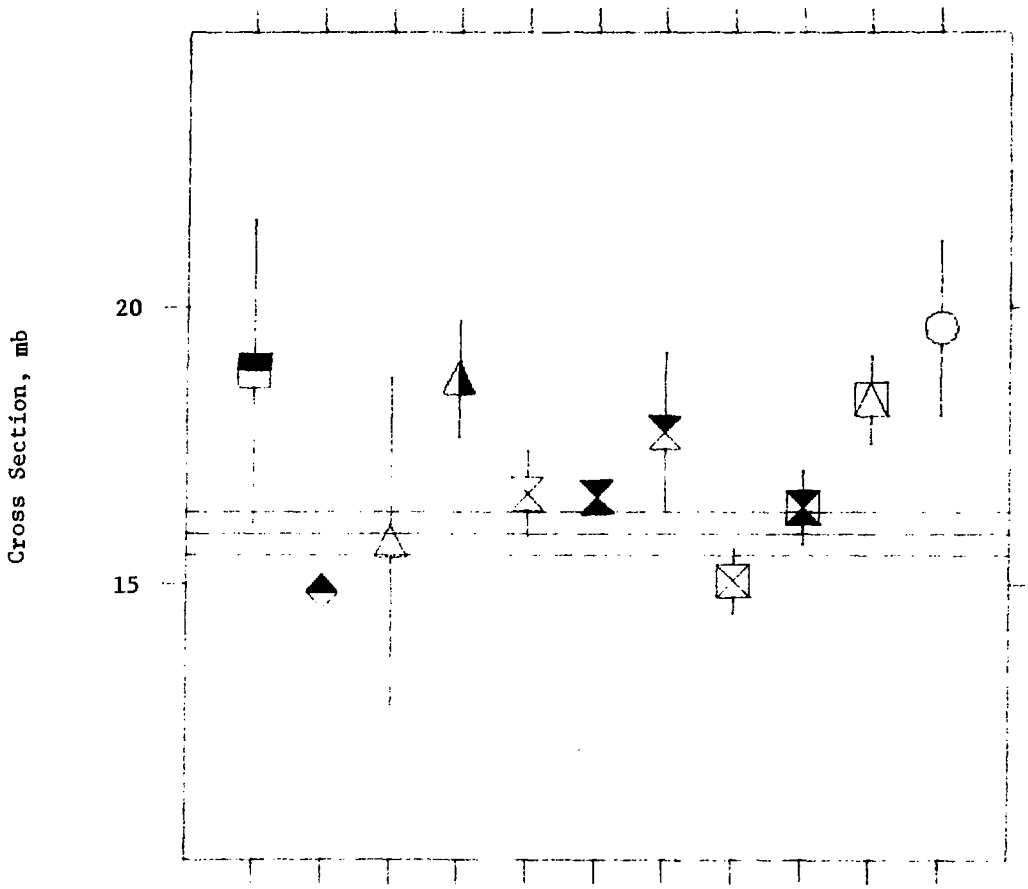

Figure 2: Evaluation of 14.7-MeV cross sections for V-51(n,alpha)Sc-48

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(H) $Cr(n,X)^{52}V$

Natural chromium has four stable isotopes [II.13]: ^{50}Cr (4.35%), ^{52}Cr (83.79%), ^{53}Cr (9.50%) and ^{54}Cr (2.36%). Only ^{52}Cr and ^{53}Cr need be considered for ^{52}V production from neutron bombardment ~ 14 MeV, for all practical purposes (see Section I). From Qaim and Stöcklin [14] we deduce that the (n,np) and (n,d) reactions on ^{53}Cr contribute at most a few percent to the production of ^{52}V. Here we will evaluate the total ^{52}V production cross section, but express it as an isotopic cross section for ^{52}Cr rather than the elemental cross section for Cr. This is the usual approach taken for activation reactions such as this, and it conforms to what is normally quoted in data files and the original papers.

^{52}V decays with a 3.746 ± 0.007 m half life entirely by β^- emission, populating levels in ^{52}Cr which decay rather promptly to the ground state via gamma ray emission [II.13]. It has been determined that a 1.434-MeV gamma ray accompanies essentially 100% of all ^{52}V decays [II.3], so no decay branch uncertainty is assumed for present purposes. However, various values for the half-life have been used for the cross section experiments reported in the literature. Use of a different half life can affect the derived cross section, but the precise effect depends upon details which are seldom reported. Therefore, we did not apply any corrections to the data for this effect; however, we increased the random error, based on some estimates of this perturbation, whenever a significantly different half life was used.

Sixteen data sets were compiled from the literature, for a total of 27 cross section values for this reaction. These data are listed in Table 1 and are plotted in Fig. 1. It has been shown that the ENDF/B-V [II.9] evaluation is not very representative of the experimental data for the (n,p) reaction at lower energies [17], therefore we have plotted the eyeguide shown in Fig. 1 of Ref. 17. One of the compiled data sets [2] was discarded because the reference standard was unorthodox. Six other data sets had to be rejected because the available information was inadequate to satisfy our needs for evaluation purposes [5,6,7,10,12 and 16]. This screening process left us with nine distinct values (none from multiple data sets). These data were adjusted for revised standards and were converted to equivalent 14.7-MeV values using the eyeguide from Ref. 17, as plotted in Fig. 1. This process provided the initial data base for evaluation using code AVERG.

It is evident that the scatter in these assembled data is considerable relative to the errors, and the normalized chi-square for this first pass was 12.19. On the basis of a three-enhanced-standard-deviation comparison, four of the data points were rejected because of inconsistency with the ensemble. Our second analysis yielded an average value of 72.493 ± 3.197 mb (4.4%) with a normalized chi-square of 6.156. Other data rejection schemes which were more biased were attempted but the results were rather similar. Clearly the data available for this reaction are rather inconsistent. Table 2 and Fig. 2 serve to summarize the main features of our evaluation.

Table 1: Compliled Data for $Cr(n,X)^{52}V$

Ref. No.	Symbol	Application	Neutron Energy (MeV)	Energy Resolution (MeV)	Reported Cross Section (mb)	Reported Cross Section Error (mb)
1	1	E	14.5	NA	77.7	10.88
2	2	D	13.73	NA	115.0	13.0
			13.84	NA	126.7	14.0
			14.01	NA	133.3	15.0
			14.28	NA	109.3	12.0
			14.52	NA	91.2	10.0
			14.52	NA	106.9	14.0
			14.52	NA	103.1	11.0
			14.74	NA	113.0	12.0
			14.99	NA	101.1	11.0
			14.99	NA	113.4	13.0
			15.06	NA	114.1	11.0
			15.44	NA	119.2	13.0
3	2A	I	14.0	NA	103.0	12.36
4	2B	E	14.8	NA	105.0	10.5
5	3	D	14.8	NA	82.7	9.0
6	3A	D	14.8	NA	118.0	16.0
7	3B	D	14.7	NA	82.0	NA
8	4	I	14.8	0.2	82.8	5.8
9	4A	I	14.8	0.4	115.0	15.0
10	5	D	14.4	NA	115.0	25.0
11	5A	E	14.8	1.0	73.0	5.0
12	6	D	14.7	0.6	94.0	10.0
13	6A	I	14.6	NA	96.1	3.0
14	7	E	14.7	0.6	80.0	6.0
15	7A	E	14.8	0.5	70.8	2.0
16	8	D	14.8	NA	84.0	8.0

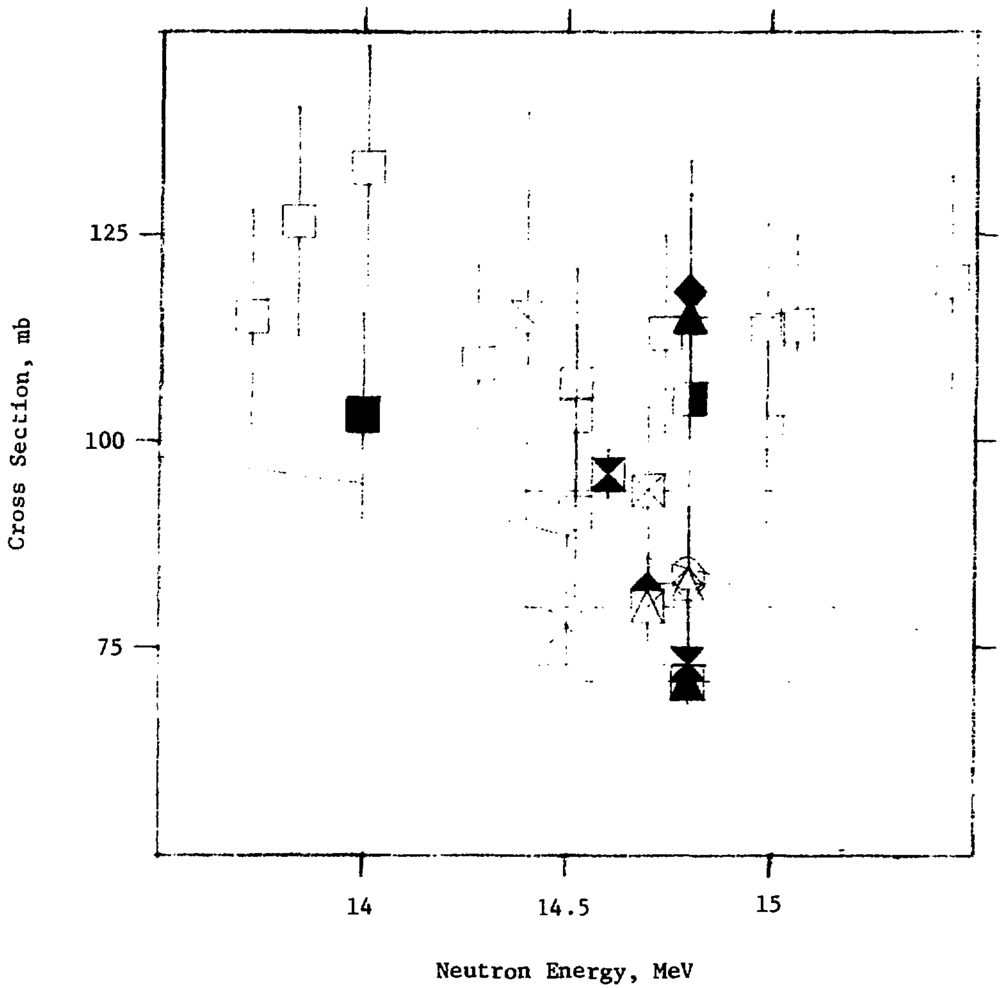

Figure 1: Compiled experimental data for Cr(n,X)V-52

Table 2: Additional Information for the $Cr(n,X)^{52}V$ Evaluation

Ref. No.	Standard	Standard Adjustment Factor	Energy Adjustment Factor	Adjusted Cross Section (mb)	Uncorrelated	Errors (%) Standard	Total
1	A	1.0	0.9713	75.47	14.1	0	14.1
4	S5	0.9914	1.0150	105.66	10.0	1.3	10.1
11	S4	0.8437	1.0150	62.51	7.4	0.6	7.5
14	S2	0.9397	1.000	75.18	5.6	0.6	5.6
15	S2	1.0107	1.0150	72.63	3.0	0.6	3.1

Evaluation Summary

Evaluated cross section: 72.493 mb

Normalized chi-square: 6.16

Standard deviation: 3.197 (4.4%) enhanced

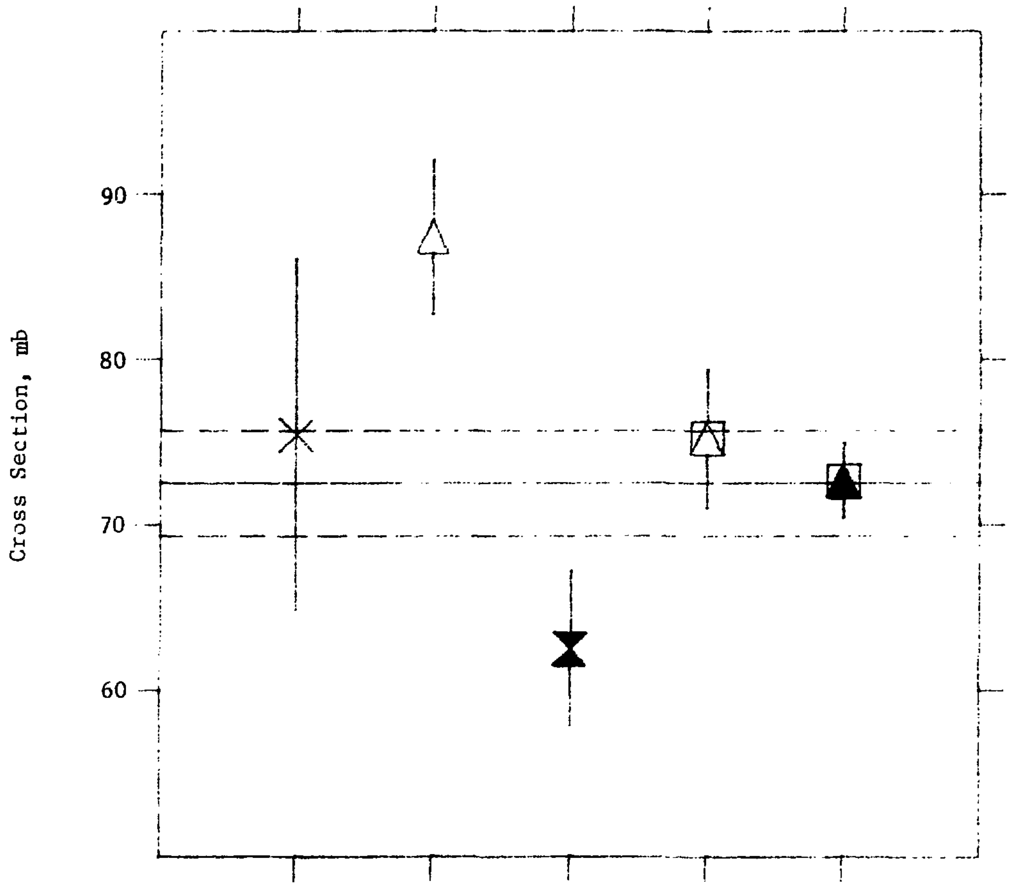

Figure 2: Evaluation of 14.7-MeV cross sections for Cr(n,X)V-52

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(I) $^{55}Mn(n,\alpha)^{52}V$

The decay of ^{52}V offers no problems insofar as comparison of the cross section data is concerned. The half life is 3.746 ± 0.007 m and the decay is entirely by β^- emission, with a 100% branch for 1.434-MeV γ-ray emission. (Ref. II.13). The accepted value for the half life has changed by no more than a fraction of a percent over the time interval spanned by the data compiled here. In all likelihood any uncertainties due to half life are < 1% and we considered them to be included among the quoted random errors for each experiment in this particular evaluation. This was not a dominant error source for this reaction.

Twenty-one cross section values were obtained from the literature. These are listed in Table 1 and plotted in Fig. 1. Eight of these were rejected on the basis of inadequate documentation of experimental details. Multiple data values were available from Gabbard and Kern [7], Borman et al. [10] and Zupranska et al. [17]. Each set used was converted to a single equivalent 14.7 MeV point, as discussed in Section II. Thus, eleven values were averaged on the first pass. Of these, four were rejected because they exceeded three enhanced standard deviations from the first average. The final evaluation is therefore derived by averaging only five adjusted values, as indicated in Table 2. These are compared with the final evaluated value of 31.21 ± 1.31 mb in Fig. 2. It is curious that not one of these values falls within the ± 4.2% uncertainty band accorded to this evaluation. The fact that the normalized chi-square for the second pass analysis was ~ 3.8 implies that the retained values were not too consistent within the estimated errors. This is evident in Fig. 2. The 1.31 mb standard deviation reflects enhancement by nearly a factor of two relative to the ~ 0.7 mb value obtained directly from the analysis with code AVERG. It is clear from Table 2 that the effect of correlated errors traceable to the standards was small, so the outcome of this evaluation depended mainly on the uncorrelated errors, several of which we had to estimate.

The solid curve in Fig. 1 is the ENDF/B-V [II.9] evaluation. According to the available documentation, that evaluation is based on a model calculation which was guided by available experimental data above ~ 12 MeV. The ENDF/B-V value at 14.7 MeV is 35.7 mb, which is 14.4% larger than our present result. No error information is provided in ENDF/B-V for this reaction, but this difference is probably large enough to constitute a significant discrepancy between these two evaluations.

Table 1: Compiled Data for $^{55}Mn(n,\alpha)^{52}V$

Ref. No.	Symbol	Application	Neutron Energy (MeV)	Energy Resolution (MeV)	Reported Cross Section (mb)	Reported Cross Section Error (mb)
1	2	I	14.5	NA	52.5	7.9
2	4A	I	14.8	0.07	39.4	8.0
3	2C	D	14.4	NA	45.0	NA
4	6A	I	14.0	NA	57.0	6.3
5	1	E	14.5	1.0	27.0	5.0
6	3A	D	14.8	NA	11.8	0.7
7	3	D	14.4	NA	31.0	5.0
			14.65	NA	33.0	4.0
			14.9	NA	34.0	4.0
8	8	E	14.7	NA	72.0	NA
9	4	I	14.8	NA	13.8	2.1
10	5	E	14.0	0.6	32.6	1.7
			15.0	0.6	35.4	2.6
11	8G	D	14.5	0.4	25.0	3.0
12	8A	D	14.8	NA	57.0	7.0
13	5A	E	14.7	NA	27.0	2.0
14	6	E	14.6	NA	27.0	4.0
15	7	D	14.6	0.2	25.2	1.7
16	8F	E	14.7	0.6	24.4	2.4
17	7C	E	14.5	0.2	27.7	1.6
			15.1	0.2	29.2	1.9

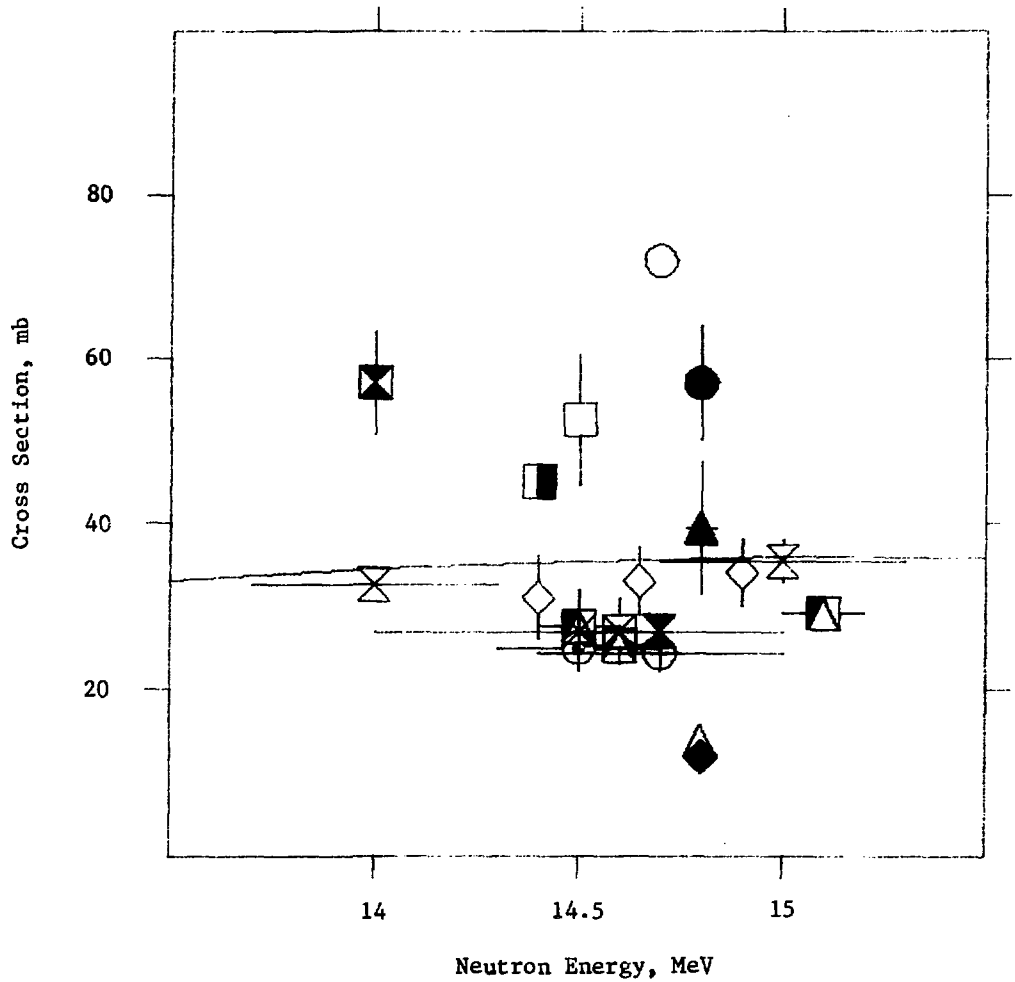

Figure 1: Compiled experimental data for Mn-55(n,alpha)V-52

Table 2: Additional Information for the $^{55}Mn(n,\alpha)^{52}V$ Evaluation

Ref. No.	Standard	Standard Adjustment Factor	Energy Adjustment Factor	Adjusted Cross Section (mb)	Errors (%) Uncorrelated	Standard	Total
5	S5	0.975	1.008	26.59	12.0	1.3	12.1
8	S2	0.455	1	32.75	5.0	0.6	5.0
10	A	1	1.032 0.992	33.64 35.10 } 33.92	3.0	0	3.0
13	S5	1.05	1	28.43	6.8	1.3	6.9
14	S4	1.041	1.004	28.22	14.3	0.6	14.3
16	S2	0.989	1	24.12	9.6	0.6	9.6
17	S1	1	1.008 0.992	29.92 28.96 } 29.44	6.0	1.0	6.1

<u>Evaluation Summary:</u>

Evaluated cross section = 31.21 mb

Normalized chi-square = 3.80

Standard deviation = 1.31 mb (4.2%) enhanced

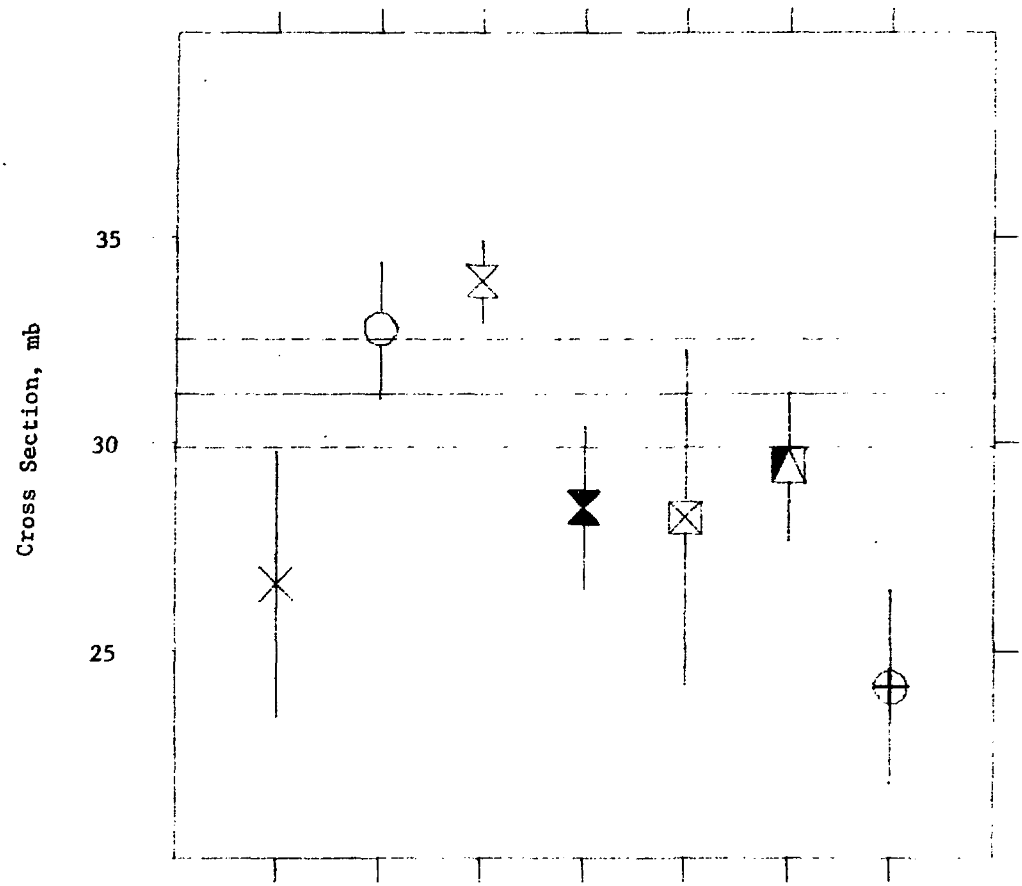

Figure 2: Evaluation of 14.7-MeV cross sections for Mn-55(n,alpha)V-52

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(J) $^{55}Mn(n,2n)^{54}Mn$

The decay of ^{54}Mn offers no problems. The half life of 312.20 ± 0.07 d is very well known and the accepted value has not changed to any significant extent for many years [II.13]. ^{54}Mn decays 100% of the time by electron capture (EC) which feeds the 0.835-MeV first-excited state of ^{54}Cr exclusively. A readily-detectable signature of this transition is the emission of an 0.835-MeV gamma ray with a half life of 8.2 ps [II.13].

The (n,2n) reaction exhibits considerable energy dependence, increasing by ~ 10% between 14 and 15 MeV according the ENDF/B-V evaluation for this reaction [II.9]. This evaluation is used in the present analysis to deduce requisite energy adjustment factors for conversion of the reported results to equivalent 14.7-MeV cross sections.

Twenty-eight cross-section values were found for this compilation, based on eighteen references from the literature. These cross sections are listed in Table 1 and are plotted in Fig. 1, except for the value from Ref. 3 which is quite obviously discrepant and would be off scale on Fig. 1. Four of the compiled cross section values were rejected at the outset. The data from Refs. 1,5 and 8 were inadequately documented, while the value from Ref. 7 is based on an unorthodox reference standard so we chose not to include it, as discussed in Section II. Multiple-value data sets were available from Paulsen and Liskien [6], Borman et at. [10] and Lu Han-Lin et al. [18]. Each set used was converted to a single equivalent 14.7-MeV point, as discussed in Section II.

Thirteen cross-section values were included in the first-pass evaluation. Five of these values were subsequently rejected because they exceeded three enhanced standard deviations from the ensemble average. A second analysis was performed in which only the eight remaining values were included. The present evaluation is based on this procedure. The evaluated results appear in Table 2 and Fig. 2. The normalized chi-square was 0.658 which indicates excellent consistency for the considered data. Our evaluated cross section is 816.65 ± 20.87 mb. The standard deviation given here is that actually calculated by code AVERG. It has not been reduced to reflect the small normalized chi-square obtained. The uncertainty in this evaluation is ~ 2.6%. The equivalent 14.7-MeV cross section from ENDF/B-V [II.9] is 5.6% larger than the present result.

Table 1: Compiled Data for $^{55}Mn(n,2n)^{54}Mn$

Ref. No.	Symbol	Application	Neutron Energy (MeV)	Energy Resolution (MeV)	Reported Cross Section (mb)	Reported Cross Section Error (mb)
1	1	D	14.1	NA	900.0	70.0
2	2C	E	14.5	0.5	825.0	185.0
3[a]	-	D	14.8	NA	1.0	NA
4	2A	I	14.0	NA	600.0	120.0
5	3	D	14.0	NA	1310.0	327.5
6	4A	I	14.05	0.25	937.0	56.0
			14.42	0.26	946.0	57.0
			14.71	0.27	945.0	57.0
			15.09	0.26	996.0	60.0
7	4	D	14.96	0.435	854.0	79.0
8	5A	D	14.1	0.1	786.0	60.0
9	5C	E	14.6	0.1	785.0	80.0
10	5	E	14.1	0.15	798.0	78.0
			15.03	0.14	834.0	82.0
11	6C	E	14.8	0.2	750.0	60.0
12	6A	I	14.36	0.07	540.0	70.0
13	6	E	14.6	0.2	866.0	65.0
14	6B	I	14.6	NA	643.0	65.0
15	7A	I	14.7	NA	680.0	300.0
16	2	E	14.6	0.1	775.0	80.0
17	7	E	14.6	NA	884.0	58.0
18	8	E	14.29	0.175	792.0	41.0
			14.44	0.075	818.0	32.0
			14.61	0.1	824.0	28.9
			14.73	0.105	826.0	32.0
			14.85	0.125	842.0	29.5
			14.90	0.125	853.0	34.0
			14.98	0.125	868.0	34.0

[a]Not plotted in Fig. 1.

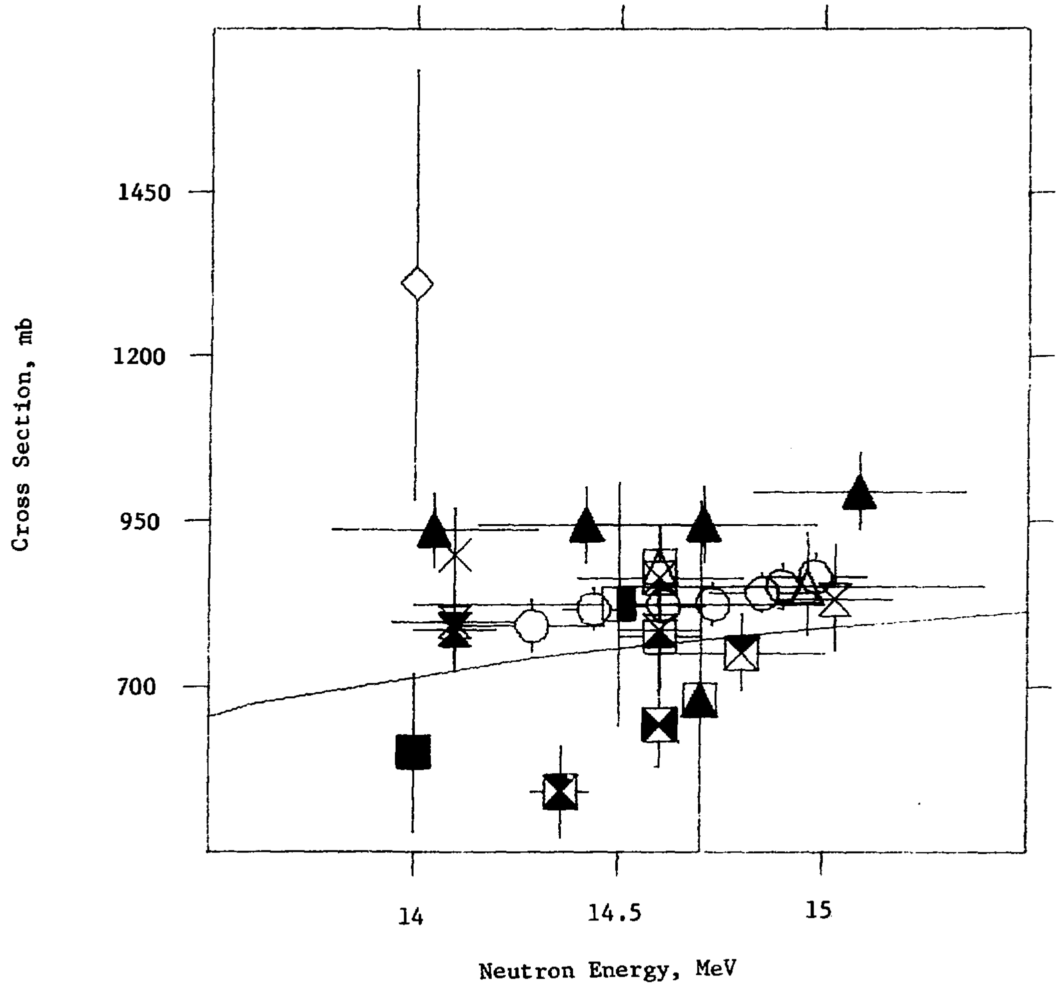

Figure 1: Compiled experimental data for Mn-55(n,2n)Mn-54

Table 2: Additional Information for the $^{55}Mn(n,2n)^{54}Mn$ Evaluation

Ref. No.	Standard	Standard Adjustment Factor	Energy Adjustment Factor	Adjusted Cross Section (mb)		Errors (%) Uncorrelated	Standard	Total
2	S6	0.9178	1.017	770.03		22.4	1.2	22.5
9	S2	0.9536	1.0082	750.97		10.2	0.6	10.2
10	S1	0.9990	1.0638 0.9744	848.05 811.82	831.15	6.9	1.0	7.0
11	S1	1.0	0.9920	744.0		8.1	1.0	8.2
13	S6	0.9944	1.0082	868.19		7.2	1.2	7.3
16	S2	1.0079	1.0082	787.51		10.3	0.6	10.3
17	S2	1.0	1.0082	891.25		6.9	0.6	6.9
18	S2	0.9808	1.0366 1.0224 1.0073 0.9976 0.9880 0.9841 0.9778	805.27 820.31 814.12 808.24 816.64 823.36 832.48	817.20	4.0	0.6	4.0

Evaluation summary:

Evaluated cross section = 816.65 mb

Normalized chi-square = 0.658 mb

Standard deviation = 20.87 mb (2.6%)

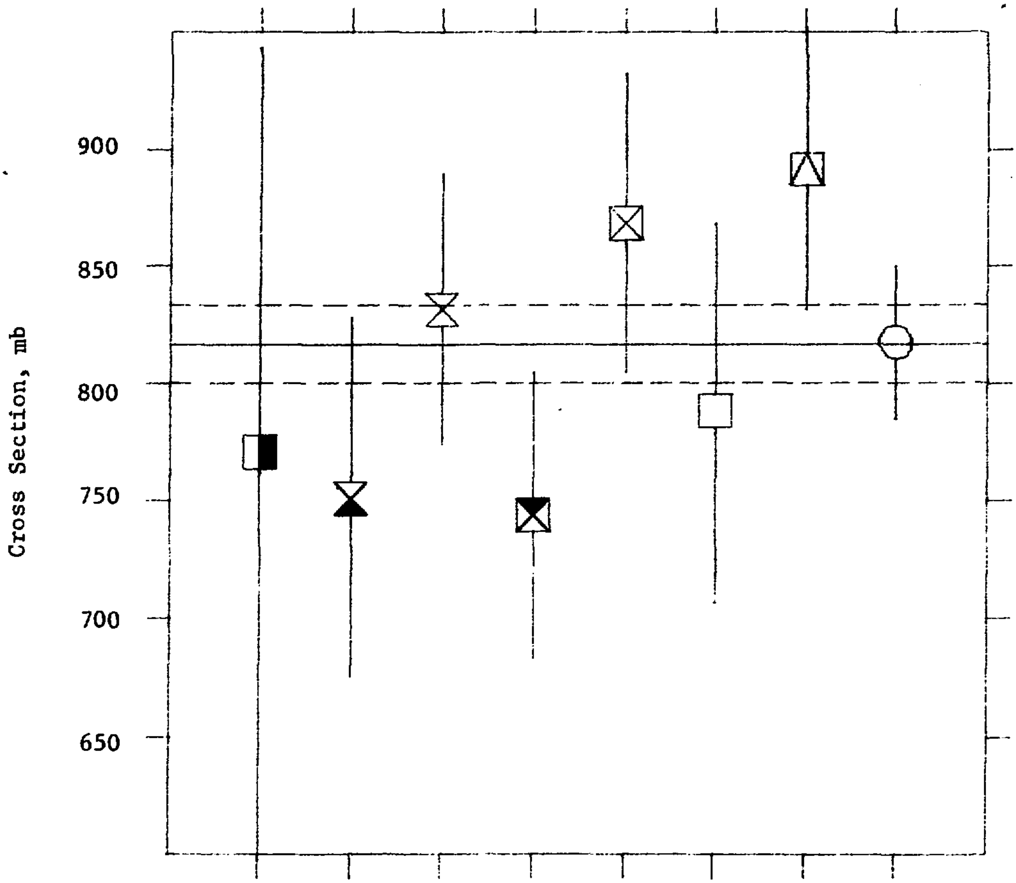

Figure 2: Evaluation of 14.7-MeV cross sections for Mn-55(n,2n)Mn-54

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(K) $Fe(n,X)^{54}Mn$

There are four stable iron isotopes: ^{54}Fe (5.8%), ^{56}Fe (91.8%), ^{57}Fe (2.15%) and ^{58}Fe (0.29%) [II.13]. Only two reactions can lead to ^{54}Mn production at energies ~ 14 MeV (Section I): $^{54}Fe(n,p)^{54}Mn$ and $^{56}Fe(n,t)^{54}Fe$. An estimate of the relative importance of these two processes can be made by referring to ENDF/B-V [II.9] and Diksic et al. [16]. We find that the (n,t) reaction probably accounts for $\lesssim$ 5% of the ^{54}Mn production in elemental iron, in spite of the predominant abundance of ^{56}Fe. In the present evaluation, we consider the isotopic cross section of ^{54}Mn production from ^{54}Fe. In other words, we seek to represent the $^{54}Fe(n,p)^{54}Mn$ isotopic cross section plus a small additional term for the contribution from ^{56}Fe, in accordance with the usual procedure for activation reactions.

^{54}Mn decays 100% of the time by electron capture (EC) to the first-excited state at 0.835 MeV in ^{54}Cr, and each of these decays is accompanied by a prompt 0.835-MeV gamma ray [II.13]. There is no uncertainty in the cross section from this origin. The decay half life is 312.20 ± 0.07 d [II.13]. Although details of the sample irradiations and counting are sketchy in all the references provided, it is very likely that all of the experimental times were considerably small than the half life of ^{54}Mn. Under these conditions, the cross sections derived by the experimenters were nearly proportional to the half lives they assumed. Some of the reported half lives differed considerably from the currently-accepted value. Consequently, the reported cross sections were adjusted for half life when it was given. An additional error was assigned in such cases. For those few sets where no half lives were given, no adjustments were made but the random errors were enhanced by 5%.

Fifteen references on cross section data were compiled from the literature, and a total of 42 cross section values around 14 MeV were obtained. These data are listed in Table 1 and are plotted in Fig. 1. The solid curve plotted in Fig. 1 is the ENDF/B-V [II.9] evaluation for $^{54}Fe(n,p)^{54}Mn$ from the Dosimetry File. Three of the data sets [11,12 and 13] were rejected at the outset because the information provided on these experiments was inadequate for the present evaluation purposes. Another data point [9] was rejected prior to performing an analysis with code AVERG because it was obviously very discrepant relative to the remaining data and would have perturbed the averaging analysis in an unfavorable manner. The remaining data were adjusted for revisions in standards, and all values were converted to equivalent 14.7-MeV points. Multiple data sets were averaged and the error reduced accordingly. However, no random error smaller than 3% was accepted for any of the points. Eleven values were thus available for the first-pass analysis with code AVERG.

The first-pass calculation with AVERG yielded a normalized chi-square of 4.49, indicating considerable inconsistency for the input data. Two values [4 and 14] were rejected, on the basis of a three-standard-deviation test, as being in significant disagreement with the remaining nine values. A second-pass analysis with code AVERG provided the final evaluated value of 284.40 mb with an enhanced standard deviation of 5.71 mb (2.0%). The chi-square obtained for this analysis was 1.50 which implies fairly good consistency for the averaged data. The results of this evaluation are summarized in Table 2 and Fig. 2.

Table 1: Compiled Data for Fe(n,X)^{54}Mn

Ref. No.	Symbol	Application	Neutron Energy (MeV)	Energy Resolution (MeV)	Reported Cross Section (mb)	Reported Cross Section Error (mb)
1	1	E	14.1	NA	254.0	27.94
2	2	E	13.58	NA	370.0	37.0
			14.07	NA	346.0	34.6
			14.73	NA	320.0	32.0
3	2A	E	14.05	0.21	368.0	29.0
4	2B	I	14.4	0.6	259.0	26.0
5	3	E	14.6	0.4	346.0	30.0
6	3A	E	14.8	0.4	300.0	20.0
7	4	E	13.6	0.46	375.0	19.0
			14.0	0.52	326.0	16.0
			14.8	0.68	249.0	13.0
			15.2	0.78	230.0	12.0
8	4A	E	14.7	0.6	332.0	30.0
9	5	I	14.5	NA	510.9	27.5
10	5A	E	14.0	0.6	334.63	12.72
11	6	D	14.8	NA	310.0	30.0
12	6A	D	14.6	NA	358.0	22.0
13	7	D	13.75	NA	344.0	NA
			14.11	NA	469.0	NA
			14.49	NA	311.0	NA
			14.86	NA	220.0	NA
14	7A	I	13.77	NA	411.0	26.0
			14.11	NA	433.0	26.0
			14.47	NA	366.0	24.0
			14.73	NA	346.0	22.0
			14.83	NA	314.0	20.0
15	8	E	13.50	0.26	387.0	14.0
			13.53	0.26	401.0	15.0
			13.57	0.94	385.0	18.0
			13.77	0.2	367.0	14.0
			13.95	0.8	366.0	17.0
			14.29	1.0	339.0	16.0
			14.42	0.3	322.0	12.0
			14.45	0.3	322.0	12.0
			14.61	0.4	316.0	11.0
			14.71	0.4	308.0	11.0
			14.73	0.5	308.0	11.0
			14.83	0.52	290.0	11.0
			14.90	0.5	294.0	11.0
			14.97	0.5	288.0	11.0
			15.33	0.9	254.0	12.0
			15.37	1.0	251.0	12.0

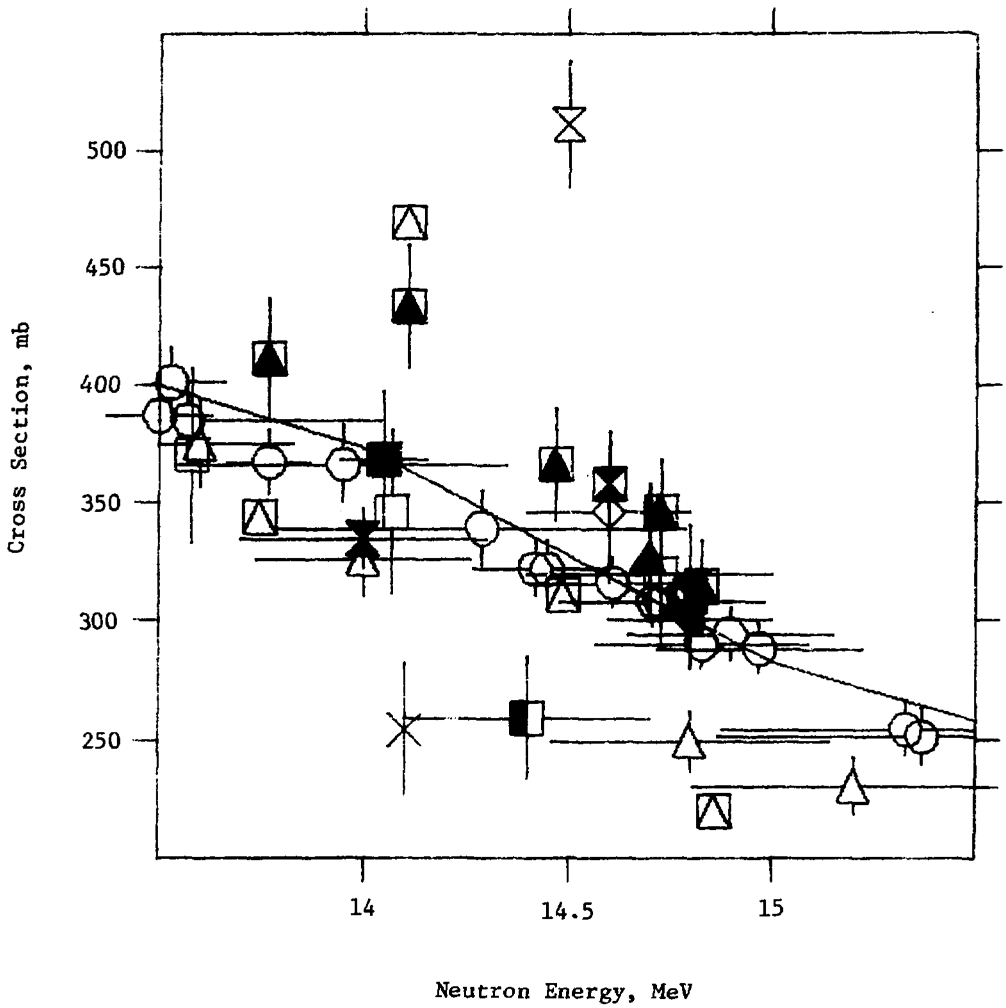

Figure 1: Compiled experimental data for Fe(n,X)Mn-54

Table 2: Additional Information for the Fe(n,X)^{54}Mn Evaluation

Ref. No.	Half Life (d)	Half Life Adjustment Factor	Standard	Standard Adjustment Factor	Energy Adjustment Factor	Adjusted Cross Section (mb)		Errors (%) Uncorrelated	Standard	Total
1	260	1.2008	A	1.0	0.8502	259.31		11.0	0	11.0
2	NA	1.0	S2	1.0139	0.7825	293.55	305.68	11.3	0.6	11.3
					0.8440	296.08				
					1.0091	327.40				
3	315	0.9911	S1	1.0	0.8399	306.33		7.9	1.0	8.0
5	NA	1.0	S2	0.9536	0.9715	320.54		10.1	0.6	10.1
6	NA	1.0	S1	1.0	1.0303	309.09		8.4	1.0	8.5
7	313	0.9974	S1	1.0	0.7846	293.46	269.96	3.0	1.0	3.2
					0.8295	269.71				
					1.0303	255.88				
					1.1368	260.78				
8	303	1.0297	S2	0.9397	1.0	321.25		7.5	0.6	7.5
10	312.3	1.0	S4	1.0	0.8295	277.58		3.0	0.6	3.1
15	312.2	1.0	S2	0.9784	0.7741	293.11	296.78	3.0	0.6	3.1
					0.7773	304.96				
					0.7815	294.38				
					0.8031	288.37				
					0.8237	294.96				
					0.8926	296.06				
					0.9241	291.13				
					0.9318	293.56				
					0.9744	301.26				
					1.00303	302.26				
					1.00909	304.09				
					1.03993	295.07				
					1.0624	305.60				
					1.08634	306.11				
					1.1646	289.42				
					1.1734	288.16				

Evaluation Summary:

Evaluated cross section: 284.40 mb

Normalized chi-square: 1.50

Standard deviation: 5.71 mb (2.0%) enchanced

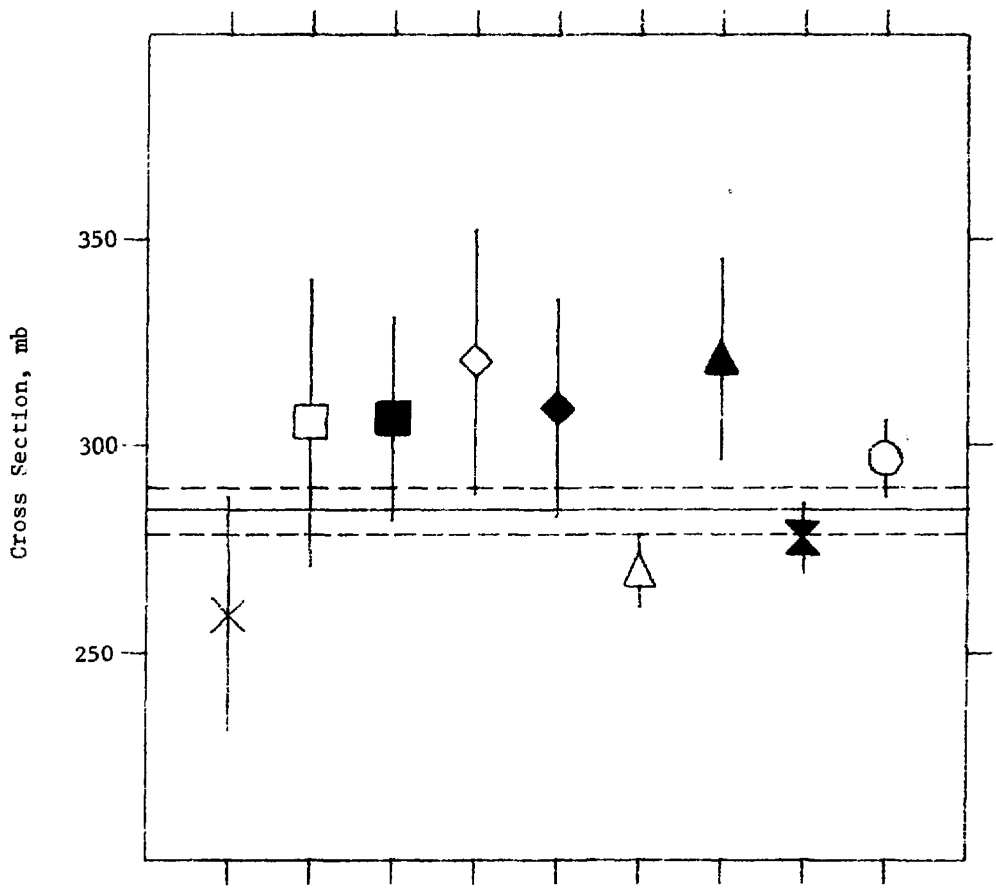

Figure 2: Evaluation of 14.7-MeV cross sections for Fe(n,X)Mn-54

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(L) $^{54}Fe(n,\alpha)^{51}Cr$

Although there are four stable isotopes in elemental iron, only the $^{54}Fe(n,\alpha)^{51}Cr$ reaction, involving the 5.8%-abundant isotope ^{54}Fe, contributes to ^{51}Cr production in fast-neutron bombardment of natural iron [II.13]. The decay of ^{51}Cr proceeds entirely by electron capture (EC) to levels in ^{51}V, with a half life of 27.701 ± 0.006 d [II.13]. Approximately 10% of all these decays populate the 0.320-MeV first-excited state of ^{51}V while the balance proceed directly to the ground state [II.13]. The first-excited state of ^{51}V de-excites with a 0.18 ns half life to the ground state via emission of a 0.320-MeV gamma ray. Apparently the best current value for the γ-ray branch is 0.0983 (± 1.4%) [II.18]. Earlier compilations suggest 0.102 [II.13] and 0.09 [II.17], respectively, as the value to use. Therefore, there is significant uncertainty surrounding this aspect of measuring the $^{54}Fe(n,\alpha)^{51}Cr$ activation cross section. For present purposes, we adjusted data from the literature to conform to the 0.0983 gamma-branch figure whenever the authors provide the pertinent information for their experiments. If they did not, we added an additional 10% random error to their quoted random error. Referring to earlier suggested values for the half life (e.g., Refs. II.13 and II.17), we concluded that the error due to half life uncertainty would not exceed ~ 1% if the author did not provide the value used. When provided, small adjustments were made to the reported cross section and no additional error was added. In our judgment this was a reasonable approach because measurement times were likely to be far less than the half life.

A survey of the literature produced twelve references containing relevant data, for a total of 21 compiled values. These are listed in Table 1. Twenty of these are plotted in Fig. 1. One data point [2] was so much larger than all the others that it was not plotted, thereby permitting use of a more favorable scale for presenting all the others. Prior to the evaluation three values were rejected, including the inconsistent one from Ref. 2 indicated above. Documentation on the work of Fukuda et al. [9] was not readily available. In particular, the standard used was not known to us. The documentation on the experiment of Artem'Ev was so sketchy that we were not able to deduce the essential information needed for the evaluation and thus rejected the data [11].

The remaining nine data sets were adjusted as required for half life, decay branch and standard values, and all results were converted to equivalent 14.7-MeV cross sections. We found some information on the shape of the $^{54}Fe(n,\alpha)^{51}Cr$ cross section from Refs. 13-15, but none of this appeared adequate. The data of Lu Han-Lin et al. [12] span the entire energy range of interest, and their results appear to be reasonably consistent. Consequently, we sketched an eyeguide through these points (see curve in Fig. 1) and used this to estimate energy adjustment values in preference to the alternative available curves. For the purpose of the evaluation, the data of Lu Han-Lin et al. [12], the only multiple-value set, were averaged after the above-mentioned adjustments. Random errors were estimated from the documentation for all the compiled data, but no error < 3% was accepted for the final evaluation analysis with code AVERG.

The first pass calculation with code AVERG produced a normalized chi-square of 13.10, indicating gross inconsistency. It was obvious that three data points [1,6 and 8] were responsible for most of the difficulty. Since these values clearly failed our three-standard-deviation test for consistency they were rejected. An analysis with the six remaining values yielded a far better result. For these data a normalized chi-square of 1.07 was obtained, indicating good consistency. Our final evaluated result is 87.855 ± 2.385 mb (enhanced standard deviation). This corresponds to an uncertainty of 2.7%, of which 1.4% can be traced to uncertainty in the decay process itself. The results of this evaluation are summarized in Table 2 and in Fig. 2.

Table 1: Compiled Data for $^{54}Fe(n,\alpha)^{51}Cr$

Ref. No.	Symbol	Application	Neutron Energy (MeV)	Energy Resolution (MeV)	Reported Cross Section (mb)	Reported Cross Section Error (mb)
1	1	I	14.1	NA	131.0	23.58
2[a]	–	D	14.8	1.8	270.0	135.0
3	2A	E	14.5	NA	94.0	10.0
4	3	E	14.05	0.210	91.6	37.1
5	3A	E	14.4	0.6	90.0	10.0
6	4	I	14.7	0.6	134.0	14.0
7	4A	E	14.6	0.4	106.0	7.0
8	5	I	14.5	NA	139.5	7.5
9	5A	D	14.6	NA	84.0	7.5
10	6	E	14.0	0.6	82.168	2.958
11	7	D	14.8	NA	90.0	15.0
12	8	E	13.53	0.26	84.80	4.4
			13.57	0.94	85.80	5.1
			13.77	0.2	87.00	4.5
			14.29	1.0	87.70	5.1
			14.45	0.3	88.70	4.6
			14.61	0.4	88.40	4.5
			14.73	0.5	88.10	4.6
			14.83	0.52	91.90	4.8
			15.33	0.9	87.80	5.2
			15.37	1.0	87.10	5.1

[a]Not plotted in Fig. 1.

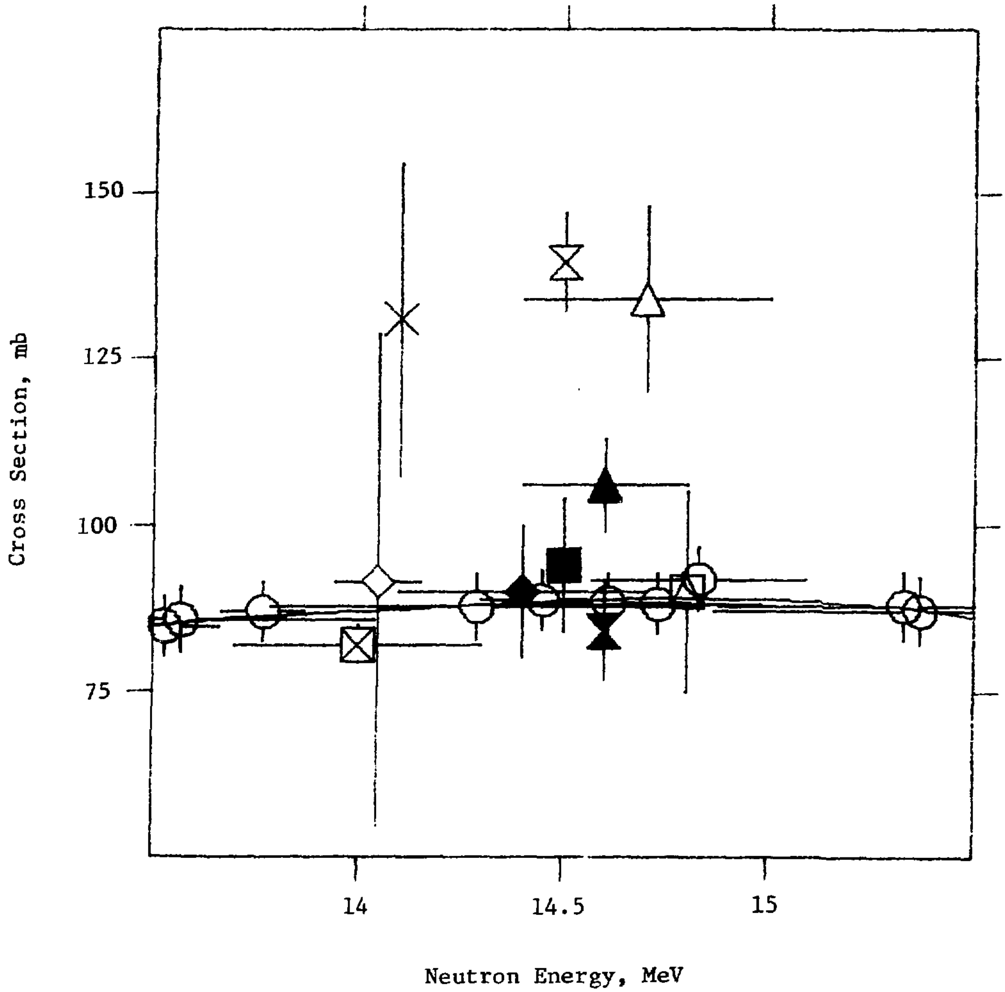

Figure 1: Compiled experimental data for Fe-54(n,alpha)Cr-51

Table 2: Additional Information for the $^{54}Fe(n,\alpha)^{51}Cr$ Evaluation

Ref. No.	Half Life (d)	Half Life Adjustment Factor	Decay Branch (%)	Decay Branch Adjustment Factor	Standard	Standard Adjustment Factor	Energy Adjustment Factor		Adjusted Cross Section (mb)	Errors (%) Uncorrelated	Errors (%) Standard	Total[a]
3	NA	1.0	NA	1.0	S2	1.0139	1.0056		95.84	14.5	0.6	14.6
4	27.8	0.9964	NA	1.0	S1	1.0	1.02125		93.21	41.7	1.0	41.7
5	27.8	0.9964	9	0.9156	S2	1.036	1.0091		85.84	9.8	0.6	9.9
7	NA	1.0	NA	1.0	S6	0.9944	1.0023		105.65	11.9	1.2	12.0
10	27.75	0.9982	9.815	0.9985	S4	1.0	1.023		83.781	3.5	0.6	3.8
12	27.70	1.0	10.2	1.0376	S2	0.9784	1.04692	90.13	90.652	3.0	0.6	3.4
							1.04348	90.89				
							1.03154	91.11				
							1.01174	90.07				
							1.00735	90.71				
							1.00207	89.93				
							1.0	89.44				
							1.00033	93.32				
							1.01726	90.68				
							1.02054	90.24				

Evaluation Summary:

Evaluated cross section: 87.855 mb

Normalized chi-square: 1.066

Standard deviation: 2.385 mb (2.7%) enhanced

[a]There is a 100%-correlated decay-branch error of 1.4% included.

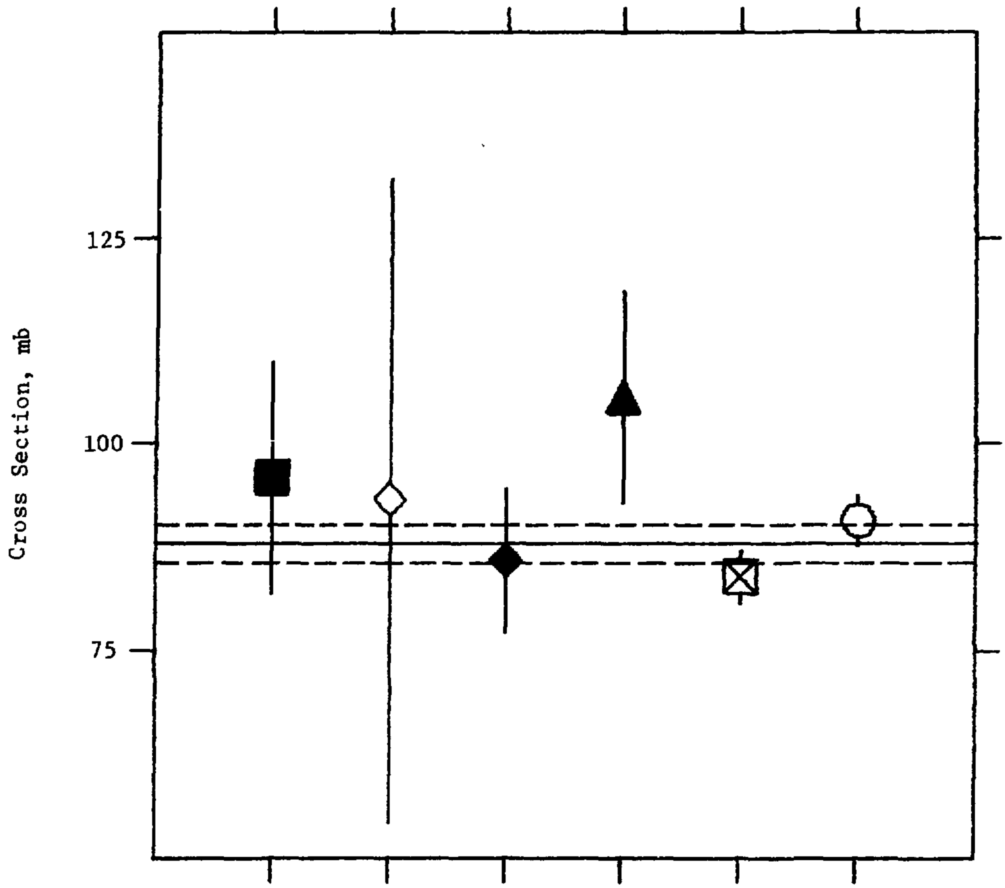

Figure 2: Evaluation of 14.7-MeV cross sections for Fe-54(n,alpha)Cr-51

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(M) $^{59}Co(n,p)^{59}Fe$

Cobalt is monoisotopic so this reaction is the only neutron-induced process which produces ^{59}Fe. The half life of ^{59}Fe is rather well known and is convenient for activation measurements. We assume the value of 44.56±0.03 d given in Lederer et al. [II.13]. Although other values have been quoted, they differ from this by < 1% so we assume that this is a negligible source of error. ^{59}Fe decays entirely by β^- emission to levels in ^{59}Co. The dominant gamma-ray branch is 1.099-MeV gamma-ray emission. According to Ref. II.13, this branch is 56.5±2.8%. There is also a 43.2±1.1% decay branch involving emission of a 1.292-MeV gamma-ray. Although the uncertainties of these branches are ~ 5% and ~ 2.5% respectively, measurements based on adding the yield of both gamma rays would be far more accurate (< 0.3% uncertainty). In some experiments reported in the literature the decay assumptions were stated while in others they were not. A more accurate value for the decay factor is quoted in Ref. II.18. It is 0.561 (± 1.8%) for the 1.099-MeV gamma ray. For present purposes, we assume a 1.8% fully-correlated decay error for the compiled experiments, and add an extra 1% error to the random uncertainty in instances where details are not clearly specified.

Ten relevant references were found in the literature, corresponding to ten distinct cross sections. These values are listed in Table 1 and are plotted in Fig. 1. Three values were rejected, either because of a lack of documentation [10], or because an unorthodox standard was used [1,6]. Another value [5] was discarded because it was obviously too large by about one order of magnitude. This value was not plotted in Fig. 1 for obvious reasons. The ENDF/B-V evaluation for this reaction is plotted in Fig. 1, and it was used for calcultion of energy adjustment factors [II.9].

Six values were thus available for evaluation using code AVERG. Since the available data for analysis were so few and no particular values were clearly discrepant, none were rejected following the first-pass analysis. Thus, the present evaluation is based on these six values. The details appear in Table 2 and the evaluated value and data upon which it is based are plotted in Fig. 2. This analysis yielded the value 56.60 ± 9.18 mb (± 16.2%). The indicated error is one enhanced standard deviation. The normalized chi square was 8.59, indicating rather poor consistency for the evaluated data. The cross section predicted by ENDF/B-V [II.9] is 63.3 mb which is 11.8% higher than the present result.

Table 1: Compiled Data for $^{59}Co(n,p)^{59}Fe$

Ref. No.	Symbol	Application	Neutron Energy (MeV)	Energy Resolution (MeV)	Reported Cross Section (mb)	Reported Cross Section Error (mb)
1	8A	D	14.8	0.45	82.0	8.0
2	4	E	14.1	0.1	75.0	15.0
3	2	E	14.5	0.5	80.0	23.0
4	3	E	14.4	0.1	48.0	5.0
5[a]	–	D	14.9	NA	534.0	70.0
6	5	D	14.8	NA	53.0	12.0
7	6	E	14.8	NA	37.0	6.0
8.	7	E	14.6	0.2	64.0	7.0
9	8	E	14.6	NA	84.1	5.7
10	1	D	14.1	NA	53.1	4.5

[a]*Not plotted in Fig. 1.*

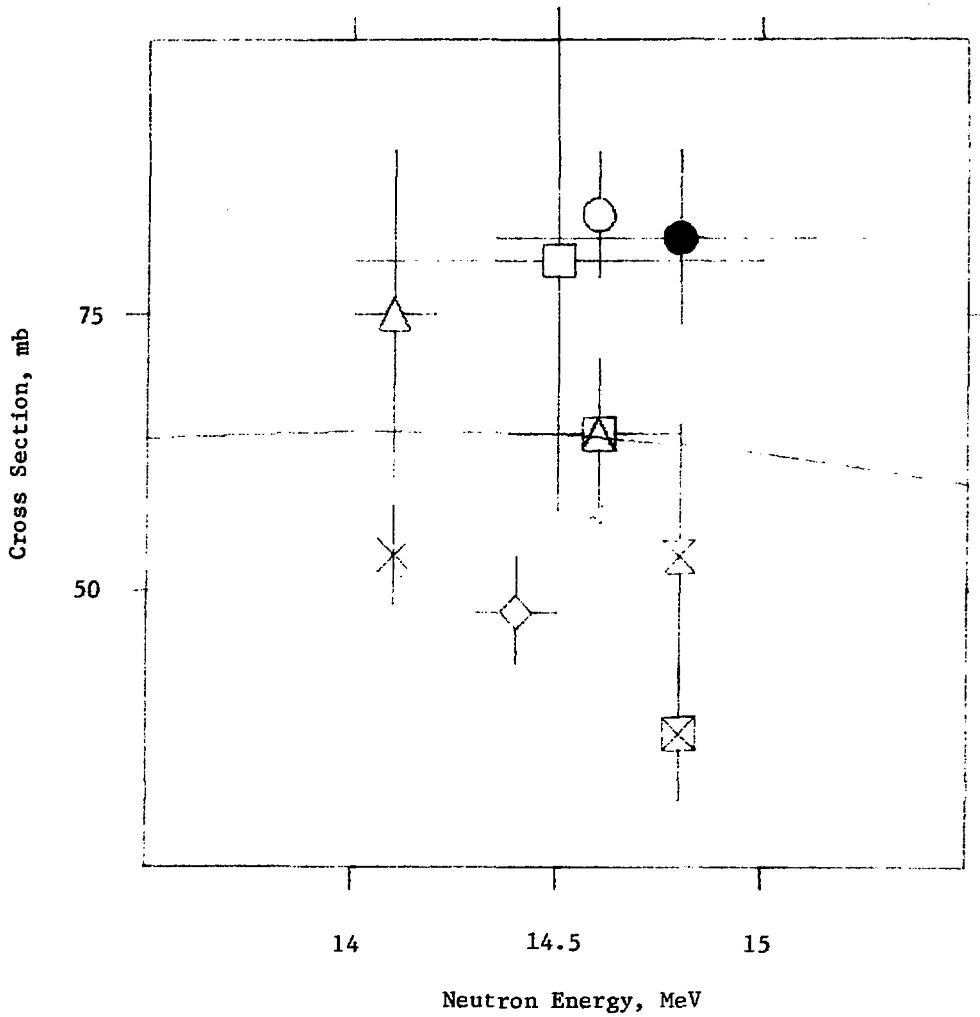

Figure 1: Compiled experimental data for Co-59(n,p)Fe-59

Table 2: Additional Information for the $^{59}Co(n,p)^{59}Fe$ Evaluation

Ref. No.	Standard	Standard Adjustment Factor	Energy Adjustment Factor	Decay Branch Adjustment Factor	Adjusted Cross Section (mb)	Errors (%) Uncorrelated	Standard	Total[a]
2	S1	1.0	0.9838	1.0	73.78	20.0	1.0	20.1
3	S6	0.9178	0.9887	0.9911	71.94	27.2	1.2	27.3
4	S1	1.0	0.9875	1.0	47.4	10.5	1.0	10.7
7	S6	0.9734	1.0057	1.0	36.22	16.3	1.2	16.4
8	S6	0.9944	0.9943	1.0	63.28	14.9	1.2	15.1
9	S4	1.0409	0.9943	1.0	87.04	6.9	0.6	7.1

Evaluation Summary:

Evaluated cross section: 56.60 mb

Normalized chi-square: 8.59

Standard deviation: 9.18 (16.2%) enhanced

[a] A decay error of 1.8% which is 100% correlated for all the references is included.

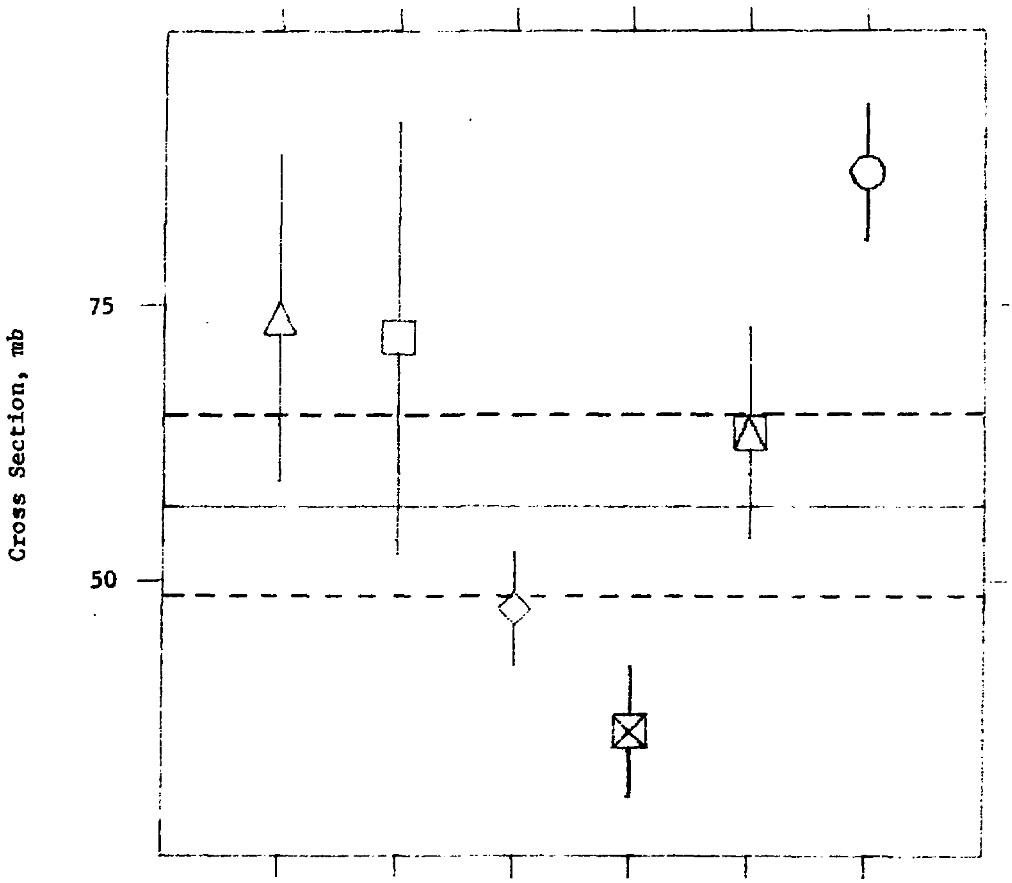

Figure 2: Evaluation of 14.7-MeV cross sections for Co-59(n,p)Fe-59

59-CO(N,P)FE-59 REFERENCES

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(N) $^{59}Co(n,\alpha)^{56}Mn$

^{59}Co is the only isotope of elemental cobalt, so no other neutron reaction channels lead to the production of ^{56}Mn. The half life of ^{56}Mn is very well known, with the value 2.5785 ± 0.0006 h accepted as the current best knowledge of this parameter [II.13]. ^{56}Mn decays to levels in ^{56}Fe by β^- emission. According to recent information from Ref. II.13, 98.87 ± 0.04% of the decays produce a characteristic gamma ray of 0.847 MeV. In references from the literature dealing with this reaction, both beta-counting and gamma-ray counting methods are employed. In general these references provide very little information about the activity measurements. An overall correlated decay branch error of 0.5% was assumed for the present evaluation, and none of the data were adjusted for decay effects.

Twenty references were compiled from the literature. Altogether, some forty cross section values were assembled. These are listed in Table 1 and are plotted in Fig. 1. The ENDF/B-V [II.9] evaluation is also plotted in Fig. 1. This evaluation was used to calculate energy adjustment factors required to generate equivalent 14.7-MeV values. One cross section value [11] was rejected at the outset because of inadequate documentation. All the other data were adjusted for energy and revised-standard effects. Multiple-data sets were averaged to produce single values. The initial analysis with code AVERG involved nineteen values. Based on a three-standard-deviation test, six of these data points were rejected as inconsistent with the remaining results [1,2,4,9,13 and 17]. The remaining values were analyzed in a second-pass calculation using code AVERG. The results appear in Table 2 and Fig. 2. The normalized chi-square for the final evaluation is 1.76 which indicates a very moderate level of inconsistency for the accepted data. The enhanced standard deviation for the evaluated cross section is ± 1.4% indicating quite good knowledge for this energy range. The present evaluated result of 30.169 mb is ~ 5.7% higher than the ENDF/B-V [II.9] value of 28.54 mb at 14.7 MeV.

Table 1: Compiled Data for $^{59}Co(n,\alpha)^{56}Mn$

Ref. No.	Symbol	Application	Neutron Energy (MeV)	Energy Resolution (MeV)	Reported Cross Section (mb)	Reported Cross Section Error (mb)
1	5A	I	14.5	NA	39.1	7.82
2	2A	I	14.8	0.035	25.0	5.0
3	4A	E	14.05	0.2775	31.0	3.0
4	5C	I	14.0	NA	29.0	6.0
5	8G	E	14.0	NA	32.0	15.0
6	5	E	14.8	0.45	30.0	3.0
7	4	E	14.1	0.2	30.0	1.02
			15.2	0.2	28.9	1.18
8	3A	E	13.9	NA	33.0	3.0
			14.3	NA	33.0	3.0
			15.05	NA	26.0	3.0
9	3B	I	14.9	NA	26.0	3.0
10	2	E	13.89	0.04	29.4	0.9
			14.24	0.04	29.0	0.9
			14.5	0.04	30.0	0.9
			14.76	0.04	29.7	0.9
11	2C	D	14.7	NA	14.7	NA
12	8A	E	14.05	0.125	28.6	2.0
			14.24	0.13	27.4	1.9
			14.42	0.13	28.4	2.0
			14.8	0.135	26.9	1.9
			14.99	0.135	27.8	1.9
			15.18	0.13	26.0	1.8
13	2H	I	14.1	NA	27.0	1.5
14	1	E	14.8	NA	32.0	5.0
15	7	E	14.8	NA	32.0	7.0
16	6	E	14.78	0.1	32.3	0.7
17	8B	I	14.6	NA	35.0	3.0
18	3	E	14.0	0.1	32.0	3.0
			15.3	0.05	29.0	3.0
19	8F	E	13.9	0.1	29.5	1.5
			14.5	0.1	27.4	1.4
			15.1	0.1	25.9	1.3
20	8	E	14.08	0.05	29.4	0.9
			14.17	0.16	29.9	1.3
			14.36	0.075	30.3	1.0
			14.61	0.125	30.2	0.9
			14.77	0.125	29.8	1.0
			14.83	0.13	30.5	1.0
			15.09	0.1	29.8	1.2

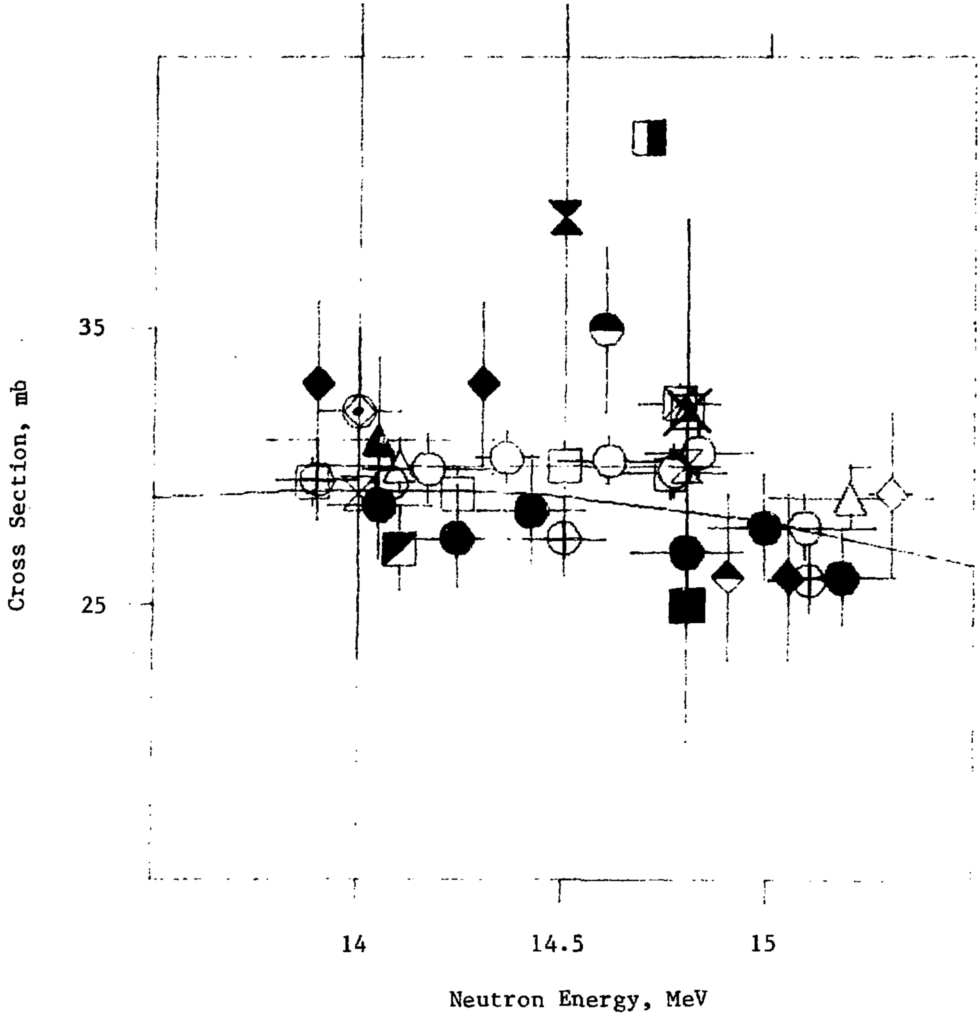

Figure 1: Compiled experimental data for Co-59(n,alpha)Mn-54

Table 2: Additional Information for the $^{59}Co(n,\alpha)^{56}Mn$ Evaluation

Ref. No.	Standard	Standard Adjustment Factor	Energy Adjustment Factor	Adjusted Cross Section (mb)		Errors (%) Uncorrelated	Standard	Total[a]
3	S4	1.0384	0.9808	31.57		10.0	0.6	10.0
5	S4	1.0418	0.9808	32.69		15.0	0.6	15.0
6	S5	0.9923	1.0063	29.96		10.0	1.3	10.1
7	S2	1.0381	0.9808	30.54	29.50	3.2	0.6	3.3
		0.9229	1.0431	27.82				
8	S4	1.0676	0.9808	34.55	32.02	5.6	0.6	5.7
		1.0398	0.9821	33.70				
		0.9537	1.0251	25.41				
10	S3	1.1195	0.9808	32.28	29.57	1.9	1.5	2.2
		1.0363	0.9808	29.48				
		0.9770	0.9875	28.94				
		0.9451	1.0039	28.18				
12	A	1.0000	0.9808	28.05	27.90	3.5	0	3.5
			0.9808	26.87				
			0.9855	27.99				
			1.0063	27.07				
			1.0186	28.32				
			1.0408	27.06				
14	S4	0.9664	1.0063	31.12		15.6	0.6	15.6
15	S5	0.9734	1.0063	31.35		18.8	1.3	18.8
16	S4	0.9681	1.0053	31.44		1.2	0.6	1.3
18	S2	0.9669	0.9808	30.35	30.44	6.9	0.6	7.0
		0.9765	1.0811	30.61				
19	S4	1.0877	0.9808	31.47	30.86	3.5	0.6	3.6
		1.1141	0.9875	30.15				
		1.1514	1.0311	30.75				
20	S2	1.0426	0.9808	30.06	29.33	1.6	0.6	1.7
		1.0434	0.9808	30.60				
		1.0153	0.9838	30.27				
		0.9626	1.0046	28.82				
		0.9583	1.0085	29.48				
		0.9353	1.0300	26.78				
		0.9796	0.9882	29.24				

Evaluation Summary

Evaluated Cross Section: 30.169 mb

Normalized chi-square: 1.76

Standard deviation: 0.425 mb (1.4%) enhanced

[a]A 100% correlated error of 0.5% is added for decay branch uncertainty.

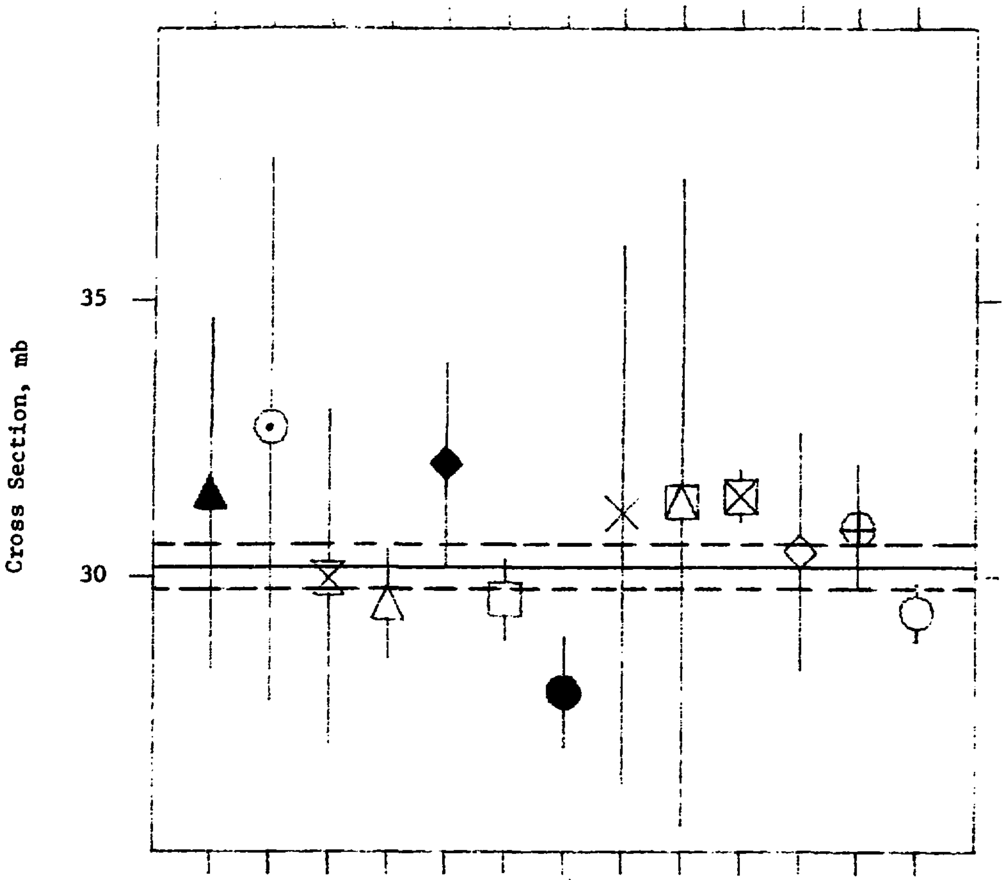

Figure 2: Evaluation of 14.7-MeV cross sections for Co-59(n,alpha)Mn-54

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(O) ^{59}Co(n,2n)^{58}Co

^{59}Co is the sole isotope of elemental cobalt, so no other reactions lead to ^{58}Co production. There is a metastable state, ^{58m}Co, at an excitation of ~ 25 keV in ^{58}Co [II.13]. It has a half life of 9.15 ± 0.10 h, and ultimately decays to the 70.87 ± 0.07 d half life ground state via an M3 electromagnetic transition. Here we are interested in the total (n,2n) cross section (i.e., the sum of the ^{58m}Co and ^{58g}Co production). This total yield can be measured provided that sufficient time is allowed for the ^{58m}Co activity to die away to pure ^{58g}Co activity. If activity measurements are made several days after the end of the irradiations, the $^{58m+g}$Co yield desired will indeed be measured. In the absence of specific comment to contrary in the original documentation, we assumed this to be the case for the data we compiled. ^{58}Co decays by β^+ emission and electron capture (EC) to levels in ^{58}Fe. The method of choice for the measurements is detection of the characteristic 0.811-MeV gamma ray which accompanies 99.44±0.02% of all ^{58}Co decays (II.13). An alternative method is measurement of 0.511-MeV gamma rays which follow annihilation of the positrons. The positron decay branch is 15.0% , so there are 30 annihilation gamma rays for each 100 decays of ^{58}Co. For the references compiled from the literature, the detection of 0.811-MeV gamma rays was the method of choice in most instances. In this work, we corrected the data to correspond to the 99.44% decay branch whenever another value was explicitly used. Otherwise, no correction was applied. The assumed fully-correlated decay uncertainty component was chosen to be 0.5%.

Twenty-one references were found in the literature, corresponding to forty-seven distinct cross sections. These values are listed in Table 1 and are plotted in Fig. 1. Also plotted in Fig. 1 is the ENDF/B-V [II.9] curve for this reaction. The energy-adjustment factors required to convert to 14.7-MeV equivalent results were deduced from this earlier evaluation. Six data sets were rejected, either because of a lack of documentation [1,7,8 and 18] or because an unorthodox standard was used [21]. One value was rejected because no error information was provided [9]. The remaining data were adjusted for changed standards, neutron-energy effects and decay effects, and multiple data sets were averaged to single values.

The first-pass analysis with AVERG involved fifteen data points. These data were highly inconsistent, as indicated by a normalized chi-square of 26.85. Based on this preliminary analysis, three data sets were rejected owing to inconsistency [6,12 and 15]. The remaining twelve data points were reanalyzed to provide the final evaluation. For these included data the normalized chi-square of 2.28 indicates some degree of inconsistency, but not to a serious extent. The results of this analysis appear in Table 2 and Fig. 2. The enhanced standard deviation in the final evaluation is 2.4%. Our value of 747.68 mb is 7.4% lower than the ENDF/B-V value [II.9].

The $^{59}Co(n,2n)^{58}Co$ reaction is typical of those reactions in the present investigation which rely on the $^{65}Cu(n,2n)^{64}Cu$ reaction (56) as a standard, to some extent, as discussed in Section II. In order to estimate the uncertainty which might follow from variation in the decay constants of ^{64}Cu, we added 8% random error to each data point included in the evaluation which is based on this standard. This error appears to be the largest one could expect in the dominant decay branches of ^{64}Cu, based on reference to the literature [II.13, II.14 and II.17]. A re-evaluation of the cross section, using the 12 values selected for the second pass, led to an evaluated cross section of 754.4 mb, which differs by 0.9% from the value accepted for this evaluation. The normalized chi-square w[illegible] somewhat reduced, but the final enhanced standard deviation was 12.5 mb ([illegible].3%), which is essentially the same as before. Thus, we conclude that the evaluation is not too sensitive to the ^{64}Cu decay, at least within the range of values which are likely to have been employed by the original authors.

Table 1: Compiled Data for $^{59}Co(n,2n)^{58}Co$

Ref. No.	Symbol	Application	Neutron Energy (MeV)	Energy Resolution (MeV)	Reported Cross Section (mb)	Reported Cross Section Error (mb)
1	2B	D	14.1	NA	870.0	0
2	5B	E	14.5	0.5	855.0	165.0
3	2	E	14.1	0.2	640.0	102.4
			15.2	0.2	671.0	100.65
4	7	E	14.0	NA	630.0	120.0
5	1	E	14.11	0.5	776.0	62.08
			14.37	0.5	767.0	61.36
			14.59	0.1	823.0	65.84
			14.77	0.125	827.0	66.16
6	2C	I	14.9	NA	508.0	70.0
7	6	D	14.1	NA	640.0	70.0
8	5C	D	14.0	NA	587.0	117.4
9	2D	D	14.7	NA	1040.0	NA
10	8	E	14.05	0.125	650.0	39.0
			14.42	0.13	677.0	41.0
			14.71	0.135	686.0	41.0
			15.09	0.13	704.0	42.0
			15.37	0.125	727.0	44.0
11	4	E	14.1	0.15	642.0	32.0
			15.2	0.15	695.0	56.0
12	2A	I	13.94	0.04	920.0	28.0
			14.27	0.04	1010.0	27.0
			14.44	0.04	996.0	18.0
			14.73	0.045	1030.0	17.0
			14.98	0.05	1105.0	30.0
13	3	E	14.12	0.07	640.1	31.3
			14.5	0.07	683.3	63.7
			14.8	0.08	669.0	34.2
			15.04	0.085	643.5	41.0
			15.25	0.11	626.6	36.0
14	8F	E	14.6	0.1	760.0	60.0
15	8B	I	14.36	0.07	570.0	75.0
16	3C	E	14.6	NA	663.0	67.0
17	8G	E	14.7	0.075	820.0	85.0
18	8A	D	14.6	NA	752.0	60.0
19	3A	E	14.0	0.1	746.0	49.0
			15.3	0.05	768.0	51.0
20	5	E	13.8	0.05	660.0	24.0
			14.08	0.16	723.0	28.0
			14.17	0.075	775.0	36.0
			14.36	0.125	778.0	28.0
			14.61	0.125	798.0	29.0
			14.83	0.135	817.0	29.0
			15.09	0.17	819.0	38.0
21	4A	D	14.8	0.15	342.0	42.0

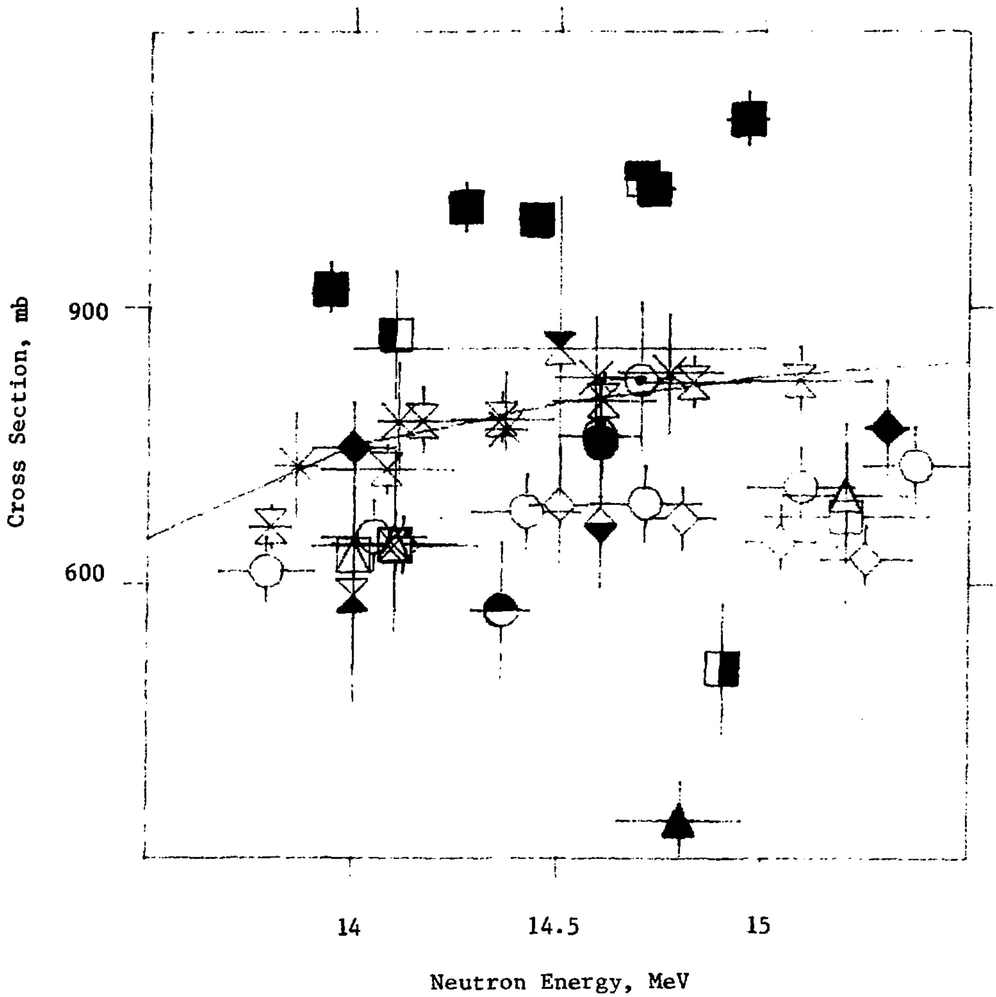

Figure 1: Compiled experimental data for Co-59(n,2n)Co-58

Table 2: Additional Information for the $^{59}Co(n,2n)^{58}Co$ Evaluation

Ref. No.	Standard	Standard Adjustment Factor	Energy Adjustment Factor	Adjusted Cross Section (mb)		Errors (%) Uncorrelated	Standard	Total[a]
2	S6	0.9178	1.0151	797.05		10.1	1.2	10.2
3	S2	1.0407	1.0632	708.14	648.4	11.8	0.6	11.8
		0.9229	0.9711	601.37				
4	S2	1.0586	1.0760	721.62		15.0	0.6	15.1
5	S6	0.8434	1.0620	695.47	738.45	6.8	1.2	6.9
		0.9029	1.0307	714.21				
		0.9257	1.0080	768.56				
		0.9427	0.9948	775.56				
10	S1	1.0	1.0696	699.13	696.51	4.3	1.0	4.4
		1.0	1.0244	697.4				
		1.0	0.9993	689.36				
		1.0	0.9761	691.02				
		1.0	0.9652	705.63				
11	S5	0.9413	1.0632	646.11	699.7	4.2	1.3	4.5
		1.2494	0.9711	836.89				
13	S6	1.0076	1.0607	687.95	699.18	3.7	1.3	3.9
		1.0457	1.0151	729.38				
		1.0768	0.9926	719.05				
		1.1023	0.9768	696.75				
		1.1244	0.9694	686.81				
14	S2	0.9536	1.0075	734.26		7.9	0.6	7.9
16	S5	0.9722	1.0075	635.04		10.1	1.3	10.2
17	S1	1.0	1.0	820.0		10.4	1.0	10.5
19	S2	0.9669	1.0760	776.13	754.39	4.7	0.6	4.8
		0.9855	0.9676	732.34				
20	S2	1.0426	1.0658	807.9	806.57	2.1	0.6	2.2
		1.0434	1.0545	857.48				
		1.0179	1.0318	821.68				
		0.9797	1.0067	791.44				
		0.9694	0.9948	773.87				
		0.9660	0.9904	786.02				
		0.9353	0.9761	751.89				

Evaluation Summary:

Evaluated cross section: 747.68 mb

Normalized chi-square: 2.28 mb

Standard deviation: 17.74 mb (2.4%) enhanced

[a]A 100%-correlated decay error of 0.5% is included.

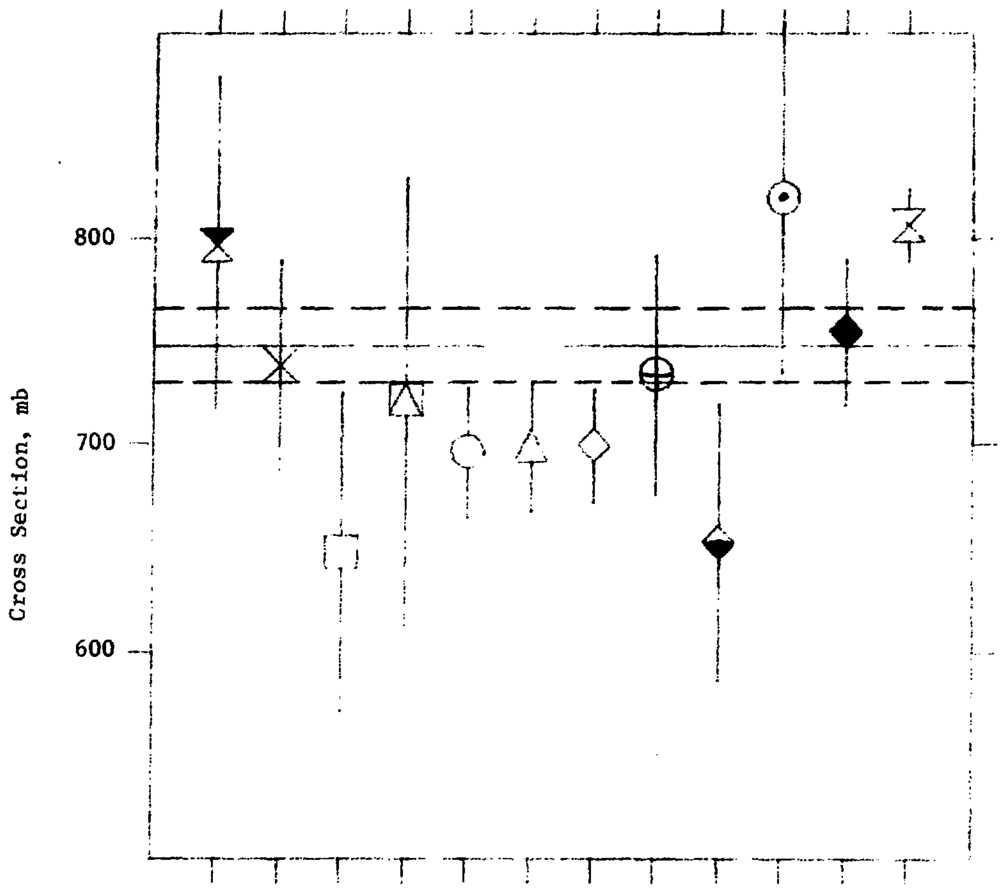

Figure 2: Evaluation of 14.7-MeV cross sections for Co-59(n,2n)Co-58

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(P) $^{65}Cu(n,p)^{65}Ni$

The reaction $^{65}Cu(n,p)^{65}Ni$ is the only neutron reaction with elemental copper which produces ^{65}Ni. This reaction product decays with a half life of 2.520 ± 0.002 h [II.13] by β^- emission to levels in ^{65}Cu. The emitted β^- spectrum is rather complicated. The predominant gamma ray which follows the decay of ^{65}Ni is the 1.482-MeV transition. This is observed in 23.5 ± 0.8% of the ^{65}Ni decays [II.13]. The uncertainty in this gamma-ray branch is 3.4% according to Ref. II.13; however, an earlier version of this reference source [II.17] fixes the decay branch for 1.482-MeV gamma-ray emission at 26%. We note that reports of previous investigations on this reaction generally fail to provide clear documention on the relevant decay information, thus we made the decision to not correct any reported results for this effect. Instead, we assumed a fully-correlated error of 3.4% and added an extra random error component of 4.3% to the other errors considered for each experimental result. The resultant 5.5% decay branch error is a dominant source of error for some of the reported values.

Twenty-three relevant experimental data sets were compiled from the literature. These results are listed in Table 1 and plotted in Fig. 1 as well. There is no specific ENDF/B evaluated curve for $^{65}Cu(n,p)^{65}Ni$; however, Hetrick et al. [24] have recently compared available data for this reaction with results of their model calculations. We show the model-calculated curve in Fig. 1 and used it in calculating energy adjustment factors for the present evaluation.

Prior to performing the first-pass evaluation, two data sets [15,23] were rejected for lack of proper documentation. The remaining data were adjusted for changes in standard cross sections and to convert to equivalent 14.7-MeV values. Multiple data sets were averaged to produce a single value per set, with an appropriate reduction in the random error in each such instance. The first-pass analysis with code AVERG indicated that a number of values ought to be rejected as either inconsistent or because the errors were large enough so the effect on the evaluation process was of no consequence [2,3,4,6,7,8,9 and 17]. The remaining thirteen values were reanalyzed in order to produce the final evaluation.

The final evaluated cross section is 20.464 ± 1.423 mb. The standard deviation is 7.0%, and it is enhanced as described in Section II to account for a normalized chi-square of 2.65. This chi-square indicates that the data retained for the evaluation are somewhat inconsistent, though to a moderate degree compared with some other reactions considered in this report. The evaluated results are summarized in Table 2 and are plotted in Fig. 2 as well.

Table 1: Compiled Data for $^{65}Cu(n,p)^{65}Ni$

Ref. No.	Symbol	Application	Neutron Energy (MeV)	Energy Resolution (MeV)	Reported Cross Section (mb)	Reported Cross Section Error (mb)
1	4A	E	14.1	NA	19.0	3.8
2	2D	I	14.8	NA	31.0	13.0
3	3	I	14.8	0.9	27.0	11.0
4	3B	I	14.1	0.2	30.0	6.0
5	2F	E	15.0	0.4	17.0	4.0
6	8A	I	14.8	NA	29.0	2.9
7	8C	I	14.1	NA	29.0	4.64
8	3D	I	14.5	0.9	29.3	3.2
9	2	I	14.7	0.2	29.3	3.2
10	8	E	14.1	0.4	25.6	8.96
			14.6	0.3	21.5	7.31
			15.2	0.4	21.1	6.75
			15.4	0.4	19.1	5.92
11	4	E	14.7	0.3	26.0	3.0
12	8B	E	14.24	0.8	20.9	1.1
			14.5	0.6	20.4	1.1
			14.76	0.6	18.9	1.0
13	1	E	14.1	0.18	19.0	2.0
			14.8	0.02	26.0	3.0
14	5B	E	14.8	NA	20.0	2.0
15	6A	D	14.4	NA	23.5	5.2
16	8E	E	14.8	0.5	18.0	2.0
17	5A	I	14.2	0.2	29.2	3.0
			14.6	0.2	31.2	3.2
18	5	E	14.6	NA	24.9	4.4
19	5C	E	14.78	0.2	26.0	0.6
20	8F	E	14.6	NA	21.5	1.9
21	8G	E	14.7	0.3	27.0	2.3
22	6D	E	14.67	0.1	18.1	0.8
			15.3	0.3	20.9	0.7
23	3A	D	14.08	0.11	25.3	3.2
			14.4	0.13	24.6	3.1
			14.62	0.14	24.1	2.6
			14.71	0.14	23.0	2.2

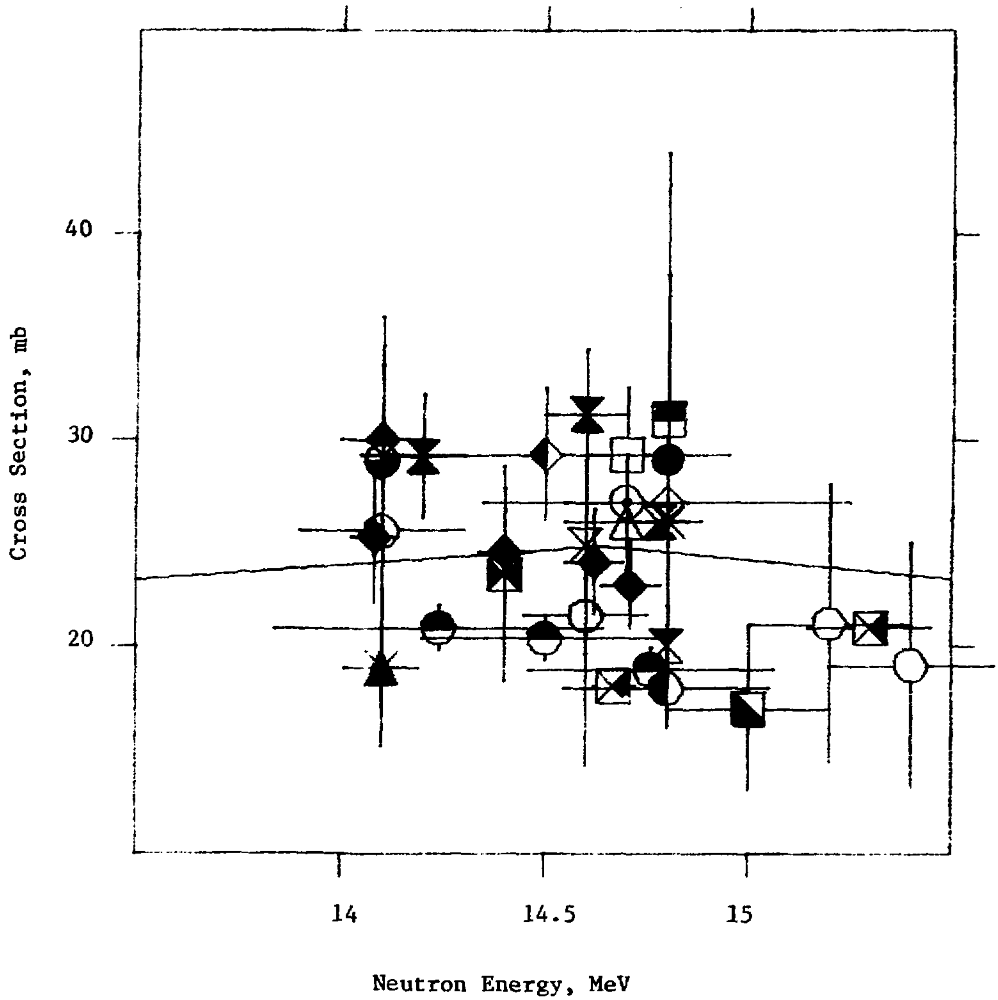

Figure 1: Compiled experimental data for Cu-65(n,p)Ni-65

Table 2: Additional Information for the $^{65}Cu(n,p)^{65}Ni$ Evaluation

Ref. No.	Standard	Standard Adjustment Factor	Energy Adjustment Factor	Adjusted Cross Section (mb)		Errors (%) Uncorrelated	Standard	Total[a]
1	A	1.000	1.0261	19.50		20.5	0	20.8
5	S5	0.9923	1.0261	17.31		18.5	1.3	18.9
10	S4	1.0124	1.0261	26.59	20.96	10.5	0.6	11.1
		0.9716	0.9964	20.81				
		0.8924	1.0386	19.56				
		0.8809	1.0544	17.74				
11	A	1.000	1.000	26.0		12.7	0	13.1
12	S3	1.0363	1.0177	22.04	20.03	5.3	1.5	6.5
		0.9770	1.0024	19.98				
		0.9451	1.0045	17.94				
13	S5	1.0409	1.0261	20.29	23.43	8.9	1.3	9.6
			1.0073	27.26				
14	S6	0.9734	1.0073	19.61		10.9	1.2	11.5
16	S4	0.8436	1.0073	15.29		11.9	0.6	12.4
18	S4	1.0410	0.9964	25.83		18.2	0.6	18.5
19	S4	0.9690	1.0061	25.34		5.2	0.6	6.2
20	S2	1.0079	0.9964	21.59		8.8	0.6	9.5
21	S2	0.9397	1.000	25.37		8.0	0.6	8.7
22	S4	1.0076	0.9980	18.20	20.17	5.6	0.6	6.6
			1.0465	22.04				

Evaluation Summary:

Evaluated cross section: 20.464 mb

Normalized chi-square: 2.65

Standard deviation: 1.423 mb (7.0%) enhanced

[a]A 100%-correlated error of 3.4% to account for decay branch uncertainty is included.

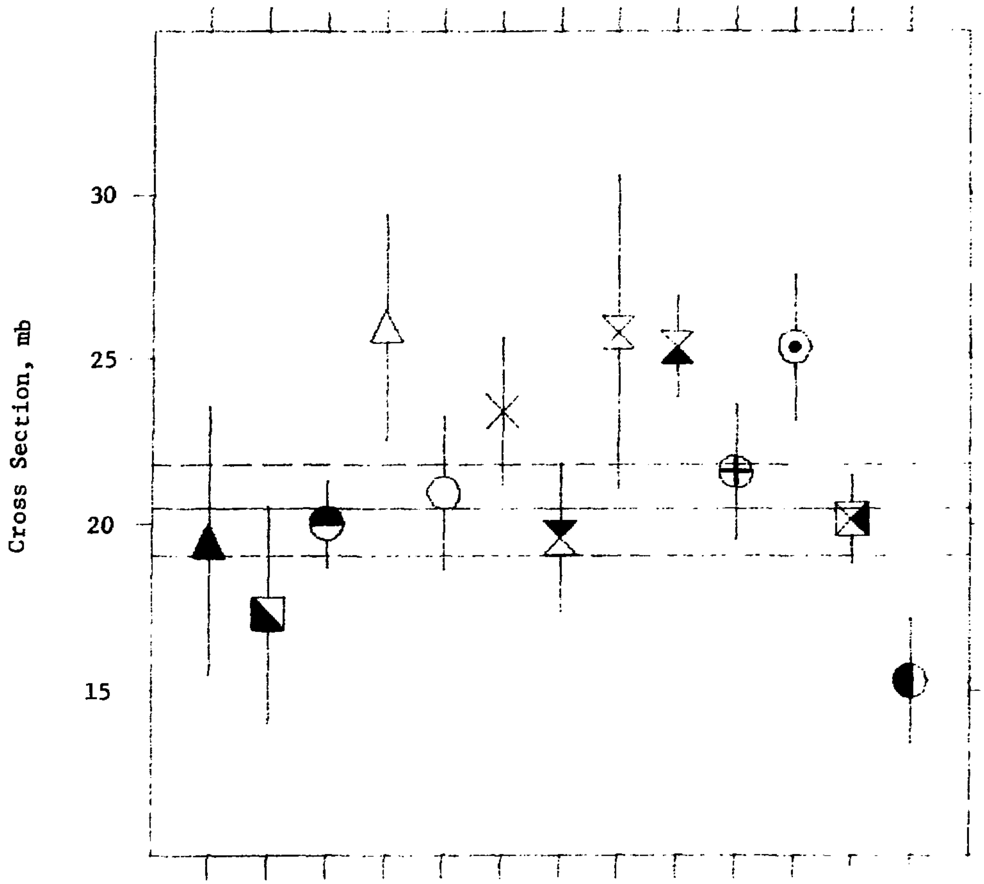

Figure 2: Evaluation of 14.7-MeV cross sections for Cu-65(n,p)Ni-65

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(Q) $Zn(n,X)^{64}Cu$

There are five stable isotopes of natural zinc with the following abundances: ^{64}Zn (48.6%), ^{66}Zn (27.9%), ^{67}Zn (4.10%), ^{68}Zn (18.8%) and ^{70}Zn (0.62%) [II.13]. However, just two of these need to be considered in the production of ^{64}Cu activity by fast neutrons ~ 14 MeV: ^{66}Zn and ^{64}Zn. One expects that the $^{64}Zn(n,p)^{64}Cu$ reaction will dominate the $^{66}Zn(n,t)^{64}Cu$ reaction to a considerable extent, but a more quantitative estimate is in order. According to the evaluation by Tagesen et al. [24], the cross section for $^{64}Zn(n,p)^{64}Cu$ is ~ 160 mb at 14.7 MeV. According to Qaim et al. [26], the (n,t) cross section for ^{64}Zn is ~ 0.06 mb. Owing to a nearly equal Q-value, and nuclear structure similarities, we anticipate a corresponding cross section magnitude for $^{66}Zn(n,t)^{64}Cu$. Based on these arguments, and the known isotopic abundances, we conclude that the ^{64}Cu production from ^{66}Zn will be $\lesssim$ 0.03% of the total. This is negligible, so for practical purposes we are concerned only with $^{64}Zn(n,p)^{64}Cu$. As discussed for other reactions in this report, we consider the isotopic ^{64}Zn cross section as the quantity of interest for present purposes.

The decay of ^{64}Cu is a rather complicated issue which requires discussion. The half life is quite well known, and we choose to refer to the recent value of 12.698±0.002 h from the work of Christmas et al. [25]. This value is almost identical to the 12.699±0.008 h value recommended in Ref. II.13. Other values reported over a period of nearly three decades differ by less than ± 1.5%. It is likely that for the measurements of interest here, the exposure, wait and counting times were all substantially shorter than ~ 12-13 hours, although such details are rarely documented. Under these conditions, the reported cross section will be approximately proportional to the half life value used in the analysis. Thus, we were able to adjust the reported data for half-life effects provided that the authors gave the value used. It was decided to enhance the random error by 1.5% when such information was not available. For measurements with the $^{65}Cu(n,2n)^{64}Cu$ standard, no error was added. This special case is discussed further below.

There are three distinct decay modes for ^{64}Cu, involving β^-, β^+ and electron capture (EC) branches. This issue has been discussed at length by Christmas et al. [25], and we have chosen to accept their decay branch parameters as being the most reliable for present purposes. The β^- decay branch leads exclusively to the ground state of ^{64}Zn. The decay branch is 39.04±0.33%, and is of interest only for beta spectrum techniques [25]. Over a period of more than two decades, the reported values for this decay branch have differed by at most ± 3% from this value. The EC decay branch populates levels in ^{64}Ni, and it amounts to 43.10 ± 0.46% [25]. Again, the values reported have tended to vary by less than ± 2%. Most EC decays populate the ground state of ^{64}Ni, but 0.471±0.011% of all ^{64}Cu decays produce a 1.346-MeV gamma ray corresponding to EC population of the first-excited state of ^{64}Ni, followed by prompt electromagnetic decay to the ground state. This signature of the ^{64}Cu decay has been used in experiments. The reported 1.346-MeV gamma-ray branches have varied by as much as 30% from the value of Christmas et al. [25] which we quote above. The β^+ emission decay branch amounts to 17.86 ± 0.14% [25], however, values differing by ± 8%

from this have been reported. For each β^+ decay, two 0.511-MeV annihilation gamma rays are ultimately produced. There is an inherent source of potential systematic error for measurements based on the detection of annihilation radiation from β^+ decay: The emitted β^+ particles must combine with electrons in matter before annihilation radiation is emitted. Thus, to perform accurate measurements one must be sure the β^+ particles stop in the sample. For larger samples most do. For thin samples surface losses and subsequent annihilation outside the sample can lead to systematic measurement difficulties. A final consideration in the present evaluation is that several data sets involve measurements relative to $^{65}Cu(n,2n)^{64}Cu$. This is favorable since for ratio measurements factors related to half life and decay branch tend to largely cancel and the uncertainties are small.

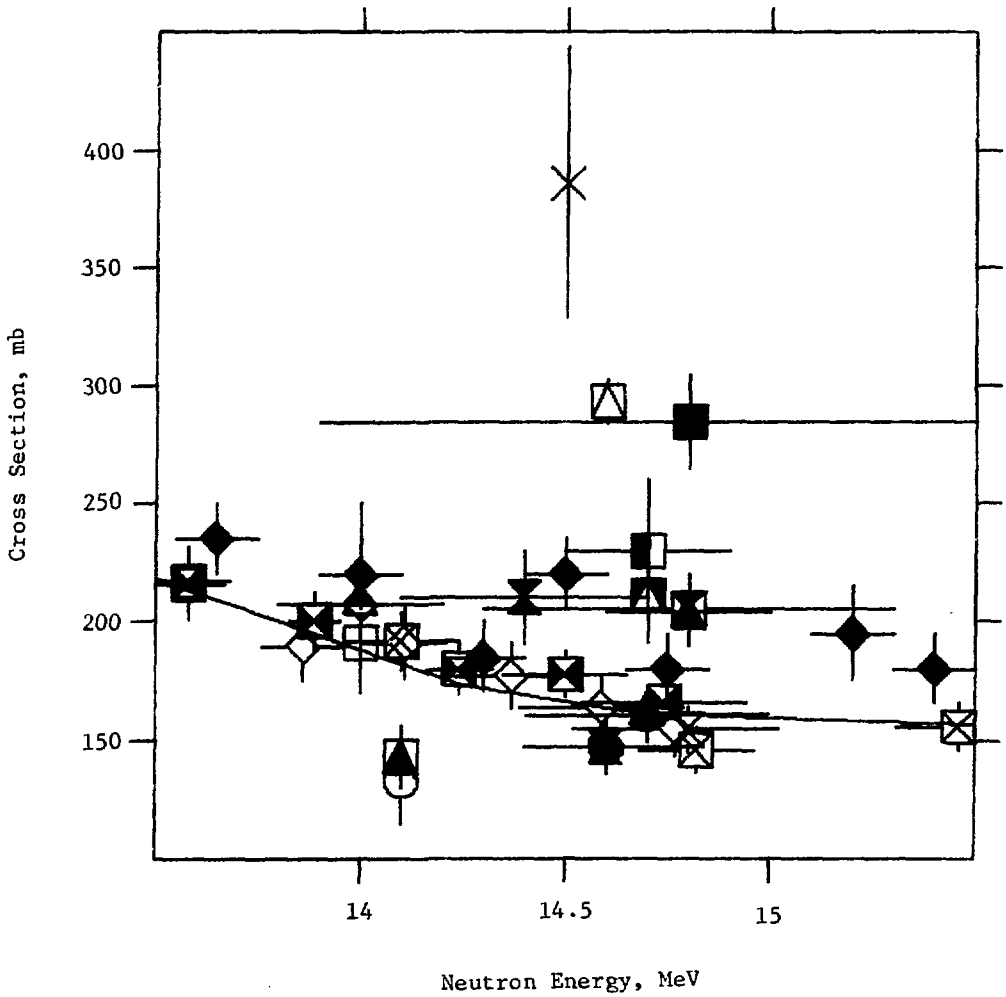
In view of the considerations indicated in the previous paragraph, we decided to approach the error assessment for decay branching as follows: First, we assumed an extra overall error of 0.8%, representing the minimum possible uncertainty in any of the decay channels. It applies to all the data, and is treated as 100% correlated. Only one of the considered experiments [12] utilized the yield of 1.346-MeV gamma rays from the EC branch. The branch factor was provided, so an extra random error of only 2.3% was added. For all the beta spectrum measurements compiled there were no details provided on the decay branching, so we added 10% random error here except in instances where $^{65}Cu(n,2n)^{64}Cu$ was the standard. Then, no extra error was added. For measurements involving gamma rays from β^+ annihilation, an extra 8% random error was added when no branching factor details were reported, but no error was added when the information was provided or when $^{65}Cu(n,2n)^{64}Cu$ was the standard.

Twenty-two distinct data sets were compiled from the literature. These data are listed in Table 1 and are plotted in Fig. 1. We also show the evaluation of Tagesen et al. [24] in Fig. 1. This evaluation was used to derive the adjustment factors needed to convert reported results to equivalent 14.7-MeV cross sections. Five of these data sets were rejected a priori because of inadequate reporting of details required for the evaluation [2,8,9, 10 and 19]. The remaining data were adjusted for revised standards, half lives and decay branching, as appropriate, and results were converted to equivalent 14.7-MeV cross sections. Multiple data sets were averaged, thereby reducing part of the corresponding random error. The resulting seventeen values were analyzed with code AVERG. This analysis yielded a normalized chi-square of 5.76, indicating considerable inconsistency. A plot was made and enchanced three-standard-deviation bands were drawn. As a result of this analysis, seven of the values were clearly seen to be inconsistent with the remaining members of the ensemble, and were thus rejected. A new analysis involving ten data points was performed using code AVERG. This calculation yielded a normalized chi-square of 1.56, which indicates that the retained data are reasonably consistent. The final evaluated cross section is 165.40 $\pm$ 4.35 mb (2.6% enhanced standard deviation). The results of this evaluation appear in Table 2 and in Fig. 2.

Our evaluated result differs by 2.3% from the 161.66 mb value at 14.7 MeV obtained by Tagesen et al. [24]. This difference is well within the uncertainties of both evaluations (~ 8-10% for Ref. 24).

Table 1: Compiled Data for $Zn(n,X)^{64}Cu$

Ref. No.	Symbol	Application	Neutron Energy (MeV)	Energy Resolution (MeV)	Reported Cross Section (mb)	Reported Cross Section Error (mb)
1	1	I	14.5	NA	386.0	57.9
2	2	D	14.0	NA	191.0	NA
3	2A	I	14.8	1.8	284.0	20.0
4	2B	I	14.7	0.4	230.0	30.0
5	3	E	13.86	0.2	190.0	15.2
			14.11	0.2	191.0	15.28
			14.37	0.3	177.0	14.16
			14.59	0.4	164.0	13.12
			14.77	0.5	155.0	12.4
6	3A	E	13.65	0.2	235.0	15.0
			14.0	0.2	220.0	15.0
			14.3	0.2	185.0	15.0
			14.5	0.2	220.0	15.0
			14.75	0.2	180.0	15.0
			15.2	0.2	195.0	20.0
			15.4	0.2	180.0	15.0
7	3B	E	14.0	0.4	207.0	14.0
8	4	D	14.0	NA	210.0	40.0
9	4A	D	14.7	NA	163.0	NA
10	4B	D	14.8	0.4	204.0	15.0
11	5	E	14.8	NA	154.0	10.0
12	5A	I	14.4	0.6	210.0	20.0
13	5B	E	14.6	0.4	147.0	10.0
14	6	E	14.1	0.28	191.7	12.4
			14.82	0.28	145.4	9.8
			15.46	0.3	155.4	10.3
15	6A	E	14.8	1.0	205.0	15.0
16	6B	E	13.58	0.18	216.0	16.0
			13.58	0.2	217.0	13.0
			13.89	0.12	200.0	12.0
			14.24	0.16	180.0	11.0
			14.50	0.3	178.0	10.0
			14.74	0.4	166.0	10.0
17	7	I	14.6	NA	292.6	9.2
18	7A	I	14.1	NA	143.0	13.0
19	7B	D	14.7	NA	211.0	20.0
20	8	I	14.1	NA	133.0	17.96
21	8A	E	14.6	NA	147.0	11.0
22	8B	E	14.7	0.6	160.0	12.0



<u>Figure 1</u>: **Compiled experimental data for Zn(n,X)Cu-64**

Table 2: Additional Information for the $Zn(n,X)^{64}Cu$ Evaluation

Ref. No.	Half Life (h)	Half-Life Adjustment Factor	Observed Decay Mode	Decay Branch (%)	Decay Branch Adjustment Factor	Standard	Standard Adjustment Factor	Energy Adjustment Factor	Adjusted Cross Section (mb)		Errors (%) Uncorrelated	Standard	Total[b]
5	12.85	1.0[a]	NA	NA	1.0[a]	S6	1.0096	0.8235	157.97	165.35	3.6	1.2	3.9
							1.0091	0.8919	171.90				
							1.0307	0.9534	173.93				
							1.023	0.9884	165.83				
							1.008	1.0055	157.10				
6	NA	1.0[a]	NA	NA	1.0[a]	S6	0.9497	0.7736	172.65	179.94	3.0	1.2	3.2
								0.8603	179.75				
								0.9428	165.64				
								0.9737	203.43				
								1.0040	171.63				
								1.0255	189.91				
								1.0328	176.55				
7	13.0	1.0[a]	$\beta^+(\gamma)$	NA	1.0[a]	S6	0.9672	0.8603	172.24		6.8	1.2	7.0
11	12.8	1.0[a]	β^+,β^-?	NA	1.0[a]	S6	0.9734	1.0079	151.09		6.5	1.2	6.7
13	NA	1.0	$\beta^+(\gamma)$	38	1.0638	S2	0.9536	0.9900	147.63		7.0	0.6	7.1
14	12.6	1.0078	γ	NA	1.0	S1	0.9990	0.8888	171.54	160.41	8.9	1.0	9.0
								1.00928	147.75				
								1.03496	161.93				
15	11.8	1.0761	β^+,β^-?	NA	1.0	S4	0.8437	1.0079	187.59		12.4	0.6	12.4
16	12.9	0.9843	γ	NA	1.0	S3	0.9770	0.7582	157.49	160.52	8.4	1.5	8.6
								0.7582	158.22				
								0.8310	159.83				
								0.9287	160.76				
								0.9737	166.67				
								1.00316	160.14				

Table 2: Additional Information for the Zn(n,X)^{64}Cu Evaluation (Continued)

Ref. No.	Half Life (h)	Half-Life Adjustment Factor	Observed Decay Mode	Decay Branch (%)	Decay Branch Adjustment Factor	Standard	Standard Adjustment Factor	Energy Adjustment Factor	Adjusted Cross Section (mb)	Errors (%) Uncorrelated	Errors (%) Standard	Errors (%) Total[b]
21	12.71	0.9991	$\beta^+(\gamma)$	38	1.0638	S2	1.0079	0.9900	155.90	7.4	0.6	7.5
22	12.70	1.0	$\beta^+(\gamma)$	38.6	1.0806	S2	0.9397	1.0	162.47	5.6	0.6	5.7

Evaluation Summary:

Evaluated cross section: 165.40 mb

Normalized chi-square: 1.56

Standard deviation: 4.35mb (2.6%) enhanced

[a]Measurements for the standard and unknown both involve analysis of ^{64}Cu activity. Adjustment factors involving half life and decay branch largely cancel.
[b]There is a 100% correlated error of 0.8% due to decay branch uncertainty included.

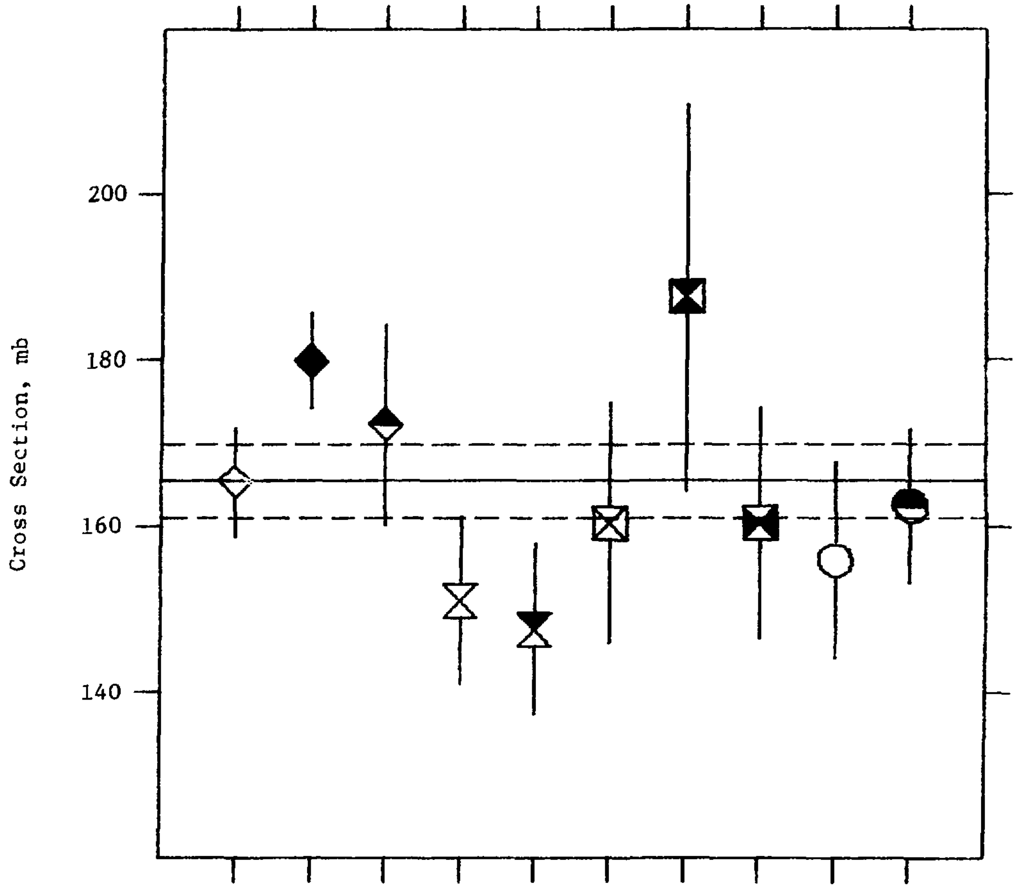


Figure 2: Evaluation of 14.7-MeV cross sections for Zn(n,X)Cu-64

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(R) $^{64}Zn(n,2n)^{63}Zn$

There are five stable isotopes of natural zinc, as discussed in subsection III.Q, but only 48.6%-abundant ^{64}Zn is involved in fast-neutron production of ^{63}Zn at ~ 14 MeV. Thus, our only concerns in preparing for this evaluation were with the decay properties of ^{63}Zn and with obtaining an appropriate neutron-energy-dependent cross section shape to use in converting reported data to equivalent 14.7-MeV values. According to Ref. II.13, the half life of ^{63}Zn is 38.0 ± 0.1 m (0.3% uncertainty). We accepted this value as the best one available for the present evaluation. Other values quoted in Ref. II.13, and the earlier version, Ref. II.17, all fall in the range 37.6-38.5 min (~ 2% spread). However, upon referring to relevant references for this reaction in the literature, we found that a considerably wider range of values has been involved in reported cross section studies. Thus, we chose to include a minimum systematic error of 0.3%, common to all evaluated data. Furthermore, we estimated the impact of the use of half lives other than 38.0 m on the cross section, for various assumed experimental scenarios, and found that the largest probable error is $\lesssim$ 5% due to half life. Thus, whenever the value of half life was not available, we added 5% random error. If the half life was given, we added to the random error in accordance with the actual deviation from our accepted half life. Note that since the experimental time scales were likely to have been of the order of the half life (though such details are rarely published) there is no simple relationship between half life and cross section which would permit adjustment of the reported data. Consequently, no data adjustments for half life were made. ^{63}Zn decays via positron (β^+) emission and electron capture (EC) to ^{63}Cu. Various counting techniques were used in the experiments reported in the literature for this reaction. These fall into two general categories: beta measurements and gamma-ray measurements. The beta measurements involve direct detection of positrons. The gamma-ray measurements have generally involved either detection of specific lines or detection of all photons above the detector sensitivity cutoff levels (usually several tens of keV). According to Ref. II.13, the β^+ branch is 93% with a 0.5% uncertainty. Detection of specific gamma rays involves 0.511-MeV β^+ annihilation radiation, and 0.669- and 0.962-MeV gamma-rays from ^{63}Cu. For the latter two gamma rays the decay branch factors are 8.4% (4.8% uncertainty) and 6.6% (6.9% uncertainty), respectively, according to Ref. II.13. We decided to include 0.5% uncertainty in the systematic error affecting all the analyzed data. This led to a total correlated error of 0.6% for inclusion in the AVERG calculations. For data sets explicitly involving the β^+ branch, no further random error was added provided that the value used for the decay branch was given and could be adjusted. If the 0.669-MeV gamma-ray alone was detected, 4.8% random error was added provided that the decay branch was given and corrected. For data sets providing no quantitative details on radiation detection, 5% random error was added. This approach represents a manageable, but sometimes approximate solution to the uncertainty assessment problem.

Our search of the literature provided 29 relevant data sets for a priori consideration in this evaluation. Of these, seven were rejected early on. Two of these [2,5] yielded only some information on the shape of the cross section, and they were not considered particularly useful for the present purposes. Two other sets [19,22] were based on unorthodox standards and therefore could not be conveniently treated by our evaluation method. The rest of the rejected sets had to be eliminated because of inadequate available information on standards or errors. All of the compiled data are listed in Table 1 and are plotted in Fig. 1.

The $^{64}Zn(n,2n)^{63}Zn$ cross section varies considerably with neutron energy over the range 13.5-15.5 MeV, so sizable adjustments were required in order to convert the reported values to equivalent 14.7-MeV cross sections. Since ^{64}Zn is only one of several Zn isotopes, and this reaction is not in the ENDF/B special purpose files, this evaluation source was of little use. Instead, we referred to the work of Davey et al. [31] for guidance. These authors fitted simple model curves to several data sets reported prior to 1975 in order to estimate model parameters. From this work, we noted that the $^{64}Zn(n,2n)^{63}Zn$ cross section varies nearly linearly with neutron energy between 13.5 and 15.5 MeV. We averaged the results of their various fits, and arrived at the approximate representation, $\sigma \approx 83.78 + 88.27\ (E - 13.5)$ mb, for the range 13.5 MeV $\leq E \leq$ 15.5 MeV. This curve is shown in Fig. 1. It appears to adequately represent the general energy dependence of the available data. From this curve, we deduced the conversion factors for generating equivalent 14.7-MeV values.

The 22 data sets accepted for inclusion in this evaluation contained a total of 64 distinct cross sections. These were adjusted for neutron energy, decay branch and standards revision, and multiple-point sets were averaged to produce single equivalent 14.7-MeV values. The resulting 22 values were analyzed with code AVERG. This first pass yielded a normalized chi-square of 4.23, indicating considerable inconsistency for the included values. On the basis of a three-standard-deviation criterion, nine of these values were rejected as being inconsistent with the ensemble. A re-analysis with the 13 remaining values yielded the evaluated result 162.17 mb with a normalized chi-square of 0.914 and a standard deviation of 3.97 mb (2.4%). The set of thirteen values accepted for the final evaluation is clearly quite consistent. The results of this evaluation are summarized in Table 2 and are plotted in Fig. 2. The present evaluated value is ~ 15% lower than the recommend 190.5 mb cross section from the work of Bődy and Csikai [30].

Table 1: Compiled Data for $^{64}Zn(n,2n)^{63}Zn$

Ref. No.	Symbol	Application	Neutron Energy (MeV)	Energy Resolution (MeV)	Reported Cross Section (mb)	Reported Cross Section Error (mb)
1	1	I	14.5	NA	224.0	44.8
2	2	D	13.9	0.3	170.0	20.0
			13.9	0.3	205.0	20.0
			14.0	0.3	150.0	30.0
			14.45	0.4	270.0	25.0
			14.65	0.3	265.0	15.0
			14.9	0.3	295.0	25.0
			15.05	0.5	265.0	20.0
			15.4	0.4	280.0	20.0
			15.5	0.6	315.0	20.0
3	2A	E	14.1	0.4	119.0	14.28
4	2B	I	14.8	1.8	254.0	20.0
5	2C	D	14.0	0.4	140.0	12.0
			14.2	0.6	170.0	15.0
6	3	E	14.4	0.6	167.0	12.69
7	3A	E	14.7	0.4	153.0	36.0
8	3B	E	13.86	0.2	96.0	7.68
			14.11	0.2	107.0	8.56
			14.37	0.3	136.0	10.88
			14.59	0.4	165.0	13.2
			14.77	0.5	182.0	14.56
9	3C	E	14.13	0.2	105.0	7.0
10	4	E	13.47	0.84	74.4	6.696
11	4A	I	14.0	0.8	102.0	17.0
			15.2	0.8	183.0	19.0
12	4B	D	13.47	0.1	96.0	7.0
			14.0	0.1	115.0	8.0
			14.47	0.2	185.0	15.0
			14.75	0.3	232.0	20.0
			15.3	0.3	230.0	15.0
			15.5	0.4	290.0	20.0
13	4C	D	14.7	NA	157.0	NA
14	5	E	13.54	0.44	79.8	5.6
			13.88	0.48	114.0	8.0
			14.05	0.5	137.0	10.0
			14.42	0.52	172.0	12.0
			14.61	0.52	196.0	14.0
			14.99	0.54	227.0	16.0
			15.18	0.52	239.0	17.0
15	5A	I	14.6	0.2	200.0	13.0
16	5B	I	15.04	NA	288.0	43.2

Table 1: Compiled Data for $^{64}Zn(n,2n)^{63}Zn$ (Continued)

Ref. No.	Symbol	Application	Neutron Energy (MeV)	Energy Resolution (MeV)	Reported Cross Section (mb)	Reported Cross Section Error (mb)
17	5C	E	14.8	0.2	165.0	16.0
18	6	I	14.8	0.2	102.0	10.0
19	6A	D	13.5	0.2	81.0	4.0
			13.6	0.2	89.0	4.0
			14.1	0.2	122.0	6.0
			14.5	0.4	148.0	8.0
			14.6	0.4	153.0	8.0
			14.7	0.4	155.0	8.0
			14.8	0.4	156.0	8.0
20	6B	I	14.4	0.6	150.0	12.0
21	6C	I	14.1	0.28	131.1	8.2
			14.82	0.28	208.1	10.8
			15.46	0.3	273.8	17.4
22	7	D	14.7	0.6	200.0	23.0
23	7A	E	14.6	NA	161.0	12.0
24	7B	E	14.1	NA	102.0	9.0
25	7C	D	14.7	NA	190.0	20.0
26	8	E	14.6	NA	146.0	11.0
27	8A	E	14.2	0.4	131.0	13.0
28	8B	I	14.2	NA	170.0	10.0
			14.5	NA	185.0	14.0
			14.8	NA	186.0	11.0
29	8C	E	14.8	0.6	175.0	30.0

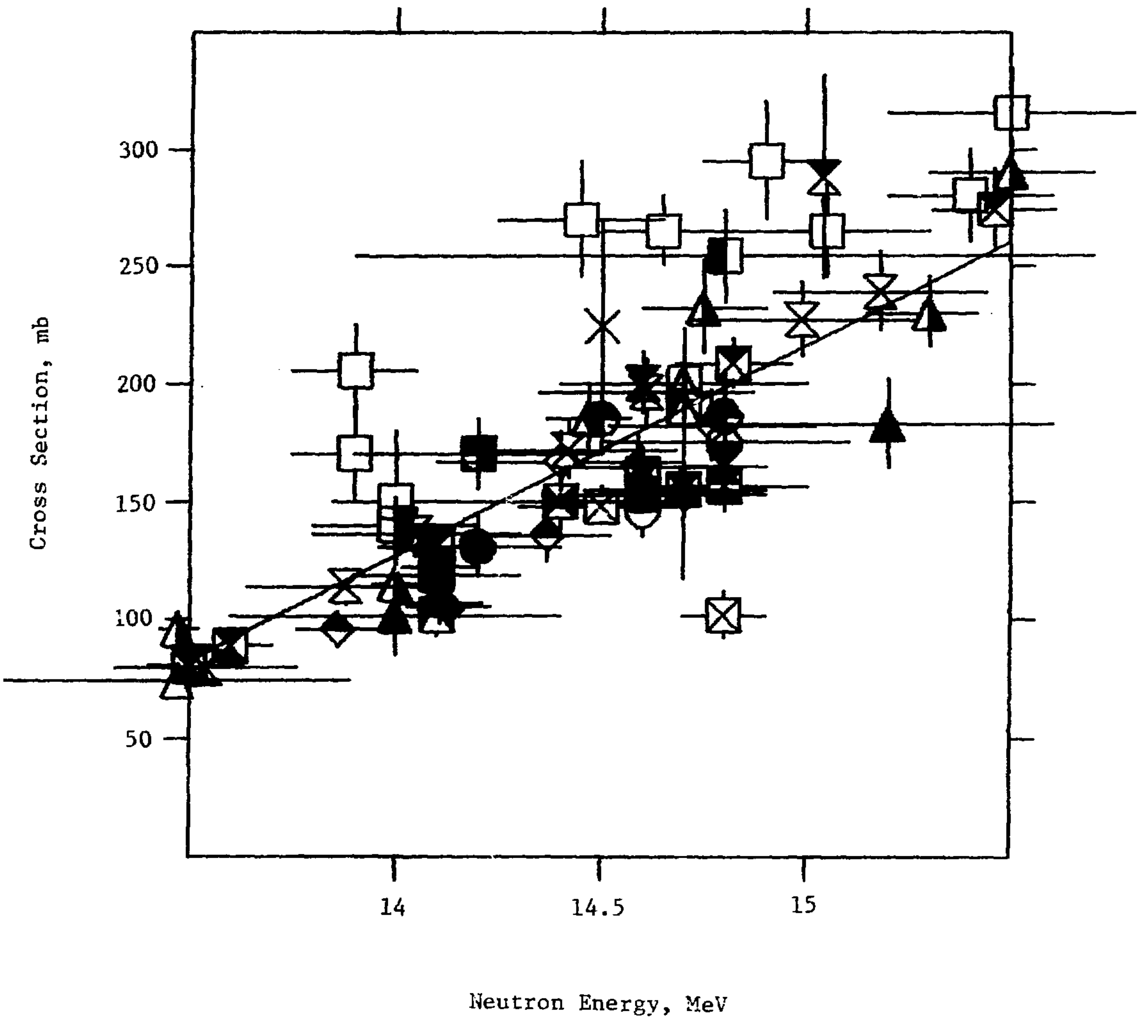

Figure 1: Compiled Experimental Data for Zn-64(n,2n)Zn-63

Table 2: Additional Information for the $^{64}Zn(n,2n)^{63}Zn$ Evaluation

Ref. No.	Half Life (m)	Observed Decay Mode	Decay Branch (%)	Decay Branch Adjustment Factor	Standard	Standard Adjustment Factor	Energy Adjustment Factor	Adjusted Cross Section (mb)		Errors (%) Uncorrelated	Standard	Total[a]
3	38.5	β^+	92.5	0.9946	A	1.0	1.387	164.16		12.1	0	12.1
6	39.9	$\beta^+(\gamma)$	90.4	0.9720	S5	0.9829	1.162	185.08		9.1	1.3	9.2
7	38.0	$\beta^+(\gamma)$?	NA	1.0	S2	0.9974	1.0	152.60		24.0	0.6	24.0
8	38.0	$\beta^+(\gamma?)$	90.4	0.9720	S5	1.002	1.644	153.71	160.98	3.6	1.3	3.9
							1.473	153.51				
							1.182	156.56				
							1.054	169.38				
							0.9689	171.74				
9	38.3	$\beta^+(\gamma)$	NA	1.0	A	1.0	1.362	143.01		8.4	0	8.4
10	39.9	$\beta^+(\gamma)$	NA	1.0	S5	0.9829	2.344	171.41		8.8	1.3	9.0
14	39.0	$\beta^+(\gamma)$	90.4	0.9720	S1	1.0	2.178	168.94	187.84	6.8	1.0	6.9
							1.618	179.29				
							1.435	191.09				
							1.150	192.26				
							1.044	198.89				
							0.8812	194.43				
							0.8176	189.95				
17	NA	$\beta^+(\gamma)$	NA	1.0	A	1.0	0.9555	157.66		12.0	0	12.0
23	38.4	$\beta^+(\gamma)$	NA	1.0	S5	0.9729	1.049	164.31		9.1	1.3	9.2
24	38.4	$\beta^+(\gamma)$	93.0	1.0	S2	1.065	1.387	150.67		8.9	0.6	8.9
26	38.6	$\beta^+(\gamma)$	NA	1.0	S2	1.008	1.049	154.38		9.2	0.6	9.2
27	NA	$\beta^+(\gamma)$	NA	1.0	S2	1.066	1.303	181.96		12.2	0.6	12.2
29	38.4	γ(670 keV)	8.0	0.9524	S2	0.9331	0.9555	148.60		17.8	0.6	17.8

Evaluation Summary:

Evaluated cross section: 162.17 mb

Normalized chi-square: 0.914

Standard deviation: 3.97 mb (2.4 %)

[a] A 100%-correlated half-life and decay-branch uncertainty of 0.6% is included.

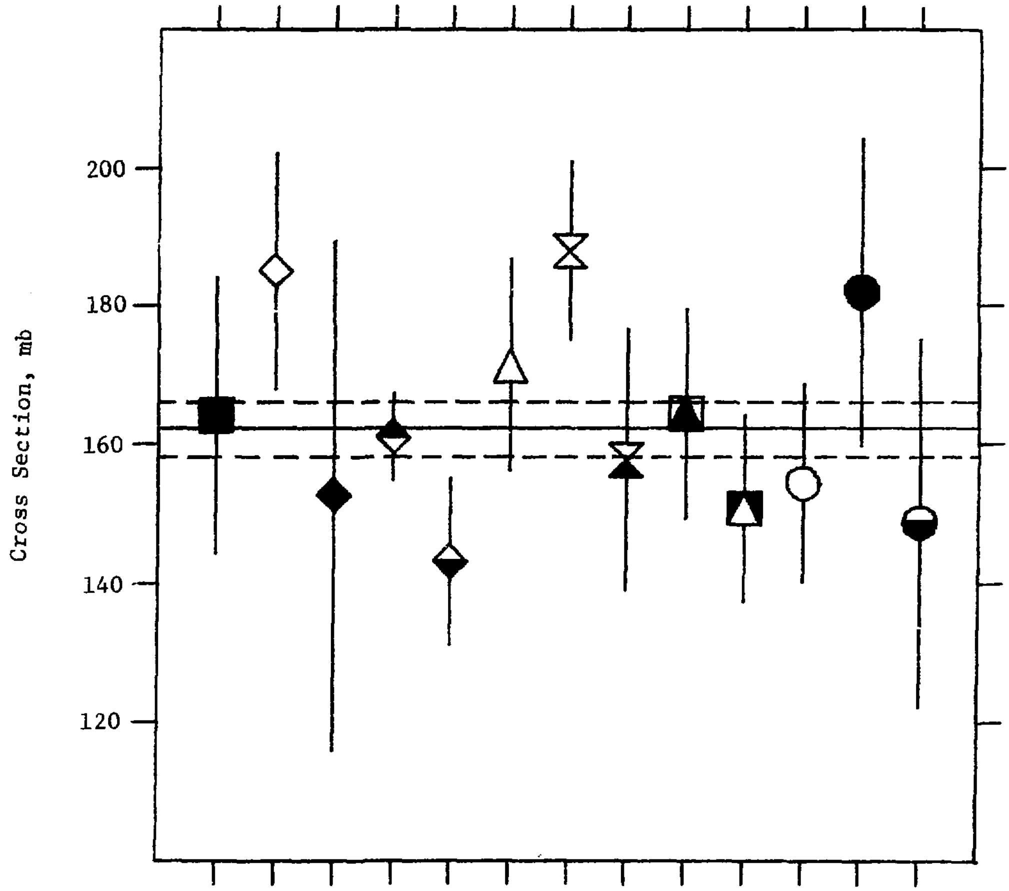

Figure 2: Evaluation of 14.7-MeV cross sections for Zn-64(n,2n)Zn-63

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(S) $^{113}In(n,n')^{113m}In$

The first excited state of ^{113}In at 0.392-MeV excitation has spin-parity $1/2^-$, and it is an isomer with a half life of 99.47 ± 0.07 m. electromagnetic decay to the $9/2^+$ ground state is inhibited by the high spin change required (L=4 or 5) [II.13]. Owing to the parity change of the isomeric transition (IT), the multipolarities allowed are M4 and E5; according to Ref. II.13 the transition is predominantly M4. There are no other decay processes to compete with this ground-state IT within ^{113}In. Uncertainty is introduced by the fact that the IT transition is internally converted to a considerable extent. According to Ref. II.13, the recommended gamma-ray branch is 64 ± 1% for the 0.392-MeV IT. This is the value assumed in the present evaluation. Values of the K-conversion coefficient α_K in the range 0.43-0.454 and (K/L+M+...) ratios from 3.75-4.30 have been compiled by Lederer and co-workers [II.13, II.17] over a period of nearly two decades. A calculation of the M4 internal conversion coefficient by Rose [II.15] in 1958 yielded α_K = 0.450, while Hager and Seltzer [II.16] obtain the value 0.451 for the corresponding quantity a decade later. So, the uncertainty of 1.6% assigned to the value in Ref. II.13 seems appropriate.

We found eight different cross section investigations for this reaction in the literature. For one of these, the work of Minetti and Pasquarelli [2], the reported results appear to be about a factor of 10 too large. No reason could be found for this discrepancy, and the same cross section value appears in both the original reference and in the CSISRS file [II.2]. Consequently, we have listed this result in Table 1, but it is not plotted in Fig. 1. It is also excluded from the evaluation. Of the remaining seven experiments, only four data sets provide sufficient documentation on parameters and procedures, and involve accepted standards, so as to be included in the evaluation (see Table 2). No internal conversion information was provided for the experiment of Kozlowski et al. [1] so we assumed they used the decay branch value from Ref. 17, made an adjustment, and then added an extra uncorrelated error of 2%. For the work of Pazsit and Csikai [4], internal conversion coefficient information was provided for ^{113m}In, but not for ^{115m}In which served as a reference standard (normalization, however, could be traced back to $^{27}Al(n,\alpha)^{24}Na$). Owing to the additional uncertainty attendant with using the $^{115}In(n,n')^{115m}In$ reaction as an intermediate reference standard, we added an extra 5% random error to the estimated uncorrelated measurement error of ~ 6.7%. This reaction is not a commonly considered one, and appears not to have been formally evaluated previously. Consequently no evaluated curve is shown in Fig. 1. In order to perform the requisite corrections for energy shift to 14.7 MeV, we employed the ENDF/B-V [II.9] shape for the very similar reaction $^{115}In(n,n')^{115m}In$. The adjusted data employed in the present evaluation appear in Table 2.

The results of the evaluation are summarized in Table 2 and are plotted in Fig. 2. The first-pass results were retained since none of the values analyzed exceeded three times the enhanced standard deviation. The normalized chi-square was 10.30 which indicates poor consistency for the input data, as is evident from Fig. 2. The evaluated value of 54.69 ± 7.98 mb is actually consistent with all of the other rejected values, except for the anomalous result of Minetti and Pasquarelli [2]. However, we chose not to compromise on our established criteria for retention or rejection of data in order to include these data in this particular evaluation.

Table 1: Compiled Data for $^{113}In(n,n')^{113m}In$

Ref. No.	Symbol	Application	Neutron Energy (MeV)	Energy Resolution (MeV)	Reported Cross Section (mb)	Reported Cross Section Error (mb)
1	1	E	14.7	NA[a]	35.0	8.0
2[a]	2	D	14.7	0.1	680.0	50.0
3	3	E	14.1	1.0	63.0	3.0
4	4	E	14.7	NA	66.0	5.0
5	5	E	14.52 15.05	0.12 0.2	42.0 30.0	9.0 8.0
6	6	D	14.5 14.74	0.15 0.2	56.4 53.9	5.6 7.1
7	7	D	14.67	0.06	51.0	3.0
8	8	D	14.3	0.2	53.4	2.1

[a]Not plotted in Fig. 1.

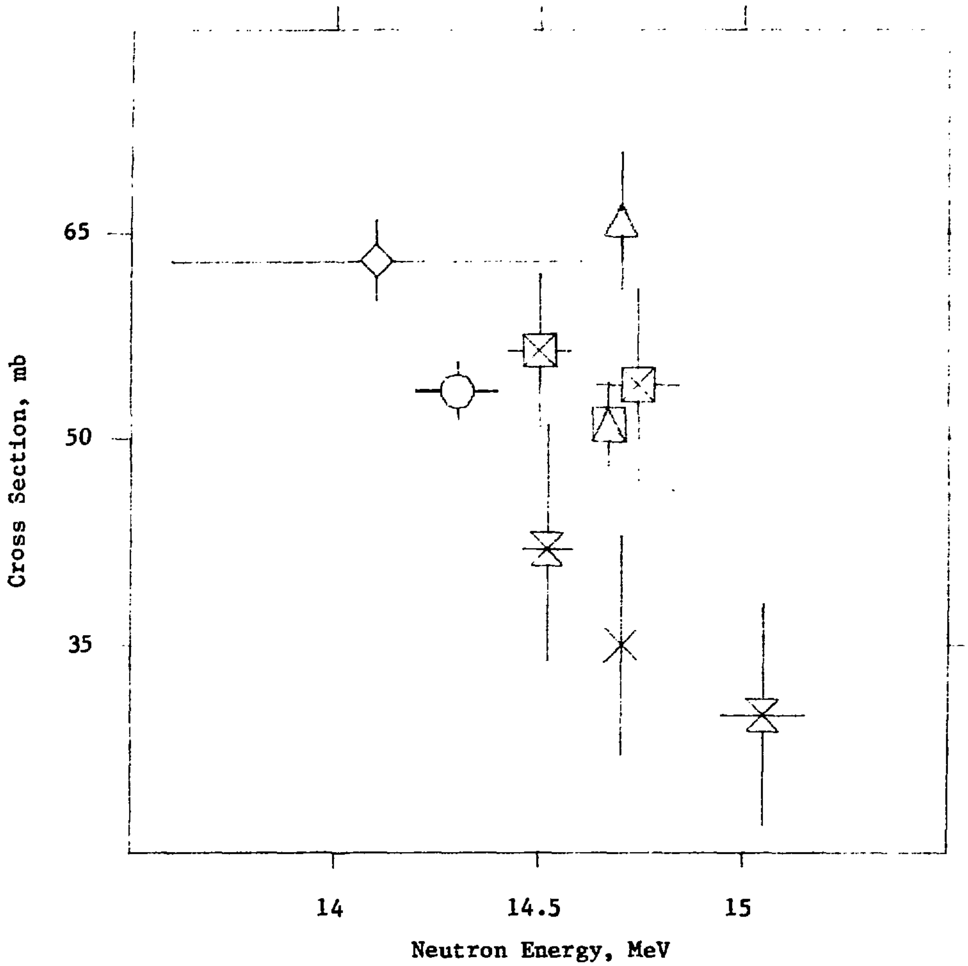

Figure 1: Compiled experimental data for In-113(n,n')In-113m

Table 2: Additional Information for the $^{113}In(n,n')^{113m}In$ Evaluation

Ref. No.	Standard	Standard Adjustment Factor	Energy Adjustment Factor	Decay Branch Adjustment Factor	Adjusted Cross Section (mb)		Errors (%) Uncorrelated	Errors (%) Standard	Total[a]
1	A	1.0	1.0	1.0213	35.75		23.1	0	23.2
3	S4	1.075	0.9315	1.0226	64.51		5.0	0.6	5.3
4	S2	0.9974	1.0	1.0213	67.23		8.4	0.6	8.6
5	S4	1.055	0.9884	1.0131	44.37	39.50	10.1	0.6	10.2
		1.051	1.0066		32.15				

Evaluation Summary:

Evaluated cross section: 54.69 mb

Normalized chi-square: 11.19

Standard deviation: 7.98 mb (14.6%) enhanced

[a]A 100%-correlated error of 1.6% is included.

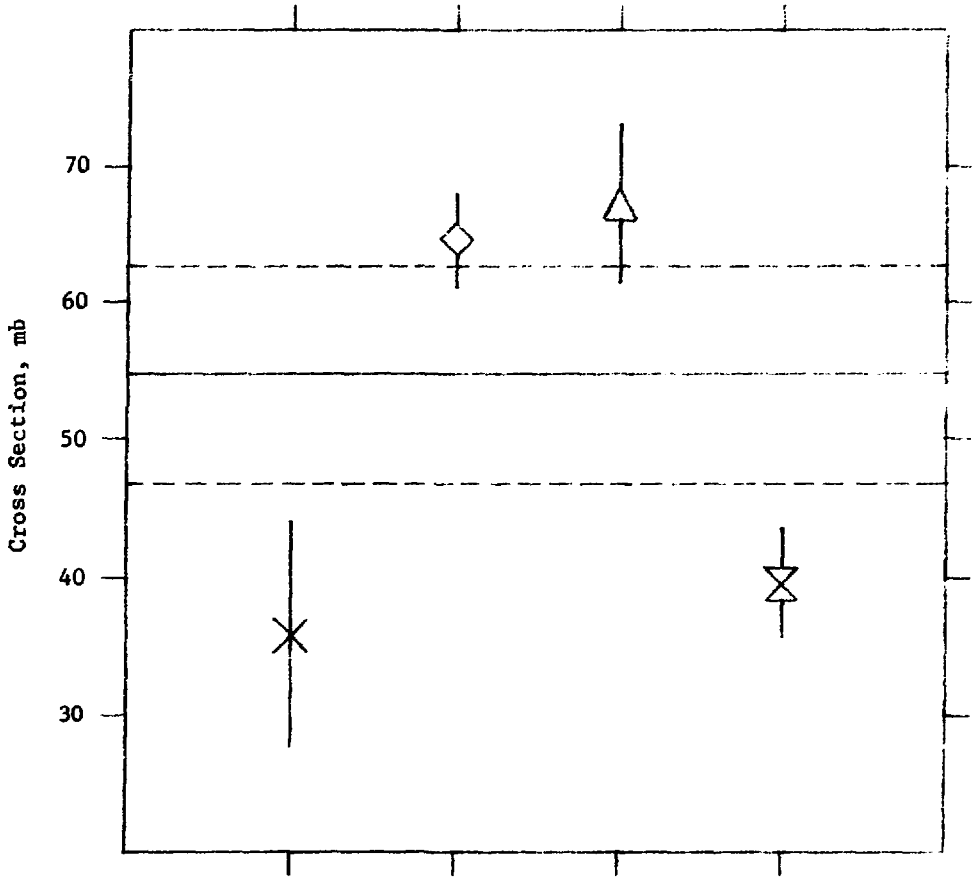

Figure 2: Evaluation of 14.7-MeV cross sections for In-113(n,n')In-113m

IN-113(N,INL)IN-113M REFERENCES

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(T) $^{115}In(n,n')^{115m}In$

The first excited state of ^{115}In at 0.336 MeV has spin-parity $1/2^-$, and it is an isomer with a half life of 4.486±0.004 h [II.13]. Decay to the $9/2^+$ ground state is inhibited by the high spin change required (L=4 or 5) [II.13]. Owing to the parity change of the isomeric transition (IT), the multipolarities allowed are M4 and E5; according to Ref. II.13 the transition is predominantly M4. Decay of ^{115m}In only proceeds via the ground-state isomeric transition 94.95% of the time. The other 5.05% of the time the decay proceeds via β^- emission to ^{115}Sn. The IT transition is strongly converted so that only 45.9±0.1% of all decays of ^{115m}In produce a 0.336-MeV gamma ray [II.13]. It is this gamma ray which is generally observed in activation cross section measurements. The gamma-ray decay branch indicated in Ref. II.13 is consistent with a value for the K-conversion coefficient of α_K=0.843 and a (K/L+M...) ratio of 3.63. Some of the authors reporting data for this reaction indicated the gamma-ray decay branch directly, others provided only the internal conversion coefficients, and some gave little or no information. In all cases where the gamma-ray decay branch was not explicitly given, we calculated it from information given, or estimated the most likely value to have been used based on the date of the work. For all cases an adjustment for the decay factor was made, and an additional uncorrelated error component (usually ~ 1%) was included to account for the increased uncertainty attributed to the decay process.

Eighteen experimental data sets were compiled from the literature for this reaction. The values are listed in Table 1 and are plotted in Fig. 1. Five data sets had to be rejected in accordance with the criteria established in Section II. Data sets with multiple-energy values were reduced to single 14.7-MeV-equivalent points prior to performing the evaluation. The first-pass application of code AVERG included thirteen values, and it resulted in a normalized chi-square of 15.083. Four more sets were then rejected on the basis of inconsistency. The second-pass evaluation, including the nine remaining values, led to the results summarized in Table 2. The value of 61.75±2.92 mb derived from this evaluation agrees very well with the value of 61.2 mb from the ENDF/B-V evaluation [II.9]. Nevertheless, the normalized chi-square associated with the second-pass analysis is 10.48, indicating far from satisfactory consistency in the data accepted for this analysis.

Table 1: Compiled Data for $^{115}In(n,n')^{115m}In$

Ref. No.	Symbol	Application	Neutron Energy (MeV)	Energy Resolution (MeV)	Reported Cross Section (mb)	Reported Cross Section Error (mb)
1	1	I	14.7	0.1	125.0	10.0
2	2C	I	14.6	NA	80.0	3.0
3	2B	E	14.6	0.2	50.0	7.8
4	2	D	14.96	0.87	61.6	6.3
5	3A	I	14.7	0.15	83.5	4.2
6	3	E	14.6	0.2	67.0	7.0
7	3B	E	14.8	0.4	69.0	5.0
8	4A	E	14.1	1.0	73.0	8.0
9	4	E	14.7	NA	63.0	4.0
10	5B	D	13.84	0.09	83.5	1.5
			14.52	0.12	83.8	1.2
			15.14	0.14	65.0	0.5
11	5	E	14.7	NA	63.0	4.0
12	6	E	14.24	0.08	60.6	2.4
			14.50	0.15	57.7	2.3
			14.74	0.2	54.5	2.2
13	6A	I	15.2	NA	50.0	10.0
14	7C	E	14.9	0.2	65.0	4.0
15	7	D	14.09	0.3	65.5	3.3
			14.63	0.3	60.4	3.1
			14.86	0.3	58.1	3.0
16	8F	D	14.75	NA	78.6	3.6
17	8	E	14.67	0.06	53.1	2.2
17	8G	D	14.3	0.2	54.3	2.0

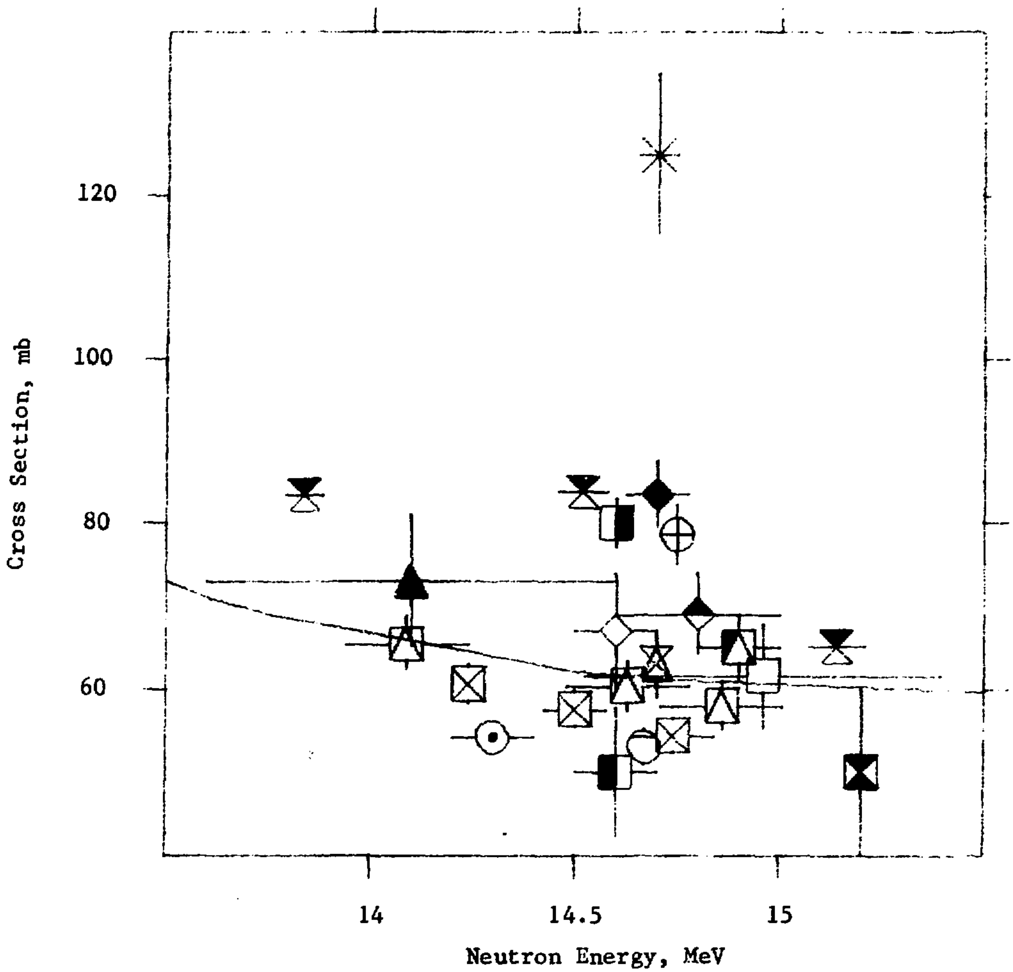

Figure 1: Compiled experimental data for In-115(n,n')In-115m

Table 2: Additional Information for the $^{115}In(n,n')^{115m}In$ Evaluation

Ref. No.	Standard	Standard Adjustment Factor	Energy Adjustment Factor	Decay Branch Adjustment Factor	Adjusted Cross-Section (mb)		Errors (%) Uncorrelated	Standard	Total[a]
3	S4	1.0612	0.9935	1.0893	57.42		7.1	0.6	7.1
6	S2	0.9536	0.9935	1.0893	69.14		3.0	0.6	3.1
7	S2	0.9733	1.006	1.0893	73.59		3.0	0.6	3.1
8	S4	1.0745	0.9310	1.0294	75.17		8.8	0.6	8.8
9	S2	0.9974	1.0	1.0388	65.27		5.4	0.6	5.4
11	S2	1.0152	1.0	1.0148	64.90		4.8	0.6	4.8
12	S3	0.9989	0.9499	1.0	57.50 55.64 54.10	} 55.75	2.3	1.5	2.8
14	A	1.0	1.0076	1.0	65.49		6.2	0	6.2
17	S4	1.005	0.9980	1.0	52.06		4.1	0.6	4.2

Evaluation Summary

Evaluated Cross Section: 61.75 mb

Normalized Chi-Square: 10.48

Standard Deviation: 2.92 mb (4.7%) enhanced

[a]A 100%-correlated decay error of 0.2% is included.

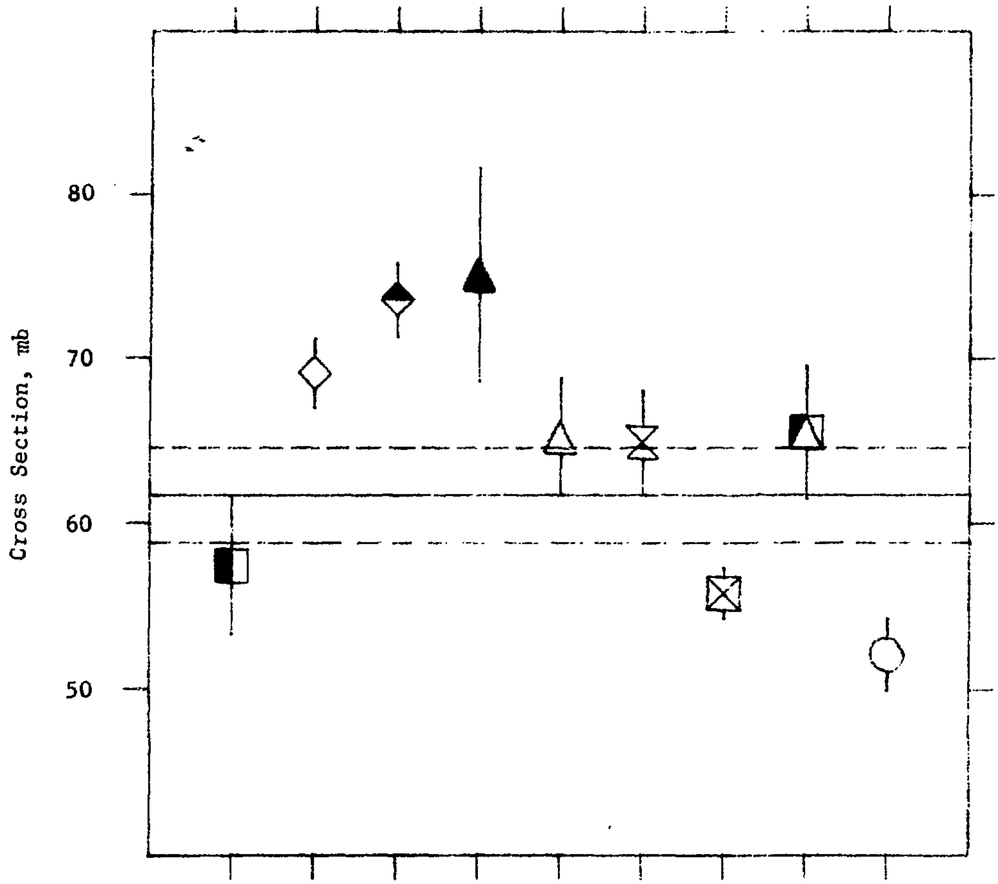

Figure 2: Evaluation of 14.7-MeV cross sections for In-115(n,n')In-115m

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IV. CONCLUSIONS

Although a number of compromises were made in this evaluation, it succeeds in yielding a clearer assessment of the status of the selected twenty reactions than was previously available. Most of the existing data were compiled and included in the analyses. These data have been adjusted on a reasonably consistent basis for such considerations as decay properties and standards. Certain apparently largely-discrepant data sets have been rejected, and the remaining values evaluated, using statistically acceptable methods. In Table 1, we summarize the results of this work. The final evaluated values are given along with the obtained standard deviations. The quality of the evaluation in each case is indicated by a chi-square parameter which was produced in the evaluation process. The ranges of values used in the analyses, relative to final evaluated values, are indicated in percentages. This information provides further insight into the relative quality of the reported evaluated results. Finally, we have sorted the various reactions into three categories with the intent of indicating where future experimental work might be focused.

It appears that 20% of the reactions fall in Category I. For these, the data used in the evaluations are reasonably consistent (normalized chi-square $\lesssim 1$) and the errors in the evaluated cross sections are rather small. It appears pointless to expend further experimental effort on these reactions unless required accuracies for certain applications become more stringent. However, investigators may wish to measure one or more of these to check the accuracy of their experimental procedures. The reactions falling in Category II (20%) have some problems, mainly to do with consistency of the evaluated data (normalized chi-square >2) even though the enhanced standard deviations are not large. It would be useful to check these evaluations with a few high-quality measurements, in certain important cases. Some 20% of the reactions we have considered fall somewhere between these two categories, and we have indicated this ambiguity in Table 1. Finally, we have found that significant improvements in the data bases are needed for 40% of the reactions, namely those in Category III.

Consistency of the existent data base (even if it is a sizable ensemble) does not guarantee that the evaluated value is close to the true physical quantity. There is always the chance that an important common systematic factor has been overlooked. However, the odds of this occuring are probably small. Evaluation of existing data is necessary in order to insure that future measurement effort will be focused where it is needed the most. Furthermore, the evaluation process itself must be as consistent and unbiased as possible, within practical limits, in order to insure that the information content of the available data bases are effectively used to provide proper best estimates of the physical quantities in question.

Table 1: Summary of Evaluated Results

Reaction	Evaluated Cross Sections (mb) Isotopic[a]	Elemental	Enhanced Standard Deviation(%)	Evaluation Normalized Chi-Square	Range of Included Values (%)[b] (+)	(-)	Category[c]
$^{27}Al(n,p)^{27}Mg$	70.464	Same	2.0	0.912	10.1	10.4	I
$Si(n,X)^{28}Al$	257.25	237.26	2.5	2.43	6.1	9.0	II
$Ti(n,X)^{46}Sc$	294.83	24.176	2.3	1.81	6.8	11.6	I,II
$Ti(n,X)^{47}Sc$	223.11	16.510	17.2	13.23	31.7	21.7	III
$Ti(n,X)^{48}Sc$	60.61	44.67	2.4	2.54	16.3	11.1	II
$^{51}V(n,p)^{51}Ti$	31.873	31.793	4.4	4.81	21.6	23.7	III
$^{51}V(n,\alpha)^{48}Sc$	15.888	15.848	2.4	7.34	18.6	5.3	II
$Cr(n,X)^{52}V$	72.493	60.742	4.4	6.16	45.8	13.8	III
$^{55}Mn(n,\alpha)^{52}V$	31.21	Same	4.2	3.80	8.7	32.3	III
$^{55}Mn(n,2n)^{54}Mn$	816.65	Same	2.6	0.658	9.1	8.9	I
$Fe(n,X)^{54}Mn$	284.40	16.495	2.0	1.5	13.0	8.8	I,II
$^{54}Fe(n,\alpha)^{51}Cr$	87.855	5.096	2.7	1.066	20.7	4.3	I
$^{59}Co(n,p)^{59}Fe$	56.60	Same	16.2	8.59	53.8	36.0	III
$^{59}Co(n,\alpha)^{56}Mn$	30.169	Same	1.4	1.76	8.4	7.5	I,II
$^{59}Co(n,2n)^{58}Co$	747.68	Same	2.4	2.28	9.7	13.3	II
$^{65}Cu(n,p)^{65}Ni$	20.464	6.303	7.0	2.65	27.0	25.3	III
$Zn(n,X)^{64}Cu$	165.40	80.384	2.6	1.56	13.4	10.7	I,II
$^{64}Zn(n,2n)^{63}Zn$	162.17	78.815	2.4	0.914	15.8	11.8	I
$^{113}In(n,n')^{113}In$	54.69	2.352	14.6	11.19	22.9	34.6	III
$^{115}In(n,n')^{115m}In$	61.75	59.09	4.7	10.48	21.7	15.7	III

[a]Cross section based on condition that all yield be attributed to a single isotope, namely that one responsible for the dominant portion of the yield from all contributing isotopes of the elemental material.

[b]The differences in percent between the largest value (+) and the smallest value (-) included in the final evaluation and the evaluated value itself. These parameters indicate the spread in the adjusted data considered for the evaluation.

[c]Category I: Data base used in the evaluation is reasonably consistent and the uncertainty in the evaluated result is relatively small. Further measurements are probably not unwarranted unless higher accuracy is required.

Category II: There are noticeable inconsistencies in the data base used for the evaluation, even though the uncertainty predicted for the evaluation appears to be at a nearly acceptable level. The evaluation should be tested by a few accurate new measurements.

Category III: There are serious inconsistencies in the data base used for the evaluation, and the accuracy level of the evaluated cross section may not be adequate for many applications. Serious attention should be given to improving the knowledge of this cross section by a series of new measurements involving several techniques and standards.

ACKNOWLEDGEMENTS

This work was supported by the U.S. Department of Energy. Two of the authors (B.P.E. and P.L.) gratefully acknowledge support provided by the American Nuclear Society International Student Exchange Program. The authors are indebted to J. W. Meadows for his help in extracting needed evaluated cross section information from the ENDF/B-V and the International Reactor Dosimetry File (IRDF-82).

APPENDIX

In the present work, all cross sections to be evaluated are transformed to equivalent quantities, namely the predicted 14.7-MeV cross section. Mathematically, then, the evaluation process is one of averaging correlated data. This problem has been discussed in Ref. 1, and the procedure will be outlined here as well for completeness.

Let $\vec{\sigma}$ denote the collection of n experimental values $\sigma_1, \ldots, \sigma_n$ which represent various attempts to obtain the generic cross section, s, which we define to be the fundamental 14.7-MeV value.

$$\begin{aligned} \sigma_1 &\approx s, \\ \sigma_2 &\approx s \\ &\vdots \\ \sigma_n &\approx s. \end{aligned} \tag{1}$$

The set of equations designated collectively as Eq. (1) can be written in matrix form as

$$\vec{\sigma} \approx \bar{A} \cdot \vec{s}, \tag{2}$$

where $\vec{\sigma}$ is a (n,1)-matrix, $\vec{s}$ is a (1,1)-matrix (the scalar s) and $\bar{A}$ is a (n,1)-matrix with unit elements, i.e.,

$$\bar{A} = \begin{bmatrix} 1 \\ \cdot \\ \cdot \\ \cdot \\ 1 \end{bmatrix} . \tag{3}$$

This defines a problem with $\nu = n-1$ degrees of freedom which we solve by the least-squares method. In Ref. 1 it is shown that the least-squares solution to Eq. (1), or the equivalent Eq. (2), is given by

$$s = \vec{s} = \bar{C} \cdot \bar{A}^T \cdot \bar{V}^{-1} \cdot \vec{\sigma} , \tag{4}$$

with

$$\bar{C} = (\bar{A}^T \cdot \bar{V}^{-1} \cdot \bar{A})^{-1}. \tag{5}$$

The matrix $\bar{V}$ is a (n,n)-matrix which must be supplied along with $\vec{\sigma}$, it is the error matrix or, more properly, the covariance matrix for the $\vec{\sigma}$. The generation of $\bar{V}$ is discussed in more detail in Section II. The diagonal elements are squares of the elements of the error vector $\vec{E}_\sigma$ and the correlation matrix $\bar{M}$ has elements M_{ij} defined by

$$M_{ij} = V_{ij}/(E_{\sigma i}E_{\sigma j}). \quad (6)$$

The matrix $\bar{V}^{-1}$ is the inverse of matrix $\bar{V}$.

The value s deduced from this analysis is the best estimate of the generic value in the least-squares sense. $\bar{C}$ is clearly a (1,1)-matrix (scalar C) and is, in fact, the variance for the solution s. The standard deviation, E_s, for s is derived from the formula

$$E_s^2 = C = \bar{C}. \quad (7)$$

Given the solution $\vec{s}$, and all other input, we can calculate the quantity χ^2 from the expression.

$$\chi^2 = (\vec{\sigma} - \bar{A} \cdot \vec{s}^T) \cdot \bar{V}^{-1} \cdot (\vec{\sigma} - \bar{A} \cdot \vec{s}). \quad (8)$$

This yields the chi-square value for this solution, which can be compared with values in chi-square test tables (e.g., Ref. 2). In particular, it is useful to consider the normalized chi-square, $\chi^2/(n-1)$. If this quantity is ~ 1, then the data $\vec{\sigma}$ are consistent within the errors indicated by $\bar{V}$. However, if $\chi^2/(n-1)>>1$ it is then known that the input data are inconsistent within the quoted errors. Perhaps only a few of the σ_i values are problematic. If the χ^2 can be improved significantly by eliminating these troublesome values from the analysis, then it is justified to do so, provided that no specific reason can be identified for their aberrant behavior. When no justification can be found for rejecting any of the considered values, but still $\chi^2/(n-1)>>1$, then one can consider revising E_s to a value E_s' such that

$$(E_s')^2 = E_s^2\ [\chi^2/(n-1)] \quad . \quad (9)$$

This is not really a mathematically rigorous step. Conceptually, doing this amounts to enlarging the error in the average value so as to "cover up" unresolved discrepancies in the input data or, equivalently, scaling up all the input errors by a fixed factor in order to achieve the same objective.

A computer program called AVERG has been written in FORTRAN to perform the analysis outlined above. Specifically, the code calculates a properly-weighted average of a set of input quantities, obtains the error in the final result, and provides a chi-square test for consistency of the input information.

The operation of this code is described next, and a listing of the FORTRAN source follows:

At the beginning of execution, the program control is from the terminal (Unit 4). The code demands IRD, IWR in 2I2.

IRD = input device for reading values (normally unit 5, the card reader).

IWR = output device for giving results (normally unit 9, the printer).

All remaining input information comes from unit IRD. For convenience, we refer to this as card input.

1st card: IOP (I5)

IOP = { 1 - input only errors, uncorrelated,
2 - input errors and correlation matrix separately,
3 - input entire covariance matrix.

2nd card: NDATA (I5) $(2 \leq \text{NDATA} \leq 40)$

NDATA = number of values to be averaged (n).

3rd card +... : (Y(I), I = 1, NDATA) (6E12.5)

Y = array of values to be averaged ($\vec{\sigma}$).

From this point hence, the input sequence depends upon choice of IOP.

IOP = 1:

Next cards: (EY(I), I=1, NDATA) (6E12.5)

EY = array of assumed uncorrelated errors ($\vec{E}_\sigma$).

IOP = 2:

Next cards: (EY(I), I=1, NDATA) (6E12.5)

EY = array of errors (at least partially correlated)

Following cards: I=1, NDATA
(QQ(I,J),J=1,I)

QQ = correlation matrix. It is symmetric so only distinct values are read (in triangular form). This is $\bar{M}$.

IOP = 3:

Next cards: I=1, NDATA
(QQ(I,J),J=1,I

QQ = covariance matrix. It is symmetric so only distinct values are read (in triangular form). This is $\bar{V}$.

The output on unit IWR is as follows:

Y = input values to be averaged,

EY = errors in input values,

VY = input covariance matrix,

CY = input correlation matrix,

P = calculated average value,

EP = standard deviation in the average value,

CHI2 = chi-square, χ^2, as defined above,

CHI2NM = normalized chi-square, $\chi^2/(n-1)$, as defined above.

The input and output for a test problem follow the listing of the source statements of AVERG near the end of this Appendix.

This code was tested by analyzing a simple hypothetical problem which could be readily solved by hand using the formulas in Ref. 1, as well as with the code. Agreement for this example indicated that AVERG is free of obvious "bugs", however, such a comparison is not readily obtained for more complicated cases.

Clearly the code should not be applied blindly for averaging compiled data from the literature. During the course of the present work we encountered several examples of data which were so obviously discrepant that their inclusion in a computer analysis would have led to serious distortion of the computational process. While the chi-square test discussed above provides guidance in regard to data consistency, the formalism cannot cope properly with serious data defects. Thus, some subjective judgment was required to screen the data bases for truly discrepant data prior to computer analysis.

Another point which the reader should keep in mind is that the averaging of partially correlated data sometimes leads to results which defy normal intuition. This point has been made, and simple examples have been provided, by several other authors (e.g., see Refs. 3-7). One of the most surprising possibilities is that under certain conditions, the average of two correlated values will lie outside the range of both values averaged! This result is perfectly valid according to the mathematics, which is based on the assumption that the best solution is that derived from the least-squares method. When data are uncorrelated, the least-squares solution indeed tends to be intuitive. However, when the data are substantially correlated the solution may not correspond to what one might select by the typical "eyeguide" method. Perey [4], Mannhart [5], Poenitz [6], and Peelle [7] discuss at length some of these oddities of least-squares solutions, and the interested reader is referred to these papers for details.

The correlations encountered for most of the data bases analyzed in the present work are not excessively large. In almost all cases, the correlations introduced by the standards are relatively small. The most influential source of correlation is usually that due to nuclear decay properties for the reaction-product activities. Occasionally the systematic errors from this origin amount to several percent and this leads to least-squares solutions which differ somewhat from what one would obtain from an uncorrelated averaging process. Usually the effect of correlation is to lower the average values in these instances. In some of the analyses performed in the present report (Section III), we have considered more than one approach. For example, we compared the results obtained by excluding the fully-correlated decay branch error before averaging (this introduces bias) with more rigorous complete least-squares calculations which included all error sources simulataneously (unbiased). We did this in order to estimate the extent to which our final result might be "method dependent".

CODE "AVERG" FORTRAN SOURCE

```
*JOB
*REW,17
*K,I05,L09,P17
*FTN
 OPT LXPC
      PROGRAM AVERG
C     AVERG - CDC 1700 - D.L. SMITH - AP 314 - X2-6021
C
C     CALCULATES AVERAGE OF 40 OR FEWER QUANTITIES AND DETERMINES
C     ERROR. USES COVARIANCE FORMALISM.
C
C     OPTION 1 - INPUT ONLY ERRORS, UNCORRELATED
C     OPTION 2 - INPUT ERRORS AND CORRELATION MATRIX
C     OPTION 3 - INPUT COVARIANCE MATRIX
C
      COMMON Y(40),EY(40),CY(1600),VY(1600),VYI(1600),A(40),E(1640),W(40
     1),QQ(40,40)
C
C     INITIALIZATION AND CONTROL
C
    1 WRITE(4,2)
    2 FORMAT(/5HAVERG)
      WRITE(4,4)
    4 FORMAT(/11HI/O DEVICES)
      WRITE(4,5)
    5 FORMAT(26HINPUT-IRD,OUTPUT-IWR (2I2)/)
      READ(4,6) IRD,IWR
    6 FORMAT(2I2)
C
C     INPUT ON UNIT IRD
C
      READ(IRD,10) IOP
   10 FORMAT(16I5)
      READ(IRD,10) NDATA
      IF(NDATA.LT.2) GO TO 1
      IF(NDATA.GT.50) GO TO 1
      KMAX=NDATA*NDATA
      READ(IRD,11) (Y(I),I=1,NDATA)
   11 FORMAT(6E12.5)
      GO TO(20,30,40),IOP
   20 CONTINUE
      READ(IRD,11) (EY(I),I=1,NDATA)
      DO 21 I=1,NDATA
      DO 21 J=1,NDATA
      CALL GETK(NDATA,I,J,K)
   21 CY(K)=0.0
      DO 22 I=1,NDATA
      CALL GETK(NDATA,I,I,K)
```

```
   22 CY(K)=1.0
      GO TO 100
   30 CONTINUE
      READ(IRD,11) (EY(I),I=1,NDATA)
      DO 31 I=1,NDATA
   31 READ(IRD,11) (QQ(I,J),J=1,I)
      DO 310 I=1,NDATA
      DO 310 J=1,I
  310 QQ(J,I)=QQ(I,J)
      DO 320 I=1,NDATA
      DO 320 J=1,NDATA
      CALL GETK(NDATA,I,J,K)
  320 CY(K)=QQ(I,J)
      GO TO 100
   40 CONTINUE
      DO 41 I=1,NDATA
   41 READ(IRD,11) (QQ(I,J),J=1,I)
      DO 410 I=1,NDATA
      DO 410 J=1,I
  410 QQ(J,I)=QQ(I,J)
      DO 420 I=1,NDATA
      DO 420 J=1,NDATA
      CALL GETK(NDATA,I,J,K)
  420 VY(K)=QQ(I,J)
C
C     CALCULATIONS
C
  100 CONTINUE
      IF(IOP.EQ.1) IY=1
      IF(IOP.EQ.2) IY=1
      IF(IOP.EQ.3) IY=2
      N=NDATA
      DO 101 I=1,NDATA
  101 A(I)=1.0
      CALL                 LLSF(IY,Y,EY,CY,VY,VYI,A,E,W,N,                  P,EP,CP,V
     1P,VPI,CHI2,CHI2NM,                 ITEST)
      IF(ITEST.EQ.0) GO TO 1
C
C     OUTPUT ON UNIT IWR
C
      IF(IWR.EQ.9) CALL AVPRT
      IF(IWR.NE.9) WRITE(IWR,200)
  200 FORMAT(//)
      WRITE(IWR,201)
  201 FORMAT(4HY,EY)
      DO 202 I=1,NDATA
  202 WRITE(IWR,203) Y(I),EY(I)
  203 FORMAT(6E12.5)
```

```
      WRITE(IWR,204)
  204 FORMAT(2HVY)
      DO 2050 K=1,KMAX
      CALL GETIJ(NDATA,K,I,J)
 2050 QQ(I,J)=VY(K)
      DO 205 I=1,NDATA
  205 WRITE(IWR,203)  (QQ(I,J),J=1,I)
      WRITE(IWR,206)
  206 FORMAT(2HCY)
      DO 2070 K=1,KMAX
      CALL GETIJ(NDATA,K,I,J)
 2070 QQ(I,J)=CY(K)
      DO 207 I=1,NDATA
  207 WRITE(IWR,203)  (QQ(I,J),J=1,I)
      WRITE(IWR,208)
  208 FORMAT(4HP,EP)
      WRITE(IWR,203)  P,EP
      WRITE(IWR,209)
  209 FORMAT(11HCHI2,CHI2NM)
      WRITE(IWR,203)  CHI2,CHI2NM
C
      GO TO 1
      END
      SUBROUTINE LLSF(IY,Y,EY,CY,VY,VYI,A,E,W,N,              P,EP,CP,VP,VPI
     1,CHI2,CHI2NM,                    ITEST)
      DIMENSION Y(2),EY(2),CY(2),VY(2),VYI(2),A(2),E(2),W(2)
      GO TO(1,3),IY
    1 DO 2 I=1,N
      DO 2 J=1,N
      CALL GETK(N,I,J,K)
    2 VY(K)=CY(K)*EY(I)*EY(J)
      GO TO 6
    3 DO 4 I=1,N
      CALL GETK(N,I,I,K)
    4 EY(I)=SQRT(VY(K))
      DO 5 I=1,N
      DO 5 J=1,N
      CALL GETK(N,I,J,K)
    5 CY(K)=VY(K)/EY(I)/EY(J)
    6 CALL MATINV(VY,VYI,ITEST,N,E,W)
      IF(ITEST.EQ.1) GO TO 9
    7 WRITE(4,8)
    8 FORMAT(6HNO INV)
      PAUSE
      RETURN
    9 CONTINUE
      VPI=0.0
      DO 10 K2=1,N
```

```
      DO 10 K1=1,N
      CALL GETK(N,K2,K1,KI)
   10 VPI=VPI+A(K2)*VYI(KI)*A(K1)
      VP=1.0/VPI
      P=0.0
      DO 11 K2=1,N
      DO 11 K1=1,N
      CALL GETK(N,K2,K1,KI)
   11 P=P+VP*A(K2)*VYI(KI)*Y(K1)
      EP=SQRT(VP)
      CP=1.0
      DO 14 I=1,N
   14  W(I)=Y(I)-A(I)*P
      CHI2=0.0
      DO 15 K2=1,N
      DO 15 K1=1,N
      CALL GETK(N,K2,K1,KI)
   15 CHI2=CHI2+W(K2)*VYI(KI)*W(K1)
      CHI2NM=CHI2/FLOAT(N-1)
      RETURN
      END
      SUBROUTINE MATINV(D,Q,NTEST,NS,E,W)
      DIMENSION D(2),Q(2),E(2),W(2)
      IP = NS + 1
      BIG = 0.0
      DO 555 I=1,NS
      DO 555 J=1,NS
      CALL GETK(NS,I,J,KD)
      ABD=ABS(D(KD))
      IF(ABD-BIG) 555,555,554
  554 BIG = ABD
  555 CONTINUE
      FACT =  SQRT(BIG)
      I = 1
    1 IF(I-NS) 2,2,20
    2 J = 1
    3 IF(J-NS) 4,4,8
    4 K = 1
    5 IF(K-NS) 6,6,7
    6 CALL GETK(NS,K,J,KD)
      CALL GETK(IP,J,K,KE)
      E(KE)=D(KD)/FACT
      K = K+1
      GO TO 5
    7 J = J+1
      GO TO 3
    8 L = 1
    9 IF(L-NS) 10,10,14
```

```
10 IF(L-I) 11,13,11
11 CALL GETK(IP,L,IP,KE)
   E(KE)=0.0
12 L = L+1
   GO TO 9
13 CALL GETK(IP,L,IP,KE)
   E(KE)=1.0
   GO TO 12
14 CALL JORDAN(NS,E,NTEST,W)
   IF(NTEST) 15,15,16
15 RETURN
16 M = 1
17 IF(M-NS) 18,18,19
18 CALL GETK(NS,I,M,KQ)
   CALL GETK(IP,M,IP,KE)
   Q(KQ)=E(KE)/FACT
   M = M+1
   GO TO 17
19 I = I+1
   GO TO 1
20 RETURN
   END
   SUBROUTINE JORDAN(N,C,INDEX,B)
   DIMENSION B(2),C(2)
   NMAX=N+1
   K=1
 1 IF(K-N) 2,2,22
 2 CALL GETK(NMAX,K,K,K1)
   IF(C(K1)) 10,3,10
 3 L=K+1
 4 IF(L-N) 5,5,21
 5 CALL GETK(NMAX,L,K,K1)
   IF(C(K1)) 7,6,7
 6 L=L+1
   GO TO 4
 7 M=1
 8 IF(M-N-1) 9,9,2
 9 CALL GETK(NMAX,K,M,K1)
   CALL GETK(NMAX,L,M,K2)
   B(M)=C(K1)
   C(K1)=C(K2)
   C(K2)=B(M)
   M=M+1
   GO TO 8
10 J=N+1
11 IF(J-K) 13,12,12
12 CALL GETK(NMAX,K,J,K1)
   CALL GETK(NMAX,K,K,K2)
```

```
      C(K1)=C(K1)/C(K2)
      J=J-1
      GO TO 11
   13 I=1
   14 IF(I-N) 16,16,15
   15 K=K+1
      GO TO 1
   16 IF(I-K) 18,17,18
   17 I=I+1
      GO TO 14
   18 II=N+1
   19 IF(II-K) 17,20,20
   20 CALL GETK(NMAX,I,II,K1)
      CALL GETK(NMAX,I,K,K2)
      CALL GETK(NMAX,K,II,K3)
      C(K1)=C(K1)-C(K2)*C(K3)
      II=II-1
      GO TO 19
   21 INDEX=0
      GO TO 23
   22 INDEX=1
   23 RETURN
      END
      SUBROUTINE GETK(N,I,J,K)
      K=N*(I-1)+J
      RETURN
      END
      SUBROUTINE GETIJ(N,K,I,J)
      I=(K-1)/N
      I=I+1
      J=K-(I-1)*N
      RETURN
      END
 MON
*EOF
*REW,17
*LGO,17
```

CODE "AVERG" TEST PROBLEM

Input

```
     3
     2
1.02          0.98
0.00083232
0.00039984    0.00124852
```

Output

```
Y,EY
 0.10200E+01  0.28850E-01
 0.98000E+00  0.35334E-01
VY
 0.83232E-03
 0.39984E-03  0.12485E-02
CY
 0.10000E+01
 0.39223E+00  0.10000E+01
P,EP
 0.10065E+01  0.26198E-01
CHI2,CHI2NM
 0.12489E+01  0.12489E+01
```

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