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A SURVEY OF SELECTED NEUTRON-ACTIVATION REACTIONS WITH SHORT-LIVED PRODUCTS OF IMPORTANCE TO FUSION REACTOR TECHNOLOGY

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Abstract

The status of the cross sections for production of short-lived radioactivities in the intense high-energy neutron fields associated with D-T fusion reactors is investigated. The main concerns relative to these very radioactive isotopes are with radiation damage to sensitive components such as superconducting magnets, the decay-heat problem and the safety of personnel during operation of the facility. The nature of the radioactivity associated with short-lived radioactive byproducts also affects how fusion reactors will behave during loss-of-coolant accidents (LOCA) or loss-of-flow accidents (LOFA). The present report surveys the status of nuclear data required to assess these problems. The study is limited to a few high-priority nuclear reactions which appear to be of critical concern in this context. Other reactions of lesser concern are listed but are not treated in the present work. Among the factors that were considered in defining the relevant reactions and setting priorities are: quantities of the elemental materials in a fusion reactor, isotopic abundances within elemental categories, the decay properties of the induced radioactive byproducts, the reaction cross sections, and the nature of the decay radiations. Attention has been focused on radioactive species with half lives in the range from about 1 second to 15 minutes. Available cross-section and reaction-product decay information from the literature has been compiled and included in the report. Uncertainties have been estimated by examining several sets of experimental as well as evaluated data. Comments on the general status of data for various high-priority reactions are offered. On the basis of this investigation, it has been found that the nuclear data are in reasonably good shape for some of the most important reactions but are unacceptable for others. Based on this investigation, the reactions which should be given the greatest attention are: $^{16}O(n,p)^{16}N$, $^{55}Mn(n,p)^{55}Cr$, $^{57}Fe(n,p)^{57}Mn$, $^{186}W(n,2n)^{185m}W$, and $^{207}Pb(n,n')^{207m}Pb$. However, the development of fusion power would benefit from an across-the-board refinement in these nuclear data so that a more accurate quantitative understanding of the effects of the decay of the short-lived radioactive byproducts can be obtained and taken into consideration in designing fusion reactors.

1. Introduction

Neutral-particle radiation transport is a well-comprehended phenomenon and the computer codes that are used for these transport calculations in both fusion and fission reactor investigations are also well understood and tested. Although there are many issues still unresolved with respect to radiation transport models, the accuracy of these codes has increased over the years to the point where the quality of results obtained depends to a large extent on the reliability of the nuclear data that are used to represent radiation interactions with the materials considered in the modeling processes. A question that must be asked by the users of these codes, the designers, the developers, and the engineers is: "How good are the nuclear data?" In particular, an effort must be made to answer the question: "How adequate are the cross sections sets used by the nuclear community (especially the fusion energy community) for its transport modeling and activation studies."

The fission community has obtained reliable answers to these questions, in the context of fission nuclear power reactor technology, through many years of practical experience in designing and operating these machines. This community has assembled a large data base to work with in addressing the tasks of designing safe nuclear power plants and managing the radioactive waste that they produce. However, the fusion community has not been given this opportunity since the fusion devices developed to date have not progressed to the point where experience can be gained under realistic conditions of intense 14-MeV neutron bombardment. The data that the fission community has assembled is of marginal value to the fusion community because of significant differences in the neutron energy spectra from these two distinct nuclear processes.

Among the many issues that are still unresolved with respect to the nuclear data applicable to fusion, one of particular interest to us concerns the delayed (secondary) sources of radiation associated with D-T nuclear fusion environments. What is involved is the generation of significant delayed sources of gamma radiation, beta radiation and other possible decay-heat sources. The delayed sources which may generate significant radiation usually involve short-lived and highly radioactive isotopes (with half lives on the order of about one second up to about 15 minutes) which are byproducts of fast-neutron reactions with fusion materials. Previously, most neutron-activation studies for fusion have been concerned with the production of significant long-lived radioisotopes which may be safety hazards to workers making repairs or present waste disposal problems. The matter of delayed radiation sources (other than from fission products) is less of a concern in fission-reactor technology than for fusion because fewer neutron reaction channels are found to be available or significant due to the much lower average energies of the degraded fission-neutron spectra.

The purpose of this study is to examine various available experimental and evaluated data sets in order to assess contemporary uncertainties in the neutron-activation cross sections for reactions of significance to fusion technology, in the specific context of short-lived radioactive byproducts. This study complements a similar investigation of long-lived radioactivities and their impact on nuclear waste disposal by Perez et al. [Per+94]. The data sets investigated involve fusion-reactor materials

which are likely to be found in significant quantities, thereby leading to the generation of large amounts of radioactive byproducts. Furthermore, since the interest is in significant production of delayed radiation sources and the decay-heat problem, the reactions investigated were confined to those where the byproducts are relatively short-lived. This constraint helped to narrow the field of reactions studied and served to identify potential future problems in fusion-reactor component designs, e.g., in providing adequate shielding for sensitive superconducting magnets.

The justification for this work was the need to identify possible nuclear data concerns with regards to neutron-induced activation reactions and delayed radiation sources. It should be noted that the selection of fusion materials considered in this work is not intended to be all-inclusive. That would be a difficult and self-defeating exercise since the potential choices of fusion-reactor component materials are in a constant state of re-evaluation by the designers. Rather, the work here examines some key issues in this field, and the approach used here should serve as a model for future, more comprehensive investigations of a similar nature. The particular choices made here are intended to reflect major candidate fusion-reactor materials that have been investigated in the past and continue to be viable contenders in conceptual designs for fusion reactors. These materials are associated with reactor structural components, coolants, multipliers and tritium-breeding blankets. Impurities are not a major concern in this context because they are found only in relatively small quantities in fusion reactors.

This paper first defines the present project and provides some background information on the studies done to date. The materials of major interest to fusion are listed and identified by priority. Those neutron-induced reactions which satisfy the criteria as generators of short-lived (between about one second and 15 minutes) radioactive byproducts are first identified and then prioritized with respect to strength of the reaction (cross section) and the relative abundance of the target isotopes. Cross-section data for the highest-priority reactions are then presented along with a pertinent analysis of their uncertainties. Each reaction is discussed briefly and particular attention is devoted to the matter of isomer activation processes, where there appears to be considerable confusion in the literature and computer data files. Finally, the overall conclusions from this survey are discussed and some recommendations for further investigation are offered.

2. Procedure

The objective of this study, as indicated above, was to identify possible neutron reactions with fusion-reactor materials that would lead to significant short-lived, delayed radiation sources. Significant delayed radiation sources are defined as those which may add noticeably to the overall transport of radiation through the various components of a fusion reactor. In other words, as a result of these delayed sources, there may be an added radiation flux, in the form of gamma rays or beta particles, that was not previously considered in the steady-state operation transport models due to their inability to account for such delayed processes. On the other hand, since these radiation sources are short-lived they tend to be overlooked during conventional after-shutdown activation analyses. In short, they tend to "fall through the cracks". However, if these additional sources prove to be of consequence, then they will have to be accounted for in augmented transport analyses. The purpose of this report is to identify some of these possible reactions and then examine the corresponding available nuclear data to see if they are adequate to the task of calculating realistic results.

Significant delayed radiation sources are likely to be present only when several conditions are satisfied: i) There are large abundances of the target isotopes involved in the neutron reactions present in the fusion-reactor materials. ii) These target isotopes must have reasonably large cross sections for those reactions which produce short-lived radioactive byproducts that emit delayed radiation [WMF84]. iii) The byproduct of the reaction must be highly radioactive. iv) The byproduct has to have a relatively short half life. The range of half lives selected for the present study is between about one second to about fifteen minutes. Half lives that are shorter were usually not considered because it was felt that their effect need not be distinguished from prompt-radiation emitting processes. Reactions leading to longer half-life byproducts are less likely to build up sufficient radioactivity to influence the short-time-scale dynamics of fusion reactor.

Identification of the materials that would satisfy the first condition (significant abundance) is easily accomplished by classifying fusion-reactor materials into four groups: structural, coolant, breeder/multiplier, and impurities (which it seems reasonable a priori to neglect). This helps to single out the most important elements representing potential reactor materials. Once the reactor materials of significant abundances are identified, all of the reactions that result in byproducts with half lives in the range of consideration were tabulated (generally excluding certain exotic reactions which were considered to be very unlikely). All the considered reactions had to have thresholds that could be exceeded by a large number of D-T fusion neutrons, so reactions with thresholds > 14 MeV were disregarded.

After identification of all such reactions, it was found that the list was quite large. Since the time frame allotted for the present study was limited, and it is mainly intended to illustrate the need for further work in this area, it became necessary to create a priority ranking of these reactions into three groupings: very important (Priority 1), important (Priority 2) and not as important (Priority 3). So, each identified reaction was assigned to one of these three priority rankings, depending on how

well it met each of the three requirements listed above, i.e., large abundance of the target isotopes, large cross section, and high specific radioactivity. The present assessment of these criteria was largely subjective. No attempt was made to define a quantitative "qualifier" that could be used in judging the importance of a particular reaction. It may be possible to do so, but this is a task for the future. This report only addresses Priority 1 reactions with any amount of detail, although reactions in the lower-priority groups are listed for reference purposes and as a guide to future work.

After these lists were produced the data collection began. The data of importance were determined to be: i) the decay schemes of the reaction products (specifically the highest-energy gamma-ray and beta-particle transitions), ii) the natural target element abundances, iii) the half lives of the reaction product, and iv) the various available evaluated and experimental cross section sets. These evaluated data were derived mostly from the National Nuclear Data Center [NNDC] at Brookhaven National Laboratory (BNL). The NNDC has a large, international data base of evaluated cross-section data including ENDF/B-VI (The United States Evaluated Nuclear Data File) [RD90], JEF-2 (Joint European File), CENDL-2 (Chinese Evaluated Nuclear Data Library), JENDL-3 (Japanese Evaluated Nuclear Data File), and BROND-2 (The Russian Nuclear Data File). The NNDC also has available, on-line, a large compilation of experimental data from many sources around the world (EXFOR File) [CINDA]. These data were extracted in the compiled-table format for comparison with the evaluated data sets. The REAC activation library [ML93], used in the REAC transmutation and decay analysis codes, and the Russian evaluated activation data library, called ADL-3 [Gru+93], were also obtained for the comparison with the above-mentioned experimental and evaluated cross-section results.

These evaluated nuclear data libraries are the principle ones used world-wide by reactor code developers and fusion-reactor designers. Since the accuracy of results obtained from any code is dependent on the accuracy of the intrinsic nuclear data it uses, it was determined that, in addition to the investigation of possible delayed radiation sources in fusion materials, one should also consider the uncertainties in these nuclear data. This is vital to determining the actual magnitude of the delayed sources, and to formulating recommendations for further improvements in the accuracy of these data. It was hoped to gain some insight into the reliability of the data currently used for this purpose by comparing all available evaluated data for the Priority 1 list. In addition, these evaluated data sets were compared with compiled experimental data. These comparisons certainly provide some idea as to what additional information might be needed for each reaction to further improve the reliability and the accuracy of the data sets actually used for fusion-reactor design calculations.

3. Materials and Isotopes

The initial step of this survey was to identify all of the major fusion-reactor materials, categorized into four groups: structural components, coolants, neutron multipliers and breeders, and impurities. Given these materials, the next step obvious step would be to identify the important neutron-induced reactions which apply. After some initial thought about the matter, the impurities group was dropped from consideration due to its failure to meet the requirement of adequate abundance. In order for any material to produce significant delayed sources of radiation there must be a large amount of this material in the reactor. It was felt that impurities would not exist in significant abundance for this purpose even though they are of concern for radioactive waste disposal purposes [SC91].

The list that was generated of major fusion-reactor materials appears in Table 1. As is evident there, most of the structural elements appear as major constituents of steel, V-15Cr-5Ti, or SiC. The addition of Cu is due to the serious consideration being given to it because of its good heat conduction properties. Aluminum may also be used in alloys. Some materials were not considered here because of their specific location in the fusion reactor, i.e., because they are found in regions where the neutron fluences are relatively low. The coolant group is fairly small due to the limited number of possible choices. The coolant choices currently included only liquid lithium and water (hence, Li and O). Helium was dropped from consideration because there are no reactions in the present category involved with this element. A comment should be made here about lithium. The element lithium is classified as a coolant, but it also can be used as a solid breeder material in its oxide form (Li_2O). In this context, the (n,p) reaction leading to ^{6}He production becomes important because of a possible decay-heat contribution in the blanket introduced by the emitted high-energy beta particles. It is recognized that this might become a problem and be of significance for fusion reactors, but for this study it was not considered sufficiently important to appear as a Priority 1 concern.

Once the major elements of interest were established, all of the reactions which produce short-lived isotopes, and that were not too improbable in nature, were identified. This listing of reactions appears in Table 2. Due to the large number of reactions listed in Table 2, it was necessary to establish priorities to guide further investigation of their roles in fusion-reactor technology. Therefore, all the reactions from Table 2 were assigned a priority rating of either 1, 2, or 3. The Priority 1 reactions appear to be the most important, and they are the ones that were looked at in this study. Priority 2 reactions are also quite important, and they should be followed up on in a subsequent study. Priority 3 reactions are considered to be of the least importance, although more detailed examinations may show that certain members of this list are worthy of consideration at a later date. These priority lists are shown in Tables 3 through 5. These tables present the isotopic abundances of the target materials, the half lives of the reaction products and some comments on why the reactions are assigned to a particular priority category. These listings are based on considerable subjectivity and merely serve to guide further work. The present investigation is only intended to provide a "first look" at the problem. There are a total of 19 reactions in the Priority 1 list, 31 reactions in the Priority 2

list, and 30 reactions in the Priority 3 list.

Reference has been made to some previous studies to help in identifying which reactions might be important to consider. Of these, the work of Smith and Cheng [SC91] and of Cheng et al. [Che+94] offer overviews of the reactions of possible importance to fusion in a more general context. There is a considerable overlap between reactions appearing on our Priority 1 list and those receiving similar emphasis by Cheng et al.

After completion of the above-mentioned priority lists, the focus of attention turned to the Priority 1 list. The main thrust of this investigation was to try to quantify the uncertainties associated with these reactions, particularly those involving the cross sections. Nuclear data were accumulated from various sources. Table 6 presents a compilation of some relevant information on the decay schemes of the reaction byproducts. As indicated above, information on the natural isotopic abundances of the targets and the half lives of the products was included in the priority lists (see Tables 3 through 5). Information on the decay schemes, isotope abundances, and half-lives were collected from the literature and referenced in footnotes to the tables.

4. Details of Reaction Processes

In this section some issues concerning the compiled data are discussed, including the significance of the reaction Q-values and neutron-energy thresholds in prioritization and the approach used in the assembly of both evaluated and experimental neutron cross section data. Finally, the reasoning behind the present interest in looking at these cross section uncertainties is discussed.

4.1 Q-Values and Thresholds

As can be seen in Table 2, most of the neutron-induced activation reactions that concern us in the present investigation are threshold reactions with neutrons, protons, deuterons and alpha particles in the exit channel. This is in contrast to fission-reactor technology where the greatest concern is with radiative capture reactions. As indicated above, this feature of fusion technology can be traced to the higher average neutron energy of the neutron spectra in fusion reactors. All of the reactions in the Priority 1 list (see Table 3) are either (n,charged particle) or neutron-emission reactions. None are (n,γ) reactions. Many of these reactions have rather negative Q-values, and therefore require fairly energetic neutrons to initiate the processes (endoergic). In short, they are insensitive to low-energy neutrons. In one sense, this simplifies the analysis because one does not have to worry about resonance phenomena in the cross sections at low energy, as is the case for non-threshold reactions (exoergic). The relationship between the Q-value and threshold energy, E_{thresh}, is well known for reactions with negative Q values, it is simply

$$E_{thresh} = - Q [(M_t + M_n) / M_t],$$

where M_n is the neutron mass and M_t is the target-atom mass.

The purpose of this survey is to study the uncertainties in the nuclear data for various activation reactions of interest to fusion. It is to be noted that many of the reactions that appear in Table 2, and subsequently the distilled list of highest priority reactions given in Table 3, have thresholds that are larger than the average energy of a pure fission-neutron spectrum (about 2 MeV). The average neutron energy is even lower in any realistic fission reactor, including fast reactors. On the other hand, the average neutron energy in a fusion reactor is much higher due to the D-T source energy (about 14 MeV). This means that many reactions which continue to be of little or no interest to the fission-reactor community, due to the high thresholds, have to be considered in fusion-reactor environments. While it is true that the prompt gamma radiation associated with the neutron inelastic scattering and capture events in fusion reactors is dominant when the reactor is operating under power, one cannot neglect the delayed gamma radiation after shutdown associated with the decay of numerous short-lived radioactive byproducts produced in D-T fusion neutron environments. The uncertainties in the decay and cross-section data associated with these processes have to be taken into

consideration in assessing their technological impact.

There is another issue that had to be considered relevant to reaction Q-values and neutron-energy thresholds. Since the present study ultimately deals with neutrons from a D-T fusion environment, it is important to limit consideration to those reactions with neutron-energy threshold that are below about 14 MeV.

4.2 Cross Section Databases

There exist a variety of evaluated neutron cross-section data bases from around the world that include activation data. Some of these data bases (e.g., the IAEA fusion library, FENDL) are hybrids that actual draw their content from other primary sources. It was decided early in this study that what was needed was to set a limit on the number of databases that were consulted in order to keep the sheer volume of information at a reasonable level. For this reason, this study draws material mainly from the major general-purpose evaluated data libraries used by the nuclear science community for neutronics analyses, as indicated in Section 2. These libraries include: the Chinese Evaluated Nuclear Data Library (CENDL-2), the Japanese Evaluated Nuclear Data Library (JENDL-3), the Joint European File (JEF-2), the United States Evaluated Nuclear Data File (ENDF/B-VI), and the Russian Library (BROND-2). These primary sources of cross-section information were supplemented by two other libraries. One of these is the Russian activation library (ADL-3). It was included because it appeared to be the most extensive one available. In particular, this library makes a careful and explicit distinction between isomer activation processes and total activation. This distinction is not as evident in some of the other cross-section libraries. The other library considered is REAC, a cross section library that has been prepared specifically for applications in widely used activation analysis codes.

All of the cross-section information mentioned above, except for the ADL-3 and REAC libraries, was readily obtained from the National Nuclear Data Center (NNDC) at Brookhaven National Laboratory (BNL). Furthermore, it was also possible to access the EXFOR experimental data files through the NNDC at BNL. These experimental data were used for comparison with the evaluated data libraries in order to shed further light on the uncertainties to be expected for the cross sections under consideration, as discussed below.

4.3 Cross-Section Uncertainties

The motivation behind conducting an uncertainty assessment of the available cross-section information is to enable analysts to determine just how accurately delayed radiation effects can be estimated in radiation transport calculations. If there are large uncertainties in the data, then an accurate calculation of the impact of these processes is not feasible. Simply put, if the nuclear data are uncertain, then the resulting calculations based on these data will be correspondingly uncertain.

There are various reasons, mainly non-technical in nature, as to why so many different data libraries exist. They are largely, but not completely, independent of each other. The common features are that the evaluators who produced these libraries used similar nuclear modeling techniques and referred to a common data base of experimental results. However, the manner in which these nuclear models were parameterized, and the procedures used to generate suggested results from the experimental data, have differed widely. Consequently, the evaluated cross sections often differ considerably in many instances. This creates difficulties for a user of such information, especially when trying to establish a degree of quality assurance for the reactor design calculations. The problem is more acute for fusion technology than for fission technology because there are limited options for performing benchmark experimental tests of data. True fusion reactors don't exist, whereas zero-power reactors could be built in developing fission power, and integral measurements in these devices provided information that aided in the adjustment of cross-section data libraries used for power-reactor design studies. Still, fusion power reactors are faced with the same requirements as for fission, namely, they have to be proved safe for licensing purposes, and projections of their economic benefit have to be made.

In the present study, several approaches were employed in assessing the cross-section uncertainties. One approach was to plot up all the available, equivalent evaluated results for a particular reaction. This offered a visual indication as to the uncertainties to be anticipated. It was then possible to refine this qualitative estimate by examining the spreads and standard deviations of results for a particular energy, in our case 14 MeV. In addition, the available experimental data were plotted to provide a good indication as to the reliability of these results. In cases where there are several apparently independent evaluations and considerable experimental data, this combination of approaches is quite successful. Otherwise, the picture is not so clear. For example, when there is only one experimental data set and several evaluations appear to follow that set, the true uncertainty hinges on the quality of the unique data set and that is hard to ascertain.

In reality, what really counts is not the value of the cross section at any particular energy or set of energies but the spectrum-averaged cross section for several fusion-neutron spectra representative of various locations in the reactor. The reason is that a large cross-section error at a particular energy may not produce much of an impact upon the neutronics of a fusion reactor because there might be relatively few neutrons in that energy range. Therefore, it is appropriate to examine not only the individual cross-section excitation functions but also their spectrum averages in assessing the "real-world" impact of these data uncertainties. Unfortunately, due to time constraints, this method was not applied in the present study, but it is planned for the future.

5. Results and Discussion

The information compiled in this study is presented in tables and figures appearing at the end of this report. The figures appear in sequential order according to the appearance of the corresponding reactions in Table 3. These reactions are ordered alphabetically by their elemental symbols rather than by importance. There is a separate figure provided for each Priority 1 reaction which shows all the corresponding evaluated cross section data for that reaction that were available for this study (as labelled). This set of figures is labeled by Figure (Reaction #).1. There is also a corresponding set of figures which focuses on experimental data from EXFOR. This second set is labelled by Figure (Reaction #).2. Each of the figures in this second set also shows a single evaluated curve (usually ENDF/B-VI) to serve as an eye guide to the plotted experimental results. Whenever ENDF/B-VI was not available, JENDL-3 was plotted on these "second" plots.

All of the evaluated data sets are available in a point-wise format except for the REAC data which exist in a group format. For ease of compilation, the REAC group format was transferred to a point-wise format by simply taking the mid-point of the group as the effective point-wise energy value corresponding to the group cross section. With all the evaluated results thus assembled in point-wise format, it was possible to plot the various results in a consistent manner. In a few instances some anomalies were observed in the REAC results due to the transformation from group to point-wise format, but these were of minor consequence for present purposes.

In order to obtain a more quantitative estimate of the cross-section uncertainties, all the available evaluated data at 14 MeV were examined. Although this over-simplifies the issue, as mentioned above, 14 MeV is an important energy since most neutrons produced in D-T fusion are emitted in the range 13-15 MeV and the "14-MeV peak" is a prominent feature of neutron spectra throughout a fusion reactor. The following calculations were carried out for each of the Priority 1 reactions: First, the average $< \sigma >$ of all the evaluated cross sections was determined. Then, the maximum cross section σ_{max} and minimum cross section σ_{min} at 14-MeV were identified and a spread $(\sigma_{max} - \sigma_{min})$ was determined. Finally, the standard deviation was calculated using the formula

$$\text{Standard deviation in } \sigma = [\ \Sigma_{k=1,n} (\sigma_k - < \sigma >)^2 / (n-1)\ ]^{1/2},$$

where the sum on k extends over n different evaluations for a particular reaction. Since the number n of available evaluations is relatively small (from 2 to 7 depending on the reaction), this computed standard deviation is not a very reliable measure of the uncertainty in the 14-MeV cross section but it was included for completeness. The spread $(\sigma_{max} - \sigma_{min})$ between the maximum and minimum values probably gives a more conservative estimate of uncertainty for present purposes. Several additional derived ratios were calculated from these quantities including $(\sigma_{max} / \sigma_{min})$, (Standard deviation in $\sigma / < \sigma >$), and $(\sigma_{max} - \sigma_{min}) / < \sigma >$. The results of this analysis are compiled in Table 7. Note that for reactions exciting an isomeric state it was found that only the REAC and ADL-3 libraries gave information directly applicable to the isomeric levels. It appears that all the other files provide only

the total reaction cross sections (involving both the ground state and isomeric level).

In the course of examining these data, it became clear that in the literature there exists considerable confusion concerning whether the cross section involves excitation only of an isomeric state or whether it includes both the isomer and the ground state (total). The distinction is very important for present purposes because in some cases only the isomer contributes to the short-lived radioactivity. In the case of the REAC and ADL-3 results this distinction was always made so no difficulties were encountered. Some of the figures in this report include both isomer and total reaction cross-section information, but a distinction is always made to avoid confusion. The curves are clearly labelled as "total" or "isomer" whenever there is a possibility for confusion concerning this issue. The experimental points shown in the figures are "total" values in all cases. This isomer question is discussed in more detail in Section 6.

The following paragraphs contain specific comments about each of the Priority 1 reactions considered in this study. The reader will want to refer to the appropriate tables and figures while reviewing this material. In particular, Tables 2, 3, and 6-8 are quite helpful in this regard.

1: $^{27}Al(n,p)^{27}Mg$

Aluminum is not considered as a primary contender for a pure structural material because of its low operating temperature limit. However, the element is included here because it may well appear as a component of certain alloys that could be used in fusion reactors. The element Al consists of only one isotope (^{27}Al). Therefore, inclusion of Al as a fusion-reactor material will require examination of this reaction because it is very important at typical neutron energies associated with D-T fusion. The half life of the reaction product is on the long side of the range considered in this study (see Table 6). ^{27}Mg is a beta emitter with a reasonable average energy, and there are two gamma rays which are released in many of the decays. These gamma rays are reasonably energetic (~ 1 MeV). Therefore, it is quite possible that this reaction could produce significant delayed gamma-ray sources in a fusion reactor. The reaction cross section peaks at about 10 MeV. The available evaluated cross-section data are quite extensive (see Fig. 1.1). The experimental data are very extensive, and only appear sparse in the region between 10 and 12 MeV (see Fig. 1.2). The only evaluated curve that has a shape which differs from the others is that from JEF-2 . It peaks at 14 MeV as opposed to about 10 MeV for the others. From a statistical point of view, the uncertainties do not appear to be very large (see Table 7), perhaps on the order of 10%. Considering the above-mentioned shape discrepancy, this is not very serious. Overall, this seems to be an important reaction with modest uncertainties in the cross section.

2: $^{9}Be(n,\alpha)^{6}He$

Beryllium is considered primarily as a neutron multiplier because of its large (n,2n) cross section, with a neutron threshold energy which is atypically low. For this reason, despite being quite expensive, Be is very likely to be used extensively in the blanket environment of fusion reactors to

enhance the neutron inventory for production of tritium from lithium. The isotope ^{9}Be constitutes 100% of natural beryllium. The present reaction has a fairly large cross section, and all the available evaluations agree upon a peak yield in the cross section at around 5 MeV (see Figs. 2.1 and 2.2). These evaluated curves lay rather close to each other and appear to follow the experimental data near threshold. It is suspicious that no errors are provided with these experimental data, so it is questionable just how well-known the cross section actually is in this energy region. The statistical analysis (see Table 7) indicates a relatively modest uncertainty around 14 MeV, since the data at higher energies scatter somewhat. However, the overall uncertainty still appears to be relatively small. This reaction generates only relatively high-energy beta particles upon decay of the reaction product. No gamma rays are produced. Therefore, most of the energy deposition will be local, but this could lead to a decay-heat problem. So, this reaction merits consideration in the present context.

3: ^{52}Cr(n,p)^{52}V

Chromium is an element appearing in alloys to be used in the structural components of fusion reactors. The target isotope exists at an abundance of 83.79% in natural chromium, so its presence in a fusion reactor via steel or vanadium alloys is reasonably high. Like most of the (n,p) reactions, this process produces a radioactive byproduct that decays by beta emission back to the original target isotope. The beta particles emitted by the radioactive byproduct have a moderately high energy. Furthermore, there is a reasonably energetic gamma ray (about 1.4 MeV) which is emitted 100% of the time. The reaction cross section is substantial, with a peak yield between 14 and 15 MeV. The various evaluated data (see Fig. 3.1) agree fairly well (within about 10%), and the available experimental data sets (see Fig. 3.2) are few at low energies but appear to be consistent. At higher energies there is considerable scatter. It would be beneficial to obtain some experimental information in the energy range 10 to 14 MeV where few results are currently available. In all, this reaction appears to have been studied with reasonable thoroughness and the uncertainties are not large.

4: ^{53}Cr(n,p)^{53}V

The target isotope, ^{53}Cr, is the other major isotope of natural chromium but it is not nearly as abundant as its sister isotope ^{52}Cr. This reaction also exhibits the (n,p)-beta recycling mentioned in the discussion for the preceding reaction. However, the cross section is relatively small. The combination of low abundance and small cross section seems to indicate that this reaction may not be very significant. Nevertheless, the radioactive byproduct is a beta emitter with a reasonably high decay energy and there are two emitted gamma rays with significant energies. There are several evaluated data sets (see Fig. 4.1). However, these results seem to show some degree of uncertainty, to the extent of disagreeing considerably on the overall shape of the cross section. The experimental data (see Fig. 4.2), although not as abundant as, e.g., for ^{27}Al(n,p)^{27}Mg, still would appear to offer a reasonably decent picture of the cross section shape near threshold. The statistical analysis indicates that the uncertainty around 14 MeV is substantial. The spread is around 44% and the standard deviation is approximately 16% of the mean at 14 MeV. This error looks even larger at lower and

higher energies. Overall, this reaction clearly needs improvement in the cross-section data. Because of this existing uncertainty, it is believed that it should remain as a Priority 1 issue. However, for practical reasons it should be kept in mind that in a fusion-reactor environment this process will always be overshadowed by more significant processes like the (n,p) reaction involving its dominant sister isotope.

5: $^{63}Cu(n,2n)^{62}Cu$

This reaction has the potential of being very important at high energies because the isotope is abundant and the cross section around 14 MeV is large. The only mitigating factor is a relatively high neutron threshold energy. The radioactive byproduct decay energy is quite high, and this decay occurs by both electron capture and positron emission. There are two gamma rays produced with moderate energies but low frequency. The available evaluated data sets are reasonably consistent (see Fig. 5.1). The same can be said about the experimental data (see Fig. 5.2). Consequently, the cross-section uncertainties appear to be relatively modest for this reaction. However, because of its importance to fusion-reactor technology it is believed that this reaction should remain on the Priority 1 list, and fusion technology ultimately would benefit from further refinement in knowledge of the cross section.

6: $^{63}Cu(n,\alpha)^{60m}Co$

The abundance of the target is high, but the cross section is fairly small. Therefore, this reaction is probably less important than some of the others in this set. The decay of the radioactive byproduct proceeds by an isomeric transition 99.75% of the time, and the decay energy is relatively low. This reaction is maintained in the Priority 1 set because of the potential decay-heat problem. The 59-keV photon which is emitted will deposit its energy in the vicinity of the source. This reaction illustrates the problems encountered in obtaining unambiguous information from the literature for reactions involving the decay of isomeric states. Most of the evaluated data (see Fig. 6.1) deal with the total (n,α) reaction cross section. In other words, it is a sum of those transitions which populate the isomer and those which populate the ground state. The situation can become even more complex if more than one isomeric level is involved, but there was no occasion to have to deal with this problem in the present study. Even when it was possible to be certain that what was presented was the isomer-reaction cross section (REAC and ADL-3), disagreement in the overall shape is evident (see Fig. 6.1). The experimental data are limited and appear to refer only to the "total" cross section (see Fig. 6.2).

7: $^{65}Cu(n,\alpha)^{62m}Co$

This reaction involves an isotopically somewhat-less-abundant isotope of Cu, and represents another example of having to deal with the isomer question discussed for the preceding reaction.

Since the cross section is smaller, and the isotopic abundance reduced relative to the corresponding reaction for ^{63}Cu, it would appear that this reaction should be less significant. However, its character is quite different because of the difference in the decay properties of the radioactive byproduct. The decay of the byproduct is by beta emission. These beta particles have a fairly high average energy and there are several major gamma rays produced with fairly high energies. The evaluated cross-section sets from the major files (see Fig. 7.1) appear to be more consistent than the corresponding reaction for ^{63}Cu. However, they deal only with the total (n,α) cross section. When one turns to the isomer excitation cross sections found only in REAC and ADL-3, the situation is much more problematic. The disagreement is considerable (see Fig. 7.1). Overall this reaction exhibits one of the largest uncertainties encountered in the present study (see Table 7). This may well be due to the scarce and apparently discrepant experimental data (see Fig. 7.2).

8: ^{57}Fe(n,p)^{57}Mn

Stainless steel is currently under consideration as one of the options for structural components in ITER. Concerning the most abundant isotope (^{56}Fe), there are no activation reactions which produce radioactive byproducts with half lives in the time range of the present study. In fact, the present reaction, ^{57}Fe(n,p)^{57}Mn, appears to be the only one of any possible consequence for elemental Fe. Because of the large abundance of the element Fe, this reaction was considered a priori to be a good Priority 1 candidate in spite of low isotopic abundance of ^{57}Fe (2.1%). This reaction has a fairly large cross section and the emitted beta particles are relatively energetic. However, the emitted gamma rays have relatively low energies and the target isotope abundance is low. The evaluated data (see Fig. 8.1) do show some interesting features. One important point is that there is widespread disagreement on the general shape of cross section. This probably can be attributed to the sparseness of the available experimental data (see Fig. 8.2). The only available data points span a small energy range above 14 MeV, and these exhibit a large scatter. The statistical analysis (see Table 7) shows that the uncertainties are the worst among the non-isomeric Priority 1 reactions. The ratio of maximum to minimum cross section at 14 MeV is about 2.8! This large uncertainty is also reflected in the spread and standard deviation of the evaluated results. This reaction may not be of supreme importance in fusion technology because of low abundance but, due to the energetic beta particles and glaring uncertainties in the cross section data, it merits further study.

9: ^{55}Mn(n,α)^{52}V

Manganese is likely to be no more than a secondary material found in various metal alloys in structural components of fusion reactors. However, its presence could still be plentiful. It is monoisotopic so only reactions with ^{55}Mn need to be considered. The radioactive byproduct decays with the emission of reasonably energetic beta particles and gamma rays so there is a potential decay-heat problem associated with this delayed gamma radiation source. The available evaluated cross-section data sets (see Fig. 9.1) for the most part seem to agree within a few percent at 14 MeV. The uncertainty is fairly low, even though the shapes do not seem to agree. A few of the data sets seem

to indicate that there might be a small resonance below 14 MeV. The experimental data (see Fig. 9.2) are more complete than for $^{57}Fe(n,p)^{57}Mn$, but they mostly pertain to energies above 14 MeV and scatter considerably. There is a single data point below 5 MeV. This might explain why the evaluated sets tend to agree reasonably well at low energies but tend to diverge at somewhat higher energies where the widely scattered experimental data are concentrated.

10: $^{55}Mn(n,p)^{55}Cr$

This reaction has a slightly larger cross section than the preceding one for Mn. The radioactive byproduct decays by beta emission, so this represents yet another (n,p)-beta cycle as described previously. The average energy of the beta particles is over 1 MeV, but the gamma-ray emission is almost negligible. Consequently, this reaction is likely to represent no more than a relatively minor contributor to localized decay heating. There are a number of evaluated data sets (see Fig. 10.1). However, these results appear to be rather discrepant. The statistical analysis (see Table 7) indicates existence of uncertainties at 14 MeV in the range of 25 to 50%, based on the spread and the standard deviation from the mean. There are very few experimental points and the errors are large (see Fig. 10.2). With this large uncertainty, and the likelihood that this reaction will be important, it is clear that further work on the nuclear data is warranted.

11: $^{60}Ni(n,p)^{60m}Co$

This reaction presents another situation involving an isomer state. The target isotope ^{60}Ni has a fairly small isotopic abundance but the presence of nickel in stainless steel is quite large so there may be a lot of this material in fusion reactors. The decay is not very energetic and it is dominated by an isomeric transition which is strongly internally-converted. The emitted gamma ray is of low energy and the branching factor is small because of internal conversion. So, this reaction might lead to a localized decay-heat problem and may be important only in the sense that there is a large probability of it occurring in a fusion reactor. Another consideration is that this reaction also contributes to the accumulation of long-lived ^{60}Co. There are several evaluated data sets (see Fig. 11.1), but once again the problem arises that many of them correspond to the total (n,p) cross section, not to the isomeric excitation alone. REAC and ADL-3 give specific guidance concerning the isomer. These two data sets seem to agree fairly well even though the shape of the REAC curve seems odd, most probably due to the group to point-wise conversion effect mentioned above. The experimental data (see Fig. 11.2) appear to be relevant to the total (n,p) cross section. On the whole, the uncertainties for this reaction appear to be fairly modest.

12: $^{16}O(n,p)^{16}N$

This may well be the most significant Priority 1 reaction to be considered for various reasons. Other investigators have already pointed out this problem (e.g., Ikeda et al. [IMC94]). The presence

of oxygen in any fusion reactor is likely to be large. Even if water is not used as a coolant, oxygen will exist in abundance through oxide materials found in the reactor. The most abundant isotope of oxygen, ^{16}O, comprises almost 100% of natural oxygen. This means that any significant activation reactions for this isotope will produce large quantities of radioactive byproducts. This reaction is potentially serious due to the nature of the reaction product's decay scheme and to its significant cross section. This reaction produces a highly radioactive isotope which decays very quickly back to oxygen through the above-mentioned (n,p)-beta cycle. This isotope of nitrogen decays with a great deal of energy. Very energetic beta particles (energies up to about 10 MeV) and gamma rays (from 6 to 7 MeV) are involved with substantial frequency in these decays. This reaction appears in each of the evaluated files considered, and there is considerable agreement between these results (see Fig. 12.1). The statistical analysis substantiates this observation (see Table 7). However, there is some concern about the apparent cross-section resonance at about 12 MeV since it is based on only a few experimental data points (see Fig. 12.2). It is important to verify that this resonance really exists. This reaction, due mainly to the large abundance of oxygen expected in a reactor (especially if water is used as a coolant), to the substantial cross section, and to the extremely high-energy nature of the decay, is obviously of great concern for its likely implications in the design of fusion reactors. If the water is activated and transported outside the reactor into an area of relatively modest shielding, the 6 to 7 MeV gamma rays can subject superconducting magnets to a potentially serious radiation dose, and may also produce a hazard to personnel of the reactor facility. Even though the experimental and evaluated cross-section data appear to be reasonably conclusive, the nuclear data for this reaction merit further investigation because of its great impact on radiation damage and safety issues.

13: $^{204}Pb(n,2n)^{203m}Pb$

This is another reaction involving an isomer. It may derive some significance if lead is used as a neutron multiplier or in shielding, in spite of the low abundance of the target isotope. The quantity of lead in a fusion reactor could be large and, as a result, the production of ^{203m}Pb could be substantial. The cross section is perhaps the largest of all of the reactions in the Priority 1 list. This also enhances the significance of this reaction. The radioactive byproduct decays by an isomeric transition with an energy of about 0.8 MeV. Most of this emerges in the form of a gamma ray. The evaluated data are limited for this reaction and, once again, only REAC and ADL-3 give information that is explicitly related to the isomer excitation process (see Fig. 13.1). There appears to be no difference between these two evaluated libraries, except possibly due to the group to point-wise format conversion artifact mentioned above. The experimental data (see Fig. 13.2) span the entire neutron-energy range of the reaction, but they are nevertheless quite sparse except in a small region around 14 MeV. Some more work needs to be done on quantifying the cross-section data of this reaction.

14: $^{207}Pb(n,n')^{207m}Pb$

This reaction is a cycle-type reaction of a different sort, namely, neutron inelastic scattering,

(n,n'). With its fairly large cross section (see Fig. 14.1) and moderate abundance, this reaction will be a prominent source of delayed radiation if lead is used in large quantities in a fusion reactor. The decay of the radioactive byproduct is by isomeric transition with strong gamma-ray emission at moderate photon energies. Again, there is the familiar problem of trying to establish whether what is given in the files is truly the isomer-excitation cross section. It is only possible to be sure of REAC and ADL-3, where it is stated specifically what levels are involved. These two libraries seem to agree fairly closely, whereas the other libraries give values which are much higher than these two except at relatively high neutron energies where they are actually lower. Therefore, it must be assumed that what is given in the general purpose files is the total neutron inelastic scattering cross section, not the quite-different cross section for specifically exciting the isomeric level. The experimental data are quite sparse (see Fig. 14.2). Clearly there is need for further experimental work on this reaction since it is potentially of considerable significance to fusion technology.

15: $^{28}Si(n,p)^{28}Al$

This reaction poses a problem due to a serious lack of data. Only one of the leading evaluated data sets considered here had any information on this reaction (JENDL-3), and even that set did not correspond very well with the REAC library (see Fig. 15.1). This reaction belongs to the class of (n,p)-beta cycle reactions discussed above. The emitted beta particles are quite energetic and each decay is accompanied by a gamma ray with energy of about 1.8 MeV. Considering that the target is a dominant isotope, that the element will be abundant in ceramic components of a fusion reactor, and that the cross section is of moderate size, it is clear that this reaction could become a dominant producer of delayed radioactivity, and could contribute noticeably to a decay-heat problem. The statistical analysis indicates that the data agree fairly well at 14 MeV (see Table 7), but the very limited evaluated data base leads to considerable uncertainty in this cross section. However, this does not mean that there is a lack of experimental data (see Fig. 15.2). As a matter of fact, the data are extremely abundant at the lower energies. The apparent large scatter in these data may be due more to resonance effects (and varying resolution) than to true discrepancies. Between 10 and 14 MeV, as usual, there are very few data. The same is true above 14 MeV. More work is needed in developing the nuclear data for this reaction because of its potential importance to fusion technology.

16: $^{29}Si(n,p)^{29}Al$

Although this isotope of silicon is not nearly as plentiful as the isotope mentioned above, its fairly large cross section and more energetic decay make it interesting enough for consideration as a Priority 1 reaction. The decay of the radioactive byproduct is via beta emission with moderate energy. Furthermore, there are a couple of fairly energetic gamma rays associated with this process (as much as 2.4 MeV). Once again, this reaction belongs to the class of (n,p)-beta cycle reactions. The same type of problems mentioned above, in conjunction with the sister reaction, exist for this reaction's evaluated data sets (see Fig. 16.1) and for the available experimental data (see Fig. 16.2). If anything, the situation is worse in the present instance, as is evident from the results from the

statistical analysis (see Table 7). However, since ^{29}Si does not exist as abundantly in nature as does ^{28}Si, this reaction is probably not as important. Nevertheless, the situation merits further investigation.

17: $^{46}Ti(n,p)^{46m}Sc$

This is a member of the class of (n,p)-beta cycle reactions, but all that concerns us here is that it involves an isomer. The data situation is poor, although it is better than for silicon. This could possibly be due to the fact that in activation measurements one also includes the reaction $^{47}Ti(n,np+d)^{46m}Sc$. Since titanium is likely to be a very important material in fusion reactors, due to its generally favorable physical properties, it is worthwhile giving the matter some attention. However, upon closer examination this reaction does not appear to be of great technological importance. The reasons are that the cross section is relatively small and the decay energy is modest. The decay is by isomeric transition. There is a gamma ray emitted in a majority of these decays but the energy is relatively low. However, since the nuclear data uncertainties are quite large, it is difficult to assess the situation with any degree of quantitative certainty. Once again, there is the problem that for the general purpose files the cross sections given generally apply to the total (n,p) cross section, not just the isomer. When REAC and ADL-3 are considered, it is found that they do not agree too well (see Fig. 17.1). The statistical analysis indicates sizeable uncertainties (see Table 7). The experimental data (see Fig. 17.2) span the critical energy range fairly well but are scattered.

18: $^{51}V(n,p)^{51}Ti$

Vanadium is considered to be a very important element for fusion. It contends favorably in the search for low-activation structural materials. The isotope ^{51}V is the most common of the vanadium isotopes found in nature, with virtually 100% abundance, so any activation reaction involving this isotope has a potential of being a major producer of radioactivity. The radioactive byproduct is a beta emitter, so this is another example of the (n,p)-beta cycle reaction class mentioned previously. The decay energy is moderate, with correspondingly energetic beta particles and gamma rays. This indicates that this reaction has the potential for contributing modestly to various delayed radiation effects including decay heat. There are few evaluated data sets (Fig. 18.1), but the sets that do exist seem to agree fairly well. The statistical analysis is summarized in Table 7. As a matter of fact, at 14 MeV, these evaluations show relatively little dispersion. The experimental data (see Fig. 18.2) seem to be fairly comprehensive except in the mid-range energy region between 10 to 14 MeV. This reaction may merit some more detailed investigation.

19: $^{186}W(n,2n)^{185m}W$

There are serious problems associated with this reaction. First, it presents us with the well-known problem associated with isomer excitations, namely, confusion over the true nature of the available cross sections. The target isotope is reasonably abundant and the cross section is quite large.

Decay of the radioactive byproduct is by a relatively energetic isomeric transition although the gamma-ray emission probability, suppressed by internal conversion, is very modest. The evaluated data sets are shown in Fig. 19.1. It is only possible to compare REAC and ADL-3 because of the above-mentioned isomer problem. These results do not agree very well. The experimental data (see Fig. 19.2) are sparse which adds further uncertainty to this situation. Even though the decay of the reaction product does not lead to copious gamma-ray production, this reaction needs further investigation because of the unfavorable data situation, the large isotopic abundance of the target, and the large reaction cross section.

6. Special Considerations for Isomer -Excitation Reactions

As was mentioned previously, and is evident from the discussions pertaining to some of the reaction cross-section data, it is difficult to obtain unambiguous information on the isomer-excitation cross sections. In the figures showing the evaluated data, the "total" reaction cross section curves usually lay well above those for the corresponding isomer excitation cross section, as is to be expected. If one were to inadvertently use the "total" reaction cross sections, when what should have been used are the isomer values, one would obtain an over-estimation of the delayed radioactivity. This could be a significant problem if the major general purpose files are used for activation calculations. Well above the respective threshold for either the total or isomeric cross-section curves one would expect, to first order, that the shapes would be roughly the same. Therefore, it was decided that it would be worthwhile to tabulate the ratios of the isomer to total cross sections at 14 MeV, as obtained from a single source, namely, ADL-3. This information has been compiled in Table 8. What is interesting is that these ratios seem to fall in a relatively narrow range (0.21 to 0.41) for all of the Priority 1 reactions on our list that involve isomers. It is well known that isomer ratios depend on the detailed nature of the level structures (densities, spins, etc.) and electromagnetic transitions between these levels. That the range above should be so narrow is surprising.

It is dangerous to reach any conclusions from such a modest sampling of the situation, but it is tempting to suggest that in the absence of specific isomer-excitation cross-section data one could generate the information by simply multiplying the total reaction cross section by a constant (perhaps around 0.3). This approach is clearly too simplistic, as is evident from an examination of the figures for the isomer and total reaction cross sections. Often the shapes are completely different and the REAC and ADL-3 data frequently are inconsistent in shape and magnitude for the same quantity. So, one cannot escape the conclusion that better data are needed to resolve this issue.

7. Conclusions and Recommendations

The present survey was carried out with the intent to provide some indication as to the uncertainties that might be expected to be present in the evaluated nuclear data sets commonly used for fusion-reactor activation analyses (and for fission reactors as well). Specifically, those reactions have been considered which lead to highly-active, short-lived radioactive byproducts that might be produced in sufficiently large quantities to be troublesome. In other words, significant processes which involve energetic decay radiations that generate decay-heat or radiation damage effects were considered. Iron was an exception to the rule of high isotopic abundance and large cross section as a criterion for Priority 1 reactions. Since the amount of iron that may be found in any fusion reactor design could be very large, it was felt that any reaction in this category should be considered so long as the cross section was not negligible. It appears that the fusion community has tended to overlook short-lived, delayed radiation sources, focusing its attention instead on prompt radiations and long-lived radioactivity production (for waste disposal). The fission energy community is concerned with the decay-heat problem but the technical issues are different because fission products dominate and the average neutron energies in fission-reactor spectra are significantly different from fusion. In fusion, the average energy is high, and many threshold reactions that are not a concern for fission have to be examined. As a result, the nuclear data for many of these reactions are deficient and this makes an accurate analysis of the situation almost impossible. The design of fusion reactors will be guided strongly by results from computer models, due to the expense of large and complex experimental "benchmark" devices. Since computer technology and modeling efficiency has increased greatly in the past few decades, these modeling approaches have become increasingly faster and inherently more accurate. However, the results from such models, in the final analysis, are no better than the nuclear data used in their application. Large data uncertainties are a problem for the data user who simply wants to take the data for granted and concentrate on his modeling applications.

The procedure followed in this study was to first identify which materials and elements might be of interest in designing a fusion reactor, and to then ascertain which of these elements might exist in large abundances in a fusion device. After the identification of the fusion-reactor elements, the next step was to list all of those reactions which produce radioactive products with a half lives in the time range of about one second to fifteen minutes. After this list was compiled, some initial estimates of the cross sections at 14 MeV were made for screening purposes. This information permitted the master list of reactions to be sorted according to priority (with Priority 1 the highest and Priority 3 the lowest). Priority 1 includes only those processes that appeared to involve relatively high abundances, cross sections, decay energies, etc., such that a significant production of delayed radiation could be expected, leading to decay-heat or gamma radiation source effects that might be troublesome. It should be borne in mind that this project is not meant to provide the definitive "last word" on this subject. It is primarily intended to stimulate more detailed and careful studies of this problem, and to show some instances where contemporary knowledge of the nuclear data requisite for fusion analyses appears to sorely inadequate.

After completing preparation of the Priority 1 list, information was collected on decay schemes for the reaction products. Cross-section data were acquired from the general-purpose evaluated data files from the NNDC at BNL. The Russian ADL-3 library was acquired from the IAEA in Vienna. Finally, the REAC activation library was obtained from files available to one of the authors (ICG). Experimental data from the EXFOR data library were also acquired from the on-line services of the NNDC. During the process of collecting these cross-section data it was observed that it was not always clear whether the cross section referred to isomeric excitations or were total reaction cross sections. It was concluded that only the REAC and ADL-3 libraries gave explicit information on isomers. The general purpose files provide information on the total reaction cross sections. The REAC library presented an additional problem in that the information was provided in group-structure format and had to be converted to an approximate point-wise representation for comparison with the other files.

For the most part, reactions that were considered to be quite important (i.e. they involve very abundant targets and energetic decay radiations) were characterized with reasonable certainty by the existing evaluated and experimental data. Some examples of these reactions were those involving ^{27}Al, ^{9}Be, and ^{16}O.

There were a total of seven reactions which are classified under the isomer category. A few of the isomer reactions were found to be somewhat less important than was originally thought, after examination of the data. An example of this is $^{63}Cu(n,\alpha)^{60m}Co$. This usually came about because of low cross sections or low energy released by the decay of the reaction byproduct. However, all of these were retained in the Priority 1 list because it was felt that even they would benefit from improvements in the nuclear data base.

Despite success in finding that the available cross section information is reasonably adequate for some of the Priority 1 reactions, it was found the nuclear data situation was quite poor for many others. As a set, those reactions leading to isomers were in the worst shape. However, some non-isomeric reactions, like $^{57}Fe(n,p)^{57}Mn$ and $^{55}Mn(n,p)^{55}Cr$, had fairly large uncertainties. In some instances, the 14-MeV results appeared to be fairly reliable but large uncertainties were evident at lower energies. In such cases, spectrum-averaged cross sections for typical fusion-reactor spectra might show up serious deficiencies. Unfortunately, it was not possible to explore this matter in the present study due to a lack of time.

In several instances it would appear that uncertainties could be reduced if more experimental data were available. However, there were instances when uncertainties appeared to persist even when there were extensive data. A case in point is ^{27}Al. There are many data points for this reaction below 10 MeV and above 13 MeV (see Fig. 1.2). Then, it becomes a matter of how an evaluation is to be performed. Presumably statistical methods need to be used once the systematic biases in these data are identified and corrected. This is a concern for evaluators and is beyond the scope of our study.

Special attention has been given to the $^{16}O(n,p)^{16}N$ reaction because large inventories of oxygen are envisioned for almost any fusion reactor design, even one not involving water coolant.

It was concluded that the cross-section data appear to be reasonably well known for this reaction but there should be some improvement, particularly in the vicinity of a strong resonance around 12 MeV. There are some differences between the various evaluated files which may or may not be minor. The experimental data base in this energy region appears to be restricted to a single data set. So the issue of data uncertainties cannot be considered as settled for this reaction. More differential data are needed and integral tests need to be performed for typical fusion-reactor neutron spectra to examine sensitivities to these data. This reaction is probably the most important one considered from the Priority 1 list, but there are others. In particular, the following reactions were selected as being the most important ones for further study: $^{16}O(n,p)^{16}N$, $^{55}Mn(n,p)^{55}Cr$, $^{57}Fe(n,p)^{57}Mn$, $^{186}W(n,2n)^{185m}W$, and $^{207}Pb(n,n')^{207m}Pb$.

Since this is a preliminary study, a few words concerning what ought to be done next is in order. It is believed that a somewhat more objective basis for estimating uncertainties is required than the simple approach of examining the differential cross section at 14 MeV. In particular, spectrum-averaged cross sections need to be calculated using the available differential evaluations and typical D-T fusion-reactor neutron spectra. This would give a much better understanding of the true uncertainties involved in estimating the performance parameters of a fusion reactor. A more thorough examination of the inventories of specific elements to be found in various parts of a fusion reactor needs to be made. It would also be beneficial to perform some energy-deposition calculations for the beta particles and gamma-rays emitted from some of the radioactive species produced by these reactions. The decay constants are important in assessing the dynamics of the reactor immediately after shutdown. Perhaps in some instances there exist sufficient experimental data and suitably refined nuclear models to permit more careful, reaction-specific evaluations to be performed. It should be noted that many of the available evaluations were global in nature (involving all reactions for a particular element or isotope), and there were compromises made in developing nuclear models for this purpose. It would also be worthwhile to extend the detailed investigation from Priority 1 to Priority 2 reactions since some of these may be more important than the present subjective estimation indicates.

An investigation of the type proposed as an extension of the present work would make a suitable thesis for a graduate student in the applied nuclear sciences. It would require quite a bit of time and effort, and careful attention to details, but it seems like a very feasible project which would involve using existing tools for collecting and processing the primary data and incorporating them in reactor modeling codes that are already available.

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Table 1: Important elements found in various components of fusion reactors

Structural Components

Al, C, Cr, Cu, Fe, Mn, Ni, Si, Ti, V, W

Coolants

He, Li, O

Neutron Multipliers

Be, Pb

Table 2: Neutron-induced reactions - half lives, Q-values and estimated 14-MeV cross sections

Reaction	$t_{1/2}$[a]	Q (MeV)[b]	E_{thresh} (MeV)[c]	σ_{ADL} (mbarn)[d]	σ_{BNL} (mbarn)[e]
STRUCTURAL MATERIALS					
Aluminum					
$^{27}Al(n,\gamma)^{28}Al$	2.2406 m	7.725	-	0.534	0.415
$^{27}Al(n,p)^{27}Mg$	9.462 m	-1.829	1.897	73.9	76
$^{27}Al(n,2n)^{26m}Al$	6.345 s	-13.286	13.783	0.439	0.100
Iron					
$^{54}Fe(n,2n)^{53}Fe$	8.51 m	-13.378	13.628	7.8	7
$^{56}Fe(n,2p)^{55}Cr$	3.497 m	-12.005	12.221	2.8×10^{-7}	-
$^{57}Fe(n,p)^{57}Mn$	1.45 m	-1.909	1.943	77.8	50
$^{58}Fe(n,p)^{58}Mn$	1.088 m	-5.539	5.635	32	10
$^{58}Fe(n,p)^{58m}Mn$	3.0 s	-5.539	5.635	7	7
$^{58}Fe(n,np+d)^{57}Mn$	1.45 m	-9.729, -11.953	9.898, 12.161	0.9742	27
Copper					
$^{63}Cu(n,2n)^{62}Cu$	9.74 m	-10.852	11.026	530.7	500
$^{63}Cu(n,\alpha)^{60m}Co$	10.47 m	1.656	-	20.15	20
$^{65}Cu(n,\alpha)^{62}Co$	1.5 m	-0.192	0.195	13.61	4.8
$^{65}Cu(n,\alpha)^{62m}Co$	13.91 m	-0.214	0.217	6.98	14
$^{65}Cu(n,\gamma)^{66}Cu$	5.10 m	7.065	-	0.4731	6
Vanadium					
$^{51}V(n,\gamma)^{52}V$	3.75 m	7.310	-	0.606	0.6
$^{51}V(n,p)^{51}Ti$	5.76 m	-1.691	1.724	29.6	42
$^{50}V(n,n\alpha)^{46m}Sc$	18.70 s	-10.028	10.231	6.5×10^{-4}	-
Silicon					
$^{28}Si(n,p)^{28}Al$	2.2406 m	-3.859	3.998	258.4	500
$^{28}Si(n,2p)^{27}Mg$	9.462 m	-13.413	13.896	2.03×10^{-7}	-
$^{29}Si(n,p)^{29}Al$	6.56 m	-2.898	2.999	140.4	130
$^{29}Si(n,np+d)^{28}Al$	2.2406 m	-10.109, -12.333	10.461, 12.762	13.893	-

Table 2 (Continued):

Reaction	$t_{1/2}$[a]	Q (MeV)[b]	E_{thresh} (MeV)[c]	σ_{ADL} (mbarn)[d]	σ_{BNL} (mbarn)[e]
$^{30}Si(n,p)^{30}Al$	3.68 s	-7.761	8.022	79.5	5
$^{30}Si(n,np+d)^{29}Al$	6.56 m	-11.283, -13.507	11.663, 13.962	3.554	-
$^{30}Si(n,\alpha)^{27}Mg$	9.462 m	-4.200	4.341	80.8	40
Titanium					
$^{46}Ti(n,p)^{46m}Sc$	18.70 s	-1.728	1.766	60.9	66
$^{47}Ti(n,np+d)^{46m}Sc$	18.70 s	-8.381, -10.605	8.561, 10.833	13.6	6.9
$^{50}Ti(n,\gamma)^{51}Ti$	5.76 m	6.371	-	0.7101	0.7
$^{50}Ti(n,p)^{50}Sc$	1.710 m	-6.107	6.238	17.5	16
Chromium					
$^{52}Cr(n,p)^{52}V$	3.75 m	-3.194	3.256	73.3	130
$^{53}Cr(n,p)^{53}V$	1.61 m	-2.654	2.705	44.1	40
$^{53}Cr(n,np+d)^{52}V$	3.75 m	-8.909, 11.133	9.079, 11.345	14.2	7.6
$^{54}Cr(n,\gamma)^{55}Cr$	3.497 m	6.246	-	1.0	-
$^{54}Cr(n,p)^{54}V$	49.8 s	-6.259	6.376	13.96	15
$^{54}Cr(n,np+d)^{53}V$	1.61 m	-10.149, -12.373	10.339, 12.604	0.68	1.6
$^{54}Cr(n,\alpha)^{51}Ti$	5.76 m	-1.557	1.586	11.94	11
Manganese					
$^{55}Mn(n,p)^{55}Cr$	3.497 m	-1.821	1.854	44.95	108
$^{55}Mn(n,\alpha)^{52}V$	3.75 m	-0.623	0.634	25.7	57
$^{55}Mn(n,^{3}He)^{53}V$	1.61 m	-12.722	12.956	-	0.8
Nickel					
$^{60}Ni(n,p)^{60m}Co$	10.47 m	-2.101	2.136	94.4	130
$^{61}Ni(n,np+d)^{60m}Co$	10.47 m	-7.697, -9.921	7.824, 10.085	21.36	3
$^{62}Ni(n,p)^{62}Co$	1.50 m	-4.540	4.614	36.2	15
$^{62}Ni(n,p)^{62m}Co$	13.91 m	-4.562	4.636	16.04	22

Table 2 (Continued):

Reaction	$t_{1/2}$[a]	Q (MeV)[b]	E_{thresh} (MeV)[c]	σ_{ADL} (mbarn)[d]	σ_{BNL} (mbarn)[e]
$^{64}Ni(n,p)^{64}Co$	0.300 s	-6.525	6.628	3.16	-
$^{64}Ni(n,np+d)^{63}Co$	27.4 s	-10.324, -12.548	10.487, 12.746	0.071	4
$^{64}Ni(n,\alpha)^{61}Fe$	5.98 m	-2.532	2.572	6.15	11
Tungsten					
$^{180}W(n,2n)^{179m}W$	6.4 m	-8.634	8.682	72.3	0.49
$^{182}W(n,\gamma)^{183m}W$	5.15 s	5.881	-	2.73	-
$^{182}W(n,p)^{182m}Ta$	15.84 m	-1.552	1.561	0.149	3.5
$^{183}W(n,np+d)^{182m}Ta$	15.84 m	-5.518, -7.742	5.548, 7.785	0.00299	-
$^{184}W(n,\gamma)^{185m}W$	1.67 m	5.558	-	4.2	-
$^{186}W(n,p)^{186}Ta$	10.5 m	-3.113	3.130	1.471	2
$^{186}W(n,2n)^{185m}W$	1.67 m	-7.390	7.430	1241	600
COOLANTS					
Lithium					
$^{6}Li(n,p)^{6}He$	0.8067 s	-2.725	3.182	8.64	-
$^{7}Li(n,\gamma)^{8}Li$	0.838 s	1.211	-	5×10^{-3}	-
Oxygen					
$^{16}O(n,p)^{16}N$	7.13 s	-9.637	10.245	40.6	35
$^{17}O(n,p)^{17}N$	4.173 s	-7.898	8.367	48.21	5
$^{18}O(n,\gamma)^{19}O$	26.91 s	3.957	-	1.11	< 0.050
$^{18}O(n,p)^{18}N$	0.630 s	-13.117	13.852	2.3	2.3
$^{18}O(n,\alpha)^{15}C$	2.449 s	-5.008	5.289	21.8	7
NEUTRON MULTIPLIERS AND BREEDERS					
Beryllium					
$^{9}Be(n,\alpha)^{6}He$	0.8067 s	-0.598	0.665	10	10

Table 2 (Continued):

Reaction	$t_{1/2}$[a]	Q (MeV)[b]	E_{thresh} (MeV)[c]	σ_{ADL} (mbarn)[d]	σ_{BNL} (mbarn)[e]
Lead					
$^{204}Pb(n,2n)^{203m}Pb$	6.3 s	-9.218	9.264	889.2	2300
$^{206}Pb(n,\gamma)^{207m}Pb$	0.796 s	5.105	-	0.265	-
$^{206}Pb(n,2p)^{205}Hg$	5.2 m	-8.004	8.043	2.3×10^{-12}	-
$^{206}Pb(n,p)^{206m}Tl$	3.76 m	-3.392	3.409	0.296	2
$^{206}Pb(n,p)^{206}Tl$	4.20 m	-0.749	0.753	1.48	2
$^{207}Pb(n,p)^{207m}Tl$	1.33 s	-1.993	2.003	1.4	1.6
$^{207}Pb(n,p)^{207}Tl$	4.77 s	-0.645	0.648	1.4	1.6
$^{207}Pb(n,2p)^{206}Hg$	8.15 m	-8.014	8.053	1.9×10^{-13}	-
$^{207}Pb(n,n')Pb^{207m}$	0.796 s	-1.633	1.641	81.85	200
$^{208}Pb(n,p)^{208}Tl$	3.053 m	-4.216	4.236	0.554	0.5
$^{208}Pb(n,\alpha)^{205}Hg$	5.2 m	6.187	-	0.471	1.6

[a] Half life of reaction product. From Ref. BF86.
[b] Reaction Q-value. From Ref. Tul90.
[c] Reaction neutron-energy threshold.
[d] σ_{ADL} : Cross sections ≈ 14 MeV from Ref. Gru+93.
[e] σ_{BNL} : Cross sections ≈ 14 MeV from Ref. MDR88.

Table 3: List of Priority 1 Reactions with Comments

Reaction	Isot. Abund.[a]	Half Life[b]	Comments
Aluminum			
1: $^{27}Al(n,p)^{27}Mg$	100%	9.462 m	Very abundant isotope. Reasonable cross section at 14 MeV. Reasonably low threshold.
Beryllium			
2: $^{9}Be(n,\alpha)^{6}He$	100%	0.8067 s	Very abundant isotope. Moderate cross section at 14 MeV. Very active reaction product. Potential decay-heat problem.
Chromium			
3: $^{52}Cr\ (n,p)^{52}V$	83.79%	3.75 m	Abundant isotope. Large cross section at 14 MeV. Reasonably low threshold.
4: $^{53}Cr(n,p)^{53}V$	9.50%	1.61 m	Modest isotopic abundance. Moderate cross section at 14 MeV. Reasonably low threshold.
Copper			
5: $^{63}Cu(n,2n)^{62}Cu$	69.17%	9.74 m	High threshold. Very large cross section at 14 MeV. Abundant isotope.
6: $^{63}Cu(n,\alpha)^{60m}Co$	69.17%	10.47 m	Relatively low effective threshold. Moderate cross section at 14 MeV. Abundant isotope. A possible decay-heat problem. Decay of ^{60m}Co leads to ^{60}Co.
7: $^{65}Cu(n,\alpha)^{62m}Co$	30.83%	13.91 m	Abundant isotope. Moderate cross section at 14 MeV.
Iron			
8: $^{57}Fe(n,p)^{57}Mn$	2.1%	1.45 m	Small isotopic abundance but large cross section at 14 MeV. Low threshold. Most significant reaction of elemental Fe.

Table 3 (Continued):

Reaction	Isot. Abund.[a]	Half Life[b]	Comments
Manganese			
9: $^{55}Mn(n,\alpha)^{52}V$	100%	3.75 m	Very abundant isotope. Moderate cross section at 14 MeV. Reasonably low threshold.
10: $^{55}Mn(n,p)^{55}Cr$	100%	3.497 m	Very abundant isotope. Moderate cross section at 14 MeV. Reasonably low threshold.
Nickel			
11: $^{60}Ni(n,p)^{60m}Co$	26.223%	10.47 m	Moderate isotopic abundance. Large cross section at 14 MeV. Potential decay-heat problem. ^{60m}Co decays to ^{60}Co.
Oxygen			
12: $^{16}O(n,p)^{16}N$	99.761%	7.13 s	Highly radioactive! Very abundant isotope. Moderate cross section at 14 MeV. High threshold but cross section increases rapidly above threshold due to a resonance. Clearly very important for fusion.
Lead			
13: $^{204}Pb(n,2n)^{203m}Pb$	1.4%	6.3 s	Small isotopic abundance. Very large cross section at 14 MeV.
14: $^{207}Pb(n,n')^{207m}Pb$	22.1%	0.796 s	Moderate isotopic abundance. Large cross section at 14 MeV. Low threshold. Only (n,n') reaction in this table.
Silicon			
15: $^{28}Si(n,p)^{28}Al$	92.23%	2.2406 m	Abundant isotope. Reasonable cross section at 14 MeV. Reasonably low threshold.
16: $^{29}Si(n,p)^{29}Al$	4.67%	6.56 m	Small isotopic abundance. Large cross section at 14 MeV. Reasonably low threshold.

Table 3 (Continued):

Reaction	Isot. Abund.[a]	Half Life[b]	Comments
Titanium			
17: $^{46}Ti(n,p)^{46m}Sc$	8.0%	18.70 s	Small isotopic abundance. Moderate cross section at 14 MeV. Reasonably low threshold. Most significant reaction of elemental Ti.
Vanadium			
18: $^{51}V(n,p)^{51}Ti$	99.750%	5.76 m	Very abundant isotope. Moderate cross section at 14 MeV.
Tungsten			
19: $^{186}W(n,2n)^{185m}W$	28.6%	1.67 m	Moderate isotopic abundance. Large cross section at 14 MeV. Very radioactive reaction product.

[a] Isotopic abundance in the natural element. From Ref. Tul90.
[b] Half life of reaction product. From Ref. BF86.

Table 4: List of Priority 2 Reactions with Comments

Reaction	Isot. Abund.[a]	Half Life[b]	Comments
Iron			
$^{54}Fe(n,2n)^{53}Fe$	5.9%	8.51 m	Small isotopic abundance. High threshold. Small cross section at 14 MeV.
Copper			
$^{65}Cu(n,\gamma)^{66}Cu$	30.83%	5.10 m	Moderate isotopic abundance. Small cross section at 14 MeV.
$^{65}Cu(n,\alpha)^{62}Co$	30.83%	1.5 m	Moderate isotopic abundance. Relatively low threshold. Small cross section.
Silicon			
$^{30}Si(n,\alpha)^{27}Mg$	3.10%	9.462 m	Low isotopic abundance. Moderate cross section.
$^{30}Si(n,p)^{30}Al$	3.10%	3.68 s	Low isotopic abundance. Small cross section.
Vanadium			
$^{51}V(n,\gamma)^{52}V$	99.750%	3.75 m	Very abundant isotope. Small cross section at 14 MeV.
Aluminum			
$^{27}Al(n,\gamma)^{28}Al$	100%	2.2406 m	Very abundant isotope. Small cross section at 14 MeV.
Lead			
$^{206}Pb(n,p)^{206m}Tl$	24.1%	3.76 m	Moderate isotopic abundance. Small cross section at 14 MeV.
$^{206}Pb(n,p)^{206}Tl$	24.1%	4.20 m	Moderate isotopic abundance. Small cross section at 14 MeV.

Table 4 (Continued):

Reaction	Isot. Abund.[a]	Half Life[b]	Comments
$^{207}Pb(n,p)^{207m}Tl$	22.1%	1.33 s	Moderate isotopic abundance. Small cross section at 14 MeV.
$^{207}Pb(n,p)^{207}Tl$	22.1%	4.77 m	Moderate isotopic abundance. Small cross section at 14 MeV.
$^{208}Pb(n,p)^{208}Tl$	52.4%	3.053 m	Abundant isotope. Small cross section at 14 MeV. Moderately low threshold.
$^{208}Pb(n,\alpha)^{205}Hg$	52.4%	5.2 m	Abundant isotope. Small cross section at 14 MeV. Moderately low threshold.
Titanium			
$^{47}Ti(n,np+d)^{46m}Sc$	7.3%	18.70 s	Low isotopic abundance. High threshold. Small cross section at 14 MeV.
$^{50}Ti(n,\gamma)^{51}Ti$	5.4%	5.76 m	Low isotopic abundance. Small cross section at 14 MeV.
$^{50}Ti(n,p)^{50}Sc$	5.4%	1.710 m	Low isotopic abundance. Small cross section at 14 MeV.
Chromium			
$^{53}Cr(n,np+d)^{52}V$	9.50%	3.75 m	Low isotopic abundance. High threshold. Small cross section at 14 MeV.
$^{54}Cr(n,np+d)^{53}V$	2.365%	1.61 m	Low isotopic abundance. High threshold. Small cross section at 14 MeV.
$^{54}Cr(n,p)^{54}V$	2.365%	49.8 s	Low isotopic abundance. High threshold. Small cross section at 14 MeV.
$^{54}Cr(n,\alpha)^{51}Ti$	2.365%	5.76 m	Low isotopic abundance. High threshold. Small cross section at 14 MeV.

Table 4 (Continued):

Reaction	Isot. Abund.[a]	Half Life[b]	Comments
Manganese			
$^{55}Mn(n,^{3}He)^{53}V$	100%	1.61 m	Very abundant isotope. High threshold. Small cross section at 14 MeV.
Nickel			
$^{61}Ni(n,np+d)^{60m}Co$	1.140%	10.47 m	Low isotopic abundance. High threshold. Small cross section at 14 MeV.
$^{62}Ni(n,p)^{62}Co$	3.634%	1.50 m	Low isotopic abundance. Moderate cross section at 14 MeV.
$^{62}Ni(n,p)^{62m}Co$	3.634%	13.91 m	Low isotopic abundance. Moderate cross section at 14 MeV.
Tungsten			
$^{182}W(n,p)^{182m}Ta$	26.3%	15.84 m	Moderate isotopic abundance. Small cross section.
$^{182}W(n,\gamma)^{183m}W$	26.3%	5.15 s	Moderate isotopic abundance. Small cross section.
$^{184}W(n,\gamma)^{185m}W$	30.7%	1.67 m	Moderate isotopic abundance. Small cross section.
$^{186}W(n,p)^{186}Ta$	28.6%	10.5 m	Moderate isotopic abundance. Small cross section.
Lithium			
$^{6}Li(n,p)^{6}He$	7.5%	0.8067 s	Small isotopic abundance. Moderate cross section. Possible decay-heat problem.

[a] Isotopic abundance in the natural element. From Ref. Tul90.
[b] Half life of reaction product. From Ref. BF86.

Table 5: List of Priority 3 Reactions with Comments

Reaction	Isot. Abund.[a]	Half Life[b]	Comments
Iron			
$^{56}Fe(n,2p)^{55}Cr$	91.72%	3.497 m	Abundant isotope. High threshold. Very small cross section.
$^{58}Fe(n,p)^{58}Mn$	0.28%	1.088 m	Small isotopic abundance. Small cross section at 14 MeV.
$^{58}Fe(n,p)^{58m}Mn$	0.28%	3.0 s	Small isotopic abundance. Small cross section at 14 MeV..
$^{58}Fe(n,np+d)^{57}Mn$	0.28%	1.45 m	Small isotopic abundance. Modest cross section. High threshold.
Vanadium			
$^{50}V(n,n\alpha)^{46m}Sc$	0.250%	18.70 s	Very low isotopic abundance. High threshold. Very small cross section at 14 MeV.
Silicon			
$^{28}Si(n,2p)^{27}Mg$	92.23%	9.462 m	Large isotopic abundance. High threshold. Small cross section at 14 MeV.
$^{29}Si(n,np+d)^{28}Al$	4.67%	2.2406 m	Small isotopic abundance. High threshold. Small cross section at 14 MeV.
$^{30}Si(n,np+d)^{29}Al$	3.10%	6.56 m	Small isotopic abundance. High threshold. Small cross section at 14 MeV.
Lead			
$^{206}Pb(n,\gamma)^{207m}Pb$	24.1%	0.796 s	Moderate isotopic abundance. Small cross section.
$^{206}Pb(n,2p)^{205}Hg$	24.1%	5.2 m	Moderate isotopic abundance. Very small cross section.

Table 5 (Continued):

Reaction	Isot. Abund.[a]	Half Life[b]	Comments
$^{207}Pb(n,2p)^{206}Hg$	22.1%	8.15 m	Moderate isotopic abundance. Very small cross section.
Aluminum			
$^{27}Al(n,2n)^{26m}Al$	100%	6.345 s	Very large isotopic abundance. High threshold. Small cross section at 14 MeV.
Oxygen			
$^{17}O(n,p)^{17}N$	0.038%	4.173 s	Very small isotopic abundance. Moderate cross section.
$^{18}O(n,\gamma)^{19}O$	0.20%	26.91 s	Very small isotopic abundance. Moderate threshold. Small cross section.
$^{18}O(n,p)^{18}N$	0.20%	0.630 s	Very small isotopic abundance. High threshold. Small cross section.
$^{18}O(n,\alpha)^{15}C$	0.20%	2.449 s	Very small isotopic abundance. Small cross section.
Chromium			
$^{54}Cr(n,\gamma)^{55}Cr$	2.365%	3.497 m	Low isotopic abundance. Small cross section.
Nickel			
$^{64}Ni(n,p)^{64}Co$	0.926%	0.300 s	Low isotopic abundance. Small cross section.
$^{64}Ni(n,np+d)^{63}Co$	0.926%	27.4 s	Low isotopic abundance. High threshold. Small cross section.
$^{64}Ni(n,\alpha)^{61}Fe$	0.926%	5.98 m	Low isotopic abundance. Small cross section.

Table 5 (Continued):

Reaction	Isot. Abund.[a]	Half Life[b]	Comments
Tungsten			
$^{180}W(n,2n)^{179m}W$	0.12%	6.4 m	Very small isotopic abundance. Small cross section.
$^{183}W(n,np+d)^{182m}Ta$	14.28%	15.84 m	Moderate isotopic abundance. Small cross section.
Lithium			
$^{7}Li(n,\gamma)^{8}Li$	92.5%	0.838 s	Abundant isotope. Small cross section.

[a] Isotopic abundance in the natural element. From Ref. Tul90.
[b] Half life of reaction product. From Ref. BF86.

Table 6: Radioactive decay data for Priority 1 Reactions

Reaction	$t_{1/2}$[a]	Mode[b]	Avg. E_β[c]	Max E_β[d]	Principle γ-rays E_γ, [B_γ (%)][e]
1: $^{27}Al(n,p)^{27}Mg$	9.462±.011 m	β^-	702	1767	844 [73] 1014 [29.1±.8]
2: $^{9}Be(n,\alpha)^{6}He$	806.7±1.5 ms	β^-	1567	3507	-
3: $^{52}Cr(n,p)^{52}V$	3.75±.01 m	β^-	1068	2542	1434 [100]
4: $^{53}Cr(n,p)^{53}V$	1.61±.04 m	β^-	1005	2430	1006 [90] 1289 [10±2]
5: $^{63}Cu(n,2n)^{62}Cu$	9.74±.02 m	ϵ, β^+	1280	3949	876 [.147±.007] 1173 [.335]
6: $^{63}Cu(n,\alpha)^{60m}Co$	10.47±.04 m	IT, β^-	1.48	1550	59 [2.01]
7: $^{65}Cu(n,\alpha)^{62m}Co$	13.91±.05 m	β^-	1058	3008	1164 [68.1±1.4] 1173 [97.9] 1719 [6.8±.4] 2004 [18.6±.5] 2105 [6.5±.3]
8: $^{57}Fe(n,p)^{57}Mn$	1.45±.03 m	β^-	1100	2677	14 [10.7±.8] 122 [10.8±.4 692 [4.15±.11]
9: $^{55}Mn(n,\alpha)^{52}V$	3.75±.01 m	β^-	1068	2542	1434 [100]
10: $^{55}Mn(n,p)^{55}Cr$	3.497±.003 m	β^-	1101	2603	1528 [.037]
11: $^{60}Ni(n,p)^{60m}Co$	10.47±.04 m	IT, β^-	1.48	1550	59 [2.01]
12: $^{16}O(n,p)^{16}N$	7.13±.02 s	β^-	2693	10419	6129 [68.8] 7115 [4.7±.3]
13: $^{204}Pb(n,2n)^{203m}Pb$	6.3±.2 s	IT	-	-	820 [6.4±.9] 825 [71.5]

Table 6 (Continued):

Reaction	$t_{1/2}$[a]	Mode[b]	Avg. E_β[c]	Max E_β[d]	Principle γ-rays E_γ, [B_γ (%)][e]
14: $^{207}Pb(n,n')^{207m}Pb$	796±2 ms	IT	-	-	569 [98±5] 1063 [89±4]
15: $^{28}Si(n,p)^{28}Al$	2.2406 ±.0005 m	β^-	1242	2863	1779 [100]
16: $^{29}Si(n,p)^{29}Al$	6.56±.06 m	β^-	977	2407	1273 [91.3] 2028 [3.51±.07] 2426 [5.2±.5]
17: $^{46}Ti(n,p)^{46m}Sc$	18.70±.05 s	IT	-	-	143 [62.0]
18: $^{51}V(n,p)^{51}Ti$	5.76±.01 m	β^-	868	2153	321 [93.0] 609 [1.18±.09] 929 [6.9±.4]
19: $^{186}W(n,2n)^{185m}W$	1.67±.03	IT	-	-	66 [5.8±.3] 132 [4.3±.3] 174 [3.29±.11]

[a] Half life of reaction product. From Ref. BF86.
[b] Decay mode: β^- = beta decay; β^+ = positron decay; IT= isomeric transition; ϵ = electron capture. From Ref. BF86.
[c] Average energy of emitted β^- or β^+ particles in keV (where applicable). From Ref. BF86.
[d] End-point (maximum) energy of emitted β^- or β^+ particle spectrum in keV (where applicable). From Ref. BF86.
[e] Dominant gamma rays. E_γ = photon energy in keV; B_γ = photons per decay in percent (i.e., 1 photon/decay ⇒ 100%). From Ref. BF86.

Table 7: Information on cross-section uncertainties at 14 MeV for Priority 1 reactions

Reaction	No. Data Sets	Min. σ	Max. σ	Spread in σ	Max./Min.
$^{27}Al(n,p)^{27}Mg$	6	0.0759	0.0870	0.0111	1.146
$^{9}Be(n,\alpha)^{6}He$	6	0.00941	0.0110	0.00159	1.169
$^{52}Cr(n,p)^{52}V$	5	0.0784	0.089	0.0106	1.135
$^{53}Cr(n,p)^{53}V$	6	0.0297	0.0481	0.0184	1.62
$^{63}Cu(n,2n)^{62}Cu$	4	0.4387	0.5041	0.0654	1.149
$^{63}Cu(n,\alpha)^{60m}Co$	2	0.0234	0.0271	0.0037	1.158
$^{65}Cu(n,\alpha)^{62m}Co$	2	0.0018929	0.0005862	0.0039691	3.097
$^{57}Fe(n,p)^{57}Mn$	6	0.0297	0.0828	0.0531	2.788
$^{55}Mn(n,p)^{55}Cr$	6	0.0309	0.0603	0.0294	1.951
$^{55}Mn(n,\alpha)^{52}V$	6	0.025	0.0326	0.0076	1.304
$^{60}Ni(n,p)^{60m}Co$	2	0.066	0.0725	0.0065	1.098
$^{16}O(n,p)^{16}N$	7	0.0428	0.0471	0.0043	1.100
$^{204}Pb(n,2n)^{203m}Pb$	2	0.8757	1.098	0.2223	1.254
$^{207}Pb(n,n')^{207m}Pb$	2	0.0879	0.192	0.1041	2.184
$^{28}Si(n,p)^{28}Al$	3	0.2301	0.2685	0.0384	1.167
$^{29}Si(n,p)^{29}Al$	3	0.1077	0.1293	0.0216	1.200
$^{46}Ti(n,p)^{46m}Sc$	2	0.0673	0.1591	0.0918	2.364
$^{51}V(n,p)^{51}Ti$	3	0.0296	0.0322	0.0026	1.088
$^{186}W(n,2n)^{185m}W$	2	1.2466	1.9544	0.7078	1.568

Reaction	Average σ	Spread in σ/Average	Std. Dev. in σ	Std. Dev. in σ/Average
$^{27}Al(n,p)^{27}Mg$	0.07898	0.140	0.0039987	0.05065
$^{9}Be(n,\alpha)^{6}He$	0.010485	0.152	0.000661	0.063
$^{52}Cr(n,p)^{52}V$	0.08488	0.125	0.0051	0.0601
$^{53}Cr(n,p)^{53}V$	0.04162	0.442	0.0065895	0.158
$^{63}Cu(n,2n)^{62}Cu$	0.4706	0.139	0.03131	0.0665
$^{63}Cu(n,\alpha)^{60m}Co$	0.02525	0.1465	0.002616	0.1036
$^{65}Cu(n,\alpha)^{62m}Co$	0.003877	1.0236	0.0028065	0.7238
$^{57}Fe(n,p)^{57}Mn$	0.06005	0.884	0.01876	0.312
$^{55}Mn(n,p)^{55}Cr$	0.04341	0.677	0.0104	0.240
$^{55}Mn(n,\alpha)^{52}V$	0.02882	0.0862	0.0027228	0.0945
$^{60}Ni(n,p)^{60m}Co$	0.06925	0.0939	0.0045962	0.1593
$^{16}O(n,p)^{16}N$	0.04458	0.0964	0.00175	0.0393
$^{204}Pb(n,2n)^{203m}Pb$	0.98685	0.2253	0.1572	0.1593
$^{207}Pb(n,n')^{207m}Pb$	0.13995	0.744	0.07361	0.5260
$^{28}Si(n,p)^{28}Al$	0.2501	0.154	0.019246	0.0768

Table 7 (Continued):

Reaction	Average σ	Spread in σ/Average	Std. Dev. in σ	Std. Dev. in σ/Average
$^{29}Si(n,p)^{29}Al$	0.12103	0.178	0.01166	0.0914
$^{46}Ti(n,p)^{46m}Sc$	0.1132	0.811	0.06491	0.5734
$^{51}V(n,p)^{51}Ti$	0.03093	0.084	0.0013013	0.0421
$^{186}W(n,2n)^{185m}W$	1.6005	0.442	0.5005	0.3127

Table 8: Cross sections and ratios at 14 MeV for Priority 1 reactions involving isomer excitations

Reaction	Isomer σ (mb)	Total σ (mb)	Isomer σ / Total σ
$^{63}Cu(n,\alpha)^{60m}Co$, $^{60g+m}Co$	20.15	67.53	0.2984
$^{65}Cu(n,\alpha)^{62m}Co$, $^{62g+m}Co$	6.98	20.59	0.339
$^{60}Ni(n,p)^{60m}Co$, $^{60g+m}Co$	94.44	135.9	0.4098
$^{204}Pb(n,2n)^{203m}Pb$, $^{203g+m}Pb$	889.2	2993	0.2971
$^{207}Pb(n,2n)^{207m}Pb$, $^{207g+m}Pb$	81.85	270.35	0.3027
$^{46}Ti(n,p)^{46m}Sc$, $^{46g+m}Sc$	60.88	294.38	0.2068
$^{186}W(n,2n)^{185m}W$, $^{185g+m}W$	1241	3200	0.388

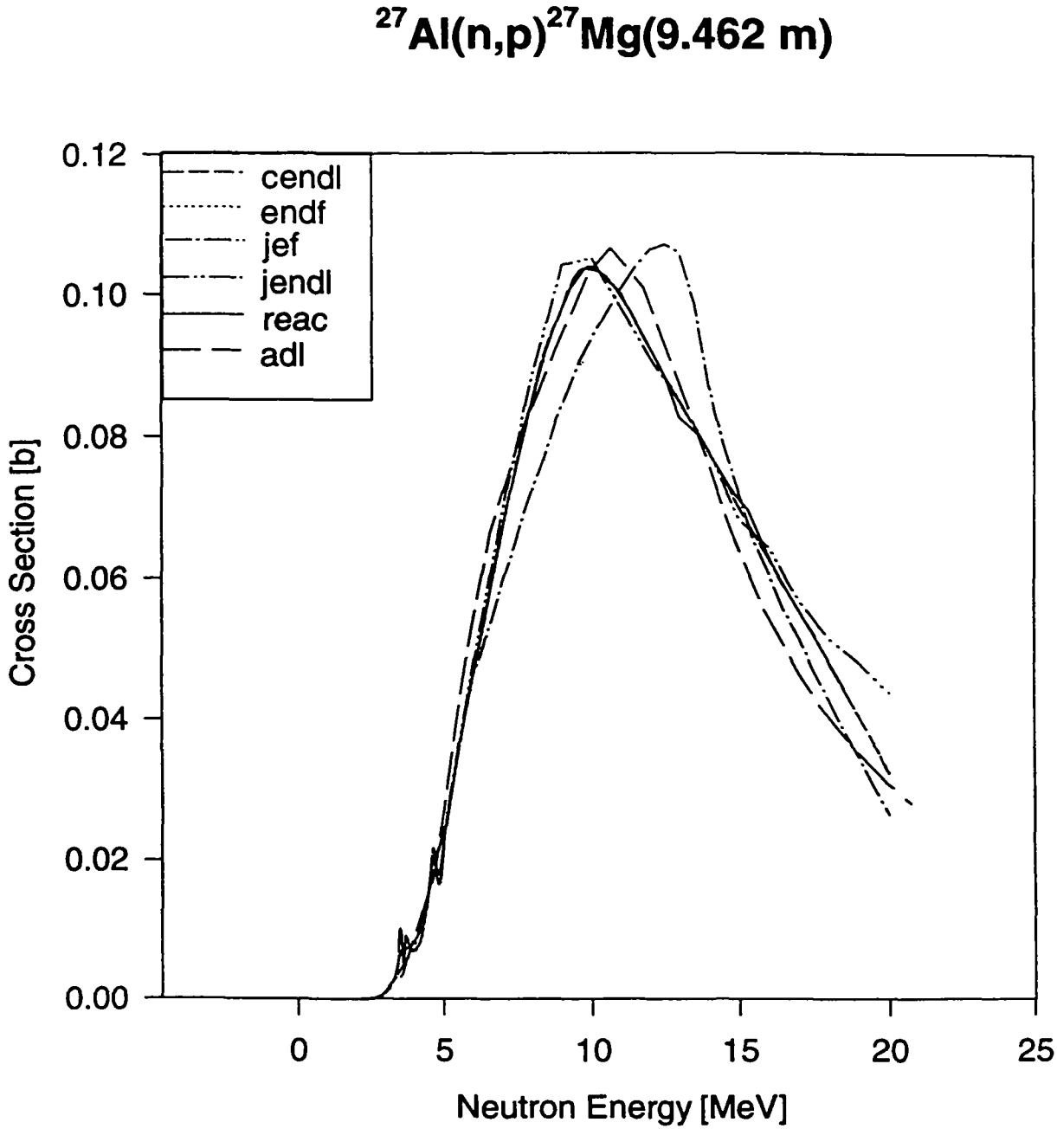

Figure 1.1 Evaluated Data. Note that Cendl and Endf are identical

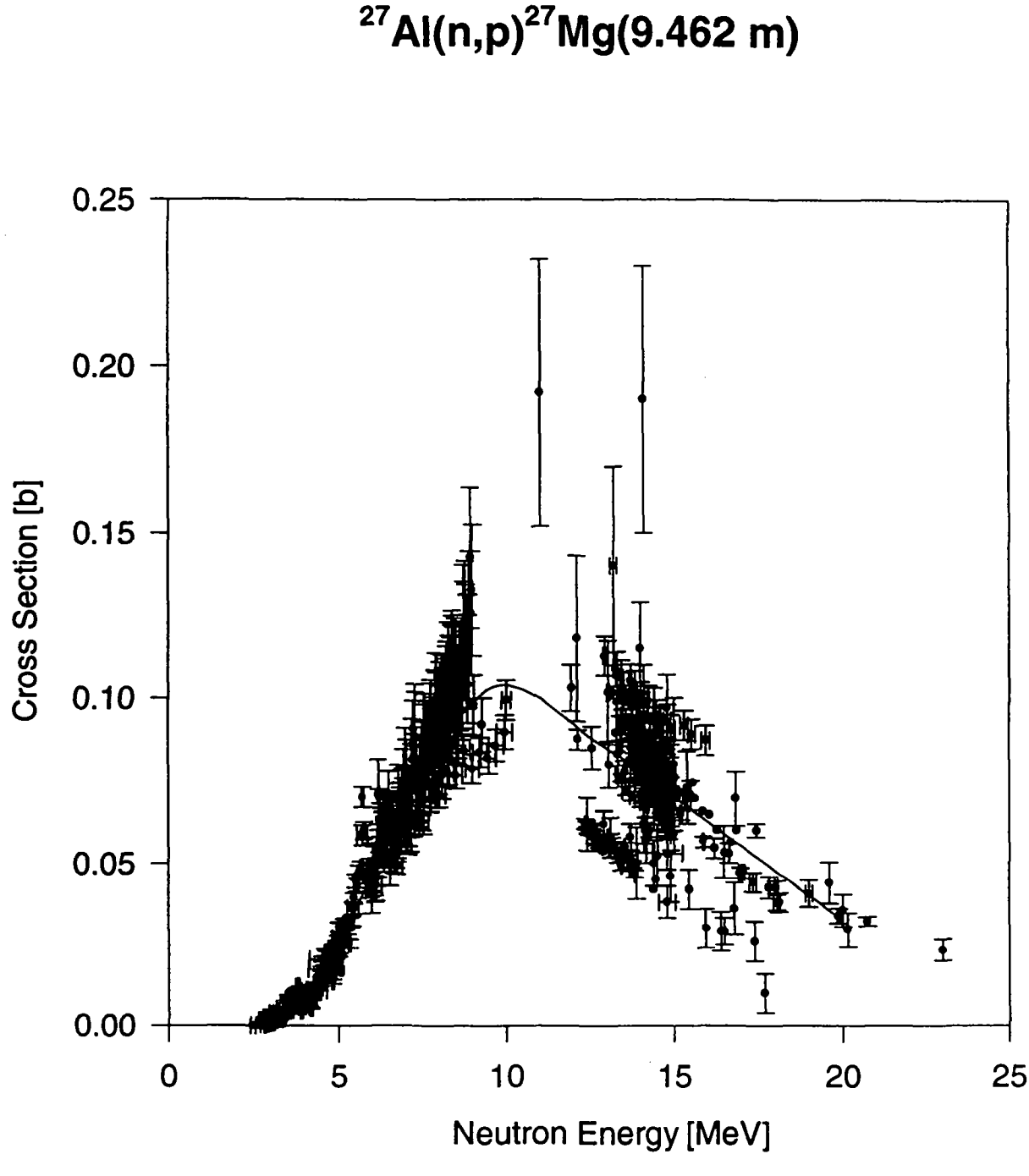

Figure 1.2 Experimental Data plus Endf Evaluated data curve

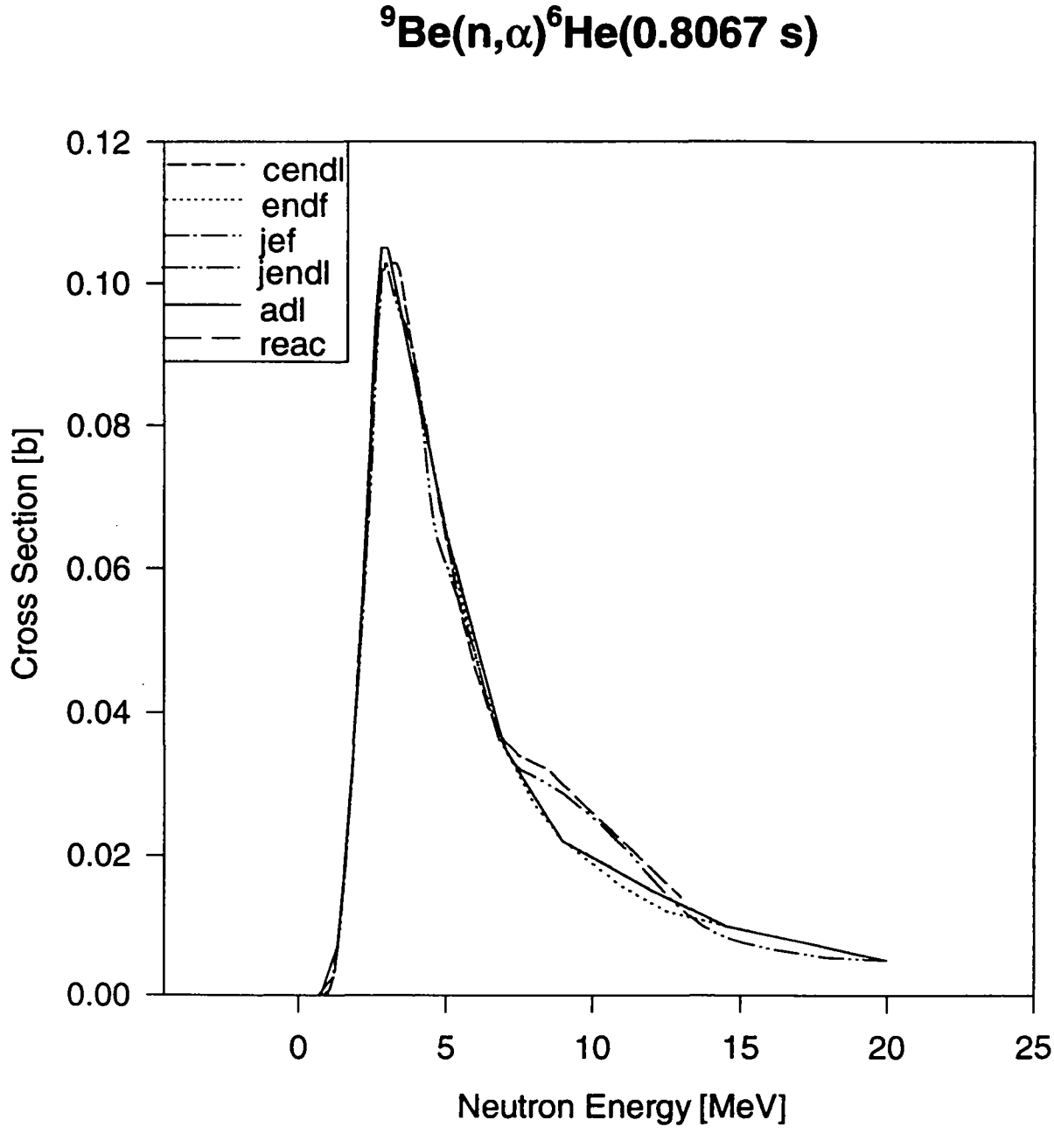

Figure 2.1 Evaluated Data

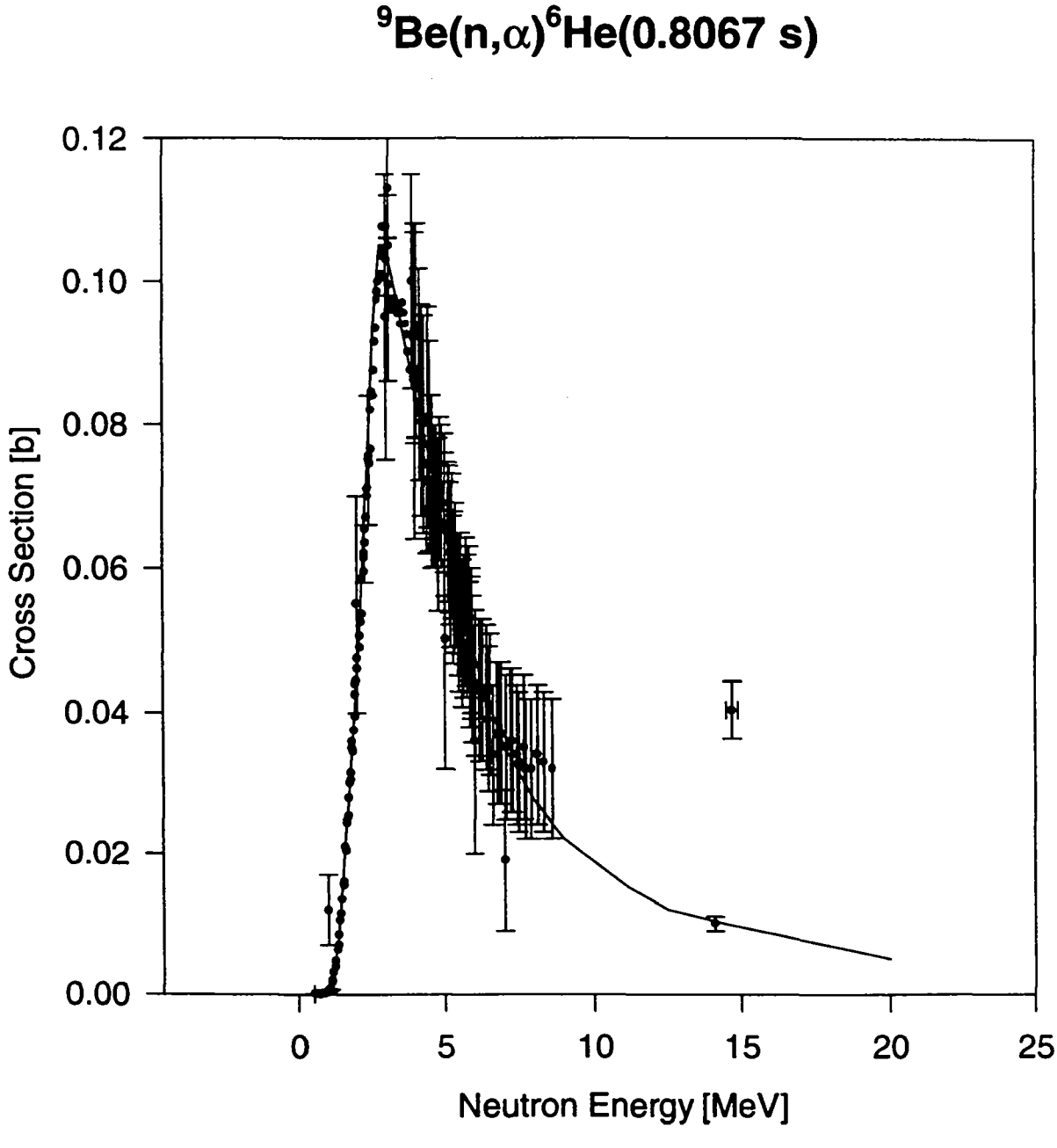

Figure 2.2 Experimental data plus Endf evaluated data curve

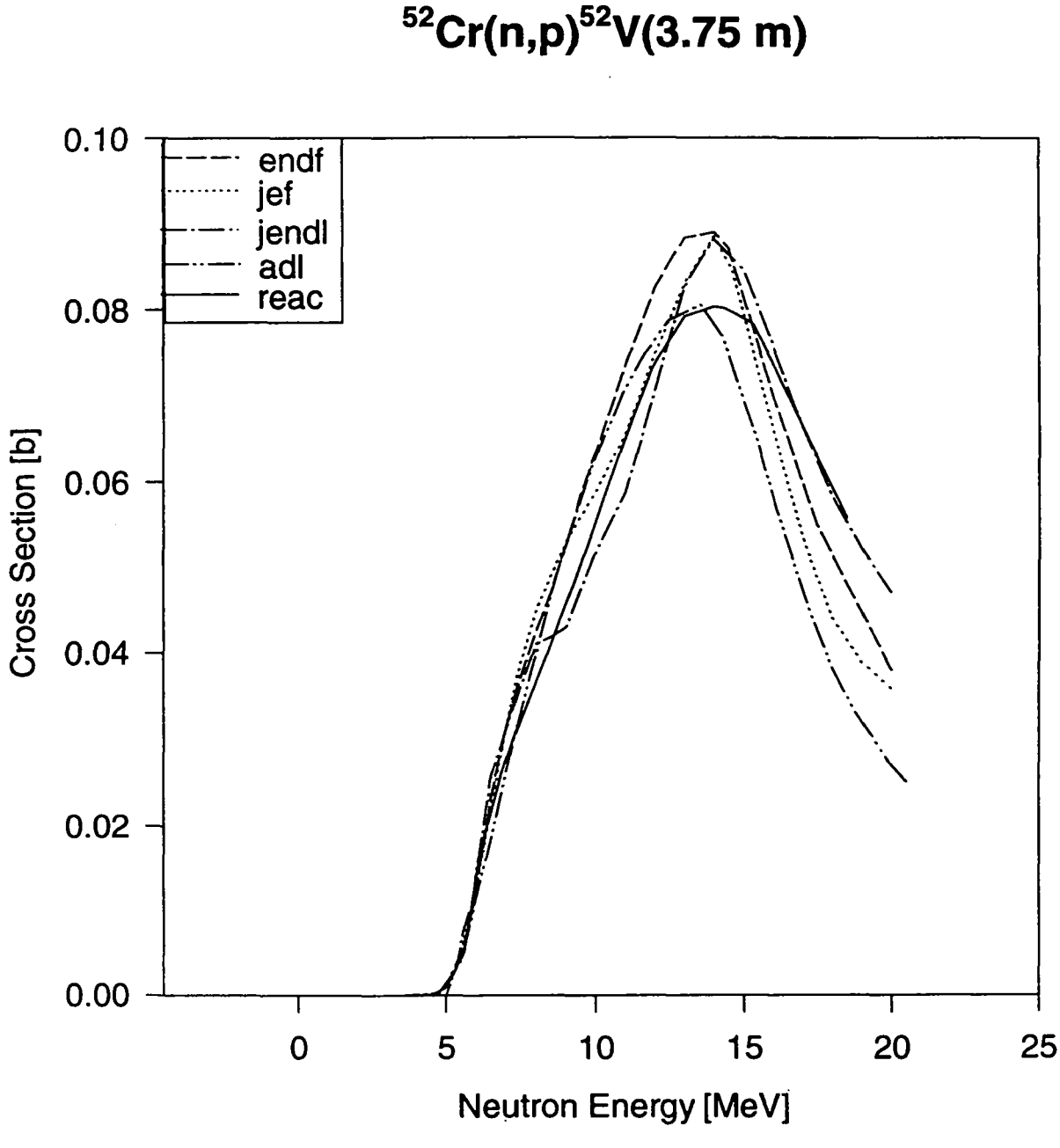

Figure 3.1 Evaluated data

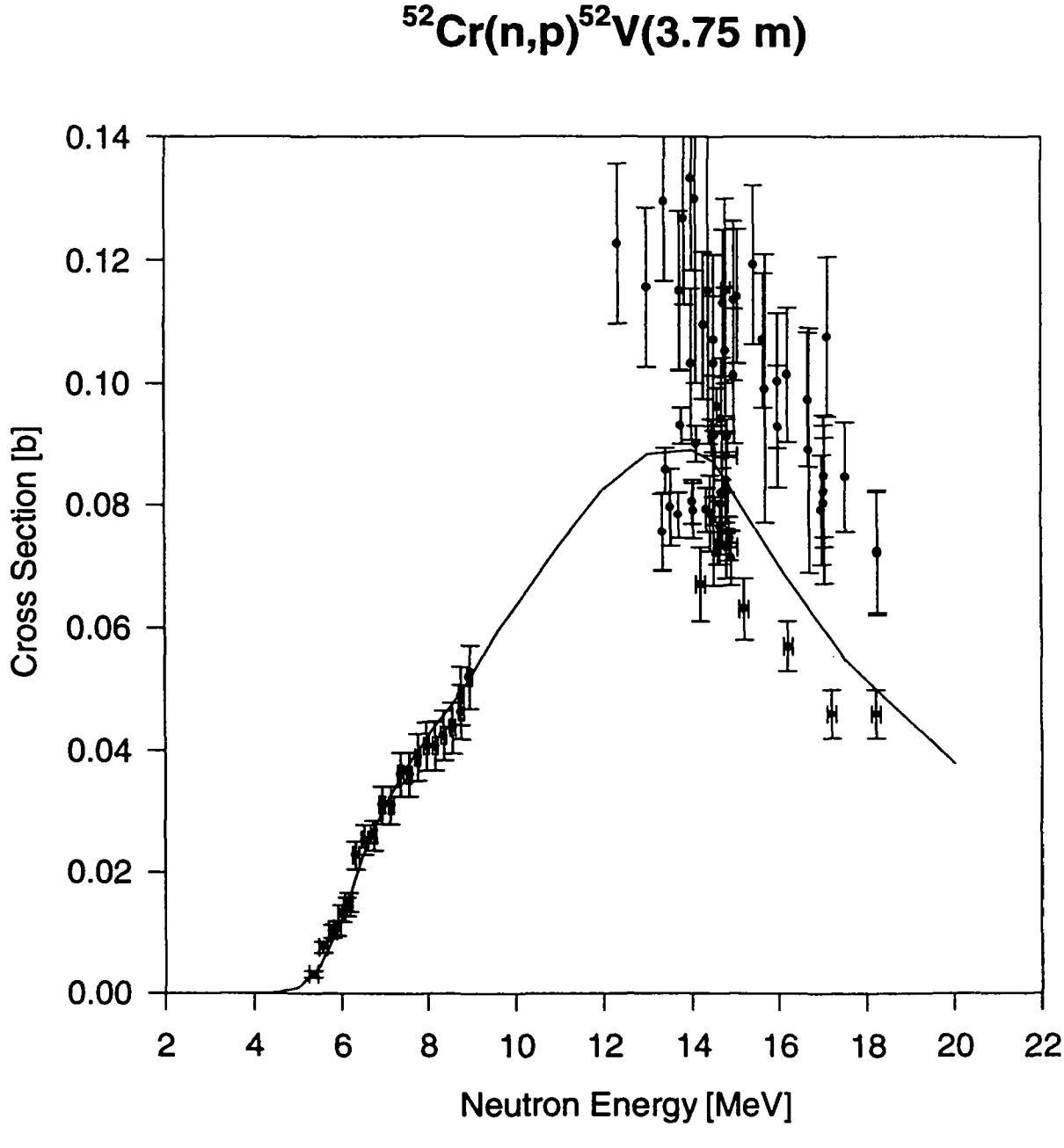

Figure 3.2 Experimental data plus Endf evaluated data curve

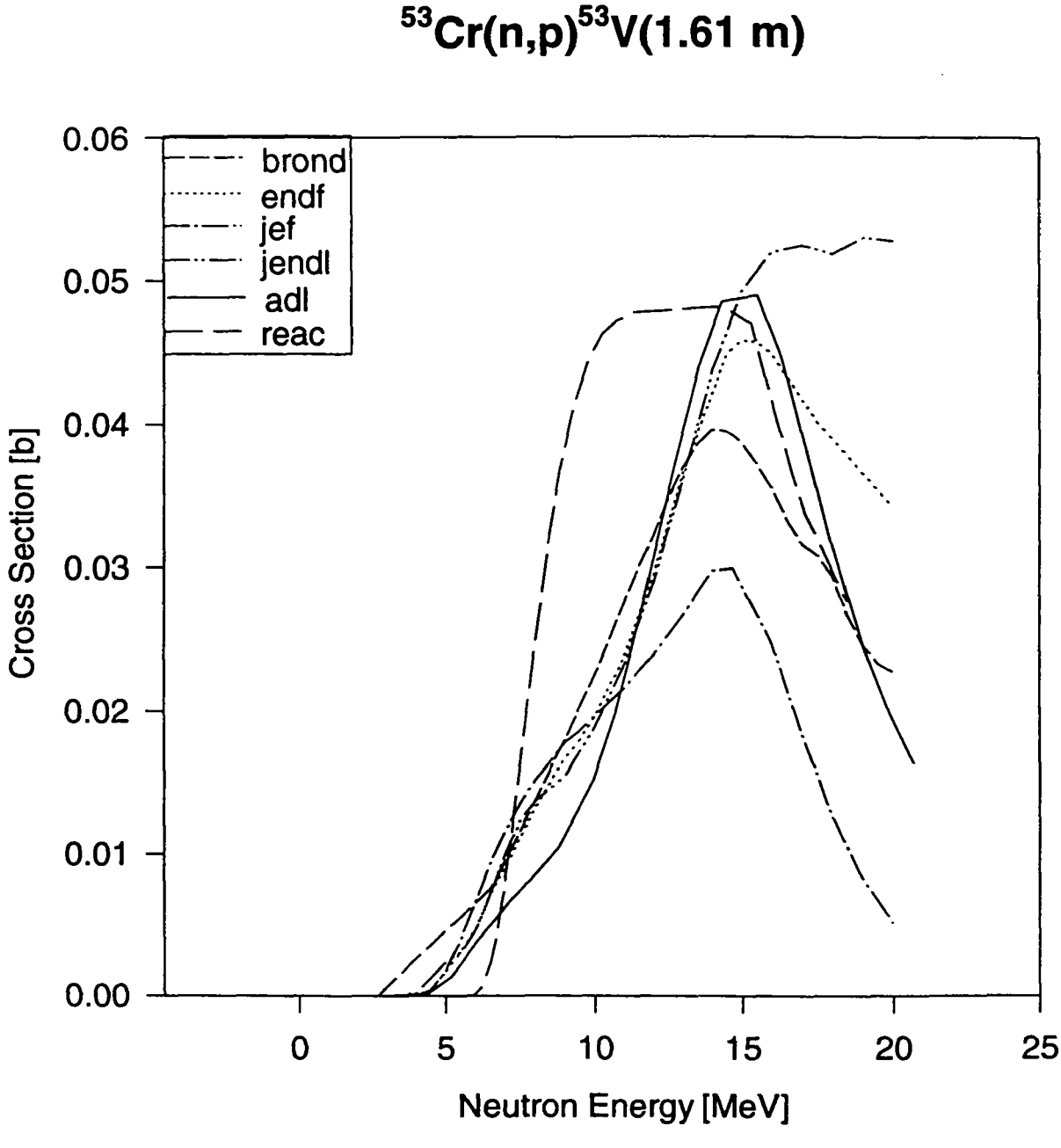

Figure 4.1 Evaluated data

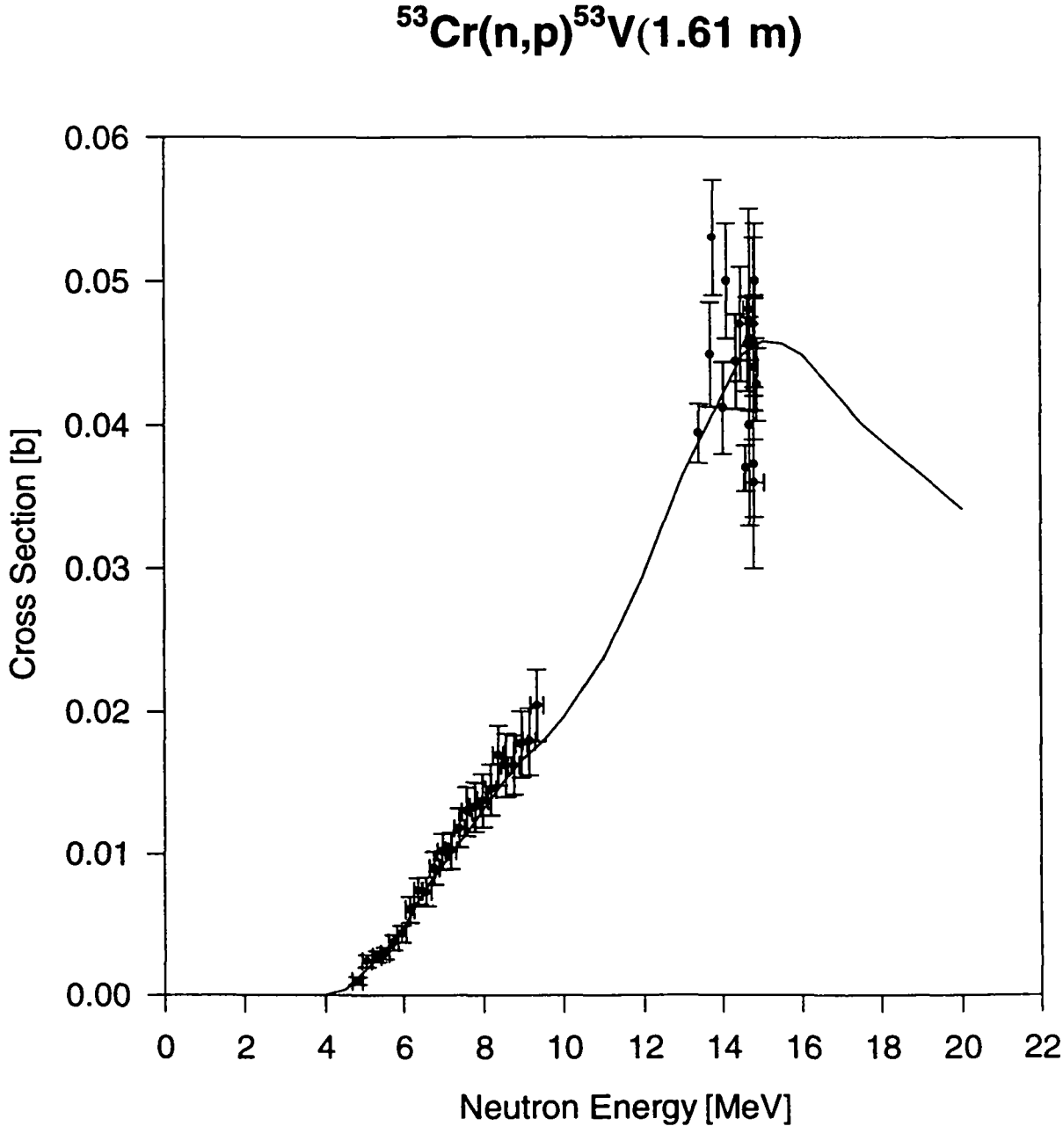

Figure 4.2 Experimental data plus Endf evaluated data curve

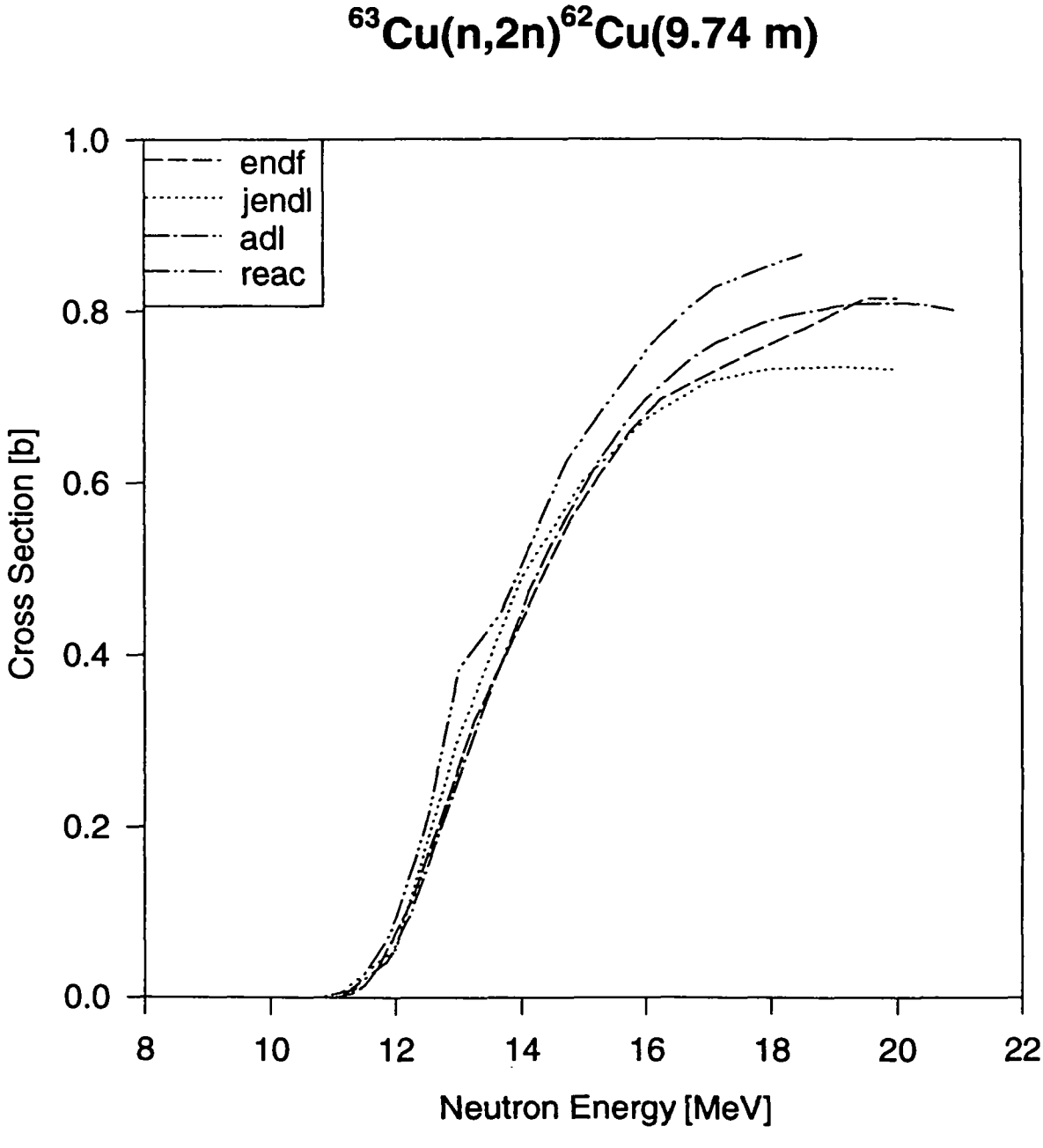

Figure 5.1 Evaluated Data

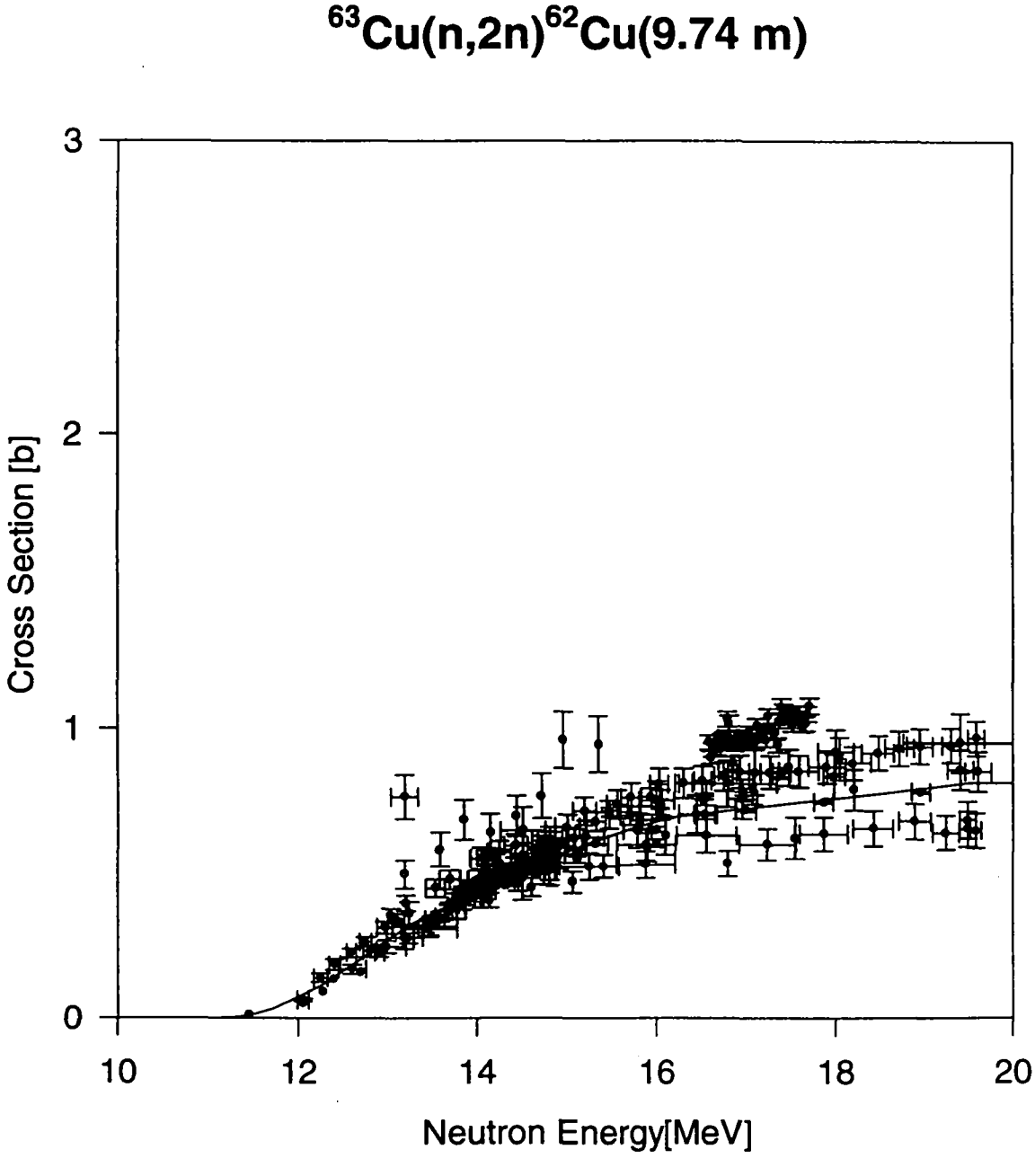

Figure 5.2 Experimental data plus Endf evaluated data curve

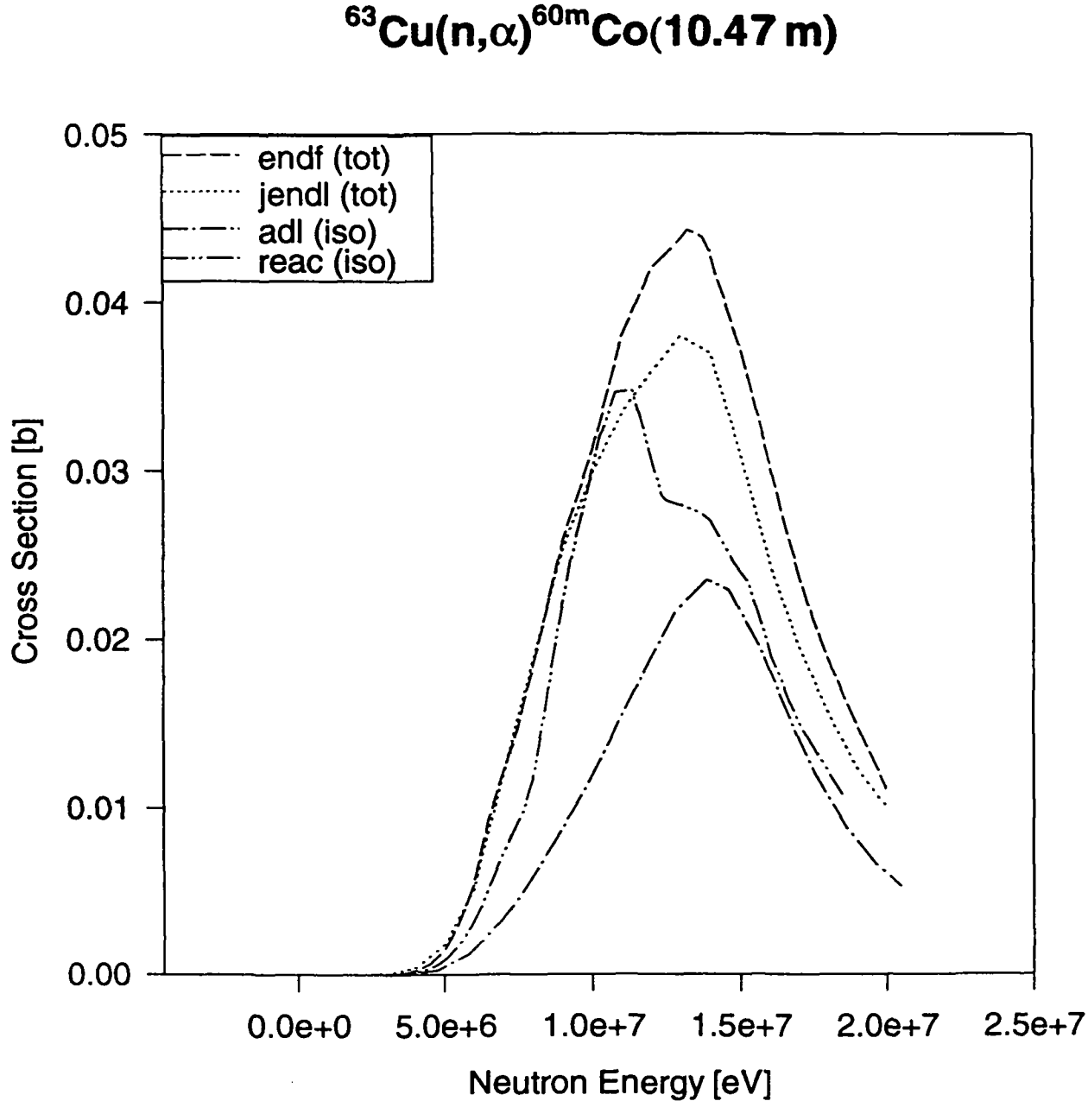

Figure 6.1 Evaluated data. Note that this is an isomer reaction

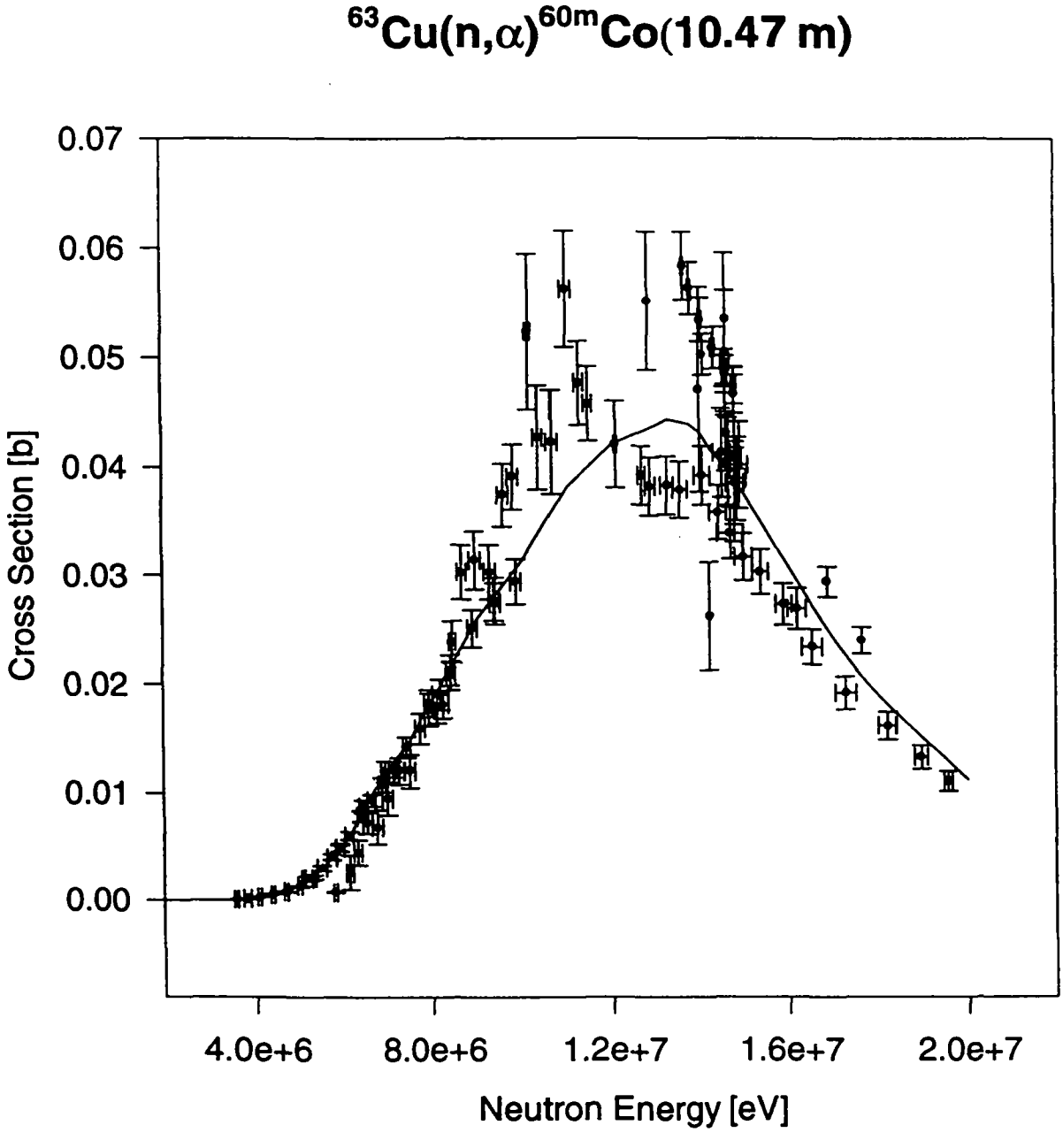

Figure 6.2 "Total" experimental data plus Endf "total" evaluated data curve

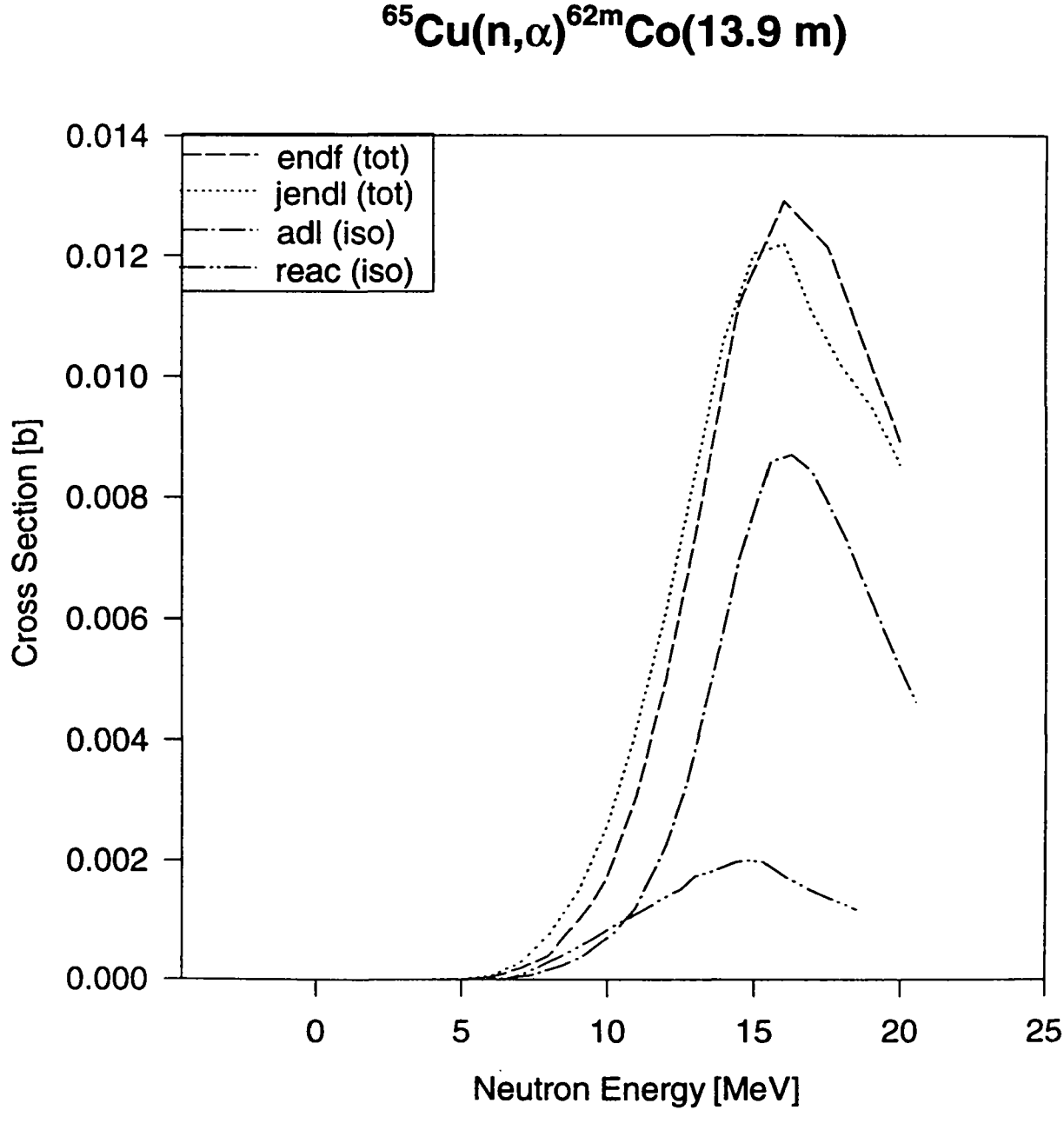

Figure 7.1 Evaluated data. Note that this is an isomer reaction

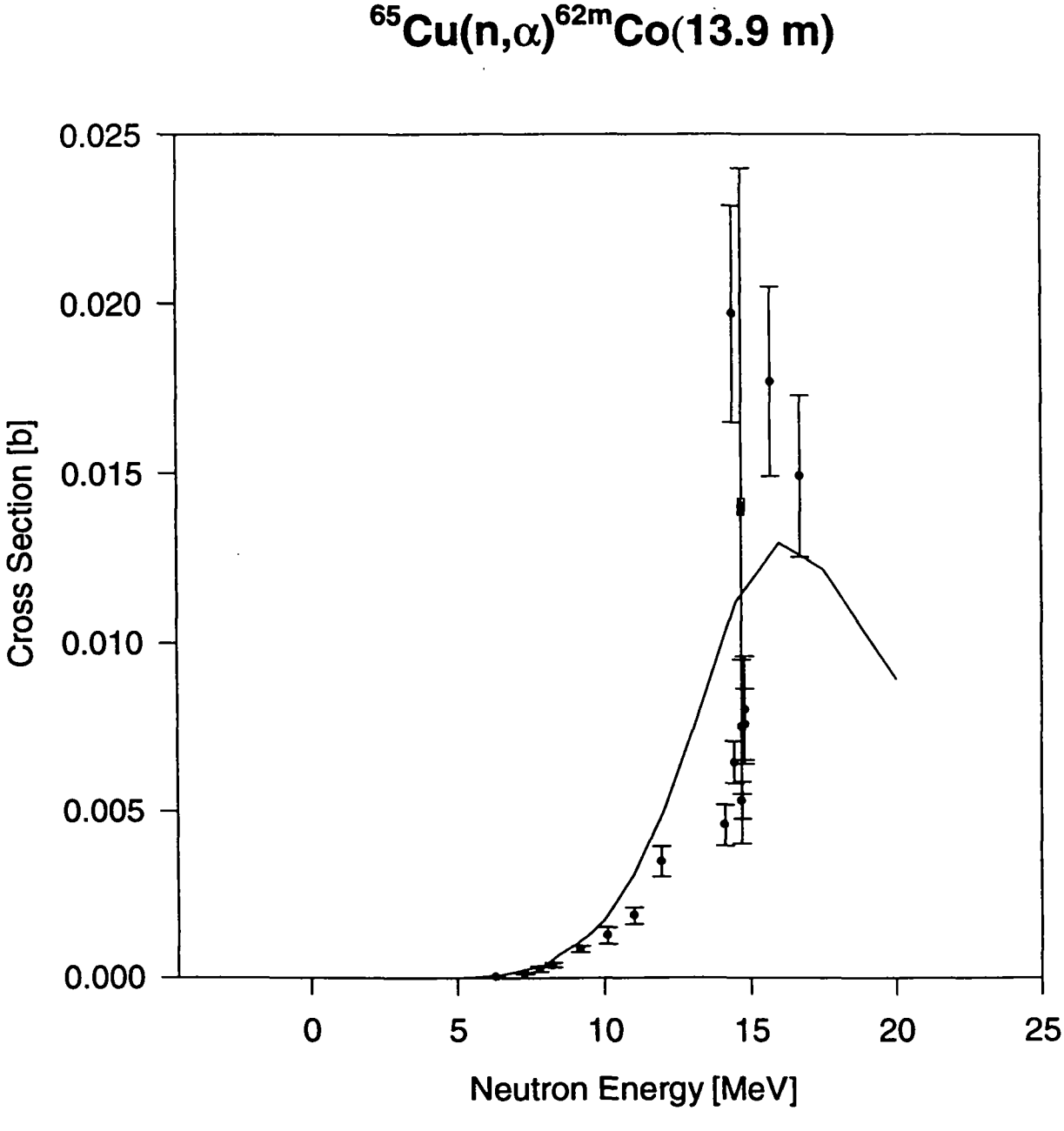

Figure 7.2 "Total" experimental data plus Endf "total" evaluated data curve

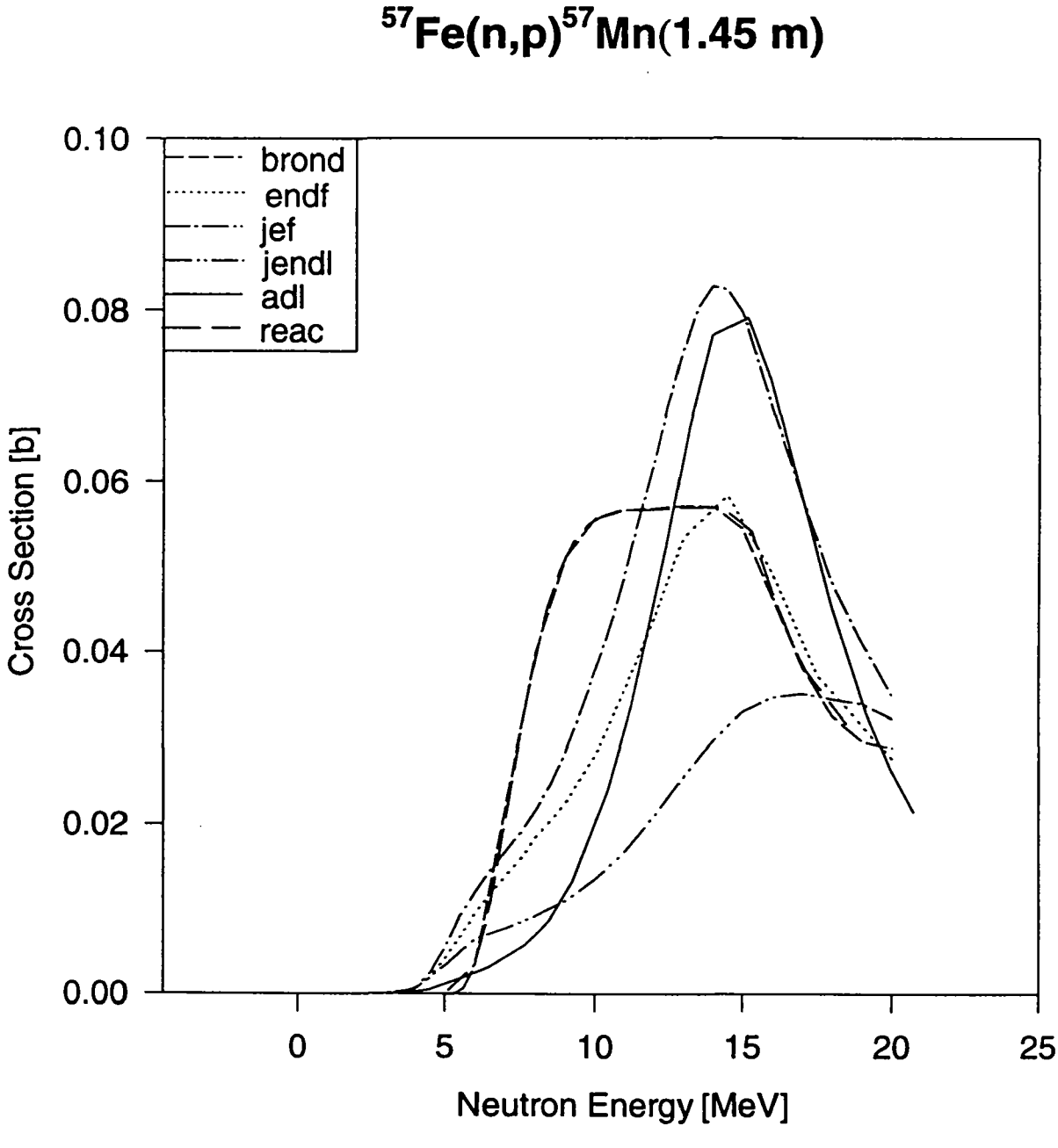

Figure 8.1 Evaluated data. Note that Brond and Reac are similar

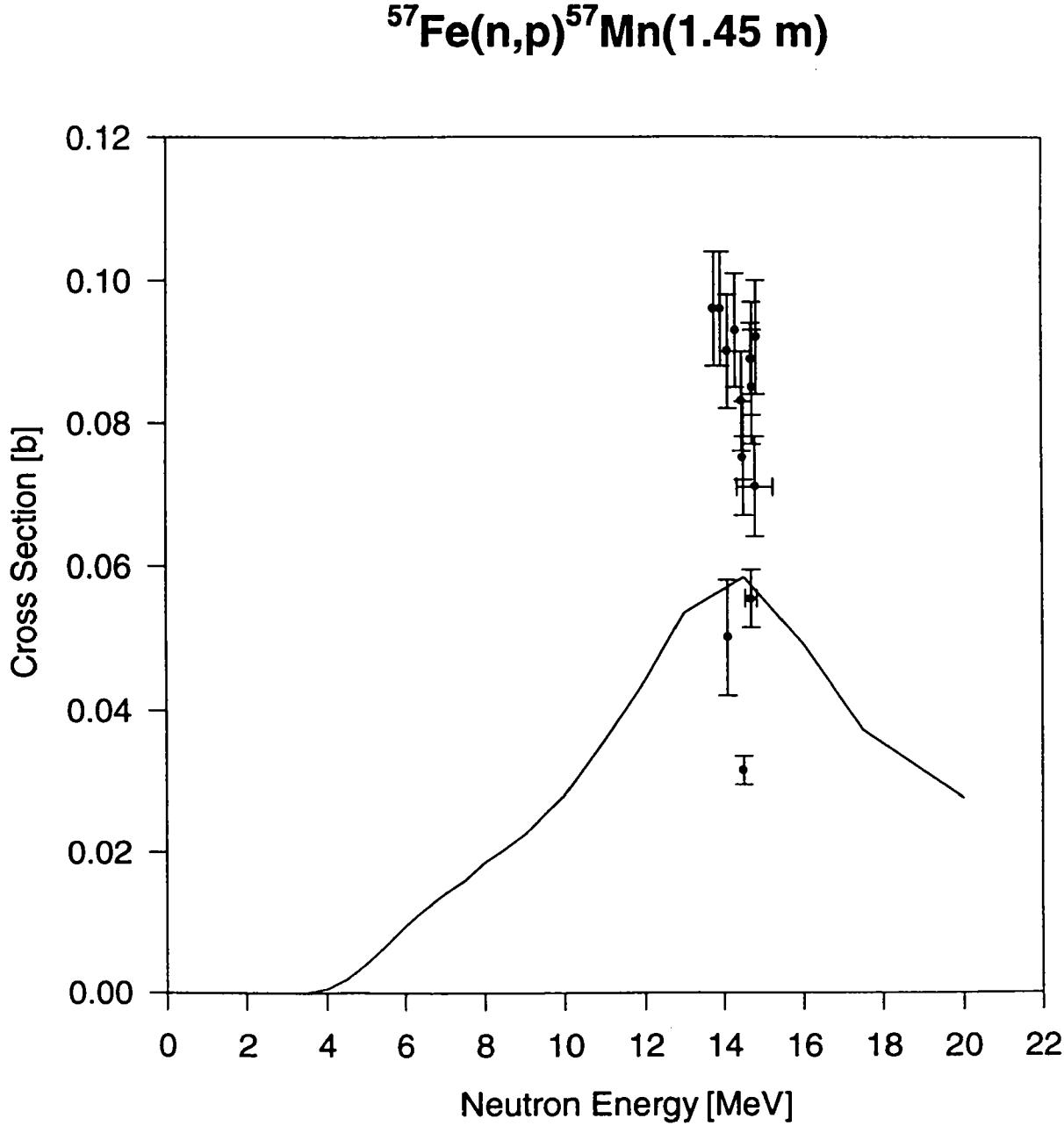

Figure 8.2 Experimental data plus Endf evaluated data curve

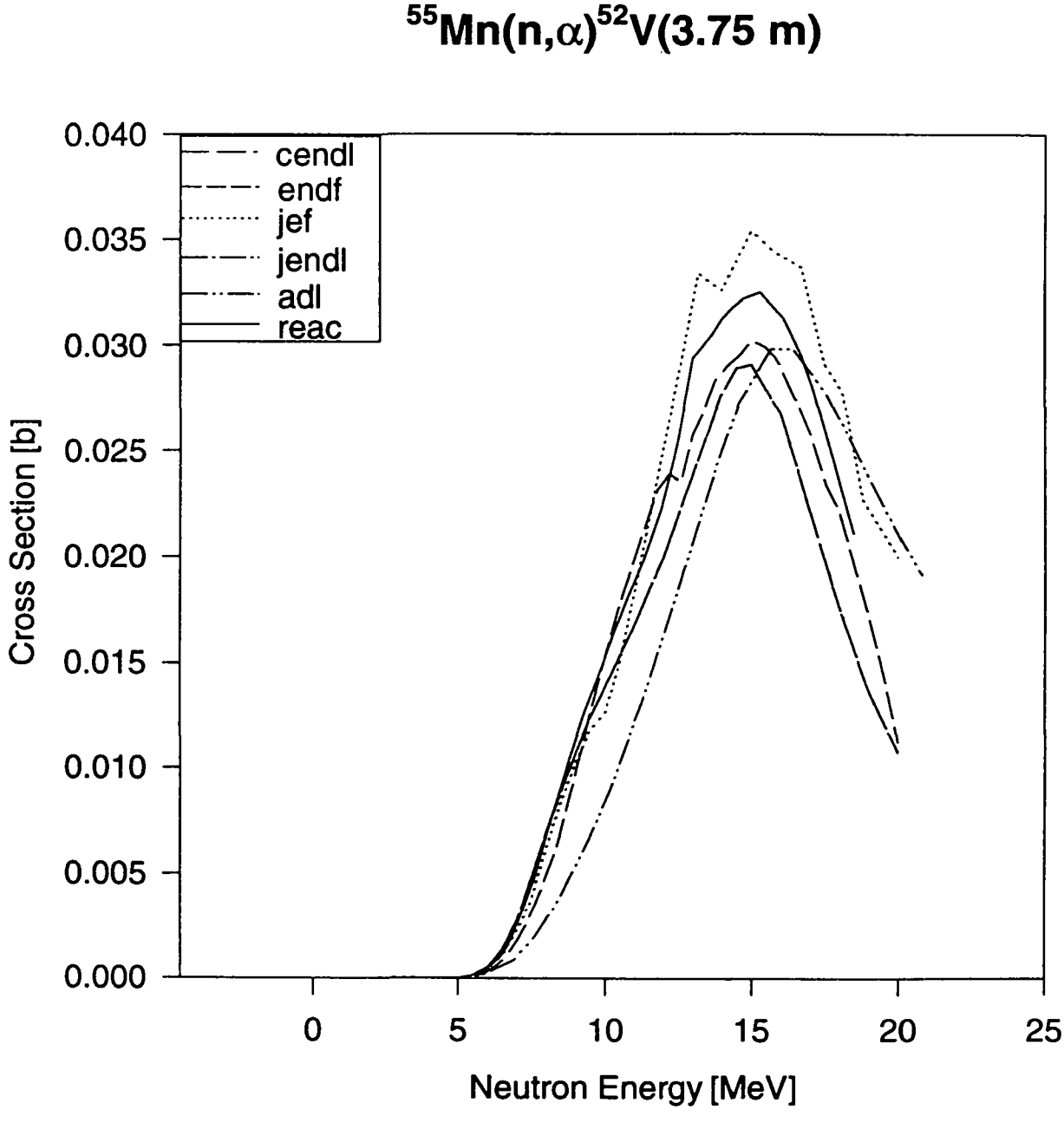

Figure 9.1 Evaluated data. Note that Jendl and Endf are identical

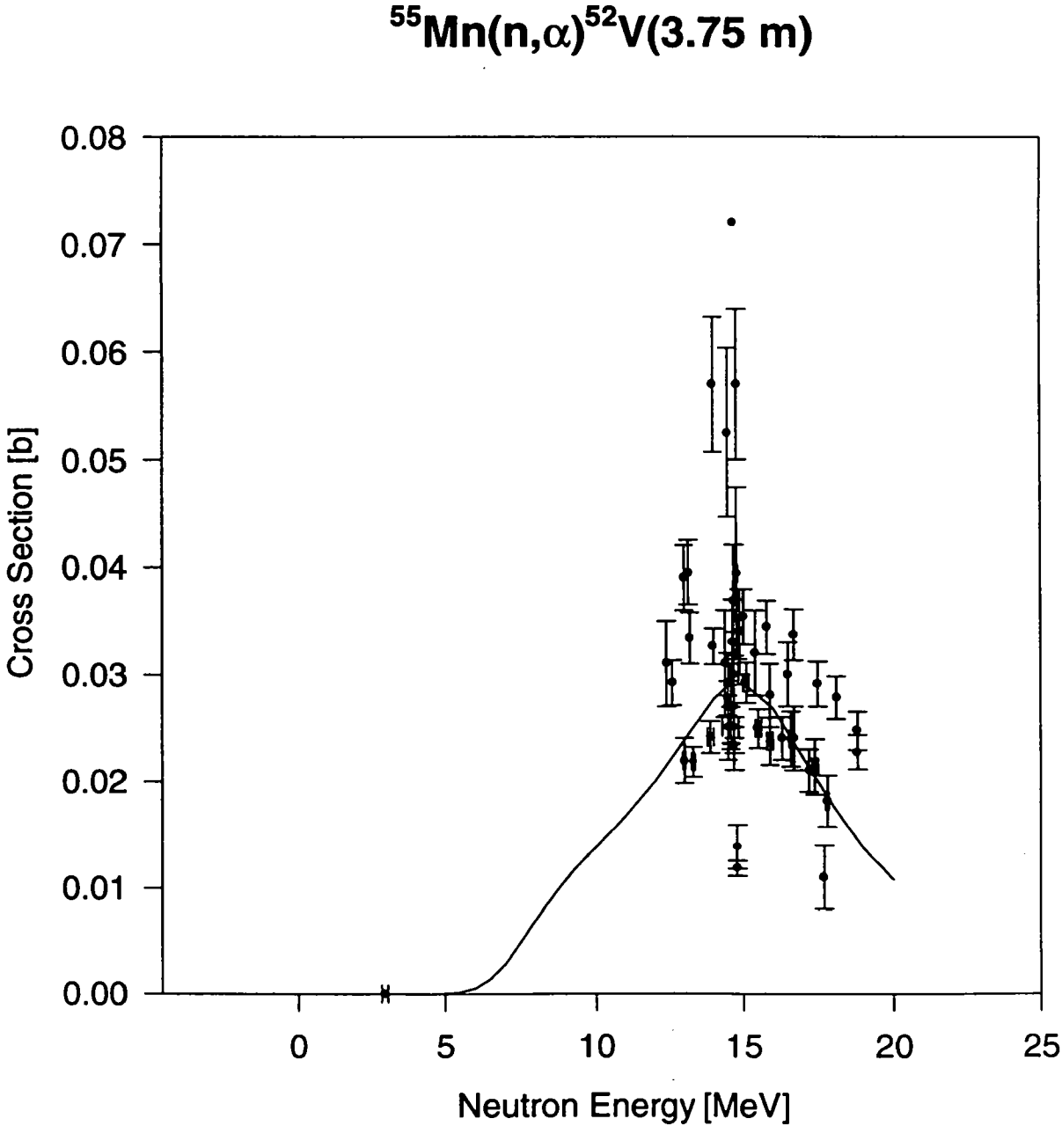

Figure 9.2 Experimental data plus Endf evaluated data curve

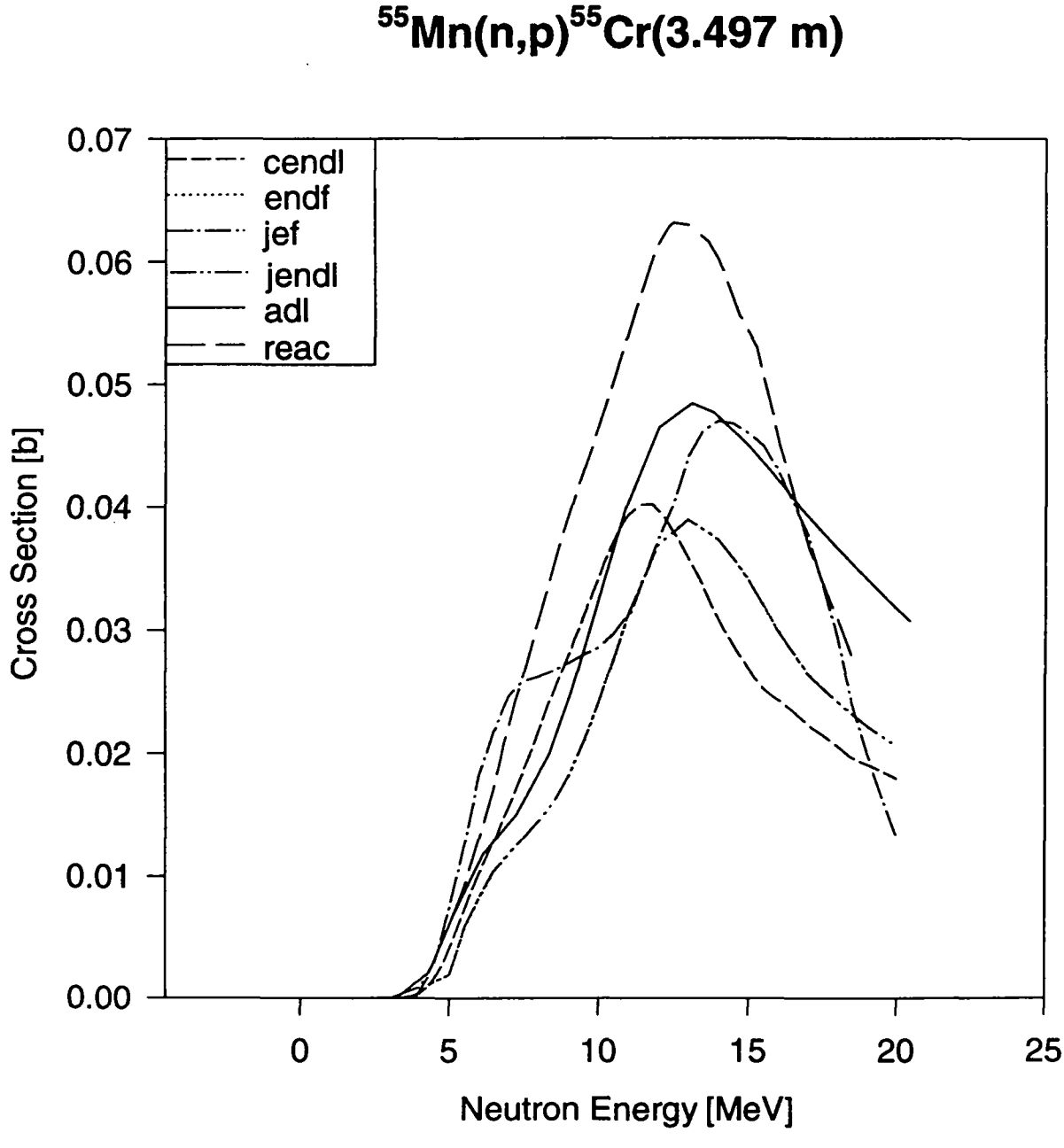

Figure 10.1 Evaluated data

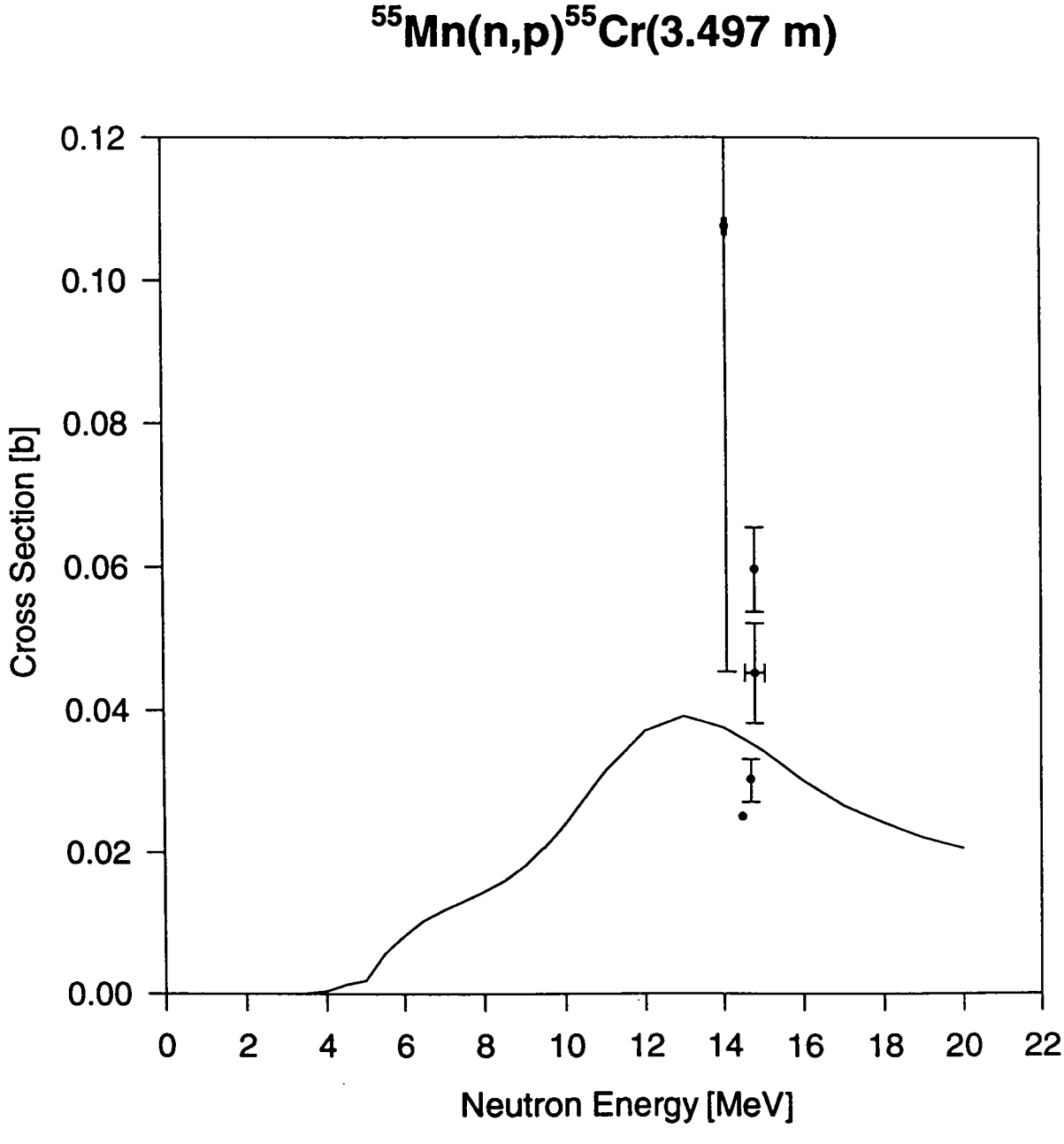

Figure 10.2 Experimental data plus Endf evaluated data curve

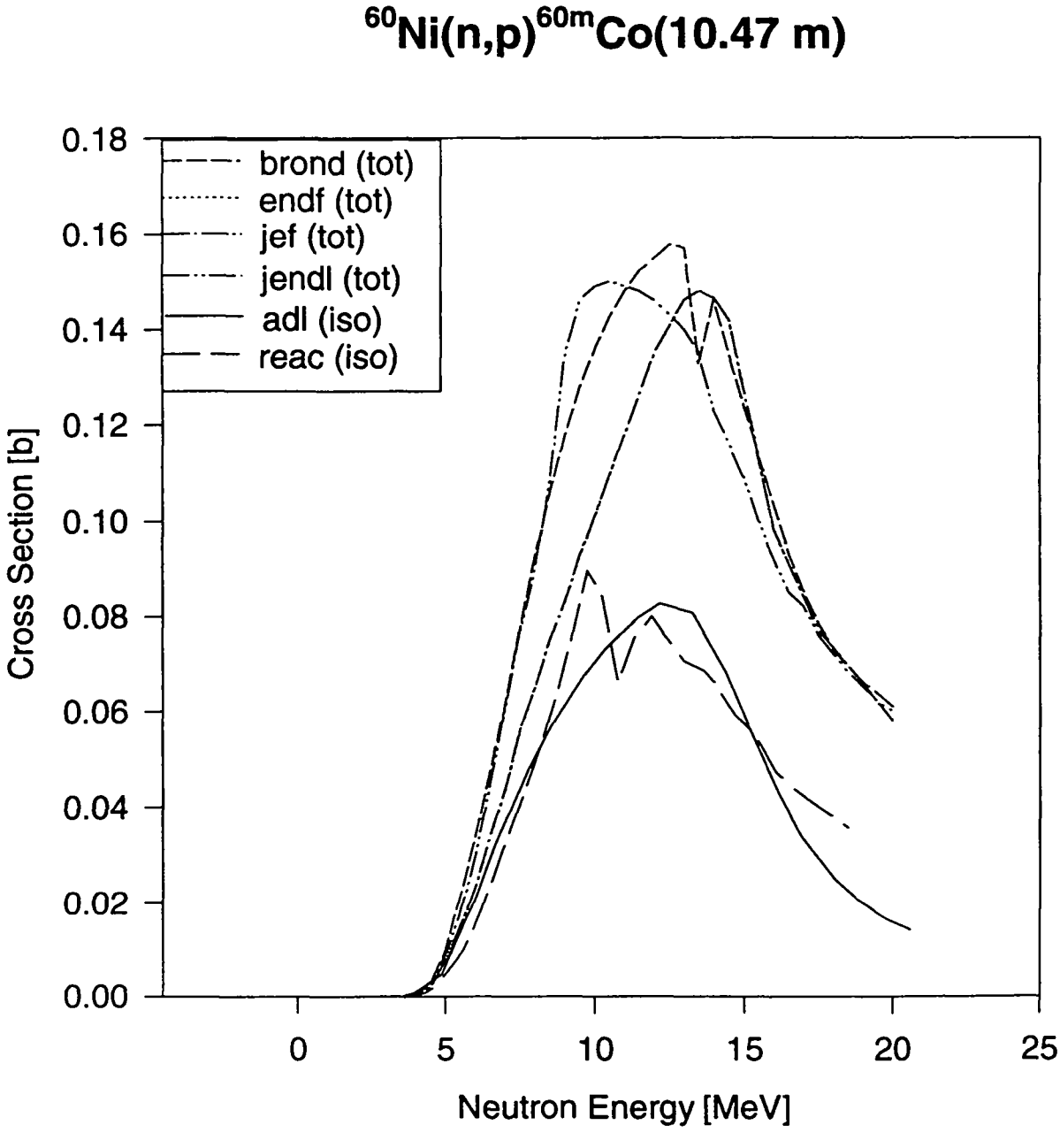

Figure 11.1 Evaluated data. Note that this is an isomer reaction

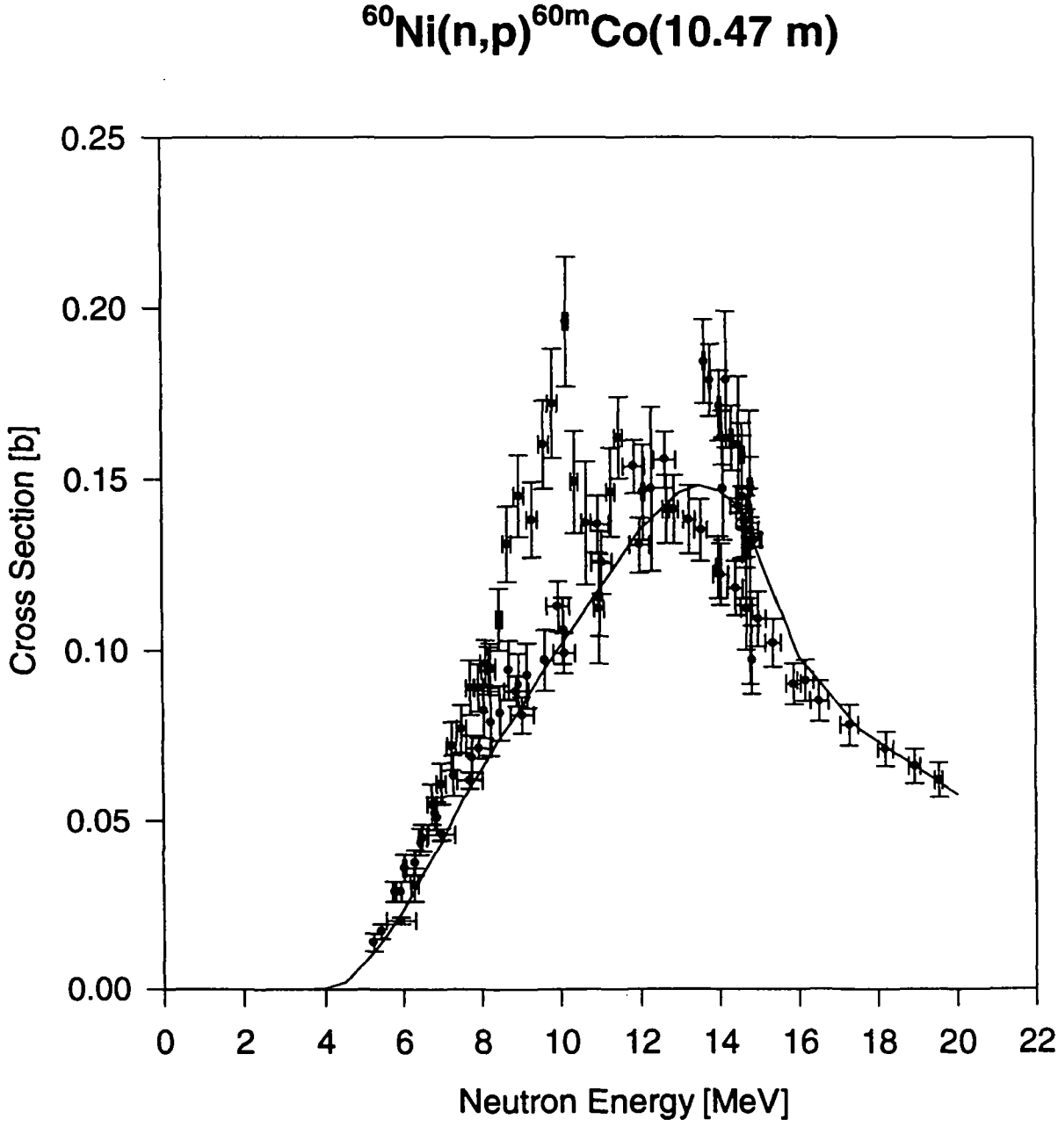

Figure 11.2 "Total" experimental data plus Endf "total" evaluated data curve

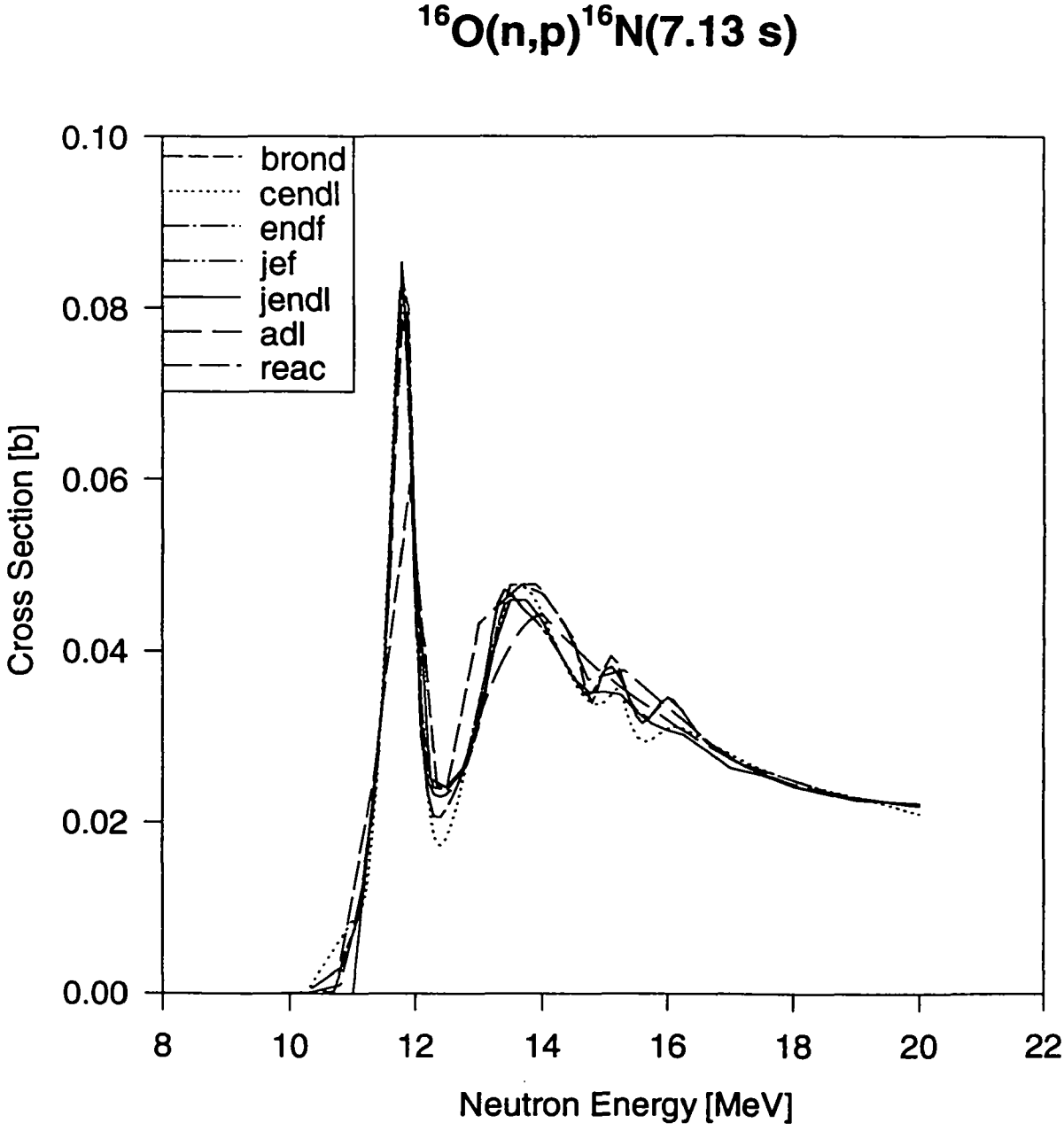

Figure 12.1 Evaluated data

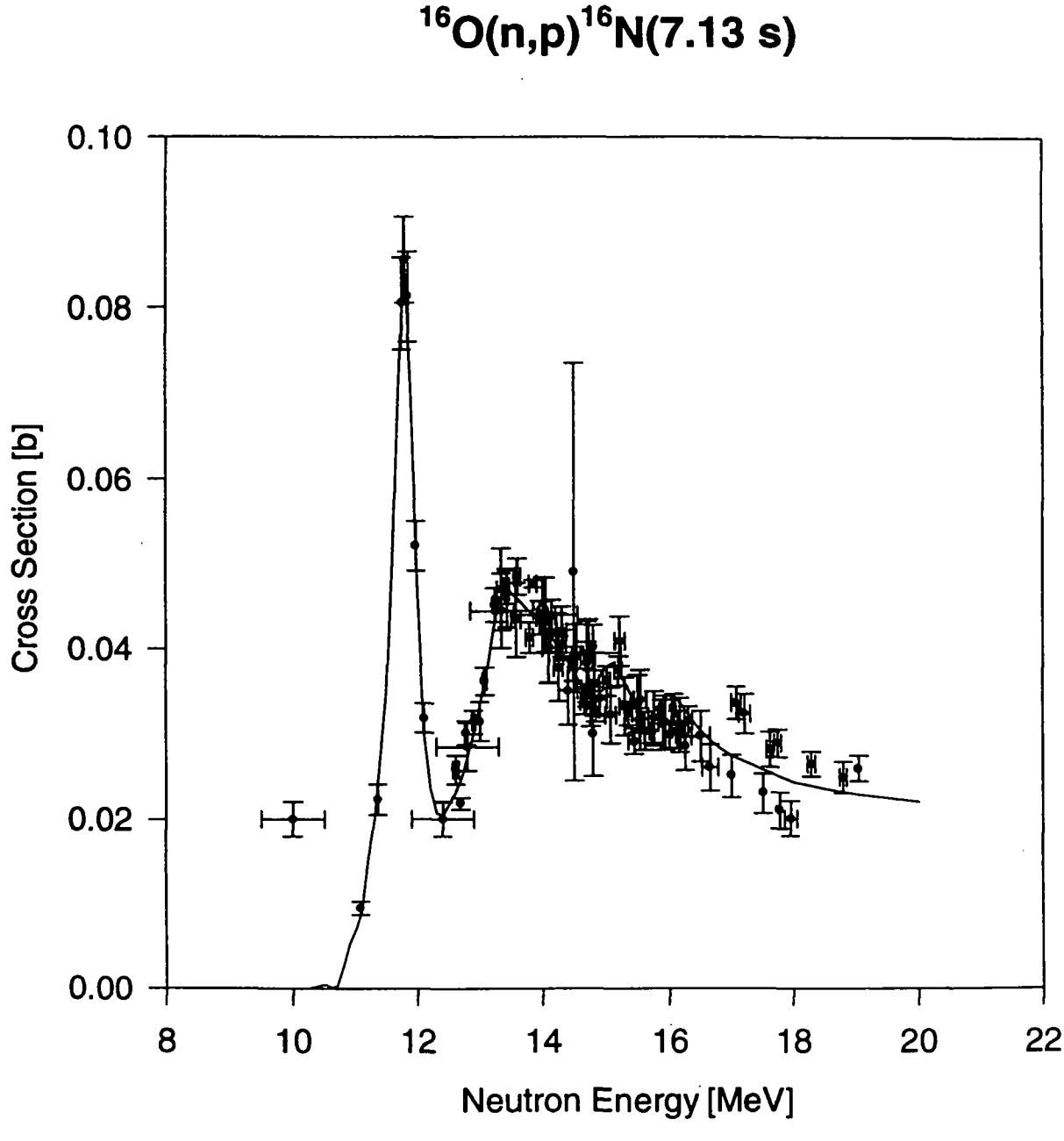

Figure 12.2 Experimental data plus Endf evaluated data curve

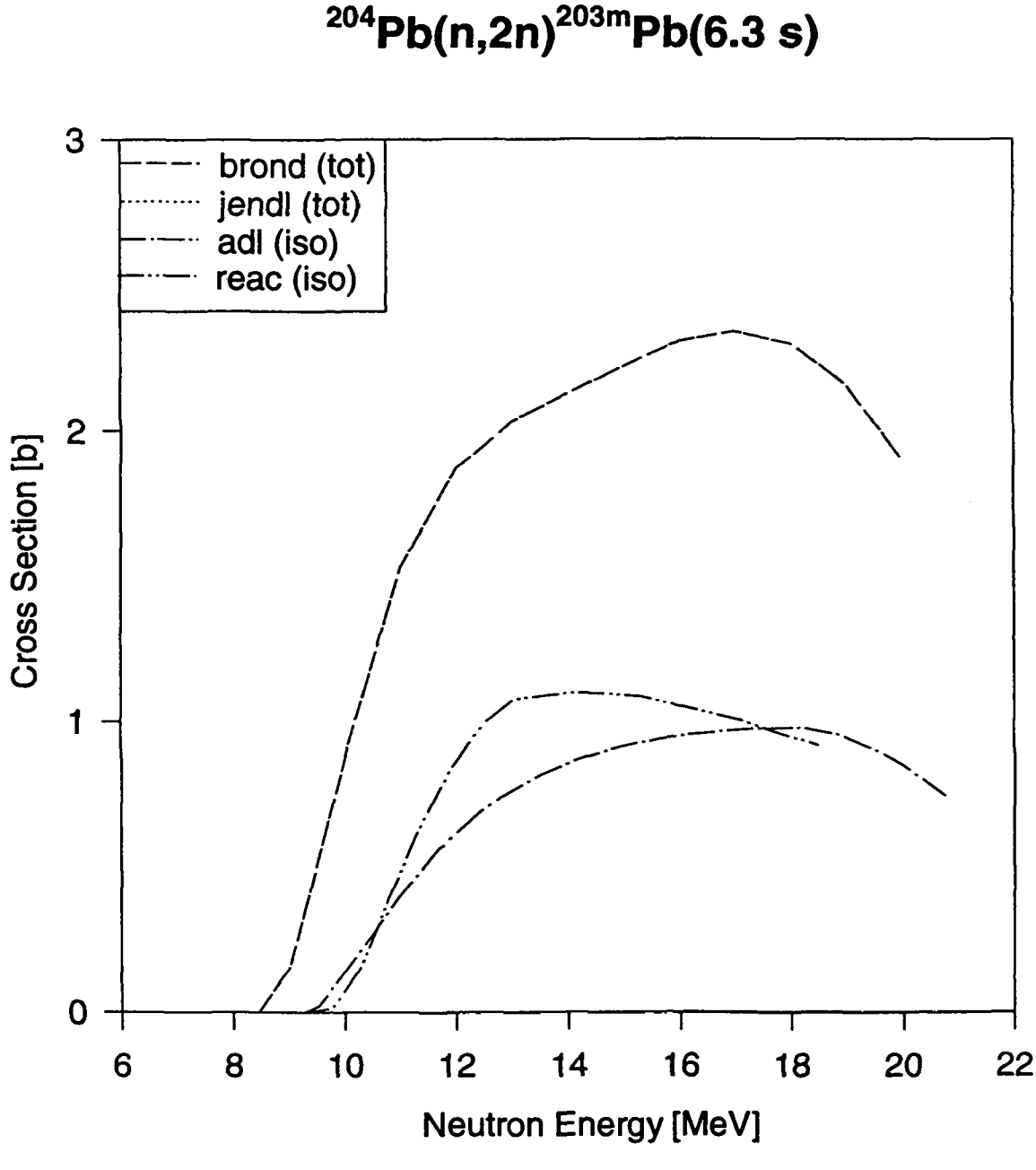

Figure 13.1 Evaluated data. Note that Brond and Jendl are identical

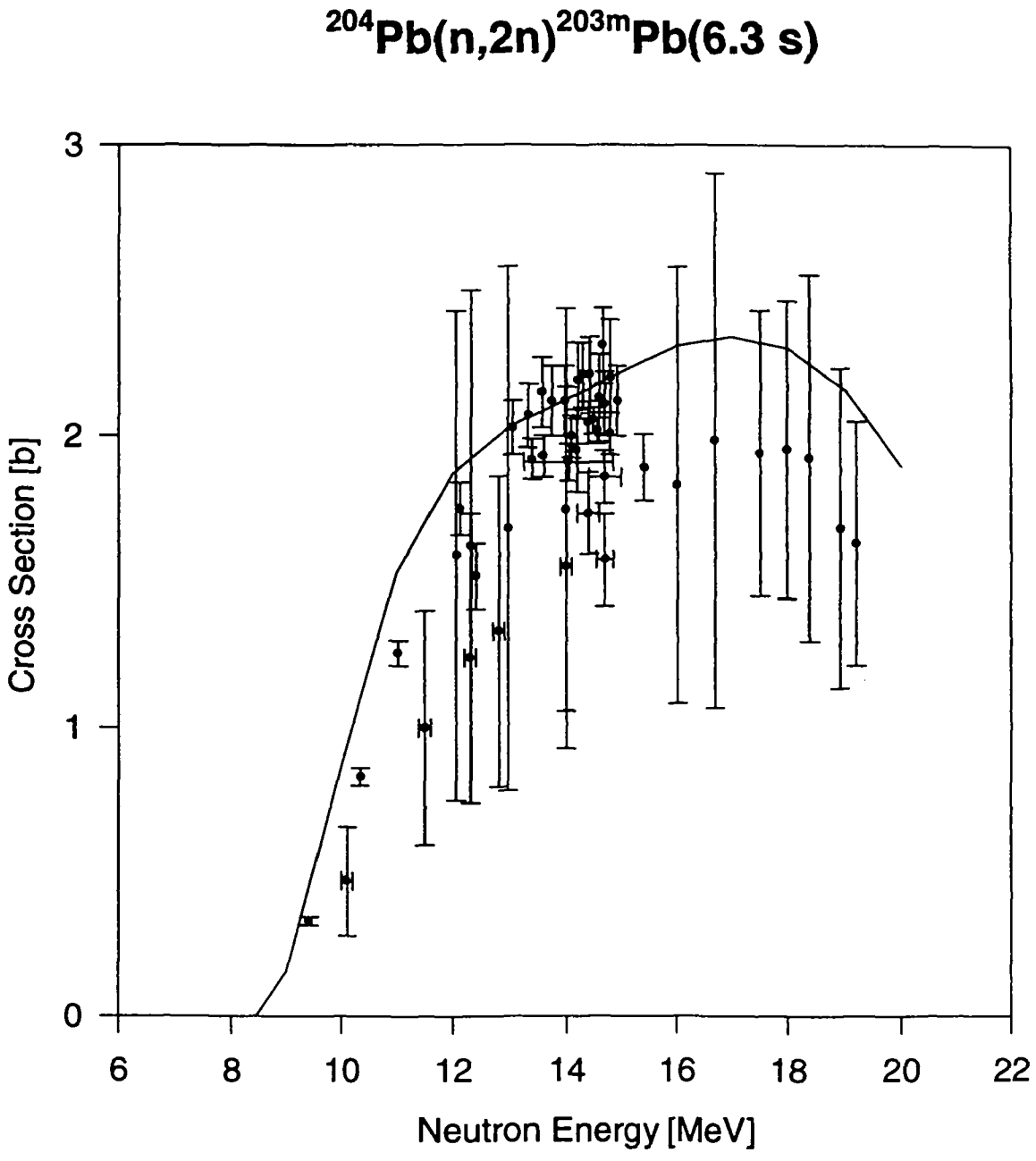

Figure 13.2 "Total" experimental data plus Jendl "total" evaluated data curve

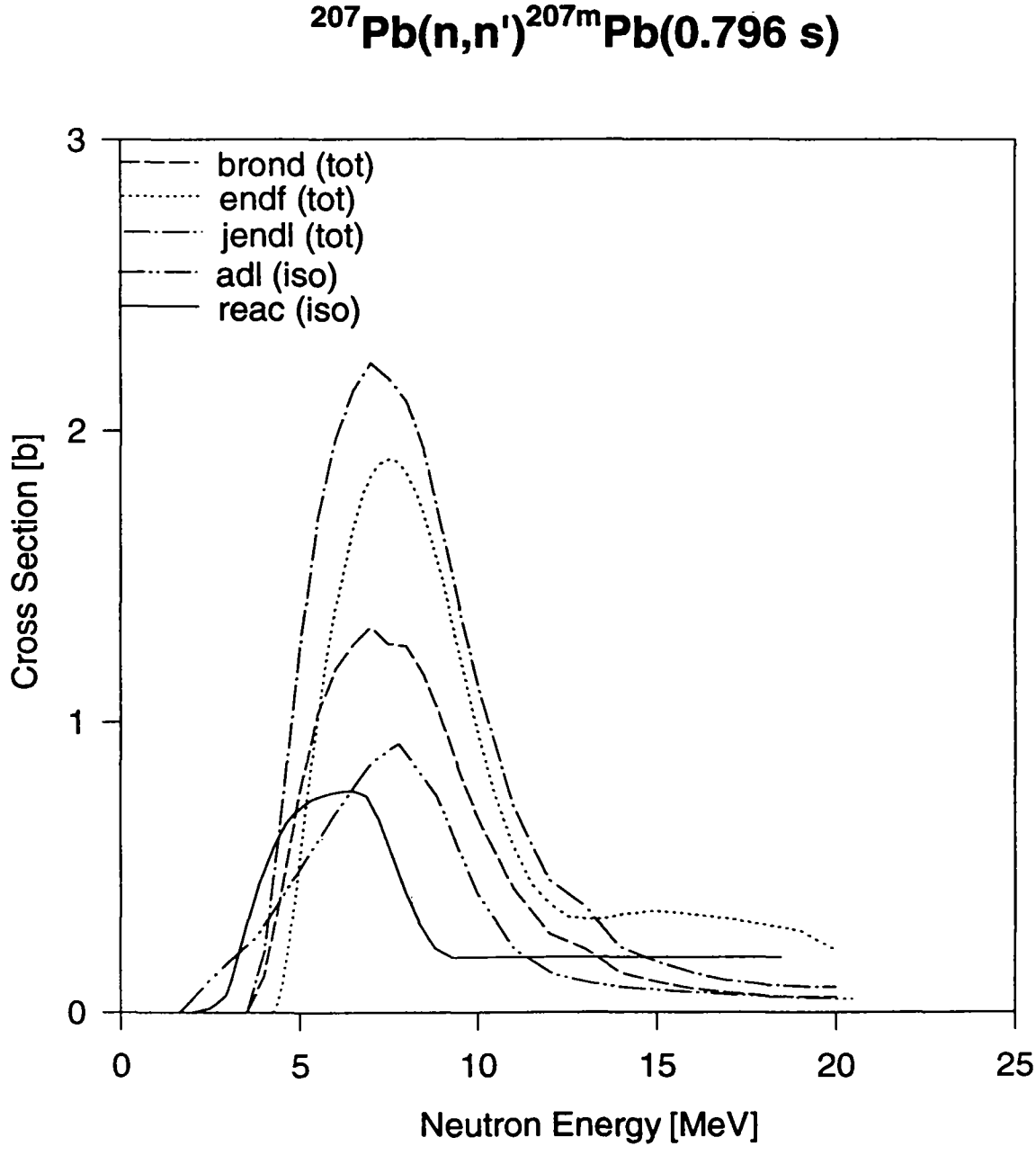

Figure 14.1 Evaluated data. Note that this is an isomer reaction

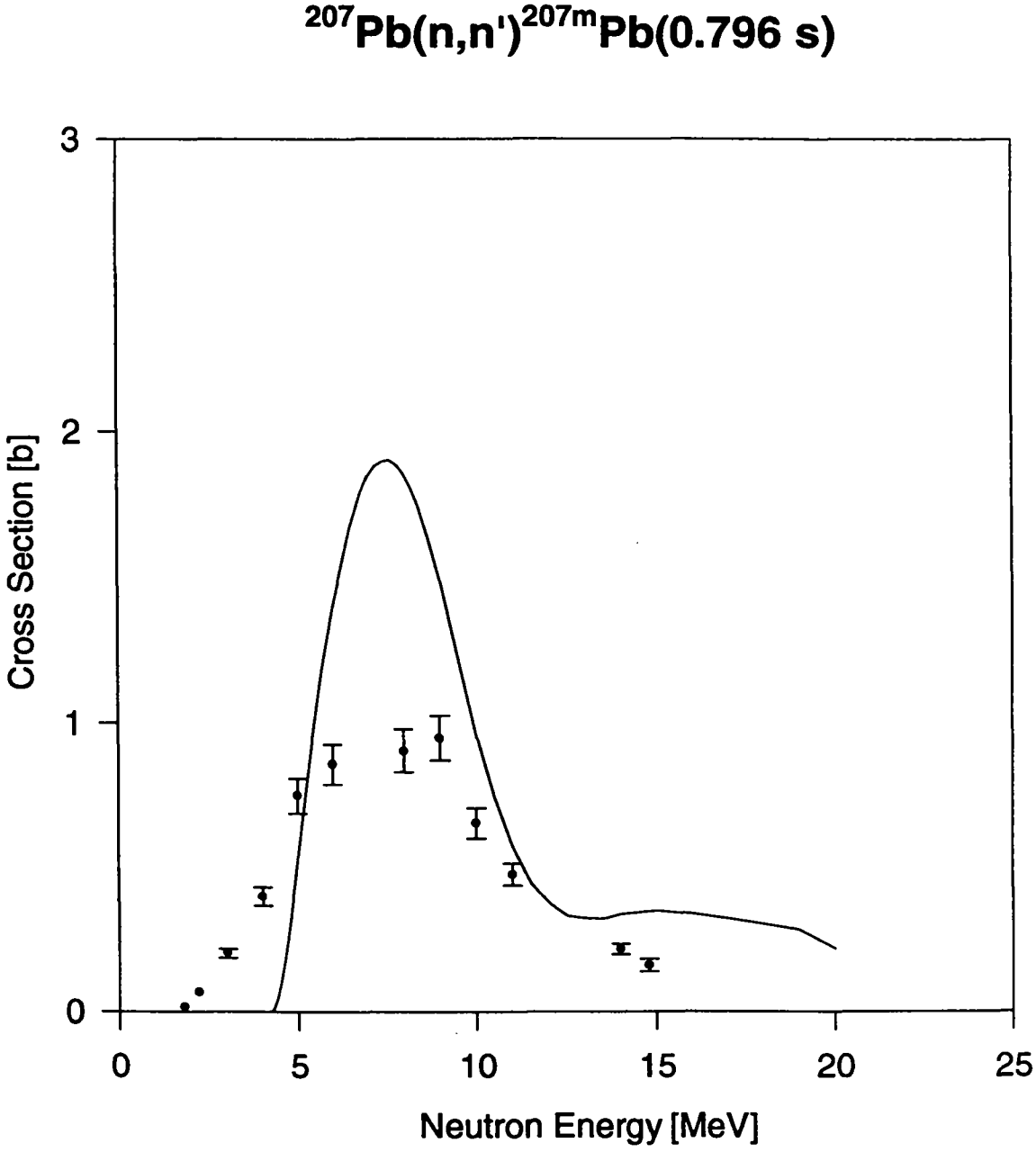

Figure 14.2 "Total" experimental data plus Endf "total" evaluated data curve

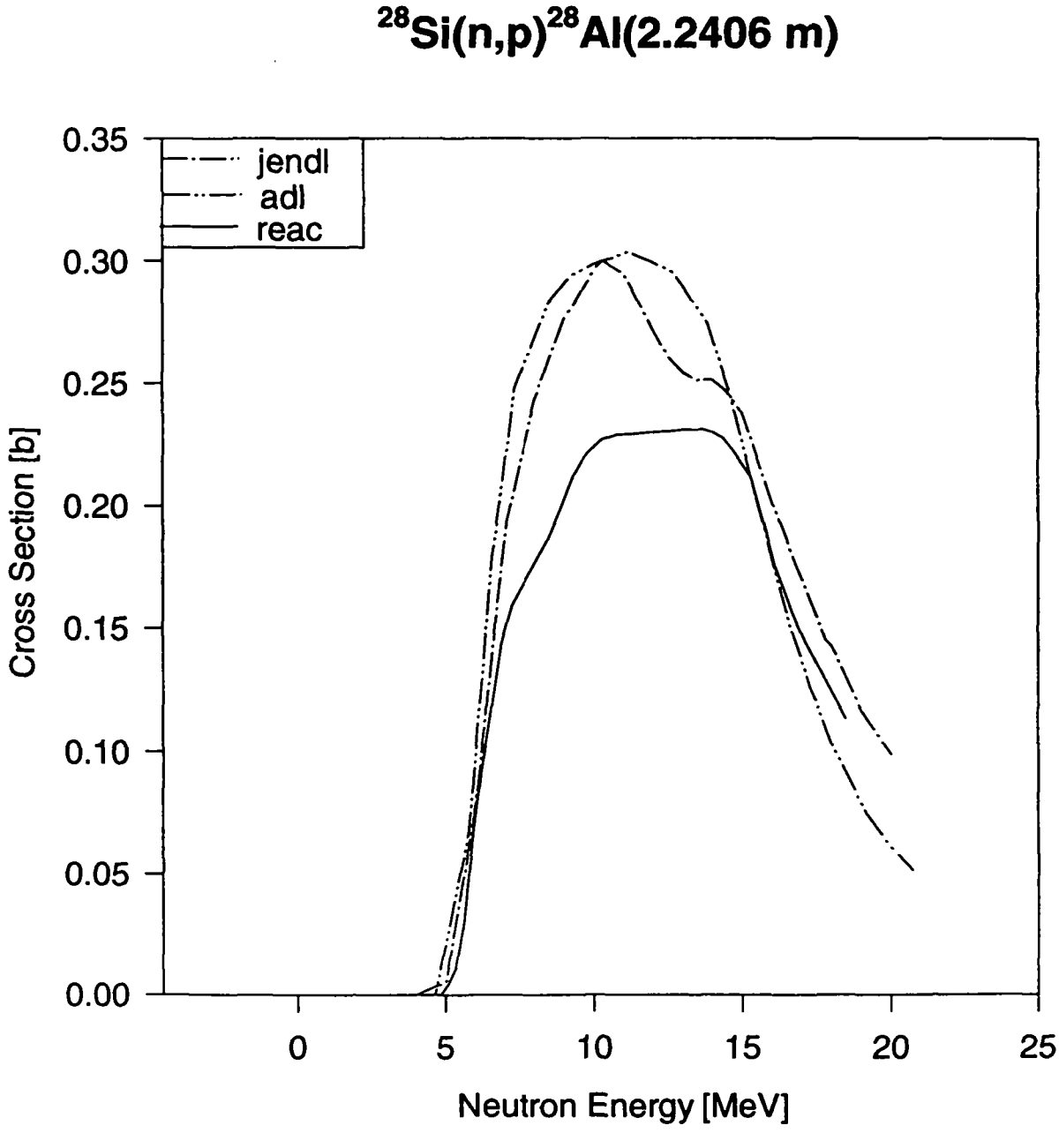

Figure 15.1 Evaluated data

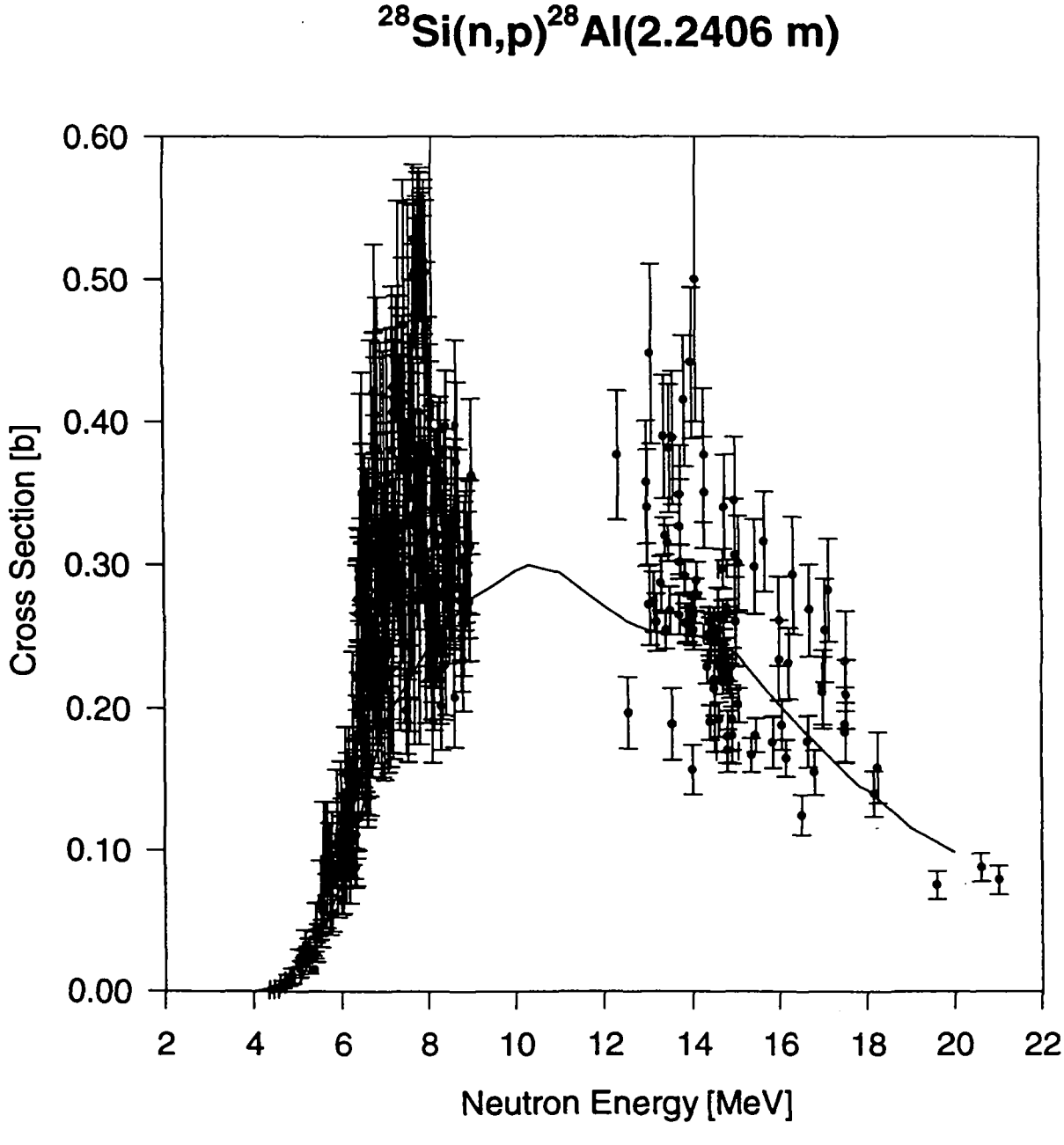

Figure 15.2 Experimental data plus Jendl evaluated data curve

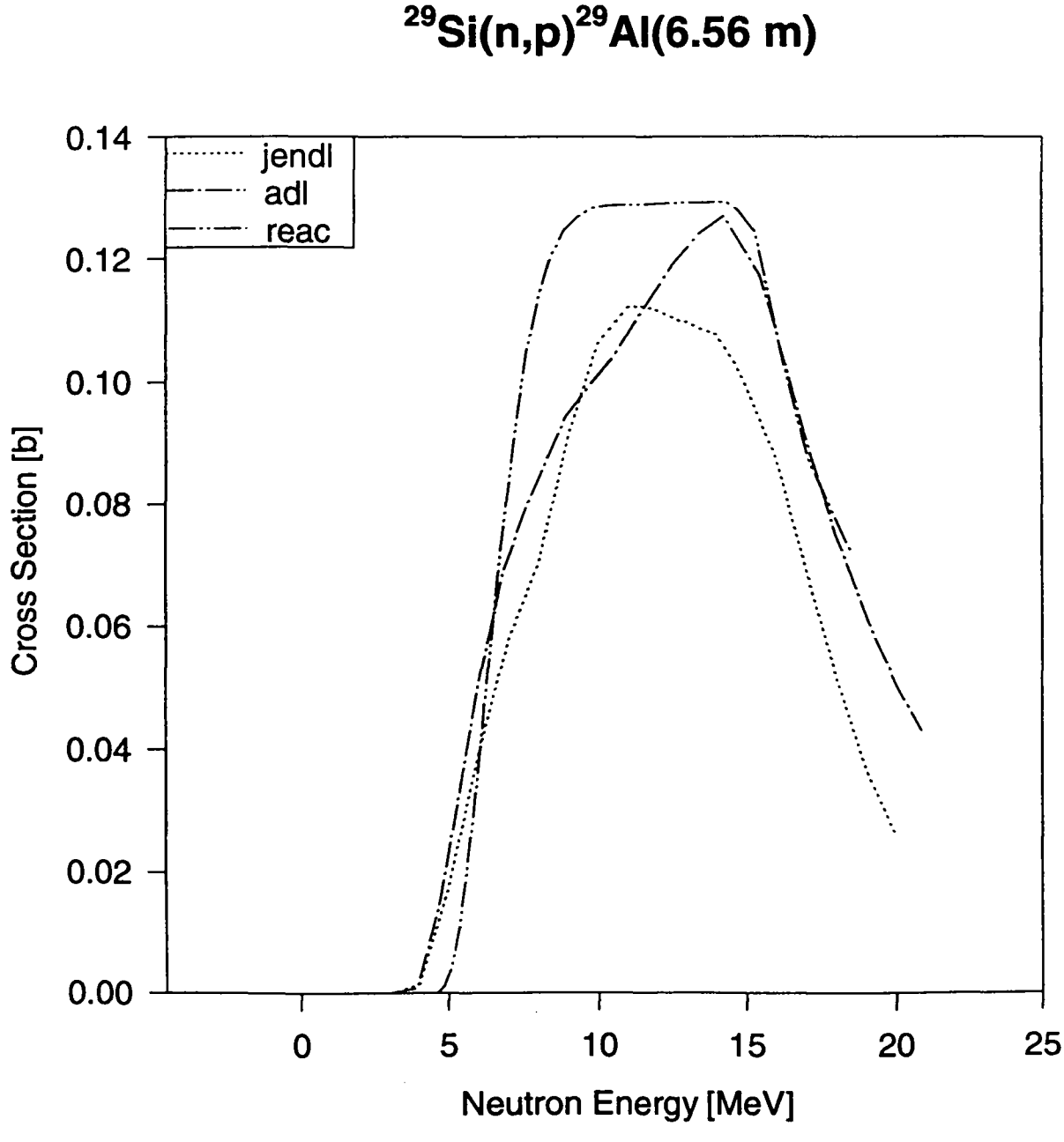

Figure 16.1 Evaluated data

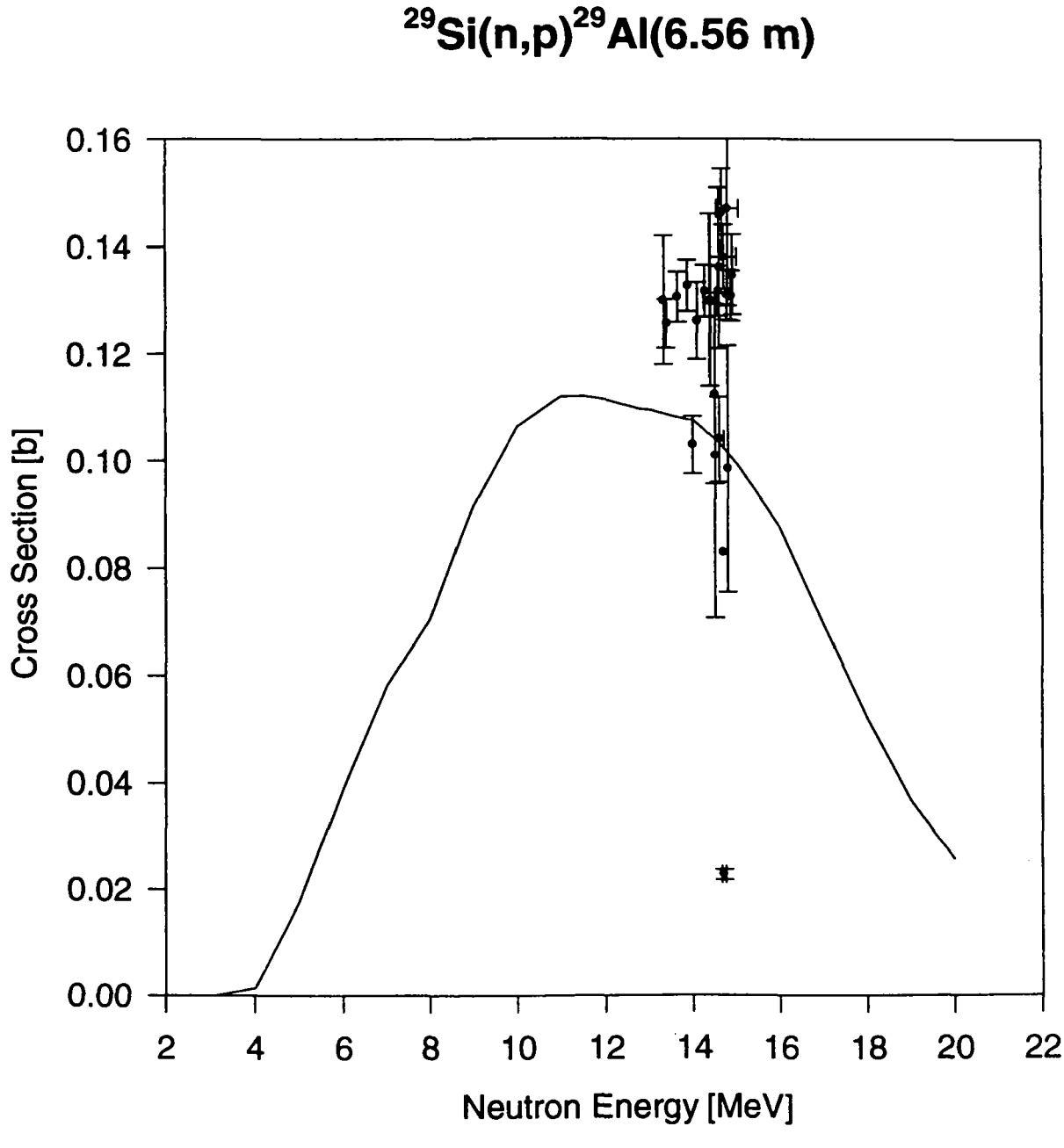

Figure 16.2 Experimental data plus Jendl evaluated data curve

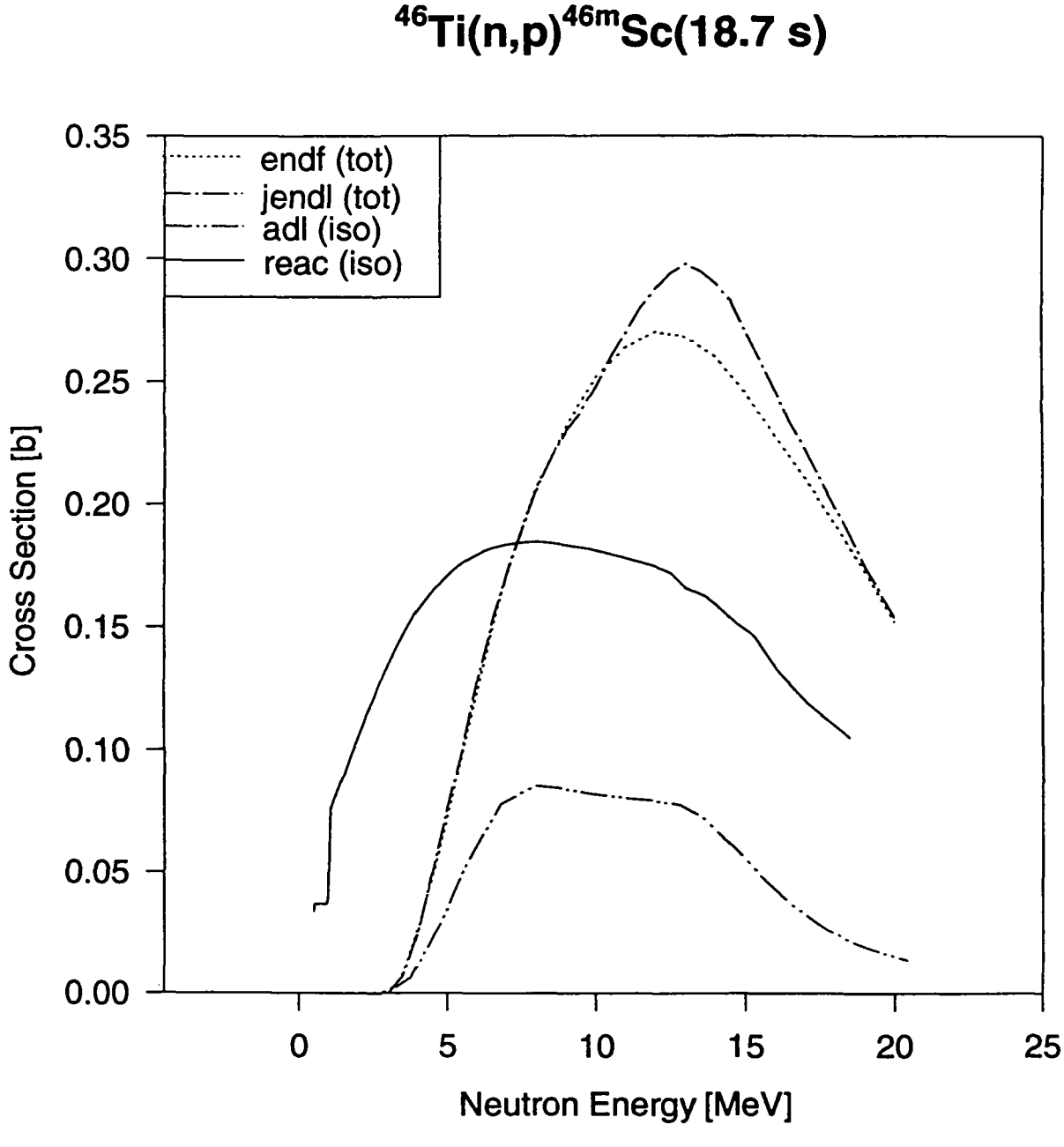

Figure 17.1 Evaluated data. Note that this is an isomer reaction

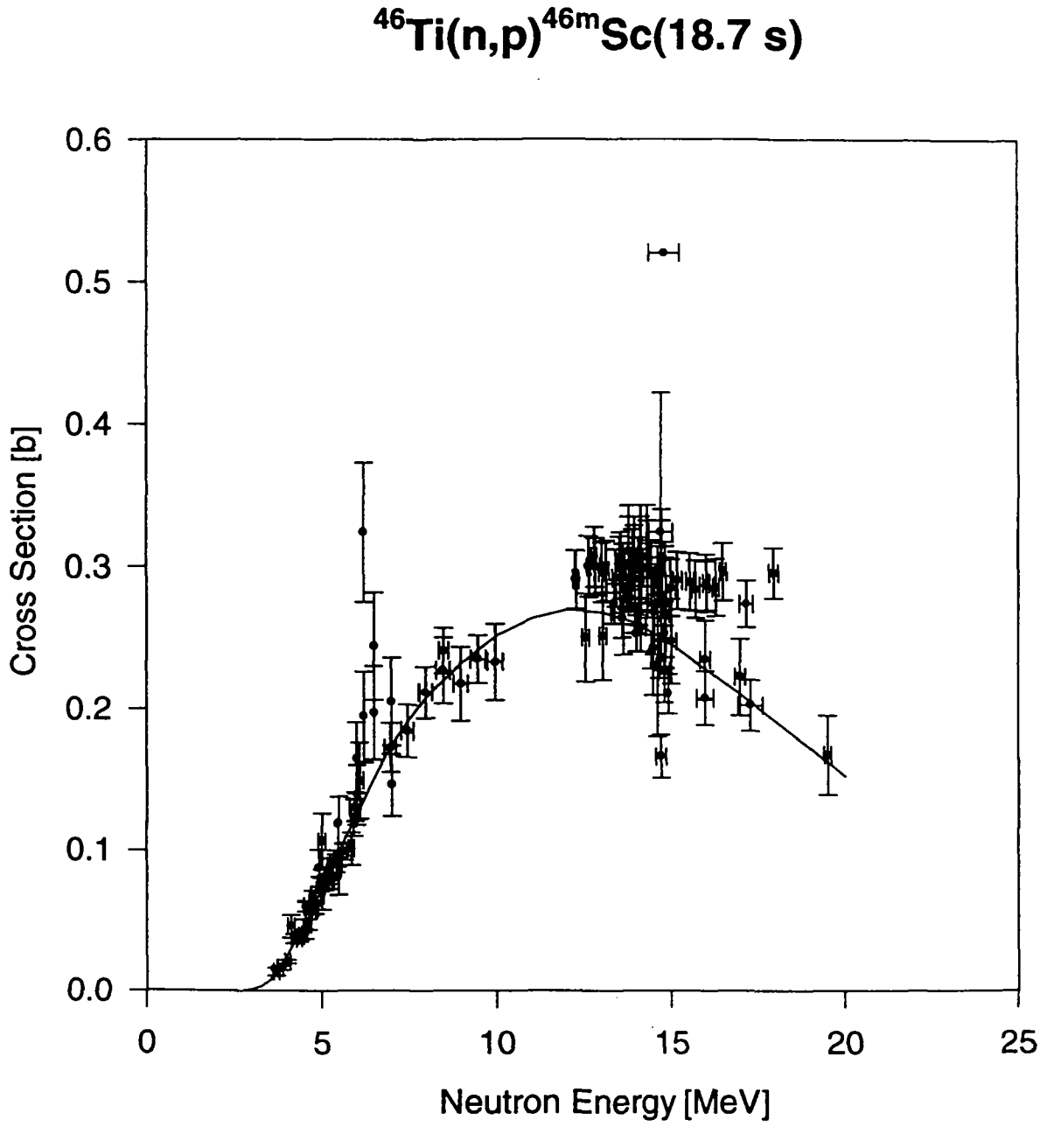

Figure 17.2 "Total" experimental data plus Endf "total" evaluated data curve

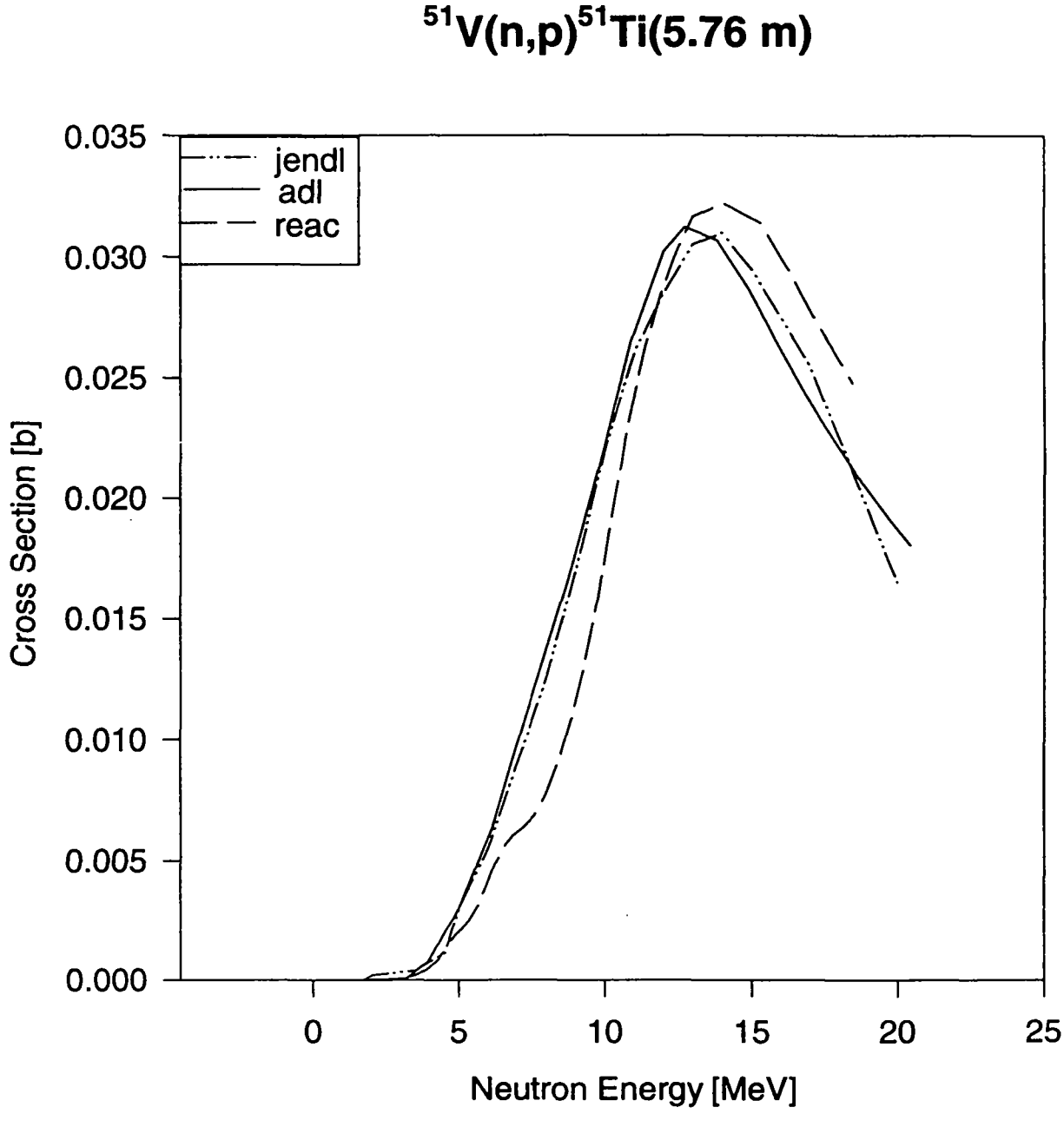

Figure 18.1 Evaluated data

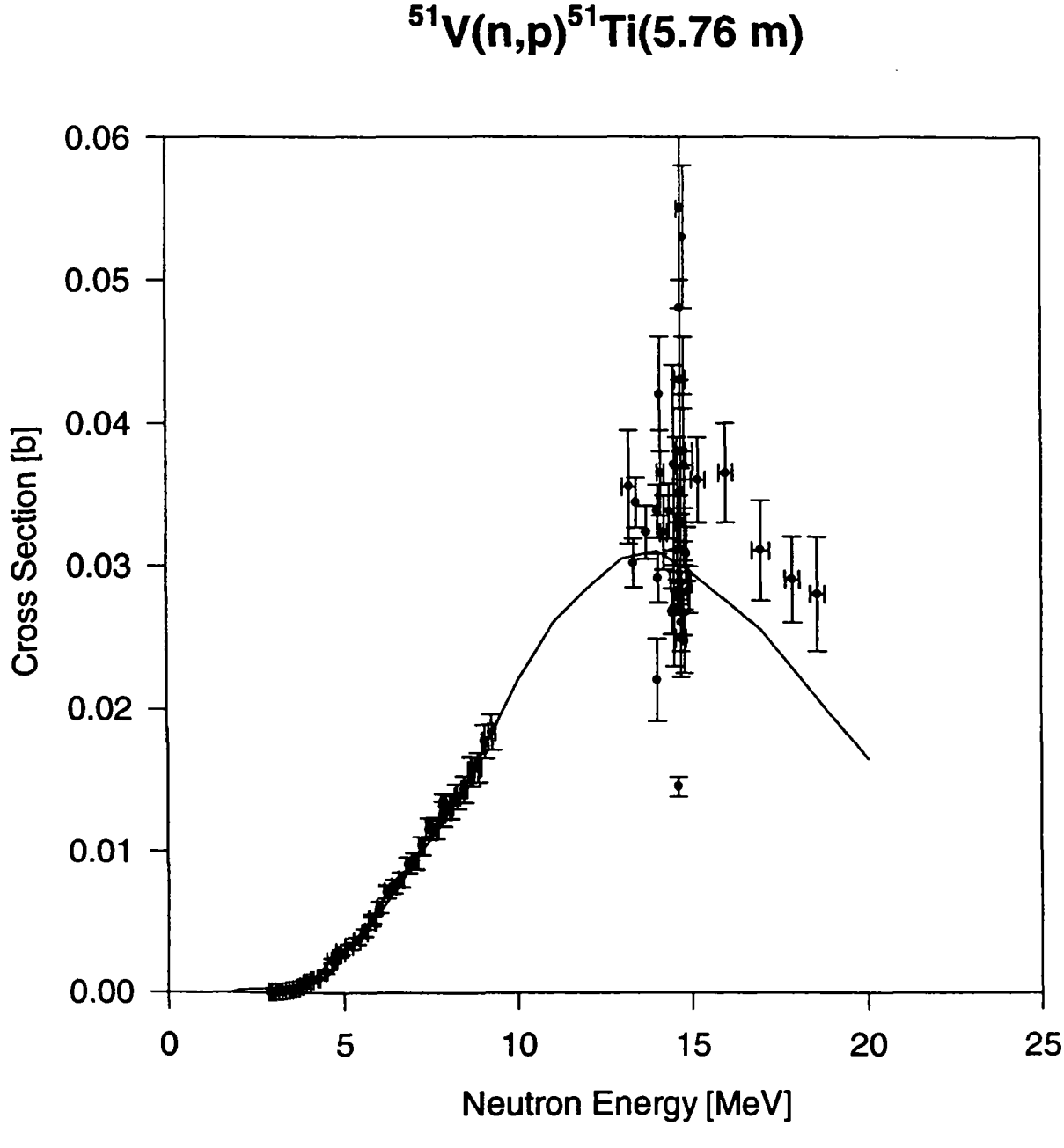

Figure 18.2 Experimental data plus Jendl evaluated data curve

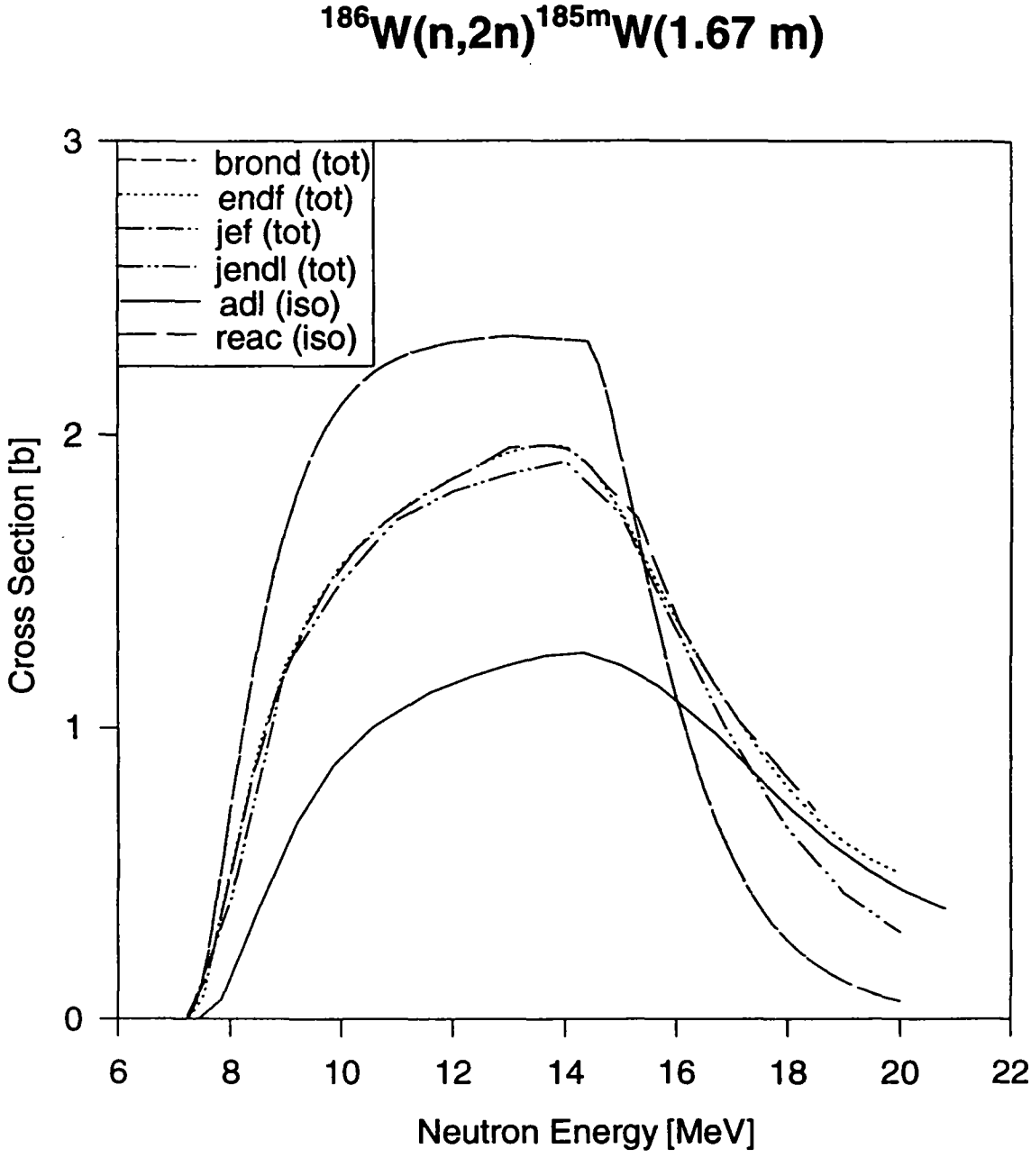

Figure 19.1 Evaluated data. Note that Brond and Jef are identical

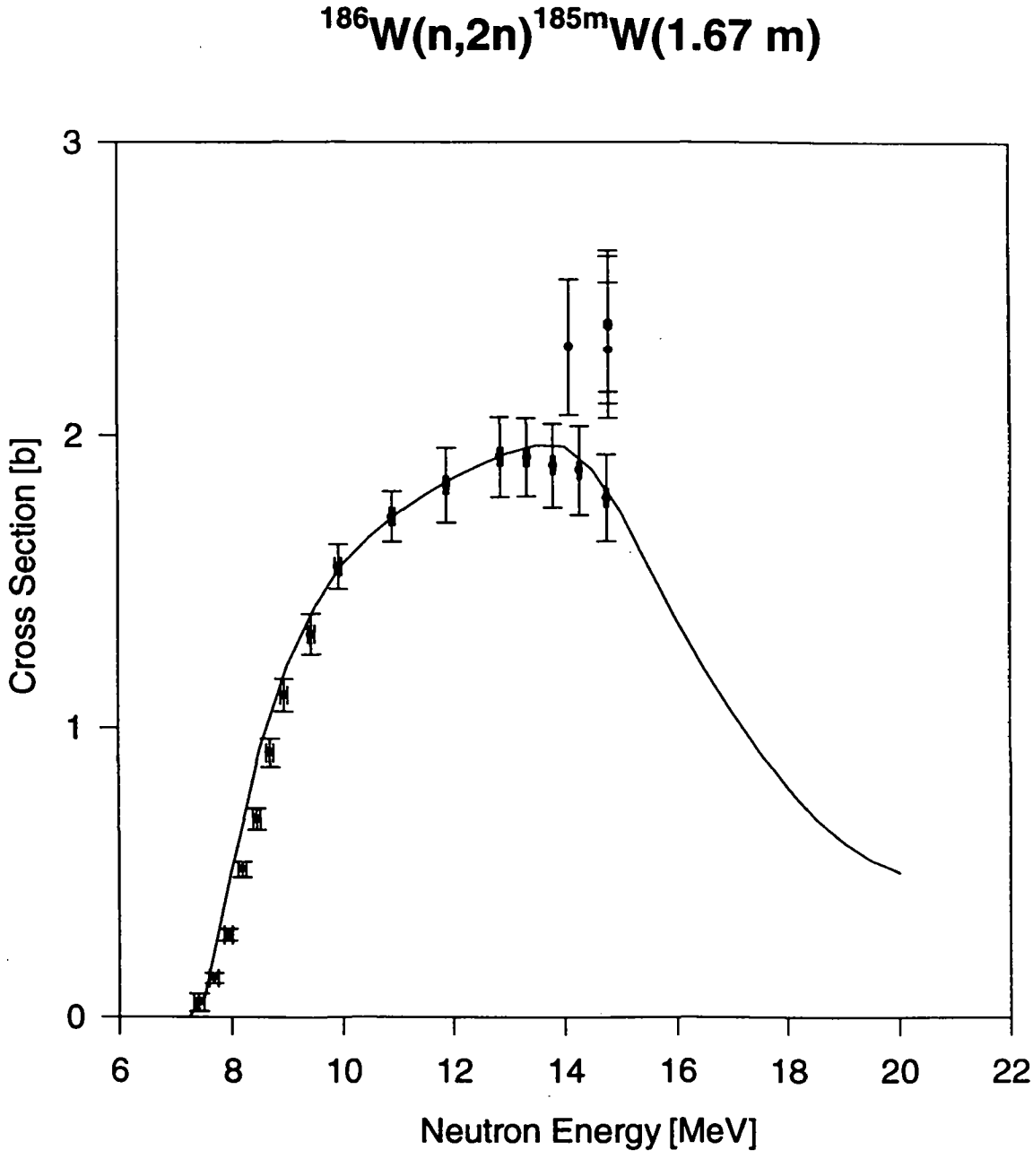

Figure 19.2 "Total" experimental data plus Endf "total" evaluated data curve

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