ENDF/B-VI NUCLEAR DATA EVALUATIONS FOR
FUSION APPLICATIONS

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BNL-NCS--41801

DE89 002187

ABSTRACT

The next release of the ENDF/B data library planned for 1989 contains improved data evaluations of interest to the fusion neutronics community. New data formats permit inclusion of energy-angle correlated particle emission spectra and recoil nucleus energy spectra. Enhanced formats for covariance information have been developed. Many new isotopic evaluations will lead to improved energy conservation and kerma factor calculations. Improved nuclear model calculations will provide reliable particle emission data where experimental information is sparse. Improved Bayesian fitting codes will provide more accurate evaluations for data rich reactions such as $\text{Li}(n,nt)\alpha$. All of the most important fusion material evaluations contain these new features.

INTRODUCTION

The Cross Section Evaluation Working Group (CSEWG) is an organization composed of representatives from United States national laboratories, universities, and private research companies who are interested in the production of evaluated nuclear data for use in nuclear physics applications. During the past 22 years, this organization has been responsible for the development of five versions of the Evaluated Nuclear Data Library (ENDF/B).

The sixth version of the Evaluated Nuclear Data File (ENDF/B-VI) is nearing completion. The previous version, ENDF/B-V, was completed in 1979. ENDF/B-V revision 2 was distributed in 1982 and included revised evaluations for a few materials such as Li-7 and W. Revision 1 was limited to corrections to existing evaluations. Therefore, most evaluations contained in ENDF/B-V are now more than ten years old.

Planning for ENDF/B-VI began in 1979. As a first step, it was decided to perform a simultaneous evaluation of the neutron "standard" cross sections. The plan was to complete ENDF/B-VI in 1984 or 1985. However, drastic cuts in funding in the United States fast breeder reactor program resulted in a reduction of more than 75 percent in the resources available for the project. Responsibility for the production of ENDF/B-VI was transferred from Reactor Technology to Energy Research within the U.S. Department of Energy. The simultaneous evaluation of the "standard" cross sections also required more time and staffing than originally envisioned, but was successfully completed in the summer of 1987.

Significant enhancements in formats for ENDF data files have been developed since ENDF/B-V was released. The formats have been extended to incorporate the following new or improved data representations:

- 1) R-function and R-matrix resonance region representations;
- 2) incident charged particle reactions;
- 3) emitted particle energy-angle distributions (File 6);
- 4) covariance formats for secondary angle distributions, secondary energy distributions, and isomer production.

ENDF/B-VI is the first version of the ENDF/B data library in which fusion data requirements have provided the major impetus for format enhancements and for evaluation improvements for the non-fissile, non-fertile nuclides. The new data evaluations provide improved calculations of radiation damage, neutron transport, shielding, activation, dosimetry, tritium breeding, heating, and energy balance. More covariance information will provide better parameter uncertainty calculations. To help meet these needs, the ENDF/B-VI data library includes, for the first

Research has been carried under the auspices of the U.S.D.O.E. under Contract No. DE-AC02-76CH00016.

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time, energy-angle correlated particle emission spectra, recoil nucleus energy spectra, and more isotopic evaluations. The library also will ensure energy conservation between emitted particles and gamma-rays for the important fusion materials. For the first time neutron standard cross sections have been evaluated simultaneously to provide self-consistent cross sections with meaningful uncertainties and correlations among these cross sections.

Release of evaluations not requiring integral benchmark testing will begin in early 1989. The final material evaluations are scheduled for release approximately six months after the heavy element evaluations are completed. A few months after release of the complete ENDF/B-VI library within the United States, the file will be transmitted to the NEA Data Bank, the IAEA Nuclear Data Section and the USSR Data Center at Obninsk for unrestricted distribution. If current schedules are met, this unrestricted release should occur in October 1989.

This paper briefly describes the new ENDF/B-VI nuclear data evaluations which are important to fusion energy research. Improvements as they relate to fusion research are described.

CHARGED-PARTICLE FUSION REACTIONS (HALE+, LANL)

One of the new capabilities of Version VI of ENDF/B that specifically addresses fusion data needs will be the availability of evaluated charged-particle reaction data. The two most important examples for fusion applications are the d-t and d-d reaction systems. Both the A=5 and A=4 mass systems have been carefully studied in comprehensive coupled-channel R-matrix analyses.^{1,2} The analyses include not only experimental data on the major fusion reactions $T(d,n)^4\text{He}$, $D(d,n)^3\text{He}$, and $D(d,p)^3\text{H}$, but also the substantial data base available for the elastic scattering reactions in both incoming and outgoing channels, total cross section data in the neutron channels, and a significant amount of analyzing power and higher order polarization measurements.

The results of the R-matrix analysis¹ for the $T(d,n)^4\text{He}$ reaction cross section up to $E_d=8$ MeV are compared with a compendium of the available experimental data in Fig. 1. The most distinctive feature of the reaction cross section is the pronounced peak near 110 KeV due to the well known $J^\pi=3/2^+$ level in ^3He . One result of this analysis has been to explain a long time controversy regarding the somewhat different energies and widths manifested by this level in the d-t and $N^4\text{He}$ channels. In particular, the resonance is found to correspond to two different S-matrix poles, one of which is a so-called "shadow pole." This analysis provides the first conclusive evidence for the existence of such poles in nuclear reactions.

$T(d,n)^4\text{He}$ Cross Section

Figure 1. Comparison of the $T(d,n)^4\text{He}$ cross section from the ENDF/B-VI R-matrix analysis¹ with a compendium of experimental data.

The d-t and d-d evaluations in ENDF/B-VI consists of precise specification of the elastic and reaction cross sections and angular distributions. Experimental measurements, which are roughly at a 1% level of accuracy, are well represented by the analysis from below 10 KeV to 120 KeV. Similar accuracies were achieved in the measurements and analysis of the $D(d,p)^3\text{H}$ and $D(d,n)^3\text{He}$ reaction cross sections at these energies.

ENDF/B-VI STANDARDS (CARLSON+, NBS)

Another unique feature of the ENDF/B-VI data file is the very careful and comprehensive cross section standards analysis that was performed. Earlier ENDF/B standards evaluations generally followed a hierarchical procedure in which the various standard reactions were analyzed sequentially, with each new reaction evaluation depending on the previous results. The ENDF/B-VI evaluation, on the other hand, was performed by simultaneously analyzing all the standard reactions that are linked through ratio measurements, as well as several other non-standard reactions that are similarly linked to the standards and for which absolute data exist. Although some of the details have

changed slightly, the basic approach followed in the analysis is described in a 1985 paper,³ and a more up-to-date account was given recently at the Mito Conference.⁴ Starting from a very accurate $^1\text{H}(n,n)^1\text{H}$ reference file, the light element standard reactions were analyzed in a coupled-channel R-matrix framework that permitted inclusion of auxiliary information such as very accurate charged-particle and neutron total cross section data. The heavier element standard cross sections, a portion of the light element data, and the thermal constants were analyzed independently using a generalized least squares program. The results of the R-matrix and least-squares analyses were then combined in a manner that took full account of all correlations in the experimental data as well as those introduced by the R-matrix analysis. The standards data file for ENDF/B-VI was completed and made available in the fall of 1987.

The most direct impact on fusion data from the standards analysis occurs in the case of the tritium-producing reaction $^6\text{Li}(n,\alpha)\text{T}$, which is one of the standard cross sections and was included in the Version VI analysis. The results of the analysis are compared to two accurate measurements included in the standards analysis in Fig. 2. The evaluation is little changed from Version V, with a maximum difference of $\sim 3\%$ occurring near the 240-keV resonance. Somewhat larger differences will likely occur at higher incident neutron energies, although that part of the analysis is not complete at this writing.

$n + ^7\text{Li}$ EVALUATION (YOUNG, LANL)

Of major interest for fusion energy applications⁵ is the cross section of the tritium breeding reaction $^7\text{Li}(n,\text{nt})^4\text{He}$. Additionally, because of the amount of ^7Li that will be present in fusion blankets, information on the other reactions that influence neutronics calculations is also important. An update of the 1981 covariance analysis⁶ of $n + ^7\text{Li}$ reactions is being provided for ENDF/B-VI. This analysis is described in detail in another paper at this conference⁷ and will only be summarized here.

The results of the 1981 ENDF/B-V.2 analysis of ^7Li data was a lowering of the $^7\text{Li}(n,\text{nt})$ cross section by about 9%. Since that time, a number of new measurements of the tritium-production cross section have been made.⁷ A major motivation of the new analysis was to include the new measurements in the analysis and to better define the input covariances, including cross correlations between different tritium-production measurements. The results obtained for the (n,nt) cross section for the energy range $E_n = 8\text{--}18$ MeV are compared with the measurements since 1981 and with the ENDF/B-V.2 evaluation in Fig. 3. There has been little change in the recommended values for the $^7\text{Li}(n,\text{nt})$ cross section over the main energy

Figure 2. ENDF/B-VI evaluation of the $^6\text{Li}(n,\alpha)\text{T}$ cross section compared to experimental data.

region of interest, with a maximum difference of $\sim 1\%$ occurring between 8 and 15 MeV. The main effect of including the experimental data is to lower the (n,nt) cross section above 15 MeV and, more importantly, to significantly lower the uncertainties on the cross section. While there is little change in the error in the elastic data, the uncertainty on the tritium-production cross section is now estimated to be $\sim 2\%$ near 14–15 MeV, down a factor of 2 from the previous ENDF/B-V.2 evaluation.

$n + ^9\text{Be}$ EVALUATION (PERKINS+, LLNL)

The large $^9\text{Be}(n,2n)$ cross section near 14 MeV (~ 0.5 b) leads to the choice of beryllium for a neutron multiplier in many fusion blanket concepts.⁵ Because calculations of neutron multiplication in beryllium have consistently overpredicted integral measurements and because of the availability of important new differential data, a major reevaluation of $n + ^9\text{Be}$ has been completed by Perkins et al.⁸ that will be incorporated into ENDF/B-VI. The analysis couples Monte Carlo techniques with recent double differential neutron emission measurements to produce an improved evaluation of the $(n,2n)$ cross section, which includes a detailed specification of the energy-angle correlated neutron emission spectra.

Figure 3. ENDF/B-VI evaluation of the ${}^7\text{Li}(n,n't){}^4\text{He}$ cross section compared to 8 and 18 MeV.

In the analysis the total ${}^9\text{Be}(n,2n)$ reaction was decomposed into four possible sequences of two-body reactions that were permitted to proceed through the various energy levels of ${}^9\text{Be}$, ${}^8\text{Be}$, ${}^6\text{He}$, and ${}^5\text{He}$ using level widths that are consistent with experimental data. The input cross sections for each of the sequences were determined as functions of neutron energy by comparison with double differential neutron emission measurements. Simple anisotropic (center of mass) angular distributions that were consistent with experimental data were included for the various decay modes included in the analysis. The recommended value for the $(n,2n)$ cross section at 14 MeV is 0.486 b in the Version VI evaluation, down 7% from ENDF/B-V.1.

A comparison between the calculated emission neutron spectra from ENDF/B-VI and experimental data from Takahashi et al.⁹ is given in Fig. 4 for 14 MeV incident neutrons and 5 emission angles. The major features of the spectra are well represented, and the quantitative agreement with the experimental data is reasonable. The double-differential neutron emission data are represented in the ENDF/B-VI evaluation using a new energy-angle correlation format. The necessary capability for handling the new formats has been developed for the NJOY processing code system, and the ${}^9\text{Be}$ evaluation has been successfully processed.¹⁰

Figure 4. ${}^9\text{Be}(n,2n)$ neutron emission spectra at 5 emission angles induced by 14 MeV neutrons. Solid curves are from the ENDF/B-VI evaluation and points are the data of Takahashi et al.⁹ Figure provided by S. T. Perkins (LLNL).

$n + {}^{11}\text{B}$ EVALUATION (YOUNG, LANL)

The fusion energy interest in ${}^{11}\text{B}$ data results from its potential presence in boron carbide shield walls.⁵ The existing ENDF/B-V data file is actually a pre-1970 United Kingdom evaluation that was converted to ENDF/B format in 1971. A great deal of improved experimental data has become available since that time, notably neutron total cross sections, elastic and inelastic scattering angular distributions, and gamma-ray production cross sections and energy distributions. The thrust of the ENDF/B-VI evaluation is to incorporate the new total cross section and elastic/inelastic angular distributions data into the evaluation. Because measurements are lacking at higher energies, optical model and Hauser-Feshbach statistical theory calculations are used to supplement the experimental data base above $E_n = 10$ MeV.

The new evaluation covers the neutron energy range from 10^{-5} eV to 20 MeV. Experimental total cross section data exists up to 14 MeV. Optical model calculations were used to extend the evaluation to 20 MeV. Figure 5 compares the evaluated total cross section to ENDF/B-V (dashed curve) and to the available experimental data. As is evident, large discrepancies exist between the experimental data represented by the present evaluation and ENDF/B-V, with differences of 40% occurring near 1 and 2.3 MeV and a systematic 8-10% difference in the range 8-17 MeV. These differences are

also evident in the integrated elastic cross section for these neutron energy ranges, with ENDF/B-V lying approximately 30% lower than Version VI near 14 MeV.

Figure 5. Comparison of evaluated and experimental values of the neutron total cross section of ^{11}B . Solid curve represents the ENDF/B-VI evaluation, dashed curve is ENDF/B-V, and the points are experimental data as indicated.

The evaluation of the inelastic cross sections to the first few excited states was done in concert, under the constraint that all cross sections sum to the relatively well-determined total cross section. Integrated cross sections as well as angular distributions were determined for elastic and inelastic scattering by fitting the measured angular distributions with Legendre expansions. The evaluated inelastic cross section to the 2.14-MeV state in ^{11}B is shown in Fig. 6, together with ENDF/B-V and representative experimental data used for the ENDF/B-VI evaluation. There is generally reasonable agreement among the recent scattering measurements.

In summary, large differences are found between the new evaluation and ENDF/B-V values for the total, elastic, and inelastic cross sections and angular distributions. Significant improvement is expected in neutron transport calculations using the ENDF/B-VI evaluation. The cross section and angular distribution analysis are complete for Version VI, and work

is in progress on obtaining the requisite energy-angle correlated spectra. Covariance data have not yet been included in the evaluation.

Figure 6. The $^{11}\text{B}(n,n')$ cross section to the 2.14 MeV first excited state of ^{11}B . See caption of Fig. 5 for details of curves and symbols.

n + C EVALUATION (FU, ORNL)

Carbon, in the form of graphite, has been suggested to protect the first wall of a fusion reactor. For this purpose, it is necessary to know the kerma factor, which determines the heat deposited in the first wall by the 14 MeV neutrons. The evaluation for carbon has been updated for ENDF/B-VI, primarily in two areas. First, a multilevel, multichannel analysis has been done for the resonance region in ^{13}C , to incorporate effects of this minor isotope. Second, a re-evaluation of the (n,n') and $(n,n'3\alpha)$ reactions is underway, using KERMA factor data in the evaluation process to insure that these cross sections will give the correct kerma factor for Version VI.

n + V EVALUATION (SMITH+, ANL)

Vanadium is present in some proposed fusion reactor designs as a refractory material for the first wall, and in filaments of superconducting magnets. Thus, the energy region of importance ranges from the resonance region (for the magnet applications) to 14 MeV (for the first wall application). A new evaluation¹¹, based

primarily on careful analysis of available experimental data and augmented by theory, has been completed for Version VI. Resonance parameters have been used for the total cross section up to 100 keV, replacing the pointwise cross sections used in previous versions. In addition, re-evaluation of the available data resulted in a reduction of the total cross section by as much as 10% in the energy range from 7 to 16 MeV.

Theoretical analyses and evaluation of recent elastic scattering measurements¹² yield cross sections which are 15% to 20% lower than ENDF/B-V from 10-14 MeV, a result which could affect neutronics calculations for the first wall region. Inelastic scattering cross sections to discrete levels have been reduced, based on the comparison of calculations to experimental data, and given at more incident energies than for Version V. The capture cross section is very small, less than 10 mb below 100 keV.

Several new measurements for the (n,p) and (n,a) reactions have resulted in a reduction of these cross sections from the ENDF/B-V values by 25% near 15 MeV. Using results from ENDF/B-VI will result in gas production cross sections significantly lower than previously obtained. Isotropic angular distributions have been assumed for all outgoing particles in the continuum, and recoil particle energy distributions are not given. Thus, File 5 is used to describe outgoing particle energy distributions, and no File 6 (energy-angle correlated data) is given.

Uncertainty information is given in File 33, based on the results of least-squares evaluation programs and the best judgments of the evaluators.

n + Cr EVALUATIONS (HETRICK+, ORNL)

Chromium is present primarily in stainless steel, still the structural material of choice in most fusion reactor designs. The evaluation for chromium for ENDF/B-VI is a total revision of Version V, incorporating new experimental data and sophisticated Hauser-Feshbach calculations¹³ which include effects of neutrons emitted in the precompound mode. Individual evaluations are given for each of the four stable isotopes for the first time in ENDF/B-VI, with the ⁵²Cr evaluation being a joint US-Japanese effort¹⁴. Since radiation damage calculations are very important for the structural materials, isotopic evaluations for the first time allow accurate calculations of heating effects, displacement damage, kerma factors, etc. which were not possible with a composite evaluation for the natural material. Such detailed evaluations are possible only with a combination of reliable experimental data and advanced multistep Hauser-Feshbach compound

precompound model codes, which provide the ability to simultaneously calculate cross sections for all reaction channels, thus insuring consistency among the resulting cross sections. Such calculated results, benchmarked against experimental data, provide the only reliable means for interpolating and extrapolating to energy regions and reactions for which the data base is inadequate. The code TNG¹⁵ was used for the chromium analyses (as well as the iron, nickel, copper, and lead evaluations). As part of the evaluations, efforts are made to insure that a combination of the individual isotopic evaluations leads to a faithful representation of experimental data for the natural material. The evaluation of the chromium isotopes is covered in more detail in another paper at this conference and will be only briefly summarized here.

For the total cross section, results of a detailed resonance parameter analysis are available for ^{50,52,53}Cr¹⁶, with the parameters for ⁵⁴Cr being taken from Ref. 17. Above the resonance region, a recent high resolution total cross section measurement for natCr¹⁸ is utilized for each isotope. Since the resonance region evaluation for Version V was done in the early 70's, significant improvements are found from Version V to Version VI.

For the minor isotopes ^{50,54}Cr (combined abundance <7%), few experimental data are available for the various reaction channels, and the evaluations are based primarily on calculated results. (n,p) and (n,a) cross section and spectral data, important for radiation damage calculations, are rather sparse for ^{52,53}Cr, and the evaluations rely heavily upon calculated results. Inelastic scattering, (n,2n) and neutron emission data are somewhat more plentiful, but not always consistent. Detailed comparisons of the calculations and available data are given in Ref. 13. Energy spectra for all outgoing particles, including neutrons, photons, charged particles, and heavy residual nuclei are given in the new File 6 format, allowing detailed calculations of radiation damage effects, heating, etc.

n + Mn EVALUATION (SHIBATA+, JAERI)

The evaluation for ⁵⁵Mn has been done by K. Shibata of JAERI as part of an ORNL-JAERI collaboration for ENDF/B-VI. Manganese is found in aluminum alloys, which are used as structural materials, and the ⁵⁵Mn(n,2n) reaction is used as a dosimeter. The resonance region covers the energy range up to 100 keV, with the parameters taken from Mughabghab et al.¹⁷, except for the four lowest resonances, where the parameters were taken from Ref. 19. Above the resonance region, the total cross section was obtained from a least-squares fit to available data. For ENDF/B-VI a direct interaction component was

included for inelastic scattering to fourteen low-lying levels, thereby raising the cross sections for these levels for neutron energies above about 6 MeV. Fig. 7 shows a comparison of the new evaluation with ENDF/B-V and JENDL-2.

Figure 7. Comparison of JENDL-2, ENDF/B-V and experimental data with new ENDF/B-VI evaluation for inelastic scattering to the 0.126 MeV level of ^{55}Mn .

The (n,α) cross section was lowered by 20% at 14.5 MeV to 29 mb, while the (n,p) cross section of 36 mb was retained. The $(n,2n)$ dosimetry cross section is essentially unchanged from Version V. The total helium and hydrogen gas production cross sections at 14.5 MeV are small (32 and 82 mb respectively). Energy-angle correlated data are given in File 6 for outgoing neutrons, gamma rays, charged particles and recoil nuclei, with non-isotropic angular distributions given only for the neutrons. Energy balance has been checked and deviations are less than 1%.

$n + \text{Fe}$ EVALUATIONS (FU+, ORNL)

Iron is the primary constituent of stainless steel, and is also important by itself as a structural material. Separate isotopic evaluations are given for ^{54}Fe , ^{56}Fe , ^{57}Fe , and ^{58}Fe for the first time in ENDF/B-VI, with the evaluations for ^{54}Fe , ^{57}Fe , and ^{58}Fe being essentially new work. With isotopic evaluations comes the advantage of accurate Q-values for the various reactions, rather than an average Q-value corrected for elemental effects used in previous versions of ENDF/B. This allows very accurate calculations of heating and kerma factors important for fusion reactor design problems. Since the iron evaluations are covered in another paper at this conference, only a brief summary will be given here.

For ^{56}Fe , results of a detailed new Reich-Moore resonance parameter analysis are available²⁰, extending the resonance region to 850 keV. From these resonance parameters the elastic scattering angular distributions can be calculated, if desired, thus obviating the need for inclusion of very detailed Legendre representations of resonance region angular distributions.

Based on analysis of differential and integral data, the inelastic scattering cross section has been reduced by an average of 8% from 3 to 8 MeV, and 3% from 8 to 20 MeV from ENDF/B-V.2. The $(n,2n)$ cross section has also changed by up to 3% for Version VI, based on the results of calculations compared with experimental data. Anisotropic angular distributions for the secondary neutrons in the $(n,2n)$, (n,np) + (n,pn) and (n,na) + (n,an) reactions have also been included. These changes, along with those in the resonance region and the inclusion of energy-angle correlated data in File 6 constitute the major changes in ^{56}Fe for ENDF/B-VI. Details of these modifications are given in Ref. 21.

The $^{54,56}\text{Fe}(n,p)$ cross sections are important dosimetry reactions, and were evaluated as part of a simultaneous Bayesian analysis²² of twelve correlated dosimetry reactions. For the first time, detailed energy-angle correlated spectral data are given for the hydrogen and helium producing reactions, allowing accurate calculations of energy deposition, heating, and other quantities of interest to the fusion designer.

Energy balance (i.e., insuring that the sum of the energies of all outgoing particles (neutrons, charged particles, gamma-rays and heavy recoil nuclei), is equal to the incident neutron energy plus the Q value of the reaction), has been checked for all reactions and agreement is better than 1% for all incident neutron energies.

n + Co EVALUATION (GUENTHER+, ANL)

Fusion interest in cobalt is primarily as a dosimeter. The (n,γ) reaction is appropriate for low energy neutrons, and the $(n,2n)$ reaction, with a Q-value of -10.46 MeV, is appropriate for high energy neutrons. A complete re-evaluation of ^{59}Co has been performed for ENDF/B-VI, and is documented in Ref. 23, so only the highlights will be summarized here. The total cross section is described by resonance parameters up to 100 keV, and by an energy averaged pointwise cross section from 100 keV to 20 MeV. The main differences from Version V are from 2.5 to 5.0 MeV, where differences of 10-15% are obtained.

The inelastic scattering cross sections have more levels given, a direct interaction component added for Version VI, and are larger by 10-20% than the Version V results. Based mainly on experimental results and a careful uncertainty analysis, the $(n,2n)$ cross section is about 10% lower above 10 MeV than the Version V evaluation. The small (n,γ) cross section suffers from a lack of experimental data and so is not well defined, and lies significantly below the Version V result. Until the data situation is clarified, its use as a dosimeter may not be appropriate.

A generalized least squares evaluation was performed for the (n,α) cross section for Version VI, and the results were found to agree with Version V within a few percent. A similar analysis was done for the (n,p) reaction, with the result that Version VI is larger than Version V by as much as 30% above 10 MeV.

n + Ni EVALUATIONS (HETRICK+, ORNL)

Nickel is the third primary component of stainless steel, proposed as the major structural and shielding material in current fusion reactor designs. It has two major isotopes (58 and 60), and three minor isotopes (61,62,64) which make up 5.6% of natural nickel. For Version VI, isotopic evaluations are given for the first time. The new evaluations for nickel are also treated in another paper at this conference, and details of comparisons of the evaluated cross sections with measured data are available in Ref. 25, so only a brief review will be given here.

Evaluations for the minor isotopes are based primarily on results of model calculations, with especial attention paid to the large $(n,2n)$ cross sections. The total cross section for natural nickel is used for the minor isotopes, except for the resonance region, where resonance parameters for the individual isotopes are given in the Reich-Moore format. Resonance region parameters for $^{58,60}\text{Ni}$ are taken from extensive Reich-Moore analyses of capture, transmission and scattering data, and

extend to 810 keV for ^{58}Ni (Ref. 26) and 450 keV for ^{60}Ni (Ref. 27). The resonance parameter regions for $^{58,60}\text{Ni}$ contain significant improvements over Version V, which was retained from Version III work done in the early 70's.

The total inelastic scattering cross section has been revised, based on new data both for the individual discrete levels in $^{58,60}\text{Ni}$, for the total inelastic itself. Energy-angle correlated spectral data for outgoing neutrons, gamma-rays, charged particles and recoil nuclei are given in File 6 formats.

The cross section for the $^{58}\text{Ni}(n,p)$ reaction is commonly used for dosimetry, and evaluation of this cross section is taken from a Bayesian analysis of twelve dosimeter cross sections.²²

n + Cu EVALUATIONS (HETRICK+, ORNL)

Fusion interest in copper is primarily as a magnet and dosimeter material. For ENDF/B-VI, separate evaluations are given for the two isotopes, $^{63,65}\text{Cu}$. Since a primary interest in copper is in the magnet region, where the neutrons have mostly attenuated down to less than 1 MeV energy, attention has been given to cross sections for high energy gamma rays produced by low energy neutron capture in copper. Resonance parameters have been utilized for Version V, and will be checked for Version VI. The evaluation for $^{63,65}\text{Cu}$ is covered in more detail in another paper at this conference, and detailed comparisons of evaluated results and experimental data can be found in Ref. 28.

Major improvements for Version VI are in the spectra for emitted neutrons, which now include effects of neutrons emitted in the precompound mode. This has the effect of increasing the number of neutrons emitted above about 6 MeV, and brings calculated results in good agreement with measured data. Requiring energy balance imposes strict conditions on the amount of gamma-ray production relative to particle production. For copper, it appears that to ensure energy conservation, most of the existing $(n,X\gamma)$ measurements provide cross sections which are too large to be consistent with energy balance and the total cross section.

The cross sections for the $^{63}\text{Cu}(n,\alpha)$ and $^{63,65}\text{Cu}(n,2n)$ reactions are commonly used for dosimetry, and evaluation of these cross sections are taken from a Bayesian analysis of twelve dosimeter cross sections.²²

n + Nb EVALUATION (SMITH+, ANL)

Niobium may exist in several places in a fusion reactor; as a structural material, in the blanket, and in the superconducting magnets. For this reason, the complete energy range from thermal to 20 MeV is of importance. The

evaluation to be included in ENDF/B VI is documented in Ref. 29, and will be briefly reviewed here. Resonance parameters are used from 8 keV to 20 MeV. The total cross section is quite well known, and agrees within uncertainties with Version V. The inelastic scattering cross sections to individual levels do not contain any direct interaction contributions, and this effect is absorbed in the continuum inelastic scattering cross section.

New experimental data for the $^{93}\text{Nb}(n,2n)$ reaction resulted in an increase in this cross section by 10-15%. The energy spectrum is represented in File 5 by an energy-dependent temperature in the Maxwellian model. The radiative capture cross section is in good agreement with Version V, there being no new data for this reaction. The proton and alpha production cross sections are small, and generally in agreement with Version V. Energy conservation was checked, and adjusted to a minimum of 10%.

The $^{93}\text{Nb}(n,n')^{93}\text{Nb}$ reaction is a prime dosimeter reaction. Evaluation of this cross section was hindered by lack of sufficient experimental data, and the cross section was derived from results of a model calculation.⁴⁴

n + W EVALUATION (YOUNG+, LANL)

The Tokamak Ignition/Burn Experimental Reactor (TIBER-II) design incorporates a tungsten shield between the plasma region and the superconducting toroidal field coils. The relative sensitivity of damage parameters of the superconducting magnet to W reaction cross sections is approximately 5.³⁰ As cryogenic cooling costs can be very large, there is considerable motivation to minimize expensive overdesign of the cooling system due to ill-defined uncertainties on the W cross section data. The existing ENDF/B-V.2 W evaluation³¹ does not include covariance data, and it has been necessary in the design studies to assume an overly conservative posture on the W data uncertainties. Therefore, an effort is underway to incorporate covariance information in the existing ENDF/B-V.2 elemental tungsten evaluation and to include the results in ENDF/B-VI.³²

n + Pb EVALUATIONS (FU, ORNL)

Lead is a primary candidate for a neutron multiplier in the blanket of a fusion reactor, and thus the main focus of the evaluations for ENDF/B-VI were on the neutron multiplication reactions $(n,2n)$ and $(n,3n)$, and their associated energy-angle distributions. Since the $(n,2n)$ Q-values for the major isotopes of lead (206, 207 and 208) are quite different, isotopic evaluations are given for lead to eliminate the problems with adopting an

"average" Q-value for this reaction, as done for Version V. Utilizing the isotopic evaluations allows accurate heating calculations to be performed for the blanket region. Lead is treated in more detail in another paper at this conference, so only the major changes are noted here.

The evaluated $(n,2n)$ cross sections are based on theoretical calculations done with the multistep Hauser-Feshbach/precompound code TNG¹⁵ which utilizes a sophisticated compound precompound model whose parameters were fine-tuned to agree with recent neutron $(n,2n)$ cross section measurements and (n,Xn) spectral data at 14 MeV. The resulting energy-angle correlated data utilize the new File 6 formats to preserve the detail of the calculated results. In particular, significantly better agreement is found between the File 6 (n,Xn) spectra and available data, compared with Version V. This is due to incorporation of a better treatment of precompound particle emission in the model codes. Fig. 8 shows a comparison of the ENDF/B-VI evaluated spectra, compared with available data.

Figure 8. Comparison of angle-integrated neutron emission data with results of the TNG calculation used for ENDF/B-VI.

NEW DATA REQUIREMENTS

Performing evaluations of cross sections for the individual isotopes of a material has a number of advantages, including accurate Q-values, inclusion of particular dosimetry and activation cross sections in the general purpose files, and a more faithful representation of the physics of the cross sections. During this process, done for the first time for ENDF/B-VI, it became apparent that there are many "holes" in the experimental data base upon which the isotopic evaluations are dependent. Cross section data for the natural material, i.e., the sum of the cross sections for each of the isotopes, weighted by their natural abundance, is useful in the global sense for checking the consistency of the isotopic results. However, model calculations, which are playing an increasingly important role in evaluation work, are by definition done for the isotopes of a material, and it is essential to have isotopic experimental data against which to benchmark the calculations. Without such data, calculations must be performed for all isotopes, weighted by the abundances, and summed to compare with experimental data for the natural material. Such comparisons are often inconclusive. Thus, the new era opened by isotopic evaluations for ENDF/B-VI will require significant new experimental data to verify the quality of the individual evaluations.

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