CONF-871186--4

CONF-871186--4

DE88 002535

# DESCRIPTION OF EVALUATION FOR $^{63,65}Cu$ FOR ENDF/B-VI

D. C. Larson, D. M. Hetrick, and C. Y. Fu
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831-6356

To be published in proceedings of IAEA Specialists' Meeting on the International Nuclear Data Library for Fusion Reactor Technology, Vienna, November 16-18, 1987.

DESCRIPTION OF EVALUATIONS FOR $^{63,65}$Cu FOR ENDF/B-VI*

D. C. Larson, D. M. Hetrick and C. Y. Fu
Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831-6356
U. S. A.

ABSTRACT

Isotopic evaluations for $^{63,65}$Cu performed for ENDF/B-VI are briefly reviewed. The evaluations are based on analysis of experimental data and results of model calculations which reproduce the experimental data. Evaluated data are given for neutron-induced reaction cross sections, angular and energy distributions, and for gamma-ray production cross sections associated with the reactions. File 6 formats are used to represent energy-angle correlated data and recoil spectra. Uncertainty files are included for the major cross sections. Full evaluations are given for $^{63,65}$Cu.

## 1. INTRODUCTION

Separate evaluations have been done for each of the stable isotopes of copper. In this report we briefly review the structure of the evaluations, describe how the evaluations were done, and note the major pieces of data considered in the evaluation process. Experimental data references were obtained primarily from CINDA, but also from the literature and reports. The data themselves were mostly obtained from the National Nuclear Data Center at Brookhaven National Laboratory and, occasionally, from the literature and reports. The TNG nuclear model code (FU80,SH86), a multistep Hauser-Feshbach code which includes precompound and compound contributions to cross sections, angular, and energy distributions in a self-consistent manner, calculates gamma-ray production, and conserves angular momentum in all steps, was the primary code used for these evaluations. Extensive model calculations were performed with the goal of simultaneously reproducing experimental data for all reaction channels with one set of parameters. This ensures internal consistency and energy conservation within the evaluation. In the case of reactions for which sufficient data were available, a Bayesian analysis using the GLUCS code (HE80) was frequently done, using ENDF/B-V or the TNG results as the prior. In cases where insufficient data were available for a GLUCS analysis and the available data were deemed to be accurate, but in disagreement with the TNG results, a line was drawn through the data and used for the evaluation. A hand-drawn line was also used for cross sections where resonant structure was felt to be important, but resonance parameters were not included. The final evaluation is thus a combination of TNG results (used where extrapolation and interpolation was required and where data sets were badly discrepant), GLUCS results (used where sufficient data existed to do an analysis), and hand-drawn curves.

*Research sponsored by the Office of Basic Energy Sciences, U.S. Department of Energy, under contract DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

In Section 2 the resonance parameters are discussed; Section 3 contains a description of the major cross sections included in the evaluation; Section 4 is devoted to angular distributions; and Section 5 to energy-angle correlated distributions. Section 6 describes the uncertainty files.

Much of this information is abstracted from Ref. HE84, a report devoted to a description of the calculations for $^{63,65}$Cu. As of this writing, the various pieces of the evaluations are being reviewed, modified if necessary, and assembled into full evaluations using the ENDF/B-VI formats, and will be submitted by May 1988 to the Cross Section Evaluation Working Group (CSEWG) for use in ENDF/B-VI.

## 2. RESONANCE PARAMETERS

Resonance parameters for $^{63,65}$Cu are taken from the compilation of Mughabghab (MU81). They cover the energy range from 0.402 to 153 keV for $^{63}$Cu and 0.230 to 149 keV for $^{65}$Cu. Average capture widths are used for neutron energies above about 50 keV. The resonance parameters should be processed with the Reich-Moore formalism.

## 3. CROSS SECTIONS

This section contains a brief discussion of the cross section files in the evaluations for $^{63,65}$Cu. The total cross section above the resonance region was taken from the isotopic experimental data described in Ref. PA77. Cross sections for inelastic scattering to discrete levels are taken from the model calculations, which included a direct interaction component and generally are in good agreement with the available experimental data. A continuum was used to represent the inelastic scattering cross section for excitation energies above the discrete levels.

The $^{63}$Cu($n$,$p$) reaction has very little data, but the calculated result agrees with the data of Qaim and Molla (QA77) and Allan (AL61). The $^{63}$Cu(n,$\alpha$) reaction has much data and is a common dosimetry cross section. The evaluated cross section for this reaction is taken from the results of a generalized least squares analysis (FU82) of twelve dosimetry reactions, which included ratio data and covariance information. The $^{65}$Cu(n,p) cross section has abundant data and is well reproduced by the TNG calculations, which are used for the evaluation. The $^{65}$Cu($n$,$\alpha$) cross section is small, and the experimental data are in disagreement. The calculated results are used for the evaluation.

The $^{63,65}$Cu($n$,2$n$) cross sections are well defined by experimental data, and the results of a GLUCS analysis was used for the evaluation. Other tertiary reaction cross section data are reproduced by the TNG calculations and are included in each evaluation.

The capture cross sections for $^{63,65}$Cu are defined by the resonance parameters and a smooth background below 150 keV, and by smooth experimental data above the resonance region. Guided by experimental data and the TNG calculation, a smooth line was drawn through the data and used for the evaluation.

## 4. ANGULAR DISTRIBUTIONS

Elastic scattering angular distributions were obtained from an optical potential derived by fitting experimental angular distribution data for $^{63,65,nat}Cu$ with GENOA (PE67). A compound elastic term was included for neutron energies below 5 MeV. Since very little difference was observed between the experimental data for $^{63}Cu$ and $^{65}Cu$, one potential was derived and used for both evaluations. Figures 1 and 2 show a comparison of the calculated and experimental data for $E_n$ = 8.05 and 14.5 MeV. The angular distributions are represented as Legendre coefficients and given in File 4/2. Angular distributions for inelastic scattering to excited levels and the continuum are given as Legendre coefficients in File 6.

## 5. ENERGY-ANGLE CORRELATED DISTRIBUTIONS (FILE 6)

Neutron emission spectra, as a function of outgoing energy and angle, are given in File 6. For copper, the measurements of Morgan et al. (MO79) give the outgoing neutron spectra at one angle for several incident neutron energies between 1 and 20 MeV, while the measurements of Hermsdorf et al. (HE75), Salnikov et al. (SA75) and Takahashi et al. (TA83) give the outgoing spectra at several angles but only near 14.5-MeV incident energy. Such complementary measurements allow a good determination of the model parameters for the calculations and, thereby, reliable interpolation and extrapolation to energies where there are no data. For these reasons, as well as ensuring energy conservation, results of the model codes, expressed in File 6 formats, were used for the evaluations. The angular distributions were expressed in terms of Legendre coefficients, while the energy distributions were expressed as tabulated probability distributions. Figures 3 and 4 show the neutron emission data of Morgan et al. (MO79) compared with the TNG calculated results for the incident neutron-energy bins from 9 to 10 MeV and 12.5 to 15 MeV, respectively. The data of Takahashi et al. (TA83) became available after the evaluation was done but are found to be in good agreement with the evaluation.

Proton and alpha emission spectra for both isotopes are available (GR79) at an incident energy of 14 MeV. The calculations are in excellent agreement with the measured spectra, including reproducing the observed sub-coulomb emission of protons. Figure 5 shows a comparison of the measured data for proton emission from $^{63}Cu$ with the TNG results. However, the observed sub-coulomb emission of alphas is not well reproduced by the TNG calculations. Figure 6 shows a comparison of the measured data for $^{63}Cu$ alpha emission, compared with the TNG results. These calculated results (at several incident neutron energies) are used for the evaluation and are placed in File 6, with isotropic angular distributions assumed.

Tabulated energy distributions for the recoil spectra associated with the various particle producing reactions are also given in File 6, and isotropic angular distributions are assumed.

Gamma-ray production spectra were also calculated as part of the TNG calculations, and compared with data sets of Rogers et al. (RO77), Morgan (MO79), Dickens et al. (DI73), and Chapman (CH76) (see Ref. HE84). Figure 7 shows a comparison of the measured data of Dickens et al. with the TNG results around 14-MeV incident energy. Note that without the use of the calculated results, a significant amount of cross section below 700-keV gamma-ray energy would not be accounted for due to gamma rays from the $(n,2n)$ reaction. Since calculated results are generally used for the evaluation, energy conservation is ensured. Sections of File 6 were used to represent the gamma-ray emission spectra for the individual reactions, and isotropic angular distributions were assumed. The cross sections for the gamma-ray production are given in corresponding sections of File 3.

As an example of the usage of File 6, consider the $^{65}Cu(n,n\alpha)$ reaction. In File 6/22, constant yields are given for the outgoing neutron, alpha and $^{61}Co$ residual, and an energy dependent yield is used for the gamma rays associated with the $(n,n\alpha)$ reaction. Normalized energy distributions are given for each outgoing product, but only the outgoing neutron has a non-isotropic angular distribution. The cross section to be used for normalization is taken from File 3/22.

Capture gamma-ray cross sections and spectra are given in Files 13 and 15, respectively, and are based on a combination of experimental data and calculation.

## 6. UNCERTAINTY INFORMATION

Uncertainty files are given only for the cross sections in File 3, and not for the resonance parameters, energy distributions or angular distributions. Fractional and absolute components, correlated only within a given energy interval, are based on scatter in experimental data and estimates of uncertainties associated with the model calculations.

## REFERENCES


AL61 D. L. Allan, *Nuclear Physics* 24, 274 (April 1961).

CH76 G. T. Chapman, *The Cu(n,xγ) Reaction Cross Section for Incident Energies Between 0.2 and 20.0 MeV*, ORNL/TM-5215 (1976).

CO58 J. H. Coon, R. W. Davis, H. E. Felthauser, D. B. Nicodemus, *Phys. Rev.* 111, 250 (1958).

DI73 J. K. Dickens, T. A. Love, and G. L. Morgan, *Gamma-Ray Production Due to Neutron Interactions with Copper for Incident Neutron Energies Between 1.0 and 20.0 MeV: Tabulated Differential Cross Sections*, ORNL-4846 (1973).

FU80 C. Y. Fu, "A Consistent Nuclear Model for Compound and Precompound Reactions with Conservation of Angular Momentum," *p. 757 in Proc. Int. Conf. Nuclear Cross Sections for Technology, Knoxville, TN, Oct. 22-26, 1979*, NBS-594, U.S. National Bureau of Standards. also, ORNL/TM-7042 (1980).

FU82 C. Y. Fu and D. M. Hetrick, "Experience in Using the Covariance of Some ENDF/B-V Dosimetry Cross Sections: Proposed Improvements and

Addition of Cross-Reaction Covariances," p. 877 in *Proc. Fourth ASTM-EURATOM Symp. on Reactor Dosimetry, Gaithersburg, Md., March 22-26, 1982, U.S. National Bureau of Standards*.

GR79 S. M. Grimes, R. C. Haight, K. R. Alvar, H. H. Barschall, and R. R. Borchers, *Phys. Rev.* C19, 2127 (1979).

HA77 R. C. Haight and S. M. Grimes, Lawrence Livermore Laboratory Report UCRL-80235 (1977).

HE75 D. Hermsdorf, A. Meister, S. Sassonoff, D. Seeliger, K. Seidel, and F. Shahin, *Zentralinstitut Fur Kernforschung Rossendorf Bei Dresden*, Zfk-277 (U), (1975).

HE80 D. M. Hetrick and C. Y. Fu, *GLUCS: A Generalized Least-Squares Program for Updating Cross Section Evaluations with Correlated Data Sets*, ORNL/TM-7341, ENDF-303 (October 1980).

HE84 D. M. Hetrick, C. Y. Fu, D. C. Larson, *Calculated Neutron-Induced Cross Sections for $^{63,65}$Cu from 1 to 20 MeV and Comparisons with Experiments*, ORNL/TM-9083, ENDF-337 (August 1984).

HO69 B. Holmqvist and T. Wiedling, Atomic Energy Company, Studsvik, Nykoping, Sweden, Report AE-366 (1969).

MO79 G. L. Morgan, *Cross Sections for the Cu(n,xn) and Cu(n,xα) Reactions Between 1 and 20 MeV*, ORNL-5499, ENDF-273 (1979).

MU81 S. F. Mughabghab, M. Divadeenam, and N. E. Holden, *Neutron Cross Sections, Vol. 1, Neutron Resonance Parameters and Thermal Cross Sections, Part A, Z=1-60*, Academic Press (1981).

PA77 M. S. Pandey, J. B. Garg, and J. A. Harvey, *Phys. Rev.* C15, 600 (February 1977).

PE67 F. G. Perey, Computer code GENOA, Oak Ridge National Laboratory, unpublished (1967).

QA77 S. M. Qaim and N. I. Molla, *Nucl. Phys.* A283, 269 (June 1977).

RO77 V. C. Rogers, D. R. Dixon, C. G. Hoot, D. Costello, and V. J. Orphan, *Nucl. Sci. Eng.* 62, 716 (1977).

SA75 O. A. Salnikov, G. N. Lovchikova, G. V. Kotelnikova, A. M. Trufanov, N. I. Fetisov, *Energy Spectra of Inelastically Scattered Neutrons for Cr, Mn, Fe, Co, Ni, Cu, Y, Zr, Nb, W, and Bi*, IAEA Nuclear Data Section, Karntner Ring 11, A-1010 Vienna (July 1974).

SH86 K. Shibata and C. Y. Fu, *Recent Improvements of the TNG Statistical Model Code*, ORNL/TM-10093 (1986).

TA83 A. Takahashi, J. Yamamoto, T. Murakami, K. Oshima, H. Oda, K. Fujimoto, M. Ueda, M. Fukazawa, Y. Yanagi, J. Miyaguchi, and K. Sumita, Oktavian Report A-83-01, Osaka University, Japan (June 1983).

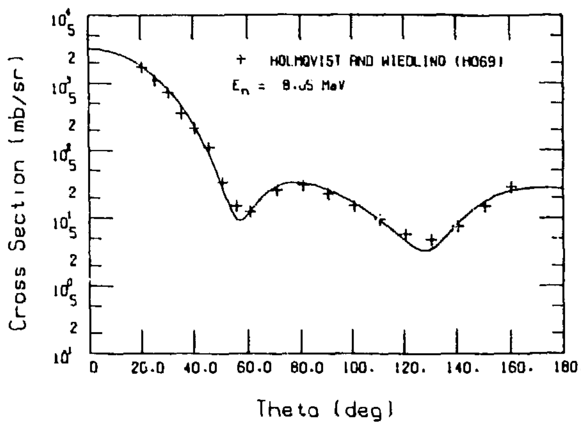


Fig. 1. Comparison of final optical-model fit with elastic scattering data of Holmqvist and Wiedling (HO69) for Cu at 8.05 MeV.

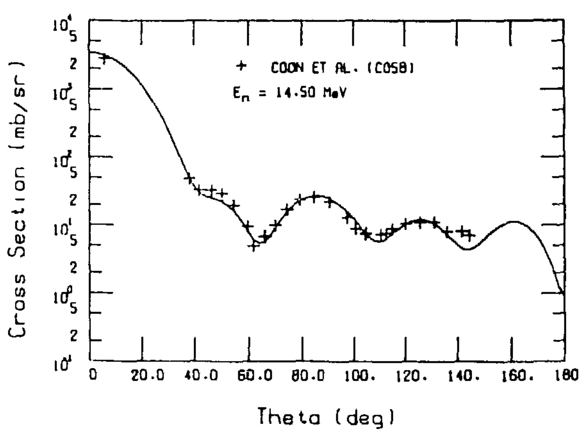


Fig. 2. Comparison of final optical-model fit with elastic scattering data of Coon et al. (CO58) for Cu at 14.5 MeV.

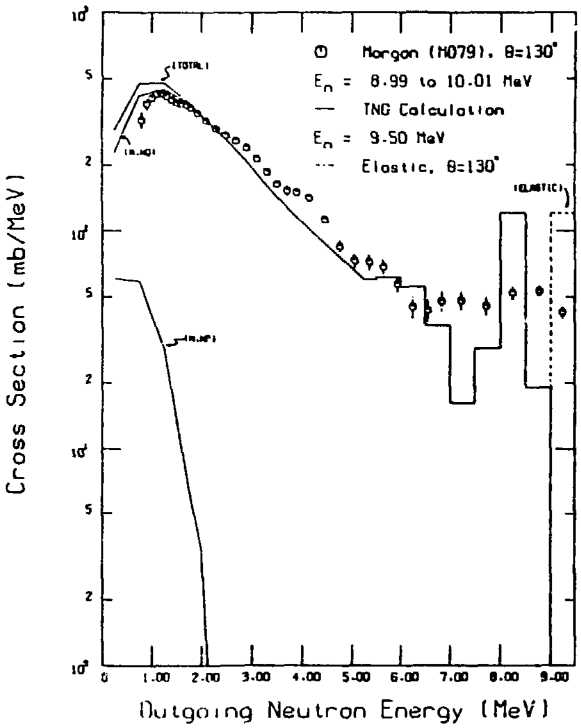


**Fig. 3.** **Neutron emission spectra from the TNG calculation compared with the data of Morgan (MO79).** The calculated elastic cross section ($\theta$=130°) is not smeared and is not in phase with the data. Contributions from the various neutron-producing components are shown (they sum to the total). The curve labeled $(n,np)$ includes the $(n,pn)$ component.

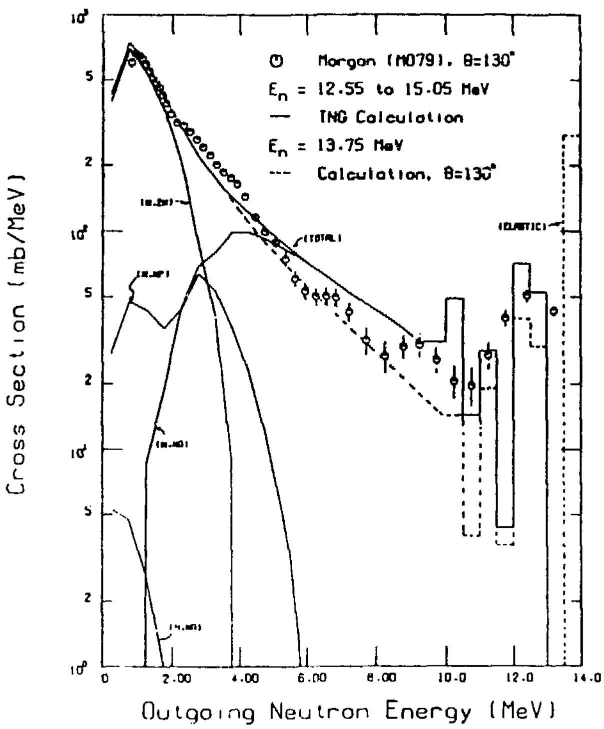


**Fig. 4.** **Neutron emission spectra from the TNG calculation compared with the data of Morgan (MO79).** Also shown is the calculation for $\theta$=130°. The calculated elastic cross section is not smeared and is not in phase with the data. Contributions from the various neutron-producing components are shown (they sum to the total). The curves labeled $(n,np)$ and $(n,n\alpha)$ include the $(n,pn)$ and $(n,\alpha n)$ components, respectively.

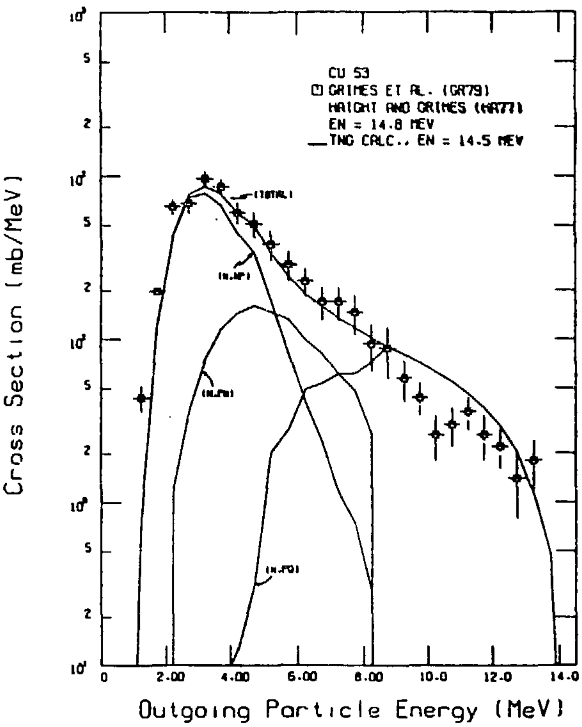


**Fig. 5.** Comparison of calculated and experimental proton production spectra for $^{63}Cu$. The measurement was taken at an incident energy of 14.8 MeV; the TNG calculation was for $E_n$ = 14.5 MeV.

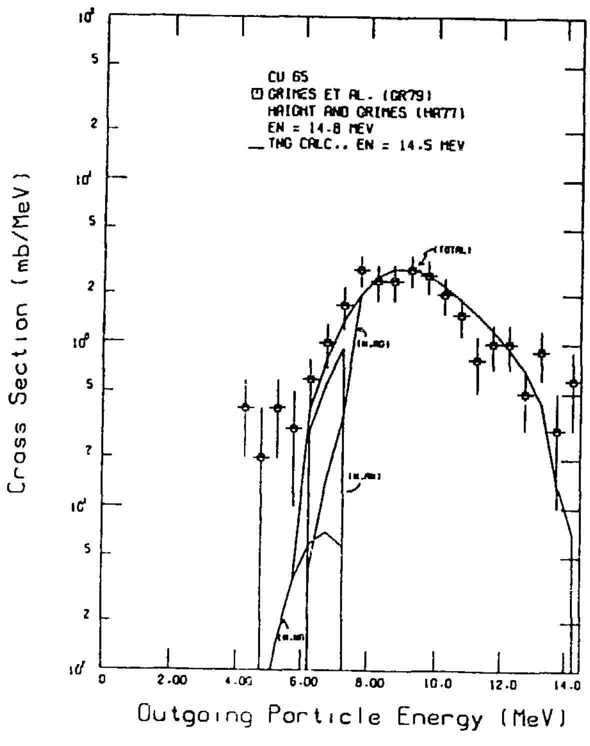


**Fig. 6.** Comparison of calculated and experimental alpha production spectra for $^{65}Cu$. The measurement was taken at an incident energy of 14.8 MeV; the TNG calculation was for $E_n$ = 14.5 MeV.

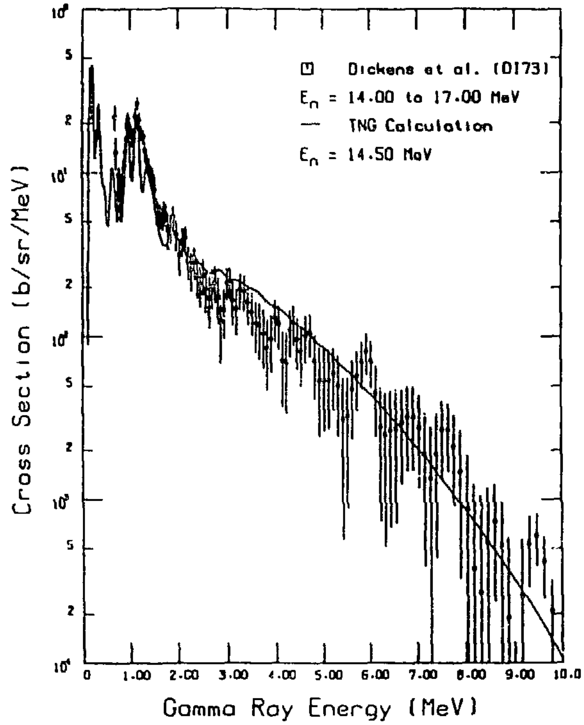


Fig. 7. Secondary gamma-ray spectra versus gamma-ray energy from the TNG calculation (incident energy $E_n$ = 14.5 MeV) compared with the data of Dickens et al. (DI73).