Evaluation of Cross Sections of ^{63}Cu and ^{65}Cu for JENDL High Energy File

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Cross sections of ^{63}Cu and ^{65}Cu for neutron and proton induced reactions have been evaluated up to 3 GeV for the High Energy File of Japanese Evaluated Nuclear Data Library (JENDL-HE). Different theoretical model codes were employed in this evaluation. For intermediate energy region between 20 and 150 MeV, GNASH based on statistical Hauser-Feshbach and preequilibrium models was used. Transmission coefficients calculated with DWUCK were used in the GNASH calculations of particle and photon emission cross sections and isotope production cross sections up to 150 MeV. The input parameters for the model codes were determined through analysis of experimental data in this energy region. For high-energy region between 150 MeV and 3 GeV, the JQMD-GEM code based on Quantum Molecular Dynamics (QMD) with statistical decay model (GEM) was employed. For energy region below 20 MeV, the existing JENDL-3.3 data were adopted. Several isotope production cross sections above 20 MeV were analyzed using the GMA code based on the generalized least-squares method or empirical fits in which experimental data were available. The results were compared with available experimental data as well as integral experiments such as thick target neutron yields.

1. Introduction

The high-energy nuclear data are important for nuclear design and safety analysis in accelerator applications such as the J-PARK project jointly conducted by JAERI and KEK. The High Energy Nuclear Data Evaluation Working Group in the Japanese Nuclear Data Committee (JNDC) continues nuclear data evaluation for neutron and proton induced reactions for energies up to 3 GeV towards completion of JENDL High Energy File (JENDL-HE).[1)] Copper is one of the first priority nuclides requested by user's community in JNDC. Guided by experimental data, we have performed a comprehensive set of nuclear model calculations for neutron and proton reactions on ^{63}Cu and ^{65}Cu for incident energies between 20 MeV and 3 GeV.

Several theoretical model codes were employed in this evaluation. For intermediate energies between 20 and 150 MeV, The GNASH code[2)] based on statistical Hauser-Feshbach and preequilibrium models was used. The Distorted Wave Born Approximation (DWBA) code DWUCK[3)] was used to determine direct-interaction cross sections needed as input for the GNASH calculations of particle and photon emission cross sections and isotope production cross sections up to 150 MeV. For high energies between 150 MeV and 3 GeV, the JQMD-GEM code[4)] based on Quantum Molecular Dynamics (QMD) with statistical decay model (GEM) was employed. For energies below 20 MeV, the existing JENDL-3.3[5)] data were adopted. Several isotope production cross sections above 20 MeV were analyzed using the GMA code[6)] based on the generalized least-squares method or empirical fits in which experimental data were available. This evaluation scheme is shown in **Fig. 1**. The optical-model parameters, discrete energy levels, and other parameters needed in the GNASH calculations were determined through analysis of experimental data in this energy region, and are discussed in Chapter 2. Comparison of calculated results to measured data including integral experiments such as thick target neutron yields (TTY) is given in Chapter 3.

2. Parameter Determination

2.1 Optical-model parameters

For high-energy data evaluation, the optical-model parameters are essential input for the nuclear model calculations, much effort was spent to determine good sets of neutron optical-model parameters for n + ^{63,65}Cu and proton optical-model parameters for p + ^{63,65}Cu so as to reproduce the elastic scattering angular-distribution data available, as well as the nonelastic, elastic and total cross sections. To obtain the neutron optical-model parameters, the experimental natural total cross-section data sets selected for fitting were those of Guenther et

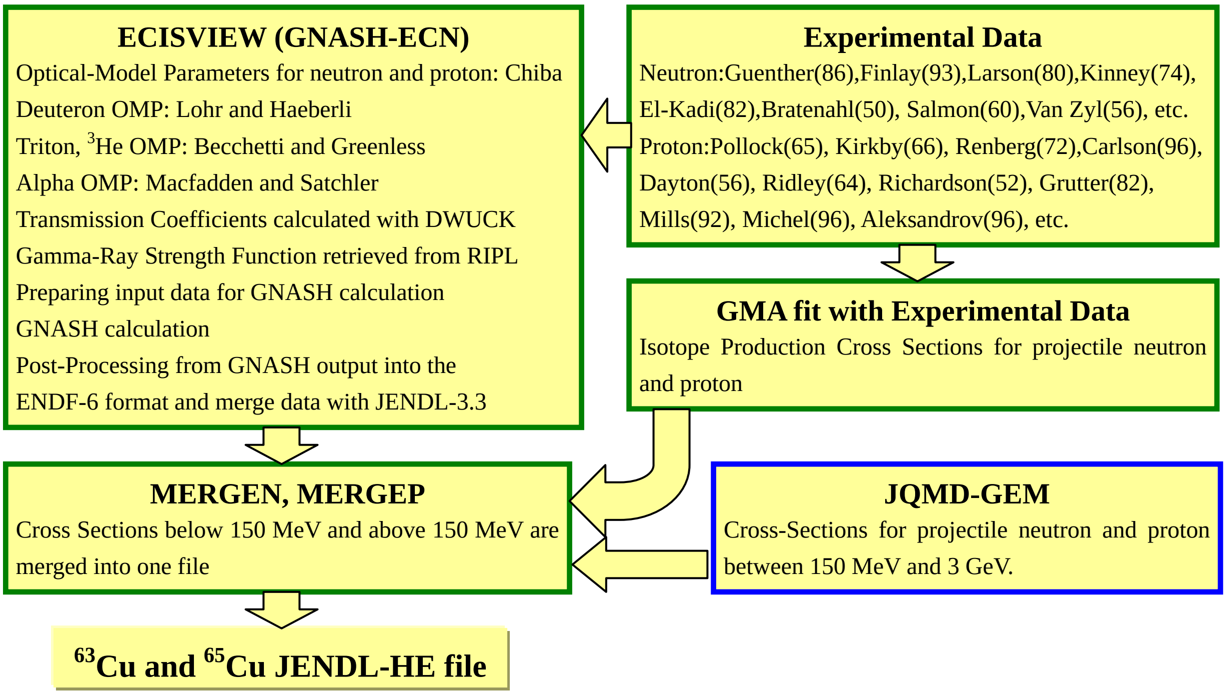


Fig. 1 Evaluation scheme of nuclear data evaluation for Cu

al.[7] from 1.2 to 4.5 MeV; Larson et al.[8] from 4.5 to 5.3 MeV; Finlay et al.[9] from 5.3 to 600 MeV; and Schimmerling et al.[10] from 379 to 1731 MeV. The experimental angular-distribution data were taken from those of Guenther et al. at 2.0, 2.5, 3.0, and 3.9 MeV; Kinney and Perey[11] at 5.5, 7.0, and 8.5 MeV; El-Kadi et al.[12] at 7.96, 9.94, 11.93, and 13.92 MeV; Bratenahl et al.[13] at 84 MeV; Salmon[14] at 96 MeV; and Van Zyl et al.[15] at 136 MeV. Kinny and Perey, and El-Kadi measured data for both ^{63}Cu and ^{65}Cu at each energy; the other data sets are for natural Cu. The angular distributions for ^{63}Cu and ^{65}Cu were similar to each other, and did not show significant isotopic dependence, so that all of the above data sets were used simultaneously to find out one set of optical-model parameters for both ^{63}Cu and ^{65}Cu. The isotopic cross sections were obtained using a $A^{2/3}$ dependence. For proton incident reactions, the experimental natural total reaction cross-section data sets selected for fitting were those of Pollock and Schrank[16] at 16.37 MeV; Kirkby and Link[17] at 99 MeV; and Renberg et al.[18] from 225 to 548 MeV. The other data were retrieved from compilation by Carlson.[19] The experimental angular-distribution data were taken from those of Dayton and Schrank[20] at 17 MeV; Ridley and Turner[21] at 30.3 MeV; and Richardson et al.[22] at 340 MeV. These measured data are for natural Cu. The isotopic cross sections were obtained using a $(1+A^{1/3})^2$ dependence.

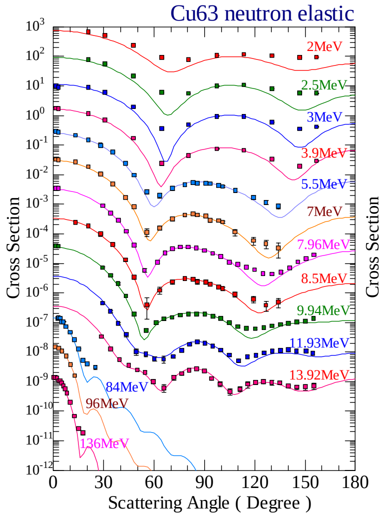
To obtain the neutron and proton optical-model parameters, we employed ECISVIEW[23] based on a modified optical-model formula developed by Chiba to fit the above selected sets of elastic scattering angular-distribution data as well as the total cross sections. The best-fit parameter set was then used for the rest of the model calculations to generate required transmission coefficients. For the other outgoing channels we used global potentials, i.e. the deuteron potential of Lohr and Haeberli,[24] the triton and ^{3}He potentials of Becchetti and Greenlees,[25] and the alpha potential of Macfadden and Satchler.[26] **Figures 2(a)** and **(b)** show comparisons of calculated results with measured elastic scattering angular-distribution data for neutrons. **Figures 3(a)** and **(b)** indicate comparisons of calculated results with measured total cross sections. **Figures 4(a)** and **(b)** also show comparisons of calculated results with measured elastic scattering angular-distribution data for protons. **Figures 5(a)** and **(b)** also indicate comparisons of calculated results with measured total reaction cross sections for protons.

2.2 The direct reaction model and parameters

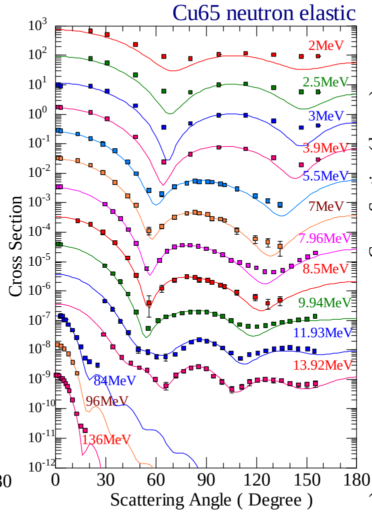
The DWBA code DWUCK was employed to calculate the direct-interaction component of the inelastic scattering cross sections to a number of levels in ^{63,65}Cu for which information was available. The deformation parameters and the energy levels for the several MeV were taken from McCarthy and Crawley,[27] and the other values were determined by considering measured data of neutron emission spectra for (n,xn) and (p,xn) reactions.

2.3 Gamma-ray strength functions, Level-density parameters and the other parameters

The gamma-ray strength function model of Uhl and Kopecky[28] was employed, and the parameters given by Jianfeng[29] compiled in the RIPL library were adopted. We used the standard level density options of the GNASH code. For the preequilibrium part, the particle-hole level density of Williams was used. For compound nucleus reactions, the Ignatyuk formula[30] was adopted, and the partial level density parameters for (p, xn) and (p, xnp) reactions were slightly modified to reproduce measured neutron emission spectra from (p,xn) reactions.

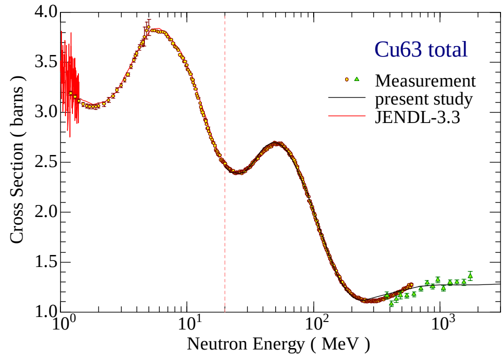


(a) for ^{63}Cu

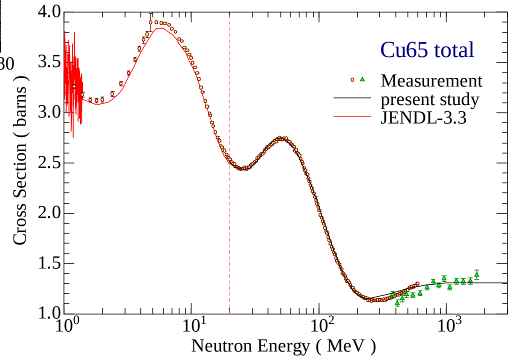


(b) for ^{65}Cu

Fig. 2 Results of elastic scattering angular distribution for Cu

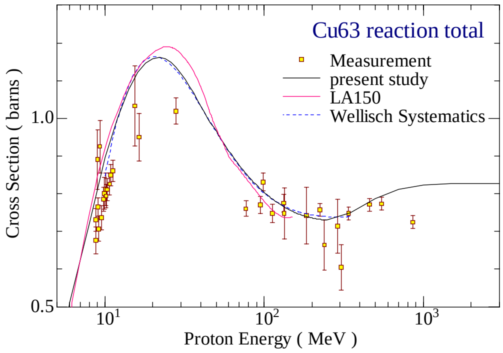


(a) for ^{63}Cu

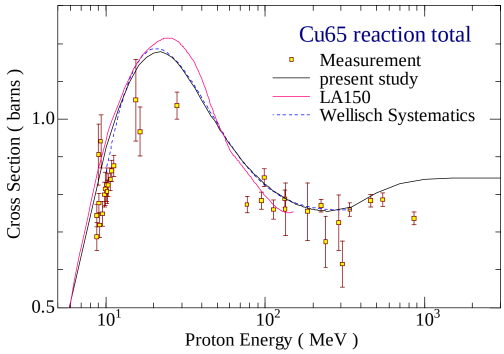


(b) for ^{65}Cu

Fig. 3 Results of total cross sections for Cu

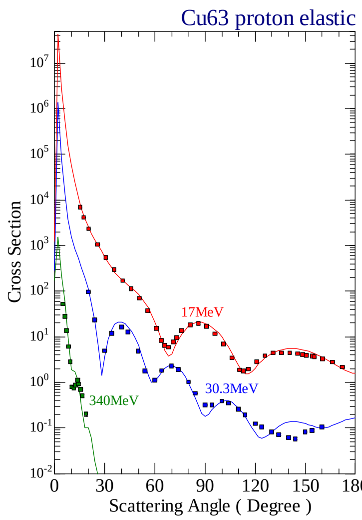


(a) for ^{63}Cu

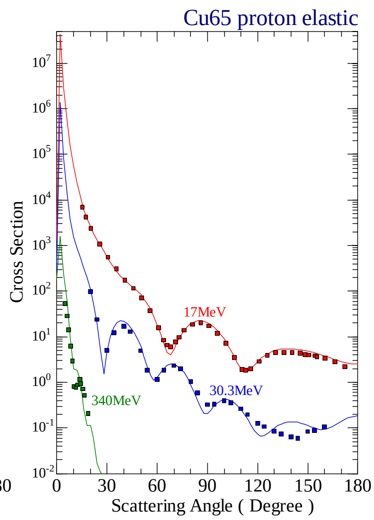


(b) for ^{65}Cu

Fig. 5 Results of total reaction cross sections for Cu



(a) for ^{63}Cu



(b) for ^{65}Cu

Fig. 4 Results of elastic scattering angular distribution for Cu

3. Comparison of calculations with experiments

3.1 Neutron emission spectra

A few measurements exist for neutron emission spectra above 20 MeV for Cu. **Figure 6** shows a comparison for 25.7 MeV ^{65}Cu(n, xn) reaction data by Marcinkowski et al.[31] A comparison of calculated energy-angle double differential cross sections (DDX) with the measurement is presented in **Fig. 7**. The calculated results are in good agreement with measurements.

For projectile proton reactions, measurements of ^{63}Cu(p, xn) reaction at 25 MeV and ^{65}Cu(p, xn) reaction at 26 MeV are shown **Figs. 8** and **9**, respectively. The DDX measurement for 26 MeV ^{65}(p, xn) reaction by Scobel et al.[32] is presented in **Fig. 10**. The calculated results are in good agreement with experiments.

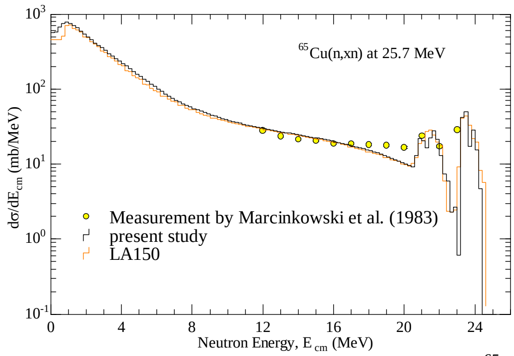


Fig. 6 Results of neutron emission spectrum for ^{65}Cu

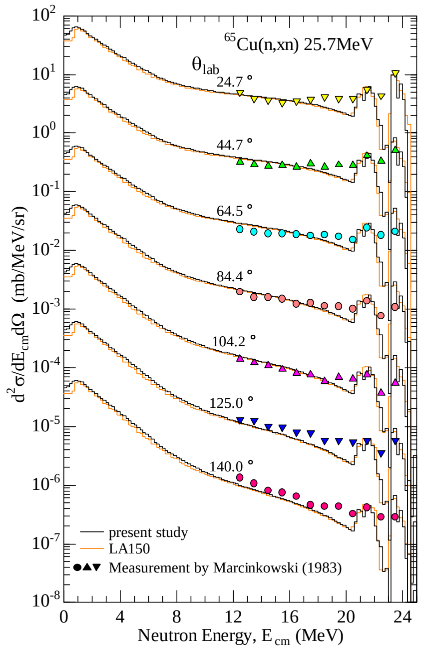


Fig. 7 Results of neutron emission spectrum for ^{65}Cu

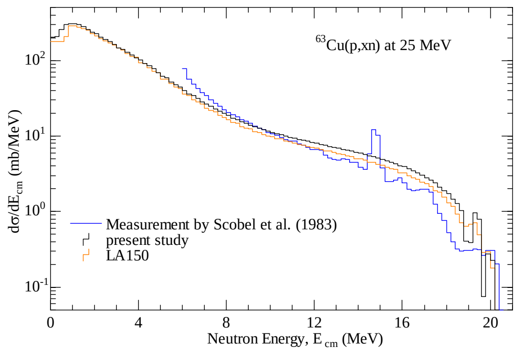


Fig. 8 Results of neutron emission spectrum for ^{63}Cu

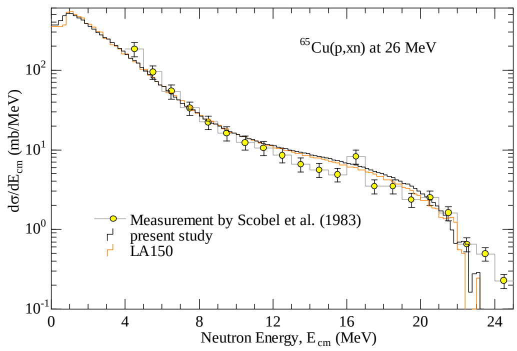


Fig. 9 Results of neutron emission spectrum for ^{65}Cu

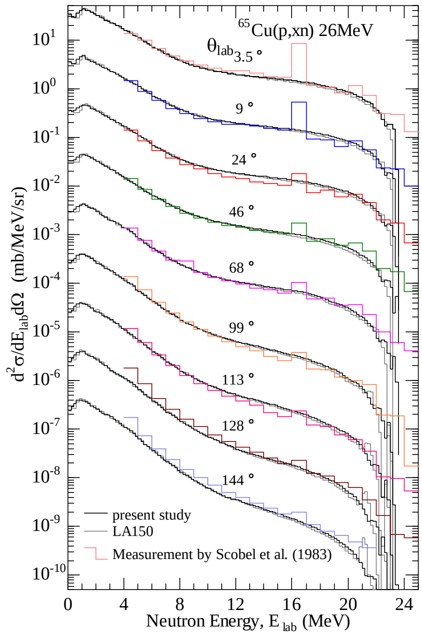


Fig. 10 Results of neutron emission spectrum for ^{65}Cu

3.2 Isotope production cross sections

Isotope production cross sections for ^{63}Cu and ^{65}Cu were simultaneously evaluated by using the GMA code in order to satisfy measured data for natural Copper in which measured data were available. **Figure 11** shows the isotope production cross sections for ^{natural}Cu(p,x)^{63}Zn reaction. In this case, ^{63}Zn isotope is mainly produced by ^{63}Cu(p, n)^{63}Zn and ^{65}Cu(p, 3n)^{63}Zn reactions. These cross sections were simultaneously evaluated by using GMA or empirical fits, and are presented in **Figs. 12** and **13**, respectively.

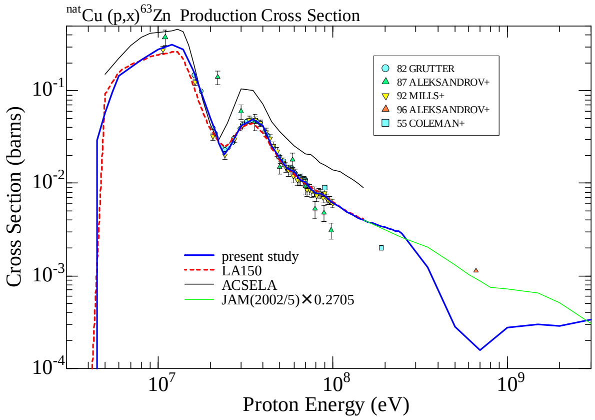


Fig. 11 Cross sections for ^{nat}Cu(p, x)^{63}Zn reaction

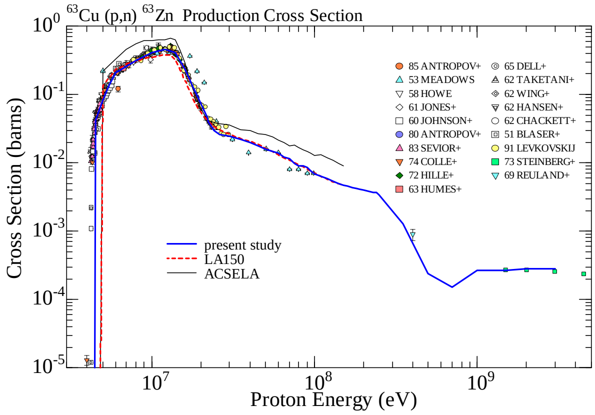


Fig. 12 Cross sections for ^{63}Cu(p, n)^{63}Zn reaction

3.3 Thick target neutron yields

Neutron spectrum measurement from thick target bombarded by protons is one of good benchmarks for integral test of nuclear data. Since high energy cross-section measurements were not available, we compared thick target neutron yields (TTY) calculated with the QMDPROD code developed by Meigo using energy-angle double differential cross section compiled in this study. Comparisons of calculated TTY with measurements for 30, 52 and 67 MeV projectile protons are shown in **Figs. 14(a)** to **(c)**, respectively. Calculated neutron emission spectra show in good agreement with measurements.

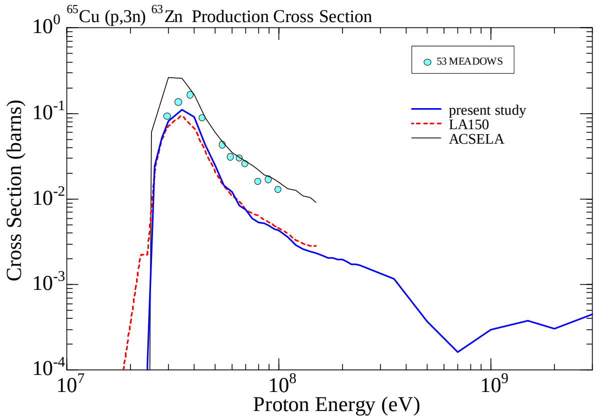
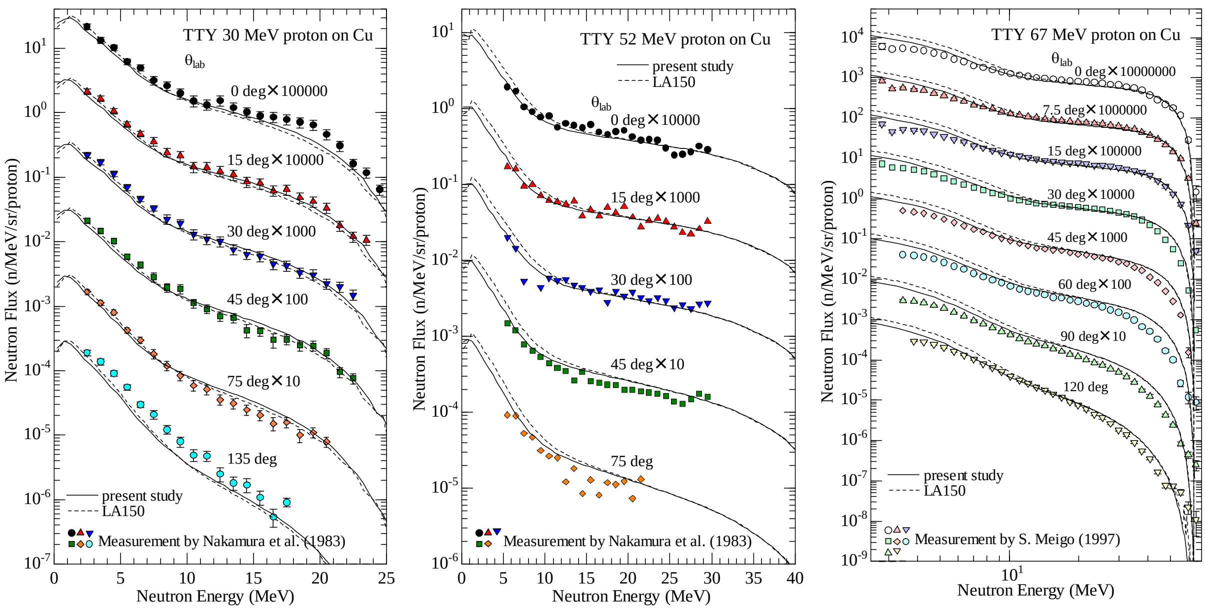


Fig. 13 Cross sections for ^{65}Cu(p, 3n)^{63}Zn reaction



(a) for 30 MeV (b) for 52 MeV (c) for 67 MeV

Fig. 14 Results of thick target neutron yields for natural Cu bombarded by protons.

4. Conclusion

Neutron and proton induced cross-section data for ^{63}Cu and ^{65}Cu have been evaluated up to 3 GeV for the High Energy File of Japanese Evaluated Nuclear Data Library (JENDL-HE). The results were compared with available experimental data and other evaluations as well as integral experiments such as thick target neutron yields, and a good agreement was obtained with measurement. However, number of energy-angle double differential cross-section measurements above 100 MeV is quite few, so that the accuracy of evaluated data is not clear in this energy region. We need cross-section measurements including DDX data in order to evaluate accurate nuclear data for high-energy accelerator applications. Integral measurement such as thick target neutron yield is valuable to validate nuclear data for projectile proton.

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