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Proton-induced Cu-63,65 nuclear data for the MCNPX calculation of Proton Linear Accelerator (KOMAC)

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The Proton Engineering Frontier Project (PEFP) is building the Korea Multipurpose Accelerator Complex (KOMAC), which consists of a high current 100 MeV proton linear accelerator and various particle beam facilities. Shielding of the KOMAC requires various numerical simulations with appropriate proton and neutron nuclear data for energies up to a few hundreds MeV. Among the proton-induced nuclear data, Cu(p,xn) reaction is crucially important since it governs the total number of neutrons in the DTL and beam dump.

This presentation provides newly evaluated proton-induced Cu-63 and Cu-65 cross section data applicable to the multi-particle Monte Carlo simulation code MCNPX. Up-to-date model calculations with ECIS, GNASH, and GSCAN codes are performed with adjusted nuclear model parameters such as optical model potentials and level densities. The resulting cross section library is then converted into the MCNPX format using NJOY code, and comparison and benchmark are also provided with available experiments and the existing LA150 library especially for the neutron production cross sections.

1 Introduction

The PEFP (Proton Engineering Frontier Project) is building the KOMAC (Korea Multi-purpose Accelerator Complex), which consists of a proton linear accelerator with a 100 MeV energy, 20 mA current, and various particle beam facilities from 2002 to 2012. One of the KOMAC's unique characteristics is its high average beam current, 4.8 mA which is 3 times higher than the ORNL's Spallation Neutron Source (SNS), 1.4 mA at 1 GeV. This high current is very challenging not only for the accelerator design itself, but also for the shielding design.

For the shielding of the KOMAC, it is necessary to get accurate information on secondary neutron production from various materials. Copper is a major element of the guiding magnet in the beam transport line, and the primary heat sink of the beam dump block. Current version of the MCNPX has two options in the use of the proton-induced cross sections, such as the LA150 [1] evaluated library and the LAHET physics modules. Since the shielding of the KOMAC mainly deals with the incident protons with energies below 100 MeV, and the intranuclear cascade physics employed in the LAHET has its weakness in nuclear structure effects. the LA150 library is a better choice.

Figure 1 compares the proton-induced non-elastic cross sections of copper from the LA150 library and the LAHET modules, with available experimental data. As shown in the figure, while the LA150 cross sections agree better with the experimental data than the LAHET modules for energies above 50 MeV, slight overestimations are observed in the LA150 cross sections for low incident proton energies. One of advantages of using a separate evaluated cross section library instead of integrated physics model in the MCNPX calculation is that users can easily replace a part of the existing LA150 with their own evaluated cross section library.

In the present work, proton-induced cross sections are newly evaluated based on Up-to-date model calculation with ECIS [2]-GNASH [3]-GSCAN [4] code system, with appropriate nuclear model parameters such as optical model potentials and level densities. The resulting cross section library are then converted into the MCNPX format using NJOY code, and then a thick target yield (TTY) benchmark is performed. Results are compared with those of LA150, LAHET physics modules, and experimnets for the neutron yield per proton (n/p).

2 Evaluation

The optical model was applied to calculate the non-elastic and elastic cross sections, and to obtain the transmission coefficients. Decay of excited nuclei was described with the Hauser-Feshbach and exciton models using the GNASH code to simultaneously handle neutron, proton, deuteron, triton, helium-3, α, and γ emissions. The GSCAN code compiles resulting cross sections into the ENDF6 format data, which is then converted into the MCNPX format library through the NJOY code.

Among the nuclear model parameters applied in the model calculation described above, Most important ones in the nuclear model calculation are optical model parameters and nuclear level densities. In our model calculation, a new set of optical model parameters were made for Cu-63 and Cu-65 instead of using conventional ones, and Generalized Superfluid Model (GSM) was applied for the clear level densities instead of the Fermi-gas or constant temperature models.

2.1 Optical Model Parameters

Optical model has been used to provide non-elastic cross sections and angular distributions for elastic scattering, and to Calculate the transmission coefficients for neutron and charged particles. The potential form factor was chosen to be of Woods-Saxon form for the real and imaginary volume terms, and derivative Woods-Saxon form for the surface imaginary term, and

Thomas-Fermi form for spin-orbit parts as

$$\begin{aligned} U(r) &= -V_r f_v(r) - iW_v \ f_w(r) \\ &\quad + 4i \ a_{wd} \ W_d \ \frac{df_{wd}(r)}{dr} - \frac{1}{r}\left(\frac{\hbar}{m_\pi c}\right)^2 \\ &\times \left(V_{so}\frac{d}{dr}f_{vso}(r) + iW_{so}\frac{d}{dr}f_{wso}(r)\right) \ \boldsymbol{l}\cdot\boldsymbol{s} \ + V_{Coul} \end{aligned} \tag{1}$$

where m_π is the mass of the pion and the form factors f_i are of the standard Woods-Saxon shape :

$$f_i(r) \ \equiv \ \frac{1}{1+exp((r-r_iA^{1/3})/a_i)}, \quad i = v, w, wd, vso, wso \tag{2}$$

Here, a_i is the diffuseness parameter, and A the target mass number.

We applied the potential energy dependencies of Lee *et al.* [5] which were validated for various isotopes below 250 MeV neutrons and protons.

2.2 Level Densities

For the description of the level densities the Fermi-gas and constant temperature models have been used frequently with parameters obtained from fitting some experimental data. But the physical assumptions upon which both these models are based are not sophisticated enough to allow them to account properly for variations of level densities over wide energy interval from the ground state to energies much higher than the neutron separation energy. Meanwhile, the Generalized Superfluid Model (GSM), developed by many authors over the last 20 years, includes shell effects, paring correlations and collective phenomena. In our model calculation, nuclear level density was obtained on the basis of the GSM with parameters fitted to cumulative number of low-lying levels and observed neutron resonance densities [6]. In case where there is no fitted parameters, slight adjustments were made to the asymptotic parameters for better agreements with the available measurements.

3 Results and Benchmark

Figure 2 shows proton-induced non-elastic cross sections evaluated in this work, compared with the LA150 library, the LAHET physics modules, and available experimental data. The non-elastic cross section is an important quantity in the proton accelerator shielding simulation since it is the initiating channel of neutron emitting reaction. Thus the absolute number of neutrons produced are absolutely dependent on the non-elastic cross section. As shown in Fig. 2, our evaluation agrees better with the experimental data for the entire energy region up to 150 MeV.

As for individual neutron emitting channels, Fig. 3 shows the our evaluation for the Cu(p,Zn-63) reaction and Fig. 4 for the Cu(p,Zn-62) reaction. These two reactions are major components of the neutron production channels for incident proton energies below 50 MeV. As shown in the figures, the Cu(p,Zn-63) evaluation reproduces well the the experiments while the Cu(p,Zn-62) evaluation slightly over-estimate the experimental data.

In Figs. 5, neutron production cross sections are plotted as a function of the incident proton energy, and compared with the LA150. Our evaluated neutron production cross sections are smaller than the LA150 ones over the entire energy region, where there is no experimental data for the neutron production cross sections except the thick target yield. Therefore, to benchmark our evaluation, resulting ENDF6 format cross sections were converted into the MCNPX format, and a TTY was modeled for several incident proton energies. As results of the TTY simulation, total number of neutrons per proton (n/p) produced in a copper target are plotted in Fig. 6. As shown in the figure, our evaluation results in lower n/p for the entire energies, and gives better agreements with the TTY experiment especially for 100 MeV of incident proton case.

Acknowledgements

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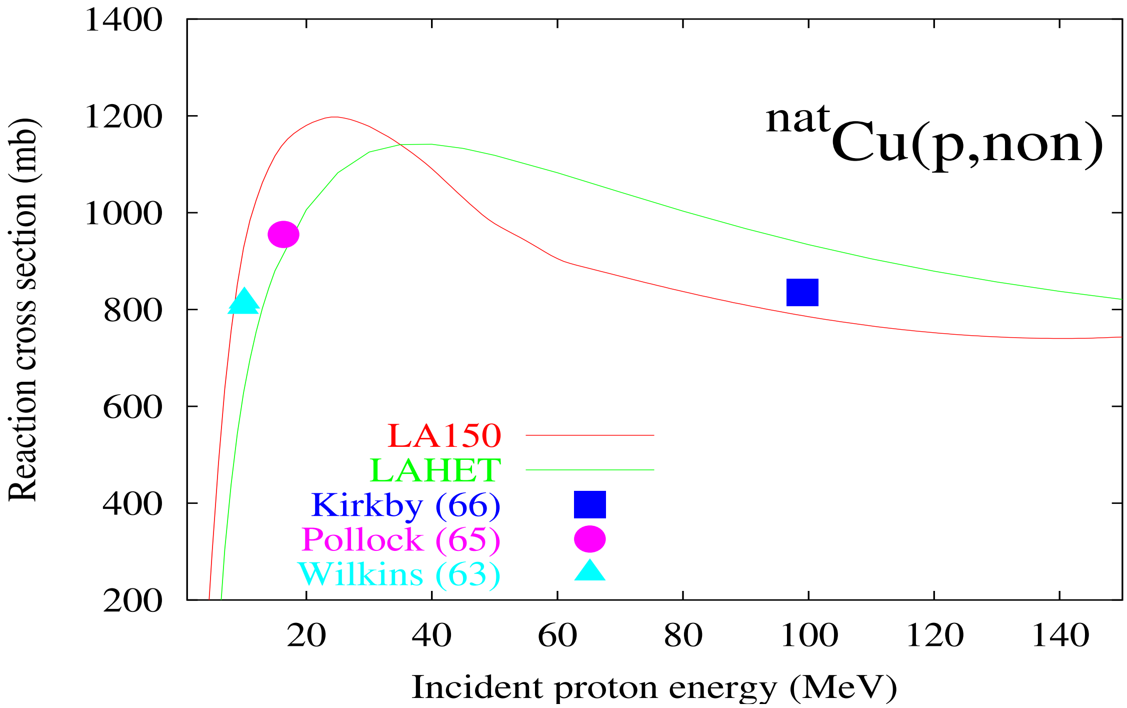

Figure 1: Proton-induced non-elastic cross sections from the LA150 library and LAHET physics modules

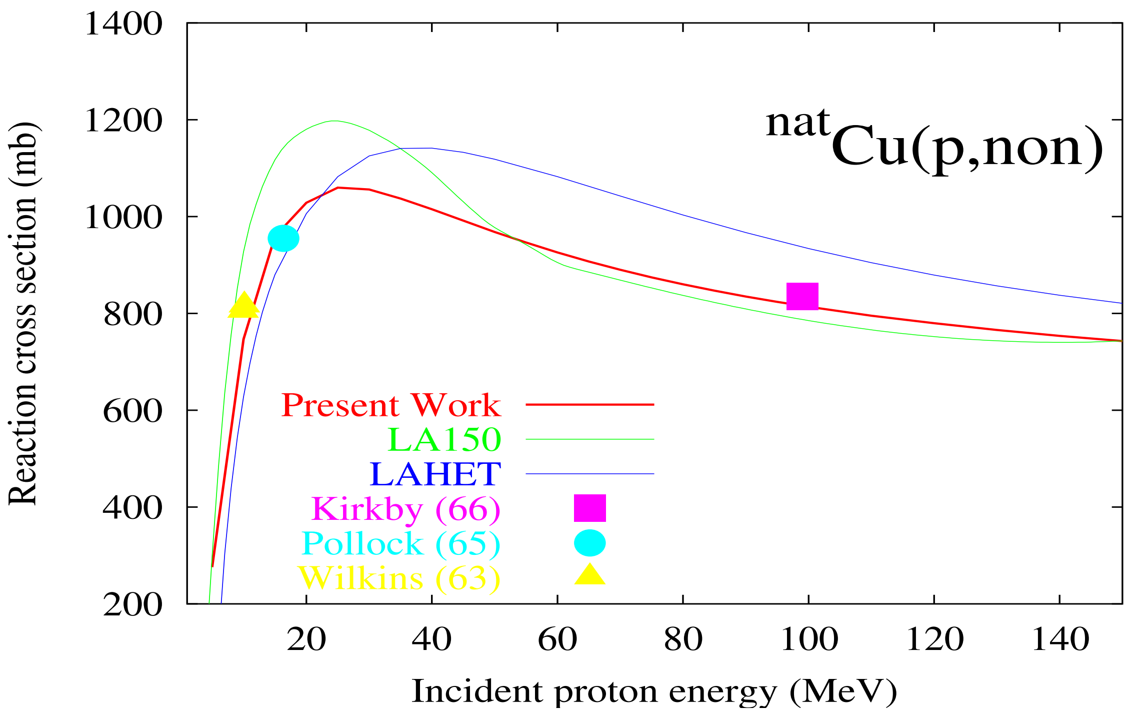

Figure 2: Evaluated proton-induced non-elastic cross sections in the presenta work, compared with the LA150 library and LAHET physics modules

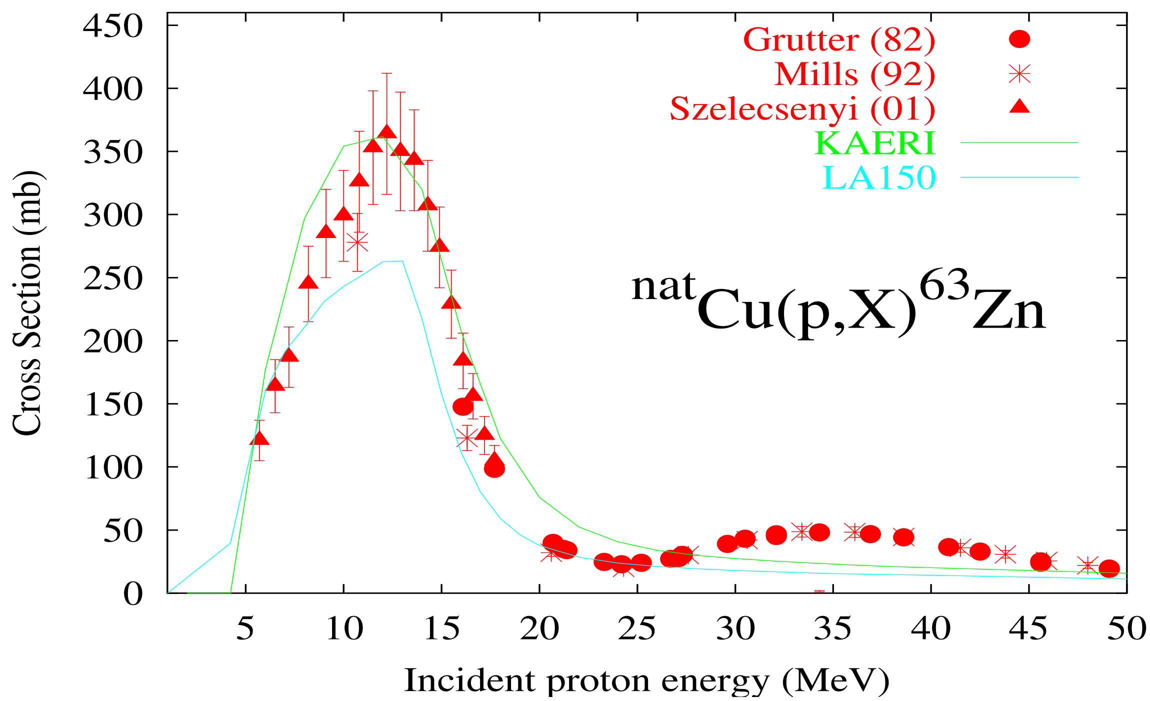

Figure 3: Evaluated ^{nat}Cu(p,x)Zn-63 reaction cross sections compared with experiental data and the LA150 library

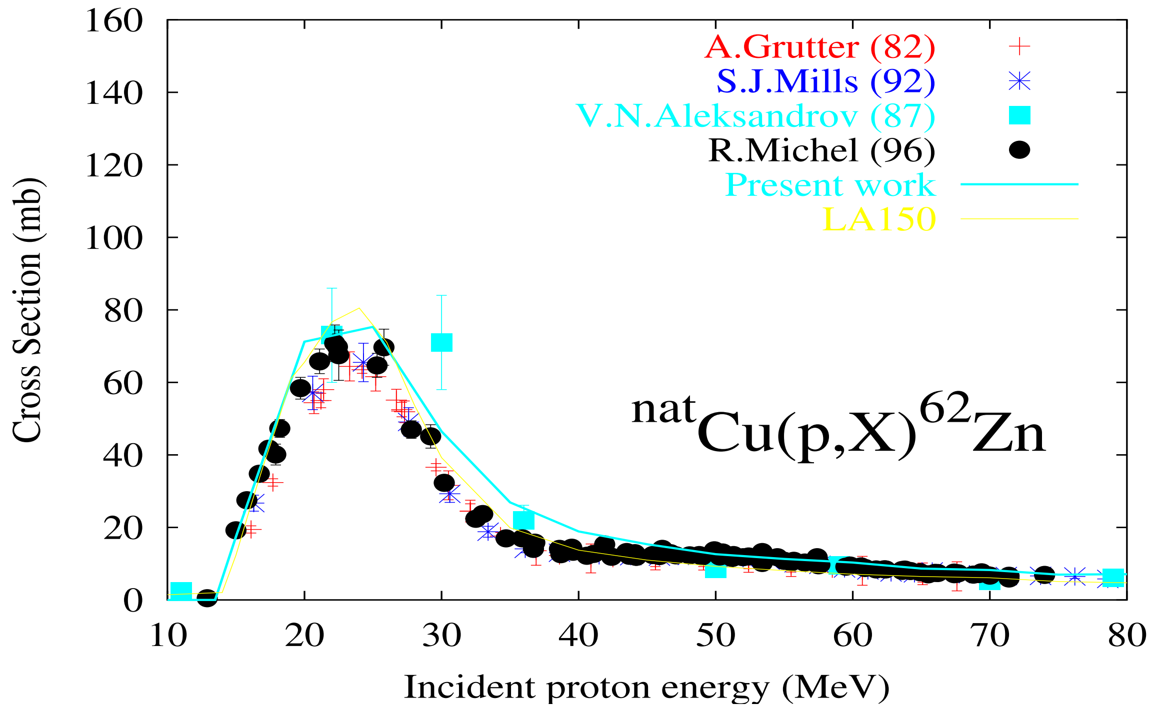

Figure 4: Evaluated ^{nat}Cu(p,x)Zn-62 reaction cross sections compared with experimental data and the LA150 library

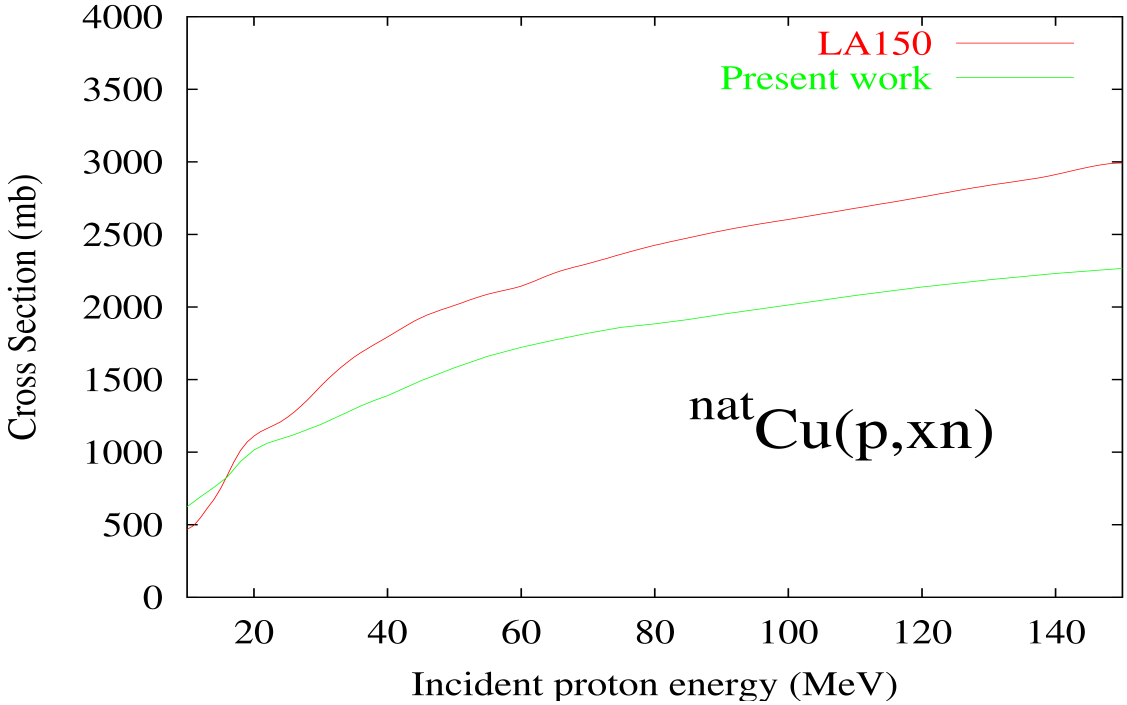

Figure 5: Evaluated ^{nat}Cu(p,xn) reaction cross sections compared with the LA150 library

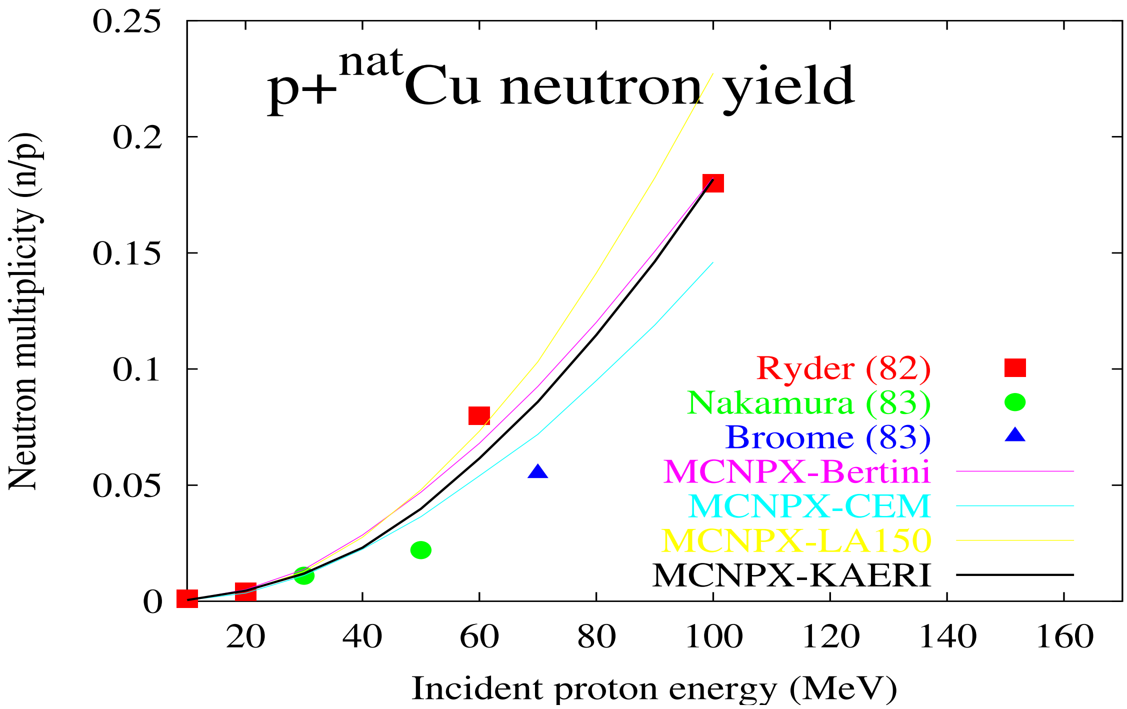

Figure 6: Number of neutrons per proton calculated in the MCNPX as a function of incident proton energies on thick copper target