Progress in the KAERI High Energy Nuclear Data Library : Proton-induced Neutron Emission Spectra

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Proton-induced neutron yields and emission spectra up to a few hundreds MeV are important nuclear data in the particle transport of the accelerator-driven system (ADS) and in the space shielding for trapped protons and solar energetic particle events. Within the framework of KAERI high energy nuclear data library evaluation, energy-angle spectra of secondary neutrons produced from the proton-induced neutron production reaction, (p,xn), of C-12, Al-27, Fe-56, and Pb-208 for energies below 400 MeV are evaluated based upon model calculations, guided and benchmarked by existing experimental data. Theoretical calculations were performed with the optical model analysis for the direct reactions and transmission coefficients, Hauser-Feshbach model for the equilibrium emission, and the exciton model for the preequilibrium emission, using the ECIS-GNASH code system.

1. Introduction

In the particle transport analysis of the target system of ADS, proton-induced nuclear data, especially neutron yields and neutron emission spectra, play a key role [1].

Calculation of space system shielding is complicated due to the production of secondary products. A large fraction of the neutrons produced through the whole shield may be transported to the dose point. Thus, neutron contribution is an important component of the secondary radiation field, especially for astronauts protected by thick shielding on lunar or Martian bases.

The present work extends previous proton-nucleus non-elastic cross sections [2]. Energy-angle spectra of secondary neutrons produced from the proton-induced neutron production reaction of C-12 Al-27, Fe-56 and Pb-208 for energies below 400 MeV are evaluated based upon model calculations guided and benchmarked by existing experimental data. Since nuclear interactions are more sensitive to specific details of nuclear structure along with quantum effects for energies below few hundred MeV, our theoretical evaluation uses the optical model for the direct reactions, Hauser-Feshbach model for the equilibrium emission, and the exciton model for the preequilibrium emission.

2. Reference Measurements

Most of the measurements for energies below 150 MeV referenced in the LA150 library evaluation were also adopted in the present evaluation, and details are found in [3, 2].

Table 1: Reference measurements of neutron double-differential emission spectra for incident proton energy above 100 MeV

Reaction	Principal Author	E_p [MeV]	Emission Angles [deg]	EXFOR entry
^{12}C(p, xn)	Meier (1989)	113.0	7.5, 30, 60, 150	O0100
	Meier (1992)	256.0	7.5, 30, 60, 150	C0168
^{27}Al(p, xn)	Meier (1989)	113.0	7.5, 30, 60, 150	O0100
	Scobel (1990)	160.3	0 - 145 (14 angles)	O0181
	Stamer (1993)	256.0	7.5, 30, 60, 150	C0511
	Meier (1992)	256.0	7.5, 30, 60, 150	C0168
^{56}Fe(p, xn)	Meier (1989)	113.0	7.5, 30, 60, 150	O0100
	Meier (1992)	256.0	7.5, 30, 60, 150	C0168
^{208}Pb(p, xn)	Scobel (1990)	120.0	0 - 145 (14 angles)	O0181
	Scobel (1990)	160.3	0 - 145 (14 angles)	O0181
	Stamer (1993)	256.0	7.5, 30, 60, 150	C0511
^{nat}Pb(p, xn)	Meier (1992)	256.0	7.5, 30, 60, 150	C0168

Additionally, important measurements of neutron emission spectra above 100 MeV of incident proton energy are referenced in Meier [4, 5], Scobel [6], and Stamer [7]. These four sets of measurements, listed in Table 1, provided important guidances in evaluating energy-angle spectra of emitted neutron for energies above 150 MeV.

3. Theoretical Models

3.1 Optical Models

The optical model supplies not only the non-elastic cross section and the angular distribution of elastic scattering, but also the particle transmission coefficients for emission model calculations, such as equilibrium and preequilibrium decay models. In this work, the energy dependent potential wells for neutrons and protons were adopted from the previous work of Korea Atomic Energy Research Institute (KAERI) high energy library evaluation task [3, 2] for particle energies up to 400 MeV.

3.2 Emission Models

For the emission reaction the latest version of the GNASH code [8] has been used. Several models and parameters are needed such as optical model transmission coefficients, gamma-ray transmission coefficients, level density models, preequilibrium components, and direct reaction effects.

The GNASH code has the exciton model in combination with the Kalbach angular-distribution systematics [9] to describe the processes of preequilibrium emission, and damping to equilibrium, during the evolution of the reaction. In the GNASH code, a simplified preequilibrium expression based upon the exciton model has been used for

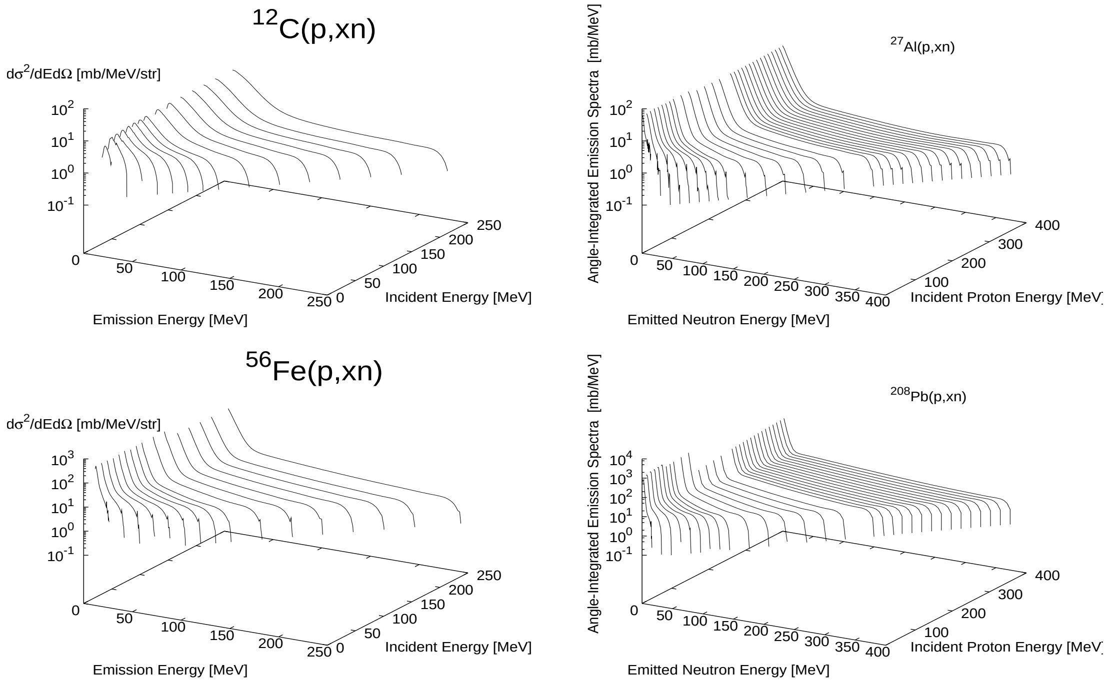

Figure 1: Evaluated angle-integrated neutron emission spectra for proton-induced ractions

correct reaction and level-excitation cross sections as well as spectra for preequilibrium effects :

$$\left(\frac{d\sigma}{d\epsilon}\right)_{preq} \propto \frac{\sigma_{\rm inv}(\epsilon)m\epsilon\sigma_R}{|M|^2 g^4 E^3} \sum_{n=3}^{\bar{n}} (U/E)^{n-2}(n+1)^2(n-1), \tag{1}$$

where E and U are the excitation energies of the compound and residual nuclei, respectively; σ_R is the incident particle non-elastic cross section; m, ϵ, and $\sigma_{inv}(\epsilon)$ are the mass, kinetic energy, and inverse cross section for the outgoing particle; g is the average single-particle level spacing from the Fermi-gas model; and n is the number of particles and holes ($n = p + h$) in the compound nucleus. The sum extends from the initial exciton number 3 to $\bar{}(n)$, the limiting value attained when equilibrium is reached. To achieve a global agreement with the emission spectra measurements, the absolute square of the damping matrix $|M|^2$ has been tuned as a phenomenological fudge factor.

The pion production channel opens at its production threshold energy (around 150 MeV), but the present model calculation does not include the pion channel, because its emission fraction to that of neutrons is at most 1 % at the higher emission energies for the energy range of our interest (see [10]).

4. Results and Comparisons

In order to give an overview of our evaluation results, Fig. 1 provides 3-dimensional plots of the angle-integrated emission spectra information of neutrons.

4.1 ^{12}C

For 113 MeV of incident proton, The first row of Fig. 2 compares our evaluation of double-differential neutron emission spectra at 7.5, 30, 60, and 150 degrees with the measurements of Meier et al. [4], together with the LA150 evaluation. Evaluated energy-angle spectra of emitted neutrons for 256 MeV of incident proton are compared with the Meier et al.'s data measured in 1992 [5], giving overall agreements.

4.2 ^{27}Al

The second row of Fig. 2 shows a comparison of our evaluation, the LA150 library, and the measurements of Meier [4] for double-differential neutron emission spectra at 7.4, 30, 60 and 150 degrees for incident protons of 113 MeV. Agreement is fairly good over the whole range of emission energies and angles except for slight overestimations for neutron energies below 20 MeV.

For incident proton energies above 150 MeV, our evaluations are compared with the measurements of Scobel [6] for 160.3 MeV and with the measurements of Stamer [7] for 256 MeV. Good agreements are shown for the 160.3 MeV case except at 145 degree, where our model calculations underestimate the measured neutron spectra. However, these discrepancies do not appear to be systematic in our model calculations since we have good agreements at 150 degree of 113 MeV and 256 MeV protons.

The 256 MeV case gives reasonable agreements except for slight overestimations at higher emission energies (preequilibrium emission) at 7.5 degree. The magnitude of the calculated preequilibrium emission spectra is determined by the Kalbach angular-distribution systematics in the GNASH code, and its accuracy is within that of of the Kalbach systematics.

4.3 ^{56}Fe

For 113 MeV of incident proton, the third row of Fig. 2 shows excellent agreements among our evaluation, LA150, and the measurements [4] for double-differential neutron emission spectra at 7.5, 30, 60, and 150 degrees. Evaluated energy-angle spectra of emitted neutrons for 256 MeV of incident proton are compared with the measurements [5], providing quite good agreements for the entire energies and angles of emitting neutrons.

4.4 ^{208}Pb

The last row of Fig. 2 shows a comparison of our evaluation, the LA150 library, and the measurements of Scobel. [4] for double-differential neutron emission spectra at 11, 45, 95 and 145 degrees for incident protons of 120 MeV. Agreement is fairly good over the whole emission energies and angles except at 145 degree, where our model calculations as well as the LA150 library are smaller than the measured data. Again, these discrepancies do not appear to be systematic in our model calculations since we have good agreements at 145 degree of 160 MeV and at 150 degree of 256 MeV protons.

For incident proton energies above 150 MeV, our evaluations are compared with the measurements of Scobel [6] for 160.3 MeV, and in Fig. **2** with the measurements of

Meier [5] and Stamer [7] for 256 MeV. While good agreements are shown for the 160.3 MeV case, the 256 MeV case gives reasonable agreements except for slight overestimations at emission energies between 15 and 50 MeV, which is due to the limitation of Kalbach angular-distribution systematics.

5. Conclusion

Below 150 MeV of incident protons, no significant differences are noticed between our evaluation and the LA150 library, giving a good consistency with the measurements. This is mainly because the reference measurements, theoretical models, and model parameters are nearly the same for our evaluation and the LA150 library except the transmission coefficients of neutrons and protons, whose effects are minimal in the inclusive emission spectra.

For energies between 150 and 400 MeV, our evaluations are made on the same reaction models as the LA150 library, but with

- utilization of the optical model parameters of neutrons and protons validated for incident energies up to 400 MeV,
- benchmark with appropriate reference measurements for energies above 150 MeV, and
- adjustment of absolute square of the damping matrix to have a global agreement with emission spectra.

As a result, fairly good agreement has been achieved in the neutron double differential emission spectra for the entire emission energy and angle range. Slight discrepancies are observed at the preequilibrium emission energies between 15 and 50 MeV for 256 MeV protons incident on ^{208}Pb, which come from the limitation of the Kalbach angular-distribution systematics.

– References –

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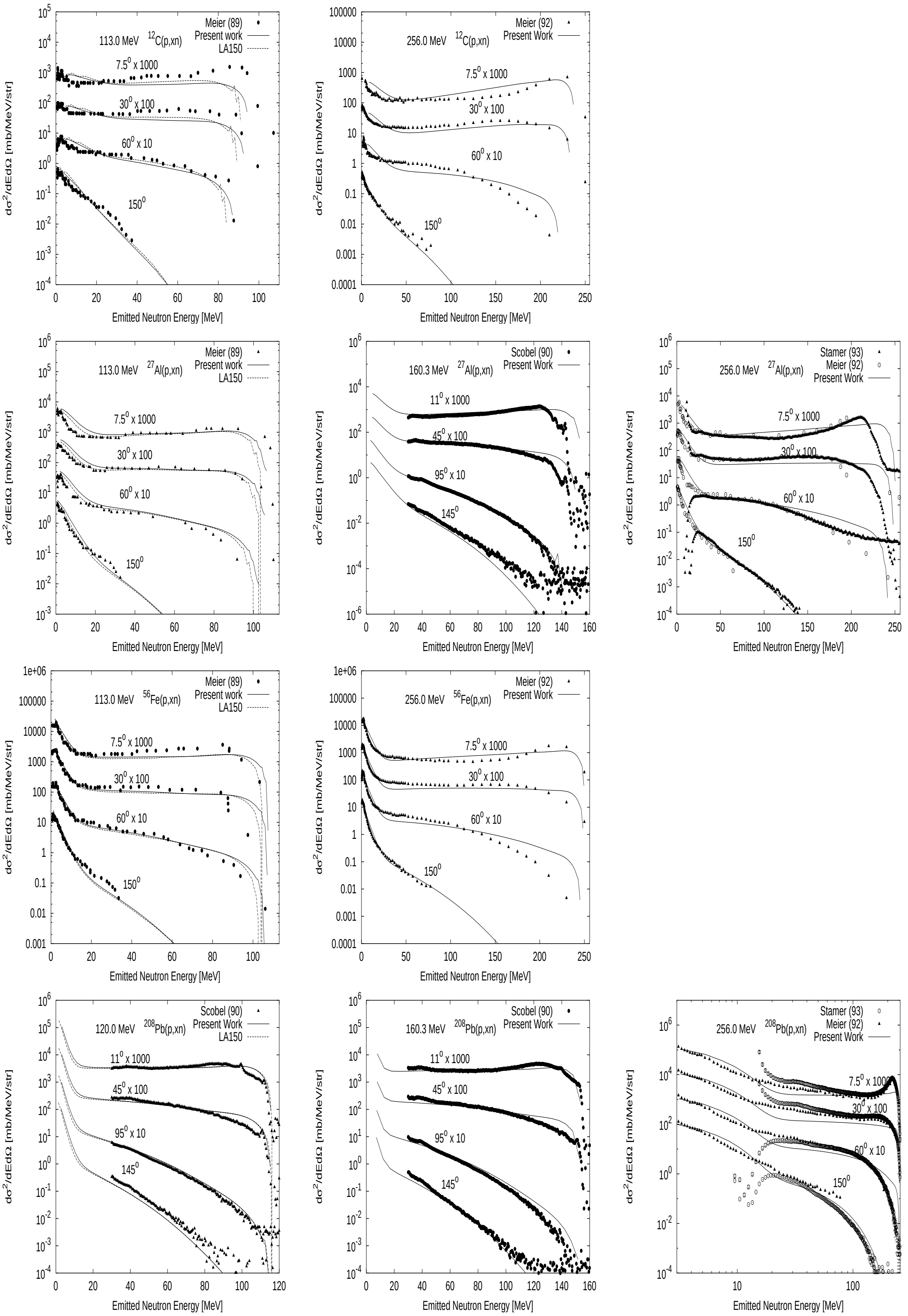

Figure 2: Evaluated double-differential neutron emission spectra compared with experimental data and the LA150 library