Parameterization of neutron production double differential cross section up to 3 GeV in terms of moving source model

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The parameterization of the double differential cross section is made for the neutron emission from proton-induced spallation reaction. The emitted neutron data for incident proton energies above 800 MeV are well analyzed by the moving source model based on the Maxwell-like energy distribution with Gaussian shape terms.

1 Introduction

Evaluated nuclear data covering incident energies up to several GeV are required in application of the spallation reaction. Neutron emission double differential cross sections, however, have been measured for several targets and incident energies. The moving source (MS) model[1] which is based on Maxwell-like distribution has been employed for analyzing the experimental neutron emission data for the proton-induced spallation reaction. The parameters obtained from this type of analysis represented well the experimental neutron spectra in the incident energy region from 113 MeV to 800 MeV[2].

In this study, the parameterization of the (p,xn) double differential cross sections is made for the neutron emission from the spallation reaction induced by protons above 800 MeV. The neutron data in incident proton energy region up to 3 GeV are analyzed by the moving source model. The experimental data[3] of the double differential cross section on neutron emission are available on C, Al, Fe, In and Pb for the incident energies of 0.8, 1.5 and 3 GeV. In addition, the quantum molecular dynamics (QMD) plus statistical decay model (SDM) code[4] is employed to calculate the cross sections which were not measured.

2 MS model

The MS model have originally been proposed to represent the high-energy collision phenomena where a locally heated spot is moving with evaporating particles in a nucleus. Since the particle emission behavior in this reaction is also explained to a considerable extent by such models as the intranuclear-cascade model, the reaction may not always produce the physical moving source. In this model, the collision phenomena are seen from an observation point moving with an appropriate velocity β (moving frame). Neutrons are assumed to be emitted isotropically with an exponential-type energy distribution of a temperature T (MeV) in the moving frame. The neutron emission double cross section is expressed by

$$\frac{d^2\sigma}{d\Omega dE_{kin}} = \frac{1}{p}\frac{A}{T}\exp\left\{-\Big(\frac{E_{kin}+m-p\beta\cos\theta}{(1-\beta^2)^{\frac{1}{2}}}-m\Big)/T\right\},$$

E_{kin} (MeV) and P (MeV/c) is kinetic energy and momentum of an emitted neutron. The parameters A, β and T are called amplitude, velocity and temperature, respectively. They are adjustable in fitting the equation with double differential cross section data. For the spallation reaction, the MS model is applied in a form of summation of three components as

$$\frac{d^2\sigma}{d\Omega dE_{kin}} = \sum_{i=1}^{3}\frac{1}{p}\frac{A_i}{T_i}\exp\left\{-\Big(\frac{E_{kin}+m-p\beta_i\cos\theta}{(1-\beta_i^2)^{\frac{1}{2}}}-m\Big)/T_i\right\}.$$

Three components correspond to the intranuclear-cascade, the preequilibrium and the nuclear-evaporation processes, respectively. Figure. 1 shows the results of fitting for the 0.8 GeV proton incidence on the Fe target. The marks stand for the experimental cross sections. The dotted lines show the calculated data by QMD+SDM. In this figure,the results by this MS model are indicated by dash-dotted-line. The MS model reproduces the experimental and calculated cross sections at whole emission angles in the energy region below 100 MeV. In the forward direction below 30°, however, the MS model underestimates the neutron data at neutron energy above 200 MeV. It is supposed that the quasi-elastic and quasi-inelastic scattering processes are dominant in the reaction, where neutron emission spectrum is known to be forward-peaked.

3 Evaluation for quasi-elastic scattering

A Gaussian shaped term is introduced into the usual MS model for analysis of the neutron spectra derived from the quasi-elastic and quasi-inelastic scattering processes, and is written as

$$\frac{d^2\sigma}{d\Omega dE_{kin}} = A_q \exp\left\{-\frac{(E_{kin}-E_0)^2}{\kappa^2}\right\} + \sum_{i=1}^{3}\frac{1}{p}\frac{A_i}{T_i}\exp\left\{-\Big(\frac{E_{kin}+m-p\beta_i\cos\theta}{(1-\beta_i^2)^{\frac{1}{2}}}-m\Big)/T_i\right\},$$

where A_q, E_0 and κ are adjustable parameters dependent on the emission neutron angle and kinetic energy. The second term in right side indicates the usual MS model. In Figs. 1 and 2, solid lines show neutron spectra by the use of MS model which includes the Gaussian shaped term for 0.8 and 1.5-proton incidence, respectively. The MS model with the Gaussian shaped term represents the experimental and calculated neutron data over the whole angle well. Parameters A_q, E_0 and κ were fitted by smooth functions as

$$A_q = c_1 e^{c_2 q}, \qquad E_0 = c_3 + c_4 E_{el}, \qquad \kappa = c_5 E_{el}.$$

where q is momentum transfer of incident proton at an neutron emission angle, E_{el} that neutron kinetic energy after elastic collision with incident proton, and c_i that adjustment parameter. Figure. 3 shows the parameters obtained from fitting for 0.8, 1.5 and 3.0 GeV proton incidence on Fe. Momentum transfer of 700 MeV/c for 0.8GeV-proton incidence is equivalent to scattering angle of 28°. The values of E_0 and κ are almost constant, while A_q arises with increasing momentum transfer.

The neutron production differential cross sections from C, Al, Fe, In and Pb were obtained by the use of the MS model with the Gaussian term for incident proton energy region up to 3.0 GeV. Figures. 4 and 5 show the results of the MS model for 1.5 GeV-proton incidence on Al and Pb, respectively. The MS model with the Gaussian shaped term reproduces the neutron production spectra from Al to Pb in the wide range of incident energy and emission angles.

The mass number dependance of parameters A, β and T for 0.8 GeV-proton incidence was shown in Fig. 6, where subscripts 1, 2 and 3 indicate the intranuclear-cascade, preequilibrium and nuclear-evaporation processes, respectively. The black marks show the present work, whereas the open ones indicate the values estimated in reference[2]. The values of β and T are nearly constant for all targets, while A depends on mass number strongly. The incident energy dependance of parameters A, β and T for the Fe target was plotted in Fig. 7. While A_2 and A_3 are monotonously increasing functions of mass number, A_1 arises with decreasing mass number. The velocity and temperature parameters are raised smoothly with the incident proton energy.

4 Conclusion

The moving source model based on Maxwell-like distribution was employed to analyze the neutron production double cross section in the incident proton energy region up to 3.0 GeV. The use of the MS model with the three components of cascade, preequilibrium and evaporation reaction reproduced the experimental neutron data and the calculated results by QMD plus SDM model on C, Al, Fe, In and Pb. In the forward direction of neutron emission, the introduction of the Gaussian term into the moving source model leads to good agreement with the experimental and calculated quasi-elastic spectra. The moving source model with the Gaussian term were found to be applicable to the nuclear data evaluation for a wide range of target masses and incident.

References

[1] Bogatoskaya, I.G., *et al.* : *Phys. Rev.* **C22**, 209 (1980).

[2] Ishibashi, K., *et al.* : *J. Nucl. Sci. Tech.,* **29**, 499 (1992).

[3] Ishibashi, K., *et al.* : *J. Nucl. Sci. Tech.,* **34**, 529 (1992).

[4] Niita, K., *et al.* : *Phys. Rev.,* **C52**, 2620 (1995).

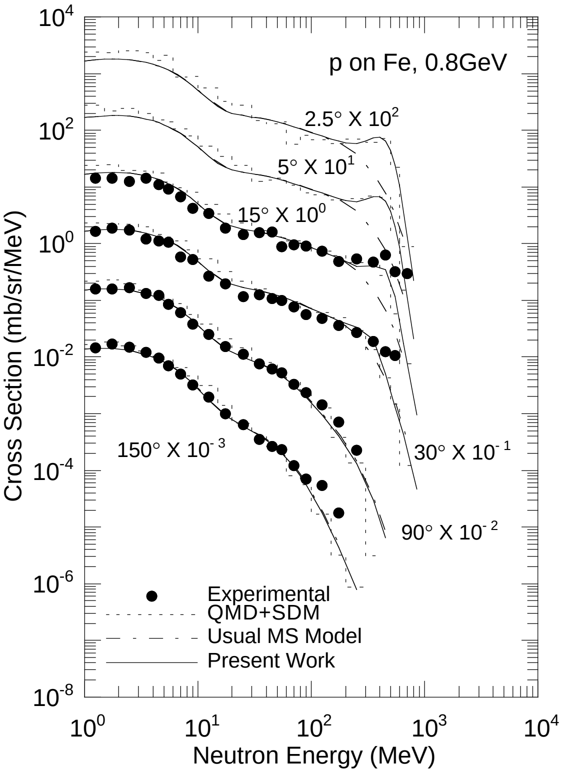

Fig. 1 Neutron production double differential cross section for 0.8GeV-proton incidence on Fe

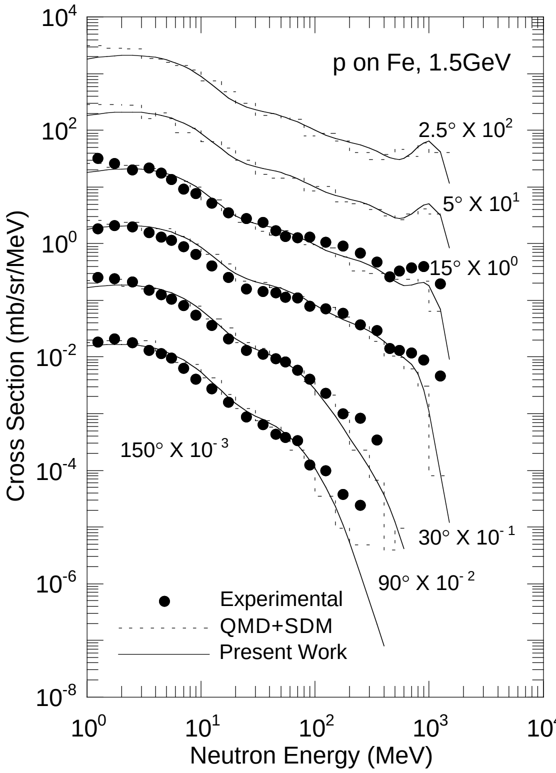

Fig. 2 Neutron production double differential cross section for 1.5GeV-proton incidence on Fe

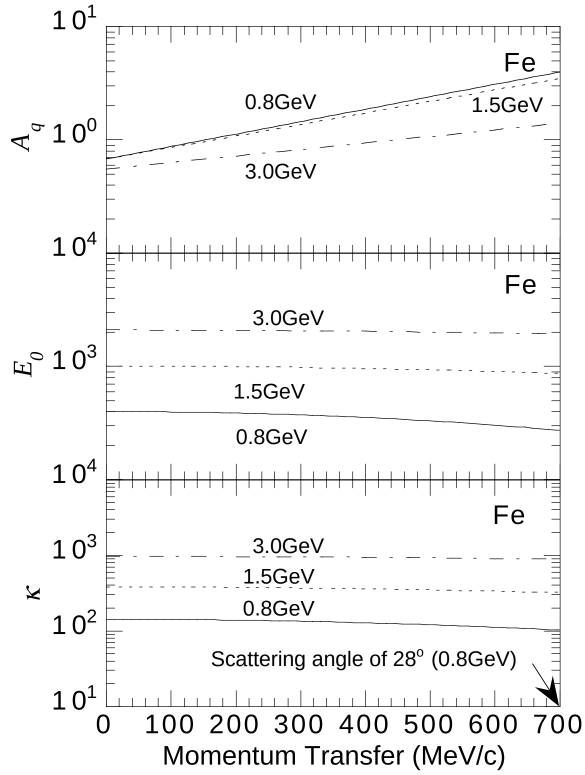

Fig. 3 Adjustable parameters A, E_0 and κ of Gaussian term obtained by fitting for the experimental and calculated neutron data. Solid, dotted and dashed-dotted lines indecate the values for the proton incident energies of 0.8, 1.5 and 3.0 GeV, respectivly

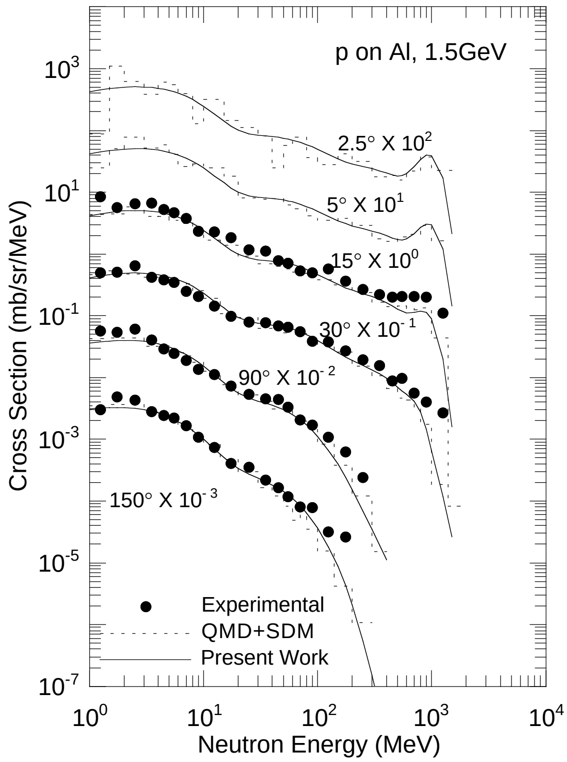

Fig. 4 Neutron production double differential cross section for 1.5GeV-proton incidence on Al

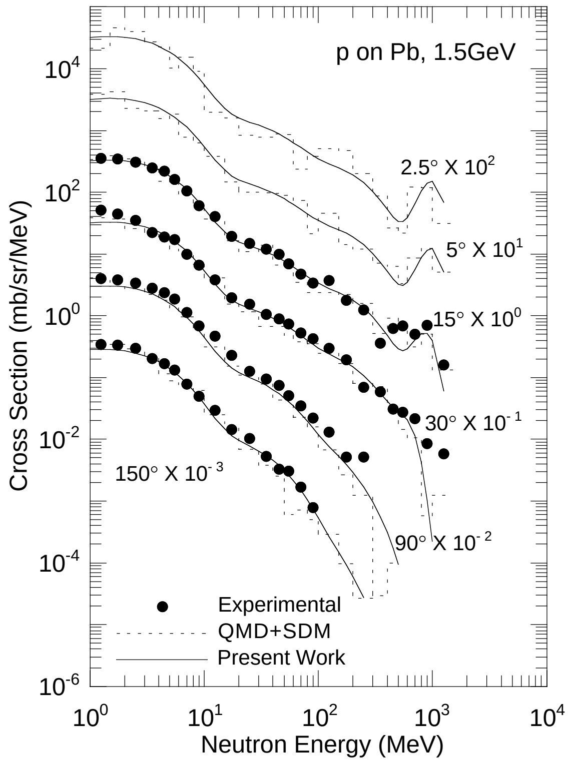

Fig. 5 Neutron production double differential cross section for 1.5GeV-proton incidence on Pb

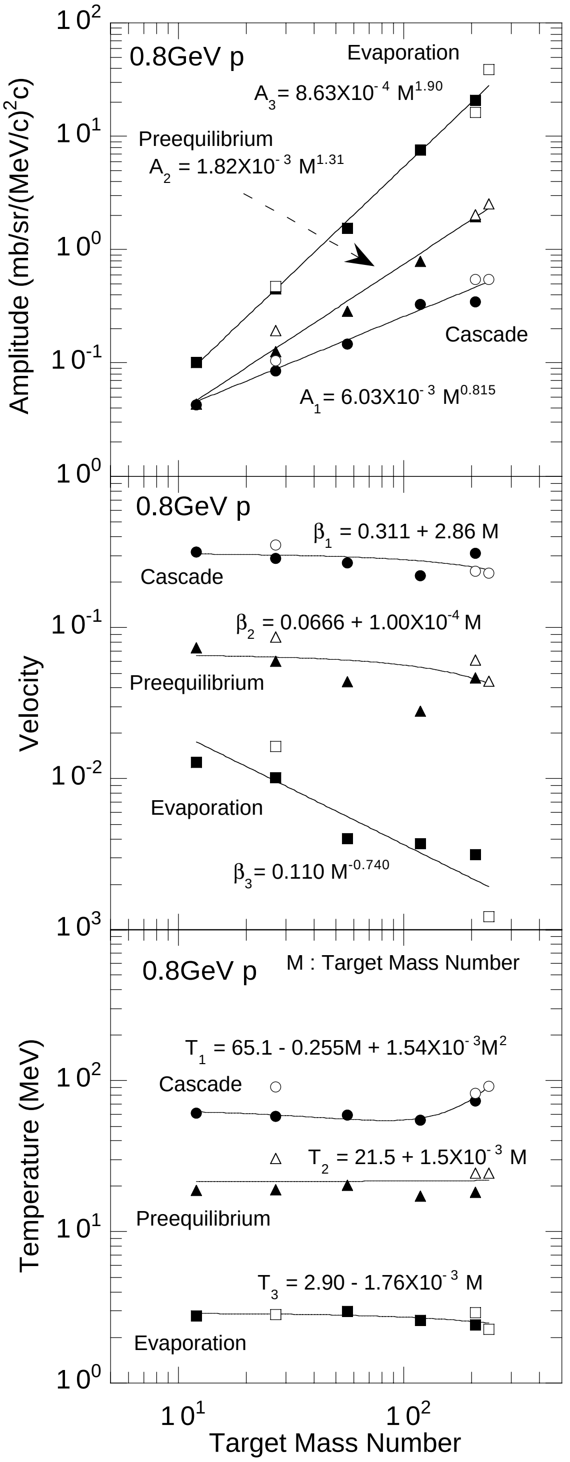

Fig. 6 Mass number dependance of parameters A, β and T for incident protns of 0.8GeV

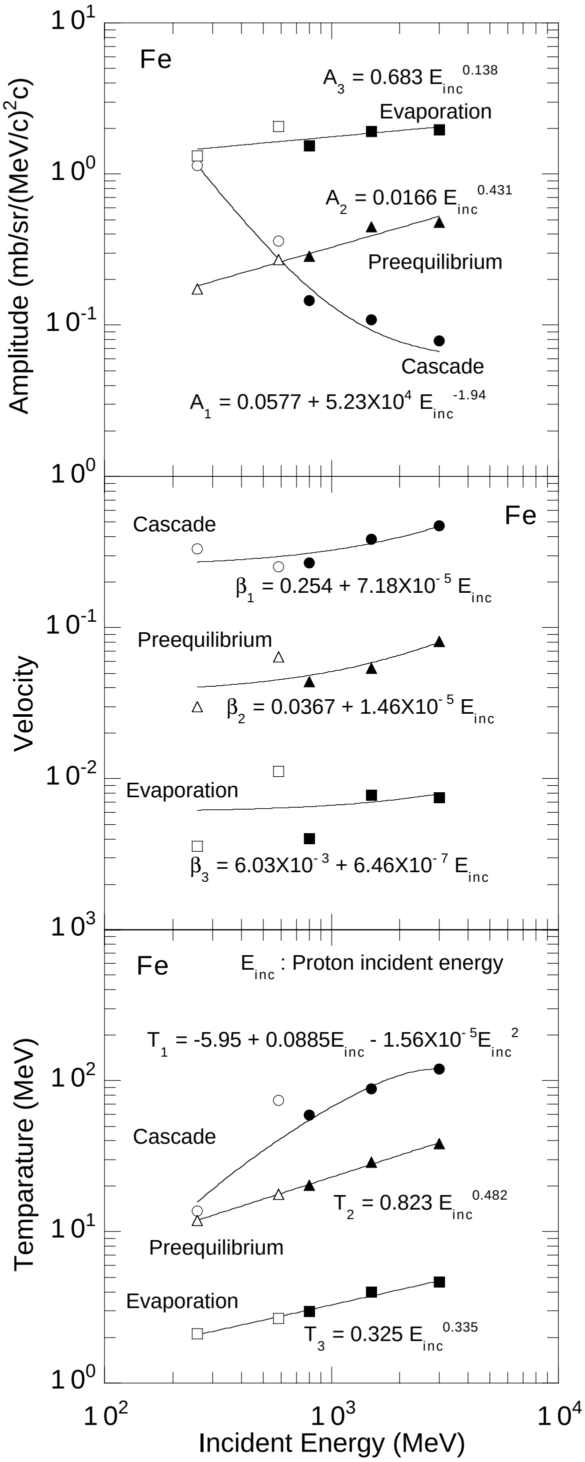

Fig. 7 Incident energy dependance of parameters A, β and T for Fe target