Parameterization of Neutron Production Double-differential Cross Section above Several Tens-MeV by the Use of Moving Source Model

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The moving source model based on the Maxwell-like energy distribution with Gaussian shape terms are employed for analyzing the neutron emission spectra from proton-induced spallation reaction. The parameterization of the double differential cross section is made for the experimental and calculated neutron data in the energy region from several-tens MeV to 3 GeV.

1 Introduction

Accurate nuclear data covering incident energies up to several GeV are required for applications such as radiation transport simulations in the cancer radiotherapy and the accelerator-driven transmutation of nuclear wastes. Neutron production double differential cross sections, however, have been measured for several targets at some incident energies. Therefore, it is important to find the systematic behaviors in the neutron data, and to parameterize them to extend to different incident energies and target nuclei. The moving source (MS) model[1] which is based on the Maxwell-like distribution has been employed for analyzing the experimental neutron emission data. The parameters obtained from this type of analysis represented well the experimental (p,xn) double differential neutron spectra in the incident energy region from 113 MeV to 800 MeV[2]. This method made use of angle-independent parameters for specifying individual components of experimental spectra, i.e. cascade, preequilibrium and evaporation processes Three parameters were required in the model for specifying each evaporation component of experimental spectra, and were determined with simultaneous consideration of whole-direction data.

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 from several tens-MeV to 3 GeV. The experimental neutron data at incident proton energies of 22 MeV[3], 25 MeV[4], 113 MeV[5], 597 MeV[6], 800 MeV, 1.5 GeV and 3.0 GeV[7] are analyzed for each component of cascade, preequilibrium and evaporation process by the MS model. In addition, HETC-3STEP[8] and QMD+SDM[9] are employed to calculate the cross sections which were not measured.

2 MS model

The MS model is based on the view that a locally heated spot is moving with isotropically evaporating particles in a nucleus. Since the particle emission behavior in the high energy 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 the MS model, the collision phenomena are at first seen from an observation point moving with an appropriate velocity β (moving frame). Neutrons are assumed to be emitted isotopically with an exponential-type energy distribution at a temperature T (MeV) in the moving frame. The neutron emission double cross section is expressed in the laboratory frame by

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

where, E_{kin} (MeV) and P (MeV/c) is kinetic energy and momentum of an emitted neutron in the laboratory frame, respectively. The parameters A (mb/sr/(MeV/c)), β and T (MeV) are called amplitude, velocity and temperature, respectively. The parameters are adjustable in fitting the equation to double differential cross section data.

For the spallation reaction, the MS model is applied in a form of summation of three components as

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

Three components of i=1 to 3 correspond to the intranuclear-cascade, the preequilibrium and the nuclear-evaporation processes, respectively. In this study,the parameters for each process are adjusted to the experimental neutron emission spectra and the calculation results by HETC-3STEP and QMD + SDM.

Figures. 1 and 2 show the results of fitting for the 22-MeV proton incidence on Fe and the 25-MeV proton incidence on W, respectively. The marks stand for the experimental cross sections[3][4]. The dotted lines show the results obtained by HETC-3STEP. The solid lines show the results of fitting for the experimental data and calculated data. This MS model reproduces the neutron spectra in the energy region below 25 MeV well.

Figures. 3 and 4 show the results of fitting for the 113-MeV proton incidence on the Fe and W target, respectively. 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 60°, however, the MS model underestimates the neutron data at neutron energy above 20 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 Consideration for quasi-elastic scattering

A Gaussian shaped term[10] is introduced into the usual MS model for analyzing the neutron spectra originated from the quasi-elastic and quasi-inelastic scattering processes. The equation is thus written as

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

where A_G (mb/sr/MeV), E_G (MeV) and σ_G (MeV) in the last term are adjustable parameters, and are dependent on the emission neutron angle at this stage. The other terms are the same one in the usual MS model of Eq. 2. The values of parameters A_G, E_G and σ_G are showed in Fig. 7, where q_{NN} (MeV/c) is momentum transfer. The marks stand for the value obtained from fitting for 113 and 597 MeV proton incidence on Fe. The solid lines show systematics of parameters obtained by smooth functions as

$$\begin{aligned} A_G &= a_1 e^{a_2 q_{NN}}, \\ E_G &= \left\{b_1 + b_2 q_{NN} + b_3 q_{NN}^2\right\} E_{NN}, \\ \sigma_G &= \left\{c_1 + c_2 q_{NN} + c_3 q_{NN}^2\right\} E_{NN}, \end{aligned} \tag{4}$$

where E_{NN} (MeV) that neutron kinetic energy after elastic collision with incident proton, a_i, b_i and c_i that adjustment parameter. The quantity of q_{NN} and E_{NN} are determined by the incident proton and the angle of emitted neutron. The values of E_G and σ_G are almost constant, while A_G depends on momentum transfer strongly. Figures 3 - 6 present neutron production double differential cross section on Fe, W and Pb target. The solid lines show the neutron spectra obtained by the MS model including the gaussian-term obtained by Eqs. 3 and 4. The marks and the dashed lines indicate the experimental data[5][6] and the calculated results by QMD+SDM, respectively. The MS model with the Gaussian shaped term represents the experimental and calculated neutron data over the whole angle well.

4 Systematics of parameters

The systematics of parameters of MS model was obtained by fitting of the experimental neutron data and the results calculated by HETC-3STEP and QMD+SDM in the incident proton energy region from several-tens MeV to 3 GeV. The parameters A, β and T for Fe and Pb target are shown as function of incident proton energy in Figs. 8 and 9, respectively. In these figures, subscripts 1, 2 and 3 indicate the intranuclear-cascade, preequilibrium and nuclear-evaporation processes, respectively. The marks present the values obtained from fitting for experimental and calculated neutron data. The solid lines show systematics of parameters A, β and T. The Amplitude A_1 for cascade process on Fe and Pb target vanish in the incident proton energy region below 100 MeV. For preequilibrium process, the amplitude A_2 on Fe target shows different behavior from one on Pb target. Temperature T_1 and T_2 are supposed to combine together at the incident proton energy around 100 MeV. The Velocity β on Pb smoothly depends on incident proton energy for each reaction process.

5 Conclusion

The experimental neutron data and the calculated results above several tens-MeV were reproduced for the three components of cascade, preequilibrium and evaporation reaction by the use of MS model. The introduction of the gaussian shaped term into MS model were found to lead to good agreement with the neutron emission spectra originated from quasi-elastic and quasi-inelastic spectra. The Maxwell MS model with the Gaussian term were found to be applicable to the nuclear data evaluation for the wide incident energy range.

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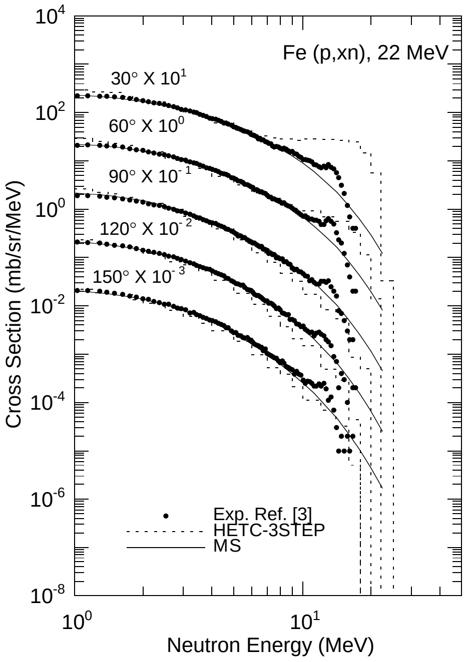

Figure 1: Neutron production double differential cross section for 22 MeV-proton incidence on Fe.

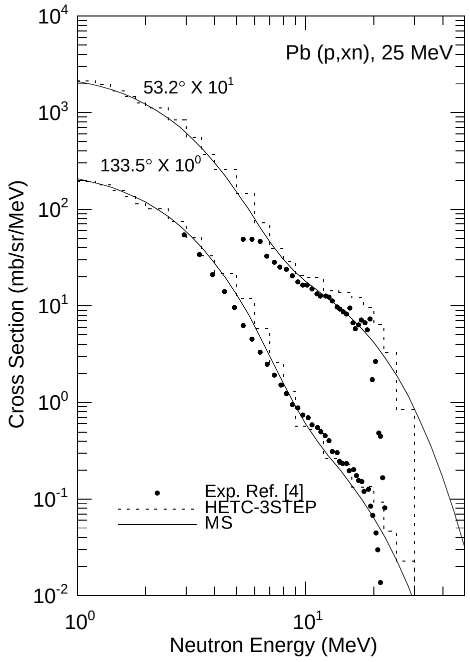

Figure 2: Neutron production double differential cross section for 25 MeV-proton incidence on Pb.

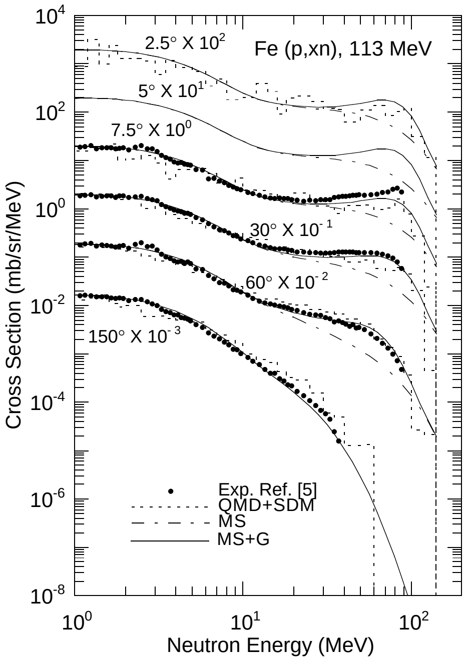

Figure 3: Neutron production double differential cross section for 113 MeV-proton incidence on Fe.

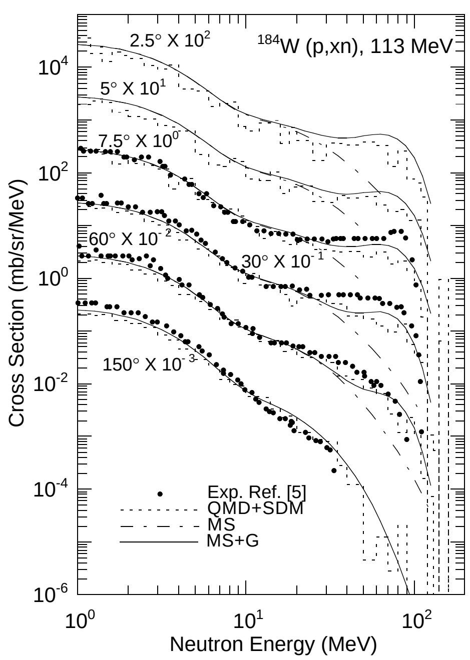

Figure 4: Neutron production double differential cross section for 113 MeV-proton incidence on W.

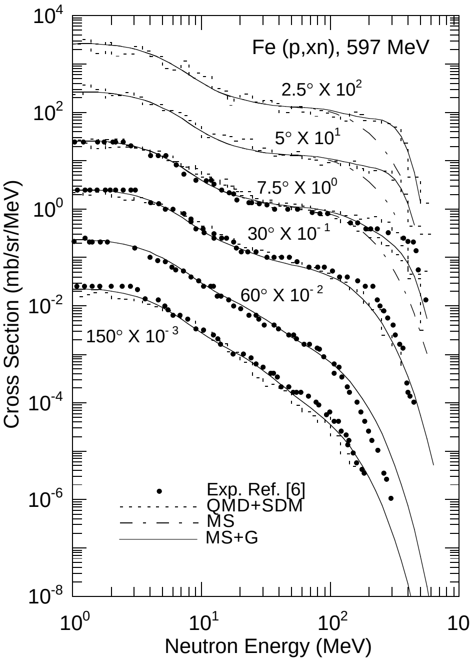

Figure 5: Neutron production double differential cross section for 597 MeV-proton incidence on Fe.

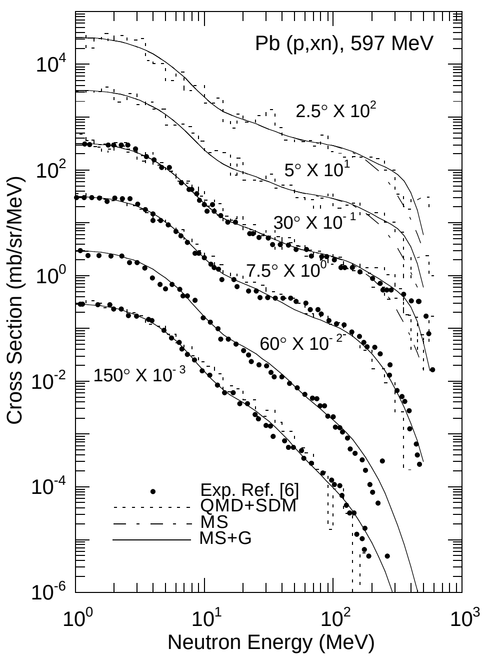

Figure 6: Neutron production double differential cross section for 597 MeV-proton incidence on Pb.

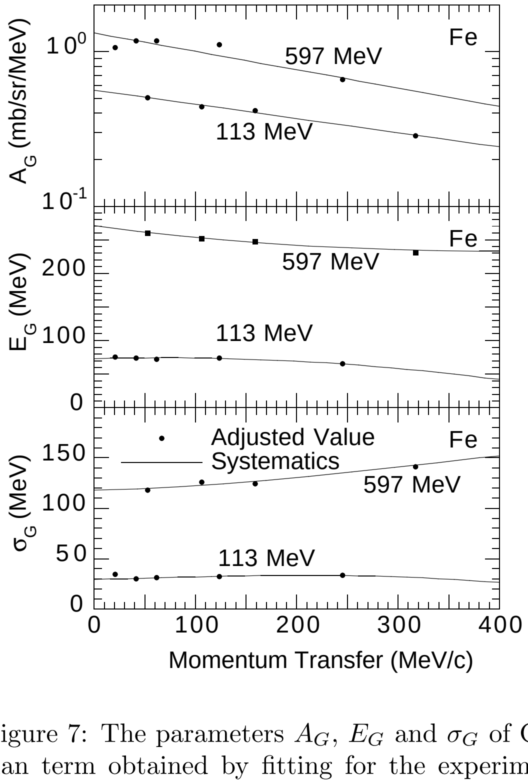

Figure 7: The parameters A_G, E_G and σ_G of Gaussian term obtained by fitting for the experimental and calculated neutron data

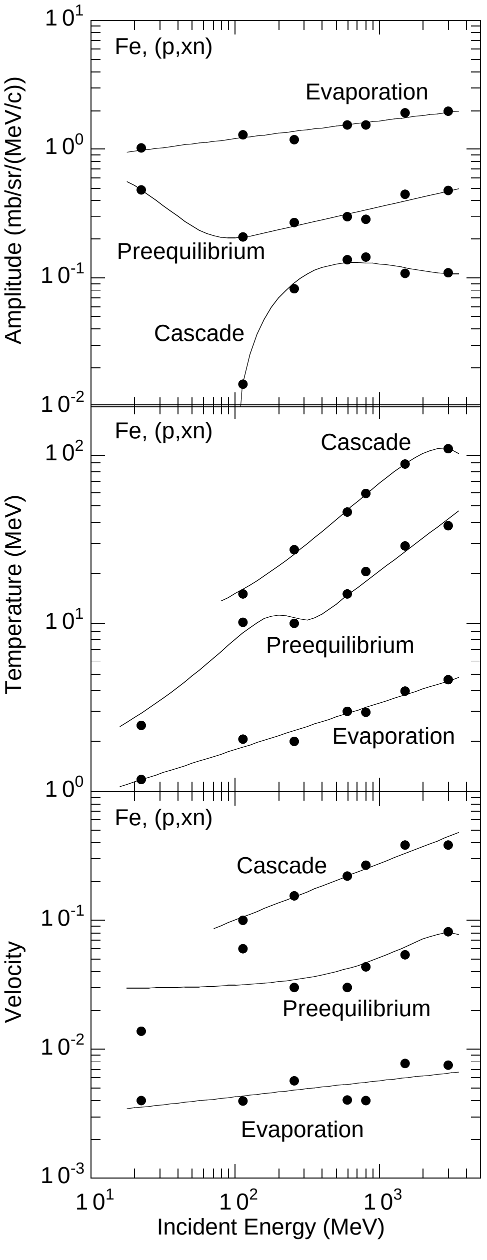

Figure 8: Incident energy dependence of parameters A, T and β on Fe target

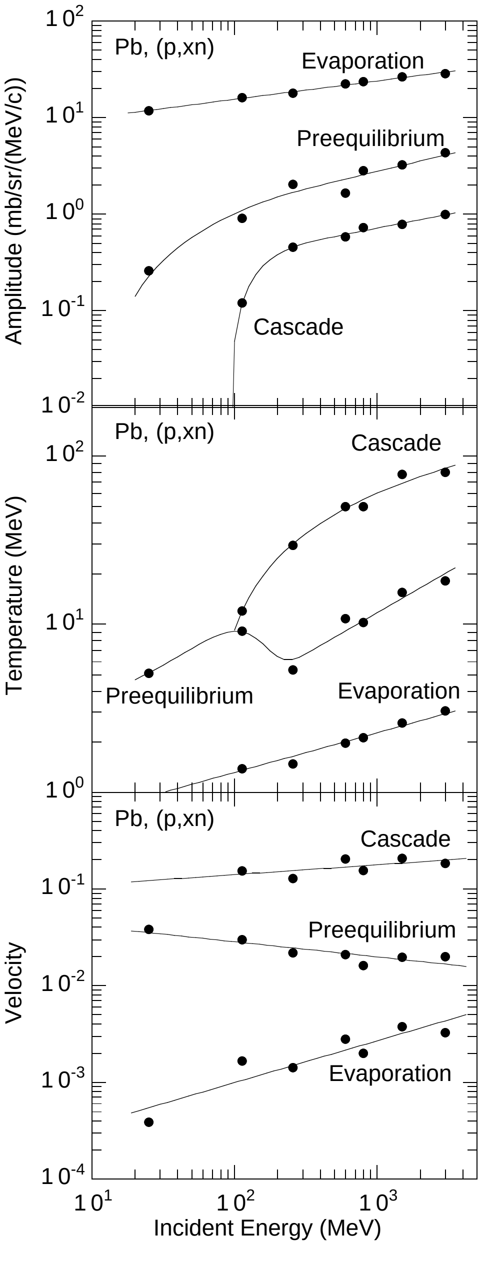

Figure 9: Incident energy dependence of parameters A, T and β on Pb target