Study on charged particle productions in proton-nucleus reactions at 392 MeV

Hiroki Iwamoto^{1,a}, Minoru Imamura¹, Naoya Koba¹, Hiroaki Fukuda¹, Genichiro Wakabayashi¹, Yusuke Uozumi¹, Tadahiro Kin^{2,b}, and Masahiro Nakano²

¹ Department of Applied Quantum Physics and Nuclear Engineering, Kyushu University, Fukuoka 819-0395, Japan

² University of Occupational and Environmental Health, Kita-Kyushu 807-8555, Japan

Abstract. Double differential cross sections of charged particle production for 392 MeV protons were measured with ΔE - E counter telescopes consisting of two surface barrier silicon detectors and a GSO(Ce) scintillator. The experimental results were compared with the INC code which was newly developed by the presenting author. The code is based on a simple INC model but has introduced two fragment production processes. From our results, a combination of these processes appears to be effective to describe charged particle productions in the intermediate-energy range.

1 Introduction

Intermediate-energy nuclear data and nuclear reaction models are of high importance in variety of sciences and technologies. Charged particle production cross sections are, in particular, indispensable for estimating the radiation heating and the radiation damage in accelerator driven system (ADS) and the radiation dose evaluation in spacecrafts. Understanding of secondary particle behaviors is necessary for a feasibility study and optimum design of the system offering high safety and low cost. These experimental data, however, are very scarce in spite of the need of them, and a fact that makes difficult to improve the existing theoretical models such as Intranuclear Cascade (INC) model [1,2], Quantum Molecular Dynamics (QMD) model [3], and Antisymmetrized Molecular Dynamics (AMD) model [4].

In this study, we measured double differential cross sections (DDXs) of charged particle productions for reaction by 392 MeV protons. And we compared them with the INC model which was newly developed by us [5].

2 Experiment

The experiment was conducted at the Research Center for Nuclear Physics (RCNP), Osaka University. The schematic view of the experimental arrangement is illustrated in figure 1. Proton beams were accelerated by the ring cyclotron up to 392 MeV, and bombarded a target in a vacuum chamber. Targets used in this experiment were ⁹Be, ¹²C, and ²⁷Al with thickness of 4.62, 34, and 2.7 mg/cm², respectively. Charged particles, ranging from protons to beryllium ions, emitted from reactions were detected by ΔE - E counter telescopes consisting of two silicon surface barrier detectors and a cubic GSO(Ce) scintillator, 43-mm on a side. Detectors were placed in vacuum chamber of 800-mm diameter. The measured angles were 20°, 45°, 60°, and 75° in the laboratory frame. Charge signals from detectors were processed with standard NIM modules,

Fig. 1. Schematic view of the experimental set-up.

and digitized data were stored on hard disks of PC through a CAMAC system. More experimental details are shown in ref. [7,6].

3 Data analysis

Double differential cross sections were obtained by following procedure through off-line analysis. First, pulse heights of signals were converted into particle energy using Bethe-Bloch formula. Then, we took into consideration the light output nonlinearity of the GSO(Ce) crystal [5]. The particle identification is performed by using the parameter PI:

$$PI = E_{\text{total}}^b - (E_{\text{total}} - \Delta E)^b, \quad (1)$$

where b is the parameter representing the range of each particle, E_{total} the total energy deposited on the spectrometer, and ΔE the amount of energy deposited on the transmission detector. A value of 1.73 was employed for the parameter b . Figure 2 is a typical two-dimensional plot of PI versus particle energy for the 392 MeV proton-induced reaction on ⁹Be at 75°. Next, we generate PI projection spectra for each of the

^a Presenting author, e-mail: iwamotoh@nucl.kyushu-u.ac.jp

^b Present address: Japan Atomic Energy Agency, Ibaraki, Japan

Fig. 2. Two-dimensional plot of PI versus particle energy for 392 MeV proton-induced reaction on ^9Be at 75° .

spectra. Finally we derived the charged particle production DDXs, where magnitude of the DDXs was determined by fitting the past DDX data [6].

4 The INC model

First, we developed a simple INC model code in order to introduce the fragment production processes into the model. Then, we merged our code with Generalized Evaporation/fission Model code GEM developed by Furihata [9]. Second, we incorporated the fragment production processes into the INC code, as will hereinafter be described in detail. In this section, we give the outline of our INC model before incorporating the fragment production processes into the INC code.

Initial nucleon positions and momenta are determined stochastically according to the Woods-Saxon type density parametrized by Negele [10] and the degenerate Fermi distribution, respectively. Nuclear potential is assumed square well potential with $V_0 = -45$ MeV. In our model, the time evolution of nucleons is described by relativistic kinematics without two-body interaction, however nucleons under the potential barrier are not allowed to move in spite of having their momentum. It is assumed that two particles collide if their relative distance is smaller than a value obtained from the NN cross section. In present calculation, we used Cugnon parametrization form [11] for the NN cross sections and the angular distributions. The Pauli blocking effect has the simple form:

$$P_{\text{block}} = 1 - \left(1 - \Theta(E_F - E'_i)\right) \left(1 - \Theta(E_F - E'_j)\right), \quad (2)$$

where E'_i and E'_j are the kinetic energies of scattered particles. Θ denotes the Heaviside function.

Generally speaking, it is well known that traditional INC calculations underestimate DDX spectra in backward directions, and our model was also not an exception. The main

Fig. 3. Neutron production double differential cross section for proton-induced reactions on ^{90}Zr at 120 MeV (left) and 160 MeV (right). Data are taken from [12].

reason may be that these models do not consider the refraction effect by the nuclear potential. Therefore, in order to correct the emitted angle, we gave a following systematics to our model:

$$\begin{aligned} \theta' &= \theta + \Delta\theta, \\ \Delta\theta &= \max\left(-0.6821\theta^2 + 3.1548\theta - 3.1789, 0\right) \quad (\text{radian}), \end{aligned} \quad (3)$$

where θ is an angle for the direction of injection. This systematics is applied when outgoing nucleon gets across the nuclear surface.

In order to check its predictive ability, we compared our model with many previous data between 100 MeV and 400 MeV for light to heavy target nuclei. Neutron/proton production DDXs calculated by our INC/GEM model are in good agreement with the experimental results in the whole angular regions except for very forward directions, in spite of the simplicity of our INC model [5] (e.g., fig. 3).

5 Comparison and discussion

5.1 Comparison between the experimental data and the INC model

The results for ^{27}Al target bombarded with 392 MeV protons are compared in figure 4. It is reasonable that proton production DDX is in good agreement with experimental data. On the other hand, although other charged particle production DDXs are reproduced in the equilibrium region, it does not agree for pre-equilibrium region, because our model does not include fragmentation (or clustering) process in the cascade stage.

Fig. 4. Particle production double differential cross sections for proton-induced reactions on ^{27}Al at 392 MeV. Circles denote the present experimental data. Triangles are taken from [6, 13].

5.2 Fragment production processes

Then we introduced the two fragment production processes into the INC model: “surface coalescence” process and “knockout” process. The procedure of “surface coalescence” is similar to Boudard’s procedure [14]. When a nucleon arrives at the nuclear surface and is going to be emitted, it is tested whether it produces a fragment. The fragment production is judged by whether the relative distance in phase space is close. The condition of fragment production is given by

$$r_{i,j}p_{i,j} \leq h_0. \quad (4)$$

In this work we use the parameter $h_0 = 1500 \text{ MeV}/c \text{ fm}$. If this condition is met, the fragment is produced. The momentum of the fragment is the total momentum of the particles composing the fragment. The fragments considered are deuteron, triton, ^3He , and ^4He . If the momentum of nucleon which gets across

Fig. 5. Deuteron production double differential cross section for proton-induced reactions on ^{392}Al at 392 MeV. Data are taken from [13].

the surface is small, the relative distance in r -space is very large. But such a fragment cannot be emitted because it cannot get above the nuclear potential or Coulomb barrier.

Although this “surface coalescence” process may partially reproduce the experimental spectra, it cannot reproduce the spectra of high energy fragments. Therefore we introduced the “knockout” process into our INC model in addition to the “surface coalescence” process. Fragment production by the “knockout” process is performed according to the following procedure:

When two particles collide, we search nucleons around the bombarded particle in r -space. If there are particles near the nucleon, which are under the Fermi momentum, we consider the group of nucleons as a cluster. The condition is given by

$$r_{i,j} \leq r_0, \quad (5)$$

where the parameter r_0 is 1.5 fm. Kinematics of collision follows N - AN collision. Since systematic experimental angular distribution data of N - AN collision do not exist, we used the Cugnon’s systematics of NN collision [11].

As shown in figures 5 and 6, the INC model which includes the “surface coalescence” process and the “knockout” process is in much better agreement than the normal INC model, although there is still room for improvement.

6 Conclusion

The charged particle production spectra from ^9Be , ^{12}C , and ^{27}Al bombarded with 392 MeV protons were measured at angles between 20° and 75° with ΔE - E counter telescopes consisting of two surface barrier silicon detectors and a GSO(Ce)

Fig. 6. ^4He production double differential cross section for proton-induced reactions on ^{27}Al at 392 MeV. Data are taken from the present experiment.

scintillator. In addition to the experiment, the experimental results were compared with the INC code which was originally developed by the authors. Results of the INC code was in good agreement with the nucleon (neutron and proton) spectra, however it could not reproduce fragment (deuteron, triton, ^3He , ^4He , etc.) spectra in the pre-equilibrium region.

We attempted to introduce two fragment process, or “surface coalescence” process plus “knockout” process into the

INC model. From comparison between this model and the experimental data, it appears that a combination of these processes is effective to describe fragment productions in the intermediate-energy region. It is necessary to research systematic energy-dependent and target mass-dependent of the parameter h_0 and r_0 . However, let us notice that there exist still some improvements needed. For this, we should measure systematic experimental data in the intermediate-energy region.

The authors would like to thank the accelerator operation staff at the RCNP cyclotron for the support and assistance of this experiment. We are also grateful to Dr K. Niita for useful discussions.

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