Development of Heavy Ion Transport Monte Carlo Code

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We developed a heavy ion transport Monte Carlo code HETC-CYRIC which can treat the fragments produced by heavy ion reactions. The HETC-CYRIC code is made by incorporating a heavy ion reaction calculation routine, which consists of the HIC, the SPAR, and the Shen's formula, into the hadron transport Monte Carlo code HETC-3STEP. The results calculated with the HETC-CYRIC were compared with the experimental data, and the HETC-CYRIC gave rather good agreement with the experiment.

1 Introduction

Recently, high-energy heavy ions have been used in various fields of nuclear physics, material physics and medical application, especially cancer therapy, and several heavy ion accelerator facilities are now operating or planned for construction. The high-energy heavy ions are also important constituents of cosmic radiation for space utilization, such as the international space station project including the JEM (Japanese Experimental Module). In this circumference, the interaction and transport of heavy ions in a medium including human body are indispensable basic informations to estimate the absorbed dose of the patients during the cancer treatment, to design the shielding of the accelerator facility and to estimate the exposure of the astronauts and the space scientists in space. There exists however only one heavy-ion transport code, HZTRAN[1], developed by NASA in the world, but this code is one-dimensional discrete ordinates calculation code. It is therefore needed to develop the three dimensional heavy-ion transport code. Here in this study, we tried to develop the three-dimensional Monte Carlo code for heavy ion transport calculation.

2 Basic Method of the Code Development

We developed a heavy ion transport Monte Carlo code by incorporating a newly-developed heavy ion routine (HIR) into the HETC-3STEP[2].

The heavy ion transport routine HIR can treat the transport and reaction of incident heavy ion and fragments produced by a chain of heavy ion reactions. For this heavy ion reaction calculation, we used the two existing Monte Carlo code, HIC[3] and ISABEL[4]. First, we compared these two codes with the experimental data in order to investigate the calculational accuracy and to decide which is suitable for the heavy ion routine. The comparisons were made for double-differential neutron production cross sections (DDX) in angle and energy by heavy ions, as shown in Fig. 1.

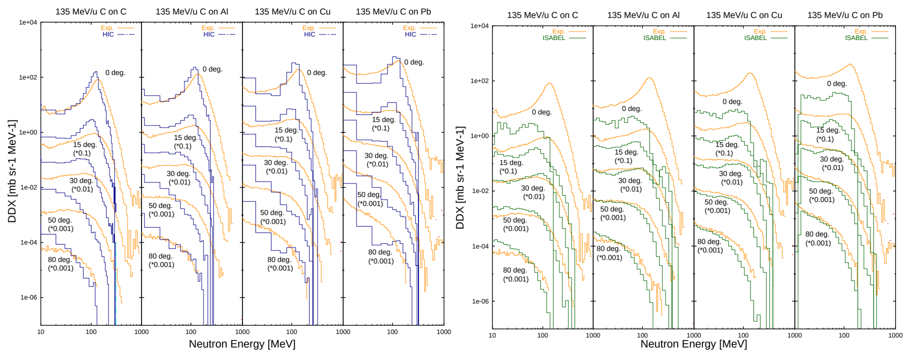

Figure 1: Comparison of HIC and ISABEL calculation; [Left] Neutron DDX calculated by HIC compared with our experimental data of 135MeV/nucleon C ion on C, Al, Cu, and Pb targets[5]. [Right]The same results between ISABEL and the experiment.

The HIC code is the Heavy Ion Code which can treat the heavy ion reaction of energy higher than 50 MeV/nucleon which is based on the intranuclear cascade model and the evaporation model. The ISABEL code includes only intranulear cascade model but this model treats a nucleus by diving into 16 segments which is more precise than 3 segments in the HIC code, and the ISABEL code also considers the reflection at a boundary of a nucleus, which can be the same effect as considering the preequilibrium process. As the results of comparisons shown in Fig. 1, the ISABEL code showed good agreement with the experimental data at angles of larger than 30 degrees, while on the other hand, the ISABEL underestimated the experimental data terribly from 0 degree to 15 degrees. The HIC results rather well with the experimental data at all angles. So, we decided to use the HIC code in heavy ion reaction calculation for the heavy ion transport routine.

We then developed the heavy ion transport routine HIR by combing the HIC code, SPAR[6] code, and Shen's formula[7]. The SPAR code can calculate the heavy ion stopping powers and ranges, and the Shen's formula can calculate the heavy ion total reaction cross sections.

The HETC-3STEP is a high energy hadron transport Monte Carlo code developed by Yoshizawa et al. This code is revised from the original HETC code[8] which includes the intranuclear-cascade evaporation process (2-step model) based on a Fermi free gas model, by adding the pre-equilibrium emission based on the exiton model (3-step model). The HETC-3STEP can also treat the heavy ion (atomic mass less than 20) transport and reaction, but the treatment is restricted to incident particles and the accuracy of heavy ion calculation is poor.

3 Procedure of the Code Development

The heavy ion transport calculation code is composed of the following steps,

1. A distance D in which a heavy ion projectile collides with a target nucleus in a medium

is decided as follows,

$$D = -\frac{ln(r)}{\Sigma_t},$$

where Σ_t is a total reaction cross section of a projectile in a medium calculated by the Shen's formula and r is a uniform random number.

2. A range R of a projectile in a medium can be calculated by the SPAR code.

3. It is decided whether a projectile collides or stops. If $D < R$, a projectile collides with a target nucleus after flying straight-forward to a distance of D and losing its energy. This energy loss can also be calculated by the SPAR code. If $D > R$, a projectile loses its energy completely without collision in a medium, and the transport of this projectile does not follow any more.

4. The heavy ion reaction calculation is performed using the HIC code. The HIC code gives the output results of many heavy ions and hadrons as fragment products. These heavy ion outputs are stored and used as an incident heavy ion for continuing the extranuclear cascade reactions. The hadron outputs on their particle types (neutron, proton and pion), energies, positions, directions and weights are stored in a file during the heavy ion calculations. This file is used as hadron sources produced by heavy ions for the hadron transport calculation using the HETC-3STEP code.

Figure 2 shows the thus-obtained HETC-CYRIC code structure.

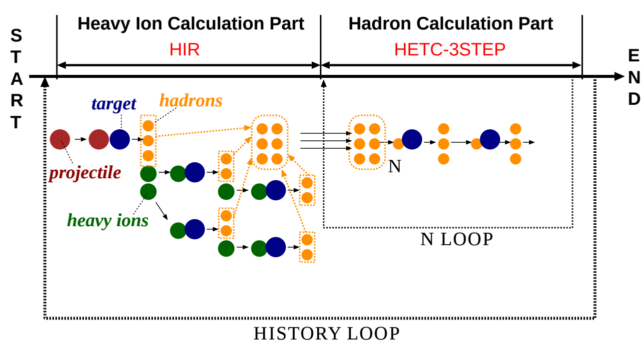

Figure 2: Structure of HETC-CYRIC

4 Comparison of HETC-CYRIC and Experimental Data

In order to investigate the accuracy of the HETC-CYRIC code, we compared the results calculated by the HETC-CYRIC with the data measured by Kurosawa et al[9]. Figures 3 and 4 show the comparison of the HETC-CYRIC results with the measured neutron spectra for 400 MeV/nucleon carbon and iron ions on stopping-length carbon and lead targets.

In Fig. 3 of C ion, the HETC-CYRIC gives good agreement with the experiment from 7.5 to 30 degrees, but gives underestimation at 0 degree and gives overestimation from

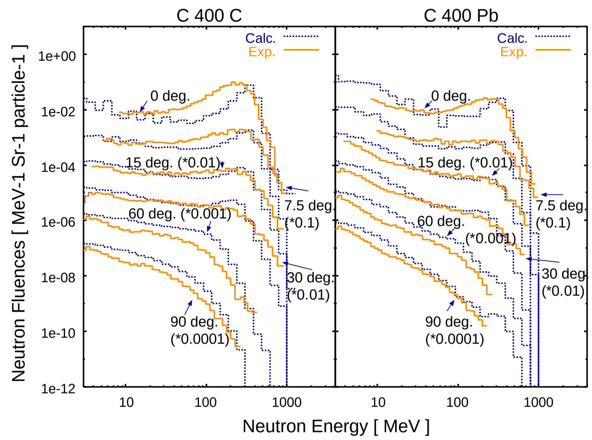

Figure 3: Comparison of the neutron spectra calculated with the HETC-CYRIC and the measured data for 400 MeV/nucleon C ion on C and Pb targets[9]

60 to 90 degrees comparing with the experiment for carbon target. In the case of lead target, the HETC-CYRIC gives good agreement as a whole excluding an overestimation in the low energy region at all angles.

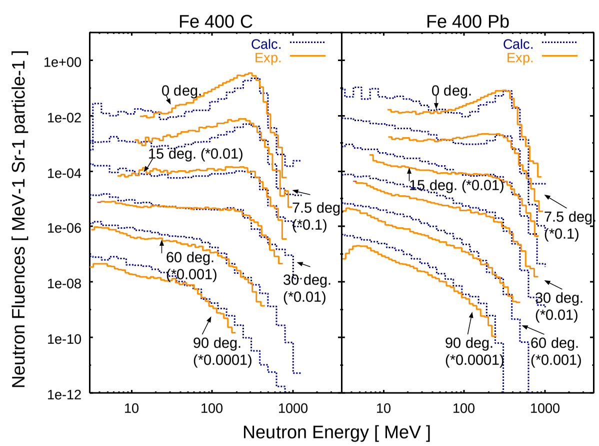

Figure 4: Comparison of the neutron spectra calculated with the HETC-CYRIC and the measured data for 400 MeV/nucleon Fe ion on C and Pb targets[9]

In Fig. 4 of Fe ion, the HETC-3STEP gives good agreement as a whole, excluding an underestimation in the forward direction comparing with the experiment for carbon target, and an overestimation in the low energy region for lead target as well as in the case of carbon ion.

This underestimation in the forward direction and overestimation at large angle and in the low energy region for heavier target material in the HETC-CYRIC code may come from the inaccurate heavy ion model of the HIC code.

We are now investigating the way to improve the present code more accurately by revising the HIC code or using the different heavy ion reaction calculation code such as the QMD code[10] based on the quantum modecular dynamics model.

5 Conclusion

We developed a heavy ion transport Monte Carlo code, HETC-CYRIC by combining the newly-developed heavy ion transport routine HIR including the HIC code and the hadron transport Monte Carlo code HETC-3STEP. The HETC-CYRIC can treat the heavy ion and hadron transport calculations. This code is still under developing and the first general-purpose heavy ion transport Monte Carlo code in the world.

References

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