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# Neutron-production Double-differential Cross Sections from Heavy-ion Interactions

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The existing data of neutron-production double-differential cross sections on C, Cu, and Pb targets bombarded with heavy-ions from He to Xe at 230-600 MeV/nucleon were revised by using a new set on neutron-detection efficiency values of an NE213-type liquid organic scintillator calculated with SCINFUL-QMD. The revised data were compared with the experimental data obtained by our new measurements, and the predictions of the Monte-Carlo particle transport codes, PHITS, FLUKA, MCNPX, and Geant4. While the revised and new experimental data showed good agreement, the Monte-Carlo codes failed to reproduce the high-energy peaks in the forward angular region.

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## I. INTRODUCTION

As the number of patients admitted for heavy-ion cancer therapy increases, the potential risk of radiation-induced second cancers has become a serious issue [1, 2]. In treatments using heavy-ion beams, various kinds of secondary particles are generated by heavy-ion induced reactions, and give an extra dose to organs outside the treatment volume. Especially, neutrons penetrate strongly through body tissue, and dominate the extra dose. In order to assess the risk of second cancers in heavy-ion cancer therapy, it is essential to evaluate the neutron-production double-differential cross sections from heavy-ion interactions.

Data of neutron-production cross sections from heavy-ion interactions have been reported by Iwata *et al.* [3]. The experiments were performed at the Heavy Ion Medical Accelerator in Chiba (HIMAC) of the National Institute of Radiological Sciences (NIRS) by using liquid organic scintillators with the time-of-flight (TOF) technique. The data are prepared for various combinations of projectile and target, and dedicated to a shielding design of heavy-ion accelerator facilities. Unfortunately, Iwata *et al.* employed neutron-detection efficiency values calculated with the CECIL code [4], and this code is known to give small values in the energy region of several hundred MeV. This leads to an overestimation of the cross sections. We have already revaluated [5] the data of secondary neutron spectra from thick targets derived with the CECIL code by Kurosawa *et al.* [6] by using a new set on neutron-detection efficiency values calculated using the SCINFUL-QMD code [7], the accuracy of which has been experimentally verified up to 800 MeV [8]. The results showed that the overestimation observed in the higher energy region was improved, and the revised data agreed better than the original data with the predictions of Monte-Carlo simulations.

In this paper, we revaluate the data of neutron-production double-differential cross sections by Iwata *et al.* [3] by correcting the neutron-detection efficiency values. The revised cross-section data are compared with those of our new measurements [9] and the predictions

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Table 1. Projectile type, incident energy per nucleon, and target thickness used in the experiments by Iwata *et al.* [3].

| Projectile type and energy (MeV/nucleon) | Target and thickness (g/cm$^2$) | | |
|---|---|---|---|
| He(230) | Al(5.40) | Cu(5.38) | |
| C (290) | C(1.80) | Cu(4.47) | Pb(2.27) |
| C (400) | C(9.00) | Cu(13.4) | Pb(9.08) |
| N (400) | C(1.78) | Cu(2.69) | |
| Ne(400) | C(1.80) | Cu(4.47) | Pb(2.27) |
| Ne(600) | C(3.60) | Cu(4.47) | Pb(4.54) |
| Ar(400) | C(0.72) | Cu(1.34) | Pb(1.70) |
| Ar(560) | C(1.08) | Cu(1.79) | Pb(2.27) |
| Kr(400) | C(0.55) | Cu(0.90) | Pb(1.02) |
| Xe(400) | C(0.27) | Cu(0.45) | Pb(0.57) |

of the Monte-Carlo particle transport codes, PHITS [10], FLUKA [11], MCNPX [12], and GEANT4 [13].

## II. REVALUATION OF NEUTRON-PRODUCTION CROSS SECTIONS

Table 1 lists the projectile and target combinations used in the experiments by Iwata *et al.* [3]. The NE213-type liquid organic scintillators with 12.7 cm diameter and 12.7 cm thickness were employed to measure the neutrons at the emitting angles of 5, 10, 20, 30, 40, 60, and 80 degrees in the laboratory frame.

Figure 1 depicts the neutron-detection efficiencies of the NE213-type liquid organic scintillator calculated by SCINFUL-QMD [7] and CECIL [4]. The threshold level of 4.0 MeVee in electron-equivalent energy was applied to the data of 5, 10, and 20 degrees, and 1.0 MeVee was set for 30, 40, 60, and 80 degrees. Because the proton events escaping from the scintillator were eliminated in the analysis of the experimental data with a pulse-shape discrimination, they were also discarded in the calculations. An increase in efficiencies is observed above 300 MeV in SCINFUL-QMD, while the results of CECIL decrease. SCINFUL-QMD equips high-energy reaction channels and cross-section data of hydrogen and carbon, which constitute an organic scintillator, up to 3 GeV. The increase in efficiency is consistent with the increase of the total cross section of carbon. On the other hand, CECIL lacks the high-energy channels and assumes the cross sections to be constant above 200 MeV. Therefore, CECIL cannot reproduce the increased efficiency in a higher energy region.

Figure 2 shows a typical example of the revaluation for the data of 600-MeV/nucleon Ne ions on Pb target. The circles represent the original data of Iwata *et al.*, whose numerical values were taken from Ref. [14]. The squares indicate the revised data correcting the neutron-detection efficiencies between the results of SCINFUL-

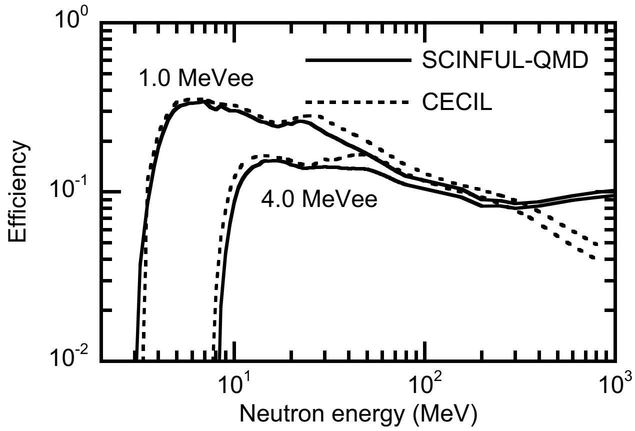


Fig. 1. Neutron-detection efficiencies of an NE213-type liquid organic scintillator (12.7 cm × 12.7 cm) with thresholds of 1.0 and 4.0 MeVee. Solid and dashed lines indicate the results of SCINFUL-QMD [7] and CECIL [4], respectively.

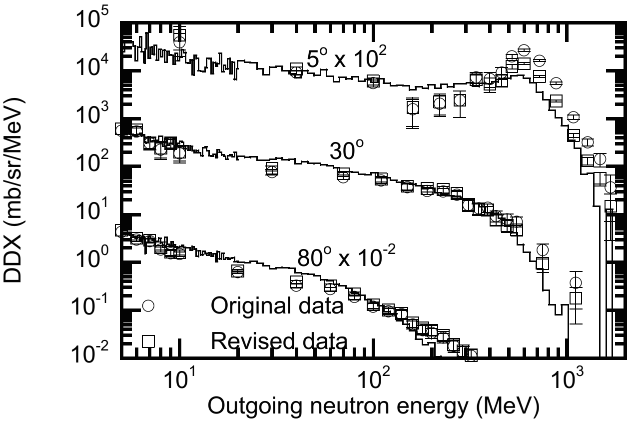


Fig. 2. Double-differential cross sections (DDX) on Pb target bombarded with Ne ion. Circle and square marks indicate the original and revised data, respectively. Solid lines are the results of FLUKA.

QMD and CECIL. The solid lines are the results calculated by the FLUKA code. A broad peak is observed at forward angles, and the energy of outgoing neutrons extends to a few GeV.

At larger angles, the energy of outgoing neutrons is lower than that at forward angles, and the effect of the correction does not appear clearly. This is because the difference between the results of SCINFUL-QMD and CECIL is small in that energy region. On the other hand, at forward angles, the absolute magnitude of the cross sections in the high energy tail of the peak was reduced by approximately a factor of two. The cross-section data producing high-energy neutrons are important in simulation analysises for both shielding design and dose assessment. The data correction discussed above is indispensable to verify the accuracy of the Monte-Carlo particle transport codes. We have corrected all data reported by Iwata *et al.*.

Table 2. Condition of cross-section calculations used in Monte-Carlo particle transport codes [10–13].

| Code | Version | Model | Nuclear data |
|---|---|---|---|
| PHITS | 2.15 | JQMD [15] | JENDL/HE-2007 [19] ENDF/B-VII.0 [20] ( ∼ 150 MeV) |
| FLUKA | 2008.3c | RQMD [16] | 260-group lib. [11] ( ∼ 20 MeV) |
| MCNPX | 2.6.0 | LAQGSM [17] | JENDL/HE-2007 [19] ENDF/B-VII.0 [20] ( ∼ 150 MeV) |
| GEANT4 | 9.3 | Binary Cascade [18] | G4NDL3.13 [18] ( ∼ 20 MeV) |

## III. MONTE-CARLO TRANSPORT CODES

Table 2 exhibits the condition of cross-section calculations in the Monte-Carlo particle transport codes, PHITS [10], FLUKA [11], MCNPX [12], and GEANT4 [13]. The different theoretical models [15–18] used to simulate nucleus-nucleus reactions were implemented code by code. The nuclear-data libraries [11,18–20] were used below the energies listed in Table 2 to transport the neutrons inside the target. The ring detectors corresponding to the emitting angles with the width of $\pm 1$ degree were employed as neutron scorers in the entire calculation. The space outside the target was defined as a vacuum.

## IV. RESULTS AND DISCUSSIONS

Figure 3 shows neutron-production double-differential cross sections of (a) 290-MeV/nucleon C ion on a C target, (b) 400-MeV/n C on C, (c) 400-MeV/n C on Pb, and (d) 560-MeV/n Ar on Pb. The square marks indicate the data revised in this work. The circles displayed in Fig. 3(a) are the results obtained by our new measurements [9]. The solid, dashed, dotted, and dot-dashed lines represent the calculation results of PHITS [10], FLUKA [11], MCNPX [12], and GEANT4 [13], respectively. In Fig. 3(a), the new data at 30 degree agree very well with the revised data of Iwata *et al.* at the same angle. This means that the experimental procedure in our measurements has been verified experimentally. The minimum energy of the new data is 2.8 MeV, and it is three times lower than that of Iwata *et al.*. Detailed discussions about the new measurements are found in our other paper submitted to these conference proceedings [9].

In comparison between the experiments and calculations, MCNPX shows a large overestimation at a high-energy tail in very forward directions upon C-ion incidents, while the code gives good agreement with the experimental data in the backward angular region. GEANT4 reproduces the height and position of the peak observed at forward angles. The models used in the GEANT4 calculations, however, suppress the emission of neutrons whose energies are beyond the incident energy, and underestimate the high-energy tail. This would be due to the problem in the model for nucleon multi-scattering, Fermi-momentum distribution, and relativistic correction in nucleus-nucleus reactions.

PHITS and FLUKA, which employ the quantum molecular dynamics (QMD) model based on a dynamical microscopic multi-body theory [21], show an overall agreement with the experimental data, except for the high-energy peak. Both codes tend to overestimate the low-energy tail of the peak. An overestimation of the peak height was found in the PHITS calculation for 400-MeV C ion incidents. From the view point of the practical use of the codes, we note that the QMD model needs a huge computational time compared with that used in the other codes, typically ten times or more depending on the combination of projectile and target. This enhances a motivation to develop a new theoretical model applicable to heavy-ion interactions with more precision and faster than the existing ones discussed here.

## V. CONCLUSION

The systematic cross-section data obtained by Iwata *et al.* [3] have been revised by using a new set on the neutron-detection efficiency values of an NE213-type liquid organic scintillator calculated by SCINFUL-QMD [7]. The overestimation in high-energy region above 300 MeV was improved in this revision. Though the revised data agreed well with our data [9], there were some situations for which the Monte-Carlo particle transport codes could not reproduce the experimental data, especially in the high-energy peak at forward angles.

We have already measured the cross sections for carbon bombarded by 290-MeV carbon ions. [9] The experiments will continue for targets of light nuclei, which are hydrogen, carbon, nitrogen, and oxygen constituting the body's tissue, to complement the experimental data in the periodic table, and a risk estimation of second cancers in heavy-ion cancer therapy will be the main focus. Furthermore, a new intranuclear cascade model [22] is under development to describe nuclear reactions properly including heavy-ion interactions, and reproduce the experimental data with a reasonable computational time. The model will be incorporated into the PHITS code [10] to be used in macroscopic transport calculations.

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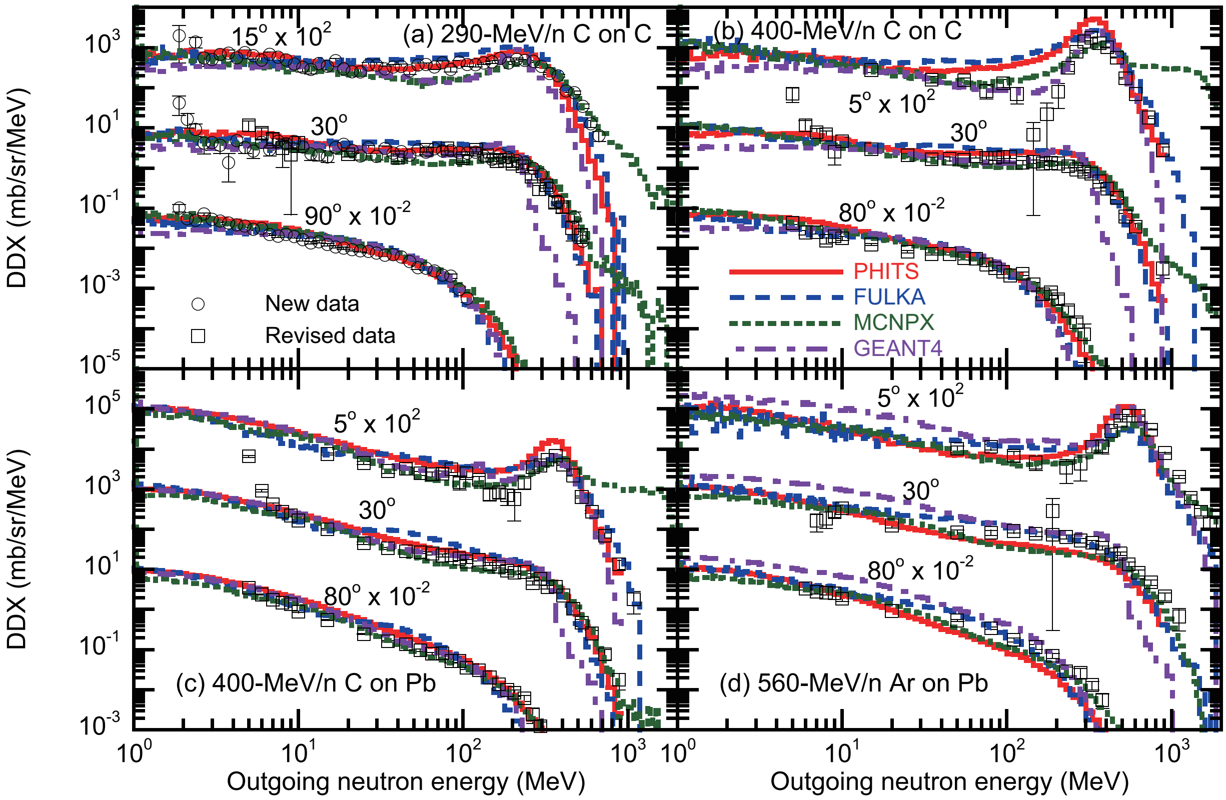


Fig. 3. (Color online) Neutron-production double-differential cross sections (DDXs) of (a) 290-MeV/n C on C, (b) 400-MeV/n C on C, (c) 400-MeV/n C on Pb, and (d) 560-MeV/n Ar on Pb.

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