Transactions of the Korean Nuclear Society Autumn Meeting
Pyeongchang, Korea, October 30-31, 2014

A Benchmarking Study of High Energy Carbon Ion Induced Neutron Using Several Monte Carlo Codes

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1. Introduction

The shielding analysis for heavy ion accelerator has been done by general-purpose Monte Carlo codes such as MCNPX, PHITS, FLUKA, MAR15 and GEANT4. However, several inter-comparison results about the production yield and the attenuation length showed some discrepancy between each Monte Carlo code [1,2].

In this study, the benchmarking study was done for the representative particle interaction of the heavy ion accelerator, especially carbon-induced reaction. The secondary neutron is an important particle in the shielding analysis to define the source term and penetration ability of radiation fields. The performance of each Monte Carlo codes were verified for selected codes: MCNPX 2.7 [3], PHITS 2.64 [4] and FLUKA 2011.2b.6 [5]. For this benchmarking study, the experimental data of Kurosawa *et al.* [6] in the SINBAD database of NEA was applied [7].

2. Methods and Results

Spectra of the double differential neutron yield at various angles were reported at the Kurosawa *et al.* [6]. The energy range of the carbon beam is 100 ~ 400 MeV/n and materials of the target are the carbon, the aluminum, the copper and the lead. The angles between the neutron detector and the direction of the projectile carbon are 0, 7.5, 15, 30, 60 and 90 degrees.

For the benchmarking calculation, the ring surface was created at 10 m distance from the target and the width of the each ring surface was set as ±0.5 degree. Spectra of the double differential neutron yield were calculated by the surface detector of each Monte Carlo code. The F2 tally in the MCNPX, the t-cross tally in the PHITS and the USRYIELD in the FLUKA were used as the surface detector.

Nuclear reaction models for each Monte Carlo code were selected as shown in Table I. The carbon beam energy of 100 ~ 400 MeV/n was considered to select reaction models. For the neutron and proton transport at the MCNPX and PHITS, libraries were also applied below the energy limit. The LA150 [8] and the JENDL-HE07 [9] were used for the MCNPX calculation and the LA150 and the JENDL-4.0 [10] were used for the PHITS calculation. The limit of upper energy of the LA150, the JENDL-HE07 and the JENDL-4.0 is 150 MeV, 3 GeV and 20 MeV, respectively.

2.1 Double differential neutron yield

The benchmarking result of 100 MeV/n carbon beam stopping in carbon target is shown in Fig. 1. The PHITS result generally shows good agreement with the experimental data except 0 degrees. The FLUKA results also shows good agreement but the slightly lower than the experimental data especially below the 100 MeV

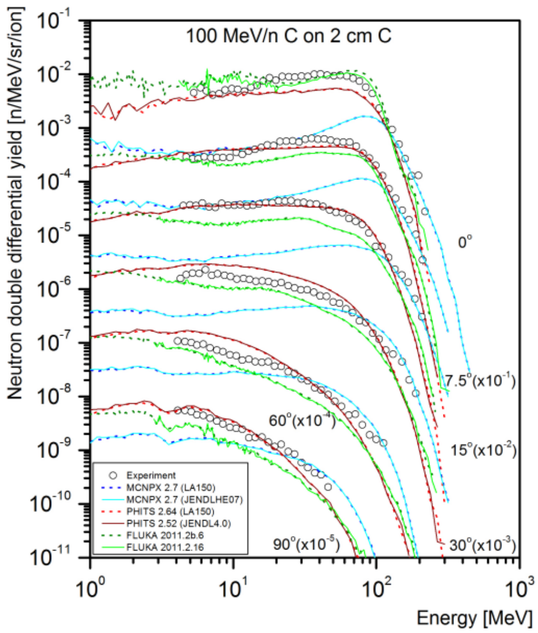

Fig. 1. Spectra of double differential neutron yield from 100 MeV/n carbon beam stopping in 2 cm carbon target.

energy and for the forward direction.

Table I: Physics Models applied in this benchmarking study

	Neutron, Proton			Light ion			Heavy ion		
	MCNPX	PHITS	FLUKA	MCNPX	PHITS	FLUKA	MCNPX	PHITS	FLUKA
Intranuclear cascade	CEM	INCL	GINC	LAQGSM	INCL	BME RQMD DPMJETIII	LAQGSM	JQMD	BME RQMD DPMJETIII
Evaporation	GEM	GEM	Weisskopf	GEM	GEM	Weisskopf	GEM	GEM	Weisskopf

The discrepancy of the calculation result between the MCNPX and other codes was very large at the forward direction. But the difference was greatly reduced at the sideward direction. This is why the evaporation model which is most effective reaction of the neutron emission for the sideward direction is similar at each code and the characteristics of intranuclear cascade reactions of each code is diminished.

The difference by using libraries of the neutron and the proton was imperceptible as shown in Fig. 1. From the comparison between two MCNPX results, the reason is that the neutron cross section is almost same at the energy region below 150 MeV as shown in Fig 2. From two PHITS results, the GEM model applied at 20 MeV ~ 150 MeV energy region (using JENDL-4.0) also produced the similar result. This reproduce clearly that those libraries have an effective role in a particle transport such as the attenuation inside the shielding material, not in a secondary particle production induced by primary ions.

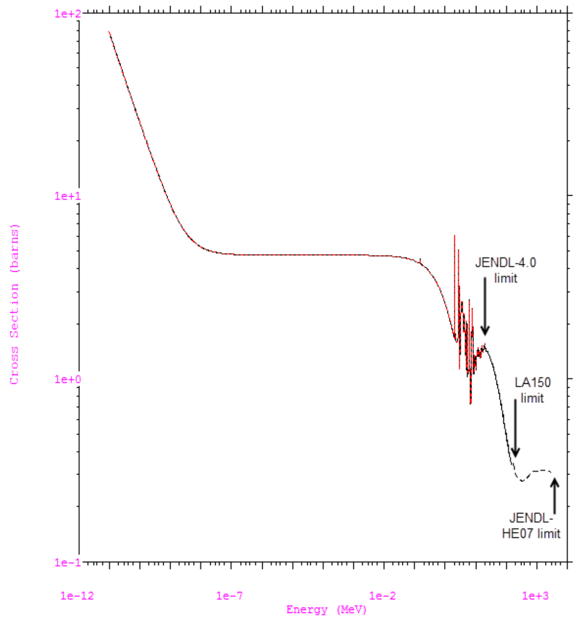

Fig. 2. Total neutron cross section for the C-12 at LA150 (black line), JENDL-HE07 (black dash) and JENDL-4.0 (red).

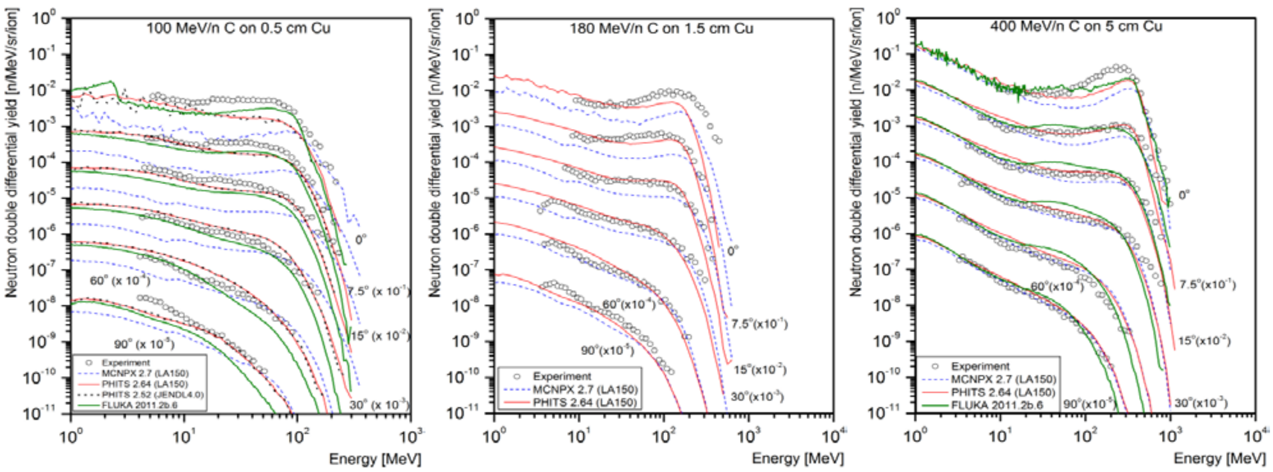

Fig. 3. Spectra of double differential neutron yield from the carbon beam with various energy stopping in the copper target.

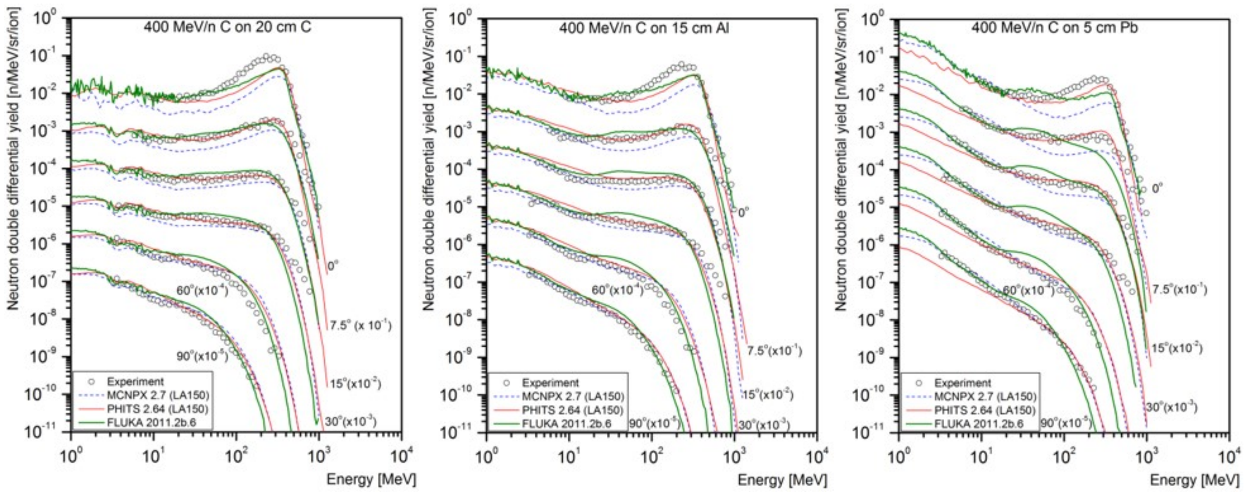

Fig. 4. Spectra of double differential neutron yield from the 400 MeV/n carbon beam stopping in various targets, Cu(see in Fig 2), C, Al and Pb.

2.2 Dependence on incident beam energy

The benchmarking result with various energy of the incident carbon beam is shown in Fig. 3. The target material is the copper. When the energy of the carbon beam is increased, the maximum energy of the neutron is increased and the amount of the high energy neutron is enhanced. The results shows that each code described well these tendencies.

At the lower energy region (100 MeV/n), the PHITS and the FLUKA result was good agreement with experimental data but slightly underestimated. The MCNPX result was greatly lower than the experimental data reflected similar result of the carbon target case. When the energy of the incident carbon beam is increased, the result of the code was approached to the experimental data. Especially, all of code results were very good agreement with the experimental data at the 400 MeV energy region with the sideward direction.

2.3 Dependence on target material

The differential yields of neutrons generated from the carbon, the aluminum, the copper and the lead target irradiated by 400 MeV/n carbon beam is shown in Fig. 3 and 4. The MCNPX results also underestimate the experimental data. Some dependence of the differential neutron yields with target materials were found even though the target thickness of each material were different each other. That is, lower energy neutron increase at high Z target relatively. It is considered that a larger amount of cascade reactions in high Z material lead are produced comparing to thicker low Z target. That was found at all used Monte Carlo codes.

3. Conclusions

The calculated results of the differential neutron yield produced from several materials irradiated by high energy carbon beam reproduced the experimental data well in small uncertainty. But the MCNPX results showed large discrepancy with experimental data, especially at the forward angle. The calculated results were lower a little than the experimental and it was clear in the cases of lower incident carbon energy, thinner target and forward angle. As expected, the influence of different model was found clearly at forward direction. In the shielding analysis, these characteristics of each Monte Carlo codes should be considered and utilized to determine the safety margin of a shield thickness.

Acknowledgement

This work was supported by the Nuclear Safety Research Program of Korea Radiation Safety Foundation (KORSAFE) and the Rare Isotope Science Project (RISP) of Institute for Basic Science (IBS)

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