Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 23-24, 2019

Evaluation of Neutron Production Yields Using Various Physics Models in Monte Carlo Simulation Codes

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1. Introduction

A multi-purpose experimental instrument using stable or rare isotope (RI) beams has been designed into Korea Broad acceptance Recoil spectrometer and Apparatus (KoBRA) for studies of various topics in low energy nuclear physics [1]. In such rare isotope beam facility dedicated to scientific research with heavy ion, simulation is necessary to support the design of components, such as prediction of radiation fields to support shielding design and safety analysis.

In this study, the effect of physics model in MCNPX 2.7.0 [2], PHITS 2.88 [3], FLUKA 2011.2x.4 [4], and GEANT4 10.5.0 [5] was investigated for the reaction of 40 MeV/u ^{40}Ar with beryllium target. Those comparisons were carried out with various combination of physics models in order to determine the models that are appropriate for the source term evaluation and shielding performance analysis.

2. Methods and Results

2.1 Korea Broad acceptance Recoil spectrometer and Apparatus (KoBRA)

Korea Broad acceptance Recoil spectrometer and Apparatus (KoBRA) has been designed for a multi-purpose experimental instrument using stable or rare isotope (RI) beams. The stable and heavy ions (e.g. helium, oxygen, carbon, and argon ions) can be provided by an Electron Cyclotron Resonance (ECR) ion source. These ions are accelerated by superconducting linear accelerator (SCL) at a 20 – 40 MeV/u. The interactions of these energetic heavy ions with targets generate not only a variety of rare isotope (RI) but also plenty of neutrons. Neutron is the most penetrating secondary particle in this reaction, and its neutron yield should be analyzed for shielding design and safety analysis. In this research, neutron yields were evaluated for the reaction between 40 MeV/u ^{40}Ar ion beams and 417 μm thin beryllium target. The ion beam intensity is 6.24e+13 pps.

2.2 Monte Carlo Simulation

Monte Carlo simulation codes have been used to predict radiation-induced damage and support radiation shielding design by calculating particle or radiation transport based on Monte Carlo technique. These simulation codes are powerful tools to provide reliable data with their own reasonable nuclear physics models. In this study, MCNPX 2.7.0 [2], PHITS 2.88 [3], FLUKA 2011.2x.4 [4], and GEANT4.10.5.0 [5] were used.

2.3 Physics Models in MCNPX, PHITS, FLUKA, and GEANT4

MCNPX provides several intra-nuclear cascade, fission and evaporation physics models. For nucleus-nucleus interactions induced by heavy-ion, Los Alamos quark-gluon string model (LAQGSM version 03.03) at energies up to ~ 1 TeV/nucleon is recommended.

PHITS is capable of simulating high-energy nucleon or light-ion interactions with the Jet AA Microscopic transport model (JAM) or INCL as intra-nuclear cascade models. JAERI Quantum Molecular Dynamics model (JQMD, JQMD2 or JAMQMD) is dedicated for simulation of nucleus-nucleus interactions. Fission and evaporation processes can be treated by the Generalized Evaporation Model (GEM), Statistical Decay Model (SDM), or Dresner-RAL model.

FLUKA treats nucleus-nucleus interactions generated by heavy ions with the Boltzmann master equation (BME) model at energies below 0.125 GeV/nucleon, with the modified Relativistic Quantum Molecular Dynamics (RQMD) model between 0.125 0.1 GeV/nucleon and 5 GeV/nucleon, and with Dual Parton Model (DPMJET-II or DPMJET-III) above 5 GeV/nucleon.

GEANT4 provides Quark-Gluon String Pre-compound model (QGSP) that is the basic physics for high energy interactions of nucleons, and INCL++ model at energies between 100 MeV and 3 GeV for nucleus-nucleus interactions induced by light ion and heavy ion. As a best combination of cascades for radiation protection, QBBC includes combination of BIC, Bertini, CHIPS, QGSP and FTFP models for nucleus-nucleus interaction.

2.3 Neutron Yields from 40 MeV/u ^{40}Ar(^{9}Be,n) reaction

Neutron yields were preliminary evaluated for the reaction between 40 MeV/u ^{40}Ar ion beam and beryllium target. Figure 1 shows neutron energy spectra from this reaction for various physical models in MCNPX, PHITS, GEANT4, and FLUKA. For the MCNPX simulation, the result of the lowest neutron yields was shown with the energy from 5 MeV to 50 MeV in MCNPX simulation. Also, this results was found to be significantly different from the results from other codes.

Table I. Total neutron yields for the combination of physics models that showed the most neutron yields in each Monte Carlo simulation in MCNPX, PHITS, GEANT4, and FLUKA.

Simulation Code	Intra-nuclear Cascade		Evaporation/Fission		SMM	Total Neutron Yields [neutrons/sec]
	Nucleons & Light ions	Heavy ions	Nucleons & Light ions	Heavy ions		
MCNPX 2.7.0	ISABEL	LAQGSM	ORNL	GEM	-	6.45E+11
PHITS 2.88	JAM	JQMD	SDM	SDM	on	3.70E+12
GEANT4.10.5.0	QBBC	QBBC	QBBC	QBBC	-	2.37E+12
FLUKA 2011.2x.4	FLUKA	BME	FLUKA	BME	-	2.31E+12

The most neutron yields were found in PHITS for the low energy from 1 MeV to 50 MeV, in FLUKA for the intermediate energy from 50 MeV to 150 MeV, and in Genat4 for the high energy from 150 MeV to 200 MeV. Table I shows total neutron yields for various physical model in MCNPX, PHITS, GEANT4, and FLUKA. The combination of physics models provided in PHITS showed the most total neutron yields 3.70E+12 neutrons/sec.

For the combination of physics models that showed the most neutron yields in each Monte Carlo simulation, neutron yields with various angles 5±5, 35±5, 65±5, 95±5, 125±5 and 155±5 degrees were analyzed as shown in Figure 2. The trend from MCNPX was significantly deviated from the trends of other codes at less than 60 degrees. At more than 60 degrees angle, the similar trends for the MCNPX, PHITS, GEANT4, and FLUKA results were found. Especially, the trend of PHITS was similar to the trend of FLUKA at all angles.

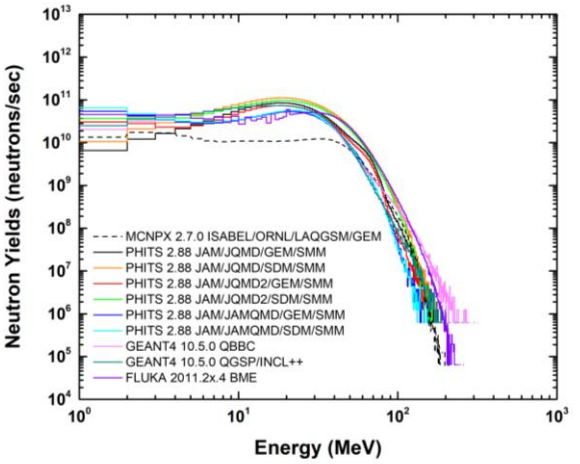

Figure 1. Neutron energy spectra from 40 MeV/u ^{40}Ar(Be, n) with various physics models in MCNPX, PHITS, GEANT4 and FLUKA.

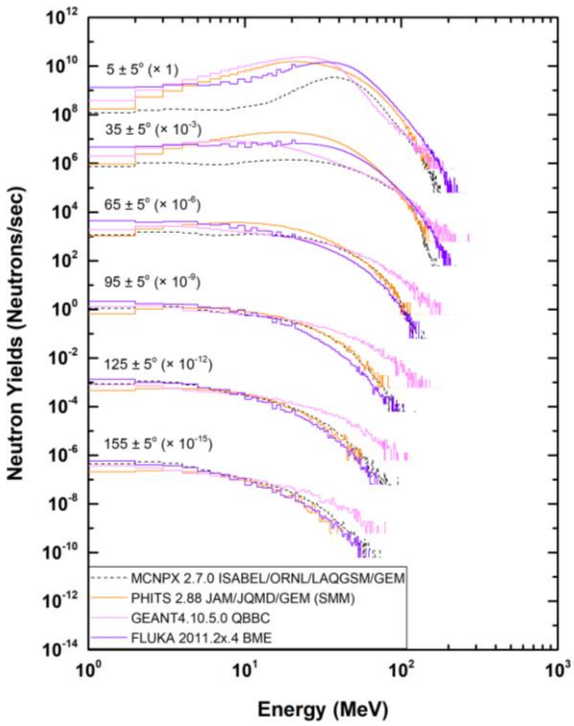

Figure 2. Neutron energy spectra with various 5±5, 35±5, 65±5, 95±5, 125±5 and 155±5 degrees from 40 MeV/u ^{40}Ar(Be, n) reaction for the combination of physics models with the most conservative results in MCNPX, PHITS, GEANT4 and FLUKA.

3. Conclusions

For prediction to radiation yields, neutron production yields were evaluated for the reaction between 40 MeV/u ^{40}Ar ion beam and beryllium target. Various physics models were used in Monte Carlo simulation codes. At a small angle that accounts for large neutron yields, the results of MCNPX showed significantly different trend from the results of other codes. The most neutron yields were found in the PHITS result. At the neutron energy spectra with angle, the trend of PHITS was similar to the trend of FLUKA at all the angles.

Hereafter, for the reasonable prediction to radiation field, the reported results in this paper will be verified with the experimental data for the ^{40}Ar(Be, n) reaction.

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