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Benchmarking study and its application for shielding analysis of large accelerator facilities

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1. Introduction

Shielding Analysis is one of subjects which are indispensable to construct large accelerator facility. Several methods, such as the Monte Carlo, discrete ordinate, and simplified calculation, have been used for this purpose. Recently the Monte Carlo methods are widely used because of the great stride of computing technology even though it treat highly complicated three-dimensional configuration and every particles are traced and counted at the estimation regions. The calculation precision is overcome by increasing the trial (history) numbers. However its accuracy is still a big issue in the shielding analysis [1,2].

In this paper, only the Monte Carlo method is discussed. At present, a few major codes, such as MCNP6(MCNPX)[3], FLUKA[4], PHITS[5], MARS [6], GEANT4[7], EGS5[8], and PENELOP[9], are used for the shielding analysis of large accelerator facility. According to properties of each codes, large discrepancy exists in those calculation results. This is crucial in determining the proper calculation method of shielding analysis with above accuracy issues.

To secure the accuracy in the Monte Carlo calculation, the benchmarking study using experimental data and the code comparison are adopted fundamentally. In this paper, the benchmarking result for electrons, protons, and heavy ions are presented as well as the proper application of the results is discussed.

2. Benchmarking calculations and Results

2.1 Benchmarking

As mentioned above, several Monte Carlo codes are available, but the codes, which can simulate multi-particles, were examined in this study. Those are MCNPX, FLUKA, PHITS and MARS. The experimental data based on the SINBAD (Shielding Integral Benchmark Archive and Databases) [10], OECD/ NEA database were used for this benchmarking calculation. Moreover, other experimental data were included to consider uranium beam and others.

The secondary particle production (source term) and transport property (attenuation length) are basic requirements in shielding analysis. Neutron is major particle to determine the shield thickness and the degree of radioactivity. Therefore, the neutron production rate by heavy ions, proton and electron were calculated and compared with experimental data. The attenuation properties of secondary neutrons during its transport in an ordinary concrete wall or an iron wall were estimated.

2.2 Proton Accelerator

Proton-induced reactions start from the intranuclear cascade. Several models have been introduced and the difference of neutron production rate depending on the models are figured out clearly in the benchmarking results. One of benchmarking results using experimental data of Tohoku univ.[11] and LANL[12,13] is shown in figure 1. The differential neutron production yields from several elements by irradiations of 52 MeV, 113 MeV and 256 MeV protons present that there is no large discrepancy between each Monte Carlo codes. Even the calculated values of neutron spectrum agree with experimental data except of several conditions. Depending on the production angle, the agreements of each codes are different. Because of relatively short reaction process in target, used physics models determine final production rate rather than the data library which contribute for lower energy range.

2.3 Heavy Ion Accelerator

In the benchmarking for heavy ions-induced reactions, the experimental data at HIMAC (carbon, xenon, etc) and GSI (uranium) are used. The differential neutron yields are shown in figure 2 in conditions, that 100 MeV/n, 180 MeV/n and 400 MeV/n strike on thick carbon target. MCNPX calculations show the results with large discrepancy to the experimental data and results of other MC calculation, especially at forward angle. This is a distinguished results to proton-induced neutron. However the discrepancy decreased dramatically at higher energy.

2.4 Electron Accelerator

The experiments of photo-neutron production are very rare and differential photo-neutron yields obtained at PAL were used for this study. This benchmarking calculation shown in figure 3 were done by using old version of each MC codes. All of codes underestimated the experimental data. This will be reviewed using the latest versions. However there are still some limitation at each code because photonuclear reactions at high energy are not studied sufficiently. MCNP(X) cover electron only up to 1GeV. PHITS can complete merging project with EGS5 to handle the high energy electron induced reactions.

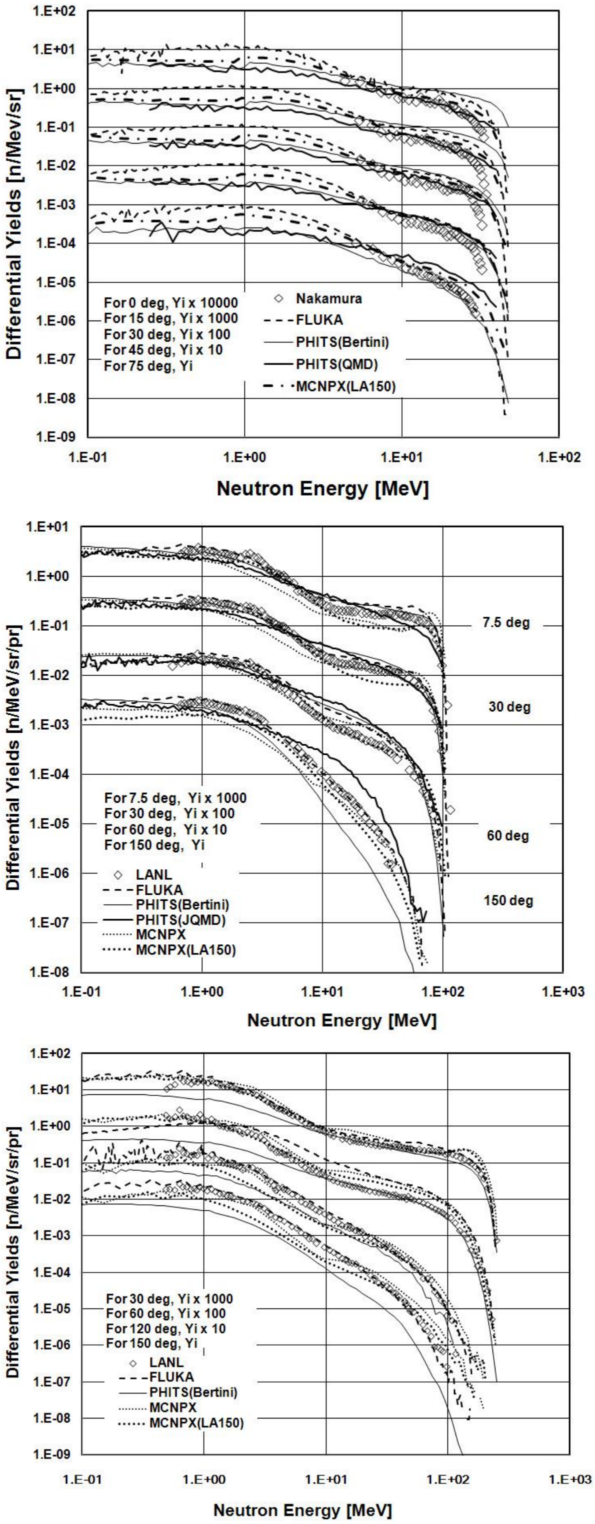

Fig. 1. Differential neutron yields from thick iron targets irradiated by protons of 52 MeV (upper), 113 MeV (Middle), and 256 MeV (Lower).

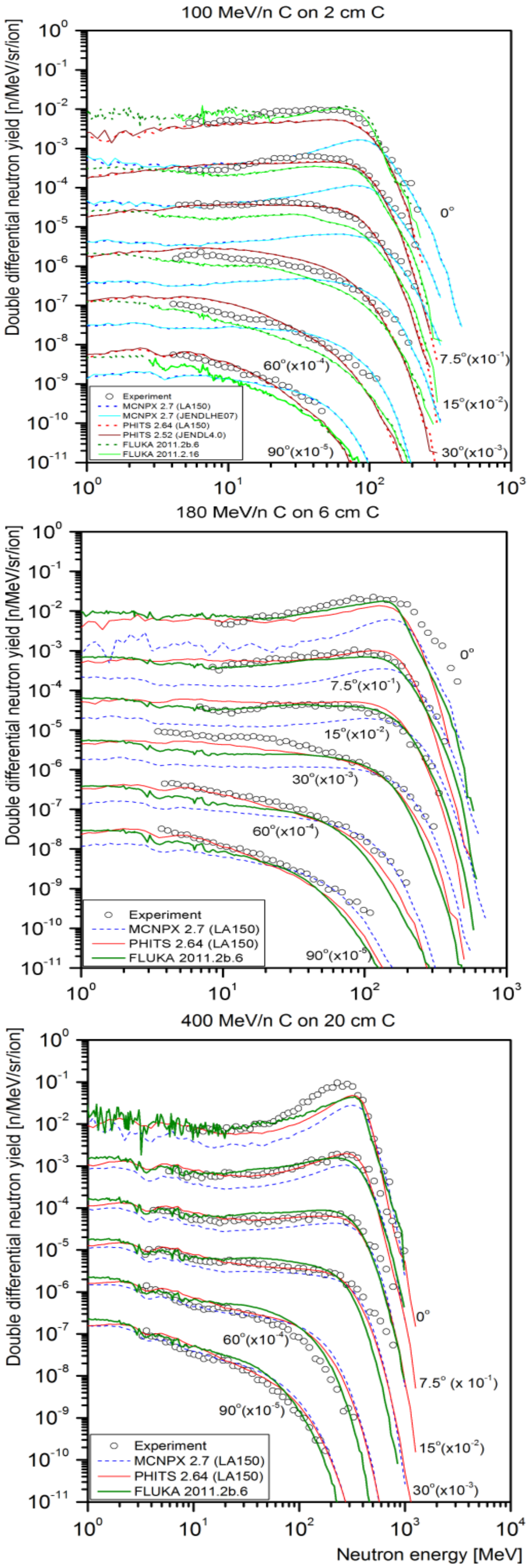

Fig. 2. Differential neutron yields from thick carbon targets irradiated by carbon beam of 100 MeV/n (upper), 180 MeV/n (Middle), and 400 MeV/n (Lower).

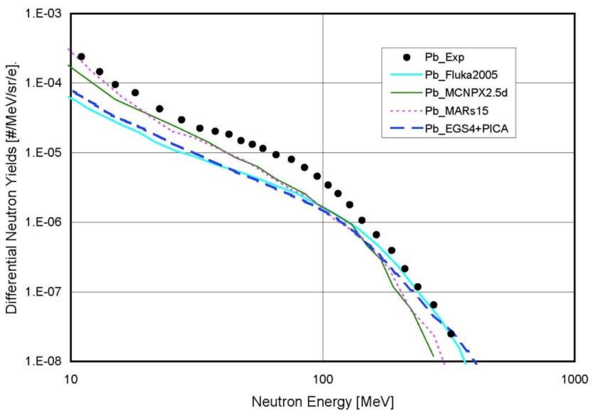

Fig. 3. Differential neutron yields from thick Pb target irradiated by electrons of 2.5 GeV.

2.5 Neutron Attenuation through ordinary concrete and iron

The second subject required in shielding analysis is an attenuation property of secondary particles, which are expressed as an attenuation length. In large accelerator facility using high energy particle beam, high energy neutron is major term to determine a shield thickness and effective dose level on outer surface of the shield. Therefore only neutrons above 20 MeV produced from targets are considered in this shielding analysis. The benchmarking results using HIMAC experimental data are shown in figure 4. The variation of neutron spectra were presented depending on the shield thickness of iron panel. The large discrepancy for neutron spectra from Cu target decrease dramatically at thick shield positions. This may result from the effect of the same data library. The dependency of data libraries, LA150 [14] and JENDHE [15]were also examined.

2.6 Application of Benchmarking Results

Recently the Monte Carlo codes have been improved remarkably, but the accuracy at the specific energy region and particle type has large uncertainty until now. That was reported several times by the expert group of SATIF. In most cases, it is the limitation acceptable in shielding analysis that the agreement between the experimental data and the calculated results is within a factor of two. As reported at SATIF meetings, the discrepancy is not small. Even one order difference was found at the specific case.

Therefore the degree of discrepancy between the experimental data and the calculated results should be considered in the shielding analysis for large accelerator facility together with the selection process of proper Monte Carlo code, physics model and data library. The discrepancy can be used to determine the safety margin of shielding design.

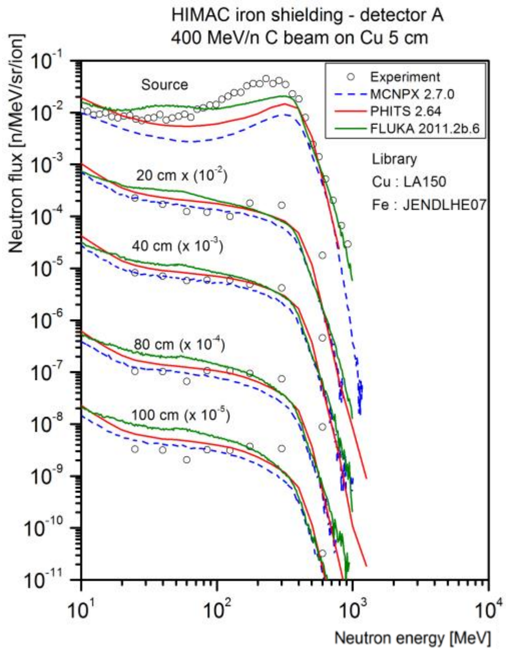

Fig. 4. Neutron spectra behind of each panel of 20 cm-thick iron shield when neutrons are produced from 5 cm Cu target irradiated by 400 MeV/n Carbon.

In the shielding analysis, the spectra itself of secondary particles like neutrons is significant factor. But the results or the decision standard of shielding analysis may be determined by the level of effective doses on the shield surface or in man-accessible region. Therefore, the benchmarking results can be reviewed in the view of effective dose. The large discrepancy of neutron spectra between the experimental data and the calculated results can become smaller.

As another issue, the attenuation length which is used popularly at simple equation method of shielding analysis can show the smaller discrepancy rather than neutron spectra. But even small difference can make big different results at the deep-penetration condition like very thick shield. The discrepancy issues of each Monte Carlo codes at the deep-penetration condition has not been solved certainly until now and improved continuously at the revised version of codes.

3. Conclusions

The benchmarking calculations, which are indispensable in the shielding analysis were performed for different particles: proton, heavy ion and electron. Four different multi-particle Monte Carlo codes, MCNPX, FLUKA, PHITS, and MARS, were examined for higher energy range equivalent to large accelerator facility. The degree of agreement between the experimental data including the SINBAD database and the calculated results were estimated in the terms of secondary neutron production and attenuation through the concrete and iron shields. The degree of discrepancy and the features of Monte Carlo codes were investigated and the application way of the benchmarking results are discussed in the view of safety margin and selecting the code for the shielding analysis. In most cases, the tested Monte Carlo codes give proper credible results except of a few limitation of each codes. In this study, the benchmarking calculation for estimating residual activities at large accelerator facility was also carried out and may be presented at the other papers.

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