Thick Target Benchmark Test for the Code Used in the Design of High Intensity Proton Accelerator Project

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In the neutronics design for the JAERI and KEK Joint high intensity accelerator facilities, transport codes of NMTC/JAM, MCNPX and MARS are used. In order to confirm the predict ability for these code, it is important to compare with the experiment result. For the validation of the source term of neutron, the calculations are compared with the experimental spectrum of neutrons produced from thick target, which are carried out at LANL and KEK. As for validation of low energy incident case, the calculations are compared with experiment carried out at LANL, in which target of C, Al, Fe, and ^{238}U are irradiated with 256-MeV protons. By the comparison, it is found that both NMTC/JAM and MCNPX show good agreement with the experiment within by a factor of 2. MARS shows good agreement for C and Al target. MARS, however, gives rather underestimation for all targets in the neutron energy region higher than 30 MeV. For the validation high incident energy case, the codes are compared with the experiment carried out at KEK. In this experiment, W and Pb targets are bombarded with 0.5- and 1.5-GeV protons. Although slightly disagreement exists, NMTC/JAM, MCNPX and MARS are in good agreement with the experiment within by a factor of 2.

1. Introduction

In the design of facility for Japan Proton Accelerator Research Complex (J-PARC), which is driven by the corporation between JAERI and KEK, transport calculation codes are used in order to obtain neutronic properties such as neutron flux, shielding, radiation dose and heat. In the design of J-PARC facilities, which consists of LINAC and synchrotron accelerators and experimental facilities of spallation pulse neutron source, accelerator driven transmutation system (ADS), and nuclear and particle physics, calculation codes of NMTC/JAM[1], MCNP-X[2] and MARS[3] are used to predict neutronic properties.

In general it is important to know predict ability of the calculation code used in the actual neutronic design. In this study, calculation results are compared with the experimental results. As for the validation of the source term of neutron, the calculations are compared with the experimental spectrum of neutrons produced from thick target, which were carried out at LANL and KEK.

2. Experiment

2.1 LANL Experiment

Thick target experiments[4, 5] were carried out at the target 2 area of Weapon Neutron Research Facility (WNR), which is shown in Fig. 1. The proton beam with energies between 113 and 800 MeV from the Los Alamos Clinton P. Anderson Meson Physics Facility (LAMPF) bombards the target at the center of the room. The experimental area is a circular of 12 m in diameter at beam elevation, which is surrounded by a compacted tuff of 10 m and a concrete wall of 0.4 m on the inside the room. Several radial penetrations view the center of the room at beam elevation, forming neutron flight paths with line of sight to the target. The flight paths were chosen from 29 to 67 m, which were valid according to the observed angles.

The time-of-flight method was applied for measuring the neutron spectra. The neutron detectors for 60 and 120 degree were BC-418 plastic scintillators of 5.08 cm in diameter and 5.08 cm long. For the shorter flight paths, scintillators of 5.08 cm in diameter and 2.54 cm long were used.

The absolute intensity of proton beam was determined by monitoring the secondary electron produced by the proton beam through a gold-plated aluminum foil with linearity to proton current within 1 % and absolute uncertainty of 5 %.

The target materials were carbon, aluminum, and iron, all in their natural isotopic abundance, and ^{238}U. Targets for each element are longer than the stopping length for 256-MeV-proton. The diameters of the targets were comparable to the lengths to minimize the escape probability of secondary proton with energy near that of the primary beam. The physical characteristics of the targets are listed in Table 1. The absolute neutron spectrum are corrected for background, dead time and attenuation of air. Uncertainties for the measurements up to 20 MeV are assigned as 20 %, and those above 20 MeV are 33 %.

2.2 KEK Experiment

Thick target experiments[6, 7] were performed at the π2 beam line of the 12-GeV proton synchrotrons at KEK. A schematic view of the experiment for lead target is shown in Fig. 2. The incident proton was supplied as the secondary particle generated by an internal target, which was placed in the 12-GeV proton beam by using slow extraction mode. After passing the bending magnet of beam channel, the secondary beam having a unique momentum was introduced to the thick target. The intensity of the incident particles was so weak (less than 10^5 particles/spill) that incident protons were counted one by one with beam scintillators. The protons were identified from π mesons produced at the internal target by the time-of-flight (TOF) technique with a pair of scintillators (Pilot U) located at a separation distance of 20 m. In order to subtract the neutrons produced from the beam scintillators, background measurements were performed without target. A beam dump consisted of a carbon block pile of 0.5x0.5 m in the area and 1 m in thickness was located at 8.5 m distance from the target.

The time-of-flight method was applied for measuring the neutron spectra. The flight paths for each detector are approximately 1.2m. The neutron detectors were NE213 liquid scintillators of 12.7 cm in diameter and 12.7 cm in length. In order to reject the detection of the charged particles, NE102A scintillators were used as veto counters. They were placed at a distance of 2 cm from the surface of the NE213 scintillators. The absolute intensity of proton beam was determined by monitoring the pair of plastic scintillators(Pilot U).

The physical characteristics of the targets are summarized in Table 2. The target was a rectangular parallelepiped 15x15x20 cm whose purity was 99.95% and 94.8% for lead and tungsten, respectively. Those targets had 20 cm in length for the beam direction, which was enough thick to stop 0.5-GeV protons completely, while it caused the partial energy loss for 1.5-GeV protons. The size of the beams had Gaussian shape with 2.0 and 1.6 cm in FWHM on the perpendicular and horizontal plains, respectively. The interval between and duration of the proton pulses were 4 and 2.5 s, respectively. The absolute neutron spectrum is corrected for background neutrons, dead time, and the attenuation at the veto counter.

3. Calculation Code

Spectrum of neutron produced from thick target was calculated with the following calculation code having the calculation option, which was exactly the same as used in the neutronics design for the J-PARC facilities.

NMTC/JAM ver 2.1[1] was employed. Default options for the calculation were used for the analysis, which are specified as 1) Bertini cascade model, 2) with in-medium nucleon-nucleon cross section (NNCS), 3) with angular distribution of 50 % isotropic and 50% at forward direction for Δ decay, 4) without pre-equilibrium process, 5) GEM evaporation model with Igunatyuk level density parameter and 6) with elastic scattering of nucleon in the transport calculation. For the analysis of the KEK experiment, also NNCS in free space was used. For the transport calculation of the neutron having the energy lower than 20 MeV, MCNP-4A was used. In the calculation of MCNP-4A, JENDL-3.2 library was employed.

MCNPX ver 2.2.6[2] was employed. Default options for the calculation are used for the analysis, which is specified as 1) Bertini model for nucleons and π mesons and with ISABEL model for other particles, 2) with pre-equilibrium model, and 3) with elastic scattering of nucleon. As for neutron library except for U-238, LA150 was employed, which is available up to 150 MeV. For U-238 case, the file is not available, so that JENDL-3.2 was employed. Also calculations by using the library for the proton of LA150 were performed.

MARS ver 14.00[3] was employed. In the calculation, whole energy spectrum was obtained without using MCNP.

4. Comparison with LANL Experiment

4-1 Carbon Target

The results for carbon target bombarded with 256-MeV protons are compared in Fig. 3. It is found that NMTC/JAM gives good agreement with the experiment for all energy and angular regions. Slight overestimation by a factor of 2 is found at 60 degree in the energy higher than 20 MeV.

The calculation results with MCNPX are also shown in this figure. MCNPX is in good agreement with the experiment in general. At backward in the angular region larger than 120 degree, MCNPX, however, overestimates by a factor of ～5. This overestimation is thought to be caused by emphasis of pre-equilibrium process after cascade model for light target nuclide.

In Fig. 3, the calculation results with MARS are shown. It is found that MARS shows good agreement with the experiment in general. At 150 degree, MARS, however, underestimates the experiment by a factor of 2 in the energy region above 15 MeV.

4-2 Aluminum Target

In Fig. 4, comparison for aluminum target bombarded with 256-MeV protons is shown. It is recognized that NMTC/JAM gives good agreement with the experiment. As well as the result for C target, slight overestimation by a factor of 2 is found at 30 degree in the energy region between 10 and 30 MeV. At 60 degree in the energy range above 15 MeV, NMTC/JAM gives slight overestimation by a factor of 2. On the other hand, NMTC/JAM at 150 degree gives underestimation by a factor of 2. This fact is mainly caused by the lack of pre-equilibrium process in this calculation.

MCNPX is in good agreement with the experiment in general. Although MCNPX for C target gives overestimation at backward angles, MCNPX for Al target shows good agreement with the experiment. MCNPX overestimates by a factor of 2 at 60 degree in the energy range above 15 MeV.

In Fig. 4, the calculation results with MARS are shown. In the energy region below 15 MeV, MARS shows good agreement with the experiment. At 60 degree in the energy range above 15 MeV, MARS overestimates by a factor of 2.

4-3 Iron Target

Figure 5 shows comparison for iron target bombarded with 256-MeV protons. NMTC/JAM are in significantly good agreement with the experiment. At 60 degree in the energy region above 20 MeV, NMTC/JAM is in good agreement with the experiment, whereas overestimates the results for C and Al target. On the contrary, in energy region below 5 MeV, NMTC/JAM gives underestimation by a factor of 2. At 150 degree, NMTC/JAM underestimates the experiment by a factor of 2, which is mainly caused by the lack of pre-equilibrium process. On the other hand for lower energy region lower than 10 MeV, it is found NMTC/JAM at backward angles gives remarkably good agreement with the experiment

MCNPX also gives remarkably good agreement with the experiment. Even for fine spectrum structure due to the resonance of neutron capture, MCNPX results at backward angles reproduce the experimental data very well. At 60 degree, MCNPX gives underestimation by a factor of 2 in the energy region below 5 MeV.

In Fig 5, MARS results are also compared. It is found that MARS shows good agreement with the experiment. At 60 degree in the energy region below 3 MeV, MARS shows underestimation by a factor of 2.

4-4 U-238 Target

In Fig. 6, comparisons for U-238 target bombarded with 256-MeV protons are shown. NMTC/JAM shows good agreement with the experiment. At 30 and 60 degree, although NMTC/JAM gives slight overestimation by a factor of 2 in the energy region between 5 and 10 MeV, NMTC/JAM shows remarkably good agreement with the experiment in the energy region above 20 MeV. At 150 degree, NMTC/JAM underestimates the experiment by a factor of 2 mainly due to the lack of pre-equilibrium.

MCNPX also gives good agreement with the experiment. Around at 20 MeV, MCNPX gives a slight overestimation by a factor of 2 except for 150 degree. At 150 degree in the higher energy than 40 MeV, MCNPX overestimates by a factor of 2. This overestimation is thought be caused by the emphasis of pre-equilibrium process.

By comparison of MARS with the experiment, it is found that MARS underestimates by a factor of 3 in the energy region around 5 MeV at whole angles. This underestimation is probably caused by the fission model used in MARS. Around at 10 MeV, MARS reproduce the experiment fairly well. However, in the energy region above 15 MeV at forward angular region, MARS overestimates the experiment by a factor of 2.

5. Comparison with KEK experiment

5-1 Tungsten Target Irradiated by 0.5- and 1.5-GeV Protons

Figures 7 and 8 shows the comparison for W target bombarded with 0.5- and 1.5- GeV protons, respectively. In these figures, NMTC/JAM, MCNPX and MARS are compared with the experiment. It is found that

NMTC/JAM shows good agreement with the experiment. In Figs 7 and .8, NMTC/JAM with free NNCS is also shown, which gives considerable underestimation by a factor of 4 in the energy region between 20 and 100 MeV. However, this disagreement is eliminated by using the in-medium NNCS, which is used as option of default calculation. Even by using in-medium NNCS, the underestimation is found by a factor of 2 at 150 degree. This underestimation is mainly affected by lack of the pre-equilibrium process.

The calculations with MCNPX are also compared in Figs 7 and 8. It is found that MCNPX is in good agreement with the experiment at whole energy and angular regions. At backward angles, MCNPX shows remarkably good agreement with the experiment.

The results with MARS are also shown in Figs. 7 and 8. By comparison, it is found that MARS gives good agreement with the experiment. However, it is found MARS gives under estimation by a factor of 2 around 6 MeV at 150 degree for 0.5-GeV protons

5-3 Lead Target Irradiated by 0.5- and 1.5-GeV Protons

Results for Pb target irradiated by 0.5- and 1.5- GeV protons are compared in Figs. 9 and 10, respectively . It is recognized that NMTC/JAM with in-medium NNCS shows good agreement with the experiment. However, NMTC/JAM with free NNCS gives considerable underestimation in the energy region between 20 and 100 MeV. At 150 degree, NMTC/JAM with in-medium NNCS shows underestimation by a factor of 2 at 150 degree mainly due to lack of the pre-equilibrium process.

The calculations with MCNPX give remarkably good agreement with the experiment. However, around at 2 MeV except for 150 degree, MCNPX overestimates by a factor of 2. At backward angles, MCNPX shows remarkably good agreement with the experiment.

The results with MARS are also shown in Figs. 9 and 10. MARS gives good agreement with the experiment. In the energy region between 2 and 10 MeV at 150 degree, MARS underestimates the experiment by a factor of 2.

5. Concluding Remarks

Comparison of spectra of neutron produced from thick target between the calculation code and the experiment are made. Although some discrepancies are found, it can be concluded that NMTC/JAM, MCNPX and MARS can predict neutron spectra within a factor of 2 except for U-238 target with MARS code.

References

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Table 1 Physical characteristics of the targets.used in LANL experiment

Element	Radius (cm)	Length in beam direction (cm)	Density (g/cm^3)
Carbon	8.00	30.00	1.646
Aluminum	8.00	20.00	2.715
Iron	8.00	8.00	7.86
^{238}U	4.00	5.00	18.98

Table 2 Physical characteristics of the targets used in KEK experiment

Element	Cross section (cm)	Length in beam direction(cm)	Density (g/cm^3)	Purity(wt%)
Tungsten	15x15	20.00	18.05	W 94.8, Cu 2.1, Ni 3.1
Lead	15x15	20.00	11.33	Pb 95.5

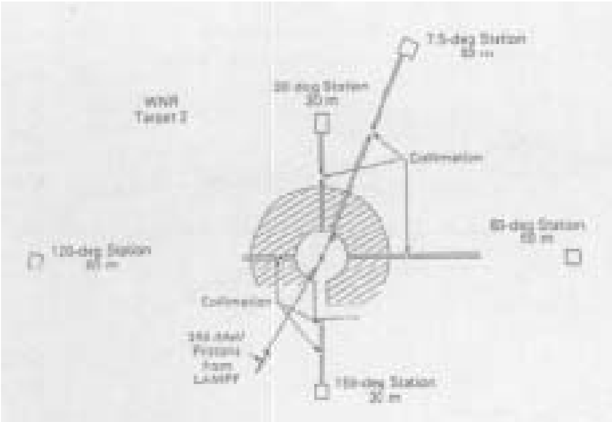

Fig. 1. Schematic view of LANL experiment set up.

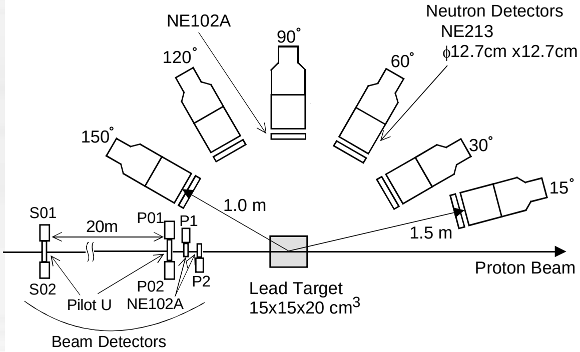

Fig. 2. Schematic view of KEK experiment set up.

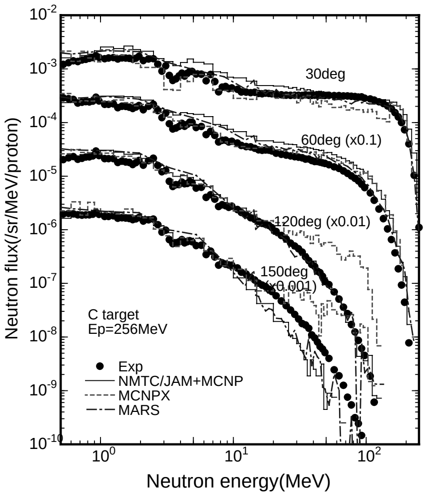

Fig. 3 Comparison of C target irradiated by 256-MeV protons

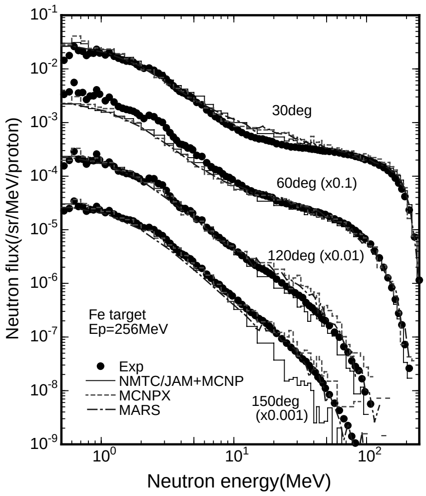

Fig. 5 Comparison Fe target irradiated by 256-MeV protons

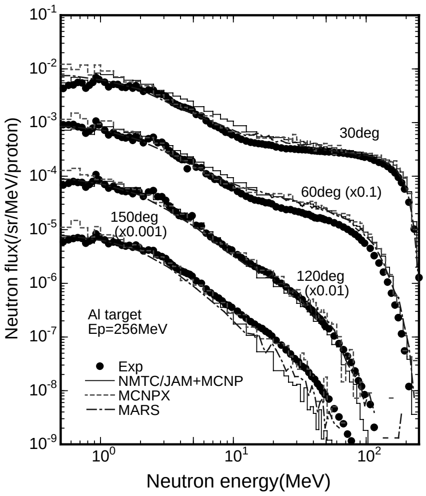

Fig. 4 Comparison of Al target irradiated by 256-MeV protons

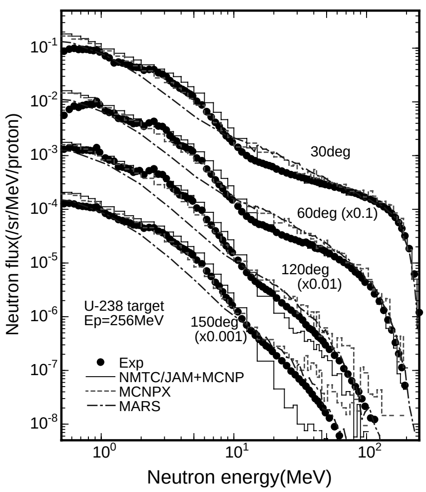

Fig. 6 Comparison of U-238 target irradiated by 256 MeV protons

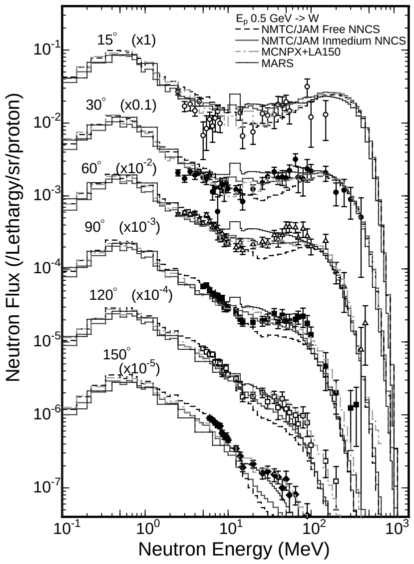

Fig. 7 Comparison of W target irradiated by 0.5 GeV protons

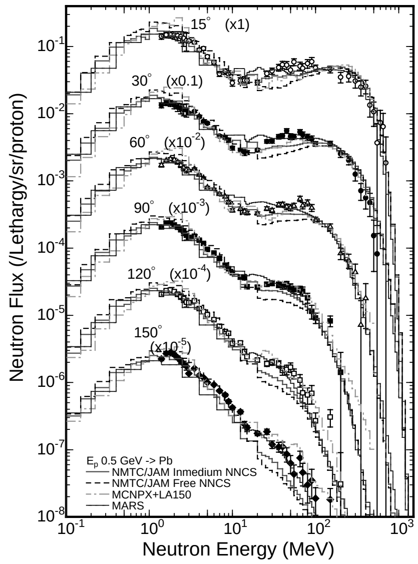

Fig. 9 Comparison of Pb target irradiated by 0.5 GeV protons

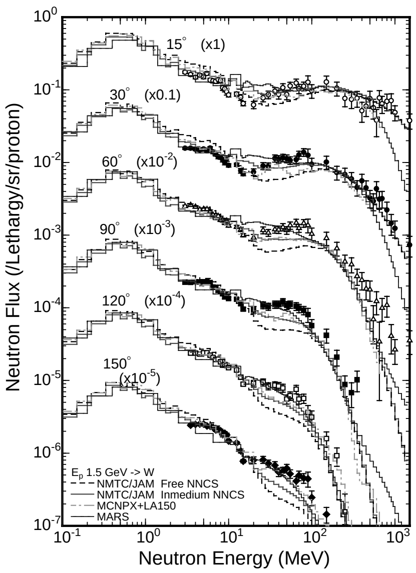

Fig. 8 Comparison of W target irradiated by 1.5 GeV protons

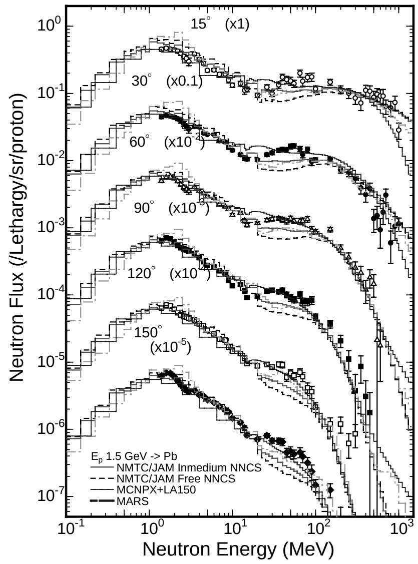

Fig. 10 Comparison of Pb target irradiated by 1.5 GeV protons