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ARTICLE

Shielding Experiments at High Energy Accelerators of Fermilab (IV) - Calculation Analyses -

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JASMIN - Japanese and American Study of Muon Interaction and Neutron detection - a program for studies of shielding and irradiation effect around high energy accelerators has been started until 2007 using high energy proton accelerators located in Fermi National Accelerator Laboratory (FNAL) as a collaboration of JAPAN and FNAL. The series of the presentations entitled "Shielding experiments at high energy accelerators of Fermilab" describes the part of the results of this collaboration regarding transport of secondary particles, neutron and muon, from 120 GeV proton induced reactions through experimental data and simulation. In this paper, calculation analyses using high energy particle transport Monte Carlo calculation codes, PHITS, MARS and MCNPX, for the experiments carried out at the anti-proton production target station were performed with a simplified two-dimensional geometry to validate the accuracy of spatial distribution of reaction rate in iron shield and the attenuation length. The calculation results were good agreement with the obtained experimental data for the spatial distribution. Neutron attenuation lengths of iron were also given by the data. Tendencies of the attenuation length of iron were found the PHITS and MARS values were larger and the MCNPX values were smaller than the data.

KEYWORDS: 120 GeV, Fermi National Accelerator Laboratory, Monte Carlo calculation code, angular distribution, attenuation length

I. Introduction[1]

The shielding experiments were performed at the anti-proton (pbar) target station in Fermi National Accelerator Laboratory (FNAL) in a collaborative research program of JASMIN (Japanese and American Study of Muon and Neutron Detection). The obtained experimental data using the activation technique provided the useful information concerning the attenuation phenomenon of high energy neutrons as a shielding data that has never been measured at incident proton energies over a hundred-GeV. These data are also useful to validate high energy particle interaction and transport simulation codes, such as PHITS[1)], MARS[2)] and MCNPX[3)] in GeV region.

An inter-comparison among calculation codes for attenuation length of neutron dose over 20 MeV was done on the SATIF-8[4)] (Shielding Aspects of Accelerators, Targets and Irradiation Facilities Eighth Meeting at the PAL, Korea in 2006) under various conditions such as, energies of incident neutrons from 20 MeV to 100 GeV. In the meeting, the calculation results by major codes including PHITS, MARS and MCNPX etc. were compared for some typical problems. One of the items of the inter-comparisons was an attenuation length of mono-energetic neutrons around a GeV region as incidents for iron and concrete shield. Since the neutron attenuation length make a big impact on shielding design of high-energy proton accelerators, the calculations should be validated properly. Though, in an actual situation, the incident neutrons to a shield are not mono-energetic, the neutron attenuation behavior is determined only by a behavior of high-energy neutrons with more than a GeV. Therefore, using the experimental shielding data for the neutron attenuation, the inter-comparison among the simulation codes can be evaluated.

In this work, shielding calculation of pbar target station by PHITS, MARS and MCNPX are carried out, and the calculation results of neutron attenuation behavior for iron shield are compared with the experimental data in a viewpoint of decreasing tendencies of reaction rates, and the neutron attenuation lengths deduced from the calculations

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are compared with the experiments. In the last section, as a final of the series papers on JASMIN, what we obtained in JASMIN and the future plans are summarized.

II. Calculation Analyses

In order to validate the calculations on neutron attenuation behavior, the calculations by PHITS, MARS and MCNPX codes were compared with the reaction rate data measured by using the activation detectors installed in the iron shield. (The measured reaction rate data in iron shield are presented as the FP Data, which is abbreviation of "Filler Plate Data", in the second paper of this series. "Filler Plate" is the name of an iron plate used to install the activation detectors.) The calculations were performed using a simplified two-dimensional (R-Z) geometry. Detail of the calculation model is described in subsection 1. For the comparison between the calculation and the measurement, the calculated neutron spectra need to be converted to reaction rates since the experimental data are expressed as reaction rates. The conversion of calculated neutron spectra to reaction rates are shown in subsection 2. In subsection 3, the calculated reaction rates by PHITS, MARS and MCNPX are compared with the experimental data as a function of the distance from the target for validation of the neutron attenuation behavior among them. In subsection 4, neutron attenuation lengths deduced by the calculations are compared with the experiments.

1. Simplified Geometry of the pbar Target Station

The simplified two-dimensional geometry was shown in **Fig. 1**. The pbar target station was composed of a target, a collection lens to focus the anti-protons, a collimator, a pulsed magnet to extract the anti-proton, and thick iron and concrete shields, which were modeled in the geometry used in the calculation. The components placed at a distance of 2 meters or farther to a downstream direction from the pulsed magnet, such as a dump to absorb the remaining protons and secondary particles, were not considered in the geometry. The pbar target made from an inconel-600 was simplified to a plate with a thickness of 8 cm by the traverse length that proton beam took to cross the target. The target room was bordered laterally by the 182.9 cm (6 feet) thick iron and also covered the outside of the 121.9 cm (4 feet) thick concrete. The densities of iron and concrete shields were approximated to be 7.87 and 2.27 g cm^{-3}, respectively.

2. Calculated Quantity

In order to check neutron attenuation tendency in the calculation, neutron spectra at various distances for lateral direction from the pbar target were calculated in these analyses. Since the experimental data are expressed as reaction rates, defined as energy integral of products between a neutron flux and a reaction cross section in **Fig.2**, the calculated neutron flux needs to be converted for the comparisons. Activation cross-section data[5], whose threshold energies is ranging from 3 to 40 MeV, were used to convert the neutron spectra to reaction rates.

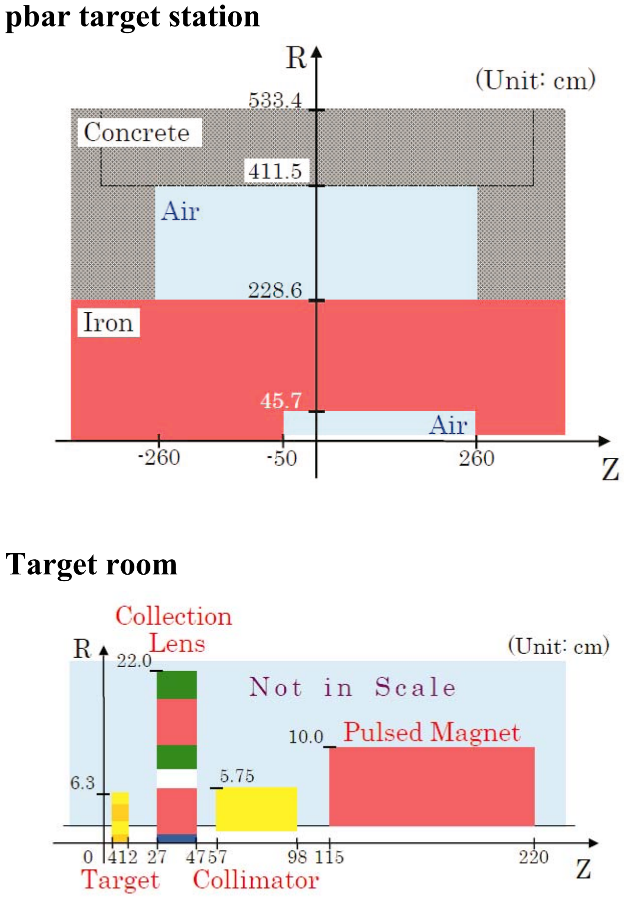

Fig. 1 Two-dimensional (R-Z) simplified geometry. The components colored by orange, yellow, blue, magenta, white, green light blue and gray shows inconnel-600, copper, lithium, iron, void, aluminum, air and concrete, respectively.

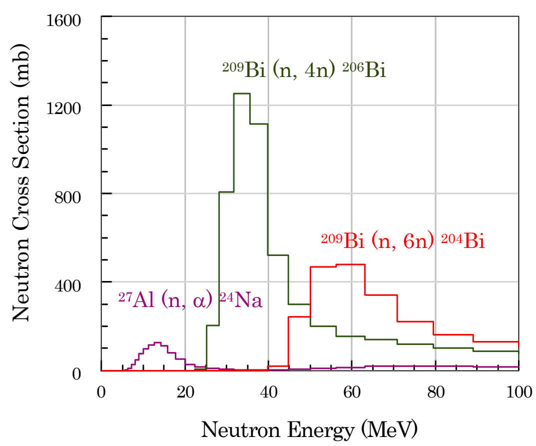

Fig. 2 Some of the neutron activation cross-sections used to convert the calculated neutron spectra to reaction rates.

3. Comparison in the Iron Shield

Typical examples of comparisons of the reaction rates between the calculated and the experimental data in the iron shield are shown in **Fig. 3**. Threshold energies of ^{27}Al (n, α) and ^{209}Bi (n, 6n) reactions are 3.24 and 38.0 MeV, respectively. These results show good agreement between the PHITS, MARS and MCNPX results and the experimental data from a big point of view. Seeing closely, we can find that the slope of the attenuation curve of MCNPX is steeper than that of PHITS and MARS, and that of the experimental data are in-between, which will be shown numerically in terms of "attenuation length" in the next subsection. In addition, we can also see that the attenuation curves of the calculations are crossing in the former region of the iron shield. This means that the calculations on source term are quite different among the codes, which will be an issue to be solved in JASMIN program in future.

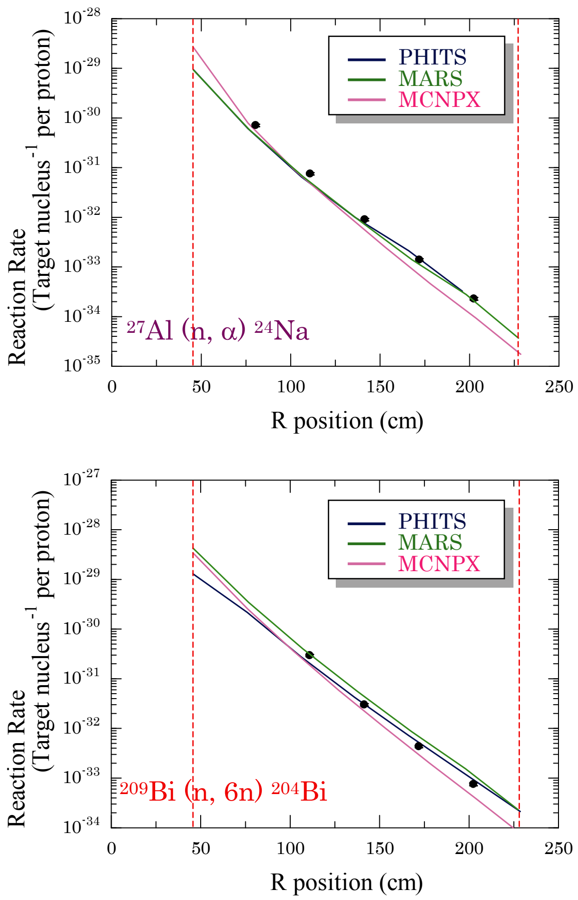

Fig. 3 The comparison between the calculation results and the experimental data in the iron shield (FP data).

4. Neutron Attenuation Length of Iron

In order to deduce the attenuation length from the calculated reaction rate data, the products of reaction rates and squared distances r_n^2 between the target and a measurement position are plotted as a function of r_n in Fig. 4. By fitting them by an exponent function of r_n, the attenuation lengths were obtained as shown in **Table 1**. For deduction of the attenuation length from the experimental reaction rate data, a special care needed to be taken for the positions of the activation detectors, because those were not lie directly on the target; the filler plate, in which the activation samples were installed, was placed at a distance of 12.7 cm to the downstream of the target. The attenuation length was deduced by correcting the slight difference. In **Table 1**, an averaged value for all reactions whose reaction rates were measured in the experiment is shown as the comprehensive experimental value.

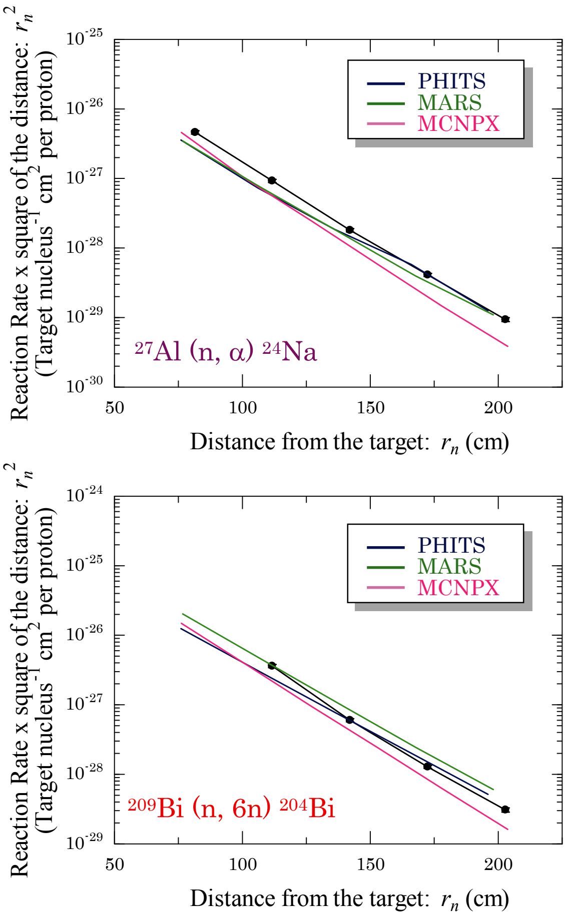

Fig. 4 The comparison of reaction rate x square of the distance r_n^2 both the calculation results and the experimental data.

Table 1 The attenuation lengths for iron.

Reactions	Expt.	PHITS	MARS	MCNPX
^{27}Al(n, α)^{24}Na	150 +/- 5	162.3	158.0	140.8
^{93}Nb(n, 2n)^{92m}Nb		160.5	157.3	138.9
^{209}Bi(n, 4n)^{206}Bi		166.8	161.6	142.0
^{209}Bi(n, 5n)^{205}Bi		168.1	160.0	143.9
^{209}Bi(n, 6n)^{204}Bi		171.1	159.4	146.2
^{209}Bi(n, 7n)^{203}Bi		174.1	160.8	148.7

The attenuation lengths of PHITS and MARS are longer than those of MCNPX, and the experimental value are between the calculations as shown in the previous subsection

Comprehensive value of the attenuation length of the iron obtained by all experimental results was 150 +/- 5 g cm^{-2} in

Table 1. This value was compared with the value presented in the inter-comparison of SATIF-8. This inter-comparison was summarized the attenuation length of iron and concrete for incident neutrons having a wide range of energies. To use the values obtained by the inter-comparison on SATIF-8, we needed to define the energy of incident neutron. So the energy was assumed by neutron spectra at the 90 degrees from the target calculated by the PHITS, MARS and MCNPX codes. The neutron spectra by all codes were given having the maximal energy around a GeV. Here, reaction rates and doses depend almost entirely on intensities of low energy neutron. Meanwhile, neutrons in the high energy region are important after achieving the equilibrium spectrum. So, the energy of incident neutrons was defined at 1 GeV in this problem. The values of attenuation lengths on SATIF-8 when the energy of incident neutron is 1 GeV, were estimated from the distributions around 150 g cm^{-2}. Although the values are widely distributed from 120 to 180 g cm^{-2}, three codes including the PHITS and MARS represent around 150 g cm^{-2} and almost results looks like showing the distributions centered at this value. The result was good agreement with the experimental values within the margin of error.

III. Conclusion

The comparisons of the spatial distribution for reaction rate in the iron shield (FP data) and the attenuation length were performed between the obtained experimental data and the calculation results by the simplified geometry. FP data were reproduced well by the PHITS, MARS and MCNPX code. The attenuation lengths of iron obtained by FP data were also good agreement with the calculation results. Tough, the tendencies of the attenuation length were found the PHITS and MARS values were larger and the MCNPX values were smaller than the experimental values for this comparison. Additionally, the value presented in the inter-comparison of SATIF-8 was good agreement with the experimental data within the margin of error.

IV. Summary of JASMIN Program

Series of presentations entitled “Shielding experiments at high energy accelerators of Fermilab” described the part of the results of the JASMIN collaboration through the experimental data using two facilities in FNAL, pbar target station (AP0) and neutrino from main injector (NuMI) and simulation. The obtained results were summarized as follows:

1) Measurement for distributions of radiation dose associated with intense muon beam using standard dosimeters at NuMI and simulation,
2) Measurement for spatial distribution of reaction rate using activation detectors at AP0 and derivation of attenuation length of iron,
3) Measurement for energy spectra of burst neutrons using current readout Bonner sphere technique at AP0 and simulation
4) Simulations for spatial distribution for reaction rate in iron and the attenuation length for secondary neutrons.

In the near future, we plan to be carried out the following experiments adding a facility, Meson Test Beam (MTest) to check the characteristics of accelerated protons and calculation analyses:

1) Measurements using activation detectors at AP0 to obtain attenuation lengths of concrete
2) Experiment for source intensity of secondary neutron from the pbar target at MTest
3) Studies of shielding and irradiation effect at MTest which come under the influence of neutron and the other secondary particles
4) Studies of nuclide production by muon at NuMI
5) Simulations using a sophisticated three dimensional geometry for AP0 experiments.

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