Shielding experiment by foil activation method at the anti-proton production target of Fermilab

Yoshimi Kasugai[1], Hiroshi Yashima[2], Norihiro Matsuda[1], Hiroshi Matsumura[3], Nikolai Mokhov[4], Anthony Leveling[4], David Boehnlein[4], Kamran Vaziri[4], Koji Oishi[5], Yukio Sakamoto[1], Hiroshi Nakashima[1]

[1]Japan Atomic Energy Agency, Japan,
[2]Research Reactor Institute, Kyoto University, Japan,
[3]High Energy Accelerator Research Organization, Japan,
[4]Fermi National Accelerator Laboratory, US,
[5]Shimizu Corporation, Japan

Abstract

The shielding experiment was carried out using the Antiproton Production Target Station (Pbar) of Fermilab under the collaboration study of JASMIN: "Japanese and American Study of Muon Interaction and Neutron detection". In the experiment, the neutron flux distributions in the shielding assembly were obtained by means of multi-foil activation method. Neutron spectra in the energy range between 1 and 100 MeV were deduced from the experimental data using the fitting method, which was newly developed in this study. The experimental data were compared with the theoretical calculation of the particle-transportation code: PHITS. The optimum value of neutron attenuation length λ was tentatively deduced by applying the experimental data to the Moyer's model.

Introduction

Intense proton accelerators with the acceleration energy higher than a few tens of GeV have been constructed recently to do research into neutrino and hadron physics. However, systematic experimental shielding data for the proton energies in such high-energy regions have been deficient. Since the current shielding design is based on the extrapolation of the experimental data for the proton energy less than 10 GeV, large safety margin is required for the shielding design due to the ambiguities of the extrapolation.

Shielding data for the energy region higher than 100 GeV are required for the proper interpolation to the higher-energy region in terms of validation of high-energy particle transportation codes, discovery of a macroscopic principle of particle behaviour and estimation of a reasonable margin.

Collaborative research between Japan and US started in 2007 in order to investigate the behaviours of high-energy neutrons and muons associated with the operation of a high-energy proton accelerator. The collaboration was named "JASMIN", which is the abbreviation of "Japanese and American study of muon interaction and neutron detection", and the experiments were carried out in Fermilab; Fermi National Accelerator Laboratory in the US. In the project, mainly two facilities were used: NuMI, Neutrino at the Main Injector, and Pbar, Antiproton production target station. In the NuMI beam line, we investigated the penetration-and-activation features of high-energy muons. The first results on the muon experiments are shown in [1].

In the Pbar station, we obtained systematic experimental data of production-and-attenuation behaviours of secondary neutrons induced by 120 GeV protons in terms of neutron attenuation in the steel-and-concrete shielding, neutron flux distribution and high-energy neutron spectra in the energy range between 1 and 100 MeV.

This paper summarises the experimental procedure and the results at the Pbar station. The first-step analysis was carried out using a particle transportation code with a simple 2-dimensional model. The comparison between the calculations and the experiments is shown and some issues on the further analysis are needed. In future it will be important to determine a neutron attenuation length for the accomplishment of proper shielding designs of high-energy proton accelerators. In order to deduce the attenuation length for steel shielding, we applied our experimental data of neutron flux distributions to the Moyer's approximation model. This paper presents the procedure of the parameter deduction, though the parameter deduced in this work has not yet been finalised.

Experiment

The experiments were carried out at the Pbar station of Fermilab. The configuration of the Pbar station is shown in Figure 1.

Figure 1 shows dimensions in units of cm. It is the drawing before the replacement of the concrete blocks to the brand-new blocks specially fabricated for the experiment in 2010 and will be described in detail in the next section.

The beam line for antiproton production consisted of an antiproton-production target, a collection lens, a pulse magnet and a bema dump. The components were covered by steel and concrete shields with thicknesses of 188 cm and 122 cm, respectively. An air gap, where the utilities of the beam line components had been installed, existed between the steel and concrete shield. The height of the air gap was 179 cm.

The target was bombarded with proton beams injected from the main injector. The proton beam energy was 120 GeV, and the typical beam intensity was 2×10^{12} protons/sec.

The multi-foil activation method was mainly used to measure neutron-flux distributions and high-energy neutron spectra in the shielding configuration. The metal foils of indium, aluminium, niobium and bismuth were placed in the various positions in and out of the shielding assembly. The sample positions are shown in Figure 1.

Figure 1 shows the samples for activation set at the positions marked as squares with crosses. Each position was labelled as FP01-05 (from bottom to top), AG01-05 and CC01-04 (up- to downstream for the proton beam direction). FP means a "filler plate" used for mounting the samples in the steel shield. AG and CC are abbreviations for "air gap" and "concrete cap", respectively.

The foil-samples were irradiated with the secondary neutrons during the beam operation, and some radioactive nuclei were induced in the samples. After the irradiation, the foils were picked up from the Pbar station, and the spectroscopy analysis of the gamma-rays emitted from the foils were performed with germanium detectors in order to measure the reaction rates of the neutron induced reactions. The reactions which we were interested in are tabulated with the half-lives of the products and the threshold energies in Table 1.

Figure 1: Cross-sectional view of the antiproton-production target station of Fermilab

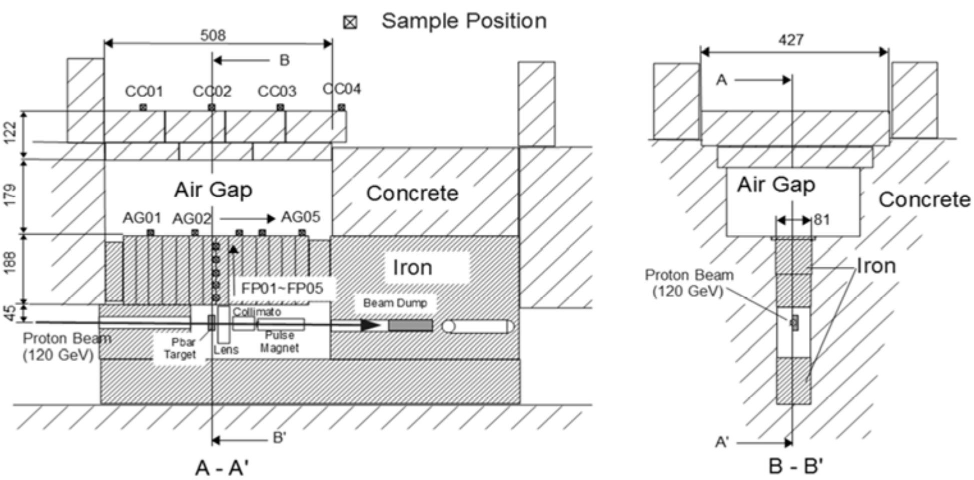


Table 1: Threshold reactions used for the foil activation

Reactions	Half-lives of products	Threshold energies (MeV)
$^{115}In(n, 2n)^{115m}In$	4.486 h	0.34
$^{27}Al(n, \alpha)^{24}Na$	14.959 h	3.25
$^{93}Nb(n, 2n)^{92m}Nb$	10.15 d	9.06
$^{209}Bi(n, 4n)^{206}Bi$	6.243 d	22.56
$^{209}Bi(n, 5n)^{205}Bi$	15.31 d	29.63
$^{209}Bi(n, 6n)^{204}Bi$	11.22 h	38.08
$^{209}Bi(n, 7n)^{203}Bi$	11.76 h	45.34

A measurement using a Bonner sphere was also carried out on the surface of the concrete shield and a deduction of a neutron spectrum with a wide energy range between 1 eV and 100 MeV succeeded. It should be noted that the neutron spectrum was consistent with the results of the multi-foil activation method. The details of the Bonner sphere measurement and the result are indicated in [2].

Short history of the experiment

The short history of the experiments at the Pbar station is summarised here.

In the first experiment in November 2007, the foil activation measurement at the air gap and on the concrete-shield surface was carried out. The measurement using a boner sphere was also carried out in the first experiment.

In 2008, we made a new steel palate with some small vacancies for the installation of the activation samples, and the experimental data of neutron attenuation in the steel shield were obtained.

Furthermore, in 2010, we constructed new concrete shielding blocks just for our shielding experiments. The shield thickness of the new blocks was the same as that of the old ones. The new blocks had sample ports for installing activation foils in the concrete blocks. That enabled us to measure neutron attenuation in the concrete shield. The concrete elements and the densities, which are essential data for the calculation analysis using a particle transportation code, were precisely measured.

The concrete blocks of the Pbar station were replaced with the brand-new blocks in November 2010. The activation samples were installed in the sample ports in the new concrete blocks in December 2010, and the radioactivity measurements were carried out in February 2011. The results are summarised in [3].

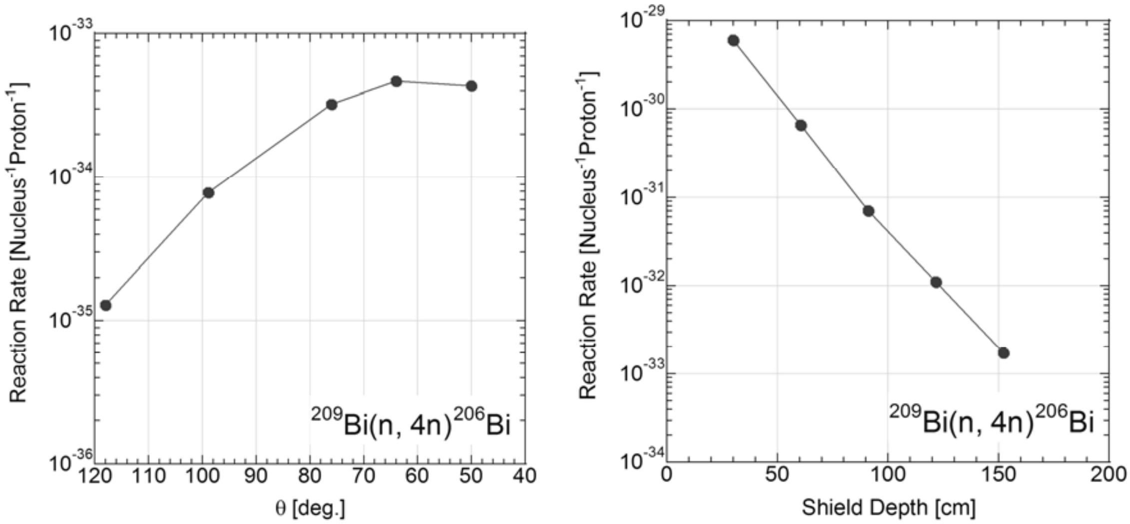
Analysis

We obtained the reaction-rate data for some threshold reactions in various positions in the shielding assembly. This means that the reaction rate distributions, corresponding to the neutron flux distributions, were obtained. Two examples of the reaction-rate distribution data obtained in this work are shown in Figure 2. The reaction rate distribution of $^{209}Bi(n, 4n)^{206}Bi$ reaction on the surface of the steel shield is shown on the left part of Figure 2, and those in the steel shields, which correspond to the neutron attenuation in the steel shied, are shown on the right part of Figure 2.

The left graph in Figure 2 shows the distribution of the surface of the steel shield as a function of the angles of the sample positions with respect to the proton beam direction from the antiproton-production target, and the right graph shows the neutron attenuation in the steel shield as a function of the steel depth from the bottom of the shield.

Using the set of the reaction-rate data at each measurement position, the neutron spectra with the energy region from 1 to 100 MeV were deduced by means of the fitting method, which was newly developed in this work [4]. The outline of the fitting method is as follows:

Figure 2: Reaction rate distributions of $^{209}Bi(n, 4n)^{206}Bi$ reaction

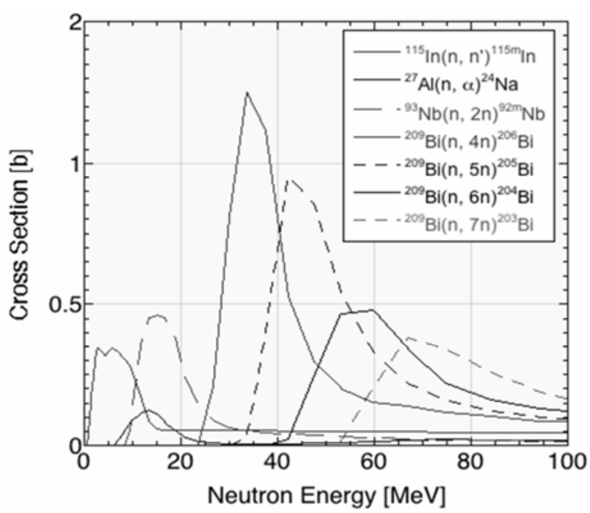


It is empirically assumed that the neutron spectra between 1 and 100 MeV can be expressed as a sum of the two exponential functions:

$$\phi_{fit} = a_1 \exp(-a_2 E) + a_3 \exp(-a_4 E), \quad (1)$$

where ϕ_{fit} is a neutron flux in unit of MeV^{-1}, E is a neutron energy in MeV, and a_i(i=1~4) are fitting parameters. The fitting parameters are determined with the non-linear least squares fit to the experimental reaction-rate data. The cross section curves [5-6], which are required in the fitting process, are shown in Figure 3.

Figure 3: Cross-section curves used for deduction of neutron spectra



The neutron spectra deduced from the experimental data were compared with the calculation using a Monte Carlo particle transportation code: PHITS. [7] As a first step of the calculation analysis, we used a simplified two-dimensional geometry as an input [8]. Figure 4 shows the experimental and calculated neutron spectra on the line at a 90-degree angle from the antiproton-production target with respect to the proton beam direction.

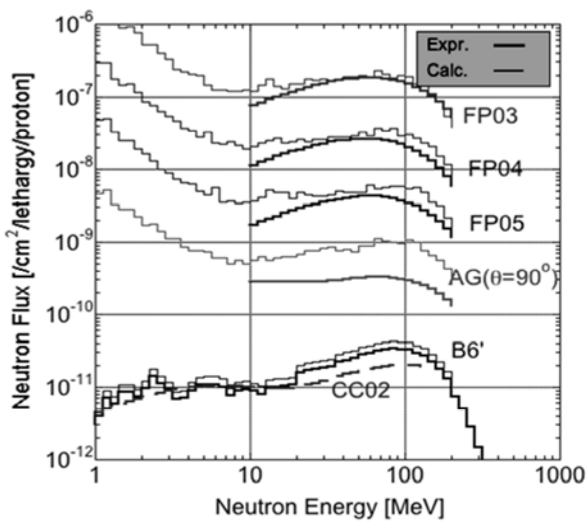
In the figure, the experimental and calculated neutron spectra are shown with bold and thin lines, respectively. The symbols of FP03, FP04 and FP05 correspond to the neutron spectra in the steel shield at the shield depths of 96.5 cm, 127.0 cm and 157.5 cm from the bottom, respectively. The symbol of AG(θ=90°) means the position on the surface of the steel shield at 90-degree direction from the antiproton production target with respect to the proton-beam direction. There is no experimental data obtained at AG(θ=90°); we could not put the activation sample at AG(θ=90°) because a target-cooling device was already placed there. The experimental data at AG(θ=90°) were deduced by interpolating the data of AG02 and AG03. The bold and thin lines of B6' is the neutron spectrum on the surface of the new concrete shield, respectively, and CC02 is the experimental data at the same position for the old concrete blocks.

The graph in Figure 4 shows that the calculation tends to overestimate the neutron fluxes in the steel shield and on the surface, but it also shows that, on the concrete top, the calculated neutron spectra show good consistency with the experimental one. It should be noted that it is very important to investigate the transition of the deviations from the iron and the concrete shield.

In the figure, we plotted the experimental data at the concrete top for both the old and new concrete blocks. The neutron flux at the concrete top increased after changing the concrete shield. It is very interesting to investigate the reason if the composition of the old concrete shield could be analysed.

We regarded the calculation results shown in this paper as a first step analysis. In the analysis presented in this paper, each beam-line component, such as the antiproton-production target, the collection lens, the collimator and the pulse magnets, can be considered as equivalent secondary-neutron sources. Therefore, it is very important to validate the source terms, which largely depends on how to model the beam-line components.

Figure 4: Experimental and calculated neutron spectra on the line at a 90-degree angle from the antiproton-production target with respect to the proton beam direction

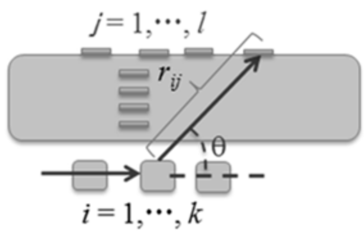


Finally we tried to deduce a neutron attenuation length by applying the Moyer's expression to the experimental reaction-rate distributions obtained in this work. As indicated above, the Pbar station is a multi-source system from the viewpoint of the neutron shielding experiment. The reaction-rate distribution can be expressed as a sum of the contributions of each source using the Moyer's expression as:

$$R_j = \sum_i R_0^{(i)} \frac{e^{-b\theta} e^{-\frac{d}{\lambda \sin\theta_{ij}}}}{{r_{ij}}^2}, \tag{2}$$

where, R_j is a reaction rate at a sample (j), d is a shied thickness, r_{ij} is a distance between a neutron source (i) and a sample (j), θ_{ij} is an angle from a neutron source (i) to a sample (j) with respect to the proton beam direction, $R_o^{(i)}$ is a contribution of a source (i), and b and λ are Moyers parameters related to an angular distribution of neutron emission from the neutron source and a neutron attenuation, respectively.

Figure 5: Moyer's model for multi-source system



For deduction of a neutron attenuation length of steel shield, the expression (2) was fitted to the experimental reaction-rate data using non-linear least-squares method by adjusting $R_0^{(i)}$ and λ, minimising χ^2 values defined as:

$$\chi^2 = \frac{1}{N} \sum_i \left(\frac{R_{\exp}^{(i)} - R_{cal}^{(i)}}{\varepsilon^{(i)}} \right)^2, \tag{3}$$

where N is a degree of freedom in the fitting process, $R^{(i)}_{exp}$ is the experimental reaction-rate data, $R^{(i)}_{fit}$ is the reaction-rate deduced with the fitting function (2), and $\varepsilon^{(i)}$ is the experimental error. The value of b was fixed in the whole fitting process at 2.3 in the unit of radian^{-1} [9], which has been commonly used in shielding design so far, and the minimum χ^2-values were deduced for a fixed λ by adjusting $R_0^{(i)}$ with the non-linear least square method. The fitting processes were carried out by changing λ from 130 to 150 g/cm^2. The fitting results of ^{209}Bi(n, 4n)^{206}Bi reactions with λ= 145 g/cm^2 are shown in Figure 6, for example. The χ^2-value of the fitting was 3.2. In the fitting, the data at the position of -135 cm, indicated in the right figure, was not used because the position was out of the application range of the Moyer's expression.

Figure 6: Fitting results of $^{209}Bi(n, 4n)^{206}Bi$ using Moyer's expression

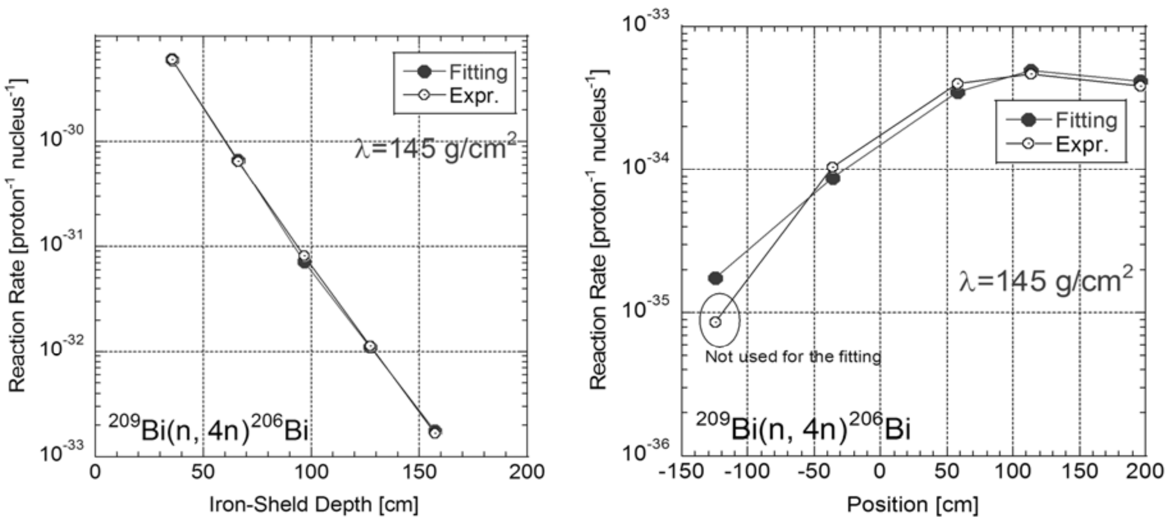
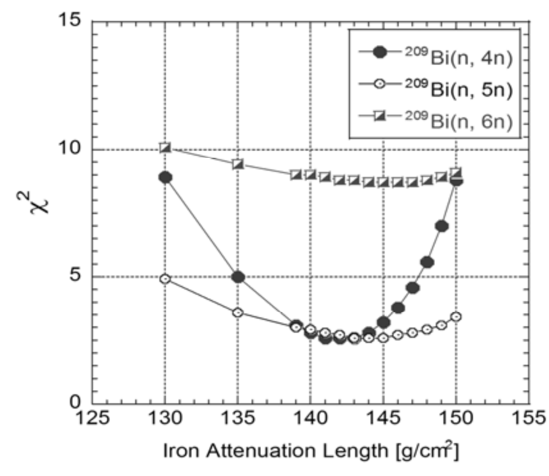


Figure 7 shows the χ^2-value as a function of λ for ^{209}Bi(n, 4n), (n, 5n) and (n, 6n) reactions. These curves show that the χ^2-values were minimised between λ=140 and 145 g/cm^2. We suppose that this result is tentative. In order to finalise the λ-value deduction, which means obtaining the most optimum λ-value from our experiment, it is necessary to consider the validity of $R_0^{(i)}$-distributions obtained in the fitting from the viewpoint of theoretical calculation.

Using a similar process, the λ- value for the concrete shield will be deduced. In order to do this, we investigate how to treat the "air-gap" in the Moyer model.

Figure 7: Variations of the χ^2-value as a function of λ for ^{209}Bi(n, 4n), (n, 5n) and (n, 6n) reactions



Summary

Experimental shielding data has been obtained at the high-energy accelerator facility with maximum proton acceleration energy over 100 GeV by means of the multi-foil activation method. The neutron spectra at various positions in the shielding assembly were deduced from the experimental reaction-rate data using the fitting method, which is newly developed in this work.

These data are remarkable and essential for validating a particle transportation code in terms of the simplicity of shielding geometry and the well-known constitution of concrete shielding.

The experimental data were compared with the calculation of the PHITS code with the simplified two-dimensional geometry.

We tentatively deduced the optimum values of a neutron attenuation length by applying the experimental reaction-rate distribution to the Moyer's approximation model. The Pbar station is a multi-source system from shielding experiment viewpoints. Therefore, comprehension of the source terms will be essential for obtaining the most optimum value of the attenuation length and for further calculation analysis.

Acknowledgements

This work is supported by grant-aid of the Ministry of Education (KAKENHI 19360432 and 21360473) in Japan. Fermilab is a US Department of Energy Laboratory operated under Contract DE-AC02-07CH11359 by the Fermi Research Alliance, LLC.

References

[1] H. Nakashima *et al.* (2009), *Nucl. Technol.*, 168, 482-486.

[2] Y. Kasugai *et al.* (2011), *J. Korean Phys. Soc.,* 59, 2063-2066.

[3] H. Yashima *et al. Progress in Nucl. Sci. and Techonol.*, 2 to be published.

[4] Y. Kasugai *et al.* (2012), *J. ASTM International* (JAI), 1550, 675-689.

[5] F. Maekawa *et al.* (2001), *ASTM Spec. Tech. Publ.*, 1398, 417–424.

[6] F. Maekawa *et al.* (2005), *Nucl. Sci. Eng.*, 150, 99-108.

[7] H. Iwase *et al.* (2002), *J. Nucl. Sci. Tecnol.*, 39, 1142–1151.

[8] N. Matsuda *et al.* (2011), *Progress in Nucl. Sci. and Techonol.*, 1, 57-60.

[9] G. Stevenson *et al.* (1982), Health Phys., 43, 13-29.