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ARTICLE

Research activities on JASMIN: Japanese and American Study of Muon Interaction and Neutron detection

Hiroshi Nakashima[a*], Nikolai V. Mokhov[b], Yoshimi Kasugai[a], Norihiro Matsuda[a], Yosuke Iwamoto[a], Yukio Sakamoto[a], David Boehnlein[b], Anthony Leveling[b], Kamran Vaziri[b], Richard Coleman[b], Douglas Jensen[b], Erik Ramberg[b], Aria Soha[b], Toshiya Sanami[c], Hiroshi Matsumura[c], Masayuki Hagiwara[c], Akihiro Toyoda [c], Hiroshi Iwase[c], Hideo Hirayama[c], Takashi Nakamura[d], Shun Sekimoto[e], Hiroshi Yashima[e], Tsuyoshi Kajimoto[f], Nobuhiro Shigyo[f], Kenji Ishibashi[f], Noriaki Nakao[g], Norikazu Kinoshita[g], Koji Oishi[g], Hee-Seock Lee[h] and Koji Niita[i]

[a] Japan Atomic Energy Agency, 2-4 Shirakata-shirane, Tokai, Naka, Ibaraki 319-1195, Japan; [b] Fermi National Accelerator Laboratory (Fermilab), Batavia, IL 60510-5011, US; [c] High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tsukuba, Ibaraki 305-0801 Japan; [d] Tohoku University, Aramaki, Aoba, Sendai, Miyagi 980-8578, Japan; [e] Kyoto University Research Reactor Institute, 2 Asashiro-Nishi, Kumatori, Sennan, Osaka 590-0494, Japan; [f] Kyushu University, Motooka, Fukuoka 819-0395, Japan; [g] Shimizu Corporation, 3-4-17 Etchujima, Koto, Tokyo 135-8530, Japan; [h] Pohang Accelerator Laboratory, POSTECH, Pohang 790-784, Korea; [i] Research Organization for Information Science & Technology, 2-4 Shirakata-shirane, Tokai, Naka, Ibaraki 319-1106, Japan

In order to investigate the accuracy of high-energy radiation transport codes based on experimental data, the collaboration; Japanese and American Study of Muon Interaction and Neutron detection (JASMIN), has been formed among many institutions and universities of Japan and U.S.A. A series of experiments have been conducted at the Fermilab Pbar target station, the NuMI beam line and the Fermilab Test Beam Facility (FTBF). In this paper the research activities are reviewed.

Keywords: high energy; accelerator; shielding; nuclear data; benchmarking; experiment

1. Introduction

Several multi-purpose particle transport codes are used in numerous applications at accelerator facilities, high-energy physics experiments and space exploration programs, especially for the upgrades and new projects. The code reliability is evaluated via benchmarking against experimental data. The JASMIN experiments - Japanese and American Study of Muon Interaction and Neutron detection – are being conducted by a collaboration of several laboratories and universities of Japan and U.S.A. The JASMIN's goals are: (1) acquisition of shielding data in a proton beam energy domain above 100 GeV; (2) further evaluation of predictive accuracies of the PHITS[1] and MARS[2] codes; (3) modification of physics models and data in these codes if needed; (4) establishment of test irradiation field for radiation effects; and (5) development of code modules for improved description of radiation effects.

A series of experiments has been performed over 5 years at Fermilab (FNAL) at the Pbar target station, downstream of the NuMI hadron absorber, and at the Fermilab Test Beam Facility (FTBF) as shown in **Figure 1**. A variety of measurements were done on radiation fields generated by the interactions of the intense 120-GeV proton beams with various targets. The secondary particles created in such interactions have been measured around the thick targets as well as through steel, concrete and rock. Nuclear data such as activation cross sections and mass distributions of

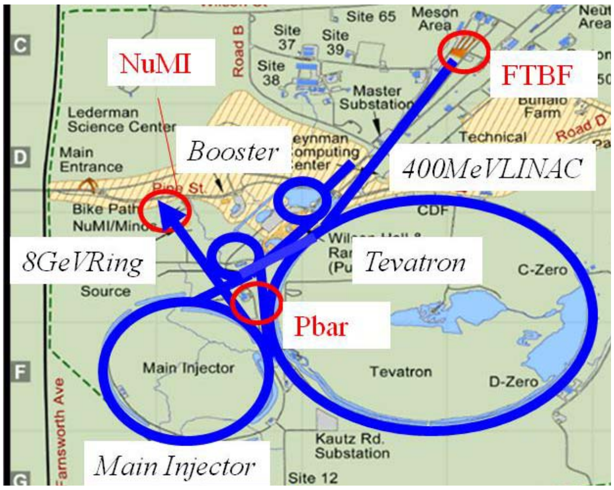

Figure 1. Accelerator complex at FNAL.

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*Corresponding author. Email: nakashima.hiroshi@jaea.go.jp residual nuclei by spallation reactions with secondary particles as well as double differential neutron production yields have been measured. The experimental data have been compared with results calculated with PHITS and MARS codes. In this paper the JASMIN results are reviewed [3-28].

2. Experiments and analyses

2.1. Experiments at the Pbar target station

Figure 2 shows a cross sectional view of the Pbar target station. An antiproton production target, consisting of Inconel 600 disks covered by Beryllium, is irradiated by 120-GeV protons with a 1.6-μs pulse width and a 2.2-sec repetition rate. The typical beam power was about 61 kW at the first set of measurements. A collection lithium lens, collimator and a pulsed magnet are placed at the down-stream of the target to focus, collimate and extract the produced antiprotons. Shields made of iron and concrete are placed above the target and magnets. The thicknesses of iron and concrete above the target are 188 and 122 cm, respectively. There is a 179-cm air gap between the iron and concrete shields [3, 9, 10].

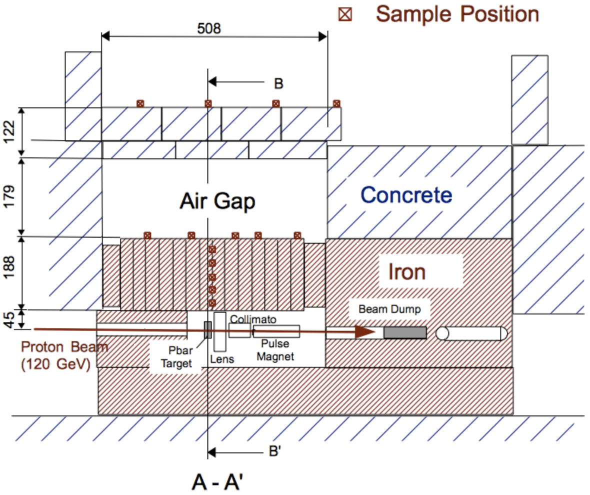

Figure 2. Cross sectional view of the Pbar target station and measured positions of neutron reaction rates [3, 9, 10].

In this experiment the following measurements have been carried out; (1) neutron attenuation in steel and concrete shields, (2) neutron flux distribution on the shield surface, (3) neutron spectra on the shield surface, (4) dose rate distribution in concrete shield, (5) activity in aerosols and gas in target room and (6) radionuclides in cooling water. In this section some typical results on neutron reaction rates are presented, and other results are presented in other papers in detail [3, 5-7, 9-11, 13, 18 -24].

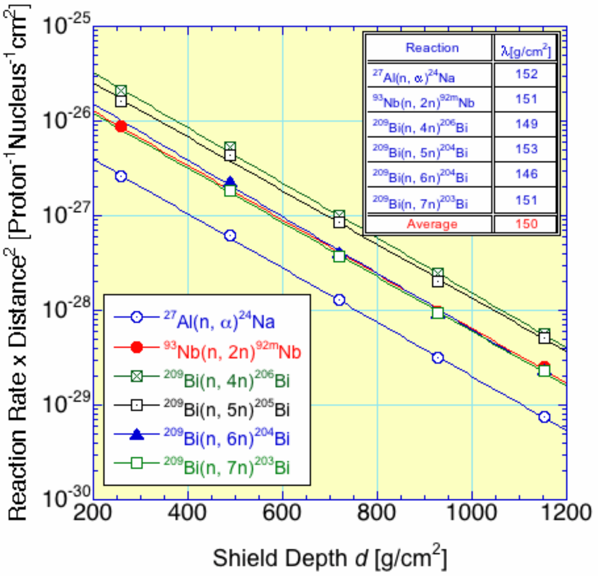

Figure 3. Reaction rate distribution in iron shield [10, 14].

Figure 3 shows neutron reaction rate distributions of various reactions measured inside an iron shield at 90 degrees to the proton beam direction as an example of the experimental data. Reactions of In, Al, Nb and Bi with various threshold energies were used: ^{27}Al(n, α)^{24}Na (E_{th}: 3.3 MeV), ^{93}Nb(n, 2n)^{92m}Nb (E_{th}: -9.1 MeV), ^{209}Bi(n, 4n)^{206}Bi (E_{th}: -22.6 MeV), ^{209}Bi(n, 5n)^{205}Bi (E_{th}: -29.6 MeV), ^{209}Bi(n, 6n)^{204}Bi (E_{th}: -38 MeV) and ^{209}Bi(n, 7n)^{203}Bi (E_{th}: -45.3 MeV). After irradiation, radioactivity produced in each sample was measured using HP-Ge detectors. Experimental errors range from ± 5% to several tens of % depending on the counting statistics. The attenuation length of neutron was deduced by fitting to the Moyer model [29] with the least square method, and the attenuation lengths λ were evaluated for each reaction rate. The average attenuation length for these measurements is 150 g/cm^2 in the energy region above 100 GeV.

The evaluated attenuation length is compared with the previous data measured as a function of maximum

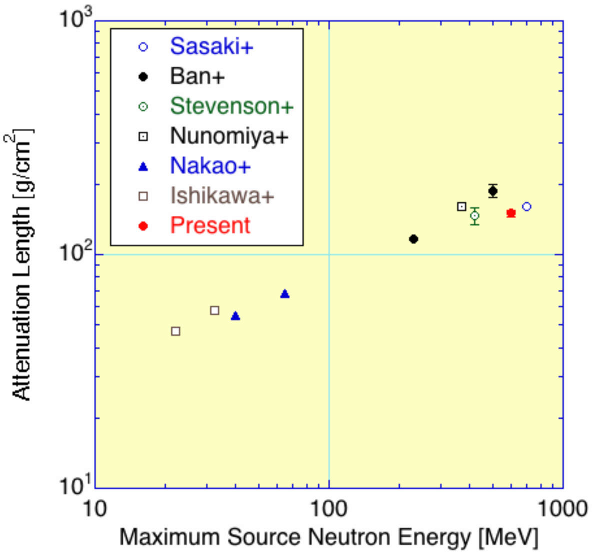

Figure 4. Comparison of attenuation length as function of maximum source neutron energy [14].

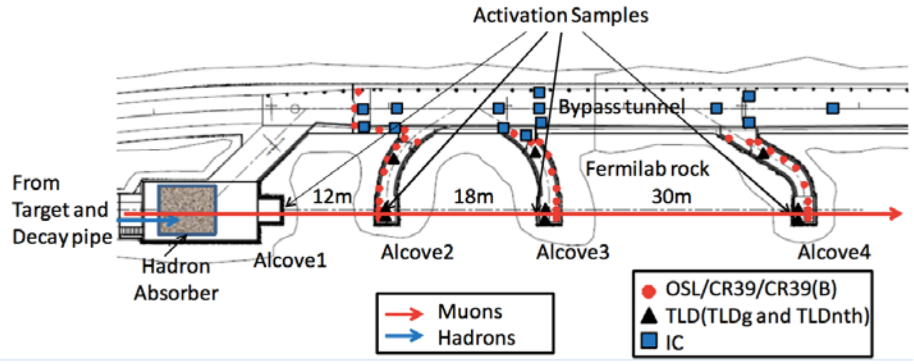

Figure 5. Schematic view of downstream of NuMI and location of dosimeters and detectors [4].

source neutron energy, as shown in **Figure 4** [14]. It is shown that the attenuation length is consistent with the previous data and increases almost linearly with the maximum source neutron energy in the neutron energy region between 20 and 1000 MeV.

In order to investigate the detailed attenuation of neutron and other particles, the data from the experiments are under analyses using PHITS and MARS with the precise geometrical model. Presently these experimental data on neutron transmission will be used for benchmarking of radiation transport codes.

2.2. Experiments at the NuMI experimental station

The NuMI experiment uses a 94-cm long graphite target which is irradiated with 120-GeV protons to generates pions and other particles. Pions are focused and directed down a 675-m long decay pipe, which then decay into muons and neutrinos. The muons and neutrinos pass through a hadron absorber made of iron and concrete located downstream of the decay pipe, while other particles such as hadrons are absorbed.

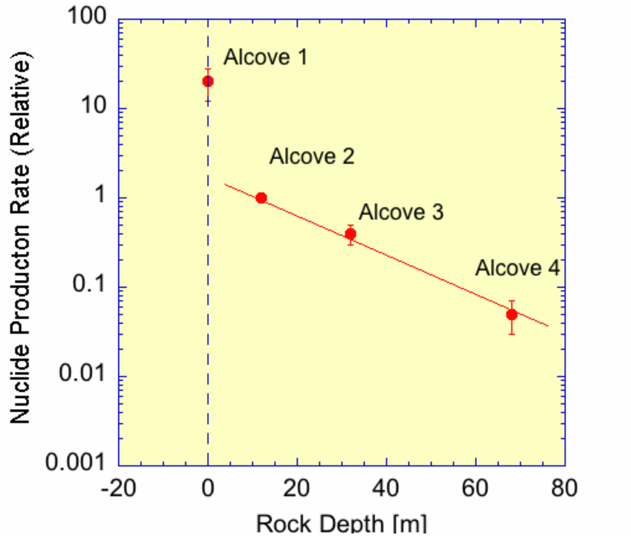

Figure 6. Attenuation profile of the mass yields due to muon reaction in rock normalized to the yield at Alcove-2 [3, 9, 12, 14].

Figure 5 shows the schematic view of downstream of NuMI decay pipe. At the downstream of the absorber, there are four caves at the distances of 0, 13.7, 33.5 and 67.1 m named “Alcove-1,” “Alcove-2,” “Alcove-3,” and “Alcove-4”, in which the dosimeters and detectors were placed as shown in the Figure 5 [4].

At NuMI the following measurements have been carried out; (1) muon attenuation in rock, (2) nuclide production by muon, (3) dose distribution due to muon, (4) radioactivity distribution in concrete shield, (5) activity in aerosols and gas in target room, (6) radionuclides in cooling water and (7) activities in materials. In this section, some results on muon attenuation and its dose distribution are presented. Some typical results are written in this paper, and the details are presented in other papers [3, 4, 8, 9, 12, 14, 19, 20, 23-28].

Activation detectors were installed in every Alcove along the beam axis and were irradiated with muons and other tertiary particles passing through the rock. Radiation doses due to the muons and other tertiary particles were also measured by OSL (Optical Stimulated Luminescence) dosimeters, TLDs (Thermo-Luminescence Dosimeters, Panasonic 813 PQ), solid state nuclear track detectors, CR39, and ionization chambers (IC) set along the beam axis and access tunnel to the Alcoves.

Mass distributions of isotopes producted in the activation foils were measured at each Alcove. The average values of the yield ratios normalized to the value at Alcove-2 as a function of the depth from the rock surface of Alcove-1 are shown in **Figure 6**. Variation of these ratios for the nuclides observed is within a factor of two. The yields from Alcove-2 show a gradual exponential decrease with the depth, while the yields decrease steeply between Alcove-1 and Alcove-2. Attenuation behavior at Alcoves-2 to -4 is consistent with the calculation by the MARS code, and the profile of the yields is similar to the calculated attenuation of muons in the rock. The reason of the large nuclide production rate at Alcove-1 is invetigated by using a thick target thick catcher foil method. The results showed that it is due to high energy photon (like virtual photon) generated by muon rather than low energy

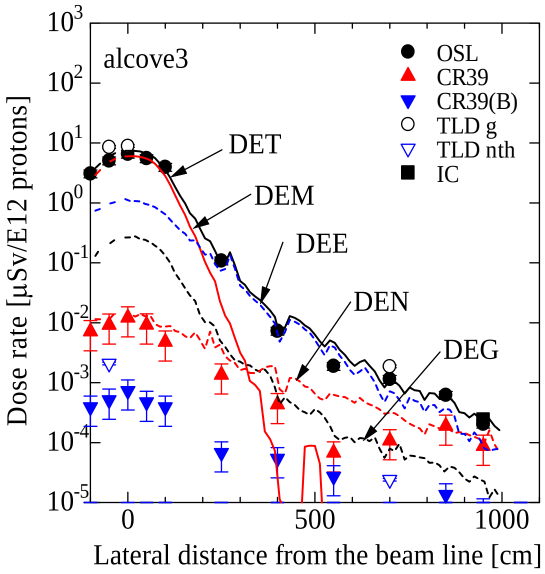

Figure 7. Dose rate distributions measured by various dosimeters at Alcove-3, compared with those of total(DET), muon(DEM), photon(DEG), electron(DEE) and neutron(DEN) calculated by MARS [4].

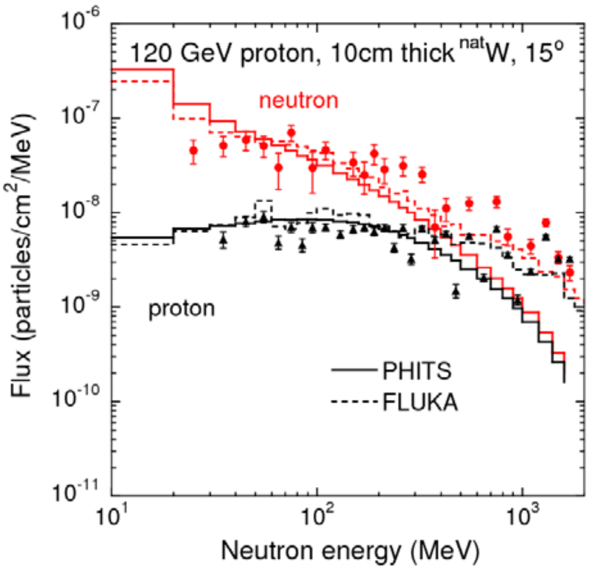

Figure 8. Neutron energy spectra for 120 GeV proton incident reaction on a 10-cm-thick tungsten target at 15° [17].

hadrons.

Figure 7 shows the measured dose rate distributions along the passage to the Alcove-3 compared with the MARS calculations as a function of transverse distance from the beam axis. In this figure, OSL, TLDg and IC show measured ambient dose equivalent rates due to mainly, muons, electrons and photons. CR39 for fast neutron, and CR39(B) and TLDnth for thermal neutron. As shown in the figure, dose rates due to muons, electrons and photons dominate around the beam axis, while dose rates due to fast neutrons, which may be generated by high-energy muon interactions, increase with the distance from the beam line. The calculated total dose rates are in excellent agreement with the ambient dose equivalent rates measured by OSL and TLDg around the beam axis. The calculation indicates that the total dose rates are mainly driven by muons around the beam axis. The electrons and photons are generated by the interaction of muons in the rock around the axis. Both measurement and calculation show that contribution of fast neutrons drastically increase at the distance larger than 4 m. An explanation is that neutrons are generated by photo-nuclear reactions induced by photons generated by muons.

2.3. Experiments at the Fermilab Test Beam Facility

Thick target particle yields and activation cross sections have been measured at the Fermilab Test Beam Facility (FTBF). The time structure of proton beam at FTBF consists of three levels. The smallest structure is the bunch of 19 ns interval. The second one is called the train which includes 20–36 bunches and has 11 μs interval. The largest structure is the spill which lasts 4 seconds long and one minute interval. The 120 GeV incident proton beam was monitored upstream of the target by multi-wire proportional counter beam profile monitors and three plastic scintillators to count the number of incident protons [15].

The thick target yields on Al, Cu and W were measured by the time-of-flight method using NE213 liquid organic scintillators (12.7 cm thick and 12.7 cm long). Plastic scintillators were set in front of the NE213 scintillators to distinguish charged particles from neutron events. For data acquisition (DAQ) two kinds of DAQ systems were used for the high-intensity beam and pile–up due to the beam. One is an ordinary CAMAC DAQ to collect the integral light output from scintillators, and the other a wave form digitizer DAQ which collects wave form of light output from scintillators as a function of time to increase actual counting rate [15, 21].

As examples, some results of thick target particle yield measurements are compared with the PHITS and FLUKA calculations in **Figure 8**. The calculated results agree well with the experimental data at 15°. Further investigation is required for the codes [17].

Details of the measurements on thick target particle yields and activation cross sections are elsewhere [26, 27].

3. Conclusion

Various experimental results on particle flux, mass distributions, activation data and cross sections were obtained by JASMIN. Shielding parameters such as neutron attenuation lengths were also measured and compared with the previous values. The results were analyzed by the codes such as PHITS, MARS and FLUKA and further investigation is in progress.

Further JASMIN collaboration plans are to characterize radiation field to study radiation damage, nuclear reactions induced by fast muons, study of colloid formation in water in contact with metallic material and study of aerosol formation in air around high energy accelerators.

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