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Measurement of the Neutron Energy Spectra by Using Organic Scintillators at the Beam Dump of the 100-MeV Proton Linear Accelerator in the KOMAC

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This paper presents the experimental results of neutron spectra measurements with organic scintillators at the copper beam dump of the 100-MeV proton linear accelerator in the Korea Multi-Purpose Accelerator Complex (KOMAC). For the measurement of the fast neutrons generated by the proton-copper nuclear reaction, two organic scintillators made of a stilbene crystal and liquid EJ-309 combined with photomultipliers and fast digitizers were utilized. Both detectors were installed inside radiation shielding structures facing the conical-shaped 100-MeV proton beam dump. The neutron transport was calculated using two Monte-Carlo codes, MCNP6 and GEANT4, with a proper physical model and a nuclear data library, along with the appropriate consideration of the detailed geometrical factors in the vicinity of the beam-dump and the neutron detectors. Each pulse signal measured in the detectors was analyzed to identify whether it was induced by a neutron or a gamma-ray in a mixed radiation field by using pulse shape discrimination technique. For operation of beam current of 5 mA and duty of 0.2%, the neutron yield was measured to be approximately 9.0E+10 n/s, which was 23% smaller than the numerically estimated value. In addition, both the measured and the estimated neutron energy spectra were compared.

Keywords: White neutron source, Proton accelerator, Organic scintillator, Monte-Carlo calculation, Neutron energy spectrum
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I. INTRODUCTION

The proton linear accelerator at the Korea Multi-Purpose Accelerator Complex (KOMAC) has been in operation since 2013 for proton. A white neutron source is a recent interest as a useful application of a secondary particle beam. Especially, industrial demand for the testing of cosmic-ray-induced radiation damage has been on the rise [1, 2]. White neutron spectra can be achieved by colliding a high-energy proton beam with any material. Figure 1 shows the KOMAC layout and the conical-shaped copper beam dump for generating white neutrons at the end of a 100-MeV proton beamline. The upcoming fast neutron facility is being prepared not only by implementation of a neutron target station but also by the introduction of fast neutron diagnostics at the KOMAC [3]. In other white neutron source facilities, the neutron activation technique is the most prevalent one used to measure neutron spectra. The neutron activation technique is itself a passive method, so it gives time-averaged information [4,5]. In our developing neutron facility, we first need an active detection system in accordance with variable beam conditions. On the other hand, the time-of-flight technique is also a traditional and reliable method to measure neutron energy spectra [6]. It, however, requires a very short pulsed beam and

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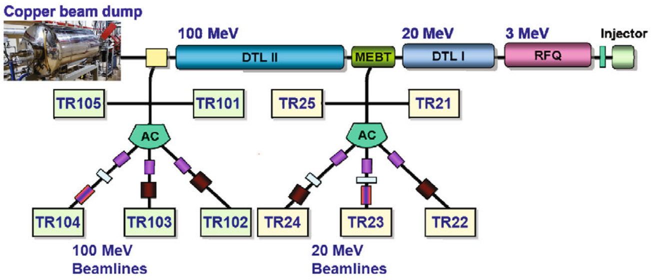

Fig. 1. KOMAC layout and copper beam dump to generate neutrons.

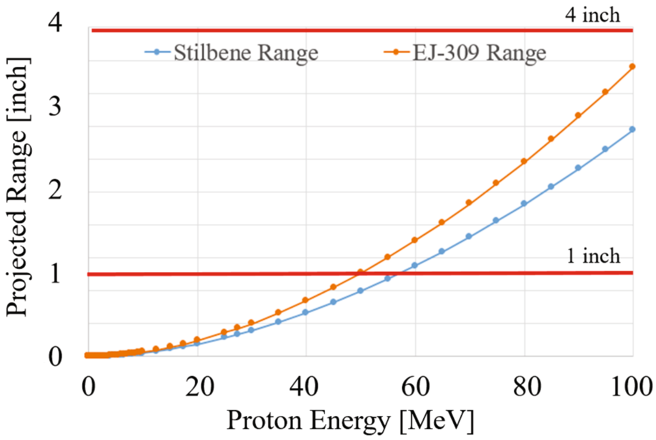

Fig. 2. Calculated projected range of protons in the scintillators.

an elaborated system. Therefore, organic scintillators were utilized in active neutron measurements as the first action for the preliminary characterization of the future KOMAC neutron facility.

II. EXPERIMENTS AND DISCUSSION

Two different organic scintillators, stilbene crystal and liquid EJ-309, were utilized to measure fast neutrons generated by using the proton-copper nuclear reaction. These types of scintillators are mainly composed of hydrocarbons, so the nucleus of a hydrogen or a carbon atom can be recoiled by an incident neutron, partially transferring kinetic energy to the scintillator. In this context, the length of a scintillator determines the maximum neutron energy that can be measured. Figure 2 shows projected ranges of protons calculated as a function of the proton energy in the two scintillators. A length of four inches was enough for 100-MeV protons to be stopped in the two scintillators, and one inch was enough for up to 50-MeV protons.

Figure 3 shows drawings of the organic scintillator assembly. The stilbene crystal was packed in a cylindrical container with an inner diameter of 1 inch and a length of 1 inch. Another cylindrical container with an inner diameter of 1 inch and a length of 4 inches was filled with liquid EJ-309. They were all enclosed in reflective tape and a light-tight aluminum housing, and were then optically coupled to photomultipliers in an electro-magnetic shield.

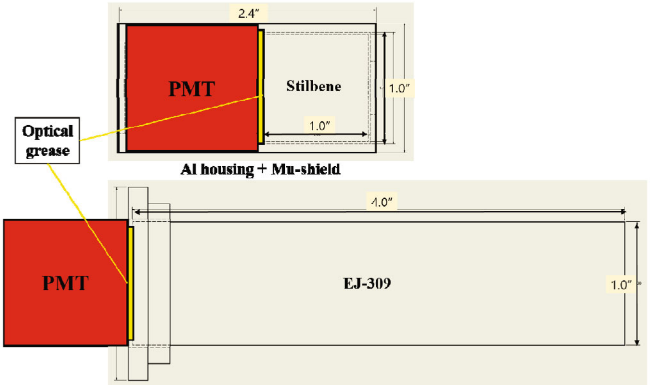

Fig. 3. Drawings of the organic scintillator assembly (stilbene, EJ-309).

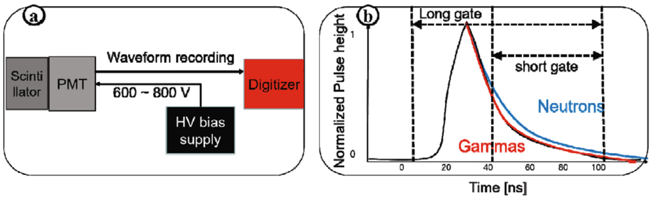

Fig. 4. Electronics and signal processing with the organic scintillator.

Figure 4 shows the electronic chain and signal processing with neutron/gamma-ray pulse shape discrimination (PSD) technique. Each detector assembly was connected to a high-voltage bias supply and a fast digitizer. The high-voltage bias was set within the input voltage range of the digitizer. Each pulse signal measured in the detectors was analyzed to identify whether it had been induced by a neutron or a gamma-ray in a mixed radiation field. Neutrons tend to induce more slowly decaying components than gamma-rays in these scintillators, so in general, they provide a good capability to discriminate neutrons from gamma-rays. An analysis was performed using the charge-integration method, which integrated the detector signals in two different timing gates - a long gate and a short gate. Long-gate integration yielded the total area of signals whereas short-gate integration yielded a partial area on the tail of the signals. The representative value, called the PSD value, was defined as the partial area divided by the total area of the signal. A larger PSD value typically indicated neutrons rather than gamma-rays.

To verify the detector response and operating characteristics, we performed a calibration experiment with quasi-mono-energetic neutrons of 2.45 MeV generated from deuterium-deuterium nuclear fusion reactions. Fig-

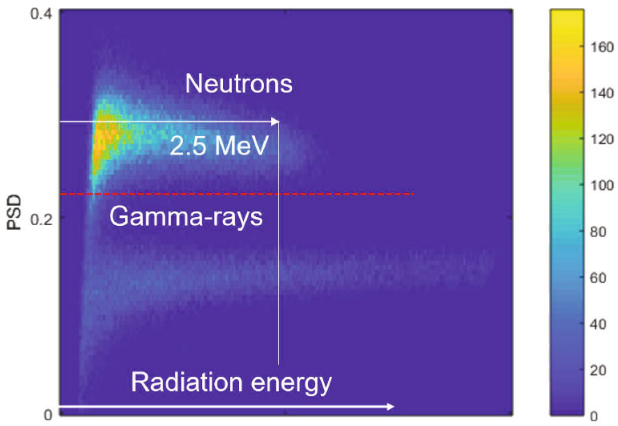

Fig. 5. Calibration results for the D-D neutron source.

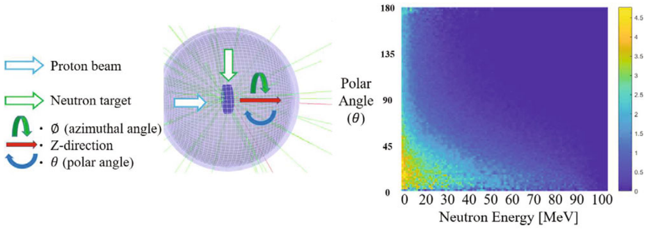

Fig. 6. Calculated angular energy distribution of white neutrons from the KOMAC beam dump.

ure 5 shows that this experiment provided a digitized channel-to-energy relation and a neutron/gamma-ray discrimination point. The measured spectra also shows plateau edge near the 2.45 MeV caused by the detector response to the quasi-mono-energetic neutrons.

Figure 6 shows calculation results for the angular energy distribution of white neutrons from the KOMAC beam dump. Neutron transport was calculated using two Monte-Carlo codes, GEANT4 and MCNP6. In GEANT4 calculations, the QBBC physics model was applied with detailed geometry in the vicinity of beam-dump and neutron detectors. In MCNP6, Bertini model, a standard nuclear physics model, was used, and showed good agreement with the GEANT4 QBBC model. Numerical simulations on neutron generation in this facility clearly showed the angular and the energy distributions of the neutrons generated and transported. Seven degrees was found to be the most suitable location for copying atmospheric neutron spectra with a 100-MeV proton beam irradiating a conical-shaped copper beam dump.

The main experiments with the 100-MeV proton linear accelerator were carried out in succession with the calibration experiments and the numerical estimates. Figure 7 shows the shielded detection system that we installed 25 m away from the neutron target and seven degrees off the beam axis. The detectors was enclosed by a lead shielding with the copper linings to absorb gamma-rays and secondary X-rays. In addition, a neutron collimator composed of borated polyethylene blocks surrounded the lead shielding. These structures played a role in mitigating back-scattered neutrons as well as X-rays and gamma-rays. Electronic devices were installed beyond the 1-m-thick concrete wall so that they would be safe from radiation damage.

Fig. 7. Overview of the neutron detection system and the shielding installed in the KOMAC.

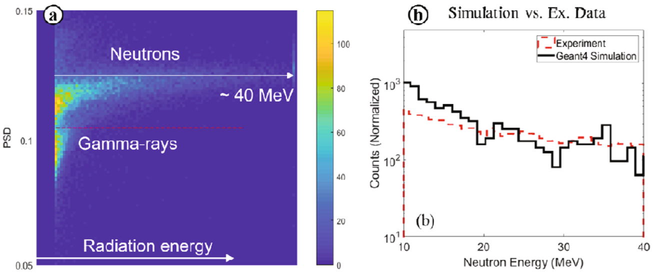

Fig. 8. (a) Spectra measured using the stilbene detector in the KOMAC beam dump, (b) Comparison between the measured neutron energy spectrum and the simulated one in the neutron energy range from 10 to 40 MeV.

Figure 8(a) shows the measured PSD spectra from the stilbene detector. It apparently discriminated neutrons from gamma-rays, although it could measure the neutron energy only up to about 40 MeV due to its small size. On the other hand, liquid EJ-309 showed a drawback in PSD performance compared to stilbene detector because EJ-309 had a four times larger detection volume, which made it more vulnerable to pulse pile-up in a strong radiation field. For operation at a beam current of 5 mA and a duty of 0.2%, the neutron yield was measured to be approximately 9.0E+10 n/s with the stilbene detector, which was similar to the numerically estimated value of 1.1E+11 n/s. Also, estimated pulse height spectra in the detector showed good agreement with the measured spectra in the case of the stilbene detector for neutrons with energies up to 40 MeV as shown in Fig. 8(b).

III. CONCLUSION

Fast neutron energy spectra were estimated by using a stilbene and EJ-309 scintillator in KOMAC beam dump, combined with Monte-Carlo simulation. The fast neutron detection system was calibrated using a mono-energetic D-D fusion neutron source. A radiation shielding and a collimator were designed and installed to cope with strong radiation field. For beam operation at a power of 0.1 kW, a set of measurements yielded 9.0E+10 n/s at the fast neutron yield, which was 23% smaller than the simulation. The pulse height spectra measured in the detector showed a small discrepancy with respect to the spectra that were simulated using GEANT4. The results presented here will be crucial not only for providing energy-calibrated neutrons to industrial companies who are interested in cosmic-ray-induced damage, but also for preparing the quantitative utilization of the KOMAC fast neutron facility in accordance with the international standard.

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