Characterization Study of Fast Neutron Sources Based on Proton Accelerators at KOMAC

P. Lee¹, J.J. Dang¹, H.S. Kim¹, H.J. Kwon¹, S.H. Lee¹

Y.S. Cho²

¹Korea Multi-purpose Accelerator Complex, Korea Atomic Energy Research Institute, Gyeongju-si, Republic of Korea
²Korea Atomic Energy Research Institute, Daejeon, Republic of Korea
E-mail: pilsoolee@kaeri.re.kr

Abstract. We introduce two neutron sources based on proton accelerators; a quasi mono-energetic neutron source driven by a 1.7MV tandem accelerator and a pulsed white neutron source based on a 100MeV linear proton accelerator, which are installed at Korea Multi-purpose Accelerator Complex (KOMAC) of Korea Atomic Energy Research Institute (KAERI). The neutron sources are characterized in terms of Monte Carlo simulations, and experiments based on various type of detectors and activation methods. In the manuscript, specifications of the neutron sources and the partial results of characterization study including energy and flux density measurements of the neutron sources are presented.

1. Introduction
Although the principles of accelerator-based neutrons sources are physically well known, the properties of the neutron sources, such as the energy, energy broadness, angular distribution, and flux density, vary significantly depending on the system and environments [1] unlike the radioactive source having continuous and fixed energy distribution with a few MeV mean kinetic energy [2]. Therefore, the characterization of such neutron sources is a crucial part in the development and utilization of the neutron sources.

In Korea Multi-purpose Accelerator Complex of Korea Atomic Energy Research Institute, two kinds of neutron sources are in operation; one is a quasi mono-energetic neutron source driven by a 1.7MV tandem accelerator and the other is a white neutron source based on a 100MeV proton linear accelerator [3]. In this paper, the properties of the neutron sources at KOMAC are introduced and the results of characterization study on the fast neutron sources are presented.

2. Mono-energetic fast neutron source for Eₙ ≤ 3 MeV
2.1. Accelerator and Target
The quasi mono-energetic neutron source is based on a 1.7MV tandem accelerator in which negative hydrogen is injected from a source of negative ion by Cesium sputtering (SNICS) manufactured by NEC. The maximum H⁻ current at the ion source is up to 10 μA. The tandem accelerator was originally installed and operated at Korea Institute of Geoscience and Mineral
Resources (KIGAM) [4]. However, the accelerator was completely moved to KOMAC of KAERI, and has been being operated since 2017 as a driver accelerator for a neutron source.

At the facility, fast neutrons are generated through the proton-induced charge-transfer reaction in $^7\text{Li}$, i.e., $^7\text{Li}(p,n)^7\text{Be}$ for the production of mono-energetic neutrons in the energy range below $E_n \leq 2\text{MeV}$. Concerning the production target, a LiF target [$\rho = 2.635 \text{ g/cm}^3$] is prepared by evaporating LiF powder on a thin Al substrate at a target thickness of $100\mu\text{g/cm}^2$, and it is installed at the end of a proton beam line dedicated for the neutron production.

It is straightforward to theoretically calculate the kinetic energy and yield of fast neutrons for a given set of input parameters; incident proton energy, target thickness, and angle based on the cross section tables for neutron production [5]. In the calculations, energy spread due to the energy loss of the proton beam in the LiF target was considered on the basis of stopping power calculated in SRIM [6]. For the $100\mu\text{g/cm}^2$ thickness, the energy spread due to the energy loss of protons in the LiF target is expected to be less than $13\text{keV}$.

2.2. Diagnostics for Mono-energetic Neutrons

The flux of mono-energetic neutrons is monitored with a long counter based on a 4 atm $^3\text{He}$ gas counter, which was experimentally validated in the standard neutron fields by G.D. Kim et. al. [4]. At present, a neutron counting efficiency curve obtained with MCNP [7] simulations is used to obtain neutron flux density on the surface of the long counter.

Meanwhile, the energy of mono-energetic neutrons was measured with Ce doped 1.5 inch Cs$_2^7\text{LiYCl}_6$ (C$^7\text{LYC}$) detectors manufactured by CapeSym. The C$^7\text{LYC}$ detectors are ideally suited for spectroscopy of neutrons having kinetic energies below $E_n = 3\text{MeV}$ [8]. For neutron-gamma separation in terms of pulse shape discrimination (PSD) [9], the outputs of the C$^7\text{LYC}$ detectors directly fed a waveform digitizer for subsequent digital signal processing, resulting the energy resolution of 5% for 1332keV gamma ray of $^{60}\text{Co}$. In the C$^7\text{LYC}$-based energy measurement system, incident fast neutrons are detected by the charge-exchange reaction, $^{35}\text{Cl}(n,p)^{35}\text{S}$, of which the reaction Q value is 615.02keV. In the energy range of neutrons of the present interest, a proton peak following the $^{35}\text{Cl}(n,p)$ reaction to the ground state of $^{35}\text{S}$ is dominantly found. One of the energy spectra obtained with the C$^7\text{LYC}$ detectors for $E_p = 2.3\text{MeV}$ is shown in Fig. 1(a). Physical analysis on the experimental data obtained with the C$^7\text{LYC}$ detectors is in progress, and details will be reported in elsewhere.

The operational neutron flux density and the energy resolution for a unit current of the proton beam on the target as a function of neutron energy at zero degrees are shown in Fig. 1(b).

3. Pulsed white neutron source for $E_n \leq 100\text{ MeV}$

3.1. Accelerator and Target

A white neutron source, that is capable of generating neutrons of up to 100MeV, based on a 100MeV proton accelerator is in operation for the studies related to terrestrial neutrons and for the researches on advanced fast and ultra-fast neutron sources.

The 100MeV proton accelerator consists of a 50-keV proton injector with microwave ion source, a four-vane type radio-frequency quadrupole (RFQ), and subsequently drift tube linac (DTL) [10]. For the generation of fast neutrons, a 1kW beam dump, which is a cone-shaped pure copper, installed at the end of the linear beam line is being utilized as a proton-neutron converter. The beam dump was designed to stop the 100MeV proton beam and it is completely sealed inside the chamber, therefore, only neutrons and photons are extracted out of the beam dump. The details of the beam dump is illustrated in Fig. 2. In the future, the beam dump would be replaced with a dedicated proton target system for enhanced neutron productions, and user facility for the secondary beam utilisation would be constructed at the reserved area.
Figure 1. (a) Energy distribution obtained with the CLYC detector at zero degrees and (b) (filled circles) neutron flux density (n·cm\(^{-2}\)·s\(^{-1}\)) and (red squares) the energy spread as a function of neutron energy. The neutron flux is normalized for a 1\(\mu\)A proton beam on the target, and the energy spread corresponds to the one standard deviation (1\(\sigma\)) of the energy distribution determined with the CLYC detectors. The lines in (b) are guide to the eye.

3.2. Monte Carlo Simulations
The characteristics of the neutron source were investigated based on simulations in the framework of Geant4 [11]. In the simulations, the details of the beam dump were implemented and the simplified model of the accelerator tunnel was described in 3-D geometries to estimate the flux density of neutrons in a wide energy range, 1meV \(\leq E_n \leq 100\)MeV. The Liège intra-nuclear cascade model [12] was used to simulate the generation and transportation of neutrons. The neutron production yield at the proton injection energy of 100MeV with the present proton-neutron converting system is estimated to be around 0.17 n/p.

In following texts, neutron flux density are normalized with respect to the injection of 100 MeV protons at the average current of 1\(\mu\)A, while the accessible proton beam current at the beam dump is up to 10\(\mu\)A on demand.

The simulated results for the differential neutron flux density (n·cm\(^{-2}\)·s\(^{-1}\)·MeV\(^{-1}\)) at 7 degrees is shown in Fig. 3(a) in comparison with the energy spectrum of terrestrial neutrons [13]. In the
Figure 2. The cross sectional view of the beam dump, which is currently used for a proton-neutron converter, installed at the end of the linear beam line.

According to the simulation results, the total flux density of neutrons in the whole energy range ($E_n \geq 1\text{meV}$) is found to be $8.13 \times 10^6 \text{n}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$, and the flux density of neutrons above 1 and 10 MeV respectively corresponds to $6.38 \times 10^6$ and $3.64 \times 10^6 \text{n}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$ for a 1 $\mu$A average current of the proton beam.

3.3. Experimental Results for Characterization

The differential flux of fast neutrons was indirectly measured for neutron energies above 6 MeV with a fast-neutron counting system based on a 10-mm thick plastic scintillation detector, feeding directly a fast waveform digitizer CAEN DT5751 model. The recorded waveform data was then processed by digital signal processing algorithm. The fast neutron counting system was able to count fast neutrons up to $10^7 \text{n}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}$ on the detector surface. The energy spectrum of fast neutrons was deduced by using unfolding techniques applied on the experimental detector response to the white neutrons (Fig. 4). It was found that the unfolded neutron flux was in the energy range between 6 to 80 MeV with the 20% systematic error. The unfolded energy spectrum (black circles with error bars in Fig. 4(b)) is found to agree well with the simulation results (red line in Fig. 4(b)) within the uncertainty.

In the future, advanced neutron counting system based on diamond detectors [14] will be introduced to the facility, and direct energy measurements in a wider energy range will be conducted based on the time-of-flight methods after the installation of a short-pulse ion source at the 100 MeV proton linac.

Meanwhile, the flux of slow neutrons were experimentally determined by employing the gold foil activation method. In the measurements, 100 $\mu$m-thick gold foils were placed, and the foils were irradiated with neutrons for 30 minutes, and the 411.8 keV $\gamma$ ray emitted in the $\beta$ decay of $^{198}\text{Au}$ was counted with a high-purity Ge detector for 24 hours.

Because the energy of neutrons extends down to meV range (Fig. 5), and the excitation
Figure 3. (a) The energy spectrum of the white neutrons at 7 degrees in comparison with the energy spectrum of neutrons induced by the cosmic rays [13]. The flux of the cosmic-ray induced neutrons is scaled up with the multiplication factor of $2 \times 10^9$. (b) Chi-square values for the energy distributions of cosmic-ray induced neutrons and fast neutrons at the beam dump as a function of polar angles. See text for details.

function for the radiative neutron capture of $^{197}$Au has large resonance peak at the resonance energy, $E_n = 4.9$ eV [15], it is expected that the measured neutron flux density based on the gold foil activation mostly corresponds to the neutron flux at around the resonance energy as shown in Fig.5. With the resonance integral $1467$ b of the cross section in $1 \leq E_n \leq 10$ eV, experimentally deduced neutron flux at the resonance energy is found to be $510 \pm 56$ n-cm$^{-2}$-s$^{-1}$, while the simulation predicts $598$ n-cm$^{-2}$-s$^{-1}$ at the same position.

4. CONCLUSION

Until now, the specifications and characteristics of the neutron sources based on proton accelerators at KOMAC of KAERI are presented. Some neutron properties are identified with experimental data, however, still many of them are waiting to be validated in the near future. With well-defined characteristics, it is hoped that the neutrons sources can be used in various
Figure 4. (a) Detector response to the fast neutrons recorded by a 10-mm thick plastic scintillation detector installed at the monitoring position, and (b) (black points) unfolded energy spectrum of fast neutrons with (red line) the energy spectrum obtained in the simulations. The uncertainty in the differential flux is evaluated to be 20%. See text for details fields of science and engineering.

Acknowledgments
This work has been supported through KOMAC operation fund of KAERI and the NRF of Korea Grant funded by the Korea government (MSIT) (No. NRF-2018M2A2A6A02071070 and NRF-2018M2A2B3A02072238).
Figure 5. The relative yield of $^{198}$Au, which is the neutron flux multiplied by the cross section of the radiative neutron capture $^{197}$Au(n,$\gamma$)$^{198}$Au, as a function of neutron energy. The inset shows the differential neutron flux (n·cm$^{-2}$·s$^{-1}$·eV$^{-1}$) in the same energy range.

References
[1] S. Cierjacks, “Accelerator-based Pulsed White Neutron Sources”, in Neutron Sources for Basic Physics and Applications, Great Britain, UK: Pergamon Press, 1983, pp. 81–132.
[2] G.F. Knoll, “Radioisotope Neutron Sources”, in Neutron Sources for Basic Physics and Applications, Great Britain, UK: Pergamon Press, 1983, pp. 7–18.
[3] Y.-S. Cho, J. Korean Phys. Soc. 66, 501 (2015).
[4] G.D. Kim, H.J. Woo, H.W. Choi, J.W. Park, T.A. Trinh, and J. Korean. Phys. Soc. 61, 529-535 (2012).
[5] H. Liskien and A. Paulsen, At. Data and Nucl. Data Tables, 11, 569 (1973).
[6] J.F. Ziegler, M.D. Ziegler, and J.P. Biersack, Nucl. Instrum. Meth. B 268, 1818-1823 (2010).
[7] C.J. Werner, et al., ”MCNP6.2 Release Notes“, Los Alamos National Laboratory, report LA-UR-18-20808 (2018).
[8] N. D’Olympia et al., Nucl. Instrum. Meth. A 763 433-441 (2014).
[9] A. Giaz, et al., Nucl. Instrum. Meth. A 810 132-139 (2016).
[10] Han-Sung Kim, J. Korean Phys. Soc. 71, 807-813 (2017).
[11] S. Agostinelli et al., Nucl. Instrum. Meth. A 506, 250-303 (2003).
[12] D. Mancusi, et. al., Phys. Rev. C 90, 054602 (2014).
[13] M.S. Gordon, et. al., IEEE. Trans. Nucl. Sci. 51, 3427-3434 (2004).
[14] C. Weise, H. Frais-Kölbl, E. Griesmayer, and P. Kavringin, Eur. Phys. J. A 52, 269 (2016).
[15] M.B Chadwick, et. al., Nuclear Data Sheets 107, 2931-3060 (2006).