Experimental analysis of neutron and background gamma-ray energy spectra of 80-400 MeV ^{7}Li(p,n) reactions under the quasi-monoenergetic neutron field at RCNP, Osaka University

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Abstract. To develop the 100-400 MeV quasi-monoenergetic neutron field, we measured neutron and unexpected gamma-ray energy spectra of the ^{7}Li(p,n) reaction with 80-389 MeV protons in the 100-m time-of-flight (TOF) tunnel at the Research Center for Nuclear Physics (RCNP) cyclotron facility. Neutron energy spectra with energies above 3 MeV were measured by the TOF method, which had been reported in our previous papers, and photon energy spectra with energies above 0.1 MeV were measured by the automatic unfolding function of the radiation dose monitor DARWIN. For neutron spectra, the contribution of peak intensity to the total intensity integrated with energies above 3 MeV varied between 0.38 and 0.48 in the proton energy range of 80–389 MeV. For gamma-ray spectra, high-energetic gamma-rays at around 70 MeV originated from the decay of π^0 were observed with proton energies higher than 200 MeV. For the 246-MeV proton incident reaction, the contribution of gamma-ray dose to neutron dose is negligible because the ratio of gamma-ray dose to neutron dose is 0.014.

1 Introduction

The expected neutron fluence spectra in such as high-energy particle accelerators and flight altitudes environments typically have a peak at approximately 100 MeV, with maximum energies reaching the GeV range. For development of high-energy neutron monitors employed in these environments, it is important to calibrate instruments in well-defined high-energy mono-energetic neutron fields during response validation.

In high-energy regions above 100 MeV, quasi-monoenergetic neutron fields [1] generated using ^{7}Li(p,n)^{7}Be (g.s. + 0.429 MeV) have been developed at 0° and 16° by iThemba [2] in energy regions of up to 200 MeV. Furthermore, the Research Center for Nuclear Physics (RCNP) cyclotron facility at Osaka University has been used to generate neutron fields in energy regions of up to 400 MeV, and neutron beams are available in the angular range of 0°–25° in the 100-m time-of-flight (TOF) tunnel. Our previous study has investigated the characterization of neutron energy spectra for 80-, 100-, 137-, 200-, 246-, 300- and 389-MeV protons in RCNP's neutron field [3,4]. The RCNP's neutron field has been widely used for various studies such as development of radiation monitors [5,6], neutron shielding experiments [7] and measurement of neutron induced activation cross sections [8]. It has been reported in the International Atomic Energy Agency (IAEA) [9] and the European Radiation Dosimetry group (EURADOS) publications [10] as a well-characterized high-energy monoenergetic neutron field.

In the high-energy neutron field, it is also important to assess the contribution of high-energetic gamma-rays generated from π^0 decay. To create a π^0 with rest energy 135 MeV, it is necessary to give the incoming proton at least 290 MeV of kinetic energy for a fixed nucleon in a target. One should note that Fermi motion of nucleons allows for π^0 production even at energies below 290 MeV [11]. Thus, it is important for calibration of radiation monitors to characterize not only neutron spectra but also high-energy gamma-ray spectra in the high-energy neutron field.

In this paper, we reported measurements of gamma-ray energy spectra and doses in the RCNP quasi-monoenergetic neutron field. Measurements of neutron energy spectra was also reported to compare neutron data with gamma-ray spectra and doses.

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2 Experiments

The experiments were carried out in the 100-m TOF tunnel of the RCNP ring cyclotron. A schematic view of the experimental arrangement is shown in **Fig. 1**. This section briefly describes the experiments. Details for neutron measurements were in our previous paper [4].

Proton beams extracted from the ring cyclotron at 80-, 100-, 137-, 200-, 246-, 300- and 389-MeV were made to strike a 1.0-cm-thick lithium target (^{7}Li 99.88%) placed in a swinger located in a vacuum chamber. Neutron energies were measured by a TOF method.

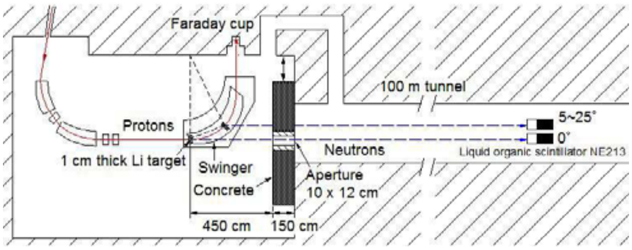

Figure 1. Illustration of experimental setup in the 100-m tunnel at RCNP cyclotron facility [4].

For neutron measurements at 0°, the target was set at the entrance of the swinger. Measurements at angles between 5° and 25° (0°, 5°, 10°, 15°, 20°, 25°) were made by moving the target downward along the curve trajectory of the proton beam in the swinger. To measure proton beam intensity, we used a swinger magnet to drive protons into a Faraday cup after they passed through the target. Neutrons produced at the target entered the 100-m tunnel through a 5-mm-thick acrylic window at the exit side of the swinger and a 10 cm × 12 cm aperture in a 150-cm-thick movable iron collimator embedded in a concrete wall located 4.5 m from the target. A clearing magnet equipped in the movable collimator served to remove charged particles from the neutron beam. The movable collimator and the swinger magnet allowed neutron emissions to be measured at angles between 0° and 25°.

The neutron TOF measurements with energies above 3 MeV were made at angles between 0° and 25° using NE213 organic liquid scintillators of two sizes (12.7 cm × 12.7 cm and 5.08 cm× 5.08 cm (in diameter × length)) with different flight path lengths between the target and detector surfaces. The neutron-detection efficiency of NE213 was calculated using the SCINFUL-QMD code [12, 13]. Finally, the energy spectra were determined on the basis of the detection efficiency, detector solid angle, and proton beam current.

Gamma-ray energy spectra with energies above 0.1 MeV were measured at 0° for 100-, 246-, 300- and 389-MeV by the automatic unfolding function of the radiation dose monitor DARWIN composed of a phoswitch-type scintillation detector, which consists of liquid organic scintillator BC501A coupled with ZnS(Ag) scintillation sheets [14].

3 Results

Figure 2 compares the measured neutron energy spectra at the RCNP quasi monoenergetic neutron filed [3]. Peak neutrons covered the range from transitions to the ground state and the first excited state of ^{7}Be to transitions to the ground state of ^{6}Be. The peak neutron energy is lower than the proton energy because of energy loss in the lithium target, and it is lower than the 1.88 MeV threshold energy of the ^{7}Li(p,n) reaction. The neutron peak intensity is 0.9–1.1 × 10^{10} neutrons/sr/μC. The contribution of peak intensity to the total intensity integrated with energies above 3 MeV varied between 0.38 and 0.48 in the incident proton energy range of 80–389 MeV.

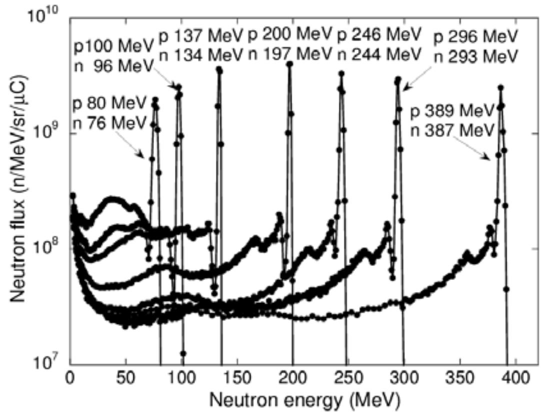

Figure 2. Neutron energy spectra at 0° for 80-, 100-, 137-, 200-, 246-, 296-, and 389-MeV Li(p,xn) reactions and 1-cm-thick lithium target [4].

Figure 3 shows gamma-ray and neutron energy spectra at 0° for 246-MeV ^{7}Li(p,xn) reactions. The unfolding function of DARWIN is useful for investigating gamma-ray and neutron spectra during the dose measurement, though it cannot clearly reproduce quasi-mono-energetic neutron peak as shown in **Fig. 3**. For gamma-ray spectra, low energy photons with energies below 20 MeV can be attributed to de-excitation of ^{7}Be, whereas high-energetic gamma-rays at around 70 MeV originate from the decay of π^0, which are created according to non-elastic nucleon-nucleon interactions [4]. The ratio of gamma-ray flux above 20 MeV to total gamma-ray flux is 0.31. At neutron and gamma-ray energies around 70 MeV, the gamma-ray flux is almost same with neutron flux. On the other hands, the contribution of gamma ray ambient dose to neutron dose is negligible because the ratio of gamma-ray dose to neutron dose is 0.014. High-energetic gamma-rays were also observed for 300- and 389-MeV protons, though it was not observed for 100-MeV proton incidence.

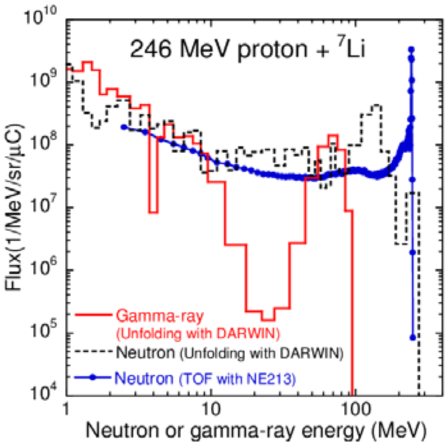

Figure 3. Neutron and gamma-ray energy spectra at 0° for 246-MeV ^{7}Li(p,xn) reactions. Solid line is gamma-ray spectrum and dashed line is neutron spectrum measured by the unfolding method with DARWIN, and full circle shows neutron TOF spectrum measured with an NE 213 liquid organic scintillator.

4 Summary

We measured neutron and gamma-ray energy spectra of the ^{7}Li(p,n) reaction with 80-389 MeV protons in the 100-m TOF tunnel at RCNP cyclotron facility. Neutron energy spectra with energies above 3 MeV were measured by the TOF method and gamma-ray energy spectra with energies above 0.1 MeV were measured by the automatic unfolding function of DARWIN. For neutron spectra, the contribution of peak intensity to the total intensity integrated with energies above 3 MeV varied between 0.38 and 0.48 in the proton energy range of 80–389 MeV. For gamma-ray spectra, high-energetic gamma-rays at around 70 MeV originate from the decay of π^0 were observed with proton energies higher than 200 MeV. For the 246-MeV proton incident reaction, the ratio of gamma-ray flux above 20 MeV to total gamma-ray flux is 0.31 and the gamma-ray flux is almost same with neutron flux at neutron and gamma-ray energies around 70 MeV. On the other hands, the contribution of gamma ray ambient dose to neutron dose is negligible because the ratio of gamma-ray dose to neutron dose is 0.014. The experimental data will be useful to consider the contribution of high-energetic gamma-rays on the response measurement of the neutron monitor in the RCNP quasi-monoenergetic neutron field.

In future work, we will analyze the experimental gamma-ray data of NE213 liquid organic scintillators with the unfolding method to deduce the spectra for all proton energies and various angles.

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References

1. H. Harano, R. Nolte, Metrologia **48**, S202 (2011).
2. M. Mosconi, E. Musonza, A. Buffler, R. Nolte, S. Röttger, F.D. Smit, Radiation Measurements **45**, 1342 (2010).
3. Y. Iwamoto, M. Hagiwara, T. Matsumoto, et al., Nucl. Inst. Method. in Phys. Res. A **690**, 10 (2012).
4. Y. Iwamoto, M. Hagiwara, D. Satoh, S. Araki, H. Yashima, T. Sato, A. Masuda, T. Matsumoto, N. Nakao, T. Shima, T. Kin, Y. Watanabe, H. Iwase, T. Nakamura, Nucl. Inst. Method. in Phys. Res. A **804**, 50 (2015).
5. V. Mares, C. Pioch, W. Rühm, H. Iwase, Y. Iwamoto et al., IEEE Trans. Nucl. Sci., **60**, 299 (2013).
6. A. Masuda, T. Matsumoto, H. Harano, J. Nishiyama, Y. Iwamoto et al., IEEE Trans. Nucl. Sci., **59**, 161 (2012).
7. M. Hagiwara, H. Iwase, Y. Iwamoto, D. Satoh, T. Matsumoto, Prog. Nucl. Sci. Technol., **4**, 327 (2014).
8. H. Yashima, S. Sekimoto, K. Ninomiya, Y. Kasamatsu, Radiat. Prot. Dosim., **161**, 139 (2014).
9. Y. Iwamoto, H. Yashima, D. Datoh, M. Hagiwara, H. Iwase et al., IAEA-TECDOC-1743 (CD-ROM), 177 (2014).
10. S. Pomp, D.T. Bartlett, S. Mayer et al., EURADOS Repost 2013-02 (2013).
11. A. Ferrari, P.R. Sala, “The physics of high energy reactions,” Proceedings of Workshop on nuclear reaction data and nuclear reactors physics, design and safety, Trieste, (1996).
12. D. Satoh, T. Sato, A. Endo, Y. Yamaguchi, M. Takada, K. Ishibashi, J. Nucl. Sci. Technol. **43**, 714 (2006).
13. D. Satoh, T. Sato, N. Shigyo, K. Ishibashi, “SCINFUL-QMD: Monte Carlo based computer code to calculate response function and detection efficiency of a liquid organic scintillator for neutron energies up to 3 GeV,” JAEA-Data/Code, 2006-023.
14. T. Sato, D. Satoh, A. Endo, Y. Yamaguchi, J. Nucl. Sci. Technol. **42**, 768 (2005).