Characterization of high-energy quasi-monoenergetic neutron energy spectra and ambient dose equivalents of 80–389 MeV $^7$Li(p,n) reactions using a time-of-flight method

Yosuke Iwamoto a,*, Masayuki Hagiwara b, i, Daiki Satoh a, Shouhei Araki c, Hiroshi Yashima d, Tatsuhiko Sato a, Akihiko Masuda e, Tetsuro Matsumoto e, Noriaki Nakao f, Tatsushi Shima g, Tadahiro Kin c, Yukinobu Watanabe c, Hiroshi Iwase b, i, Takashi Nakamura f, h

a Japan Atomic Energy Agency (JAEA), 2-4 Shirakata, Tokai, Naka, Ibaraki 319-1195, Japan
b High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan
c Cyclotron and Radioisotope Center, Tohoku University, 6-1 Aramaki, Aoba, Sendai 980-8578, Japan
d Research Center for Nuclear Physics (RCNP) cyclotron facility at Osaka University [6–8], Osaka, Osaka 567-0047, Japan
e Shimizu Corporation, Etchujima 3-4-17, Koto-ku, Tokyo 135-8530, Japan
f Research Reactor Institute, Kyoto University, 2-1010 Asashiro-nishi, Kamatori, Sennan, Osaka 590-0494, Japan
g High Energy Accelerator Research Organization (KEK), 1-1 Oho, Tsukuba, Ibaraki 305-08568, Japan
h Department of Accelerator Science, Graduate University for Advanced Studies (SOKENDAI), 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan

A R T I C L E   I N F O

Article history:
Received 6 July 2015
Accepted 3 September 2015
Available online 26 September 2015

Keywords:
Quasi-monoenergetic neutron field
$^7$Li(p,n) reaction
Time of flight
Subtraction method
Ambient dose equivalent

A B S T R A C T

We completed a series of measurements on mono-energetic neutron 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 cyclotron facility. For that purpose, we measured neutron energy spectra of the 80-, 100- and 296-MeV proton incident reactions, which had not been investigated in our previous studies. The neutron peak intensity was $0.9–1.1 \times 10^{10}$ neutrons/sr/μC in the incident proton energy region of 80–389 MeV, and it was almost independent of the incident proton energy. The contribution of peak intensity of the spectrum 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, and it was almost independent of the incident proton energy. The contribution of peak intensity of the spectrum 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. To consider the correction required to derive a response in the peak region from the measured total responses of neutron monitors in the 100-m TOF tunnel, we proposed the subtraction method using energy spectra between 0° and 25°. The normalizing factor $k$ against 25° neutron fluence to equalize it to 0° neutron fluence in the continuum region ranges from 0.74 to 1.02 depending on the incident proton energy and angle measured. Even without the TOF method, the subtraction method with the $k$ factor almost decreases the response in the continuum region of a neutron spectrum against the total response of neutron monitors.

A B S T R A C T

1. Introduction

Research on high-energy neutrons with energies above 20 MeV is important because such neutrons consider approximately half of the ambient dose-equivalent at typical flight altitudes and outside the shield of high-energy particle accelerators. The expected neutron fluence spectra in such 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 monoenergetic neutron fields during response validation.

In high-energy regions of up to 200 MeV, quasi-monoenergetic neutron fields [1] generated using $^7$Li(p,n)$^7$Be (g.s.+0.429 MeV) have been developed by TRIUMF [2], iThemba [3], RIKEN [4], and TIARA [5]. Furthermore, the Research Center for Nuclear Physics (RCNP) cyclotron facility at Osaka University [6–8] 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 studies have investigated the characterization of neutron energy spectra for...
The 246- and 389-MeV $^7\text{Li}(p,n)^7\text{Be}$ reaction, subtracting the neutron energy range of 80

particularly important because the neutron facility. The 80- and 100-MeV proton incident reactions were spectra in the 100-m TOF tunnel within the RCNP cyclotron systematic measurements of monoenergetic neutron energy and 389-MeV data. These neutron energy spectra were compared neutron energy spectra at an intermediate level between the 246- and 389-MeV data. These neutron energy spectra were compared with other experimental data and results calculated using PHITS [13] and MCNPX [14] codes.

We also discuss the systematics of neutron energy spectra at 0° for proton energies of 80–389 MeV. The ambient dose equivalent $H'(10)$ at 0° obtained using the TOF method was compared with that obtained by direct measurement [15] using high-energy neutron monitors, DARWIN [16,17] and WENDI-II [18]. Finally, we propose the correction required to derive the peak region response from the measured total response for high-energy neutron monitors using 0° and 25° data obtained from the 100-m TOF tunnel in the RCNP ring cyclotron.

2. Measurement and data analysis

2.1. Neutron energy spectra

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 conducted at 80, 100, and 296 MeV. The experimental setup and electronic circuitry were almost the same as those for previous measurements at 137, 200, 246, and 389 MeV in [10,11].

Proton beams extracted from the ring cyclotron at 80, 100, and 296 MeV were transported to the neutron experimental hall and made to strike a 1.0-cm-thick lithium target ($^7\text{Li}$ 99.88%) placed in a swinger located in a vacuum chamber. The available beam current in the facility ranged from several nanoamperes to 1 μA. For TOF measurement, the beam current was kept at 5–60 nA. The time width of the proton beam bunch was 1 ns. The time intervals between successive proton beam pulses were 53.6 ns (18.64 MHz) for 80 MeV, 98.8 ns (10.12 MHz) for 100 MeV, and 64.9 ns (15.42 MHz) for 296 MeV. To avoid contamination with neutrons of lower energy when using the TOF method, the time interval between beam pulses was increased to 375 ns for 80 MeV, 494 ns for 100 MeV, and 648 ns for 300 MeV using a beam chopper.

For neutron measurements at 0°, the target was set at the entrance of the swinger. Measurements at angles between 5° and 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. Furthermore,

![Image](image1.png)

**Table 1**
Summary of detector settings in measurement of neutron energy for 80-, 100-, and 296-MeV proton incidences.

<table>
<thead>
<tr>
<th>Neutron energy range</th>
<th>3 MeV &lt; $E_n$ &lt; 20 MeV</th>
<th>20 MeV &lt; $E_n$ &lt; 100 MeV</th>
<th>100 MeV &lt; $E_n$ &lt; 296 MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector diameter and thickness</td>
<td>5.08 cm</td>
<td>12.7 cm</td>
<td>12.7 cm</td>
</tr>
<tr>
<td>Flight path length at 0°</td>
<td>7.2 m</td>
<td>17.8 m</td>
<td>59 m</td>
</tr>
</tbody>
</table>

![Image](image2.png)

**Fig. 1.** Illustration of experimental setup in neutron experimental hall and 100-m tunnel [10,11].

137-, 200-, 246-, and 389-MeV protons in RCNP’s neutron field [9–11]. The quasi-monoenergetic neutron spectrum has not only peak neutrons but also a low-energy tail associated with breakup and spallation reactions. According to Nolte et al. [12], subtracting the spectrum obtained at 16° from that at 0° yields a true monoenergetic spectrum at the cyclotron facility in iThemba because the spectrum of the continuum component is almost the same at 0° and 16°. For calibrating neutron monitors at RCNP, it is necessary to consider the subtraction method for the incident proton energy range of 80–389 MeV. Previous studies have found that for the 246- and 389-MeV $^7\text{Li}(p,n)^7\text{Be}$ reaction, subtracting the neutron spectra at 20–25° from the 0° data efficiently eliminates the continuum component.

In the present study, we measured the neutron energy spectra for the 80-, 100-, and 296-MeV $^7\text{Li}(p,n)^7\text{Be}$ reactions as part of systematic measurements of monoenergetic neutron energy spectra in the 100-m TOF tunnel within the RCNP cyclotron facility. The 80- and 100-MeV proton incident reactions were particularly important because the neutron fluence spectra behind shielding and those of cosmic rays generally peak at approximately 100 MeV. The 296-MeV data add to experimental information on neutron energy spectra behind 296 MeV were transported to the neutron experimental hall and made to strike a 1.0-cm-thick lithium target ($^7\text{Li}$ 99.88%) placed in a swinger located in a vacuum chamber. The available beam current in the facility ranged from several nanoamperes to 1 μA. For TOF measurement, the beam current was kept at 5–60 nA. The time width of the proton beam bunch was 1 ns. The time intervals between successive proton beam pulses were 53.6 ns (18.64 MHz) for 80 MeV, 98.8 ns (10.12 MHz) for 100 MeV, and 64.9 ns (15.42 MHz) for 296 MeV. To avoid contamination with neutrons of lower energy when using the TOF method, the time interval between beam pulses was increased to 375 ns for 80 MeV, 494 ns for 100 MeV, and 648 ns for 300 MeV using a beam chopper.

For neutron measurements at 0°, the target was set at the entrance of the swinger. Measurements at angles between 5° and 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. Furthermore,
proton beam intensity was monitored using plastic scintillators by counting the protons scattered by a 100-μm-thick plastic film set in front of the lithium target. The uncertainty of the beam current measurement was estimated to be 1% from the result of target-in and target-out measurements. 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 150-cm-thick 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 were made at various angles (0°, 5°, 10°, 15°, 20°, 25° for 100 and 296 MeV and 0°, 15°, 25° for 80 MeV) 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. Table 1 summarizes detector settings such as beam size, detector efficiency, and proton beam current.

Data were recorded using a conventional computer-automated measurement and control (CAMAC) system in the event-by-event mode. The neutron-detection efficiency of NE213 was calculated using the SCINFUL-QMD code [17,19]. Finally, the energy spectra were determined on the basis of the detection efficiency, detector solid angle, and proton beam current.

To investigate the effect of the neutrons scattered in the 5-mm-acrylic window, the collimators on the wall and the floor, and the neutron energy spectra at the detector position were calculated using PHITS in our previous study [10]. The results indicate that the number of background neutrons above 3 MeV in the detector is less than 1% of the number of foreground neutrons. Uncertainties in TOF measurements were due to statistical and systematic errors. The statistical uncertainties were less than 1% for peak neutrons and less than 3% for the continuum. The total systematic error arose mainly from neutron detection efficiency, which we estimated to be 10% for neutron energies less than 80 MeV and 15% for those greater than 80 MeV [17,19]. The energy resolution defined as a standard deviation [20] was 1.9 MeV for 80-MeV neutrons and 1.3 MeV for 96-MeV neutrons at 18 m, and 1.3 MeV for 296-MeV neutrons at 59 m.

2.2. Ambient dose equivalent H*(10)

TOF neutron energy spectra were folded with the ambient dose equivalent H*(10) using the fluence-to-H*(10) conversion coefficient for the purpose of comparison with the H*(10) values obtained by high-energy neutron monitors. The numerical values of the conversion coefficient were taken from EXPACS [21].

3. Results and discussions

3.1. Neutron energy spectra at 0°

Fig. 2 compares the measured neutron energy spectra at 0° for 80-, 100-, and 296-MeV protons incident on a 1 cm 7Li target with previous data for 137-, 200-, 246-, and 389-MeV neutrons [10,11]. Peak neutrons covered the range from transitions to the ground state and the first excited state of 7Be to transitions to the ground state of 7Be. The small peaks observed at 10 and 30 MeV below the peak arose from the transition to the highly excited state of 7Be. The continuum arose mainly from the three-body breakup process of 7Li (p,n3He) [22], while the low-energy part with $E_n < 20$ MeV could be ascribed to evaporation processes. Most of the continuum of data came directly from the nuclear reaction because there are less than 1.5% room-scattered neutrons with $E_n > 3$ MeV relative to the number of reaction neutrons [11]. Table 2 summarizes the characterizations of neutron energy spectra at 0° for 80-, 100-, 137-, 200-, 246-, and 389-MeV neutrons. 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 7Li(n,p) reaction. The neutron peak intensity is 0.9–1.1 × 1010 neutrons/sr/μC. The contribution of peak intensity, $\Phi_{peak}$ to the total intensity integrated with energies above 3 MeV, $\Phi_{total}$ varied between 0.38 and 0.48 in the incident proton energy range of 80–389 MeV.

Fig. 3 shows the peak cross-sections at 0° for the 7Li(p,n) reaction in the LAB system using data from our previous study [10,11], Watson [23] and Taddeucci [24]. The peak cross-sections at 0° for the 7Li(p,n) reaction in this study, our previous study [10,11], Watson et al. [23], and Taddeucci et al. [24].

Table 2

<table>
<thead>
<tr>
<th>Proton energy (MeV)</th>
<th>80</th>
<th>100</th>
<th>137</th>
<th>200</th>
<th>246</th>
<th>296</th>
<th>389</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak neutron energy (MeV)</td>
<td>76</td>
<td>96</td>
<td>134</td>
<td>197</td>
<td>244</td>
<td>293</td>
<td>387</td>
</tr>
<tr>
<td>Peak neutron fluence $10^{10}$ (n/sr/μC)</td>
<td>$0.92 \pm 0.18$</td>
<td>$0.87 \pm 0.17$</td>
<td>$0.98 \pm 0.20$</td>
<td>$1.07 \pm 0.17$</td>
<td>$1.01 \pm 0.17$</td>
<td>$1.00 \pm 0.20$</td>
<td>$0.96 \pm 0.15$</td>
</tr>
<tr>
<td>$\Phi_{peak}/\Phi_{total}$ ($E_n &gt; 3$ MeV)</td>
<td>0.38</td>
<td>0.41</td>
<td>0.39</td>
<td>0.43</td>
<td>0.48</td>
<td>0.44</td>
<td>0.39</td>
</tr>
</tbody>
</table>

Fig. 3. Peak cross-sections at 0° for 7Li(p,n) reaction in LAB system in this study, our previous study [10,11], Watson et al. [23], and Taddeucci et al. [24].
30–33 mb, and experimental data recorded in RCNP agreed with other data within an error bar.

3.2. Comparison of experimental and calculated results for 80, 100, and 296 MeV

Figs. 4–6 show the neutron energy spectra for 80, 100, and 296 MeV $^7\text{Li}(p,xn)$ reactions at 0°, 15°, and 25°. The RIKEN data for 100-MeV protons at 0° agree well at energies above 30 MeV. All experimental spectra in the energy region below 50 MeV were comparable, and in the case of the 296-MeV proton incidence, the shape of the continuum in the quasi-free elastic scattering region above 100 MeV considerably changed with the angle. The experimental data were compared with the PHITS and MCNPX calculations made using theoretical models, in particular, INCL+DWBA/GEM [25–27] and JQMD/GEM [28] in PHITS, and ISABEL/ABLA [29,30] code in MCNPX. INCL+DWBA is a theoretical model that combines Intra-Nuclear Cascade of Liege (INCL) model and distorted-wave Born approximation (DWBA) to describe neutron spectra of proton- and deuteron-induced reactions for lithium and beryllium targets [25]. The INCL+DWBA model also considers the angular distribution of the peak neutron yield based on quantum mechanical effects. The Japan Atomic Energy Research Institute (JAERI) quantum molecular dynamics model (JQMD) describes the dynamic phase of nucleus–nucleus interactions [28]. The ISABEL model is an intranuclear cascade (INC) model based on the Monte Carlo method for hadron–nucleus and nucleus–nucleus interactions in the energy range of 100 MeV–1.5 GeV [29]. After the INC is stopped, an evaporation model is generally appended to consider the full nuclear reaction process. The generalized evaporation model (GEM) is based on the classical Weisskopf–Ewing approach [26]. The ABLA in MCNPX is a statistical model that describes de-excitation of compound nuclei through the evaporation of light particles and fission [30].

In general, the JQMD and ISABEL models cannot reproduce the neutron spectra well for the $^7\text{Li}(p,n)^7\text{Be}$ reaction because of lack of transitions to discrete states of $^7\text{Be}$ and difficulty in spallation reaction for lighter nuclei. INCL+DWBA can reproduce the peak neutron at forward angles below 15° and for all incident energies because the peak is the summation of neutrons produced by discrete levels of $^7\text{Be}$ and adjusted to reproduce an experimental peak neutron yield at 0°. However, INCL+DWBA cannot reproduce the neutron energy spectra for regions other than the peak region. Therefore, the evaluated nuclear data for the protons incident on lithium based on the experimental data are needed for applications using monoenergetic neutron fields.

Fig. 7 shows a comparison of measured peak cross-sections for an emitted angle in the LAB system with the results calculated using the Taddeucci formula [24], which was deduced by fitting with other experimental data. The measured peak cross-sections
Fig. 5. Neutron energy spectra at 0°, 5°, 10°, 15°, 20°, and 25° for 100-MeV $^7$Li(p,n) reaction. The circle at 0° indicates the experimental data recorded at RIKEN [4]. The solid red line shows the results calculated by PHITS with the INCL4+DWBA/GEM model, dashed line shows those calculated with the JQMD/GEM model, and the solid blue line shows the results calculated by MCNPX with ISABEL/ABLA. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 3
Characteristic properties of normalization factor $k$ in Eq. (1) and $H^*(10)$-normalized peak neutron fluence in Eq. (2) against incident proton energies and subtracted angle. Fluence-to-$H^*(10)$ conversion coefficient at peak neutron energy was taken from EXPACS [21].

<table>
<thead>
<tr>
<th>Proton energy/Peak neutron energy (MeV)</th>
<th>80/76</th>
<th>100/96</th>
<th>137/134</th>
<th>200/197</th>
<th>246/244</th>
<th>296/293</th>
<th>389/387</th>
</tr>
</thead>
<tbody>
<tr>
<td>Subtracted angle (degree)</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>20</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td>$k$ in Eq. (1)</td>
<td>1.02</td>
<td>0.86</td>
<td>0.74</td>
<td>0.79</td>
<td>0.89</td>
<td>0.92</td>
<td>0.90</td>
</tr>
<tr>
<td>$H^*(10)$ normalized peak neutron fluence obtained by Eq. (2) (pSv cm$^2$)</td>
<td>331</td>
<td>286</td>
<td>273</td>
<td>269</td>
<td>299</td>
<td>299</td>
<td>315</td>
</tr>
<tr>
<td>Fluence to $H^*(10)$ conversion coefficient taken from EXPACS [21] (pSv cm$^2$)</td>
<td>323</td>
<td>289</td>
<td>253</td>
<td>260</td>
<td>281</td>
<td>304</td>
<td>329</td>
</tr>
</tbody>
</table>
agreed well with the results of the Taddeucci formula at angles below 15° and were slightly higher than the calculated results at angles above 15°.

3.3. Ambient dose equivalents obtained using TOF method

Fig. 8 compares the $H^*(10)$ deduced from the TOF spectra at 0°, 5°, 10°, 15°, 20°, and 25° for 296-MeV $^7\text{Li}(p,n)$ reaction. The solid red line shows the results calculated by PHITS with the INCL4 + DWBA/GEM model, dashed line shows those calculated with the JQMD/GEM model, and solid blue line shows the results calculated by MCNPX with ISABEL/ABLA. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Fig. 6. Neutron energy spectra at 0°, 5°, 10°, 15°, 20°, and 25° for 296-MeV $^7\text{Li}(p,n)$ reaction. The solid red line shows the results calculated by PHITS with the INCL4 + DWBA/GEM model, dashed line shows those calculated with the JQMD/GEM model, and solid blue line shows the results calculated by MCNPX with ISABEL/ABLA. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The unit of $H^*(10)$ is normalized by the beam current. DARWIN is a phoswitch-type scintillation detector comprising liquid organic scintillator BC501A coupled with ZnS(Ag) scintillation sheets doped with Li-6 [16]. WENDI-II is a neutron REM meter with a tungsten carbide powder added to a polyethylene moderator to generate spallation neutrons in tungsten nuclei. A counter tube is located in the center of the cylindrical polyethylene moderator assembly [18]. Both monitors were set at a distance of 41 m from the lithium target [15].
The TOF doses are independent of proton energies with energy ranges above 100 MeV. While the DARWIN dose is up to 40% higher than the TOF dose at 389 MeV protons, the WENDI-II dose is up to 32% lower than the TOF dose at 246 MeV. The observed discrepancies may reflect uncertainties in the estimation of detector responses in the high-energy region and differences in the measured energy range. The contribution from neutrons below 3 MeV is approximately 10% of the total neutron dose [15].

Fig. 9 shows the angular distributions of $H'(10)$ obtained overall and in the tail and peak at a distance of 41 m from the target. The integrated energy range of the peak neutron is 93–100 MeV for the 100-MeV proton, and 290–296 MeV for the 296-MeV proton. The total component is integrated with energies above 3 MeV, and the tail component is obtained by integrating the neutron spectrum with the energies in the tail part. The peak part decreases with angle, and the total comprises mostly the tail component at 20° or 25° in the case of all proton energies.

3.4. Subtraction method

To obtain the response function of neutron detectors for monoenergetic neutrons, we considered the subtraction method [12] using the measured neutron energy spectra above 3 MeV and the following equations:

$$\phi_{\text{corr}}(E) = \phi_{0^\circ}(E) - k \cdot \phi_{25^\circ}(E)$$  \hspace{1cm} (1)

$$H_{\text{corr}} = \int_{3 \text{ MeV}}^{E_{\text{max}}} P(E)\phi_{\text{corr}}(E)dE$$  \hspace{1cm} (2)

where $\phi_{\text{corr}}$ is the corrected neutron energy spectrum for monoenergetic energy, $\phi_{0^\circ}$ and $\phi_{25^\circ}$ are neutron energy spectra at 0° and 25°, respectively, $k$ is a normalization factor that equalizes neutron fluence in the continuum region, $H_{\text{corr}}$ is the $H'(10)$ using the corrected neutron energy spectrum, and $P(E)$ is the fluence-to-$H'(10)$ conversion coefficient [21]. The upper panels of Fig. 10 show neutron energy spectra at 0° and 25° ($\phi_{0^\circ}$ and $\phi_{25^\circ}$), and the spectrum at 25° normalized to the neutron fluence in the continuum region ($k\phi_{25^\circ}$) with $E_n < 93$ MeV for 100-MeV proton incidence and $E_n < 290$ MeV for 296-MeV proton incidence. The lower panels of Fig. 10 show the corrected spectrum obtained by subtracting the normalized 25° spectrum from the 0° spectrum ($\phi_{\text{corr}}$).

Table 3 lists the characteristic properties of the normalization factor $k$ in Eq. (1) and $H'(10)$-normalized peak neutron fluence obtained by Eq. (2), and the fluence-to-$H'(10)$ conversion coefficient at peak neutron energy taken from EXPACS [21] against the incident proton energies and subtracted angle. Note that the data corresponding to 20° were used for the 246- and 389-MeV protons because experimental measurements at 25° were not conducted for these energies. The value of $k$ ranges from 0.74 to 1.02 depending on the incident proton energy and the measured angle. Given that the $H'(10)$-normalized peak neutron fluence obtained by Eq. (2) is in good agreement with the fluence-to-$H'(10)$ conversion coefficient, the $k$ factors work well for obtaining $H'(10)$ for monoenergetic neutron energy using the subtraction method. Based on the relationship between Eqs. (1) and (2), $H'(10)$ for the monoenergetic neutron can also be written as follows:

$$H_{\text{corr}} = H_0 - k \cdot H_{25^\circ}$$  \hspace{1cm} (3)

where $H_0$ and $H_{25^\circ}$ are the $H'(10)$ values at 0° and 25°, respectively.

Even without the TOF method, one can subtract $k \times H_{25^\circ}$, obtained by a neutron monitor at 25° from $H_0$, obtained by a monitor at 0°. To check the subtraction method without the TOF method, we measured the $H'(10)$ for 293-MeV monoenergetic neutrons at 0° and 25° using DARWIN. As a result, we obtained $H_0 = 732$ pSv cm², $H_{25^\circ} = 480$ pSv cm², and $H_{\text{corr}} = 291$ pSv cm², which agree well with the fluence-to-$H'(10)$ conversion coefficient taken from EXPACS [21], 304 pSv cm². Thus, the subtraction method using Eq. (3) can almost decrease the response in the continuum region of neutron fluence against the total response of neutron monitors in the 100-m TOF tunnel in the RCNP cyclotron facility.

4. Summary

We completed a series of TOF measurements of monoenergetic neutron energy spectra for the $^7\text{Li}(p,n)$ reaction using 80–389-MeV protons in the 100-m TOF tunnel of the RCNP cyclotron facility. For that purpose, we measured the neutron energy spectra of 80-, 100-, and 300-MeV proton incident reactions, which had not been investigated in our previous studies. In the comparison of experimental data with calculations made using PHITS and
MCNPX codes, nuclear reaction models in the codes cannot reproduce the neutron spectra because of lack of transitions to the discrete states of $^7$Be. The neutron peak intensity was $0.9 \text{–} 1.1 \times 10^{10}$ neutrons/sr/$\mu$C in the 80–389 MeV incident proton energy region and was almost independent of the incident proton energy. The contribution of peak intensity of the spectrum 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. To consider the correction required to derive a response in the peak region from the measured total response of neutron monitors, we proposed the subtraction method using energy spectra between $0^\circ$ and $25^\circ$. The normalizing factor $k$ against the $25^\circ$ neutron fluence that equalizes the $0^\circ$ neutron fluence in the continuum region ranges from 0.74 to 1.02 depending on the incident proton energy and the measured angle. Even without the TOF method, the subtraction method with the $k$ factor almost leads to decreased response in the continuum region of neutron spectrum against the total response of neutron monitors.

Fig. 9. Angular distribution of ambient dose equivalent H*(10) obtained using ambient dose equivalent coefficient taken from [21] and measured neutron energy spectra of 100 and 296 MeV protons.

Fig. 10. (Upper panels) Neutron energy spectra at $0^\circ$ and $25^\circ$ for 100- and 296-MeV proton incidences on a 1-cm-thick enriched $^7$Li target, and spectrum at $25^\circ$ normalized to equalize neutron fluence in continuum region ($E_n < 93$ MeV for 100-MeV protons and $E_n < 290$ MeV for 296-MeV incidence). (Lower panels) Corrected spectrum obtained by subtracting the normalized $25^\circ$ spectrum from the $0^\circ$ spectrum.
Acknowledgment

The authors wish to thank the staff at RCNP for providing the beams and for their assistance during the experiments.

References