Characterization of a 40–90 MeV $^7\text{Li}(p,n)$ neutron source at TIARA using a proton recoil telescope and a TOF method

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Abstract

The intensity and energy spectra of a quasi-monoenergetic $^7\text{Li}(p,n)$ neutron source at TIARA of Japan Atomic Energy Research Institute (JAERI) have been measured for eight incident proton energies between 43 and 87 MeV, using a proton recoil telescope (PRT) of annular geometry and a time-of-flight (TOF) method employing organic scintillators (BC501A, NE213) calibrated prior to the experiment. By combining the two data, we deduced energy spectra of the source neutrons absolutely down to a few MeV, and the cross section of the peak neutron production reaction, $^7\text{Li}(p, n_0^0, n^1_1)^{^7}\text{Be}$. The continuum component of the energy spectrum in the source proved to be described consistently by assuming a three-body phase-space distribution corresponding to the $^7\text{Li}(p,n^3\text{He})\alpha$ reaction as a main component. The annular PRT achieved a good compromise between energy resolution and detection efficiency with a good signal-to-noise ratio.

Keywords: TIARA; TOF method; PRT data

1. Introduction

Utilization of large accelerators is growing in diverse applied and basic fields [1]. For shielding design and efficient utilization of the facilities, accurate knowledge is required on the neutron transport and the nuclear data in the energy region beyond 20 MeV [1]. To promote experiments in the energy region, an appropriate neutron source is indispensable.

In the energy region above 20 MeV, a $^7\text{Li}(p,n)$ neutron source has been employed as an intense and quasi-monoenergetic neutron source in various
laboratories: the Crocker Nuclear Laboratory, University of California, Davis (En \(\leq 65\) MeV) [2], the Institut de Physique Nucléaire, Louvain-la-Neuve (\(\leq 75\) MeV) [3], TRIUMF (Tri-University Meson Factory), Vancouver (200–500 MeV) [4], the Svedberg Laboratory (TSL), Uppsala (50–150 MeV) [5], and at Cyclotron Laboratory, Indiana University, Bloomington (30–200 MeV) [6].

A \(^{7}\text{Li}(p,n)\) neutron source for the 40–90 MeV range has been established at TIARA\(^1\) of Takasaki Establishment, Japan Atomic Energy Research Institute (JAERI), to promote the experiments on accelerator shielding and neutron nuclear data measurements [7]. At the facility, neutron transmission experiments through bulk shielding media [7–10] and measurements of activation and charged-particle emission cross sections have been conducted [11,12].

For the analysis of the experiments using the source, the intensity and the energy spectrum of the source should be known accurately. The neutron spectrum data are indispensable because the \(^{7}\text{Li}(p,n)\) source is not monoenergetic but accompanied with unwanted continuum neutrons which give rise to background in shielding and activation experiments. However, the cross section and the energy spectrum of the \(^{7}\text{Li}(p,n)\) reaction are not known quantitatively.

For this reason, we have measured the intensity and the spectrum of the \(^{7}\text{Li}(p,n)\) neutron source with a proton-recoil counter-telescope (PRT) and a time-of-flight (TOF) method employing organic liquid scintillation detectors calibrated prior to the experiment. PRT is the most reliable device for absolute measurements of neutron spectra in the 20–100 MeV energy range because the detection efficiency of a PRT can be determined accurately by the calculation based on the well-known differential n–p scattering cross section and the geometry between the proton radiator and the proton detector, but its very low detection efficiency restricts the application. We have developed a PRT with an annular geometry which provides higher detection efficiency without degradation of the energy resolution and signal-to-noise ratio. The annular PRT employs an annular-shaped proton radiator and a proton detector placed on the neutron beam axis which is shadowed from the neutron beam. This geometry proved to provide better energy resolution and signal-to-noise ratio than conventional geometry PRTs having comparable detection efficiency (cf. Section 3).

In the case of conventional organic scintillation detectors like NE213, the detection efficiency is rather uncertain in this energy region because the neutron-carbon interaction in the scintillator and the light output of the reaction products are not known sufficiently well [13,14]. Therefore, concurrently with the PRT experiments, response functions of BC501A and NE213 liquid scintillation detectors were measured absolutely in the neutron flux determined by the PRT at various neutron energies [13,14]. Using the measured response functions, Monte Carlo codes for response function calculation were examined and revised to reproduce the experimental data [13,14]. Then, the scintillation detectors were applied to the source spectrum measurements.

Using the PRT and the TOF method employing NE213 and BC501A, the spectrum of the \(^{7}\text{Li}(p,n)\) source was measured at eight incident energy points of 43, 48, 53, 58, 63, 67, 78 and 87 MeV. From the measurements, we obtained data on the intensity of the peak neutrons, and the shape of the continuum. The neutron energy spectra by PRT and by TOF were consistent generally. Further, the energy spectra of continuum neutrons were analyzed to find an appropriate analytic description for the analysis of experimental data, and the cross section of the peak neutron production reaction, \(^{7}\text{Li}(p,n_{0,1})^{7}\text{Be}\), was deduced.

2. \(^{7}\text{Li}(p,n)\) neutron source at TIARA

Fig. 1 shows the layout of the monoenergetic source facility at TIARA. A proton beam from a \(K = 110\) AVF cyclotron is transported to a \(^{7}\text{Li}(99.8\%)\) target which is a rolled plate of metallic \(^{7}\text{Li}, 35\)-mm diam. The \(^{7}\text{Li} \) target is mounted on a remotely-controlled and water-cooled

\(^{1}\)Takasaki ion accelerators for advanced radiation application
The neutron production rate is monitored by current in the beam dump Faraday cup (fc0), and the count rate of $^{238}$U and $^{232}$Th fission chambers placed around the $^7$Li target (Fig. 1). The monitor counts agreed within $\sim 2\%$ in normal conditions. The beam current incident on the $^7$Li target is read occasionally by another movable Faraday cup (fc1) just upstream of the $^7$Li target because fc0 underestimates the proton beam by several percent because of a limited acceptance of fc0 and the proton scattering in the target.

The experimental area is about 5 m away from the $^7$Li target. In the case of the activation cross-section measurements which requires a higher neutron flux, samples are irradiated at the exit of the rotary shutter, $\sim 4$ m from the $^7$Li target [11].

In some experiments, a large background peak was observed in the middle of the proton spectrum by the PRT. The peak event could be eliminated almost entirely by placing a brass or copper plate with thickness close to the range of the incident proton beam. Therefore, it was attributed to hydrogen atoms neutralized around the $^7$Li target. The observed particle energy was lower than the incident energy by about energy loss in the window for the vacuum end. In these cases, the plates were left in the neutron beam to eliminate the events. Insertion of the plates did not bring appreciable increase of background events in the PRT.

Table 1
Neutron fluence of the TIARA $^7$Li(p,n) neutron source

<table>
<thead>
<tr>
<th>Proton energy (MeV)</th>
<th>$^7$Li target thickness (mm)</th>
<th>Neutron energy$^a$ (MeV)</th>
<th>Neutron fluence$^b$ $10^9$ n (Sr $\mu$C)$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>43</td>
<td>3.60</td>
<td>40.5</td>
<td>3.46 ($\pm 3.3%$)</td>
</tr>
<tr>
<td>48</td>
<td>3.80</td>
<td>45.4</td>
<td>2.70 ($\pm 3.2%$)</td>
</tr>
<tr>
<td>53</td>
<td>4.30</td>
<td>50.9</td>
<td>3.82 ($\pm 4.6%$)</td>
</tr>
<tr>
<td>58</td>
<td>4.70</td>
<td>55.3</td>
<td>4.45 ($\pm 3.5%$)</td>
</tr>
<tr>
<td>63</td>
<td>5.00</td>
<td>60.6</td>
<td>4.17 ($\pm 3.3%$)</td>
</tr>
<tr>
<td>68</td>
<td>5.20</td>
<td>65.2</td>
<td>4.82 ($\pm 3.9%$)</td>
</tr>
<tr>
<td>78</td>
<td>6.00</td>
<td>75.0</td>
<td>5.34 ($\pm 4.5%$)</td>
</tr>
<tr>
<td>87</td>
<td>6.75</td>
<td>84.6</td>
<td>6.35 ($\pm 6.2%$)</td>
</tr>
</tbody>
</table>

$^a$ The energy of peak neutrons.

$^b$ Neutron fluence at light ion room 3.
3. Proton recoil telescope

3.1. Annular proton recoil telescope

Fig. 2(a) and (b) show the setup of the PRT and the schematic view of the proton detector, respectively. The PRT consisted of a proton radiator, proton detector and a shadow bar. They were set in a rigid support frame to be readily aligned. The radiator was located around 5.5 m from the $^7$Li target.

For simple handling, the PRT is placed in air without a vacuum chamber. The proton detector is placed on the neutron beam axis and shielded from the neutron beam by the brass shadow bar (5.5-cm diam. by 50-cm long) to avoid neutron-induced backgrounds. In the conventional geometry of the PRT shown in Fig. 3, backgrounds are eliminated by placing the proton detector outside the neutron beam.

The proton detector was a $\Delta E-E$ telescope consisting of an E-detector, 5-cm diam by 3-cm thick NaI(Tl), and an Si (PIPS) $\Delta E$-detector, 900-mm$^2$ with a depletion layer of 150-$\mu$m or 300-$\mu$m. An NaI(Tl) detector was adopted owing to the good linearity of the light output vs the energy deposition. The radiator was a polyethylene plate, typically 9.6-cm in outer diameter and 6-cm in inner diameter. The central hole was necessary to define clearly the effective area of the polyethylene plate exposed to the neutron beam. The radiator was 1.0–0.12 mm thick, and supported by thin nylon strings on a stainless steel frame. The frame was placed outside the neutron beam.

The energy resolution of the PRT is dominated by the proton energy loss in the radiator and the kinematical energy spread of protons due to the finite solid angle. The former is dominated by the radiator thickness, and the latter by the geometry between the radiator and the detector. A Monte Carlo program was written and used to search an optimal geometry and a radiator thickness that achieves energy resolution comparable with the source neutron energy spread with a minimal loss of detection efficiency. The radiator-telescope distance was taken to be around 40 cm. In this geometry, the energy resolution is significantly better than in the conventional geometry with equivalent detection efficiency, because the average recoil angle of protons (6.4° lab.) is very close to 180° (c.m.) where the n–p scattering cross section is at maximum, and the kinematical energy spread of

![Diagram](image-url)
the recoil protons is at minimum. Such a forward angle is not possible in the conventional geometry without extending the radiator-detector distance greatly. In this case, the main background source proved to be neutron-induced charged particles from nitrogen and oxygen in air. Its magnitude in the annular geometry proved to be markedly smaller than in the conventional geometry because of the smaller volume of the air exposed to the neutron beam and viewed by the telescope. Consequently, this annular geometry achieves a better signal-to-noise ratio as well as good energy resolution without loss of detection efficiency.

The shadow bar was supported by two thin steel pins to minimize the distortion of the neutron beam. To check the interference by the shadow bar, the neutron spectrum behind the shadow bar was calculated using the Monte Carlo code MORSE with the DLC87 data set, and proved to be free from neutrons scattered by the shadow bar (< 1%).

Data were taken using conventional NIM electronics shown in Fig. 4. Three signals, \( \Delta E \), \( E \) and the timing signal between the \( \Delta E \) and \( E \) detectors, were accumulated event by event in a multi-parameter data acquisition system, MPC-1600, and stored in a magnetic-optical disk.

### 3.2. Source spectrum measurement

In the source spectrum measurement, first, the energy of the peak neutrons was measured by the TOF method using a BC501A or NE213 scintillation detector. Then, PRT measurements were done for polyethylene, blank and carbon samples by normalizing the runs with the beam current or the fission chambers counts. The carbon data were measured using a carbon plate with the same energy loss as the polyethylene plate and used for subtraction of the \( \text{C(n,\alpha)} \) backgrounds. The average beam current during the PRT measurement was 1–3 \( \mu \)A. With the beam current, 1–1.5 h measurements provided sufficient counting statistics.

### 3.3. Data reduction

First, protons were selected from the \( \Delta E-E \) two-dimensional spectra and the proton energy spectra were deduced. Fig. 5 illustrates an example of the \( \Delta E-E \) spectrum and the deduced proton spectrum. Protons are separated clearly from deuterons and tritons over the energy range, and the signal-to-noise ratio is fairly good. As noted above, backgrounds proved to come mainly from the surrounding air, and the contribution of carbon was not significant (< 8%) even at the highest neutron energy of 87 MeV.

The proton spectrum consists of a peak component induced by the \( ^7\text{Li}(p,n^{0,1}) \) reactions \( (Q = -1.644 \) and \(- 2.075 \text{ MeV, respectively}) and continuum parts. The energy scale of the proton spectrum was calibrated on the basis of the linearity between the light-output of a NaI(Tl) scintillator and proton energy [15]. The observed peak channel was normalized to the peak energy which was estimated by a calculation for the source neutron energy measured by a TOF method. The calculation was done using a Monte Carlo method to take into account the finite geometry between the radiator and the telescope.

The proton spectrum was corrected for the (1) sample-out backgrounds, (2) carbon backgrounds,
and for the (3) proton energy loss in the sample and detector elements. For the energy loss correction, the contribution of the radiator, the air between the radiator and telescope, entrance window of PIPS (20-μm thick Al), the PIPS detector, and the window of NaI(Tl) (100-μm thick Al), were taken into account. The correction was made by shifting the spectrum by the average energy loss over possible proton paths. For the correction in low energy regions, the above method is not appropriate and an unfolding technique was applied.

The peak neutron yield was deduced by correcting for the count loss by proton nuclear reactions in the detectors [16]. Then, the \(^{7}\text{Li}(p,n_{0,1})^{7}\text{Be}\) reaction cross section was also derived after the correction for the neutron attenuation by window materials between the \(^{7}\text{Li}\) target and the PRT.

The corrected proton spectrum, \(Y(E_p)\) (yield/MeV), was transformed into the neutron energy spectrum \(F(E_n)\) according to the following equation:

\[
F(E_n) = \frac{1}{4\pi S^2} \frac{dE_p}{dE_n} Y(E_p)
\]  

where \(S\) is the distance between the \(^{7}\text{Li}\) target and the radiator, and \(\varepsilon(E_n)\) is the neutron detection efficiency of the PRT per source neutrons. The efficiency \(\varepsilon(E_n)\) was obtained by the analytic formulae Eqs. (2) and (3) [17], and by the Monte Carlo method.

\[
\varepsilon(R) = \varepsilon(R_0) - \varepsilon(R_*)
\]

\[
\varepsilon(R_*) = \frac{N \tau D}{4\pi} \int_0^{R_*} dr_s \int_0^{2\pi} d\omega \int_0^{r_s} dr_d \int_0^{2\pi} d\phi \frac{\sigma(\theta_{np})}{s^2 d^3}
\]

\[
s^2 = S^2 + r_s^2 - 2S r_s \cos \omega \sin \theta
\]

\[
d^2 = D^2 + r_s^2 + r_d^2 - 2r_s r_d \cos (\omega - \varphi)
\]

where \(\varepsilon(R)\) is the efficiency for the radiator with outer radius \(R_0\), inner radius \(R_*\), \(R_d\) is the radius of detector aperture, \(N\) is the density by number of hydrogen atoms in the radiator, \(\tau\) is the radiator thickness, \(\sigma(\theta_{np})\) is the differential n–p scattering cross section, and the other parameters are indicated in Fig. 6.

The efficiency was calculated using the differential n–p scattering cross-sections parametrized by Shen and Zhan [18] on the basis of recent experimental data. The detection efficiency calculated by the analytic method agreed with that by the Monte Carlo method. The calculated efficiency was validated for 14 and 18 MeV neutrons by the relative measurements with another PRT which had been calibrated with the associated particle method for 14 MeV neutrons [19]. Besides, the calculated response functions for monoenergetic 14, 18 MeV neutrons and the peak neutrons of the \(^{7}\text{Li}(p,n)\) source agreed with measured ones if the energy width of the source neutrons was taken into account.

The neutron spectrum was obtained down to \(\sim 12\) MeV. The low limit is due to the proton energy loss in the detector elements and the air between the radiator and the proton detector.
4. TOF measurements

The TOF measurement was carried out on the neutron beam axis using a BC501A and an NE213 scintillation detector, 12.5-cm diam. and 12.5-cm thick. Details of the experiments are described in Refs. [13,14]. The duration of proton pulse was around 1.5 ns in FWHM. The repetition rate of the neutron beam was reduced down to 3.3 MHz by a beam chopper system to avoid the effect of wrap-around, and measurements were made at various flight path lengths from 6 to 15 m to cover a wide range of neutron energy. The TOF measurements were started by the detector signal and stopped by a chopper trigger signal when the beam chopper was operated, or by the RF signal from the cyclotron. The TOF data were converted into energy spectra using relativistic kinematics. The position of the prompt gamma-ray peak was determined by employing a copper target in place of the $^7$Li target which emits only low-energy gamma-rays.

As described in Refs. [13,14], response functions calculated by the widely used Monte Carlo codes, SCINFUL and CECIL, showed marked differences from the measured ones because of deficiencies for cross-sectional data and the light output curve of the scintillating media. Therefore, response functions of the detectors were measured absolutely in the neutron flux calibrated with the PRT, and the data and parameters in the codes were revised to reproduce the measured response functions [13,14]. The detection efficiency for the spectrum derivation was obtained by integration of the response functions calculated with the revised codes.

5. Results and discussion

5.1. Neutron intensity and spectra

Fig. 7(a) and (b) show the neutron spectra of the TIARA $^7$Li(p,n) source for protons between 43 and 88 MeV which were measured by PRT and TOF. During the TOF measurements, the beam current had to be reduced by more than two decades due to very high sensitivity of the detector, and monitor counts were too few to make reliable normalization with the PRT measurement. Therefore, the absolute values of the TOF data were determined by normalizing its peak yield to that of the PRT data. The PRT data were obtained around 5.5 m from the $^7$Li target.

The neutron spectra consist of the full-energy peak due to the $^7$Li(p,n) reaction and a smooth continuum component attributable to a multi-body breakup process (cf. next section). The bump around 70 MeV in the 87 MeV PRT data is attributed to protons moderated from the peak energy by transmission through the aperture of the PIPS (Fig. 2) which was not thick enough for the peak protons of this energy. In other measurements, apertures employed were sufficiently thick for incident proton energies. The weird shape of the full-energy peak in 87 MeV TOF measurements is due to the instability of the accelerator.

Except for the bump, the PRT data are generally consistent with the TOF data. For $E_p = 48, 53$ and 78 MeV, however, the continuum parts in the PRT data are significantly higher than in the TOF data. As a possible cause of the discrepancies, we checked the effects of the proton energy loss by reactions in the detectors and the aperture transmission noted above for the 87 MeV PRT data, but they did not account for the difference consistently. The TOF data, on the other hand, will be free from the problem and extend to lower energies. Therefore, the TOF data were adopted for the continuum spectrum.

The results of the peak neutron fluence are summarized in Table 1. The experimental errors for the peak fluence were evaluated considering error sources of (1) counting statistics, (2) n–p scattering cross section, (3) geometry, and (4) systematic error due to relative monitoring. The error of the n–p...
scattering cross section was estimated from the differences between the parametrization and recent experimental data [20–23]. The results are summarized in Table 2.

5.2. Magnitude and spectrum shape of continuum neutrons

Data on the magnitude and the spectrum of the continuum neutrons are also required for the data analysis of the experiments using the $^7$Li(p,n) source. The fraction of the peak neutrons relative to overall neutrons above 15 MeV is about 55% for $E_p = 45$ MeV in agreement with the value reported by Jungerman et al. [24], and decreases with the proton energy.

We attempted to describe the spectra of the continuum neutrons with a simple analytic function and found that a phase-space distribution [25] corresponding to the three-body breakup process $^7$Li(p,n$^3$He)$\alpha$ ($Q = -3.231$ MeV) reproduces the present experimental data constantly. The energy
Table 2
Error sources in the PRT measurements

<table>
<thead>
<tr>
<th>Error source</th>
<th>Error (%)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Counting statistics</td>
<td>1.7–2.0</td>
<td></td>
</tr>
<tr>
<td>Normalization</td>
<td>1.0–2.0</td>
<td></td>
</tr>
<tr>
<td>Solid angle</td>
<td>0.6</td>
<td></td>
</tr>
<tr>
<td>Number of hydrogen atoms</td>
<td></td>
<td></td>
</tr>
<tr>
<td>n-p scattering cross section</td>
<td>1.8 (43 MeV)–5.4 (87 MeV)</td>
<td>Ref. 18–23</td>
</tr>
<tr>
<td>Count-loss of protons</td>
<td>0.4 (43 MeV)–1.3 (87 MeV)</td>
<td>Ref. 16</td>
</tr>
<tr>
<td>Total</td>
<td>3.3 (43 MeV)–6.2 (87 MeV)</td>
<td></td>
</tr>
</tbody>
</table>

The spectrum for the three-body breakup process was assumed to be

$$d^2\sigma = C\langle \phi_i | M | \phi_f \rangle^2 \rho(E_n)$$

$$\rho(E_n) = C\sqrt{E_n(E_{n}^{\text{max}} - E)}$$

in the center-of-mass (CM) system of $^8\text{Be}$, where $\rho(E_n)$ is the CM three-body phase-space distribution for neutrons of $E_n$, $E_{n}^{\text{max}}$ is the maximum neutron energy, and $\phi_i$ and $\phi_f$ are the wave functions for the initial and final states, respectively. The CM spectrum was transformed into the laboratory.

Fig. 8. Comparison of experimental $^7\text{Li}(p,n)$ spectra (solid lines) with the three-body phase-space distributions for the $^7\text{Li}(p,n^3\text{He})$ reaction (dot lines). (a) for 43, 48, 53 and 58 MeV protons, and (b) for 63, 68, 78 and 87 MeV protons.
system assuming isotropic angular distribution in the CM system.

The calculated phase-space distribution is normalized appropriately to the experimental continuum spectra. As shown in Fig. 8(a) and (b), the calculation reproduces consistently the experimental spectra, while it tends to underestimate the low-energy parts of the spectrum for lower incident energies. In low-energy parts, it may be possible that the breakup reactions with deeper $Q$-values, e.g., $^7\text{Li}(p,np)^6\text{Li}$ ($Q = -7.52$ MeV) etc, or final state interactions have significant contributions and soften the spectra.

Experimental data for the energy spectra of low-energy neutrons are very few [26]. Recently, Schumacher et al. reported the $^7\text{Li}(p,n)$ spectrum data down to around 2 MeV using a $^{238}\text{U}$ fission chamber for 25–70 MeV protons [27]. Their data do not indicate a significant increase of low-energy neutrons and seem to be consistent with the description above if a correction is made for the contribution of low energy neutrons from the carbon beam stop just behind the $^7\text{Li}$ target. Besides, the present description works fairly well too for the lower incident energies of $E_p = 33$ and 22 MeV [28]. The present model, therefore, will be useful to estimate the low-energy part of the spectrum which is difficult to measure, although further studies are desirable for the low-energy region in the cases of lower proton energies. It should be noted, however, that in the data for $E_p = 139$ and $E_p = 200$ MeV in Ref. [26], the continuum spectra are harder than the three-body phase space.

5.3. $^7\text{Li}(p,n_{0,1})^7\text{Be}$ cross section

The $0^\circ$ cross section for the peak neutron production, $^7\text{Li}(p,n_{0,1})^7\text{Be}$, was deduced from the present data by integration of the spectra over the peak area. The results are shown in Fig. 9 together with other experimental data [29–37]. Numerical values are presented in Table 3. The present values are nearly constant around 33–35 mb/sr except for the data at $E_p = 48$ MeV, and in agreement with the extrapolation from higher proton energy ranges [38]. By employing the present data, it is possible to estimate the neutron production rate per proton within around 10% if the thickness of the $^7\text{Li}$ target is given.

6. Summary

The energy spectra of a quasi-monoenergetic $^7\text{Li}(p,n)$ neutron source at TIARA of Japan Atomic Energy Research Institute (JAERI) have been measured relative to the differential n–p scattering cross section for eight incident proton energies between 43 and 87 MeV, using a proton recoil telescope of annular geometry and a TOF method using calibrated organic scintillators. The annular telescope achieved a good compromise between energy resolution and detection efficiency as well as a good signal-to-noise ratio, and provided neutron spectrum data down to around 12 MeV. The organic
scintillators were characterized in the neutron field calibrated by the PRT, and used for source spectrum measurements.

By combining the PRT and TOF data, we deduced the energy spectra of the source neutrons down to a few MeV, and the cross section of the peak neutron production reaction, \(^7\text{Li}(p,n)\)\(^7\text{Be}\), and found that a simple analytic description assuming a three-body breakup reaction \(^7\text{Li}(p,n\alpha)\)\(^\alpha\text{He}\) describes consistently the continuum component of the \(^7\text{Li}(p,n)\) source.

Numerical tables of the source spectrum measurements are available from the author on request.

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### References


