

Experiment ^7Be production cross section from the $^6\text{Li}(d,n)^7\text{Be}$ and $^7\text{Li}(d,2n)^7\text{Be}$ reactions at deuteron energies from 8.5 to 20 MeV

Daniil Koliadko ^{a,*}, Jaromír Mrázek ^b, Milan Štefánik ^b, Mitja Majerle ^b,
Eva Šimečková ^b, Jan Novák ^b, Martin Ansorge ^b, Axel Klix ^a,
Dieter Leichtle ^a

^a Karlsruhe Institute of Technology, Hermann-von-Helmholtz-Platz 1, Eggenstein-Leopoldshafen, 76344, Germany

^b Nuclear Physics Institute of the CAS, Hlavní 130, Rez, 25068, Czech Republic

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ABSTRACT

The $^7\text{Li}(d,2n)^7\text{Be}$ reaction is considered as a neutron source for modern irradiation facilities such as IFMIF-DONES. For the neutron converters, it is planned to use $^{\text{nat}}\text{Li}$. So, the $^6\text{Li}(d,n)^7\text{Be}$ reaction will interfere. While generating neutrons, it will also produce radioactive ^7Be . Production estimations of this isotope are important for radio-protection design and following licensing of the facility. There are tension between the experimental data sets and latest evaluations. In the present paper, we introduce the results of the irradiation experiments at cyclotron U120-M of NPI CAS, Rez.

1. Introduction

The development of intense neutron sources is a key requirement for the qualification of materials in fusion energy systems. The IFMIF-DONES (International Fusion Materials Irradiation Facility–DEMO-Oriented Neutron Source) project aims to provide a high-flux neutron environment that closely reproduces the damage conditions expected in future fusion reactors [1]. In this context, deuteron-induced reactions on lithium, in particular the $^7\text{Li}(d,2n)^7\text{Be}$ channel, play a central role as the primary neutron-producing mechanism.

Extensive experimental and theoretical efforts have been devoted to the characterization of the $^7\text{Li}(d,xn)$ reactions over the past decades. Evaluated nuclear data libraries, including those discussed in the comprehensive report by Simakov [2], provide recommended cross sections for applications in fusion technology. However, significant discrepancies remain between experimental datasets and evaluated results, particularly in the energy range relevant for IFMIF-DONES operation. These inconsistencies introduce uncertainties in neutron yield predictions and activation assessments.

In addition to neutron production, the $^7\text{Li}(d,2n)^7\text{Be}$ reaction leads to the formation of radioactive ^7Be , which is of practical importance for radiological safety, target handling, and facility maintenance. Accurate knowledge of ^7Be production cross sections is therefore essential for reliable activation modeling and the design of lithium-based targets [3].

Despite numerous measurements, the available experimental database for ^7Be production in deuteron-induced reactions on lithium isotopes remains incomplete and, in some cases, inconsistent. In particular, differences between results obtained using various experimental techniques, such as time-of-flight neutron measurements and activation methods, highlight the need for new high-precision data.

* Corresponding author.

E-mail address: daniil.koliadko@kit.edu (D. Koliadko).



Fig. 1. Process of cutting the lithium.

Table 1
Characteristics of individual irradiation runs.

E_d (MeV)	Li composition	Duration (s)	Q (μC)
19.25	Pure ^7Li	532	4.89
16.64	Pure ^7Li	678	8.74
19.85	95% of ^6Li	605	6.93
18.70	95% of ^6Li	612	6.29
13.58	95% of ^6Li	606	6.88

In the present work, we report on new measurements of ^7Be production in the $^6\text{Li}(d,n)$ and $^7\text{Li}(d,2n)$ reactions using the stacked-target technique. The experiment was performed on the variable energy cyclotron U120-M at NPI, Řež, and the induced activity was determined via high-resolution gamma-ray spectrometry using high-purity germanium detectors. The obtained results are compared with existing experimental data and evaluated libraries to reduce current discrepancies and improve the nuclear data relevant for IFMIF-DONES applications.

2. Experimental details

2.1. Target preparation

Metallic lithium chunks with two isotopic compositions, enriched 100% ^7Li (Sigma-Aldrich product) and 95% ^6Li with 5% ^7Li (American Elements product), were rolled into thin foils with a thickness of approximately 0.5 mm by CAMEX. Circular targets with a diameter of 14 mm were subsequently cut from these foils inside a glove box under a controlled argon atmosphere. The preparation procedure is shown in Fig. 1. The target thicknesses were checked using a micrometer. The variation of the thickness was treated as uncertainty.

2.2. Irradiation

A stacked-foil target configuration was used. Since the total beam energy loss in the target stack was only a fraction of the initial beam energy, it was possible to irradiate up to three samples simultaneously while covering a wider energy range. In front and between the lithium foils, $^{\text{nat}}\text{Cu}$ and $^{\text{nat}}\text{Al}$ foils with declared by Goodfellow parameters 25 μm thickness, purity 99.9 and 50 μm thickness, purity 99.99% respectively were inserted as beam degraders and monitors of the deuteron beam. The diameter of the foils in the stack target was 15 mm, and the beam cross-section was about 1.5 mm in diameter. These foils were weighted to reduce the thickness uncertainty specified by the manufacturer.

The irradiations were carried out at the U-120M cyclotron operated in negative-ion acceleration mode [4]. Beam energy was controlled by setting the magnetic induction and extraction radius [5]. The irradiation chamber, charge collection and charge integrator were identical to those used in [6].

The irradiation runs lasted approximately 10 minutes at a low beam current of about 15 nA. Incident deuteron energies and other irradiation parameters are presented in Table 1. After irradiation, the stacked-foil target was disassembled inside the glove box. Each lithium sample was inspected for signs of melting or other damage that could have been caused by excessive temperatures. No damage was observed, and the samples were subsequently stored in mineral oil to prevent oxidation. Each foil was later measured using a calibrated HPGe detector.

2.3. Gamma-spectra measurements

After production in the (d,xn) reactions, the ${}^7\text{Be}$ nuclei remained implanted in the lithium foils. ${}^7\text{Be}$ decays with a half-life of 53.22 days via electron capture to ${}^7\text{Li}$. In 10.44% of decays, the first excited state of ${}^7\text{Li}$ is populated, followed by the emission of a 477.6 keV γ -ray photon [7].

The HPGe detector efficiency was determined using point-like calibration sources with well-known activities: ${}^{152}\text{Eu}$, ${}^{54}\text{Mn}$, ${}^{57}\text{Co}$, ${}^{60}\text{Co}$, ${}^{133}\text{Ba}$, ${}^{137}\text{Cs}$, and ${}^{88}\text{Y}$. The measurements were corrected for the true coincidence summing effect estimated using TrueCoinc [8].

To keep the detector dead time low and below 2%, the measurements were performed using different geometries. For each geometry, the efficiency was known with an accuracy of 1%. The measurement times were adjusted for each sample such that the uncertainty of the peak area remained below 1%.

After completing the standard measurement routine, several samples from each lithium foil set (${}^7\text{Li}$ and ${}^6\text{Li}$) were remeasured to check for parasitic activities or other effects that could interfere with the peak of interest. The results agreed within the 1% calibration uncertainty.

Additionally, the monitor foils located behind the investigated lithium samples were checked for ${}^7\text{Be}$ decay. The corresponding gamma line was not observed in their spectra.

2.4. Data analysis

The cross sections (σ) of the ${}^6\text{Li}(\text{d},\text{n}){}^7\text{Be}$ and ${}^7\text{Li}(\text{d},2\text{n}){}^7\text{Be}$ reactions were obtained through a standard activation analysis procedure. The number of produced nuclei during the irradiation is given by

$$N(A) = \frac{S \cdot \lambda}{\epsilon_p(E) \cdot I_\gamma(E)} \frac{C_t}{COI \cdot C_g \cdot C_s} \frac{t_{real}}{t_{live}} \frac{t_{irr} \cdot e^{\lambda t_0}}{(1 - e^{-\lambda t_{irr}})(1 - e^{-\lambda t_{real}})}, \quad (1)$$

where S is the area of the peak of interest, λ is the decay constant, and $I_\gamma(E)$ is the absolute intensity of the γ line with energy E , the full-energy peak efficiency of the HPGe detector for γ photons of the corresponding energy is denoted by $\epsilon_p(E)$. Since ${}^7\text{Be}$ is a single-line emitter and the detector-to-sample distance was sufficiently large, the coincidence summing correction (COI) and geometry correction (C_g) were negligible. Owing to the low density of metallic lithium, the self-absorption correction (C_s) was also neglected. Therefore, the only applied correction factor was that accounting for beam current fluctuations (C_t). The formula also accounts for radioactive decay during the irradiation time t_{irr} , the cooling time t_0 , and the detector dead-time correction introduced through the ratio between t_{real} and t_{live} .

The reaction cross section was then calculated as

$$\sigma(E_d) = \frac{N(A)}{\Phi \cdot N_{tar}}, \quad (2)$$

where E_d is the average deuteron energy inside the target calculated using PHITS simulations [9] version 3.341, Φ is the integral deuteron flux through the target, and N_{tar} is the number of target atoms per unit area. The latter was calculated from the thickness measured d and densities ρ for different lithium enrichments [10,11], Avogadro's number N_A , and molar mass M :

$$N_{tar} = \frac{d \cdot \rho \cdot N_A}{M}. \quad (3)$$

Since two sets of lithium foil samples with different isotopic abundances were used, it was possible to extract the cross sections for each isotope from

$$\begin{cases} C_6^{(1)} \sigma_6 + C_7^{(1)} \sigma_7 = \frac{N^{(1)}(A)}{\Phi^{(1)} \cdot N_{tar}^{(1)}} \\ C_6^{(2)} \sigma_6 + C_7^{(2)} \sigma_7 = \frac{N^{(2)}(A)}{\Phi^{(2)} \cdot N_{tar}^{(2)}} \end{cases}, \quad (4)$$

where C denotes the abundance of the respective isotope ${}^6\text{Li}$ or ${}^7\text{Li}$ in the foils, and the superscripts (1) and (2) correspond to irradiation sessions.

Since the incident deuteron energies for the ${}^7\text{Li}$ - and ${}^6\text{Li}$ -enriched irradiation sessions were different, the values of σ_7 were approximated using the corresponding data obtained with pure ${}^7\text{Li}$ samples.

The main contributions to the total uncertainty originated from the peak area determination, HPGe efficiency calibration, charge measurement, ${}^7\text{Be}$ escape correction, and the determination of the number of target nuclei. Each measurement was performed with more than 10^4 counts in the peak of interest, resulting in a peak area uncertainty of approximately 1%. The uncertainty of the HPGe efficiency calibration was estimated to be 1.5%, while the uncertainty of the charge measurement was 2%. The uncertainty associated with ${}^7\text{Be}$ nuclei escaping from the lithium foils due to production close to the surface was estimated using PHITS simulations with the JENDL5 library, and other settings set to default. It was evaluated as the ratio between the number of produced nuclei and the number of nuclei escaping from the sample. This uncertainty was energy dependent and approximately 1%. The dominant contribution originated from the determination of the number of target nuclei in the foils through thickness measurements and reached up to 8%.

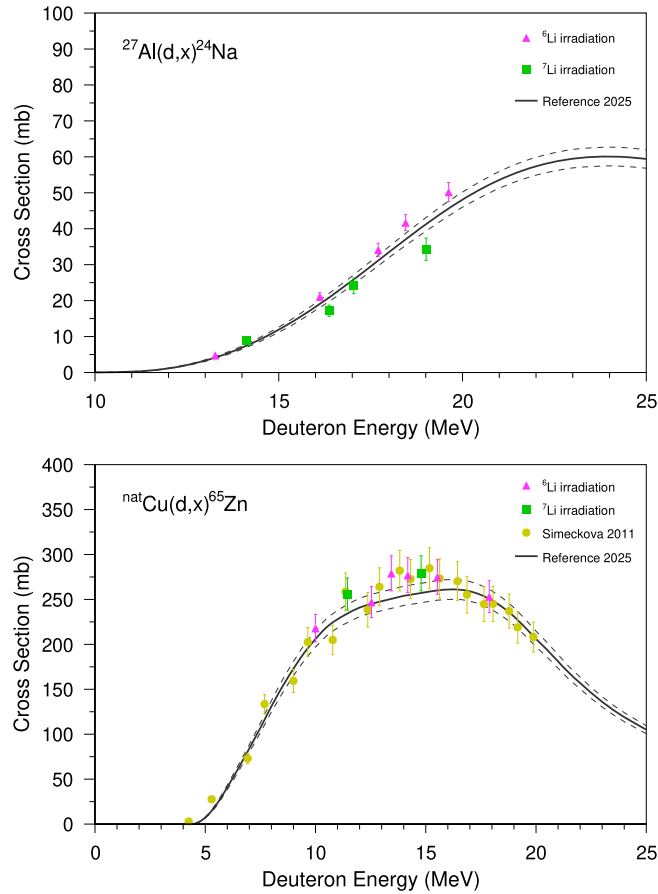


Fig. 2. Comparison of the measured monitor reaction cross sections with the recommended reference data. The solid line is the reference, dashed lines are the uncertainties bounds.

3. Results

3.1. Monitors

In each irradiation session, the studied lithium samples were interleaved with ^{nat}Al and ^{nat}Cu monitor foils. The resulting experimental cross sections for the production of ^{24}Na ($t_{1/2} = 14.956$ h, $E_\gamma = 1368$ keV, $I_\gamma = 99.99\%$) [12] in the $^{nat}\text{Al}(d,x)^{24}\text{Na}$ reaction and ^{65}Zn ($t_{1/2} = 243.93$ d, $E_\gamma = 1115$ keV, $I_\gamma = 50.04\%$) [13] in the $^{nat}\text{Cu}(d,x)^{65}\text{Zn}$ reaction were compared with the recommended reference data from [14]. For the ^{nat}Cu monitor reaction, previously measured data by Šimečková [6] at NPI and available on EXFOR were also used in comparison.

From the comparison shown in Fig. 2, it is apparent that no normalisation of the experimental data was required. Although the cross sections for ^{24}Na production in the irradiation sessions with ^7Li were generally lower than the recommended reference values, the cross sections for ^{65}Zn production were systematically higher than the corresponding reference data in both irradiation sessions. In the case of the copper monitor reaction, the newly measured data were also in agreement with the previous measurements from 2011. These observations indicate that both the incident deuteron beam energy and the deposited charge were well controlled during the irradiations.

3.2. $D + {}^6\text{Li}$

The resulting cross sections are shown in Table 2 and compared with data available in EXFOR and with evaluated data in Fig. 3. While most of the measurements were performed using the activation technique [15–19], the data from Paneru were obtained from measurements of neutron angular distributions [20]. That work also includes activation data; however, it has not been included in EXFOR. At low energies < 12 MeV, the present results are in satisfactory agreement with the data from Generalov and Guzhovskij [15,19] and are systematically higher than those reported by Vysotskij [18]. Overall, the new data follow the expected trend. ENDF/B-VII.1 [21] underestimates the total ^7Be production, as it includes only the ${}^6\text{Li}(d,n_0){}^7\text{Be}$ reaction channel. JENDL-5 [22] and TENDL-

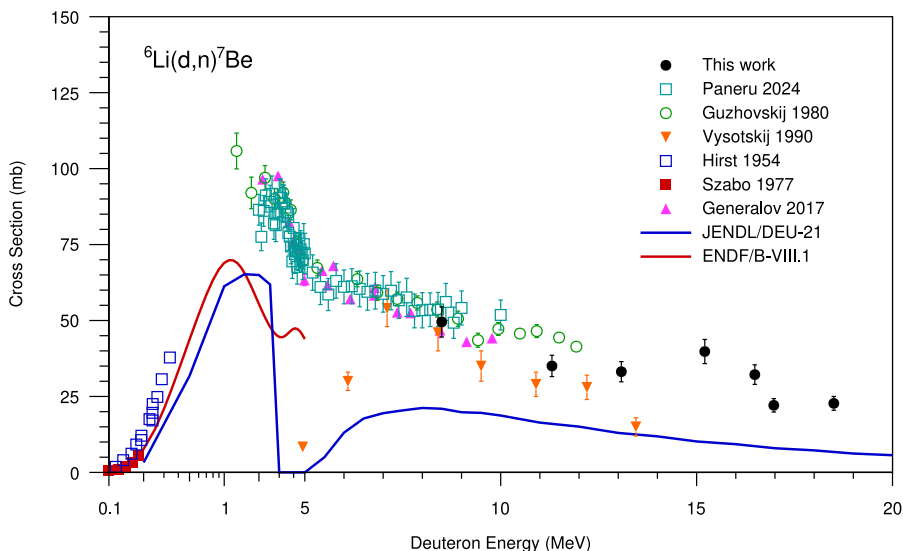


Fig. 3. ${}^6\text{Li}(d,n){}^7\text{Be}$ cross section. Present results compared with evaluated libraries and data from other authors. From 0.1 to 5 MeV the logarithmic scale is used. The scale is linear from 5 to 20 MeV.

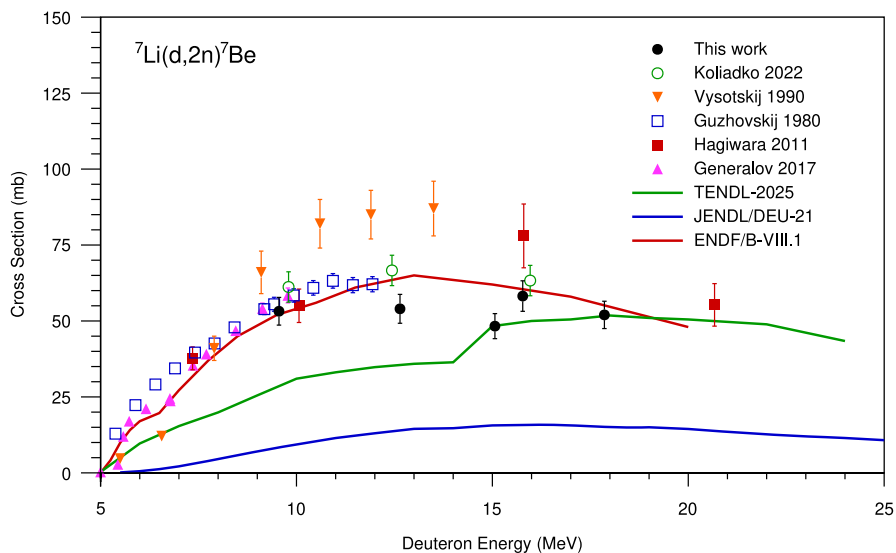


Fig. 4. ${}^7\text{Li}(d,2n){}^7\text{Be}$ cross section. Present results compared with evaluated libraries and data from other authors.

Table 2

Cross sections of the ${}^6\text{Li}(d,n){}^7\text{Be}$ and ${}^7\text{Li}(d,2n){}^7\text{Be}$ reactions.

Irradiation number	E_d (MeV)	σ_7 (mb)	σ_6 (mb)
1	17.86	52.0 ± 4.5	
1	15.8	58.2 ± 5.0	
2	15.1	48.3 ± 4.1	
2	12.6	54.0 ± 4.8	
2	9.6	53.2 ± 4.6	
3	18.5		22.7 ± 1.7
3	16.5		32.2 ± 2.5
4	16.9		22.1 ± 1.8
4	15.2		39.8 ± 3.0
4	13.1		33.2 ± 2.5
5	11.3		35.1 ± 2.7
5	8.5		49.5 ± 3.8

2025 [23] also do not reproduce the experimental data satisfactorily. The latter is not shown in Fig. 3, as its value differs by more than factor of three.

3.3. $D + {}^7\text{Li}$

In EXFOR, only a limited dataset exists for the ${}^7\text{Li}(d,2n)$ reaction cross section. It was measured below 14 MeV in activation experiments [15,18,19]. At higher energies, only the measurement by M. Hagiwara [24] with natural lithium is available. The data for natural lithium are presented as-is, since the contribution from the ${}^6\text{Li}(d,n){}^7\text{Be}$ reaction is not negligible.

The new data are presented in Table 2 and Fig. 4. As previously, the results for ${}^7\text{Li}$ at low energies are in satisfactory agreement with Guzhovskij [19] and Generalov [15], and are significantly lower than those reported by Vysotskii [18]. In the energy range 10–15 MeV, the present results do not fully coincide with our previous measurements using Li_2CO_3 pellets [25]. They also lay below the results of Hagiwara [24]. Among the evaluated libraries, JENDL-5 shows the largest underestimation of the cross section.

4. Conclusions

The cross sections for ${}^7\text{Be}$ production in ${}^6,{}^7\text{Li}$ induced by deuterons were measured in the energy range 9.5–19.5 MeV. The new experimental data are generally in satisfactory agreement with previously published results, particularly with the data reported by Generalov and Guzhovskij. At energies below 15 MeV, the present results differ from the data of Vysotskij, while at energies above 15 MeV discrepancies were observed with the measurements on ${}^{\text{nat}}\text{Li}$ of Hagiwara.

The obtained results provide new experimental information for the ${}^6\text{Li}(d,n){}^7\text{Be}$ and ${}^7\text{Li}(d,2n){}^7\text{Be}$ reactions in an energy region where experimental data remain limited. Comparisons with evaluated nuclear data libraries showed that none of the considered evaluations reproduces the experimental data satisfactorily over the entire investigated energy range. The present results contribute to the experimental database required for fusion-related applications involving lithium-containing materials namely target systems at IFMIF-DONES. It also may support future improvements of evaluated nuclear data libraries for deuteron-induced reactions on lithium.

CRediT authorship contribution statement

Daniil Koliadko: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Conceptualization; **Jaromír Mrázek:** Conceptualization, Supervision; **Milan Štefánik:** Conceptualization, Supervision, Writing–review and editing; **Mitja Majerle:** Methodology, Investigation; **Eva Šimečková:** Methodology, Conceptualization; **Jan Novák:** Software; **Martin Ansorge:** Software, Methodology; **Axel Klíx:** Methodology; **Dieter Leichtle:** Writing – review & editing, Supervision, Methodology.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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