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100 keV deuteron induced reactions on natural lithium

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The angular distributions of protons and α particles emitted in ^{6}Li(d,p)^{7}Li, ^{6}Li(d,α)^{4}He, and ^{7}Li(d,α)^{5}He(g.s.) reactions induced by 100 keV deuterons were studied at 30°, 50°, 90°, 120°, and 140° laboratory angles. The differential cross sections and the total reaction cross sections have been estimated from the measured angular distribution data.

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I. INTRODUCTION

Studying the differential cross sections of the reactions for the emission of charged particles is of general interest in investigations of nuclear structures. Lithium is an important element for nuclear reactor technology, and therefore the nuclear reactions induced by charged particles with lithium have been studied extensively [1–8]. Lithium is also an important element for production of neutrons, and charged particles through nuclear reactions. Among other several reactions, the Li(d,α) reactions are important because of their high Q values. Moreover, the required deuteron energy is ∼150 keV to obtain a reasonable yield of α particles. A literature study indicates that only a few measurements of the differential and total cross sections of ^{6}Li(d,p)^{7}Li and ^{6}Li(d,α)^{4}He have been reported that too mostly at 90° scattering angle. Moreover, the total cross section of the ^{7}Li(d,α)^{5}He(g.s.) reaction around 100 keV deuteron energy has not been studied.

In view of the complexity of the low-energy deuteron interaction with lithium, the contradicted experimental results observed in previous studies, and the importance of the cross sections of deuteron induced reactions on lithium, we feel justified in doing measurements for 100 keV deuteron induced reactions on natural lithium, and the results are reported in the present paper.

In the present work, 100 keV deuteron induced reactions on natural lithium have been studied, and the differential and derived total cross sections have been presented. The motivation behind these studies is mainly from the applications of these data in fusion reactor technology. Low-energy deuteron induced reactions on light nuclei are also important for understanding nucleosynthesis.

Table I shows some of the exothermic reactions of deuterons with natural lithium.

II. EXPERIMENTAL PROCEDURE

A stainless-steel (SS) cylindrical shape chamber, of diameter ∼300 mm and height ∼200 mm, was used in this experiment. The chamber had four ports, 90° apart from each other on the curved surface. The bottom and the top sides of the chamber were closed with demountable SS flanges. The SS chamber was connected to the accelerating column of the ion accelerator through a T-shaped SS coupler, mounted on a vacuum system, consisting of rotary diffusion pumps. A special type of mechanical assembly was fitted on the bottom flange for holding a silicon surface barrier (SSB) detector and scattering target foil. Using this mechanical assembly, the SSB detector could be moved along a circular path around the natural lithium scattering foil mounted on the holder at the center of the bottom flange. One of the ports of the chamber was closed with a SS flange fitted with three BNC connectors. Each of these BNC were connected in such a way that the signal from the SSB detector mounted inside the chamber could be obtained outside the chamber, without any attenuation. The SSB detector output was connected to one of the BNC connectors inside the chamber. In this manner, the output of the SSB detector could be fed to a preamplifier with biasing facility. The output of the preamplifier was connected to an amplifier and a multichannel analyzer (MCA).

Ten natural lithium targets each of diameter ∼15 mm and thickness ∼2.7 mg/cm^2 were made in the laboratory. One lithium target was mounted in the experimental chamber attached to the accelerating column of the 200 keV ion accelerator. Deuteron ions of 100 keV energy were bombarded on the lithium target. The emitted protons and α particles were recorded at 30°, 50°, 90°, 120°, and 140° with respect to the deuteron beam direction using a silicon surface barrier detector.

A schematic diagram of the experimental arrangement inside the chamber is shown in Fig. 1. During the experiment, a pressure ∼1×10^{-6} Torr was maintained in the SS chamber. The separation between the lithium target and the SSB detector was ∼35 mm. The lithium target holder was electrically isolated from the SS chamber and connected to one of the BNC connectors. The other end of this BNC connector was connected to a current integrator. In this way, the lithium target holder could also serve as a Faraday cup for measuring the deuterium ion current. An 80-V potential was applied to the lithium target holder, which acts as a Faraday cup for the deuterium ions to suppress the secondary electrons.

The SSB detector had an active area of 25 mm^2 and a thickness of ∼100 μm; α particles up to 12 MeV produced through the (d,α) reaction could be stopped in the SSB

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TABLE I. Possible 100 keV deuteron induced reactions on natural lithium.

Reaction	Q value (MeV)
(1) ^{7}Li(d,α)^{5}He(g.s.)	14.15
(2) ^{7}Li(d,α)^{5}He*(2.6 MeV)	11.55
(3) ^{7}Li(d, n)^{8}Be	15.03
^{8}Be $\rightarrow \alpha + \alpha$	0.094
(4) ^{6}Li(d,α)^{4}He	22.36
(5) ^{6}Li(d, p_0)^{7}Li	5.03
(6) ^{6}Li(d, p_1)^{7}Li*(0.478 MeV)	4.55

detector. The SSB detector could be positioned at any angular position in the range 0° to 140° with respect to the center of the lithium foil target. The plane of the lithium target could also be kept 45° or 90° with respect to the direction of the incident deuterons. The SSB detector was calibrated using 5.48 MeV α particles emitted by an Am-241 source.

During the experiment, 100 keV deuterium ions were bombarded on the lithium target foil. Initially, the lithium target foil was positioned at 45° and the SSB detector at 90° with respect to the deuterium ion beam, as shown in Fig. 2(a). The energy-intensity spectrum of the emitted charged particles was recorded on a 4096-channel analyzer for 900 s.

Immediately after completion of the irradiation period, the accelerator was switched off, and the SSB detector was rotated to the 120° angular position. The experiment was repeated by bombarding 100 keV deuterons on the lithium target and the spectra of the emitted protons and α particles were recorded for 900 s. The experiment was repeated by positioning the detector at 140° and keeping all the experimental conditions identical to that of 90° and 120° angular positions.

In the measurements made at 90°, 120°, and 140°, the charged particles did not have to travel through the whole thickness of the lithium foil target. For the measurements at 30° and 50°, the lithium foil target was rotated in such a way that it subtended a 45° angle with the incident deuterium ion beam, as shown in Fig. 2(b). In this position, the α particles and protons produced in the reactions have to travel through

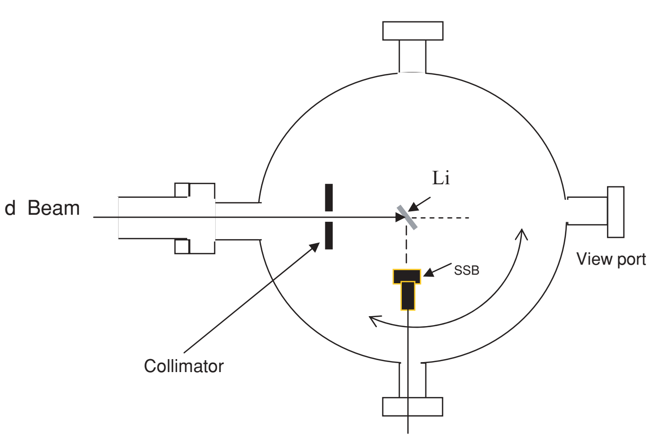

FIG. 1. (Color online) A schematic view of the experimental setup used for the measurement of angular distributions of charged particles.

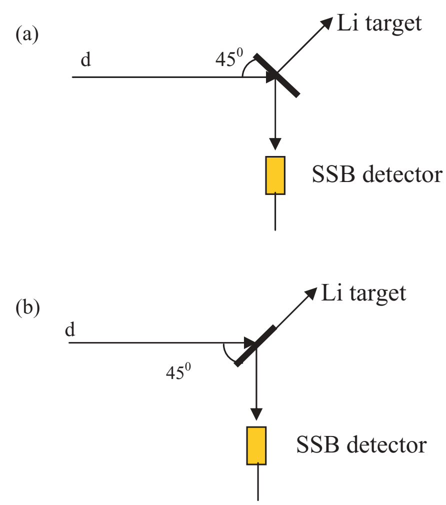

FIG. 2. (Color online) (a) Target position 1 and (b) target position 2.

the lithium foil target. The energies and intensities of the charged particles emitted at 90° could be compared for the two positions of the lithium foil target.

III. DATA ANALYSIS

The energy loss of the charged particles in the lithium foil was estimated by Monte Carlo calculations using the computer program SRIM-2006 [9]. The recorded charged particle spectrum was corrected for the energy loss in the scattering foil. From the recorded charged particle spectrum, the differential cross-section was estimated [10,11] by using the following relation;

$$\sigma(E,\theta) = \frac{C(E,\theta)}{k_E \phi_d N dE d\Omega_E/4\pi}, \quad [\mathrm{cm}^2/(\mathrm{sr\ MeV})] \qquad (1)$$

where $C(E,\theta)$ is the counting rate for the charged particles of energy E at scattering angle θ, k_E is the efficiency of the SSB detector (for charged particles, $k_E = 1$), φ_d is the deuteron flux, N is the number of target nuclei, dE is the detector resolution, and $d\Omega$ is the solid angle of the detector.

The total cross section was obtained by fitting the angular differential cross section with polynomials of a few orders. The integration was carried out over angles from 0° to 180°.

Because 100 keV deuterons have only an ~2.63 μm range in natural lithium, and our target thickness was 50.6 μm, this made it difficult to estimate the effective target thickness and the average deuteron energy, and this was the maximum source of error in the experimental analysis in the present work.

In the present work, the deuterium current was ~10 μA. It can be seen from Fig. 3 that the count rate of particles for 100 keV incident deuterons is low but just good enough for analysis. We also carried out experiments for the same deuteron current as that of 100 keV for incident energies of 50, 60, 70, 80 keV, but for the same counting time; no significant contributions were observed. Especially for 50, 60, and 70 keV, no peaks were observed. Hence we are confident that the cross

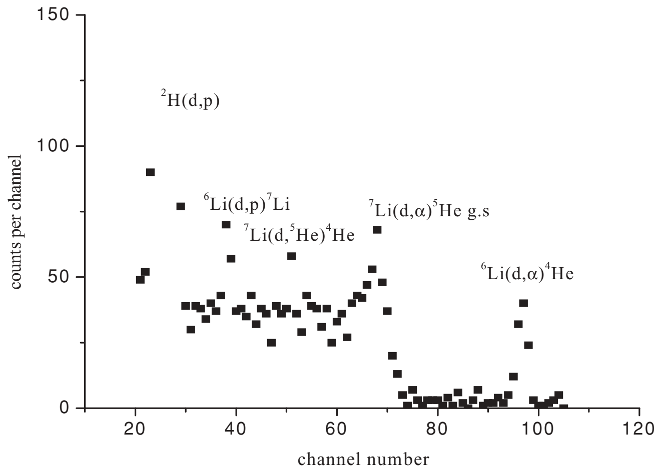

FIG. 3. Typical spectrum of the charged particles emitted at 90° when the lithium target at position 1 was bombarded by 100 keV deuterium ions.

sections for lower energy deuterons with lithium are very small for the beam current used in the present work.

The average deuteron energy, which is defined as that energy at which the measured cross section is equal to the true cross section, was determined following the approach of Elwyn *et al.* [8], in which the true cross section at the energy $\bar{E}_d$, $\sigma(\bar{E}_d)$, was set equal to the measured cross section and is given by the expression

$$\sigma(\bar{E}_d) = \int_0^t \frac{dE}{dx}\sigma(E)dx \Bigg/ \int_0^t \frac{dE}{dx}dx, \tag{2}$$

where t is the target thickness and dE/dx is the atomic stopping power of natural lithium, which is calculated using the SRIM-2008 program [9]. By evaluating Eq. (2) numerically, the average laboratory energy of the incident deuteron in the target foil was estimated to be ∼93 keV.

The effective target thickness was determined by lowering the beam energy to the average energy ∼93 keV and then doubling that thickness. The number of atoms, N, in Eq. (1) was then determined from the effective target thickness and was then substituted into Eq. (1) to determine the differential cross section. We quoted 10% uncertainty in the target thickness or number of nuclei.

From the total cross sections $\sigma(E_d)$ and E_d, the average energy in the center-of-mass frame estimated within the target from the incident energy of the ion beam and the energy loss of the beam in the target, the astrophysical S factor can be derived by the following expression [12]:

$$S(E) = \frac{1}{4\pi}\sigma(E_d)E_d \exp\left(\sqrt{\frac{E_G}{E_d}}\right), \tag{3}$$

where E_G is the Gamow energy given by

$$E_G = 0.989 Z_1^2 Z_2^2 \mu, \ \ [\text{MeV}] \tag{4}$$

where μ is the target projectile reduced mass in amu and Z_1 and Z_2 are the projectile and target charge number, respectively.

IV. RESULTS AND DISCUSSION

Figure 3 shows a typical spectrum of the charged particles emitted at 90° when the lithium target at position 1 was bombarded by 100 keV deuterium ions. The spectra of the charged particles emitted in the reactions ^{7}Li$(d,\alpha)^{5}$He(g.s.), ^{7}Li(d,^{5}He)^{4}He, ^{6}Li$(d,\alpha)\alpha$, and ^{6}Li$(d,p)^{7}$Li, as well as in the ^{2}H(d,p) reactions, are clearly seen in Fig. 3.

The uncertainty contributions to the cross section are mainly from the errors in (i) the target thickness (∼10%), (ii) the deuteron current (∼2%), (iii) the distances between the lithium target to the SSB detector (∼0.25%), (vi) the solid angle subtended by the detector (∼1%), (vii) counts due to the contributions from the electronic and detector dead time (∼2%), and (vii) the energy calibration of the detector (∼0.5%). In addition, an error of ∼10% to the cross section also appears from the analysis and extraction of the peak sum and uncertainty in estimating the total cross section from the polynomial. After adding all these errors in quadrature, the final estimated value of the uncertainty in the total cross section was ∼14%.

A. ^{6}Li$(d,\alpha)^{4}$He reaction

Figure 4 shows the angular distributions of the α particles emitted in the ^{6}Li$(d,\alpha)^{4}$He reaction induced by bombarding a natural lithium target with 100 keV deuterium ions. The data points are the experimental differential cross sections whereas the solid line represents the polynomial fit to the experimental angular distributions. The spectrum of the α particles emitted in the ^{6}Li$(d,\alpha)^{4}$He reaction is clearly observed at ∼11.3 MeV laboratory energy in Fig. 3.

From the plot of the angular distribution, shown in Fig. 4, it is observed that the intensity of the emitted particles is maximum near 0° and decreases gradually with the angle of emission. These results therefore reveal that the α particles are emitted predominantly through the process of direct reaction.

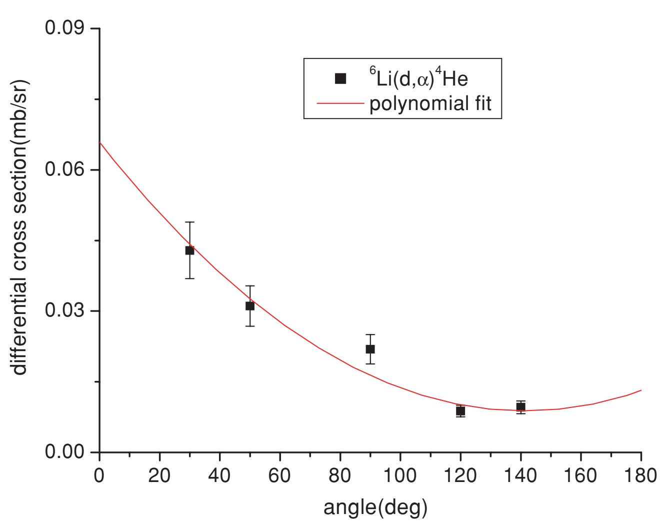

FIG. 4. (Color online) Angular distributions of α particles in the ^{6}Li$(d,\alpha)^{4}$He reaction. The data points are the measured values. The solid line is the polynomial fit to the experimental data points.

Elwyn *et al.* [8] reported an isotropic distribution up to ∼200 keV deuteron energy whereas the results of Feddenden and Maxson [6] suggested a highly forward peaked at 170 keV deuteron energy.

In the present experiment, we have observed that the thickness and angle of the target plane to the incident deuteron beam make changes in the intensities and energy distributions. For angles greater than 90°, target position 1 is ideal for recording the charged particle spectra. In this target position, thick aluminium backing can be put behind the lithium target, which helps in target cooling as well as in making it convenient to measure the fluence of the deuterium ions bombarded on the lithium foil. For any scattering angles less than 90°, the lithium target can be positioned at target position 2, as shown in Fig. 2(b). In this case, for the forward angle measurements, the charged particles have to travel through the whole thickness of the lithium target. The requirement of having a thin target is very stringent in this case.

In the present experiment, since the natural lithium target is of thickness ∼2.7 mg/cm^2, the charged particle spectra were recorded at 90° for both positions 1 and 2 of the target. The differences in the intensities and energies were identified and used in the analysis of the 30° and 50° spectra.

The total cross section of the ^{6}Li(d,α)^{4}He reaction estimated by integrating the differential cross sections over angles from 0° to 180° is ∼0.4819 ± 0.0675 mb.

B. ^{6}Li(d,p_0)^{7}Li and ^{6}Li(d,p_1)^{7}Li*(0.478 MeV) reaction

Figure 5 shows the angular distributions of protons from the ^{6}Li(d,p_0)^{7}Li and ^{6}Li(d,p_1)^{7}Li*(0.478 MeV) reactions. For the ^{6}Li(d,p_0)^{7}Li reaction, the peak in the proton spectrum recorded at 90° is observed at ∼4.4 MeV laboratory energy in Fig. 3. Moreover, as observed in Fig. 3, the protons from ^{6}Li(d,p_0)^{7}Li and ^{6}Li(d,p_1)^{7}Li* (0.478 MeV) reactions could be separated in energies in the spectrum recorded at 90°. However, in the spectrum recorded at angles less than 90°, it is rather difficult to separate out protons emitted from ^{6}Li(d,p_0)^{7}Li and ^{6}Li(d,p_1)^{7}Li*(0.478 MeV) reactions. In the present work, therefore, the sum of the energies of the protons emitted in these two reactions were considered for estimating the differential as well as the total reaction cross sections for the emission of protons. As seen in the Fig. 5, although the angular distribution is close to isotropic, the protons are still emitted favorably in the forward directions compared to the backward angles.

The total cross section for the emission of protons in ^{6}Li(d,p_0)^{7}Li and ^{6}Li(d,p_1)^{7}Li*(0.478 MeV) reactions estimated by integrating the differential cross sections over angles from 0° to 180° is 1.2135 ± 0.1699 mb.

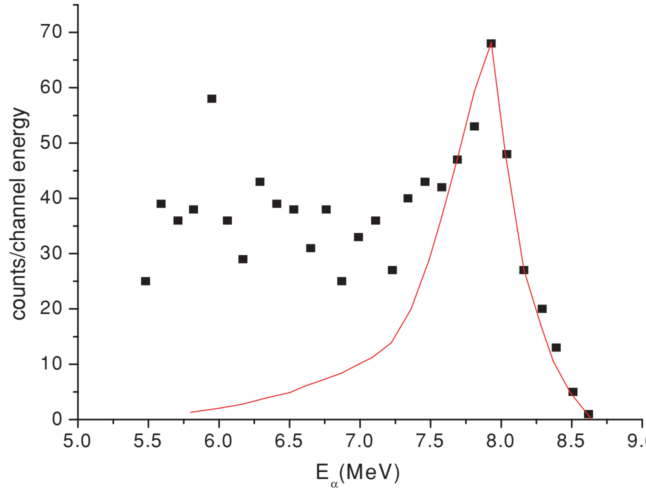

FIG. 6. (Color online) The energy spectrum of the α particles in the ^{7}Li(d,α)^{5}He(g.s.) reaction. The data points are the measured values of the present work. The solid line represents the theoretical α spectrum obtained by following the approach of Weber [4].

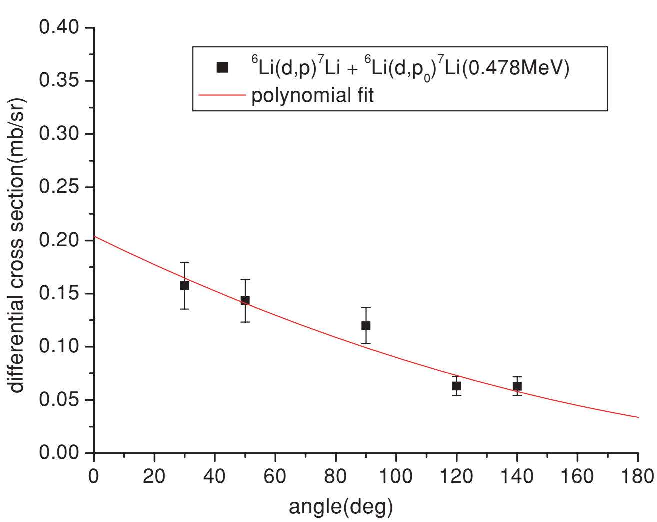

FIG. 5. (Color online) Angular distributions of protons from ^{6}Li(d,p_0)^{7}Li and ^{6}Li(d,p_1)^{7}Li*(0.478 MeV) reactions. The data points are the experimental values of the present work. The solid line is the polynomial fit to the experimental data points.

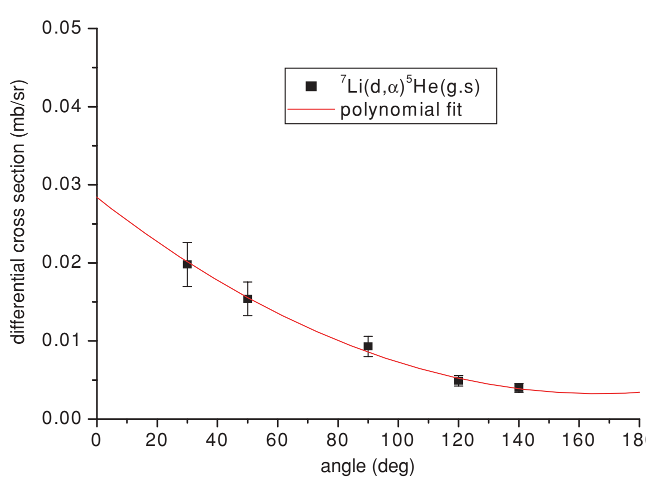

FIG. 7. (Color online) Angular distributions of the α particles emitted in the ^{7}Li(d,α)^{5}He(g.s.) reaction. The data points are the measured values of the present work. The solid line is the polynomial fit to the experimental data points.

TABLE II. Present experimental results along with literature values.

Reaction	Present cross section (mb)	Literature cross section (mb)	S factor (B MeV)
^{6}Li(d,α)^{4}He	0.4819 ± 0.0675	0.537 ± 0.0535 [13] 0.55 ± 0.05 [14] 0.3846 ± 0.011 [15]	6.11 ± 0.92
^{6}Li(d, p_0)^{7}Li + ^{6}Li(d, p_1)^{7}Li*(0.478 MeV)	1.2135 ± 0.1699	–	15.39 ± 2.31
^{6}Li(d, p_0)^{7}Li		0.76 ± 0.07 [14] 0.76 ± 0.07 [13]	
^{7}Li(d,α)^{5}He(g.s.)	0.2088 ± 0.0292	no data available	4.40 ± 0.66

C. ^{7}Li(d,α)^{5}He ground-state reaction

The α spectrum expected from $d + {}^7$Li is very complex, containing all groups originating in two possible reactions [5]:

(i) $d + {}^7\text{Li} \rightarrow ({}^9\text{Be}^*) \rightarrow {}^8\text{Be}^* + n \rightarrow 2\alpha + n$,
(ii) $d + {}^7\text{Li} \rightarrow ({}^9\text{Be}^*) \rightarrow {}^5\text{He} + \alpha \rightarrow 2\alpha + n$.

To estimate the differential cross section of the ^{7}Li(d,α)^{5}He(g.s.) reaction from the spectrum observed in Fig. 3, it is therefore necessary to remove the background. The background subtraction is done by fitting the theoretical α spectrum on the experimental spectrum as suggested by Weber [4], and the peak sum is then obtained. Figure 6 shows the energy spectrum of the α particles in the ^{7}Li(d,α)^{5}He(g.s.) reaction. The data points are the measured values of the present work. The solid line represents the theoretical α spectrum obtained by following the approach of Weber [4]. Weber assumed the (d,α) reaction to proceed via a compound state in ^{9}Be. The relative probability of the α particle being emitted with an energy E is given by the probability of ^{9}Be for α decay to the ^{5}He ground state times the density of final states [4], that is,

$$\frac{dN(E)}{dE} = \Gamma_\alpha(Q_1)\frac{\Gamma_n(Q_2)}{\left[E_{3/2} + \Delta_{3/2}(Q_2) - Q_2\right]^2 + \left[\frac{1}{2}\Gamma_n(Q_2)\right]^2}, \tag{5}$$

where $Q_1 + Q_2 = 15.11$ MeV and $E = (5/9)Q_1 + (1/3)E_d$; Q_1 and Q_2 are the Q values for the reactions ^{7}Li(d,α)^{5}He and $^5\text{He} \rightarrow {}^4\text{He} + n$, respectively; $\Gamma_\alpha(Q_1)$ and $\Gamma_n(Q_2)$ are the corresponding partial widths; and $E_{3/2}$ is the level energy of ^{5}He and $\Delta_{3/2}(Q_2)$ is the level shift. Figure 7 shows the angular distributions of the α particles in the ^{7}Li(d,α)^{5}He(g.s.) reaction induced by 100 keV deuterium ions. The data points are the measured values of the differential cross sections of the present work. The solid line represents the polynomial fit to the experimental angular distributions. As observed in Fig. 3, in the recorded spectrum of the α particles emitted in the ^{7}Li(d,α)^{5}He(g.s.) reaction, the peak of the cross section appeared at ~8.2 MeV laboratory energy. A literature survey indicates that so far no experimental differential nor total cross section values exist below 150 keV deuteron incident energy for this reaction.

The total cross section of the ^{7}Li(d,α)^{5}He(g.s.) reaction obtained by integrating the differential cross sections over angles from 0° to 180° is 0.2088 ± 0.0292 mb. The measured values of the total reaction cross sections along with the corresponding literature values of the cross sections at 100 keV incident deuteron energy are presented in Table II. Moreover, the values of the S factor have been derived and are also given in Table II.

V. CONCLUSION

The angular distributions of the emitted protons and α particles in the reactions induced by bombarding natural lithium with 100 keV deuterium ions have been studied. The differential cross sections have been estimated, and the total cross sections have been derived by integrating the differential cross sections over angles from 0° to 180°. As observed in Table II, the present experimental cross sections agree with the literature values. A literature survey indicates that this is the first time the total cross section for the ^{7}Li(d,α)^{5}He(g.s.) reaction induced by 100 keV deuterium ions has been measured.

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[1] J. H. Williams, W. G. Shepherd, and R. O. Haxby, Phys. Rev. **52**, 390 (1937).
[2] E. N. Strait, D. M. Van Patter, W. W. Buechner, and A. Sperduto, Phys. Rev. **81**, 747 (1950).

[3] S. H. Levine, R. S. Bender, and J. N. McGruer, Phys. Rev. **97**, 1249 (1954).
[4] G. Weber, Phys. Rev. **110**, 529 (1958).
[5] P. Paul and D. Kohler, Phys. Rev. **129**, 2698 (1963).
[6] P. Fessenden and D. R. Maxson, Phys. Rev. **133**, B71 (1963).
[7] M. Manalis and J. E. Henkel, Phys. Rev. **136**, B1741 (1964).
[8] A. J. Elwyn, R. E. Holland, C. N. Davis, L. Meyer-Schtzmeister, J. E. Monahan, F. P. Mooring, and W. Ray Jr, Phys. Rev. C **16**, 1744 (1977).
[9] J. F. Ziegler, SRIM-2006.02 version (c), 2006, http://www.srim.org/.
[10] K. Kondo, S. Takagi, I. Murata, H. Miyamaru, A. Takahashi, N. Kubota, K. Ochiai, and T. Nishitani, Fusion Eng. Des. **81**, 1527 (2006).
[11] B. Lalremruata, S. D. Dhole, S. Ganesan, and V. N. Bhoraskar, Nucl. Phys. **A821**, 23 (2009).
[12] J. Yan, F. E. Cecil, J. A. McNeil, and M. A. Hofstee, Phys. Rev. C **55**, 1890 (1996).
[13] Z. T. Body, J. Szabo, and M. Varnagy, Nucl. Phys. **A330**, 495 (1979).
[14] J. Szabo, M. Varnagy, Z. T. Body, and J. Csikai, Nucl. Instrum. Methods Phys. Res. **154**, 557 (1978).
[15] G. A. Sawyer and J. A. Phillips, Nucl. Phys. **A269**, 61 (1976).