Measurement of ^{2}H(^{8}Li, ^{9}Be)$_n$ Reaction Relevant to Primordial Nucleosynthesis *

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The angular distribution of the ^{2}H(^{8}Li, ^{9}Be)$_n$ (ground state) reaction, important to primordial nucleosynthesis in the inhomogeneous model, has been measured at $E_{\rm c.m.} = 8.1$ MeV using a secondary ^{8}Li beam. Cross section of this reaction was determined to be 9.0 ± 3.4 mb. According to the cross section, the astrophysical S-factor was calculated to be 272 ± 103 keV b. It is shown that ^{2}H(^{8}Li, ^{9}Be)$_n$ (ground state) reaction is important for creating ^{9}Be, but less important for destroying ^{8}Li in primordial nucleosynthesis.

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In a large variety of astrophysical objects, nuclear reactions play a pivotal role for both energy production and nucleosynthesis. The standard model[1−3] is known to be in fairly good agreement with primordial abundances of nuclides up to mass number $A = 7$, and to produce very tiny abundances of the high-mass elements primarily due to the lack of stable particles at $A = 5$ and 8. The recently developed inhomogeneous models[4−8] predict considerably higher abundances for ^{7}Li and heavier nuclides than the standard model. This occurs because the inhomogeneous models assume a universe with regions of high-density proton-rich material surrounded by those of low-density neutron-rich materials, while the standard model assumes a homogeneous isotropic early universe. Due to these inhomogeneities, short-lived isotopes are created, which allow for more reaction pathways to the heavier elements. On the other hand, reactions involving short lived nuclei are of particular interest in nuclear physics and nuclear astrophysics because they relate to the unusual isospin, spin and energy transfer.

The ^{8}Li(d,n) ^{9}Be (ground state) reaction ($Q =$ 14.663 MeV) is potentially important because it not only destroys ^{8}Li but also creates ^{9}Be, which acts as a precursor to heavier isotopes. Because of the high Q value, the ^{8}Li(d,n) reactions leading to the excited states of ^{9}Be are also possible, whereas they mainly result in the destruction of ^{8}Li since these excited states decay primarily through particle emission. An earlier measurement of the ^{8}Li(d,n) ^{9}Be (ground state) reaction, performed at $E_{\rm c.m.} = 1.5$–2.8 MeV,[9] presented the cross sections and astrophysical S factors.

In this Letter, we briefly report our experiment of the ^{8}Li(d,n) ^{9}Be(ground state) reaction at $E_{\rm c.m.} =$ 8.1 MeV in inverse kinematics with a secondary ^{8}Li beam and the analysis of the angular distribution.

The experiment was carried out using the secondary beam facility GIRAFFE[10] of the HI-13 tandem accelerator at the China Institute of Atomic Energy, Beijing. The experimental setup was similar to that previously illustrated.[11,12] A 44-MeV ^{7}Li beam from the tandem impinged on a D_2 gas cell at a pressure of 1.5 atm, produced ^{8}Li ions through the ^{2}H(^{7}Li, ^{8}Li) ^{1}H reaction. The front and rear windows of the gas cell were Havar foils, each with a thickness of 1.9 mg/cm^2. After the magnetic separation and focus with a dipole and a quadruple doublet, the 40.38 MeV ^{8}Li beam was delivered. Typical purity of the ^{8}Li beam was about 88%, the main contaminants were ^{7}Li ions from the Rutherford scattering of the primary beam in the gas cell windows and the beam tube. The typical beam intensity on the target was approximately 400 pps. The beam energy spread on the target was 0.52 MeV full width half maximum (FWHM) for long term measurement.

The ^{8}Li beam was then collimated by an aperture with a diameter of 3 mm and directed onto a $(CD_2)_n$ target with a thickness of 1.5 mg/cm^2 to study the ^{2}H(^{8}Li, ^{9}Be)$_n$ reaction. A carbon target in thickness 1.8 mg/cm^2 was used to measure the background. The reaction products were detected and identified by using a $\Delta E - E_r$ (residue energy) counter telescope. In the telescope, the ΔE detector was a 19.3-μm-thick silicon detector; the E_r detector consisted of a 300-μm-thick three-ring silicon detector and an independent silicon detector placed at the central hole. The inverse kinematics of the ^{2}H(^{8}Li, ^{9}Be)$_n$ reaction restricted the maximum emission angle of ^{9}Be ions to about 16.4°. The experimental setup is shown in Fig. 1 covered an angular region up to 12°.

The experimental setup also enabled us to determine the accumulated quantity of incident ^{8}Li ions precisely because the ^{8}Li themselves were recorded

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by a counter telescope simultaneously. The measurement for the $(CD_2)_n$ target accumulated approximately 7.9×10^7 ^{8}Li events, while the background measurement with the carbon target accumulated about 2.4×10^7 ^{8}Li events.

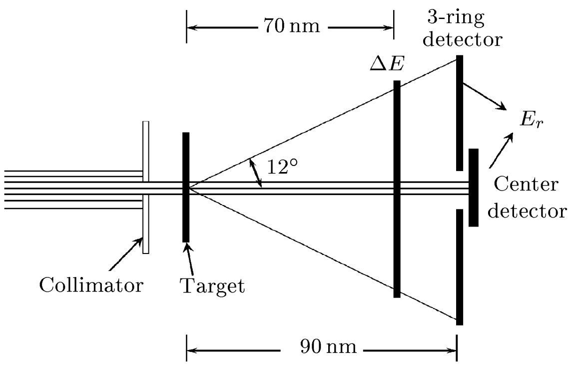

Fig. 1. Experimental setup.

The scatter plot of ΔE versus E_r from a few runs with the $(CD_2)_n$ target recorded by the first ring of the detector is shown in Fig. 2. In order to make particle identification, we constructed the scatter plot of E_t (total energy) versus θ_{lab} for the events within the ^{9}Be gate in Fig. 2, where the gray zone is the kinematics region of ^{9}Be ground state, based on Monte Carlo simulation, as shown in Fig. 3. This figure shows further that the events within the ^{9}Be gate in Fig. 2 are the true ^{9}Be products. We have obtained 21 ± 8 ^{9}Be events, and have not found any background in the ^{9}Be gate for the C target measurement. After correcting the dead gaps of the three-ring detector, we have obtained 24 ± 10 ^{9}Be events.

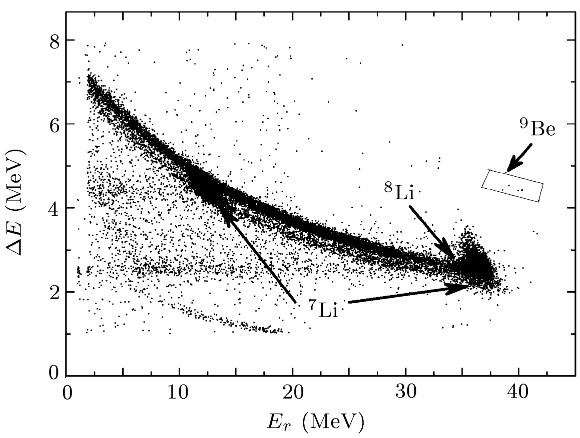

Fig. 2. Scatter plot of ΔE versus E_r for the first ring of the detector.

The angular distributions in the c.m. system are shown in Fig. 4. The zero-range distorted-wave Born approximation (DWBA) code was adopted in the analysis of data. The mechanism of a deuteron stripping reaction or a transfer reaction at small angles has been well established. The ambiguities in the DWBA calculation are due to the choice of parameters of optical potentials. The angular distributions calculated using two different sets of optical potential parameters were presented in Fig. 4. The parameters used in the DWBA calculation are listed in Table 1. All the exit channel parameters were taken from Ref. [13], the entrance channel ones from Refs. [13] and [14]. The total cross section calculated by the integration over full angular range was 9.0 ± 3.4 mb. The uncertainty of the cross section results mainly from the difference of calculated angular distributions with two sets of optical potentials as well as the statistical error of the measurement. The astrophysical S factor at the present energy was 272 ± 103 keV b.

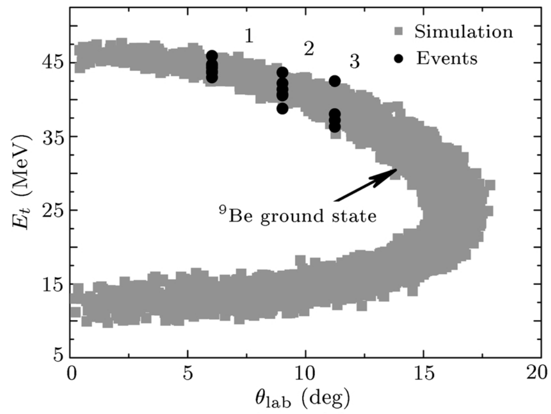

Fig. 3. Scatter plot of E_t versus q_{lab} for the events within the ^{9}Be gate in Fig. 2. The ring numbers are indicated.

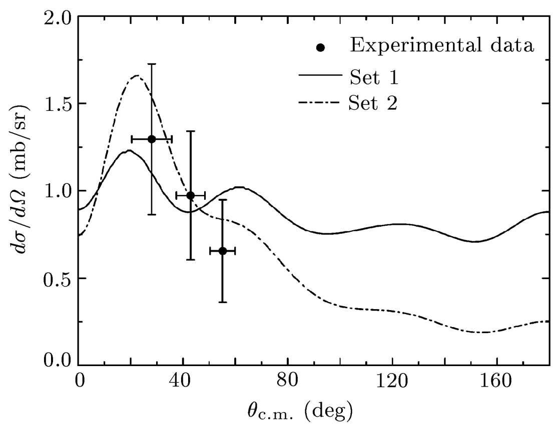

Fig. 4. Angular distribution of ^{2}H(^{8}Li, ^{9}Be)$_n$ reaction, compared with two DWBA calculations.

Table 2 lists the results for ^{8}Li(d,n) ^{9}Be (ground state) reaction, obtained in this work and the earlier experiment.[9] It can be seen that the cross sections and astrophysical S factors, at several energies ranging from 1.5 to 8.1 MeV are roughly unchanged within the errors. The cross section of ^{8}Li(d,n) ^{9}Be (ground state) reaction is considerably smaller than those of

Table 1. The optical potential parameters used in the DWBA calculation. V and W in units of MeV, r and a in units of fm.

Set	Channel	V	r	a	W	r_W	a_W	W_D	r_D	a_D	V_{SO}	r_{SO}	A_{SO}	r_C
1	Entrance[13]	118.0	1.0	0.94				6.87	1.98	0.59	8.5	1.00	0.94	1.30
	Exit[13]	40.7	1.4	0.62				22.2	1.40	0.39	5.0	1.40	0.62	
2	Entrance[14]	87.2	1.2	0.73	0.12	1.3	0.66	12.3	1.32	0.66	7.0	1.07	0.66	1.30
	Exit[13]	45.5	1.2	0.75	4.0	1.3	0.58	5.34	1.26	0.58	6.2	1.01	0.75	

Table 2. The cross sections and astrophysical S factors for ^{2}H(^{8}Li, ^{9}Be$_{\mathrm{g.s.}}$)$_n$ reaction at different energies.

$E_{\mathrm{c.m.}}$ (MeV)	σ_{tot} (mb)	S-factor (keV b)	
1.5 ± 0.1	6.9 ± 1.9	220 ± 61	Ref. [9]
2.0 ± 0.1	4.6 ± 1.7	132 ± 49	
2.4 ± 0.1	6.2 ± 2.4	168 ± 65	
2.8 ± 0.1	8.9 ± 1.9	236 ± 50	
8.1 ± 0.5	9.0 ± 3.4	272 ± 103	Present

^{8}Li(αn) ^{11}B[15] and ^{8}Li(d,t) ^{7}Li[9] reactions which are thought to be of importance for ^{8}Li destruction.

In summary, the angular distribution of the ^{8}Li(d,n) ^{9}Be (ground state) reaction was measured at $E_{\mathrm{c.m.}} = 8.1\,\mathrm{MeV}$ by using ^{8}Li secondary beam. By the DWBA analysis of the experimental data, we determined the cross section and astrophysical S factor to be 9.0 ± 3.4 mb and 272 ± 103 keV b, respectively. Our result implies that the ^{8}Li (d,n) ^{9}Be (ground state) reaction is important for creating ^{9}Be, but less important for destroying ^{8}Li in the primordial nucleosynthesis. However, the cross section of ^{8}Li (d,n) ^{9}Be* reaction leading to ^{9}Be excited states may be significantly larger than that to the ^{9}Be ground state. If one takes all the open channels into account, then the ^{8}Li(d,n) ^{9}Be reaction might play an important role for ^{8}Li destruction. It is therefore highly needed to carry out the experimental study of ^{8}Li(d,n) ^{9}Be* reaction.

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