Astrophysical Reaction Rates of the ^{8}Li(p,γ)^{9}Be$_{\rm g.s.}$ Direct Capture Reaction *

SU Jun(苏俊), LI Zhi-Hong(李志宏)**, GUO Bing(郭冰), LIU Wei-Ping(柳卫平), BAI Xi-Xiang(白希祥), ZENG Sheng(曾晟), LIAN Gang(连钢), YAN Sheng-Quan(颜胜权), WANG Bao-Xiang(王宝祥), WANG You-Bao(王友宝)

China Institute of Atomic Energy, PO Box 275(46), Beijing 102413

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Based on the angular distribution of the ^{8}Li(d,n)^{9}Be$_{\rm g.s.}$ reaction at $E_{\rm c.m.}$ = 8.0 MeV and distorted wave Born approximation analysis, the single particle spectroscopic factor $S_{1,3/2}$ for the ground state of ^{9}Be = ^{8}Li$\otimes p$ is derived to be 0.64 ± 0.21. In addition, we deduce the astrophysical S-factors and rates of the ^{8}Li(p,γ)^{9}Be$_{\rm g.s.}$ direct capture reaction at energies of astrophysical interests.

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The standard big-bang model (SM),[1–3] which assumes a homogeneous isotropic early universe, has proven to be very successful for predicting the primordial abundances of the light elements up to ^{7}Li, but it does not produce significant yields beyond $A = 7$ because of the particle instability gap at $A = 8$. However, the inhomogeneous models (IMs)[4–9] allow a higher production of $A > 8$ nuclides because the IMs assume a universe with regions of high-density proton-rich materials surrounded by those of low-density neutron-rich ones. In these inhomogeneous environments, unstable isotopes can be generated to open up more reaction pathways to the heavier nuclides. Among them, the ^{8}Li(α,n)^{11}B reaction plays a crucial role in bridging the $A = 8$ gap. Since the synthesis of the heavier nuclides via ^{8}Li scales with the ^{8}Li abundance during primordial nucleosynthesis, all the reactions which create or destroy ^{8}Li are important in the IMs.

The ^{8}Li(p,γ)^{9}Be$_{\rm g.s.}$ reaction is of importance because it not only destroys ^{8}Li but also leads to the production of ^{9}Be, which serves as a precursor to heavier nuclides. Moreover, ^{8}Li(p,γ)^{9}Be$_{\rm g.s.}$ is involved in the extend reaction network for the r-process nucleosynthesis occurring with type-II supernovae.[10,11] To the best of our knowledge, there has not yet been any experimental information concerning ^{8}Li(p,γ)^{9}Be$_{\rm g.s.}$ cross section.

In this Letter, the single particle spectroscopic factor for the ground state of ^{9}Be = ^{8}Li$\otimes p$ is extracted from the ^{8}Li(d,n)^{9}Be$_{\rm g.s.}$ angular distribution, based on the distorted wave Born approximation (DWBA) analysis. We then deduce the astrophysical S-factors and rates of the ^{8}Li(p,γ)^{9}Be$_{\rm g.s.}$ direct capture reaction at energies of astrophysical interests.

Recently, we have measured the ^{8}Li(d,n)^{9}Be$_{\rm g.s.}$ angular distribution in inverse kinematics using 40-MeV secondary ^{8}Li beam. The experiment was carried out using the secondary beam facility GIRAFFE[12,13] of the HI-13 tandem accelerator at China Institute of Atomic Energy, Beijing. A 44-MeV primary ^{7}Li beam from the tandem accelerator bombarded a deuterium gas cell with the pressure of 1.5 atm to yield ^{8}Li ions via the ^{2}H(^{7}Li, ^{8}Li)^{1}H reaction. The front and rear windows of this gas cell are both Havar foils with the thickness of 1.9 mg/cm^2. The ^{8}Li ions were selected from the contaminants by using the magnetic separation and focusing system composed of a dipole and a quadrupole doublet. The ^{8}Li beam with the energy of 40 MeV was collimated by a ϕ5 mm and a ϕ3 mm apertures and then directed onto a 1.5 mg/cm^2 thick deuterated polyethylene (CD$_2$)$_n$ target to study the ^{8}Li(d,n)^{9}Be$_{\rm g.s.}$ reaction. The experiment details have been reported elsewhere.[14] Figure 1 shows the measured ^{8}Li(d,n)^{9}Be$_{\rm g.s.}$ angular distribution.

The ^{8}Li(d,n)^{9}Be$_{\rm g.s.}$ cross section is dominated by the proton transfer to 1p3/2 orbit in ^{9}Be. The differential cross section can be computed by

$$\frac{d\sigma}{d\Omega}(\theta)_{\rm EXP} = S_d S_{1,3/2}\frac{d\sigma}{d\Omega}(\theta)_{\rm DWBA}, \qquad (1)$$

where $\frac{d\sigma}{d\Omega}(\theta)_{\rm EXP}$ and $\frac{d\sigma}{d\Omega}(\theta)_{\rm DWBA}$ refer to the measured and DWBA differential cross sections, respectively; S_d and $S_{1,3/2}$ are the spectroscopic factors for deuteron and the ground state of ^{9}Be = ^{8}Li$\otimes p$, respectively. In our calculation, S_d is extracted to be 0.859 based on the asymptotic normalization coefficient (ANC) of 0.872 fm$^{-1/2}$ from Ref. [15]. Because the transfer differential cross section at forward angles is insensitive to the parameters of optical potential,[16] we only use the first two experimental points to derive $S_{1,3/2}$.

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** Email: junsu@iris.ciae.ac.cn

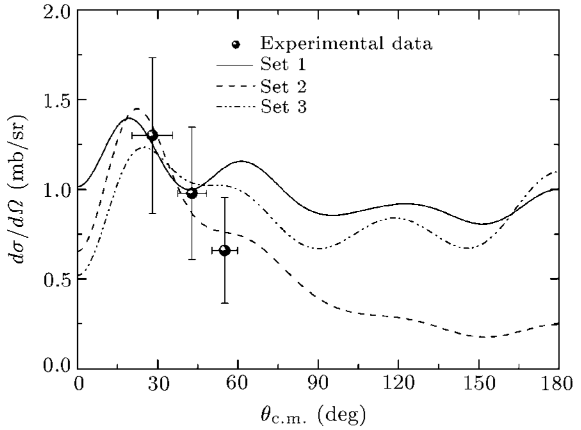

Fig. 1. Measured angular distribution of ^{8}Li$(d,n)^9$Be$_{\rm g.s.}$ at $E_{\rm c.m.} = 8.0$ MeV, together with DWBA calculations using three sets of optical potential parameters.

The zero-range DWBA code DWUCK4[17] is employed in the analysis of experimental data. The uncertainty in the DWBA calculation is mainly caused by the choice of optical potential parameters. We adopt three sets of optical potential parameters for d+^{8}Li from Refs. [18–20] and n+^{9}Be from Refs. [18,21], as listed in Table 1. Fig. 1 presents the normalized angular distributions, each curve corresponding to one $S_{1,3/2}$, the average value of the spectroscopic factors is found to be 0.64 ± 0.21 with the "standard" bound state potential parameters (radius $r_0 = 1.25$ fm, diffuseness $a = 0.65$ fm). The uncertainty results from the statistical error of the measurement (25%) and the difference of the optical potential parameters used in the DWBA calculation (21%).

Table 1. The optical potential parameters used in DWBA calculation and the corresponding spectroscopic factors, where V and W are in units of MeV, r and a in fm, the geometrical parameters of single particle bound state are set to be $r_0 = 1.25$ fm and $a = 0.65$ fm.

Set No.	1		2		3	
Channel	in [18]	out [18]	in [19]	out [18]	in [20]	out [21]
V_r	118.0	40.7	87.2	45.5	124.4	50.3
r_r	1	1.4	1.2	1.2	0.9	1.1
a_r	0.94	0.62	0.73	0.75	0.86	0.57
W			0.12	4		
r_w			1.3	1.3		
a_w			0.66	0.58		
W_s	6.87	22.2	12.3	5.34	5.1	8.1
r_s	1.98	1.4	1.32	1.26	1.54	1.13
a_s	0.59	0.39	0.66	0.58	0.79	0.5
V_{so}	8.5	5	7	6.2	7	5.5
r_{so}	1	1.4	1.07	1.01	1.64	1.13
a_{so}	0.94	0.62	0.66	0.75	0.81	0.57
r_c	1.3		1.3		1.63	
$S_{1,3/2}$	0.69 ± 0.17		0.74 ± 0.19		0.49 ± 0.12	

In a low energy region of astrophysical relevance, the ^{8}Li$(p,\gamma)^9$Be$_{\rm g.s.}$ cross section is believed to be dominated by the E1 radiative capture of s-wave proton to the ground state of ^{9}Be. The cross section for E1 capture of proton can be expressed as

$$\sigma_t = \frac{16\pi}{9}\left(\frac{E_\gamma}{\hbar c}\right)^3 \frac{e_{\rm eff}^2}{k^2}\frac{1}{\hbar v}\frac{(2I_f+1)}{(2I_1+1)(2I_2+1)} S_{l_f j_f} \times \left|\int_0^\infty r^2 w_{l_i}(kr) u_{l_f}(r) dr\right|^2, \tag{2}$$

where E_γ is the γ-ray energy, v is the relative velocity between proton and ^{8}Li, I_1, I_2 and I_f are the spins of proton, ^{8}Li and ^{9}Be, respectively; $e_{\rm eff} = eN/A$ represents the proton effective charge for the E1 transition in the potential produced by a target nucleus with mass number A and atomic number Z; $w_{l_i}(kr)$ refers to the distorted radial wavefunction for the entrance channel, and $u_{l_f}(r)$ is the radial wavefunction of the bound state of ^{9}Be which can be calculated by solving the respective Schrödinger equation.

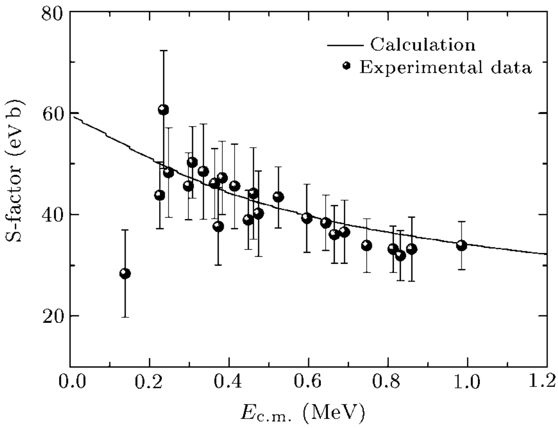

Fig. 2. S-factors for the ^{6}Li$(p,\gamma)^7$Be$_{\rm g.s.}$ direct capture reaction, the experimental data (filled circles) are taken from Ref. [22].

Presently, the optical potential for the low energy proton scattering on unstable nucleus ^{8}Li remains unavailable experimentally. We assume that the imaginary part of the potential is so small that it can be neglected because of the small flux into other reaction channels. For the real part, a Wood–Saxon potential is adopted, for which r_0 and a are set as the same as those for the bound state of ^{9}Be = ^{8}Li$\otimes p$, and the depth is adjusted to reproduce the volume integral of potential per nucleon. Usually, the optical potential changes considerably for different nuclei, whereas the volume integral of potential per nucleon is relatively a more stable quantity. We use the same r_0 and a to calculate the ^{6}Li$(p,\gamma)^7$Be$_{\rm g.s.}$ reaction, whose direct capture cross sections have been measured at low energies,[22] as shown in Fig. 2. By fitting the experimental data, we find the volume integral of potential per nucleon $\mathrm{J_V/A} = 563 \pm 37$ MeV fm^{-3}.

The energy dependence of direct capture cross section for the ^{8}Li$(p,\gamma)^9$Be$_{\rm g.s.}$ reaction is then calculated with the spectroscopic factor and the optical potential model. We have also computed the astrophysical S-factor as a function of the center-of-mass energy $E_{\mathrm{c.m.}}$, as shown in Fig. 3. The zero energy S-factor is then found to be $S(0) = 0.16 \pm 0.08\,\mathrm{keV\,b}$. The error results from the uncertainties of spectroscopic factor (33%) and the volume integral of potential per nucleon (39%).

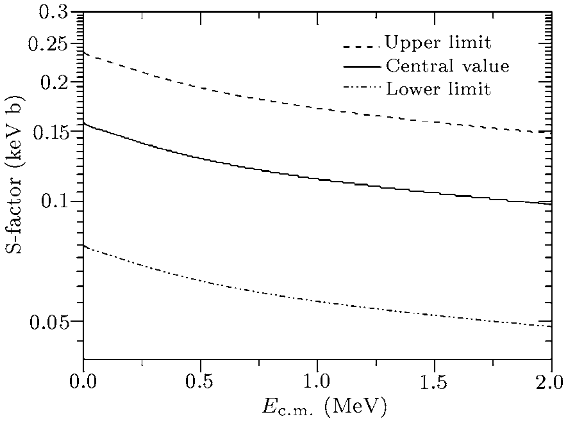

Fig. 3. S-factors for the $^8\mathrm{Li}(p,\gamma)^9\mathrm{Be}_{\mathrm{g.s.}}$ direct capture reaction.

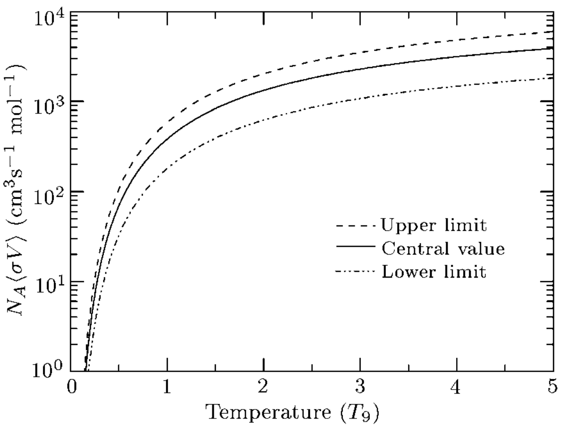

Fig. 4. Reaction rates for the $^8\mathrm{Li}(p,\gamma)^9\mathrm{Be}_{\mathrm{g.s.}}$ direct capture reaction at the temperatures of astrophysical interest.

Usually, the temperature dependence of reaction rate for the direct capture can be calculated by

$$N_A\langle\sigma v\rangle = N_A\left(\frac{8}{\pi\mu}\right)^{1/2}\frac{1}{(k_BT)^{3/2}} \times\int_0^\infty S(E)\exp\left[-\frac{E}{k_BT}-\frac{b}{E^{1/2}}\right]dE, \tag{3}$$

where N_A is the Avogadro number, μ is the reduced mass of the system, k_B is Boltzmann constant, and b is given by

$$b = \frac{(2\mu)^{1/2}\pi e^2 Z_1 Z_2}{\hbar}, \tag{4}$$

the square of b is so-called the Gamow energy.

By substituting the S-factors given in Fig. 3 into Eq. (3), we obtain the $^8\mathrm{Li}(p,\gamma)^9\mathrm{Be}_{\mathrm{g.s.}}$ direct capture reaction rates at temperatures of astrophysical relevance, as shown in Fig. 4. The solid, dashed and dashed-dotted lines are the central value, upper limit and the lower limit, respectively.

In summary, we have extracted the single particle spectroscopic factor for the ground state of $^9\mathrm{Be} = {}^8\mathrm{Li}\otimes p$ through the DWBA analysis of the experimental angular distribution for $^8\mathrm{Li}(d,n)^9\mathrm{Be}_{\mathrm{g.s.}}$ By using the spectroscopic factor, we derive the astrophysical S-factors and rates for the $^8\mathrm{Li}(p,\gamma)^9\mathrm{Be}_{\mathrm{g.s.}}$ direct capture reaction of astrophysical relevance, for the first time.

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