Astrophysical Rates for the ^{6}He(p, γ)^{7}Li Reaction *

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Angular distribution of the ^{6}He$(d,n)^7$Li reaction at $E_{\rm c.m.}$=9.1 MeV is measured in inverse kinematics for the first time. The proton spectroscopic factors for the ground and first excited states of ^{7}Li are derived by using the distorted wave Born approximation analysis. The astrophysical rates of ^{6}He$(p,\gamma)^7$Li reaction are then deduced and fitted with an expression of REACLIB.

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The standard Big Bang nucleosynthesis (SBBN) model provides a reliable framework for understanding the origin and evolution of the Universe because of the success in explaining the large abundance of ^{4}He with accuracy of one percent. The SBBN model is also successful in predicting primordial abundances of ^{2}H and ^{3}He. However, there are clear discrepancies between calculations and observations of lithium abundances since the discovery of a plateau for lithium abundance in mental-poor halo stars by the Spites.[1]

According to the SBBN model, the abundances of hydrogen, deuterium, helium and lithium only depend on the baryon to photon ratio η. Using the precise value of $\eta = (6.14 \pm 0.25) \times 10^{-10}$ determined by Wilkinson Microwave Anisotropy Probe (WMAP),[2] the ^{7}Li to hydrogen ratio in mass fraction is predicted to be $(^7{\rm Li/H})_p = (4.15^{+0.49}_{-0.45}) \times 10^{-10}$,[3] while the primordial lithium abundance is determined to be $({\rm Li/H})_p = 1.23^{+0.68}_{-0.32} \times 10^{-10}$ [4] in metal-poor stars on the Spite plateau, about a factor three lower than calculation. Even worse, the abundance of ^{6}Li is about three orders of magnitudes higher than that predicted by the SBBN model.

Those differences between calculations and observations are called the lithium problems. In the past few years, some groups attempted to explain the large discrepancies via the studies of both astrophysical observation and nucleosynthesis calculation, yet none of them have been successful up to now. In the SBBN network, ^{6}He may be produced by the ^{4}He$(2n,\gamma)^6$He reaction,[5] and then affects the abundances of ^{6}Li and ^{7}Li through its β^- decay and ^{6}He$(p,\gamma)^7$Li reaction, respectively.

In this Letter, angular distribution of the ^{6}He$(d,n)^7$Li reaction is measured in inverse kinematics at $E_{\rm c.m.} = 9.1$ MeV for the first time. The proton spectroscopic factors for the $\langle^7{\rm Li}_{g.s.}|^6{\rm He}+p\rangle$ and $\langle^7{\rm Li}_{0.48}|^6{\rm He}+p\rangle$ bound systems are derived based on the distorted wave Born approximation (DWBA) analysis. The astrophysical S-factors and rates of the ^{6}He$(p,\gamma)^7$Li which include the contributions of ^{6}He$(p,\gamma)^7$Li$_{\rm g.s.}$ and ^{6}He$(p,\gamma)^7$Li$_{0.48}$ reactions are then deduced.

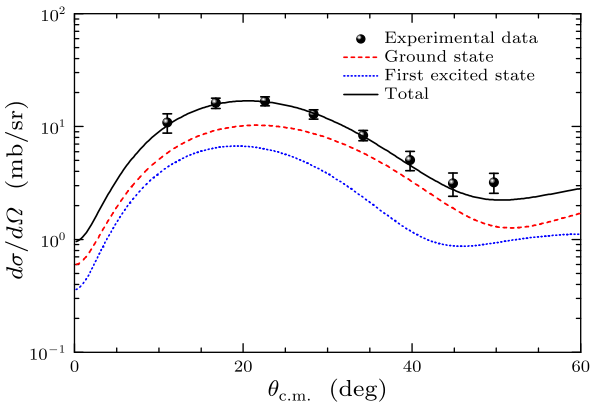

Fig. 1. Angular distribution of the ^{6}He$(d,n)^7$Li reaction at $E_{\rm c.m.} = 9.1$ MeV together with the DWBA calculations.

The experiment is carried out at the secondary beam facility[6−8] of the HI-13 tandem accelerator, Beijing. The setup and more details have been described in Ref. [9] and the measured ^{6}He$(d,n)^7$Li angular distribution is shown in Fig. 1, which includes the contributions from the ground and first excited states in ^{7}Li because these two states can not be separated for their energy difference is less than the energy spread of ^{6}He beam. According to the theoretical calculation, the proton spectroscopic factors in ^{7}Li ground and first excited states are equal to each

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other.[10] The DWBA code is adopted in the analysis of data and the calculated angular distributions are presented in Fig. 1. The proton spectroscopic factors for the ground and first excited states of ^{7}Li are deduced to be 0.42–0.06.

In the energy region of astrophysical interest, the ^{6}He$(p,\gamma)^7$Li$_{\rm g.s.}$ and ^{6}He$(p,\gamma)^7$Li$_{0.48}$ cross sections are dominated by $E1$ radiative capture of s-wave proton into the ground and first excited states of ^{7}Li. According to the traditional direct capture model,[11,12] the cross section can be expressed as

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

where E_γ is the emitted γ-ray energy; v is the relative velocity between target nucleus and proton; I_1, I_2 and I_f are the spins of target nucleus, proton and compound nucleus, respectively; $e_{\rm eff} = eZ/A$ 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; $k = \sqrt{2\mu E_{\rm cm}}\hbar$ stands for the incident wave number; $S_{l_f j_f}$ is the proton spectroscopic factor of the compound nucleus; $w_{l_i}(kr)$ refers to the distorted radial wave function for the entrance channel; $u_{l_f}(r)$ denotes the radial wave function of the bound state proton in compound nucleus which can be calculated by solving the respective Schrödinger equation. A Woods–Saxon potential with the standard geometrical parameters $r_0 = 1.25$ fm and $a = 0.65$ fm is adopted and the depths are automatically adjusted to reproduce the proton binding energies.

In order to extrapolate the cross section down to the low energies of astrophysical interest, the astrophysical S-factor is defined as

$$S(E) = E\sigma(E)\exp(-2\pi\eta), \quad (2)$$

where η is the Sommerfeld parameter,

$$\eta = \frac{Z_1 Z_2 e^2}{\hbar v} = 0.1575 Z_1 Z_2 \left(\frac{\mu}{E}\right)^{\frac{1}{2}}, \quad (3)$$

μ is the reduced mass of the system, Z_1 and Z_2 are the atomic number of target nucleus and proton.

To calculate the wave function $w_{l_i}(kr)$ in Eq. (1), one has to know the optical potential parameters of the elastic scattering of the ^{6}He$+p$ system at $E_{\rm c.m.}$ <1 MeV, which can be obtained by analyzing the ^{6}He$(p,p)^6$He angular distribution. However, no experimental data are available at such low energy presently. We assume that the imaginary part of the potential is negligible.[13] A Wood–Saxon potential is adopted for the real part, the radius and diffuseness parameters are set to be the standard values $r_0 = 1.25$ fm and $a = 0.65$ fm.

In general, the potential depth of the continuum state plays an important role. To investigate the importance of the potential depth V_0 on the direct radiative capture cross section, we calculate the astrophysical S-factors $S(E, V_0)$ at $E = 0$, which are scaled to the S-factors calculated with pure Coulomb wave function $S(0,0)$, for the ^{6}He$(p,\gamma)^7$Li$_{\rm g.s.}$ and ^{6}He$(p,\gamma)^7$Li$_{0.48}$ reactions. The results are present in Fig. 2, it demonstrates the sensitivity of the astrophysical S-factors to the choice of the scattering potential depth V_0. In such a case, the depth must be fixed by fitting the volume integral of potential per nucleon.[14,15] Although the optical potential changes considerably for different systems, the volume integral of potential per nucleon is relatively a more stable quantity.

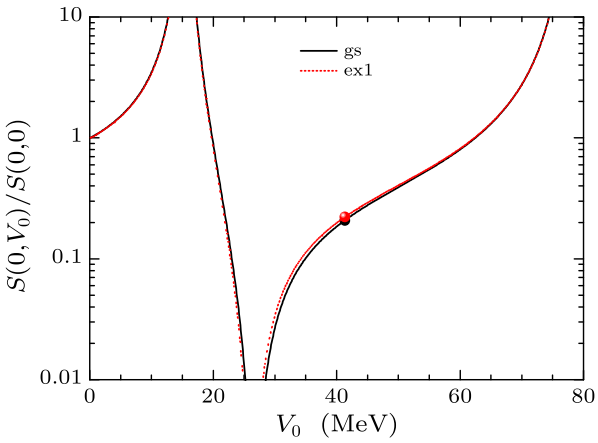

Fig. 2. S-factors at energy $E = 0$ as a function of the depth V_0 scaled to the S-factors $S(0,0)$ for the ^{6}He$(p,\gamma)^7$Li$_{\rm g.s.}$ and ^{6}He$(p,\gamma)^7$Li$_{0.48}$ reactions. The depths V_0 used in the calculations are indicated.

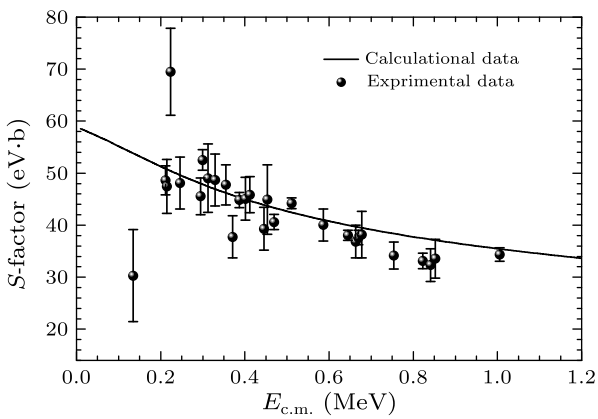

Fig. 3. S-factors for the ^{6}Li$(p,\gamma)^7$Be$_{\rm g.s.}$ reaction, the experimental data (filled circles) are taken from Ref. [16].

The ^{6}Li$(p,\gamma)^7$Be$_{\rm g.s.}$ reaction, whose cross sections have been measured at low energies,[16] is shown in Fig. 3. The potential depth of ^{6}Li$+p$ system is determined to be 41.3±2.0 MeV by fitting the experimental

data using the weight least square method, which can be used by ^{6}He+p system since both ^{6}Li and ^{6}He have the same atomic number.

The cross sections for the $^6\mathrm{He}(p,\gamma)^7\mathrm{Li}$ reaction are extracted with the obtained spectroscopic factor and the potential parameters ($V_0 = 41.3 \pm 2.0$ MeV, $r_0 = 1.25$ fm, $a = 0.65$ fm). Compared with the theoretical results calculated by Timofeyuk,[17] our results are higher than that from the folding model and complex optical potential calculations, while lower than that using the standard nuclear potential and pure Coulomb potential calculations. However, our results are in agreement with the folding model calculation when the difference of the spectroscopic factor is considered.

According to Eq. (2), the energy dependence of the astrophysical S-factor for the $^6\mathrm{He}(p,\gamma)^7\mathrm{Li}$ reaction is extracted as shown in Fig. 4, which contains the contributions of $^6\mathrm{He}(p,\gamma)^7\mathrm{Li}_{\mathrm{g.s.}}$ and $^6\mathrm{He}(p,\gamma)^7\mathrm{Li}_{0.48}$ reactions. The $S(0)$ factor is found to be 111.9 ± 21.6 eV b. The error results from the uncertainties of spectroscopic factor (14%) and the potential parameters (13%).

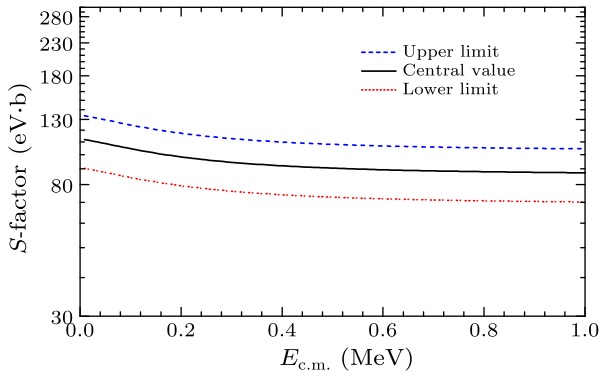

Fig. 4. Astrophysical S-factors as a function of $E_{\mathrm{c.m.}}$ for the $^6\mathrm{He}(p,\gamma)^7\mathrm{Li}$ reaction, which contain the contributions of $^6\mathrm{He}(p,\gamma)^7\mathrm{Li}_{\mathrm{g.s.}}$ and $^6\mathrm{He}(p,\gamma)^7\mathrm{Li}_{0.48}$ reactions.

Usually, the temperature dependence of reaction rate for the direct capture can be calculated by[18]

$$N_A\langle\sigma v\rangle = N_A\left(\frac{8}{\pi\mu}\right)^{1/2}\frac{1}{(k_BT)^{3/2}}\int_0^\infty S(E) \times \exp\left[-\frac{b}{E^{1/2}}-\frac{E}{kT}\right]dE, \quad (4)$$

where N_A is the Avogadro number, k_B represents the Boltzmann constant and b is given by

$$b = \frac{(2\mu)^{1/2}\pi e^2 Z_1 Z_2}{\hbar}, \quad (5)$$

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

By substituting S-factors given in Fig. 4 into Eq. (4), the $^6\mathrm{He}(p,\gamma)^7\mathrm{Li}$ direct radiative capture reaction rates are obtained, as shown in Fig. 5, which also contains the contributions of $^6\mathrm{He}(p,\gamma)^7\mathrm{Li}_{\mathrm{g.s.}}$ and $^6\mathrm{He}(p,\gamma)^7\mathrm{Li}_{0.48}$ reactions.

The present total reaction rates as a function of temperature T_9 (in units of 10^9 K) are fitted with an expression used in the astrophysical reaction rate library REACLIB:[19]

$$N_A\langle\sigma v\rangle = \exp\left[15.638 - 0.0428983T_9^{-1} - 4.05561T_9^{-1/3} - 4.37573T_9^{1/3} + 0.32091T_9 - 0.0224889T_9^{5/3} + 1.21365\ln T_9\right]. \quad (6)$$

The fitting errors are less than 1% in the temperature range from $T_9 = 0.01$ to $T_9 = 10$.

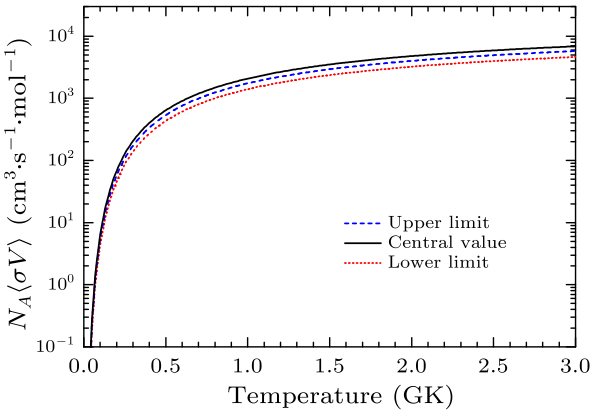

Fig. 5. Temperature dependence of the $^6\mathrm{He}(p,\gamma)^7\mathrm{Li}$ reaction rates. The solid, dashed and dotted lines are the central value, upper and lower limit, respectively.

In summary, the measurement of differential cross sections for the $^6\mathrm{He}(d,n)^7\mathrm{Li}$ transfer reaction has been carried out at $E_{\mathrm{c.m.}} = 9.1$ MeV. The S-factors and astrophysical rates for $^6\mathrm{He}(p,\gamma)^7\mathrm{Li}$ direct radiative capture reaction are then deduced by using the extracted proton spectroscopic factors. The BBN network calculation which includes $^4\mathrm{He}(2n,\gamma)^6\mathrm{He}(\beta^-\bar{\nu})^6\mathrm{Li}$ and $^4\mathrm{He}(2n,\gamma)^6\mathrm{He}(p,\gamma)^7\mathrm{Li}$ is underway.

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