Proton Spectroscopic Factor in $^7$Li from $^2$H($^6$He,$^7$Li)$n$

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The angular distribution of the $^2$H($^6$He,$^7$Li)$n$ reaction was measured with a secondary $^6$He beam of 36.4 MeV for the first time. The proton spectroscopic factor of $^7$Li ground state was extracted to be $0.41 \pm 0.05$ by the normalization of the calculational differential cross sections with the distorted-wave Born approximation to the experimental data. It was found that the uncertainty of extracted spectroscopic factors from the one-nucleon transfer reactions induced by deuteron may be reduced by constraining the volume integrals of imaginary optical potentials.

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I. INTRODUCTION

The essential constituents of nuclear shell model are the single particle orbits of the mean field which are occupied by protons and neutrons under Pauli principle. The spectroscopic factor describes the overlap between the initial and final states and yields the information on the occupancy of a given single particle orbit, which plays an important role in a variety of topics on nuclear reaction and nuclear astrophysics. Single nucleon transfer reactions such as ($d,p$) or ($d,n$) have been used extensively to extract the spectroscopic information of the single nucleon orbits in nuclei located at or near the stability line [1, 2, 3]. The spectroscopic study of exotic nuclei becomes feasible since the production of radioactive ion beams [4, 5, 6]. These measurements allow the extraction of the spectroscopic factors by normalizing the calculational differential cross sections with the distorted-wave Born approximation (DWBA) to the experimental ones at forward angles.

The ($^7$Li,$^6$He) reaction is a valuable spectroscopic tool in the study of nuclear reactions because the shape of its angular distribution can be well reproduced by the DWBA calculations [7]. In the calculations of ($^7$Li,$^6$He) reactions [8, 9, 10, 11], the spectroscopic factor of $^7$Li ground state was taken to be 0.59 given by Cohen and Kurath [12]. F. P. Brady et al. [13] extracted the spectroscopic factor of $^7$Li ground state to be $S(p_{3/2}) = 0.62$ from the $^7$Li($n,d$)$^6$He reaction with 56.3 MeV neutrons. L. Lapikás et al. [14] deduced the proton spectroscopic factor in $^7$Li to be $0.42 \pm 0.04$ via the measurement of the $^7$Li($e,e'p$) reaction. This value is 32% smaller than that from the $^7$Li($n,d$)$^6$He reaction. Thus, further measurement of the $^7$Li spectroscopic factor is highly desired.

In the present work, the angular distribution of the $^2$H($^6$He,$^7$Li)$n$ reaction was measured by using a secondary $^6$He beam of 36.4 MeV, and analyzed with DWBA. The proton spectroscopic factor in $^7$Li was then extracted and compared with the existing ones.

II. MEASUREMENT OF THE ANGULAR DISTRIBUTION

The experiment was carried out using the secondary beam facility [12, 13] of the HI-13 tandem accelerator, Beijing. A 46 MeV $^7$Li primary beam from the tandem impinged on a 4.8 cm long deuterium gas cell at a pressure of about 1.5 atm. The front and rear windows of the gas cell are Havar foils, each in thickness of 1.9 mg/cm$^2$. The $^6$He ions were produced via the $^2$H($^7$Li, $^6$He)$^3$He reaction. After the magnetic separation and focus with a dipole and a quadruple doublet, a 37.6 MeV $^6$He secondary beam was delivered and then collimated with a $\phi 7\times \phi 5$ mm collimator complex. The $^6$He beam was then recorded by a 23 $\mu$m thick silicon $\Delta E$ detector, which served as both particle identification and beam normalization. The typical purity and intensity of the $^6$He beam are 99% and 3000 pps. The main contaminants were $^7$Li ions out of Rutherford scattering of the primary beam in the gas cell windows as well as on the beam tube.

[FIG. 1: Schematic layout of the experimental setup]

The experimental setup is shown in Fig. [1]. A (CD$_2$)$_n$ foil and a carbon foil, both in the thickness of 1.7 mg/cm$^2$, were used as the targets to measure the $^2$H($^6$He,$^7$Li)$n$ reaction and background, respectively. The energy of $^6$He ions at the middle of the (CD$_2$)$_n$ was 36.4 MeV. A 300 $\mu$m thick multi-ring semiconductor de-
proximately 2\textdegree. As an example, Fig. 2 displays the action is around 20\textdegree.

The DWBA calculation predicts that the first experimental angular distribution at the backward angles is 0\textdegree to 11\textdegree.

The angular distribution measured in this work includes the contributions of the ground and first excited states in ^7Li populated by the ^2H(^6He, ^7Li)n reaction. The events of these two states can not be separated because their energy difference is only 0.48 MeV which is less than the energy spread (0.62 MeV) of the ^6He beam.

The ^2H(^6He, ^7Li)n reaction leading to the first excited state of ^7Li is a (3/2^−, 1/2^+) \rightarrow (0^+, 1) transition. Parity and angular momentum considerations dictate that only 1p_{3/2} pickup is possible. In the same way, the ^2H(^6He, ^7Li^∗) reaction leading to the first excited state of ^7Li is a (1/2^−, 1/2^+) \rightarrow (0^+, 1) transition and only 1p_{1/2} pickup contributes to the reaction. The relationship among the experimental differential cross sections, the DWBA calculations and the spectroscopic factors can be expressed as

\[ \frac{d\sigma}{d\Omega}_{\text{exp}} = S_d S_{^7Li} \frac{d\sigma}{d\Omega}_{gs} + S_d S_{^7Li^*} \frac{d\sigma}{d\Omega}_{ex1}, \] (1)

where \( \frac{d\sigma}{d\Omega}_{\text{exp}} \) is the experimental differential cross section, \( \frac{d\sigma}{d\Omega}_{gs} \) and \( \frac{d\sigma}{d\Omega}_{ex1} \) are the calculational differential cross sections for the ^2H(^6He, ^7Li)n and ^2H(^6He, ^7Li^*) reactions. \( S_d \) is the spectroscopic factor for d \rightarrow p + n, which is derived to be 0.859 from Ref. [18]. \( S_{^7Li} \) and \( S_{^7Li^*} \) are the proton spectroscopic factors of the ground and first excited states in ^7Li. According to the translationally invariant shell model [19] calculation with the code DESNA [20], and Boyarkina’s wave function tables [21], the ratio of \( S_{^7Li}/S_{^7Li^*} \) is 1.0 [22]. Thus, the proton spectroscopic factors in ^7Li can be extracted through Eq. (1) by the normalization of DWBA calculations to the experimental data.

The code FRESCO [23] was used to compute the angular distribution of the ^2H(^6He, ^7Li)n reaction leading to the ground and first excited states of ^7Li. Following our previous work in Ref. [24], the effective deuteron potential was calculated with the adiabatic model of Johnson and Soper [25, 26]. The optical potential parameters for the nucleon-nucleus were derived by the CH89 global

FIG. 2: (Color online) \( \Delta E \) vs. \( E_r \) scatter plots of (CD$_2$)$_n$ target (top panel) and pure carbon target (bottom panel) measured by the fourth ring of MRSD. The red curves are the calculational \( \Delta E \) vs. \( E_r \) for the particle identification of ^7Li, ^6Li and ^6He. The two-dimensional gate with blue color is the ^7Li kinematics region from the ^2H(^6He, ^7Li)n reaction, corresponding to the fourth ring.

The accumulated quantity of incident ^6He was approximately 2.71 \times 10^6 for the (CD$_2$)$_n$ target measurement, and 8.41 \times 10^7 for background measurement with the carbon target. As an example, Fig. 2 displays the \( \Delta E - E_r \) scatter plots of both (CD$_2$)$_n$ and carbon tar-

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IV. THE UNCERTAINTY ANALYSIS

In general, the uncertainties of the extracted spectroscopic factor by the DWBA calculations originate from the ambiguity of the optical potential parameters for both the entrance and exit channels, and that of binding potential parameters in the bound state. The optical potential parameters for nucleon-nucleus in Refs. [27, 28, 29, 30, 31, 32] were used in the present calculations, and it is found that the potential parameters taken from the CH89 global systematics can give a best fit in the first peak of the $^6\text{He}(d,n)^7\text{Li}$ angular distribution. In order to study the uncertainties of the spectroscopic factor associated with the various $^6\text{He} + d$ optical potentials, we used the additional four sets of $^6\text{He} + d$ potential parameters to extract the proton spectroscopic factor of $^7\text{Li}$. They are labeled as D2, D3, D4 and D5 respectively, as listed in Table I. Set D2 is obtained from the analysis of an extensive set of data [33], which includes the results of both polarized and unpolarized elastic deuteron scattering on the nuclei from $^{27}\text{Al}$ to $^{238}\text{Th}$ in the energy range of $E_d = 12 - 90$ MeV. Recently, the expression for D2 has been extrapolated to the nuclei of $A < 27$ [17]. Set D3 is based on the analysis of the elastic scattering of 52 MeV deuterons from 27 nuclei [34]. Set D4 is deduced from the elastic scattering of 30 MeV polarized deuterons from 10 nuclei [35]. Set D5 is the deuteron global potential for the nuclei of $Z \geq 12$ with deuteron energies from 12 to 25 MeV [31]. As a comparison, Fig. 4 shows the angular distributions calculated with all the five sets of the deuteron optical potentials together with the present experimental data. One can see that the experimental angular distribution is fairly reproduced by all the five sets of optical potentials. The extracted spectroscopic factors are 0.40, 0.37, 0.36, 0.45 and 0.46, respectively. Their average is 0.41 with a standard deviation of 0.05.

In order to estimate the uncertainty of the spectroscopic factor from the potential of $^6\text{He} + p$ bound state in $^7\text{Li}$, we have tested the influence of the geometrical parameters ($r_0$ and $a$) on the spectroscopic factor. The radius was changed from 1.10 to 1.40 fm while the diffuseness was adjusted to reproduce the rms radius of the valence proton in $^7\text{Li}$ which was calculated with the charge rms radii of $^6\text{He}$ and $^7\text{Li}$ in Refs. [36, 37] according to

$$r_{Li}^2 = \frac{1}{Z+1} \left( Z r_{He}^2 + r_p^2 + \frac{Z}{Z+1} r_0^2 \right),$$

where $r_{Li}$, $r_{He}$ and $r_p$ are the charge rms radii for $^7\text{Li}$, $^6\text{He}$ and proton, respectively. $r_0$ is the rms radius of the

\begin{table}[h]
\centering
\caption{Optical potential parameters used in DWBA calculations, where $V$, $W$ are in MeV, $r$ and $a$ are in fm, the geometrical parameters of single particle bound state are set to be $r_0 = 1.25$ fm and $a = 0.65$ fm.}
\begin{tabular}{|c|c|c|c|c|c|c|}
\hline
Set No. & D1 & D2 & D3 & D4 & D5 & N1 \\
\hline
$V$ & 97.79 & 86.32 & 76.41 & 86.80 & 80.53 & 41.54 \\
$a_v$ & 1.13 & 1.17 & 1.25 & 1.13 & 1.15 & 1.41 \\
$a_o$ & 0.72 & 0.73 & 0.77 & 0.80 & 0.81 & 0.50 \\
$W_V$ & 2.05 & 0.18 & 13.91 & 12.33 & 13.0 & 12.0 & 17.31 & 13.58 \\
$W_p$ & 13.91 & 12.33 & 13.0 & 12.0 & 17.31 & 13.58 \\
$r_w$ & 1.10 & 1.325 & 1.25 & 1.56 & 1.34 & 1.35 \\
$a_w$ & 0.72 & 0.66 & 0.65 & 0.68 & 0.68 & 0.20 \\
$V_{so}$ & 5.90 & 6.98 & 6.0 & 5.2 & 5.50 & 5.50 \\
$r_{so}$ & 0.68 & 1.07 & 1.25 & 0.85 & 1.15 & 1.15 \\
$a_{so}$ & 0.63 & 0.66 & 0.77 & 0.48 & 0.50 & 0.50 \\
$r_c$ & 1.30 & 1.30 & 1.30 & 1.30 & 1.30 & 1.15 \\
Ref. & [26] & [33] & [34] & [35] & [31] & [27] \\
\hline
\end{tabular}
\end{table}
FIG. 4: Comparison of the angular distributions of $^2$H($^6$He,$^7$Li)$n$ with 5 sets of optical potential parameters.

The $^7$Li ground state is extracted to be $0.41 \pm 0.05$, which is in good agreement with those from the $^7$Li($e,e'p$) reaction \cite{14} and the $^7$Li($d,^3$He)$^6$He reaction \cite{39}.

The error (12%) of the spectroscopic factor given in our work mainly arises from the uncertainty (11%) of the optical potentials. Thus it is important to further investigate the influence of optical potentials. It is found that the volume integrals for the real part of five sets potentials only differ by a factor of 3%, while those for the imaginary part deviate up to 20%. The uncertainty of the spectroscopic factor mainly arises from the uncertainty of the imaginary optical potentials. We found a linear relationship between the volume integrals of the imaginary part and the spectroscopic factors, as shown in Fig. 6. Therefore, the uncertainty of the extracted spectroscopic factors can be reduced by constraining the imaginary volume integral for deuteron-nucleus correctly. Generally speaking, the angular distribution of the elastic scattering can provide fairly good information on the real part of the optical potential. However, it can only give relatively poor information on the imaginary part of the optical potential. Consequently, it is of importance for extracting the imaginary potential parameters to study the deuteron-nucleus reactions other than elastic scattering.
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