ISSN: 0256-307X

中国物理快报
Chinese Physics Letters

Volume 27 Number 5 May 2010

A Series Journal of the Chinese Physical Society
Distributed by IOP Publishing

Online: http://www.iop.org/journals/cpl
http://cpl.iphy.ac.cn

CHINESE PHYSICAL SOCIETY

CHIN. PHYS. LETT. Vol. 27, No. 5 (2010) 052101

Neutron Spectroscopic Factors of ^{7}Li and Astrophysical ^{6}Li(n,γ)^{7}Li Reaction Rates *

SU Jun(苏俊)**, LI Zhi-Hong(李志宏), GUO Bing(郭冰), BAI Xi-Xiang(白希祥), LI Zhi-Chang(李志常), LIU Jian-Cheng(刘建成), WANG You-Bao(王友宝), LIAN Gang(连钢), ZENG Sheng(曾晟), WANG Bao-Xiang(王宝祥), YAN Sheng-Quan(颜胜权), LI Yun-Ju(李云居), LI Er-Tao(李二涛), FAN Qi-Wen(樊启文), LIU Wei-Ping(柳卫平)

China Institute of Atomic Energy, PO Box 275(10), Beijing 102413

(Received 22 October 2009)

Angular distributions of the ^{7}Li(^{6}Li, ^{6}Li)^{7}Li *elastic scattering and the* ^{7}Li(^{6}Li, ^{7}Li$_{g.s.}$)^{6}Li, ^{7}Li(^{6}Li, ^{7}Li$_{0.48}$)^{6}Li *transfer reactions at* $E_{c.m.} = 23.7$ *MeV are measured with the Q3D magnetic spectrograph. The optical potential of* ^{6}Li + ^{7}Li *is obtained by fitting the elastic scattering differential cross sections. Based on the distorted wave Born approximation (DWBA) analysis, spectroscopic factors of* ^{7}Li = ^{6}Li $\otimes$ n *are determined to be* 0.73 ± 0.05 *and* 0.90 ± 0.09 *for the ground and first exited states in* ^{7}*Li, respectively. Using the spectroscopic factors, the cross sections of the* ^{6}*Li*$(n, \gamma_{0,1})^7$*Li direct neutron capture reactions and the astrophysical* ^{6}*Li*$(n, \gamma)^7$*Li reaction rates are derived.*

PACS: 21. 10. Jx, 25. 60. Bx, 25. 60. Je, 26. 35. +c DOI: 10.1088/0256-307X/27/5/052101

Recently, lithium isotopes have attracted an intense interest because the abundance of both ^{6}Li and ^{7}Li from big bang nucleosynthesis (BBN) is one of the puzzles in nuclear astrophysics. According to the baryon density determined by the Wilkinson microwave anisotropy probe (WMAP),[1] the primary abundances for ^{6}Li and ^{7}Li predicted by the standard BBN (SBBN) model deviate clearly from the observations of the metal-poor halo stars,[2] where the lithium abundances exhibit a "plateau" behavior.[3] Several investigations for both astrophysical observation and nucleosynthesis calculation have been attempted to explain the large discrepancies, but none of them has been successful up to now. In addition, due to the difference between the depletion speeds of ^{6}Li and ^{7}Li in stars, the ^{6}Li/^{7}Li ratio could stand for a measure of the time scale for stellar evolution. In the above scenario, ^{6}Li$(n, \gamma)^7$Li is believed to be one of the important reactions in the SBBN network,[4,5] its reaction rates would affect the abundances of both ^{6}Li and ^{7}Li.

The cross sections of ^{6}Li$(n, \gamma)^7$Li at astrophysically relevant energies are most likely dominated by the E1 transitions into the ground and the first exited states in ^{7}Li. To date, only one direct measurement of the ^{6}Li$(n, \gamma)^7$Li cross sections with three data points at stellar energies has been performed.[6] The cross sections of direct radiative capture reaction can also be calculated by the direct capture model with the spectroscopic information extracted from the single particle transfer reaction.[7–10] In previous studies, the spectroscopic factors were mostly derived by ^{6}Li$(d, p)^7$Li and ^{7}Li$(p, d)^6$Li reactions,[11–15] the results are correlative with the neutron spectroscopic factor of deuteron. Thus, it is highly desired to extract the spectroscopic factors through a self-contained reaction without a third-participant, which can provide an independent verification.

The elastic-transfer reaction is a good tool for extracting the single nucleon spectroscopic factors, which have been used to determine the spectroscopic factor of ^{9}Be = ^{8}Li $\otimes$ p with the ^{9}Be(^{8}Li,^{9}Be)^{8}Li reaction.[16] In such an approach, the events from elastic scattering and elastic-transfer reaction can not be distinguished, but the theoretical calculation shows that their mutual contributions at the respective forward angles are negligibly small. As a result, the effective differential cross sections at forward angles of the two processes can be obtained, respectively. The obvious advantages of this approach are (i) the elastic scattering and elastic-transfer reaction have the same entrance and exit channels, the spectroscopic factor can be derived by one set of optical potential deduced from the elastic scattering and (ii) the elastic-transfer reaction does not involve third participant in the entrance and exit channels, and thus results in a reduction of experimental result uncertainty.

For the above reasons, we choose the ^{7}Li(^{6}Li,^{7}Li)^{6}Li elastic-transfer reaction to extract the spectroscopic factors of the ^{7}Li = ^{6}Li $\otimes$ n. This reaction has been measured in 1998 at E_{lab} = 9–40 MeV,[17] unfortunately the minimum angle reached in that experiment is about 30° in the center of mass frame (for transfer process), which is not

*Supported by the National Basic Research Program of China under Grant No 2007CB815003, the National Natural Science Foundation of China under Grant Nos 10675173, 10720101076, 10735100 and 10975193.

**Email: junsu@ciae.ac.cn

suitable to derive the spectroscopic factor. In the present work, we measure the angular distributions of the ^{7}Li(^{6}Li,^{6}Li)^{7}Li elastic scattering and ^{7}Li(^{6}Li,^{7}Li$_{\rm g.s.}$)^{6}Li, ^{7}Li(^{6}Li,^{7}Li$_{0.48}$)^{6}Li transfer reactions at $E_{\rm c.m.} = 23.7$ MeV. The neutron spectroscopic factors for the ground and first exited states in ^{7}Li are determined by comparing the experimental results with the distorted-wave Born approximation (DWBA) calculations, and then used to calculate the cross sections and astrophysical rates of ^{6}Li$(n,\gamma)^7$Li direct capture reaction.

The experiment was carried out at the Beijing HI-13 tandem accelerator. A 44 MeV ^{6}Li beam with an intensity of about 100 pnA impinged on the natural LiF target with a thickness of 530 μg/cm^2, which is evaporated on a 50 μg/cm^2 carbon foil. The beam was collected by a Faraday cup behind the target for counting the number of ^{6}Li. The Faraday cup covered an angular range of ±6° and confined the attainable minimum angle in the measurement. The reaction products were focused and separated by Q3D magnetic spectrograph. The accepted solid angle of Q3D was set to be 0.23 mSr for a good angular resolution. A two-dimensional position sensitive silicon detector (PSSD) was set at the focal plane of Q3D, the $X-Y$ information from PSSD enabled the products emitted into the accepted solid angle of Q3D to be fully recorded, and the corresponding energy signals were used to remove the impurities with the same magnetic rigidity. The absolute differential cross sections were determined by normalizing the measurements of the ^{7}Li(^{6}Li,^{6}Li)^{7}Li elastic scattering and the ^{7}Li(^{6}Li,^{7}Li$_{\rm g.s.}$)^{6}Li, ^{7}Li(^{6}Li,^{7}Li$_{0.48}$)^{6}Li transfer reactions to the elastic scattering of ^{6}Li on the gold target at $\theta_{\rm lab} = 25°$.

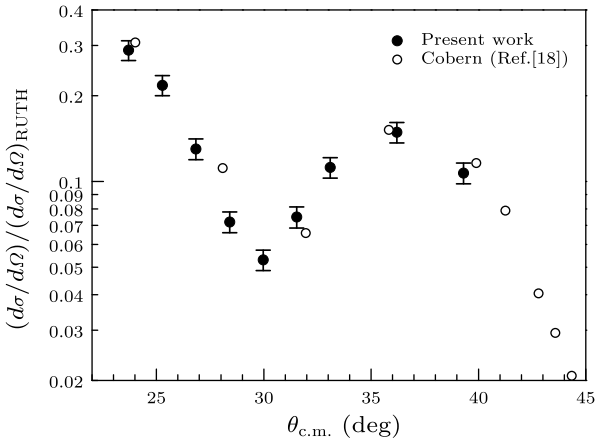

Fig. 1. Comparison of the ^{12}C(^{7}Li,^{7}Li)^{12}C angular distributions at $E_{\rm lab} = 36$ MeV, the solid and open circles denote the data obtained in the present experiment and in an earlier work,[18] respectively.

The experimental setup was tested beforehand by measuring the angular distribution of ^{12}C(^{7}Li,^{7}Li)^{12}C elastic scattering at $E_{\rm lab} = 36$ MeV. As shown in Fig. 1, our result is in fair agreement with that reported in Ref. [18], indicating a reliable overall performance of our setup and data analysis procedure.

In the measurements of ^{7}Li(^{6}Li,^{6}Li)^{7}Li elastic scattering and ^{7}Li(^{6}Li,^{7}Li$_{\rm g.s.}$)^{6}Li, ^{7}Li(^{6}Li,^{7}Li$_{0.48}$)^{6}Li transfer reactions, the magnetic fields of Q3D were set to focus ^{6}Li and ^{7}Li, respectively. The elastic scattering and transfer processes were measured in the angular ranges of $7° \le \theta_{\rm lab} \le 30°$ and $7° \le \theta_{\rm lab} \le 17°$ in steps of 1°, respectively.

The differential cross sections for elastic scattering are shown in Fig. 2, with uncertainties from the errors of statistics and target thickness. The angular distribution of ^{7}Li(^{6}Li,^{6}Li)^{7}Li elastic scattering was analyzed by employing the code PTOLEMY[19] and optical model using real and imaginary potentials with Woods-Saxon form. The optimized potential parameters obtained by fitting the experimental data are listed in Table 1. The fitting results are shown in Fig. 2 together with the experimental data. Figure 2 also exhibits the contribution of transfer processes, which is less than 1% within the experimental angular range.

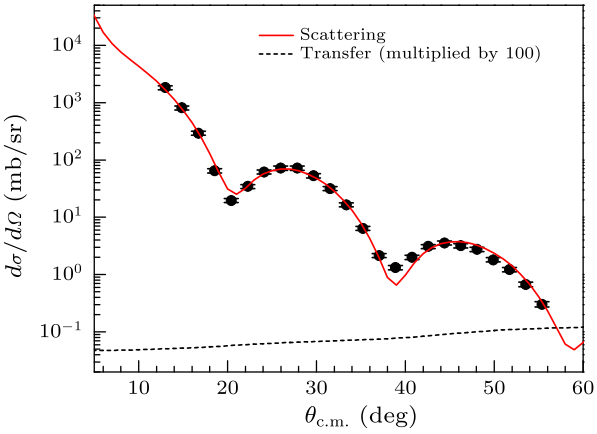

Fig. 2. Differential cross sections for ^{7}Li(^{6}Li,^{6}Li)^{7}Li elastic scattering at $E_{\rm c.m.} = 23.7$ MeV together with the optical model calculation. The dashed line denotes the contribution of transfer processes (multiplied by a factor of 100).

Table 1. Optical potential parameters for ^{6}Li + ^{7}Li system at $E_{\rm c.m.} = 23.7$ MeV. The depths and geometrical parameters are in MeV and fm, respectively.

U_V	r_R	a_R	W_V	r_I	a_I	r_c	χ^2/point
73.4	0.5	0.92	32.6	1.0	0.8	1.25	4.0

The angular distributions of ^{7}Li(^{6}Li,^{7}Li$_{\rm g.s.}$)^{6}Li and ^{7}Li(^{6}Li,^{7}Li$_{0.48}$)^{6}Li transfer processes are shown in Fig. 3, which are also analyzed with the code PTOLEMY. As can clearly be seen from Fig. 3, the contribution of elastic scattering is very small. In the calculation, we utilize the ^{6}Li + ^{7}Li optical potential parameters listed in Table 1 for both the entrance and

exit channels. For the bound states, a Woods–Saxon potential with the standard geometrical parameters $r_0 = 1.25\,\text{fm}$ and $a = 0.65\,\text{fm}$ is adopted and the depths are adjusted to reproduce the neutron binding energies of ^{7}Li.

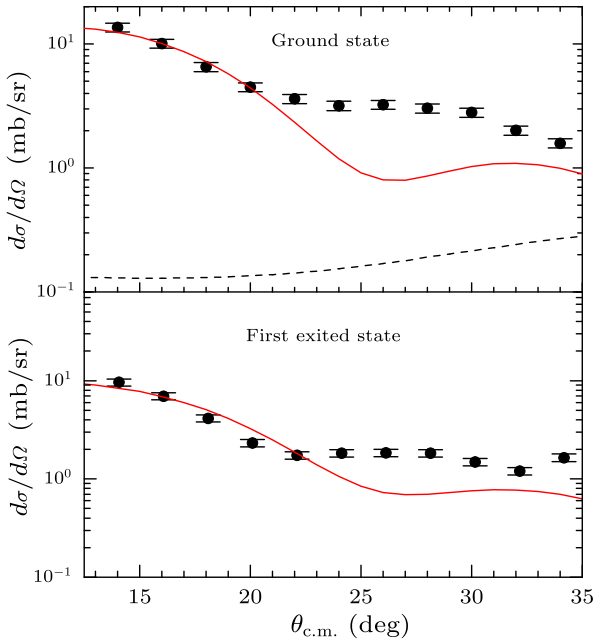

Fig. 3. Angular distribution of ^{7}Li(^{6}Li,^{7}Li$_{\text{g.s.}}$)^{6}Li and ^{7}Li(^{6}Li,^{7}Li$_{0.48}$)^{6}Li at $E_{\text{c.m.}} = 23.7$ MeV together with the DWBA calculations normalized to the first three data at forward angles. The dashed line denotes the contribution of elastic scattering (multiplied by a factor of 1000).

The spectroscopic factor $^7\text{Li} = {}^6\text{Li} \otimes n$, denoted as $S_{^7\text{Li}}$, can be derived by normalizing the DWBA calculations to the experimental data according to the expression

$$\left(\frac{d\sigma}{d\Omega}\right)_{\text{EXP}} = S^2_{^7\text{Li}} \left(\frac{d\sigma}{d\Omega}\right)_{\text{DWBA}}. \quad (1)$$

Generally, the experimental data in the first peak of angular distributions at the forward angles are suitable for extracting the spectroscopic factor[20] because the differential cross sections of other angles are more sensitive to some high-order processes. In our calculation, only the first three data at the forward angles were used to extract the spectroscopic factors. For the ^{7}Li(^{6}Li,^{7}Li$_{\text{g.s.}}$)^{6}Li channel, both of the neutron transfers to the $1p_{3/2}$ and $1p_{1/2}$ orbits of ^{7}Li were taken into account, consequently the result was the coherent sum of their contributions. Since the $1p_{3/2}$ and $1p_{1/2}$ components can not be distinguished experimentally, their ratio was taken to be 1.5 based on the calculation,[21] then the spectroscopic factor of $^7\text{Li}_{\text{g.s.}} = {}^6\text{Li} \otimes n$ was determined to be 0.73 ± 0.05, the uncertainty results from the measurement, scattering potential fitting and the divergence of the values derived from three different angles. For the first exited state in ^{7}Li, only the neutron transfer to the $1p_{3/2}$ orbit was considered because the contribution of $1p_{1/2}$ orbit is merely about 4%,[21] then the spectroscopic factor of $^7\text{Li}_{0.48} = {}^6\text{Li} \otimes n$ is derived to be 0.90 ± 0.09. The spectroscopic factors obtained in several theoretical and experimental investigations are listed in Table 2, our results agree well with the theoretical calculation[21–24] and the experimental data.[12,13]

Table 2. Theoretical and experimental neutron spectroscopic factors for the ground and first exited states in ^{7}Li.

$S_{^7\text{Li}_{\text{g.s.}}}$	$S_{^7\text{Li}_{0.48}}$	Experiments or theory	Reference
0.72	0.89	Theory	[21]
0.80	0.98	Theory	[22]
0.79	0.97	theory	[23]
0.77	1.07	Theory	[24]
0.90	1.15	^{6}Li(d,p)	[11]
0.71		^{7}Li(p,d)	[12]
0.72 ± 0.1		^{7}Li(p,d)	[13]
0.87		^{7}Li(p,d)	[14]
1.85 ± 0.37		^{6}Li(d,p)	[15]
0.73 ± 0.05	0.90 ± 0.09	^{7}Li(^{6}Li,^{7}Li)	Present work

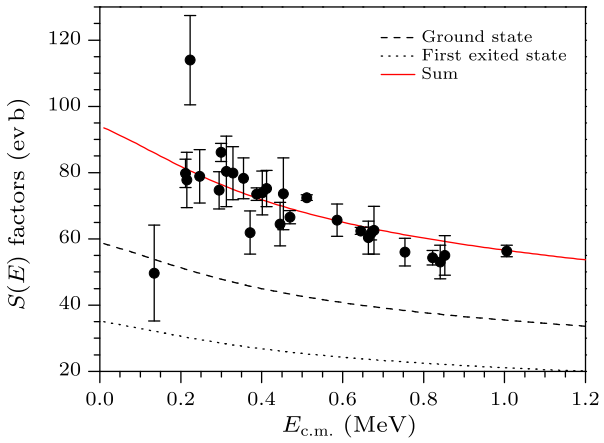

Fig. 4. Astrophysical $S(E)$ factors of the ^{6}Li(p,γ)^{7}Be reaction. The experimental data are taken from Ref. [26].

At low energies of astrophysical interest, the ^{6}Li$(n,\gamma)^7$Li direct capture cross sections are dominated by the E1 transition from incoming s-wave to the bound state, the contribution of d-wave neutrons is negligible. In the computation we used the code RADCAP[25] and Woods–Saxon form potential with the standard geometrical parameters. The potential depths of the ^{7}Li bound states are adjusted to reproduce the neutron binding energies of its ground and first excited states, respectively. For the scattering potential, the depth can be fixed by fitting the well measured ^{6}Li$(p,\gamma)^7$Be cross sections at low energies[26] because the difference between $n+{}^6$Li and $p+{}^6$Li potentials is only a Coulomb modification of depth, which is given by $\Delta V = 0.4Z/A^{1/3}$.[27]

The ^{6}Li$(p,\gamma)^7$Be cross sections are also calculated by the same code. The neutron spectroscopic factors of ^{7}Li derived above are correspondingly taken as the proton spectroscopic factors for the ground and first

exited states in ^{7}Be owing to the charge symmetry. Here the depth of scattering potential is constrained to be 41.3 ± 2.0 MeV in reproducing the experimental data. The calculated astrophysical $^6\mathrm{Li}(p,\gamma)^7\mathrm{Be}$ $S(E)$ factors are shown in Fig. 4 together with the experimental results. In addition to a good agreement between the calculated and measured total $S(E)$ factors, our calculation also indicates that the contributions of ground and first exited states are about 63% and 37%, respectively, which are very close to the experimental values 61% and 39%.[27]

Considering the Coulomb modification, the scattering potential depth of $n+^6\mathrm{Li}$ is chosen to be 40.6 ± 2.0 MeV. Then the $^6\mathrm{Li}(n,\gamma)^7\mathrm{Li}_{\mathrm{g.s.}}$ and $^6\mathrm{Li}(n,\gamma)^7\mathrm{Li}_{0.48}$ cross sections are calculated using the spectroscopic factors and optical potentials extracted above, and compared with the experimental data,[6] as shown in Fig. 5. Our result is consistent with the direct measurement, showing an approximate $1/v$ behavior, so that the reaction rates are almost constant at energies of astrophysical interest.

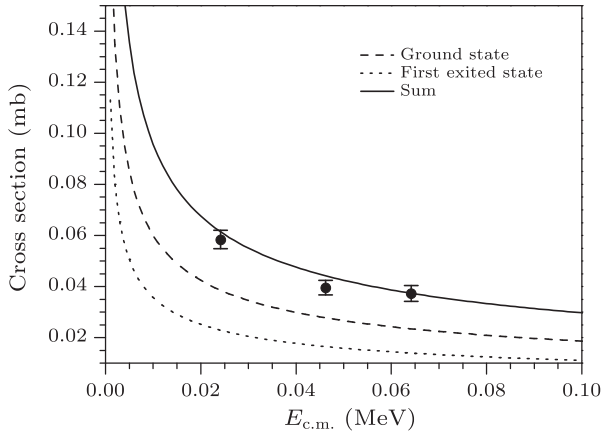

Fig. 5. Cross sections of the $^6\mathrm{Li}(n,\gamma)^7\mathrm{Li}$ reaction. The experimental data are taken from Ref. [6].

The astrophysical $^6\mathrm{Li}(n,\gamma)^7\mathrm{Li}$ direct capture reaction rate is then calculated by the expression[25]

$$N_A\langle\sigma v\rangle = 3.73 \times 10^{10} A^{-\frac{1}{2}} T_9^{-\frac{3}{2}} \times \int_0^\infty \sigma E \exp\left(\frac{-11.6E}{T_9}\right) dE, \quad (2)$$

where A is the reduced mass in atomic unit, T_9 is the temperature in units of 10^9 K. E, σ and reaction rate are given in MeV, barns and $\mathrm{cm^3 mol^{-1} s^{-1}}$, respectively. The reaction rate is found to be $(8.5 \pm 1.7) \times 10^3\,\mathrm{cm^3 mol^{-1} s^{-1}}$, with the error resulted from the uncertainties of spectroscopic factors and scattering potential depth.

In summary, the measurements of differential cross sections for the $^7\mathrm{Li}(^6\mathrm{Li},^6\mathrm{Li})^7\mathrm{Li}$ elastic scattering and $^7\mathrm{Li}(^6\mathrm{Li},^7\mathrm{Li}_{\mathrm{g.s.}})^6\mathrm{Li}$, $^7\mathrm{Li}(^6\mathrm{Li},^7\mathrm{Li}_{0.48})^6\mathrm{Li}$ transfer reactions have been carried out at $E_{\mathrm{c.m.}} = 23.7$ MeV, in which the angular distributions for transfer processes are obtained in the range of $14^\circ \lesssim \theta_{\mathrm{c.m.}} \lesssim 34^\circ$ for the first time. By using the optical potential of $^6\mathrm{Li} + ^7\mathrm{Li}$ extracted from the elastic scattering, the spectroscopic factors of $^7\mathrm{Li} = ^6\mathrm{Li} \otimes n$ are deduced with the DWBA analysis, the results are in agreement with those reported previously.[12,13,21–24] Then the $^6\mathrm{Li}(n,\gamma)^7\mathrm{Li}$ direct capture cross sections have been derived and compared with the direct measurement data. The astrophysical reaction rate is found to be higher by a factor of 1.7 than the value adopted in previous reaction network calculations.[4,5]

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