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Nuclear reactions of astrophysical interest for lithium isotopes

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This paper describes the systematic studies of nuclear astrophysical reactions for lithium isotopes using the unstable ion beam facility GIRAFFE in CIAE. We have measured the angular distributions of some single nucleon transfer reactions, such as ^{8}Li(d,p)^{9}Li, ^{8}Li(d,n)^{9}Be and ^{8}Li(p,d)^{7}Li in inverse kinematics, and derived the astrophysical S-factors or reaction rates for ^{8}Li(n,γ)^{9}Li and ^{8}Li(p,γ)^{9}Be by using asymptotic normalization coefficient (ANC) or spectroscopic factor.

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1. Indirect measurement

One proton transfer reactions like (d,n) can be used to determine the (p,γ) reaction cross sections indirectly, using ANC or spectroscopic factor extracted from the measured angular distributions [1]. As an example, we measured the ^{7}Be(d,n)^{8}B angular distribution in inverse kinematics at $E_{\rm cm}$ = 5.8 MeV and extracted the ANC for the virtual decay ^{8}B $\rightarrow$ ^{7}Be + p based on distorted wave Born approximation (DWBA) analysis. The astrophysical S-factor for the ^{7}Be(p,γ)^{8}B reaction at zero energy was derived by ANC method, for the first time [2]. This method was also used to indirectly determine astrophysical S-factors for the ^{11}C(p,γ)^{12}N [3] and ^{13}N(p,γ)^{14}O [4] reactions.

The similar approach may be used to determine the (n,γ) reaction rates based on the measurement of (d,p) reactions. In this case, however, the situation is complicated for s-wave neutron capture reactions, since the contribution from the inner of nucleus is not negligible, and thus the ANC approach is no more valid. Fortunately, we have found a way to deduce the (n,γ) cross sections with spectroscopic factors by constraining the optical potential parameters with their volume integrals per nucleon. It is demonstrated that the volume integral per nucleon is nearly a constant for 1p shell [5]. For the (d,p) reaction in inverse kinematics, the atomic number of recoil is identical to that of the projectile, and the recoil should be identified by the proton-recoil coincidence measurement.

2. Measurement of the nuclear reactions of astrophysical relevance for lithium isotopes

2.1 Astrophysical significance

In the reaction network calculation of primordial nucleosynthesis and other astrophysical scenarios, the reactions involving lithium isotopes play an important role. All the reactions producing or destroying unstable nucleus ^{8}Li, including ^{8}Li(α,n)^{11}B, ^{8}Li(n,γ)^{9}Li, ^{8}Li(d,p)^{9}Li, ^{8}Li(d,n)^{9}Be, ^{8}Li(p,γ)^{9}Be, ^{8}Li(d,t)^{7}Li, ^{8}Li(p,αn)^{4}He, ^{8}Li(p,d)^{7}Li etc., are especially important for inhomogeneous Big Bang nucleosynthesis (IBBNs) and for the seed-nuclide production of the r-process in Type II supernovae [6]. In these scenarios, the stability gap at mass number A=8 can be bypassed via the reaction chains containing ^{8}Li to synthesize A>8 nuclides. For IBBNs, ^{6}Li(n,γ)^{7}Li is another reaction of importance [7]. In addition, the astrophysical significance of the ^{6}Li(n,γ)^{7}Li reaction is that the ^{6}Li/^{7}Li ratio stands for a measure of the time scale for star evolution [8]. The direct- and indirect measurements of the above reactions are highly desired.

2.2 Measurement of the ^{8}Li(d,p)^{9}Li reaction and determination of the astrophysical ^{8}Li(n,γ)^{9}Li and ^{8}B(p,γ)^{9}C reaction rates

The angular distribution of ^{8}Li(d,p)^{9}Li reaction at $E_{\rm cm}$ = 7.8 MeV was measured in inverse kinematics, for the first time. The experimental setup is shown in Fig. 1. Two 300 μm thick Multi-Ring Semiconductor Detectors (MRSDs) with center holes were used. The upstream one aimed at detection of the recoil protons, and the downstream one, backed by an independent 300 μm thick silicon detector placed at center hole, served as a residue energy E_r detector which composed a $\Delta E - E_r$ silicon counter telescope with a 21.7 μm thick silicon ΔE detector. This setup enabled the coincidence measurement of ^{9}Li and recoil proton. Based on DWBA analysis, the single particle

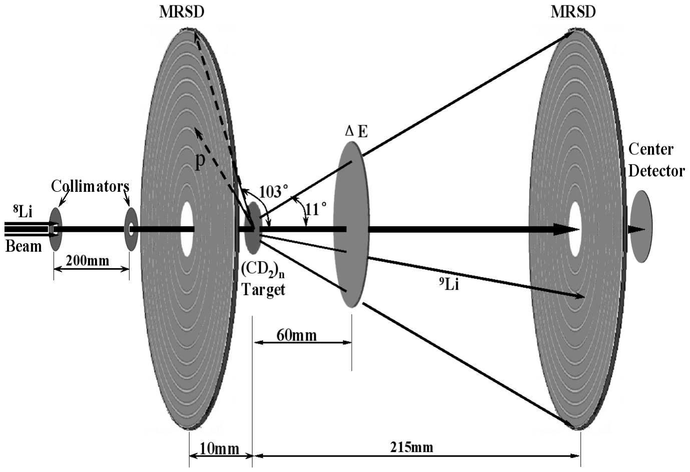

Figure 1: The experimental setup for ^{8}Li(d,p)^{9}Li reaction measurement.

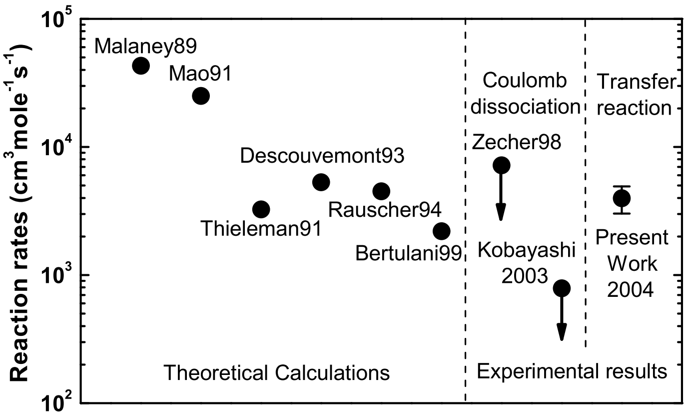

Figure 2: The astrophysical ^{8}Li(n,γ)^{9}Li reaction rates at T_9=1 derived from our indirect measurement together with those of theoretical calculations and Coulomb dissociation measurements [5] and references therein.

spectroscopic factor for the ground state of ^{9}Li → ^{8}Li + n was derived, and then used to calculated the ^{8}Li(n,γ)^{9}Li direct capture cross sections and astrophysical reaction rate. This work obtained the first experimental constraint for the ^{8}Li(n,γ)^{9}Li reaction rates of astrophysical relevance. Figure 2 displays the astrophysical ^{8}Li(n,γ)^{9}Li reaction rates at T_9=1 derived from our indirect measurement together with those of theoretical calculations and Coulomb dissociation measurements [5] and references therein.

According charge symmetry, the derived ANC for the virtual decay ^{9}Li → ^{8}Li + n was also used to extract the ANC for the virtual decay of mirror nucleus ^{9}C → ^{8}B + p, which was then applied to the calculation of astrophysical S-factors and reaction rates for the direct capture in ^{8}B(p,γ)^{9}C at energies of astrophysical interest [9].

2.3 Measurement of the ^{8}Li(d,n)^{9}Be$_{g.s.}$ reaction and determination the astrophysical ^{8}Li(p,γ)^{9}Be$_{g.s.}$ S-factors and reaction rates for direct capture

The angular distribution of the ^{8}Li(d,n)^{9}Be$_{g.s.}$ reaction at E$_{c.m.}$ = 8.0 MeV was measured in inverse kinematics. Through DWBA analysis, the single particle spectroscopic factor S$_{1,3/2}$ for the ground state of ^{9}Be → ^{8}Li + p was derived and then used to deduce the astrophysical S-factors and reaction rates for direct capture in ^{8}Li(p,γ)^{9}Be$_{g.s.}$ [10].

2.4 Measurement of the angular distribution for the ^{8}Li(p,d)^{7}Li reaction

The angular distribution of ^{8}Li(p,d)^{7}Li reaction at backward angles was measured at E$_{c.m.}$ = 4.0 MeV in inverse kinematics, for the first time, with a secondary ^{8}Li beam [11]. A set of $\Delta E - E_r$ telescope consisting of a 63 μm thick double sided silicon strip detector (DSSSD) and a 982 μm thick quadrant silicon detector (MSQ) was adopted in place of the detectors used for the above ^{8}Li(d,p)^{9}Li reaction.

In the measurement, the events leading to ground and first excited states in ^{7}Li were mixed together. The ratio of the contributions from ^{8}Li(p,d$_0$)^{7}Li and ^{8}Li(p,d$_1$)^{7}Li was then estimated through a detailed analysis. The ^{8}Li(p,d$_0$)^{7}Li component accounts for 40% in the measured differential cross sections, which is approximately in agreement with the result deduced from the existing data of ^{7}Li(d,p)^{8}Li reaction via the principle of detailed balance. The details can be found in Ref. [11].

2.5 Study of the ^{6}Li(n,γ)^{7}Li reaction

To date, no direct measurement data of ^{6}Li(n,γ)^{7}Li reaction at energies of astrophysical interest have been available. As mentioned before, the astrophysical ^{6}Li(n,γ)^{7}Li reaction rate can be studied via one-neutron transfer reaction ^{7}Li(^{6}Li,^{7}Li)^{6}Li. The spectroscopic factor of ^{7}Li → ^{6}Li + n can be deduced and then used to derive the cross sections of ^{6}Li(n,γ)^{7}Li. The advantage of this system is that no other reaction is needed to get the spectroscopic factor of ^{7}Li → ^{6}Li + n because the same spectroscopic factors appear at both vertices of elastic neutron exchange amplitude. In addition, the optical potential parameters of entrance- and exit channels can be extracted simultaneously through ^{6}Li + ^{7}Li elastic scattering.

The experiment was performed with Q3D spectrometer, using a ^{6}Li beam from the HI-13 tandem accelerator and a ^{7}LiF target. The focal plane detector was a 2-dimensional position sensitive silicon detector. Fig. 3 shows the angular distribution of ^{6}Li+^{7}Li elastic scattering. The DWBA analysis for one-neutron transfer reaction is in progress.

References

[1] H. M. Xu, C. Gagliardi, R. Tribble, *Overall Normalization of the Astrophysical S Factor and the Nuclear Vertex Constant for ^{7}Be(p,γ)^{8}B Reactions, Phys. Rev. Lett.* **73** (1994) 2027.

[2] W. P. Liu, X. X. Bai et al., *Angular Distribution for the ^{7}Be(d,n)^{8}B Reaction at E$_{c.m.}$=5.8 MeV and the S$_{17}$(0) Factor for the ^{7}Be(p,γ)^{8}B Reaction, Phys. Rev. Lett.* **77** (1996) 611.

[3] W. P. Liu, Z. H. Li, X. X. Bai et al., *Determination of ^{11}C(p,γ)^{12}N astrophysical S-factor via measurement of ^{11}C(d,n)^{12}N reaction, Nucl. Phys.* **A728** 2003 275.

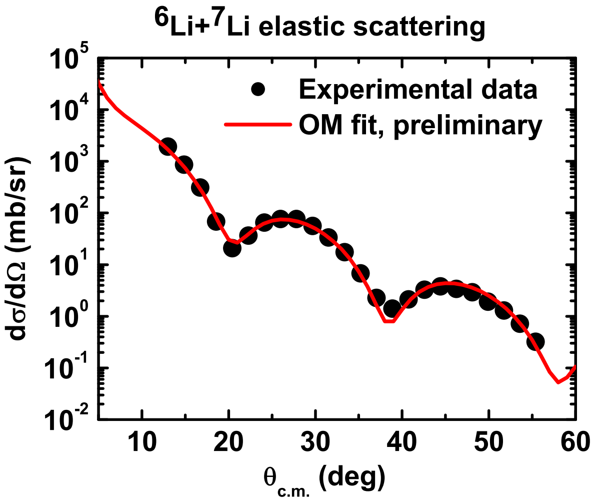

Figure 3: The angular distribution of ^{6}Li+^{7}Li elastic scattering.

[4] Z. H. Li et al., *The ^{13}N(d,n)^{14}O Reaction and the Astrophysical ^{13}N(p,γ)^{14}O Reaction Rate*, *Phys. Rev.* **C74** (2006) 035801.

[5] Z. H. Li, W. P. Liu et al., *The ^{8}Li(d,p)^{9}Li reaction and the astrophysical ^{8}Li(n,γ)^{9}Li reaction rate*, *Phys. Rev.* **C71** (2005) 052801(R).

[6] T. Kajino and R. N. Boyd, *Production of the light elements in primordial nucleosynthesis*, *Astrophys. J.* **359** (1990) 267.

[7] K. Jedamzik et al, *Lithium-6: A Probe of the Early Universe*, *Phys. Rev. Lett.* **84** (2000) 3248.

[8] M. Forestini et al, *Low-mass stars: pre-main sequence evolution and nucleosynthesis*, *Astron. Astrophys.* **285** (1994) 473.

[9] B. Guo, Z. H. Li, W. P. Liu et al., *The ^{8}Li(d,p)^{9}Li reaction and astrophysical ^{8}B(p,γ)^{9}C reaction rate*, *Nucl. Phys.* **A761** (2005) 162.

[10] J. Su et al., *Astrophysical Reaction Rates of ^{8}Li(p,γ)^{9}Be$_{g.s.}$ Direct Capture Reaction*, *Chin. Phys. Lett.* **23** (2006) 55.

[11] Y. J. Li et al., *Measurement of Angular Distribution for the ^{8}Li(p,d)^{7}Li Reaction*, *Chin. Phys. Lett.* **25** (2008) 455.