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NUCLEAR PHYSICS A

Nuclear Astrophysics Experiments at CIAE

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This paper describes nuclear astrophysical studies using the unstable ion beam facility GIRAFFE. We measured the angular distributions for some low energy reactions, such as ^{7}Be(d, n)^{8}B, ^{11}C(d, n)^{12}N, ^{8}Li(d, n)^{9}Be and ^{8}Li(d, p)^{9}Li in inverse kinematics, and indirectly derived the astrophysical S-factors or reaction rates of ^{7}Be(p, γ)^{8}B,^{11}C(p, γ)^{12}N, ^{8}Li(n, γ)^{9}Li at astrophysically relevant energies.

1. Description of unstable ion beam facility GIRAFFE

Aiming at the studies of nuclear astrophysics, the secondary beam facility [1] has been constructed at the HI-13 tandem laboratory in 1993. The facility made use of the transfer and charge exchange reactions in inverse kinematics to produce some beams of unstable ions (A $<$ 20) near the β-stability line with the acceptable intensities (10^4 - 10^6 pps). It comprises a primary reaction chamber, a dipole-quadrupole doublet (D-Q-Q) and a secondary reaction chamber, as shown in Fig. 1. Up to now, the ion beams of ^{6}He, ^{7}Be, ^{8}Li, ^{11}C, ^{13}N, ^{15}O and ^{17}F have been delivered, as summarized in Table 1. A velocity filter will be installed between quadrupole doublet and focal plane by the end of 2004, which will greatly upgrade the secondary beam purity.

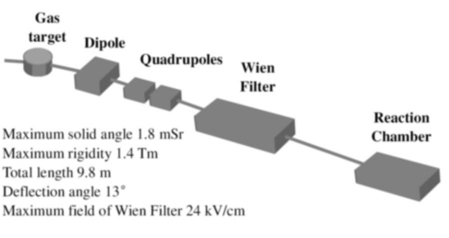

Figure 1. Sketch of GIRAFFE.

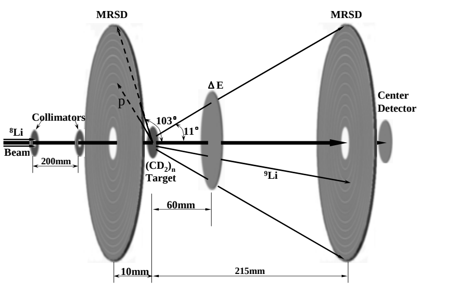

Figure 2. Experimental setup for ^{8}Li(d, p)^{9}Li.

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Table 1
Summary of the produced unstable ion beams at GIRAFFE

RNB	Reaction	Energy (MeV)	FWHM (MeV)	Purity (%)	Beam intensity (pps)[a]
^{6}He	^{2}H(^{7}Li, ^{6}He)^{3}He	35.3	0.5	90	500
^{7}Be	^{1}H(^{7}Li, ^{7}Be)n	23.0	1.3	92	1000
^{8}Li	^{2}H(^{7}Li, ^{8}Li)^{1}H	39.0	0.5	90	500
^{11}C	^{1}H(^{11}B, ^{11}C)n	38.2	2.7	85	1000
^{13}N	^{2}H(^{12}C, ^{13}N)n	65.7	2.3	6	500
^{15}O	^{2}H(^{14}N, ^{15}O)n	74.3	3.8	50	800
^{17}F	^{2}H(^{16}O, ^{17}F)n	74.9	4.8	24	2000

[a]With 2 mm diameter collimator and primary beam intensity 10-100 enA.

2. Experiments and theoretical analyses

The experimental setup for ^{8}Li(d, p)^{9}Li is shown in Fig. 2. A 1.5 mg/cm^2 thick $(CD_2)_n$ target was used to study ^{8}Li(d, p)^{9}Li in inverse kinematics, and a 1.8 mg/cm^2 thick C target for the background measurement.Two ϕ100 mm Multi-Ring Semiconductor Detectors (MRSDs) with center holes were used, each in thickness of 300 μm. The upstream one aimed at detection of the recoil protons, and the downstream one served as a residue energy ($E_{\rm r}$) detector which composed a ΔE - $E_{\rm r}$ counter telescope together with a 21.7 μm thick silicon ΔE detector and a 300 μm thick silicon center $E_{\rm r}$ detector. This setup enabled the ^{9}Li -recoil proton coincidence measurement. The setup for ^{7}Be(d, n)^{8}B and that for ^{11}C(d, n)^{12}N were described elsewhere [2,3], respectively.

The astrophysical S-factor for the ^{7}Be(p, γ)^{8}B reaction at solar energies is an important nuclear physics input for the "solar neutrino problem". The S-factor can be indirectly determined through the asymptotic normalization coefficient (ANC) [4] extracted from the proton pickup reaction of ^{7}Be. 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 DWBA [5] analysis. The astrophysical S-factor for ^{7}Be(p, γ)^{8}B at zero energy was found to be $S_{17}(0) = 27.4 \pm 4.4$ eV b [2]. Our experimental data were re-analyzed by other groups. Figure 3 shows the comparison of ^{7}Be(p, γ)^{8}B $S_{17}(0)$ factor with other measurements described in Ref. [6,7] and references therein.

One of the key reactions in the hot pp chains is ^{11}C(p, γ)^{12}N which is believed to play a pivotal role in the evolution of Pop III stars. As a result of the low Q-value, its cross section at astrophysically relevant energies is likely dominated by the direct capture into the 1$^+$ ground state of ^{12}N, and the resonant captures into the first and second excited states of ^{12}N at 2$^+$ 0.960 MeV and 2$^-$ 1.191 MeV, respectively. Angular distribution of ^{11}C(d, n)^{12}N at $E_{\rm cm}$ = 9.8 MeV was measured with the secondary ^{11}C beam. The experimental data were analyzed with DWBA calculations and thereby the (ANC)^2 was extracted to be 2.86 $\pm$ 0.91 fm^{-1} for the virtual decay ^{12}N $\rightarrow$ ^{11}C + p. The zero energy astrophysical S-factor for the direct capture ^{11}C(p, γ)^{12}N reaction was then derived to be 157 $\pm$ 50 eV b [3]. We have also estimated the contributions from resonant captures into the first and second excited states of ^{12}N and the interference between direct capture into the ground state and resonant capture into the second excited state. The astrophysical S-factors of ^{11}C(p, γ)^{12}N in the astrophysically relevant energies are illustrated in Fig. 4. This work shows that the direct capture dominates the ^{11}C(p, γ)^{12}N in the wide energy range of astrophysical interest except the ranges corresponding to two resonances.

In the baryon inhomogeneous big-bang models for primordial nucleosynthesis (IBBNs)

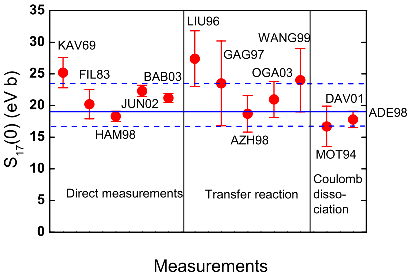

Figure 3. ^{7}Be(p, γ)^{8}B S-factor by different approaches. ADE98 is evaluated value.

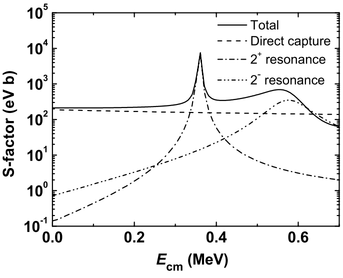

Figure 4. Deduced ^{11}C(p, γ)^{12}N astrophysical S-factors.

[8,9], the reaction chains ^{7}Li(n, γ)^{8}Li(α, n)^{11}B and ^{7}Li(n, γ)^{8}Li(n, γ)^{9}Li are found to play a crucial role, in which ^{8}Li(α, n)^{11}B and ^{8}Li(n, γ)^{9}Li are the key reactions to bridge the stability gap at mass number A = 8. These models predict a higher production of elements beyond ^{7}Li and a larger universal mass-density parameter of baryons Ω_B. We measured the angular distribution of ^{8}Li(d, p)^{9}Li at E_{cm} = 7.8 MeV, through coincidence detection of ^{9}Li and recoil proton, and obtained the cross section. By using the spectroscopic factor deduced from the ^{8}Li(d, p)^{9}Li$_{g.s.}$ angular distribution, we have successfully derived the ^{8}Li(n, γ)^{9}Li direct capture cross section and astrophysical reaction rate for the first time.

Figure 5 demonstrates the angular distribution of ^{8}Li(d, p)^{9}Li, where set1 to set4 refer to four sets of optical potential parameters. Figure 6 displays the reaction rate of ^{8}Li(n, γ)^{9}Li derived through transfer reaction approach and those of theoretical calculations as well as Coulomb dissociation measurements presented in Ref. [10] and references therein. The experimental results of above reactions are summarized in Table 2.

3. Summary

In summary, GIRAFFE, a tandem based one stage unstable beam facility proved to be effective to produce beams suitable for the study of nuclear astrophysics reactions. Angular distribution measurements of transfer reaction in inverse kinematics, together with DWBA/ANC theoretical approach have been used to study the astrophysical reactions indirectly. The astrophysical S-factors and/or reaction rates for ^{7}Be(p, γ)^{8}B, ^{11}C(p, γ)^{12}N, ^{8}Li(n, γ)^{9}Li were deduced by using the measurements of ^{7}Be(d, n)^{8}B, ^{11}C(d, n)^{12}N, and ^{8}Li(d, p)^{9}Li reactions at the energies of astrophysical interest.

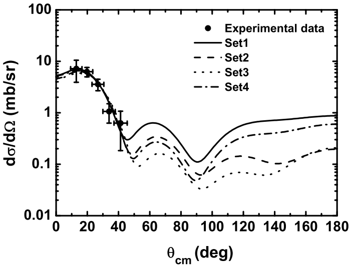

Figure 5. Angular distribution of ^{8}Li$(d,\,p)^{9}$Li at $E_{\mathrm{cm}} = 7.8$ MeV.

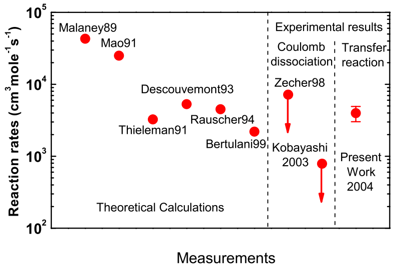

Figure 6. Comparison of theoretical and experimental reaction rates of ^{8}Li$(n,\,\gamma)^{9}$Li.

Table 2
Summary of results of astrophysical experiments

Reaction	E_{cm} (MeV)	σ_{tot} (mb)	$(\mathrm{ANC})^2$ (fm^{-1})	Objective Reaction	S-factor or reaction rate	Reference
^{7}Be$(d,\,n)^{8}$B	5.8	58 ± 8	0.711 ± 0.090	$(p,\,\gamma)$	27 ± 4 eV b	[2]
^{7}Be$(d,\,n)^{8}$B	8.3	28 ± 3	0.62 ± 0.12	$(p,\,\gamma)$	24 ± 5 eV b	[11]
^{11}C$(d,\,n)^{12}$N	9.8	23 ± 5	2.86 ± 0.91	$(p,\,\gamma)$	157 ± 50 eV b	[3]
^{8}Li$(d,\,p)^{9}$Li	7.8	7.9 ± 2.0		$(n,\,\gamma)$	3970 ± 950 cm^{3}mole^{-1}s^{-1}	

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