Measurements of stellar and explosive nuclear astrophysics reactions*

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Abstract This paper described the nuclear astrophysical studies using the unstable ion beam facility GIRAFFE in CIAE, by indirect measurements. We measured the angular distributions for some single proton or neutron transfer reactions, such as ^{7}Be(d,n)^{8}B, ^{11}C(d,n)^{12}N, ^{8}Li(d,p)^{9}Li and ^{13}N(d,n)^{14}O in inverse kinematics, and 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, ^{13}N(p,γ)^{14}O by asymptotic normalization coefficient, spectroscopic factor, and R-matrix approach at astrophysically relevant energies. Some most recent progress of nuclear astrophyiscal work in CIAE are also summarized.

Key words transfer reaction, indirect measurement, astrophysical s-factor, reaction rate

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1 Introduction

Nuclear astrophysics answers the questions about energy production and element synthesis in primordial and stellar objects. For corresponding network calculations, ones need nuclear reaction and decay inputs. Both one involves unstable nuclei in one hands and energy range in Gamow window in the other. To account for the short half and extremely low reaction cross section, novel indirect approach is often the only solution. One of such approach is using direct reaction which involves same proton or neutron transfer as in radiation capture, by using the beams of low energy unstable nuclei. This technique uses DWBA analysis of experimental angular distribution to extract asymptotic normalization constants or nuclear spectroscopic factors. Then this radical contribution is inserted to capture rates calculations. This approach is tested to be reliable with the precision mainly limited by the ambiguity of optical potentials. This paper reviews the progress of activities of this kind in CIAE, such as determination of ^{7}Be(p,γ)^{8}B and ^{8}Li(n,γ)^{9}Li astrophysical s-factors and reaction rates, they are related to solar neutrino production and primordial nuclear syntheses respectively.

2 Description of unstable ion beam facility GIRAFFE

Aiming at the studies of nuclear astrophysics, the secondary beam facility (GIRAFFE)[1, 2] for producing and utilizing low energy beams of unstable nuclei 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 yield some beams of unstable ions ($A<20$) near the

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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) magnetic separation and focusing system, as well as 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, ^{17}F and ^{10}C, and other beams, have been delivered. They are summarized in Table 1. A Wien filter is installed between quadrupole doublet and focal plane by the end of 2004, which greatly improved the secondary beam purity.

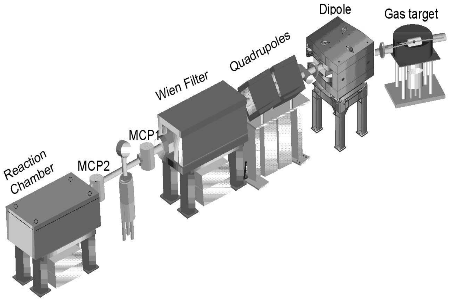

Fig. 1. Sketch of GIRAFFE.

Table 1. Summary of the produced unstable ion beams at GIRAFFE.

RNB	reaction	energy /MeV	purity (%)	intensity /pps
^{6}He	^{2}H(^{7}Li,^{6}He)^{3}He	35.7 ± 0.5	92	500
^{7}Be	^{1}H(^{7}Li,^{7}Be)n	30.8 ± 1.3	99	900
^{8}Li	^{2}H(^{7}Li,^{8}Li)^{1}H	40.0 ± 0.5	88	500
^{10}C	^{1}H(^{10}B,^{10}C)n	55.9 ± 3.5	96	200 ‡§
^{11}C	^{1}H(^{11}B,^{11}C)n	63.4 ± 2.7	80	1000
^{13}N	^{2}H(^{12}C,^{13}N)n	57.8 ± 2.1	92	1200 ‡
^{15}O	^{2}H(^{14}N,^{15}O)n	66.0 ± 3.6	91	800 ‡
^{17}F	^{2}H(^{16}O,^{17}F)n	76.1 ± 3.7	90	2000 ‡
^{18}F	^{3}He(^{16}O,^{18}F)^{1}H	75.7 ± 2.2	85	800 ‡
^{19}Ne	^{4}He(^{16}O,^{19}Ne)n	56.6 ± 3.4	47	120 ‡§
	^{3}He(^{19}F,^{19}Ne)^{3}H	68.6 ± 3.8	42	70 ‡§
^{22}Na	^{4}He(^{19}F,^{22}Na)n	52.9 ± 1.9	57	100 ‡¶

† through ϕ3 mm collimator. ‡ with velocity filter. § primary beam intensity can be 2 times stronger. ¶ primary beam intensity can be one order stronger.

3 Experiments and theoretical analysis

The astrophysical S-factor for the ^{7}Be(p,γ)^{8}B reaction at solar energies is a crucial nuclear physics input for the “solar neutrino problem”. The S-factor can be indirectly determined through the asymptotic normalization coefficient (ANC)[3] extracted from the proton pickup reaction of ^{7}Be, with accuracy comparable to that from direct radiative capture or Coulomb Dissociation reaction, and thus can provide a significant cross examination. 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→^{7}Be+p based on DWBA[4] analysis. The astrophysical S-factor for the ^{7}Be(p,γ)^{8}B reaction at zero energy was found to be $S_{17}(0)$ = 27.4±4.4 eV b[5]. Our experimental data were reanalyzed by other groups, as shown in Fig. 2.

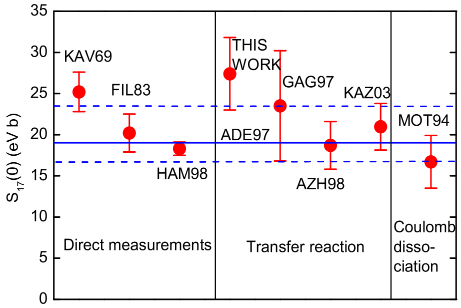

Fig. 2. The ^{7}Be(p,γ)^{8}B S-factor by different approach.

One of the key reactions in the hot pp chains is the ^{11}C(p,γ)^{12}N which is believed to play an important 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 the ^{11}C(d,n)^{12}N reaction 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±0.91 fm^{-1} for the virtual decay ^{12}N→^{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±50 eV b. 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-factor of ^{11}C(p,γ)^{12}N in the astrophysically relevant energies are illustrated in Fig. 3. The temperature dependence of the direct capture, resonant capture and total reaction rates for ^{11}C(p,γ)^{12}N were derived[6]. 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.

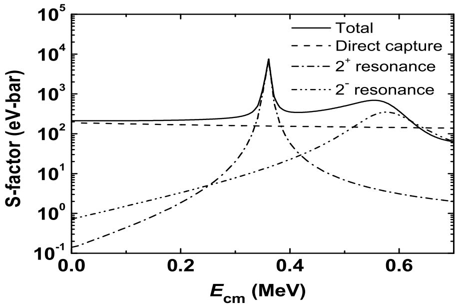

Fig. 3. Deduced ^{11}C(p,γ)^{12}N astrophysical S-factors.

More over, we will conduct a direct measurement of ^{11}C(p,γ)^{12}N reaction. Excitation function at $E_{\mathrm{cm}} = 0.2$—1.0 MeV will be measured in inverse kinematics with the ISAC accelerated ^{11}C beam in TRIUMF. This approved proposal[7] aims at clarifying discrepancies through the direct measurement of excitation function by using high precision DRAGON spectrometer. Based on the measured excitation function, we will be able to derive the energy dependence of astrophysical S-factors for direct capture into the ground state of ^{12}N and resonant captures into the first and second excited states of ^{12}N at 2^+ 0.960 MeV and 2^- 1.191 MeV, as well as the interference in between. The experiment will be performed in the year of 2008.

In the baryon inhomogeneous big-bang models for primordial nucleosynthesis, (IBBNs)[8], many nuclear reactions of unstable nuclei are involved, which can bridge the stability gap at mass number A=8, and predict a higher production of elements beyond ^{7}Li and a larger universal mass-density parameter of baryons Ω_{B}. The reaction chains involving unstable nuclei ^{8}Li, ^{9}Li, ^{8}B, etc. are found to play a pivotal role in IBBNs. The production of succeeding heavier elements scales with the abundances of these unstable isotopes during primordial nucleosynthesis and thus all the reactions for generating or destroying them are of importance. We have measured the angular distribution of ^{8}Li(d,p)^{9}Li reaction at $E_{\mathrm{cm}} = 7.8$ MeV, through coincidence detection of ^{9}Li and recoil proton, and obtained the cross section and astrophysical S-factor. By using spectroscopic factor deduced from the ^{8}Li(d,p)^{9}Li$_{\mathrm{g.s.}}$ 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[9].

The typical experimental setup for the ^{8}Li(d,p)^{9}Li reaction is shown in Fig. 4, the setup of ^{7}Be(d,n)^{8}B reaction and that of ^{11}C(d,n)^{12}N were described elsewhere[5, 6], respectively. Two Multi-Ring Semiconductor Detectors (MRSDs) with center hole were used in this experiment. The upstream one aimed at detection of the recoil protons, and the downstream one served as a residue energy (E_{r}) detector which composed a $\Delta E - E_{\mathrm{r}}$ silicon counter telescope. This setup enabled the ^{9}Li -recoil proton coincidence measurement. We applied the similar experimental setup to other reactions except upstream MRSD. Such a detector configuration covered the full laboratory angular region. This setup also facilitated to precisely determine the accumulated quantity of incident unstable beams because the beams themselves were recorded by the counter telescope simultaneously.

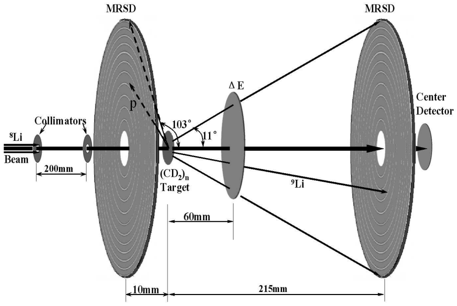

Fig. 4. ^{8}Li(d,p)^{9}Li experimental setup.

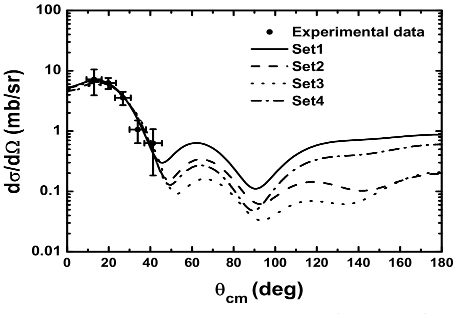

Fig. 5. Angular distribution of ^{8}Li(d,p)^{9}Li at $E_{\mathrm{cm}} = 7.8$ MeV.

As examples, Fig. 5 demonstrates the angular distribution of ^{8}Li(d,p)^{9}Li reaction, where set1 to set4 refer to four sets of optical potential parameters; Fig. 6 displays the reaction rate of ^{8}Li(n,γ)^{9}Li derived through transfer reaction approach and those of theoretical calculations and Coulomb dissociation measurements presented in Ref. [10] and references therein. This data was also used to extract the ANC of mirror system, by assuming the identical nuclear spectroscopic factor as a result of mirror symmetry[11]. Base on this approach, the reaction rate for ^{26}Si(p,γ)^{27}Mg was also deduced[12].

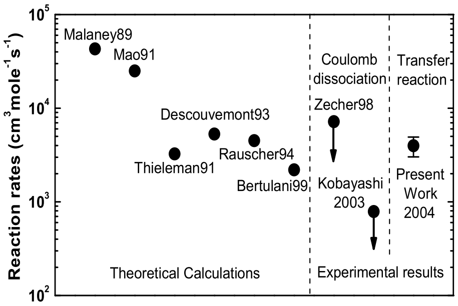

Fig. 6. Comparison for reaction rates of ^{8}Li(n,γ)^{9}Li.

$^{13}N(p,\gamma)^{14}O$ is important reaction in the hot CNO cycle which occurs at stellar temperatures around $T_9 \geqslant 0.1$. But some uncertainties still exist for the direct capture component. The angular distribution of the ^{13}N(d,n)^{14}O reaction at $E_{\mathrm{c.m.}} = 8.9$ MeV has been measured in inverse kinematics, for the first time. Based on DWBA analysis, the ANC, $C^{^{14}O}_{1,1/2}$, for the ground state of $^{14}O \to {}^{13}N+p$ is derived to be 5.42 ± 0.74 fm$^{-1/2}$. The ^{13}N(p,γ)^{14}O reaction was analyzed with the *R*-matrix approach, its astrophysical *S*-factors and reaction rates at energies of astrophysical relevance are then determined with the ANC. The present result is in good agreement with that extracted from the ^{14}N (^{13}N, ^{14}O)^{13}C transfer reaction[13]. *S*-factors for direct and resonant captures is then derived, as demonstrated in Fig. 7, and reaction rate is deduced[14]. The implications of the present reaction rates on the evolution of novae are then obtained with the reaction network calculations.

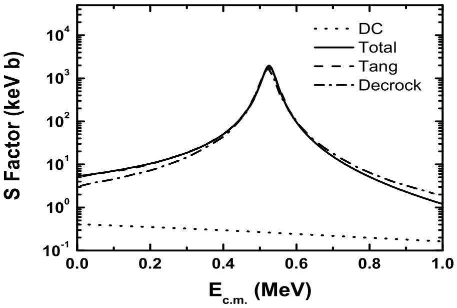

Fig. 7. *S*-factors for the ^{13}N(p,γ)^{14}O reaction. The dotted line is from the direct proton capture. The solid lines indicate the total from this work.

All astrophysical reactions and their deduced parameters are summarized in Table 2.

Table 2. Summary of astrophysics experiment results.

reaction	E_{cm} /MeV	σ_{tot} /mb	(ANC)^2 /fm^{-1}	indirect reaction	S(0)/(eV·b) or rate for DC part.
^{7}Be(d,n)^{8}B	5.8	58±8	0.711±0.090	(p,γ)[5]	27±4
^{7}Be(d,n)^{8}B	8.3	28±3	0.62±0.12	(p,γ)[15]	24±5
^{11}C(d,n)^{12}N	9.8	23±5	2.86±0.91	(p,γ)[6]	157±50
^{8}Li(d,p)^{9}Li	7.8	7.9±2.0	1.25±0.25	(n,γ)[9]	3970±950cm^3·mole^{-1}·s^{-1}
^{8}Li(d,p)^{9}Li	7.8	7.9±2.0	1.10 ± 0.23	(p,γ)[11] For ^{8}B(p,γ)^{9}C mirror system.	42 ± 9
^{13}N(d,n)^{14}O	8.9	7.4±1.1	29.4±5.3	(p,γ)[14]	417± 4
^{26}Mg(d,n)^{27}P	-	-	1840±240	(p,γ)[12]	87000±11000

4 More recent progress and proporsal

The ^{13}N+p elastic resonance scattering has been studied in inverse kinematics via thick-target method. A ^{13}N secondary beam of 47.8±1.5 MeV was used to bombard a 9.33 mg/cm^2 $(CH_2)_n$ target. The excitation function of ^{13}N(p,p) was obtained in the energy interval of E_{CM} of 0.5—3.2 MeV, and was analyzed by using a *R*-matrix code MULTI. Several low-lying excited states in ^{14}O were surveyed, our results confirm the recent 2^- assignment to the 6.8 MeV level, and agree with the observation of a new 0^- level at 5.7 MeV in ^{14}O with a slightly different width of 300±100 keV[16].

Temperature dependence of nuclear decays in metallic environments is a controversial issue. We measured the temperature dependence of the β^+-decay half-life of ^{22}Na implanted into the metal host of palladium. We have found that the β^+-decay half-life of ^{22}Na in the metal Pd cooled to T=15 K was shorter by 0.46±0.14% than that at room temperature. The result is consistent in sign with, but clearly smaller than, the estimated one by the Debye model[17].

Angular distribution of the ^{8}Li(p,d)^{7}Li reaction, which plays an important role in the inhomogeneous Big Bang nucleosynthesis, was measured in inverse kinematics at $E_{\mathrm{CM}} = 4.0$ MeV by using ^{8}Li secondary beam for the first time. The present result is in agreement with the data of ^{8}Li(p,d$_0$)^{7}Li reaction deduced from its inverse reaction[18].

Up to now, r-process which is responsible for production of elements heavier than Fe, is lack of nuclear data. In 2007, we proposed a experiment SHARP[19], the nuclear astrophysical studies using the unstable ion beam facility RIBF/BigRIPS in RIKEN, by indirect measurements. We plan to measure single neutron transfer reactions ^{134}Sn(d,p)^{135}Sn, to derive the astrophysical reaction rates of ^{134}Sn(n,γ)^{135}Sn by nuclear spectroscopic factor, based on our well established theoretical framework. The input of DC component of (n,γ) reaction rates will help to get more reliable nuclear input for r-process network calculation, the (d,p) reaction data itself, can give a useful input to investigate the possible shell quenching phenomena in Sn region. At the moment, the feasibility study of this experiment is still going on, aiming at solving the problem of large energy spread introduced by a energy degrade Sn beams, that is required by energy range requirement DWBA treatment.

We also proposed to measure the angular distribution of the ^{12}N(d,n)^{13}O reaction leading to the ground state of ^{13}O in inverse kinematics with CRIB in RIKEN, and then derive the ANC and spectroscopic factor of ^{13}O$_{\mathrm{g.s}}$ through distorted wave Born approximation analysis. Its astrophysical S-factors and reaction rates of direct captures will be obtained using the experimental ANC, for the first time.

5 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, ^{13}N(p,γ)^{14}O were deduced by using the measurements of ^{7}Be(d,n)^{8}B ,^{11}C(d,n)^{12}N, ^{8}Li(d,p)^{9}Li and ^{13}N(d,n)^{14}O reactions at the energies of astrophysical interest. Some most recent progress are also given.

References

1 BAI X, LIU W, QIN J et al. Nucl. Phys. A, 1995, **588**: 273c—276c
2 LIU W, LI Z, BAI X et al. Nucl. Instrum. Methods B, 2003, **204**: 62—70
3 XU H, Gagliardi C, Tribble R. Phys. Rev. Lett., 1994, **73**: 2027
4 Kunz P. computer code DWUCK4
5 LIU W, BAI X, ZHOU S et al. Phys. Rev. Lett., 1996, **77**: 611—614
6 LIU W, LI Z, BAI X et al. Nucl. Phys. A, 2003, **728**: 275—284
7 LIU W et al. TRIUMF proporsal E983
8 Kajino T, Boyd R N. Astrophys. J., 1990, **359**: 267
9 LI Z, LIU W et al. Phys. Rev. C, 2005, **71**: 052801-1—4(R)
10 Kobayashi H, Ieki K, Horvath A et al. Phys. Rev. C, 2003, **67**: 015806
11 GUO B, LI Z, LIU W et al. Nucl. Phys. A, 2005, **761**: 162—172
12 GUO B, LI Z, BAI X, LIU W et al. Phys. Rev. C, 2006, **73**: 048801-1—4
13 TANG X et al. Phys. Rev. C, 2004, **69**: 055807
14 LI Z et al. Phys. Rev. C, 2006, **74**: 035801
15 WANG Y, LIU W, BAI X et al. Chin. Phys. Lett., 1999, **16**: 873—875
16 WANG Y et al. Phys. Rev. C (submitted.)
17 LIAN G et al. Chin. Phys. Lett. (submitted.)
18 LI Y et al. Chin. Phys. Lett. (submitted.)
19 LIU W et al. SHARP proposal NP0702-RIBF-024, 2007 (unpublished)