International Journal of Modern Physics E
Vol. 15, No. 8 (2006) 1899–1907
© World Scientific Publishing Company

World Scientific
www.worldscientific.com

INDIRECT MEASUREMENTS OF NUCLEAR ASTROPHYSICS REACTIONS USING UNSTABLE NUCLEAR BEAMS

WEI-PING LIU, ZHI-HONG LI, XI-XIANG BAI, YOU-BAO WANG, GANG LIAN, BING GUO, SHENG ZENG, SHENG-QUAN YAN, BAO-XIANG WANG, JUN SU, NENG-CHUAN SHU and YONG-SHOU CHEN

CIAE, China Institute of Atomic Energy
P. O. Box 275(1), Beijing 102413, P. R. China
wpliu@iris.ciae.ac.cn

Received 1 October 2006

This paper described the nuclear astrophysical studies using the unstable ion beam facility GIRAFFE, 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,n)^{9}Be, ^{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.

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] 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 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 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.

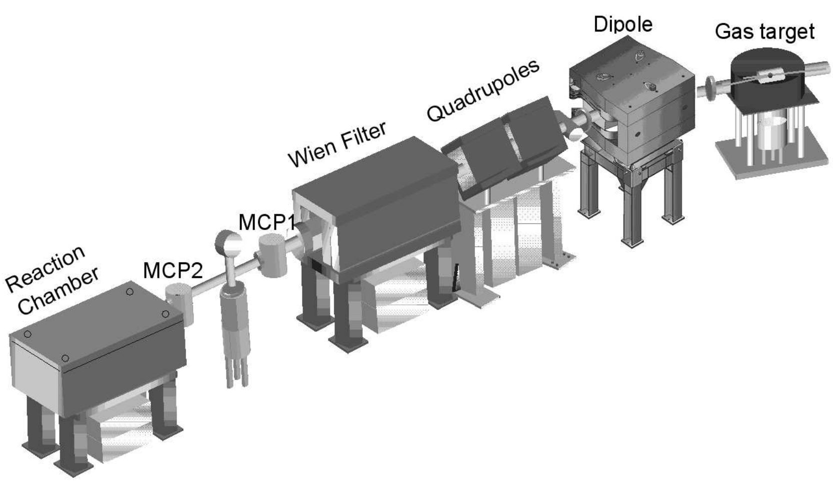

Fig. 1. Sketch of GIRAFFE.

Table 1. Summary of the produced unstable ion beams at GIRAFFE. (With 2-3 mm diameter collimator and primary beam intensity 100-700 enA, ^{8}Li without Wien filter.)

RNB	Reaction	Energy (MeV)	FWHM (MeV)	Purity (%)	Beam Intensity (pps)
^{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	30.8	1.3	99	1000
^{8}Li	^{2}H(^{7}Li, ^{8}Li)^{1}H	39.0	0.5	90	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	85	1000
^{13}N	^{2}H(^{12}C, ^{13}N)n	57.8	2.1	92	1500
^{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

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 $E_{\mathrm{cm}} = 5.8$ MeV and extracted the ANC for the virtual decay $^8\mathrm{B} \to {}^7\mathrm{Be} + \mathrm{p}$ 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 $S_{17}(0) = 27.4 \pm 4.4$ eV b.[5] Our experimental data were re-analyzed by other groups, as shown in Fig. 5.

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 $E_{\mathrm{cm}} = 9.8$ 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 $^{12}\mathrm{N} \to {}^{11}\mathrm{C} + \mathrm{p}$. 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

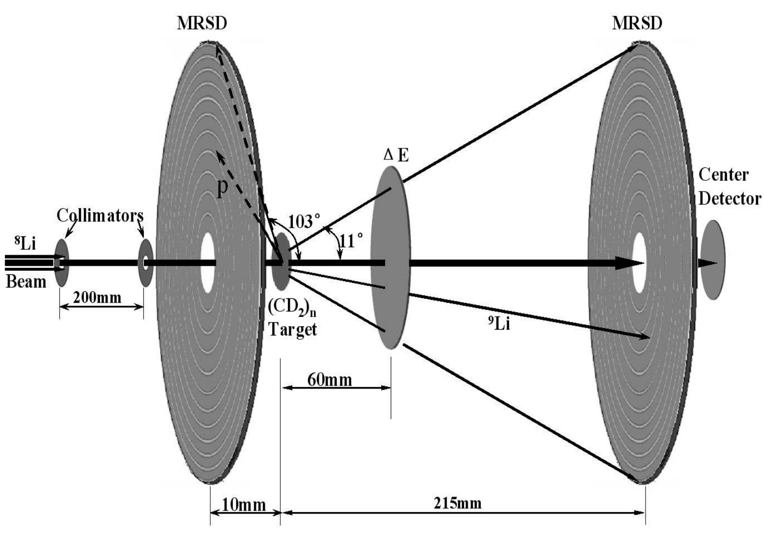

Fig. 2. Experimental setup.

astrophysical S-factor of $^{11}C(p,\gamma)^{12}N$ in the astrophysically relevant energies are illustrated in Fig. 3. The temperature dependence of the direct capture, resonant capture and total reaction rates for $^{11}C(p,\gamma)^{12}N$ were derived.[6] This work shows that the direct capture dominates the $^{11}C(p,\gamma)^{12}N$ 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),[7] 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 $^8Li(d,p)^9Li$ reaction at $E_{\rm cm} = 7.8$ 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 $^8Li(d,p)^9Li_{g.s.}$ angular distribution, we have successfully derived the $^8Li(n,\gamma)^9Li$ direct capture cross section and astrophysical reaction rate for the first time.[11]

The typical experimental setup for the $^8Li(d,p)^9Li$ reaction is shown in Fig. 2, the setup of $^7Be(d,n)^8B$ 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 $\Delta E - E_r$ silicon counter telescope. This setup enabled the ^{9}Li -recoil proton coincidence measurement. We applied the similar experimental setup

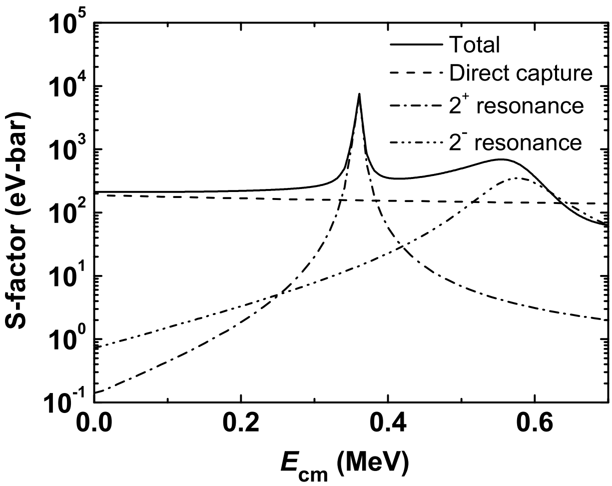

Fig. 3. Deduced $^{11}C(p,\gamma)^{12}N$ astrophysical S-factors.

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.

As examples, Fig. 4 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. 5 shows the comparison of ^{7}Be(p,γ)^{8}B $S_{17}(0)$ factor with other measurements described in Ref.[8] and references therein; Fig. 6 displays the reaction rate of ^{8}Li(n,γ)^{9}Li derived through transfer reaction approach and those of theoretical calculations and

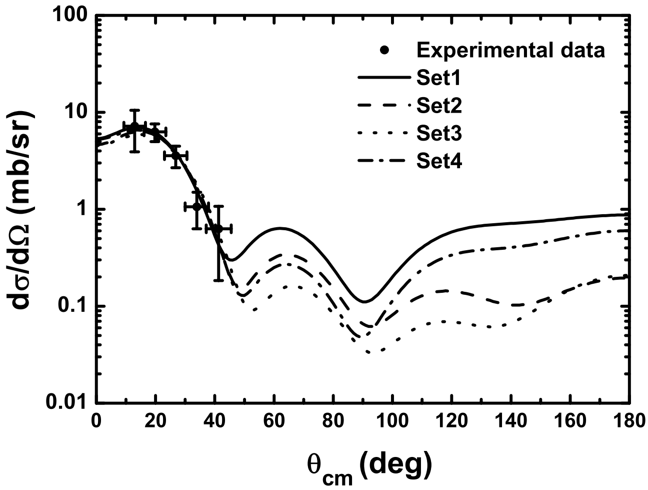

Fig. 4. Angular distribution of ^{8}Li(d,p)^{9}Li at E_{cm} = 7.8 MeV.

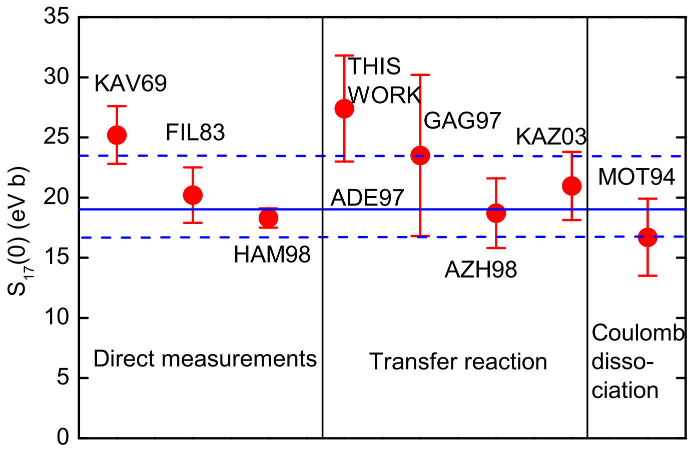

Fig. 5. The ^{7}Be(p,γ)^{8}B S-factor by different approach.

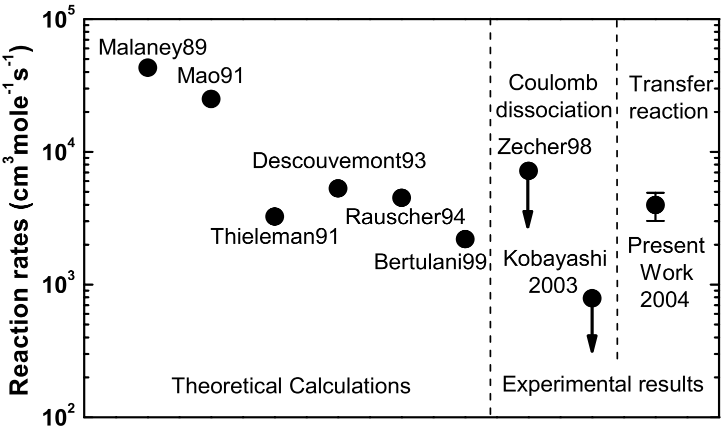

Fig. 6. Comparison for reaction rates of ^{8}Li(n,γ)^{9}Li.

Coulomb dissociation measurements presented in Ref.[9] 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.[12]

^{13}N$(p, \gamma)^{14}$O is important reaction in the hot CNO cycle which occurs at stellar temperatures around $T_9 \geq 0.1$. But some uncertainties still exist for the direct capture component. The angular distribution of the ^{13}N$(d, n)^{14}$O reaction at $E_{\rm c.m.}$ = 8.9 MeV has been measured in inverse kinematics, for the first time, as shown in Fig. 7. Based on DWBA analysis, the ANC, $C^{14O}_{1,1/2}$, for the ground state of ^{14}O $\rightarrow$ ^{13}N + p is derived to be 5.42 ± 0.74 fm$^{-1/2}$. The ^{13}N$(p, \gamma)^{14}$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. 8, 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.

More over, we will conduct a direct measurement of nuclear astrophysical reaction. Excitation function of the ^{11}C$(p, \gamma)^{12}$N at $E_{\rm cm}$=0.2-1.0 MeV will be measured in inverse kinematics with the ISAC accelerated ^{11}C beam at DRAGON. There are large discrepancies in the existing indirect measurements and theoretical calculations of this reaction for both direct and resonant captures. The approved proposal[15] aims at clarifying these 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 between the direct capture into the

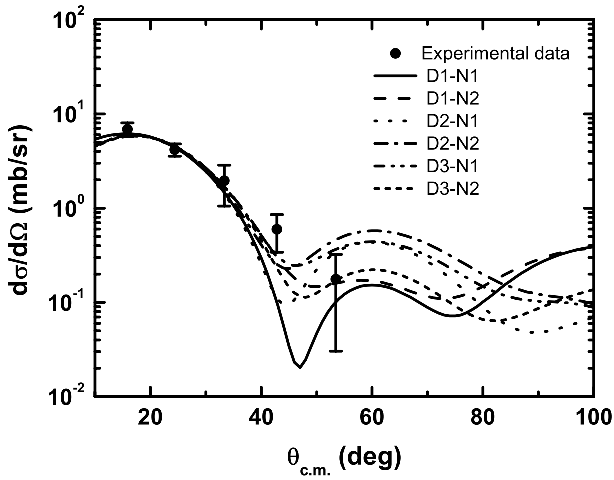

Fig. 7. The angular distribution of the $^{13}N(d,n)^{14}O$ reaction at $E_{c.m.} = 8.9$ MeV, together with DWBA calculations using different optical potential parameters.

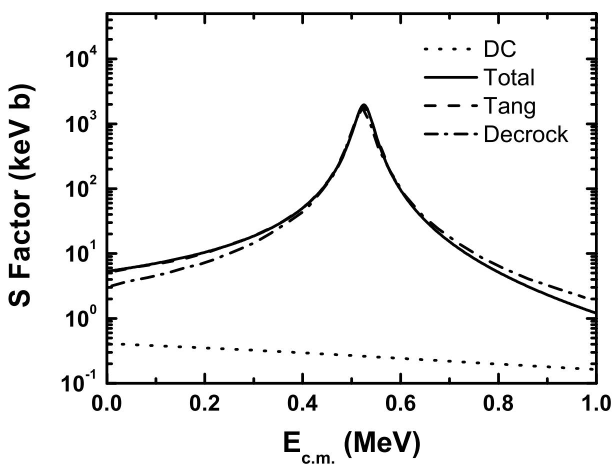

Fig. 8. Astrophysical S-factors as a function of $E_{\rm c.m.}$ for the $^{13}{\rm N}(p,\gamma)^{14}{\rm O}$ reaction. The dotted line is the contributions from the direct proton capture. The solid, dashed, and dashed-dotted lines indicate the total S-factors from the present work, and those of Tang et al.[13] and Decrock et al., respectively.

ground state and resonant capture into the second excited state. The temperature dependence of direct capture-, resonant capture- and total reaction rates will be given. Recently, a proof of principle approach for the production of intense ($10\ ^8$/s) radioactive ion beams, which differs from the standard ISOL (Isotope Separation On-Line), has been demonstrated successfully taking ^{11}C at the TRIUMF facility,[16] as a test case. This approach uses 13 MeV protons and should be useful for a range of radioisotopes of interest to the nuclear astrophysics research program.

Table 2. Summary of astrophysics experiment results. (Reaction rates (3970) for DC component only, in the unit of $cm^3 mole^{-1} s^{-1}$. ^{8}Li(d,p)^{9}Li was also used for ^{8}B(p,γ)^{9}C mirror system, as indicated in the second raw of ^{8}Li results.)

Reaction	E_{cm} (MeV)	σ_{tot} (mb)	$(ANC)^2$ (fm^{-1})	Indirect Reaction	S(0) (eV b) or Rate	Reference
^{7}Be(d,n)^{8}B	5.8	58 ± 8	0.711 ± 0.090	(p,γ)	27 ± 4	5
^{7}Be(d,n)^{8}B	8.3	28 ± 3	0.62 ± 0.12	(p,γ)	24 ± 5	10
^{11}C(d,n)^{12}N	9.8	23 ± 5	2.86 ± 0.91	(p,γ)	157 ± 50	6
^{8}Li(d,p)^{9}Li	7.8	7.9 ± 2.0	1.25 ± 0.25	(n,γ)	3970 ± 950	11
^{8}Li(d,p)^{9}Li	7.8	7.9 ± 2.0	1.10 ± 0.23	(p,γ)	42 ± 9	12
^{13}N(d,n)^{14}O	8.9	7.4 ± 1.1	29.4 ± 5.3	(p,γ)	417 ± 74	14

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

4. Summary

In summary, GIRAFFE, a tandem based D-Q-Q-WF electro-magnetic separation facility has been used to produce low energy unstable nuclear beams for the study of nuclear astrophysics reactions. Angular distribution measurements of direct reaction in inverse kinematics, together with DWBA/ANC theoretical approach have been applied to study the astrophysical (p,γ) and (n,γ)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.

Acknowledgements

The above research programs were supported by the Major State Basic Research Development Program under Grant Nos. G200077400 and 2003CB716704, the National Natural Science Foundation of China under Grant Nos. 19935030, 10025524, 103750966 and 10575137).

References

1. X. Bai, W. Liu, J. Qin et al., Nucl. Phys. A 588 (1995) 273c.
2. W. Liu, Z. Li, X. Bai et al., Nucl. Instr. Meth. B 204 (2003) 62.
3. H. Xu, C. Gagliardi, R. Tribble, Phys. Rev. Lett. 73 (1994) 2027.
4. P. Kunz, computer code DWUCK4.
5. W. Liu, X. Bai, S. Zhou et al., Phys. Rev. Lett. 77 (1996) 611.
6. W. Liu, Z. Li, X. Bai et al., Nucl. Phys. A 728 (2003) 275.
7. T. Kajino and R. N. Boyd, Astrophys. J. 359 (1990) 267.
8. K. Ogata, M. Yahiro, Y. IseriH et al., Phys. Rev. C 67 (2003) 011602(R).
9. H. Kobayashi, K. Ieki, A. Horvath et al., Phys. Rev. C 67 (2003) 015806.

10. Y. Wang, W. Liu, X. Bai et al., Chin. Phys. Lett. 16 (1999) 873.
11. Z. H. Li, W. P. Liu, Z. H. Li et al., Phys. Rev. C 71 (2005) 052801(R)
12. B. Guo, Z. H. Li, W. P. Liu et al., Nucl. Phys. A 761 (2005) 162
13. X. Tang et al., Phys. Rev. C **69**, 055807 (2004)
14. Z. H. Li et al., Phys. Rev. C, in press.
15. W. P. Liu et al., TRIUMF proporsal E983.
16. B. Guo, W. P. Liu et al., High Ene. Phys. and Nucl. Phys. 30,(2006)675 (In Chinese.)