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Study of Stellar Reactions in Explosive Hydrogen Burning with CRIB

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With using low-energy RI beams from an in-flight RIB separator, CRIB, the most crucial stellar reaction ^{14}O(α,p)^{17}F for the onset of the high-temperature rp-process was directly investigated and the transitions through the states at around 6.2 MeV in ^{18}Ne were first observed, confirming the importance predicted before. The (α,p)reaction leading to the first excited state in ^{17}F was also found to have a large contribution. A proton resonance search experiment of ^{23}Mg + p was also discussed, which is a part of our series of resonance search studies relevant to the early stage of the rp-process.

1. INTRODUCTION

Hydrogen burning process is one of the interesting subjects in nuclear astrophysics as hydrogen is the most abundant element and thus has a variety of occasions that this process takes place. Specifically, this process attracts a lot of interest in relation to various observations of elements and isotopic abundances.

Many critical nuclear reactions under explosive conditions involve proton-rich unstable nuclei. To investigate directly these reactions one needs a high-intense, low-energy RI beams. The Center for Nuclear Study of the University of Tokyo (CNS) has installed such an RI beam separator of in-flight type, named CRIB [1,2], in the RIKEN accelerator research Facility. This low-energy RI beam facility has been developed including the ion source, the AVF cyclotron, the beam line, and CRIB which consists of a double achromatic separator together with a Wien filter section. It has also a window-less gas target system with a recirculation function, and high-power Faraday cups along the walls of the first dipole magnet. Several experiments were already performed at the double achromatic focal plane F2. Some of the experimental results are discussed in this paper.

The Wien filter section gives a capability of better particle separation and also provides good features to investigate for other interesting studies. The velocity separation section has a 1.5 m-long electric plates that have the maximum voltages of ± 200 kV for a gap of 8 cm, giving 50 kV/cm. The maximum velocity dispersion designed was about 0.8 cm/%. The separation capability was verified with an ^{14}O beam produced from the ^{1}H(^{14}N,^{14}O) reaction at F0. It gave almost 100 % purity at F3. Another favorable feature of the RI beam from the filter is that the beam quality at F3 can be better roughly by a factor of two, about 4 - 5 mm in FWHM in diam., than the beam obtained usually with a degrader.

The present in-flight method is very useful for nuclear astrophysics. We obtained quite reasonable beam intensities like a little over 10^6 for ^{14}O with a primary beam of 200 pnA. This intensity is currently limited by the production target as the gas target windows do not stand with high beam currents, which is one of the major subjets under developments.

2. THE DIRECT MEASUREMENT OF THE ^{14}O(α,p)^{17}F REACTION

The high-temperature rp-process may typically take place in X-ray bursts, which is considered to be an event on the surface of a neutron star with accretion of hydrogen gas from the companion star in a main sequence phase. Here, the critical stellar reaction for the ignition from the Hot-CNO cycle is the ^{14}O(α,p)^{17}F reaction. There were many experiments performed by indirect methods [3,4], but not by the direct method with an ^{14}O beam. Two experiments were made previously using the time-reverse reaction ^{17}F(p,α)^{14}O. Only some transitions through resonances above Ecm = 3 MeV in ^{18}Ne were reported[5,6]. Note that the most critical energy region is around Ecm = 1 - 2 MeV for the present problem. Here, this reaction has been successfully investigated at F2 using a high intense ^{14}O beam from CRIB.

A low-energy ^{14}O was produced by the ^{1}H(^{14}N,^{14}O) reaction at 8.4 MeV/u, and separated. The intensity and the purity of the beam was 1.6 x 10^6 and 85 %, respectively, at F2. The momentum spread of the beam was defined by setting an aperture at F1, the momentum dispersive focal plane, to be 1 %. The secondary target of He was cooled down to about 30 K, so that the target length was shortened roughly by a factor of 10, which made the present experiment possible. The detail is described in ref. [7].

For the measurement of the ^{14}O(α,p)^{17}F reaction, we applied the thick-target method [8], which has been developed in the last decade for low-energy RIB experiments and applied for proton resonance searches. Under certain conditions, this method was successfully applied for the present case. Figure 1 displays a proton spectrum measured at 0° with a Silicon counter telescope. Several peaks are clearly seen that correspond mostly to the (α,p) reaction leading to the ground state in ^{17}F. The transitions through the 6.15 and 6.29 MeV states in ^{18}Ne were seen for the first time. These transitions were considered to be the main contributors for the stellar reactions under the X-ray burst condition [3]. The

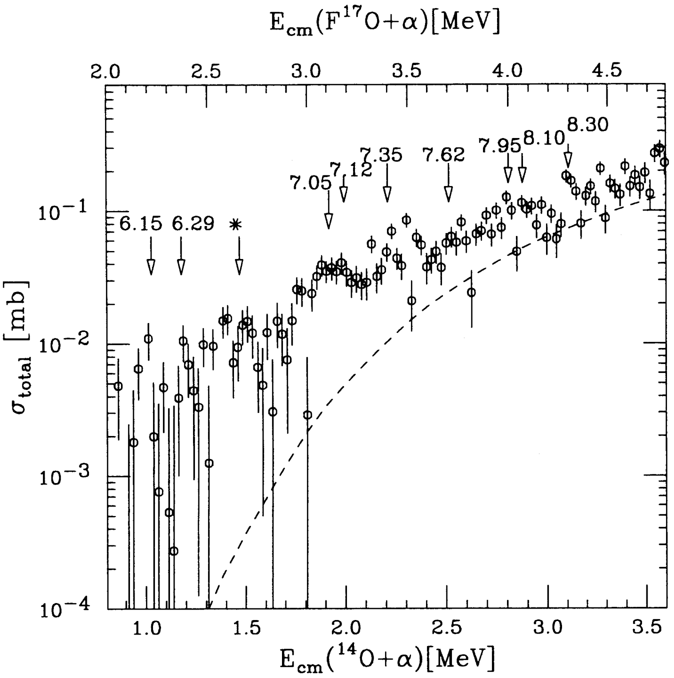

Figure 1. Proton spectrum from the $^{14}O(\alpha,p)^{17}F$ reaction measured at $\Theta_{Lab} = 0°$.

cross sections are roughly the same as predicted in ref. [3], thus cofirming the primary importance of the two contributors. The transitions through the states at 7-8 MeV are also clearly observed. The peak at around 6.5 MeV is considered to be the transition through $^{18}Ne^*$(Ex=7.1) decaying to the first excited state at 0.495 MeV in ^{17}F. Since there is no state of a large proton width in the ^{17}F + p scattering [6], and the states in this energy region in ^{18}Ne can not have a large α width as it is so close to the α threshold, the peak around 6.5 MeV can be concluded not due to a state in ^{18}Ne, but most probably the transition to the fist excited state in ^{17}F in the exit channel. This implies that the transition through the 7.1 MeV state in ^{18}Ne has a larger reaction rate roughly by 50 %. Note that the reaction study with the time-reverse reaction ignores this process.

3. SEARCH FOR PROTON RESONANCES RELEVANT TO THE EARLY STAGE OF THE rp-PROCESS

The mechanism of the early stage of the rp-process is of great interest, although it is not well understood. Previously, we studied by indirect methods the excited states near and above the proton threshold, relevant to the early stage of the rp-process [9], where many new states were identified. However, the reaction rates are not well determined yet because the resonance properties are not known. Thus, we have started to investigate the properties of these proton resonances by the direct method. So far, we studied the proton resonant scattering of ^{21}Na+p, ^{22}Mg+p, ^{23}Mg+p, ^{25}Al+p and ^{26}Si+p as well as ^{24}Mg+p for testing the thick target method [8] with the preset experimental setup. The data of ^{24}Mg+p are very well reproduced by the R-matrix calculation [11] with known

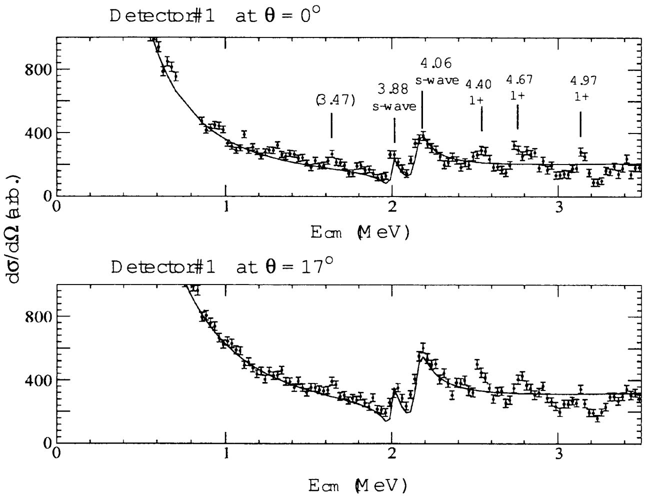

Figure 2. Elastic scattering of ^{23}Mg+p measured at $\Theta_{Lab} = 0°$ and $17°$. The solid line is a fit with R-matrix analysis. Arrows indicate excitation energies in ^{24}Al.

resonance parameters. The scattering of ^{25}Al+p and ^{26}Si+p are presented elsewhere [10] in this symposium.

Figure 2 displays the proton excitation functions of ^{23}Mg+p. This is the first experiment to investigate ^{24}Al by a proton resonance scattering, and thus, no resonance parameters were known before for the states in ^{24}Al [12]. We can see clearly two resonances at 3.88 and 4.06 MeV, which are fitted well by s-wave resonance. Previously, states at 3.885 and 4.059 MeV were known there [12]. We can also see three resonances that could be the 1^+ states known by the beta decay study of ^{24}Si [13]. Detailed analysis is in progress.

The present result demonstrates that one can investigate interesting stellar reactions of the rp-process very efficiently at CRIB.

REFERENCES

1. S. Kubono, et al., Eur. Phys. J. **A 13** (2002) 217.
2. Y. Yanagisawa, S. Kubono, et al., submitted to Nucl. Instr. Meth. (2004).
3. K.I. Hahn, et al., Phys. Rev. **C54** (1996) 1999.
4. I.S. Park, et al., Phys. Rev. **C59** (1999) 1182.
5. B. Harss, et al., Phys. Rev. Lett.**82** (1999) 3964.
6. J.C. Blackmon, et al., Nucl. Phys. **A688** (2001) 142c.
7. M. Notani, S. Kubono, T. Teranishi, et al., Nucl. Phys. **A738** (2004) 411.
8. S. Kubono, Nucl. Phys. **A 693** (2001) 221, and references therein.
9. S. Kubono, Prog. Theor. Phys. **96** (1996) 275.
10. J.Y. Moon, et al., article in this proceedings.
11. J.M. Blatt and L.C. Biedenharn, Rev. Mod. Phys. **24** (1952) 258.
12. S. Kubono, T. Kajino, and S. Kato, Nucl. Phys. **A588** (1995) 521.
13. V. Banerjee, et al., Phys. Rev. **C67** (2002) 024307.