PoS PROCEEDINGS OF SCIENCE

Determination of astrophysical nuclear reaction rates using light neutron-rich RNBs

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Excitation functions of ^{8}Li(α, n), (d, t) and ^{12}B(α, n) reactions were directly measured in the energy region of astrophysical interest using low-energy radioactive nuclear beams of ^{8}Li and ^{12}B. Each measured excitation function is strongly affected by one or more resonances through a compound nucleus. The measured excitation functions are presented. Dominant r-process paths through ^{8}Li at various temperatures are discussed and our future experimental plan is also presented.

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1. Introduction

It is pointed out that nuclear reactions on light neutron-rich radioactive nuclei play important roles to produce so called 'seed' nuclei and determine the ratio of 'seed' to neutrons at the preceding stage of the r-process. Especially, nuclear reactions through ^{8}Li are thought to be important because of filling a gap of atomic mass number A = 8 [1]. A systematic study of astrophysical nuclear reaction rates on light neutron-rich nuclei using low-energy radioactive nuclear beams (RNB) is in progress at the tandem facility of Japan Atomic Energy Agency (JAEA). In this report, the measured excitation functions of ^{8}Li(α, n), (d, t) and ^{12}B(α, n) reactions are shown and dominant reaction paths through ^{8}Li during the r-process are discussed. Our future experimental plan is also presented.

2. Experiment

There exists two kinds of RNB generators at the tandem facility; one is a recoil mass separator (RMS) as an in-flight secondary beam separator [2]. The other is an ISOL-based RNB facility, named Tokai Radioactive Ion Accelerator Complex (TRIAC) [3], which was constructed and is operated under a joint project of High Energy Accelerator Research Organization (KEK) and JAEA. Using the ^{8}Li and ^{12}B beams from the RMS with fixed energies of 14.6 MeV and 24 MeV, respectively, direct cross-section measurements of ^{8}Li(α, n)^{11}B [4] and ^{12}B(α, n)^{15}N reactions were performed with a gas chamber surrounded by neutron detector arrays [5]. The gas chamber works not only as a gas counter, but also a He gas target [5]. Using the ^{8}Li beam from the TRIAC with various energies of 0.18 – 0.75 MeV/u, direct measurement of the ^{8}Li(d, t)^{7}Li reaction was carried out using a CD_2 target and large-area position-sensitive silicon detectors [6]. For more detailed experimental technique, please see the cited references.

3. Excitation functions

The excitation function of the ^{8}Li(α, n)^{11}B reaction was measured in center-of-mass energies (E_{cm}) from 0.7 to 2.6 MeV. The resultant cross sections were roughly two times smaller than previous measurements. A resonance-like structure was found at around E_{cm} = 0.85 MeV, corresponding to the excited state located at E_x = 10.9 MeV in ^{12}B. For more detail, please see reference [4].

The excitation function of the ^{12}B(α, n)^{15}N reaction was measured in the energy region of E_{cm} = 1.1 – 3.6 MeV, as shown in Fig.1. It covered the Gamow peaks of T_9 = 2 – 5. The resultant cross sections were almost consistent with the theoretical estimation by Fowler and Hoyle [7]. At E_{cm} = 1.4 – 1.5 MeV, a resonance-like structure was observed and may correspond to one or more excited states located at E_x = 11.61, 11.70, 11.75 MeV in ^{16}N. The cross section at E_{cm} = 1.5 MeV is about four times larger than the theoretical estimation. The astrophysical reaction rate is directly deduced from measured cross sections by applying the following formula:

$$N_A < \sigma v >= N_A \left(\frac{8}{\pi \mu} \right)^{1/2} \frac{1}{kT^{3/2}} \int_0^{\infty} \sigma(E) E \exp\left(-\frac{E}{kT} \right) dE \qquad (1)$$

Where σ(E) is the cross section, N_A is Avogadro's number, m is the reduced mass, k is Boltzmann's constant, and T is the temperature. In the energy region below E_{cm} = 1.1 MeV and above 3.8 MeV, we used cross section data estimated by Fowler and Hoyle. The resultant reaction rate is roughly two times faster at around T_9 = 3 than the theoretical estimation [7].

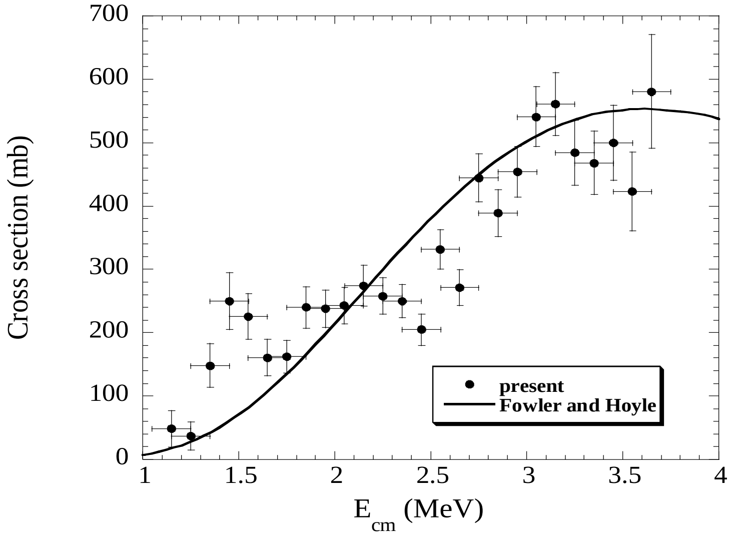

Figure 1: Excitation function of the $^{12}B(\alpha, n)^{15}N$ reaction. Black circles show present results. The solid line indicates the theoretical estimation by Fowler and Hoyle [7].

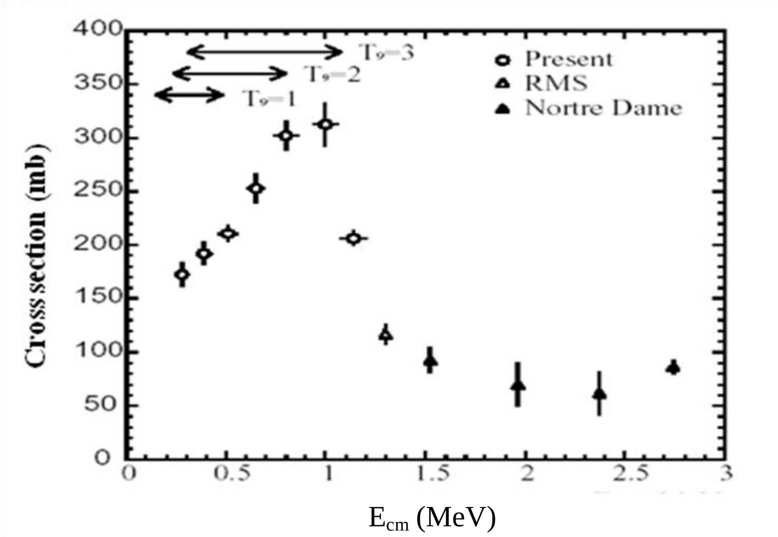

Figure 2: Excitation function of the $^{8}Li(d, t)^{7}Li$ reaction. Open circles show the present results. The open triangle shows our measurement using the ^{8}Li beam from the RMS. Black triangles indicate the previous results by Balbes et al. [8].

The excitation function of the $^{8}Li(d, t)^{7}Li$ reaction was measured in the energy region of E_{cm} = 0.3 -1.2 MeV, as shown in Fig. 2. It covers the Gamow peaks of T_9 = 1 - 3. Previous measurement by Balbes et al. [8] was performed in higher energy region over E_{cm} = 1.5 MeV. At around E_{cm} = 0.8 MeV, a resonance-like structure was observed and its energy corresponds to the E_x = 22.4 MeV state in ^{10}Be. The reaction rate was deduced from present data by applying the formula (1). In the energy region above 1.5 MeV, we used the cross section data in previous measurement [8]. The cross section below E_{cm} = 0.3 MeV were estimated by linear extrapolation from the present data point at E_{cm} = 0.3 MeV to 0.0 MeV. The resultant rate is higher by one order of magnitude at around T_9 = 1 than the previously reported values [8] due to the resonance-like structure around E_{cm} = 0.8 MeV.

4. Reaction rates and dominant reaction paths via ^{8}Li

In order to identify main flow paths through ^{8}Li at various temperatures during the r-process, relative reaction rates ($Y_x Y_{8Li} \langle\sigma v\rangle$) on ^{8}Li were calculated, as shown in Fig. 3. The Y_x is fraction of each light element, proton (Y_p), neutron (Y_n), deuteron (Y_d) and alpha particle (Y_α). Those values were deduced by a network calculation in the r-process using the exponential model [9]. Initial parameters of the network calculation were set at Ye (electron fraction) = 0.45, τ_{dye} (dynamic time scale) = 5 ms and s/k (entropy) = 250. Those values are typical ones to reproduce the r-process abundances under the neutrino-driven wind model in the Type II supernovae. The Y_{8Li} is fraction of ^{8}Li and is set to unity. The reaction rates of $^{8}Li(d, t)$ and $^{8}Li(\alpha, n)$ are deduced from present results. The $^{8}Li(p, \alpha)$ and the $^{8}Li(n, \gamma)$ rates are from references [10] and [11], respectively.

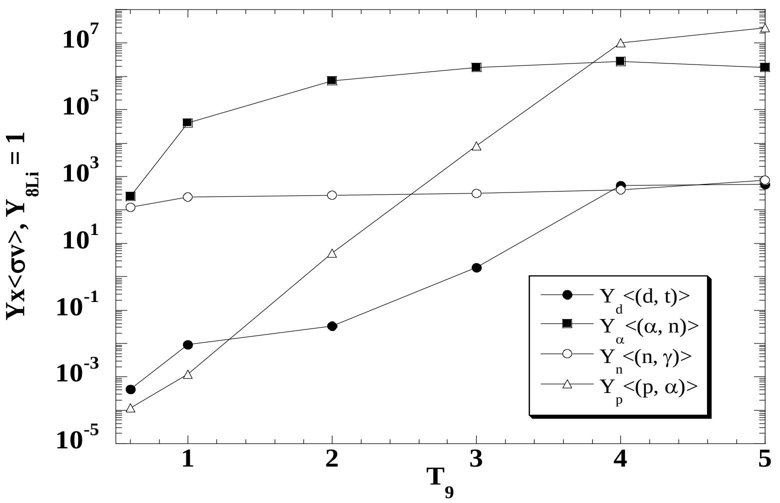

Figure 3: Relative reaction rates ($Y_x Y_{8Li} \langle\sigma v\rangle$) on ^{8}Li. The Y_x is fraction of light element and the Y_{8Li} is fraction of ^{8}Li. For more detail, please see the text.

As can be seen in Fig. 3, at $T_9 > 3.7$, the ^{8}Li(p, α)αn reaction is the fastest reaction, which destroys the ^{8}Li. In $T_9 = 0.7 – 3.7$, the ^{8}Li(α, n)^{11}B reaction becomes the main path from the ^{8}Li. The ^{8}Li(d, t)^{7}Li rate is so slow that this reaction gives little effect to the r-process abundances.

The relative reaction rates on ^{11}B and ^{12}B were calculated with the above mentioned procedure. As the result, dominant reaction paths through ^{8}Li at various temperatures are identified as below;

$T_9 = 2.7 – 3.6$: ^{8}Li(α, n)^{11}B(p, α)^{8}Be(2α),
$T_9 = 1.7 – 2.7$: ^{8}Li(α, n)^{11}B(α, n)^{14}N,
$T_9 = 0.5 – 1.7$: ^{8}Li(α, n)^{11}B(n, γ)^{12}B(n, γ)^{13}B.

5. Future plan

The measured cross sections of the ^{8}Li(α, n)^{11}B reaction have relatively large errors of 20-30 % [4] in the energy region below E_{cm} = 1.0 MeV, corresponding to $T_9 = 1 – 2$. To improve statistics and energy resolution of cross sections, we have a plan to measure the cross sections below E_{cm} = 1.0 MeV using the ^{8}Li beam from the TRIAC with the intensity of $10^{5\text{-}6}$ pps and the energy resolution of 2 %. The present gas chamber, named MSTPC [5], works well up to 10^4 pps injection-rate. Under higher injection rate, the gain instability occurs due to space charge gain limitation around anode wires. We therefore decided to exchange the anode wires for gas-electron-multiplier (GEM) foils for high-rate capability. For experimental requirement, gas multiplication of the GEM-MSTPC should be enough high (over 10^3) with He + CO_2 (10%) gas and low gas pressure (about 100 Torr). A 400 μm thick GEM foil was selected and gave 10^3 gas gain successfully. An off-line test of the GEM-MSTPC for higher rate capability is in progress.

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