RIB induced reactions: Studying astrophysical reactions with low-energy RI beam at CRIB

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Abstract. Astrophysical reactions involving radioactive isotopes (RI) often play an important role in high-temperature stellar environments. The experimental studies on the reaction rates for those are still limited mainly due to the technical difficulties in producing high-quality RI beams. A direct measurement of those reactions would be still challenging in many cases, however, we can make a reliable evaluation of the reaction rates by an indirect method or by studying the resonance prorerties. Here we introduce recent examples of experimental studies on such RI-involving astrophysical reactions, performed at Center for Nuclear Study, the University of Tokyo, using the low-energy RI beam separator CRIB. One is for the neutron-induced destruction reactions of ^{7}Be in the Big-Bang nucleosynthesis, and the other is the study on the ^{22}Mg(α, p) reaction relevant in X-ray bursts, which was performed with the resonant scattering method from the inverse reaction channel.

1 Introduction

Astrophysical reactions involving radioactive isotopes (RI) often play an important role in explosive stellar environments. Although the RI are seldom seen on the earth due to the finite lifetime, they do exist in stars, and contribute to the evolution and thermal dynamics of stellar objects. In this context, many experimental studies have been made on such RI-involving reactions, in spite of the technical difficulties. In a normal experimental condition, short-lived RI can only be used as the beam, not as the target. Then the reaction measurements could suffer from the limitation of the beam intensity, since the typical RI beam intensity is as small as 10^5 particles per second (pps) or less, while $> 10^{14}$ pps is available for light-ion beams. This great difference in the beam intensity is fundamental for the feasibility of the measurement.

Here we discuss possible approaches to study RI-involving reactions, introducing recent representative results from the low-energy RI beam facility CRIB [1–3] of the University of Tokyo. CRIB is an RI beam separator of Center for Nuclear Study (CNS), the University of Tokyo, located at the RIBF facility of RIKEN Nishina Center. CRIB can produce low-energy (< 10 MeV/u) RI beams by the in-flight technique with primary heavy-ion beams accelerated at the AVF cyclotron of RIKEN. A diagram to show the RI beams ever produced at CRIB is found in [3]. Most of the RI beams are produced via 2-body reactions such as (p, n), (d, p) and (^{3}He, n), taking place at an 8-cm-long gas target with a maximum pressure of 760 Torr.

The typical intensity of the RI beam at CRIB is 10^4–10^6 pps. The maximum intensity attained was 2-3 × 10^8 pps by the ^{7}Be beam produced with a cryogenic target system, in which the target gas can be cooled down to about 90 K [4]. One problem in producing such intense RI beams with a gas target is the density-reduction effect. A high-current beam can deposit heat to disperse the target gas around the beam track, resulting in a reduction of the local gas density along the beam. According to a previous work [5], a density reduction by 30 % was observed with a beam depositting heat of 60 mW/mm. We constructed a target system with a feature of forced circulation of the gas [4], by which we found a flow rate of 55 standard liters per minute (slm) was effective in eliminating the density reduction of the hydrogen gas, caused by a heat deposition of 65 mW/mm with the ^{7}Li primary beam. A high heat-proof target to further increase the RI beam intensity is under development. So far we have performed preliminary studies on the material dependence of the heat capacity, by changing the materials of the gas cell and its gas-sealing foils. Changing the sealing foils from Havar to molybdenum, the heat capacity was found to be doubled.

We introduce below two latest works at CRIB [6, 7], in which RI-involving astrophysical reactions were indirectly studied at astrophysical energies.

2 ^{7}Be+n reaction measurement with the Trojan horse method

The primordial production of light nuclides is well described with the standard model of Big Bang nucleosynthesis (BBN), however, the ^{7}Li/H abundance remains overestimated by a factor of 3–4, known as the cosmological lithium problem. We have studied the ^{7}Be$(n, p_0)^7$Li, ^{7}Be$(n, p_1)^7$Li*and ^{7}Be$(n, \alpha)^4$He reactions, which may affect the primordial ^{7}Li abundance [6]. To study the reactions of two unstable particles (^{7}Be and n), we applied the Trojan horse method (THM, see References in [6, 8]), which is an indirect method to study a 2-body reaction via a 3-body reaction measurement under a quasi-free kinematical condition. The ^{7}Be$(n, \alpha)^4$He reaction had been measured with the THM in a previous work [8], and our new work expanded the sensitivity also to the ^{7}Be$(n, p_0)^7$Li and ^{7}Be$(n, p_1)^7$Li* reactions, by achieving a sufficient energy resolution to separate the contributions of these two reactions.

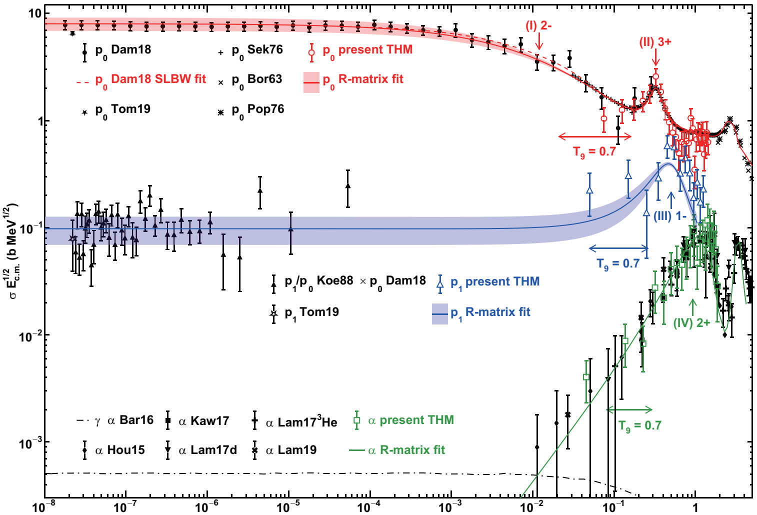

Figure 1. The cross sections multiplied by $\sqrt{E_{\rm cm}}$ of the ^{7}Be$(n, p_0)^7$Li, ^{7}Be$(n, p_1)^7$Li*and ^{7}Be$(n, \alpha)^4$He reactions in [6] are shown as open red circles, blue triangles, green squares, respectively. The previous experimental data are also shown for comparison. See [6] for details.

The cross sections multiplied by $\sqrt{E_{\rm cm}}$ obtained in this work are shown in Fig.1. The ^{7}Be$(n, p_0)^7$Li and ^{7}Be$(n, \alpha)^4$He rates were basically consistent with the previous works, but we assigned a smaller uncertainty on the ^{7}Be$(n, p_0)^7$Li reaction rate compared to the previous work at CERN n_TOF [9]. The ^{7}Be$(n, p_1)^7$Li* reaction was measured at the BBN energy for the first time in this work. With the simulation using `PRIMAT` code [10], we demonstrated the new reaction rate, including the ^{7}Be$(n, p_1)^7$Li* contribution, could reduce the primordial ^{7}Li abundance by $\sim$ 10–15%.

3 ^{25}Al+p elastic resonant scattering for the ^{22}Mg(α, p) reaction

(α, p) reactions often make significant contributions in explosive stellar environments, such as X-ray bursts. A typical situation is that the reaction has a positive Q-value and the rate is dominated by resonant reactions. In this case, the properties of the resonances just above the α-threshold would be the key information. Resonant scattering is one possible method to study resonances. However, in such cases the α-resonant elastic scattering from the entrance channel does not allow us to derive relevant resonance parameters, because those resonances are located at low center-of-mass energies, buried under the Rutherford scattering, and hardly seen. On the other hand, those resonances could be studied from the exit channel with the proton resonant scattering, since the proton threshold is located at a lower energy in this typical situation. We have carried out measurements with this idea [7, 11, 12], namely, the resonant scattering from the inverse reaction channel.

The latest study was for the ^{22}Mg(α, p) reaction, known to be one of the most relevant reactions in X-ray bursts, greatly affecting to the light curve. The reaction rate had not been precisely known, and the first direct measurement on this reaction has been performed only recently, but at an energy region higher than the Gamow energy [13]. Our measurement was performed at CRIB with an ^{25}Al RI beam at an intensity of 2 $\times 10^5$ pps with essentially the same method as previous experiments [11, 14]. Fig. 2 shows the obtained excitation functions of the elastic and inelastic scatterings. We successfully observed resonances just above the α particle threshold, as indicated in the figure, and their parameters were deduced with an R-matrix analysis. The parameters were employed in a new X-ray burst model calculation, and we obtained a better agreement with the observed light curves of GS 1826–24 clocked burster and SAX J1808:4–3658 PRE burster compared to the previous works.

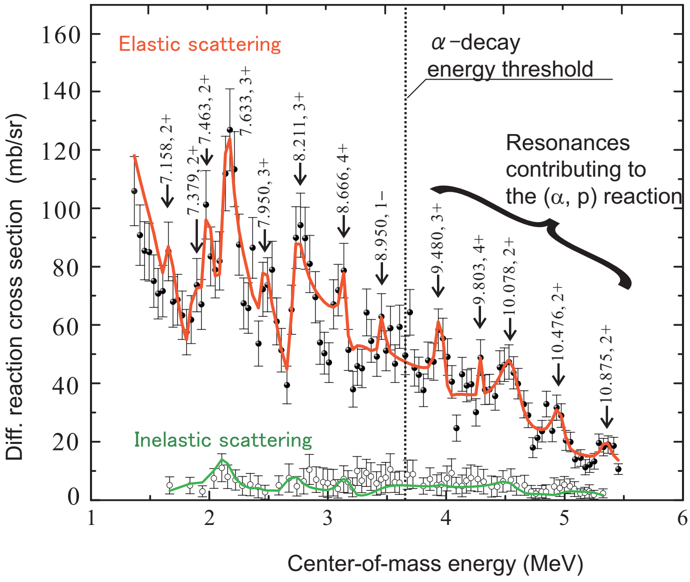

Figure 2. Excitation function of ^{25}Al+α scatterings with an R-matrix analysis. See [7] for details.

4 Summary

Astrophysical reactions involving RI are often difficult to study experimentally, mainly due to the limitation of the present RI beam technique. In the above two examples, we demonstrated that such astrophysical reactions can be studied even with a low-intensity RI beam, by employing an indirect method (THM) or studying resonance parameters.

The experiments were performed at RI Beam Factory operated by RIKEN Nishina Center and CNS, the University of Tokyo. This work was partly supported by JSPS KAKENHI (No. 18H01218, and 19K03883) from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of Japan.

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