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Nuclear Astrophysics with Exotic Beam; Thick-target Measurements 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 information on those reactions is still limited mainly due to the technical difficulties in producing high-quality and intense RI beams. Although a direct measurement of those reactions at astrophysical energy would be still challenging, we may take several alternative approaches to determine the reaction rates, by applying other mesurement methods or improving the target and detectors. Here we mainly discuss the thick-target method in inverse kinematics (TTIK) based on the successful examples of experimental studies performed at Center for Nuclear Study, the University of Tokyo, using the low-energy RI beam separator CRIB.

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 burning 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.

There are several possible approaches to overcome this difficulty: to use another indirect measurement method, such as the Trojan Horse Method [1–4] or Asymptotic Normalization Coefficients (ANC) [5], to study the resonance properties and apply the resonant reaction formula, to use a thicker target (the thick-target method), or to improve the detection efficiency, *e.g.*, with an active target.

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Here we mainly discuss the thick-target method combined with the inverse-kinematics condition as a possible approach to efficiently study RI-involving reactions, introducing the results from the low-energy RI beam facility CRIB [6–8].CRIB is an RI beam separator of Center for Nuclear Study (CNS), the University of Tokyo, located at the RI Beam Factory (RIBF) of RIKEN Nishina Center. CRIB can produce low-energy (< 10 MeV/u) RI beams by the in-flight technique using primary beams accelerated at the AVF cyclotron of RIKEN. A diagram to show the RI beams ever produced at CRIB is found in [8]. 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 beams at CRIB is 10^4–10^6 pps. The highest intensity ever achieved was 2–3 $\times$ 10^8 pps by the production of a ^{7}Be beam with a cryogenic target system, in which the target gas was cooled down to about 90 K [9]. Development of new beams is still going on at CRIB. In 2021, a ^{6}He beam was first produced at CRIB via the ^{7}Li(d, ^{3}He)^{6}He reaction. Introducing multi-wire drift chambers (MWDC) as the beam-monitoring detectors, a ^{6}He beam optimized at 7.5 MeV/u was produced with an intensity of 5 $\times$ 10^5 pps for a main measurement of the ^{6}He+p elastic scattering in 2023.

2 Thick-target method in inverse kinematics (TTIK)

In a traditional nuclear physics experiment, the target is usually kept as thin, so that the reaction energy in the target becomes almost constant in order to avoid worsening of the energy resolution. The idea of the "thick-target method" is to use a much thicker target, in which the beam energy is degraded significantly. Under this condition, reactions could occur at different energies in a certain range, but the detected particles prodcued by the reaction still carry the information of the reaction energy. By performing a kinematic reconstruction based on the energy and angle of the reaction products, we can identify at which depth in the target the reaction has occured. In other words, the thick-target measurement is an efficient method since it could be equivalent to many thin-target measurements.

This "thick-target method" has already been known in old days, such as by Daehnick and Sherr in 1964 [10]. In 1990, the thick-target method was coupled with an inverse-kinematics (*i.e.*, heavier beam partcile than target) condition by Artemov *et al.* [11]. This "thick-target in inverse kinematics" (TTIK) was first demonstrated for a stable ^{12}C beam with a helium target, but is applicable also for RI beams. TTIK has several favorable features, such as, 1) it can be applied for a short-lived RI that are only avaliable as beams, 2) an efficient data-taking is possible as a single measurement covers a certain range of energy, and no need to change the incoming beam energy for each data point, 3) a measurement at $\theta_{\mathrm{c.m.}}$=180° is possible when the beam is completely stopped in the target and lighter ions are detected, 4) the $E_{\mathrm{c.m.}}$ resolution can be better than the original beam energy dispersion or the energy resolution of the recoiled particle, due to the kinematics. Note that 1) and 2) are particularly useful features for RI-beam experiments.

At CRIB, the TTIK method has been extensively applied for various experiments for proton-resonant scattering [12–19], α-resonant scattering [20–23], as well as direct measurement of (α, p) reactions [24, 25]. They are mainly for the interests on the astrophysical reactions induced by light-ions, or the nuclear structure including the α-clustering.

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

Some of the (α, p) reactions on RI make significant contributions in explosive stellar environments, such as X-ray bursts [26, 27]. A typical situation is that the (α, p) reaction has a positive Q-value and the rate is dominated by resonant reactions. In this case, the parameters 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 basically located at too low $E_{\mathrm{c.m.}}$, 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. Several measurements have been carried out at CRIB with this idea namely, the resonant scattering from the inverse reaction channel [16, 17, 19].

The most recent 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 [26]. The reaction rate had not been precisely known, and the first direct measurement on this reaction has been performed only recently [28]. However, the measurement was at an energy region higher than the Gamow energy, and the cross section was extrapolated down to the astrophysical energies with a statistical model calculation. One concern was that if such an extrapolation is still valid at low energies, where the nuclear level density becomes lower. The resonant scattering measurement at CRIB was performed with an ^{25}Al RI beam at an intensity of 2×10^5 pps based on the same method as previous experiments [13, 16]. Figure 1 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 new reaction rate was employed in a 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 [19].

Another direct measurement performed recently [29] showed that there are discrepancies of factor 2–4 among the reaction rates between the two direct measurements and the resonant reaction evaluation, suggesting that further works would be still required to confirm the reaction rate with a high precision.

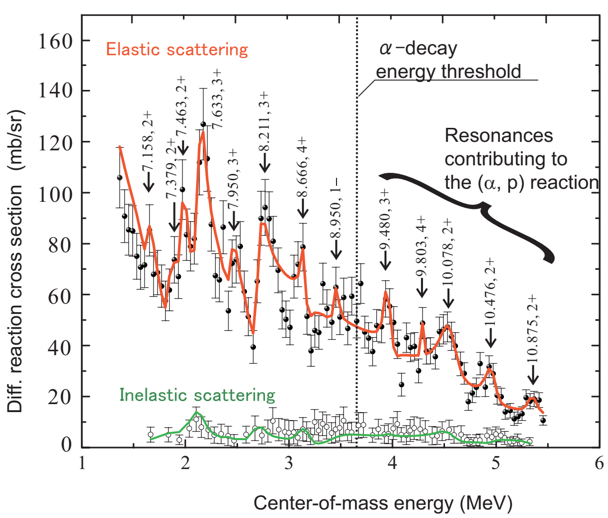

Figure 1. Excitation functions of the ^{25}Al+α scattering fitted with an R-matrix calculation. See [19] for details.

4 TTIK with active target

One disadvantage of the TTIK method is the possible misidentification of two reaction channels producing the same kind of ions. For example, elastic and inelastic scatterings could be observed in a single experiment, but the energy and angular distributions of the detected particles for those two scattering processes can overlap each other. In that case, we may not able to clearly tell if a detected particle is from an elastic or an inelastic scattering. This problem can be avoided by introducing an active target, in which a gas chamber serves as a target and simultaneously as a detector. With a time projection chamber (TPC) type active target, the reaction position can be deduced from the particle tracking information, enabling us to identify the reaction channel. Another advantage of the active target is that even low-energy particles could be detected with a high efficiency, which is not easy for a setup with a thick static target and separated detectors.

The ^{30}S+α scattering experiment at CRIB [23] was performed with an active target, referred to as “GEM-MSTPC” [30]. The GEM-MSTPC was a time projection chamber (TPC) using Gas-Electron Multipliers (GEM) to measure 3-dimentional tracks of the particles in the chamber. In the work of [23], however, the tracking resolution was limited and the TPC did not contribute much to the event identification.

In 2023, another TTIK measurement using the active target “TexAT” of Texas A&M University [31] was performed at CRIB, under the proposal by Korean researchers at Institute for Basic Science. The experiment was to directly measure the astrophysical ^{14}O(α, p) reaction cross section, which still has a large uncertainty at low energies. By performing the measurement, we successfully identified candidates of the reaction events, and the results are to be presented in future publications.

5 Summary

Astrophysical reactions involving RI are often difficult to study experimentally, mainly due to the limitation of the present RI beam intensity. The TTIK method is one benetifical technique to overcome the difficulty of the RI-beam experiments, as shown in the experiments performed at CRIB. The TTIK method can be further improved by using an active target, with which we can perform a clear identification of the reaction with a high efficiency.

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