Alpha-induced astrophysical reactions studied at CRIB

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CRIB (CNS Radioactive Ion Beam separator) is a low-energy RI beam separator at the Center for Nuclear Study (CNS) of the University of Tokyo. Studies on proton and alpha resonance scatterings, (α, p) reactions, and other types of measurements (β-decay lifetimes etc.) have been performed using RI beams at CRIB, motivated by interests on astrophysical reactions and exotic nuclear structure. Among the studies at CRIB, the measurement of ^{7}Li+α resonant scattering is presented.

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1. Introduction

CRIB [1,2] is a radio-isotope (RI) beam separator of CNS, University of Tokyo, located in the RIBF facility of RIKEN Nishina Center. CRIB can produce low-energy (< 10 MeV/u) RI beams in flight, using primary heavy-ion beams from the AVF cyclotron of RIKEN (K=70). RI beams are produced via direct reactions such as (p, n), (d, p), and $(^3\text{He}, n)$, taking place at an 8-cm-long gas target with a maximum pressure of 760 Torr. Solid targets such as beryllium can also be used as the production target. The intensity of the secondary beam is typically 10^4–10^6 pps. For a more intense RI beam production, a cryogenic target system, in which the target gas can be cooled down to about 90 K, is currently available at CRIB. For example, a ^7Be beam of 2×10^8 pps was produced using the cryogenic target system [3]. The secondary beam is purified with an magnetic analysis using dipole magnets, and with a Wien filter, which can separate the beams according to their velocities. For relatively light RI beams such as ^7Be, we can obtain a purity of almost 100% after the Wien filter.

A major topic of our interest is alpha-induced reactions, which can be studied using heavy-ion beams and a helium gas target. Several (α, p) reactions, such as $^{14}\text{O}(\alpha, p)$ [4], $^{11}\text{C}(\alpha, p)$, $^{21}\text{Na}(\alpha, p)$, $^{18}\text{Ne}(\alpha, p)$, and $^{30}\text{S}(\alpha, p)$ have been measured at CRIB. The elastic resonant scatterings of alpha particle using ^{14}O, ^{21}Na, ^7Li and ^7Be beams have also been measured. These measurements are related to astrophysical (α, γ) reaction rates, and are relevant for studying nuclear cluster structure. Among the studies, the one on $^7\text{Li}+\alpha$ measurement, which is related to the cluster structure of ^{11}B, is presented below.

The exotic cluster structures in the ^{11}B and ^{11}C nuclei are attracting much attention in recent years [5]. The $3/2_3^-$ state in ^{11}B at the excitation energy E_ex=8.56 MeV is regarded as a dilute cluster state [6], where two α particles and ^3He are weakly interacting. In particular, the alpha cluster structure in ^{11}B was studied by measuring its isoscalar monopole and quadrupole strengths in the $^{11}\text{B}(d,d')$ reaction, and the 8.56-MeV state was suggested to have a dilute cluster structure [7,8]. A natural method to study the α cluster structure of ^{11}B is to form such a cluster state by the elastic scattering of ^7Li and α.

The $^7\text{Li}+\alpha$ system is also related to the astrophysical reaction $^7\text{Li}(\alpha, \gamma)^{11}\text{B}$. In the low temperature stellar environment which ignites the *p-p* chains, ^7Li is destroyed via the $^7\text{Li}(p, \alpha)^4\text{He}$ reaction, and the $^7\text{Li}(\alpha, \gamma)^{11}\text{B}$ reaction is much weaker in comparison. However, in some high temperature phenomena, the $^7\text{Li}(\alpha, \gamma)^{11}\text{B}$ reaction should play important roles. For example, in the ν-process in core-collapse supernovae [9] ^{11}B is mainly produced via $^4\text{He}(\nu, \nu'p)^3\text{H}(\alpha, \gamma)^7\text{Li}(\alpha, \gamma)^{11}\text{B}$, but the production can be enhanced with the $^{12}\text{C}(\overline{\nu_e}, e^+n)^{11}\text{B}$ reaction. A precise comparison between the observed abundance ratio of $^{11}\text{B}/^7\text{Li}$ in stars and a calculation using the experimental $^7\text{Li}(\alpha, \gamma)^{11}\text{B}$ reaction rate may provide a constraint on the neutrino mixing parameter θ_{13}, as suggested in Ref. [9].

2. Experimental Method

In many measurements we used the thick-target method in inverse kinematics [10], which is suitable for the low-energy beams at CRIB. In that method, the beam energy is degraded in a thick reaction target, and reactions occur at various center-of-mass energies. We detect light par-
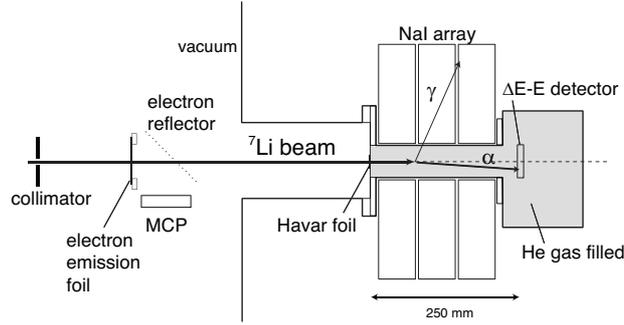
**Figure 1:** Arrangement of the detectors and targets in ^{7}Li+α measurement.

ticles emitted after reactions, and reconstruct the kinematics. This method has several advantages, namely, (a) we can perform simultaneous measurements of cross section of various excitation energies without varying the incoming beam energy, and (b) we can perform measurement at 180° in center-of-mass angle, where the Coulomb scattering is minimal. Many fruitful results have been obtained at CRIB with this method [4, 11–15].

Figure 1 schematically shows the experimental setup for the ^{7}Li+α scattering measurement. A ^{7}Li beam was accelerated at the AVF cyclotron and transported to the final focal plane (F3) of CRIB. The beam had a well-defined energy of 13.7 MeV, and collimated by a 3 × 3-mm square aperture at F3. An MCP (Micro-Channel Plate) was used to measure the position and timing of the beam. A CsI-evaporated 0.7-μm-thick aluminum foil was placed on the beam axis for the secondary electron emission. The secondary electrons were reflected by 90° at a biased thin-wire reflector and detected at the MCP with a delay-line readout. The gas target consisted of a 50-mm-diameter duct and a small chamber. The helium gas was housed in a 50 mm diameter duct and a small target chamber. The helium gas was at 920 Torr and sealed with a thin (2.5 μm) Havar foil as a beam entrance window. Alpha particles recoiling to the forward angles in the laboratory frame were detected by the "ΔE-E detector", which consisted of 20-μm- and 480-μm-thick silicon-strip detectors, placed directly in the gas chamber. The effective area of the detector was 20 cm^2. The silicon-strip detectors had a position sensitivity of 3 mm. The effective target length, namely, the distance from the beam entrance window to the detector, was 250 mm. To measure 478-keV gamma rays from inelastic scattering to the first excited state of ^{7}Li, NaI detectors were placed around the duct. We used ten NaI crystals, each with a geometry of 50 × 50 × 100 mm^3. They covered 20–60% of the total solid angle, depending on the reaction position in the target. The photopeak efficiency of the NaI detectors were measured at various positions in the gas target, using gamma-ray sources. The measurement was performed for 2.9 ×10^{10} ^{7}Li particles injected into the gas target over 60 hours.

3. Experimental results

Our measurement corresponds to E_{ex}=10–13 MeV and the center-of-mass angles of 160–180°. The excited states of ^{11}B in this energy region have been studied by ^{7}Li+α elastic scattering [16,

17] or using other methods [18]; however, some of the resonance parameters are still uncertain. Especially, the alpha widths for most of the resonances were not determined with a good precision. Using inverse kinematics, the excitation function around $180°$ in the center-of-mass system was measured for the first time.
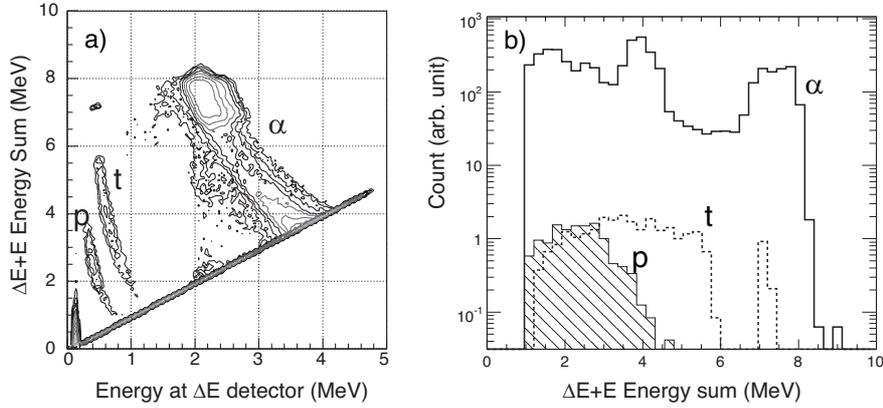

Figure 2: a) Two dimensional energy plot for the ΔE-E counter for particle identification. b) Energy spectra of the alpha, proton and triton for > 1 MeV.

The particle identification performed with the ΔE-E counter is shown as a two-dimensional energy plot in Figure 2a. As illustrated, α particles, protons, and tritons were clearly separated. Since the gas target was sufficiently thick to stop the ^{7}Li beam, particles heavier than lithium were not expected to reach the detector, even if produced. α particles from the elastic scattering were dominant in the measured particles, while comparably small numbers of protons and tritons, possibly from the ^{7}Li(α, p) reaction and break up of ^{7}Li respectively, were also observed, as compared in Figure 2b. Considering that there is no strong reaction to produce ^{3}He, the detected particles which deposited energy more than 1 MeV on the first layer should be mostly α particles.

By kinematical calculations with a consideration of the energy loss in the gas target, the measured energy of the α particle was converted to a center-of-mass energy for the ^{7}Li+α system, and an excitation function was obtained. The excitation function in the present work is shown in Fig. 3 with previous results [16, 17], and a structure having peaks consistent with previous elastic scattering measurements [16, 17] was observed. New information on the resonance parameters of ^{11}B, especially on the alpha resonant widths, are expected to be obtained with our data.

4. Summary

We performed a measurement of ^{7}Li+α elastic resonant scattering using the thick-target method in inverse kinematics for the first time. The resonance parameters to be determined in this study, such as the spin, parity and alpha width,would provide valuable information for the α-cluster structure in the high excited states, and the astrophysical ^{7}Li(α, γ) reaction rate in high-temperature phenomena.
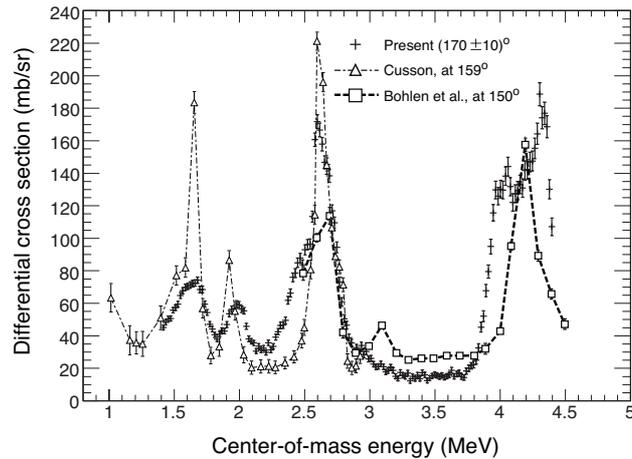
Figure 3: Excitation function of the ^{7}Li+α elastic scattering cross section, compared with previous measurements [16, 17].

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