

Nuclear astrophysics projects at the low-energy RI beam separator CRIB

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Abstract. Studies on nuclear reactions relevant for astrophysics have been performed using the radioactive-isotope (RI) beams at the low-energy RI beam separator CRIB, operated by Center for Nuclear Study (CNS), the University of Tokyo. A type of measurement to study astrophysical reactions at CRIB is by the elastic resonant scattering with the thick-target method in inverse kinematics. We introduce the α resonant scattering with ^7Be beam, related to the astrophysical $^7\text{Be}(\alpha,\gamma)$ reactions, which is relevant in the hot p - p chain and νp -process in supernovae. Other α resonant scattering measurements with ^{30}S , ^{10}Be , ^{15}O , and ^{18}Ne beams have been performed at CRIB, using the thick-target method.

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1 Introduction

CRIB [1, 2] is a radioactive-isotope (RI) beam separator operated by Center for Nuclear Study (CNS), the University of Tokyo, installed at the RIBF facility of RIKEN Nishina Center. CRIB can produce low-energy (< 10 MeV/u) RI beams by the in-flight technique, using primary heavy-ion beams accelerated at the AVF cyclotron of RIKEN ($K=70$). Most of the 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. A cryogenic target system, in which the target gas can be cooled down to about 90 K, is currently available, and an intense ${}^7\text{Be}$ beam of 2×10^8 pps was produced using the system [3]. A list of typical parameters of RI beams produced at CRIB is found in [4]. New RI beams recently developed at CRIB are ${}^{16}\text{N}$ (1×10^6 pps), ${}^{10}\text{Be}$ (2×10^4 pps), ${}^{15}\text{O}$ (1×10^6 pps), and ${}^{26}\text{Al}$ (1×10^5 pps). The ${}^{26}\text{Al}$ beam was developed to obtain an isomeric ${}^{26m}\text{Al}$ beam, related to the production rate of the galactic γ rays from ${}^{26}\text{Al}$.

A recent major topic of our interest is the measurement of alpha-induced reactions. Several (α, p) reactions, such as ${}^{14}\text{O}(\alpha, p)$ [5], ${}^{11}\text{C}(\alpha, p)$ [6], ${}^{21}\text{Na}(\alpha, p)$, and ${}^{18}\text{Ne}(\alpha, p)$ have been studied by direct measurement at CRIB. Measurements on the elastic resonant scatterings with a helium target and beams of ${}^7\text{Li}$ [7] and ${}^7\text{Be}$ [8], ${}^{30}\text{S}$, ${}^{10}\text{Be}$, ${}^{15}\text{O}$, and ${}^{18}\text{Ne}$ have also been performed. These measurements provide information on the resonances to evaluate astrophysical (α, γ) reaction rates, and also on the nuclear cluster structure of the compound nuclei.

2 ${}^7\text{Be}+\alpha$ elastic resonant scattering

Here we introduce the ${}^7\text{Be}+\alpha$ scattering measurement as a typical resonant scattering experiment at CRIB. The measurement allows us to evaluate the rate of the ${}^7\text{Be}(\alpha, \gamma)$ reaction, which is considered to play an important role in the hot p - p chain and related reaction sequences [9]. In the νp -process in core-collapse supernovae [10], the ${}^7\text{Be}(\alpha, \gamma)$ reaction may contribute as much as the triple- α process to the synthesis of elements heavier than boron at the relevant temperature of $T_9 = 1.5$ – 3 , according to a theoretical calculation [11]. The Gamow energy window at the highest temperature $T_9 = 3$ corresponds to the excitation energy $E_{\text{ex}}=8.2$ – 9.6 MeV in ${}^{11}\text{C}$.

We performed the measurement of the ${}^7\text{Be}+\alpha$ resonant elastic and inelastic scatterings with the thick-target method in inverse kinematics at CRIB [8]. A low-energy ${}^7\text{Be}$ beam at 14.7 MeV was produced with a typical intensity of 1 – 2×10^5 per second. The main measurement was performed for 4 days, injecting 2.9×10^{10} ${}^7\text{Be}$ particles into the helium target. We obtained an excitation function of the elastic scattering with several peaks, corresponding to the resonance structure in ${}^{11}\text{C}$. The obtained excitation is shown in the left panel of Figure 1. An R-matrix analysis was performed to deduce the parameters of the resonances, as the calculated curve also shown in the figure. The resonances observed in the present work might contribute to the astrophysical ${}^7\text{Be}(\alpha, \gamma){}^{11}\text{C}$ reaction rate at high temperature, $T_9 > 1.5$. The resonant reaction rates were calculated for three resonances using analytical formula described in [12], and plotted in Fig. 1. In conclusion, the resonances at 8.90 MeV and 9.20 MeV have a possibility to give significant contributions to the reaction rate for $T_9 = 1.5$ – 3 , although they are evaluated as one order of magnitude smaller contribution than the dominant 8.420-MeV resonance.

3 ${}^{10}\text{Be}+\alpha$ elastic resonant scattering

Another study was performed on the ${}^{10}\text{Be}+\alpha$ system, mainly on the interest of an exotic cluster structure, while ${}^{10}\text{Be}(\alpha, n)$ or ${}^{10}\text{Be}(\alpha, \gamma)$ reaction may play a role in the big-bang nucleosynthesis [13] or other high-temperature environments.

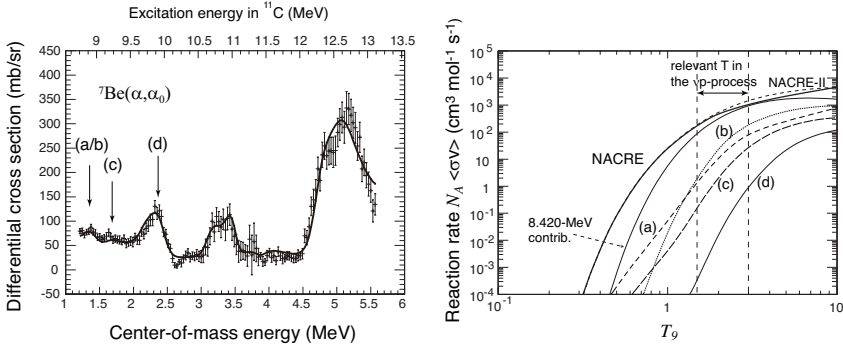


Figure 1. Excitation function of ${}^7\text{Be}+\alpha$ elastic scattering with an R-matrix fit curve (left panel) and resonant reaction rate of ${}^7\text{Be}(\alpha, \gamma)$ for the 8.90, 9.20, and 9.97-MeV resonances, calculated by the analytical formula. The evaluation by NACRE and NACRE-II are shown for comparison. The contribution by the 8.420-MeV resonance, included in NACRE, is also shown.

In 1956, Morinaga [14] came up with the novel idea of a particular cluster state: the linear-chain cluster state (LCCS). Now the LCCS is commonly considered as extreme and exotic, due to its presumed propensity to exhibit bending configurations. A theoretical prediction of LCCS in ${}^{14}\text{C}$ was made by Suhara and En’yo [15, 16] with an antisymmetrized molecular dynamics (AMD) calculation, yielding a prolate band ($J^\pi = 0^+, 2^+, 4^+$) that has a configuration of an LCCS at a few MeV or more above the ${}^{10}\text{Be}+\alpha$ threshold.

We applied the ${}^{10}\text{Be}+\alpha$ resonant scattering method in inverse kinematics to identify the predicted LCCS band in ${}^{14}\text{C}$ [17]. The ${}^{10}\text{Be}$ beam had a typical intensity of 2×10^4 particles per second, and the beam purity was better than 95%. The ${}^{10}\text{Be}$ beam at 25.8 MeV impinged on the gas target, which was a chamber filled with helium gas at 700 Torr and covered with a 20- μm -thick Mylar film as the beam entrance window. The measured ${}^{10}\text{Be}$ beam energy at the entrance of the helium gas target, after the Mylar film, was 24.9 ± 0.3 MeV. α particles recoiling to the forward angles were detected by ΔE - E detector telescopes. We obtained an excitation function of the ${}^{10}\text{Be}+\alpha$ resonant elastic scattering for 13.8–19.1 MeV. We performed an R-matrix calculation to deduce the resonance parameters, and we

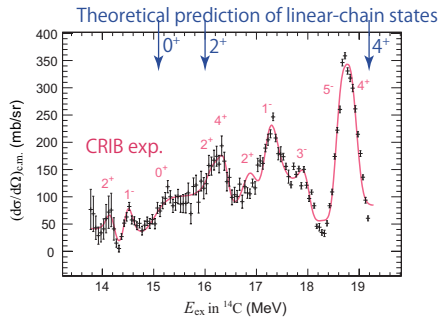


Figure 2. Excitation function of the ${}^{10}\text{Be}+\alpha$ resonant scattering for $\theta_{\text{lab}}=0\text{--}8^\circ$.

identified three resonances well-corresponding to the predicted LCCS band; J^π are identical, and their

energies and spacings are consistent with the theoretical prediction. The J^π for the 2^+ and 4^+ levels were assigned with a complex analysis of unresolved doublets, but they were supported by the angular distribution as well. We claim this as the strongest indication of the LCCS ever found. It can be also shown that both sets of level energies can be plotted almost on a line, $E_J = E_0 + \hbar^2/2\mathfrak{I}(J(J+1))$, where \mathfrak{I} is the moment of inertia of the nucleus. The linearity allows us to interpret the levels as a rotational band, and the low $\hbar^2/2\mathfrak{I} = 0.19$ MeV implies the nucleus could be strongly deformed, consistent with the interpretation of an LCCS.

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