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Studies on nuclear astrophysics and nuclear clustering with low-energy RI beams at CRIB

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Studies on nuclear astrophysics, nuclear structure, and other interests 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. The elastic resonant scattering is a striking tool to study astophysical reactions and nuclear clusters. In particular, when it is coupled with a thick target and inverse kinematics, the measurement can be very efficient and even feasible with RI beams. By measuring resonant scattering, we can study the properties of resonant states which could play an important role in the astrophysical reaction, or have an exotic nuclear structure. Measurements based on the indirect technique of the reaction measurement, such as the Trojan horse method, have also been performed at CRIB.

KEYWORDS: Nuclear reaction, Nuclear structure, Nuclear cluster, RI beam

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 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. A cryogenic target system, in which the target gas can be cooled down to about 90 K, is currently available, and an intense ^{7}Be beam of 2×10^{8} pps was produced using the system [3]. One main feature of the target system is the forced circulation of the target gas. We have found that the circulation of the target gas at a rate of 55 standard liters per minute (slm) was effective in eliminating the density reduction, caused by heat deposition of the beam. The secondary beam is purified with a magnetic analysis using dipole magnets, and with a Wien filter, which separates the beams according to their velocities. For relatively light RI beams such as ^{7}Be, we obtained a purity close to 100% after the Wien filter. The Wien filter is operated with high voltages of ±50–100 kV, supplied for a pair of 1.5-m long electrodes with a gap of 8 cm. For a stable operation at a higher voltage, we are making improvements on the insulators and other parts of the system. A list of typical parameters of RI beams produced at CRIB is found in [4].

The low-energy RI beams at CRIB are particularly suitable for studies on astrophysical reactions and nuclear resonant structure. An experimental method extensively used is the thick-target method in inverse kinematics [5]. 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 particles emitted after reactions, and reconstruct the kinematics. This method has several advantages, namely, (a) using inverse kinematics, we can study reactions with short-lived RI which cannot be used as the target, (b) we can perform simultaneous measurements of cross sections at various excitation energies without varying the incoming RI beam energy, and (c) when the beam is stopped in the target, we can perform measurements at 180° in center-of-mass angle. Many measurements have been performed at CRIB with this method [6–14].

A major topic of our interest is the measurement of alpha-induced reactions. Several (α, p) reactions, such as ^{14}O(α, p) [15], ^{11}C(α, p) [16], ^{21}Na(α, p), and ^{18}Ne(α, p)have been studied at CRIB. For some of the recent measurements, an active target, referred to as "GEM-MSTPC" [17], has been used. Measurements of the elastic resonant scatterings with a helium target and beams of ^{7}Li [9] and ^{7}Be [11], ^{30}S [14], ^{10}Be [18], ^{15}O [19], and ^{18}Ne have also been performed. These measurements can provide information on astrophysical (α, γ) reaction rates or nuclear cluster structure of the compound nuclei.

There are other projects for the determination of the astrophysical reactions using indirect methods with RI beams. The indirect measurement of the ^{12}N(p, γ) reaction, which is a key reaction to synthesize nuclei heavier than carbon, was performed by measuring ^{12}N(d, n) reaction in inverse kinematics. Using the asymptotic normalization coefficient (ANC) method, the reaction rate was reevaluated [20]. Another type of indirect reaction measurement we performed was with the Trojan horse method (THM) [21–23]. The first measurement using the THM with an RI beam was performed at CRIB [24], to study the ^{18}F$(p, \alpha)^{15}$O reaction at astrophysical energies via the three body reaction ^{2}H(^{18}F, α^{15}O)n. The ^{18}F$(p, \alpha)^{15}$O reaction rate is particularly responsible for the 511-keV γ ray emission in the nova explosion phenomena. The measurement at CRIB was performed with a ^{18}F RI beam at the intensity of 2×10^{6} pps. A CD_2 target with a thickness of 150 μg/cm^2 was irradiated by the beam, and 3-body reaction events were detected by a silicon detector array, referred to as ASTRHO, with additional double-sided silicon strip detectors. We successfully evaluated the reaction cross section at the novae temperature and even below experimentally for the first time (see [24] for further details). The ^{7}Be(n, p) and (n, α) are possible destruction reactions that explain the discrepancy in ^{7}Li between the Big-bang nucleosynthesis model and the observed ^{7}Li abundance. We performed a THM measurement with ^{7}Be beam at CRIB in 2016, as one of the first applications of THM for neutron induced reactions [25].

2. ^{7}Be+α elastic resonant scattering

Here we discuss the measurement of the ^{7}Be+α scattering, as a typical example of the resonant scattering experiment at CRIB. This measurement allowed us to evaluate the rate of the ^{7}Be(α, γ)

reaction, which is considered to play an important role in the hot *p*-*p* chain and related reaction sequences [26]. Several reaction sequences including the ^{7}Be(α, γ) reaction should take place in some high-temperature environments at $T_9 > 0.2$, where T_9 is the temperature in GK. In the νp-process in core-collapse supernovae [27], the ^{7}Be(α, γ) 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 [28]. The Gamow energy window at the highest temperature T_9 = 3 corresponds to the excitation energy $E_{\rm ex}$=8.2–9.6 MeV in ^{11}C. By our study, the resonant reaction rate was evaluated with the experimental α widths of the high-energy resonances. The measurement was also for studying the cluster structure in ^{11}C. ^{11}B nucleus was known by previous works [9, 29] to have a 3-body (2α+*t*) cluster configuration, comprising a negative-parity band structure. ^{11}C is the mirror nucleus of ^{11}B, and expected to have a similar cluster structure, which could be studied by the resonant scattering.

We performed the measurement of the ^{7}Be+α resonant elastic scattering with the thick-target method in inverse kinematics at CRIB [11]. A low-energy ^{7}Be beam at 14.7 MeV was produced using a 2.3-mg/cm^2-thick hydrogen gas target and a primary ^{7}Li beam at 5.0 MeV/u. The typical ^{7}Be beam intensity used in the measurement was 1–2 × 10^5 per second at the secondary target. We obtained an excitation function of the elastic scattering with several peaks corresponding to the resonance structure in ^{11}C. The obtained excitation function 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. A similar measurement was independently carried out by M. Freer *et al.* at other facilities [30], but our measurement included γ-ray detection to identify inelastic scattering events, and several differences were found in the obtained spectra [11].

The resonances observed in the present work might contribute to the astrophysical ^{7}Be(α, γ)^{11}C reaction rate at high temperature, $T_9 > 1.5$. We calculated the resonant reaction rates and compared them with the total reaction rate evaluated in NACRE [31, 32]. In the evaluation reported in NACRE, only two resonances at 8.1045 and 8.420 MeV were included. These two resonances dominate the reaction rate $N_{\rm A}\langle\sigma v\rangle$ up to the temperature $T_9 \sim 3$, and a Hauser-Feshbach calculation was used to provide the reaction rate at higher temperatures. With our data, the resonant reaction rates were calculated for three resonances using analytical formula described in [31], as in Fig. 1. In conclusion,

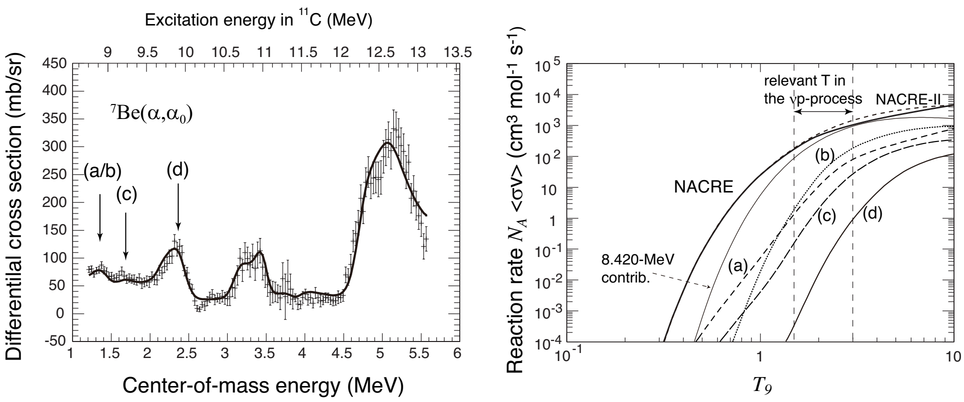

Fig. 1. Excitation function of ^{7}Be+α elastic scattering with an R-matrix fit curve (left panel) and evaluated resonant reaction rates of the ^{7}Be(α, γ) reaction for the 8.90, 9.20, and 9.97-MeV resonances, calculated by the analytical formula. The evaluation by NACRE and NACRE-II are shown for comparison.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

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 unlikely to exceed the dominant contribution of the 8.420-MeV resonance. As for the nuclear cluster, we proposed a new negative parity band in ^{11}C, similar to the one in the mirror, ^{11}B.

3. ^{10}Be+α elastic resonant scattering

Another study was performed on the ^{10}Be+α system mainly on the interst of an exotic cluster structure. In 1956, Morinaga [33] 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}C was made by Suhara and En'yo [34,35] 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}Be+α threshold.

We applied the ^{10}Be+α resonant scattering method in inverse kinematics to identify the predicted LCCS band in ^{14}C [18]. The ^{10}Be beam had a typical intensity of 2×10^4 particles per second, and the beam purity was better than 95%. The ^{10}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. α particles recoiling to the forward angles were detected by ΔE-E detector telescopes. We obtained an excitation function of the ^{10}Be+α resonant elastic scattering for $E_{\rm ex}$=13.8–19.1 MeV. An R-matrix calculation was performed to deduce the resonance parameters,

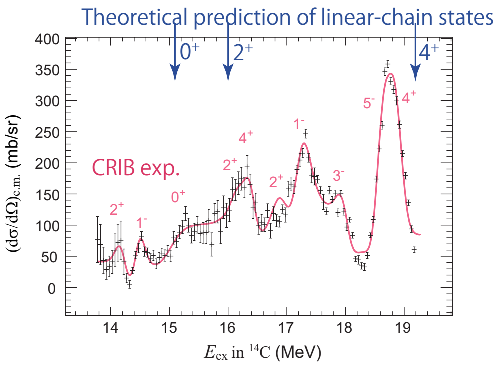

Fig. 2. Excitation function of the ^{10}Be+α resonant scattering for $\theta_{\rm lab}$=0–8°.

and we identified three resonances perfectly corresponded to the predicted LCCS band; J^π are identical, and their energies and spacings are consistent with the theoretical prediction. We claimed 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, $E_J = E_0 + \hbar^2/2\Im(J(J+1))$, where $\Im$ is the moment of inertia of the nucleus. The linearity allows us to interpret the levels as a rotational band, and the low $\hbar^2/2\Im$ = 0.19 MeV implies the nucleus could be strongly deformed, consistent with the interpretation of an LCCS.

In spite of the agreement between the theoretical and experimental energy levels of the LCCS [36], the existense of LCCS still could not be regarded as unambiguously confirmed, because of the unresolved resonances and possible backgrounds arising from secondary beam contamination and inelastic scatterings in this work. To obtain higher resolution data, another experiment at INFN-LNS, referred to as "CHAIN", was proposed in 2018. The measurement was completed, and the analysis is under way.

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