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Nuclear clusters studied with alpha resonant scatterings using RI beams at CRIB

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Abstract. Alpha resonant scattering is a simple and promising method to study α-cluster structure in nuclei. It has several good features which enable us to perform measurements with short-lived and relatively low-intense RI beams.

Several measurements on alpha resonant scattering have been carried out at CRIB (CNS Radioactive Ion Beam separator), which is a low-energy RI beam separator at Center for Nuclear Study (CNS) of the University of Tokyo. Recent α resonant scattering studies at CRIB, using 7Li, 7Be and 10Be beams with a helium gas target, are discussed.

1. Introduction

CRIB [1, 2] is a radio-isotope (RI) beam separator operated by Center for Nuclear Study (CNS), the University of Tokyo, installed 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). Most of the RI beams are produced via direct reactions such as (p, n), (d, p) and (3He, 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 7Be beam of 2 × 10^8 pps was produced using the
system [3], as the production target. 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 $^7$Be, we can obtain a good purity of almost 100% after the Wien filter.

The low-energy RI beams at CRIB are suitable for studies of astrophysical reactions and nuclear structure. An experimental method extensively used is the thick-target in inverse kinematics method [4]. In that method, the beam energy is degraded in a thick target, and thus reactions can occur at various center-of-mass energies in the same target. 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 section of various excitation energies without varying the incoming RI beam energy, and (c) we can perform measurements at 180° in center-of-mass angle, where the Coulomb scattering is minimal. Many fruitful results have been obtained at CRIB with this method [5–10].

A recent major topic of our interest is the measurement of alpha-induced reactions. Several $(\alpha, p)$ reactions, such as $^{14}\text{O}(\alpha, p)$, $^{11}\text{C}(\alpha, p)$, $^{21}\text{Na}(\alpha, p)$, $^{18}\text{Ne}(\alpha, p)$, $^{30}\text{S}(\alpha, p)$, and $^{22}\text{Mg}(\alpha, p)$ have been measured at CRIB. The elastic resonant scatterings of alpha particle using $^{14}\text{O}$, $^{21}\text{Na}$, $^7\text{Li}$ [10] and $^7\text{Be}$ [11] beams have also been measured. These elastic-scattering measurements are relevant both for the astrophysical $(\alpha, \gamma)$ reaction rates, and $\alpha$ cluster structure in nuclei.

Using an $\alpha$ particle as the probe, we can selectively study $\alpha$-cluster like states as resonances. Recent results of $\alpha$ resonant scattering measurements are presented below.

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

The exotic cluster structures in the $^{11}\text{B}$ and $^{11}\text{C}$ nuclei are attracting much attention in recent years [12]. The 3/2$^-$ state in $^{11}\text{B}$ at the excitation energy $E_{\text{ex}}=8.56$ MeV is regarded as a dilute cluster state [13], where two $\alpha$ particles and $^4\text{He}$ are weakly interacting. In particular, the alpha cluster structure in $^{11}\text{B}$ 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 [14,15]. A natural method to study the $\alpha$ cluster structure in $^{11}\text{B}$ is to form such a cluster state by the elastic scattering of $^7\text{Li}$ and $\alpha$.

The $^7\text{Li}+\alpha$ system is also related to the astrophysical reaction, $^7\text{Li}(\alpha, \gamma)^{11}\text{B}$. Studies on the resonance parameters should contribute to the precise determination of the $^7\text{Li}(\alpha, \gamma)^{11}\text{B}$ reaction rate at high temperature ($T_\beta > 1$). In the low temperature stellar environment which ignites the $p-p$ chains, $^7\text{Li}$ 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 may play important roles. For example, in the $\nu$-process in core-collapse supernovae [16] $^{11}\text{B}$ 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 $^{12}\text{C}(\gamma, e^+n)^{11}\text{B}$ 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 $\theta_{13}$, as suggested in Ref. [16].

Figure 1 schematically shows the experimental setup for the $^7\text{Li}+\alpha$ scattering measurement. A $^7\text{Li}$ 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 $3 \times 3$-mm square aperture at F3. An MCP (Micro-Channel Plate) was used to measure the position and timing of the beam. 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 $\mu\text{m}$) 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-$\mu\text{m}$ and 480-$\mu\text{m}$-thick silicon-strip detectors, placed directly in the gas chamber. The measurement was performed for $2.9 \times 10^{10}$ $^7\text{Li}$ particles injected into the gas target over 60 hours.
Figure 1. Arrangement of the detectors and targets in $^7$Li+α measurement.

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 [17, 18] or using other methods [19]; 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, and we observed strong resonant structure as shown in the left panel in Figure 2.

Rotational bands in $^{11}$B and $^{11}$C, which might be related to the cluster structure, had been discussed in [20, 21]. Based on the experimental result, we proposed a negative-parity cluster band which was later found to be consistent with a theoretical calculation [22]. The theoretical interpretation of these cluster states in the band was that they have a 3-body $(2\alpha+t)$ cluster configuration.

Figure 2. Excitation functions of $^7$Li+α (left) and $^7$Be+α (right) elastic scattering around $\theta_{c.m.}=170^\circ$. The curves are by R-matrix calculation.
3. $^7\text{Be} + \alpha$ elastic resonant scattering

The measurement of $^7\text{Be} + \alpha$ scattering can be associated with the $^7\text{Be}(\alpha, \gamma)$ reaction. The $^7\text{Be}(\alpha, \gamma)$ reaction is considered to play an important role in the hot $p$-$p$ chain and related reaction sequences [23]. Several reaction sequences including the $^7\text{Be}(\alpha, \gamma)$ reaction should take place in some high-temperature environments at $T_9 > 0.2$, where $T_9$ is the temperature in GK. In the $\nu p$-process in core-collapse supernovae [24], the $^7\text{Be}(\alpha, \gamma)$ reaction may contribute as much as the triple-$\alpha$ process to the synthesis of elements heavier than boron at the relevant temperature of $T_9 = 1.5–3$, according to a theoretical calculation [25]. The Gamow energy window at the highest temperature $T_9 = 3$ corresponds to the excitation energy $E_{ex} = 8.2–9.6$ MeV in $^{11}\text{C}$. By our study, the resonant reaction rate should be evaluated more precisely by determining $\alpha$ widths for the resonances at high temperatures.

In 2010, we performed the measurement of $^7\text{Be} + \alpha$ resonant elastic and inelastic scatterings with the thick-target method in inverse kinematics at CRIB [11]. The setup was almost identical to the one used in the above-described $^7\text{Li} + \alpha$ measurement. A low-energy $^7\text{Be}$ beam at 14.7 MeV was produced using a 2.3-mg/cm$^2$-thick hydrogen gas target and a primary $^7\text{Li}$ beam at 5.0 MeV/u. The typical $^7\text{Be}$ beam intensity used in the measurement was $1–2 \times 10^5$ per second at the secondary target, and the main measurement using a thick helium-gas target was performed for 4 days, injecting $2.9 \times 10^{10}$ $^7\text{Be}$ particles into the target. We obtained an excitation function with several peaks, which correspond to the resonance structure in $^{11}\text{C}$. The obtained excitation function of the elastic scattering is shown in the right panel in Figure 2. An R-matrix analysis was performed to deduce the parameters of the observed resonance structure. A similar measurement was independently carried out at other facilities [26], but our measurement was with $\gamma$-ray detection to identify inelastic scatterings, and some differences in the energy and cross section were found in the obtained spectra [11].

The obtained excitation function of the elastic scattering is shown in the right panel in Figure 2. An R-matrix analysis was performed to deduce the parameters of the observed resonance structure. A similar measurement was independently carried out at other facilities [26], but our measurement was with $\gamma$-ray detection to identify inelastic scatterings, and some differences in the energy and cross section were found in the obtained spectra [11].

As for the cluster levels, a similar discussion as $^{11}\text{B}$ can be applied to $^{11}\text{C}$. Two positive-parity rotational bands, $K = 3/2^+$ and $5/2^+$, had been suggested in [21]. We observed a strong resonance with $J^\pi = 9/2^+$ at 12.4 MeV in $^{11}\text{C}$, and it can be the missing member of the $K = 3/2^+$ rotational band. We propose a new negative-parity band also in $^{11}\text{C}$, as shown in Fig. 4. The members of the band could have a $2\alpha-^3\text{He}$ cluster structure. The head is the 8.10-MeV ($J^\pi = 3/2^-$) state, the mirror of the 8.56-MeV state in $^{11}\text{B}$. The second member is the 9.78-MeV state, assigned as $J^\pi = 5/2^-$ previously. The third member can be the state at 11.03 MeV. Our assignment was either $J^\pi = 5/2^-$ or $7/2^-$, and the latter assignment agrees
with the systematics of this negative band. The systematics predicts there can be a $J^\pi = 9/2^-$ state around 13 MeV. A candidate is the 12.65-MeV state. In the present work, this state was regarded to form a doublet together with the 12.4-MeV state. A similar doublet was observed in the mirror nucleus [10], and the higher state was considered to have $J^\pi = 9/2^-$. If the tentative assignment in another work of $J^\pi = 7/2^+$ was wrong, the 12.65-MeV state may have $J^\pi = 9/2^-$, as in the mirror nucleus. Another candidate is the resonance at 13.4 MeV [27], which is known to have a certain $\alpha$ width, but its $J^\pi$ has not been determined. In Fig. 4, these states are shown as circles and connected as dotted lines under the assumption that they have $J^\pi = 9/2^-$. The energy of the band head (8.10 MeV) appears as lower than the systematics expected from the higher state. This lowering is in agreement with the mirror state [10, 22].

4. $^{10}$Be+$\alpha$

Another interest is on the clustering in the $^{14}$C nucleus. Suhara and En’yo [28, 29] obtained a band ($0^+_5$, $2^+_1$, $4^+_0$) in $^{14}$C which could be explained as linear-chain cluster levels. It was predicted that these levels appear a few MeV or more above the $^{10}$Be+$\alpha$ threshold. The investigation in [29] shows that the AMD wave function has a configuration in which two $\alpha$ particles and two neutrons are closely located, while the remaining $\alpha$ particle is more distant. This implies states having such a linear-chain configuration could be accessed from the $^{10}$Be+$\alpha$ channel. Therefore we are planning a measurement of $^{10}$Be+$\alpha$ resonant scattering at CRIB. In Jan. 2014, we carried out the first $^{10}$Be beam production test at CRIB and successfully produced a $^{10}$Be beam with $2 \times 10^4$ pps, at an energy of 2.0 MeV/u. Using the beam, we are going to perform a measurement of resonant scattering and we expect to observe $\alpha$-cluster states in $^{14}$C.

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