Study on $\alpha$-cluster levels in non-4n nuclei using low-energy RI beams

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Abstract. Alpha resonant scattering is a simple and promising method to study $\alpha$-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 $\alpha$ resonant scattering studies at CRIB, using $^7$Li, $^7$Be and $^{10}$Be 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) [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 $^7$Be, we can obtain a high purity of almost 100% after the Wien filter.

An experimental method extensively used is the thick-target method in inverse kinematics (TTIK) [4]. In that method, the beam energy is degraded in a thick reaction target, and reactions occur at various center-of-mass energies. Many experiments on proton resonant scatterings have
been successfully performed at CRIB with the TTIK method [5–11], most of which are related to the astrophysical \((p, \gamma)\) reactions. Measurements on the \(\alpha\) elastic resonant scatterings with a helium gas target and heavy-ion/RI beams, \(^{14}\)O, \(^{21}\)Na, \(^{30}\)S, \(^{7}\)Li [12] and \(^{7}\)Be [13], have been performed at CRIB. These measurements are to study astrophysical \((\alpha, \gamma)\) reaction rates, and also \(\alpha\)-cluster structures of the compound nuclei. Direct measurement of \((\alpha, p)\) reactions, such as \(^{14}\)O(\(\alpha, p\)) [14], \(^{11}\)C(\(\alpha, p\)) [15], \(^{21}\)Na(\(\alpha, p\)), \(^{18}\)Ne(\(\alpha, p\)), \(^{30}\)S(\(\alpha, p\)), and \(^{22}\)Mg(\(\alpha, p\)), have also been performed with the TTIK method using RI beams at CRIB. Recent results on \(\alpha\) resonant scattering measurements are discussed below.

2. \(^{7}\)Li/\(^{7}\)Be+\(\alpha\) elastic resonant scattering and clustering in \(^{11}\)B and \(^{11}\)C

The exotic cluster structures in the \(^{11}\)B nucleus and its mirror, \(^{11}\)C, are attracting much attention in recent years [16]. The \(3/2^{-}\) state in \(^{11}\)B at the excitation energy \(E_{\text{ex}}=8.56\) MeV is regarded as a dilute cluster state [17], where two \(\alpha\) particles and \(^{3}\)He are weakly interacting. In particular, the alpha cluster structure in \(^{11}\)B was studied by measuring its isoscalar monopole and quadrupole strengths in the \(^{11}\)B(\(d, d'\)) reaction, and the 8.56-MeV state was suggested to have a dilute cluster structure [18, 19].

Using the TTIK method at CRIB, the excitation function of \(^{7}\)Li+\(\alpha\) elastic scattering around 180° in the center-of-mass system was measured for the first time, and we observed strong resonant structure in the spectrum [12]. 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 in \(^{11}\)B, 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.

We also performed the measurement of \(^{7}\)Be+\(\alpha\) resonant elastic and inelastic scatterings at CRIB [13], to study the symmetry in the mirror system. An R-matrix analysis was performed to deduce the parameters of the observed resonance structure, and we proposed a negative parity band in \(^{11}\)C as well. A similar measurement was independently carried out at other facilities [23], 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 [13].

3. Linear-chain cluster levels in \(^{14}\)C

In 1956, Morinaga [24] came up with the novel idea of a particular cluster state: the linear-chain cluster state (LCCS). Despite the pursuit by many scientists for more than half a century, up until now the LCCS has been only hypothetical. 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 [25] with an antisymmetrized molecular dynamics (AMD) calculation, yielding a band (\(J^\pi = 0^+, 2^+, 4^+\)) that has a configuration of an LCCS at a few MeV or more above the \(^{10}\)Be+\(\alpha\) threshold. A further investigation [26] showed that the AMD wave function has a configuration in which two \(\alpha\) particles and two neutrons are located close to each other, while the remaining \(\alpha\) particle is relatively further away. This implied that such an LCCS could be experimentally accessible from the \(^{10}\)Be+\(\alpha\) channel in a single step.

We applied the \(^{10}\)Be+\(\alpha\) resonant scattering method in inverse kinematics [4] to identify the predicted LCCS band in \(^{14}\)C. Our experimental setup was similar to the previous one in the \(^{7}\)Be+\(\alpha\) experiment [13], but we placed an extra silicon detector telescope to cover a broader angular range, instead of the NaI detectors. The new setup enabled us to perform a reliable analysis on the angular distribution. The \(^{10}\)Be beam was produced at CRIB with a typical intensity of \(2 \times 10^7\) particles per second, and the beam purity was better than 95%. The beam was counted with two parallel-plate avalanche counters (PPACs), separated by 30 cm. The \(^{10}\)Be beam at 25 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 ∆E-E detector telescopes. We used two sets of detector telescopes in the gas-filled chamber, where each telescope consisted of two layers of silicon detectors with the thicknesses of 20 μm and 480 μm. The main measurement using the helium-gas target was performed for 2 days, injecting $2.2 \times 10^9$ $^{10}$Be particles into the gas target as valid events.

We selected events in which the $^{10}$Be beam particle was injected into the target and an α particle was detected at the telescope in coincidence. The scattering position, or equivalently the center-of-mass energy $E_{c.m.}$, was determined by a kinematic reconstruction on an event-by-event basis. The number of events for each small energy division was converted to the differential cross section ($d\sigma/d\Omega$)$_{c.m.}$, using the solid angle of the detector, the number of beam particles, and the effective target thickness. Finally we obtained the excitation function of the $^{10}$Be+α resonant elastic scattering for 13.8–19.1 MeV, where events with $\theta_{\text{lab}} = 0–8^\circ$ ($\theta_{\text{c.m.}} = 164–180^\circ$) were selected, as in Fig. 1. At energies above 15.7 MeV, the excitation function shows a reasonable agreement in the spectral shape with one of the recent measurements [27]. A structure with resonances which may correspond to the theoretical prediction of the LCCS was observed in the spectrum. The resonant information including $J^\pi$ will be obtained by an analysis with an R-matrix calculation.

![Figure 1.](image-url) Excitation function of the $^{10}$Be+α resonant scattering for $\theta_{\text{lab}}=0–8^\circ$.

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