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Study on α -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 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 ${}^7\text{Li}$, ${}^7\text{Be}$ and ${}^{10}\text{Be}$ 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 a 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 ${}^7\text{Be}$, 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 , γ) reactions. Measurements on the α elastic resonant scatterings with a helium gas target and heavy-ion/RI beams, ^{14}O , ^{21}Na , ^{30}S , ^7Li [12] and ^7Be [13], have been performed at CRIB. These measurements are to study astrophysical (α , γ) reaction rates, and also α -cluster structures of the compound nuclei. Direct measurement of (α , p) reactions, such as $^{14}\text{O}(\alpha, p)$ [14], $^{11}\text{C}(\alpha, p)$ [15], $^{21}\text{Na}(\alpha, p)$, $^{18}\text{Ne}(\alpha, p)$, $^{30}\text{S}(\alpha, p)$, and $^{22}\text{Mg}(\alpha, p)$, have also been performed with the TTIK method using RI beams at CRIB. Recent results on α resonant scattering measurements are discussed below.

2. $^7\text{Li}/^7\text{Be}+\alpha$ 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 $3/2_3^-$ state in ^{11}B at the excitation energy $E_{\text{ex}}=8.56$ MeV is regarded as a dilute cluster state [17], 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 [18, 19].

Using the TTIK method at CRIB, the excitation function of $^7\text{Li}+\alpha$ 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 $^7\text{Be}+\alpha$ 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 γ -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 $^{10}\text{Be}+\alpha$ threshold. A further investigation [26] showed that the AMD wave function has a configuration in which two α particles and two neutrons are located close to each other, while the remaining α particle is relatively further away. This implied that such an LCCS could be experimentally accessible from the $^{10}\text{Be}+\alpha$ channel in a single step.

We applied the $^{10}\text{Be}+\alpha$ 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 $^7\text{Be}+\alpha$ 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 2×10^4 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 ΔE - 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 2.2×10^9 ^{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 $E_{\text{c.m.}}$, 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 $(d\sigma/d\Omega)_{\text{c.m.}}$, 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 $^{10}\text{Be}+\alpha$ resonant elastic scattering for 13.8–19.1 MeV, where events with $\theta_{\text{lab}} = 0\text{--}8^\circ$ ($\theta_{\text{c.m.}} = 164\text{--}180^\circ$) 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^π will be obtained by an analysis with an R-matrix calculation.

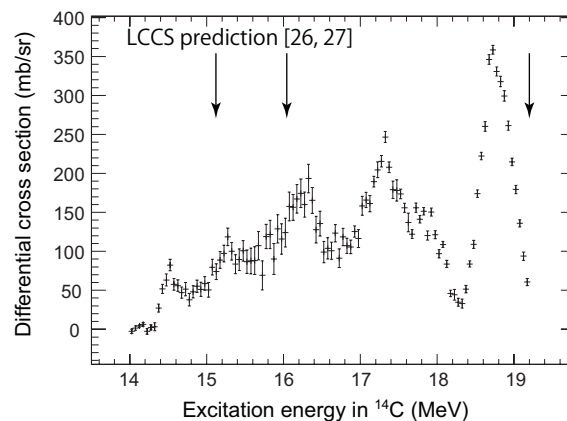


Figure 1. Excitation function of the $^{10}\text{Be}+\alpha$ resonant scattering for $\theta_{\text{lab}}=0\text{--}8^\circ$.

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