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Overview of the activities at the low-energy beam separator CRIB

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Summary. — CRIB (CNS Radio-Isotope Beam separator) is a low-energy RI beam separator of Center for Nuclear Study (CNS), the University of Tokyo. Studies on nuclear astrophysics, nuclear structure, and other interests have been performed using the RI beams at CRIB, forming international collaborations. Measurements of proton and α resonant scatterings have been performed at CRIB for many nuclides using RI beams. Projects to study astrophysical reactions with direct and indirect methods are also in progress.

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 ($< 10\,\mathrm{MeV/u}$) 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}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

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velocities. For relatively light RI beams such as ^{7}Be, we obtained a purity close to 100% after the Wien filter. A list of typical parameters of RI beams produced at CRIB is found in [4]. New RI beams recently developed at CRIB are ^{16}N (1×10^6 pps), ^{10}Be (2×10^4 pps), ^{15}O (1×10^6 pps), and ^{26}Al (1×10^5 pps). The ^{26}Al beam was developed to obtain an isomeric ^{26m}Al beam, related to the production rate of the galactic γ rays from ^{26}Al. The low-energy RI beams at CRIB are particularly suitable for studies on astrophysical reactions and nuclear resonant structure, as discussed below.

2. – Recent achievements at CRIB

An experimental method extensively used is the thick-target method in inverse kinematics (TTIK) [5]. 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 with the TTIK method [6-14], 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, ^{7}Li [15] and ^{7}Be [16], have been performed at CRIB for astrophysical interests. These measurements are to study astrophysical (α, γ) reaction rates, and also the α-cluster structure of the compound nuclei. Direct measurement of (α, p) reactions, such as ^{14}O(α, p) [17], ^{11}C(α, p) [18], ^{21}Na(α, p), ^{18}Ne(α, p), ^{30}S(α, p), and ^{22}Mg(α, p), have also been performed with the TTIK method using RI beams at CRIB. For some of the recent measurements, an active target, referred to as "GEM-MSTPC" [19], was used.

There are other experimental projects at CRIB 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]. The first measurement using the Trojan horse method (THM) [21-23] with an RI beam has been performed at CRIB [24]. The measurement was to study the ^{18}F(p, α)^{15}O reaction at low energies relevant to astrophysics via the three body reaction ^{2}H(^{18}F, α^{15}O)n. The ^{18}F(p, α)^{15}O reaction rate is particularly responsible for the 511 keV γ ray emission in nova explosion phenomena.

3. – Linear-chain cluster levels in ^{14}C

In 1956, Morinaga [25] 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 [26] 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+α threshold. A further investigation [27] 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}Be+α channel in a single step.

We applied the ^{10}Be+α resonant scattering method in inverse kinematics [5] to identify the predicted LCCS band in ^{14}C. Our experimental setup was similar to the previous

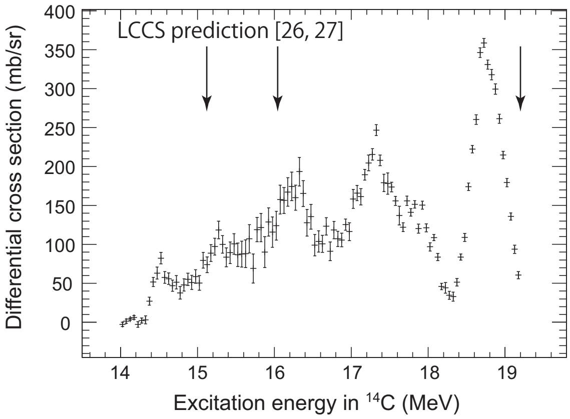

Fig. 1. – Excitation function of the ^{10}Be+α resonant scattering for $\theta_{\rm lab} = 0$–$8°$.

one in the ^{7}Be+α experiment [16], 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 central telescope was located 555 mm downstream of the beam entrance window exactly on the beam axis, and the other telescope was at an angle of 9° from the beam axis, as viewed from the entrance window position. Each detector in the telescope had an active area of $50 \times 50\,\text{mm}^2$, and 16 strips for one side, making pixels of $3 \times 3\,\text{mm}^2$ altogether. 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 $E_{\rm cm}$, 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 $({\rm d}\sigma/{\rm d}\Omega)_{\rm c.m.}$, 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 $\theta_{\rm lab} = 0$–$8°$ ($\theta_{\rm c.m.} = 164$–$180°$) 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 [28]. 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 with an analysis with R-matrix calculation.

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