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Experimental Studies of Light-ion Nuclear Reactions Using Low-energy RI Beams

H Yamaguchi[1], D. Kahl[1,2], S. Hayakawa[1,3], Y. Sakaguchi[1], K. Abe[1], H. Shimuzu[1], Y. Wakabayashi[4,1], T. Hashimoto[5,1], S. Cherubini[3,6], M. Gulino[3,7], C. Spitaleri[3,6], G.G. Rapisarda[3,6], M. La Cognata[3], L. Lamia[6], S. Romano[3,6], S. Kubono[4,1], N. Iwasa[8], T. Teranishi[9], T. Kawabata[10], Y.K. Kwon[5], D.N. Binh[11,1], L.H. Khiem[12], N.N. Duy[13,12], S. Kato[14], T. Komatsubara[5], A. Coc[15], N. de Sereville[16], F. Hammache[16], G. Kiss[17,4], and S. Bishop[4,18].

[1] *Center for Nuclear Study (CNS), University of Tokyo, Wako, Saitama, Japan*
[2] *School of Physics and Astronomy, the University of Edinburgh, Edinburgh, UK*
[3] *Istituto Nazionale Fisica Nucleare - Laboratori Nazionali del Sud, Catania, Italy*
[4] *RIKEN Nishina Center, 2-1 Hirosawa, Wako, Saitama, Japan*
[5] *Institute for Basic Science, Daejeon, Republic of Korea*
[6] *Dipartimento di Fisica e Astronomia, Università di Catania, Catania, Italy*
[7] *Università di Enna KORE, Enna, Italy*
[8] *Department of Physics, Tohoku University, Sendai, Miyagi, Japan*
[9] *Department of Physics, Kyushu University, Fukuoka, Japan*
[10] *Department of Physics, Kyoto University, Kyoto, Japan*
[11] *30 MeV Cyclotron Center, Tran Hung Dao Hospital, Hanoi, Vietnam*
[12] *Institute of Physics, Vietnam Academy of Science and Technology, Hanoi, Vietnam*
[13] *Dong Nai University, Bui Trong Nghia Street, Dong Nai province, Vietnam*
[14] *Department of Physics, Yamagata University, Yamagata, Japan*
[15] *Centre de Spectrometrie Nucleaire et de Spectrometrie de Masse, Orsay, France*
[16] *Institut de Physique Nucleaire, Orsay, France*
[17] *Institute for Nuclear Research (MTA-ATOMKI), Debrecen, Hungary*
[18] *Technische Universität München, Garching, München, Germany*

E-mail: yamag@cns.s.u-tokyo.ac.jp

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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. A striking method to study astrophyiscal reactions involving radioactive nuclei is the thick-target method in inverse kinematics. Several astrophysical alpha-induced reactions have been be studied with that method at CRIB. A recent example is on the α resonant scattering with a radioactive ^{7}Be beam. This study is related to the astrophysical ^{7}Be(α,γ) reactions, important at hot p-p chain and νp-process in supernovae. There have been measurements based on several indirect methods, such as the asymptotic normalization coefficient (ANC) and Trojan horse method (THM). The first THM measurement using an RI beam has been performed at CRIB, to study the ^{18}F(p, α)^{15}O reaction at astrophysical energies via the three body reaction ^{2}H(^{18}F, α^{15}O)n. The ^{18}F(p, α)^{15}O reaction rate is crucial to understand the 511-keV γ-ray production in nova explosion phenomena, and we successfully evaluated the reaction cross section at novae temperature and below experimentally for the first time.

KEYWORDS: Nuclear reaction, Nuclear structure, 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). Figure 1 shows the overview of CRIB. 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. Solid targets such as beryllium foils can also be used as the production target. 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]. 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 low-energy RI beams at CRIB are particularly suitable for studies on astrophysical reactions and nuclear resonant structure, as discussed below.

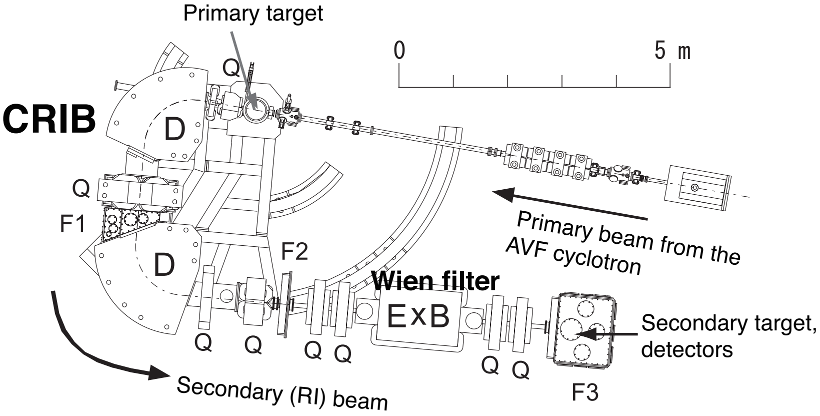

Fig. 1. CRIB overview. D, Q, and F represent a dipole magnet, a quadrupole magnet, and a focal plane, respectively.

2. Alpha resonant scattering

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. 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, where the Coulomb scattering is minimal. Many experiments have been successfully performed with this method [6–11].

Measurements on the α elastic resonant scatterings of a helium gas target and heavy-ion beams, ^{14}O, ^{21}Na, ^{30}S, ^{7}Li [9] and ^{7}Be [12] have been performed at CRIB for astrophysical interests. These measurements provide information on astrophysical (α, γ) reaction rates, and are also very suitable for studying nuclear cluster structure of the compound nuclei.

A typical example of the resonant scattering experiment is the one on the ^{7}Be+α scattering measurement. The measurement of the ^{7}Be+α scattering allows 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 [13]. 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 [14], 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 [15]. 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 should be evaluated more precisely by determining α widths for the resonances at high temperatures. We performed the measurement of the ^{7}Be+α resonant elastic and inelastic scatterings with the thick-target method in inverse kinematics at CRIB [12]. 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 $\times 10^5$ per second at the secondary target, and the main measurement using a thick helium-gas target was performed for 4 days, injecting 2.9×10^{10} ^{7}Be particles into the target. We obtained an excitation function of the elastic scattering with several peaks, corresponding to the resonance structure in ^{11}C. The obtained excitation is shown in the left panel of Figure 2. 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 [16], but our measurement included γ-ray detection to identify inelastic scattering events, and several differences were found in the obtained spectra [12].

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 rate and compare it with the total reaction rate evaluated in NACRE [17, 18]. In the evaluation reported in NACRE, only 2 resonances at 8.1045 and 8.420 MeV are 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. The resonant reaction rates were calculated for three resonances using analytical formula described in [17], and plotted in Fig. 2. In conclusion, 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 be more than the contribution of the 8.420-MeV resonance, which dominates the reaction rate.

3. Direct measurement of (α, p) reactions

Direct measurement of (α, p) reactions, such as ^{14}O(α, p) [19], ^{11}C(α, p) [20], ^{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. Several (α, p) reactions have been studied at CRIB. For some of the recent measurements, an active target, referred to as “GEM-MSTPC” [21], was used.

The ^{14}O(α, p)^{17}N reaction has been considered as an important breakout reaction from hot-CNO cycle, and direct measurements of the ^{14}O(α, p)^{17}N reaction have been performed using RI beam. The first measurement [22] may had problems in the identification of the resonances and the calculation

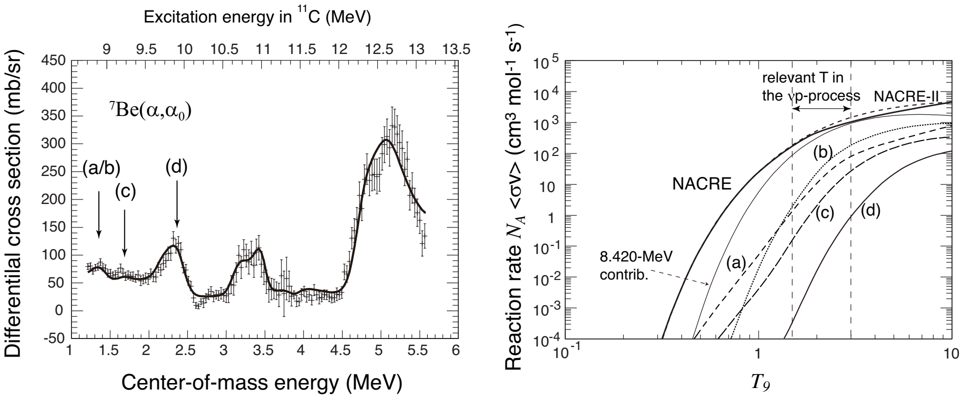

Fig. 2. Excitation function of ^{7}Be+α elastic scattering with an R-matrix fit curve (left panel) and resonant reaction rate of ^{7}Be(α, γ) for the 8.90, 9.20, and 9.97-MeV resonances, calculated by the analytical formula. The evaluation by NACRE and NACRE-II are shown for comparison. The contribution by the 8.420-MeV resonance, included in NACRE, is also shown.

of the cross section. Another measurement [23] reported considerable contribution of 2-proton decay events. In our recent publication [19], we presented an evaluation of the resonant reaction rates based on the measurement of the cross section for $E_{\mathrm{c.m.}} > 2.1$ MeV. The result shows the dominance of the 6.15- and 7.05-MeV resonant reactions below 2 GK, and the higher resonances we observed may dominate the rate above that temperature.

The ^{11}C(α, p)^{14}N can enhance the synthesis of CNO- and higher-mass nuclei in high-temperature environments, and particularily may play an important role in the core-collapse supernovae [15]. In our ^{11}C(α, p)^{14}N direct reaction measurement [20], it was demonstrated that the reactions with the excited ^{14}N nucleus in the exit channel can be identified with the time-of flight information. The reaction had been studied with the reverse reaction of ^{14}N(p, α)^{11}C, and the measurement from the ^{11}C+α channel was performed for the first time in this work. We presented the first experimental evaluation of the ^{11}C(α, p_1)^{14}N* and ^{11}C(α, p_2)^{14}N* reaction rates, which may enhance the total reaction rate by 20%.

4. Indirect measurements

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 [24].

The first measurement using the Trojan horse method (THM) [25–27] with an RI beam has been performed at CRIB [28]. 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. The relevant temperature in novae is corresponding to the Gamow energy of 100–400 keV. A direct measurement of the ^{18}F(p, α) reaction was recently performed at TRIUMF [29], reaching to thee energy as low as 250 keV, but the reaction rate below that energy has been totally unknown experimentally.

The measurement at CRIB was performed with a ^{18}F RI beam, of which maximum intensity was 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. The analysis was performed by following a standard scheme of the Trojan horse method. 3-body events were selected according to the kinematical relationship of the detected charged particles, and converted into a Q-value spectrum. The momentum distribution for the *p*-*n* intercluster motion was in agreement with a Hulthén function, which proves the dominance of the quasi-free mechanism. Then the three-body cross section was converted into the two-body cross section, using the momentum distribution of the *p*-*n* intercluster motion and a kinematical factor (see [28] for further details). We successfully evaluated the reaction cross section at the novae temperature and even below experimentally for the first time. Because of the limited statistics due to the RI beam experiment, we could not uniquely determine the spin and parity (J^π) of each level from the angular distribution. As a result, we had to assume J^π for some of the resonances to obtain the total reaction cross section. The S-factor greatly deviated according to the J^π assignment for the 6460-keV resonance, which indicates the importance of the determination of J^π. To confirm the J^π assignments, we performed another measurement in 2015 with statistics more than one order-of-magnitude greater than the previous measurement, and the data analysis is under way.

5. Acknowledgements

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