Experiments on astrophysical reactions with low-energy unstable nuclei beams at CRIB

H. Yamaguchi\textsuperscript{1,2}, S. Hayakawa\textsuperscript{1}, N.R. Ma\textsuperscript{1}, H. Shimizu\textsuperscript{1}, L. Yang\textsuperscript{22}, D. Kahl\textsuperscript{1,3}, K. Abe\textsuperscript{1}, T. Suhara\textsuperscript{5}, N. Iwasa\textsuperscript{6}, A. Kim\textsuperscript{7,8}, D.H. Kim\textsuperscript{7}, S.M. Cha\textsuperscript{8}, M.S. Kwag\textsuperscript{8}, J.H. Lee\textsuperscript{8}, E.J. Lee\textsuperscript{8}, K.Y. Chae\textsuperscript{8}, Y. Wakabayashi\textsuperscript{9}, N. Imai\textsuperscript{1}, N. Kitamura\textsuperscript{1}, P. Lee\textsuperscript{10}, J.Y. Moon\textsuperscript{11,12}, K.B. Lee\textsuperscript{11}, C. Akers\textsuperscript{11}, H.S. Jung\textsuperscript{12,10}, N.N. Duy\textsuperscript{11,13}, L.H. Khiem\textsuperscript{14}, C.S. Lee\textsuperscript{10}, S. Cherubini\textsuperscript{15,16}, M. Gulino\textsuperscript{15,17}, C. Spitaleri\textsuperscript{15,16}, G.G. Rapisarda\textsuperscript{15,16}, M. La Cognata\textsuperscript{15}, L. Lamia\textsuperscript{15}, S. Romano\textsuperscript{15,16}, A. Coc\textsuperscript{18}, N. de Sereville\textsuperscript{19}, F. Hamma\textsuperscript{15,19}, G. Kiss\textsuperscript{20,15}, S. Bishop\textsuperscript{21}, T. Teranishi\textsuperscript{22}, T. Kawabata\textsuperscript{23}, Y.K. Kwon\textsuperscript{11}, and D.N. Binh\textsuperscript{24,1}

1 Center for Nuclear Study (CNS), University of Tokyo, Wako, Saitama, Japan.
2 National Astronomical Observatory of Japan, Mitaka, Tokyo, Japan.
3 China Institute of Atomic Energy, Beijing, China.
4 School of Physics and Astronomy, the University of Edinburgh, Edinburgh, UK.
5 Matsue College of Technology, Matsue, Shimane, Japan.
6 Department of Physics, Tohoku University, Sendai, Miyagi, Japan.
7 Department of Physics, Ewha Womans University, Republic of Korea.
8 Department of Physics, Sungkyunkwan University, Suwon, Republic of Korea.
9 RIKEN Nishina Center, 2-1 Hirosawa, Wako, Saitama, Japan.
10 Department of Physics, Chung-Ang University, Seoul, Republic of Korea.
11 Institute for Basic Science, Daejeon, Republic of Korea.
12 Wako Nuclear Science Center (WNSC), KEK, Wako, Saitama, Japan.
13 Dong Nai University, Dong Nai, Vietnam.
14 Institute of Physics, Vietnam Academy of Science and Technology, Hanoi, Vietnam.
15 Istituto Nazionale Fisica Nucleare - Laboratori Nazionali del Sud, Catania, Italy.
16 Dipartimento di Fisica e Astronomia, Università di Catania, Catania, Italy.
17 Università di Enna KORE, Enna, Italy.
18 Centre de Spectrometrie Nucleaire et de Spectrometrie de Masse, IN2P3, Orsay, France.
19 Institut de Physique Nucleaire, IN2P3, Orsay, France.
20 Institute for Nuclear Research (MTA-ATOMKI), Debrecen, Hungary.
21 Technische Universität München, Garching, München, Germany.
22 Department of Physics, Kyushu University, Ito, Fukuoka, Japan.
23 Department of Physics, Kyoto University, Kita-Shirakawa, Kyoto, Japan.
24 30 MeV Cyclotron Center, Tran Hung Dao Hospital, Hoan Kiem District, Hanoi, Vietnam.

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

Abstract.

Studies on nuclear astrophysics, nuclear structure, and other interests have been performed using the radioactive-isotope (RI) beams at the low-energy RI beam separator CRIB, operated by Center for Nuclear Study (CNS), the University of Tokyo. The elastic resonant scattering is a striking tool to study astrophysical reactions and nuclear clusters. In particular, when it is coupled with a thick target and inverse kinematics, the measurement can be very efficient and even feasible with RI beams. By measuring resonant scattering, we can study the properties of resonant states which could play an important role in the astrophysical reaction, or have an...
exotic nuclear structure. The $^{10}$Be+$\alpha$ elastic scattering has been measured at CRIB, and three resonances which are in agreement with the prediction of a linear-chain structure by Suhara-En’yo were observed, giving a strong indication of the existence of such an exotic structure. Measurements based on the indirect technique of the reaction measurement, such as the Trojan horse method, have also been performed at CRIB.

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]. Figure 1 shows an overview of CRIB. Most of the RI beams are produced via 2-body 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 $2 \times 10^8$ 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 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 ($1 \times 10^6$ pps), $^{10}$Be ($2 \times 10^4$ pps), $^{15}$O ($1 \times 10^6$ pps), and $^{26}$Al ($1 \times 10^5$ pps). The $^{26}$Al beam was developed to obtain an isomeric $^{26m}$Al beam, related to the production rate of the galactic $\gamma$ rays from $^{26}$Al [5]. The low-energy RI beams at CRIB are particularly suitable for studies on astrophysical reactions and nuclear resonant structure. An experimental method extensively used is the thick-target method in inverse kinematics [6]. 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. Many measurements have been performed at CRIB with this method [7–18].

A major topic of our interest is the measurement of alpha-induced reactions. Several (α, p) reactions, such as 14O(α, p) [19], 11C(α, p) [20], 21Na(α, p), and 18Ne(α, p) have been studied at CRIB. For some of the recent measurements, an active target, referred to as “GEM-MSTPC” [21], has been used. Measurements of the elastic resonant scatterings with a helium target and beams of 7Li/7Be [12, 14], 30S [18], 10Be [22], 15O [23], and 18Ne have also been performed. These measurements can provide information on astrophysical (α, γ) reaction rates or nuclear cluster structure of the compound nuclei.

There are other projects for the determination of the astrophysical reactions using indirect methods with RI beams. The indirect measurement of the 12N(p, γ) reaction, which is a key reaction to synthesize nuclei heavier than carbon, was performed by measuring the 12N(d, n) reaction in inverse kinematics. Using the asymptotic normalization coefficient (ANC) method, the reaction rate was reevaluated [24]. Another type of indirect reaction measurement we performed was with the Trojan horse method (THM) [25–27]. The first application of the THM with an RI beam was in an experiment at CRIB [28], where the 18F(p, α)15O reaction at astrophysical energies was studied, as discussed later. The 7Be(n, p) and (n, α) are possible destruction reactions that explain the discrepancy in 7Li between the Big-bang nucleosynthesis model and the observed 7Li abundance. We performed a THM measurement with 7Be beam at CRIB in 2016, as one of the first applications of THM for neutron induced reactions [29].

The energy of the RI beams at CRIB is of the same order of the Coulomb barrier height between nuclei, and unique experiments to study reaction mechanisms around the Coulomb barrier were also performed at CRIB. The recent experiments were for the systems of 9B+Pb [30] and 17F+Ni [31], using RI beams of nuclei with a weakly-bound proton.

2. 10Be+α elastic resonant scattering

α resonant scattering with light nuclei is an efficient tool to study α-induced astrophysical reactions, and also special α-cluster structure in compound nuclei. 7Li+α and 3Be+α resonant elastic scattering were measured at CRIB [12, 14], to study the resonances which possibly contributing to the astrophysical reaction rates in explosive phenomena, as well as new cluster bands with high momenta of inertia.

Another study was performed on the 10Be+α system mainly on the interest of an exotic cluster structure. In 1956, Morinaga [32] came up with the novel idea of a particular cluster state: the linear-chain cluster state (LCCS). 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 14C was made by Suhara and En’yo [33, 34] with an antisymmetrized molecular dynamics (AMD) calculation, yielding a prolate band (Jπ = 0+, 2+, 4+) that has a configuration of an LCCS at a few MeV or more above the 10Be+α threshold.

We applied the 10Be+α resonant scattering method in inverse kinematics to identify the predicted LCCS band in 14C [22]. The experimental setup is shown in Figure 2. The 10Be beam had a typical intensity of 2 × 10^4 particles per second, and the beam purity was better than 95%. The 10Be beam at 25.8 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 obtained an excitation function of the 10Be+α resonant elastic scattering for E_{ex}=13.8–
19.1 MeV. An R-matrix calculation was performed to deduce the resonance parameters, and we identified three resonances perfectly corresponded to the predicted LCCS band; \( J^s \) are identical, and their energies and spacings are consistent with the theoretical prediction. We claimed this as the strongest indication of the LCCS ever found. It can be also shown that both sets of level energies can be plotted almost on a line, \( E_J = E_0 + \hbar^2 / 2\mathbf{3}(J(J + 1)) \), where \( \mathbf{3} \) is the moment of inertia of the nucleus. The linearity allows us to interpret the levels as a rotational band, and the low \( \hbar^2 / 2\mathbf{3} = 0.19 \) MeV implies the nucleus could be strongly deformed, consistent with the interpretation of an LCCS.

In spite of the agreement between the theoretical and experimental energy levels of the LCCS [35], the existence of LCCS still could not be regarded as unambiguously confirmed, because of the unresolved resonances and possible backgrounds arising from secondary beam contamination and inelastic scatterings in this work. To obtain higher resolution data, another experiment at INFN-LNS, referred to as “CHAIN”, was proposed in 2018. The measurement was completed, and the analysis is under way.

3. Study with the Trojan horse method using an RI beam
The first THM measurement with an RI beam has been performed at CRIB [28]. The measurement was to study the \(^{18}\text{F}(p, \alpha)^{15}\text{O}\) reaction at low energies relevant to astrophysics via the three body reaction \(^2\text{H}(^{18}\text{F}, \alpha^{15}\text{O})n\). The \(^{18}\text{F}(p, \alpha)^{15}\text{O}\) reaction rate is particularly

Figure 3. Excitation function of the \(^{10}\text{Be}+\alpha\) resonant scattering for \( \theta_{\text{lab}}=0^\circ-8^\circ \).
responsible for the 511-keV $\gamma$ 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($p$, $\alpha$) reaction was recently performed at TRIUMF [36], reaching to the 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 $2 \times 10^6$ pps. A CD$_2$ target with a thickness of 150 $\mu$g/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, as shown in Fig. 4. Because of the limited statistics due to the RI beam experiment, we could not uniquely determine the spin and parity ($J^\pi$) of each level from the angular distribution. As a result, we had to assume $J^\pi$ for some of the resonances to obtain the total reaction cross section. The $S$-factor greatly deviated according to the $J^\pi$ assignment for the 6460-keV resonance, which indicates the importance of the determination of $J^\pi$. In 2015, another measurement with greater statistics was performed, and the analysis is in progress.

![Figure 4](image-url)

**Figure 4.** The astrophysical $S$-factor of the $^{18}$F($p$, $\alpha$)$^{15}$O reaction [28]. The filled and open circles show the $S$-factor obtained by the THM experiment at CRIB assuming $J^\pi = 3/2^+$ and $5/2^-$ for the 6460-keV resonance, respectively. The solid and dashed curves are calculations discussed in [36].

**Acknowledgments**

The experiments were performed at RI Beam Factory operated by RIKEN Nishina Center and CNS, the University of Tokyo. We are grateful to the RIKEN and CNS accelerator staff for their help. This work was partly supported by JSPS KAKENHI (Nos. 16K05369, and 16H03980 and 19K03883) from the Ministry of Education, Culture, Sports, Science and Technology (MEXT) of
Japan, and the National Research Foundation Grant funded by Korea Government (Grants Nos. NRF-2016R1D1A10991746, NRF-2016R1A5A1013277, and NRF-2016K1A3A709005579).

References

[1] Kubono S, Yanagisawa Y, Teranishi T, Kato S, Kishida T, Michimasa S, Ohshiro Y, Shimoura S, Ue K, Watanabe S and Yamazaki N 2002 Eur. Phys. J. A13 217
[2] Yanagisawa Y, Kubono S, Teranishi T, Ue K, Michimasa S, Notani M, He J J, Ohshiro Y, Shimoura S, Watanabe S, Yamazaki N, Iwasaki H, Kato S, Kishida T, Morikawa T and Mizoi Y 2005 Nucl. Instrum. Meth. Phys. Res., Sect. A 539 74–83
[3] Yamaguchi H, Wakabayashi Y, Amadio G, Hayakawa S, Fujikawa H, Kubono S, He J, Kim A and Binh D 2008 Nucl. Instrum. Meth. Phys. Res., Sect. A 589 150–156
[4] Kahl D, Hashimoto T, Duy N N, Kubono S, Yamaguchi H, Binh D N, Chen A A, Cherubini S, Hayakawa S, He J J, Ishiyama H, Iwasaki H, Kato S, Kishida T, Kim A, Kim D H, Kim M J, Kubono S, Kwag M S, Liang J, Moon J Y, Nishimura S, Oka S, Park S Y, Psaltis A, Teranishi T, Ueno Y and Yang L 2018 AIP Conference Proceedings 1947 020003
[5] Artemov K P, Belyanin O P, Vetoshkin A L, Wolskj R, Golovkov M S, Gol’dberg V Z, Madeja M, Pankratov V V, Serikov A N, Timofeev V A, Shadrin V N and Szmidt J 1990 Sov. J. Nucl. Phys. 52 108
[6] Teranishi T, Kubono S, Shimoura S, Notani M, Yanagisawa Y, Michimasa S, Ue K, Iwasaki H, Kurokawa M, Satou Y, Morikawa T, Saito A, Baba H, Lee J H, Lee C S, Fülop Z and Kato S 2003 Phys. Lett. B 556 27–32
[7] Teranishi T, Kubono S, Yamaguchi H, He J J, Saito A, Fujikawa H, Amadio G, Nishimura S, Shimosono S, Wakabayashi Y, Nishimura M, Moon J Y, Lee C S, Odahara A, Sohler D, Khiem L H, Li Z H, Lian G and Liu W P 2007 Phys. Lett. B 650 129–134
[8] He J J, Kubono S, Teranishi T, Notani M, Baba H, Nishimura S, Moon J Y, Nishimura M, Iwasaki H, Yanagisawa Y, Hokiwa N, Kibe M, Lee J H, Kato S, Gono Y and Lee C S 2007 Phys. Rev. C 76 055802
[9] Yamaguchi H, Wakabayashi Y, Kubono S, Amadio G, Fujikawa H, Teranishi T, Saito A, He J, Nishimura S, Tanog Y, Kwon Y, Nishimura M, Iwasaki H, Kishida T, Kato S, Kishida T, Kim A, Kim D H, Kim M J, Kubono S, Kwag M S, Liang J, Moon J Y, Nishimura S, Oka S, Park S Y, Psaltis A, Teranishi T, Ueno Y and Yang L 2018 AIP Conference Proceedings 1947 020003
[10] Yamaguchi H, Kahl D, Kawabata Y, Kubono S, Amadio G, Fujikawa H, Teranishi T, Saito A, He J, Nishimura S, Tanog Y, Kwon Y, Nishimura M, Iwasaki H, Kishida T, Kato S, Kishida T, Kim A, Kim D H, Kim M J, Kubono S, Kwag M S, Liang J, Moon J Y, Nishimura S, Oka S, Park S Y, Psaltis A, Teranishi T, Ueno Y and Yang L 2018 AIP Conference Proceedings 1947 020003
[11] Yamaguchi H, Hashimoto T, Hayakawa S, Binh D N, Kahl D, Kubono S, Wakabayashi Y, Kawabata T and Teranishi T 2011 Phys. Rev. C 83 034306
[12] Jung H S, Lee C S, Kwon Y K, Moon J Y, Lee J H, Yoon C C, Kubono S, Yamaguchi H, Hashimoto T, Kahl D, Hayakawa S, Choi S, Kim J M, Kim Y H, Kim Y, Park J S, Kim E J, Moon C B, Teranishi T, Wakabayashi Y, Iwasaki H, Yoon C, Kubono S, Tanog Y, Kwon Y, Nishimura S, Iwasaki H, Kishida T, Kato S, Kishida T, Kim A, Kim D H, Kim M J, Kubono S, Kwag M S, Liang J, Moon J Y, Nishimura S, Oka S, Park S Y, Psaltis A, Teranishi T, Ueno Y and Yang L 2018 AIP Conference Proceedings 1947 020003
[13] Jung H S, Lee C S, Kwon Y K, Moon J Y, Lee J H, Yoon C C, Kubono S, Yamaguchi H, Hashimoto T, Kahl D, Hayakawa S, Choi S, Kim J M, Kim Y H, Kim Y, Park J S, Kim E J, Moon C B, Teranishi T, Wakabayashi Y, Iwasaki H, Yoon C, Kubono S, Tanog Y, Kwon Y, Nishimura S, Iwasaki H, Kishida T, Kato S, Kishida T, Kim A, Kim D H, Kim M J, Kubono S, Kwag M S, Liang J, Moon J Y, Nishimura S, Oka S, Park S Y, Psaltis A, Teranishi T, Ueno Y and Yang L 2018 AIP Conference Proceedings 1947 020003
[14] Yamaguchi H, Khali D, Kahl D, Yamaguchi H, Kubono S, Hashimoto T, Hayakawa S, Kawabata T, Iwasaki H, Kishida T, Kato S, Kishida T, Kim A, Kim D H, Kim M J, Kubono S, Kwag M S, Liang J, Moon J Y, Nishimura S, Oka S, Park S Y, Psaltis A, Teranishi T, Ueno Y and Yang L 2018 AIP Conference Proceedings 1947 020003
[15] Yamaguchi H, Kahl D, Hashimoto T, Kubono S, Teranishi T, Notani M, Baba H, Nishimura S, Moon J Y, Nishimura M, Iwasaki H, Yanagisawa Y, Hokiwa N, Kibe M, Lee J H, Kato S, Gono Y and Lee C S 2007 Phys. Rev. C 76 055802
[16] Yamaguchi H, Wakabayashi Y, Kubono S, Amadio G, Fujikawa H, Teranishi T, Saito A, He J, Nishimura S, Tanog Y, Kwon Y, Nishimura M, Iwasaki H, Kishida T, Kato S, Kishida T, Kim A, Kim D H, Kim M J, Kubono S, Kwag M S, Liang J, Moon J Y, Nishimura S, Oka S, Park S Y, Psaltis A, Teranishi T, Ueno Y and Yang L 2018 AIP Conference Proceedings 1947 020003
[20] Hayakawa S, Kubono S, Kahl D, Yamaguchi H, Binh D N, Hashimoto T, Wakabayashi Y, He J J, Iwasa N, Kato S, KomatsuBara T, Kwon Y K and Teranishi T 2016 Phys. Rev. C 93(6) 065802
[21] Hashimoto T, Ishiyama H, Ishikawa T, Kawamura T, Nakai K, Watanabe Y, Miyatake H, Tanaka M, Fuchi Y, Yoshikawa N, Jeong S, Katayama I, Nomura T, Furukawa T, MitsuoKsa N, Nishio K, Matsuda M, Ikekoe H, Fukuda T, Das S, Saha P, Mizoi Y, Komatsubara T, Yamaguchi M and Tagishi Y 2006 Nuclear Instruments and Methods in Physics Research Section A 556 339 – 349 ISSN 0168-9002
[22] Yamaguchi H, Kahl D, Hayakawa S, Sakaguchi Y, Abe K, Naka T, Suhara T, Iwasa N, Kim A, Kim D, Cha S, Kwag M, Lee J, Lee E, Chae K, Wakabayashi Y, Imai N, Kitamura T, Lee P, Moon J, Lee K, Akers C, Jung H, Duy N, Khien L and Lee C 2017 Phys. Lett. B 766 11–16 ISSN 0370-2693
[23] Kim D, Kim G, Park S, Kim A, Hahn K, Abe K, Beliuskina O, Hayakawa S, Imai N, Kitamura N, Sakaguchi Y, Yamaguchi H, Cha S, Chae K, Kwag M, Hong S, Lee E, Lee J, Lee E, Moon J, Bae S, Choi S, Kubono S, Panin V, Wakabayashi Y, Iwasa N, Kahl D and Chen A A 2018 Journal of the Korean Physical Society 73 265–270
[24] Guo B, Su J, Li Z H, Wang Y B, Yan S Q, Li Y J, Shi N C, Han Y L, Bai X Y, Chen Y S, Liu W P, Yamaguchi H, Binh D N, Hashimoto T, Hayakawa S, Kahl D, Kubono S, He J J, Hu J, Xu S W, Iwasa N, Kume N and Li Z H 2013 Phys. Rev. C 87(1) 015803
[25] Baur G 1986 Physics Letters B 178 135–138 ISSN 0370-2693
[26] Cherubini S, Kondratyev V N, Lattuada M, Spitaleri C, Miljanic D, Zadro M and Baur G 1996 Astrophys. J. 457 855
[27] Spitaleri C, Lamia L, Tumino A, Pizzone R G, Cherubini S, Del Zoppo A, Figuera P, La Cognata M, Musumarra A, Pellegriti M G, Rinolf C, Romano S and Tuddisco S 2004 Phys. Rev. C 69(5) 055806
[28] Cherubini S, Gulino M, Spitaleri C, Rapisarda G G, La Cognata M, Lamia L, Pizzone R G, Romano S, Kubono S, Hayakawa H, Sakaguchi Y, Yamaguchi H, Iwasa N, Kato S, KomatsuBara T, Teranishi T, Cac O, de Sérèville N, Hammache F, Kiss G, Bishop S and Binh D N 2015 Phys. Rev. C 92(1) 015805
[29] Hayakawa S, Abe K, Beliuskina O, Cha S M, Chae K Y, Cherubini S, Figuera P, Ge Z, Gulino M, Hu J, Inoue A, Iwasa N, Kahl D, Kim A, Kim D H, Kiss G, Kubono S, Cognata M L, Commarra M L, Lamia L, Lattuada M, Lee J E, Moon J Y, Palmerini S, Parascandolo C, Park S Y, PierrotSakou D, Pizzone R G, Rapisarda G G, Romano S, Shimizu H, Spitaleri C, Tang X D, Trippella O, Tumino A, Vi P, Yamaguchi H, Yang L and Zhang N T 2018 AIP Conference Proceedings 1947 020011
[30] Mazocco M, Keeley N, Boiano A, Boiano C, La Commarra M, Manea C, Parascandolo C, Pierrotsakou D, Signorini C, Strano E, Torresi D, Yamaguchi H, Kahl D, Acosta L, Di Meo P, Fernandez-Garcia J P, Glodariu T, Greboz J, Guglielmetti A, Hirayama Y, Imai N, Ishiyama H, Iwasa N, Jeong S C, Jia H M, Kim Y H, Kimura S, Kubono S, La Rana G, Lin C J, Lotti P, Marquina-Durán G, Martell I, Miyatake H, Mukai M, Nakao T, Nicoletto M, Pakou A, Rusek K, Sakaguchi Y, Sánchez-Benítez A M, Sava T, Sgouros O, Soukertas V, Soramel F, Stiliaris E, Stroe L, Teranishi T, Tonioni L, Wakabayashi Y, Watanabe Y X, Yang L, Yang Y Y and Zhang H Q 2019 Phys. Rev. C 100(2) 024602
[31] Ma N R, Yang L, Lin C J, Yamaguchi H, Wang D X, Sun L J, Mazocco M, Jia H M, Hayakawa S, Kahl D, Cha S M, Zhang G X, Yang F, Yang Y Y, Signorini C, Sakaguchi Y, Abe K, La Commarra M, Pierrotsakou D, Parascandolo C, Strano E, Kim A, Chae K Y, Kwag M S, Zhang G L, Fan M, Xu X X, Wen P W, Zhong F P, Sun H H and Guo G 2019 The European Physical Journal A 55 87 ISSN 1434-601X
[32] Morinaga H 1956 Phys. Rev. 101(1) 254–258
[33] Suhara T and Kanada-En’yo Y 2010 Phys. Rev. C 82(4) 044301
[34] Suhara T and En’yo Y K 2011 Phys. Rev. C 84(2) 024328
[35] Baba T and Kimura M 2017 Phys. Rev. C 95(6) 064318
[36] Beer C E, Laird A M, Murphy A S J, Bentley M A, Buchman L, Davids B, Davinson T, Diget C A, Fox S P, Fulton B R, Hager U, Howell D, Martin L, Ruiz C, Ruprecht G, Salter P, Vockenhuber C and Walden P 2011 Phys. Rev. C 83(4) 042801