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Experimental study of the ^{9}Li breakup reaction on Pb target

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Abstract The breakup reaction of ^{9}Li on a Pb target has been measured at 32.7 MeV/nucleon for the first time. Two peaks of ^{6}He + t coincident fragments at 9.8 and 12.5 MeV were observed and agreed with the results of the generator coordinate method calculation. The experiment was carried out thanks to a specially arranged detection system around zero degrees at the Heavy Ion Research Facility in Lanzhou, Radioactive Ion Beam Line in Lanzhou (HIRFL–RIBLL).

Keywords Breakup reaction · Nuclear cluster states · Invariant mass method

Dedicated to Joseph B. Natowitz in honour of his 80th birthday

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1 Introduction

In recent years, with the development of RIB facilities, a large number of weakly bound nuclei are produced and have been extensively studied. Breakup reaction processes of weakly bound nuclei are important in the spectroscopy since the observables in the breakup reactions are strongly correlated to the microscopic structures of the ground and continuum states of weakly bound nuclei. These breakup reactions of weakly bound nuclei play important roles in researching the cluster resonance structure. Elucidating the mechanism of clustering in nuclei is of fundamental importance not only for nuclear many-body dynamics, but also for understanding some key processes in nuclear astrophysics [1]. The interest in nuclear clustering has been pushed strongly due to the study of neutron-rich and exotic weakly bound nuclei [2]. Many theoretical and experimental studies have been devoted to the cluster structure in nuclei in the past decades [3–9]. The missing mass method and invariant mass method can be applied to determine the excitation energy in the breakup reaction process. Several experimental studies of light nuclear clustering at HIRFL–RIBLL were performed. The RIBLL has been constructed at HIRFL and has been in operation since 1998. Consisting of four dipoles and sixteen quadrupoles, RIBLL is designed as a double-achromatic anti-symmetry separator with three focal points (F0, F2, and F4) and two focal planes (F1 and F3). RIBLL is a projectile fragmentation (PF) type facility with a large momentum acceptance and solid angle [10, 11]. In a representative example carried out at HIRFL–RIBLL, new resonances close to the respective cluster separation thresholds were observed in ^{12}Be for the ^{4}He $+^8$ He and ^{6}He $+^6$ He decay channels based on an inelastic excitation experiment performed with a ^{12}Be beam at 29 MeV/u on a carbon target [12, 13]. The strong clustering in ^{12}Be with 0^+ state at 10.3 MeV is well demonstrated by using the model-independent angular correlation analysis and the extracted largely enhanced monopole transition matrix element of $7.0 \pm 1.0\,\mathrm{fm}^2$ for this state.

For the neutron-rich nucleus, ^{9}Li, many theoretical descriptions of the cluster structures have been studied, but experimental investigations are scarce. The cluster structures of ^{6}He + t, α + t + 2n, and t + t + t in excited states of ^{9}Li were predicted by references [14–19]. In 1968, Ikeda et al. proposed a threshold rule for cluster formation, which suggests appearances of developed cluster states near the corresponding threshold energy [20]. They speculated that at the vicinity of an energy threshold for cluster separation, the nucleus tends to expand its size and favor the cluster formation in consequence [21]. From the point of view of Ikeda's threshold rule, excitation energies of developed two-body cluster states in neutron-rich nuclei can be understood systematically. The possible appearance of ^{6}He + t cluster states near the ^{6}He + t threshold energy in excited states of ^{9}Li can be expected [17]. To describe various cluster and shell structures that may appear in the ground and excited states of light nuclei, studies of Suhara et al. [15] show that, in the prolate region along the $\gamma = 0°$ line, two-body cluster structures or linear-chainlike structures develop well as the deformation parameter, β, becomes large. They show a ^{6}He + t cluster configuration when $(\beta \cos\gamma, \beta \sin\gamma) = (1.03, 0.04)$.

The present experiment was carried out thanks to a specially arranged detection system around zero degrees at HIRFL–RIBLL to observe the cluster structures in ^{9}Li through analyzing the coincident breakup fragments.

2 Description of the experiment

The primary beam is ^{12}C of 53.7 MeV/u delivered by the HIRFL. The RIBs were produced by bombarding the production target, Be with a thickness of 3038 μm, and analyzed and delivered to the secondary reaction chamber at the second focal point by RIBLL. We obtained a 32.7 MeV/nucleon secondary ^{9}Li beam with an intensity of about 1.1×10^3 particles per second and a purity of about 99%. The beam particle identification was realized event by event using the measured time-of-flight (TOF) and energy loss (ΔE) values (see Fig. 1). The Pb target was a self-supported foil with a thickness of $526.9\,\mathrm{mg/cm}^2$.

In Fig. 2, a schematic view of the detector setup is given. Three position-sensitive parallel-plate avalanche counters (PPACs) [22] provided the position of the incoming beams with a position resolution better than 1 mm. Each PPAC had 51 gold-plated tungsten wires in both X and Y directions and a sensitive area of 50 × 50 mm. We successively placed the PPAC1, PPAC2, and PPAC3 at 1207, 817, and 112 mm before the target. The position and incident angle of the beam particles at the target were determined by extrapolating the position information provided by PPACs event by event. A telescope consisted of two detectors and an E detector covering the angles 0°–10°. The two detectors are double-sided silicon strip detectors (DSSDs) with a thickness of 523 μm for the DSSD1 and 527 μm for the DSSD2 and a sensitive area of 49 × 49 mm, which is divided into 16 strips with the width of 3 mm and the interval of 0.1 mm between each two of them in each side. These two DSSDs were also applied to determine the position of the outgoing particles with a position resolution better than 3 mm. The E detector is a CsI(Tl) scintillator array, which is composed of 8 × 8 CsI(Tl) crystals [23]. The active area of each scintillator unit is $21 \times 21\,\mathrm{mm}^2$ for the front side and $23 \times 23\,\mathrm{mm}^2$ for the back side; the length of each crystal is 5 cm. The DSSD1, DSSD2, and scintillator were successively placed at 40, 133, and 583 mm behind the target. A typical particle identification is given in Fig. 3 where ΔE is the energy

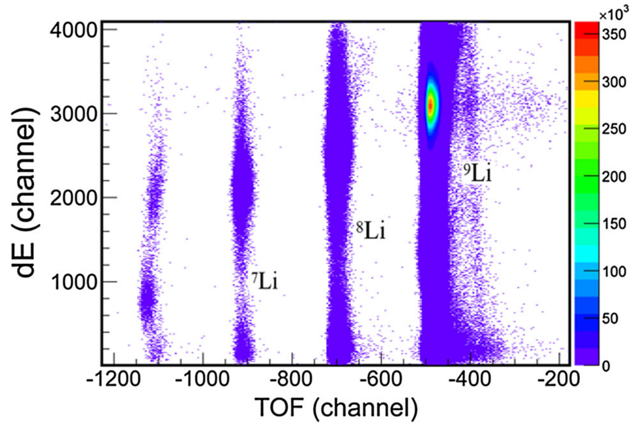

Fig. 1 (Color online) ΔE–TOF spectrum for identifying particles of the secondary beam

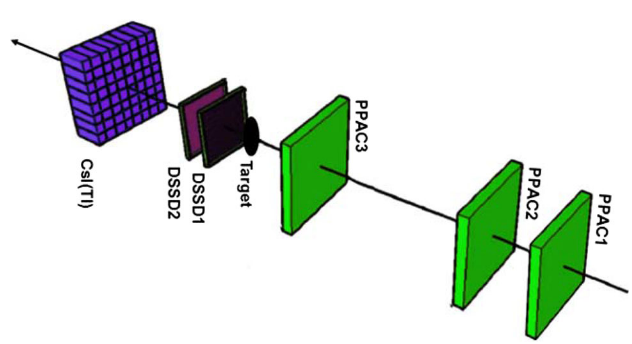

Fig. 2 (Color online) Schematic view of the detector setup; see text for details

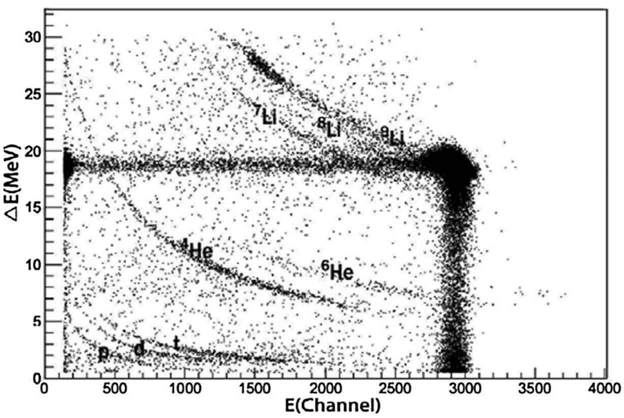

Fig. 3 (Color online) A typical particle identification spectrum obtained in the telescope array. The shown nuclei p (proton), d (deuton), t (triton), ^{8}Li, ^{7}Li, ^{6}He, and α are the breakup fragments from ^{9}Li on Pb target

loss of particles in the detector DSSD2 and E is the residue energy deposited in the CsI(Tl) crystal. A clear separation of different nuclei is obtained. The shown nuclei p, d, t, α, ^{6}He, ^{7}Li, and ^{8}Li, are the breakup fragments from ^{9}Li on the Pb target. In our present investigation, we mainly take into account the two fragments recorded in coincidence. We applied the recorded positions by the detectors (PPACs, DSSDs, and CsI(Tl)) to reconstruct the tracks of the two charged fragments from the ^{9}Li breakup reaction on the Pb target. Energy calibrations of the telescope were achieved using beams of ^{9}Li, ^{6}He, ^{4}He, and ^{3}H produced from the ^{12}C primary beam. The energy resolutions are about 65 keV for DSSD1 and 47 keV for DSSD2 measured with a single-component (^{241}Am) and a three-component (^{241}Am $-^{238}$ Pu $-^{239}$ Pu) alpha source. The estimated energy resolution of the CsI scintillators is 7–8% determined with a three-component (^{239}Pu $-^{241}$ Am $-^{244}$ Cm) alpha source. For a proton beam at the energy of 15 MeV, the resolution is 2.6%. A description of this kind of telescope array can be found in Refs. [24, 25].

In the present work, the relative energy (E_{rel}) of a pair of fragments was reconstructed from their kinetic energies (T_1, T_2) and the opening angle (θ_{12}). According to the invariant mass method, the excitation energy of a resonance state is expressed as [26]

$$\begin{aligned} M^2 &= \sum_{i=1,2}(E_i^2 + \overrightarrow{\mathrm{P}}_i^2) \\ &= M_1^2 + M_2^2 + 2(M_1+T_1)(M_2+T_2) \\ &\quad - 2\sqrt{(T_1^2+2M_1T_1)(T_2^2+2M_2T_2)}\cos(\theta_{12}), \\ E_{\mathrm{x}} &= M - M_0, \\ E_{\mathrm{rel}} &= E_{\mathrm{x}} - E_{\mathrm{thres}}, \end{aligned} \tag{1}$$

where M_0 is the rest mass of projectile; E_{thres} is the threshold energy of the corresponding decay; E_i and $\overrightarrow{\mathrm{P}}_i$ are the energy and momentum of the fragment, i, respectively; E_{x} is the excitation energy. The reconstructed excitation energy of ^{6}He + t decay is shown in Fig. 5.

Through analyzing the telescope array, the coincident charged particles ^{6}He and t were identified and investigated. To estimate the resolution of the E_{rel} and the detection efficiency (acceptance) for these ^{6}He+t events, the Monte Carlo simulation was performed considering the energy and spacial resolutions of the detectors. The simulation is plotted in Fig. 4a, b. Where, the detection efficiency (peak at 37%) for the ^{6}He + t channel is shown in Fig. 4a. The drop down of distribution of the detection efficiency in case of small relative energies is due to the ineffectiveness of the coincident measurement for ^{6}He + t fragments, which enter into the same unit of the DSSDs or CsI(Tl) scintillator; the slow decrease of that (distribution of the detection efficiency) in case of large relative energies is due to one or both of coincident fragments may escape from the detector array with appreciable probabilities. As shown in the Fig. 4b, the simulated resolution of

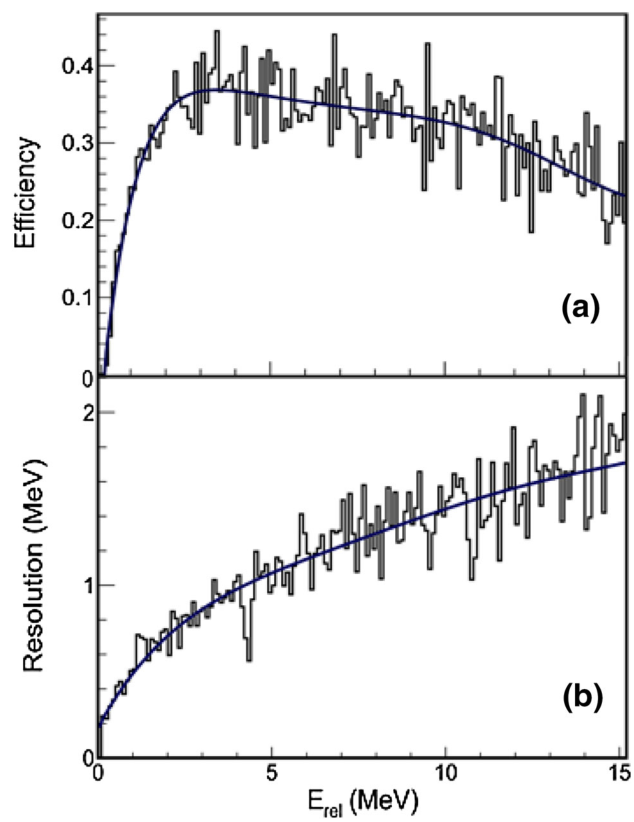

Fig. 4 (Color online) The detection efficiency (**a**) and the resolution of the E_{rel} (**b**) for the ^{6}He + t events produced by the Monte Carlo simulation

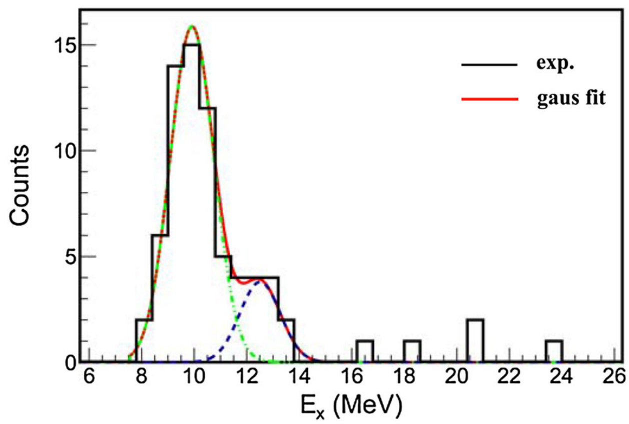

Fig. 5 The E_x spectrum with Gaussian function fitting for ^{9}Li, reconstructed from the ^{6}He + t coincident fragments

the E_{rel} is about 0.8 MeV at an E_{rel} of 2.5 MeV and increases to 1.1 MeV at an E_{rel} of 5.0 MeV.

3 Results and discussion

In the present experimental study of a ^{9}Li breakup reaction on Pb target, we reconstructed the excitation energy spectrum of ^{6}He + t decay. As displayed in Fig. 5, two resonance peaks just above the threshold energy (7.588 MeV) were obtained. We made a double-Gaussian function fitting and got the peaks at 9.8 MeV for the first and 12.5 MeV for the second. The GCM calculation for ^{6}He + t cluster states in ^{9}Li in Ref. [17] suggests that the energies of the third $3/2^-$ and the second $1/2^-$ states with relative orbital angular momentum $L = 1$ lie within the range of the first peak at around 9.8 MeV, and those of the second $5/2^-$ and $7/2^-$ states with $L = 3$ lie within the range of the second peak at around 12.5 MeV. The experimental values are slightly larger than the theoretical ones. However, it can be considered that the obtained values reproduce the data fairly well. Based on the present experimental analysis and the theoretical predictions, the picture of ^{6}He + t clustering just above the ^{6}He + t threshold energy in ^{9}Li might be supported. With considering the detection efficiency of the ΔE–E telescope and the effective incident beam particles at a target determined by extrapolating the position information provided by PPACs event by event, the experimental breakup cross section was deduced to be 1.5 ± 0.3 (stat.) mb for ^{6}He + t decaying channel.

4 Summary

In summary, the experiment of the ^{9}Li breakup reaction on a Pb target was carried out thanks to a specially arranged ΔE–E telescope system around zero degrees at the HIRFL–RIBLL. The breakup fragments p, d, t, ^{8}Li, ^{7}Li, ^{6}He, and α were identified by the ΔE–E telescope. Combining the analysis of tracks of the two charged fragments, coincident charged particles, ^{6}He and t, were identified and investigated. The excitation energy of ^{6}He + t decay was reconstructed by using the invariant mass method. Two resonant energies at 9.8 and 12.5 MeV were observed, which agree with the GCM calculations. The present experimental analysis and the theoretical predictions might support the appearance of ^{6}He + t cluster states in ^{9}Li.

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References

1. M. Chernykh, H. Feldmeier, T. Neff et al., Structure of the Hoyle State in ^{12}C. Phys. Rev. Lett. **98**, 032501 (2007). https://doi.org/10.1103/PhysRevLett.98.032501
2. W. von Oertzen, M. Freer, Y. Kanada-En'yo, Nuclear clusters and nuclear molecules. Phys. Rep. **432**, 43–113 (2006). https://doi.org/10.1016/j.physrep.2006.07.001
3. M. Ito, N. Itagaki, H. Sakurai et al., Coexistence of covalent superdeformation and molecular resonances in an unbound region of ^{12}Be. Phys. Rev. Lett. **100**, 182502 (2008). https://doi.org/10.1103/PhysRevLett.100.182502
4. N. Soić, S. Blagus, M. Bogovac, et al. ^{6}He + alpha clustering in ^{10}Be. Europhys. Lett., **34**: 7–12 (1996). https://doi.org/10.1209/epl/i1996-00407-y
5. J.A. Liendo, N. Curtis, D.D. Caussyn et al., Near threshold three-body final states in ^{7}Li+^{7}Li reactions at E_{lab} = 34 MeV. Phys. Rev. C **65**, 034317 (2002). https://doi.org/10.1103/PhysRevC.65.034317
6. M. Milin, M. Zadro, S. Cherubini et al., Sequential decay reactions induced by a 18 MeV ^{6}He beam on ^{6}Li and ^{7}Li. Nucl. Phys. A **753**, 263–287 (2005). https://doi.org/10.1016/j.nuclphysa.2005.02.154
7. M. Freer, E. Casarejos, L. Achouri et al., α:2n:α Molecular band in ^{10}Be. Phys. Rev. Lett. **96**, 042501 (2006). https://doi.org/10.1103/PhysRevLett.96.042501
8. M. Freer, J.C. Angélique, L. Axelsson et al., Exotic molecular states in ^{12}Be. Phys. Rev. Lett. **82**, 1383–1386 (1999). https://doi.org/10.1103/PhysRevLett.82.1383
9. M. Freer, J.C. Angélique, L. Axelsson et al., Helium breakup states in ^{10}Be and ^{12}Be. Phys. Rev. C **63**, 034301 (2001). https://doi.org/10.1103/PhysRevC.63.034301
10. Z. Sun, W. Zhan, Z. Guo et al., Separation and identification of isotopes produced from ^{20}Ne+Be reaction by radioactive ion beam line in Lanzhou. Chin. Phys. Lett. **15**, 790 (1998). https://doi.org/10.1088/0256-307X/15/11/004
11. Z. Sun, W.-L. Zhan, Z.-Y. Guo et al., RIBLL, the radioactive ion beam line in Lanzhou. Nucl. Instrum. Methods A **503**, 496 (2003). https://doi.org/10.1016/S0168-9002(03)01005-2
12. Z.H. Yang, Y.L. Ye, Z.H. Li et al., Observation of enhanced monopole strength and clustering in ^{12}Be. Phys. Rev. Lett. **112**, 162501 (2014). https://doi.org/10.1103/PhysRevLett.112.162501
13. Z.H. Yang, Y.L. Ye, Z.H. Li et al., Helium–helium clustering states in ^{12}Be. Phys. Rev. C **91**, 024304 (2015). https://doi.org/10.1103/PhysRevC.91.024304

14. K. Arai, Y. Ogawa, Y. Suzuki et al., Microscopic multicluster description of light exotic nuclei with stochastic variational method on correlated gaussians. Prog. Theor. Phys. Suppl. **142**, 97–156 (2001). https://doi.org/10.1143/PTPS.142.97
15. T. Suhara, Y. Kanada-En'yo, Quadrupole deformation β and γ constraint in a framework of antisymmetrized molecular dynamics. Prog. Theor. Phys. **123**, 303–325 (2010). https://doi.org/10.1143/PTP.123.303
16. K. Muta, T. Furumoto, T. Ichikawa et al., Three triton states in ^{9}Li. Phys. Rev. C **84**, 034305 (2011). https://doi.org/10.1103/PhysRevC.84.034305
17. Y. Kanada-En'yo, T. Suhara, ^{6}He-triton cluster states in ^{9}Li. Phys. Rev. C **85**, 024303 (2012). https://doi.org/10.1103/PhysRevC.85.024303
18. T. Furumoto, T. Suhara, N. Itagaki, Investigation of the $3/2_2^-$ state of ^{9}Li with microscopic structure and reaction models. Phys. Rev. C **87**, 064320 (2013). https://doi.org/10.1103/PhysRevC.87.064320
19. Y. Kanada-En'yo, Monopole transitions to cluster states in ^{10}Be and ^{9}Li. Phys. Rev. C **94**, 024326 (2016). https://doi.org/10.1103/PhysRevC.94.024326
20. K. Ikeda, N. Takigawa, H. Horiuchi, The systematic structure-change into the molecule-like structures in the self-conjugate 4n nuclei. Prog. Theor. Phys. Suppl. **E68**, 464–475 (1968). https://doi.org/10.1143/PTPS.E68.464
21. K. Ikeda, H. Horiuchi, Chapter I. Introduction to comprehensive nuclear structure study based on cluster correlations and molecular viewpoint. Prog. Theor. Phys. Suppl. **68**, 1–28 (1980). https://doi.org/10.1143/PTPS.68.1
22. P. Ma, C.G. Lu, J.S. Wang et al., Capability of PPAC in investigation of resonant properties in ^{18}Ne via ^{17}F+p. Atomic Energy Sci. Technol. **45**(3), 356–359 (2011). (in Chinese)
23. X.W. Yao, Y.Y. Yang, J.S. Wang et al., Development of 8×8 CsI(Tl) array detector. Atomic Energy Sci. Technol. **44**(3), 358–361 (2010). (in Chinese)
24. S.L. Jin, J.S. Wang, Y.Y. Yang et al., A Δ-E telescope array for radioactive beam experiments. Nucl. Instrum. Methods Phys. Res. Sect. B **317**, 728–730 (2013). https://doi.org/10.1016/j.nimb.2013.07.044
25. S.L. Jin, J.S. Wang, M. Wang et al., Application of ΔE-E telescope in ^{9}C fragmentation reaction. Atomic Energy Sci. Technol. **46**, 385–389 (2012). (in Chinese)
26. Z.X. Cao, Y.L. Ye, J. Xiao et al., Recoil proton tagged knockout reaction for ^{8}He. Phys. Lett. B **707**, 46–51 (2012). https://doi.org/10.1016/j.physletb.2011.12.009