^{9}Be + p breakup at 5.67A MeV in a full kinematics approach

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The exclusive breakup of the Borromean nucleus ^{9}Be incident on a proton target at 5.67 MeV/nucleon was studied with a triple coincidence requirement between the two breakup α fragments and the recoiling proton. The analysis was performed using an event-by-event code in a full kinematics approach, and Q-value spectra, relative spectra, and energy spectra of all reaction products were determined. Clear signatures of the three breakup modes: $\alpha + \alpha + n$, ^{8}Be $+ n$, and ^{5}He $+$ ^{4}He were observed in the recoiling proton spectra and the rates of these modes were quantified.

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I. INTRODUCTION

In mathematics the topology of the Borromean rings is found in knot theory as a Brunnian link, a nontrivial link that becomes a set of trivial unlinked circles if any one component is removed. In fact no two loops can be directly linked. In a typical picture the Borromean rings look like geometrically ideal circular objects, but it is well established that they cannot be so [1]. Although the symbol of three interlocked rings goes back to early Christian iconography and Norse mythology, its proliferation in crests and statues adopted in the 15th century by the Italian Borromeo family established its etymology. The realization of a Borromean rings assembly from DNA was reported in 1997 by biologists Chengde Mao and coworkers [2]. In molecular physics, in 2003 the chemist Fraser Stoddart and coworkers utilized coordination chemistry to construct a set of rings in one step from 18 components [3]. In nuclear physics the quantum-mechanical analog of the Borromean rings is a halo or Efimov state, predicted in 1970 [4].

Among the most interesting weakly bound nuclei a prominent position, with severe consequences for nuclear structure, nuclear dynamics, and nuclear astrophysics, is taken by the Borromean nuclei exhibiting neutron halos. The lightest radioactive Borromean nucleus is ^{6}He [5] and the heaviest is ^{22}C [6]. On the other hand, there is only one stable weakly bound Borromean nucleus, ^{9}Be, bound only in its ground state with a binding energy of 1.57 MeV below the $\alpha + \alpha + n$ threshold. All its excited states lie above the three-body threshold, validating its Borromean nature. ^{9}Be attracts a vivid interest due to its role in astrophysical problems and clustering theories. In fact, the strength of any three-body $\alpha + \alpha + n$ clustering and the two-body ^{8}Be $+ n$ and ^{5}He $+$ ^{4}He cluster configurations has received renewed attention, since it is believed that in neutron-rich astrophysical environments, such as core-collapse supernovae, the three-body $\alpha + \alpha + n \rightarrow$ ^{9}Be reaction followed by ^{9}Be(α, n) ^{12}C may provide a route for building up the heavy elements and triggering the r-process [7–12]. The point which should be underlined here is that such calculations are hampered by a severe lack of experimental information on the partial widths of the various channels. This is also emphasized in Refs. [11,13]. In most of the calculations, and we mention here only the NACRE

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compilation [14] and the work of Sumiyoshi *et al.* [13], the rate of the $\alpha(\alpha n,\gamma)$ ^{9}Be reaction, which is finally followed by the ^{9}Be(α, n) ^{12}C one, does not include the $5/2^-$ state of ^{9}Be. While for the other low-lying resonances in ^{9}Be ($1/2^+$, $1/2^-$, $5/2^+$) their $n+$ ^{8}Be character is well known, for the $5/2^-$ resonance at 2.43 MeV the question of its $n+$ ^{8}Be and/or ^{5}He + ^{4}He character remains in dispute. The $5/2^-$ state with $\Gamma = 0.77 \pm 0.15$ keV lies at $E_x = 2.4294$ MeV ± 1.3 keV below the ^{5}He + ^{4}He threshold energy (2.467 MeV). However, since the ground state of ^{5}He has a large width (0.60 ± 0.02 MeV) [15], the state can decay into the low-energy tail of the ground state. In this respect Buchmann *et al.* [16] recalculated the rate including the ^{5}He $+\alpha$ and ^{8}Be$(2^+) + n$ channels, suggesting the important role of the former configuration, after experimental evidence in this direction by Gete *et al.* [17] following a recent measurement of ^{9}C β decay. A strong ^{5}He $+\alpha$ decay breakup channel was later reported but not quantified in Refs. [18,19]. This evidence was subsequently contradicted in Refs. [20–22] by breakup studies of ^{9}Be on the following targets: ^{6}Li, ^{12}C, and ^{208}Pb. On the other hand, a more recent transfer measurement speaks again for a substantial ^{5}He + ^{4}He contribution [23]. More insight into these processes may be found in Ref. [24]. Calculations by Buchmann *et al.* resulted in a reaction rate that is one order of magnitude smaller than through the $n+$ ^{8}Be channel, at least for higher energies $T_9 \geqslant 2$. Such differences can have a tremendous impact on the r-process nucleosynthesis yields. As outlined by Kajino *et al.* [25] (Fig. 3 in this reference) variations of the order of 2 in the reaction rates can lead to drastic changes in the $A \approx 195$ abundance peak.

^{9}Be is also an excellent example of a nucleus that may be described by clustering theories [26,27] or microscopic cluster theories [28,29]. States in nuclei based on α particles and other strongly bound substructures with $N = Z$ are typically not found in ground states but are observed as excited states close to the cluster decay thresholds, as was suggested in 1968 by Ikeda [30]. It has become evident that additional valence neutrons do not destroy these structures, instead interesting nuclear structures described by molecular concepts can emerge. For example, ^{9}Be may be considered as composed of two α particles and a valence neutron, forming at larger $\alpha + \alpha$ separations a ^{5}He nucleus where the neutron resides in a $p_{3/2}$ orbital. The linear combinations of two such orbitals give rise to nuclear molecular σ and π bonds in ^{9}Be.

The above theories in either astrophysics or nuclear structure require the determination of the decay rates of ^{9}Be to the three configurations: $\alpha + \alpha + n$, ^{8}Be $+n$, ^{5}He $+\alpha$. While the breakup of ^{9}Be via the ^{8}Be$_{\text{g.s.}}$ has been measured for many of the low-lying excited states of ^{9}Be and is well established, the breakup branching of the 2.43-MeV resonance via the first-excited 2^+ state of ^{8}Be and ^{5}He + ^{4}He remains uncertain, while no attention has been given to the direct $\alpha + \alpha + n$ three-body breakup. All β-decay measurements [17–19,23,31,32] agree that the ^{5}He + ^{4}He mode is a strong one for the breakup decay of the 2.43 MeV state but give different percentage rates for the two modes: ^{5}He + ^{4}He and ^{8}Be $+n$. On the other hand, inelastic excitation measurements with various heavy targets (^{6}Li, ^{12}C, ^{208}Pb) [20–22] give the ^{8}Be $+n$ mode as the predominant one with only a small contribution of the order of ≈6% or <5% from the ^{5}He + ^{4}He process.

In this context, in the present article we report an innovative exclusive breakup measurement employing inelastic scattering on the simplest and lightest target, the proton. It follows our previous breakup studies of the weakly bound ^{6,7}Li incident on proton targets [33,34]. The experiment was designed to excite the 2.43-MeV resonance of ^{9}Be and probe all three configurations: the $\alpha + \alpha + n$, the ^{8}Be$(2^+) + n$, and the ^{5}He $+\alpha$. The decay via ^{8}Be (g.s.) $+ n$ was out of the breakup cone of our setup and therefore not accessible. However, according to previous studies this decay is considered negligible [20–22] if the breakup decay occurs from the 2.43-MeV excited state of ^{9}Be, which is the case here. The advantage of the present experiment versus previous inelastic scattering measurements is based on an additional tool, the kinematics of the recoiling proton. While relative energy spectra are similar for the two decay modes by using a light target such as the proton and under specific experimental conditions we can obtain in principle differentiation of the two modes via the kinematics of the recoiling proton, although certain overlaps depending on angle can not be avoided. In what follows, Sec. II includes the experimental details, Sec. III the analysis of the data in a full kinematics approach with a short description of our simulation code, and, finally, in Sec. III we summarize our concluding remarks.

II. EXPERIMENTAL DETAILS

The experiment was performed at the MAGNEX facility [35] of the Istituto Nazionale di Fisica Nucleare Laboratori Nazionali del Sud (INFN-LNS) in Catania, Italy. A ^{9}Be^{4+} beam was accelerated to 51 MeV by the LNS TANDEM Van de Graaff accelerator and impinged on a 450-μg/cm^2 CH_2 target. The α particles were recorded in MAGNEX in triple coincidence mode with α particles acquired in the first stage of a telescope—a module of the EXotic PArticle DEtection System (EXPADES) array [36,37]—and with recoiling protons observed in the same telescope and discriminated via the ΔE-E technique. MAGNEX covered the angular range between 2.5° and 14° and was operated with full horizontal and vertical angular acceptance. The α fragments were momentum analyzed by MAGNEX and detected by the focal plane detector [38,39]. The ray reconstruction of their trajectories was performed offline according to Refs. [40–43]. Most of the elastically scattered ^{9}Be ions were swept out by appropriate magnetic fields, allowing the detection of αs in an energy slice between 15 and 25 MeV, corresponding, according to our simulations [44], to ≈70% of our energy phase space. The EXPADES module consisted of a double-sided silicon strip detector (DSSSD) ΔE and an E pad, each 300 μm thick, located between ≈4.5° and 34°. Both detectors, the pad and the DSSSD, had active areas of 64×64 mm^2, with the DSSSD having 32 strips per side, orthogonally oriented to define 2×2 mm^2 pixels. Details of how the detector signals were handled may be found in Ref. [36]. The EXPADES module was masked by a 49.6-μm-thick tantalum foil to prevent deterioration from Rutherford scattering. Due to losses in this

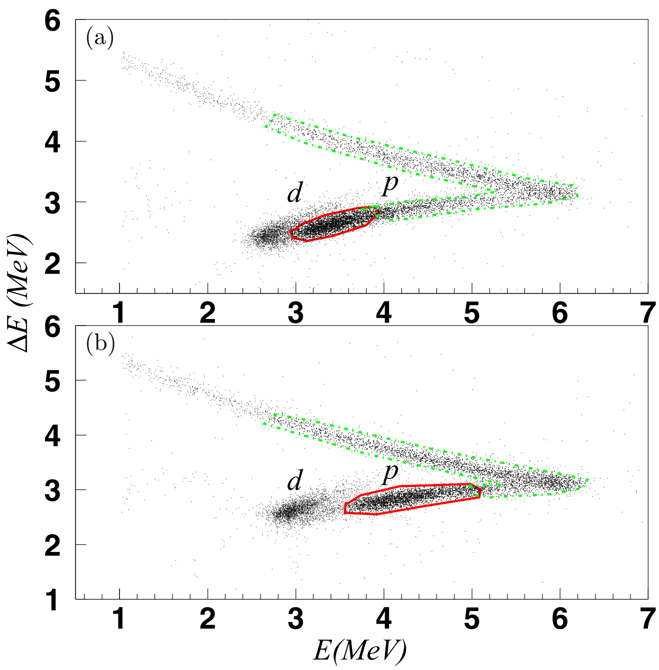

FIG. 1. ΔE-E spectrum obtained by the EXPADES module. (a) Strip 16, corresponding to $\theta_{\rm lab} = 14.6^\circ$, and (b) strip 8, corresponding to $\theta_{\rm lab} = 20.2^\circ$, in coincidence with MAGNEX. Both panels present part of the spectra zoomed on protons. Some punched through deuterons are also distinguished. Gates related to the ^{8}Be $+ n$ mode and the ^{5}He $+$ ^{4}He mode are defined by the solid (red) and dot-dashed (green) curves, respectively.

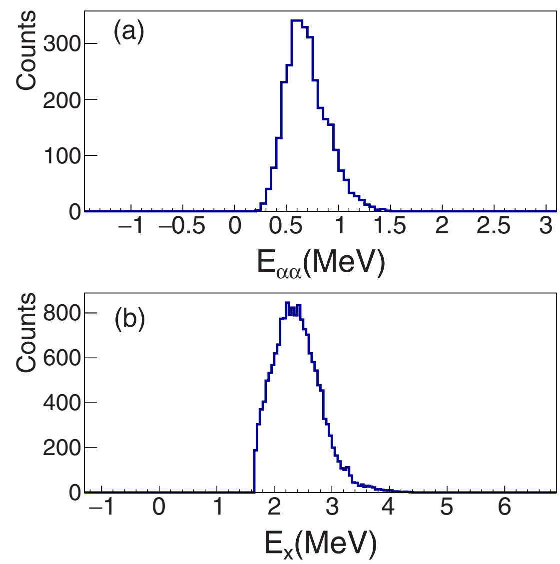

FIG. 2. (a) Reconstructed α-α relative energy spectrum with α-α-p triple coincidence event-by-event requirement. (b) Reconstructed excitation spectrum of ^{9}Be, see text.

foil as well as the thresholds of the silicon detectors, restrictions in the energy of α particles stopped in the first stage of the telescope, the restriction to an energy slice of α particles recorded in MAGNEX, and, finally, the triple coincidence requirement, the final phase space coverage was reduced to 15%. Protons were well discriminated from α particles and for most of the angles from deuterons originating from transfer reactions (^{9}Be $+ p \rightarrow$ ^{8}Be $+ d$). The $\alpha - \alpha$-proton triple coincidence requirement excluded all transfer events from the carbon included in the CH_2 target (^{9}Be $+$ ^{12}C $\rightarrow$ ^{8}Be $+$ ^{13}C).

III. DATA ANALYSIS

An event-by-event code was developed for the analysis and a search within the appropriate energy regions was performed, looking for α particles detected in MAGNEX in coincidence with α particles stopped in the ΔE detector, identified via kinematics and energy loss algorithms, and protons identified by the ΔE-E technique (Fig. 1) in the EXPADES telescope in triple coincidence mode. The proton gates related to each mode will be described later. The triple coincidence requirement gives clear evidence of a breakup event. When such an event was found, tagged by energy and angle (i.e., the momentum vector), the energy of the undetected neutron, E_n, was determined by applying the momentum conservation law. The total kinetic energy, $E_{\rm tot}$, and the Q value of the four-body reaction can then be reconstructed:

$$Q = E_{\alpha 1} + E_{\alpha 2} + E_n + E_p - E_{\rm beam} = E_{\rm tot} - E_{\rm beam}, \quad (1)$$

where $E_{\alpha 1}$ is the kinetic energy of the α particle detected in MAGNEX, $E_{\alpha 2}$ is the kinetic energy of the α particle detected in the first stage of the EXPADES telescope where it stops, E_n is the kinetic energy of the undetected neutron, E_p is the kinetic energy of the recoiling proton identified in EXPADES, and $E_{\rm beam}$ is the beam energy after crossing half of the target. Requesting only negative Q values for the breakup events, the relative energy between the two α particles in a triple coincidence requirement was determined and is presented in Fig. 2 (top), where there is an obvious peak at ≈650 keV. No peak appears at 92 keV, as expected, since our setup does not include the breakup cone due to feeding of the ^{8}Be(g.s.). According to Refs. [20–22,24,32] the observed peak may be attributed to breakup either through the broad excited state of ^{8}Be (2^+) at 3.030 MeV with width $\Gamma = 1.5$ MeV (here we observe the tail of this broad resonance) and/or the broad ground state of ^{5}He with width $\Gamma = 600$ keV. These states are populated by the decay of the excited state in ^{9}Be at 2.43 MeV, as can be seen from our reconstructed excitation spectrum, displayed in Fig. 2 (bottom).

The big challenging question now is as follows: To what extent are each of the two configurations involved in the breakup process? The main problem is that the energy shared between the three particles is small and the energy correlations between the decay particles are the same irrespective of the intermediate step in the decay. In one of the previous [20] studies of ^{9}Be breakup on a lithium target an attempt was made at separation by adopting in simulations the angular distribution of the breakup fragments. No firm answer was given in this case either, since the authors were only able to do it for the ^{8}Be case. The fact that their experimental energy and angular distributions were understood using the

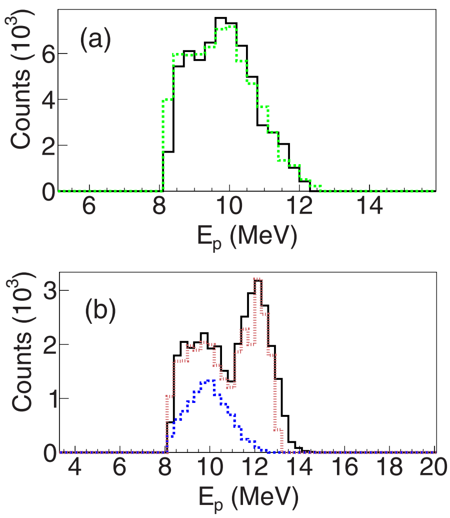

FIG. 3. Experimental energy spectrum of recoiling protons observed in the angular range 4.5° to 34°, obtained from our event-by-event code after corrections for energy losses in the tantalum foil and for punching through the second stage of the telescope. (a) Restricted to protons due to the ^{5}He + ^{4}He mode kinematics, determined via the code MULTIP. Example cuts for $\theta_{\rm lab} = 14.6^\circ$ and 20.2° adopted for this mode are designated in Fig. 1 by the dashed line (green). Data are designated with the solid line (black) while the simulation with the dashed line (green) (b) restricted to protons due to the ^{8}Be + n mode. Example cuts for $\theta_{\rm lab} = 14.6^\circ$ and 20.2° for this mode are designated in Fig. 1 by the solid line (red). The dashed line (blue) denotes our simulation for the ^{5}He mode in the specific angular range where a kinematical overlap between the two decay modes exists. The dotted curve (brown) is the sum of both simulations.

^{8}Be(2^+) + n channel alone is not in itself sufficient evidence that the ^{5}He + α channel does not contribute. On the other hand, under the appropriate experimental conditions of the present experiment, the recoil kinematics could serve for this separation and for the first time a clear signature of the two sequential modes and finally of the direct mode was obtained.

An inspection of Fig. 1 discloses this signature of the sequential breakup modes, denoted by the intense spots in the proton ΔE-E spectra, with the remainder coming from direct excitation to the continuum. For a full understanding of these spectra we have adapted our Monte Carlo code MULTIP, the principles of which are described in Ref. [44]. The program was extended to include the two sequential modes as well as the direct mode as described in this experiment. We briefly mention the following details, pertinent to the present work. In our code the continuum excitation is treated as a two-body-like reaction leading to ^{9}Be* + p. The energy bin associated with the excitation of ^{9}Be to its 2.43-MeV resonance is not defined via the width of the 2.43-MeV resonance itself, which is extremely narrow. It is defined through the width of the 2^+ excited state of ^{8}Be at ≈3 MeV, $\Gamma \approx 1.5$ MeV and the width of the ground state of ^{5}He, $\Gamma \approx 0.6$ MeV. The hint for the choice of the energy bins, expressed as the excitation energy of ^{9}Be, is given by the relative $E_{\alpha\alpha}$ spectrum, which peaks at ≈0.7 MeV. After the ^{9}Be* is excited it decays in its rest frame into $\alpha + \alpha + n$ for the direct mode or into ^{8}Be + n (^{5}He + ^{4}He) for the two sequential modes. Appropriate Galilean transformations and rotations are then applied for the transformation of the fragments' momenta from the ^{9}Be* rest frame to the laboratory frame. Finally, for the two sequential modes, the breakup of ^{8}Be (^{5}He) is considered in the rest frame of each nucleus followed by the appropriate transformation in order to evaluate the momenta of the fragments in the laboratory reference frame. It should be noted that for each energy bin in the direct breakup a flat angular distribution was adopted, while for the sequential decays both distributions of a preliminary Continuum Discretized Coupled-Channels (CDCC) calculation as well as flat distributions were adopted, leading to similar results. Differences between the two choices were included as uncertainty in the final determined rates.

Following the kinematics of the reaction through MULTIP, appropriate cuts under the specific conditions of the experiment were applied to each strip of the telescope (and therefore for each angle between 4.5° and 34°) for the ^{8}Be + n and ^{5}He + α configurations, denoted by the solid red and dot-dashed green curves in Fig. 1, respectively. We have assumed that the rest of the protons may be related to the direct three-body mode. The event-by-event reconstruction was therefore repeated three times: once with a contour around a region in the ΔE-E plot identified as originating from the ^{5}He + α mode—the dot-dashed green curve in the example spectra of Fig. 1; once with a contour around a region identified in the ΔE-E plot as originating from the ^{8}Be + n mode—the solid red curve of the example spectra of Fig. 1 and finally with a contour around all the protons. The proton spectra from our event-by-event code integrated over all angles between 4.5° to 34° for the first, second, and third cases are shown in Figs. 3 (top), 3 (bottom), and 4, respectively. It should be noted that at several angles protons punched through the second stage of the telescope and therefore corrections were applied in our event-by-event code to obtain the total accumulated energy, adopting the program LISE, based on the Ziegler stopping powers [45]. We also note that the peak of Fig. 3 top for ^{5}He + ^{4}He mode corresponds, according to our simulation, to the second kinematic solution with the lower energy of ^{5}He (due to inverse kinematics, for each angle of the intermediate nucleus, here the ^{5}He one, there correspond two solutions in energy). Of the two peaks in Fig. 3 (bottom), that at the higher energy corresponds to the second kinematic solution of the excited ^{8}Be and that at the lower energy partly to the first kinematic solution for ^{8}Be (with the higher energy) and partly to the second kinematic solution for ^{5}He.

To evaluate the contribution of each mode to the breakup, extensive simulations were performed with our code MULTIP [44]. For the sequential modes our simulation results are presented in Figs. 3 (top) and 3 (bottom), scaled according to the overall strength of the data and presenting an excellent description of them. These simulations, as scaled to the sequential mode data, are also presented in Fig. 4 together with our simulation of the direct part. The sum of all three simulations should represent the total breakup data and apparently does so excellently. Finally, the efficiencies for each mode were extracted by dividing the obtained simulated areas, restricted

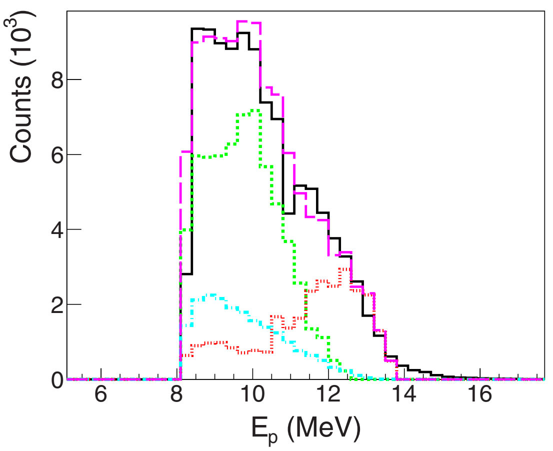

FIG. 4. Experimental energy spectrum of recoiling protons obtained by our event-by-event reconstruction code in a full kinematics approach, after corrections for punching through the second stage of the telescope. Protons were observed in the angular range 4.5° to 34°, including all protons (cuts were applied to each of the ΔE-E spectra). The simulations of each of the three modes are designated by dashed (green) and dotted (red) lines for the ^{5}He + ^{4}He and ^{8}Be + n sequential modes, respectively, and the dotted-dashed line (cyan) for the direct mode. Their sum is designated by the long dashed line (magenta) and is in excellent agreement with the data, represented by the solid line (black).

under the experimental conditions, by the unrestricted ones, and the rate of each process was determined as: 29 ± 8%, 22 ± 4%, and 49 ± 12% for the $\alpha + \alpha + n$, ^{8}Be + n, and ^{5}He + ^{4}He modes, respectively. The source of the assigned errors is related mainly to the adopted angular distributions in our simulations. These assumptions based to either flat or CDCC angular distributions resulted on slightly different efficiencies and slightly different gates for the two sequential modes on the ΔE-E proton spectra. Although the resulting uncertainties are large, especially for the ^{5}He + α mode, it is obvious that this mode is strong, a result which agrees qualitatively with the findings from β-decay experiments such as those of Gete *et al.* [17] and Prezado *et al.* [18] as well as Refs. [31,32]. It should be noted that our results exclude the observation of breakup decays via the ^{8}Be$_{\mathrm{g.s.}}$ due to the specific setup as well as decays via the 1.684-MeV excited state of ^{9}Be. In principle, decays via the 2.8-MeV state may be present and unresolved from events via the 2.43-MeV excited state of ^{9}Be (see Fig. 2). However, such events, if any, are expected to be few in number as the majority of breakup events go via the ^{5}He + α mode with $Q = -2.4$ MeV, and this mode is inaccessible with our beam energy of $E_{\mathrm{c.m.}} = 5.1$ MeV.

IV. CONCLUSIONS

In summary, we have studied the breakup of the Borromean nucleus ^{9}Be incident on a proton target at 5.67 MeV/nucleon in inverse kinematics. The data analysis was based on a triple coincidence full kinematics approach. A clear signature of the three breakup modes of ^{9}Be was tagged in our recoiling proton spectra. The three modes were quantified after applying efficiency corrections via a Monte Carlo simulation of our experimental system. It was found that the strongest contribution to breakup is via the ^{5}He + ^{4}He mode, quantified at 49%, while lesser contributions are due to the direct and the ^{8}Be + n modes. It was also verified that the breakup of ^{9}Be occurs after excitation to its 2.43-MeV state. Hopefully these results will make substantial impact in the fields of astrophysics and cluster structure as discussed in the introduction. The substantial contribution of the ^{5}He + ^{4}He breakup decay of the Borromean nucleus ^{9}Be found here should initiate new reaction rate calculations for the $\alpha(\alpha n, \gamma)$ ^{9}Be reaction similar to that reported by Buchmann *et al.* with the expected dramatic changes in the r-process nucleosynthesis yields.

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[1] M. H. Freedman and R. Skora, J. Diff. Geom. **25**, 75 (1987).
[2] C. Mao, W. Sun, Z. Shen, and N. C. Seeman, Nature **386**, 137 (1997).
[3] K. S. Chichak, S. J. Cantrill, A. R. Pease *et al.*, Science **304**, 1308 (2004).
[4] V. Efimov, Phys. Lett. B **33**, 563 (1970).
[5] I. Tanihata, T. Kobayashi, O. Yamakawa *et al.*, Phys. Lett. B **160**, 380 (1985).
[6] K. Tanaka, T. Yamaguchi, T. Suzuki *et al.*, Phys. Rev. Lett. **104**, 062701 (2010).
[7] S. E. Woosley and R. D. Hoffman, Astrophys. J. **395**, 202 (1992).
[8] B. S. Meyer, G. J. Mathews, W. M. Howard *et al.*, Astrophys. J. **399**, 656 (1992).
[9] W. M. Howard, S. Goriely, M. Rayet, and M. Arnould, Astrophys. J. **417**, 713 (1993).
[10] S. E. Woosley, J. R. Wilson, G. J. Mathews *et al.*, Astrophys. J. **433**, 229 (1994).
[11] R. Alvarez-Rodriguez, H. O. U. Fynbo, A. S. Jensen, and E. Garrido, Phys. Rev. Lett. **100**, 192501 (2008).
[12] J. Casal, M. Rodriguez-Gallardo, J. M. Arias, and I. J. Thompson, Phys. Rev. C **90**, 044304 (2014).
[13] K. Sumiyoshi, H. Utsunomiya, S. Gokob, and T. Kajino, Nucl. Phys. A **709**, 467 (2002).
[14] C. Angulo *et al.*, Nucl. Phys. A **656**, 3 (1999).
[15] F. Ajzenberg-Selove, Nucl. Phys. A **490**, 1 (1988).
[16] L. Buchmann, E. Gete, J. C. Chow *et al.*, Phys. Rev. C **63**, 034303 (2001).
[17] E. Gete *et al.*, Phys. Rev. C **61**, 064310 (2000).

[18] Y. Prezado, M. J. G. Borge, C. Aa. Diget, L. M. Fraile *et al.*, Phys. Lett. B **618**, 43 (2005).
[19] R. J. Charity, T. D. Wiser, K. Mercurio, R. Shane, L. G. Sobotka, A. H. Wuosmaa, A. Banu, L. Trache, and R. E. Tribble, Phys. Rev. C **80**, 024306 (2009).
[20] P. Papka, T. A. D. Brown, B. R. Fulton *et al.*, Phys. Rev. C **75**, 045803 (2007).
[21] T. A. D. Brown, P. Papka, B. R. Fulton *et al.*, Phys. Rev. C **76**, 054605 (2007).
[22] B. R. Fulton, R. L. Cowin, R. J. Woolliscroft *et al.*, Phys. Rev. C **70**, 047602 (2004).
[23] S. M. Lukyanov, M. N. Harakeh, M. A. Naumenko *et al.*, J. Phys.: Conf. Ser. **724**, 012031 (2016).
[24] R. Rafiei, R. du Rietz, D. H. Luong, D. J. Hinde, M. Dasgupta, M. Evers, and A. Diaz-Torres, Phys. Rev. C **81**, 024601 (2010).
[25] T. Kajino, S. Wanajo, and G. J. Mathews, Nucl. Phys. A **704**, 165 (2002).
[26] W. von Oertzen, M. Freer, and Y. Kanada En'yo, Phys. Rep. **432**, 43 (2006).
[27] E. Cravo, A. C. Fonseca, and Y. Koike, Phys. Rev. C **66**, 014001 (2002).
[28] K. Arai, P. Descouvemont, D. Baye, and W. N. Catford, Phys. Rev. C **68**, 014310 (2003).
[29] P. Descouvemont, Eur. Phys. J. A **12**, 413 (2001).
[30] K. Ikeda, N. Tagikawa, and H. Horiuchi, Prog. Theor. Phys. Suppl. E **E68**, 464 (1968).
[31] A. S. Denikin *et al.*, Phys. Part. Nucl. Lett. **12**, 703 (2015).
[32] G. Nyman *et al.*, Nucl. Phys. A **510**, 189 (1990).
[33] V. Soukeras, A. Pakou, F. Cappuzzello *et al.*, Phys. Rev. C **95**, 054614 (2017).
[34] A. Pakou, O. Sgouros, V. Soukeras, F. Cappuzzello, N. Keeley, L. Acosta, C. Agodi, X. Aslanoglou, S. Calabrese, D. Carbone *et al.*, Phys. Rev. C **95**, 044615 (2017).
[35] F. Cappuzzello, C. Agodi, D. Carbone, and M. Cavallaro, Eur. Phys. J. A **52**, 167 (2016).
[36] D. Pierroutsakou, A. Boiano, C. Boiano *et al.*, Nucl. Instrum. Methods A **834**, 46 (2016).
[37] E. Strano, A. Anastasio, M. Bettini *et al.*, Nucl. Instrum. Methods B **317**, 657 (2013).
[38] M. Cavallaro, F. Cappuzzello, D. Carbone *et al.*, Eur. Phys. J. A **48**, 59 (2012).
[39] D. Carbone, F. Cappuzzello, and M. Cavallaro, Eur. Phys. J. A **48**, 60 (2012).
[40] F. Cappuzzello, M. Cavallaro, A. Cunsolo *et al.*, Nucl. Instrum. Methods A **621**, 419 (2010).
[41] F. Cappuzzello, D. Carbone, and M. Cavallaro, Nucl. Instrum. Methods A **638**, 74 (2011).
[42] M. Cavallaro, F. Cappuzzello, D. Carbone *et al.*, Nucl. Instrum. Methods A **648**, 46 (2011).
[43] M. Cavallaro, F. Cappuzzello, D. Carbone *et al.*, Nucl. Instrum. Methods A **637**, 77 (2011).
[44] O. Sgouros, V. Soukeras, and A. Pakou, Eur. Phys. J. A **53**, 165 (2017).
[45] O. B. Tarasov and D. Bazin, Nucl. Instrum. Methods B **266**, 4657 (2008).