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A clear signature of the breakup modes for ^{9}Be on a proton target at 5.6 MeV/nucleon

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Abstract. The breakup of ^{9}Be is studied via an inelastic scattering experiment on a proton target at 5.6 A MeV in inverse kinematics. Two of the three cluster constituents (α and α) as well as the proton target recoil were recorded in a triple coincidence mode allowing a full kinematics approach analysis. In this respect relative α - α and α - n, Q-value and ^{9}Be excitation spectra, energy spectra for all fragments as well as the energy spectrum of the recoil proton were reconstructed. A clear signature of the two breakup sequential modes (^{5}He + ^{4}He and ^{8}Be + n) was identified via the recoiling proton reconstructed spectra together with the direct breakup decay. A strong ^{5}He + ^{4}He mode was observed compatible with previous beta decay experiments.

1. Introduction

With the advent of radioactive beam facilities, studies with weakly bound nuclei either radioactive or the stable ones, have been pursued in several laboratories. Breakup cross sections have been measured with the aim of extracting structure properties which have to do either with conventional models or clustering models, for providing information relevant to astrophysics and for exploring coupling channel effects. Amongst the most interesting weakly bound nuclei, the Borromean nuclei attract a vivid interest in the nuclear physics community. The topology of the Borromean rings found a fertile ground not only in Nuclear Physics but also in Biophysics and Molecular Physics. The realization of a Borromean rings assembly in DNA was reported in 1997 by biologists Chengde Mao and coworkers [1] and in Molecular Physics, in 2003 by the chemist Fraser Stoddart and coworkers who utilized coordination chemistry to construct a set of rings in one step from 18 components [2]. In Nuclear Physics the quantum-mechanical analog of the Borromean rings is the halo or Efimov state, predicted in 1970 [3].

The ^{9}Be nucleus is the only stable Borromean nucleus, which is interesting due to its role in astrophysical problems [4, 5, 6, 7, 8, 9] and is an excellent example in clustering structure theories [10, 11, 12, 13]. Such theories request an accurate determination of the ^{9}Be branching to the three configurations: α + α + n (Q= -1.57 MeV), ^{8}Be + n (Q= -1.665 MeV), ^{5}He + α (Q= -2.46 MeV). While the breakup of ^{9}Be via the $^8\mathrm{Be}_{g.s.}$ has been measured for many of the low-lying excited states of ^{9}Be and is well established, the breakup branching via the first-excited 2^+ state of ^{8}Be and via ^{5}He + α remains uncertain while no attention has been given to the direct process α + α + n. Contradictory results are given for the above decay rates. Most of the beta decay experiments [14, 15, 16, 17, 18] agree in qualitative but not quantitative basis, that the strongest breakup decay mode is the ^{5}He +^{4}He one. On the other hand, inelastic excitation experiments on light (^{6}Li) [19, 20] or heavy targets (^{208}Pb) [21] give as a predominant decay mode the ^{8}Be + n one.

In this work we suggest an alternative novel technique, in which the 2.43 MeV resonance in ^{9}Be is inelastically excited but on the lightest existing target, the proton. The measurement is performed in inverse kinematics and the signature of the sequential modes is tagged on the proton recoiling spectra and not only in relative spectra as other inelastic techniques do. In what follows, Chapter 2 deals with experimental details and the data reduction, while in Chapter 3 we summarize the final results and our conclusions.

2. Experimental details and Data Reduction

The experiment was conducted at the MAGNEX facility [22, 23] at the Istituto Nazionale di Fisica - Nucleare Laboratori Nazionali del Sud (INFN - LNS) in Catania, Italy. A $^9\mathrm{Be}^{4+}$ beam at 51 MeV was delivered by the TANDEM Van de Graaff accelarator of INFN - LNS onto a 450 μg/cm^2 CH_2 target. The experiment was designed to study the breakup of ^{9}Be inelastically scattered from a proton target, in a full kinematics approach by detecting the two alphas and the recoiling proton in a triple coincidence mode. In this respect, the energy and momentum of the undetected particle, the neutron, can be determined and all properties of the reaction, such as Q-values, excitation energies and relative energies between the breakup fragments can be formed.

The MAGNEX spectrometer [22, 24, 25] was adopted to detect one of the alphas in an almost full angular range. The elastically scattered ^{9}Be ions were most of them swept out by appropriate magnetic fields, allowing the detection of alphas in an energy slice between 15 and 25 MeV corresponding, according to our simulation [26], to $\sim$ 70% of our energy phase space. For the data reduction we followed the same technique as in our previous studies [27, 28] which is based on the software ray reconstruction technique [29, 30, 31, 32]. The other alpha breakup fragment and the proton recoil were detected in a ΔE - E silicon module of the EXPADES array [33, 34] in coincidence with MAGNEX. The module comprised a ΔE Double Sided Silicon Strip Detector (DSSSD), and an E pad with thicknesses of 300 μm each. Details of how the detector signals were handled may be found in Ref. [34]. The EXPADES module was masked by a 49.6 μm thick tantalum foil to prevent the detector deterioration from Rutherford scattering. Due

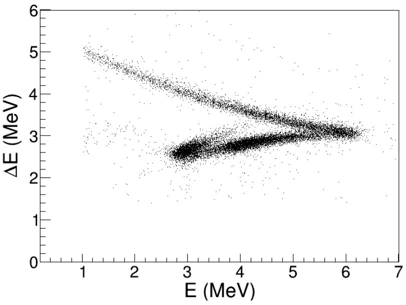

Figure 1. ΔE - E spectrum recorded by the strip 8 of the EXPADES module, corresponding to $\theta_{\text{lab}} = 20.2°$ in coincidence with MAGNEX.

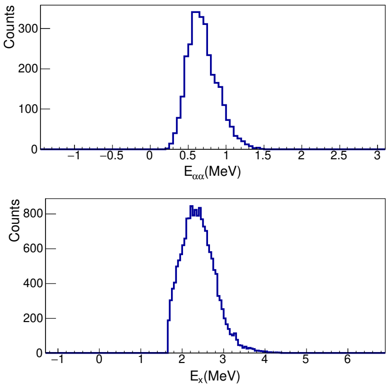

Figure 2. Upper: Reconstructed α - α relative energy spectrum by imposing the α - α - p triple coincidence event-by-event requirement. Lower: Reconstructed excitation energy spectrum of ^{9}Be.

to the foil, the threshold of the silicon detectors and the triple coincidence requirement, finally the proton phase space was reduced to 15%. The α - α - proton triple coincidence requirement, excluded all transfer events from the carbon component included in the CH$_2$ target (^{9}Be + ^{12}C $\rightarrow$ ^{8}Be + ^{13}C), while the contamination from α - α - d events was very small below 4% and only for the most forward or very backward angles, where some overlap of protons and deuterons occurred, since both light particles were punched through the second stage of the telescope (Figure 1).

A clear evidence of a breakup event was sought in our event by event code looking within the appropriate energy regions for alpha particles detected in MAGNEX in coincidence with alpha particles stopped in the ΔE stage of the EXPADES telescope and identified via kinematics and energy loss algorithms and protons identified by the ΔE - E technique in the same telescope. This requirement gives a clear evidence of a breakup event. When such an event was found, tagged by an energy and an angle (i.e the momentum vector), the energy of the undetected neutron, E$_n$, was determined by applying the momentum conservation law. In this respect, the total kinetic energy, E$_{tot}$, the Q value of the four body reaction, the excitation energy spectrum of ^{9}Be and spectra of relative energies between the breakup fragments can be reconstructed. We present in the upper part of Figure 2 the relative energy spectrum between the two alphas, one detected in MAGNEX and one in the first stage of the DSSSD telescope and in the lower part an excitation energy spectrum of ^{9}Be. The relative energy spectrum, peaked at $\sim$ 0.7 MeV, indicates that the sequential decays occur via the tail of the 2$^+$ excited state of ^{8}Be at $\sim$ 3 MeV, $\Gamma\sim$1.5 MeV or/and the ground state of ^{5}He with $\Gamma\sim$ 0.6 MeV (see Refs [19, 20, 21]), while the excitation energy spectrum indicates that the breakup decay occurs mainly via the 2.43 MeV resonance of ^{9}Be.

The question which then arises is to what extent the decay occurs via one and/or the second sequential decay mode and also to what extent occurs via the direct mode. The indication of Figure 1, where an intense wide spot is observed, is that obviously we have the existence of sequential decays. The identification of these modes as well as the detection efficiency of our system for each one of them was sought via our simulation code, MULTIP, comprehensively outlined by Sgouros et al. in Ref. [26]. For the specific case here we can note the following. The continuum excitation is treated as a two body-like reaction leading to ^{9}Be* + p. Then

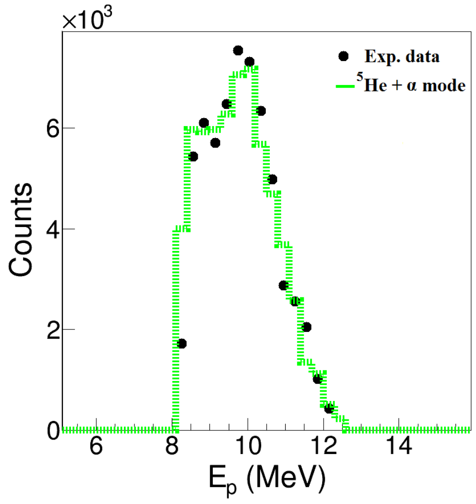

Figure 3. Experimental energy spectrum of recoiling protons observed in the angular range 4.5 to 34°. The proton gate corresponds to intense part of a ΔE - E spectrum relevant to the ^{5}He + ^{4}He mode. Data are designated with the black circles while our simulation, scaled to the data, with the green line.

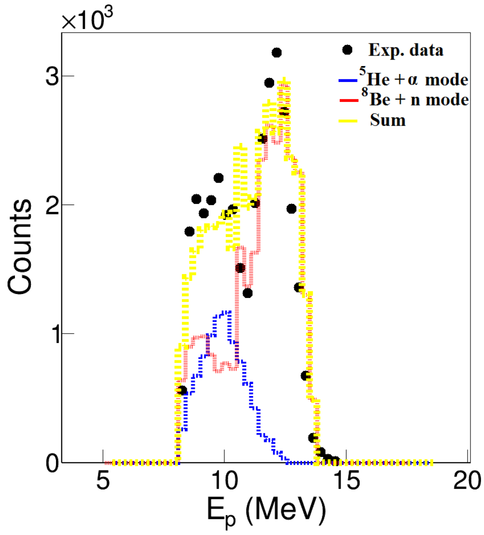

Figure 4. Experimental energy spectrum of recoiling protons observed in the angular range 4.5 to 34°. The proton gate corresponds to intense part of a ΔE - E spectrum relevant to the ^{8}Be +n mode. Data are designated with the black circles while our simulation, with the red line. With the blue line is designated our simulation for the ^{5}He + ^{4}He mode, due to the overlap of gates for the two sequential modes. The sum of the two is designated with the yellow line, scaled to fit the data.

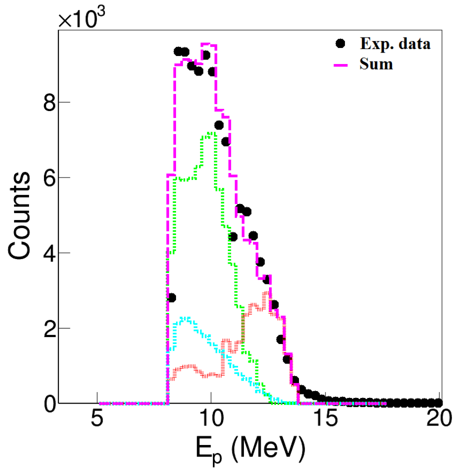

Figure 5. Experimental energy spectrum of recoiling protons in the angular range 4.5 to 34°, including all protons (cuts were applied to each of the ΔE - E spectra to all protons). The simulations of each of the three modes are designated by green and red lines for the ^{5}He + ^{4}He and ^{8}Be + n sequential modes, respectively and with the cyan line for the direct mode. Their sum is designated by the magenta line and is in excellent agreement with the data, represented by the black dots.

the ^{9}Be* decays in its rest frame into α + α + n for the direct mode or into ^{8}Be + n (^{5}He + ^{4}He) for the two sequential modes. Then appropriate Galilean transformations and rotations are applied for the transformation of the fragments' momenta from the ^{9}Be* rest frame to the laboratory one. 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 also 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 CDCC calculation as well as flat distributions were adopted leading to similar results. Differentiations between the two choices can be included as uncertainty in the final determined rates. With the kinematics for the two sequential decays extracted from MULTIP, appropriate gates for each angle between 4.5 to 34 degrees (the angular range spanned by the EXPADES telescope) were applied to ΔE - E spectra, and the integrated proton spectra to all angles for the ^{5}He + ^{4}He and ^{8}Be + n modes were formed and are displayed in Figures 3 and 4 respectively. Finally, in Figure 5 we present an integrated proton spectrum with a gate on the total ΔE - E spectrum. For the sequential modes our simulation results are presented in Figures 3 and 4, scaled according to the overall strength of the data and presenting an excellent description of them. These simulations, scaled to the sequential mode data, are also presented in Figure 5 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 of each mode were extracted by dividing the obtained simulated areas restricted under the experimental conditions with the unrestricted ones. The analysis for extracting the rates is under progress. Preliminary results indicate that beyond any doubt the 2.43 MeV resonance of ^{9}Be decays mainly via the ^{5}He + ^{4}He mode, while the direct mode and the ^{8}Be + n mode via the excited 2^+ resonance of ^{8}Be contribute to a lesser extent. Our findings are in accordance on a qualitative basis with all the beta decay experiments [14, 15, 16, 17, 18] but not the inelastic ones [19, 20, 21].

3. Summary - Conclusions

The breakup of the borromean stable weakly bound ^{9}Be nucleus on a proton target was studied in inverse kinematics at 5.6 A MeV. A triple coincidence requirement between the two α fragments and the recoiling proton allowed the development of a reconstruction code in a full kinematics approach, where Q-value spectra, excitation energy spectra, relative energy spectra and energy spectra of all fragments were determined. With the assistance of our comprehensive simulation code, MULTIP, the two sequential modes were tagged in the proton ΔE - E spectra, partly in energy overlap between them in some of the angles, where they had left their signatures. Remaining protons in the ΔE - E spectra were assumed as coming from the direct breakup of ^{9}Be and the three breakup decay modes were determined. It was found:

- At the specific energy of 5.6 A MeV the excitation of continuum goes mainly via the 2.43 MeV resonance.
- kinematics of the two sequential modes were determined by the overlap of the 2.43 resonance and the tail of the resonance of ^{8}Be* at ~ 3 MeV (2^+) as well as the tail of the ground state of ^{5}He.
- Despite some overlap in the kinematics between the two sequential modes, the recoiling proton can carry their signature in a clear way, unobtainable via relative spectra, a method adopted previously.
- The 2.43 MeV resonance of ^{9}Be decays mainly via the ^{5}He + ^{4}He mode and in a lesser extend via the ^{8}Be + n mode. This is in a qualitative accordance with all beta decay experiments while contradicts previous inelastic experiments, possibly because the last were based solely on relative spectra.
- Within this work a new technique is established, to pin down the involvement of various decay modes in four body problems, taking into account in advance well selected experimental conditions related with energies, angles and breakup cones.

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