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Abstract

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Keywords

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Search for $4n$ contributions in the reaction ^{14}Be(CH$_2$,X)^{10}He

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Abstract. A previously published measurement of the ground state resonance of ^{10}He, populated by a reaction of a 59 MeV/u ^{14}Be beam on a deuterated polyethylene target, was further analyzed to search for $4n$ emission resulting from $2p$ removal. No evidence for $4n$ events was found. A lower limit of about 1 MeV was determined for a possible resonance in ^{12}He.

1 Introduction

There is some controversy over the location of the ground state of ^{10}He. Recently, a missing-mass measurement performed at JINR in Dubna populated ^{10}He via a (t,p) reaction on ^{8}He and found the ground state to be at 2.1(2) MeV [1] in contrast to another measurement done at GSI using proton knockout from ^{11}Li, which found the ground state to be lower at 1.54(11) MeV [2]. It has been suggested by Grigorenko and Zhukov that the observed peak in the 3-body spectrum of the GSI measurement could be shifted by the halo nature of the ^{11}Li beam [3], apparently reconciling the discrepancy between the Dubna and GSI results.

In addition, a recent measurement at the NSCL populated ^{10}He through 2p2n removal from ^{14}Be and found the 3-body resonance to be at 1.6(25) MeV [4]. This reaction was considered to be more dissipative and so the invariant mass spectrum should not be influenced by the proposed initial state effects – yet a lower energy was observed. In this experiment, the 2p2n removal could proceed multiple ways. Here we consider α-knockout and 2p removal to produce ^{10}He, the latter process populating ^{12}He. In this work we investigate possible evidence for direct cluster removal and search for a potential resonance in ^{12}He.

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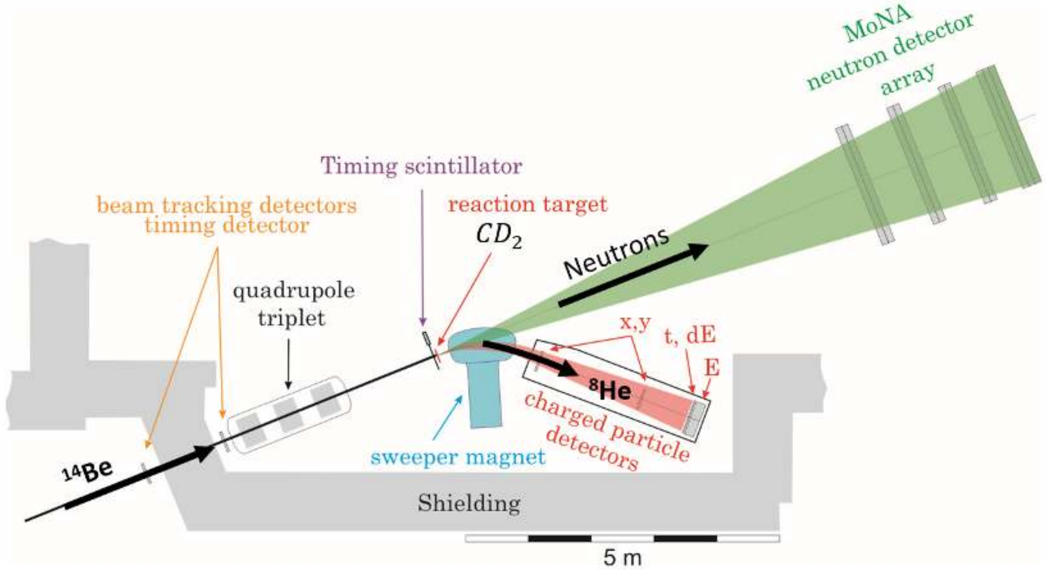

FIGURE 1: Schematic drawing of the experimental setup at the NSCL.

2 Experimental Method

The experiment was performed at the National Superconducting Cyclotron Laboratory where a 3196 mg/cm^2 ^{9}Be target was bombarded with an ^{18}O beam at 120 MeV/u. The A1900 fragment separator allowed for selection of the ^{14}Be secondary beam which continued on to impinge a 435 mg/cm^2 deuterated polyethylene target in the experimental area. The resulting charged fragments were bent 43.3° by a 4-Tm superconducting sweeper magnet [5] into a collection of charged-particle detectors, which allowed for element and isotope identification. The neutrons emitted in-flight traveled undisturbed by the magnet towards MoNA (Modular Neutron Array), which provided time-of-flight and position information. Together, MoNA and the Sweeper provide a full kinematic measurement of the neutrons and the charged fragments from which the N-body decay energies of ^{8}He + Xn can be determined. Additional experimental details can be found in Ref. [4]. Figure 1 shows a schematic of the experimental setup.

2.1 Analysis

Depending on the reaction path ($\alpha/2p2n$ or $2p$ removal), a different number of neutrons is emitted. Thus the analysis was extended from 2- to 5-body spectra corresponding to the decays of $^{9-12}$He. The N-body decay energy is defined as :

$$E_{\text{decay}} = M_{\text{Nbody}} - M_{^8\text{He}} - \sum_{i=1}^{i=N-1} m_{\text{n}},$$

where M_{Nbody} is the invariant mass of the N-body system, $M_{^8\text{He}}$ the mass of ^{8}He, and m_{n} the mass of a neutron. The invariant mass of an N-body system was calculated from the experimentally measured four-momenta of ^{8}He and the first $N-1$ time-ordered interactions in MoNA.

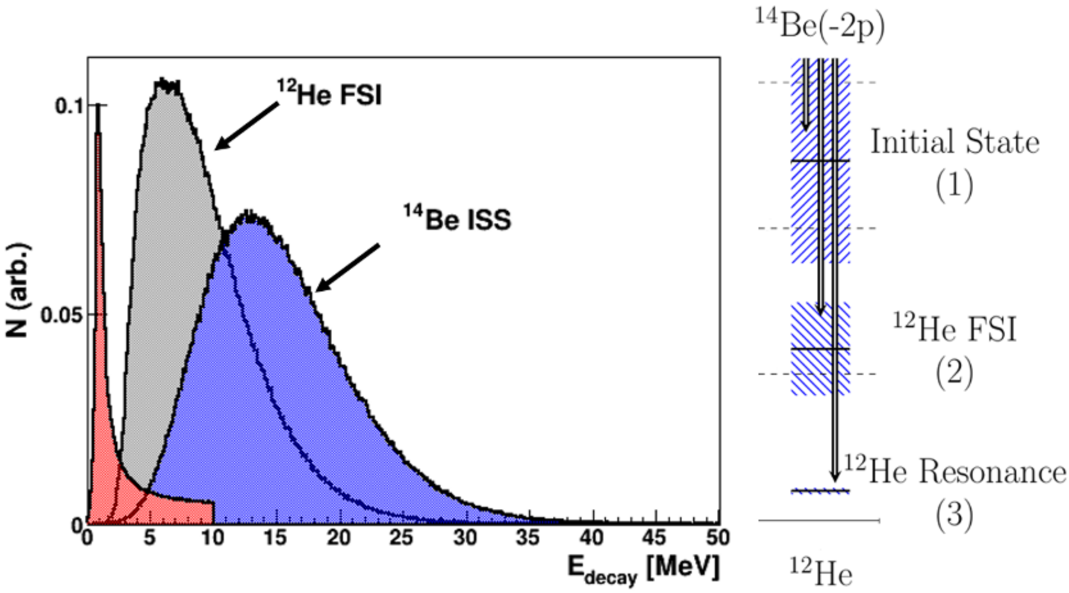

FIGURE 2: Input 5-body distributions for the ^{8}He + 4n system. (1) Shown in blue is a distribution influenced by the halo structure of ^{14}Be [10]. (2) In grey is a resonant final-state interaction [10]. (3) In red is a low-lying 1 MeV Breit-Wigner lineshape.

In order to extract information from the invariant mass spectra, detailed Monte-Carlo simulations were performed. These simulations include the beam characteristics, the reaction mechanism, and decay mechanism. Using GEANT4 [6] and MENATE_R [7], the resolution, efficiency and acceptances of MoNA and the charged particle detectors were fully incorporated into the simulations making them directly comparable to data.

Multi-neutron decay reconstruction is very sensitive to detector response effects, and multiple scattering within the array must be properly taken into account. In the case of 2n events (^{10}He), this is accomplished by applying causality cuts on relative distance and velocity as described in Ref. [4]. One extension to 4n events could be to apply causality cuts on each pair of interactions, of which there are six. However, a typical causality cut has an efficiency on the order of 30%, and applying this cut six-fold is not feasible. Instead, a 4n-signal can be indirectly searched for by a simultaneous χ^2 minimization on several decay energy spectra of varying multiplicities described in Ref. [8]. A similar method was used to search for 3n events coming from ^{15}Be in another study [9]. Since a 4n event will induce more scattering than a 2n event, a simultaneous fit across several multiplicities is sensitive to the number of neutrons emitted. Using this method, it was found in this analysis that there is no need to invoke a 4n model to describe the data [8], as the data can be completely described by 2n events coming from either α-knockout or 2p2n removal.

However, contributions from the 2p removal reaction could be present in the data up to some statistical limit. For this reason we consider several possibilities for the ^{12}He 5-body system illustrated in Figure 2. Three different cases for the population of ^{12}He were considered, of varying energy : (1) a distribution influenced by the initial halo structure of ^{14}Be (Initial State Structure [10]), (2) a resonant final-state interaction (^{12}He FSI) [10] peaking at roughly 6.5 MeV, and (3) a low-lying Breit-Wigner lineshape centered at 1 MeV. The 5-body spectrum for ^{8}He is most sensitive to the presence of a $4n$ component and so it is useful to track the log-likelihood ratio, $Ln\,[\lambda]$ of this spectrum. Since the data can be described entirely with $2n$ events, the best-fit parameters from α/2p2n-knockout are used as a baseline. The quality of the fit and the parameters used for ^{9}He and ^{10}He can be found in Ref. [8]. The $4n$ component from a hypothesis is then added to the spectrum and its amplitude is incremented. Plotting the log-likelihood as a function of the ratio of $4n$ to $2n$ events gives the statistical limits for each model. The result of this procedure is shown in Figure 3.

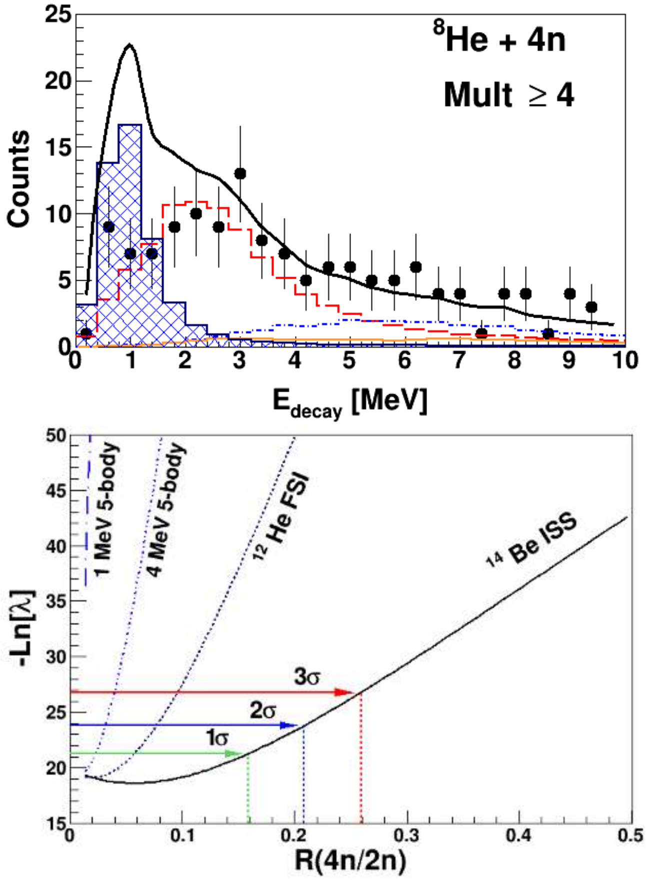

FIGURE 3: Figures from Ref. [8]. (Top) Five-body decay energy spectrum for all multiplicities ≥ 4. The hatched blue histogram is the contribution from a five-body breakup of ^{12}He at E = 1 MeV with $R(4n/2n)$ = 1.5%. The dash, dot-dashed, and solid lines are contributions from direct population of ^{10}He. (Bottom) Maximum likelihood for the five-body decay spectra (and multiplicity) as a function of the ratio of 2p to α or $2p2n$ removal for several possibilities in ^{12}He. For more details refer to Ref. [8]

Figure 3 (top panel) shows the result of including a low-lying resonance in ^{12}He with a strength of only 1.5% that of the net α or $2p2n$ components. A large excess at low E_{decay} is evident in the 5-body spectrum and the prediction is at odds with what is observed. Since one would expect a distinct resonance in ^{12}He to be populated from $2p$ removal, the data do not show evidence for a low-lying state below 1 MeV. The other scenarios, which cover a broad range of energies, do not minimize in favor of $2p$ removal. The ratio $R(4n/2n)$ does not exceed 30% for any case considered here while remaining within 3σ confidence – implying that the data are dominated by α/2p2n-knockout. The amount of contribution from $2p$ removal increases with the 5-body energy primarily due to a drop-off in efficiency for higher decay energies. It should be noted that for this experiment the sweeper magnet was set for lower rigidities and only the low-energy tail of the overall momentum distribution for ^{8}He was recorded. These events probably originate from more dissipative reactions which could bias the data towards α/2p2n removal relative to 2p removal.

3 Conclusions

A complete analysis of multi-neutron decay energy spectra is a tool to explore neutron unbound systems which decay by emission of three or four neutrons. Even if the statistics are not sufficient to extract spectra with clean identification of each neutron, the presence of additional neutrons can be inferred through the multiplicity and the relative intensities of the decay spectra. In low-energy cases where the experimental sensitivity is high a limit can be established. In the present case, the data are dominated by $\alpha/2p2n$-knockout and there is no evidence for the existence of a low-lying ($\leq$ 1 MeV) resonance in ^{12}He.

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