Clustering in ^{10}Be

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There is a strong experimental evidence that some states in ^{10}Be exhibit a molecular-like α:2n:α configuration [1,2,3]. Theoretically, these exotic structures can be explored microscopically in the antisymmetrized molecular dynamics (AMD) plus Hartree-Fock approach [4] or in the Molecular Orbital model [5]. Based on these theoretical studies, it appears that the 6.179 MeV 0^+ state in ^{10}Be has a pronounced α:2n:α configuration with an α-α inter-distance of 3.55 fm. This is 1.8 times the corresponding value for the ^{10}Be ground state. The 2^+ resonance at 7.542 MeV in ^{10}Be is believed to be the next member of this rotational band [6]. The state at 10.2 MeV was identified as a 4^+ member [1, 3]. The algebraic model [7] predicts that a 6^+ state at around 13 MeV is the next member of this band. It would be of paramount importance to identify this 6^+ state experimentally and to conclusively establish the α:2n:α rotational band. This would become the most striking and well established case of molecular-like configurations in nuclei and an important step towards a better understanding of clustering phenomena in atomic nuclei.

We performed an experiment to search for the 6^+ state in ^{10}Be at around 13 MeV excitation energy using ^{6}He+α scattering. The Cyclotron Institute Momentum Achromat Recoil Separator (MARS) facility was used to produce a secondary ^{6}He beam at 7.0 MeV/u from the production reaction of ^{7}Li(d,^{3}He). A sketch of the experimental setup is shown in Fig. 1. The modified thick target inverse

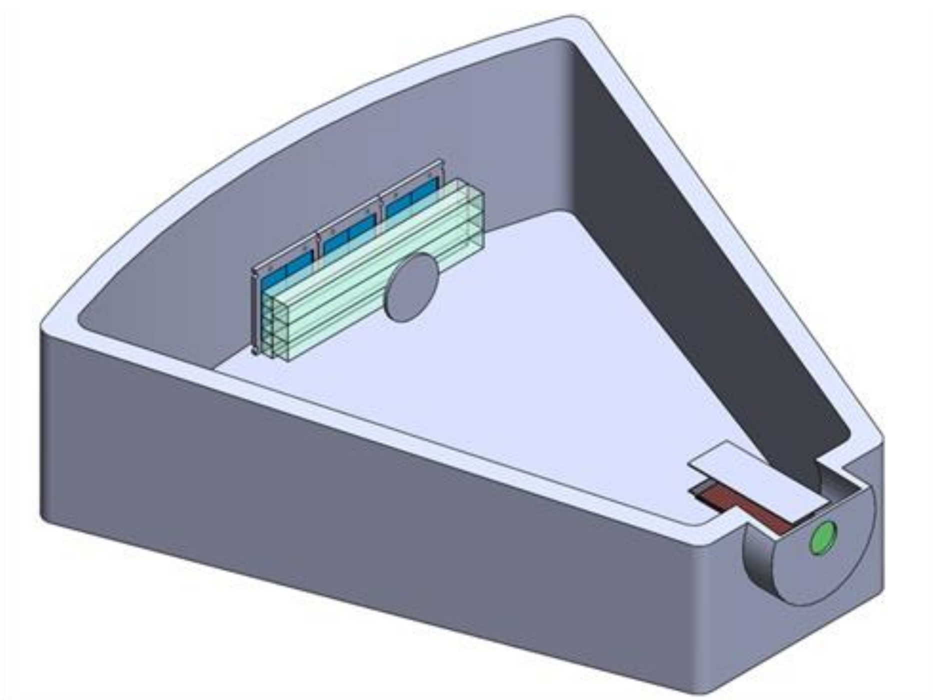

FIG. 1. Sketch of the experimental setup to measure the ^{6}He+α excitation function of ^{10}Be excitation energy.

kinematics approach [8] was used to measure the ^{6}He+α excitation function. Details of the experimental setup can be found in [9]. The energy of the ^{6}He beam was reduced down to 22 MeV by a thick scintillator foil located in front of the scattering chamber filled with a helium+CO_2 96:4 gas mixture at a pressure of 1700 Torr.

We have observed a distinct peak in the α particles energy spectrum that could be a result of the resonance in the ^{6}He+α excitation function which we were looking for. This peak in the α spectrum was verified to be associated with the incoming ^{6}He beam particles and not the other beam contaminants, the dominant of which is tritium. Given the nature of the set up, we expect the highest energy α particles (between 12 and 15 MeV) to correspond to pure elastic scattering. At lower energies, admixtures from α particles due to inelastic scattering and breakup are also possible. Based on the shape of the spectrum compared to Monte Carlo simulations (Fig 3), the experimental yield and angular dependence of the cross section, we can conclude that the α spectrum is dominated by the breakup of ^{6}He into α+2n at energies below 8 MeV.

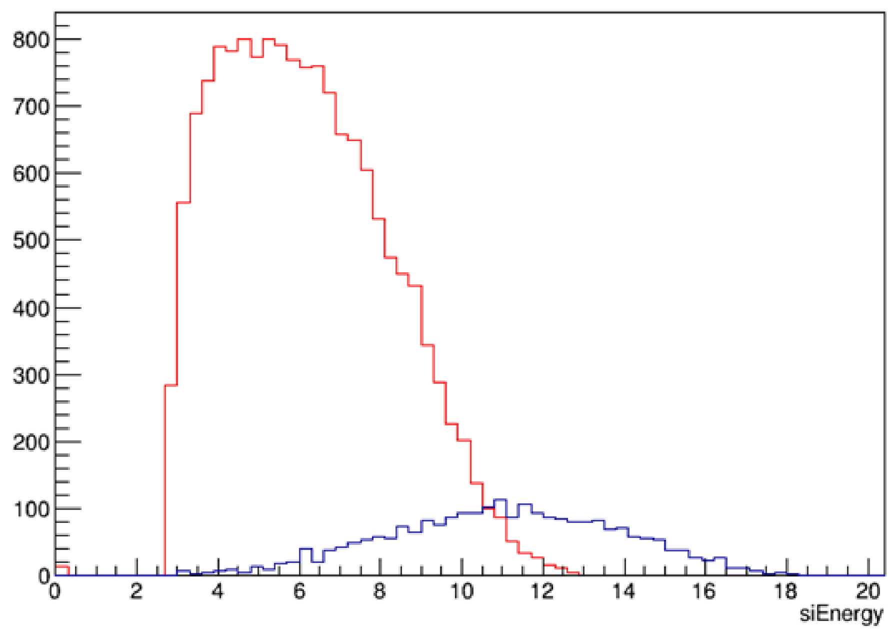

FIG. 2. Monte Carlo simulation of α particles spectrum due to breakup of ^{6}He. The (red) curve at lower energy shows α particles from ^{6}He decay. The (blue) curve at higher energy shows α particles due to elastic scattering.

For analysis purposes, we have divided the three different angles in our set up into regions. The detector at forward angles corresponds to Region 1. The other two angles (170° and 162° in the center of mass frame) correspond to Region 2 and Region 3 respectively. The peak in the α spectrum due to the hypothetical 6^{+} state at 13.5 MeV [10,11,12] would appear in the vicinity of 8 MeV in the lab frame in Region 2 and 6.5 MeV in Region 3 (Fig. 2). We also expect the inelastically scattered α particles to show a peak around 6 MeV and 4 MeV in the lab frame in Regions 2 and 3 respectively. There is no indication for a resonance-like structure in our spectrum at that energy at any angle that is statistically significant enough to be observed above the breakup contribution. Since we can't conclusively claim the origins of the α particles in the entire spectrum, we were not able to extract a clean excitation function for $^{6}He+\alpha$ elastic scattering.

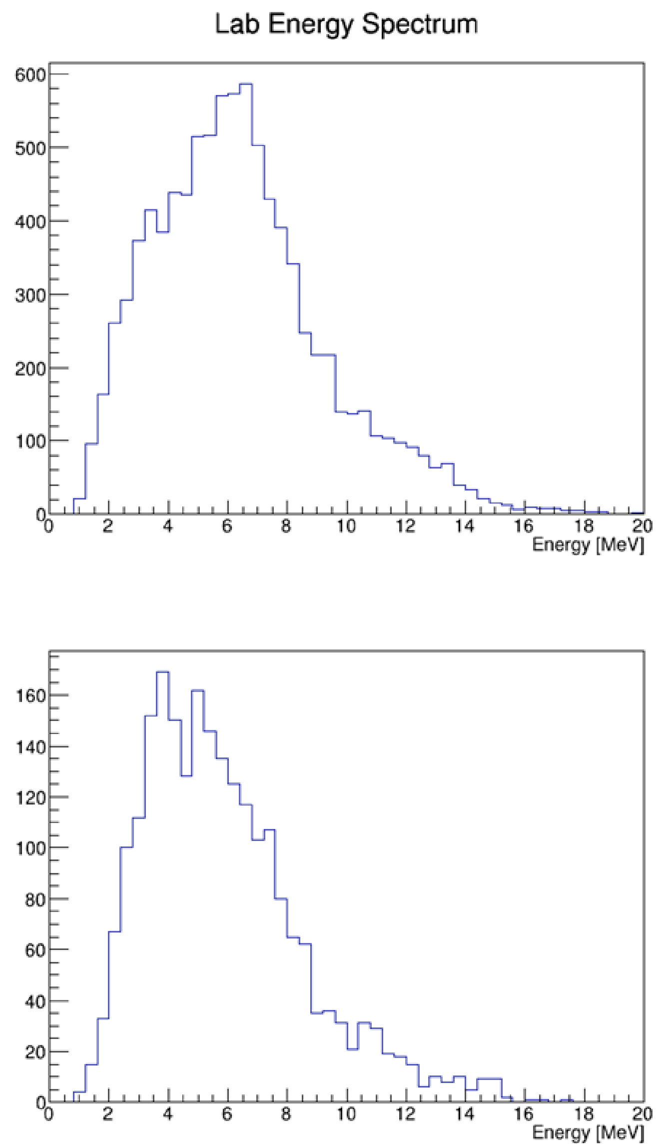

FIG. 3. Spectrum of α particles measured by the off-center Si detectors. The peak at 7 MeV is a result of ^{6}He decay into α + 2n (see text for details).

We performed further GEANT4 simulations to better characterize the experimental spectra. In these simulations, we scaled the reactions (elastic and inelastic scattering) using the cross sections obtained from our R-Matrix analysis. Spectroscopic factors provided by [13] along with parameters provided by [12] were used. These reactions were further scaled by the absolute normalization from the experiment. The results from the simulations can be seen in Fig. 4. We then subtracted the contribution

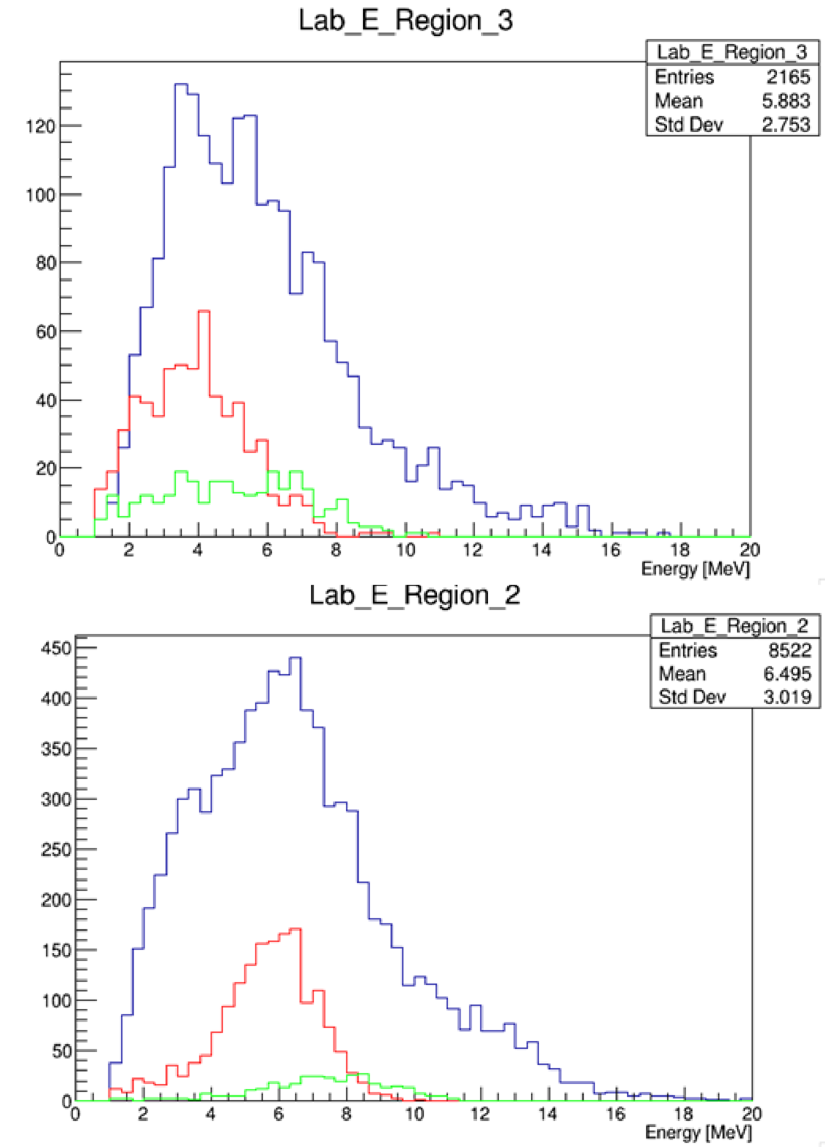

FIG. 4. Blue curve represents our experimental spectrum. Red and green curves represent the simulated inelastic and elastic contributions respectively. Widths resulting from spectroscopic factors (0.1 for elastic and 0.66 for inelastic) provided in [13] were used for the simulations.

from the elastic and inelastic simulations from the experimental spectra to see whether the remaining spectrum is consistent with the breakup process. We also performed a chi-squared hypothesis test to check this (Fig 5). Based on this, we can conclude that the parameters from [12] are **inconsistent** with a 6^+ state at 13.5 MeV. However, if we modify the parameters of the 6^+ state at 13.5 MeV to those from [13] and assume that there is also a breakup that is described by Maxwell-Bolzman distribution then a good description of the observed spectrum can be achieved.

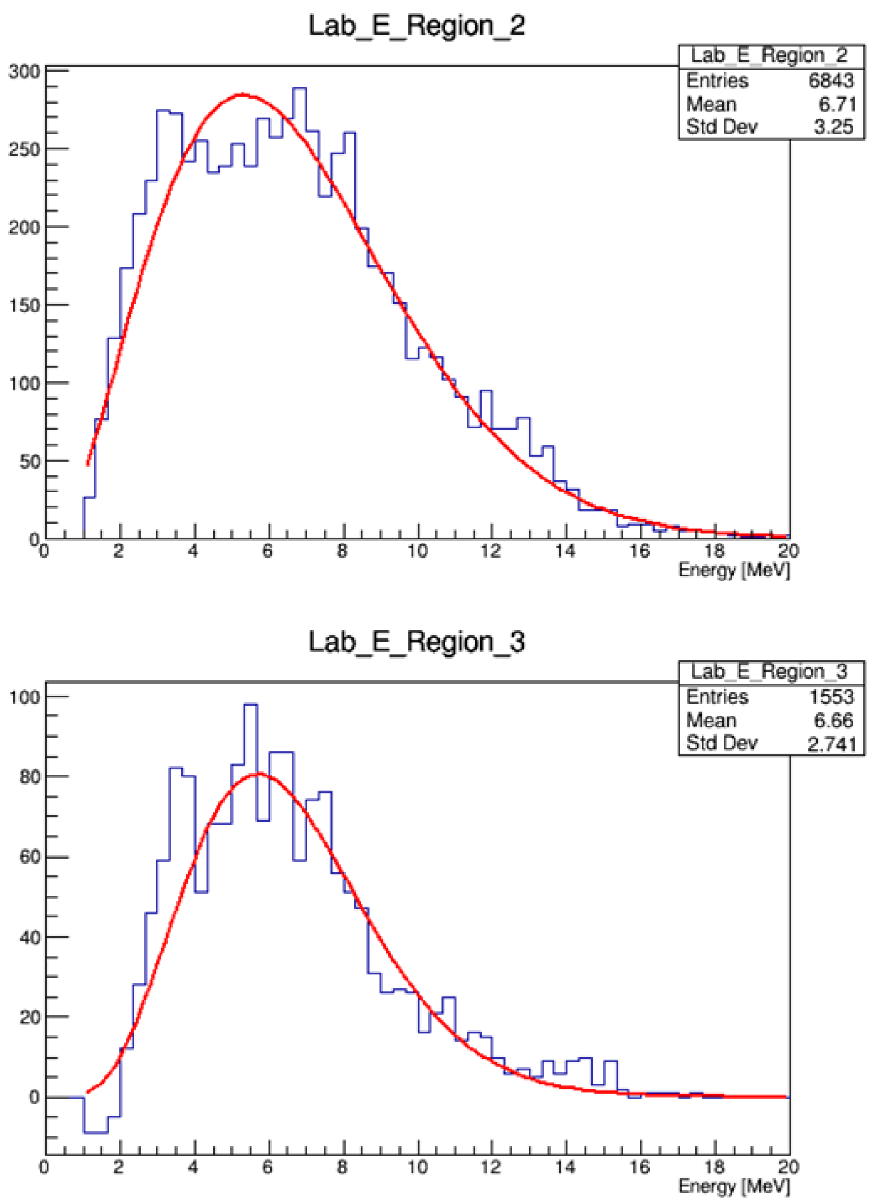

FIG. 5. Blue curve is the resulting spectrum after the simulated elastic and inelastic contributions from Fig. 4 have been subtracted. The red curve is a poisson distribution fit.

In summary, we have performed a search for the lowest 6^+ state in ^{10}Be, which was suggested as the next member of the molecular α:2n:α rotational band [7], in the excitation function for ^{6}He+α. No evidence for strong resonance have been observed in the energy range between 11 and 15 MeV (it was expected at 13 MeV). However, if we assume that the dominant configuration for this state is ^{6}He(2^+)+α, and that the coupling to the ^{6}He(g.s.)+α channel is relatively small, as suggested in [13], than the experimentally observed spectrum can be reproduced as a breakup of ^{6}He plus a resonance at 13.5 MeV in ^{10}Be that decays predominantly to the first excited state of ^{6}He. This experimental information provides important constraints on the theoretical models describing clustering in ^{10}Be and lends support to predictions made in [13]. It is clear, however, that further experiments are needed to confirm possible existence of this state in ^{10}Be and to further characterize its properties.

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