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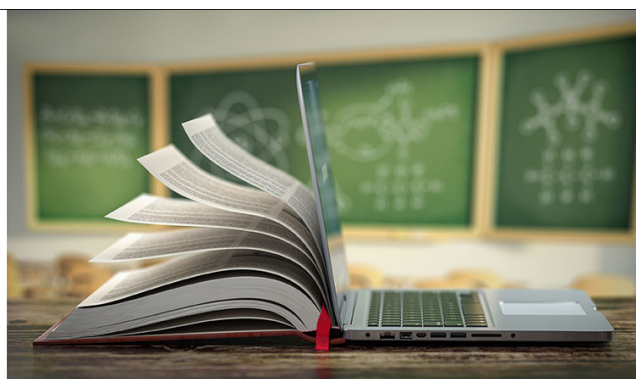 G. Belanger, K. Benakli, M. Goodsell et al.

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Study of β-delayed charged particle emission of ^{11}Li: evidence of new decay channels

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Abstract.
The break-up of the 18.2 MeV state in ^{11}Be was studied in a ^{11}Li β-decay experiment. We report here on the study of the dominating breakup channels involving $n\alpha^6$He or $3n2\alpha$ in the final state, with special emphasis dedicated in this contribution to the three-particle channel. The two emitted charged particles were detected in coincidence using a highly segmented experimental set-up. The observed experimental energy-vs-energy scatter plot indicates a sequential break-up where nuclei of mass 4, alpha particles, and mass 7, ^{7}He, are involved. A Monte-Carlo simulation of the sequential channel, ^{11}Be$^* \to \alpha + {}^7$He $\to n\alpha^6$He was performed and compared to the experimental data and to a simulation of the direct break-up of the 18.2 MeV state $n\alpha^6$He by phase space energy distribution. The energy-versus-energy plot are explained by the sequential simulation but not by the phase space simulation.

1. Introduction

The development of new experimental and theoretical tools has recently renewed the interest in studying exotic structures in Be isotopes. On the experimental side, new experimental measurements allowed the spin and parity of several excited states to be obtained for ^{9}Be [1], ^{10}Be [2], ^{11}Be [3] and ^{12}Be [4, 5]. Moreover, in the ^{10}Be and ^{12}Be cases, the presence of highly deformed rotational bands was interpreted as the presence of developed molecular states. On the theoretical side, the description of Be isotopes including alpha clusterization has been successful in explaining and predicting several unusual features of their structure. A recent work [6], using a three-body ($2\alpha n$) model of the initial ^{9}Be wavefunction, has been successful in explaining the controversial [7, 8, 9] break-up of the $5/2^-$ state at 2.43 MeV in ^{9}Be. Besides, the Antisymmetrized Molecular Dynamics (AMD) method was able to describe the low energy

level scheme of ^{10}Be [10] and ^{11}Be [11] and, furthermore, to predict the presence of a significant cluster structure for the members 0_2^+ rotational band in ^{10}Be. This band was subsequently confirmed when its 4^+ member was found at 10.15 MeV [2], and the calculated band's moment of inertia indicated high deformation.

However, the experimental situation is not as promising for ^{11}Be. A neutron-γ coincidence experiment using a ^{11}Li polarized beam [3] obtained the spin and parity of many of the low energy levels in ^{11}Be, validating the prediction of spin and parity assignment of several levels obtained from AMD calculations [11]. The situation is completely different at energies above the charged particle threshold. There are only two known states in ^{11}Be above the charged particle emission threshold at 10.5 MeV [12, 13, 14, 15] and at 18.2 MeV [13, 14] that decay into four possible channels, nα^6He (7.9 MeV above the ^{11}Be ground state), 2α3n (8.8 MeV), ^{8}Li+t (15.7 MeV) and ^{9}Li+d (17.9 MeV). The previous ^{11}Li β-decay coincidence study of charged particles [13] found that the 10.6 MeV state in ^{11}Be decays through an intermediate resonance in ^{10}Be at 9.5 MeV. On the other hand, the 18.2 MeV state in ^{11}Be was assumed to decay into five particle phase space.

We present in this work the charged particle spectrum following ^{11}Li β-decay measured in coincidence. Our recent studies on β-delayed multi-particle break-up have shown that full-kinematics coverage allows to univocally determine the decay mechanism. This technique has been successfully applied to determine the decay mechanism of the states in ^{9}Be [1], ^{9}B [16] and ^{12}C [17]. Our aim is to use these new techniques to determine the decay mechanism of the 18.2 MeV state.

2. Experiment

The experiment took place at ISOLDE, CERN. The ^{11}Li beam was obtained using the ISOL technique. A 1.4 GeV protons from the PS-Booster proton synchrotron impinged on a Ta target coupled to a tungsten ionization source. A 30 kV voltage was used to extract the spallation products. The ^{11}Li 1^+ were selected using the GPS isotope separator. The beams were stopped in a 60 μg/cm^2 carbon foil to study the decay at rest. The implantation energy was chosen to reduce the thickness of the carbon foil and optimize the path of the emitted charged particles inside the carbon foil.

The set-up consisted on 4 telescopes with thin DSSSD detectors in front stacked in thick silicon pads, for β detection, mounted on the surfaces of a 10x10x10 cm cubic frame, covering 4% of 4π each. Charge collection in these DSSSD's is carried out by 16 vertical and 16 horizontal strips, constituting 256 individual pixels. Thus, it allows a high angular coverage while having enough spatial resolution and high total efficiency.

3. Analysis

In this work we are going to study the ^{11}Li β-delayed double coincidences detected in two DSSSD's, D2 and D4 which are sitting in front of each other. The covered angles between the detected particles were between 127° and 180°. This reduces the number of possible detectable decay channels detected to two, 2α3n and nα^6He. Other channels emitting charged particles, ^{10}Be+n, ^{9}Be+2n, ^{9}Li+d and ^{8}Li+t either emit one charged particle, as in the first three cases, or one of the particles is very difficult to detect in coincidence because of their low energy, as in the last two decay channels. Therefore the charged particle spectrum has to be explained as a combination of 3-body, nα^6He, and 5-body, 2α3n, decay. Figure 1 shows the E$_{D2}$ vs E$_{D4}$ scatter plot for all detected coincidences. The main features of the plot are a transverse line crossing the axis at 2.2 MeV, a low energy bump and a smooth event distribution at high energies.

Figure 2 shows the E$_{D2}$+E$_{D4}$, E$_{sum}$ spectrum in continuous line and the result of the Monte-Carlo simulation described later in this paper in dashed line. The energy sum spectrum corresponds to the projection along the diagonal line in the scatter plot of figure 1, so the
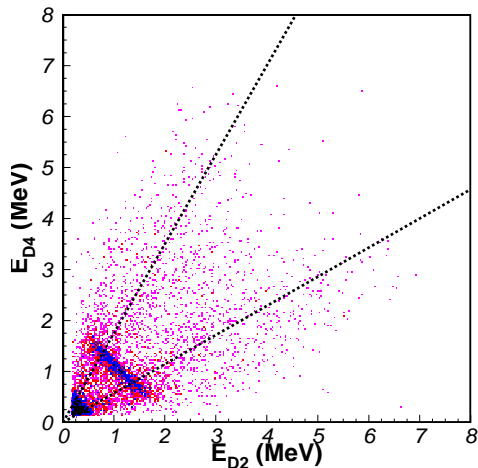
Figure 1. The figure shows the E_{D2} vs E_{D4} scatter plot for all recorded events. The two superimposed dotted lines highlight the 4/7th and 7/4th slopes (see text). The main features of the scatter plot are the low energy bump and transverse line, related to the decay of the 10.5 MeV state in ^{11}Be [13, 15], and the smooth distribution at higher energies. The smooth distribution tends to be aligned along the two superimposed lines at the highest energy part, indicating a sequential decay involving mass 7 and mass 4.
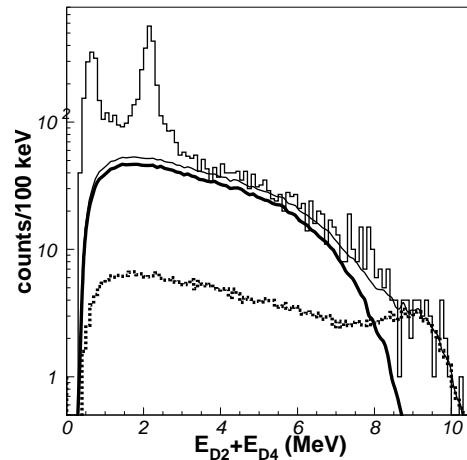

Figure 2. The E_{D2}+E_{D4} spectrum corresponds to the projection along the diagonal axis of figure 1. The low energy bump and the transverse line of figure 1 appear as the 0.6 and 2.2 MeV peaks in this spectrum, whereas the scatter part corresponds to the continuous distribution in this plot. The bold dotted histogram corresponds to the Monte-Carlo simulation of the proposed ^{11}Be(18.2)$\rightarrow$ $\alpha+^7$He$\rightarrow^6$He$+\alpha+$n while the bold continuous histogram shows the 5-body, $2\alpha3$n , break-up simulation, and the thin continuous line shows the sum of the two. It shows that the major contribution above 9 MeV corresponds to the three body channel.

transverse line appears as a peak. A transverse line in a E vs E scatter plot corresponds to a 3-body break-up through a intermediate resonance formed by the two detected particles. For that reason, following the work by Langevin and collaborators [13], it can be identified as the break-up of the 10.6 MeV state in ^{11}Be into the 3-body nα^6He channel through the intermediate state at 9.5 MeV in ^{10}Be. Moreover, the low energy peak and continuous distribution were assigned to the 5-body $2\alpha3$n break up described by phase space energy distribution of the 10.6 MeV and 18.2 states in ^{11}Be respectively [13]. The three body decay of the 10.6 MeV state in ^{11}Be is further covered in [15], while the full charged particle spectrum is studied in detail in [19]. In this paper we are going to concentrate in the study of the high energy part of the smooth distribution, related to the break-up of the 18.2 MeV.

If we look at the scatter plot of figure 1, it shows a subtle tendency in the high energy part, similar to two elongated bumps, highlighted by the two dashed lines. This tendency contradicts the interpretation of [13], as the break-up of ^{11}Be(18.2) described by phase space energy distribution will have a smooth distribution in the scatter plot. In fact, two bump of different slopes in the E_{D2}vsE_{D4} scatter plot correspond to a mass asymmetric two body break-

up where the original state was wide and being the slope of the bumps the mass ratio. On the other hand, as stated above, there is no measurable two body break-up following ^{11}Be β-decay. But a sequential three body break-up of a wide state, where the energy of the second emitted particle is very low, will be very similar to a true two-body break-up. The two elongated bumps show a slope close to 4/7th and 7/4th, as shown by the two dotted lines superimposed in figure 1. This tendency hints a sequential break-up in which the first stage involves nuclei of mass 7 and mass 4.
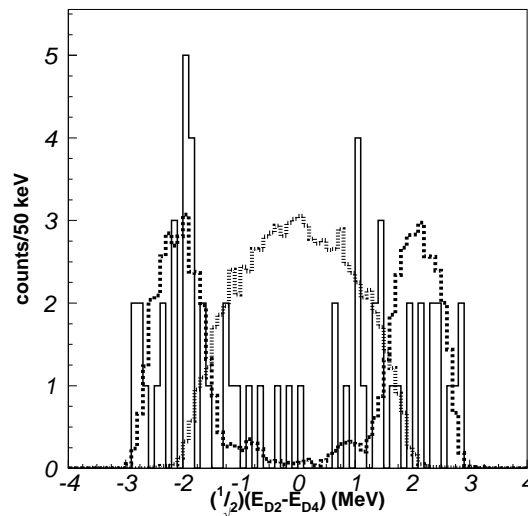

Figure 3. The figure shows the experimental E'=$(1/\sqrt{2})$(E$_{D2}$-E$_{D4}$) spectrum in continuous line for events of E$_{sum}$ > 9 MeV, where we expect the contribution from the 18.2 MeV state in ^{11}Be to be maximum from figure 2. The dashed histogram corresponds to the Monte-Carlo simulation of the sequential decay through ^{7}He+α and the thin continuous histogram to the simulation of the break-up described by phase space energy distribution. The experimental shape composed of two peaks and a dip in the middle is reproduced by the sequential Monte-Carlo simulation but not by the phase space simulation, which peaks in the middle.

As discussed in the introduction, alpha emission is common to all Be isotopes. On that ground, we expect the mass 4 nuclei mentioned above to be ^{4}He. This leaves ^{7}He as the only possibility for the recoil nucleus in the first break-up. The ^{7}He(gs) is the only resonance in ^{7}He decaying only into ^{6}He+n, thus it is a natural choice as intermediate state in the 3-body break up of ^{11}Be. A Monte-Carlo simulation of the proposed ^{11}Be(18.2)$\rightarrow \alpha+^7$He$\rightarrow \alpha+$n$+^6$He decay was performed. The involved resonances, ^{11}Be(18.2) and ^{7}He(gs), were described using the R-Matrix formalism. The centroid, 18.2 MeV, and width, 0.8 MeV, of the 18.2 MeV state in ^{11}Be were taken from the fit of the singles charged particle spectrum of [14] whereas we used for the ^{7}He(gs) the level energy, 0.43 MeV above the ^{6}He+n threshold, and FWHM, 0.4 MeV, from the latest compilation [18]. This simulation is part of a broader Monte-Carlo sim that fits the E$_{sum}$ spectrum of figure 2 [19]. Thus each channel ratio is weighted so that they reproduce the experimental intensity. The resulting E$_{D2}$+E$_{D4}$, E$_{sum}$, spectrum for the ^{7}He+α channel is plotted in dashed line in figure 2, whereas the thin continuous histogram corresponds to the five body, 2α3n, channel. It shows that the high energy part, E$_{sum}$ > 9 MeV, of the spectrum is dominated by the ^{7}He+α channel, as expected from the shape of the scatter plot. To further

check the simulation we selected events of $E_{sum} >9$ MeV and plotted their projection along a transverse line E', defined as the subtracted energy E'=$(1/\sqrt{2})$(E_{D2}-E_{D4}). Figure 3 shows the experimental E' plot in continuous line, the sequential decay simulation of the ^{7}He+α channel in dashed line and the simulation of the 3-body break-up described by phase space energy distribution in dotted line. The experimental data show a two-peak structure with a depression around 0 MeV. This experimental structure clearly favor the sequential ^{7}He+α channel over the phase space description, as the latter has its maximum precisely at around 0 MeV.

4. Summary and outlook

In this work we have studied the three body nα^6He break-up of the 18.2 MeV state in ^{11}Be. This state was previously identified to decay into five body 2α3n [13, 14] and three body nα^6He [14], where the break-up was described by phase space energy distribution. Careful inspection of the data presented in this work reveals a subtle tendency in the high energy part of the scatter plot. This tendency, in the form of two bumps of 4/7th and 7/4th slopes, hints a sequential decay involving the emission of an alpha particle from ^{11}Be, leaving a recoiling ^{7}He resonance which decays into ^{6}He+n. A Monte-Carlo simulation of this decay mechanism was performed and compared to the experimental data and a simulation of the break-up described by phase space energy distribution. The experimental E'=$(1/\sqrt{2})$(E_{D2}-E_{D4}) plot, corresponding to a projection along the transverse axis, shows a two peak and a middle dip structure that is reproduced in the sequential ^{7}He+α simulation but not in the break-up simulation described by phase space energy distribution.

The direct emission of α particles opens new possibilities to study the cluster structure of ^{11}Be, as the spin and parity of high energy states can be obtained from the angular correlation between the emitted particles. A previous n-γ coincidence study using a spin-polarized ^{11}Li [3] beam obtained the spin and parity for several low lying states in ^{11}Be, identifying states corresponding to rotational bands where significant clusterization was expected from AMD [11]. With this in mind we performed a new ^{11}Li β-decay experiment at ISOLDE. The new and improved experimental set-up allowed us to record a factor of five more coincidence events. The new data confirms unambiguously the ^{7}He+α channel and we look to obtain the spin and parity value for (several) high energy states in ^{11}Be.

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