IS-417
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This document summarizes the current status of the analysis of the ^{11}Li β-decay data taken in 2007 at ISOLDE. The analysis concentrated in studying the ^{7}He(gs) break-up channel following ^{11}Li β-decay. Two levels in ^{11}Be at 16 and 18 MeV excitation energy have been found to contribute to this channel. The study of the angular correlations and kinematics of the breakup of these two states through this channel favors a spin and parity assignment of $3/2^{-}$ for both of them. The presence of unaccounted coincidence statistics indicates the possible role of other states in ^{11}Be.

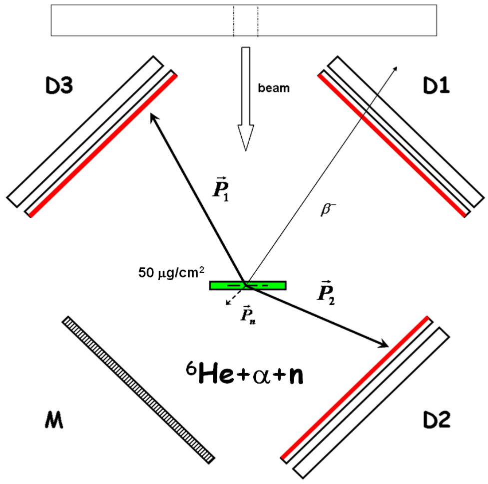

Figure 1. Schematic view of the set-up used in IS417 in 2007. An example of ^{11}Li β-decay followed by $n\alpha^6$He breakup is shown.

1 Introduction and experimental set-up

The ^{11}Li β-decay was measured at ISOLDE, CERN with a multiple DSSSD set-up optimized for the detection of charged particles in coincidence. The ^{11}Li β-delayed charged particle channels include nα^6He, 2α3n, ^{8}Li+t and ^{9}Li+d[1, 2, 3]. The main goal of this run was to study our previously proposed new ^{11}Li β-delayed decay channel involving the ground state of ^{7}He [4], which is a subset of the nα^6He channel.

The set-up consisted of 3 DSSSD and a prototype monolithic detector (for testing purposes) as shown in Fig. 1. The detectors on the back side of the carbon foil, DSSSD's D1 and D3, were 5 cm away from the foil, thus covering ∼4% of 4π. DSSSD D2 was 3.7 cm away from the source, covering ∼7.2% of 4π. The 64 detector elements of the monolithic detector have a combined angular efficiency of ∼1.8% of 4π.

The geometry of the setup defines three possible types of two-particle coincidences, depending on which detectors were hit. Hits in DSSSD D2 and DSSSD D3 (see Fig. 1), classified as *180^o* coincidences, covered angles from 120^o to 180^o between the detected particles. Hits in DSSSD D1 and either DSSSD D2 or DSSSD D3, classified as *90^o* coincidences, covered angles from 31^o to 149^o between the detected particles. Finally, coincidences detected in the same detector, classified as *0^o* coincidences, covered angles from 0^o to 50^o between the detected particles for detectors D1 and D3 and between 0^o and 68^o for D2.

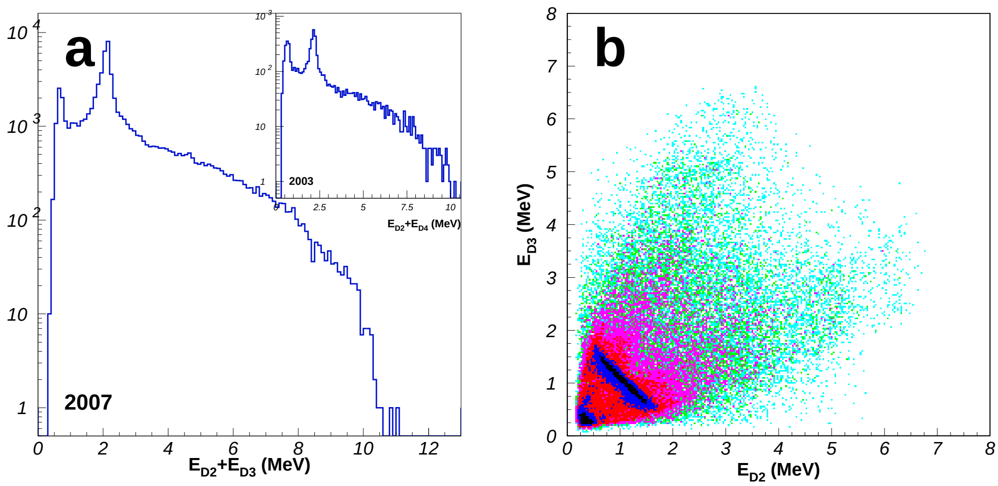

Figure 2. Left: *180º* coincidences sum energy with a Monte-Carlo simulation of the decay shown on red dashed line. The simulation includes the different decay channels proposed in [4] plus the ^{7}He+α breakup of the 16.2 and 18.3 MeV states in ^{11}Be discussed in this summary. The different branching ratios were adjusted from the last experiment [4], except for the 16.2 and 18.3 MeV states in ^{11}Be decaying through ^{7}He, which were adjusted directly to the intensity observed in Fig. 3*b*. Please see the text for further information on the discrepancies between the simulation and the data. Right: *180º* coincidences scatter plot. There are two clear groupings of data along bands of 7/4 and 4/7 slopes, indication of ^{7}He+α breakup.

2 Analysis

2.1 180 coincidences

Following the work presented in [4], we first concentrate in *180º* coincidences as defined above. The sum energy spectrum for *180º* coincidences in 2007 data is shown in Fig. 2*a*, compared to the 2003 spectrum shown in the inset. The data from 2007 yielded 10 times more statistics than the on from 2003. There are four β-delayed particle channels in ^{11}Li that could possibly contribute to this spectrum, n+α+^{6}He, 2α+3n, ^{8}Li+t and ^{9}Li+d. The low recoil energy of the ^{9}Li ions ($\leq$ 160 keV) makes the last channel undetectable in our set-up. Given that the branching ratio of the ^{8}Li+t channel is a factor of 40 smaller, accorgin to the published ratios [3, 6], than the ratios of the 2α+3n and n+α+^{6}He channels, its contribution to the sum energy spectrum is expected to be very small, around 3% of coincidence events.

The scatter plot corresponding to the 180^{o} coincidences is shown in Fig 2*b*. The main features observed in the scatter plot are the low energy grouping, corresponding

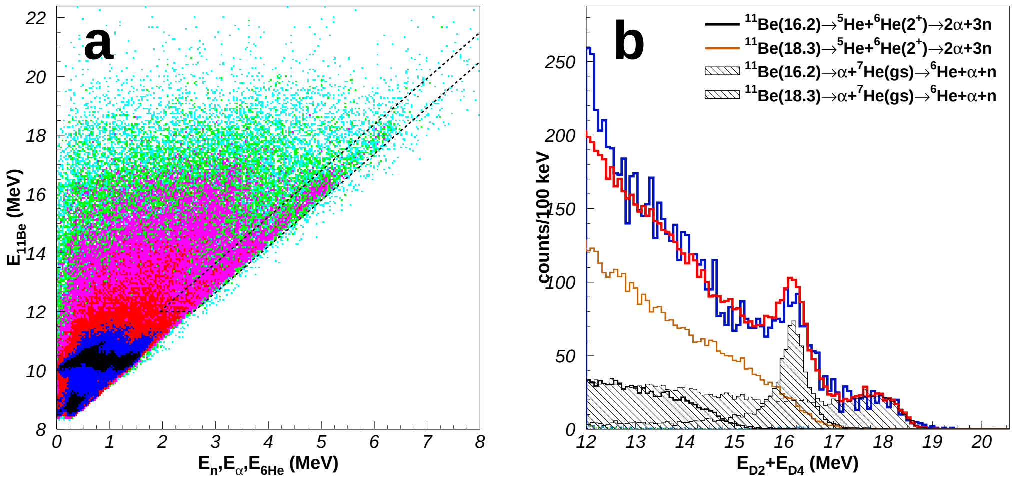

Figure 3. Left: *180º* individual n, α and ^{6}He energies plotted against the ^{11}Be excitation energy. Please bear in mind there are three horizontal points for each ^{11}Be excitation energy. The two dashed lines indicate the gate around the 11/7 band corresponding to breakup through ^{7}He(gs). Right: ^{11}Be excitation energy corresponding to events gated on the band shown on the left. The red line corresponds to a Monte-Carlo simulation of two states at 16.2 and 18.3 MeV in ^{11}Be decaying through ^{7}He(gs) including background components from 5-body breakup. The different components are shown with color code as shown in the legend.

to the 0.7 MeV peak in the sum energy spectrum, the transverse line, corresponding to the 2.2 MeV peak in the sum energy spectrum, and a broad distribution of points scattered at higher energies. Interestingly, some events in the broad distribution of points are seen grouping along two bands of 7/4 and 4/7 slope, as expected from a sequential break-up of states in ^{11}Be through the ^{7}He(gs) resonance [4].

To further investigate the origin of these bands we used the individual neutron, α and ^{6}He energies vs excitation energy in ^{11}Be plot for *180º* coincidences, Fig. 3*a*. The neutron energy is calculated using energy and momentum conservation, assuming that the particle detected with the lowest energy is the ^{6}He. The advantage of this plot is that, for sequential break-up of broad states, the first emitted particle will group along a line whose slope and offset are given by the fragment mass ratio to ^{11}Be and the Q value respectively. The obvious disadvantage is that most of the *180º* events are α-α coincidences from the 5-body channel, which we cannot correctly identify in this way as we cannot calculate the energy of the three undetected neutrons. Therefore, the 5-body events scatter randomly in the plot and act like a background for any 3-body channel present. The *180º* coincidence events in the 'fynbo' plot are shown in Fig. 3*a*. There are two distinct features of the plot. A

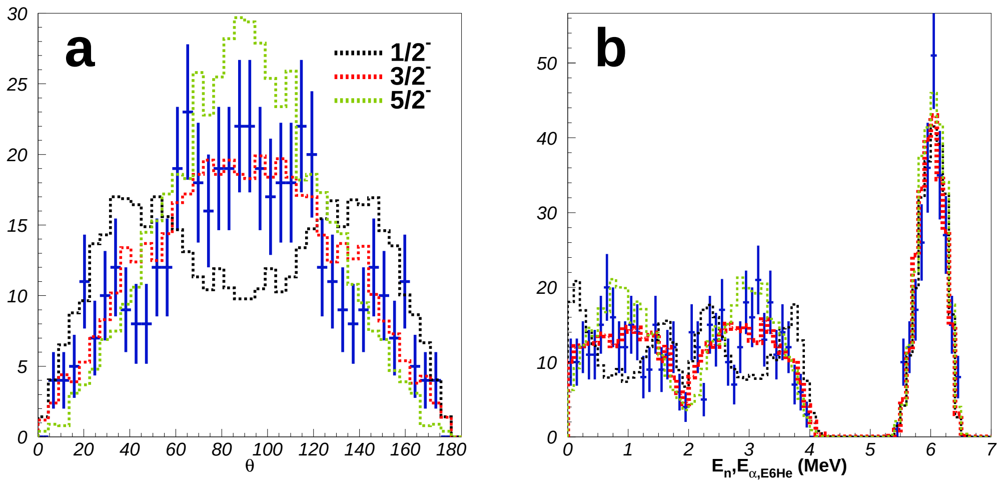

Figure 4. Left: *180º* coincidences angular correlations for events gated on the 18.3 MeV state in ^{11}Be. The different simulations of the possible spins and parities are color coded as shown in the legend. Right: individual n, α and ^{6}He energy for the same gate as in the left. The simulations have the same color code as in the left. χ^2 test of the simulations for both angular correlations and the individual energy plots favor a $3/2^-$ assignment for this level.

horizontal line at 10.6 MeV ^{11}Be excitation energy, corresponding to the break-up of the $5/2^-$ state at that energy in ^{11}Be and a line of 11/7 slope and 8.33 offset, which corresponds to α particles emitted in the break-up of ^{11}Be states through the ^{7}He(gs) resonance. There are two groupings of data at around 16 MeV and 18 MeV in ^{11}Be, indicating the presence of states in ^{11}Be at this energies.

Having sorted out the ^{7}He+α from the remaining decay channels, it is trivial to select events from this decay channel. We used an 1 MeV wide gate on α particles which are on the 11/7 line on the 'fynbo' plot, shown by the two dotted lines in Fig. 3*a*. The ^{11}Be excitation energy for events on this gate and excitation energy greater than 12 MeV is shown in figure 3*b*. A Monte-Carlo simulation was performed including the decay of two levels, modeled using non-interfering single-channel R-matrix formalism, on top of the 5-body 2α+3n channels acting as background. Currently the level centroids, 16.25 MeV and 18.3 MeV, and widths used, 0.55 and 1.0 MeV respectively (shown in Table 1), have been optimized to the data by hand. We currently use parameters from [6] for the 5-body break-up of the ^{11}Be state at around 18 MeV, which are different from those obtained fitting the peak observed in the ^{7}He channel. Proper χ^2 analysis on the ^{7}He channel should be done before any conclusion can be reached.

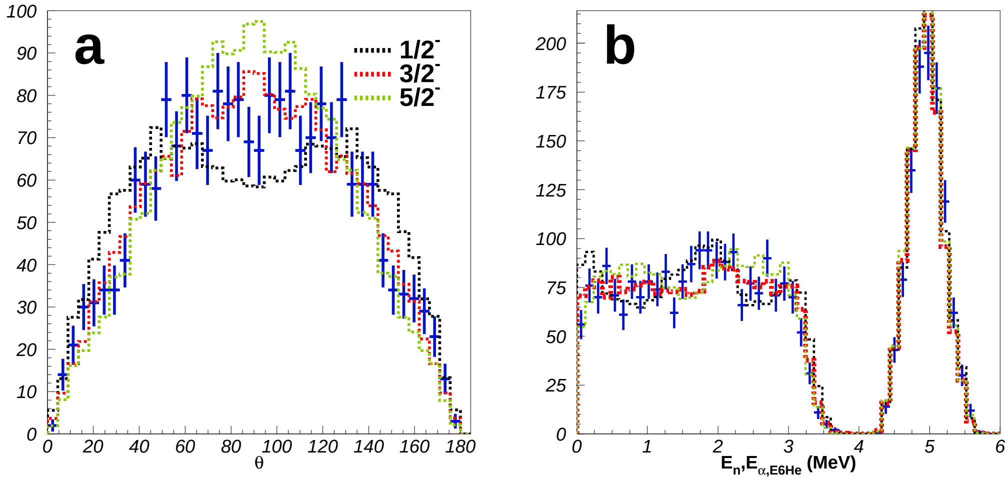

Figure 5. Left: *180º* coincidences angular correlations for events gated on the 16.2 MeV state in ^{11}Be. The different simulations of the possible spins and parities are color coded as shown in the legend. In all the cases the contribution of the 18.3 MeV level in ^{11}Be was fixed to $3/2^{-}$, from Figs. 4 *a* and *b*. Right: individual n, α and ^{6}He energy for the same gate as in the left. The simulations have the same color code as in the left. χ^2 test performed over the simulations for both angular correlations and individual energy favor a $3/2^{-}$ assignment.

To investigate the nature of the two levels decaying through ^{7}He we studied their angular correlations and kinematics, comparing them to different simulations of the levels modifying their spin and parity. In all cases the spin and parity of the intermediate ^{7}He state in the simulation is $3/2^{-}$, which is the tentative assignment from the last compilation [7]. Figure 4*a* shows the angular correlations for events gated around the 18.3 MeV state, and Figure 4*b* the individual n, α and ^{6}He energy. Simulations are shown for different spins and parities, $1/2^{-}$ in black, $3/2^{-}$ in red and $5/2^{-}$ in green. χ^2 tests for the simulations for both the angular correlations and the decay kinematics, shown in Table 2, favor a $3/2^{-}$ assignment.

Figure 5*a* shows the angular correlations for events now gated on the 16.2 MeV peak, and 5*b* the individual n, α and ^{6}He energy. This case is a little bit more complicated than the state at 18.3 MeV, as there are underlying contributions from 5-body breakup and from the ^{7}He+α break up of the state at 18.3 MeV. From the simulation shown in figure 3*b* one can calculate that 27% of the intensity in the gate around the 16.2 MeV state is from the ^{7}He decay of the state at 18.3 MeV and 22% is 5-body break up of the same state. From the previous χ^2 analysis we can fix the spin and parity of the state at 18.3 MeV to $3/2^{-}$ and study the spin and parity of

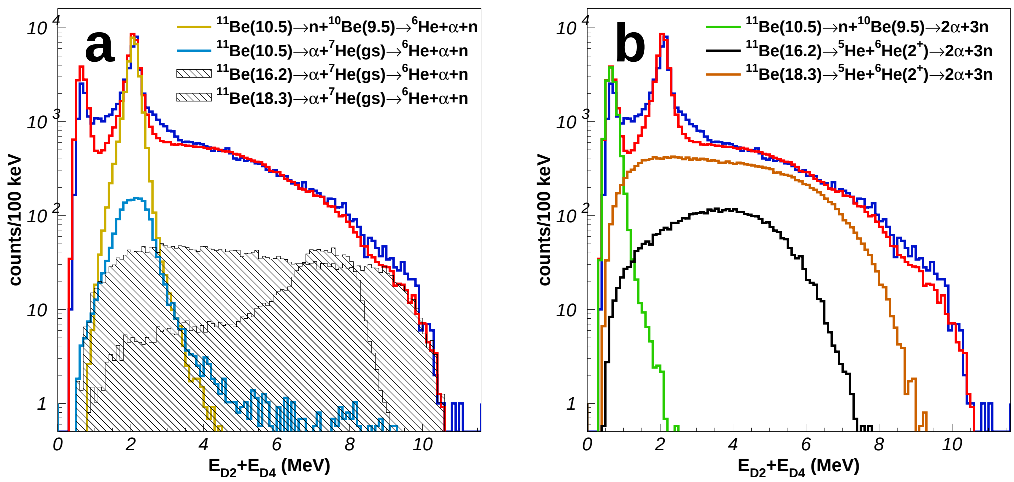

Figure 6. Left: the contribution of the 3-body channels to the Monte-Carlo simulation, in red, is shown. Right: contribution of the 5-body channels to the Monte-Carlo simulation. Possible background influence apart from the ^{7}Li+α peak at 1 MeV should be considered before the differences between data and simulation can be taken into account as new decay channels.

the state at 16.2 MeV alone, as shown in the different simulations on Figs. 5 *a* and *b*. Again χ^2 analysis of the different simulations, shown in Table 2, favors a $3/2^-$ spin and parity assignment for the 16.2 MeV state.

The red dashed line in Figs. 6 *a* and *b* corresponds to a Monte-Carlo simulation of the breakup of states in ^{11}Be including the previously known channels [1, 4] plus the ^{7}He+α breakup of the 18.3 and 16.2 MeV states discussed above. The three body breakup channels are shown in Fig. 6*a* while the five body are shown in Fig. 6*b* for clarity. There are three main discrepancies between the simulation and the data. First at ∼1 MeV, where we expect the ^{7}Li+α breakup of ^{11}B to contribute but it has not been yet implemented in the simulation. Then, at ∼2.5 MeV, which corresponds with a zone of increased statistics in the 7/4 and 4/7 bands Fig. 2*b*. This hints the presence of a state in ^{11}Be at around 11 MeV decaying through ^{7}He(gs). However, no direct evidence is found in Fig. 3*a*, which is likely to be explained by incorrect ^{6}He and α identification, thus preventing us to properly reconstruct the neutron energy. Finally, the experimental intensity at ∼9 MeV is slightly higher than the simulation. This region is expected to be dominated by the breakup of the 18.3 MeV state in ^{11}Be through ^{7}He, which was adjusted to the observed intensity in Fig. 3*b*. The discrepancy in statistics indicates the presence of a small contribution of another channel.

Table 1. Level centroid and reduced widths used in the R-Matrix description of the states modeled in the Monte-Carlo code. The Γ was obtained from a gaussian fit of the R-matrix peak directly.

	E_0 (MeV)	γ^2 (MeV)	Γ (MeV)	Ref.
^{11}Be(10.59 MeV)	10.59	0.21	0.227	[5]
^{11}Be(16.2 MeV)	16.25	0.05	0.55	
^{11}Be(18.3 MeV)(3-body)$\dagger$	18.3	0.1	1.0	
^{11}Be(18.15 MeV)(5-body)	18.15	0.06	0.8	[6]
^{10}Be(9.5 MeV)	9.52(2)	0.21	0.30(4)	This work
^{7}He(gs)	$0.43^{\ddagger}$	0.4	0.148(1)	[7]
^{6}He(2^+)	1.8	0.113	0.117(1)	[7]
^{5}He(gs)	$0.895^{\S}$	2.5	0.658(4)	[7]

† optimized to fit the ^{11}Be excitation energy reconstructed from the ^{7}He channel (see text).
‡ above the ^{6}He+α threshold.
§ above the α+n threshold.

2.2 Summary and outlook for 180 coincidences.

The analysis of *180º* coincidences confirms and expands previous findings [4]. The presence of ^{11}Be three body breakup through the ground state of ^{7}He is directly confirmed by the observation of its signature in the kinematics nα^6He plot. By gating on this signature we were able to identify two states in ^{11}Be at 16.2 and 18.3 MeV. Moreover, the study of the two states angular correlations and kinematics indicates a $3/2^-$ spin and parity assignment for both states.

To improve the analysis of the ^{7}He channel one should use take into account

Table 2. Results of the χ^2 test performed over the simulations for both the angular correlations (θ) and the individual n, α and ^{6}He energy plot (kinematics).

	^{11}Be(16.2)		^{11}Be(18.3)	
	$\chi^2(\theta^\dagger)$	χ^2(kinematics‡)	$\chi^2(\theta^\dagger)$	χ^2(kinematics‡)
$1/2^-$	63	162	70	152
$3/2^-$	21	51	18	48
$5/2^-$	55	84	30	64

† N_{free}=19
‡ N_{free}=49

interference effects between the two levels, as they are likely to have the same spin and parity. χ^2 minimization of the level centroid and reduced widths have to be performed before publication.

3 To-do list

- Subtract background from Figs. $2a$ and $3a$ by selecting a 60 ms sample of delayed events (at least one second after proton release).
- Study *90º* coincidences.
- Include DSSSD D1 in the Monte-Carlo code to simulate *90º* coincidences.
- Reproduce in the Monte-Carlo the experimental relative intensity between the *180º* and *90º* coincidences.
- Study *0º* coincidences.
- Estimate intensity of the ^{8}Li+t channel in *180º* coincidences.
- Look for correlations between ^{8}Li events in *180º* coincidences and delayed 2α events.
- Estimate the delayed ^{8}Li$\rightarrow \alpha+\alpha$ intensity.
- Calculate the theoretical proportion of ^{8}Li that should stay in the carbon foil, thus producing delayed 2α events with momentum matching their emission from the foil.
- Calibrate the time after proton release (tshort) plot.
- Obtain the tshort plot for *180º* coincidences.
- Look for ^{9}Li events is delayed *90º* coincidences.
- Theory: Otsuka, Brown & Morrissey, Gabriel Martinez Pinedo.

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