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Study of the β-delayed multiple particle break-up of the 2.43 MeV state in ^{9}Be.

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The aim of this work is to study the β-delayed multiparticle break-up of the $5/2^-$ state in ^{9}Be at 2.43 MeV excitation energy. This process is relevant as it has been proposed recently that this level plays a role in the $\alpha(\alpha n,\gamma)^9$Be reaction. This state breaks-up in 2α+n, and sequential as well as direct ("democratic") decay have previously been considered. In our work energy and direction of the two emitted α particles has been measured, while those of the neutron have been reconstructed. The sequential decay is considered using the R-matrix formalism. For the democratic decay the hyper-spherical harmonics functions are used. The different decay processes are compared with the data using the Monte-Carlo method. Our preliminary results indicate that the data is better described when democratic decay is assumed.

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1. Motivation and Introduction

In neutron rich environments, like those found in the hot bubble of a core-collapse supernova or the He layer of low-mass Asymptotic Giant Branch stars, the $\alpha(\alpha n,\gamma)^9$Be and ^{9}Be($\alpha$,n)^{12}C reactions become significant in bridging the mass 5 gap into heavier elements, since the triple-α reaction becomes slow. The $\alpha(\alpha n,\gamma)^9$Be reaction occurs mainly through the ground and 2^+ states in ^{8}Be [1, 2] populating the first and third excited states in ^{9}Be. Recent calculations by Buchmann et al. [1] show that, at high temperatures, reaction channels through excited states in ^{9}Be above the $1/2^+$ are favoured. Calculations using the microscopic cluster model [3, 4] and a recent experiment [5, 6] show that the ^{5}He+α channel is dominant for high spin states. Therefore, if one wants to precisely know the reaction rate in a wide range of temperatures it will be necessary to take into account this channel. Up to date the decay mechanism of the $5/2^-$ state is not yet settled and both sequential and direct decay have been considered. The different experiments agree in a partial branch of 7% to the ^{8}Be(gs) [7] from the 2.43 MeV state.

Our recent studies [8, 9, 10] on β-delayed multi-particle break-up have shown that full kinematic coverage allows to univocally determine the decay mechanism. This technique has been successfully used to determine the decay mechanism of the low-energy states in ^{9}Be [6]. However the $5/2^-$ state at 2.43 MeV was not thoroughly studied. The purpose of this experiment is to extend the study to this state, determining its break-up mechanism, whether it is sequential or democratic, and if the former is confirmed find out which intermediate levels are involved.

2. Experiment

The experiment took place at ISOLDE, CERN. The ^{9}Li beam was obtained using the ISOL technique. A Ta target, bombarded by 1.4 GeV protons from the PS-Booster proton synchrotron from CERN, was combined with a tungsten ionization source. A 30 kV voltage was used to extract the spalation products. The ^{9}Li 1^+ beam was selected among them using the GPS isotope separator. The 30 keV ^{9}Li$^+$ pure beam was stopped in a 60 μg/cm^2 carbon foil.

The set-up consisted in 4 telescopes with thin DSSSD detectors in front stacked in thick silicon pads, mounted on the surfaces of a 10x10x10 cm cubic frame, covering 4% of 4π each (two of them have ultra-thin deadlayer to increase the sensitivity at low energy [11]). Charge collection in these DSSSD's is carried out by 16 vertical and 16 horizontal strips, constituting 256 individual detectors. Thus, it allows a high angular coverage while having enough spatial resolution. 1.5 mm thick silicon detectors were placed behind each DSSSD for β detection. A ΔE-E (1μm-400μm thick) silicon telescope was placed for test on one of the faces of the cube (it covered 0.5% of 4π). The neutrons were detected using part of the neutron time of flight detector TONNERRE [12]. The array used consisted in 16 scintillator plastic bars 160 cm long, 20 cm wide and 4 cm thick with a 120 cm curvature radius placed around the experimental chamber. The array had a large angular acceptance (as installed at ISOLDE up to 25% of 4π), with an energy resolution of 80 keV for 1 MeV neutrons and intrinsic efficiency of 50%. The energy range for neutrons covered from 300 keV to 5 MeV.

3. Results

The high granularity of the DSSSD detectors allows a precise reconstruction of the momentum of the incoming particles. The ^{9}Be states populated in the decay of ^{9}Li break-up into three particles, two α and a neutron. If we neglect the recoil due to the β emission, the break-up of states in ^{9}Be fed in the β decay occurs at rest. In this case, if we detect two of the emitted particles, using energy and momentum conservation, we can calculate the energy of the missing particle. This is specially important in the decay of ^{9}Li, since one of the emitted particles is a neutron, which is difficult to detect in coincidence with other particles. Figures 1a and 1b show the ^{9}Li reconstructed β-delayed break-up events (^{9}Li$\rightarrow$ β+^{9}Be*$\rightarrow$2α+n). The y-axis represents the total energy of the three particles (which is the excitation energy in ^{9}Be minus the 1.57 MeV 2α+n threshold energy), while the x-axis represents the individual energy of the three emitted particles. Thus, there are three points for each event. In this kind of representation the decay channel is easily determined, as the slope of the lines is related to the mass of the first emitted particle [8]. On the left part "a" the α particles are detected in opposite detectors (angle between the detected particles will be in the range from 127° to 180°). On the right part , "b", the α particles are detected in the same detector (angle between 3.5° and 53°). Visual inspection of the figures reveals the decay through the ^{5}He(gs) and ^{8}Be(2^+) (part a) and ^{8}Be(gs) (part b). The state at 2.43 MeV in ^{9}Be (the region below 0.9 MeV sum energy in the plot) is expected to decay mainly through the ^{5}He(gs) as shown in figure 1a. However, decay via the tail of ^{8}Be*(2^+) has not been discarded [13]. Decay to the continuum has also been considered [14]. The ^{5}He(gs) and ^{8}Be(2^+) cannot be easily resolved, as it can be seen in figure 1a. The tail of the level 2^+ state in ^{8}Be overlaps with the ^{5}He ground state. The decay through the ^{8}B(gs) could not be measured in this experiment, as the line connected to this decay mode (see figure 1b) has no events below 2 MeV sum energy. But all previous experiments agree that the partial contribution of the decay of this state via the ^{8}Be(gs) is 7% [7].

To test the remaining possible decay channels, sequential decay through ^{5}He(gs) and ^{8}Be*(2^+) or direct decay Monte-Carlo simulations were performed. These simulations include the geometry of the set-up and the low-energy cut-offs imposed in the data analysis. This is necessary since the energy range experimentally detectable at low energies distorts the emitted alpha phase space.

The sequential decay of states and resonances were reproduced using the R-matrix theory, where the probability of ^{9}Li decaying to a certain state in ^{9}Be and a subsequent decay to a resonance in ^{5}He (or ^{8}Be) is given by

$$w(E_{^9Be},E_{^5He}) = f_\beta(E_{^9Be})\frac{\Gamma_{^9Be}}{(E^0_{^9Be}-E_{^9Be})^2+(\Gamma_{^9Be}/2)^2}\cdot\frac{\Gamma_{^5He}}{(E^0_{^5He}-E_{^5He})^2+(\Gamma_{^5He}/2)^2} \tag{3.1}$$

were $f_\beta(E)$ is the fermi function, $\Gamma=2\gamma^2$P(E) is the level width (γ is the reduced width and P(E) is the penetrability) and E^0 is the level centroid. Both E^0 and the levels widths are taken from [7]. The interaction radii used are R(^{9}Be)=4.5 fm, R(^{5}He$_{gs}$)=6.2 fm and R(^{8}Be$_{2^+}$)=6.2 fm. In the case of democratic decay a three-body decay was used. The probability of emitting the particles in a given solid angle is given by the sum of hyper-spherical harmonics of grand momentum K=3 following the formulation of Bochkarev et al. [15]

$$\frac{d^3p}{dyd\Omega_\alpha d\Omega_{\alpha N}} = a\frac{2^3}{\pi^3}y^{3/2}(1-y^{5/2})\sin^2\phi + b\frac{2^4}{7\pi^3}y^{3/2}(1-y)^{5/2}(2+\cos^2\phi) \tag{3.2}$$

where the first term corresponds to grand orbital momentum L=2 and the second term to L=3. The constants *a* and *b* are arbitrarily chosen to best fit the experimental spectrum, and y is related to the

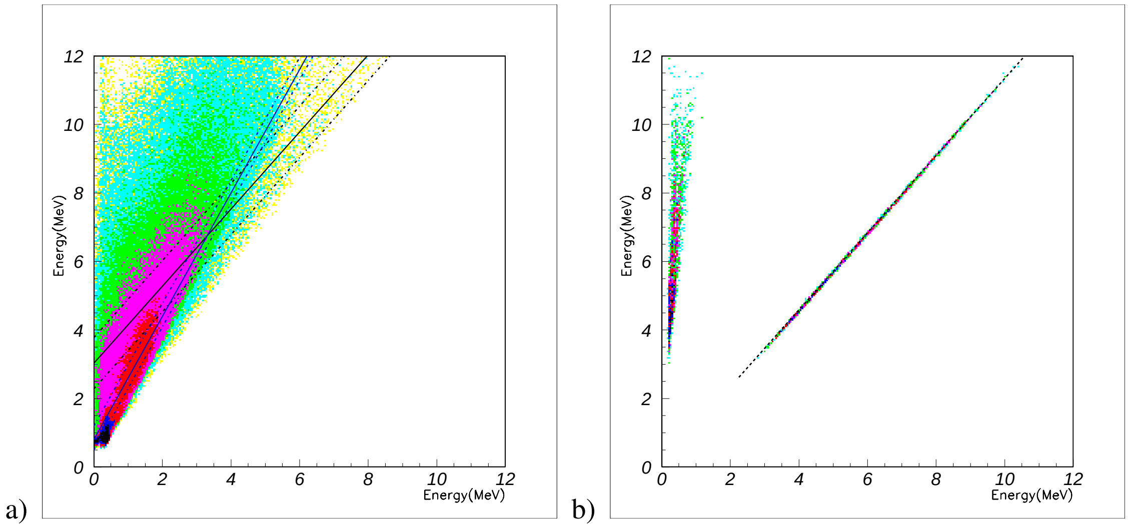

Figure 1: The scatter plots show the reconstructed energy of the 2α+n events after ^{9}Li β-decay. On the y-axis it is shown the sum energy equal to the excitation energy in ^{9}Be minus the threshold energy. The plot on the left ("a") shows the events observed in opposite detectors (α particles with angles between 127°and 180°). The solid lines of slopes 9/8 and 5/8 indicate the centroid of decay through the ^{8}Be(2^+) (black line) and ^{5}He(2^+) (blue line) respectively. The dash-dotted lines indicate the Γ-width of these states. The plot on the right ("b") shows the events corresponding to α particles detected in the same detector (with angles between 3.5°and 53°). The dashed black line locates the sequential decay through the ground state of ^{8}Be. By combining these two plots a similar distribution to that of figure 2 of ref. [5] can be obtained.

energies of the emitted particles as y=$\frac{9E_\alpha}{5(E_{^9Be}-1.57)}$. Several combinations of *a* and *b* were tested in the democratic decay simulation, obtaining the best agreement with the data using *a*=0 and *b*=1.

The results of the simulations compared to the experimental data are shown in figures 2a and 2b. Figure 2a shows the coincidence spectrum imposing that the sum energy of the three particles is less than 0.9 MeV. Figure 2b shows the singles alpha energy in the detector facing the foil as it had the lowest energy cut-off. The best agreement with the data is obtained assuming democratic decay. Furthermore, the sequential decay simulations through ^{5}He or ^{8}Be cannot reproduce individually or combined the shape of the coincidence and singles data.

4. Summary

The break-up of the level at 2.43 MeV in ^{9}Be following the β-decay of ^{9}Li has been studied using a full kinematic set-up. The data is compared with simulations where sequential decay through ^{5}He and/or ^{8}Be(2^+) states as well as democratic decay are considered. The simulated singles and coincidence spectra favor the democratic break-up described by hyper-spherical harmonics of grand orbital momentum L=3. The decay of the level through the ground state of ^{8}Be could not be measured in this experiment as it involves very low energy α particles well below our energy cut-off of 200 keV. This experiment supports the results obtained from a previous experiment realized by our group in 2002 (unpublished).

Careful check of the different energy cut-offs as well as better reconstruction of the α-α coincidences at very low energy is needed before firm conclusions can be obtained.

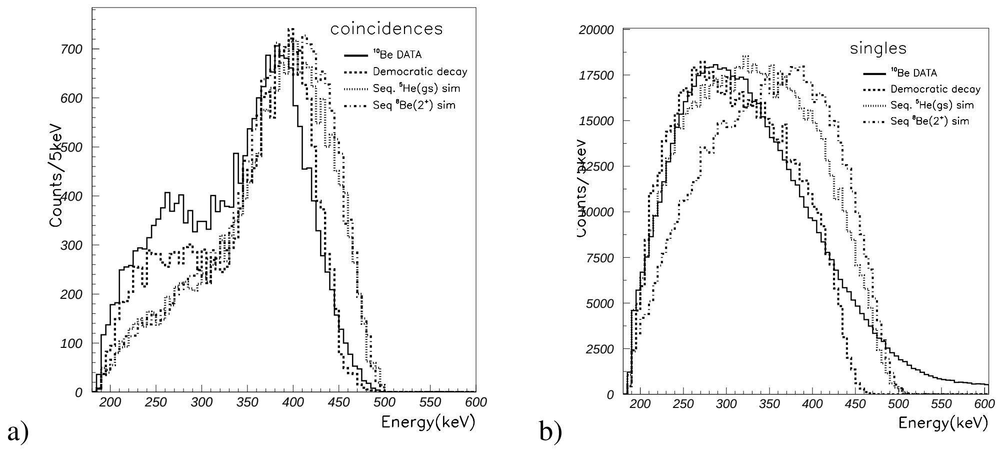

Figure 2: Comparison between the experimental data (continuous line) and the democratic decay (dashed line), sequential decay through the ground state of ^{5}He (dotted line) and sequential decay through the 2^{+} state in ^{8}Be (dotted-dashed histogram). Figure a) shows the coincidence data and figure b) the singles data taken in one of the detectors. Democratic decay is favored by the coincidence data. And it clearly reproduces the singles data better than the simulationsof sequential decay. The energy region above 450 keV that cannot be described by the democartic decay is assigned to the break-up of a level at 5 MeV in ^{9}Be [6].

References

[1] L. Buchmann et al, Phys. Rev. C 63(2001)034303

[2] K. Sumiyoshi et al., Nucl. Phys. A 709(2002)467.

[3] P. Descouvemont, Eur. Phys. J. A 12(2001)413.

[4] K. Arai et al., Phys. Rev. C 43(1991)1758.

[5] Y. Prezado et al., Phys. Lett. B 576(2003)55.

[6] Y. Prezado et al., Phys. Lett. B 618(2005)43.

[7] D.R. Tilley et al., Nucl. Phys. A 745(2004)155.

[8] U.C. Bergmann et al., Nucl. Phys. A 692(2001)427.

[9] H.O.U. Fynbo et al., Phys. Rev. Lett 91(2003)82502.

[10] H.O.U. Fynbo et al., Nature 433(2005)136.

[11] O. Tengblad et al., Nucl. Inst. and Meth A 525 (2004) 458.

[12] A. Buta et al., Nucl. Inst. and Meth A 455 (2000) 412.

[13] Y.S. Chen, T.A. Tombrello and R.W. Kavanagh, Nucl. Phys. A 146(1970)136.

[14] C.L. Cocke and P.R. Christensen, Nucl. Phys. A 111(1968)623.

[15] O.V. Bochkarev et al, Nucl. Phys. A 505(1989)215.