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Viñals, S., Borge, M., Tengblad, O. et al (2020)
The experiments to determine the electron capture and ß-decay of 8B into the highly excited states of 8Be
Journal of Physics: Conference Series, 1643(1)
http://dx.doi.org/10.1088/1742-6596/1643/1/012130

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Journal of Physics: Conference Series **1643** (2020) 012130 doi:10.1088/1742-6596/1643/1/012130

The experiments to determine the electron capture and β-decay of ^{8}B into the highly excited states of ^{8}Be

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Abstract.

The main goal of this work is to study the structure of the highest energy states in ^{8}Be populated following the β^{+}-decay and the electron capture (EC) of ^{8}B. With this aim, two experiments were performed at ISOLDE-CERN in 2017 and 2018. The first experiment had the aim to resolve the 2^{+} doublet at 16.6 and 16.9 MeV, in order to study their isospin mixing. The second experiment aimed to determine a value or give an experimental upper limit to the branching ratio of the exotic EC-p decay.
In this paper, we present the experimental setups and we discuss the analysis and present the preliminary results obtained so far.

1. Introduction

The ^{8}B nucleus is interesting both from astrophysics and nuclear structure point of view. As far as is known the ^{8}B decay by allowed transitions to the 2^{+} states in ^{8}Be that break into two alphas (see figure 1). The β^{+}-decay of the ^{8}B is the main source of solar neutrinos above 2 MeV, thus the shape of the β^{+}/EC-decay α-spectrum has thus been studied in detail in numerous occasions (see reference in [1] and reference therein). The interest of the present study focuses on the ^{8}B nuclear structure and the study of the population to high excited states in the daughter ^{8}Be.

^{8}B is the paradigm of nucleus with a proton halo configuration in its ground state. This structure has been studied via cross section measurements in scattering reactions experiments [2, 3, 4], however this complex structure has not been connected to any sign in the decay experiments. The presence of proton halo structure should manifest via the enhancement of the population

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of the 1^+ T=1 state at 17.640(1) MeV of ^{8}Be via electron capture (EC) process as the β^+-decay is not energetically allowed (Q=17.9799(10) MeV). This state is 385 keV above the ^{7}Li+p threshold and its known from reactions to decay mainly by proton emission. As explained in [5], it can be assumed that the ^{8}B has a halo structure with a ^{7}Be core plus a proton. If we assume that the EC process occurs in the core part, then, the transition matrix element can be estimated to be the same than for the ground state of ^{7}Be decaying into the ground state of ^{7}Li. Scaling by the half-life an upper limit of the branching ratio of the EC-p transition can be set to 2.3×10^{-8}. A previous experiment of our collaboration established an experimental upper limit of this branching ratio of 2.6×10^{-5} [5]. This limit is poor due to the low statistics of the experiment and that the setup used was not optimized for this purpose.

In addition, we are interested in the structure of the 2^+ doublet in ^{8}Be at 16.626(3) MeV and 16.922(3) MeV which it is assumed to be strongly isospin-mixed [6]. This doublet have dominant configurations as ^{7}Li+p and ^{7}Be+n respectively. The lower state is 332 keV below the endpoint of the β-decay phase space meanwhile the 16.922 MeV state is 36 keV above (see figure 1). Knowing the β-decay phase space of each state, the ratio between the β^+-decay between these two states in absence of EC is 1.5×10^{-5}. However, it has been shown experimentally that the decay-rate between the feeding of these two states is three orders of magnitude higher why it is mandatory to include the electron capture phase space to obtain the right ratio. Including both β-decay and EC, the ratio is 2.4×10^{-2} [1].

The feeding in β^+/EC decay of the 16.922 MeV state was first seen, but with very low statistics, in a previous experiment performed at IGISOL by our collaboration, where 5 counts at the end of the energy excitation spectrum of ^{8}Be were assigned to the 16.922(3) MeV to be compared with the 180 counts into the 16.626 MeV state [1]. Higher statistics for the feeding of both states are necessary to learn more about the isospin mixing of the 2^+ doublet.

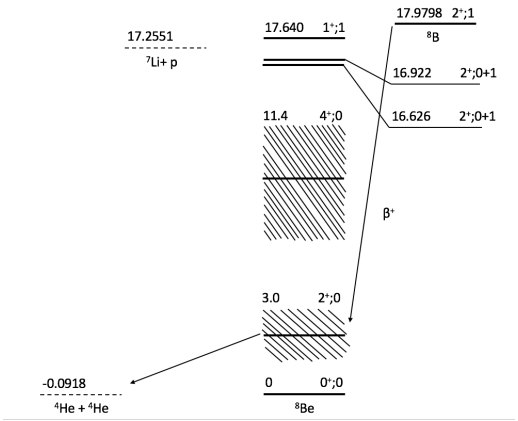

Figure 1. Level scheme of ^{8}B decay into ^{8}Be. Energies from [7].

To this purpose, two different experiments were performed at ISOLDE-CERN and they were focused each on one of the objectives explained above . The first one (IS633A) was done in 2017 at the ISOLDE Decay Station (IDS) beamline. The aim was to observe and resolve the feeding to the 2^+ doublet at 16.6 and 16.9 MeV in ^{8}Be with enough statistics. The second experiment (IS633B) done at ISOLDE in 2018 was optimized to determine or set the limit of the EC-p branching ratio to the 17.640 MeV state.

2. Experimental setups and beam production

In this section, the two experimental setups used and the characteristics of the ^{8}B beam are detailed.

2.1. IS633A

For the first experiment, a diamond configuration of four Si-telescopes was used. The telescopes were composed by a thin ΔE-DSSD (40 μm and 60 μm) with 16 strips each side backed by thicker Si-detector of 1000 μm and 1500 μm respectively. The detectors were fixed into a 3D-printed plastic structure to avoid any movement during the experiment and facilitate the reproducibility of the geometrical conditions of the experiment during the use of external alpha sources. The plastic was fixed to the electronic board where the connectors for each detector were assembled. In addition, a Double-sided Stripped Silicon Detector (DSSD) was placed on the bottom. Its thickness was of 1000 μm and used to detect mainly the β contribution.

The figure 2 shows a photo of the setup while figure 3 shows a schematic view of the detectors placement surrounding the carbon-catcher foil (C-foil of 31μg/cm^2) where the beam perpendicular to the foil was implanted.

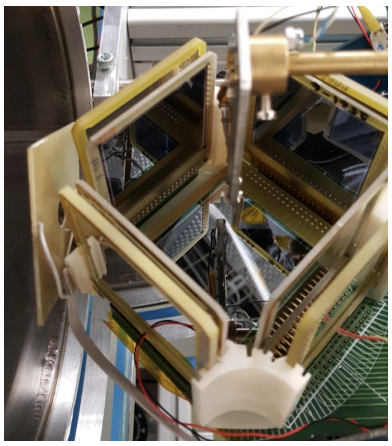

Figure 2. Picture of the chamber used in IS633A experiment and the detectors mounted on it

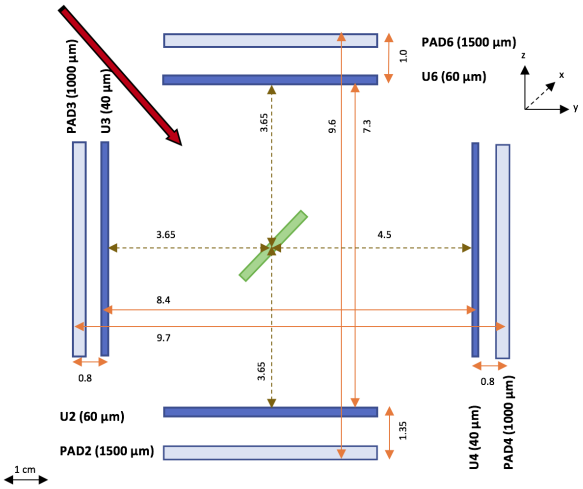

Figure 3. Scheme of the setup were the distances and thickness of the detectors are shown for IS633A experiment. The red thick arrow is the incoming ^{8}B beam.

Two different front detector thickness were used in the telescope; the thicker ΔE-DSSD of 60 μm assure the full detection of the highest energy α. The thinner ΔE-DSSD of 40 μm were placed to search for the delayed proton emission as in this case a low β^{+}-response background is mandatory. The solid angle covered by the setup is 50.33(23)% of 4π. As seen in figure 3 the setup is not fully symmetric being the distance between the 60 μm ΔE-DSSD detector of 7.3 cm while between the 40 μm ΔE-DSSD detectors is of 8.4 cm. Thus the α-α coincidence efficiency is different. Therefore the analysis we will present below is based in the α-α coincidence of the 60 μm + 1500 μm telescopes.

2.2. IS633B

This experiment that took data in 2018 had a setup composed by three Si-detectors, two of them are in a telescope configuration. The telescope detector, consisted of a small sized Si surface barrier detector 30 μm thick and with 100 mm^2 of active area in front used as a ΔE and behind a big E-detector 500 μm thick with an active area of 50×50 mm^2.The third detector was opposite at the other side of the implantation point. The detector was a PAD of 500 μm thickness and 50×50 mm^2 of active area. A schematic view of the setup is shown in figure 4, and a photo of this setup is displayed in figure5.

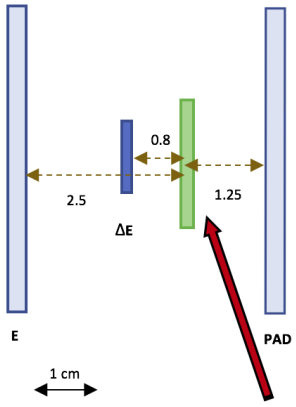

Figure 4. Scheme of the setup used in the experiment IS633B. The red arrow is the incoming beam.

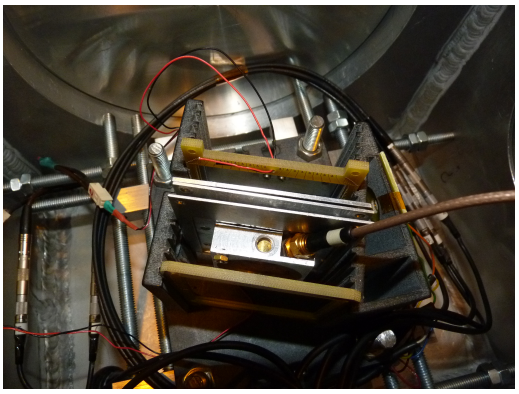

Figure 5. Picture of the chamber used in IS633B experiment and the detectors mounted on it

The setup was optimized to use the PAD detector in anticoincidence with the ΔE. The solid angle covered by the PAD and the ΔE are 28% and 9% of 4π, respectively. Due to the difference in sizes of the detectors chosen for this configuration it is assured that any α detected on the ΔE-detector, its pair will be detected in the PAD. The E detector of the telescope has been used to VETO the β response in the ΔE.

2.3. Production of the ^{8}B beam at ISOLDE-CERN

Since boron has a high chemical reactivity and high boiling point, it does not come out of the target easily. It is mandatory to extract the ^{8}B beam as a molecule with a fluorination agent as together form a relatively inert fluorides. The formation of the molecules must be fast, stable at operation temperature, inert towards reaction with the materials surrounding and with sufficiently large cross sections. It is shown in [8] that the best compound is a boron trifluoride (BF_3) where the fluorine is carried as a sulphur hexafluoride (SF_6). The main issue is that for different materials, fluorine has to be in excess to form the BF_3 molecules. Once the ionization is done, the most abundant specie is BF_2^+, which is expected to arise from dissociative ionization of BF_3. To extract the isotope, the best target is multi-walled carbon nanotubes as it presents a large porosity and a small grain size to enhance the diffusion. The identification of effective molecular beams opens the avenue to refractory element production in ISOL-facilities.

3. Methodology and Results

3.1. Calibration and response function of a DSSD

We have calibrated the detectors using a triple-α source (^{239}Pu, ^{241}Am and ^{244}Cm) plus ^{148}Gd.

To correct the effect of the dead layers of each detector, a *Geant4* simulation has been done characterizing each detector used. In the simulation, the different layers of a DSSD were adjusted to mimic the response of the monochromatic source ^{148}Gd in order to obtain the response function of each detector. The response function was then checked with the triple-α source with excellent agreement.

With the response function of each detector, an unfolding of the spectrum using the Richardson-Lucy [9] method is done to obtain the real α-decay spectrum [10]. Once the method is validated, the next step will be to apply the unfolding code to the ^{8}Be excitation spectrum to obtain the pure β-feeding spectrum.

3.2. ^{8}Be Excitation spectrum

In our experiments, the particles detected are β and α. To get the ^{8}Be spectrum, first is necessary to remove the β-response as it will give rise to β-summing to the α-detection. To remove the β-response, a coincidence analysis of the data has been done. The requirements are:

- At least, two particles in opposite detectors are detected in the same event.
- If only two particles have been detected:
  - The difference in energy of both particles have to be less than 200 keV.
  - The point of emission, reconstructed from the detection pixels, has to be within the C-foil and inside the beam-interaction-spot.
- If three or more particles are detected, the same procedures than for two are done but if it is not conclusive, the event will be neglected.
- The inter-strip events (charge sharing) have been removed.

Once the coincidences are defined, the spectrum is corrected for the energy loss in the C-foil and the separation-energy in the α-breakup, -91.8 keV according with figure 1. With these corrections, the ^{8}Be excitation-spectrum is obtained and shown in figure 6 for the telescopes of (60+1500) μm detectors (U2 and U6). The 2^{+} doublet is observed and we can confirm the success of our first part of the experiment. There is enough statistics to proceed with an R-matrix analysis to disentangle the isospin mixing of the two states.

3.3. Experimental limit for the EC-p branch

In the analysis done so far of the second experiment (IS633B) we have determined the sensititvity of the system and we have been able to reduce the background of our setup in the region of interest (200-400 keV) by doing anti-coincidence of the ΔE detector with the other two detectors used (E and PAD).

We define our region of interest centered around the energy of the proton calculated by kinematics (E_p = 337 keV) plus the resolution of the ΔE detector (20 keV). These limits define the range to estimate the sensitivity that will allow us the determination of the upper limit of the EC-p branch search for in the interval from 310 keV to 360 keV. Moreover, we only consider the events that are self-triggered by the ΔE.

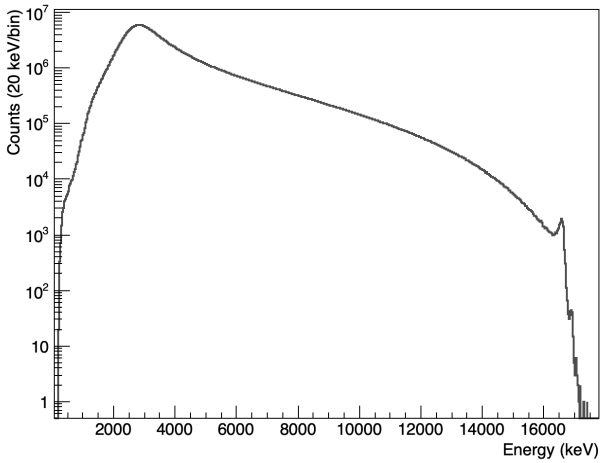

Figure 6. ^{8}Be E_x spectrum obtained from the opposite telecopes of (60+1500) μm thickness with the conditions and corrections explained at text.

With these conditions, we determine our background level to be 10^{-3}. A *Geant4* simulations is being prepared to determine which is the preliminary experimental upper limit that can be extracted from the IS633B experiment.

4. Summary and Outlook

We have performed two experiments dedicated to study the ^{8}B β^{+}/EC-decay to 2^{+} doublet at 16.6 and 16.9 MeV in ^{8}Be and to the 1^{+} to the 17.6 MeV. The aim was twofold, on one side learn about the isospin mixing of the 2^{+} doublet and identify or put a limit to the exotic EC-p decay favoured by the proton halo structure of the ^{8}B nucleus. Both experiments were very successful and the analysis progressing very well. We see the two contributions from the feeding to the16.6 and 16.9 MeV states so we expect to be able to establish experimentally the degree of mixing of these two states. A rather strict limit has already been established for the EC-p branch, although before it publication a few more checks are needed.

Acknowledgements

Work partially supported by the Spanish research grant FPA2015-64969-P and FPA2017-87568-P (MINECO) and the grant ENSAR2 from the H2020 program of the European Union under grant agreement No 654002.

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