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β-decay studies of states in ^{12}C

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The interest in experimental studies of the ^{12}C nucleus is partly due to the astrophysical interest in its spectroscopic properties, which determine the triple alpha reaction rate, and partly motivated by the structure of this nucleus, which is not fully explained theoretically. Some aspects are described in the shell model and others by a cluster structure of three alpha particles, but both cannot so far be combined in a unified model. New experiments have been performed to address these problems. The focus of this work is on an implantation experiment, which took place in April 2006 at KVI.

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1. Introduction

In the early 1950s Fred Hoyle proposed a state in ^{12}C at just 0.3 MeV above the 3α threshold which would enhance the rate of helium burning by the triple-alpha reaction in red giant stars [1]. The state was soon after found experimentally at 7.654 MeV and a giant leap was taken towards understanding element formation in stars after the Big Bang.

Our collaboration has performed a series of experiments with ISOL beams of ^{12}N and ^{12}B at the facilities ISOLDE at CERN and IGISOL in Jyväskylä, Finland [3 – 5]. In the β-decay of ^{12}N and ^{12}B one is populating states with spin and parity: 0^+, 1^+ and 2^+ in ^{12}C, where the 0^+ and 2^+ states can contribute to the triple-alpha reaction rate. The detector setups consisted of multiple Double Sided Si Strip Detectors (DSSSDs) covering a large solid angle surrounding the beam collection foil. In this way it has been possible to measure coincidences of the alpha-particles in the break-up of ^{12}C and new information on the break-up mechanism for different states has been revealed.

One of the main results from these experiments has been to determine the properties of the elusive state near 10 MeV. A detailed R-matrix fit has been made to the spectrum including interference between this state and the 7.654 MeV state showing that the state has spin and parity 0^+, and determining its energy, width and decay-channels. Furthermore the decay mechanism of the 12.7 MeV state has been determined, and a new, broad 2^+ state found at 14 MeV.

After the success with coincidence measurements a new experiment has taken place to complement and complete this work. The beam was here implanted in a segmented silicon detector to reach lower energies in ^{12}C avoiding energy loss in the collection foil and detector dead layer (see [6] for a description of the method). Thus it is possible to check if we have missed a state just below the energy cut-off, and whether interference between the 7.654 and 10 MeV states is enough to explain the spectrum at lower energy. Another advantage with the new method is the possibility to measure absolute branching ratios to the states by comparing the number of implanted nuclei during beam on with the decay spectrum during beam off. The Gamow-Teller matrix elements which can be extracted from these branching ratios are of high interest for state of the art calculations of the structure of ^{12}C [7 – 10]. It might even be possible to determine the total width of the 7.654 MeV state, $\Gamma = \Gamma_\alpha + \Gamma_\gamma + \Gamma_{e^+e^-} \approx \Gamma_\alpha$, which could reduce the uncertainty of the triple-alpha reaction rate, since we would find a rate independent of the pair branch for the 7.654 MeV state [11].

2. Experimental method

The experiment took place at the KVI (Kernfysisch Versneller Instituut) in Groningen, the Netherlands in April 2006. At this facility it was possible for us to produce beams of ^{12}B and ^{12}N with sufficient energy to implant them in the middle of our detector, and to get a very good separation to avoid contaminants in the beams.

The beams were made using the superconducting AGOR cyclotron. We used a beam of ^{12}C impinging on a hydrogen gas target [12] to produce ^{12}N, and a ^{11}B beam on deuterium gas to produce ^{12}B. The separator of the TRIμP[1] facility [13] then filtered the beam for contaminants

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[1] Trapped Radioactive Isotopes: μicro-laboratories for Fundamental Physics

and defocused the beam to take advantage of the entire detector area. It was necessary to place a detector in front of the DSSSD to lower the energy, and it also worked as a telescope for beam identification. The implantation energies of the beams were 31(2) MeV and 19(7) MeV for ^{12}N and ^{12}B respectively, and the intensities were approximately 2kHz for ^{12}B and 5kHz for ^{12}N.

The detector consists of 48×48 strips and the total active area is 16×16 mm^2 [6]. It has a thickness of 78μm and α-particles from the decay of a nucleus implanted in the centre of the detector will deposit all of their energy inside the detector. β-particles will only deposit little of their energy in the detector, and some of these are detected depositing some of their energy in a detector behind the segmented detector.

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3. Results

Decay spectra for ^{12}B and ^{12}N are shown in figure 1. The lower abscissa shows the measured sum energies of the alpha particles, which is related to energies in ^{12}C as $E_{3\alpha} = E_{^{12}C} - S_{3\alpha}$, where $S_{3\alpha} = 7.275$ MeV. The spectra plotted on top are efficiency corrected spectra from the previous β-decay experiment on ^{12}C at the IGISOL facility in 2004. The new spectrum shows much more statistics, and has no cut-off at low energy. The lowest peak in the spectra is due to β-particles from the decay and it is well separated from the 7.654 MeV peak at 0.3-0.4 MeV. The Q-value for ^{12}N is 9 MeV and for ^{12}B it is 6 MeV giving the energy ranges seen on the spectra. The new spectrum

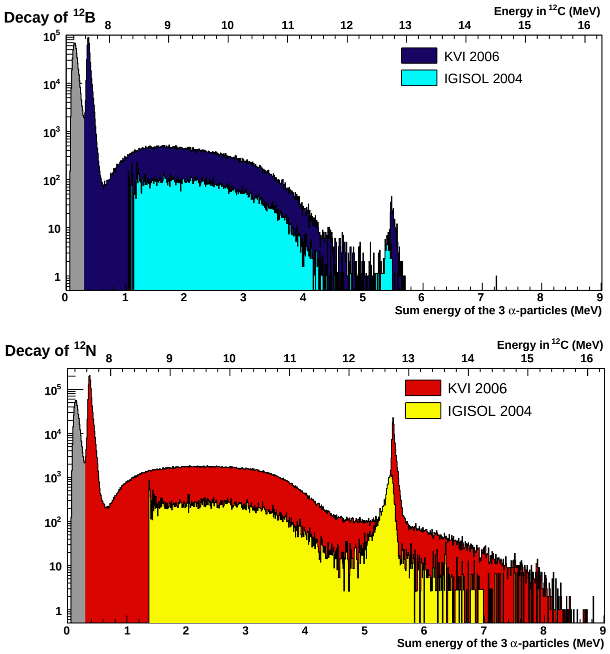

Figure 1: Figure showing the spectra from the KVI experiment with the spectra from IGISOL plotted on top for comparison. In the IGISOL experiment another setup was used, so the spectra have been corrected for the different efficiency. The lowest peak shown in gray is β-particles from the decay. The 3α energies are transformed to levels in ^{12}C by addition of $S_{3\alpha} = 7.275$ MeV.

is, due to summing with the β- particle in the decay, slightly shifted to higher energies. That is especially clear from the peak at 5.4 MeV corresponding to the 12.7 MeV state in ^{12}C.

In the new spectra there does not seem to be a state between the cut-off for the IGISOL experiment and the 7.654 MeV state, and if there is it has to be very broad. This is one of the things we need to check in the further analysis. Because we have much more statistics in the new experiment the spectrum for ^{12}N also shows the shape of the broad resonance above the 12.71 MeV state more clearly.

If isospin symmetry is valid the matrix element for the decay of ^{12}B to a certain energy in ^{12}C is equal to that for ^{12}N. To test this the two spectra for ^{12}B and ^{12}N are therefore compared after division by the phase space function. The conclusion of this test is that the two spectra are consistent with each other within statistical uncertainty.

Branching ratios for the β-decay of ^{12}B and ^{12}N are not very well determined in the literature, and we have already found improved values using the IGISOL data set, where we find mutually consistent results using two independent methods. Using the new data set from KVI we expect to achieve even higher accuracy. We have the possibility to calculate the absolute branching ratios directly by comparing the number of implantations with the number of subsequent decays, and a preliminary analysis gives the values in table 1. These values provide a cross check for our results from the IGISOL analysis.

^{12}B decay, B.R.(%)		^{12}C	^{12}N decay, B.R.(%)	
Literature value	KVI experiment	Energy level (MeV)	Literature value	KVI experiment
97.22(30)	98.16(4)	g.s.	94.55(60)	96.20(10)
1.201(17)		4.43891(31)	1.898(32)	
1.5(3)	$0.53(3)^{*}$	7.6542(15)	2.7(4)	$1.26(6)^{*}$
0.08(2)	0.106(5)	10.3(3)	0.46(15)	0.52(3)
?	$2.95(15)\cdot 10^{-4}$	12.710(6)	0.31(12)	0.119(6)
-	-	15.110(3)	4.4(15)x10-3	?

Table 1: Preliminary values for the branching ratios compared to literature values. Systematic errors are not yet known and therefore conservative errors of 5% are put in by hand. The ground state branching ratio is calculated as 1 minus the branching ratios to higher energy states where the branching ratio to the 4.4 MeV state is taken from TUNL [14]. *The branching ratios to the 7.654 MeV state may be different since we have not yet checked that the trigger threshold is below the peak corresponding to this state.

4. Outlook

We have so far only done a very preliminary analysis of the experimental data. One important task is to correct for β-summing in the spectra giving the small shifts towards higher energy. Summing of multiple events must also be investigated, and we have to check that the alpha particles deposit all of their energy in the strip detector. For each strip in the DSSSD it is also necessary to check if the trigger threshold is below the 7.654 MeV peak, so we calculate the correct branching ratio to this state. After this work has been completed, we will perform detailed R-matrix fits to the spectra and deduce more precise values for the branching ratios to the broad states and verify if our description of the interference between the 7.654 MeV and 10 MeV states suffices to describe the spectra at low energies. Also it will be important to test the possibility of extracting the total width of the 7.654 MeV state which could improve the accuracy of the triple-alpha reaction rate. As a final comment, this work provides a new demostration that the method of implanting energetic beams with relatively good energy definition in segmented detectors is mature and can be applied to many decay studies focussing on weak charge particle decay channels.

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