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Study of the β-decay of ^{12}B

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Abstract

We propose to study the β-decay of ^{12}B with a modern segmented Si-detector array to get new and much improved information on states in ^{12}C above the α-threshold. These states mainly decay into final states of three α-particles and their study therefore is a challenge for nuclear spectroscopy. The properties of these states is of high current interest for nuclear astrophysics and for the nuclear many-body problem in general. We ask for a total of 15 shifts.

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1 Introduction

There is a long standing interest in the spectrum of the lowest states in ^{12}C. The structure of ^{12}C was long ago suggested to be that of three α-particles, forming either an equilateral triangle or a linear structure, with corresponding different rotational bands predicted [1, 2]. In the near future much more precise calculations will become possible for this system making new experiments very relevant. The astrophysical importance of the low energy resonances in ^{12}C is also well established.

Two years ago we prepared a proposal for the study of the decay of ^{12}B at ISOLDE (P122) [3]. At that time the motivation was the study of the breakup mechanism of the 12.71 MeV state in ^{12}C which is a problem still with high interest today mainly due to searches for two-proton radioactivity, see e.g. [4, 5]. P122 was withdrawn when it became clear that this study could be better performed at the IGISOL beamline of the JYFL accelerator lab in Finland [6]. Here we succeeded in producing for the first time an ISOL beam of the isotope ^{12}N which in its beta-decay feeds the 12.71 MeV state with a much higher B.R. than in the decay of ^{12}B. This experiment was completed in February 2001, and is now under analysis [7].

With this proposal we return to the case of ^{12}B with the different aim of elucidating the exciting region in ^{12}C between the 7.654 MeV state and the 12.71 MeV state.

2 Physics motivation for studying ^{12}B

Surprisingly little is known experimentally about the excited states in ^{12}C just above the 0^+ state at 7.65 MeV [8]. A broad state at 10.3 MeV has been observed in the β-decays of ^{12}N and ^{12}B where it is fed in allowed transitions [9]. From these decay studies it could only be determined that the spin of this state is either 0^+ or 2^+. It was even at one point suggested that the strength interpreted as the 10.3 MeV state is the “ghost” of the 7.65 MeV state, and therefore not a separate state at all [10]. Although there are many indications that there are overlapping contributions from 0^+ and 2^+ states in this region, we will refer to it as *the 10.3 MeV state* in the following.

It is well known that the 7.65 MeV state plays an important role in astrophysics by enhancing the reaction rate of the triple-α process in red giant stars by orders of magnitude [11, 12, 13]. The European compilation of astrophysically relevant reaction rates NACRE [14] assumes in addition a 2^+ state at 9.2 MeV, which at temperatures above 4×10^9 K significantly speeds up the triple-α process. This state has not been observed in experiment and its existence is only deduced from cluster type calculations [15]. Also, if the spin of the 10.3 MeV state is 0^+ it will interfere with the 7.65 MeV state in a way dependent on the width and position of the 10.3 MeV state, which both are poorly known. This could also affect the reaction rate of the triple-α process in a wider temperature region.

In the cluster physics community the position of the second 2^+ state in ^{12}C is considered an outstanding problem which should receive renewed attention, indeed it was recently suggested that the decays of ^{12}B and ^{12}N should be remeasured with modern detectors [16]. This state is seen as the second member of a rotational band built upon the 7.65 MeV state and its position gives direct information about the moment of inertia of this band and thereby the structure of the underlying state.

Recently the existence of n α cluster condensed states in N = Z nuclei near the n α thresholds was conjectured [17]. These states are seen as nuclear analogies of atomic Bose-Einstein Condensates. The 7.65 MeV state in ^{12}C is mentioned in support of this conjecture, and the measurement of α-α correlations from that state, and other states near it, is suggested.

Whereas the shell model has problems in reproducing the ^{12}C level structure due to the molecular-like α-cluster structures of some of the states, a recent cluster model has been quite successful in predicting both the cluster states and shell-model-like states [18]. There has recently been much progress in performing large scale no-core shell model calculations for light nuclei such that much more reliable predictions should become available in the near future [19]. At the same time the very precise (so called "exact") Green-function and variational Monte-Carlo calculations performed by the Argonne-Urbana groups will become feasible for the A=12 system in 1-2 years [20]. From group theoretical arguments it has also recently been demonstrated that precise predictions are possible for states with cluster structure [21].

We have obtained numerical predictions from both the antisymmetrised molecular dynamics (AMD) [22] and group theoretical [23] cluster calculations for the position of 0^+ and 2^+ states above the 7.65 MeV state. Both these calculations predict a second 2^+ state at 9-10 MeV and a third 0^+ state at 10-12 MeV. The AMD calculations also predict the ft-values for the beta-decay to these states from ^{12}B and ^{12}N. In order to better test these theoretical calculations, and those which in the near future will become available from the shell-model and exact Monte-Carlo calculations, it would clearly be beneficial to better determine the spectroscopic properties of the excited states in ^{12}C, and in particular to attempt to determine the position of the 0^+ and 2^+ states above the 7.65 MeV state.

3 Previous knowledge of the decay

In the following we review the experimental information on the decays of ^{12}N and ^{12}B obtained up to our experiment on ^{12}N (with main focus on states just above the 7.65 MeV state). A summary is provided in Figure 1 and Table 1. The given branching ratios are taken from the tabulation by Ajzenberg-Selove [8]. The dashed lines indexed by 1-3 on Figure 1 are the 3α-threshold at 7.285 MeV, the α^8Be(0^+) threshold at 7.377 MeV and the α^8Be(2^+) threshold at 10.27 MeV respectively. Note that the latter is a broad resonance with a width of 1.5 MeV, thus it may also play a role for states in ^{12}C below

Table 1: Experimental information about the beta-decay of ^{12}B and ^{12}N from [8]. The branching ratio to the 12.71 MeV state in the decay of ^{12}B has not been measured.

^{12}B decay		^{12}C level			^{12}N decay	
B.R. (%)	log(ft)	E (MeV)	Γ (keV)	J$^\pi$, T	log(ft)	B.R. (%)
97.22(30)	4.066(2)	g.s.	-	0^+; 0	4.120(3)	94.55(60)
1.201(17)	5.136(6)	4.43891(31)	$10.8(6) \times 10^{-6}$	2^+; 0	5.149(7)	1.898(32)
1.3(4) 1.7(5) 1.5(3)	4.13(9)	7.6542(15)	$8.5(10) \times 10^{-3}$	0^+; 0	4.34(6)	2.2(6) 3.0(5) 2.7(4)
0.13(4) 0.07(2) 0.08(2)	4.2(2)	10.3(3)	3000(700)	(0^+,2^+); 0	4.36(17)	0.85(6) 0.44(16) 0.46(15)
?		12.710(6)	$18.1(28) \times 10^{-3}$	1^+; 0	3.52(14)	0.31(12)
-		15.110(3)	$43.6(13) \times 10^{-3}$	1^+; 1	3.30(13)	$4.4(15)\times10^{-3}$

the shown threshold.

In general spectroscopic information from β-decay may be obtained either from studying the beta-spectrum and e.g. applying the traditional Kurie plot, or by measuring the delayed radiation, in this case either γs or αs. The former becomes difficult when broad states are fed in the decay, and the level density becomes high.

A number of early experiments on ^{12}B used the Kurie plot to deduce properties of the states fed in the decay. The properties of the 7.65 MeV state were established in the impressive work of Cook, Fowler, Lauritsen and Lauritsen [24] where the first evidence for higher energy α-particles was also provided. This was followed up in [25] and also in Wilkinson *et al.* [26] using a magnetic spectrometer and a Si detector respectively to measure the delayed α-spectrum. The two values for the branching ratios in Table 1 correspond to these two measurements. Feeding to the 12.71 MeV state has not been observed in the decay of ^{12}B.

Evidence for high-energy α-particles from ^{12}N was communicated already in 1950 by Alvarez who used protons to bombard a ^{10}BF$_3$ proportional counter, serving both as target and detector. Interestingly this was an attempt to produce the first example of β-delayed proton emission from either ^{9}C or ^{17}Ne [27]. The decay of ^{12}N was measured by Wilkinson *et al.* [26] and Glass *et al.* [28], the latter using a Kurie-plot to deduce the branching ratios. The two values for the branching ratios in Table 1 correspond to these two measurements. Schwalm and Povh [9] measured both decays using a set-up consisting of two Si detectors in close geometry. Their value for the width of the 10.3 MeV state is the one used in the literature (Table 1). ^{12}N was later remeasured in 1978 with improved set-up and statistics. Figure 5 shows the sum-spectrum from this experiment which is a combination of events where 2 and 3 α-particles were detected in the two detectors of that experiment [30]. This experiment obtained an increased accuracy for the properties of the 10.3 MeV state, but it was never published.

Previously the determination of the spin of the 10.3 MeV states has been attempted by comparing R-matrix fits to the data, but the accuracy of the data did not permit to distinguish between the two possible spins (0^+ or 2^+).

By using the ft-value from the decay of the mirror nucleus ^{12}N we estimate the branching ratio to the 12.71 MeV state in the decay of ^{12}B. The result of this procedure is a branching ratio of 0.00065 %, two orders of magnitude less than that to the 10.3 MeV state. Hence, the α-spectrum from the β-decay of ^{12}B will be dominated by the 7.65 MeV and 10.3 MeV states, which is an advantage for the study proposed here (see section 5).

4 Preliminary results from the experiment on the decay of ^{12}N

The fact that these states in ^{12}C break-up into final states of three α-particles has prevented information beyond that which was obtained in the 50s, 60s and 70s with magnetic spectrometers and conventional solid state detectors. In addition, all the experiments mentioned above used the reactions ^{11}B(d,p)^{12}B and ^{10}B(^{3}He,n)^{12}N to produce the activity, which was measured *in beam*. Thus a common problem was the energy loss of the delayed α-particles in the target. Corrections for this are based on assumptions on the source position and are therefore model dependent. Since the conclusions on branching ratios, break-up mechanisms and the determination of energy and width of participating resonances are based on a detailed analysis of the spectra of the delayed α-particles (which are already complicated by the kinematics of the three-body breakup), this problem is a significant limitation.

In the experiment at JYFL we overcame these important short comings, in part by using a compact detection system of two double sided Si strip detectors, and in part by using the IGISOL technique for the production of the isotope ^{12}N. The former permits measuring in coincidence all three α-particles emitted from the breakup, and the latter to stop the activity in a thin Carbon collection foil thus significantly reducing the problem of energy loss in the target.

In the central part of Figure 3 we show a scatter plot with the sum-energy of the three detected particles against each of the three individual energies, each break-up event is represented by three dots on the same horizontal line; the right part of the figure shows the projection onto the sum-energy axis, and the left part the position of the relevant thresholds and energy levels. In the projection the 10.3 MeV (6000 events) and 12.71 MeV (670 events) states are readily identified, whereas a weak peak is observed at the expected position for the 15.11 MeV (IAS) state (4 events). The scatter plot provides an overview of the properties of the decay and subsequent break-up: the diagonal line represents the sequential break-up via the narrow ground state of ^{8}Be, which is characterized by the presence of one high energy and two low energy α-particles in the event. The break-up pattern of the 12.71 MeV and 15.11 MeV states is clearly different from that of the 10.3 MeV state, with the α-energies distributed in three separated regions. The huge improvement in resolution can be appreciated by comparing to Figure 5.

We have performed R-matrix fits of the high energy tail of the 10.3 MeV peak with the preliminary result that interference is needed for a good fit. However we then cannot simultaneously fit the low energy part. We understand this to be an effect of the trigger threshold in the detector electronics, which in this experiment prevented detection in multiplicity 3 below 9 MeV. Therefore these data do not allow a secure determination of the properties of the state. Although additional information from analysis of lower multiplicity data will reduce this ambiguity somewhat, the high interest in this problem justifies a dedicated remeasurement.

The β-decay of ^{12}B has not been measured with the crucial improvements described for the ^{12}N study. This proposal aims for precisely that with additional improvements in the detectors and electronics. In addition the product of yield and B.R. for ^{12}B at ISOLDE is significantly higher than for ^{12}N at JYFL.

5 The proposed production method, experimental set-up and analysis method

Boron is a difficult element for any ISOL facility to produce due to the high chemical affinity to most target and ion source materials, presently no ^{12}B ISOL beams are available. Recently, however, good yields of ^{12}Be were achieved. The latter decays with a B.R. of 99.5 % to ^{12}B and therefore provides a good way to indirectly produce ^{12}B. Beryllium is selectively ionized with the resonance ionisation laser ion source (RILIS). Up to now the best yield of ^{12}Be was achieved with a special thin foil (2 μm thick foils) tantalum target. From the detection of beta-delayed neutrons with a 4π neutron long counter a yield of $5 \cdot 10^4$ ions per μC of primary proton beam could be deduced.

Since the yields of very exotic nuclei fluctuate from one target unit to another we will use in the following the conservative yield estimate of 10^4 ions per μC.

The experimental set-up planned is shown in Figure 4. Whereas the set-up shown in Figure 2 had to detect two kinematically different breakup modes, we have here selectively optimised for breakups via the narrow ground state of ^{8}Be. The activity is stopped in a thin carbon foil ($\simeq$ 30 μg/cm^2). By reducing the high voltage of the separator to 30 kV we will be able to stop the beam in this thin foil and thereby reduce the energy loss. The collection point is viewed by two thin ($\simeq 60\ \mu$m) double sided Si strip detectors, which are both backed by thick Si-pad detectors. One of these is a new development with reduced deadlayer, again improving detection of low energy α-particles. Naturally, these thin detectors will have very little β-response, thus in 60μm of Si, minimum ionizing electrons will deposit $\simeq$ 20 keV whereas up to 9 MeV α-particles will be stopped. Compared to Figure 2 we have moved the DSSSDs further apart to achieve better angular resolution in detection of the two low energy αs from ^{8}Be, which are emitted in a narrow cone.

Towards the beam direction the collection foil is viewed by the new ISOLDE Si-ball, which is an array of 40 1 mm thick Si detectors (160 segments) presently under development [31]. By analysing the pulse shape using dedicated electronics, it will be possible to distinguish between βs and αs in these detectors. We will use this array to obtain an independent trigger for βs (for absolute normalisation of branching ratios) and increased coverage for αs. Finally, opposite to the Si-ball is placed a small standard ΔE-E telescope with a thin ΔE-detector. This will be used to record a clean singles α-spectrum. This could be complemented by singles spectra of some of the detectors in the Si-ball. In the space opposite the Si-ball we will possibly position prototypes of new compact Si-telescopes consisting of 1μm thick ΔE detector. These are currently under development for use in a second generation Si-detector array [32].

The problem of controlling the trigger threshold will be tackled in the following ways. We have already mentioned the use of a lower high voltage of the separator, which allows the use of a thinner collection foil, and the use of a new DSSSD with much reduced deadlayer. With these steps we will get a higher energy transmitted to the active detector area and consequently with the same threshold setting on the electronics a lower threshold energy. We are also implementing new preamplifiers, which provide a factor of 3 higher amplification without an increase in noise level. Thirdly we can directly measure the trigger thresholds in all detectors by recording the α-spectrum from a suitable source with the vacuum chamber left in air. This method was thoroughly tested over the summer with one of the ISOLDE summer students and found to be a very simple method of providing a known distribution of low energy α-particles, which permit the thresholds to be directly extracted [33]. Finally, in the offline analysis we can selectively choose events triggered by βs in the Si-array and hence unaffected by trigger thresholds in the DSSSDs.

The analysis will then proceed by comparing the data through Monte-Carlo simulations with extended R-matrix fits as recently achieved for the similar case of ^{9}C [34, 35]. By comparing results obtained for events of different multiplicity and the singles spectra (which is facilitated by the week feeding to the 12.71 MeV state) the sensitivity to thresholds should be strongly reduced. A very interesting possibility opened by the presence of the Si-ball is to measure the β-α angular distribution, which in principle allows a direct decomposition between 0^+ and 2^+ components. Such a decomposition might also be achieved from identifying decays via the 2+ state in ^{8}Be. The branching ratio for such channels should differ strongly for 0^+ and 2^+ states in ^{12}C due to the difference in barrier penetrabillity. In addition for the break-up of a 0^+ state in ^{12}C via the 2+ state in ^{8}Be there will be a non-uniform angular correlation, whereas a 2^+ state will have a uniform angular correlation. The statistics in the ^{12}N experiment did not permit such an analysis. One attractive possibility for further elucidation of the 0^+ versus 2^+ problem would be to complement the experiment discussed here with γ-spectroscopy measurements. The TAGS spectrometer could be the best instrument for such a study although beta-bremsstrahlung currently seems to limit such possibilities.

Table 2: Production values relevant for beam time estimate

Item	Produced/pulse	Produced/Shift	Mode
^{12}B	4.8×10^4	4.8×10^8	-
7.654 MeV	720	8.6×10^6	0^+
10.3 MeV	40	4.8×10^5	0^+
12.71 MeV	0.32	3.8×10^3	2^+

Table 2 gives relevant numbers for the estimate of beam time. These numbers are based on the assumed yield of 10^4 ions per μC and the normal intensity of 3×10^{13} protons per pulse. It is assumed that we would get 50 % of the pulses from the PS-BOOSTER. The numbers given in Table 2 do not take into account the detection efficiency of the set-up, which obviously depends on the precise geometry and threshold conditions. The set-up can now be optimised in a compromise between solid angle and resolution in detecting the two α-particles from the break-up of ^{8}Be. With a separation of 10 cm between the DSSSDs the multiplicity 3 detection efficiency is of the order of 3 %, and the detection efficiency for break-ups via the ^{8}Be 2+ state is still reasonable due to the presence of the Si-ball. Thus in 12 shifts an estimated 1.7×10^5 events could be collected from the 10.3 MeV state. A small part of the radioactive beamtime will be devoted to calibration with ^{20}Na, which is produced from the same target-ionsource combination.

6 Summary and Beam request

We propose to measure the decay of ^{12}B to study the properties of 0^+ and 2^+ states just above the α-threshold, a region of high interest for astrophysics and the nuclear many-body problem in general. The most recent evaluation of this region is based on experiments performed mainly in the 50s and 60s [8]. Since then there have been important new developments in detector technology and production methods for radioactive beams. We have demonstrated these improvements in our work on ^{12}N. Compared to this work we will further improve the set-up to enable measurement of lower energy particles. This experiment, if accepted, will significantly improve our knowledge of this region in ^{12}C.

We ask for a total of 12 radioactive shifts from a thin foil Ta target and in addition 3 shifts for stable beam adjustments and source calibrations.

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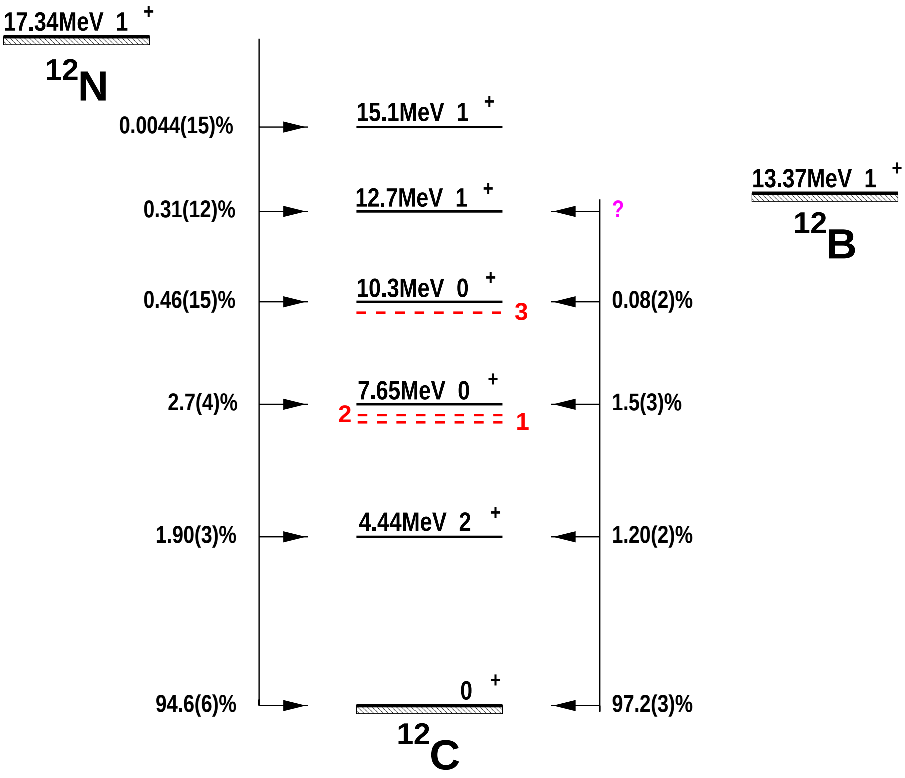

Figure 1: Decay schemes of ^{12}B and ^{12}N.

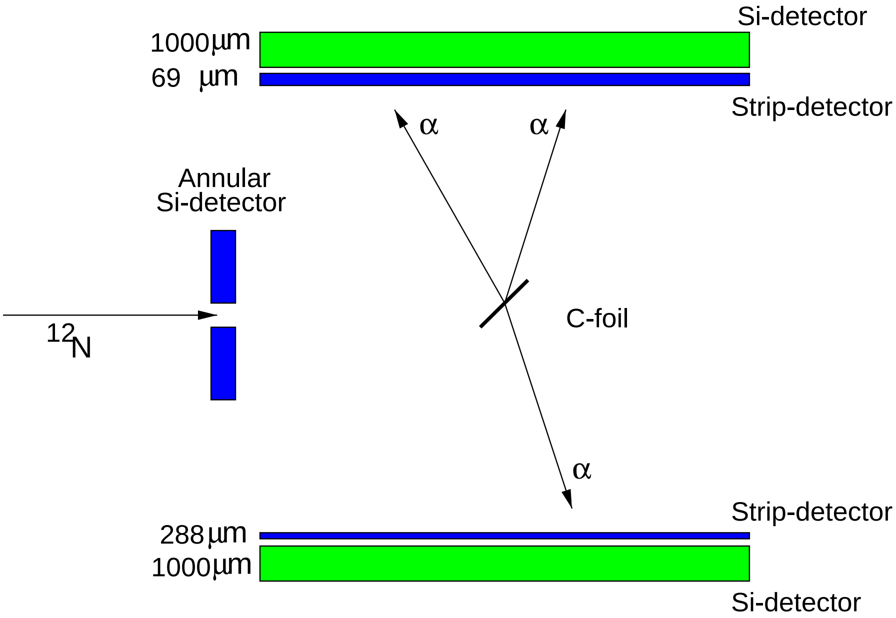

Figure 2: The experimental set-up used at the experiment at JYFL, Finland. The set-up consisted of two DSSSDs backed by thick unsegmented Si-detectors. Only one of the DSSSDs was thin enough to have negligible beta-response.

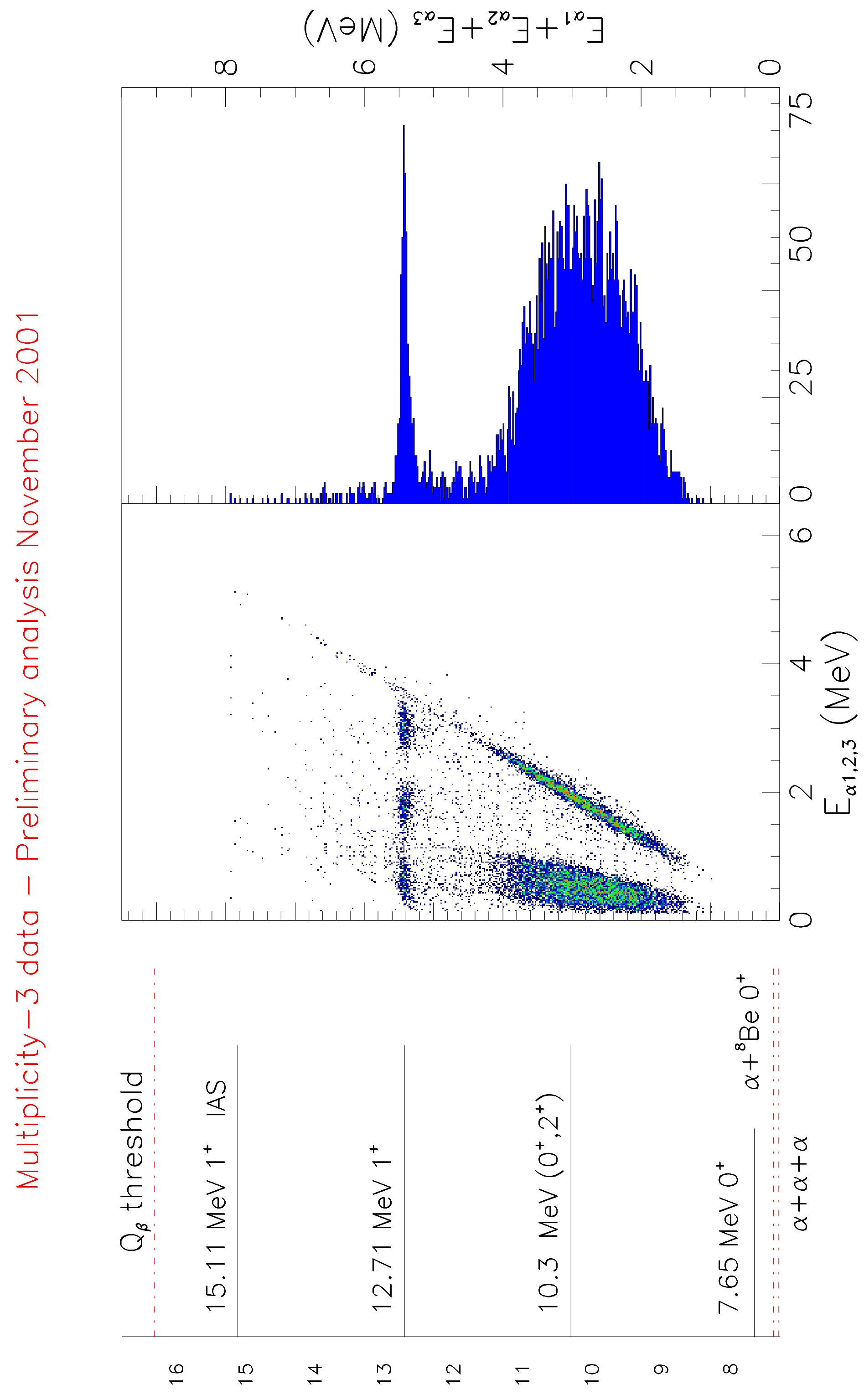

Figure 3: Triple coincidence data from the β-decay of ^{12}N. In the centre is shown a scatter plot of the summed energy of the three detected α-particles against the energy of the individual particles, hence each break-up event is represented by three dots on the same horizontal line. To the right is shown the projection on the sum energy axis, where the peaks can be identified as the 10.3 MeV and 12.71 MeV exited states of ^{12}C. The position of these states is also indicated in the schematic level scheme in the left part of the figure.

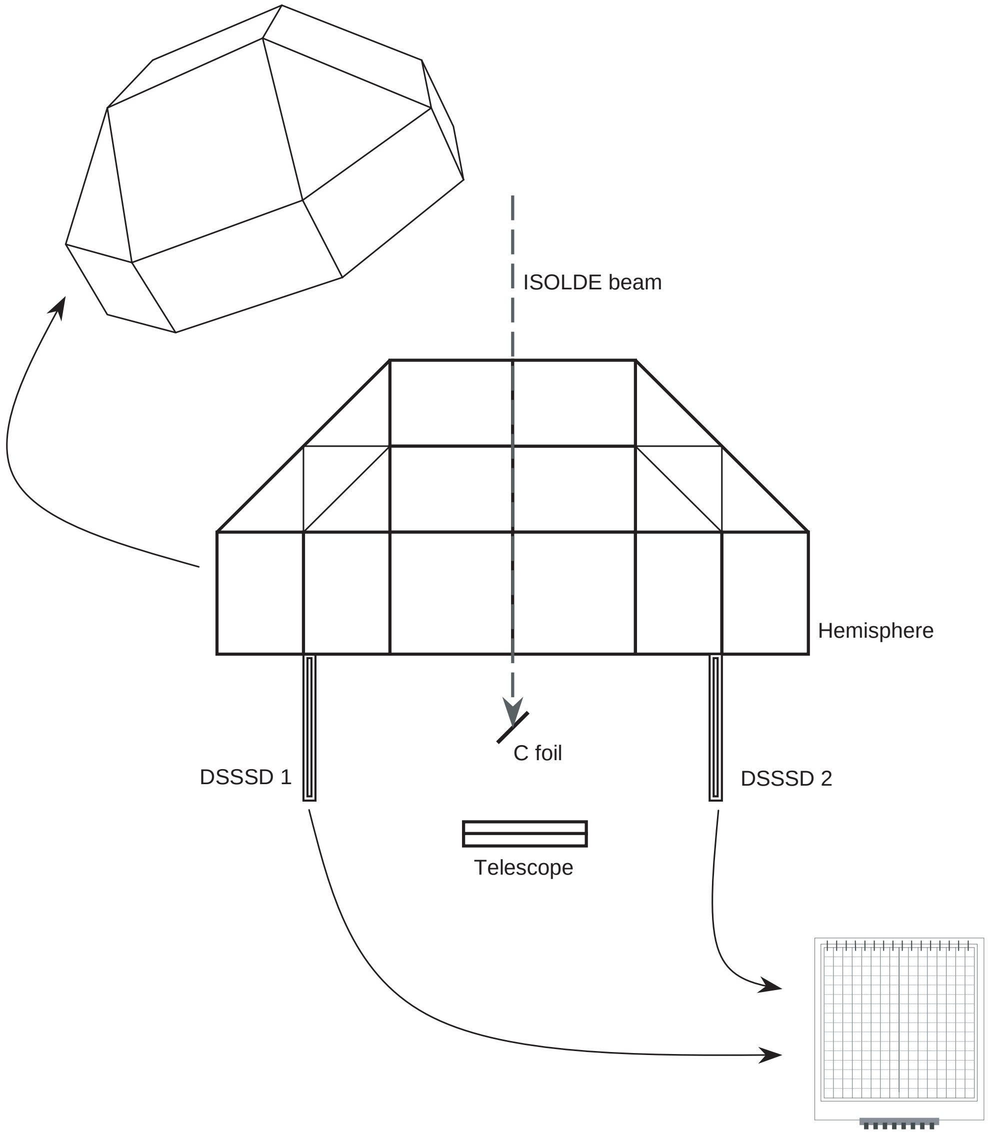

Figure 4: The proposed experimental set-up for the measurement of the β-decay of ^{12}B at ISOLDE.

Figure 5: Results from the experiment of Gergely and Schwalm [30]. The spectrum shows a combination of events where 2 and 3 α-particles are detected in a setup consisting of two conventional Si-detectors. Three α-particles could only be detected by summing of two particles in one detector. Compare to Figure 3 to appreciate the improvements introduced by modern segmented detectors and the ISOL technique. Note, however, that the statistics in [30] was much larger.