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Three-particle breakup of ^{12}C in the beta-decay of ^{12}B

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Abstract

The study of beta-decay to final states with high multiplicities has recently become more feasible with the advent of highly segmented particle detectors adjusted to nuclear physics experiments. This development has made it possible to address the question of the mechanism of break-up to such final states fed in beta-decay and in nuclear reactions. Here we propose to study final states of three alpha-particles from the break-up of states in ^{12}C fed in the beta-decay of ^{12}B. We ask for a total of 10 shifts of on-line data taking plus 3 additional shifts for stable beam adjustment and calibration measurements.

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1 Introduction

A number of light nuclei have considerable branching ratios in beta-decay to final states consisting of three (or more) particles : ^{9,11}Li, ^{9}C, ^{12}B, ^{12}N, ^{17}Ne and several cases of β-delayed two-proton emission. Until recently it has been difficult to measure detailed properties of these decay branches due to low efficiency for coincident detection of two or more particles, thus only singles spectra could be accessed experimentally. However, due to kinematical recoil broadening and intrinsically broad states the interpretation of singles spectra from such decays has to be based on assumptions of the mechanisms of the break-up.

The introduction of strip detectors optimized for nuclear physics purposes have drastically changed this situation. This is illustrated by two measurements performed at PSB-ISOLDE of the β-delayed two-proton branches of ^{31}Ar in 1995 and 1997. The former used a setup consisting of conventional detectors whereas the latter used a setup consisting of a strip detector and an array of 15 conventional detectors. Figure 1 compares the two-proton data obtained from the two experiments which collected roughly the same number of nuclei.

From the ^{31}Ar experiment our collaboration has built up considerable expertise in using strip-detectors and developed methods for analyzing events with more than a hundred channels efficiently. One example of this is the method of kinematical reconstruction illustrated in Figure 1. This expertise was demonstrated in our recent measurement of the β-decay of ^{9}C, a decay which always leads to final states consisting of two α-particles and a proton. Figure 2 provides an overview of this decay from events with all three particles

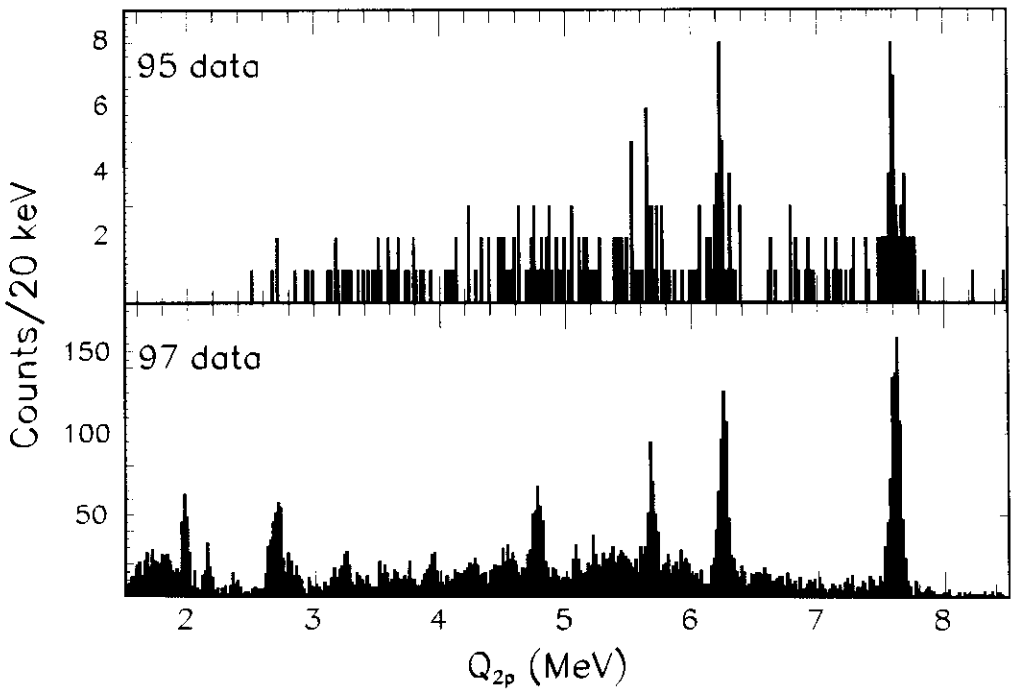

Figure 1: Comparison of recoil corrected total energy (Q_{2p}) plots from two-proton events detected following the beta-decay of ^{31}Ar. The top spectrum was obtained with a setup consisting of three conventional Si-detectors, and the lower spectrum with a setup containing a double sided Si strip detector and an array of 15 P-I-N diode detectors (FUTIS). The two measurements collected roughly the same number of nuclei on the collection foil.

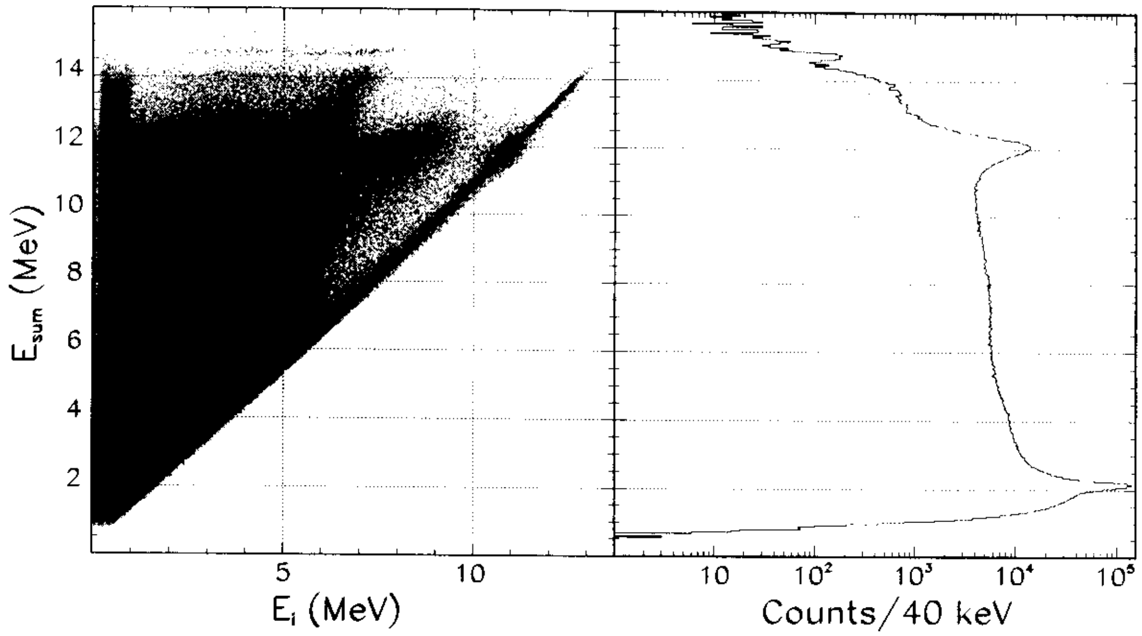

Figure 2: Overview of the decay of ^9C from events where the proton and two alpha-particles from the break-up of the beta-daughter ^9B are measured in coincidence. To the left is shown a contour plot (log scale) of the sum energy of the three particles against the energy E_i of the individual particles. Each event is represented by three points lying on the same horizontal line. The right part is the projection onto the sum-energy-axis. The diagonal lines in the contour plot reveal the sequential break-up through resonant states in the binary subsystems ^8Be and ^5Li.

measured in coincidence. The scatter plot gives the summed energy of the three particles against the individual energies, thus each event is represented by three dots on the same horizontal line - one for each detected particle. This type of plot, developed in the analysis of our ^{31}Ar experiments [1], permits a straight forward method to identify and separate different mechanisms of break-up, and thus constitutes an important tool for this kind of study.

With this proposal we wish to use these powerful tools for the case of ^{12}B. The physics interest in measuring this decay is presented in section 2.

2 Physics motivation for ^{12}B

When a quantum mechanical N-body state breaks up into two fragments the break-up is fully determined by momentum and energy conservation; the two fragments will always be emitted back to back. However, when the final state consists of more than two particles, the mechanism of the break-up is not fully determined by conservation laws. In three-body break-up there are three binary subsystems, where each may have resonances influencing the break-up; that is, the break-up can in principle proceed via each of these resonances sequentially. Alternatively, one may have the situation where the state breaks up directly into the three body continuum. In nuclear physics literature this has been referred to as "direct", "democratic" or "simultaneous" break-up.

All previous experimental studies of the mechanism of (beta-delayed) break-up have shown that if narrow (compared to the available energy) resonances in the binary subsystems exist, then the break-up will proceed sequentially through these resonances. Our previous studies of the decays of ^{31}Ar and ^{9}C provide good examples of this. Sequential break-up is well described in the R-matrix formalism, which has been tested in many cases since the 1950's.

Cases where none of the binary subsystems posses narrow resonances are discussed by Korsheninnikov [2]. He argues that if the width of the binary resonance is larger than the available energy, then the break-up of the binary subsystem proceeds so fast that the presence of the third particle is still felt and therefore the seq iential picture is inconsistent. He subsequently develops a formalism for expanding the decay amplitude in a set of basis functions (hyper-spherical harmonics) that fully describe the *final state* of three particles. When no narrow resonances are present in the binary subsystems, the first few terms of this expansion suffice and the three body decay is termed "democratic". This formalism has been applied to the break-up of resonances in ^{6}Be, ^{6}He, ^{6}Li, ^{9}Be and ^{9}B, see [2] for references to this work.

However, since in most cases where the democratic decay formalism has been applied, the data could equally well be described in the R-matrix formalism (the case of the 0^+ resonance in ^{6}Be being the only exception), the democratic decay formalism has received very little testing in cases where its predictions are different from those of the R-matrix formalism. Korsheninnikov suggests that the break-up of the 12.71 MeV 1^+ states in ^{12}C is particularly interesting for testing this description, due to predicted large correlations between the three α-particles (note that decay via the narrow 0^+ ground state of ^{8}Be is forbidden due to conservation of parity). The reason for the large expected correlations is that the minimum hyper-momentum (the equivalent of the orbital angular momentum for two-particle break-ups) in this case is K=8.

One may see sequential decay and democratic decay as limiting cases where the width of the binary resonances are much smaller and much larger than the available energy respectively. In the general case the width can be either much smaller, larger or of the same order as the available energy. An important contribution to this discussion comes from a calculation of the width of the astrophysically important second 0^+ state in ^{12}C [3] (assuming this state has a structure of three α-particles). These authors solve the Faddeev equations in coordinate space using an adiabatic hyper-spherical expansion method, which takes into account the position and width of the resonances in ^{8}Be in a three-body calculation. The success of this method in calculating this very small width suggests that the mechanism of the decay is treated correctly, however, the width of this state was also reproduced in a calculation assuming sequential break-up through the ground state of ^{8}Be [4]. A comparison of the predicted energy spectra of α particles from the calculation in Ref. [3] to those obtainable from a sequential calculation would be interesting. Similar calculations for the 1^+ state at 12.71 MeV could be compared to the predictions from democratic decay given in [2]. A comparison between such calculations and data obtained from the experiment proposed here would be an important input to the study of such break-ups. We note that the break-up of ^{12}C states are particularly attractive for such studies since the final state particles have spin zero and well-understood internal interactions, this will make the extraction of the decay mechanism easier, and comparison to theoretical calculations less model-dependent.

It should be noted that the mechanism of break-up should also reflect the degree to which the *initial state* has the structure of the final state of three (or more) fragments. The 0^+ states in ^{12}C are expected to have an α-cluster structure, whereas this is not the case for the 1^+ state. On a somewhat longer time-scale it would be interesting to compare exact 12-body calculations on these states with the data obtainable from the experiment proposed here (similarly for our data on ^{9}C, see Figure 2). This may be able to place constraints on the phenomenological three-body interaction used in such calculations.

In conclusion, our interest in the decay of ^{12}B is primarily in the direct measurement of the decay modes of the states above the 3α-threshold in ^{12}C. The same information can be accessed from the decay of the mirror nucleus ^{12}N, but, for reasons of production, we focus on ^{12}B in this proposal, see the discussion in section 4.

3 Previous knowledge of the decay

In the following we review the previous experimental information on the decays of ^{12}B and ^{12}N, which is summarized in Figure 3 and Table 1. The given branching ratios are taken from the tabulation by Ajzenberg-Selove [5] except that for the feeding to the 12.71 MeV 1^+ state in the decay of ^{12}B, which is discussed below. The dashed lines indexed by 1-3 on Figure 3 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 3 MeV, thus it may also play a role for states in ^{12}C below the shown threshold.

Cook *et al.* [6] and Wilkinson *et al.* [7] measured the delayed alpha activity from ^{12}B using a magnetic spectrometer and a Si detector respectively. The two values for the branching ratios in Table 1 correspond to these two measurements. Cook *et al.* deduced from the shape of their single spectrum that less than 4 % of the decays of the 10.3 MeV

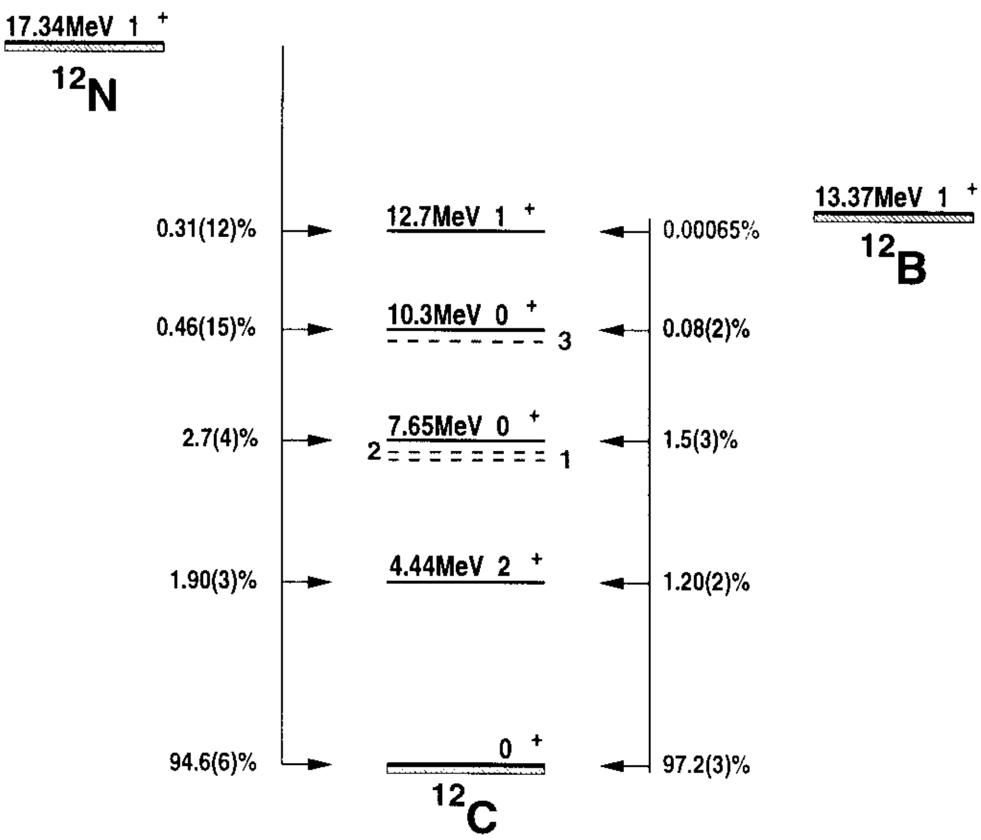

Figure 3: Decay schemes of ^{12}B and ^{12}N to states in ^{12}C. The branch to the 12.71 MeV 1^+ state in the decay of ^{12}B has not been observed. The indicated branching ratio is calculated from the mirror transition in the decay of ^{12}N. See text.

Table 1: Experimental information about the beta-decay of ^{12}B and ^{12}N from [5]. The branching ratio to the 12.71 MeV state in the decay of ^{12}B is estimated from the mirror transition.

^{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) × 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) × 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^+); 0	4.36(17)	0.85(6) 0.44(16) 0.46(15)
0.00065		12.710(6)	18.1(28) × 10^{-3}	1^+; 0	3.52(14)	0.31(12)
-		15.110(3)	43.6(13) × 10^{-3}	1^+; 1	3.30(13)	4.4(15)× 10^{-3}

state proceed through the 2^+ exited state of ^{8}Be. Feeding to the 12.71 MeV state has not previously been observed in this decay.

The decay of ^{12}N was measured by Wilkinson *et al.* [7] and Glass *et al.* [8], the latter using a magnetic beta-spectrometer and an end-point based analysis to deduce the branching ratios in the decay. The two values for the branching ratios in Table 1 correspond to these two measurements. Alburger *et al.* [9] measured the branching ratio to the 12.71 MeV state from the gamma-decay of that state. Schwalm and Povh [10] measured both decays using a setup consisting of two Si detectors in close geometry. They could not exclude small contributions from the 2^+ exited state of ^{8}Be in the decay of the 10.3 MeV state and they note that such a contribution would modify their deduced values for the width of the 10.3 MeV state. This value is the one used in the literature. They also concluded that the 12.71 MeV state decays sequentially via the 2^+ exited state of ^{8}Be.

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. 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 somewhat model dependent. Since the conclusions on branching ratios, break-up mechanisms and the determination of energy and width of participating resonances are based on detailed analysis of the spectra of the delayed α-particles, this problem is a significant limitation.

Balamuth *et al.* [11] studied the breakup of the 12.71 MeV state by feeding this state directly in the ^{13}C(^{3}He,α)^{12}C* reaction. They fit the single α-spectrum from this state using an R-matrix expression, taking into account order-of-emission interference effects (the symmetrization of the decay amplitude due to the α-particles being identical bosons). Note, the same single α-spectrum was used by Korsheninnikov [2] as support for democratic decay of this state, indicating that the single spectrum is a too inclusive observable to distinguish between the two break-up mechanisms.

To obtain a value for the branching ratio to the 12.71 MeV state in the decay of ^{12}B we use the ft-value from the decay of the mirror nucleus ^{12}N. The result of this procedure

Table 2: Estimates for the number of detected events based on a request of 1000 multiplicity-3 events detected from the 12.71 MeV state. This corresponds to 3 × 10^9 ^{12}B nuclei collected on the foil. We give the number of detected events with multiplicity 1, 2 and 3 for the three states expected to play a role in the decay. The estimates rely on assumption on the decay modes of the states. We have assumed sequential break-up through the 0^+ and 2^+ states of ^{8}Be.

E (MeV)	N_1	N_2	N_3	Mode
7.654	1.6×10^7	1.2×10^7	2.1×10^5	0^+
10.3	2.7×10^5	2.4×10^5	4.3×10^5	0^+
12.71	5.9×10^3	4.2×10^3	10^3	2^+

is a branching ratio of 0.00065 %. The proposed experimental setup and details of the beam-time calculation based on the calculated branching ratio is presented in section 4. In Table 2 we summarize the expected statistics that would be collected by this experiment. Note that besides identifying the branch to the 12.71 MeV state, the experiment will also collect a large number of events from the 7.654 MeV and 10.3 MeV states, thus further motivation for this proposal comes from providing much improved information about the decay of these two states. Indeed, the high number of events from the 10.3 MeV state may cause concern in that the high energy tail of this state will provide counts in the expected region for the 12.71 MeV state. But since the ft-value for the 12.71 MeV state is expected to be significantly smaller than that of the 10.3 MeV state, this will not be a problem.

4 The proposed experimental set-up

Beams of the element Boron are difficult to produce for most ISOL facilities due to its high chemical affinity to most target and ion source materials, thus presently no ^{12}B beams are available at ISOLDE. However, recently good yields of ^{12}Be were achieved. With a beta-decay branching ratio of 99.5 % to the ground state of ^{12}B this provides a good

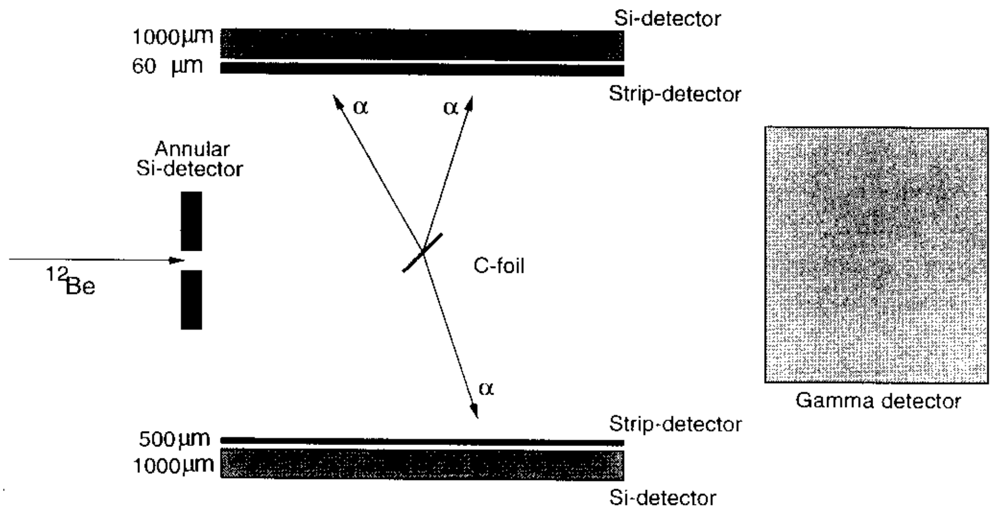

Figure 4: The proposed experimental setup envisaged for the measurement of the three-particle break-up of ^{12}C states. The gamma-detector is used for monitoring the beam intensity for the extraction of absolute branching ratios.

method of producing ^{12}B indirectly. Beryllium is selectively ionized with the resonance ionization laser ion source (RILIS). Up to now the best yield of ^{12}Be was achieved with a special thin tantalum foil target (2 μm thick foils). From the detection of beta-delayed neutrons with a 4π neutron counter a yield of 5×10^4 ions/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 a conservative yield estimate of 10^4 ions/μC. A further development of a dedicated target (e.g. a tantalum foil target with still thinner foils to further reduce the diffusion delay) is very welcome, but not required for this proposal.

Alternatively, the relevant states in ^{12}C could be fed in the beta-decay of ^{12}N. While a large yield of ^{13}N exist at ISOLDE, no beam of ^{12}N exist presently. During our ^{9}C experiment we searched for ^{12}N from a CaO target on both the ^{12}N^{14}N and ^{12}N^{16}O molecular side-bands, but saw no activity that could be assigned to this isotope.

The experimental setup planned to be used is shown in Figure 4. The activity is stopped in a thin carbon foil ($\simeq$ 40 μg/cm^2) which is viewed by two double sided Si strip detectors, which are both backed by thick Si-pad detectors. The main experimental problem will be the discrimination between low energy α-particles and beta-particles. Since we will not have to measure high energy protons in this experiment, this problem is diminished by using thin Si-detectors. Thus in 60μm of Si, minimum ionizing electrons will deposit $\simeq$ 20 keV whereas up to 9 MeV α-particles will be stopped. The gamma-detector serves to measure the 4.44 MeV gamma ray from the first excited state of ^{12}C, this will provide absolute normalization of the detected branches.

The detection efficiency for events with 1, 2 and 3 detected α-particles is dependent on the kinematics of the break-up. For the beam-time estimates we have performed Monte-Carlo simulations of the decay, details can be found in section 6. Figure 5 shows the resulting detection efficiencies as a function of the energy of the excited state in ^{12}C for sequential break-up through the 0^+ (left) and the 2^+ (right) states of ^{8}Be. The solid lines given in the right part are the detection efficiencies calculated from the democratic

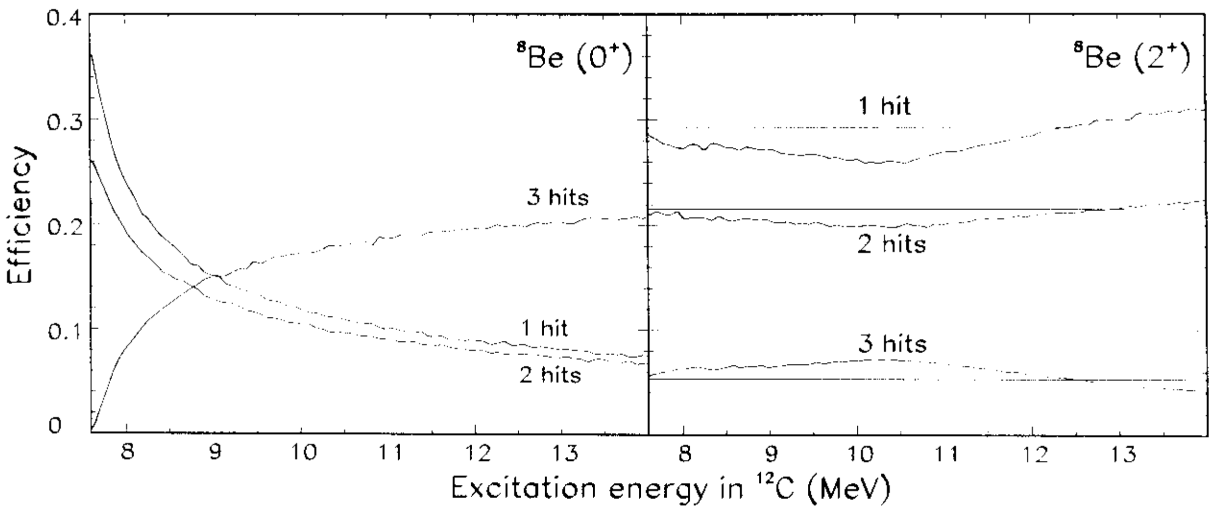

Figure 5: Detection efficiency for events with 1, 2 and 3 detected α-particles for break-up of ^{12}C via the 0^+ ground state (left) and the 2^+ excited state (right) of ^{8}Be. The efficiencies are plotted as functions of the excitation energy in ^{12}C. The solid lines in the right part of the figure are the (energy independent) detection efficiencies for the democratic decay mode.

decay mode. Note that the detection efficiency for the 12.71 MeV state varies very little between the democratic decay mode and sequential decay via the 2^+ state (both $\simeq$5 %). For the beam-time calculation we require 1000 multiplicity-3 events detected from the 12.71 MeV state. Using the branching ratio calculated in section 2 and the detection efficiency extracted from the Monte-Carlo simulation this corresponds to 3×10^9 ^{12}B nuclei collected on the foil. With 6 proton pulses per super-cycle of 16 pulses this requires 8.5 shifts of beam-time, hence we conservatively require 10 shifts for the measurement.

5 Summary and Beam request

We propose to measure the decay of ^{12}B with a setup sensitive to the 3α-particle break-up channels of this decay. If approved this experiment will significantly improve our knowledge of these states in ^{12}C and identify for the first time the decay branch to the 12.71 MeV state. The decay of these state are of fundamental importance to the study of the mechanism of break-up to final states with more than two fragments.

We request a total of 10 shifts of on-line data taking from a Ta-foil target with the RILIS source. We ask for a further 3 shifts for stable beam adjustment and calibration measurements. For reasons of low background we request the LA1 beam-line.

6 Appendix. Monte-Carlo simulation of the experiment.

We have developed a Monte-Carlo simulation for the break-up of ^{12}C states and their subsequent detection in the detector system of Figure 4. The β-particle and recoil effects from the β-decay are neglected. The geometry and energy resolution of each detector are taken into account. The break-up is simulated with the event generator GENBOD from the CERN libraries [12]. This generator provides particle energies and momenta for the break-up into N particles with given masses and total energy. The energies and angles of emission are distributed according to phase-space only, but sequential decay mechanisms can be simulated by modifying the event weights by appropriate expressions (Breit-Wigner) for the position and width of binary resonances. Order-of-emission interference effects were not included in the simulation.

The main purpose of the Monte-Carlo simulation for this proposal is the calculation of detection efficiencies which are sensitive to the kinematics of the break-ups. Figure 5 shows the detection efficiency for events with 1, 2 and 3 detected α-particles for break-up of ^{12}C via the 0^+ ground state (left), the 2^+ excited state (right) of ^{8}Be and for democratic decay. The efficiencies are plotted as functions of the excitation energy in ^{12}C.

Figure 6 shows contour plots of the energy-energy correlations for the 12.71 MeV state assuming sequential break-up through the 0^+ ground state and the 2^+ excited state of ^{8}Be (top), and assuming phase-space determined kinematics and democratic decay (bottom). The phase space distribution is very similar to that of the 2^+ state due to the large width of this state.

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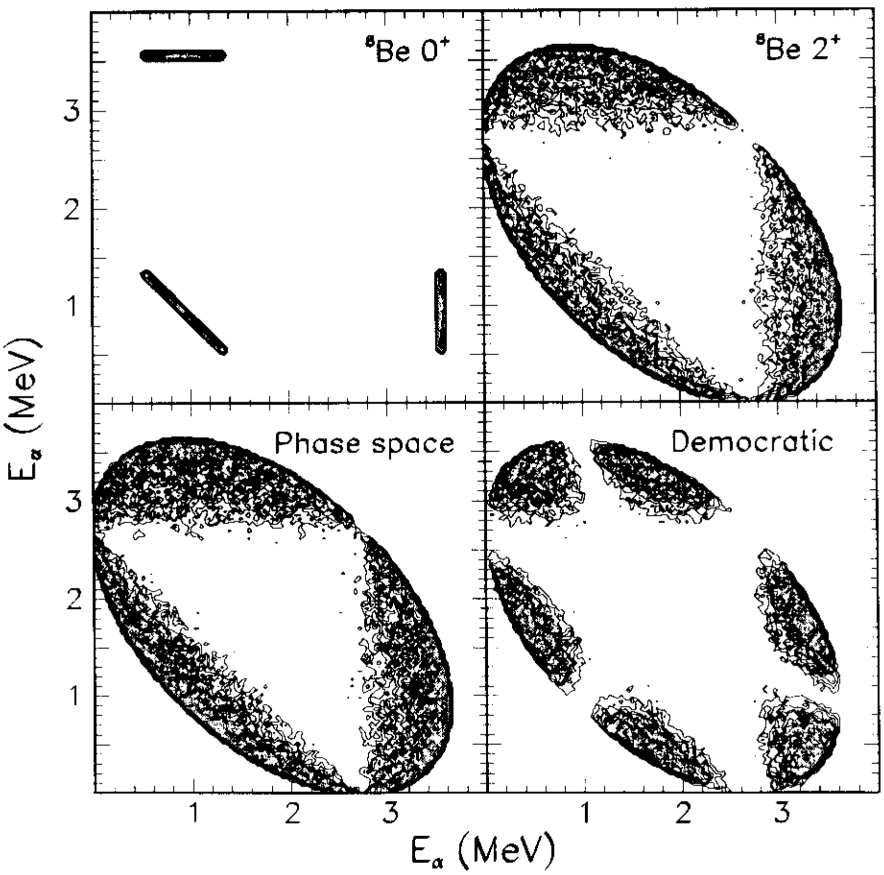

Figure 6: Contour plots of the energy-energy correlations for the 12.71 MeV state. The upper part shows sequential break-up through the 0^+ ground state (left) and the 2^+ excited state (right) of ^{8}Be. The lower part shows the phase-space distribution (left) and the distribution expected from the democratic decay mode. The phase space distribution is very similar to that of the 2^+ state due to the large width of this state.