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Correlated emission of three α-particles in the β-decay of ^{12}N

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Abstract. The β-decay of ^{12}N is used to populate α-emitting excited states in ^{12}C. The α-particles from the break-up of both the 10.3 MeV and 12.71 MeV states were measured in coincidence with an efficient detector setup consisting of two double-sided Si strip detectors. The break-up of the 12.71 MeV 1^+ state is an interesting testing ground for the different descriptions of multi-particle break-up, whereas the properties of the 10.3 MeV state, which under some astrophysical conditions is relevant for the production of ^{12}C in stars, are poorly known. First results from the analysis of the data is presented and compared with Monte Carlo simulations.

PACS. 21.45.+v Few-body systems – 21.10.Hw Spin, parity, and isobaric spin – 27.20.+n $6 \leq A \leq 19$

1 Introduction

Break-up of nuclear states fed in reactions or beta-decay has long been an object of study and a central tool for nuclear physics. Whereas the vast majority of studies have concentrated on processes involving two particles, there has recently been increased interest in final states of three (or more) particles [1–5]. The kinematics of such break-ups is not completely restricted by conservation laws as in the two-particle case. Instead the energy and angular distributions of the fragments reflect different possible break-up mechanisms.

Ten years ago it was suggested that the excited states of ^{12}C decaying into 3α final states provide an ideal testing ground for new descriptions of such break-ups [6]. The normal-parity states can decay sequentially via the narrow 0^+ ground state of ^{8}Be, whereas this decay mode is hindered for the 1^+ and 2^- states due to parity conservation. This leaves only sequential decay via the broad 2^+ excited state of ^{8}Be or direct decay possible. The α-spectrum from the most interesting 1^+ state at 12.71 MeV as measured by Balamuth [7] has been analysed both in terms of direct decay [6] and sequential decay taking into account the correct quantum-statistical symmetrisation of the decay amplitude [7]. In [6] it was suggested that a measurement in complete kinematics would be highly interesting in order to determine the correct description of the break-up.

The 10.3 MeV state in ^{12}C has only been observed in the β-decays of ^{12}N and ^{12}B where it is fed in allowed transitions. The two possible spin-parities of $(0, 2)^+$ will give significantly different interference patterns between the 10.3 MeV state and the astrophysically important 0^+ state at 7.65 MeV. This interference also depends on the width and position of the 10.3 MeV state, which are poorly known. It has even been suggested that the strength interpreted as the 10.3 MeV state is the tail (ghost) of the 7.65 MeV state, and therefore no state at all [8].

We have used the β-decay of ^{12}N to access the α-decaying states in ^{12}C and used a compact detection system to measure all three α-particles in coincidence. In sect. 2 we discuss our experimental approach, using compact setups of double-sided Si strip detectors in close geometry, and in sect. 3 we compare the results of a preliminary analysis to Monte Carlo simulations.

2 Experiment

All previous experiments used the reaction ^{10}B(^{3}He, n)^{12}N to produce the activity and measured the decay fragments

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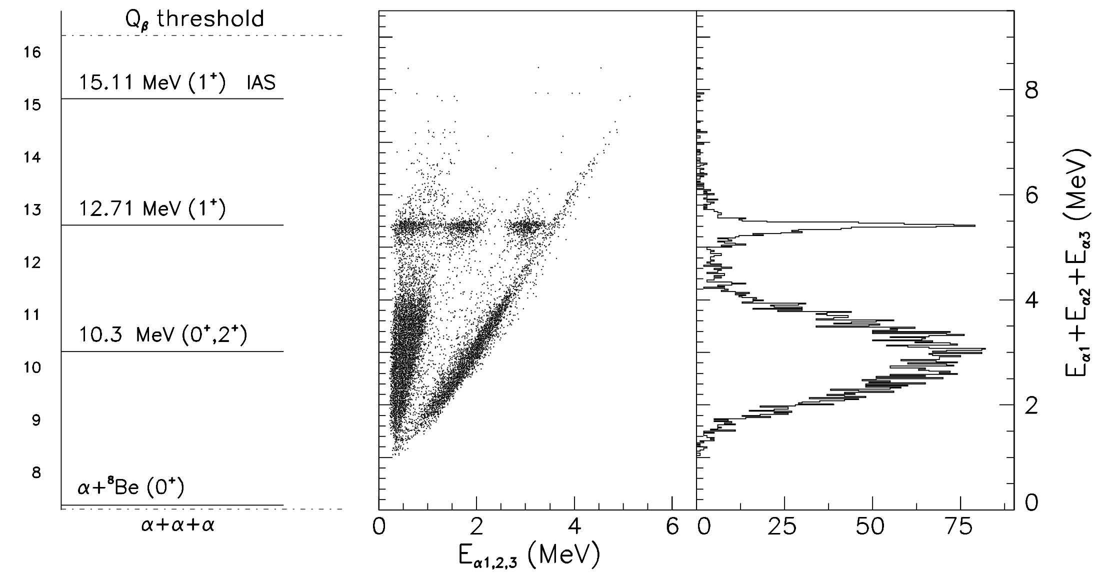

Fig. 1. Triple coincidence data from the β-decay of ^{12}N. In the centre is shown a scatter plot of the summed energy of the three detected α-particles against the energy of the individual particles, hence each break-up event is represented by three dots on the same horizontal line. To the right is 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.

from within the target. Hence a common problem was the energy loss of the delayed α-particles in the target. The source position will in this case be extended in a way determined by the dependence of the production cross-section and the energy loss of the primary beam in the target. Corrections for this are 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 a detailed analysis of the spectra of the delayed α-particles, this problem is a significant limitation.

The present experiment was performed at the IGISOL facility of the Jyväskylä Accelerator Laboratory (JYFL), Finland. The activity was produced with the $^{12}\mathrm{C(p,n)}^{12}\mathrm{N}$ reaction with the $10\,\mu$A proton beam from the cyclotron and the produced nuclei subsequently accelerated to 40 keV, mass separated and led to the detection system where they were stopped in a 50 μg/cm^2 carbon foil (see [9] for a review of the IGISOL technique). The yield obtained at the detection system was of the order of 100 ions/s. The obvious advantage in using an ISOL beam for this study is that the problem of energy loss in the target is strongly diminished, although correction for the energy loss in the collection foil is still important due to the presence of very low-energy α-particles. Also the good beam properties of the ISOL beam are essential for having a small source size on the collection foil, which is required for a good position determination in the reconstruction of the events.

The detection system consisted of two double-sided Si strip detectors (DSSSDs) placed on either side of the collection foil. This detection system is described in detail in [10]. Important here is that the system provides an efficient detection (total solid angle of the order of 25%) of both energy and position of the emitted particles, allowing us to record the break-up in *complete kinematics*. Due to the high segmentation of 16×16 effective pixels of both DSSSDs the high total efficiency is obtained while maintaining a low summing probability. On the other hand, the use of DSSSDs in close geometry presents us with new problems not usually encountered in delayed particle spectroscopy. Contacts on the surface of the detectors act as a thin dead layer, and as the angle of incidence of the measured particles is different for each pixel, the energy loss in this dead layer is not easily included in the energy calibration. Also, this effect gives the different strips different low-energy detection and trigger thresholds. The handling of these problems is described in detail in [11].

A complete characterization of the break-up is possible for events where two or three of the emitted α-particles are detected (multiplicity two or three); in the first case the energy and position of the undetected particle may be reconstructed from energy and momentum conservation as demonstrated in [3]. The preliminary analysis presented here is based entirely on the more straightforward multiplicity-three events.

3 Data and Monte Carlo simulations

In the central part of fig. 1 we show a scatter plot with the sum energy of the three detected particles against each of the three individual energies, hence 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 thresholds and energy levels relevant for the β-decay of ^{12}N. In the projection the 10.3 MeV (6000

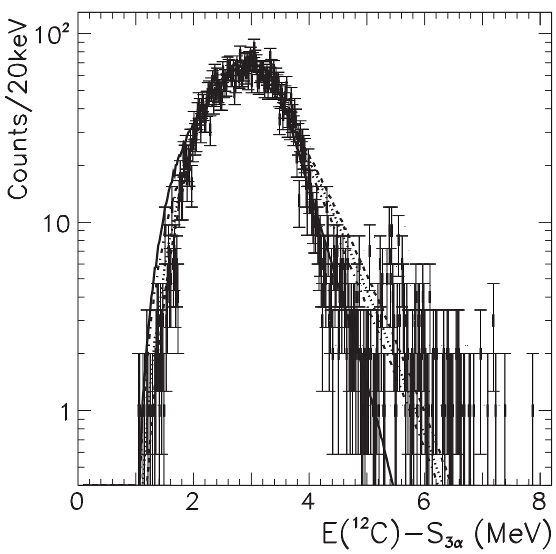

Fig. 2. The nature of the 10.3 MeV state is studied by comparing the peak obtained by gating on the diagonal in fig. 1 with Monte Carlo simulations of different models. The dotted curve is for a single state with spin 0^+, the dashed line for a single state with spin 2^+, the dot-dashed curve is for a 2^+ state on top of the tail (ghost) of the 7.65 MeV 0^+ state, and finally the full curve is a 0^+ state together with the 7.65 MeV state where the interference between the two is taken into account.

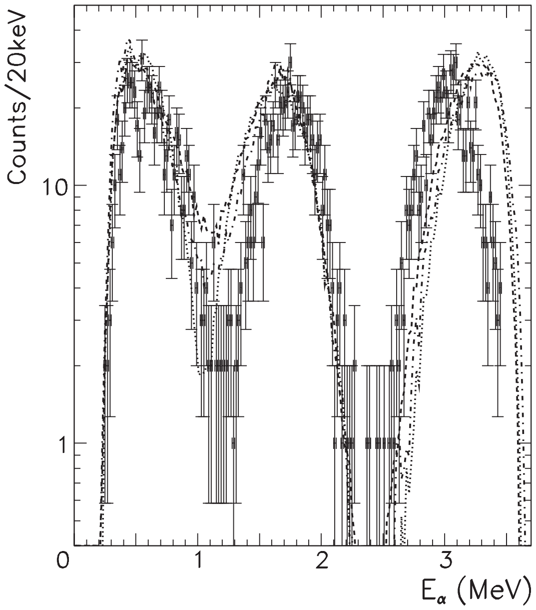

Fig. 3. The mechanism of the break-up of 12.71 MeV 1^+ state in ^{12}C is studied by comparing the measured α-spectrum with Monte Carlo simulations of three different break-up models. The dotted curve is the predictions of the democratic model, the dashed line that of a standard R-matrix model, and the dot-dashed a sequential model taking into account the correct quantum-statistical symmetrisation of the amplitude.

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 consistent with the observation of Balamuth *et al.* [7].

In this paper we wish to address two questions:

– what is the nature of the state(s) breaking up via the ground state of ^{8}Be ?
– which is the break-up mechanism of the 12.71 MeV (and 15.11 MeV) states ?

To approach an answer to these questions we perform Monte Carlo simulations to visualize how different answers (models) combined with the acceptance of the detector setup compare to the experimental data.

As the break-up mechanism via the ^{8}Be ground state is unambiguous, the purpose of the Monte Carlo simulation is to determine the detection efficiency of the setup as a function of the total energy of the three α-particles. To study the 10.3 MeV state in detail we first gate on the diagonal shown in fig. 1 to enhance the ^{8}Be ground state channel. The result of this is the data shown in fig. 2. We then compare this data with R-matrix calculated peak shapes under different assumptions of the nature of the state, corrected for the simulated detection efficiency.

The models tested here are those of a single broad level with spin-parity 0^+ or 2^+ with and without the tail (ghost) of the 7.65 MeV state included. In each case the reduced width and position of the broad level were allowed to vary in a fit. The fits were limited to the region between 2.1 MeV and 4.2 MeV, which is estimated to be unsensitive to details of the acceptance function and possible contributions of higher energy levels. The preliminary results of this procedure are the curves shown in fig. 2. Clearly the best agreement is obtained for a broad 0^+ state together with the tail of the 7.65 MeV state, where the interference between the two states allows one to reproduce the high-energy slope of the peak, which is not possible in any of the other models. The counts above the region of the fit are partly from the 12.71 MeV state, which is not fully removed by gating on the diagonal. In addition, the diagonal seems to extend to significantly higher energies than suggested by the curves in fig. 2. This observation is in agreement with the findings of [12] where a new state at 13 MeV was suggested.

We next turn to the question of the break-up mechanism of the 12.71 MeV state. This break-up has previously been described in three different models. First Schwalm and Povh [13,12] used a standard R-matrix description for the sequential break-up via the 2^+ excited state of ^{8}Be. Balamuth *et al.* [7] extended this by including the correct quantum-statistical symmetrisation of the break-up amplitude; this essentially takes into account that in any given event it cannot be determined which of the emitted α-particles was the one first emitted, and hence the amplitudes for the three possible assignments should be added and squared to determine the correct break-up probabilities and fragment spectra. Finally Korshenninikov [6] suggested that the sequential picture itself is inconsistent due to the large width of the ^{8}Be 2^+ state compared to the total energy available for the break-up. Essentially, the secondary break-up happens so quickly that the first α-particle still feels the interaction of the secondary particles. Instead he describes the break-up through an expansion in hyperspherical harmonic functions, where, if final-state interactions can be ignored, only the first terms should be required to describe the data (the break-up is then called *democratic*). We have tested these three models by inserting the corresponding amplitudes into a Monte Carlo simulation. The preliminary results are shown in fig. 3. The three descriptions give very similar predictions of the α-spectrum, but the democratic description clearly reproduces best the dip between the first and second peaks. However, none of the models describe adequately the shape of the highest peak.

4 Conclusion and outlook

We have for the first time measured in triple coincidence the three α-particles emitted from ^{12}C states fed in the β-decay of ^{12}N. By using an ISOL beam we could significantly improve the resolution of the summed spectrum compared to previous in-beam measurements. This permits a more precise analysis of the nature of the 10.3 MeV state and the break-up mechanism of the 12.71 MeV state. The results of the preliminary analysis indicate a spin of 0^+ of the 10.3 MeV state, and democratic decay of the 12.71 MeV state. In agreement with earlier measurements we find evidence for higher-lying states decaying through the ^{8}Be 0^+ ground state.

The preliminary analysis presented here can be improved in several points. For the 10.3 MeV state a better subtraction of the 12.71 MeV state should be possible by including additional gating, and for the 12.71 MeV state we will search for observables which in a more transparent way can display the differences between the three models suggested for the break-up. Also, it should be studied whether the similarity of the predicted α-spectra of the democratic and sequential models is accidental, or a more general feature.

Future measurements to increase the statistics would clearly be very beneficial, in particular to better access the high-energy part of the decay where new strength clearly is present. Increased yields of ^{12}N may become available at the SPIRAL beam line at GANIL or at CERN-ISOLDE when an ECR ion source becomes available in the near future. Alternatively, much of the same information can be accessed from the β-decay of the mirror-nucleus ^{12}B.

Finally, we would like to encourage new theoretical work on the problems discussed here. The question of the break-up mechanism of the 1^+ states could serve as a testing ground for the models currently in use for the predictions of possible signatures for ^{2}He emission from nuclei [2,1]. Also precise Greens functions Monte Carlo and variational Monte Carlo *ab initio* calculations should soon be possible also for $A = 12$ and could be used to better understand the structure of the excited states of ^{12}C.

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