Complete kinematics measurement of the ^{11}B(p,γ)3α reaction

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Abstract. One of the first nuclear reactions measured after the invention of the accelerator by Cockroft and Walton was ^{11}B+p, measured by Rutherford and Oliphant in 1933 [1, 2]. This reaction, however, is not yet fully understood at low incident proton energies [3], and the present paper therefore presents a new measurement with complete-kinematics data utilising modern large-area segmented silicon-strip detectors. The aim of the measurement is twofold: firstly, to fully characterise the triple-α decay of the T=1, 2^+ state at 16.11 MeV in ^{12}C; secondly, to search for γ decay of the 2^+ state to lower lying states, in particular the newly suggested 2^+ state around 9–10 MeV [4]. The isovector M1 population of lower lying 2^+ states is strongly favoured over isovector E2 transitions to 0^+ states, and the method is therefore a promising method to elucidating this timely question.

1. Introduction

The present line of work was initiated in the 1930s when the triple-α breakup mechanism following the ^{11}B(p,)3α reaction was studied through an investigation of the range of the emitted α particles [1, 2, 5]. Dee and Gilbert [6] similarly measured the detailed range distribution of the α particles and thereby found the energy distribution to peak strongly around 4 MeV, and additionally obtained some information on the kinematics of the three-body breakup.

Twenty years later, the also α-decaying second 0^+ state in ^{12}C was suggested by Hoyle and soon found experimentally [7, 8]. The subsequent identification of a broad structure around 10 MeV, triggered the interpretation by Morinaga of the structure as the 2^+ rotational excitation of the Hoyle state supporting an α-chain interpretation of the Hoyle state [9, 10]. We now know that the 10 MeV structure is predominately 0^+ in nature, but the search for the Morinaga 2^+ state continues. In recent years, several suggestions have thus arisen for the position of the 2^+ state [4, 11, 12, 13, 14, 15, 16, 17, 18]. These generally fall in the 9.5–11.5 MeV range.

In our collaboration we have also investigated this, in this case using β-delayed triple-α breakup measured in compete kinematics [19, 20, 21] at CERN-ISOLDE [22] and JYFL-IGISOL [23] and implantation-decay experiments [24, 25] at KVI-TRIμP [26]. Here we have found some indication for a 2^+ state around 11 MeV, similar to the energy of the so-called "10 MeV" state [27].

2. Experimental methodology

We here present an new way of obtaining the necessary selectivity between 0^+ and 2^+ states, in which the states are fed by γ decays of higher-lying states in ^{12}C. Because of the broad nature of most states in the triple-α continuum and the extremely weak γ branches to the states, such a measurement is, however, impossible using conventional methods of γ-decay detection. We therefore detect not the emitted γ ray but the subsequent triple-α breakup. The ^{12}C state of interest is populated in proton and ^{3}He induced reactions in boron targets. In these, the beam is made to impinge on a thin target in the centre of a compact detector setup such as the setup shown in Fig. 1. In the p+^{11}B reaction the initially populated excitation energy in ^{12}C is uniquely determined by the choice of beam energy. In the ^{3}He+^{10}B reaction the initially populated excitation energy in ^{12}C is uniquely determined by the momentum of the outgoing proton. Following the reaction the coincident detection of the three emitted α particles then determine the energy of the γ-delayed triple-α breakup.
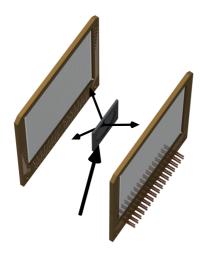

Figure 1. Compact highly-segmented detector setup for reaction-induced multi-particle coincidence detection. Shown here is the detector geometry used for the ^{11}B$(p,)3\alpha$ measurement.

2.1. Proof-of-principle: ^{10}B(^{3}He,p)^{12}C*

As a first assessment of the method, we have populated the 15.11 MeV, 1^+, $T = 1$ state via the ^{10}B(^{3}He,p)^{12}C* reaction. The populated ^{12}C state was identified from the kinematics of the reaction through measurement of the outgoing proton. The M1 γ decay of the 1^+ state is similar to the Gamow-Teller decay of its isobaric analogues (the ground states of ^{12}B and ^{12}N). The γ decay should therefore populate 0^+, 1^+, 2^+ states in ^{12}C at intensities similar to the breakup-spectrum measured in the β-delayed triple-α decay experiments, apart from phase-space factors. This correspondence has indeed been observed, with the only difference being the observation of a suppressed E1 γ transition to the 11.83 MeV 2^- state. This component of the decay is, however, easily separated out as the breakup of the 2^- state proceeds exclusively through the ^{8}Be first excited (2^+) state at 3 MeV, and the breakup dynamics therefore is markedly different from that of the 0^+ and 2^+ states in the region which predominantly break up through the ^{8}Be ground state. For further details, see Ref. [28].
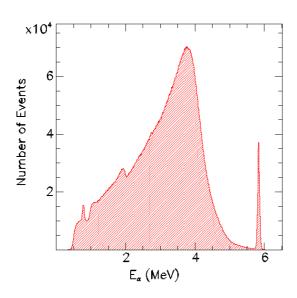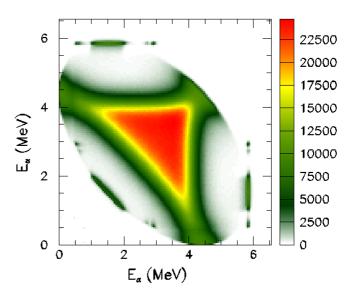
3. Measurement of the ^{11}B$(p,)3\alpha$ reaction

Through the ^{11}B$(p,)$ reaction we selectively populate the ^{12}C, 2^+, $T = 1$ state at 16.11 MeV utilising a 165(3) keV proton beam impinging on a $10\,\mu$g/cm^2 natural boron target (80% ^{11}B). Surrounding the target, as seen in Fig. 1, are two double-sided silicon-strip detectors (DSSSDs) for the coincident detection of the three emitted α particles.

3.1. Breakup of the 16.11 MeV state

In Fig. 2 is shown the single-α energy spectrum from breakup of the populated 16.11 MeV state. For another recent measurement of α-breakup distributions induced by this reaction, see Ref. [3]. Double α-particle coincidences from the breakup of the 16.11 MeV state are shown in Fig. 3. These may assist the interpretation of the single-particle spectrum, as it is seen that the distribution is dominated by two distinct components for the breakup of the state in relation to the sharing of the total 8.84 MeV energy available. The α particles in the narrow peak near the maximum energy correspond to the the energy of the first α particle emitted in the sequential decay through the ^{8}Be 0^+ ground state, for which 8.75 MeV is available in the first stage of the breakup, yielding a well-defined energy of 5.83 MeV for the α particle with the ^{8}Be nucleus taking the remaining kinetic energy. The subsequent breakup of the ^{8}Be ground state (with 92 keV center-of-mass energy) results in the structure clearly visible in the 1–2 MeV region of the coincidence plot and similarly seen as a slight enhancement in the corresponding region of the single-α spectrum. The predominant feature in the coincidence spectrum corresponds in energy to what should be expected from breakup of the 16.11 MeV state through the ^{8}Be 2^+ first excited state at 3 MeV. However, caution should be taken in this interpretation, as the breakup may not be strictly sequential.

Figure 2. Single-α energy spectrum from the 16.11 MeV, 2^+, $T = 1$ state.

Figure 3. Double-α coincidence energies for the breakup of the 16.11 MeV state in ^{12}C.

3.2. Triple-α breakup following γ-decay of the 16.11 MeV state

Now investigating full triple-α coincidence data, we plot the individual α-particle energy against the ^{12}C excitation energy, as deduced from the total triple-α energy (Fig. 4). This is naturally dominated by the direct breakup of the 16.11 MeV state as described above, for which the intensity exceeds the scale of Fig. 4 by two orders of magnitude. However, by focusing on the low-intensity breakup channels present in the 8–14 MeV excitation-energy range, we see clearly the population and breakup of lower-lying states in the triple-α continuum. None of the states seen in this region can be populated with reactions induced by the low-energy proton beam – regardless of the assumed target – and we therefore conclude that all states seen have been populated through γ decay of the 16.11 MeV state. Most predominately, we see the 10.8 MeV 1^-
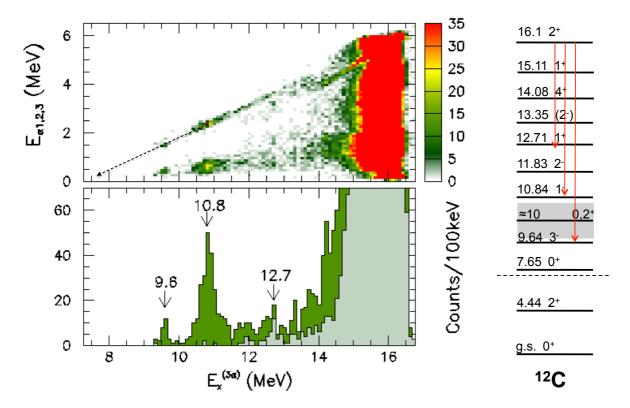
Figure 4. Triple-α coincidence events with individual α energy plotted against the ^{12}C energy (upper). Projected spectra for each of the two breakup channels: ^{8}Be ground state and higher energies in ^{8}Be in dark and light green respectively (lower).

Figure 5. ^{12}C levels with 3-α threshold and measured γ decays of the 16.11 MeV state indicated.

state populated in the E1 transition from the 16.11 MeV state, below which we see population of the 9.6 MeV 3^- state (see Fig. 5 for a list of relevant levels in ^{12}C). The breakup dynamics of these states are, as expected, dominated by breakup through the ^{8}Be ground state, which is seen through the fact that one of the three α particles always lies on the line of slope 2/3 (α-^{8}Be energy sharing) which intersects the energy axis 92 keV above the triple-α threshold (the ^{8}Be ground-state energy). Each of the two remaining α particles carry approximately a quarter of that energy. The low-energy part of the breakup channel other than the ^{8}Be ground state is dominated by the 1^+ state at 12.7 MeV (light green in lower part of Fig. 4). Very intriguingly, an additional natural-parity contribution of approximately 50 triple-α events in the 11.5–12 MeV range may be indicated. The natural-parity nature of the component is indisputable based on its clear decay through the ^{8}Be ground state (see upper frame of Fig. 4. As the E2 isovector decay to 0^+ states is expected to be suppressed by approximately two orders of magnitude compared to M1 isovector decay to 2^+ states, it is unlikely to be of 0^+ nature. As no additional 1^- and 3^- states are expected in this region, it is more likely a 2^+ state.

4. Summary
In conclusion, we have identified γ decay from the 16.11 MeV, $T = 1$, 2^+ state to lower-lying states in the triple-α continuum, in particular to the 3^-, 1^-, and 1^+ states at 9.6 MeV, 10.8 MeV, and 12.7 MeV respectively. The γ decays have been measured indirectly through detection of the subsequent triple-α breakup in complete kinematics using a compact, segmented, silicon-detector setup. In addition to the three expected states, we see a clear natural-parity contribution to

the breakup in the 11.5–12 MeV region, and we suggest that this contribution could be a 2^+ state based on the strong suppression of 0^+ states in the decay of the 16.11 MeV state. Though the suggestion based on the present data is very tentative, it nevertheless warrants further investigation, and will direct further studies utilising γ-decay in the triple-α continuum.

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