Complete kinematics study of the p + $^{11}$B $\rightarrow$ $^{12}$C reaction

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Abstract. New data and preliminary results from an experimental study of the p + $^{11}$B reaction are presented. Using proton energies in the range of 167 - 170 keV the 2$^+$ resonance in $^{12}$C at an excitation energy of 16.11 MeV was populated. Detecting the emitted $\alpha$-particles in full kinematics allows us to study $^{12}$C resonances and their properties. In addition to the 3-$\alpha$ break-up of the 16.11 MeV resonance we observe $\gamma$-transitions to lower lying resonances. Transitions to the 3$^-$ state at 9.64 MeV, the 1$^-$ state at 10.84 MeV and the 1$^+$ state at 12.71 MeV are clearly seen. The transitions to the 1$^-$ state has not been observed previously. In addition we see decays to structures of natural parity at excitation energies around 11 - 13 MeV. The results illustrate that the indirect detection of $\gamma$-decays is an effective technique for studying the low lying resonance spectrum of $^{12}$C.

1. Introduction
The nature of the second 0$^+$ state in $^{12}$C, known as the Hoyle state, is one of the most eminent tests of our understanding of structure in light nuclei. Since its prediction and first observation much work has been focussed on describing the structure of this state. Morinaga gave a structural interpretation in 1956 as a linear chain of $\alpha$-particles. Advanced no-core shell model calculations fail to reproduce the excitation energy of the Hoyle state (see e.g. Ref. [1]) whereas its properties are well described in cluster models. Even in fermionic molecular dynamical calculations, which are able to describe both cluster and shell model like configurations, the Hoyle state has cluster structure (see e.g. [2]). Indeed the Hoyle state is believed to have a triple $\alpha$ cluster structure. The detailed structure, such as whether it is in a triangular or linear form or even some other arrangement, is however still a subject of much debate.

A test of how the three $\alpha$-particles arrange themselves in the Hoyle state is to measure the moment of inertia of the rotational band build upon it, if it exists. Therefore much effort has been directed on observing the first 2$^+$ excitation (2$^+_2$) and recently there have been significant experimental progress in this area. Evidence for a 2$^+_2$ excitation in the region of interest has emerged from experiments using inelastic alpha scattering [3], inelastic proton scattering [4], an intense $\gamma$-ray beam [5] and $\beta$-decay [6]. Work still needs to be done on establishing more precisely its properties and searching for new broad states will continue to be important in order to reveal information concerning the detailed structure of the Hoyle State [7].

This contribution presents new results on low lying $^{12}$C resonances populated by $\gamma$-decays.

1 Probably not the same 2$^+$ state as found in the other experiments.
2. Experiment: \( p + ^{11}B \)

We have used the \( p + ^{11}B \) reaction to populate the \((J^\pi, T) = (2^+, 1)\) resonance at 16.11 MeV. This resonance predominantly breaks up into three \( \alpha \)-particles. Measuring these will allow information about the resonance and the break up mechanism to be extracted. It is known as reported in Ref. [8] that this state decays by emitting \( \gamma \) rays. This contribution deals with \( \gamma \)-decays to unbound resonances leaving results on direct 3-\( \alpha \) decay for later publications.

2.1. Method

Motivated by the need for a more detailed experimental understanding of the \( ^{12}C \) resonance spectrum our idea is to address low lying resonances in \( ^{12}C \) by using \( \gamma \)-decays from the 16.11 MeV resonance (see Figure 1). This approach introduces selectivity between states of different spin and parity due to the electromagnetic transition rules. Transitions to the broad \( 0^+ \) state around 10 MeV and the \( 3^- \) state at 9.64 MeV can complicate the observation of \( 2^+ \) states as was the case in earlier experiments. In the present case (see Table 1) isovector M1 transitions to \( 2^+ \) states will be favoured over isovector E2 transitions to \( 0^+ \) states as there is no expected collective enhancement of isovector E2 transitions. E1 transitions can populate the \( 3^- \) state, but since this state is quite narrow it is likely to pose less of a problem than the broad \( 0^+ \). Choosing the \( 0^+ \) resonance at 17.76 MeV (\( E_{\text{proton}} = 2.0 \) MeV) could be more advantageous with no transitions to \( 0^+ \) states and negligible \( 3^- \) \( \gamma \)-population. See the contribution from O. S. Kirsebom where this case is studied.

The small \( \gamma \)-branching (of the order \( 10^{-4} \) to unbound resonances) and the fact that most states in the 3-\( \alpha \) continuum are broad makes this experimental approach quite difficult. Certainly it would be an immense challenge when doing conventional \( \gamma \)-spectroscopy. As this contribution shows we are able to identify new transitions to at least one broad state by detecting the \( \gamma \)'s indirectly.

Instead of detecting the decay \( \gamma \)'s directly we detect the \( \gamma \)-delayed \( \alpha \)-particles in full kinematics. This means that the energies and directions are detected for two or all the three

\[ E_p = 163 \text{keV} \]

\[ \begin{align*}
16.11 & \rightarrow 2^+ \\
15.96 & \rightarrow p + ^{11}B \\
15.11 & \rightarrow 1^+ \\
14.08 & \rightarrow 4^+ \\
13.35 & \rightarrow 4^- \\
12.71 & \rightarrow 1^+ \\
11.83 & \rightarrow 2^- \\
10.84 & \rightarrow 1^- \\
10.3 & \rightarrow 0^+ \\
9.64 & \rightarrow 3^- \\
\end{align*} \]

**Figure 1.** Level scheme showing low energy \( ^{12}C \) resonances. A specific decay sequence leading to the 3-\( \alpha \) continuum is shown in the figure.
α’s. This gives full kinematical information about the break up. The results presented here are based on multiplicity 3 events only. The $^{12}$C excitation energy from where the triple α break-up originated is calculated in the p + $^{11}$B center of mass frame (CM) as

$$E_{\text{exc.}}^{^{12}\text{C}} = 3 \sum_{i=1} E_{\alpha} + 7274.8 \text{ keV},$$

(1)

where 7274.8 keV is the 3-α threshold energy. Equation (1) works exactly for the 3-α break-up of the 16.11 MeV level and due to the small recoil energy following a γ-decay it gives the energy of γ-populated levels within 1 keV.

Table 1. Possible spin and parities for states to be reached by E1, M1 and E2 transitions from a $2^+$ state.

| El/MI   | 16.11 MeV, $2^+$ |
|---------|------------------|
| E1      | $1^-, 2^-, 3^-$  |
| M1      | $1^+, 2^+, 3^+$  |
| E2      | $0^+, 1^+, 2^+, 3^+, 4^+$ |

2.2. Setup

The experiment was carried out at the 400 keV Van de Graaff accelerator at Aarhus University, Denmark. Our detection setup consisted of two double sided silicon strips detectors. Both are 60 µm thick with front deadlayer thicknesses of 200 nm and 700 nm. The typical energy resolution in a given detector strip was around 20 keV ($1\sigma$). The detectors typically covered CM polar angles in the range of 55° - 160° and 30° - 120° respectively. The total solid angle coverage was $\sim$ 18%. For each recorded data event both ADC (energy) and TDC (time) information was stored.

The experiment was carried out with proton energies in the range from 167 keV to 170 keV with beam currents in the order of 1 - 2 nA. The target foils consisted of natural boron (typically 10 µg/cm$^2$) with a backing layer of carbon (4 µg/cm$^2$). The beam spot size at the target was in the order of 4 mm$^2$. Calibration of the detectors were done with a $^{228}$Th source. Calibration runs was carried out many times during the period of the experiment (4 months). The multiplicity-3 data presented here was acquired over a period of 250 hours.

2.3. Data and analysis

The single α-particle energy spectrum recorded in one of the detectors is shown in Figure 2. The sharp peak near 6 MeV is due to the first emitted α when the break up proceeds through the $^8$Be ground state. The broad distribution is both due to the secondary emitted α-particles in the $^8$Be ground state channel and the α-particles emitted when going through the broad ($\Gamma = 3$ MeV) first excited state of $^8$Be.

In Figure 3 the reconstructed $^{12}$C excitation energy spectrum is shown. It is calculated by use of Eq. (1) using all triple coincidence energies. We mainly observe the decay of the 16.11 MeV state. At lower energies we also see triple events which could be candidates for γ-decays.

In order to remove the background events we need to impose several cuts to the data. The source of the background is mainly from random coincidence events containing two α-particles from the same physical break-up with and a third detector-hit caused by either noise, protons from the beam or a different α-particle. The most important cuts we apply are

- Time cut by use of TDC data. Removes more than 95% of random coincidences.
Figure 2. Single α energy spectrum in detector 1 for a subset of the total data collected.

Figure 3. Reconstructed $^{12}$C excitation energy where no cuts have been applied to the data.

- Momentum cut. In the CM frame the total momentum ($\sum_{i=1}^{3} P_\alpha$) and its components ($\sum_{i=1}^{3} P_{x,y,z,\alpha}$) should equal zero.
- Different cuts on the angles of the α-particles (sum of the relative angles should give 360° and the three momentum vectors should all lie in the same plane)

Figure 4 shows in the top part how the total momentum for triple-α events that survive the time cut are distributed as function of excitation energy. Clear background tails are visible stretching into the region of high sum momentum. Besides from the maximum intensity region, resulting from the 3-α break-up of the 16.11 MeV level, we notice interesting events at low sum momentum. The dotted red line shows a typical cut level applied in the analysis.

3. Results
The final excitation energy spectrum, after applying all cuts, is seen in the bottom part of Figure 5. We now clearly see evidence for $\gamma$-decays giving rise to distinct structures. We identify them as the 3$^-$ state at 9.64 MeV, the 1$^-$ state at 10.84 MeV and the 1$^+$ state at 12.71 MeV. The fact that we see transitions to the broad 1$^-$ state, which are seen for the first time in this work, illustrates the applicability of this technique for studying the low energy excitation spectrum of $^{12}$C.

With our detection technique we can discriminate the break-up decays proceeding through the $^8$Be ground state. Those decays are represented by the hatched blue histogram in Figure 5, whereas the red histogram is due to decays taking a different route. Since parity conservation forbids break up via $^8$Be (gs) for unnatural parity states the 12.71 MeV state cannot decay by this route. This is consistent with our observation. We see events in the region around 11.6 - 11.8 MeV. It is unclear if these are from the 2$^-$ state at 11.83 MeV.

The top part of Figure 5 illustrates how each of the three α-particle energies are distributed as function of excitation energy. A useful feature in this plot is that the energy of the first emitted α will be on the diagonal line (slope of 2/3) when it goes to the $^8$Be (gs). Looking at the events between 11 MeV and 13 MeV this indicates decays to states of natural parity. This is of high interest as there are no known natural parity states in this region. The observation of e.g. a 3$^-$ state, which could be likely through E1 transitions, would be important for different models pinning down the exact structure of the Hoyle state (see e.g. the discussion in [7]). Additional data on this reaction is clearly necessary in order to analyze this in more detail. A future experiment is already planned on this reaction with an improved detection setup consisting of
4 detectors.

**Figure 4.** Top part: Excitation energy plotted against the total momentum of the three recorded particles. Bottom part: projection of top figure on the momentum axis. The red dotted line illustrates the cut on the total momentum.

**Figure 5.** Top part: \(\alpha\)-particle energies vs. excitation energy with all cuts applied. Bottom part: Projection on first axis. The hatched blue histogram correspond to decays through the \(^{8}\text{Be}\) ground state while the red one corresponds to decays not going through that channel.

4. Summary
Through indirect detection of \(\gamma\)-decays from the 16.11 MeV \(2^+\) state in \(^{12}\text{C}\) we investigate the low energy resonance spectrum of this nucleus. Through this method, where the three emitted \(\alpha\)-particles are detected in full kinematics, we observe clear evidence for decays to three known states. One of these has never been seen populated before from the 16.11 MeV level. Left as an open question and motivation for future studies we observe transitions to natural parity states in a region where no such states are known.

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