Search for the 2+ excitation of the Hoyle state in 12C using the 12C(12C,3)12C reaction

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Abstract. A search for the 2^+ excitation of the Hoyle state in ^{12}C has been performed using the ^{12}C(^{12}C,3α)^{12}C reaction at a beam energy of 101.5 MeV. An angular correlation analysis was used to suppress known contributions to the excitation energy spectrum, enhancing the experimental sensitivity. No strong evidence was found for new states in ^{12}C between 9 and 11 MeV; rather upper limits for their excitation in the ^{12}C+^{12}C inelastic scattering reaction are determined.

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1. Introduction

The structure of the nucleus ^{12}C is fascinating for a variety of reasons. For example, it lies at the present limit of the range of *ab initio* calculations such as the Quantum Monte Carlo approach [1, 2], and provides an important test as it has a rather rich range of structural possibilities. The ground-state has an oblate-structure which is well represented in the shell-model. However, the next 0^+ state at 7.65 MeV is not well described within this framework. Shell model calculations, for example those of Karataglidis *et al.* [3] reproduce, rather well, the energy of the first 2^+ excitation, but in the region of the second state, the 0^+_2 (7.65 MeV), there is a void in the calculations; the energy of this state cannot be reproduced. This in itself points to the rather unusual structure. A similar conclusion is reached in no-core shell model calculations [4]. Indeed, in Ikeda's classification of the structure of light nuclei in 1968 it was assumed that

this state should have a 3α cluster structure. Analysis of electron inelastic scattering data [5, 6, 7, 8] indicates that the 7.65 MeV state has a radius which is ∼1.5 times that of the ^{12}C ground-state, i.e. a volume some 3-4 times larger. This larger volume reduces the overlap of the α-particles and may allow them to obtain their quasi-free characteristics in something approaching an α-particle gas, or perhaps a bosonic condensate [9]. It should be noted though that whilst FMD calculations predict a structure dominantly composed of three weakly bound α particles [10], they also suggest a ^{8}Be + α structure. This is in contradiction to a strict interpretation of a Bose-Einstein condensate and highlights the danger of taking the interpretation too literally.

The 7.65 MeV 0^+ state has a rather central role in stellar nucleosynthesis. It acts as the gateway through which ^{12}C is formed via the triple-α process. Its existence was first predicted by Hoyle [11] in order to explain the observed abundance of ^{12}C and was later experimentally confirmed by Fowler and co-workers [12]. It has subsequently become called the Hoyle-state. In order to arrive at a detailed understanding of the structure associated with this state it is important to determine the nature of possible collective excitations. Determining of location of the associated 2^+ will allow the moment of inertia, and hence a measure of the deformation, to be found. To date no firm evidence for such an excitation has unambiguously been found. However, Itoh *et al.* have reported evidence for a 2^+ state close to 9.7 MeV with a width which is a few hundred keV [13]. These measurements were performed using the ^{12}C(α,α') inelastic scattering reaction, and multipole decomposition of the angular distributions was used to extract the possible 2^+ strength. Similar measurements using the ^{12}C(p,p') reaction also indicate a broad (600 keV) 2^+ state close to 9.6 MeV [14]. Both FMD [10] and AMD [15] calculations also suggest the possible existence of a 2_2^+ excitation in the region of 9-12 MeV.

Here we present measurements of the ^{12}C(^{12}C,^{12}C*) reaction in which the angular correlation technique is used to search for a 2^+ signature close to 9.7 MeV.

2. Experimental Details

The present measurement was performed using the 14UD tandem Van der Graaff Pelletron accelerator facility at the the Australian National University (ANU). A 101.5 MeV ^{12}C beam was used to bombard a 50 μgcm^{-2} ^{12}C foil target; the beam current was typically 10 enA and the charge state of the beam was 6^+.

The reaction studied was ^{12}C(^{12}C,3α)^{12}C and the three α-particles were detected in coincidence in an array of four detector telescopes (two primary and two secondary). These provided an angular coverage in the range of $\theta^* \approx 5^\circ - 30^\circ$ (in the laboratory frame); this suitably covered the range of excitation energies being investigated. The array allowed coverage of the complete azimuthal range. The primary detector telescopes consisted of three elements: a (50 × 50) mm^2, 70 μm thick, double-sided Si strip detector (DSSD) placed in front of a (50 × 50) mm^2, 500 μm thick, position-sensitive Si resistive strip detector (RS) which was in turn located in front of a 10 mm thick CsI scintillator. The DSSDs were divided into two sets of 16 independent 3 mm wide strips, the 16 strips

on the front face having a horizontal orientation and the 16 on the back face vertical. The RS detectors were separated into 16 position sensitive strips; these provided position information with a (FWHM) resolution of $\sim$ 0.3 mm (in-plane) and $\pm$ 1.5 mm (out-of-plane). The CsI scintillators were used to stop any highly energetic particles that passed completely through both the Si detectors. These latter detectors provided a software veto, removing any high energy events in which there was not full energy deposition in the Si elements (due to the CsI scintillators' inability to resolve multiple hits into a telescope). The two secondary telescopes consisted of a (50 $\times$ 50) mm^2, 70 μm thick, Si quad detector in front of a 500 μm thick DSSD (with the same strip arrangement as in the primary detectors), which were located in front of a 10 mm thick CsI scintillator. The Si quadrant detectors were separated into 4 (25 $\times$ 25) mm^2 segments (quadrants). The elements in both telescopes provided $\triangle$E - E particle identification information to distinguish α-particles as required. The detectors and amplifiers were calibrated using a combination of two techniques: a 3-line α-source (^{239}Pu, ^{241}Am and ^{244}Cm), and 45 MeV ^{12}C ions elastically scattered from a ^{197}Au target. The energy resolution was $\sim$ 150 keV (FWHM) for the silicon detectors and $\sim$ 1.5 % (FWHM) for the CsI scintillators.

3. Analysis and Results

The ^{12}C(^{12}C,3α)^{12}C reaction was used to investigate the possible existence of a 2^+ excitation of the Hoyle state in the 9.7 MeV region. This was performed by considering the reverse of the 'triple-alpha' process by which ^{12}C is formed in stellar nucleosynthesis. Techniques were then employed which allowed the suppression of a known 3^- resonance which also exists at this energy. Analysis was primarily undertaken in decays through the $^8\mathrm{Be}_{g.s.}$ + α reaction channel as this is a pre-requisite for the angular correlation technique used.

In order to improve statistics, events were selected in which only 3α-particles were detected. i.e. the ^{12}C recoil particle was undetected. This was performed using $\triangle$E - E particle identification spectra. Following this selection, the total energy (E_{tot}) was then calculated from $E_{tot} = E_1 + E_2 + E_3 + E_{rec} = E_{beam} + Q$. Here E_{1-3} correspond to the energies of the three detected α-particles, E_{beam} the beam energy, Q the Q-value of the break-up reaction (Q=-7.272 MeV) and E_{rec} the recoil energy of the undetected ^{12}C nucleus. E_{rec} was determined by applying momentum conservation between the beam and the final-state particles, whilst assuming the mass of the recoil particle, $m_{rec} = 12$ amu.

The E_{tot} spectrum is shown in Figure 1 and shows a series of peaks. The highest energy peak corresponds to a Q-value of $\sim$ -7.5 MeV which is consistent with the Q-value of α-break-up of ^{12}C (-7.272 MeV). The remaining peaks correspond to excited states of the ^{12}C recoil nucleus. The peak at $\sim$ 90 MeV is consistent with the recoil ^{12}C being emitted in its first excited state at 4.4 MeV, the second member of a rotational band built on the ground state configuration. The peak at $\sim$ 84 MeV corresponds to the recoil nucleus being emitted in the 9.64 MeV 3^- state. By gating on the highest-

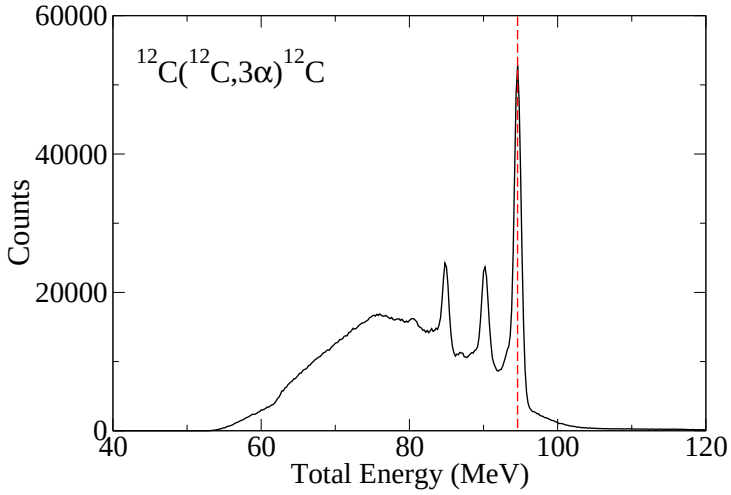

Figure 1. Total energy spectrum. The marked peak corresponds to events in which the recoil nucleus was formed in its ground state. Peaks at lower energy correspond to the 4.4 and 9.6 MeV excitations of the recoil nucleus.

energy peak, only events in which the recoil nucleus was formed in its (0^+) ground state were selected; this is a requirement of the angular correlation method used later. The background events that extend to E_{tot} values greater than the beam energy are believed to most likely arise from pile-up events and from events in which the detected particles are produced from different beam-target interactions.

The break-up of ^{12}C into 3α-particles occurs sequentially in two steps:

$$^{12}\mathrm{C} \longrightarrow {}^{8}\mathrm{Be} + \alpha \ , {}^{8}\mathrm{Be} \longrightarrow \alpha + \alpha \ ,$$

where the lifetime of the ^{8}Be nucleus is sufficiently short so as not to affect the overall kinematics. The decay of the intermediate ^{8}Be nucleus was reconstructed and compared with the Q-value for the ^{8}Be break-up (Q_{Be}=92 keV). The decay energy was calculated using

$$E_{decay} = \sum_{i=1}^{2} E_{\alpha_i} - \frac{{P_{Be}}^2}{2M_{Be}} \ , \tag{1}$$

where E_{α_i} are the energies of two of the three α-particles, P_{Be} is the momentum of the ^{8}Be nucleus, and M_{Be} is the mass of the ^{8}Be nucleus. All possible permutations of 2α-pairs were checked and events filtered to include those for which an appropriate Q-value existed for only one pairing.

A ^{12}C excitation energy spectrum was constructed by a similar method to that used to reconstruct the ^{8}Be break-up:

$$E_{ex} = \sum_{i=1}^{3} E_{\alpha_i} - \frac{{P_C}^2}{2M_C} + E_{th} \ , \tag{2}$$

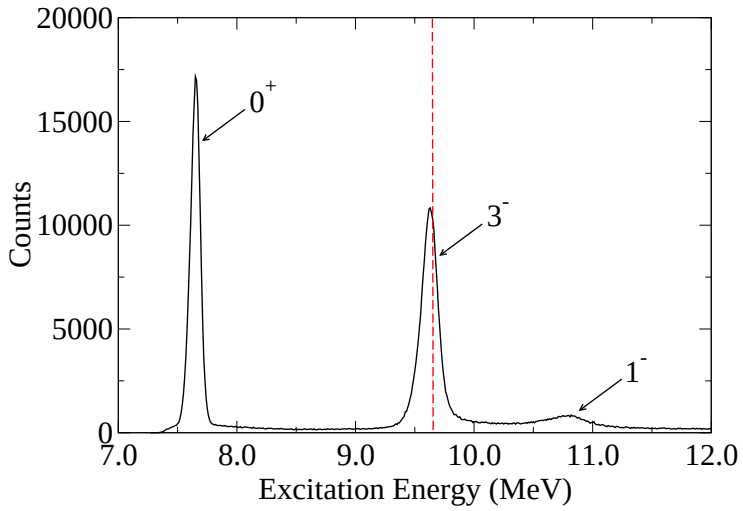

Figure 2. Excitation energy spectrum for the break-up of ^{12}C into 3α-particles. The dashed lines correspond to the energy at which the 2^+ excitation was found in Ref. [13, 14].

where the terms are analogous to those in equation 1 with the addition of E_{th}, which accounts for the missing break-up energy (E_{th} = 7.272 MeV). Figure 2 shows the excitation energy spectrum for the break-up for ^{12}C for decays via $^8\mathrm{Be}_{gs}$; a number of known energy levels are labeled, along with the proposed location of the 2^+ resonance associated with the Hoyle state identified in the inelastic scattering measurements [13, 14]. The widths of the peaks is dominated by the experimental resolution which is 90 keV for the 7.65 MeV peak and 175 keV (FWMH) at 9.64 MeV.

In an attempt to 'look beneath' the 3^- resonance, which coincides with the proposed location of the 2^+ state, angular correlation analysis has been used. The correlations depend on the angles which describe the two different stages of the reaction process (see Figure 3). The angle θ^* describes the centre-of-mass emission angle of the excited ^{12}C nucleus, measured with respect to the beam axis. The second angle, ψ, corresponds to the emission angle of the first α-particle in the centre-of-mass frame of the ^{12}C nucleus, again measured with respect to the beam axis. As all of the initial and final state particles are spin zero, then for a scattering angle θ^*=0 the ^{12}C excited state is constrained to be populated in the m=0 magnetic substate. The subsequent α-particle emission thus follows that of a squared Legendre-Polynomial of order J (the spin of the state in ^{12}C); $|P_J(\cos(\psi))|^2$. Away from zero degrees other m-substates may contribute which gives rise to a phase shift in the Legendre polynomial; $|P_J(\cos(\psi + \Delta\psi))|^2$, where

$$\Delta\psi = \Delta\theta^* \frac{l_i - J}{J} \ . \tag{3}$$

Here l_i is the entrance channel grazing angular momentum [16]. This results in a ridge structure in the $\theta^* - \psi$ plane. Thus, the angular correlation spectrum is characterised

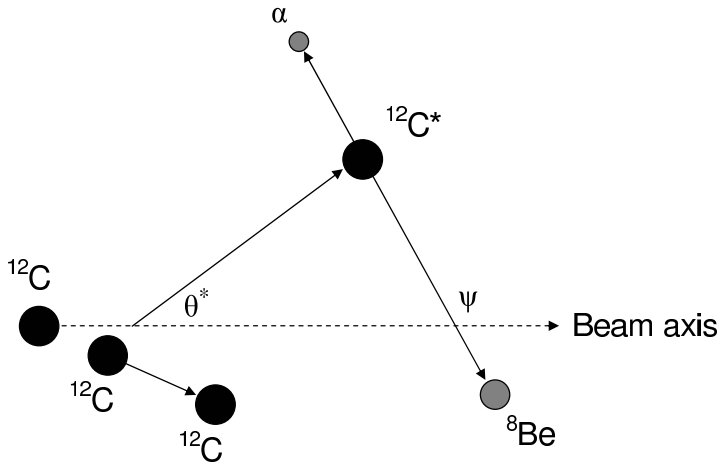

Figure 3. The definition of the correlation angles θ^* and ψ used in the present analysis (from Ref. [17]).

by the spin of the state both in terms of the frequency of the oscillations as a function of ψ and also the gradient of the loci in the $\theta^* - \psi$ plane [17]. A more complete discussion of the correlation technique can be found in Ref. [17]. This implies there will be regions in which the contribution from a 3^- state will be minimal and a 2^+ state maximal. The simulated angular correlations for a 2^+ and 3^- state are shown in the top part of Fig. 4. The Monte Carlo simulations performed simulated both the initial ^{12}C + ^{12}C interaction and also the resulting two stage sequential $^{12}\mathrm{C} \longrightarrow 3\alpha$ break-up. The simulations considered energy lost by the beam in the target, as well as the beam spot size and beam divergence; for the decay fragments energy loss, energy straggling and angular straggling in the target and also energy loss and angular straggling in the detectors was considered. Finally, positional resolution and energy resolution of the detectors was included. These simulations reproduce the ^{12}C(^{12}C,3α) reaction and the decay via the ^{8}Be ground state and reproduce the observed width of the 3^- peak (175 keV). It can be seen that at the location of the minimum in the 3^- correlation that the ridge in the 2^+ distribution is close to being maximal. Thus, gating in the "valley" of the 3^- correlation pattern should enhance any 2^+ contribution.

The experimental angular correlations for the 3^- region are also shown in Fig. 4. The ridge pattern is similar to that observed in the simulations. To gain an impression of the factor by which the 3^- contribution is suppressed by selecting data in the correlation minimum the variation in intensity has been measured. Between the peak of most intense ridge and the valley the yield is reduced by a factor of 2.5, whilst for the less intense ridge at lower values of θ^* the reduction is by a factor of 1.3. Thus, on average the 3^- strength is reduced by a factor of ~ 2 (calculated from the simulations). A software window (window (ii), Figure 4) was placed over the region where the ratio of the 2^+ to 3^- strength was expected to be largest. An excitation energy spectrum for the ^{12}C break-up was created for events located within this window. This spectrum was normalised by dividing the channel contents by the integrated number of counts in the 3^- peak. The

resulting spectrum was compared with a similarly normalised spectrum obtained from a region containing most of the data at an energy range across the 3^- peak (window (i), Figure 4). The two spectra in Figure 5 appear to indicate a difference between the peak shapes with the data in the 3^- minimum showing a very slight enhancement at higher values of E_{ex}. When the normalised peaks are subtracted from one another then there is a small remainder in the candidate region for a 2^+ state.

In order to characterise this difference a fitting function was devised which was composed of two Gaussian functions (equation 4). This was then fitted to the experimental difference data. The fitting function used was

$$f(E_x) = \frac{\exp\left[-\left(\frac{E_x-c_1}{\sqrt{2}\sigma_1}\right)^2\right] + \alpha\exp\left[-\left(\frac{E_x-c_2}{\sqrt{2}\sigma_2}\right)^2\right]}{\sqrt{2\pi}\,(\sigma_1+\alpha\sigma_2)} - \frac{\exp\left[-\left(\frac{E_x-c_1}{\sqrt{2}\sigma_1}\right)^2\right] + \beta\exp\left[-\left(\frac{E_x-c_2}{\sqrt{2}\sigma_2}\right)^2\right]}{\sqrt{2\pi}\,(\sigma_1+\beta\sigma_2)} \tag{4}$$

where c_1 and c_2 are the centroid positions of the peaks (c_1 = 9.64 MeV), σ_1 and σ_2 are controlled by the widths of the peaks (the width of the 3^- state, 150 keV (FWHM), was limited by the experimental resolution), and α and β are the 2^+ contribution in each software window. Whilst c_1, σ_1 were known, c_2, σ_2 and β-α were optimised by the fitting routine. In order to simplify Equation 4 it can be re-written as

$$f(E_x) = \frac{\alpha-\beta}{(\sigma_1+\alpha\sigma_2)\,(\sigma_1+\beta\sigma_2)}\left[-\frac{\exp\left[-\left(\frac{E_x-c_1}{\sqrt{2}\sigma_1}\right)^2\right]}{\sqrt{2\pi}}\sigma_1 + \frac{\exp\left[-\left(\frac{E_x-c_2}{\sqrt{2}\sigma_2}\right)^2\right]}{\sqrt{2\pi}}\sigma_2\right]. \tag{5}$$

If $\alpha\sigma_2$ and $\beta\sigma_2$ are both smaller than σ_1 then equation 5 may be written as

$$f(E_x) \simeq (\alpha-\beta)\left[-\frac{\exp\left[-\left(\frac{E_x-c_1}{\sqrt{2}\sigma_1}\right)^2\right]}{\sqrt{2\pi}\sigma_1} + \frac{\sigma_2^2}{\sigma_1^2}\frac{\exp\left[-\left(\frac{E_x-c_2}{\sqrt{2}\sigma_2}\right)^2\right]}{\sqrt{2\pi}\sigma_2}\right]. \tag{6}$$

This shows that the fitting function should have a bipolar form, with a negative going component described by a Gaussian whose width is represented by that of the 3^- peak and amplitude by the difference $\alpha-\beta$, whilst the positive component is associated with a second Gaussian with a width determined by σ_2 and amplitude $(\alpha-\beta)\sigma_2^2/\sigma_1^2$.

The above function was fitted to the difference data shown in Fig. 5 and produced values of c_2 = 9.67-9.71 MeV, σ_2 = 32-83 keV (FWHM = 75-195 keV) and $\beta-\alpha$ = -0.3 to +0.2 %. The quantity $\beta-\alpha$ evaluates the change in relative 2^+ and 3^- contributions for the two selected regions. A value of zero indicates no additional contribution. It

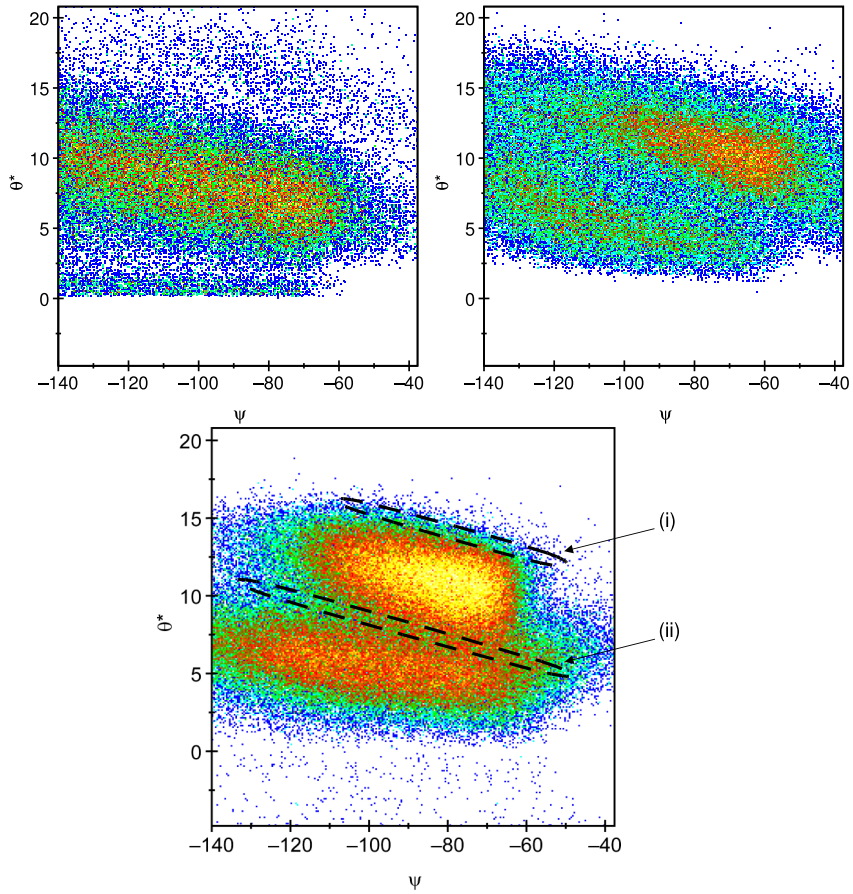

Figure 4. Angular correlations. *Top left* Simulation of the angular correlation for the decay of a $J^\pi = 2^+$ state at 9.7 MeV. *Top right* Simulation of the angular correlation for the decay of a $J^\pi = 3^-$ state at 9.64 MeV. *Bottom* The angular correlation for the experimental data in the region of the 9.64 MeV 3^- resonance. The windows indicate positions of software gates used (see text for further details).

should be noted that the range of widths explored in the present analysis exceed the experimental resolution and so the Gaussian line-shape that has been used is only an approximation to the resonance profile. This approximation does not substantially affect the conclusions.

3.1. Simulations

In order to understand the above result more precisely Monte Carlo simulations were performed which replicated the 3^- resonance and background contributions as seen in the experimental data. These simulations were used to explore the sensitivity of the current technique and also any effect of the precision of the alignment of the detection system.

In the first stage of this analysis separate simulations for a 3^- and 2^+ decay were performed using the correlation function described by Eqn. 5, where a value of

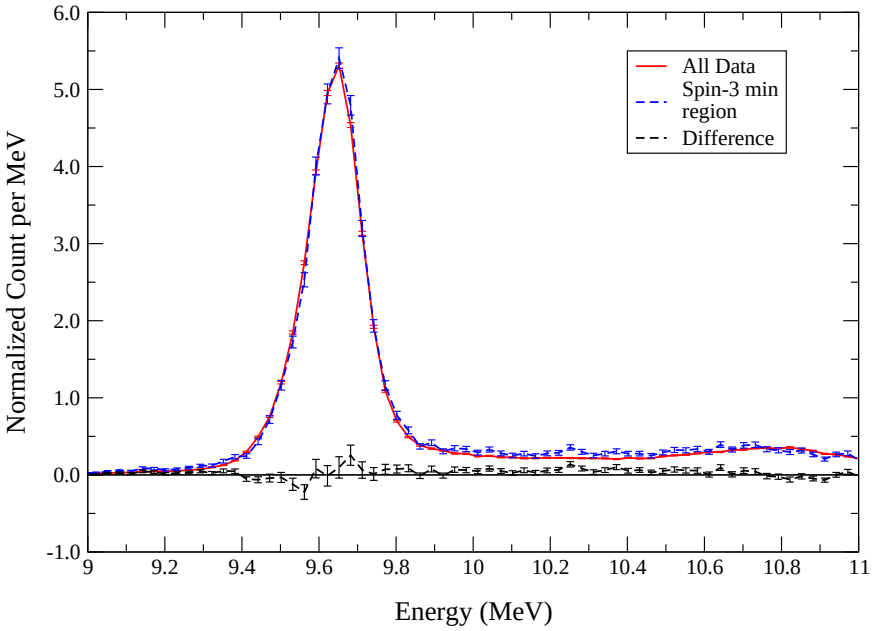

Figure 5. Result of subtracting a spectrum from the dominant 3^- region from a spectrum of a region at which a J^π=2^+ resonance would be maximal.

l_i = 22 $\hbar$ was used. The results of these simulations are shown in Fig. 4. The events from the simulations were analysed using the same analysis procedures as used for the experimental data. In this way different contributions from a 2^+ state could be added to the simulated 3^- decay data. In addition, a smooth background was added at the level that was observed below the 9.64 MeV peak in Fig. 5 and also a contribution from the 10.84 MeV, 1^-, state was included at the level observed in the experimental data. The simulations and background contributions were combined such that the number of counts were the same as in the data such that the same statistical sensitivity was achieved in the simulations. A number of simulations were performed for the generated 2^+ resonance; varying centroid positions (9.70 MeV, 9.85 MeV and 10.0 MeV) and of varying widths (FWHM = 250 keV, 500 keV and 750 keV). Each 2^+ resonance was then combined with the 3^- and background simulation in a ratio of 15:85 (i.e. a 15 % level). Similar calculations were also performed with 10, 5 and 2 % contributions from a 2^+ state.

The resulting angular correlations were processed in the same way as described for the experimental data; i.e. gating in windows (i) and (ii), normalising the two corresponding excitation energy spectra and computing the difference. A number of initial 'guess' parameters were tried with the fitting routine in order to probe the sensitivity of the fit (equation 4), and by minimising the χ^2 value the optimal fit was obtained. At the 15% level the fitting routine was successfully able to distinguish the

Centroid (MeV)	Width (keV)	15%	10%	5%	2%
9.70	250	✓	×	×	×
	500	✓	×	×	×
	750	✓	×	×	×
9.85	250	✓	✓	×	×
	500	✓	×	×	×
	750	✓	×	×	×
10.0	250	✓	✓	✓	✓
	500	✓	✓	✓	×
	750	✓	✓	×	×

Table 1. Levels at which a resonance can be detected for various centroids and widths.

2^+ from the background under all conditions. The ratio was then altered (10, 5, 2 %), reducing the size of the 2^+ resonance, until the fitting routine was no longer able to verify its existence (defined as when the fit parameters no longer matched the known characteristics of the peak entered into the simulation). This allowed a relationship to be found between the position/centroid and the strength of a resonance in order that it might be detected by the techniques employed in this analysis (table 1). Examples of some of the simulations and optimal fits are given in Fig. 6. Table 1 indicates that for a 2^+ state well separated from the 9.64 MeV, 3^-, state (e.g. at 10.0 MeV and 250 keV width) it is possible to unambiguously pick out this contribution down to very low levels (2 %). Larger contributions (15 %) can be distinguished for all widths at all peak separations down to 60 keV. Unambiguous identification of the peak parameters becomes more difficult the smaller the separation from the 3^- state and the larger the width – as might be expected.

A number of Monte Carlo simulations were performed in order to investigate the sensitivity of the results with regard to the position of the detector telescopes; simulations were performed which introduced displacements in the position of both a detector-telescope (Fig. 7) and also the position of the beam with respect to the detector-array (Fig. 8). Figure 7 shows the unaltered Monte Carlo simulation (i), the effect of one telescope being offset from the intended position (ii and iii), and the effect of one telescope being rotated by a small amount (iv and v). The effect of one telescope being offset is independent of the direction in which the offset occurs and causes the single 3^- peak to separate in two components. The effect is however more pronounced if the offset is in a direction parallel to the direction of the detector strips (ii) than in a direction perpendicular to the detector strips (iii). The effect of rotating one detector telescope by a small amount is dependent on the point about which the rotation occurs but is consistent in that it causes a broadening of the 3^- peak, and to a greater extent in the suppressed 3^- subset than in the entire data set. Simulations to investigate moving the position of the beam suggest a similar effect to those seen when a single telescope is offset, but also indicate the sensitivity is much greater. It also appears that the effects

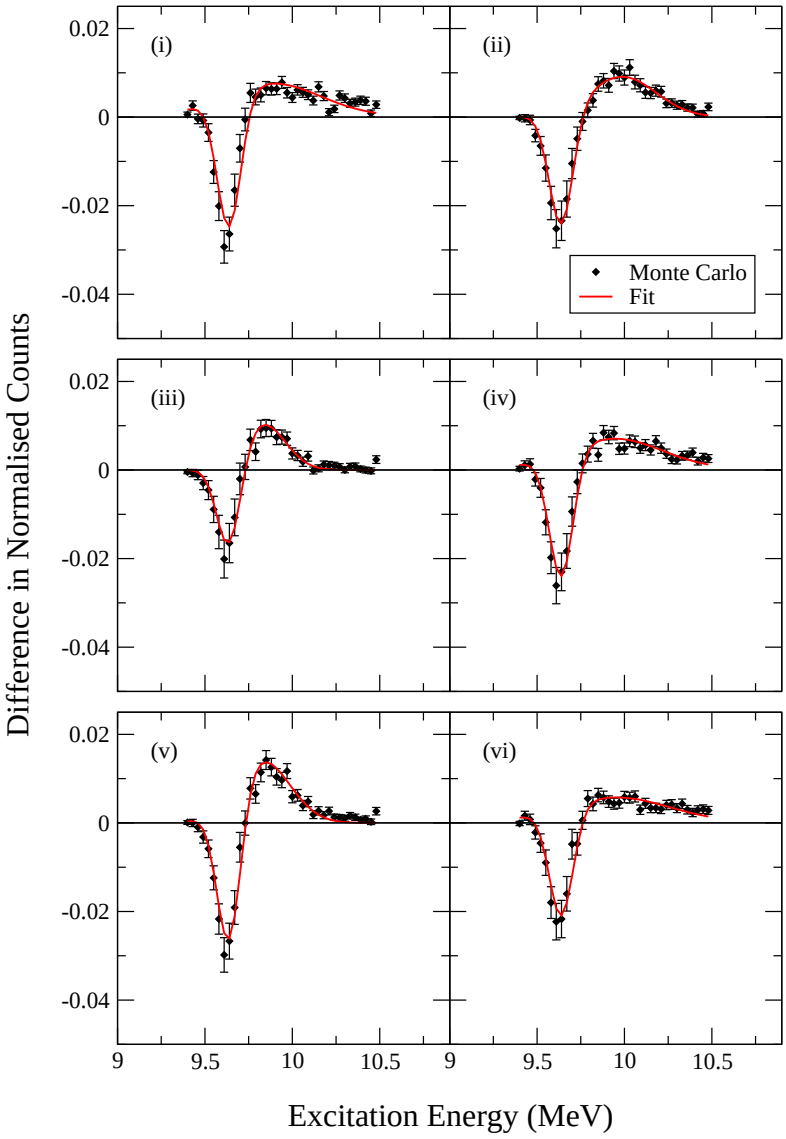

Figure 6. Spectra showing the Monte Carlo simulations and optimised fits. (i) and (ii) show the effect of varying the centroid position of a 250 keV wide 2^+ resonance from 9.7 MeV to 10.0 MeV for a 10 % 2^+ contribution; (iii) and (iv) show the effect of varying the width of a 2^+ resonance at 9.85 MeV from 250 keV to 750 keV, again for a 10 % 2^+ contribution; (v) and (vi) show the difference between a 15 % and 2 % contribution of a 2^+ resonance at 9.85 MeV and 250 keV wide.

of shifting the beam in different directions are the same as if a telescope was offset in the same direction.

These simulations show that for the most part the types of structures misalignments of the detectors would cause have a different type of structure to that which would occur if an additional state would exist below the 9.64 MeV, 3^-, peak.

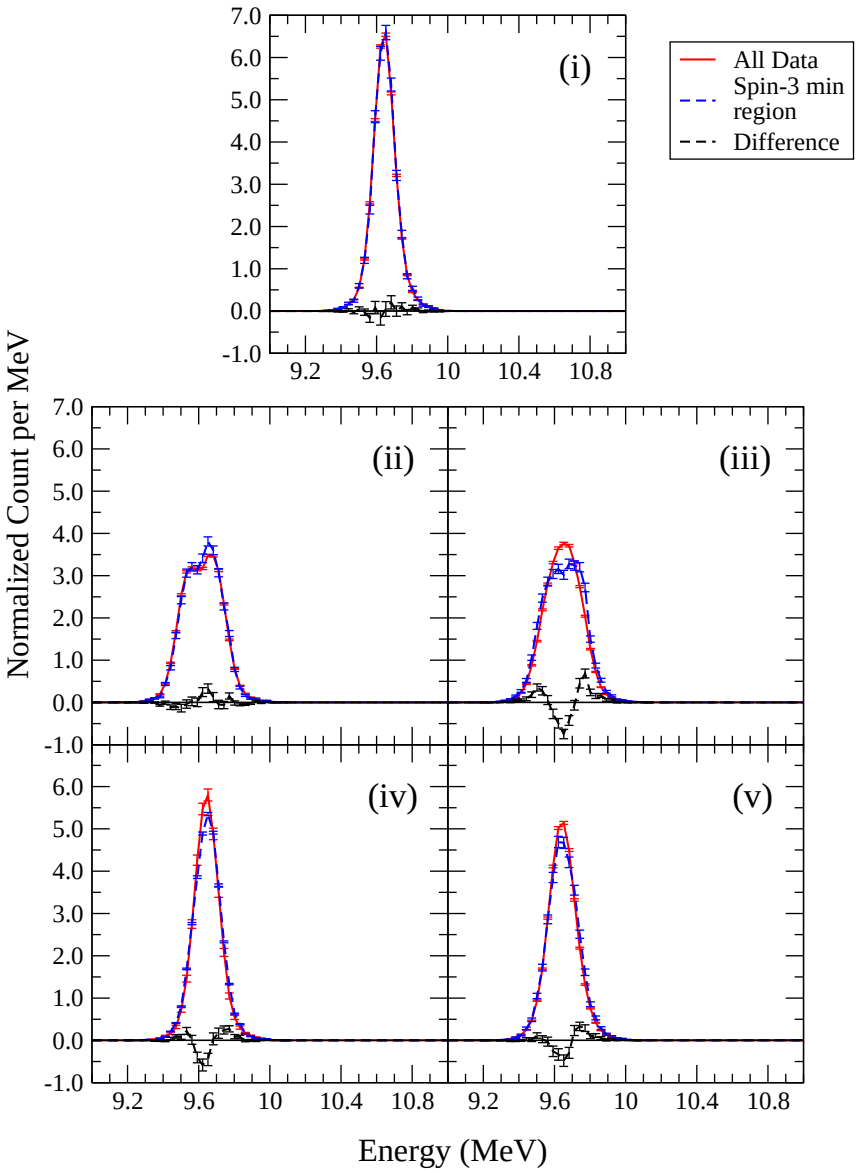

Figure 7. The effect that shifting a detector telescope can have on the excitation energy spectrum as calculated by using Monte Carlo simulations; (i) the unaltered 3^- peak, (ii) shifting one telescope 2 mm away from the beam in the direction of the detector strips, (iii) shifting one telescope 2 mm in a direction perpendicular to the detector strips, (iv) rotating a telescope 2° clockwise about the beam axis, (v) rotating a telescope 2° clockwise about its centre.

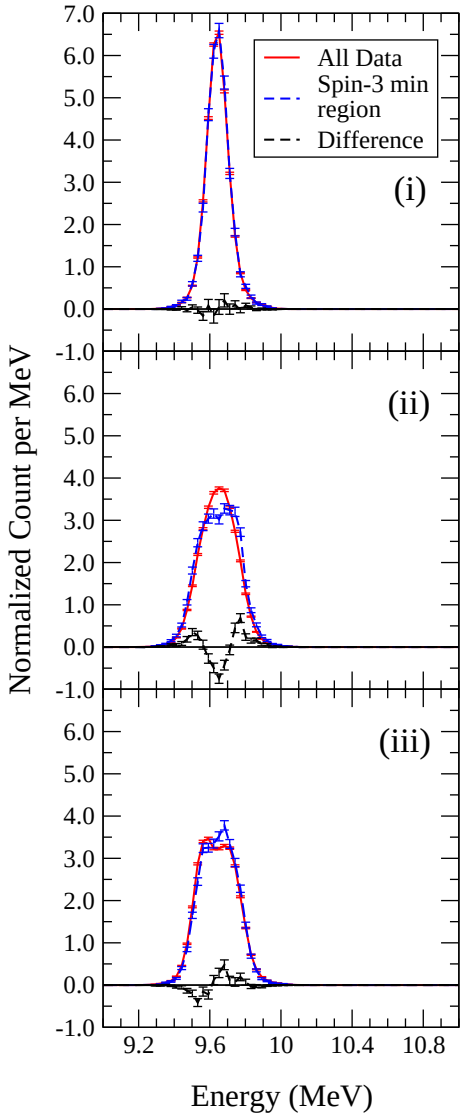

Figure 8. The effect of the beam not passing through the central axis of the detector array: (i) Monte Carlo simulation of a 3^- peak with the beam aligned with the central axis, (ii) the same simulation as (i) but with the beam shifted 1 mm towards one detector, (iii) the same simulation as (i) but with the beam shifted 1 mm in a direction perpendicular to the detector-strips.

4. Discussion and Conclusions

The experimental difference data (Fig. 5) show a small amplitude deviation from zero ($\pm$ 0.01). This is best described by an additional contribution to the 3^- peak at an energy of 9.67-9.71 MeV which corresponds to a very small change in intensity between the two windows used in the analysis (β-α = -0.3 to 0.2 %). This would correspond to a very small 2^+ contribution. Note the negative value would indicate a reduction in the 2^+ strength. The width found from the fit was in the range 75 to 195 keV, close to the width of the 3^- peak. These values are inconsistent with those extracted in the inelastic scattering data [13, 14]. It is thus likely that the deviation observed in the experimental difference data (Fig. 5) is actually related to an experimental artifact, e.g. a slight misalignment of the detectors – as observed in the simulations. If a 600 keV wide 2^+ state exists at 9.6 MeV, then it is populated in the present reaction at a strength which lies below the present experimental sensitivity. The summary of the Monte Carlo simulations shown in Table 1 indicates that for a state of the above parameters then this strength is less than $\sim$ 10 % of the strength of the 3^- state. If the width and centroid of the additional peak in equation 4 are set to 600 keV and 9.6 MeV respectively (rather than allowed to be free parameters) then the values of β-α are smaller than 0.1 %, i.e. representing virtually no change in the line-shape between the two windows used in the analysis of the angular correlations. In other words a broad 2^+ state with a strength above 15 % is not found in the present data.

It can be concluded from this analysis that if an additional 2^+ resonance exists in the present data which has a width of less than 250 keV, then it must have a population strength of less than $\sim$ 10 % of the 3^- peak and an excitation energy of less than 9.85 MeV. If the width lies in the range of 500 to 750 keV then to be clearly identified it should have an excitation energy of $\sim$10 MeV and a population strength of 5 %. If it lies at lower energy much stronger strengths are required for unambiguous identification.

In conclusion, a search has been made for a 2^+ state close to 9.6 MeV in ^{12}C using the ^{12}C(^{12}C,^{12}C[3α]) reaction. Angular correlation techniques have been used to enhance any 2^+ contribution to the excitation energy spectrum, compared with a dominant 3^- contribution. These measurements fail to find any evidence for a new state at this energy. It is clear that in order to provide much more stringent limits increased experimental sensitivity is required. Improved excitation energy resolution would help define the excitation energy spectrum and improved energy and angular resolution would help better emphasise the minima in the angular correlation pattern.

Recent R-matrix analysis of the decay of ^{12}N and ^{12}B suggest that the 2^+ excitation of the Hoyle state may lie at a higher energy ($\sim$11 MeV) [15]. We have performed an analysis of this region using the angular correlation technique described here and can find no strong evidence for a 2^+ state.

Inelastic scattering experiments using either the ^{12}C(p,p')^{12}C or ^{12}C(α,α')^{12}C reaction are both candidate methods for better exploring the 3^- region. A recent ^{12}C(p,p')^{12}C experiment has found evidence suggesting a broad 2^+ state lying slightly

lower in energy than the 9.64 MeV 3^- state [14]. Future measurements are also planned which would combine the α-particle decay measurements with a magnetic spectrometer. The enhanced excitation energy resolution afforded by this technique would permit a more sensitive correlation analysis to be performed.

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