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## Rotational excitation of the Hoyle state in $^{12}\text{C}$

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# Rotational excitation of the Hoyle state in $^{12}\text{C}$

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**Abstract.**  $^{12}\text{C}$  is synthesised in stars by fusion of three  $\alpha$  particles. This process occurs through a resonance in the  $^{12}\text{C}$  nucleus, famously known as the Hoyle state. In this state, the  $^{12}\text{C}$  nucleus exists as a cluster of  $\alpha$  particles. The state is the band-head for a rotational band with the  $2^+$  rotational excitation predicted in the energy region 9 - 11 MeV. This rotational excitation can affect the triple- $\alpha$  process reaction rate by more than an order of magnitude at high temperatures ( $10^9$  K). Depending on the energy of the resonance, the knowledge of the state can also help determine the structure of the Hoyle state. In the work presented here, the state of interest is populated by beta decay of radioactive  $^{12}\text{N}$  ion beam delivered by the IGISOL facility at JYFL, Jyväskylä.

## 1. Introduction

The  $^{12}\text{C}$  nucleus has a cluster structure in the Hoyle state, which is a  $0^+$  resonance just above the triple- $\alpha$  threshold. With the non-spherical structure of the state,  $^{12}\text{C}$  has a rotational band built upon this state. A recent measurement by Zimmerman *et al.* [1], along with the other observations [2–5] suggest that the first excitation of this band, the  $2^+$  state, is to be found in 9 – 11 MeV energy region. The second and higher lying member of this rotational band,  $4^+$  has been found experimentally [6], but the  $2^+$  excitation has proven difficult to study because of the the presence of a broad  $0^+$  resonance at 10.3 MeV [4, 7].

At higher temperature in stars ( $10^9$  K), this rotational excitation state becomes relevant to the triple- $\alpha$  process, affecting the reaction rate. In addition to its importance in determining the  $^{12}\text{C}$  production rate, the state is also important when considering the structure. With the energy of this first rotational excitation known, the determined moment of inertia can settle the debate on the structure of the  $^{12}\text{C}$  nucleus in the Hoyle state as different theoretical models predict different arrangements of the cluster in the Hoyle state [8].

The experiment was performed at JYFL, Jyväskylä, Finland. The IGISOL (Ion-Guide Isotope Separator OnLine) facility delivered a beam of the radioisotope  $^{12}\text{N}$  which  $\beta$  decays to  $^{12}\text{C}$ , populating the states of interest. Due to the selection rules of  $\beta$  decay, this method gives



some selectivity over the spin-parity of states populated. From the parent nucleus,  $^{12}\text{N}$ , with  $1^+$  spin-parity ground state, only  $0^+$ ,  $1^+$  and  $2^+$  states are populated in the daughter nucleus,  $^{12}\text{C}$ . This prevents the strong states, such as the  $3^-$  at 9.6 MeV to affect the spectra.

## 2. $^{12}\text{N}$ beam production and detector arrangement

The IGISOL facility at JYFL uses the ion-guide method to produce radioactive ion beams. In this technique, the ions are produced via a nuclear reaction of an energetic beam on a target foil. The ions recoil out of the target and are transported to the extraction electrode via a buffer gas through a skimmer. After the extraction, they are mass separated using a magnetic field.

The beam is stopped at a thin carbon foil in the experimental chamber. In total, 5.9% of the decays of  $^{12}\text{N}$  populate states above the triple- $\alpha$  threshold [9]. Such decays are typically followed by the breakup of  $^{12}\text{C}$  into three  $\alpha$  particles which were detected using an array of detectors. Figure 1 shows the cubic arrangement of six DSSDs (Double-sided Silicon Strip Detectors) around the foil. These detectors are made from  $50\text{mm}\times 50\text{mm}$  silicon wafers, segmented into 16 strips, both on front and back. Five of these (except the one on the outside), are thin detectors to detect  $\alpha$ -particles. The sixth is a thick detector for detecting  $\beta$ -particles. One HPGe (High Purity Germanium) detector was also used for the detection of  $\gamma$ -particles.

## 3. Analysis and Results

### 3.1. Energy calibrations

Energy calibrations were carried out using the radioactive sources,  $^{239}\text{Pu}$ ,  $^{241}\text{Am}$  and  $^{244}\text{Cm}$ , which emit  $\alpha$ -particles of known energies, 5157, 5486 and 5805 keV respectively. For calibrating the thick backing detector and Ge detector, the electron source  $^{207}\text{Bi}$  and the  $\gamma$ -ray source  $^{60}\text{Co}$  were used respectively. In order to extrapolate these calibrations to the low energy region, two main corrections are to be applied. They are explained in the following.

*3.1.1. Calibration offsets and non-linearity for beta particle detection:* The Compton scattered events between the thick DSSD and the HPGe detector have been used to check the linearity of amplification gains as a function of energy. For this, it is required that the  $^{60}\text{Co}$  source is placed such that the radiation has to pass through the Si detector to reach the Ge detector.  $\gamma$  particles that are scattered from Si at a low angle before reaching the Ge detector deposit part of their energy in both detectors. Such events can be seen as two diagonal lines in Figure 2, which shows the energy deposited in Si detector plotted against the energy deposited in HPGe (similar to work in Ref [10]). The intercepts made by these lines on x axis are 5 -10 keV off from 1173 and 1332 keV ( $^{60}\text{Co}$   $\gamma$  rays energies), indicating offset in calibrations of Si detector towards the lower energy. The pulser data also indicates slight non-linearity in the calibrations. The correction will be done using the pulser data and cross-checked against the  $^{60}\text{Co}$  data as in Figure 2.

*3.1.2. Detector dead-layer and source thickness effects:* The dead layer on the surface of the DSSDs vary from 50 - 500 nm depending upon the detector.  $\alpha$  particles lose

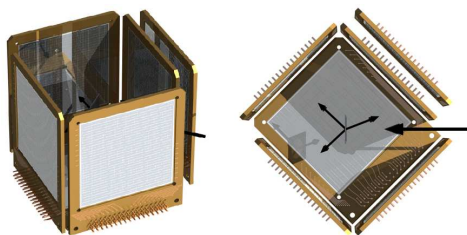


Figure 1: 3D model of DSSD arrangement. (Side view and top view respectively)

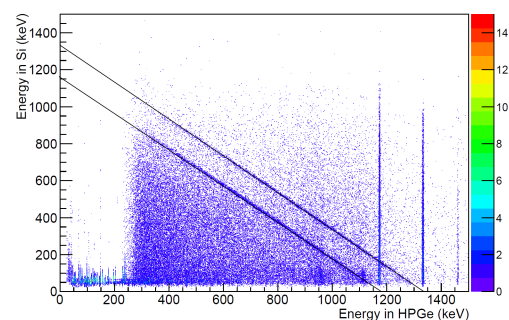


Figure 2:  $\gamma$ -ray energy deposited in DSSD vs HPGe.

20 - 160 keV energy in the dead-layer before reaching the active material of the detector, with the loss being a nonlinear function of energy. Similarly, the  $\alpha$  particles lose energy while exiting the source. Corrections of these effects have not yet been fully applied in Figure 3, which explains the energy offset of 200 keV for the 12.7 MeV state.

### 3.2. $\beta$ -triple- $\alpha$ coincidences

To begin with the analysis on data, we identify the  $^{12}\text{C}$  state's energy and constrain the spin-parity. The excitation energy is reconstructed by adding the energies of all three  $\alpha$ -particles to the triple- $\alpha$  threshold energy (7.275 MeV). To constrain the spin-parity, the events are gated on the breakup channel.  $^{12}\text{C}$  breakup can either be sequential, or it can be a three-body breakup. The sequential breakup involves the  $^8\text{Be}$  nucleus via either the  $0^+$  ground state or the  $2^+$  excited state.  $0^+$  and  $2^+$  states predominantly breakup through the  $^8\text{Be}$  ground state. In such breakups, the first  $\alpha$ -particle takes approximately two-thirds of the excitation energy above the threshold. In Figure 3, the diagonal line with the slope  $2/3$  corresponds to the first  $\alpha$ -particle from such events. This channel is prohibited for the  $1^+$  state. The selection on the  $^8\text{Be}$  (g.s.) channel therefore cleans the data of  $1^+$  component.

### 3.3. Future work on $\beta$ - $\alpha$ angular correlation

To discriminate between the  $2^+$  and  $0^+$  component, we will use of the angular correlation between the  $\beta$ -particle and the first  $\alpha$ -particle from the breakup. If the emitted  $\beta$ -particle in a decay is relativistic, the daughter nucleus is left in a polarised state along the axis defined by the  $\beta$ -particle emission direction. This results in an angular correlation between subsequent radiation and the  $\beta$ -particle. With the high Q-value (16.316 MeV [2]) of  $\beta$ -decay of  $^{12}\text{N}$ , the relativistic assumption is applicable here. Figure 4 shows the difference in angular correlations for  $0^+$  and  $2^+$  states. Work on the detailed correlation analysis is ongoing. The data shown in Figure 3 is  $\beta$ -triple- $\alpha$  coincidence data, and will be used in correlation study.

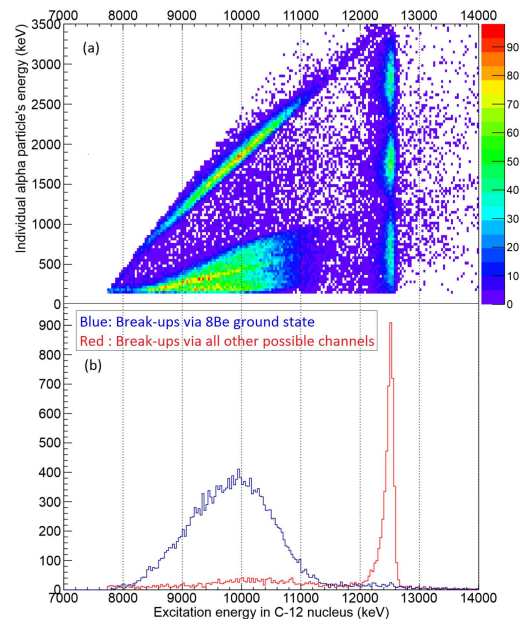


Figure 3: (a) Individual  $\alpha$ -particle energy against excitation energy. (b) Projection of the above, gated on breakup channels.

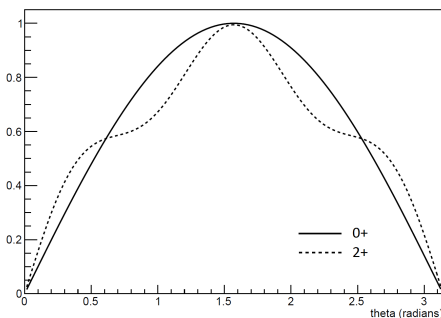


Figure 4: Predicted angular correlation of first  $\alpha$ -particle and the  $\beta$ -particle.

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