Jyväskylän yliopiston julkaisuarkisto
Jyväskylä University Digital Archive

UNIVERSITY OF JYVÄSKYLÄ

This is an electronic reprint of the original article.
This reprint *may differ* from the original in pagination and typographic detail.

Author(s): ISISOL Collaboration

Title: Rotational excitation of the Hoyle state in 12C

Year: 2018

Version:

Please cite the original version:

ISISOL Collaboration. (2018). Rotational excitation of the Hoyle state in 12C. In Nuclear Physics in Astrophysics VII (NPA7 2015) York, UK, May 18-22, 2015 (Article 012043). IOP Publishing. Journal of Physics : Conference Series, 940. https://doi.org/10.1088/1742-6596/940/1/012043

All material supplied via JYX is protected by copyright and other intellectual property rights, and duplication or sale of all or part of any of the repository collections is not permitted, except that material may be duplicated by you for your research use or educational purposes in electronic or print form. You must obtain permission for any other use. Electronic or print copies may not be offered, whether for sale or otherwise to anyone who is not an authorised user.

Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

Rotational excitation of the Hoyle state in ^{12}C

To cite this article: R Garg *et al* 2018 *J. Phys.: Conf. Ser.* **940** 012043

View the article online for updates and enhancements.

This content was downloaded from IP address 130.234.74.34 on 01/02/2018 at 11:18

IOP Conf. Series: Journal of Physics: Conf. Series **940** (2017) 012043 doi:10.1088/1742-6596/940/1/012043

Rotational excitation of the Hoyle state in ^{12}C

R Garg,[1,*] C Barton,[1] C Aa Diget,[1] S Courtin,[2] G Fruet,[2] H O U Fynbo,[3] A Howard,[3] A Illana,[4,†] D G Jenkins,[1] I Marroquin,[4] O S Kirsebom,[3] M V Lund,[3] I Moore,[5] A Perea,[4] J Refsgaard,[3] J E Riley,[1] S Rinta-Antila,[5] L Sinclair,[1] O Tengblad[4] and The IGISOL Collaboration[5]

[1] Department of Physics, University of York, YO10 5DD, UK
[2] Institut Pluridisciplinaire Hubert Curien, 67037 Strasbourg Cedex 2, France
[3] Department of Physics and Astronomy, University of Aarhus, 8000 Arhus C, Denmark
[4] Instituto Estructura de la Materia, CSIC, Serrano 113bis, E-28006, Madrid, Spain
[5] Department of Physics, University of Jyväskylä, FIN-40351 Jyväskylä, Finland
[†] Present address: IKS, Leuven, Belgium

E-mail: *rg847@york.ac.uk

Abstract. ^{12}C is synthesised in stars by fusion of three α particles. This process occurs through a resonance in the ^{12}C nucleus, famously known as the Hoyle state. In this state, the ^{12}C nucleus exists as a cluster of α 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-α 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}N ion beam delivered by the IGISOL facility at JYFL, Jyväskylä.

1. Introduction

The ^{12}C nucleus has a cluster structure in the Hoyle state, which is a 0^+ resonance just above the triple-α threshold. With the non-spherical structure of the state, ^{12}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-α process, affecting the reaction rate. In addition to its importance in determining the ^{12}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}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}N which β decays to ^{12}C, populating the states of interest. Due to the selection rules of β decay, this method gives

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI.
Published under licence by IOP Publishing Ltd

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

2. ^{12}N beam production and detector arrangement

The IGISOL facility at JYFL uses the ion-guide method to produce radioactice 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}N populate states above the triple-α threshold [9]. Such decays are typically followed by the breakup of ^{12}C into three α 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 50mm$\times$50mm 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 α-particles. The sixth is a thick detector for detecting β-particles. One HPGe (High Purity Germanium) detector was also used for the detection of γ-particles.

3. Analysis and Results

3.1. Energy calibrations

Energy calibrations were carried out using the radioactive sources, ^{239}Pu, ^{241}Am and ^{244}Cm, which emit α-particles of known energies, 5157, 5486 and 5805 keV respectively. For calibrating the thick backing detector and Ge detector, the electron source ^{207}Bi and the γ-ray source ^{60}Co were used respectively. In order to extrapolate these calibrations to the low energy region, two main corrections are to 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}Co source is placed such that the radiation has to pass through the Si detector to reach the Ge detector. γ 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}Co γ 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}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. α particles lose

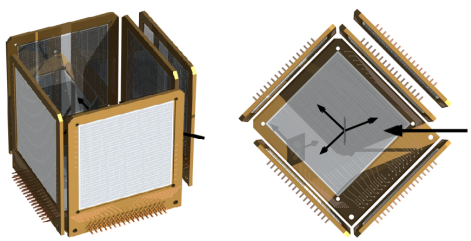

Figure 1: 3D model of DSSD arrangement. (Side view and top view respectively)

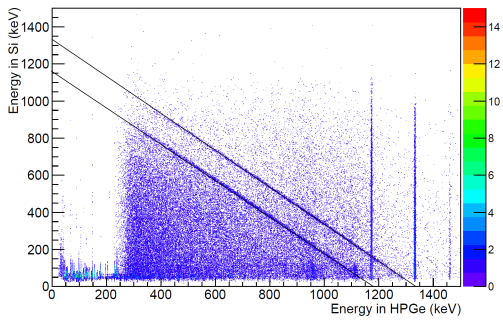

Figure 2: γ-ray energy deposited in DSSD vs HPGe.

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 α 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. β-triple-α coincidences

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

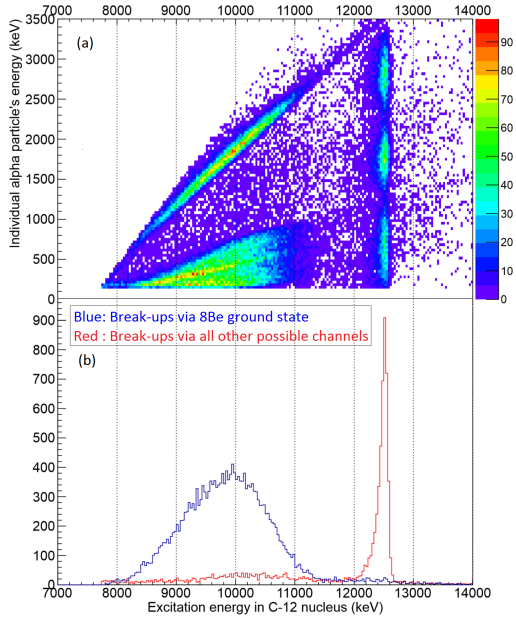

Figure 3: (a) Individual α-particle energy against excitation energy. (b) Projection of the above, gated on breakup channels.

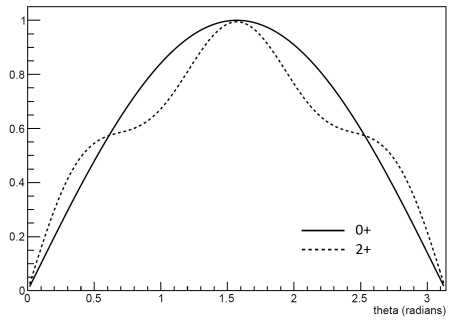

Figure 4: Predicted angular correlation of first α-particle and the β-particle.

3.3. Future work on β-α angular correlation

To discriminate between the 2^+ and 0^+ component, we will use of the angular correlation between the β-particle and the first α-particle from the breakup. If the emitted β-particle in a decay is relativistic, the daughter nucleus is left in a polarised state along the axis defined by the β-particle emission direction. This results in an angular correlation between subsequent radiation and the β-particle. With the high Q-value (16.316 MeV [2]) of β-decay of ^{12}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 β-triple-α coincidence data, and will be used in correlation study.

References

[1] Zimmerman W R *et al.* 2013 *Phys. Rev. Lett.* **110** 0152502
[2] Fynbo H O U and Diget C A 2014 *Hyperfine interactions* **223** 1–3
[3] Hyldegaard S *et al.* 2010 *Phys. Rev. C* **81** 024303
[4] Itoh M *et al.* 2011 *Phys. Rev. C* **84** 054308
[5] Freer M *et al.* 2009 *Phys. Rev. C* **80** 041303
[6] Ogloblin A *et al.* 2014 *EPJ Web of Conferences* **66** 02074
[7] Ajzenberg-Selove F 1990 *Nucl. Phys. A.* **506**
[8] Epelbaum E *et al.* 2012 *Phys. Rev. Lett.* **109** 252501
[9] Hyldegaard S *et al.* 2009 *Phys. Rev. C.* **80** 044304
[10] Bildstein V *et al.* 2012 *Eur. Phys. J. A* **48** 85