Exciting the Hoyle state in ^{12}C selectively populated using the $^{10}B(^6Li,^4He)^{12}C$ reaction

J. Carter[1], M. B. Ajani[1], S. John[1,2], F. Moosa[1] and I. T. Usman[1]

[1]School of Physics, University of the Witwatersrand, Johannesburg, 2050, South Africa
[2]Department of Physics, Nasarawa State University, Keffi, Nigeria

E-mail: john.carter@wits.ac.za

Abstract. An excited state in ^{12}C close to the 3α-breakup was predicted by Fred Hoyle in 1954 and was later identified by Cook *et al*. in 1957 as the 0^+ state lying at an excitation energy of 7.65 MeV. It was the key to understanding the production of ^{12}C and heavier elements in the core of young stars. Fusion of two α-particles leads to the production of excited $^8Be^*$ and then the capture of another α-particle (α + ^8Be) produces excited $^{12}C^*$ close to the Hoyle state. Subsequently, as opposed to 3α-breakup of $^{12}C^*$, γ-decay from the Hoyle state to the 4^+ (4.43 MeV) state and down to the ^{12}C ground-state 0^+ (0.0 MeV) results in the production of stable ^{12}C. However, the observed enhanced ^{12}C production rate in older hotter stars was speculated to proceed through excited states of the Hoyle state. Existence of the broad excited Hoyle states $^{12}C(2^+$, 9.6 MeV) and $^{12}C(4^+$, 13.3 MeV) has been reported only relatively recently, previously not identified because of other nearby strongly-excited states in ^{12}C. The $^{10}B(^6Li,\alpha)^{12}C^*$ reaction selectively excites 2^+ states in ^{12}C and because of the high Q-value = +23.713 MeV the high energy α-particles are easily identified with good energy resolution. Measurements were taken at the EN Tandem Van de Graaff accelerator of iThemba LABS (Gauteng) using ^6Li beams at and close to E_{Lab} = 20 MeV incident on thin ^{10}B targets. The observed high-energy α-particles correspond to states excited in ^{12}C up to and above the second excited Hoyle state.

1 Introduction

Production of ^{12}C by nucleosynthesis in the core of younger stars was postulated by Fred Hoyle in the early 1950's. The abundance of ^{12}C is due to the triple-α process by which it is created. The triple-α process is a set of nuclear fusion reactions by which three ^4He nuclei are transformed into ^{12}C. At normal stellar temperatures the energies of the nuclei are too low to overcome the Coulomb barrier and therefore to initiate fusion reactions. However, because of quantum mechanical tunneling through the Coulomb barrier, there is a possibility that the fusion reaction will occur. In the first reaction of the triple-α process, two α-particles fuse to form ^8Be. The Q-value for this reaction is − 93.7 keV. Since ^8Be nuclei are unstable they rapidly decay back into two α-particles within a timescale of the order 10^{-16} s. However, at sufficiently high temperatures and densities there will always be a small but non-negligible fraction of ^8Be present. There is, therefore, a finite probability for a third α-particle to tunnel in and form ^{12}C. The reaction rate for charged particles is determined by the Maxwell-Boltzmann velocity distribution and the probability of tunneling through the Coulomb barrier. Multiplication of the Maxwell-Boltzmann velocity distribution by the tunneling probability results in the so-called Gamow window [1]. Given the two-stage nature of the triple-α process, Hoyle pointed out that the reaction rate would be very slow at normal stellar temperatures and densities being unable to account for the observed abundance of ^{12}C. To overcome this, Hoyle suggested that ^{12}C must have an excited state [2] with an energy slightly above the α + ^{8}Be ground-state energy (E_x = 7.37 MeV in ^{12}C) very nearly equal to the most effective energy for tunneling at normal stellar temperatures (10^8 K) [3]. This excited state of ^{12}C with an energy of 7.65 MeV and total angular momentum/parity $J^{\pi} = 0^+$ was discovered experimentally in 1957 by Cook *et al*. [4] and is known as the Hoyle state. If the Hoyle state did not exist or if its energy were slightly different, the abundance of ^{12}C would be reduced and so would organic life. It should be noted that the Hoyle state lies slightly above the 3α-decay threshold in ^{12}C at E_x = 7.28 MeV.

Although numerous investigations have been made of the excited states in ^{12}C, the study of the structure of the Hoyle state and its possible excited states is still a subject of great interest. The Hoyle state was originally conjectured to be a linear chain of 3 α-particles (non-spherical) by Haruhiko Morinaga in 1956 [5], and as a result the $J^{\pi} = 0^+$ Hoyle state should be accompanied by excited states forming a $J^{\pi} = 0^+, 2^+, 4^+$… rotational band. It should be noted that in hotter stars for the observed ^{12}C production rate, solar models included an assumed excited 2^+ Hoyle state at E_x = 10 MeV in ^{12}C in the Nuclear Astrophysics Compilation of Reaction Rates (NACRE) in the 1980's. Only relatively recently has experimental evidence been presented for the 2^+ excitation of the Hoyle state (E_x = 9.6 MeV in ^{12}C) in 2009 by Freer *et al*. [6] using ^{12}C(p,p') at E_p = 66 MeV, and in 2011 by Itoh *et al*. [7] using ^{12}C(α,α′) at E_α = 386 MeV, while for the 4^+ excitation of the Hoyle state (E_x = 13.3 MeV in ^{12}C) in 2011 by Freer *et al*. [8] using ^{12}C(α,3α)α at E_α = 22 MeV.

The aim of this work is to identify excited states in ^{12}C with particular reference to the Hoyle state and its excited states using the ^{10}B(^{6}Li,α)^{12}C reaction with a Q-value = + 23.713 MeV. Here, the relatively high positive Q-value allows states in ^{12}C to be excited up and above the second excited Hoyle state using ^{6}Li beams provided by a relatively small accelerator.

2 Experimental Details

The experimental work was undertaken at iThemba LABS(Gauteng), Johannesburg, South Africa. Beams of ^{6}Li were provided by the EN Tandem Van de Graaff accelerator at energies close to E_{Lab} = 20 MeV, some three times the Coulomb barrier for the ^{6}Li + ^{10}B system. The ^{6}Li beam was incident on a thin self-supporting ^{10}B target of areal density 60 μg/cm^2 inside a small scattering chamber. A high-resolution ΔE-E Gas Ionisation Detector (GID) was attached to the rotatable offset-lid of the scattering chamber and could be positioned at scattering angles from θ_{Lab} = 0° to 130°. After going through a thin parylene entrance-window, the scattered particles ΔE energy-loss signals were obtained by passing through the iso-butane gas volume of the GID to be stopped by a silicon surface-barrier detector providing E_{stop}. The ΔE and E_{stop} signals (providing $E_{\text{total}} = E_{\text{stop}} + \Delta E$) were processed by CAMAC based multi-parameter data acquisition system. Figure 1 shows a typical ΔE *versus* E_{total} 2-dimensional plot, providing clear separation of the various Z products.

After conversion from channels to measured energy in MeV, Fig. 2 shows the resulting spectrum for the Z = 2 locus displayed in Fig. 1, noting that both ^{3}He and ^{4}He products can be present. The upper part of the spectrum has been multiplied up by a factor of x15 and is shown in red. As can be seen, the first excited state ^{12}C(2^+, 4.43 MeV) and the fourth excited state ^{12}C (3^-, 9.64 MeV) are quite prominent with the ground state and Hoyle state, both 0^+, being quite weak. This apparent selectivity of the first 2^+ state excited in ^{12}C was confirmed in an angular distribution from θ_{Lab} = 15° to 130°.

3 Results and Analysis

An energy spectrum of the states excited in ^{12}C via the ^{10}B(^{6}Li,α)^{12}C reaction was obtained using a kinematic conversion of the measured alpha energy spectrum and is shown in Fig. 3 by the black histogram for a scattering angle of θ_{Lab} = 15° (best energy resolution and good count rate). Here, known states excited in ^{12}C are identified in red and the known Hoyle excited states are shown in black. The smooth continuous blue line underneath the measured histogram is a six-order polynomial representing a background of evaporation α-particles from the ^{6}Li + ^{10}B scattering reaction. The continuous purple line represents a fit to the histogram with all of the components while the dashed purple line excludes the Hoyle excited states. As can be seen, there is a reasonably good fit to the measured histogram using all of the components identified below which deteriorates with the exclusion of Hoyle excited states. However, such a fitting procedure is not entirely satisfactory and is

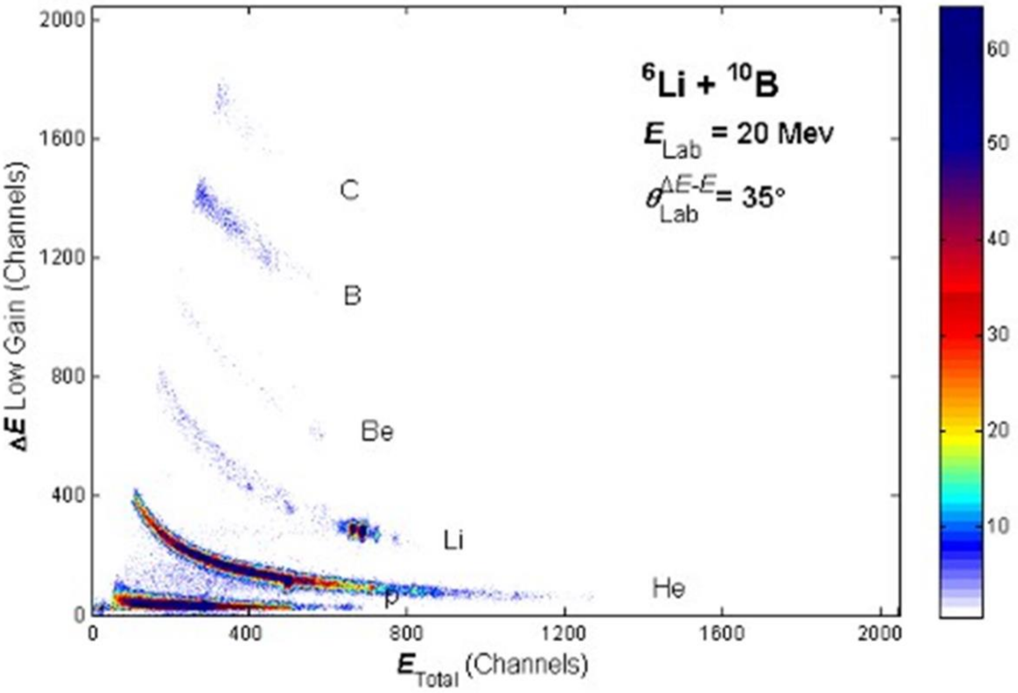

Figure 1: Typical 2-dimensional plot of the ^{6}Li + ^{10}B reaction products showing clear separation in *Z*.

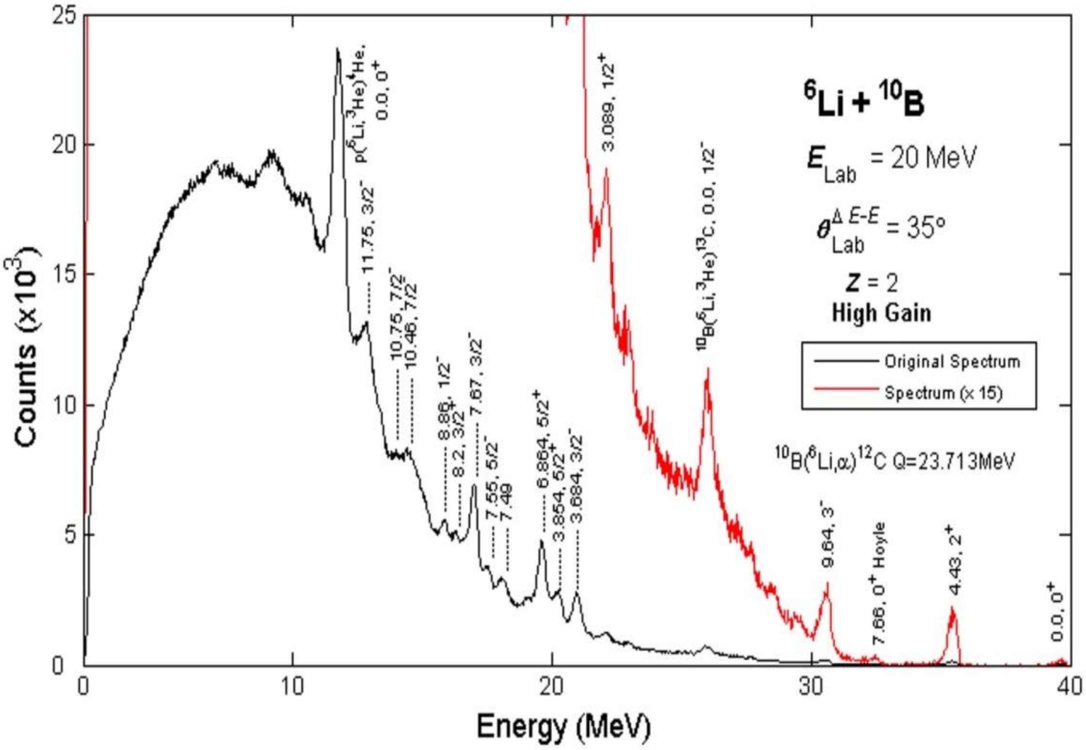

Figure 2: The *Z* = 2 locus of Fig. 1 projected down onto the energy axis in MeV.

subjective since some positions and widths of excited states may not have been determined from previous investigations. In addition, the exact formulation of the evaporation α-background is uncertain which could lead to ambiguities in the final fit to the data. A more conventional representation of measured ^{12}C excitation energy spectrum is shown in the top panel of Fig. 4 resulting from the subtraction of the evaporation α-particle background from the measured spectrum. Here, the well-known excited states in ^{12}C are shown by the red peaks and the previously identified excited Hoyle state peaks are shown in black.

The use of Wavelet Analysis (details can be found in Refs [9]), however, overcomes the problems of a multi-parameter fit to measured excitation energy spectra. The positions and widths of states excited can be extracted directly from the two-dimensional plot of Wavelet coefficients. A Mother wavelet is chosen that best represents the features of the spectrum measured which in the present case (which is fitted with Gaussian peaks) would be a Complex Morlet (a cosine folded with a Gaussian function). Starting with a narrow Mother wavelet it is moved along the measured excitation energy spectrum and the overlap with the data is determined as a function of excitation energy. The process is repeated by stretching the Mother wavelet to increase its width until a coefficient plot is obtained of scale *versus* excitation energy, as shown in the lower panel of Fig. 4.

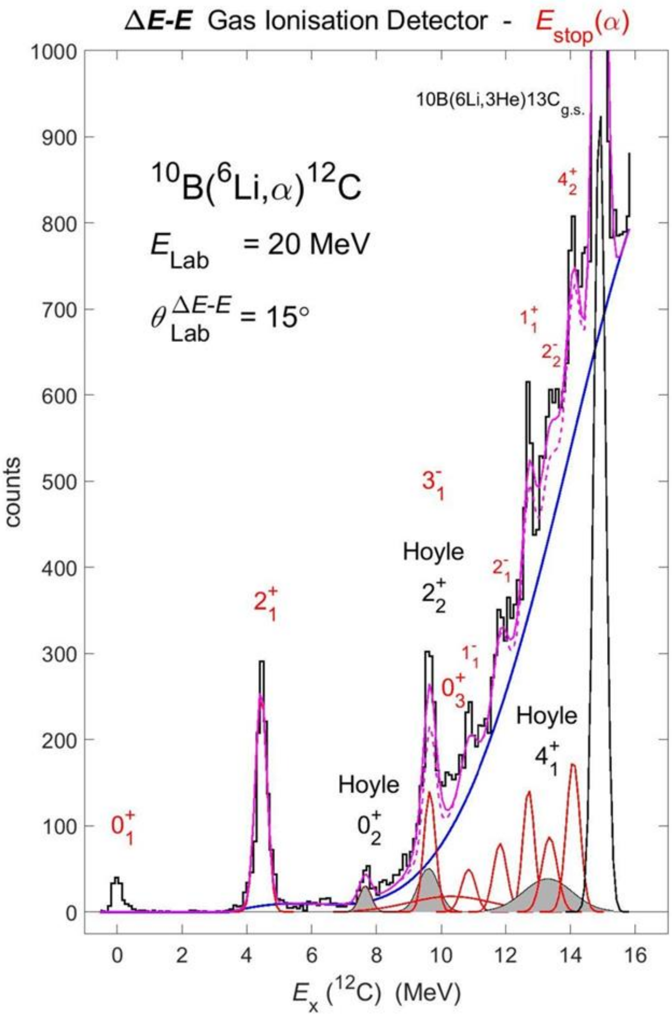

Figure 3: Excitation energy spectrum for ^{12}C obtained using a kinematic conversion from the measured α-channel for the reaction $^{10}B(^{6}Li,\alpha)^{12}C$ (see text).

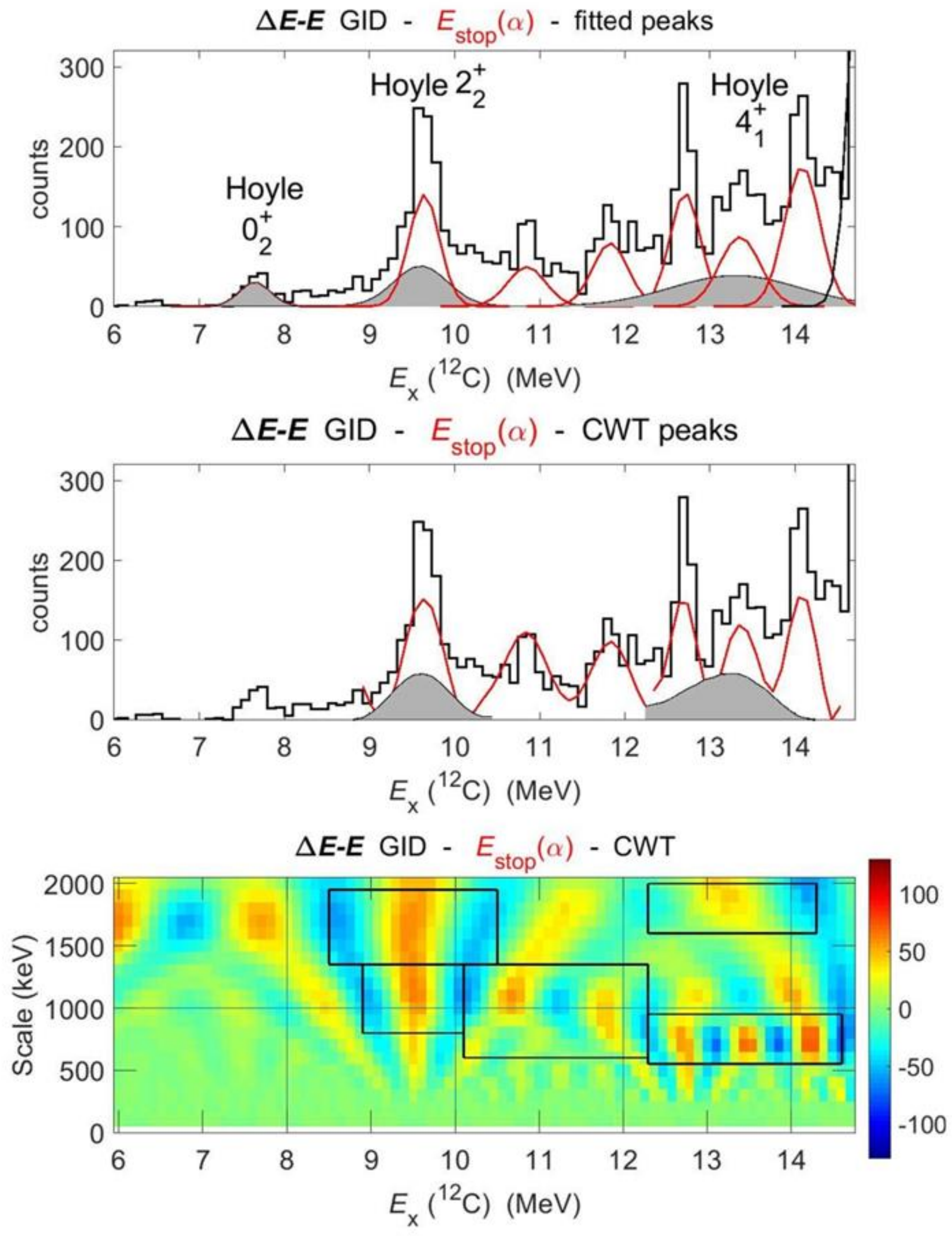

Figure 4. Top panel: resulting ^{12}C excitation energy spectrum after subtraction of the evaporation α-background from the measured α-channel data following kinematic conversion. Middle panel: measured ^{12}C excitation energy spectrum as in top panel with narrow peaks in red from the three lower rectangles and the excited Hoyle state peaks in black from the upper two rectangles indicated in the CWT coefficient plot of the lower panel. Lower panel: CWT coefficient plot for the measured ^{12}C excitation energy spectrum (see text for details).

It should be noted that subtraction of the smooth continuous α-background from the measured ^{12}C excitation energy spectrum does not influence the fine structure (peak positions and widths) extracted. Regions identified by the three lower rectangles in the lower panel of Fig. 4 indicate the presence of clear maxima and minima in the coefficient plot which, after summing along the scale axis, represent the known 12C excited states (red peaks shown in the middle panel of Fig. 4). The two upper rectangles in the lower panel of Fig. 4 indicate broader peaks and the presence of the underlying first and second excited Hoyle states (black shaded peaks also shown in the middle panel of Fig. 4). It can be seen that there is an excellent correspondence between the fitted peaks in the top panel of Fig. 4 and the extracted peaks from Wavelet Analysis in the middle panel of Fig. 4.

4 Summary and Outlook

The $^{10}B(^{6}Li,\alpha)^{12}C$ reaction at Tandem energies allows access to excited states in ^{12}C up to about 20 MeV due to the very large positive *Q*-value of + 23.713 MeV. States $J^{\pi} = 0^{+}$ are weakly populated, notably $^{12}C(0^{+}$, ground state) and the Hoyle state $^{12}C(0^{+}$, 7.6 MeV), while states $J^{\pi} = 2^{+}$ and above are strongly populated, notably the first excited state $^{12}C(2^{+}$, 4.43 MeV). As a result, the first excited Hoyle state $^{12}C(2^{+}$, 9.6 MeV) and the second excited Hoyle state $^{12}C(4^{+}$, 13.3 MeV) are prominently indicated in the Wavelet Analysis procedure. The novel use of Wavelet Analysis was able to identify the specific excited states in the measured ^{12}C excitation energy spectrum. As such, it was possible to extract and confirm the existence of the first and second excited Hoyle states in ^{12}C. This was as opposed to a multi-parameter fitting procedure to measured excitation energy spectra which relies on a previous knowledge of states excited or an inference of possible states for an improved fit. The width of the first excited Hoyle state was found to be consistent with the width determined previously but the width of the second excited Hoyle state was found to be somewhat smaller by about 15% than the previous determination. A $^{10}B(^{6}Li,\alpha)^{12}C$ coincidence measurement α and ^{12}C for excited Hoyle states is ongoing.

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