

## Further limit on $3\alpha$ decay of Hoyle state

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**Abstract.** The quantitative contributions of various direct three alpha decay mechanisms in the decay of the famous Hoyle state, the  $0_2^+$  resonant excited state of  $^{12}\text{C}$  at excitation energy of 7.65 MeV, has been estimated using 60 MeV  $\alpha$  inelastic scattering on  $^{12}\text{C}$  target in complete kinematical measurement. Simultaneous optimisation of three different distributions (the relative energy of  $^8\text{Be}$  like pairs, the root mean square energy deviation and the radial projection of symmetric Dalitz plot) derived from the experimental data with those generated from the Monte Carlo simulated event sets, have been done to arrive at a consistent estimation of the contributions of various direct decay modes.

### 1 Introduction

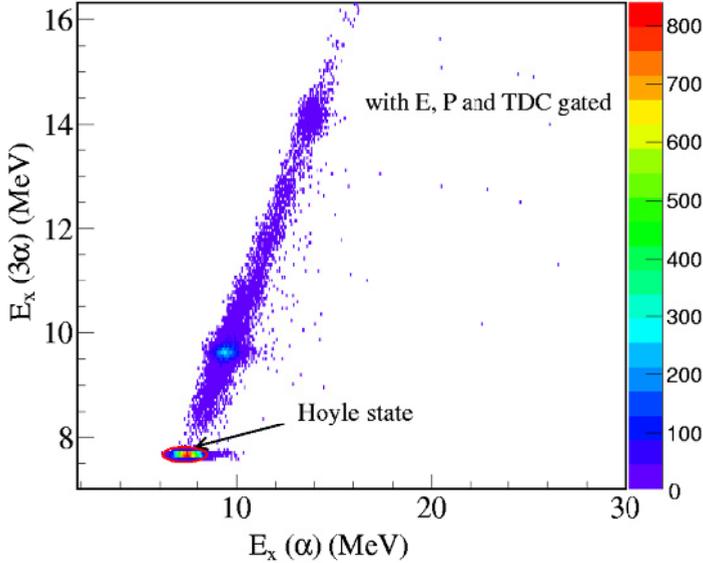
The Hoyle state, second  $0_2^+$  resonant excited state of  $^{12}\text{C}$  at an excitation energy of 7.654 MeV, plays an important role to understand a variety of problems of nuclear astrophysics such as elemental abundance as well as the stellar nucleosynthesis process as a whole [1,2]. The triple alpha reaction rate calculation assumed implicitly that the decay mechanism of Hoyle state in  $^{12}\text{C}$  is exclusively through sequential two-step process, i.e. through the intermediate ground state of  $^8\text{Be}$  nucleus [3]. However, the structure of this state has unusual in nature, as from nuclear structure point of view, there are many unanswered questions regarding the configuration of this state; from the cluster model, it has a linear chain like structure of three alpha particles [4] and at the same time from inelastic scattering it was found that this state has an abnormally larger radius compare to the ground state of  $^{12}\text{C}$  [5] and also found possesses a gas like structure i.e., loosely bound  $3\alpha$  [6, 7]. All these unusual properties of this state may change the decay mode of  $^{12}\text{C}$ , from which reaction rates for carbon as well as other heavy elements have been calculated [8]. Deviation from the two-step process has been predicted to modify the relative abundance of  $^{12}\text{C}$ , and thereby affect the future evolution of stars in the universe [9]. So, it is crucial to determine the quantitative contributions of all direct processes other than sequential decay to get a clear picture of the Hoyle state decay.

In recent years, several experiments have been performed to investigate and quantify the roles of various decay modes i.e. sequential decay (SD) and  $3\alpha$  direct decay (DD) [10-13]. In addition, attempts have also been made to identify and differentiate between various types of direct decays, such as decay into equal energies (DDE), decay in linear chain (DDL) and direct decay in phase space ( $\text{DD}\Phi$ ), and quantify their contributions in the exotic structure of the Hoyle state. In a recent work, Raduta et al. identified two direct decay branches, DDE and DDL, with a combined branching

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percentage of 17(5) %, and argued that the DDE branch corresponds to the signature of  $\alpha$  condensate like structure [13]. This direct decay branches of  $\sim 17$  (5) % implies a corresponding percentage of reduction in the reaction rate calculation in the temperature range of triple alpha fusion ( $10^8 - 10^9$  K), which is larger than the current estimate of uncertainty on the reaction rate calculation. However, all measurements ref[10-12] except that of ref[13] indicate that the direct decay modes are very small fractions; therefore, exclusive experiments with higher statistics of Hoyle events are needed to verify and cross check the recent experimental results and to reach a consensus on this issue. Here, we report a complete kinematical measurement of inelastic scattering of  $\alpha$  on  $^{12}\text{C}$  at 60 MeV to study the various decay channels of Hoyle state with relatively higher in statistic compare to the previous measurement.



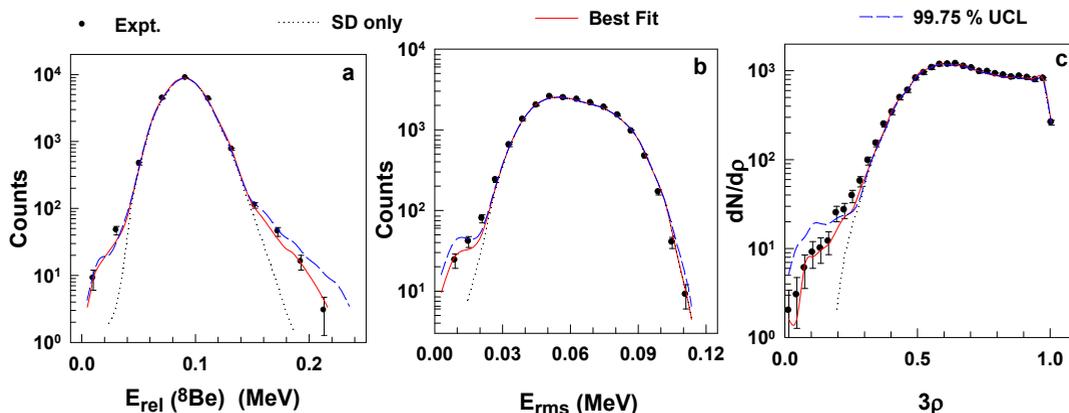
**Figure 1.** Two dimensional plot between the excitation energy of  $^{12}\text{C}$  reconstructed from inelastic alpha ( $E_x(\alpha)$ ) and decay  $3\alpha$  of Hoyle state ( $E_x(3\alpha)$ ) with TDC time gated as well as energy, momentum gated. Red oval line is the gate over which events of interest have been selected and analysed for decay structure of Hoyle state.

## 2 Experimental Details

The experiment has been performed at the Variable Energy Cyclotron Centre, Kolkata, using 60 MeV  $\alpha$  beam from the K130 cyclotron on  $^{12}\text{C}$  target (thickness  $\sim 90 \mu\text{g}/\text{cm}^2$ ). Two double sided Si-strip detectors (DSSD) (each consists of 16 strips (each  $50\text{mm} \times 3\text{mm}$ ) per side in mutually orthogonal directions) of  $500 \mu\text{m}$  thickness have been used in forward direction (covering the angular range of  $20^\circ - 92^\circ$ ) to detect  $3\alpha$  decay from  $^{12}\text{C}^*$  and one telescope consisting of a  $50\mu\text{m}$   $\Delta E$  single-sided silicon strip detector (SSSD) (16 strips, each of dimension  $50\text{mm} \times 3\text{mm}$ ) and  $500\mu\text{m}$  as E (DSSD) in backward direction (covering the angular range of  $88^\circ - 132^\circ$ ) to detect the inelastically scattered alpha particle. The two DSSD detectors and strip detector telescope were placed at kinematically correlated angles for coincident detection of inelastically scattered  $\alpha$  and the three  $\alpha$ -particles from decay of  $^{12}\text{C}^*$ . A VME-based on-line data acquisition system was used for the collection of data on event-by-event basis. Typical beam current used for the experiment was  $\sim 5$  nA. The true Hoyle events have been extracted by filtering the raw data with proper cuts on the TDC time signal as well as energy and momentum gates. Two dimensional plots between excitation energy of  $^{12}\text{C}$  reconstructed from inelastic alpha and the same reconstructed from decay  $3\alpha$  has been shown in Figure 1. In total, nearly  $\sim 20000$  completely detected events within the Hoyle state were collected in the present experiment (within the gate (red circle) as shown in Figure 1), which have been analysed further to extract the structure of the Hoyle state.

### 3 Results and discussion

In order to estimate the various direct decay modes of Hoyle state (other than the most dominant mode, sequential decay, of the Hoyle state), an event-by-event Monte Carlo simulation has been performed for each three body decay scenario. In these simulations, we have taken into account, in addition to the sequential decay, three types of direct decay mechanisms (DDE - representing the decay mode where equal energy sharing occurs among three  $\alpha$ -particles, DDL - representing the decay of a linear chain like configuration, leading to one  $\alpha$ -particle at rest and the other two moving with equal but opposite velocities, and, DD $\Phi$  - characterising uniform sampling of phase space by the decay products, all in the rest frame of  $^{12}\text{C}$ ). In all these simulations, we have considered all experimental effects, such as, geometrical coverage, dead area, angular and energy resolutions of the strip detectors, event rejection due to multiple hit in single strip, etc. To determine the contributions of different decay modes of the Hoyle state, three different methods have been used as described below.



**Figure 2.** (a)  $^8\text{Be}$  like pairs distribution; (b) rms energy deviation distribution and (c) Radial projection of Dalitz plot distribution (see text for details).

#### 3.1 The distribution relative energy of $^8\text{Be}$ like pairs ( $E_{\text{rel}}$ )

This is the distribution of the lowest relative energy between any two  $\alpha$ -particles in each  $3\alpha$  decay event of Hoyle state [10, 11]. So, all SD events decaying through  $^8\text{Be}$  ground state will contribute to the peak at relative energy of 92 keV i. e. the ground state breakup energy of  $^8\text{Be}$ . On the other hand, for DD mode of decay, it should be around the tail region of the peak. The relative energy distribution of the  $^8\text{Be}$  like pairs in the experimental data (filled circles) is displayed in Fig. 2a.

#### 3.2 The distribution of root mean square (rms) energy deviation ( $E_{\text{rms}}$ )

The root mean square energy deviation,  $E_{\text{rms}}$ , has been defined as [11, 13],

$$E_{\text{rms}} = \sqrt{\langle E_{\alpha}^2 \rangle - \langle E_{\alpha} \rangle^2} \quad (1)$$

Where,  $E_{\alpha}$  are the energies of the  $\alpha$ -particles from the decay of Hoyle state, and the average is over the energies of the  $3\alpha$ -particles of each event. So,  $E_{\text{rms}}$  is the root mean square deviation of the energies of the  $\alpha$ -particles of each Hoyle state decay event in  $^{12}\text{C}$  rest frame. Fig. 2b displays the distribution of  $E_{\text{rms}}$  for the fully detected events (experimental data, filled circles). It is clear from Eq. 1 that, in this case DDE should contribute prominently in the neighbourhood of  $E_{\text{rms}} \approx 0$  in the distribution, subject to finite broadening due to the total instrumental resolution.

### 3.3 The distribution of radial projection of symmetric Dalitz plot

The radial projection of Dalitz plot is very useful; in particular for this case of isotropic decay of a state (spin zero state) into three equal mass particles, to gain deeper insight into the decay mechanism [12, 14]. The radial coordinate of the symmetric Dalitz plot,  $\rho$  is given by

$$(3\rho)^2 = (3\epsilon_i - 1)^2 + 3(\epsilon_i + 2\epsilon_j - 1)^2 \quad (2)$$

where,  $\epsilon_{i,j,k} = E_{i,j,k}/(E_i + E_j + E_k)$  are the normalized  $\alpha$  particle energies in the  $^{12}\text{C}$  frame and  $E_i > E_j > E_k$ . Fig. 2c displays the distribution of radial coordinate of symmetric Dalitz plot for the fully detected events (experimental data, filled circles).

The experimental results have been compared with those obtained using simulated data sets containing contributions of different decay processes in varied proportions. Simultaneous optimisation of three different distributions (the relative energy of  $^8\text{Be}$  like pairs, the root mean square energy deviation and the radial projection of symmetric Dalitz plot) derived from the experimental data with those generated from a simulated event set, have been done with  $\chi^2$  minimization to arrive at a consistent estimate of the contributions of various direct decay modes. The optimisation procedure was further repeated for a large number of times with different sets of simulated data sampled randomly from a much larger pool of simulated events to extract the complete range and distribution of the best fit values for each mode. Finally, these distributions have been used to obtain the optimum values of the contributions of various direct decay modes [15]. In figure 2, solid circle are the experimental data, dotted line (black), solid line (red) and the dash line (blue) are the SD, best fit and the upper limit with 99.75 % confidence limit, respectively. Hence, from the present analysis, we conclude that, at 99.75 % confidence limit, the upper limits of the DDL is 0.1 % and the estimated value for fractional contributions of other two direct decays mode are  $0.60 \pm 0.09$  % for  $\text{DD}\Phi$ , and  $0.3 \pm 0.1$  % for DDE.

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