Physics Letters B 793 (2019) 130–133

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

New high precision study on the decay width of the Hoyle state in ^{12}C

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ARTICLE INFO

Article history:
Received 3 December 2018
Received in revised form 9 April 2019
Accepted 11 April 2019
Available online 17 April 2019
Editor: D.F. Geesaman

Keywords:
3α cluster state
^{12}C$(\alpha, \alpha)3\alpha$ reaction
Complete kinematics reaction
The Hoyle state decay
Direct *versus* sequential decay
Inelastic scattering

ABSTRACT

Precise estimation of the rare direct 3α decay of the Hoyle state of ^{12}C has been made to unveil its unusual α-cluster configurations ranging from linear 3α chain structure to diffuse Bose gas as well as Bose Einstein condensate. The present new high precision, nearly zero background experimental study with 1.6×10^5 Hoyle events has converged on the upper limit for direct decay at $\sim$0.019% with 95% confidence limit, which is more than a factor of 2 lower than the limit obtained in the previous studies.

The enormous experimental and theoretical efforts have been devoted within last few decades and still going on to understand the precise nature of the element carbon-12. This element is the backbone for the existence of life on earth; it is also crucial for the formation of all observed heavier elements in the stellar environment. Elements heavier than ^{4}He have been produced in stars through stellar nucleosynthesis process, which starts from hydrogen burning process leading to the formation of ^{4}He by fusion of four ^{1}H nuclei; subsequently, other heavier elements are synthesised in steps [1]. However, this process meets a roadblock after the first step itself, as no stable nuclei of masses 5 and 8 exist in nature. The proposed mechanism for production of ^{12}C through 3α-process during helium-burning phase of the stars attempted to establish a bridge between the mass gap A=4 and A=12 and facilitate the continuation of nucleosynthesis further for production of other heavy elements. In this reaction, ^{12}C is produced through a non-resonant two-step process [2,3]; in the first step two αs combine to form short-lived ^{8}Be (half life $\sim 10^{-16}$ s), followed by the capture of another α to form ^{12}C*, which undergoes radiative transition and forms stable ^{12}C. However, the non-resonant capture process was not sufficient to explain the observed abundance of ^{12}C on earth. This led Fred Hoyle to postulate the existence of an unbound excited state of ^{12}C, close to its 3α decay threshold (7.27 MeV), enabling resonant capture of α in the 2nd step ($^8\text{Be} + \alpha \rightarrow {}^{12}C$) of the 3α-process which would enhance the yield of ^{12}C by several orders of magnitude [4]. This state (excitation energy $E_x \simeq 7.654$ MeV, $J^\pi = 0^+$) was soon confirmed experimentally [5], which is known as the Hoyle state.

The Hoyle state plays a massive role in stellar helium burning at temperatures $\sim 10^8$–10^9 K, when the element carbon is synthesized exclusively through sequential 3α resonant capture process and even a small change in the rate of this reaction would influence the stellar abundances; subsequently, this may lead to significant change in our present understanding of the stellar evolution scenario [6]. However, the characteristics of the Hoyle state decay is determined by its intrinsic structure, corresponding to different geometrical configurations of its constituent α-particles. Therefore, the structural features of the state may significantly affect the stellar nucleosynthesis process as a whole, rendering it important to

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https://doi.org/10.1016/j.physletb.2019.04.028
0370-2693/

thoroughly investigate the special structural features of the Hoyle state and their relationship with its decay. From nuclear structure point of view, the Hoyle state is 'different' from other excited states of Carbon, which is manifested in its 3α-cluster configuration [7]; standard as well as no-core shell model calculations failed to reproduce the energy of the state [8]. Various theoretical models predicted very different structures of the state, *e.g.*, molecular structure in various configurations (linear 3α-chain [9], obtuse angle/bent arm triangle [10,11]), Bose gas of weakly interacting α-particles [12], or even nuclear Bose-Einstein condensate (BEC) [13–15]. Each of the configurations has the potential to modify the sequential decay rate and vis-a-vis the stellar nucleosynthesis process as a whole [16]. Therefore, unveiling the structure of the Hoyle state is a challenge, which is having major implications for nuclear physics and nuclear astrophysics.

Experimentally, the imprint of the structure of the Hoyle state is extracted from the kinematic correlation between its (3α) decay products. Apart from sequential decay mentioned above, the Hoyle state may also undergo direct $(^{12}C \rightarrow 3\alpha)$ decay (DD). Even the DD has been characterised in three different types, one is the direct decay in linear 3α chain (DDL), where two αs move with equal energy but in opposite directions and the third α is left with zero energy, the direct decay by emission of 3 equal energy αs (DDE), and the direct decay associated with uniform phase space distribution of 3αs (DDΦ). In contrast, the sequential decay is characterised by two correlated αs corresponding to ^{8}Be decay. There has not been much theoretical effort towards predicting the direct link between 3α decay of the Hoyle state and its structure. Using Faddeev equation calculation, successfully predicting the non-sequential decay branch ($<1\%$) and indicates that the change in structure from small to large distances from the decay of the Hoyle-state is very small, therefore the final state distribution in this case indeed can be taken as a rather direct probe of its α-cluster structure [17]. Hence, this direct experimental observable should be one of the most sensitive probes of its 3α structure. Each configuration is identified by its signature DD mode [18,19]. Since DD constitutes a small fraction ($\sim$1% or less) of the total decay, its unambiguous quantitative determination remained a difficult task. Several experiments have been performed till date with increasing precision and statistics [19–25], which restricted the limit of total DD to $\lesssim 1\%$. Recently, two new high precision, high statistics measurements [26,27] have further lowered the upper limit of total DD to $\sim$0.043%, down by nearly an order of magnitude of all previous measurements. Since this new result has a considerable impact on the nucleosynthesis rate calculations as well as probing the structure of the Hoyle state, further high precision study at similar or higher statistics level is necessary for confirmation of these results. Interestingly, two recent theoretical studies [28,29] predicted quite differently on the percentage of DD in the Hoyle state decay; whereas Faddeev formalism based calculation [28] predicted $<1\%$ contribution of DD, *ab-initio* calculation [29] indicates the possibility of nearly 11% admixture of DD in the decay. More recent theoretical calculation including the one and two dimensional tunnelling effect has estimated the contribution of DD even one order lower limit than recent experimental limit [30]. In this letter we report a new high resolution (almost zero background), high statistics, kinematically complete measurement of the Hoyle state decay using inelastic α-scattering from ^{12}C. The present results are critically compared with the recently performed similar high precision experiments [26,27].

The Hoyle state has been populated by bombarding 15 MeV/A α beam from the K130 cyclotron at Variable Energy Cyclotron Centre, Kolkata, on $\sim$50 μg/cm^2 ^{12}C target. The α-particles emitted in the decay of the Hoyle state have been detected in coincidence with the inelastically scattered ^{4}He using two 1000 μm double-sided silicon strip detectors (DSSD: 16 strips (each 50 mm × 3 mm) per side in mutually orthogonal directions) at forward angles (coverage $\sim$19° to 90°). The inelastically scattered ^{4}He was detected on the other side of the beam axis using two telescopes (coverage $\sim -18°$ to $-93°$), each consisting of a 50 μm ΔE single-sided silicon strip detector (SSSD: 16 strips, each of dimension 50 mm × 3 mm) and a $\sim$1030 μm DSSD E-detector. The beam current has been kept very low, $\sim$0.25 pnA, during the whole run in order to minimize the background. Valid events were triggered by minimum 2 hits between all detectors. The time delays between the event trigger and individual groups of detectors and telescopes placed on either sides of beam axis in standalone as well as coincidence modes have been separately recorded using respective constant fraction discriminator outputs. All strip detectors were read out individually using standard readout electronics on event-by-event basis. All strip detectors were calibrated using Pu-Am and ^{229}Th α-sources and typical energy resolution was $\sim$40 keV. The data being presented here were collected in a single run of around 2 weeks of which actual data collection time was $\sim$315 Hrs. The stability of the electronics and detectors were carefully monitored throughout the run in several ways; firstly, the absolute energy calibrations of the strips were carried out using Pu-Am and ^{229}Th α-sources at the beginning and the end of the run and were compared. Secondly, stability of the electronics was checked at regular intervals using precision pulser. Finally, the in-beam stability of the system was continuously monitored throughout the whole run by checking the temporal shift (if any) of the elastic α/recoil peak position in each strip. Throughout the whole run, the elastic peak remained robustly fixed (variation $\lesssim$0.01%), which ensured extremely good quality low background data, which was crucial for the present measurement requiring highest precision.

The experiment was primarily aimed at precise measurement of the three α-particles emitted in the decay of the Hoyle state; Only complete kinematical 4αs events (three from ^{12}C* decay and the inelastic α) have been used for the present analysis. The data analysis has been carried out in several steps. The genuine Hoyle events have been extracted by filtering the raw data with proper cuts (gates) on the measured time, total energy and momentum. The stringent time gate (in present $\sim$12 ns was taken) is very important to remove the background coming from mostly other events as well as inelastic scattering [31]. Under certain circumstances, the use of strip detector is known to introduce some background because of position identification ambiguity (PIA) [20,22]. To remove this background due to PIA, following offline steps were taken. Firstly, the position identification of multiple particle hits in a strip detector has been done using a minimization routine which compares the energy difference between the front and back strips for all possible pairs to identify the proper hit positions. Secondly and more importantly, all such events in which any two particles incident on the same detector (but on different strips) were having energies lying within the minimal overlapping limits of the detector energy resolution were rejected from the final data set as these events are more prone to cause PIA in DSSD [27]. With these offline filtering of the raw events, starting from a primary data set of 1.95×10^5 events, we were left with 1.60×10^5 filtered events for final analysis, which is $\sim$2–6 times higher than the number of events considered in any of the similar high precision experiments reported in recent years [26,27].

The excitation energy spectrum reconstructed from the invariant mass of the three decay α-particles gated with inelastic Hoyle state has been shown in the Fig. 1a. In the expanded view of the background region of the Hoyle state (shown in Fig. 1b), apart from the flat background at the level of 1 count/bin in the vicinity of the Hoyle state, a broad hump is also seen in the higher energy

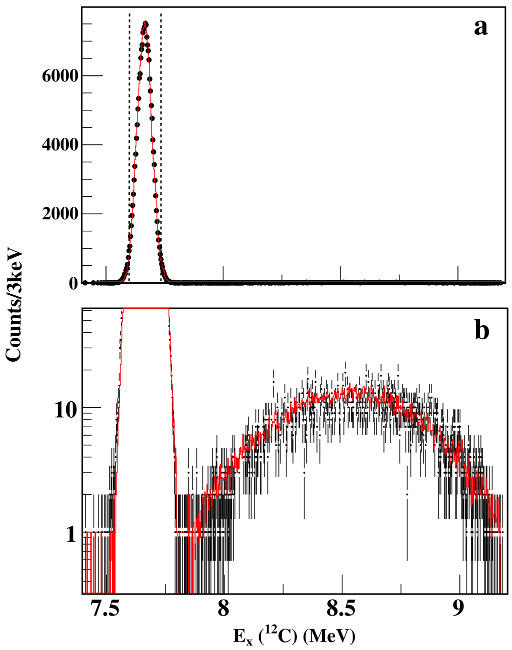

Fig. 1. (a) The excitation energy spectrum reconstructed from the invariant mass of the three detected decay α (solid circle) along with simulation (red solid line). Black dotted line is the gate used for further analysis. (b) The background shown is in logarithm scale (see text).

side (in the region of ~8–9 MeV). This hump is due to the contribution from the tail of the resonance at 10.3 MeV (0_3^+) of ^{12}C. Therefore, any realistic simulation of the Hoyle state decay should properly include the effect of this resonance along with the mixed events [26,27], as has been done in the present case. The experimental background in the data, estimated with respect to the total area within the Hoyle state gate (as shown in black dotted line in Fig. 1a), is found to be extremely low, ~0.016%. In order to estimate the quantitative contribution of each decay branch, detailed Monte Carlo simulation has been performed which incorporated all experimental effects including the angular coverage, energy resolution of the detectors. Simulations for the SD events and all types of DD events have been performed independently. The measured Hoyle state excitation energy spectrum has been compared with simulation spectrum with backgrounds along with the tail of the 10.3 MeV (0_3^+) of ^{12}C for 100% SD (red solid line) is shown in Fig. 1. Excellent agreement of the simulation results with the experiment is clear demonstration of the success of the simulation in reconstruction of the measured Hoyle state decay. Similar agreement was obtained for DDΦ, DDL and DDE.

Investigation on the nature of decay of the Hoyle state (sequential vs. direct) has been carried out using symmetric Dalitz plot technique [32], whose coordinates are given by

$$x = \sqrt{3}(e_2 - e_3) \tag{1}$$

$$y = 2e_1 - e_2 - e_3 \tag{2}$$

where $e_i = E_i / \sum_i E_i$ $(i = 1, 2, 3)$ are the normalized α particle energies in the ^{12}C frame and $E_1 > E_2 > E_3$. The symmetric Dalitz plot of the present Hoyle state experimental data are displayed in Figs. 2(a) and (b) before and after the rejection of events responsible for PIA as explained earlier. Similar plots (for same number of events) generated by Monte Carlo simulation for each individual decay mode (SD, DDΦ, DDL and DDE (all 100%)) have been displayed in the Figs. 2(c–f), respectively, for comparison. From these figures, it is evident that the experimental data are, at least qualitatively, in excellent agreement with the SD simulation events and other modes, even if present, are likely to contribute very little to the total spectrum. Therefore, high statistics and utmost precision are crucial for unambiguous determination of the weak contributions of the DD modes. In this respect, the present as well as the two recently reported [26,27] experiments provide very high quality, high statistics data that are almost background-free. So the present experimental results will be thoroughly compared only with the results of [26,27] to reach consensus on the DD of Hoyle state.

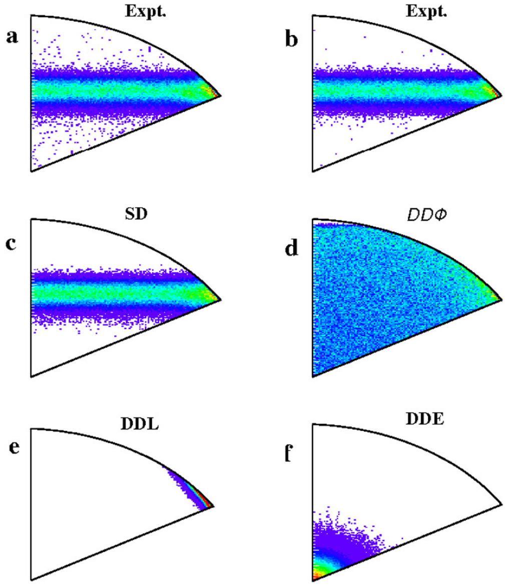

Fig. 2. Symmetric Dalitz plot. (a, b) Experimental data before and after rejection, (c–f) Monte Carlo simulations (see text).

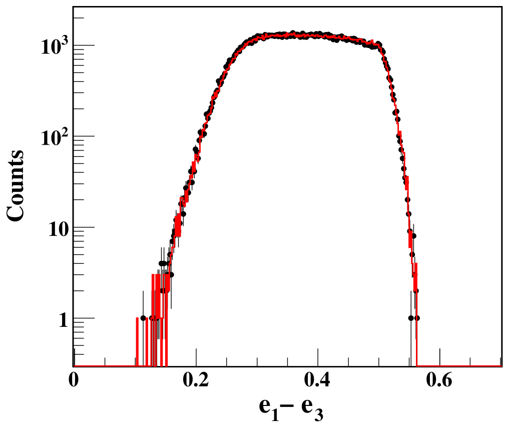

Fig. 3. The distributions of normalized energy difference between highest and lowest energy of the α particle in the ^{12}C frame. Filled circles are the experimental data and the red solid line correspond to 100% SD simulations (see text).

The quantitative contribution of each decay branch has been extracted by fitting the distribution of the normalized energy difference between the highest and lowest energies of α particle, e_1-e_3, in the ^{12}C frame. The e_1-e_3 distributions for experimental as well as simulation data are displayed in Fig. 3. Using this normalized energy difference, the contributions of various kinds of decays (particularly DDE, DDL and SD) can be easily separated out because of the kinematics. The experimental data is found be distributed from 0.1 to 0.57, which is completely described by the SD simulation events. To estimate the branching ratio of direct decays contributing to the width of the Hoyle state, the experimental data was compared with the Monte Carlo simulation result assuming 100% SD (red solid line on Fig. 3). It is seen that the simulation with 100% SD is almost completely matching with the data. It is still possible, using likelihood procedure [23], to estimate the limits of the branching ratio for each rare direct decay mode. The upper limits thus calculated separately for three direct decay modes are, $<0.019\%$ for DDΦ, $<0.004\%$ for DDL, and $<0.012\%$ for DDE, at 95% confidence limit.

To sum up, a high precision, complete kinematical study of the decay mechanism of the Hoyle state of ^{12}C has been done using inelastic scattering of α at 60 MeV on ^{12}C. After proper filtering of the data, $\sim 1.6 \times 10^5$ fully detected (4α) nearly zero background events have been used to extract unambiguously the contributions of the various modes of the Hoyle state decay. The χ^2-minimization of normalised energy distribution of the decay αs has led to the upper limit for direct decay as 0.019% with 95% upper confidence limit; the present value is more than a factor of 2 lower than the limit obtained recently in similar high precision studies [26,27]. It may be emphasised here that it is the highest statistics and almost background free nature of the present measurement – which marks the difference between the present and all other previous measurements, as well as the choice of proper analysis technique that are the three crucial factors which rendered this precise estimation of decays of the Hoyle state.

The authors would like to thank the cyclotron operating staff for smooth running of the machine during the experiment. Two of the authors (S.B. and A.R.) acknowledge the financial support received as Raja Ramanna Fellowship from the Department of Atomic Energy, Government of India. We wish to acknowledge H.O.U. Fynbo for fruitful discussions/comments on the present data and for carefully going through the manuscript.

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