Structure and decay mechanism of Hoyle state

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The second 0^+_2 state of ^{12}C at excitation energy of 7.654 MeV, the famous Hoyle state, has been found to be of great interest not only in nuclear synthesis but also in nuclear structure and reactions. The existence of this state was first proposed by Hoyle [1] and experimentally confirmed soon afterward [2]. However, the structure of the above state is still not known properly and remains a mystery, which makes a subject of great interest in recent year [3,4]. The standard shell model approaches, even the advanced no-core calculations failed to reproduce the state [5]; however, recent ab-initio calculation using chiral effective field theory and Monte Carlo lattice simulation technique has been able to find a resonance in ^{12}C having the characteristics of the Hoyle state [6]. It has been proposed that this state has a linear chain structure of three α-clusters [7]. On the other hand, from the microscopic α-cluster model that this state has not a linear chain structure but a gas like α-cluster structure [8]. It is evident from the above that the structure of the Hoyle state is still poorly understood, theoretically as well as experimentally. In this paper we report, an exclusive measurement of complete kinematic correlations between the α particles emitted in the decay of Hoyle state.

Experiment has been performed at Variable Energy Cyclotron Centre using alpha beam of 60 MeV on a self supporting ^{12}C target of thickness ~ 90 $\mu g/cm^2$. The Hoyle state in ^{12}C nuclei were produced through inelastic scattering of α from ^{12}C. Two telescopes, each consist of three elements, 50 μm ΔE single-sided Silicon-strip detector (16 strips, each dimension 50 mm X 3 mm), 500 μm E/ΔE double-sided Silicon-strip detector (16 strips, (dimension 50 mm X 3 mm), in both side mutually orthogonal to each other) and back by four CsI(Tl) detectors of thickness 6 cm, have been used for particles detection. Typical experimental setup is shown in Fig. 1. Two telescopes were placed at a distance ~11 cm downstream from the target and at kinematically correlated angle in both sides of beam axis for the coincident detection of inelastically scattered α in the backward angle telescope (T_2) and the three α particles originating from the decay of the Hoyle state of the recoiling ^{12}C at the forward angle telescope (T_1). Typical angular resolution was 1.5^0 between the two strips. A VME based data acquisition system, developed at VECC, has been used for collection of data in event by event mode.

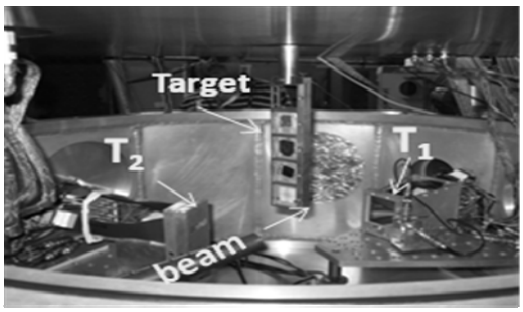

Fig. 1: Typical experimental setup

The Hoyle state decay events were extracted by filtering the forward telescope data with a gate on the corresponding inelastically scattered α particle spectrum at the backward angle telescope. Typical 2D spectrum of Q-value vs. excitation energy reconstructed from filtered events has been shown in Fig. 2. It is seen that the excitation energy and Q-value of the Hoyle state has been reproduced correctly. It is clear from the above that the selected events have been thoroughly consistent in all respect to be used for investigating into the detailed nature of the decay of the Hoyle state (sequential: $^{12}C^* \rightarrow {}^8Be + \alpha \rightarrow \alpha+\alpha+\alpha$ vs. direct: $^{12}C^* \rightarrow 3\alpha$). The study has been carried out using Dalitz plot technique [9]. The relative energy spectra and the corresponding Dalitz plots for the Hoyle state

have been shown in Fig. 3. Here the relative energy indices 1, 2 and 3 refer to the particles emitted with highest, second highest and lowest energies respectively.

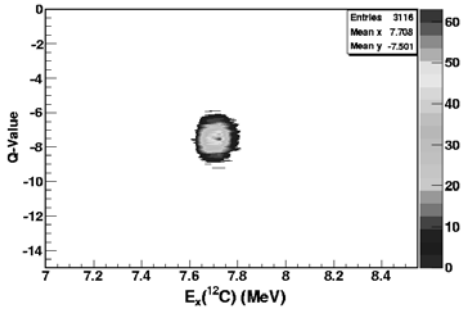

Fig. 2: 2D spectrum of Q-value Vs excitation energy E_x of ^{12}C in ^{12}C (α, α) 3α reaction.

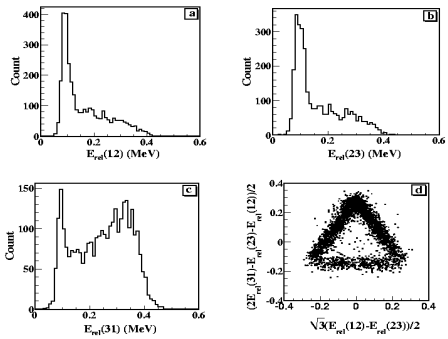

Fig. 3: (a, b, c) Relative energy spectra for the three α particles and, (d) the Dalitz plot, for the decay of the Hoyle state.

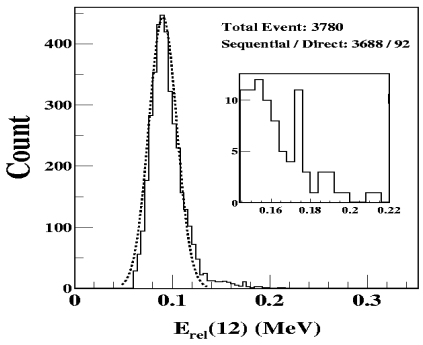

Fig. 4: Relative energy spectra of ^{8}Be like α particle pairs (see text).

The Dalitz plot (Fig. 3d) has been generated using the Dalitz parameters $\sqrt{3}($ $E_{rel}(12)-E_{rel}(23))/2$ and $(2E_{rel}(31)-E_{rel}(23)-E_{rel}(12))/2$, where $E_{rel}(ij)$ is the relative energy between i^{th} and j^{th} particle. The triangular locus in Fig. 3d indicates that the decay is mostly sequential in nature (sequential : $^{12}C^* \rightarrow {}^8Be + \alpha \rightarrow \alpha + \alpha + \alpha$). Very few events are observed in the central region of the triangle indicating that contribution from direct break up is very small [10]. A quantitative estimate of the direct decay contribution has been made in the following way. From each event, the pair of α particles having relative energy closest to the $^8Be_{gs}$ breakup energy (92 keV) has been identified; the corresponding relative energy spectrum has been displayed in Fig. 4. The numbers of sequential decay events (area under the $^8Be_{gs}$ peak- Fig. 4.) and direct decay events (the area excluding the ^{8}Be peak - inset of Fig. 4) have been estimated and found direct decay of the Hoyle state is insignificant (typically 2.4 %) in comparison with sequential decay (97.6 %).

In summary, three alpha configuration of Hoyle state has been studied in α + ^{12}C reaction at 15 MeV/A in complete kinematics. It has been found that decay mechanism of Hoyle state is mostly sequential in nature (97.6%) and rest (2.4 %) are due to direct decay. Details further analysis is in progress.

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