Search of 2_2^+ state of Hoyle state of ^{12}C

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The famous Hoyle state [1], the resonant excited 0_2^+ state of ^{12}C at the excitation energy (E_x) of 7.65 MeV, plays an important role to understand a variety of problems of nuclear astrophysics, like elemental abundance in the universe as well as the stellar nucleosynthesis process as a whole [2]. From nuclear structure point of view too, there are many unanswered questions regarding the configuration of this state; theoretically, it is conjectured as the lowest state corresponding to a different configuration (member of either a β- band of the three-α molecule like structure [3-5] or a Bose Einstein condensate like structure (BEC) [6]) originating from 3α clustering in ^{12}C, and the standard shell model approaches, even the advanced no-core shell model calculations failed to reproduce the state [7].

According to the above models, the 3α cluster configuration of the Hoyle state at an excitation energy 7.65 MeV should also have higher excited states, the lowest excited state has been predicted to be a 2^+ state at excitation energy E_x ~ 10 MeV [3,4,6]. This 2^+ state is strongly coupled to the 0_2^+ Hoyle state and is likely to decay mostly via the Hoyle state. However, in spite of vigorous experimental efforts in the recent years, there is no conclusive evidence so far. In inelastic proton scattering ^{12}C(p, p′)^{12}C* experiments, small angle angular distribution measurement near the diffractive minimum of the broad 0_3^+ background has indicated the presence of a 2^+ possible state at 9.6 (1) MeV of width ~ 600 keV [8, 9]. Recent inelastic scattering angular distribution studies also indicated the presence of a 2^+ state at ~ 9.8 MeV of width ~ 1 MeV [10]. On the other hand the study of ^{12}C*, produced in the Beta decay of ^{12}N and ^{12}B, decaying into 3α continuum has however, not found clear evidence about the existence and nature of the 2^+ state at 10 – 12 MeV excitations [11, 12]. Recently, gamma induced ^{12}C dissociation studies via ^{12}C(γ, 3α) reaction have also indicated the presence of a 2^+ state below 10 MeV [13].

It is thus clear that even though there are definite indications about the existence of the elusive 2_2^+ state (the first excited state of the Hoyle state), clear identification of this state is still missing. A complete kinematic measurement of the inelastic α particles emitted in the ^{12}C(α, α′) 3α reaction in coincidence with the decay of the Hoyle state reported here. The present study clearly demonstrates the presence of an excited state of ^{12}C at the excitation energy of 9.65 ± 0.02 MeV which has a width (FWHM) of 607 ± 55 keV. Since this new state is decaying via the 0_2^+ Hoyle state and no direct 3-α decay, it may be taken as the excited state of the Hoyle state.

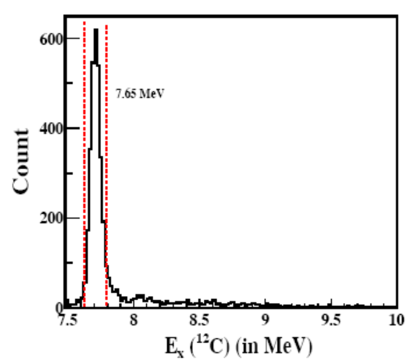

Fig. 1: Excitation energy of recoiling ^{12}C reconstructed from the three 3α particles emitted in the ^{12}C decay. The red dotted lines indicate the gate used for further analysis (see text).

The experiment was performed at the Variable Energy Cyclotron Centre, Kolkata, using 60 MeV α beam from the K130 cyclotron on ^{12}C target (self supported, thickness ~ 90μg/cm^2). The complete experimental setup has been described in reference [14].

The analysis of the data has been carried out in steps. In the first step, the energies and momenta of the three α particles detected in the forward telescope (only completely detected events) have been used to reconstruct the excitation energy of the recoiling $^{12}C^*$, which has been displayed in Fig. 1. It is seen that the excitation energy has only one prominent peak at E_x (^{12}C) ~ 7.65 MeV, which corresponds to the Hoyle state. In the next step the ^{12}C excitation energy spectrum has been generated from the inelastic scattering data of the backward telescope in coincidence with a gate on the observed Hoyle state in Fig. 1, which has been shown in Fig. 2.

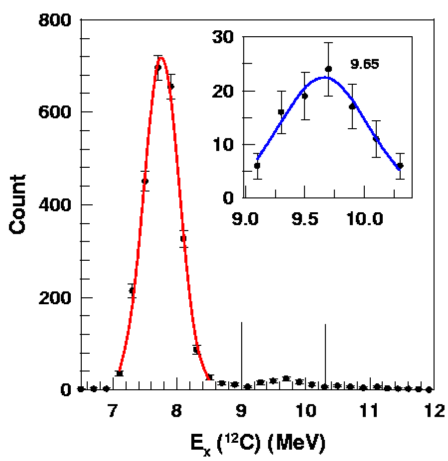

Fig.2: Excitation energy spectrum of ^{12}C from inelastic α-scattering data gated with Hoyle state. The zone marked by the lines has been shown in the inset. The symbols represent the data and the lines are the corresponding fits to the data (see text).

It is clearly seen in Fig. 2 that the ^{12}C excitation energy spectrum obtained from the inelastic scattering contains two peaks. The first peak at 7.73 ± 0.09 MeV is the 0_2^+ Hoyle state. In addition, there is a small peak also seen at excitation energy 9.65 ± 0.02 MeV (see inset of Fig. 2). The excited state observed at 9.65 ± 0.02 MeV is having a large intrinsic width, which is estimated to be ~ 607 ± 55 keV, obtained after correcting for the kinematic broadening. Since this state has been seen in coincidence with the Hoyle state, it is likely to be an excited state of ^{12}C, which is decaying via Hoyle state. However, since there are quite a few states at around the same energy, it warrants a thorough introspection of the whole scenario.

It may therefore be concluded that the 9.65 ± 0.02 MeV excited state of ^{12}C seen in the inelastic α scattering spectrum in coincidence with the Hoyle state reconstructed from kinematically complete events, is most likely a new excited state decaying via Hoyle state. This state is likely to be a candidate for 2_2^+ first excited of Hoyle state, the existence of which has recently been indirectly evidenced from the recent inclusive inelastic scattering studies [10].

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