Clustering in light nuclei

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Introduction

Clustering phenomena is subject of great interest in nuclear physics since the first proposition of α-chains as possible building blocks of even–even nuclei in the late 1960s [1]. Extensive efforts have been made both theoretically and experimentally to search for the α-cluster structure in self conjugate (N=Z) nuclei. The highly sophisticated *ab initio* calculations have shown pronounced cluster features in the ground state of a large number of light nuclei [2]. Constrained density functional approaches have also consistently found clear α-cluster correlations in all light and medium–heavy even–even nuclei at excitation energies around the break up threshold into constituent clusters [3-6]. The rotational bands consistent with α-cluster structures have been identified experimentally, in different even–even light nuclei and shown to persist even along their isotopic chains [7]. In recent years, extensive studies are being carried out for the spectroscopy of ^{12}C and ^{16}O α- like nuclei. The renewed interest in ^{12}C was mainly focused to a better understanding of the nature of the so called "Hoyle" state [8].

The Hoyle state, second 0_2^+ resonant excited state of ^{12}C at 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 nucleo synthesis process as a whole. Hoyle state possesses very exotic nature, from nuclear structure point of view also. This state has long been considered as a classic example of α-cluster nuclear states in light nuclei [9,10, 11] as well as a candidate for exotic 3α linear chain configuration [9, 12]. It has also been predicted that this state has a relatively large radius compared to that in the ground state [13], supportive of facts that the α-clusters in the Hoyle state may remain in quasi-free gas like state. Due to the Bosonic characters of α-particles and the fact that the initial states of all three α-particles, as well as the final (Hoyle) state are in the same (0+) state, it was conjectured that the state may be described in terms of a nuclear Bose-Einstein condensate (BEC) [14,15,16]. On the other hand, the calculations using fermionic molecular dynamics (FMD) have shown that the α-cluster structure of the Hoyle state was mostly resembling ^{8}Be plus α configuration [11], and verified in the observed sequential nature of its decay [17].

In nucleosynthesis reaction rate calculation, it is assumed that the decay of the Hoyle state proceeds exclusively via sequential two-step process,

$$(\alpha + \alpha \rightarrow {}^8\mathrm{Be};\ {}^8\mathrm{Be} + \alpha \rightarrow {}^{12}\mathrm{C}^*)$$

However, a small deviation from the two step process will modify the theoretical value of abundance of ^{12}C in addition it will also affect directly the future evolution of star in the universe. So, precise quantitative measurement of all direct processes (deviation from sequential) in Hoyle state decay is crucially important from nuclear structure as well as astrophysics points of view.

Hence, it remained as a nucleus of intense theoretical and experimental activities over past few decades. In recent years, there have been several attempts to improve the understanding of the structure of the Hoyle state using precision experimental tools and novel theoretical techniques. Still there are ambiguities regarding the structure of the "Hoyle" state as experimental results of its direct decay into three α particles are found to be in disagreement [17, 18, 19, 20, 21, 22].

Similarly search for an experimental signature of BEC in ^{16}O is of highest priority in the present scenario. The most recent theoretical predictions for BEC in ^{16}O in the excitation energy region above 15 MeV have been presented in [14]. On the other hand, using double folding model and the coupled channels method Ohkubo et al. [23] have proposed α-chain state in ^{16}O. It has been suggested that the α-chain state should have an α + ^{12}C* [7.65 MeV, 0^+_2] structure, where the three α particles in the ^{12}C* [7.65 MeV, 0^+_2] Hoyle state are assumed to be in condensed. Funaki et al. [24] has also predicted a state in ^{16}O at about 15.1 MeV (the 0_6^+ state) with the structure of "Hoyle" state in ^{12}C coupled to an α particle , the energy of which is ≈700 keV above the 4α-particle breakup threshold. Though an extensive efforts are being done, the prediction of four alpha – linear chain states in ^{16}O is still an open problem .

So detailed study of clustering in light α conjugate (N=Z) nuclei and their isotopic chains is the one of the current interest for the better understanding of the nuclear structure as well as from the nuclear astrophysical point of view.

Recently, we have undertaken a program at VECC to study such exotic states of ^{12}C and ^{16}O, using complete kinematical measurements [21,25,26], the details of which will be presented in this talk.

Apart from these, in a recent study of fragment emission from decay of fully energy relaxed composites, it has been observed that clustering plays a crucial role in the fragment emission which will also be discussed in the present talk.

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