Experimental evidence for alpha-particle condensation from the Hoyle state deexcitation

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Abstract. Fragmentation of quasi-projectiles from the nuclear reaction $^{40}$Ca+$^{12}$C was used to produce excited states candidates to alpha-particle condensation. The methodology relies on high granularity $4\pi$ detection coupled to multi-particle correlations. Complete kinematic characterization reveals that $7.5\pm4.0\%$ of the Hoyle state particle decays correspond to direct decay into three equal-energy alpha-particles. This is the first direct evidence for alpha-particle condensation in nuclei.

1. Introduction

Bose-Einstein condensation is known to occur in weakly and strongly interacting systems such as dilute atomic gases and liquid $^4$He. Since more than ten years it was also theoretically shown that for symmetric nuclear matter, below a critical density, $\alpha$-particle condensation is favored [1]. It is expected to occur at densities smaller than a fifth of the nuclear saturation density. This new possible phase of nuclear matter may have its counterpart in low-density states of self conjugate lighter nuclei, in the same way as superfluid nuclei are the finite-size counterpart of superfluid nuclear and neutron matter. This means that under some circumstances, the alpha condensation, i.e. bosonic properties, might dominate over the nucleon properties even in finite nuclei. Thus, by showing that the Hoyle state (i.e. the first excited state $0^+$ at 7.654 MeV of $^{12}$C) and the sixth $0^+$ state at 15.097 MeV of $^{16}$O are described by $\alpha$-particle condensate type functions, [2, 3] advance the idea that these states are candidates to observe $\alpha$ condensation. A common feature of these states is their diluteness. For instance, calculations [2] and recent data analysis [4] show that the rms radius of the Hoyle state exceeds by 45% the radius of $^{12}$C in its ground-state. According to the present understanding of the Hoyle state: a gas-like structure of 3 $\alpha$-particles which occupy dominantly the lowest S orbit, to obtain a direct evidence of $\alpha$-particle condensation we must search for a simultaneous emission of 3 $\alpha$-particles with very low kinetic energy dispersion. As it is experimentally difficult to identify and measure $\alpha$-particles with low kinetic energy, probably the most appropriate strategy should involve high velocity reaction products in the laboratory (to take advantage of velocity boosts) detected by a high granularity-high solid angle particle array (to precisely reconstruct the directions of velocity vectors).

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2. Experimental selection of the Hoyle state

The data reported here have been obtained with the nuclear reaction $^{40}$Ca$^{+12}$C at 25 MeV per nucleon incident energy performed at INFN, Laboratori Nazionali del Sud in Catania, Italy. The beam impinging on a thin carbon target (320 $\mu$g/cm$^2$) was delivered by the Superconducting Cyclotron and the charged reaction products were detected by the CHIMERA 4$\pi$ multi-detector [5]. The beam intensity was kept around $10^7$ ions/s to avoid pile-up events. CHIMERA consists of 1192 silicon-CsI(Tl) telescopes mounted on 35 rings covering 94% of the solid angle, with very high detection granularity at forward angles. Details on A and Z identifications can be found in [5]. The energy resolution for alpha particles varies between 1.0 and 2.5%.

Invariant $v_{par} - v_{per}$ plots have shown the dominant binary character of the collisions with the formation of two emitting sources, a quasi-target (QT) and a quasi-projectile (QP). These latter may be easily separated according to the smaller or larger velocity of reaction products with respect to $v_{proj}/2$. After a first event filtering according to the total $\alpha$ multiplicity ($m_\alpha \geq 3$) and the total detected charge ($Z_{tot} \leq Z_P + Z_T = 26$), we have focused exclusively on QP decay products with $m_\alpha = 3$ to study in particular the Hoyle state deexcitation. Then, we have used multi-particle correlation functions (CF) [6, 7] to judge the quality of energy calibrations and select the Hoyle state. Multi-particle CF are defined as:

$$1 + R(E) = \frac{Y_{corr}(E)}{Y_{uncorr}(E)}.$$  (1)

The correlated yield $Y_{corr}$ corresponds to the physical spectrum, while the uncorrelated yield $Y_{uncorr}$ is built by mixing particles belonging to different physical events. The role of the generic variable $E$ is usually played by the total kinetic energy of the particles of interest in their center-of-mass frame $E_{tot}$ or by the excitation energy of their emitting source/state, $E_{ex} = E_{tot} - Q$.

The CF plotted in figure 1 corresponds to the whole lot of events with $m_\alpha = 3$. The distribution plotted with full symbols correspond to the case in which the uncorrelated spectrum was built by taking each particle from a different event (full event mixing). It shows two peaks centered at $E_{ex}=7.61$ MeV ($\Gamma=0.33$ MeV) and at $E_{ex}=9.62$ MeV ($\Gamma=1.14$ MeV). The first peak corresponds to the Hoyle state ($E_{exc}=7.654$ MeV, $\Gamma_{exc}=8.5$ eV), while the second one is due to the complex excited region characterized by the strong $E_{exc}=9.64$ MeV, $2^-\alpha$ state and by the broad $E_{exc}=10.3$ MeV, $0^+\alpha$ state submerging a possible $2^+\alpha$ state at 9.7 MeV [8, 9]. The broadening of correlation peaks is the genuine consequence of detector finite granularity and energy resolution. Numerical simulations indicate that the experimental distributions are compatible with an average energy resolution $R_E$ of 2%. The CF stability in the resonance regions was checked against the way in

![Figure 1. Correlation functions in excitation energy for 3-\alpha emission.](image)
which the background is built. The open symbol curve corresponds to the case in which partial event mixing (PEM) [10] is employed in order to mimic sequential decays proceeding via $^8$Be. As one may notice, neither the centroids of the two peaks nor their widths are sizably modified. The CF peak height dependence on the recipe according to which the background is built is a first qualitative indication of a decay mechanism competition for the Hoyle state.

### 3. Evidence for alpha-particle condensation

We demonstrated so far that the $^{40}$Ca+$^{12}$C nuclear reaction at 25 MeV/nucleon populates excited states of $^{12}$C nuclei which decay by 3-$\alpha$ emission. We have shown in [11] that the complex excited region around 9.6 MeV deexcites via $^8$Be. Let us focus on the Hoyle state. One has to identify the direct decays and estimate their branching ratio. This may be done by comparing the experimental distribution with numerical simulations filtered by the multidetector replica. We have considered $^{12}$C nuclei excited in the Hoyle state with the experimental velocity distribution and make them to decay by considering the following pure cases: direct alpha decay with equal energies (DDE), sequential decay proceeding via the g.s. of $^8$Be with isotropic emission out of $^8$Be (SD) and direct alpha decay from a linear chain (DDL) [12, 13]. In each situation and, for SD at each decay step, the available energy ($E_{ex}+Q$) is shared among the decay products such as to conserve the linear and angular momenta. Detection efficiencies are obtained and vary from 41 to 49% depending on the different decays. Analyses of filtered simulations show, as expected, very little sensitivity of $Y_{corr}(E_{ex})$ or, equivalently, $Y_{corr}(<E_\alpha>)$ on the decay mechanism even if the energy resolution is not perfect. Here $<E_\alpha>$ stands for the average alpha kinetic energy in the $^{12}$C center-of-mass. By contrast, the kinetic energy dispersion (RMS) in the emitter center-of-mass allows one to discriminate among the different decays. For the CHIMERA granularity and $R_E=2\%$, $Y_{corr}(\text{RMS})$ are peaked at 30, 70 and 90 keV for DDE, SD and, respectively, DDL. For this reason, we adopt the best agreement between experimental and simulated $Y_{corr}(<E_\alpha>,\text{RMS})$ as the criterion to quantify each decay channel. For a better

![Figure 2](image.png)

**Figure 2.** Three-$\alpha$ correlation function expressed as a function of average kinetic energy - RMS of $\alpha$ particles. The uncorrelated yield is built such as to allow for decay through $^8$Be.

![Figure 3](image.png)

**Figure 3.** Same as figure 2 for simulated three-$\alpha$ (with equal energies) correlation function.
reproduction of the experimental data we add to the pure simulated events the same proportion of background events that exists in the data. These are produced by PEM of experimental events. The comparison is restricted to the excitation energy domain, $7.40 \leq E_{\text{ex}} \leq 7.80$ MeV to reduce the importance of background events to 40%. Applying a $\chi^2$ minimization procedure and correcting for efficiencies, the following contributions are derived: DDE = $7.5\pm4.0\%$, DDL = $9.5\pm4.0\%$ and SD = $83.0\pm5.0\%$. Error bars are estimated by taking into account statistical, $\chi^2$ and background errors. Note that a limitation to DDE and SD as possible decays leads to a significant increase of the $\chi^2_{\text{min}}$ without changing the DDE percentage.

To better visualize the results, the CF expressed as function of $<E_\alpha>$ and RMS, for data, is plotted in figure 2. The relative separation in terms of RMS among DDE, SD and DDL allows one to identify, with the help of the simulation, the three competing mechanisms. The peak localized at very low RMS $\leq 25$ keV corresponds to an equal sharing of the available energy of the Hoyle state among the three $\alpha$ particles as demonstrated by the simulation (figure 3). The broad peak around $<E_\alpha> = 100$-$150$ keV and RMS $\approx 70$ keV corresponds to the sharing of the available energy between the two $\alpha$s of $^8$Be and the remaining $\alpha$. Finally the peak at $<E_\alpha> = 120$-$140$ keV and RMS = 90 keV corresponds to the direct decay of a linear chain with an $\alpha$ at rest and an equal sharing of the available energy of the Hoyle state between the two other $\alpha$ particles.

4. Conclusion
The Hoyle state is known to play a decisive role in stellar nucleosynthesis of $^{12}$C [14, 15, 16] with the assumption that the only contribution to the alpha-particle width comes from the $^8$Be$_{g.s.} + \alpha$ reaction. Up to now an upper limit of 4%, obtained from a low incident energy experiment, was proposed for the contribution from the direct $3\alpha$ channel to the alpha width [16]. Supposing that equal values of kinetic energy of the direct emitted $\alpha$-particles represent a sufficient criterion for deciding in favor of $\alpha$-particle condensation, we found that $7.5\pm4.0\%$ of events corresponding to the Hoyle state decay fulfil this criterion. To our knowledge, this is the first direct proof of $\alpha$-particle condensation in nuclei. This work also demonstrated the presence of direct emission from a linear $\alpha$-chain.

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