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Search for α-particle condensation in nuclei from the Hoyle state deexcitation

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Abstract. Heavy ion reactions induced by few tens MeV/nucleon beams constitute an ideal framework for producing and studying nuclear excited states close to the decay threshold. The fragmentation of quasi-projectiles from the nuclear reaction ^{40}Ca+^{12}C at 25 MeV/nucleon performed at LNS-Catania was employed in order to populate the Hoyle state of ^{12}C and investigate the theoretically predicted molecular structures. Complete kinematic characterization of individual decay events, made possible by the CHIMERA high-granularity 4π charged particle multi-detector, reveals that 7.5±4.0% of the particle decays of the Hoyle state correspond to direct decays in three equal-energy α-particles and thus fulfill the decay criteria of an α-particle condensate. Moreover, events with increased kinetic energy dispersion in the ^{12}C center of mass, which amount to 9.5±4.0%, point toward the occurrence of a second competing molecular configuration, a linear α-chain type. Both α-particle condensate and linear chain structures have been theoretically predicted but, to our knowledge, not experimentally confirmed so far.

1. Introduction

The idea that, under certain conditions, nuclei may be made out of clusters dates back from the beginning of nuclear physics when, analyzing one of the most basic observables - the binding energy per nucleon, it was realized that by far the most bound nuclei are those which have even and equal numbers of neutrons and protons. Later on, in the '60, it was realized that in order for a nucleus to develop a cluster structure, this has to be energetically possible. This occurs if the considered nucleus possesses an excited state in the vicinity of the cluster decay threshold. This condition is remarkably fulfilled up to large masses, as systematically depicted by the Ikeda diagrams.

Recent sophisticated molecular dynamics calculations confirm this scenario. For instance, according to the Fermionic Molecular Dynamics model, the ground-state of ^{12}C and the Hoyle state, that is the first excited 0^+ state of ^{12}C, correspond to a mixture of different cluster configurations where one may even identify a pre-formed ^{8}Be [1]. Moreover, cluster structures seem to be peculiar not only to Nα nuclei: neutron and proton-rich nuclei could show molecular-like structures, as well. Two examples in this sense are given by various excited states in ^{13}Be and ^{11}B that show advanced cluster configurations [2].

A conceptually more challenging scenario is the one which regards α-clusters as α-condensation states. Where could this come from? It is known that dilute nuclear matter is unstable with respect to cluster formation. Taken into account that ^{4}He is the most bound nucleus, one may expect αs to dominate in dilute symmetric matter. Theoretical works indicate that, indeed, symmetric dilute nuclear matter may be exclusively made out of αs or deuterons and that for densities lower than one fifth of the normal nuclear density quartetting dominates over pairing [3, 4, 5].

A rightful and not trivial question is to what extent this feature survives in nuclei. A promising signal in this sense was the excellent description of the Hoyle state in terms of condensate wave functions [6]. The result is impressive given that the shell model in both standard and no-core shell model failed to describe it. The localization of the Hoyle state at 378 keV above the α-decay threshold and its diluteness support the picture of a quasi-free gas. ^{12}C is not the only example in this sense, as condensate wave functions were proven able to describe also the sixth 0^+ state in ^{16}O [6, 7]. These pieces of information lead to the conjecture that α-condensate states might occur also in other light or medium mass self-conjugated 4N nuclei close to the α-decay threshold [8, 9].

From the experimentalist's perspective it is clear that *i)* in order to possibly detect slowly moving particles stemming from resonant states situated few hundreds keV above the decay threshold, one needs to have very low detection and identification thresholds and/or take advantage from the decaying source boost and *ii)* in order to kinematically characterize each decay event, very good geometric and energetic resolutions are required.

In this conference, we report on the recently obtained results corresponding to a quasi-projectile fragmentation experiment performed in 2003 at LNS-Catania (Italy) aiming to populate α-particle condensation candidate states in heavy ion collisions at intermediate energies. By similitude with atomic condensates, we expect a nuclear one to decay simultaneously into particles with nearly equal kinetic energy.

2. The experiment

The data we report on have been obtained in the nuclear reaction ^{40}Ca+^{12}C at 25 MeV/nucleon performed at LNS-Catania. The beam impinging on a thin carbon target (320 μg/cm^2) was delivered by the Superconducting Cyclotron and the charged reaction products were detected by the CHIMERA 4π multi-detector [10] which covers, with a granularity which depends on the azimuthal angle, 94% of the total solid angle. In order to avoid event pile-up, the beam intensity was limited to 10^7 ions/s. The mass and charge of the detected nuclei were determined by the energy-time of flight method (in case of light charged particles stopped in silicon detectors) and $E - \Delta E$ ($Z > 5$) and shape identification ($Z \leq 5$) techniques for charged products stopped in CsI(Tl). The energy of detected nuclei was measured by the Si detectors calibrated using proton, carbon and oxygen beams with energies between 10 and 100 MeV. In order to reach the best possible energy resolution, a dedicated calibration was realized for $Z = 2$ using the fast

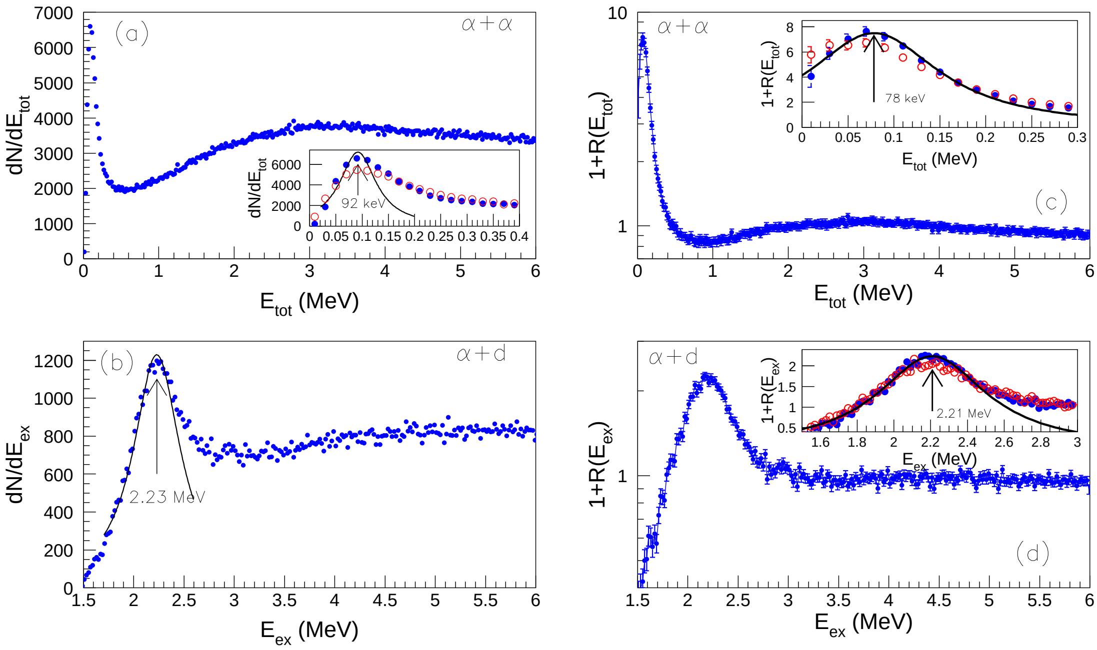

Figure 1. Yields of correlated $\alpha-\alpha$ (a) and α-d (b) emissions out of QP expressed as a function of total kinetic energy (a) or excitation energy (b) and corresponding correlation functions (c and d). The insets in (a) and (c) correspond to zooms on the ^{8}Be(g.s.) peak. The inset in (d) details the α-d correlation function in the domain of ^{6}Li(2.19 MeV). Peak fits using Breit-Wigner distributions are illustrated with solid lines, while centroids are pointed by arrows. Full and open symbols in the insets correspond to different ways of calculating the angle under which the detected particles were emitted (see Ref. [14] for details). Figure taken from Ref. [14].

component of CsI(Tl)-light. As such, the energy resolution for α-particles, which depends on the detection module, ranges between 1 and 2.5%.

The quality of the energy calibration for $Z = 1, 2$ has been additionally checked by comparing the location of the peaks in the two-particle correlation spectra and functions (CF) with the excitation energy values of the corresponding particle emitting states. As shown in Fig. 1, the α-α (top) and α-d (bottom) correlations allow to access, with an accuracy of less than 40-50 keV, the g.s. (Q =-92 keV, Γ =5.57 eV) and the first excited state (E_{ex} =3.03 MeV, Γ =1.5 MeV) of ^{8}Be and, respectively, the first excited state (E_{ex} =2.186 MeV, Γ =24 keV) of ^{6}Li. While, considering the complexity of the apparatus, such a precision may be considered satisfactory, some words of caution should be nevertheless said. First of all, it is worthwhile to notice that all considered two-particle correlated peaks are much wider than assumed by their finite life-time and that this widening monotonically increases with the excitation energy. Monte-Carlo simulations show that this is a genuine consequence of the non-ideal granularity and, to a smaller extent, finite energy resolution. Then, $dN/dE_{ex}(E_{ex})$ distributions (left panels) show that by increasing the excitation one not only looses the accuracy, but he also faces a more and more important background event contamination. This may be easily explained taking into account the exponential increase of decay channels opening. We remind that, being defined as the ratio between the correlated and uncorrelated spectra, CFs account for how much the correlation within the physical event differs from the underlying single-particle phase space and offer a practical recipe for highlighting true decays.

The complete kinematical characterization of the reaction products on an event-by-event

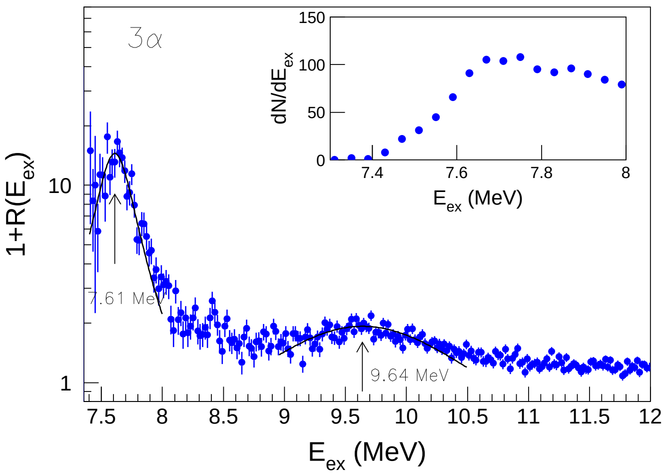

Figure 2. 3-α correlation function as a function of excitation energy. The arrows correspond to centroids of Breit-Wigner distributions (solid lines). Inset: zoom of the correlated distribution in the energy domain of the Hoyle state. Figure taken from Ref. [14].

basis allowed us to identify the particle emitting sources using invariant velocity plots in the $\gamma\beta_\perp$ vs. $1/2\log\left[(E+p_{\|})/(E-p_{\|})\right]$ plane and select the quasi-projectile decay events by asking the emitted particles to have a parallel velocity larger than one half of the projectile velocity. The data discussed hereafter exclusively refer to quasi-projectile decay events with α-multiplicity (m_α) strictly equal to 3.

3. 3-α correlations

The reasoning applied for two-particle correlations can be extended for multi-particle correlations. Thus, by doing 3-α correlation studies, one expects to reveal those excited states in ^{12}C that decay by 3-α emission. The confirmation is obtained in Fig. 2, where the peaks of the CF correspond to the Hoyle state (0_2^+, E_{ex}=7.654 MeV) and, respectively, the complex region of excitations characterized by the strong E_{ex}=9.64 MeV (Γ =34 keV) 3^- state and by the broad E_{ex} =10.3 MeV 0^+ state submerging a possible 2^+ state at 9.7 MeV. As before, the two peak widths are much larger than the natural ones and the background event contamination is important. In particular, in the Hoyle state region background events are as numerous as the true decay events, as one may infer out of the inset in Fig. 2.

The problem we face now is how to discriminate among the various theoretically possible decay mechanisms corresponding to a given excited state which, in our present case, is the Hoyle state. Let us first review some of the possible decay mechanisms. The certainly most important one is the sequential decay via the g.s. of ^{8}Be (SD) whose branching ratio amounts, according to Ref. [11], to at least 96%. Then, if we agree that a gas-like structure of three pre-formed α-particles may correspond to the dilute Hoyle state, we have to allow for a direct decay. How the available energy is shared among the emitted particles is again a matter of choice. In the most general case, the available energy may be randomly shared provided that the conservation laws are obeyed while, in the particular case of a condensate state, it is expected that the emitted particles equally share the energy (DDE). Then if we allow for more exotic chain-like configurations, other energy partitions could be allowed. For instance the direct decay of a linear chain (DDL), theoretically predicted by Uegaki et al. [12], would lead to one particle at rest in the center of mass of the emitter and the other two sharing the whole available energy.

It is clear from the above considerations that, in principle, each decay mechanism is characterized by a certain energy sharing and will produce, in the appropriate space of relative kinetic energies, specific patterns. The questions which arise now are whether the information survives the detection distortions and whether it may be highlighted out of the background contamination. To answer the first concern, we have performed Monte-Carlo numerical

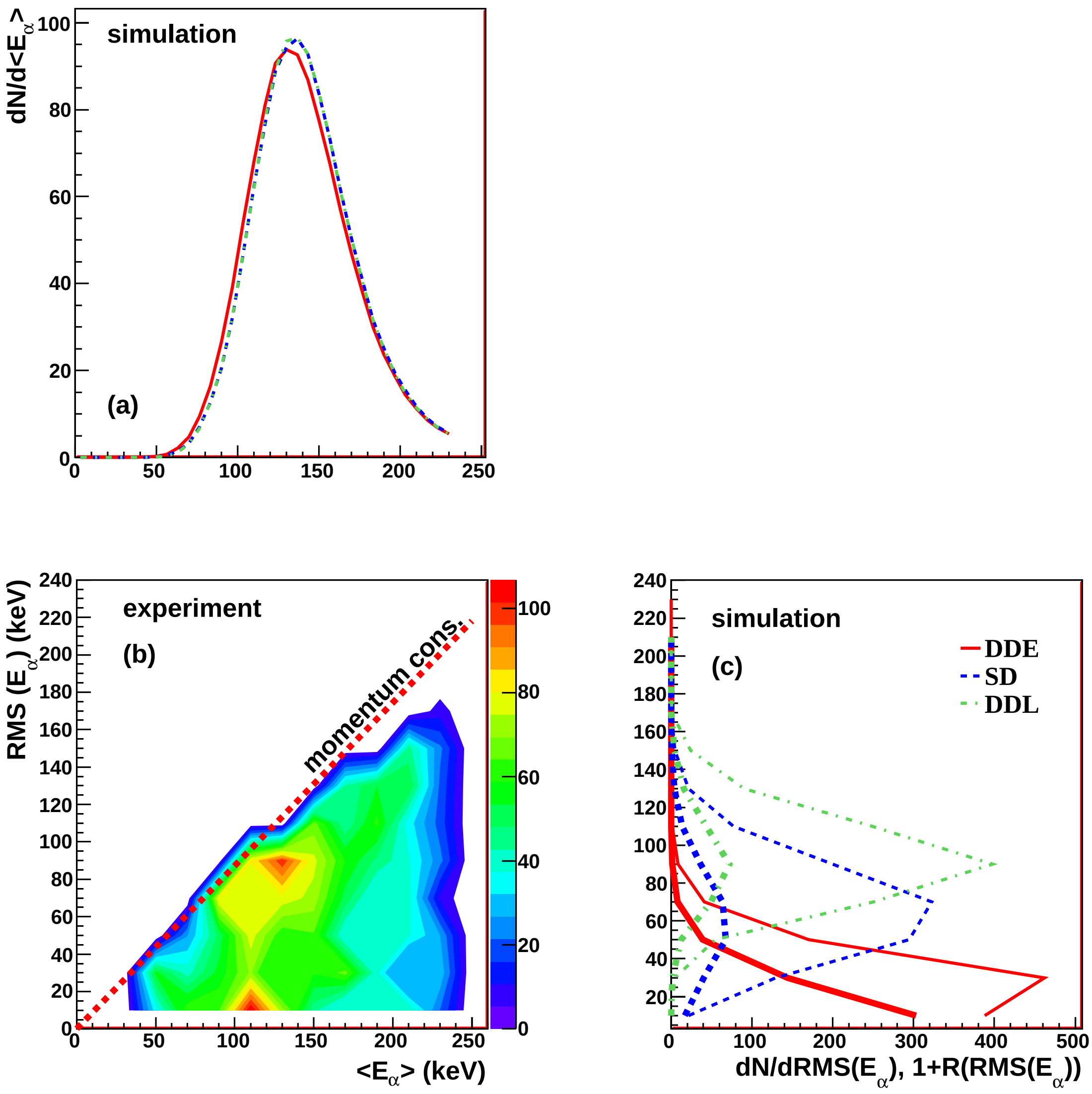

Figure 3. Three-α correlation function (b) expressed as a function of average kinetic energy - RMS of α particles corresponding to 1072 experimental events with $7.37 \leq E_{ex} \leq 7.97$ MeV. The uncorrelated yield is built such as to allow for decay through ^{8}Be. The dotted line marks the maximum RMS compatible with momentum conservation. $< E_\alpha >$ (a) and RMS (c) spectra (normalized to 1072 events) of simulated DDE (solid lines), SD (dashed lines) and DDL (dot-dashed lines) decays of the Hoyle state after filtering through the detector replica with R_E=2%. Panel (c) presents also the RMS projection of $Y_{corr}(< E_\alpha >, RMS)/Y_{uncorr}(< E_\alpha >, RMS)$ (thick lines). Figure taken from Ref. [14].

simulations that we subsequently filtered through the software replica of the CHIMERA multi-detector. A comparison of filtered and normalized DDE (full), SD (dashed) and DDL (dot-dashed) simulations is depicted with thin lines in Fig. 3 as a function of $< E_\alpha >$ (a) and RMS=$\sqrt{< E_\alpha^2 > - < E_\alpha >^2}$ (c); $< E_\alpha >$ is the average kinetic energy of α-particles in their CM reference frame. Very little sensitivity on the decay mechanism of $Y_{corr}(E_{ex})$ or, equivalently, $Y_{corr}(< E_\alpha >)$ is observed, which seems mostly related to angular resolution. By contrast, the kinetic energy dispersion (RMS) in the emitter CM manifests measurable sensitivity to the decay mechanism. For the CHIMERA granularity and a perfect energy resolution $Y_{corr}(RMS)$ are peaked at 10, 70 and 90 keV for DDE, SD and, respectively, DDL while for the average value R_E=2% the corresponding values are 30, 70 and 90 keV. This suggests that searching for the best agreement between experimental and simulated $Y_{corr}(< E_\alpha >, RMS)$ constitutes a pertinent procedure to quantify each decay channel.

The major remaining problem is the background contamination. Our attempt to overcome it consists in two steps. A first *qualitative* analysis aimed to identify more than one decay pattern in the $< E_\alpha > -RMS$ space based on the correlation function technique. This choice is clearly motivated by the CF ability of removing background effects. A second *quantitative* analysis aimed to estimate the branching ratio of each identified decay mechanism. Here we face the weakest point of our data: the important background contamination that we *arbitrarily mimic* by mixing experimental correlated events.

Fig. 3(b) illustrates the CF in $< E_\alpha > -RMS$ coordinates corresponding to experimental events with $m_\alpha = 3$ and $7.37 \leq E_{ex} \leq 7.97$ MeV. It manifests two narrow peaks located at ($< E_\alpha >= 110$ keV, $RMS = 10$ keV) and, respectively, ($< E_\alpha >= 120 - 140$ keV, $RMS = 90$ keV). The thick lines in Fig. 3(c) depicting $Y_{corr}(RMS)/Y_{uncorr}(RMS)$ as obtained out of simulated DDE, SD and DDL suggest that the low RMS-peak corresponds to DEE, the high RMS-peak corresponds to DDL while the broad region around $< E_\alpha >= 90 - 130$ keV and $RMS \approx 70$ keV originates from the predominant SD-decays.

To obtain the branching ratio we mix - in different proportions - simulated DDE, SD and DDL events with the same amount of background events that exists in the experimental data and search for the minimum χ^2. Background events are produced by partial event mixing [13] technique in order to take into account the supposedly abundant ^{8}Be decays. By restricting the comparison domain to $7.4 \leq E_{ex} \leq 7.8$ MeV, where the background contamination amounts to only 40%, we find that 7.5 ± 4.0 % of events correspond to DDE, 9.5±4.0 % to DDL and the remaining 83.0± 5.0 % to SD. Error bars are estimated by taking into account statistical, χ^2 and background errors.

We have performed the same analysis for the complex region centered at 9.64 MeV where the statistics is much higher. No indication was found in favor of a direct 3α decay with equal energies, in agreement with recent results of Ref. [15].

These data have been recently published in Ref. [14] and inspired two other groups to re-consider some older high-statistics low-background-contamination data produced in direct reactions in order to check our conclusions [15, 16]. In both cases direct decays out of the Hoyle state are found to amount to at most 0.45 and, respectively, 0.5 %. A new experiment is planned with the aim of more precisely studying both the Hoyle state and possible condensate structures in ^{16}O. To do this, different production mechanisms (inelastic scattering, direct break-up and fragmentation) will be used and the results compared. Moreover, in order to improve the angular resolution - which is of dramatic importance in spectroscopic studies as the desired ones -, we plan to couple CHIMERA with modules from the new FARCOS correlator array [17].

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