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Alpha-particle clustering in excited alpha-conjugate nuclei

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Abstract. The nuclear reaction ^{40}Ca+^{12}C at 25 MeV per nucleon incident energy was used to produce excited alpha-conjugate fragments from projectile fragmentation mechanism. From a careful selection provided by a complete detection and from comparisons with models of sequential and simultaneous decays, evidence in favor of α-particle clustering from excited light alpha-conjugate nuclei is reported.

1. Introduction

Clustering is a generic phenomenon which can appear in homogeneous matter when density decreases; the formation of galaxies as well as the disintegration of hot dilute heavy nuclei into lighter nuclei are extreme examples occurring in nature. As far as nuclear physics is concerned, the nucleus viewed as a collection of α-particles was very early discussed and in the last forty years both theoretical and experimental efforts were devoted to clustering phenomena in nuclei. Very recently the formation of α-particle clustering from excited expanding self-conjugate nuclei was revealed in two different constrained self consistent mean field calculations [1, 2]. The aim of the present work was to search for experimental evidence of α-particle clustering from very excited and consequently expanding alpha-conjugate nuclei. The chosen experimental strategy was to use the reaction ^{40}Ca+^{12}C at an incident energy (25 MeV per nucleon) high enough to possibly produce some hot expanding reaction products, associated with a high granularity, high solid angle particle array (to precisely reconstruct directions of velocity vectors). Then, by selecting the appropriate reaction mechanism and specific events the required information was inferred.

2. Experiment and event selection

The experiment was performed at INFN, Laboratori Nazionali del Sud in Catania, Italy. 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 [3]. The beam intensity was kept around 10^7 ions/s to avoid pile-up events and random coincidences, which is mandatory for high multiplicity studies. CHIMERA consists of 1192 telescopes (ΔE silicon detectors 200-300 μm thick and CsI(Tl) stopping detectors) mounted on 35 rings covering 94% of the solid angle, with very high granularity at forward angles. Details on A and Z identifications and on the quality of energy calibrations can be found in [3, 4, 5, 6]. Energy resolution was better than 1% for silicon detectors and varies between 1.0 and 2.5% for alpha particles stopped in CsI(Tl) crystals.

As a first step in our event selection procedure, we want to exclude poorly-measured events. Without making any hypothesis about the physics of the studied reaction one can measure the total detected charge Z_{tot} (neutrons are not measured). In relation with their cross-sections and with the geometrical efficiency of CHIMERA, the well detected reaction mechanisms correspond to projectile fragmentation (PF) [7, 9] with Z_{tot} = 19-20 (target reaction products not detected) and to incomplete/complete fusion with Z_{tot} = 21-26 [8]. At this stage we can have a first indication of the multiplicity of α-particles, M_α, emitted per event for well identified mechanisms ($Z_{tot} \geq 19$ - see figure 1). M_α extends up to thirteen, which means a deexcitation of the total system into α-particles. Moreover a reasonable number of events exhibit M_α values up to about 6-7.

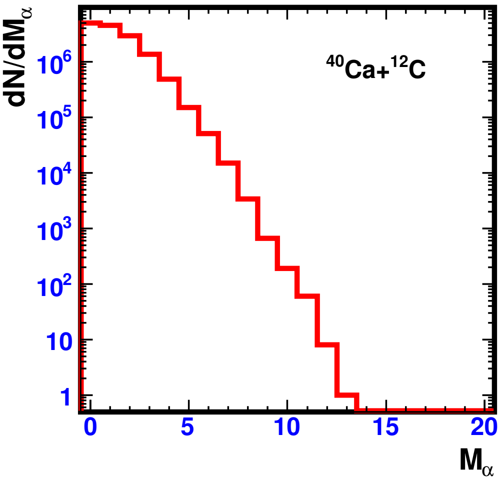

Figure 1. Distribution of α-particle multiplicity, M_α, for well detected events ($Z_{tot} \geq 19$).

The goal is now to tentatively isolate, in events, reaction products emitting α-particles only. References [10, 11] have shown that, at incident energies close to ours, ^{20}Ne or ^{32}S PF is dominated by alpha-conjugate reaction products. Based on this, and expecting the same for ^{40}Ca, we restrict our selection to completely detected PF events ($Z_{tot} = 20$) composed of one projectile fragment and α-particles. Charge conservation imposes $Z_{frag} = 20 - 2M_\alpha$. An example of the mass disribution of the single fragment can be seen in [6].

After this double selection, the question is: from which emission source are the α-particles emitted? Several possible candidates are present and further selections must be done before restricting our study to alpha-sources emitting exclusively the M_α observed (called $N\alpha$ sources in what follows). Possibilities that we must examine are the following:

I) considering the incident energy of the reaction and the forward focusing of reaction products, it is important to identify the possible presence of preequilibrium (PE) α-particles in our selected PF events. With the hypothesis that all the α-particles are emitted from their center-of-mass reference frame, we noted an energy distribution which resembles a thermal one with the presence of a high energy tail starting at 40 MeV, which signs PE emission. To prevent errors on alpha emitter properties, it is necessary to remove events in which such PE emission can be present; an upper energy limit of 40 MeV , found irrespective of M_α was imposed to the α-particle energy.

II) α-particles can be emitted from deexcitation of PF events via unbound states of ^{12}C, ^{16}O, ^{20}Ne and not directly from excited expanding $N\alpha$ sources. We want, for instance, to exclude from the selection an event composed of two fragments (^{24}Mg and ^{12}C*) and one α-particle finally producing one single fragment (^{24}Mg) and four α-particles. Multi-particle correlation functions [12, 5] were used to identify unbound states α-particle emitters and to suppress a small percentage of events (1.6-3.9%).

III) it must be verified that the fragments associated with M_α are not the evaporation residues of excited Ca projectiles having emitted sequentially α-particles only.

As far as the two first items are concerned the effect was to suppress from 8.5 to 12.8% of previously selected events; more details can be found in [6]. The last item will be discussed in the following section.

To conclude on this part, one can also indicate that if excited $N\alpha$ sources have been formed their excitation energy thresholds for total deexcitation into α-particles vary from 20 to 60 MeV when $N\alpha$ moves from 4 to 7. Their mean excitation energy per nucleon is rather constant around 3.3-3.5 MeV which indicates that average lowest densities around 0.7 the normal density may have been reached due to thermal pressure [13, 14]. This density value is a crude estimation.

3. Evidence for alpha-particle clustering

Before discussing different possible deexcitations involved for retained events, information on projectile fragmentation mechanism is needed. Global features of PF events are reproduced by a model of stochastic transfers [9]. Main characteristics for primary events with Z_{tot}=20 are the following: i) excitation energy extends up to about 200 MeV, which allows the large excitation energy domain (20-150 MeV) measured for $N\alpha$ sources when associated to a single fragment and ii) angular momenta extend up to 24 $\hbar$, which gives an upper spin limit for Ca projectiles or $N\alpha$ sources.

Are α-particles emitted sequentially or simultaneously? To answer the question α-energy spectra can be compared to simulations. For excited Ca projectiles and $N\alpha$ sources, experimental velocity and excitation energy distributions as well as distributions for spins are used as inputs. Results of simulations are then filtered by the multi-detector replica including all detection and identification details. Simulated spectra are normalized to the area of experimental spectra.

For sequential emission the GEMINI++ code [15] was used. Before discussing decays of $N\alpha$ sources, we must consider the possible evaporation from Ca projectiles as stated previously. Excitation energy for projectiles is deduced from E^{*}=$E^{*}(N\alpha)$+E_{rel}+Q. E_{rel} is the relative energy between the $N\alpha$ source and the associated fragment (evaporation residue). Comparisons of simulations with experimental energy spectra of α-particles are displayed in figures 2 and 6 of [16, 6] for $M\alpha$ from 4 to 6. They show a rather poor agreement indicating that such an hypothesis seems not correct. Note that no more ^{24}Mg, ^{20}Ne or ^{16}O evaporation residues associated to $M\alpha$ from 4 to 6 are produced in simulations for ^{40}Ca spin distributions centered

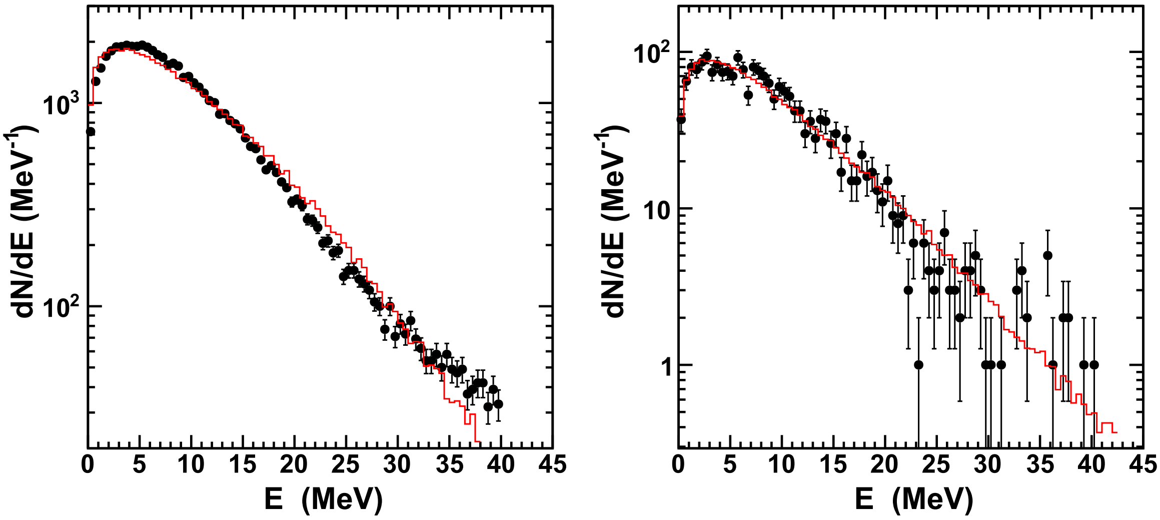

Figure 2. Particle spectra from N_α sources: ^{16}O* (left) and ^{28}Si* (right). Black dots with statistical error bars correspond to experimental data. Histograms superimposed on data correspond to filtered simulations of a simultaneous decay process (see text).

at values larger than $25\hbar$.

Considering now sequential deexcitation of $N\alpha$ sources it appears, as it is shown in figures 3 and 5 of [16, 6], that the agreement between data and simulations becomes poorer and poorer when $N\alpha$ value decreases. Moreover an important disagreement between data and simulations is observed for the percentages of $N\alpha$ sources which deexcite via ^8Be emission [6].

For simultaneous emission from $N\alpha$ sources, a dedicated simulation was done which mimics a situation in which α clusters are early formed when the $N\alpha$ source is expanding [1, 2] due to thermal pressure. By respecting the experimental excitation energy distributions of $N\alpha$ sources, a distribution of $N\alpha$ events is generated as starting point of the simulation. Event by event, the $N\alpha$ source is first split into α's. Then the remaining available energy $(E^* + Q)$ is directly randomly shared among the α-particles such as to conserve energy and linear momentum [17]. Histograms in figure 2 are the results of such a simulation for $N\alpha = 4$ (^{16}O*) and $N\alpha = 7$ (^{28}Si*), which show a good agreement with data even if for the observed ^{28}Si* statistics is low. Similar calculated energy spectra were also obtained with simulations containing an intermediate freeze-out volume stage where α-particles are formed and then propagation of particles in their mutual Coulomb field. In this case angular momentum distributions of $N\alpha$ sources at freeze-out can also be deduced: they exhibit a Maxwell-like shape extending up to $25\hbar$ for $N\alpha = 7$ while mean values vary from 6.7 to $10.4\hbar$ when $N\alpha$ moves from 4 to 7. Note that ^8Be emission is out of the scope of the present simulation.

From these comparisons with both sequential and simultaneous decay simulations it clearly appears that sequential emission is not able to reproduce experimental data whereas a remarkable agreement is obtained when an α-clustering scenario is assumed. Same conclusion is derived for $N\alpha$ equal 5 or 6 [16, 6]. However one cannot exclude that a small percentage of $N\alpha$ sources, those produced with lower excitation energies, sequentially deexcite.

4. Conclusion and perspectives

The reaction ^{40}Ca+^{12}C at 25 MeV per nucleon bombarding energy was used to produce and carefully select specific classes of projectile fragmentation events from which excited $N\alpha$ sources can be unambiguously identified. Their excitation energy distributions are derived with mean values around 3.4 MeV per nucleon and a crude estimation of their mean minimal densities, around 0.7 the normal density, can be deduced.

Their energetic emission properties were compared with two simulations, one involving sequential decays and a second for simultaneous decays. For excited expanding $N\alpha$ sources composed of 4, 5, 6 and 7 α-particles, evidence in favour of simultaneous emission (α-particle clustering) is reported. Those results support mean field calculations of [1, 2].

Work in progress shows that breakup/clustering temperature can be derived from the impressive agreement between α-particle energy spectra and fits with a volume Maxwellian distribution [18]. Finally one can also expect to derive information on the clustering density from the yield of ^{8}Be measured. Indeed within an α-particle clustering picture the production of ^{8}Be can be strongly related to α-α interaction in the freeze-out volume.

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