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Pre-equilibrium emission to study clustering in nuclei

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Abstract. Clustering structural properties in medium-mass systems have been investigated studying the competition between the evaporation and pre-equilibrium particle emission in central collisions. At variance with light nuclei, in the case of heavier nuclei there are no experimental evidences of such structure effects, since the determination of pre-formed clusters within nuclear matter is less obvious.
The two systems ^{16}O + ^{65}Cu and ^{19}F + ^{62}Ni , leading to the same compound system ^{81}Rb*, have been studied at the same beam velocity (16 AMeV). The experiments have been performed using the GARFIELD + RCo multi-detection system at the Legnaro National Laboratories.
Recent results of the data analysis and of the comparison of the experimental data with different statistical and dynamical model calculations are reported in this contribution.

1 Introduction

The concept that cluster of nucleons might be pre-formed prior to emission from nuclei has a history of more than 50 years and, actually, the α-cluster model is one of the oldest models which was used to describe the nucleus. The original idea was introduced by Hafstad and Teller in 1938 [1]. Examining the binding energy per nucleon of light nuclei as a function of the mass number, they hypothesized that nuclei, with even and equal number of protons and neutrons, are particularly stable and their ground state could be described in terms of geometric arrangments of α-particles [2]. These so called α-conjugate nuclei are typically observed as excited states close to the decay threshold into clusters. This has been summarized, in the late sixties, in the Ikeda diagram [3] which links the energy required to liberate the cluster constituents to the excitation energy at which the cluster structure prevail in the host nucleus. Moreover, in neutron-rich nuclei there is the possibility that additional neutrons may act as valence particles and can be exchanged between the α-particle cores. These covalent neutrons stabilize the unstable multi-cluster states, giving rise to nuclear structure which can be described by molecular concepts. The extended Ikeda diagram is a new threshold diagram which describes the structure of these non-alpha conjugate nuclei [4].

Clustering effects can show up in several ways along the nuclear chart, from the stability to the drip-lines. While for light nuclei several links between cluster emission and its connection with nuclear structure and dynamics have been pointed out [4] [5], this is less obvious moving towards heavier systems. In fact, in reactions involving mediun-mass nuclei the determination of pre-formed clusters in nuclear matter is more complicated. These pre-formed clusters have been observed especially close to the nuclear surface, making strong the link between pre-equilibrium emission and cluster structure.

An interesting way to investigate the structural properties of medium-mass systems is to study the competition between evaporation and pre-equilibrium particles emis-

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sion in central collision, as a function of different entrance channel parameters. Pre-equilibrium light charged particles and/or neutrons are fast, forward focused particles emitted during the very early stages of the collision before the attainment of full statistical equilibrium of the compoud system. Comparing such particles with those emitted after thermal equilibration it is possible to derive information on the interplay between equilibrium and non equilibrium processes. Moreover, structural properties, like cluster pre-formation probabilities, may be evidenced both from the experimental comparison between different entrance channel leading to the same compound system and from the comparison of experimental data with model predictions. Two opposite mechanisms have been suggested for cluster emission in pre-equilibrium reactions: on one side, the α-particle is assumed to be pre-formed inside the nucleus and it can be treated as a single strongly coupled object. On the other side, the coalesence models assume that clusters (not only α-particle) are formed, in a dynamical way, during the course of the reaction [5].

Many attempts have been done to shed light on these structures, but there is still a lack of experimental data capable to give a direct feedback to the theoretical predictions.

2 Previous studies

In the past, the system ^{16}O + ^{116}Sn has been investigated with the aim of identifying the amount of pre-equilibrium emission in asymmetric entrance channel reactions, in an energy range (E/A = 8÷16 AMeV) where pre-equilibrium emission is expected. Experimental spectra of protons and α-particles have been compared with the predictions of Moscow Pre-equilibrium Model (MPM) [6]. This model is a modified version of the statistical code PACE2 where a non-equilibrium stage before the complete thermalization of the compoud nucleus has been inserted. The relaxation processes occurring during the fusion reaction is accounted for by the exciton model, based on the Griffin model [7], in which the description of the angular distribution of the fast emitted particles is still an intricate question [8]. The main parameter to be set is the initial number of excitons (n_o=$n_{particles}$+n_{holes}) in the projectile, which can be estimated from the empirical trend obtained in the work of N. Cindro et al. [9]. In the present case of ^{16}O this number is n_o= 17 (16p + 1h).

The proton spectra have been quite well reproduced by the model at all the incident energies considered over the measured angular range. On the contrary, an enhanced fast α-particles production was observed, especially at the most forward measured angles, indicating that pre-equilibrium emission contribution is not sufficient to explain the increased prodution of α-particles. A possible esplanation might be related to the α-cluster structure of the ^{16}O projectile.

The effect of the projectile clustering structure has been taken into account introducing in the model a preformation cluster probability. A second starting configuration has been considered in which the ^{16}O projectile is supposed to be divided into ^{12}C plus an α-particle. The probability of occurence of this configuration with respect to the original one (i.e. ^{16}O projectile as a whole) is a free parameter to be determined from the comparison with the experiment. The comparison of the data with the model predictions with different percentages of α-clustering probability has shown that the proton distributions seem to be described with no-clustering in the projectile nucleus. For alpha-particles, on the contrary, a quite large clustering probability has to be considered to try to describe the spectral shape of the energy distribution at forward angles.

3 The experiment

To further investigate, in a model independent way, the possible effects of the α-cluster structure of the projectile, two different entrance channel reactions have been studied in an energy range where fast particle emission was predicted. The decay of ^{81}Rb* compund nucleus populated by the two fusion reactions ^{16}O + ^{65}Cu and ^{19}F + ^{62}Ni have been studied at 16 AMeV incident energy. The same projectile velocity has been chosen since the pre-equilibrium emission is expected to mostly depend on this parameter [10] As a consequence, the non-equilibrium processes are predicted to be almost the same for the two systems, while some little differences may appear in the evaporative part of the emitted particle spectra due to the slightly different initial excitation energies of the compound nucleus (E*=209 MeV and E*=240 MeV respectively for ^{16}O and ^{19}F induced reactions). The observation of any difference of fast α-particles in the experimental spectra between the two reactions could be interpreted, in a model independent way, as possible influence of the projectile α-structure effect.

The ^{16}O and ^{19}F beams have been provided by the ALPI-TANDEM XTU accelerator complex at the Laboratori Nazionali di Legnaro (Italy). The experimental set-up used is the GARFIELD detection array implemented with the Ring Counter (RCo), at the most forward angles, fully equipped with digital electronics [11].

The GARFIELD apparatus consists of two large volume cylindrical drift chambers, each equipped with Micro-Strip Gas Chambers (MSGC) as amplified ΔE stage followed by CsI(Tl) scintillators residual energy detectors. Intermediate mass fragments and light charged particles are detected in an angular range from $\theta = 29^o$ to 151^o. The Ring Counter is a three stage annular detector, covering the $\theta = 5^o$- 17^o angular range, with an Ionization Chamber (IC) as first stage, followed by reverse mounted nTD Silicon Strip detectors (Si) and CsI(Tl) scintillators.

The GARFIELD plus RCo apparatus can perform complete high quality charged particle identification (both Z and A) and energy determination in a nearly 4π coverage ($\theta = 5^o$- 151^o) for light charged particles and, in the most forward direction ($\theta = 5^o$- 17^o), also for fragments with charge up to Z=14.

Light charged particles, detected in GARFIELD and RCo, have been measured in coincidence with Evaporation Residues (ER) collected in the first two stages (IC-Si) of the RCo within the angulare range $\theta = 8.6^o$- 17^o, just beyond the grazing angle. The ERs have been selected

setting proper gates in the reconstructed Z versus Energy distributions.

4 Experimental results and preliminary analysis

The double differential proton and alpha energy spectra, in coincidence with ERs, have been sorted out and the spectra obtained from the two systems have been compared. An example is shown in Fig 1, where the comparison between proton and α-particles spectra, normalized to the maximum, at the most backward and forward angle of the GARFIELD angular range are reported. The two reactions show very similar proton spectra except for a small difference at the most forward angles. Effect that can be ascribed to the slightly larger excitation energy in the ^{19}F induced reaction. A much larger difference is, on the contrary, observed in the α-particles spectra. The predicted emission spectra performed with an evaporative code like PACE2 (or PACE4), which takes into account the difference in the compound nucleus excitation energies, confirm that the purely statistical emission spectra should be very similar for the two systems, supporting the idea that a second fast emission source for both systems is needed when comparing with experimental data.

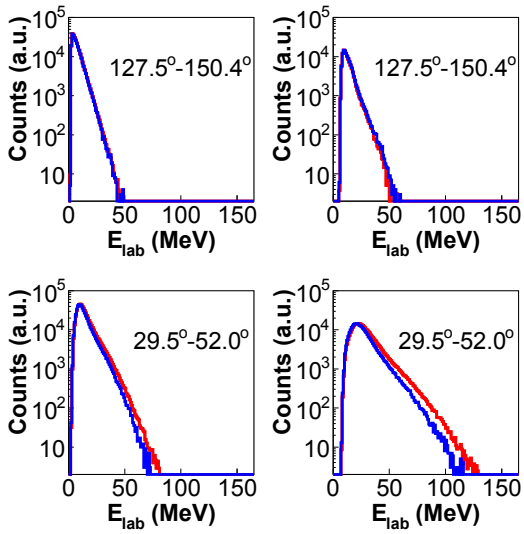

Figure 1. Double differential energy spectra in the laboratory frame (normalized to the maximum) for protons (left panels) and α-particles (right panels) for the two reactions 256 MeV ^{16}O + ^{65}Cu (blue line) and 304 MeV ^{19}F + ^{62}Ni (red line) at different detected angles (θ = 139^o- 151^o, θ = 29^o- 41^o).

In the preliminary analysis, a first estimate of the expected amount of fast emission in the two cases has been performed comparing the data with the predictions of the Moscow Pre-equilibrium Model (MPM). The calculations, done with an initial exciton number of n_o= 17 (16p + 1h) for the ^{16}O + ^{65}Cu case, reasonably describe the shape of the α-particles spectra, except for an understimation at the forward angles in GARFIELD, but, with the same initial n_o, the model strongly overstimates the pre-equilibrium protons emission. Performing the same comparison in the case of ^{19}F + ^{62}Ni reaction, with an initial n_o= 20 (19p + 1h), a quite similar results have been obtained, with an overproduction of fast α-particles even larger than in the ^{16}O case, while the fast protons are largely overstimated. A possible explanation for the extra yield of fast α-particles in both systems, may be due to the fact that even the ^{19}F can have an alpha structure and, in particular, that its α+^{15}N state is characterized by an energy (4.01 MeV) even smaller than the α+^{12}C (7.2 MeV) of the ^{16}O. An example of these comparisons, at the most forward angles in GARFIELD θ = 29^o- 41^o, for both systems are shown in Fig.2.

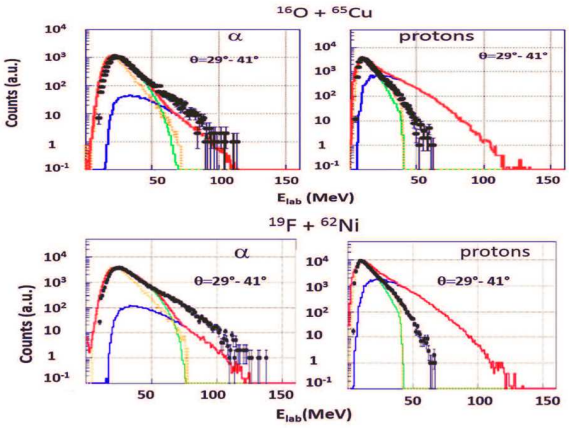

Figure 2. Comparison of laboratory energy spectra (normalized to the area) (black dots) for α-particles and protons for the two reactions ^{16}O + ^{65}Cu (upper panels) and ^{19}F + ^{62}Ni (lower panels) at θ = 29^o- 41^o with preliminary calculations from MPM (red line). The model evaporative PACE2 (green line) and pre-equilibrium (blue line) are shown. Evaporative PACE4 calculations (orange dots) are also reported.

By changing the initial configuration parameters (i.e. diminishing the exciton number) the description of the α-particles sligtly improves, but, on the contrary, the proton spectra description becomes worse. A unique set of initial parameters of the MPM model seems not to be able to describe both protons and α-particles decay channels (like in the ^{16}O + ^{116}Sn case) indicating that some implementations to the model has to be introduced. For example in the used calculation no light charged particle isotopes are considered and this may strongly influence the relative proton and alpha decay probability [12] [13].

For a further analysis other theoretical approaches have been considered in order to follow the evolution of the reaction in an event-by-event base. Only in this way it is possible, then, to filtrate the model prediction through a software replica of the experimental set-up, taking into account the geometry of the apparatus, the energy threshols, the energy resolutions and the solid angle of each detector, for a realistic comparison with the experimental data.

First, simulations have been performed with the statisical-model code GEMINI++ [14], which describes the decay of hot nuclei formed in fusion reactions, using

a Monte Carlo code, and generates light charged particles distribution emitted after the thermal equilibrium is reached.

Moreover, to take into account the dynamical part of the reaction, two models have been considered: the first one is the Stochastic Mean Field (SMF) [15], implemented in the TWINGO code [16], which simulates the time evolution of the nuclear matter through transport equations of one-body distribution function. In this model each nucleon is considered to be composed of many test particles which are subject to a mean field. The second model is the Antisymmetrized Molecular Dynamics (AMD) [17] in which the dynamics of the reaction is treated through the equation of motion of single nucleons, considered as gaussian wave packet, and the clustering effects of the colliding partners can be taken into account through the nucleon-nucleon correlations term.

Dynamical models generate primary excited fragments distributions, which then undergo to a statistical de-excitation. To predict the secondary fragments distributions the statistical code GEMINI++ has been applied, as afterburner, to the results of TWINGO and AMD, and the final results have been directly compared to the experimental data.

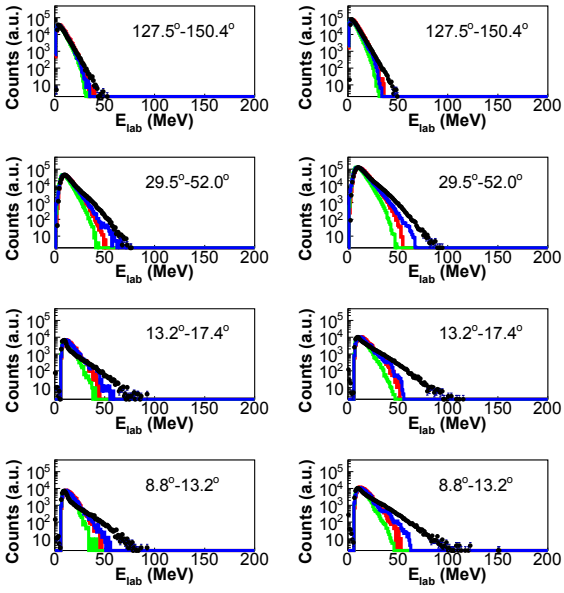

Figure 3. Comparison of protons laboratory energy spectra (normalized to the maximum) (black dots) for the two reactions ^{16}O + ^{65}Cu (left panels) and ^{19}F + ^{62}Ni (right panels) with GEMINI++ (red line), TWINGO coupled GEMINI++ (green line) and AMD coupled GEMINI++ (blue line), at different angular range in GARFIELD and RCo.

The experimental energy spectra of protons and α-particles, in coincidence of Evaporation Residues, have been first compared with the predictions of GEMINI++ alone and then with TWINGO and AMD coupled with GEMINI++ for both systems. GEMINI++ and TWINGO give similar information, apart from the temperature of the emitting thermalized source. In fact, the SMF approach does not reconstruct properly the nucleons (due to the test particle method) and in particular the clusters (due to the mean field approach) but it only defines the fragment size, number and excitation at a certain collision time. Therefore, only those particles emitted from the produced excited fragments, the decay of which is established by the after-burner, are finally implemented in the spectra. No pre-equilibrium spectra can therefore be provided. On the contrary, AMD is able to reconstruct fast nucleons and clusters, like it can be observed in Fig. 3 for the proton spectra. In this case also the most forward spectra from the Ring Counter have been sorted out.

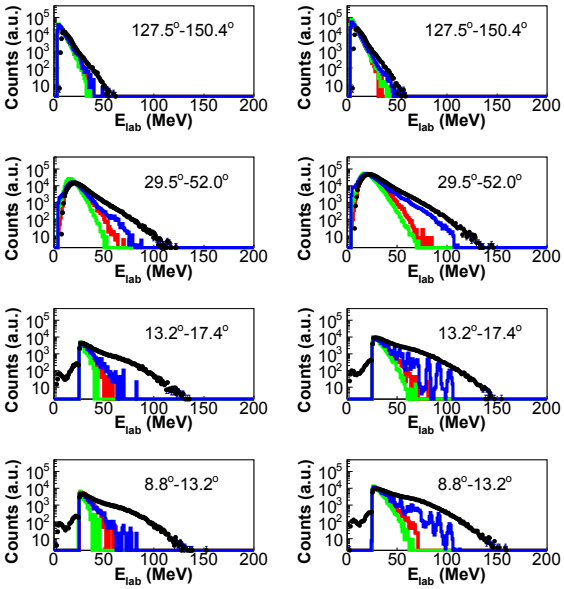

Figure 4. Comparison of α-particles laboratory energy spectra (normalized to the maximum) (black dots) for the two reactions ^{16}O + ^{65}Cu (left panels) and ^{19}F + ^{62}Ni (right panels) with GEMINI++ (red line), TWINGO coupled GEMINI++ (green line) and AMD coupled GEMINI++ (blue line), at different angular range in GARFIELD and RCo.

In the case of α-particles, at forward angles, the component of fast emission is more evident in the experimental spectra. This effect is partially described by the predictions from the AMD+GEMINI code, which include a possible influence of alpha clustering structure in the projectile, as shown in Fig. 4. However, the statistics of simulated events with AMD has still to be incremented to better describe the experimental spectra, avoiding unphysical statistical fluctuations. Moreover, further calculations can be provided, varying the input parameters in the code related to the clusterization effects to look for an optimization in the description of the data.

As a further step, the total multiplicity distributions of light charged particles, in coincidence of Evaporation Residues, have been obtained. The comparison between the two systems has evidenced that the ^{19}F induced reaction emits, in general, more protons and α-particles than the ^{16}O induced one, this can be understood because of the slightly higher excitation energy of the ^{19}F + ^{62}Ni system. Moreover, in Fig. 5 are shown the comparison between the experimental proton and α-particle multeplicity distri-

butions with the different models predictions for the two systems, normalized to the number of ER. From these first results, one can notice that the AMD predictions overstimate, in general, the experimental protons and α's multiplicities, while TWINGO calculations predict always less particles emission. Moreover, the measured proton multeplicities are always lower then the predictions of GEMINI++. This observation is also true for the α-particles emitted in the ^{16}O + ^{65}Cu reaction, while in the ^{19}F induced reaction the α's are correctly reproduced by GEMINI++ calculations. The difference between the two systems is very interesting and further analysis is ongoing, looking to specific decay channels.

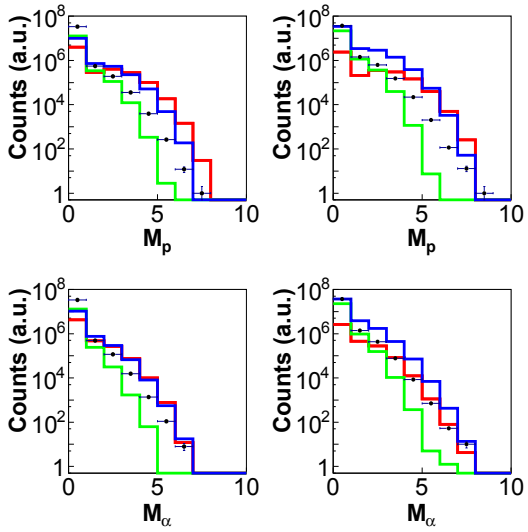

Figure 5. Protons (upper panels) and α-particles (lower panels) multeplicitiy distributions, in coincidence with ER, (black dots) for the two reactions in comparison with GEMINI++ (red line), TWINGO coupled GEMINI++ (green line) and AMD coupled GEMINI++ (blue line).

5 Conclusions

Secondary particle emission from ^{16}O + ^{65}Cu and ^{19}F + ^{62}Ni reactions at the same beam velocity 16 AMeV have been investigated to probe possible α-clustering effects in medium-mass systems. From the first comparison between the two systems a difference in the fast α-decay channel has been evidenced, which can be related to the difference in the projectile structure. The comparison of proton and α-particle energy spectra, in coincidence with evaporation residues, with the predictions of Moscow Pre-equilibrium Model, which takes into account both the pre-equilibrium and evaporation emission, shows that the model, with a unique set of initial parameters, is not able to describe protons and α-particles at the same time. The model has to be upgraded paying more attention to the clustering structure effects, introducing a correct filter in the Evaporation Residues distribution and including all possible decay channels.

Preliminary results show that experimental spectra cannot be described by both GEMINI++ and TWINGO predictions: the first simulation only considers complete fusion processes, while the second one, even if it is considers the dynamics of the reaction, is not able to reconstruct properly the fast emitted nucleons and clusters. The AMD model, which includes cluster structure effects in the projectile, in turns, seems to be more in agreement with the experimental data with respect to SMF model, giving a better description of the fast α-particles production. However, the AMD input parameters need to be further adjusted to have a more complete description of the data.

The data analysis is still undergoing to study more exclusive observables, like for example particle-particle correlations in events with multiplicities of light charged particles greater than two, and to compare them to different model simulations.

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