Possible effects of clustering structure in the competition between fast emission processes and compound nucleus decay

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Abstract

The attention to nuclear clustering has been renewed due to the study of weakly bound nuclei at the drip lines. In particular, clustering structural properties in medium-mass systems have been studied by looking at the competition between the evaporation and pre-equilibrium particle emission in central collisions. Although for light nuclei at an excitation energy close to the particle separation value there are experimental evidence of such structure effects, this is still not the case for heavier systems since the determination of pre-formed clusters within nuclear matter is less obvious.

Two systems, leading to the same ^{81}Rb* compound nucleus, have been studied at the same beam velocity 16 AMeV: ^{16}O + ^{65}Cu and ^{19}F + ^{62}Ni. The experiment has been performed using the GARFIELD + RCo detection system installed at the Legnaro National Laboratories. Light charged particles energy distributions and multiplicities have been compared with different statistical and dynamical model calculations. 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. Recent data analysis results and comparisons with model calculations are presented in this contribution.

Key words: *cluster model; nuclear decay; cluster emission model; equilibrium; comparative evaluations; Legnaro National Laboratory*

Posibles efectos de estructura de agrupamiento en la competencia entre los procesos de emisión rápida y desintegración del núcleo compuesto

Resumen

La atención a la agrupación nuclear se ha renovado debido al estudio de núcleos débilmente unidos en las líneas de goteo. En particular, se han estudiado las propiedades estructurales del agrupamiento en sistemas de masa media al observar la competencia entre la evaporación y la emisión de partículas de preequilibrio en colisiones centrales. Aunque para núcleos ligeros a una energía de excitación cercana al valor de separación de la partícula hay evidencia experimental de tales efectos de estructura, este no es el caso para sistemas más pesados ya que la determinación de agrupamientos preformados dentro de la materia nuclear es menos obvia.

Se han estudiado dos sistemas, que conducen al mismo núcleo compuesto ^{81}Rb *, a la misma velocidad de haz 16 AMeV: ^{16}O + ^{65}Cu y ^{19}F + ^{62}Ni. El experimento se ha realizado utilizando el sistema de detección GARFIELD + RCo instalado en los Laboratorios Nacionales Legnaro. Las distribuciones de energía y las multiplicidades de partículas de carga ligera se han comparado con diferentes cálculos de modelos estadísticos y dinámicos. Desde la primera comparación entre los dos sistemas, se ha evidenciado una diferencia en el canal de desintegración α rápida, que se puede relacionar con la diferencia en la estructura del proyectil. En esta contribución se presentan los resultados del análisis de datos recientes y las comparaciones con los cálculos del modelo.

Palabras clave: *modelo de haz; desintegración nuclear; modelo emisión de núcleos agrupados; equilibrio; evaluaciones comparativas; Laboratorio Nacional Legnaro*

Introduction

One of the oldest model used to describe the nucleus is the α-cluster model based on the concept that clusters of nucleons might be pre-formed prior to emission from nuclei [1]. Examining the binding energies per nucleon of light nuclei in their ground state, as a function of the mass number, a systematic trend has been observed for α-conjugate nuclei (even and equal number of protons and neutrons)well described by the liquid drop model as due to a shell structure effect [2]. A nucleus is a finite quantum many-body system consisting of protons and neutrons interacting via nuclear forces. Its ground state has shell structure, in which nucleons move almost independently in a mean field. On the other hand, because of nuclear attraction, spatial correlations between nucleons can be rather strong giving rise to cluster structures in which nucleons are confined, mainly at the surface of the nucleus. Due to their strong binding energy, the α– particle is the most probable cluster subsystem in nuclei and it isthe main ingredient in the concept proposed by Ikeda in his diagram [3], where highly clustered states are predicted at excitation energies around the energy threshold for the decomposition into specific cluster channels. Moreover, in neutron-rich nuclei there is the possibility that additional neutrons may act as valence particles which can be exchanged between the α particles 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 needed to describe the structure of these non-alpha conjugate nuclei. Recently, nuclear clustering has gained large interest due to the study of weakly bound nuclei at the drip lines, where clustering might be the preferred structural mode, especially in the case of light nuclei [1].

Many nuclear reactions involve the emission or capture of clusters of nucleons and these cluster reactions are particularly interesting to investigate the interplay between nuclear structure and reaction dynamics. In fact, such clusters can participate in nuclear reactions and this enables their properties to be studied.

The coexistence of cluster and mean-field aspects points out several phenomena in nuclear many-body systems as a function of excitation energy and isospin degree of freedom and many exotic and new features of clustering have been discovered [4].

While for light nuclei several links between cluster emission and its connection with nuclear structure and dynamics have been pointed out [1] [5], this is less obvious moving towards heavier systems. In fact, in reactions involving medium-mass nuclei the determination of pre-formed clusters in nuclear matter is more complicated.

An interesting way to investigate the structural properties of medium-mass systems is to study the competition between evaporation and pre-equilibrium particle emission in central collisions, as a function of different entrance channel parameters. In fact, the pre-formed clusters have been observed especially close to the nuclear surface, making strong the link between pre-equilibrium emission and cluster structure.

Pre-equilibrium light charged particles and/or neutrons are fast and forward focused particles emitted during the very early stages of the collision, before the formation of thermally equilibrated compound system. 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 coalescence models assume that clusters (not only α–particles) are formed, in a dynamical way, during the course of the reaction [5].

Comparing pre-equilibrium particles with those emitted after thermal equilibration is possible to derive information on the interplay between equilibrium and non-equilibrium processes. In particular, information on structural properties, like cluster pre-formation probabilities, may be derived from the experimental comparison between different entrance channels leading to the same compound system and comparing the experimental data with model predictions.

Materials and methods

To investigate 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 two fusion reactions $^{16}O + ^{65}Cu$ and $^{19}F + ^{62}Ni$, leading to the same $^{81}Rb^*$ compound nucleus and with different N/Z projectile structure, 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 [6]. 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 andE*=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 reaction scouldbein terpreted,in a model independent way, as possible influence of the projectile α–structure effect.

The experiment has been performed at the Legnaro National Laboratories in Legnaro (Italy). The beams have been provided by the ALPI-TANDEM XTU accelerator complex and 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 [7].

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 $\theta = 29^o$ to151^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 angular 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.

Results

The selection of central events have been performed asking for the detection of the ER in the forward direction (i.e. in the RCo) in coincidence with one or more light charged particles in the all remain apparatus.The ER, characterized by a velocity close to the center of mass velocity of the reaction, have been selected looking at the correlation between the detected charge and the energy distribution in the laboratory frame.

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 forward angle range of GARFIELD are reported. The two reactions show very similar proton spectra on the angular range measured, except for a small difference at the most forward angles (upper panels). This effect can be ascribed to the slightly larger excitation energy in the ^{19}F induced reaction. On the contrary, a much larger difference is observed in the α–particles spectra. The predicted emission spectra performed with the statistical model code GEMINI++ [8] (bottom panels), which describes only statistical emission from complete fusion reactions and 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.

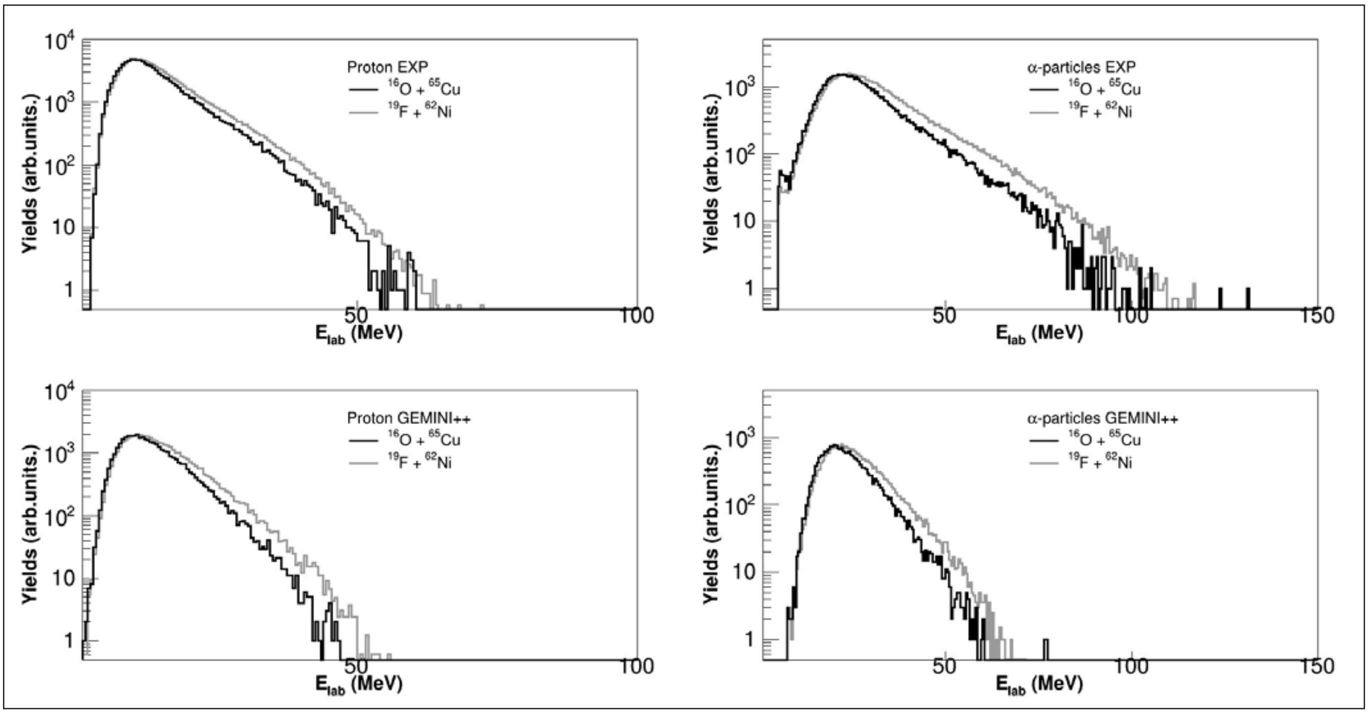

Figure 1. Double differential energy spectra in the laboratory frame (normalized othe maximum) for protons (left panels) and a-particles (right panels) for the two reactions 256 MeV ^{16}O + ^{65}Cu (black line) and 304 MeV ^{19}F + ^{62}Ni (grey line) at $\theta = 29^o$- 41^o detected angles. Experimental data (upper panels) GEMINI++ predictions (bottom panels).

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) [9], which 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 [10], in which the description of the angular distribution of thefast emitted particles is stillan intricate question [11]. 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. [12]. The calculations done for the ^{16}O + ^{65}Cu case (with an initial excit on number of n_o= 17 (16p + 1h)) and for the ^{19}F + ^{62}Ni reaction (with n_o= 20 (19p + 1h)) show quite similar results: the shape of the α-particles spectra are reasonably described in the case of ^{16}O + ^{65}Cu, while in the ^{19}F induced reaction an overproduction of fast α-particles is evident. In both cases the proton spectra are largely overstimated. A possible explanation for the extrayieldoffast 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) evens mallerthan the α+^{12}C (7.2MeV) of the ^{16}O. A unique set of initial parameters of the MPM model seems not to be able to describe both proton sand α-particles decay channel sindicating that some implementations to themodel has to be introduced [13].

As next step of the analysis, different theoretical approaches have been considered in order to follow the evolution of the reaction on an event-by-event basis.

First, the energy distributions of the light charged particles, in coincidence with evaporation residues, have been compared with simulations performed with the statistical model code GEMINI++ [8], which describes the decay of hot nuclei formed in fusion reactions, usinga Monte Carlo code, and generates light charged particles distribution emitted after the thermal equilibrium is reached. The Monte Carlo code generates an event file,which can be filtered through a software replica of the experimental set-up taking into account the geometry of the apparatus (energy thresholds, energy resolutions, detectors solid angles) for a realistic comparison with the experimental data.

Then, to take into account the dynamical part of the reaction, two models have been considered: the first is the Antisymmetrized Molecular Dynamics (AMD) [14] in which the dynamics is considered by the equation of motion of Gaussian wave packets representing the colliding nucleons. The clustering e□ects of the colliding partners can be taken into account through the nucleon-nucleon correlations term. The second model is the Stochastic Mean Field (SMF) [15], implemented in the TWINGO code [16], which considers each nucleon as composed of many test particlessubjected to a mean field. GEMINI++ has been applied, as afterburner, to the results of AMD and TWINGO to generate the secondary fragments distributions to be directly compared to the experimental data.

Discussion

Protons and α–particles experimental energy spectra, in coincidence with ER, have been compared first with the predictions of GEMINI++ alone and then with AMD and TWINGO coupled with GEMINI++ for both systems and at all the detected angles. In general, the backward spectra are well reproduced by GEMINI++ alone, while a fast component is more and more evident going towards the most forward angles, this component is more pronounced for the ^{19}F + ^{62}Ni system.

In Fig. 2 proton spectra, for selected angles, are shown. GEMINI++ and TWINGO givesimilar 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 as a consequence it describes better the spectra even at the forward angles.

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. 3. 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, in Fig. 4 experimental proton and α–particles multiplicity distributions, in coincidence with ER, are shown. The distributions, for the two systems, have been normalized to the number of ER and compared with the different model predictions. The predictions of GEMINI are always slightly higher than AMD calculations and seem to reproduce correctly the α–particles multiplicityfor both systems. The AMD predictions are reproducing better the multiplicities of protons, for the two systems, while TWINGO calculations predict always less particles emission. In general, all the models are not able to reproduce the multiplicities of channels with the emission of more than 6 or 7 particles. Further analysis is ongoing looking to specific decay channels.

Conclusions

Possible α–clustering effects in medium mass nuclei have been investigated by analyzing the secondary particle emission from ^{16}O + ^{65}Cu and ^{19}F + ^{62}Ni at

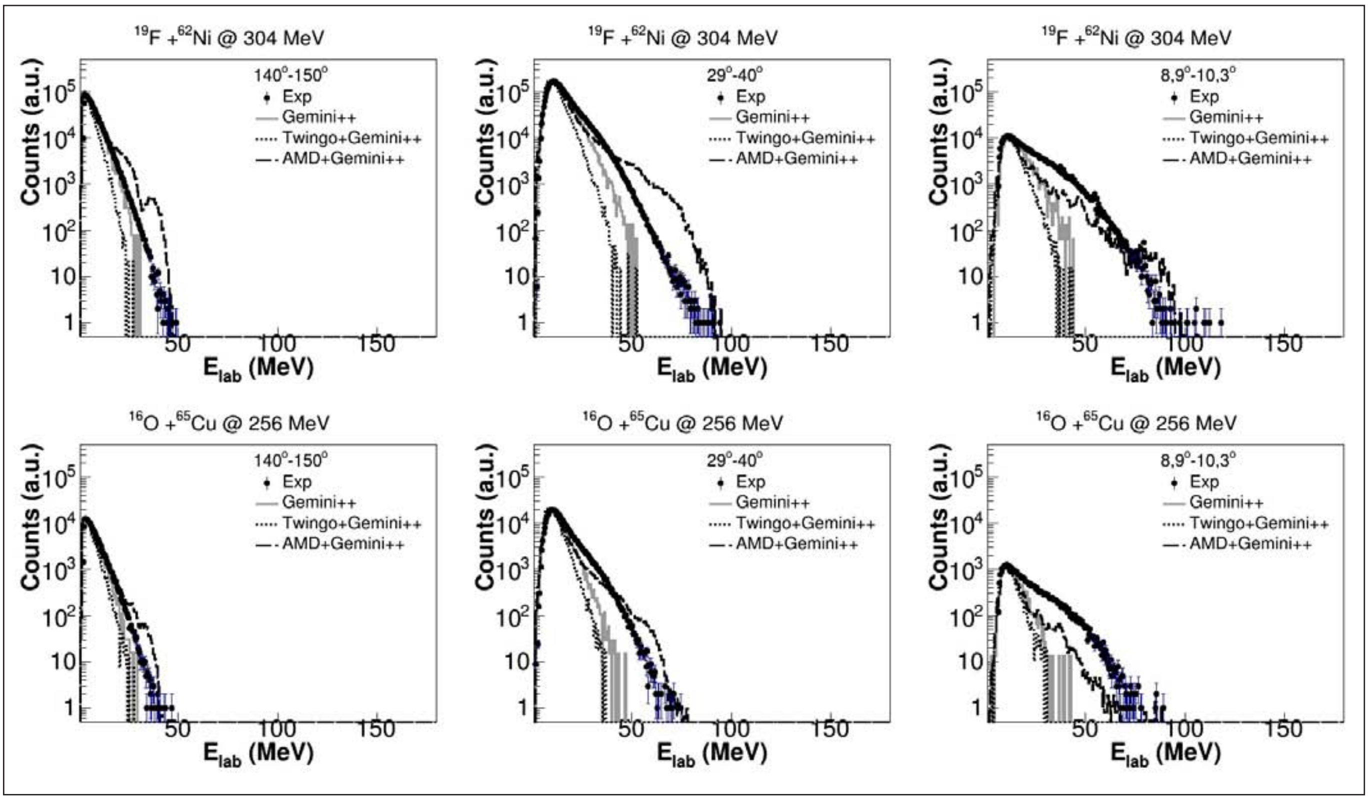

Figure 2. Experimental energy distributions of protons (dots), in coincidence with ER, for the two reactions ^{19}F + ^{62}Ni (upper panels) and ^{16}O + ^{65}Cu (lower panels) compared with predictions of GEMINI (solid line), TWINGO + GEMINI++ (dotted line) and AMD + GEMINI++ (dashed line), at selected angular range in GARFIELD and RCo.

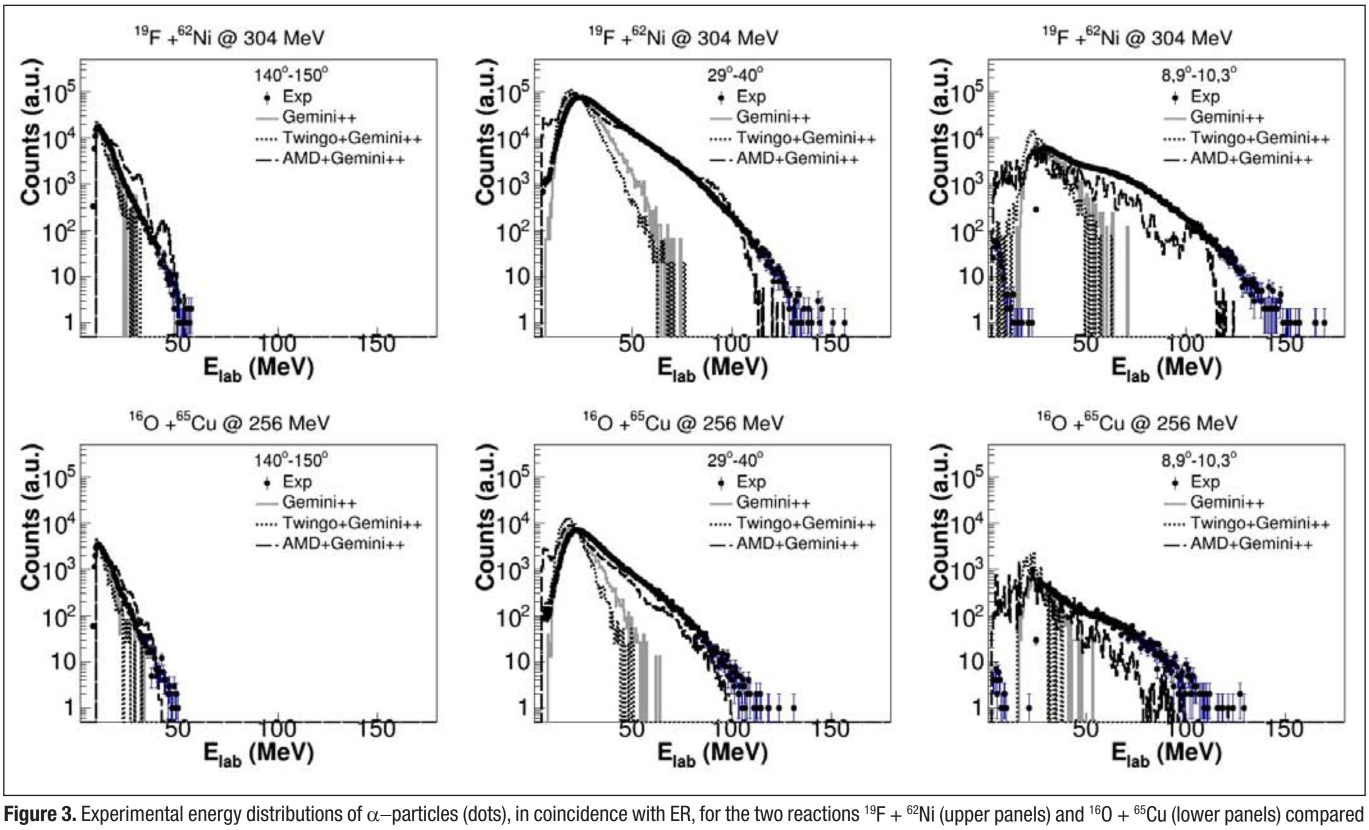

Figure 3. Experimental energy distributions of α–particles (dots), in coincidence with ER, for the two reactions ^{19}F + ^{62}Ni (upper panels) and ^{16}O + ^{65}Cu (lower panels) compared with predictions of GEMINI (solid line), TWINGO coupled GEMINI++ (dotted line) and AMD coupled GEMINI++ (dashed line), at selected angular range in GARFIELD and RCo.

the beam velocity 16 AMeV, in particular studying the competition between evaporation and pre-equilibrium particle emission. Indeed, a difference in the fast α–particles component of the emitted spectra of the two systems has been evidenced, which can be related to the difference in the projectile structure. Experimental energy spectra of protons and α–particles, in coincidence with evaporation residue, have been compared with different model predictions. The predictions of the Moscow Pre-equilibrium Model, which takes into account both the pre-equilibrium and evaporation emission, show that the model is not able to describe, with a unique set of initial

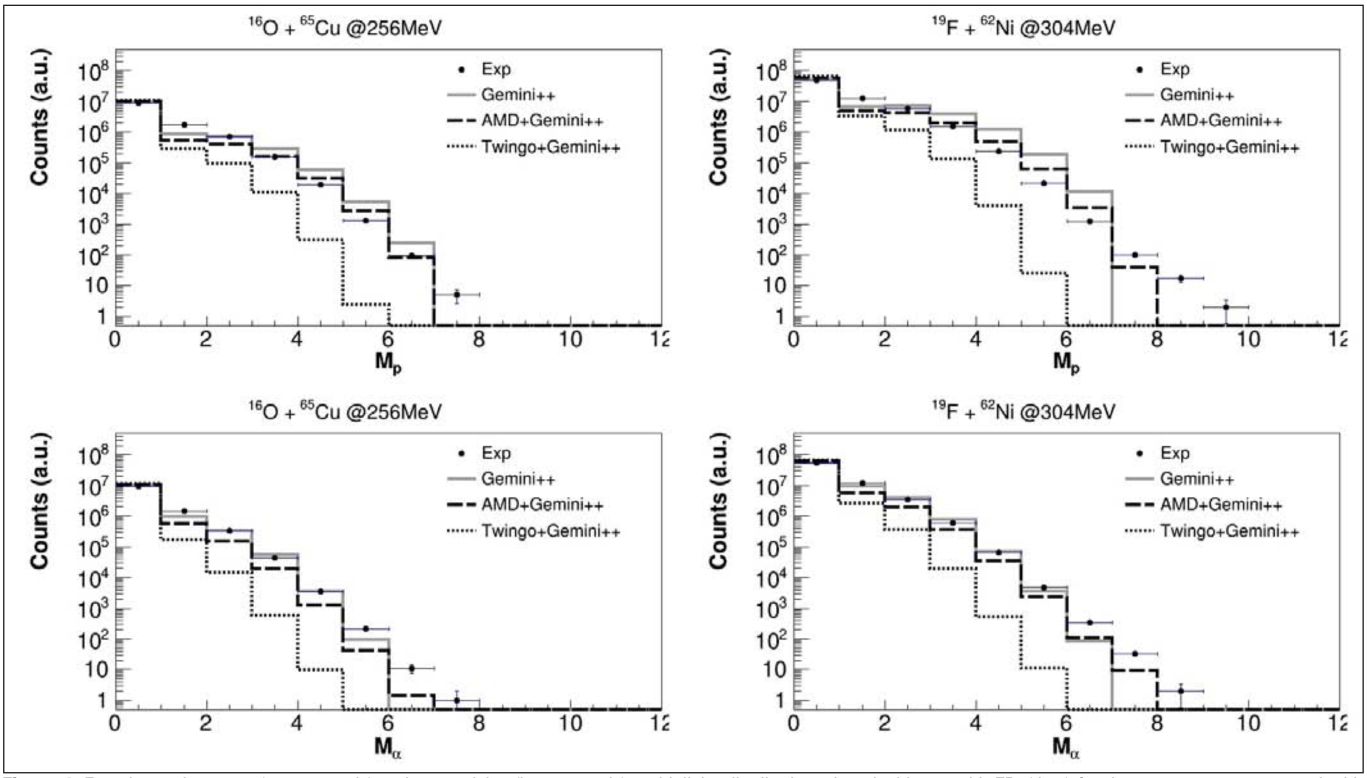

Figure 4. Experimental protons (upper panels) and α–particles (lower panels) multiplicity distributions, in coincidence with ER, (dots) for the two systems compared with GEMINI++ (solid line), TWINGO coupled GEMINI++ (dotted line) and AMD coupled GEMINI++ (dashed line).

parameters, protons and α–particles at the same time. The model is being upgrading, improving the introduction of clustering structure effects and a correct filter in the evaporation residues distribution. GEMINI++, which considers only complete fusion processes, and TWINGO, which considers the dynamics of the reaction but is not able to reconstruct correctly the fast emitted nucleons and clusters, both cannot describe the experimental spectra. On the contrary, AMD model, which includes cluster structure effects in the projectile, seems to have a better agreement with the experimental data. However, the input parameters need to be further adjusted.

The data analysis is still going on to study more exclusive channels, in particular particle-particle correlations in events with α–particles multiplicities greater than two. As first attempt, the minimum, medium and maximum energy distributions of events in which 3 α–particles are emitted, in coincidence with any evaporation residues, have been sorted out for the two systems. The comparison with the predictions of GEMINI++ shows that the faster particles are not completely reproduced by the code, this means that, even in events with emission of three α–particles, there is evidence of pre-equilibrium emission of α–particles. This effect is more evident for the system $^{19}F + ^{62}Ni$ also for medium velocity particles.

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