Clustering in light nuclei and their effects on fusion and pre-equilibrium processes

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Abstract

The study of heavy ion nuclear reactionis an important tool to observe and disentangle different and competing mechanisms, which may arise in the different energy regimes. In particular, at relatively low bombarding energy, it is quite interesting the comparison between pre-equilibrium and thermal emission of light charged particles from hot nuclear systems [1-6]. Indeed, the nuclear structure of the interacting partners can be strongly correlated to the dynamics, especially at energies close to the Coulomb barrier, and this effect emerges when some nucleons or clusters of nucleons are either emitted or captured. In particular, a major attention has been devoted, in the last years, to the possible observation of cluster structure effects in the competing nuclear reaction mechanisms, especially when fast processes are involved. At this purpose, the four reactions $^{16}O+^{30}Si$ at 111 MeV, $^{16}O+^{30}Si$ at 128 MeV, $^{18}O+^{28}Si$ at 126 MeV, $^{19}F+^{27}Al$ at 133 MeV have been measured to study the onset of pre-equilibrium in an energy range where, for central collisions, complete fusion is expected to be the predominant mode. Experimental data were collected using the GARFIELD + RCo array [7], fully equipped with digital electronics at the LegnaroNational Laboratories. The comparison between experimental data and different model predictions have been performed: in particular, both dynamical models based either on Stochastic Mean Field (TWINGO) or Anti-symmetrized Molecular Dynamics and fully statistical models (GEMINI++) have been considered. Simulated events are filtered through a software replica of the apparatus, to take into account all possible distortions of the experimental distributions due to the finite size of the apparatus.

Key words: *heavy ion reactions; experimental data; light nuclei; HAUSER-FESHBACH theory; energy spectra.*

Agrupamiento de núcleos ligeros y sus efectos en la fusión y procesos de pre-equilibrio.

Resumen

El estudio de la reacción nuclear iónica pesada es una herramienta importante para observar y esclarecer los diferentes mecanismos que compiten entre sí, que pueden surgir en los diferentes regímenes energéticos. En particular, a una energía de bombardeo relativamente baja, es bastante interesante la comparación entre el preequilibrio y la emisión térmica de partículas ligeras cargadas por sistemas nucleares calientes [1-6]. De hecho, la estructura nuclear del grupo que interactúa puede estar fuertemente correlacionada con la dinámica, especialmente en energías cercanas a la barrera de Coulomb, y este efecto surge cuando se emiten o capturan algunos nucleones o grupos de nucleones. En particular, se ha dedicado una gran atención, en los últimos años, a la posible observación de los efectos de la estructura del agrupamiento en los mecanismos de reacción nuclear competitivos, especialmente cuando se trata de procesos rápidos. Para este propósito, las cuatro reacciones ^{16}O + ^{30}Si a 111 MeV, ^{16}O + ^{30}Si a 128 MeV, ^{18}O + ^{28}Si a 126 MeV, ^{19}F + ^{27}Al a 133 MeV se han medido para estudiar el inicio del preequilibrio en un rango de energía en el cual, para colisiones centrales, se espera que la fusión completa sea el modo predominante. Los datos experimentales se recogieron utilizando la matriz GARFIELD + RCo [7], totalmente equipada con electrónica digital en los Laboratorios Nacionales Legnaro. La comparación entre los datos experimentales y las diferentes predicciones de modelos se han llevado a cabo: en particular, se han considerado los modelos dinámicos basados en el Campo Medio Estocástico (TWINGO) o Dinámica Molecular Antisimétrica y modelos completamente estadísticos (GEMINI ++). Los eventos simulados se filtran a través de una réplica de software del aparato, para tener en cuenta todas las posibles distorsiones de las distribuciones experimentales debido al tamaño finito del aparato.

Palabras clave: *reacciones de iones pesados; datos experimentales; núcleos ligeros; teoría de HAUSER-FESHBACH; espectros de energía.*

Introduction

The formation of transient excited nuclear systems, up to the continuum, can be obtained using heavy ion nuclear collisions, which are produced at excitation energies well above the particle emission threshold and, some time, even above the much larger emission threshold of fragments. Therefore, important studies can be performed aiming at studying the nuclear matter in extreme conditions of density, temperature, angular momentum and isospin. However, since normally very short interaction times are involved, such systems can be studied only through their decay products and their correlations. These experiments are very challenging both from the point of view of the detection systems and from the complex analysis, made on an event-by-event basis, which have to deal with a quite large number of decay products in the exit channels.

In particular, the present study is mainly dedicated to the decay of light composed systems. The description of an excited light nucleus is a matter of debate since it is not clear whether a pure statistical decay framework can be used to describe such small systems. The study of fusion reaction which bring to light excited systems is, moreover, interesting since it is the only mode to access the level density above the particle threshold: exclusive measurements may give new and interesting information on this subject and on the possible coupling to the continuum. Moreover, it is known that light nuclei may present pronounced cluster structures, which may influence even the dynamic of the reactions, changing the relative competition yield.

Last, but not less important, is the fact that light nuclei are those fragments produced in multi-fragmentation phenomena: a specific knowledge of their decay may permit the back-reconstruction of the primary partitions in the freeze out volume, from which one can obtain important information on the Nuclear Equation of State, especially on the Symmetry Energy term.

In order to detect the most complete event as possible, very complex apparatus are used, based on a ~ 4π geometry, with high granularity and low detection and identification thresholds.

In particular, the GARFIELD – RComultidetector [6] has been used to perform the experiments hereafter described.

Moreover, to get information on both the decaying sources and the competing mechanisms, it is necessary to perform complex analysis, looking for exclusive observables, which are able to evidence signatures of the different involved processes, when compared to specific theoretical models.

In this contribution, some results obtained in different measurements performed at the TANDEM XTU accelerator of the Legnaro National Laboratory of INFN, will be presented.

Materials and methods

The experiments have been performed at the Legnaro National Laboratory, where beams of ^{12}C, ^{14}Ni, ^{16,18}O and ^{19}F have been used in two different campaigns onto several thin targets, in order to study fusion-evaporation mechanisms and their competition with fast emission processes. The experimental apparatus used in both experimental measurements was the GARFIELD+RCo 4π detector, which is mainly composed by two drift chambers, with micro-strip read out for the ΔE signal and CsI(Tl) detectors for the residual energy signal. They provide the simultaneous identification of low energy light charged particles and massive fragments. The two drift chambers cover the angular range $30° < \theta < 150°$. They are filled with CF_4 gas at a pressure of about 50 mbar. Moreover, a three stage annular telescopic array (RCo) is positioned in the forward direction ($7° < \theta < 17°$).

It is made of an Ionization Chamber (IC) divided in 8 sectors, followed by an 8 Strip silicon detector and 6 CsI(Tl) for each sector. The entire apparatus is read-out with digital electronics, designed on purpose. Mass identification can be obtained in the whole space through the PSA in CsI for light charged particles and in the forward angle for Z up to Z=10 for the fragments. Z identification is obtained for all fragments in the whole angular range with an energy threshold of 0.8-1 MeV/A.

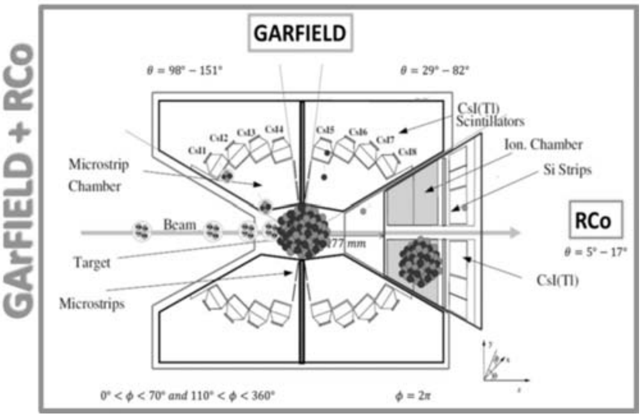

Figure 1. Layout of the GARFIELD +RCo array.

Major details on the energy and angular resolutions and of the overall performances are reported in ref. [7]. A sketch of the layout of the apparatus is shown in Fig. 1.

In order to carry out a dedicated analysis, event selection must be performed. Mainly two kind of events have been selected in the following analysis: i) central collisions asking for the detection of a fragment (Evaporation Residue) in the forward direction, and,in coincidence, one or more light charged particles detected in the whole apparatus; ii) peripheral collisions, mainly corresponding to the inelastic reactions in which the projectile is excited and can decay through a multiple α-particle channel. A velocity close to the center of mass velocity of the colliding systems characterizes the Evaporation Residue (ER). A distribution, which correlates the total detected charge versus the total longitudinal momentum, is built in order to classify the different kind of detected events. An example is shown in Fig. 2 for the $^{12}C+^{12}C$ reaction at 95 MeV: complete fusion- evaporation events are close to 1 (upper right corner) in Z_{tot}/Z_{p+t} and q_z/q_{beam}. The ^{12}C excited projectile is, instead, in the region of large q_z/q_{proj} and ~0.5 z_{tot}/z_{p+t}.

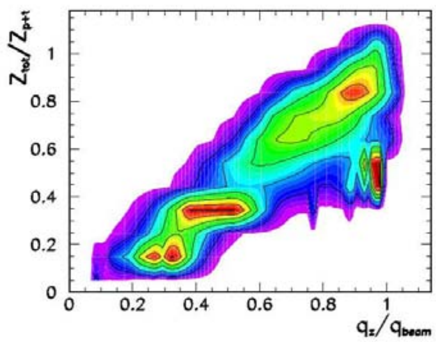

Figure 2. $^{12}C+^{12}C$ at 95 MeV: distribution of the total detected charge versus the total detected longitudinal momentum.

Results & discussion

The $^{12}C+^{12}C$ and $^{14}N+^{10}B$ cases

The $^{12}C+^{12}C$ reaction at 95 MeV have been studied for the formation of the excited compound nucleus ^{24}Mg. A dedicated Hauser Feshbach model (HFℓ)have been developed introducing in the code all the level from NUDAT database [1,8].

Comparing the experimental data to HFℓ statistical model calculation, some particular features have been observed: in particular an underestimation of the code of yield of the Z=4 and Z=6 fragments together with an underestimation of the yields in the 2α and higher multiplicity channels. An exception is observed for the 6α channel, which, on the contrary, seems to be well represented.

Moreover, a difference in the energy spectra of α particles in coincidence with specific residues has also been observed (in particular with Z=8) together with some discrepancies in the branching ratios of specific channels, obtained from calorimetry.

The Q-value distributions, for specific decay channels, have been reconstructed and compared to model predictions to better study the observed discrepancies. It was observed, as an example, that in the O+2α+n channels the shape of the Q-value spectra is similar with what expected by the model, but the relative yields of the so called more dissipative (Q<) towards the less dissipative (Q>) reaction are not described. In the data a much larger cross section was present in the less dissipative Q> region. This was ascribed either to possible residual effects of the entrance channel, which are not possible to disentangle experimentally or to possible residual effects of α-cluster structure that enhance the pure 2α decay channels with respect to pure statistical behavior.

Moreover, discrepancies with respect to model predictions are also observed when looking to the shape of the exclusive α energy spectra obtained with a strict request on the decay channel: for example the pure 2α channel is not well reproduced by the model while a more “standard “ one (α+2H, with H equal to Z=1 particles) seem to be better described.

To better disentangle if the differences are related to entrance channel effects or to different issues related either to non-statistical behaviors and or to clustering memories, the comparison with a different entrance channel have been performed and, in particular, the $^{14}N+^{10}B$ reaction was studied. A common pattern in the Q-value distributions was observed in both cases, even if some differences were observed in the relative yield of the less dissipative versus the more dissipative (Q>/Q<) populations. Entrance channel effects have been confirmed, with a partial contribution of direct reactions in the C+C case. However, still differences remain with respect to a pure statistical behavior and, in particular, exit channels with Carbon, Oxygen and Neon residues show in both cases a preferential α decay. This may be ascribed to residual α - structure correlations in the excited ^{24}Mg or in its daughter nucleus. More details on the specific analysis can be found in the works of L. Morelli et al. [1,2,9].

The $^{16}O+^{30}Si$, $^{18}O+^{28}Si$ and $^{19}F+^{27}Al$ cases

A comparative study of the four reactions $^{16}O+^{30}Si$, $^{18}O+^{28}Si$ and $^{19}F+^{27}Al$ at 7 MeV/n and $^{16}O+^{30}Si$ at 8 MeV/n has been done, in order to continue an extensive program on the competition between complete fusion and fast processes and its possible relation with cluster structure effects of the colliding partners. The idea was to study these systems, firstly, at the onset of the fast emission and then to perform a following study of the same systems at higher bombarding energies, where the pre-equilibrium part is well assessed. The first measurement is object of this paper.

Cluster emission from hot composite systems has been a matter of debate for many years, since it is not yet known if their presence is due to a pre-formation either in the colliding partners or in the compound nucleus it-self or they are formed in the dynamical path of the collision. One possibility to evidence this phenomenon is to observe the de-excitation of nuclear systems formed with different entrance channels, especially observing the competition between pre-equilibrium emission of clusters with respect to statistical emission and analyze all possible differences through correlation studies.

For central impact parameters, and in case of complete fusion, the studied reactions all lead to the same compound nucleus $^{46}Ti^*$, even if with slightly different excitation energies. The main characteristics of the studied reactions are reported in Table 1.

One of the main problems observed in the measurements was related to a high level of contamination of O in the Si target and a smaller one in the Al target. Dedicated measurements were performed on the targets themselves with RBS technique [10] in order to define quantitatively the amount of contaminants and it resulted a ratio of ~1 of O with respect to both ^{30}Si and ^{28}Si targets, while of ~ 0.3 for the ^{27}Al one. The effects of such contamination on experimental spectra can be observed looking to the energy spectra previously published, where almost no visible evidence is observed in the proton spectra, while the α-particle spectra are strongly affected (see Fig. 5 in ref [4]), giving rise to a wrong conclusion on fast emission particles.

In order to avoid contaminated events, a strict selection was performed on the data to be further analyzed, asking for an almost complete event reconstruction: in particular a $Z_{tot}/Z_p+Z_t>16$ and a $0.5<q_z/q_{beam}<1.2$ was required as it is shown in Fig. 3.

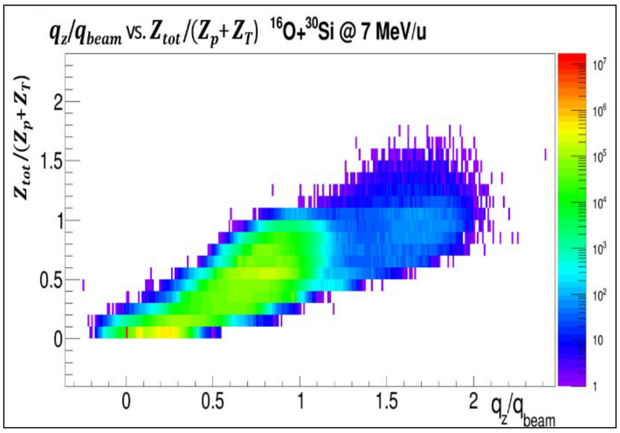

Figure 3. $^{16}O+^{30}Si$ at 111 MeV: distribution of the total detected charge versus the total detected longitudinal momentum. Selections on $Z_{tot}/Z_p+Zt>16$ and $0.5<q_z/q_{beam}>1.2$ have been performed to avoid target contamination and random coincidences.

Moreover, in these selected events, to define central collisions the detection of an evaporation residue (ER) in the forward direction (RCo) in coincidence with one or more light charged particles in the remaining apparatus has been requested. The correlation between the detected charge and the energy in the laboratory frame is shown in Fig.4 for the total events (left panel) and for the selected central events (right panel) for the reaction $^{16}O+^{30}Si$ at 7 MeV/n. In the right panel it is evident the region of contamination due to the presence of O in the target, close to the region of $8<Z<13$.

The energy distributions of the light charged particles in coincidence with a residue have been studied and compared to those obtained through model predictions. In particular, the statistical code GEMINI++ [11], which is based on a complete fusion hypothesis, has been used.

Moreover, dynamical codes, followed by an afterburner have been also considered.

In particular, the comparison to prediction from two dynamical codes, based on very different assumptions have been done: the TWINGO code [12], based on Stochastic Mean Field approximation, where each nucleon is described through a certain number of test particles (100 in our case) and the Antisymmetrized Molecular Dynamics (AMD) code [13], which follows the time evolution of single particle wave functions described by Gaussian wave packets.

Table 1. Main characteristics of the studied reactions

Entrance Channel Parameters				Compound Nucleus properties			
Projectile	Elab(MeV)	Target	Entrance Channel Mass asymmetry	CN	Fusion Cross section (mb)	CN – Excitation Energy (MeV)	CN– Lab Velocity
^{16}O	7.0	^{30}Si	0.30	^{46}Ti	1081	88.0	1.28
^{16}O	8.0	^{30}Si	0.30	^{46}Ti	1070	98.4	1.37
^{18}O	7.0	^{28}Si	0.22	^{46}Ti	1110	98.5	1.44
^{19}F	7.0	^{27}Al	0.17	^{46}Ti	1100	103.5	1.52

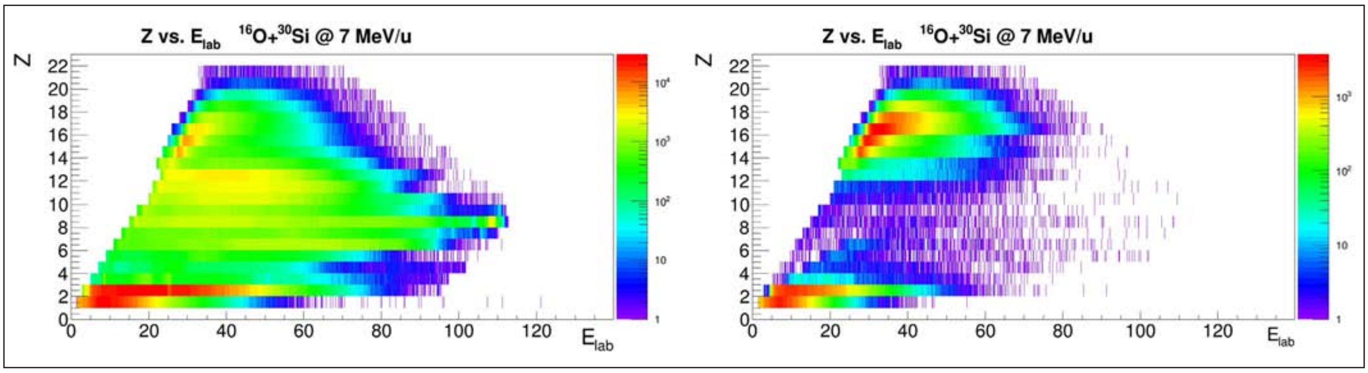

Figure 4. $^{16}O+^{30}Si$ at 111 MeV: Correlation between the detected charge Z and the Energy for total events (left panel) in which the contamination from the reaction on O is evident (mainly $8<Z>13$) and for selected central events (right panel) with the constrain on $Z_{tot}/Z_p+Z_{t>0.7}$ and $q_z/q_{beam}<1.2$ (almost complete events).

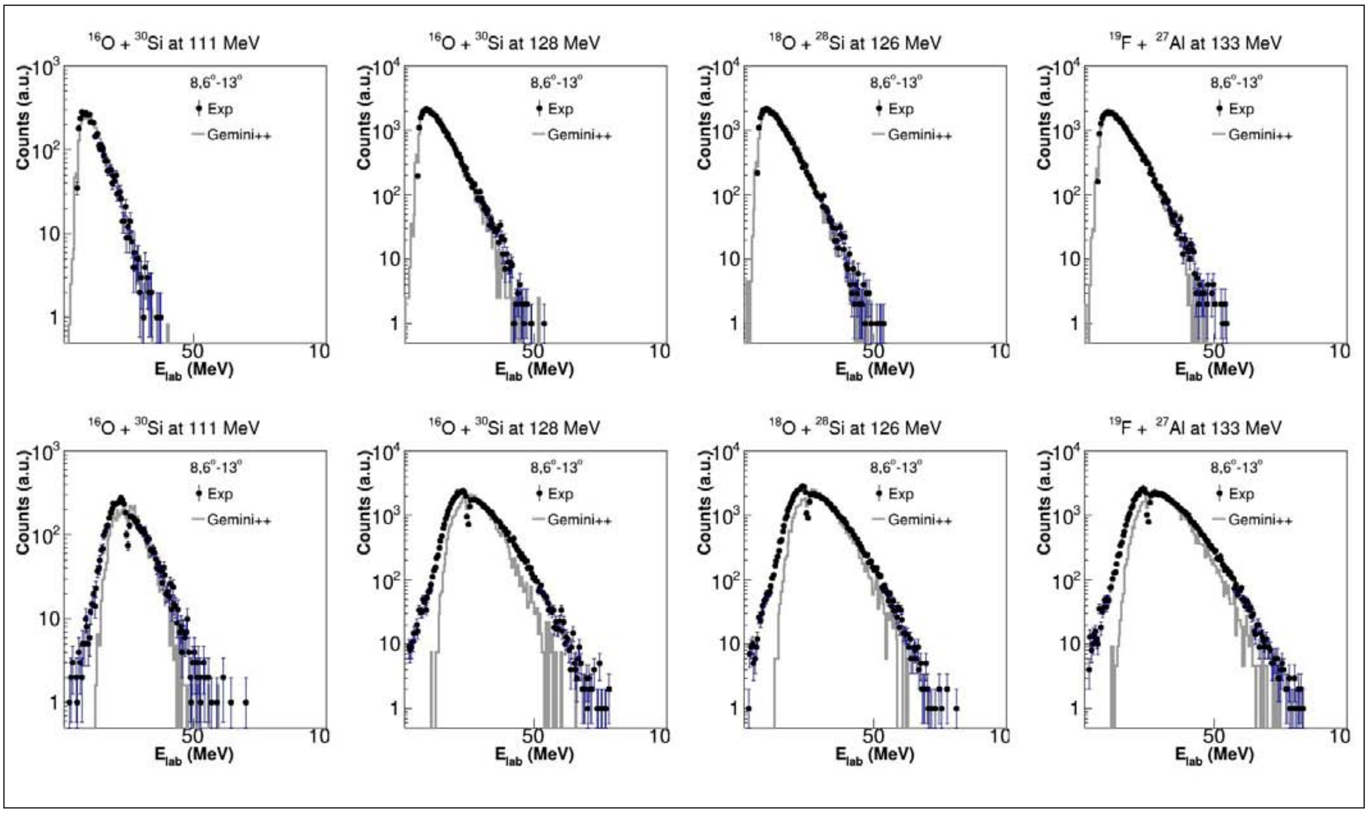

Figure 5. Proton and α-particle energy distributions at the forward angle in the RCo: as it can be observed proton spectra are well described by GEMINI++ for the four reactions, while only the lower energy in the case of $^{16}O+^{30}Si$ is well accounted for in the case of α-particles.

In the last one, particle-particle correlations are considered and cluster structure of the interacting partners can be taken into account.

From preliminary results, almost all the cross section seem to be well described in term of complete fusion, since the Gemini prediction well describe all the light charged particle spectra.

Only at the very forward angles, in fact, a small discrepancy can be observed when looking to α-particle spectra for the higher bombarding energy in the ^{16}O induced reaction, as expected due to the higher beam velocity involved. However, smaller deviations are also observed in the case of $^{18}O+^{28}Si$ and $^{19}F+^{27}Al$, which have to be studied more in detail to give a correct interpretation, but they are quite reasonably in agreement with the systematics in literature.

However looking at more exclusive observables, one can observe interesting differences between the studied reactions, which cannot be taken into account simply by the statistical code GEMINI++.

These discrepancies, that have been, preliminarily, observed in the multiplicity distributions (see Fig. 6) and in the reconstructed Q-values distributions in selected multiple α-decay channels, need to be further studied and cross checked before addressing any conclusion, but may indicate that interesting and new information can be obtained by the study of light decay systems.

As it can be observed proton spectra are well described by GEMINI++ for the four reactions, while only the lower energy in the case of $^{16}O+^{30}Si$ is well accounted for in the case of α-particles.The major discrepancy is observed in the case of $^{16}O+^{30}Si$ at the higher bombarding energy, while smaller deviations are observed in the case of $^{18}O+^{28}Si$ and $^{19}F+^{27}Al$

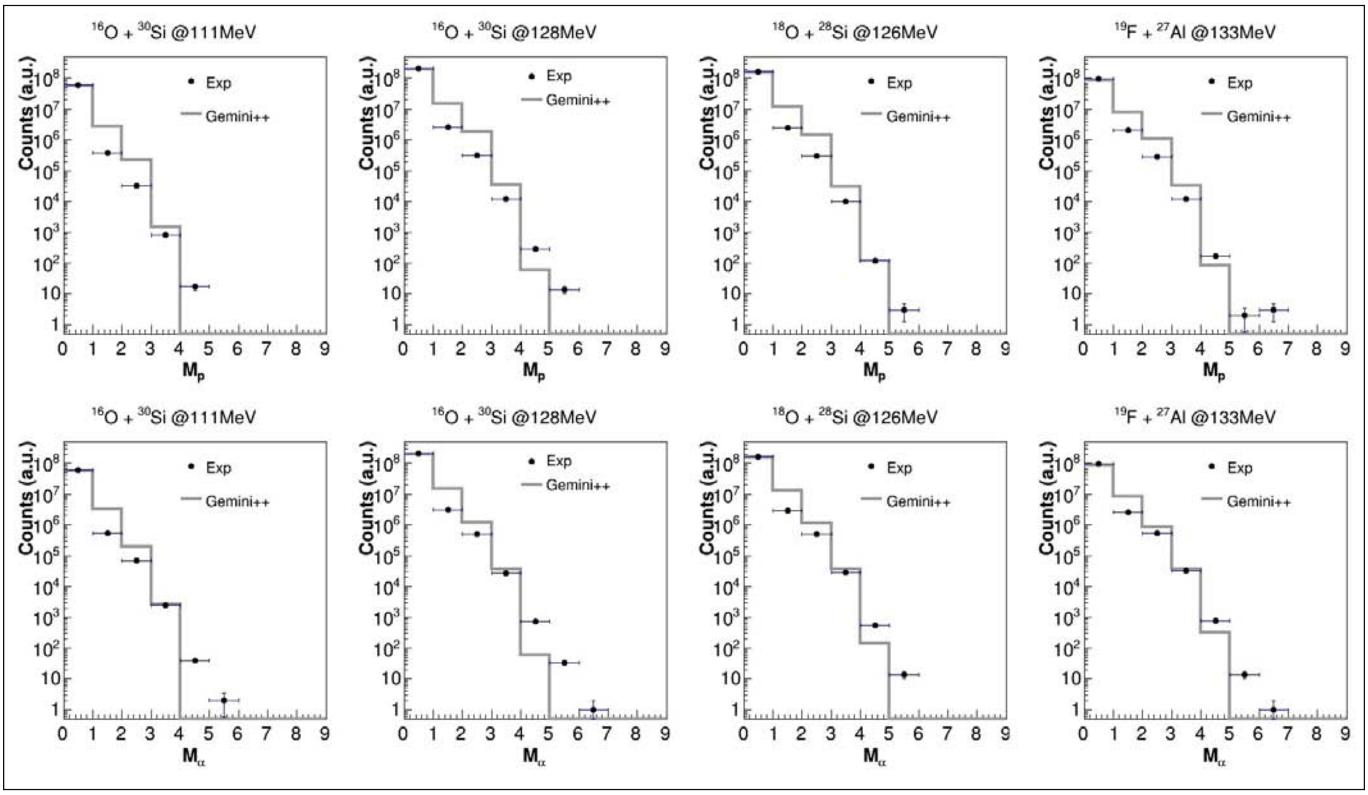

Figure 6. Experimental proton (upper panel) and α-particle (lower panel) multiplicity spectra in coincidence with ER for the four studied reactions.

Conclusions

We have presented some results related to the ^{24}Mg* decay: the decay branching ratios seems to depend on the number of α-particles in the exit channel: the channels with Carbon, Oxygen and Neon residues show a preferential α decay: this can be ascribed to residual α-structure correlations in the excited ^{24}Mg or in its daughter nuclei. Conversely, the probability of a complete vaporization in 6 α-particles it has been observed to bein agreement with a statistical decay leading to *afinal unstable* ^{8}Be residue. These results have been published on the papers by L. Morelli et. al. [1,2,9].

In connection to the light system decay modes, but also related to the problems of the competition between thermal emission and fast emission processes, thepre-equilibrium and clustering effects on dynamics is being studied through four different entrance channels: ^{16}O+^{3}0Si,^{18}O+^{28}Si and ^{19}F+^{27}Al at 7 MeV/n and ^{16}O+^{30}Si at 8 MeV/n. Studying the decay of ^{46}Ti*, the compound nucleus formed for all the reactions in case of complete fusion, from the preliminary data analysis we can remark that the major part of the observed light charged particle energy spectra are compatible with a standard statistical decay, except for a small pre-equilibrium effect in the α-particle emission channel pointed out in the case of ^{16}O projectile on ^{30}Si target at the higher bombarding energy (8 MeV/n) as expected from systematics. However, the analysis is still preliminary and the difference has to be quantitatively addressed. In particular, exclusive channels are being studied, showing differences in specific multiplicity channels and Q value spectra, that have to be further studied in comparison to model predictions, even those in which clustering can be described (AMD). Analysis of correlations between *LCP particles*, especially in multi- α particle ($M\alpha \geq 3$) events are needed to constraint the dynamics and to draw possible conclusions on the differences between the studied systems. New measurements of the same systems at *higher bombarding energies* are needed, where larger pre-equilibrium yields are foreseen. Analysis of the peripheral reactions for the *de-excitation of the projectile* are in progress to study possible resonance states in projectile like, for example, the predicted Hoyle state configuration in O.

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