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^{16}O + ^{65}Cu and ^{19}F + ^{62}Ni at 16 A MeV reaction mechanisms comparison: Pre-equilibrium vs. clustering

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Summary. — Cluster structure effects in nuclei have been investigated looking to the pre-equilibrium particles emitted in the ^{16}O+^{65}Cu and ^{19}F+^{62}Ni reactions at the same beam velocity of 16 A MeV which lead to the same ^{81}Rb* compound nucleus. Despite the slight difference in excitation energies, the same fast emission should be expected from the two systems; unless major effects induced by the projectile's cluster structure, which should influence the pre-equilibrium α-particle production during the non-equilibrium stage, are present. The experimental data have been collected with the GARFIELD+RCo apparatus at Laboratori Nazionali di Legnaro. In this contribution we report on the preliminary spectra of light-charged particles, obtained in coincidence with evaporation residues, and their comparison with the results obtained from model calculations.

1. – Introduction

The idea that a nucleus can be viewed as a collection of α-particles was discussed in the early days of nuclear physics, even before the actual formulation of nuclear shell model. Investigation on the structure of nuclei with N=Z, particularly even Z and N nuclei, is very interesting and important from nuclear structure as well as astrophysical points of view. In 1938, Hafstad and Teller conjectured that nuclei with $N = Z$ were particularly stable and their ground state could be described in terms of geometric arrangements of α-particles known as α-clusters [1]. In the late sixties, Ikeda and co-workers found that a cluster structure should not be manifest in the ground-state but emerges as the internal energy of the nucleus becomes close to the cluster decay threshold (depicted in Ikeda diagram, [2]). More recently, 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, has gained more interest [3]. These exotic structures have been mainly described so far by theory. However, we still lack experimental data, mainly due to the low intensity of exotic beams presently available. While awaiting for the availability of the new generation of radioactive beam facilities like SPES, HIE-ISOLDE and SPIRAL2 [4], it is therefore of particular interest to search for α-clustering effects in non-traditional observables, like those deriving from pre-equilibrium process studies, which may bring new insights to the cluster formation process.

In a previous work [5, 6], the decay of the ^{132}Ce compound nucleus (^{16}O+^{116}Sn) has been investigated in order to identify the amount of pre-equilibrium emission in asymmetric entrance channel reactions at various incident energies ranging from 8 to 16 A MeV; an energy range in which pre-equilibrium emission is expected. Experimental spectra of protons and α-particles have been compared with results from the Hybrid Exciton Model calculations. This model uses a modified version of the statistical code PACE2 in which a non-equilibrium stage in the fusion reaction before thermalization has been inserted. While a general good agreement was observed between experimental data and model calculations for protons at all energies over the measured angular range, experimental data for α-particles have shown an enhanced production at forward angles which could not be explained by the pre-equilibrium emission contribution. This significant increase of α-particle yields in the pre-equilibrium part of the spectra was attributed to the α-cluster structure of the ^{16}O projectile. In addition, by introducing the effect of the cluster structure in the projectile nucleus in the model in terms of pre-formation probability of clusters, the model was able to fairly describe the experimental data with a sizable probability of α-clustering pre-formation.

To better investigate, in a model independent way, the effect of the projectile α-cluster structure on the observed extra production of α-particles in the pre-equilibrium part, ^{16}O+^{65}Cu and ^{19}F+^{62}Ni fusion reactions have been studied at 16 A MeV incident energy in order to directly compare their light charged particle emission spectra and yield ratios. It is expected a small difference in the evaporative part due to the excitation energy difference ($E^* = 209$ MeV and $E^* = 240$ MeV, respectively). However, the fast emission process should almost be the same for both reactions. Any observed difference and overproduction of fast α-particles between the two cases would suggest, in a model-independent way, a possible influence of the projectile α-structure effect (a double magic α-cluster, ^{16}O, and a non-magic α-cluster projectile, ^{19}F).

2. – Experimental details

The experiment has been performed at the Laboratori Nazionali di Legnaro, with the ^{16}O and ^{19}F beams provided by the TANDEM-ALPI acceleration system. The GARFIELD+RCo experimental setup, fully equipped with digital electronics, was used. A detailed description of the apparatus can be found in refs. [7, 8]. Fully identified light-charged particles have been measured both in single and in coincidence with Evaporation Residues (ERs), detected in the RCo. Due to the high countrate of elastic scattering, the small angles were shielded through an opportune collimation. The ERs, selected setting

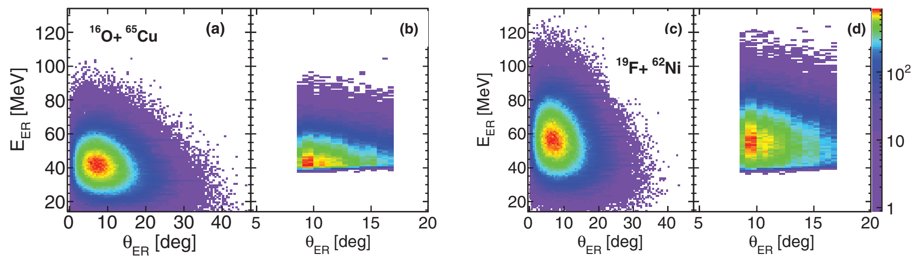

Fig. 1. – ER energy distribution as a function of its emission angle from the predictions of GEMINI++ code without (panels (a) and (c)) and with experimental cuts (panels (b) and (d)). Panels (a) and (b) ((c) and (d)) refer to the reaction ^{16}O+^{65}Cu (^{19}F+^{62}Ni). The detector threshold can be located, as a first approximation, around 40 MeV.

proper gates in the IC-Si ΔE-E energy spectra of the RCo, have been collected in an angular range $\theta = 8.6°$ and $17°$ (just beyond the grazing angles).

3. – Preliminary results

In order to carry out a better comparison between simulated and experimental data, it is necessary to filter simulated events through experimental conditions. These conditions are produced from the features of the experimental array, such as the geometry, the energy thresholds, the energy resolution and the solid angle for each detector, and the gas pressure in the ionization chambers. Figure 1 shows, for the two systems, the effect of the experimental cuts on the ER energy distribution as a function of its emission angle obtained with GEMINI++ simulations [9]. It is observed that the ER detection energy threshold seems to be quite important especially for the ^{16}O+^{65}Cu reaction for which the peak of maximum yield is cut if only ERs reaching the RCo silicon detectors are considered. This difference in detecting ERs has to be taken into account when comparing the results from the two reactions.

In the preliminary analysis reported here, we have only considered the double-differential proton and alpha energy spectra obtained in the GARFIELD angular range, in coincidence with ERs. The two reactions show very similar proton spectra except for a small difference at the most forward angles. This effect can be ascribed to the slightly larger excitation energy of the ^{19}F induced reaction. A much larger difference is, however, observed in the case of the α-particle emission spectra. As an example, fig. 2 shows the comparison between experimental proton and α-particle energy spectra at the most forward GARFIELD angular range ($\theta = 29°$–$41°$), normalized to the maximum, obtained for the two systems. It is tempting to speculate that the observed difference between the α-particle decay in the two systems may be essentially due to the lower energy needed to break up the ^{19}F nucleus into α+^{15}N (4.01 MeV) with respect to the ^{16}O to be divided into α+^{12}C (7.2 MeV). In refs. [10-12], the results from the evaporation code PACE4 have shown similar evaporation contributions for both systems; and experimental spectra could only be better described with an additional fast emission source. The expected amount of fast emitted particles was evaluated by means of the Hybrid Exciton model [5, 6]. Using the same initial parameters, the α-particle spectra were reasonably reproduced whereas the fast emitted protons were largely overestimated. Some discrepancies still remain as to the predictions of particle multiplicities; implying that a more complete analysis is needed to fully understand the process.

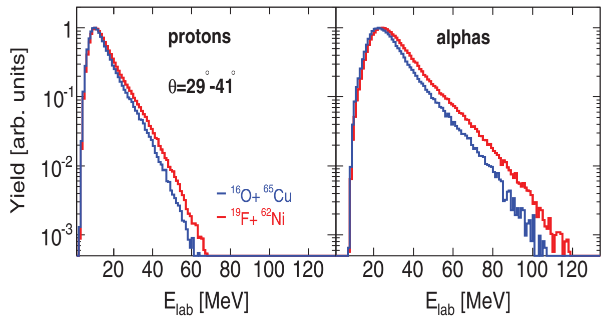

Fig. 2. – Comparison of experimental energy spectra in the laboratory frame (normalized to the maximum) of protons (left panel) and α-particles (right panel) for the two reactions at the angular range $\theta = 29°–41°$.

To further analyze experimental pre-equilibrium α-particle spectra, other theoretical approaches have been considered. We have performed simulations with a statistical-model GEMINI++ [9], the SMF [13, 14] and the AMD [15] dynamical codes coupled to GEMINI++ as an afterburner. The first results of the simulations compared to experimental data are displayed in fig. 3. One sees that for both cases, GEMINI++ and SMF results are similar and describe essentially the evaporative part of proton and α-particle spectra. The AMD model which includes clusters, however, describes fairly well experimental proton spectra for both cases. In the case of α-particles the effect of the clustering structure in the projectile starts to be evidenced even though there is still an underestimation of the experimental yield in the pre-equilibrium part of the energy spectra, especially in the case of the ^{16}O induced reaction. The AMD+GEMINI++ results suggest that a proper description of the clustering structure of the projectile can lead to a better description of the kinetic spectra of α-particles.

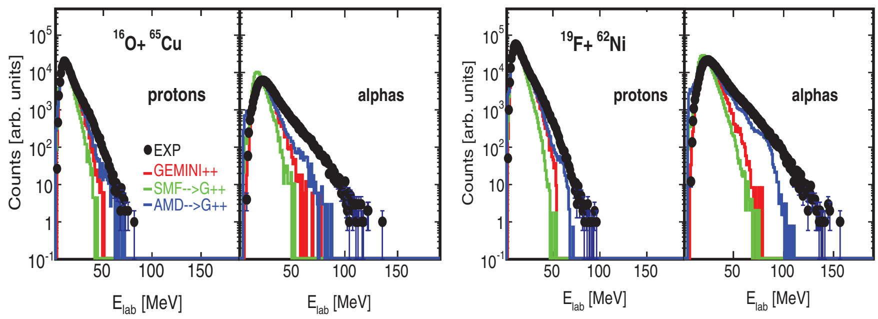

Fig. 3. – Proton (left panel) and α-particle (right panel) experimental energy distributions in the laboratory frame for the two reactions at the angular range $\theta = 29°–41°$ compared to GEMINI++ (red curve), SMF+GEMINI++ (green curve) and AMD+GEMINI++ (blue curve) model predictions; as indicated in the legend. The distributions are normalized to the total area.

4. – Conclusions and outlook

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 reactions at the same beam velocity of 16 A MeV which lead to the same ^{81}Rb* compound nucleus. From the preliminary 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. Preliminary experimental spectra of proton and α-particle detected in GARFIELD in coincidence with evaporation residues have been analyzed applying theoretical models capable to describe evaporative and pre-equilibrium processes. The Hybrid Exciton model, which still needs to be improved, has predicted energy spectra of α-particles comparable to data but has failed to reproduce those of protons. The SMF code, on the other hand, was only able to reproduce the statistical emission of protons and α-particles. The AMD code which includes clusters, in turn, reasonably reproduces proton spectra and gives a proper indication of the fast α-particle production even though still underestimates it, especially in the case of the ^{16}O induced reaction. This indicates that the α-cluster structure of the projectile nuclei should be considered in models to understand the fast emission process. Thus the present data call for further investigations.

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