ONSET OF PRE-EQUILIBRIUM: A COMPARATIVE STUDY OF FOUR REACTIONS*

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The study of the emitted particles, comparing pre-equilibrium and thermal components, is a useful tool to examine the nuclear structure. Possible clustering effects, which may change the expected decay chain probability, could be highlighted on the competition between different reaction mechanisms. The NUCL-EX Collaboration (INFN, Italy) has carried out an extensive research campaign on pre-equilibrium emission of light charged particles from hot nuclei. In this framework, the reactions ^{16}O+^{30}Si, ^{18}O+^{28}Si, ^{19}F+^{27}Al at 7 MeV/u and ^{16}O+^{30}Si at 8 MeV/u have been performed using the GARFIELD+RCo array at Legnaro National Laboratories.

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1. Introduction

Often in nuclear collisions, the term *incomplete fusion* is used to indicate the emission of particles from the projectile and/or target before the occurring of complete thermalization of the remnants. A complete understanding of the reaction mechanisms associated with such emissions, *e.g.* break-up and pre-equilibrium emissions, is still missing despite the achieved improvement in the knowledge of the incomplete fusion reactions reached in the past decades [1–3]. Since several years, our collaboration (NUCL-EX, INFN, Italy) has carried out an extensive research campaign on pre-equilibrium emission of light charged particles from hot nuclei [4–8].

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At bombarding energy above 10 MeV/u, the pre-equilibrium particle emission becomes an increasingly important process as a function of the bombarding energy; even though at these energies usually a complete thermalization occurs. The pre-equilibrium particles are forward focused and emitted in the very early stages of the collision before the attainment of full statistical equilibrium of the compound system [9, 10]. Peculiar structures, such as clusters, of the projectile and/or of the target play an important role in the reaction dynamics; for such a reason fast emission processes have been observed even in the energy region of 5–10 MeV/u. This projectile break-up mechanism [11–14], as well as the pre-equilibrium, influence the following formation and decay of the hot source.

2. The experiment

In this framework, four reactions were investigated [15, 16] at Legnaro National Laboratories (INFN-LNL, Pd, Italy) using the GARFIELD+RCo 4π array for charged particles, fully equipped with digital electronics [17]. The four used beams were: ^{16}O at 7 and 8 MeV/u, ^{18}O at 7 MeV/u and ^{19}F at 7 MeV/u, impinging, respectively, on ^{30}Si, ^{28}Si and ^{27}Al. For the sake of comparison, the beam velocity was kept constant (7 MeV/u) for three reactions, since the abundance of pre-equilibrium particles is demonstrated to be dependent on it [18]: in such a way, the non-equilibrium processes are expected to be almost the same. Finally, the reaction ^{16}O+^{30}Si has been also measured at a beam energy of 8 MeV/u to populate the ^{46}Ti* at the same excitation energy of the ^{18}O+^{28}Si at 7 MeV/u to obtain a similar statistical component. The main characteristics of studied reactions, in the case of complete fusion, are reported in Table I.

TABLE I

Summary of the main characteristics of the four reactions.

Entrance channel	Mass asymmetry	E_{lab} [MeV/u]	CN	E^{*}_{CN} [MeV]
^{16}O+^{30}Si	0.30	7	^{46}Ti	88.0
^{16}O+^{30}Si	0.30	8	^{46}Ti	98.4
^{18}O+^{28}Si	0.22	7	^{46}Ti	98.5
^{19}F+^{27}Al	0.17	7	^{46}Ti	103.5

3. The data analysis

The complete analysis has been performed on an event-by-event basis; a detail description of this analysis is given in Ref. [15]. In the present paper, we focus the attention on the complete events ($Z_{TOT}^{detected} = Z_{projectile} + Z_{target}$) in almost central collisions: in those events, one and only one heavy ($Z_{frag} > 5$) fragment, ER (evaporation residue), is detected in coincidence with light charged particles (LCP).

Comparing the four reactions, a clear dependence of the yields on the excitation energy of the compound nucleus (E_{CN}^*) and on the center-of-mass velocity (v_{cm}) is observed in the experimental global observables (*e.g.* charge distribution and multiplicities of the emitted light charged particles). Similarly, the experimental angular distribution depends on v_{cm}, even though a strong over-production of LCP (more important in the case of the α-particles) appears at very forward angles (8.8°–17.4°). In Fig. 1, the comparison of the experimental angular distributions for the four reactions is shown in the case of α-particles.

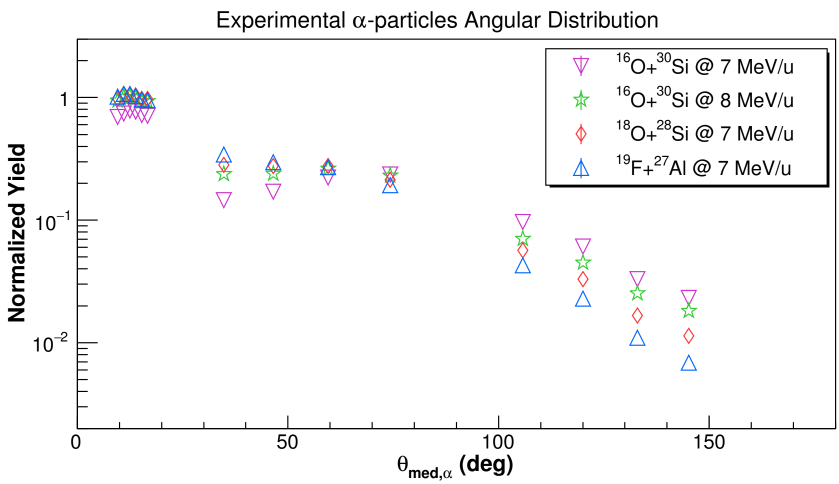

Fig. 1. Experimental angular distribution of α-particles: comparison of the four studied reactions. The distributions are normalized to the number of complete events. The error bars are inside the experimental points.

4. The statistical code

In order to have a theoretical feedback, the experimental data have been compared with simulations performed with the statistical code GEMINI++ [19], which describes the decay of the excited compound nucleus. The simulated events were filtered through a software replica of the experimental setup and, then, selected in the same way of the experimental events [15].

In Fig. 2, the comparison of experimental and simulated angular distributions of α-particles is shown for the four reactions. In order to have the comparison of (experimental *vs.* simulated) angular distribution for the four reactions in the same graph, the plot of the three reactions ^{16}O+^{30}Si at 8 MeV/u, ^{18}O+^{28}Si at 7 MeV/u and ^{19}F+^{27}Al at 7 MeV/u are drawn with a multiplication factor of, respectively, 10, 100 and 1000. The experimental trend and dependence on $v_{\rm cm}$ are reproduced in the angular region from 29.5° to 150.5°, while at very forward angles (8.8°–17.4°) significant deviations from the experimental angular distribution are observed. Quantitatively, the divergences between the simulated and experimental angular distributions are shown in Fig. 3, where the ratios between the experimental and simulated α-particles yields are shown as a function of the detection

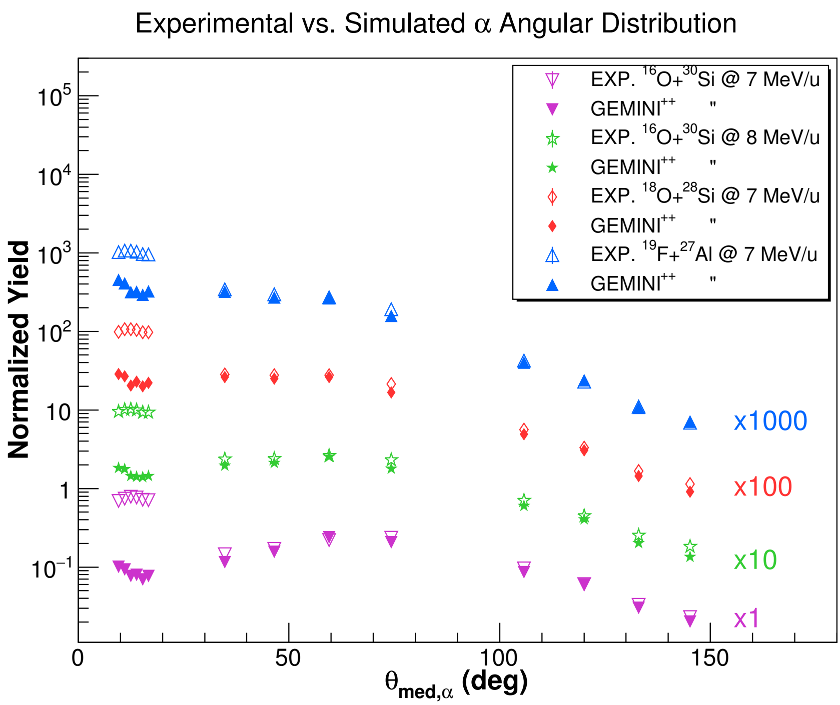

Fig. 2. Comparison of α-particles angular distribution: experimental *versus* GEMINI++ for the four studied reactions. The distributions are normalized to the number of complete events. For the sake of synthesis, the four comparisons are inserted in the same graph: the three reactions ^{16}O+^{30}Si at 8 MeV/u, ^{18}O+^{28}Si at 7 MeV/u and ^{19}F+^{27}Al at 7 MeV/u are, respectively, plotted with a multiplication factor of 10, 100 and 1 000. The error bars for the experimental are inside the points.

angle of the particles. As it can be observed, in the angular region from 29.5° to 150.5°, the experimental yields of α-particles are compatible with a statistical emission from the compound nucleus. Otherwise, the observed over-production of experimental α-particles is present at very forward angles (8.8°–17.4°). According to the literature [18], such over-production of forward focused α-particles should be related to fast emissions from non-equilibrium processes, characterizing the early stage of the reactions; it depends both on the entrance channel mass asymmetry (η) and on the beam velocity (v_{beam}). However, in our case, we observe some peculiar behavior: the α-energy spectra are reproduced in shape and the forward missing α-yields are distributed over all the possible energies [15].

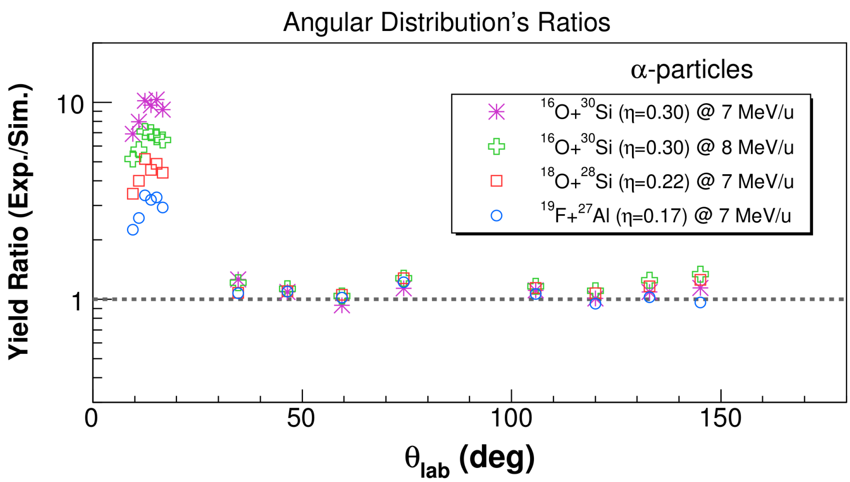

Fig. 3. Ratio of experimental and simulated and α-particles (right panel) yields as a function of the detection angle of the particles for the four studied reactions.

Moreover, at variance with what expected, when we compare the results of the two reactions with the same η (the same entrance channel: ^{16}O+^{30}Si), we observe a larger ratio (Exp./GEMINI++) of forward emitted α-particles yields (Fig. 2) in the case of the reaction at the lower v_{beam} (7 MeV/u). When comparing the three reactions with the same v_{beam} (7 MeV/u), an increase of the ratio at forward angles is seen as the η increases. Despite the small difference in η, this effect seems to be larger than expected, suggesting that the internal structure of the interacting nuclei may also play an important role. For the studied systems, the major part of the forward peaked α-particles is correlated to the exclusive channel with larger Z of residues [15]. In particular, in the Ca-residue exit channels, a strong inversion of population of $1\alpha + xn$ and $2p + xn$ channels is observed with respect to GEMINI++.

5. Conclusions

We analyzed complete events of four reactions having different entrance channels (η) and/or different beam velocity (and then different $v_{\rm cm}$). The observed differences among the four reactions can be ascribed to either entrance channels or structure properties of the reacting partners. Strong dissimilarities between experimental data and statistical model simulation are highlighted especially related to cluster-emission probability. In particular, enhanced pure α-emission has been observed, which, in some cases, become the dominant emission channel at variance with statistical model predictions.

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