A STUDY ON 4 REACTIONS FORMING $^{46}$Ti*

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Abstract. The NUCL-EX collaboration is carrying out an extensive research program on pre-equilibrium emission of light charged particles from hot nuclei. The ultimate goal is to study how cluster structures affect nuclear reactions [1,2,3,4]. Indeed, a strong correlation between nuclear structure and reaction dynamics emerges when some nucleons or clusters of nucleons are emitted or captured [5]. At this purpose, the four reactions $^{16}$O+$^{30}$Si, $^{16}$O+$^{32}$Si, $^{18}$O+$^{28}$Si and $^{19}$F+$^{27}$Al have been measured at about 120 MeV projectile energy. Experimental data were collected at Legnaro National Laboratories, using the GARFIELD+RCo array, fully equipped with digital electronics [6]. Following an initial identification of particles and the energy calibration procedures, the complete analysis is being performed on an event-by-event basis. Experimental data are then compared to the theoretical predictions where events are generated by numerical codes based on pre-equilibrium and statistical models and then filtered through a software replica of the setup. Differences between the experimental data and the predicted data put into evidence effects related to the entrance channel and to the cluster nature of the colliding ions. After a general introduction on the experimental campaign, this contribution will focus on the preliminary results obtained so far.

1. Introduction

The idea of $\alpha$-cluster structure in nuclei has been known since a long time [7]. The first $\alpha$-cluster structure model of nucleus was proposed in the sixties by Ikeda, to describe the structure of the $\alpha$-
conjugated nuclei (2Z=2N); the α-cluster structure appear at excitation energies close to the α-decay threshold. Nowadays, the nuclear clustering theories have gained new momentum due to the study of neutron-rich and exotic weakly-bound nuclei [8]. The clusters in nuclear systems could be pre-formed inside them or related to their dynamical formation. While for light nuclei the interplay between clusters emission with nuclear structure and reaction dynamics has been pointed out [7,5], in medium-mass nuclei the presence of clusters is much more complicated. Here, the interplay between preformation and coalescence plays a significant role. It is not evident whether the emission or capture of α-cluster implies that such an α-cluster is permanently present in the nucleus: it could be formed or dissolved at the instant of emission or capture.

Therefore, an interesting way to investigate the structural properties of medium mass systems is to search for the α-clustering effects in non-traditional observables, like those deriving from studies of pre-equilibrium process. In central collisions, the competition between evaporation and pre-equilibrium particles emission as a function of entrance channel parameters could provide information about the α-particles coalescence and cluster pre-formation probabilities in compound nuclei [5].

In this framework, since some years, the NUCL-EX collaboration has been engaged in an experimental campaign to study clustering structure effects in nuclei looking at the pre-equilibrium emission of light charged particles. The analysis of $^{16}$O+$^{116}$Sn at 8, 12, 16 AMeV [3,4] brought to the observation of an over-production of α-particles emitted during the non-equilibrium stage of fusion nuclear reactions. The main hypothesis was to ascribe the α-particle excess to the effects induced by the cluster structure in the $^{16}$O projectile nucleus. Following these results, a new experiment was proposed to obtain an evaluation of clustering effects in a model independent way: the comparative study of light charge particles emission from two different fusion reactions with different isospin ratio, $^{16}$O+$^{65}$Cu and $^{19}$F+$^{56}$Cu at 16 AMeV [2]. Although the analysis is still in progress, evidences of an α-particle fast production excess have been observed for both systems. A slight overproduction is moreover observed in the $^{19}$F induced reaction with respect to the $^{16}$O one. This might be ascribed to the lower energy of the predicted cluster state of the $^{19}$F.

2. The Experiment

In order to continue the extensive experimental campaign, a comparative study of four nuclear reactions: $^{18}$O+$^{28}$Si, $^{16}$O+$^{30}$Si and $^{19}$F+$^{27}$Al at 7 AMeV and $^{16}$O+$^{30}$Si at 8 AMeV has been performed. The reactions main characteristics are reported in Table 1.

| Entrance Channel | $E_{\text{beam,lab}}$ (AMeV) | $\theta_{\text{grazing}}$ (deg) | $E^*_{\text{CN}}$ (MeV) | $\sigma_{\text{fus}}$ (mb) | $\nu_{\text{lab, res}}$ (cm/ns) | E.R. Distrib. | $\delta_{\text{lab}}$ (deg) |
|------------------|-----------------------------|-------------------------------|------------------------|-----------------------------|------------------------|--------------------------|-----------------------------|
| $^{16}$O+$^{30}$Si | 7                           | 10.1                          | 88.0                   | 1081                        | 1.28                   | 0-30                     |                             |
| $^{16}$O+$^{30}$Si | 8                           | 8.8                           | 98.4                   | 1070                        | 1.37                   | 0-30                     |                             |
| $^{18}$O+$^{30}$Si | 7                           | 9.0                           | 98.5                   | 1110                        | 1.44                   | 0-28                     |                             |
| $^{19}$F+$^{27}$Al | 7                           | 8.9                           | 103.5                  | 1100                        | 1.52                   | 0-28                     |                             |

For central impact parameters and when the complete fusion occurs, all the studied reactions lead to the formation of the same compound nucleus, the $^{46}$Ti$^*$, even if with slightly different excitation energies ($E^*_{\text{CN}}$); therefore, a small difference in their de-excitation chain is expected. Otherwise, the choice of the same beam energy (7 AMeV) implies that the non-equilibrium processes should be almost the same [5]. The $^{16}$O+$^{30}$Si reaction at 8 AMeV has been used to produce the compound nucleus at the same excitation energy of the $^{18}$O+$^{28}$Si at 7 AMeV, hence the same statistical component.

The main goal of the experiment is to study the competition between fast emission and compound nucleus thermal evaporation and its possible relation to the structure of the colliding partners. For this purpose, the pre-equilibrium component of the particle emission spectra for these systems, especially
the alpha-particle emission, has been measured and compared since it may be related either to the pre-
formation of clusters in nuclei or to their formation during the collision dynamics. Both types of particles
emission are produced in central events, which could be selected imposing the coincidence between an
evaporation residue and one or more light charged particles.

In these medium-mass systems, the influence of possible structure effects, especially those related to
the alpha-clustering, can be derived from the comparison of the different entrance channels, where the
neutron and proton numbers of the colliding partners have been varied. Some information on the fast
emission mechanism and its competition with statistical evaporation can be extracted from the
comparison between statistical and pre-equilibrium light charged particle multiplicities and from the
ratios of yields in specific exit channels.

2.1. The Experimental Details

The experiment has been performed at the Legnaro National Laboratories, with the $^{16,18}\text{O}$ and $^{19}\text{F}$ beams
provided by the TANDEM-ALPI acceleration system. The GARFIELD plus RCo experimental setup,
fully equipped with digital electronics [6], was used to detect light charged particles, in the whole
apparatus, and heavier particles (like evaporation residues) in RCo. The performances of the apparatus
permit the full event reconstruction and the study of many-body correlations. The apparatus has 488
detecting cells with a geometrical coverage of the order of 80% of $4\pi$.

The GARFIELD array covers the polar angles $\vartheta = 30^\circ$-$150^\circ$. It consists of two drift chambers, filled
with CF$_4$ gas at a pressure of 50 mbar, with gas microstrip read-out for the energy loss, $\Delta E$, signals; they
are divided in subsectors, each of which covering $\sim 7^\circ$ in azimuthal angle. In each sector four CsI(Tl)
sclintillators define four polar angle regions of about 14° and allow to detect the residual energy. The
particles identification in charge and energy has been made via $\Delta E$-$E$ (μstrips-CsI(Tl)) technique and
Fast vs. Slow pulse shape analysis of the CsI(Tl) signals technique; this last technique allows to obtain
also light charged particle masses. The accuracy of energies is of the order of few percent with a 0.8-1
AMeV threshold.

The Ring Counter (RCo), covering $\vartheta = 7^\circ$-$17^\circ$, is a three-stage telescope consisting of an ionization
chamber (IC), filled with CF$_4$ gas at a pressure of 25 mbar and divided in eight azimuthal sectors; behind
each sector, an eight strip 300 μm thick silicon pad (Si) forms the second stage, followed by the third
stage composed of 6 CsI(Tl) scintillators. Using the gas section, particles and fragments have been
identified in charge with energy thresholds of 0.8-1 A MeV via $\Delta E$-$E$ (IC-Si) technique. Moreover, the
mass determination for light fragments stopped in the silicon is obtained, using the pulse shape analysis
(PSA) technique in Si, with a quite lower threshold (~2-3 AMeV). The lighter charge particles have
been identified via $\Delta E$-$E$ (Si-CsI(Tl)) technique and/or through the Fast vs. Slow pulse shape analysis
of the CsI(Tl) signals technique. A percent accuracy in the determination of the particle and fragment
energy is possible in the RCo detector. Due to the high counting rate of elastic scattering, the smallest
angles were shielded through an appropriate collimation system. The Evaporation Residues (ER) have
been collected in an angular range $\vartheta =8.6^\circ$-$17^\circ$, just beyond the grazing angles.

2.2. The Events Selection

To carry out a dedicated analysis, separate groups of events have been selected. The first one, which
will be discussed in this paper, is related to central events; it was fulfilled asking for the detection of the
evaporation residue in the forward direction (RCo) in coincidence with at least one light charged particle
in the whole apparatus (GARFIELD+RCo). The coincidences with evaporation residue have been
selected setting proper gates in the IC vs. Si $\Delta E$-$E$ energy spectra of the RCo and asking for any
coincident particle in the entire apparatus. The evaporation residues are characterized by a velocity close
to the center of mass velocity of the reaction (see Table 1). Since a high oxygen contamination of silicon
target was observed, a very strict selection on experimental data was performed for the sub-sequent
analysis. The only considered events are those for which the total charge has been at least the 70% of
the expected total charge ($Z_{\text{projectile}}+Z_{\text{target}} =22$): therefore, $Z_{\text{tot}} >16$, which is the maximum possible charge
related to the contaminated events. A correlation between the detected charge vs. the energy distribution
in the laboratory system for the reaction $^{16}$O+$^{30}$Si at 8 AMeV is shown in Figure 1 for the total events (left panel) and for the selected central events (right panel) for the experimental data set.

![Figure 1. Correlation between the detected particles charge Z and their laboratory energy $E_{\text{lab}}$ in the case of total events (left panel) and in the case of only central events (right panel) for the $^{16}$O+$^{30}$Si at 8 AMeV.](image)

3. Experiment vs. Simulation: Preliminary Results

A preliminary analysis has been performed on an event-by-event basis; the experimental observables have been studied and compared with those obtained by model predictions performed either with the statistical model GEMINI++ [9], based on a complete fusion hypothesis, and with some dynamical codes, like SMF [10] or AMD [11] codes, followed by GEMINI++ as afterburner. The effects of the experimental apparatus on the theoretical events have been taken in account through a software replica of the experimental array.

The GEMINI++ code [9] describes the thermalized emission from a compound nucleus; it is based on Hauser-Feshbach model, in which the Weisskopf description of evaporation mechanism is coupled with a quantum description of angular momentum and it gives information on the differences between the four reactions connected to the major part of the cross section, which is related to the de-excitation of a thermalized source.

The TWINGO code [10], based on the Stochastic Mean Field approximation, simulates the dynamical part of the reactions. Each nucleon is described by a set of test particles, arranged in a phase-space lattice and subject to a mean field. The time evolution of the one-body distribution function $f(\mathbf{r}; \mathbf{p}; t)$ is described using the Boltzmann-Nordheim-Vlasov (BNV) transport equation, that is substantially the Vlasov equation including the collision term. Related to initial impact parameter, this code produces the primary fragment distributions as a function of the impact parameter; these primary fragments are the hot ions produced in the earlier stage of the reaction and they can decay by emitting particles, gamma-rays and/or fissioning. To simulate the secondary particle emission, the GEMINI++ code has been used as afterburner.

The AMD (Antisymmetrized Molecular Dynamics) [11] is based on a Stochastic equation of motion for the Gaussian wave-packets representing the colliding nucleons and takes into account the particle-particle correlations with the possibility of describing and varying the degree of clusterization of the interacting partners.

3.1. Preliminary Results

The experimental energy distributions of the light charged particles in coincidences with residues have been compared with the predictions of the theoretical models. From the preliminary results, one can observe a slight difference in the four systems when compared to the complete fusion scenario.

Focusing on predictions of the statistical model simulated with GEMINI++, the first comparison between the single particle emission spectra and the simulated statistical component of the reactions, shows very similar experimental and simulated proton spectra on the whole angular range, and also $\alpha$-particle spectra at backward angles; therefore, the complete fusion seems to account for almost all the
central collision available cross section. On the contrary, a slight difference is observed in the α-particle spectra at the most forward angles, as signature of a small component of α-particle pre-equilibrium emission.

As shown in the Figure 2, for the angular region $8.6^\circ \leq \theta \leq 13.2^\circ$ (RCO), the results from the GEMINI++ complete fusion predictions (red lines in Figure 2) are in good agreement with the data for the proton, while a slight difference for α-particles is observed. From the comparison of the different systems with their own statistical predictions, one can observe a slight difference in fast emission for the different entrance channels. For example, looking at the three systems at 7 AMeV, a similar overproduction compared to the statistical spectra are present for the $^{16}$O and $^{18}$F cases while almost no effect is observed for $^{16}$O, even if they have the same projectile velocity. In $^{16}$O+$^{30}$Si at 8 AMeV case, the higher the beam incoming energy, the higher the α-overproduction.

![Figure 2](image_url)

**Figure 2.** Experimental energy distributions (black full dots) collected at $8.6^\circ \leq \theta \leq 13.2^\circ$ for protons (top panels) and α-particles (bottom panels), for the four studied reactions, respectively from left to right: $^{16}$O+$^{30}$Si at 7 AMeV, $^{16}$O+$^{30}$Si at 8 AMeV, $^{18}$O+$^{28}$Si at 7 AMeV and $^{18}$F+$^{27}$Al at 7 AMeV. In all panels comparison to model predictions are provided: GEMINI statistical model (red line) and SMF+GEMINI++ (green lines) and AMD+GEMINI++ (blue lines). Model prediction are filtered through a software replica of the apparatus. The distributions have been normalized to the experimental maximum.

When we look at dynamical model simulations, Figure 2 shows some irregular trends. The SMF code (green lines in Figure 2), shows up some limitations in the description of the pre-equilibrium phenomenon: many nucleons emitted before the equilibrium cannot be properly reconstructed in the final event due to the impossibility to reconstruct them from scattered test particles; moreover, TWINGO, being based on Stochastic Mean Field approximation, is not even able to build up clusters like α-particles and also these fast particles are missing in the final spectrum; therefore, only statistical decay of the primary fragments can be taken in account. However, from this first comparison we observe a system which has anyway lost some nucleons and clusters in the early stage of the reaction and therefore results in colder emission spectra with respect to GEMINI++ alone. In this case, hence, the predictions on the fast emission can then be obtained only as a difference to the experimental spectra.

Finally, the AMD+GEMINI++ simulation (blue lines in Figure 2), being able to describe nucleon-nucleon correlations, can give several information. The simulated spectra reproduce quite well the experimental ones; apart from a secondary peak, lower in energy than the barrier which appear in the α-particles AMD-spectra and it is not present in the data. The physical meaning of this peak is under study.
Several calculations are planned to change and optimize the input parameters, especially related to the clusterization factor; unfortunately, the AMD code is very time expensive, therefore, the time needed to run the code for a sufficient number of events to compare to exclusive data is very long.

4. Conclusions and Perspectives
In order to probe pre-equilibrium and possible α-clustering effects in nuclei, the preliminary results for the $^{48}$Ti* compound system, formed through four different entrance channels: $^{16}$O+$^{30}$Si at 8 A MeV and $^{16}$O+$^{28}$Si, $^{18}$O+$^{30}$Si and $^{19}$F+$^{27}$Al at 7 A MeV have been studied. Even if the analysis is still preliminary, from the proton and α-particle spectra of all the reaction we can infer that, as expected at this bombarding energies, most of the cross section is well described by fusion-evaporation. However, some small differences can be observed at forward angles in the α-particle spectra which can be ascribed to pre-equilibrium emission.

A deeper analysis is needed to understand the pre-equilibrium process; to better disentangle the pre-equilibrium emission, it is planned to use the Moscow Pre-equilibrium Model [4], based on the Hybrid model, which takes into account a pre-equilibrium stage before a second thermalized emission stage and allows to take into account possible clusters pre-formation in the colliding partners, especially the projectile.

A further analysis will be performed to get a better insight on the reaction interplay, studying the particle-particle correlations with selection of specific decay channels (1α, 2α, 3α ...).

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