

PAPER • OPEN ACCESS

Pre-equilibrium emission and clustering in medium-mass nuclei: ^{46}Ti from $^{16}\text{O} + ^{30}\text{Si}$, $^{18}\text{O} + ^{28}\text{Si}$, $^{19}\text{F} + ^{27}\text{Al}$

To cite this article: M Cicerchia *et al* 2017 *J. Phys.: Conf. Ser.* **863** 012057

View the [article online](#) for updates and enhancements.

Related content

- [Di-neutron dynamics in medium-mass neutron-rich nuclei](#)
M Matsuo, Y Serizawa and K Mizuyama
- [N/Z effect on reaction mechanisms cross sections in the \$^{78}\text{Kr} + ^{40}\text{Ca}\$ and \$^{86}\text{Kr} + ^{48}\text{Ca}\$ collisions at 10 A MeV](#)
B Gnoffo, S Pirrone, G Politi et al.
- [NUCLEAR GAMMA-RAY DE-EXCITATION LINES AND CONTINUUM](#)
R. J. Murphy, B. Kozlovsky, J. Kiener et al.

Pre-equilibrium emission and clustering in medium-mass nuclei: ^{46}Ti from $^{16}\text{O} + ^{30}\text{Si}$, $^{18}\text{O} + ^{28}\text{Si}$, $^{19}\text{F} + ^{27}\text{Al}$

M Cicerchia^{1,2}, T Marchi³, F Gramegna¹, M Cinausero¹, J Mabilia¹, D Fabris⁴, A Caciolli^{2,4}, G Collazuol^{2,4}, D Mengoni^{2,4}, M Degerlier⁵, L Morelli⁶, M Bruno⁶, M D'Agostino⁶, S Barlini⁷, M Bini⁷, G Pasquali⁷, S Piantelli⁷, G Casini⁷, G Pastore⁷, D Gruyer⁷, P Ottanelli⁷, S Valdrè⁷, N Gelli⁷, A Olmi⁷, G Poggi⁷, E Vardaci⁸, I Lombardo⁸, D Dell'Aquila⁸, S Leoni⁹, N Cieplicka⁹ and B Fornal¹⁰

¹INFN Laboratori Nazionali di Legnaro, Legnaro (PD), Italia.

²Dipartimento di Fisica e Astronomia, Univ. di Padova, Padova, Italia.

³KU Leuven, Department of Physics and Astronomy Instituut voor Kern- en Stralingsfysica, 3001 Leuven, Belgium.

⁴INFN Sezione di Padova, Padova, Italia.

⁵Science and Art Faculty, Physics Department, Nevsehir Haci Bektas Veli Univ., Nevsehir, Turkey.

⁶INFN Sezione di Bologna e Dipartimento di Fisica e Astronomia, Univ. di Bologna, Bologna, Italia.

⁷INFN Sezione di Firenze e Dipartimento di Fisica e Astronomia, Univ. di Firenze, Firenze, Italia.

⁸INFN Sezione di Napoli e Dipartimento di Fisica, Univ. Federico II Napoli, Napoli, Italia.

⁹INFN Sezione di Milano e Dipartimento di Fisica, Univ. di Milano, Milano, Italia.

¹⁰Institute of Nuclear Physics, Polish Academy of Sciences Krakow, Poland.

E-mail: cicerchia@lnl.infn.it

Abstract. The study of nuclear cluster states bound by valence neutrons is a field of recent large interest. In particular, it is interesting to study the pre-formation of α -clusters in α -conjugate nuclei and the dynamical condensation of clusters during nuclear reactions. The NUCL-EX collaboration (INFN, Italy) is carrying out a research campaign studying pre-equilibrium emission of light charged particles and cluster properties of light and medium-mass nuclei. For this purpose, a comparative study of the three nuclear reactions: $^{16}\text{O} + ^{30}\text{Si}$, $^{18}\text{O} + ^{28}\text{Si}$ and $^{19}\text{F} + ^{27}\text{Al}$, has been recently carried out using the GARFIELD+RCO 4π setup. After a general introduction on the experimental campaign, the preliminary results for the three systems are presented.

1. Introduction

The idea of α -cluster structure in nuclei has been known since a long time [1]. Nowadays, interest in nuclear clustering has gained new momentum due to the study of neutron-rich and exotic weakly-bound nuclei [2]. In light mass nuclei, clustering emission is a good tool to study the interplay between nuclear structure and reaction dynamics. The presence of clusters in medium-mass nuclei is much



more complicated. Here, the interplay between preformation and coalescence plays an important role. It is not evident that 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, it is of particular interest to search for α -clustering effects in non-traditional observables, like those deriving from pre-equilibrium process studies. The pre-equilibrium spectra could provide information about the α pre-formation probabilities in compound nucleus [3].

In these past few years, the NUCL-EX collaboration has been engaged in an experimental campaign to study a possible α -cluster structure in α -conjugate nuclei probing pre-equilibrium emission of light charged particles (LCP) at excitation energies close to LCP emission threshold. In particular, the analysis of $^{16}\text{O} + ^{116}\text{Sn}$ at 8, 12, 16 A MeV [4] brought to the observation of an overproduction of α -particles emitted during the non-equilibrium stage of fusion nuclear reactions. One of the hypothesis for the α -particle excess is to be ascribed to the effects induced by the cluster structure in the ^{16}O projectile nucleus. Following these results, a new experiment was proposed to probe the α -cluster structure in ^{16}O in a model independent way: the comparative study of $^{16}\text{O} + ^{65}\text{Cu}$ and $^{19}\text{F} + ^{62}\text{Ni}$ at 16 A MeV [5]. 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 can be ascribed to the lower energy of the predicted cluster state of the ^{19}F .

2. Experimental details and preliminary results

To continue the previous campaign, we have performed a comparative study of four nuclear reactions: $^{16}\text{O} + ^{30}\text{Si}$, $^{18}\text{O} + ^{28}\text{Si}$ and $^{19}\text{F} + ^{27}\text{Al}$ at 7 A MeV and $^{16}\text{O} + ^{30}\text{Si}$ at 8 A MeV. The most important features of these reactions are reported in Table 1.

Table 1. The most important features of the reactions.

Projectile		Target	Grazing		Compound Nucleus				
Ion	E_{lab} (A MeV)	Isotope	θ_{lab} (deg)	Isotope	Mass Asymm.	σ_{fus} (mb)	E* (MeV)	Lab. Vel. (cm/ns)	E.R. Distrib. θ_{lab} (deg)
^{16}O	7.0	^{30}Si	10.1	^{46}Ti	0.30	1081	88.0	1.28	0-30
^{16}O	8.0	^{30}Si	8.8	^{46}Ti	0.30	1070	98.4	1.37	0-30
^{18}O	7.0	^{28}Si	9.0	^{46}Ti	0.22	1110	98.5	1.44	0-28
^{19}F	7.0	^{27}Al	8.9	^{46}Ti	0.17	1100	103.5	1.52	0-28

The main goal of the experiment was to measure and compare the pre-equilibrium component of the particle emission spectra for the three different systems. The ratios between statistical and pre-equilibrium LCP multiplicities and between different exit channels allows to extract information about the influence of α -clustering in these medium-mass systems. In the three reactions at 7 A MeV, the beam velocity was kept constant, as this parameter strongly determines the evolution of pre-equilibrium processes. The $^{16}\text{O} + ^{30}\text{Si}$ reaction at 8 A MeV was used to populate the ^{46}Ti at the same excitation energy as in the $^{18}\text{O} + ^{28}\text{Si}$ at 7 A MeV.

The experiment has been performed at the LNL, with the beams provided by the TANDEM-ALPI acceleration system. The GARFIELD array coupled with RCo, fully equipped with digital electronics [6,7], was used to detect LCP and evaporation residues. The performances of the apparatus permit the full event reconstruction and the study of many-body correlations.

Following an initial identification of particles and the energy calibration procedure, a preliminary analysis was performed on an event-by-event basis. The experimental data were initially compared with the simulated events from a statistical model, GEMINI++ [8], where the effects of the filter related to the apparatus replica were taken into account. The GEMINI code can describe only the

thermalized emission from a compound nucleus, but it can give information on the differences between the three reactions connected to the major part of the cross section, which is related to the de-excitation of a thermalized source.

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. On the contrary, a much larger difference is observed in the α -particle spectra at the most forward angles. Waiting for the calibration procedure to be completed, for a first estimate of the expected fast emission in the four cases, the data have been compared with the predictions of the statistical model simulated with GEMINI++. Figure 1 shown the comparison of proton and α -particles experimental vs. calculated spectra for $^{18}\text{O} + ^{28}\text{Si}$ at 7 A MeV. The shape of other reactions spectra are similar.

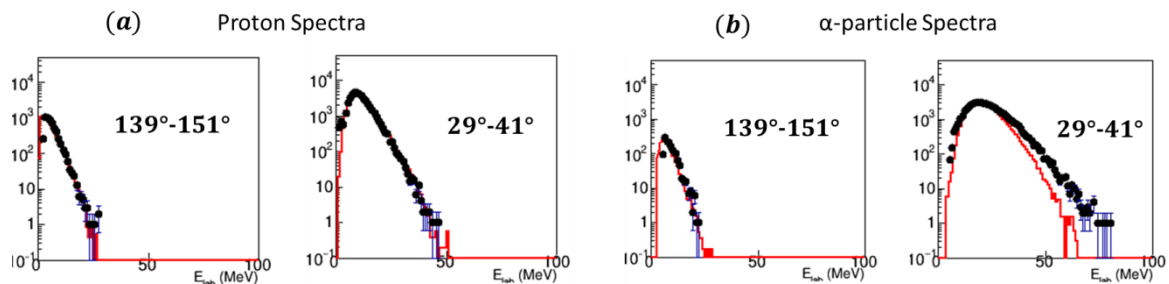


Figure 1. Comparison of laboratory energy spectra (black dots) of protons (a) and α -particles (b) for the system $^{18}\text{O} + ^{28}\text{Si}$ at 7 A MeV with preliminary calculations from GEMINI++ code (red line). The distributions have been normalized to the total area.

3. Conclusion

We have studied the light particle emission from the reactions: $^{16}\text{O} + ^{30}\text{Si}$, $^{19}\text{F} + ^{27}\text{Al}$ and $^{18}\text{O} + ^{28}\text{Si}$ at 7 A MeV and $^{16}\text{O} + ^{30}\text{Si}$ at 8 A MeV in order to probe pre-equilibrium and possible α -clustering effects in nuclei. The first preliminary comparison between the experimental and the simulated spectra evidenced that the shape of the proton spectra in the whole angular range and of the α -particle spectra at backward angle are reasonably reproduced by the statistical model. While at forward angle the experimental α -particle spectra show a slightly overproduction of α -particles at higher energies. A more complete analysis is needed to understand the process, looking to pre-equilibrium models which also take into account other types of clusters. This will permit to better disentangle the pre-equilibrium emission. A complete analysis will be performed to correlate the velocity and angular ranges of the heavy fragments and light charged particles. On the other hand, the use of dynamical codes such as the SMF [9] followed by an afterburner decay code and pre-equilibrium models such as the Hybrid model [10] is under study.

References

- [1] Von Oertzen W *et al* 2006 *Phys. Rep.* **432** 43
- [2] Freer M *et al* 2007 *Rep. Progr. Phys.* **70** 2149
- [3] Hodgson P E and Běták E 2003 *Phys. Rep.* **374** 1
- [4] Kravchuk V L *et al* 2010 *EPJ WoCs* **2** 10006
- [5] Fabris D *et al* 2013 *PoS (X LASNPA)* 061.D
- [6] Gramegna F *et al* 2004 *Proc. of IEEE Nucl. Symposium* Roma Italy 0-7803-8701-5/04
- [7] Bruno M *et al* 2013 *Eur. Phys. Jour.* **A49** 128
- [8] Charity R J 2010 *Phys. Rev.* **C82** 014610
- [9] Colonna M *et al* 1998 *Nucl. Phys.* **A642** 449
- [10] Fotina O V *et al* 2010 *Phys. Atom. Nucl.* **73** 1317