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Pre-equilibrium Emission and α -clustering in Nuclei

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Abstract. The study of nuclear states built on clusters bound by valence neutrons in their molecular configurations is a field of large interest, which is being renewed by the availability of exotic beams: clustering is, in fact, predicted to become very important at the drip-line, where weakly bound systems will prevail. Although for light nuclei at an excitation energy close to the particle separation value there are experimental evidences of such structure effects, this is still not the case for heavier nuclear systems. Many attempts have been done using preformation alpha clustering models, but there is still a lack of experimental data capable to give a direct feedback. In particular, searching for alpha clustering effects in medium mass systems is still a challenge, which can give new hints in this subject. In the past we have studied the reactions 250, 192 and 130 MeV $^{16}\text{O} + ^{116}\text{Sn}$, observing a significant increase in the fast emitted α -particle yield. This effect was ascribed to the presence of pre-formed α -clusters in the ^{16}O projectile nucleus. In order to investigate these aspects, in a model independent way, a new experimental campaign has been performed with the GARFIELD + RCo set up, to compare results from two different reactions: a double magic α -cluster (^{16}O) and a non-magic α -cluster projectile (^{19}F) at the same beam velocity (16 AMeV) have been chosen, impinging respectively on ^{65}Cu and ^{62}Ni targets, thus leading to the same $^{81}\text{Rb}^*$ compound nucleus. The angular distributions and the light charged particles emission spectra in coincidence with evaporation residues have been measured and analyzed. The preliminary results of the data analysis and the main features of the theoretical model used for their interpretation are presented.

1. Introduction

The idea that cluster of nucleons might be pre-formed prior to emission from nuclei has been discussed since many years and was originally proposed by Hafstad and Teller in 1938 [1]. More recently a large interest has been re-addressed to the problem of clustering in nuclei, due to 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 [2]. Examining the binding energies of nuclei in their ground state as a function of the mass number, the particular behaviour found shows a systematic trend, well described by the liquid drop model as due to a shell structure effect. In particular the specific property of the nucleon–nucleon force, for which a saturation arises due to the coupling to zero of both the spin and the isospin quantum numbers, produces a very strong binding of α -particles which can therefore be recognized as a unique cluster subsystem in nuclei. The α -particle is the main ingredient in the concept proposed by Ikeda in his diagram [3], where highly clustered states are predicted at excitation energies around the energy threshold for the decomposition into specific cluster channels. In the extended Ikeda diagram, moreover, it is suggested that in neutron-rich systems neutrons may act as valence particles which can be exchanged between the α -particle cores, in a similar way electrons are exchanged in atomic molecules. In the nuclear case the covalent neutrons stabilize the unstable multi-cluster states, giving rise to nuclear structures which may be described by molecular concepts. These concepts are well reproduced in model independent approaches like the Fermionic Molecular Dynamics (FMD) by Feldmeier et al. [4,5] or the Antisymmetrized Molecular Dynamics (AMD) with effective N-N forces by Horiuchi and Kanada-En'Yo [6-7].

Up to now, these structures are mainly described by theory, but still a lack of experimental data is present, mainly due to the low intensity of exotic beams presently available. Therefore, while waiting for the availability of the next generation of radioactive beam facilities like SPES [8], HIE-ISOLDE [9] and SPIRAL2 [10], it is 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 information on the cluster formation process.

2. Previous measurements

In a previous campaign the formation of the ^{132}Ce compound nucleus by means of ^{16}O induced reaction on ^{116}Sn at various incident energies has been studied with the aim of identifying the amount of pre-equilibrium emission in asymmetric entrance channel reactions. During this campaign an extra yield was observed for pre-equilibrium α -particle emission, which was not reproduced by a Hybrid Exciton Model based prediction [11]. The model was using a modified version of the PACE2 code, where the main variation was the introduction of a non-equilibrium stage before the complete thermalization and compound nucleus formation. The relaxation process which occurs during the fusion reaction is firstly accounted for by the exciton model, based on the Griffin prescription [12], in which the description of the angular distribution of the fast emitted particles is still an intricate question [13]. The main parameter to be set is the initial number of excitons ($n_0 = n_{\text{particles}} + n_{\text{holes}}$), that can be estimated from the empirical trend described in the work by N. Cindro et al. [14] and it is mainly related to the projectile properties. In the case of the considered ^{16}O induced reactions this number is $n_0 = 17 = 16p + 1h$.

Starting from such initial exciton number, a general good description was obtained by model prediction when compared to double differential cross section proton energy spectra at all the incident energies considered. On the contrary, an enhanced fast α -particle production was observed experimentally, especially at the most forward measured angles, which was not accounted for by the calculated distributions. A possible explanation of this enhanced α -particle emission might be the effects induced by the α -cluster structure in the ^{16}O projectile [15].

This effect has therefore been taken into account in the model introducing a pre-formation cluster probability. The combination of different initial configurations has been considered: in particular a second configuration has been chosen in which the ^{16}O projectile is supposed to be divided into a ^{12}C core plus an α particle. The probability of occurrence of this last pattern with respect to the original one (i.e. ^{16}O projectile as a whole) is the free parameter to be determined from the comparison to the experiment. The data have been better reproduced with a quite sizeable probability (up to 50%) of α -cluster pre-formation. However, while the shape of the energy spectra seems to be better described, still

problems are present in the reproduction of total multiplicities of light charged particle, which needs to be understood. Results are shown in Fig.1 where the experimental multiplicity obtained at 250MeV $^{16}\text{O}+^{116}\text{Sn}$ are compared with the predicted values both for the evaporative and the fast emission part. As it can be noticed the calculated values of the total (mainly evaporative) multiplicities for alpha and protons are too large and this is due to the PACE2 prediction which seems to underestimate the neutron emission. Similar results have been observed in literature [16].

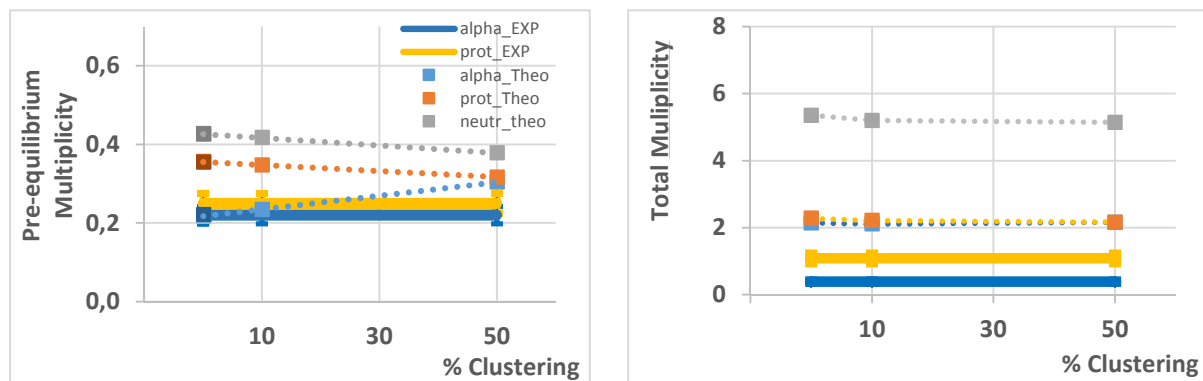


Figure 1. Comparison with calculated and experimental multiplicity for the $^{16}\text{O}+^{116}\text{Sn}$ reaction at 250 MeV. On the left pre-equilibrium multiplicity, on the right total (pre-equilibrium plus evaporative multiplicities). The calculations have been performed with the Hybrid Exciton Model +PACE2 code (see text) with different pre-formation cluster probability (0%, 10% and 50%).

For what it concerns the fast emission still an overestimation is observed for proton multiplicities, while more reasonable values are obtained with α -particles. However, the percentage of fast α -particles with respect to the total ones emitted in the experimental data is not at all reproduced by the calculation ($[M^{\alpha}_{\text{pre}}/M^{\alpha}_{\text{tot}}]_{\text{exp}} \sim 0.5$; $[M^{\alpha}_{\text{pre}}/M^{\alpha}_{\text{tot}}]_{\text{theo}} \sim 0.1$). Further experimental data and more exclusive observables are therefore needed to compare models and data for a better understanding of the whole process.

In order to obtain, in a model independent way, a confirmation of possible effects of α -cluster structure in the projectile, two different entrance channel reactions have been studied in an energy range where fast emission was predicted: in particular a double magic α -cluster (^{16}O) and a non-magic α -cluster projectile (^{19}F) have been chosen, impinging respectively on ^{65}Cu and ^{62}Ni targets, thus leading to the same $^{81}\text{Rb}^*$ compound nucleus.

3. The Experiment

The two fusion reactions $^{16}\text{O} + ^{65}\text{Cu}$ and $^{19}\text{F} + ^{62}\text{Ni}$ have been studied at 16 A MeV incident energy in order to directly compare their light charged particle emission spectra and yield ratios. The same projectile velocity was chosen since the pre-equilibrium emission is expected to mostly depend on this parameter [17]. In this situation, even with an expected small difference in the evaporative part due to the excitation energy ($E^* = 209$ MeV and $E^* = 240$ MeV respectively for ^{16}O and ^{19}F induced reactions), the fast emission process is predicted to be almost the same for both reactions. Any observed difference and overproduction of fast α -particle between the two cases would suggest, in a model independent way, a possible influence of the projectile α -structure effect.

The experiment has been performed at the Legnaro National Laboratory where the ALPI-TANDEM XTU accelerator complex was used for the ^{16}O and ^{19}F beam production and acceleration. The experimental apparatus was the GARFIELD array, implemented with the Ring Counter (RCo) at the most forward angles, fully equipped with digital electronics [18]. The GARFIELD set-up consists of two large drift chambers employing micro-strip gas chamber (MSGC) as amplified ΔE stage and CsI(Tl)

scintillators as residual energy detectors. It can identify light charged particles and fragments in an angular range from $\theta = 29^\circ$ to $\theta = 151^\circ$. The RCo is a three-stage annular detector made by Ionization Chamber as first stage, a reverse mounted nTD strip silicon detector as second one, CsI(Tl) crystals as final stage. It covers the angular range between $\theta = 5^\circ$ and $\theta = 17^\circ$.

The coupled GARFIELD plus RCo apparatus can perform complete high quality particle identification (both Z and A) and energy determination in a nearly 4π coverage ($\theta = 5^\circ$ - 151°) for light charged particles and, in the most forward direction ($\theta = 5^\circ$ - 17°) even for fragments with charge up to $Z=14$. Z identification is provided up to $Z=28$ -30 in the whole subtended angular range.

4. Preliminary Results

Fully identified light charged particles have been measured both in single and in coincidence with Evaporation Residues (ERs), detected in the RCo in the range $\theta = 8.6^\circ$ - 17° (just beyond the grazing angle). The ERs have been selected setting the proper gates in the IC-Si ΔE -E spectra.

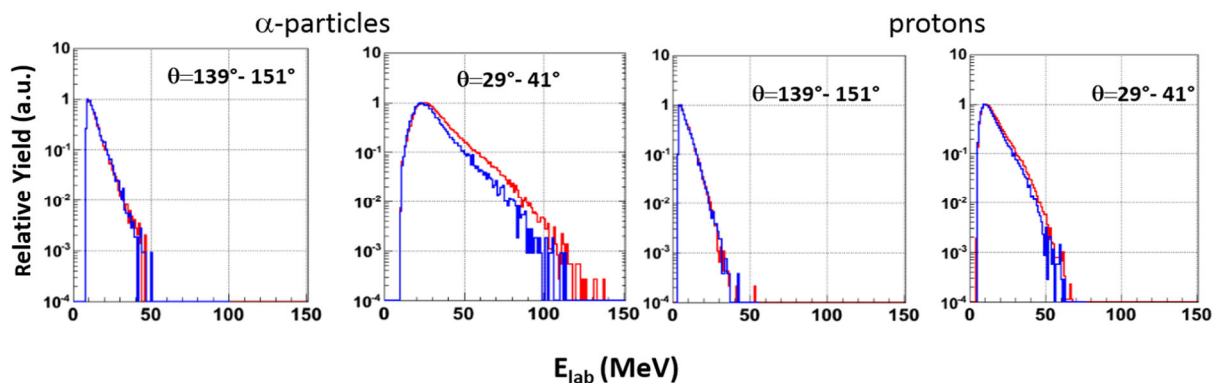


Figure 2. Double differential energy spectra in the laboratory frame (normalized to the maximum) for α -particles (left panel) and for protons (right panel) for the two reactions 256 MeV $^{16}\text{O} + ^{65}\text{Cu}$ (blue line) and 304 MeV $^{19}\text{F} + ^{62}\text{Ni}$ (red line) at two different detecting angles ($\theta = 29^\circ$ - 41° , $\theta = 139^\circ$ - 151°).

In this preliminary analysis, only the double differential energy spectra obtained in coincidence with ERs for α -particles and protons and detected in the GARFIELD drift chambers have been sorted out. The α -particle and proton spectra, normalized to the maximum, obtained for the two systems have been compared, as shown, as an example, in Fig.2. The two reactions show very similar proton spectra on the whole angular range, except for a small difference at the most forward angle, which can be ascribed to the slightly larger excitation energy of the ^{19}F induced reaction. A much more evident difference is, on the contrary, observed in the case of the α -particle emission spectra, especially at the most forward GARFIELD detection angles. The calculated emission spectra performed with an evaporative code like PACE2 (or PACE4), which mainly takes into account the difference in the excitation energy of the Compound Nucleus, confirms a small difference for the two systems and compatible to that one experimentally observed in the proton decay channel. When compared to the data, they also support the idea that a second fast emission source is needed for both systems, to better describe mainly the α -particle decay channel. In the meanwhile that the data sorting and calibration procedure will be concluded, which will permit an complete experimental comparison between the two systems, a first evaluation of the expected amount of fast emission in the two cases was performed by means of the prediction of the Hybrid Exciton Model. The calculation was done starting from an initial exciton number of $n_0=17(16p+1h)$ in the case of $^{16}\text{O} + ^{65}\text{Cu}$. With this configuration the calculation seems to reasonably describe the shape of the α -particle spectra, except for an underestimation at the most

forward angle in GARFIELD, but, with the same initial parameter, it strongly overestimates the proton pre-equilibrium emission. In Fig.3 the comparison of the calculation is shown for α -particles and protons in the $^{16}\text{O}+^{65}\text{Cu}$ system at the most forward GARFIELD angular range ($\theta=29^\circ\text{--}41^\circ$).

Performing the same comparison in the case of the $^{19}\text{F}+^{62}\text{Ni}$ reaction, where an initial exciton configuration of $n_0=20(19\text{p}+1\text{h})$ was used, a quite similar result is obtained, as shown in Fig. 4 for the same angular range as in Fig.3. In the ^{19}F induced reaction case, the experimental fast α -particle overproduction is even larger than in the ^{16}O induced reaction, while the fast protons are, again, largely overestimated. A tentative explanation for the observed difference between the α -particle decay in the two systems may be the lower energy needed to break up the ^{19}F nucleus into $\alpha+^{15}\text{N}$ (4.01 MeV) with respect to the ^{16}O to be divided into $\alpha+^{12}\text{C}$ (7.2 MeV).

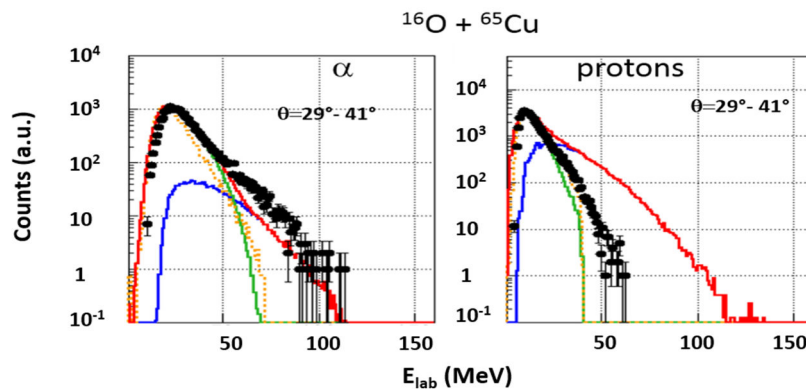


Figure 3. Comparison of experimental laboratory energy distribution (black dots) at $\theta=29^\circ\text{--}41^\circ$ of α -particles (left panel) and protons (right panel) for the system $^{16}\text{O}+^{65}\text{Cu}$ with preliminary calculations from the Hybrid Exciton Model (red line total, green line evaporative (PACE2), orange dots evaporative (PACE4), blue line pre-equilibrium). The normalization has been done at the area (exp. – total).

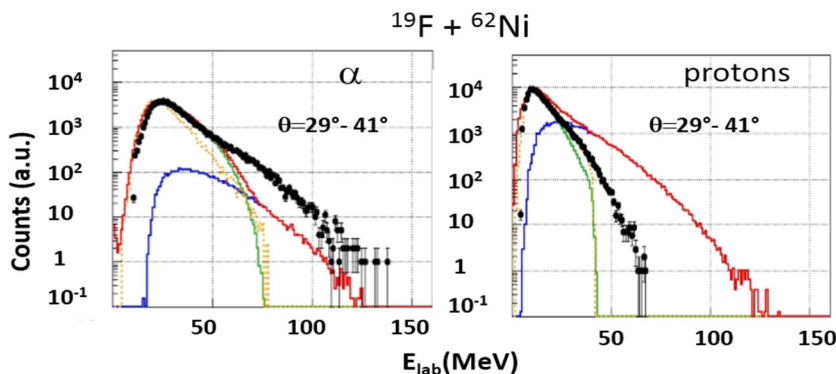


Figure 4. Same as Fig.3 for the $^{19}\text{F}+^{62}\text{Ni}$ system.

By changing the initial configuration parameter (i.e. diminishing the exciton number) the description of the α -particle slightly improves, but, on the contrary, this worsen the proton description. Once again, like it was observed in the $^{16}\text{O}+^{116}\text{Sn}$ case, a unique initial parameter in the Hybrid Exciton model is not able to describe both the proton and α -particle channels suggesting that some more attention has to be paid to the clustering structure effects. For example in the used calculation no deuteron emission is considered, which may strongly influence the relative proton decay probability. However part of the problem may be also in the total multiplicity, which is mainly related to the evaporative code used after the fast process steps [16], as observed in our previous data. This is to be further analysed.

5. Conclusions

In order to probe possible α -clustering effects in medium nuclei we are studying the secondary particle emission from the 256MeV $^{16}\text{O}+^{65}\text{Cu}$ and 304MeV $^{19}\text{F}+^{62}\text{Ni}$ systems. From the preliminary comparison between the two reactions a difference has been evidenced related to the fast α -decay channel, which can be linked to the difference in the projectile structure. In the meanwhile that the data analysis and calibration for the whole apparatus is completed, the experimental spectra detected in GARF in coincidence with ERs have been compared with the Hybrid Exciton Model proposed by O.V. Fotina [11,15]. At least in the GARFIELD angular range analysed up to now, using an initial exciton number estimated by the empirical trend reported in [14], the α -particle spectra seem to be reasonably reproduced as far as the shape is concerned, except for a small part at the most forward angles. On the contrary, using the same initial parameters, the fast emission of protons is largely overestimated. In a similar way, the model was not able to reproduce both protons and α -particle with the same initial parameters in our previous measurement related to the $^{16}\text{O}+^{116}\text{Sn}$ reaction study: in that case, however a better description of protons was obtained, while some added pre-formation probability was needed to describe the α -particle spectra. Moreover, looking more into details, an overestimate of the charged particle total multiplicity was also evidenced for that system, together with a lower weighting factor between fast and thermal emission especially for α -particles ($[M^{\alpha}_{\text{pre}}/M^{\alpha}_{\text{tot}}]_{\text{exp}} \sim 0.5$; $[M^{\alpha}_{\text{pre}}/M^{\alpha}_{\text{tot}}]_{\text{theo}} \sim 0.1$).

This demonstrates that a more complete analysis is needed to understand the process: in particular, due to the better performances reached in the present experiment in terms of identification and resolutions, the possibility of studying all different light charged particles decay channels will be possible. Moreover the larger angular range in which the particles have been identified will permit to better disentangle and study the pre-equilibrium emission. It will be needed to extract multiplicities, angular distributions and to study exclusive α - α , α -N correlation channels. From the theoretical point of view the Hybrid Exciton Model calculations has to be upgraded, following all particles and studying the coupling of fast emission with different evaporation codes. Moreover, it is under study the possible application of other theoretical approaches, like for example the dynamical AMD [19] code.

Due to the high resolution of the apparatus, even more peripheral collisions like the decay of the projectile (break-up) can be studied, in order to compare the ^{16}O and ^{19}F cases for what concern their α -structure through a complete reconstruction of the projectile-like decay.

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