PROCEEDINGS OF SCIENCE

Pre-equilibrium α-particle emission as a probe to study α-clustering in nuclei

D. Fabris[1,a], T. Marchi[b], F. Gramegna[b], M. Degerlier[c], V. L. Kravchuk[d] , M. Cinausero[b], S. Appannababu[b], G. Baiocco[e], L. Morelli[e], G. Casini[f], S. Barlini[f], M. Bini[f], S. Carboni[f], N. Gelli[f], A. Olmi[f], G. Pasquali[f], S. Piantelli[f], G. Poggi[f], S. Valdrè[f], O. V. Fotina[g], S. A. Goncharov[g], D. O. Eremenko[g], O. A. Yuminov[g], Yu. L. Parfenova[g], S. Yu. Platonov[g], V. A. Drozdov[g], A. Brondi[h], R. Moro[h], E. Vardaci[h].

[a] *INFN Sezione di Padova, Padova, Italy*

[b] *INFN, Laboratori Nazionali di Legnaro, Legnaro (Padova), Italy*

[c] *Nevsehir Haci Bektas Veli University, Science & Art Faculty, Physics Department, Nevsehir, Turkey*

[d] *National Research Center "Kurchatov Institute", Moscow, Russia*

[e] *Dipartimento di Fisica e Astronomia dell'Università di Bologna and INFN, Bologna, Italy*

[f] *Dipartimento di Fisica e Astronomia dell'Università di Firenze and INFN, Firenze, Italy*

[g] *Skobeltsyn Institute of Nuclear Physics, Moscow state University, Moscow, Russia*

[h] *Dipartimento di Scienze Fisiche, Università "Federico II" di Napoli, Napoli, Italy*

The same entrance channel velocity of 16 MeV/n was used in the reactions induced by an α-cluster structured ^{16}O projectile on ^{65}Cu and by a non α-cluster ^{19}F projectile on ^{62}Ni target, in order to produce an excited ^{81}Rb compound nucleus. This study was mainly devoted to compare pre-equilibrium α particle emission from the two systems. In fact, despite the slight different excitation energy, the same fast emission is expected from the two systems, unless major effects induced by the ^{16}O α-clustering structure influence the pre-equilibrium α particle production during the non-equilibrium stage. The experimental study of this effect is a perspective way for investigation of alpha clusterization in exotic neutron-rich nuclei, produced by neutron-rich radioactive beam facilities such as SPES at the Laboratori Nazionali di Legnaro. The preliminary experimental results and the comparison with calculations of the Hybrid Exciton Model, recently developed by our group, are reported in this paper.

X Latin American Symposium on Nuclear Physics and Applications (X LASNPA)
1-6 December 2013
Montevideo, Uruguay

[1] Speaker, e-mail: `fabris@pd.infn.it`

PoS(X LASNPA)061

1. Introduction

The idea that clusters of nucleons might be pre-formed prior to emission from nuclei has been known since a long time. The original idea was introduced by Hafstad and Teller in 1938 [1]. Examining the binding energy per nucleon of light nuclei, they hypothesized that nuclei as ^{8}Be, ^{12}C, ^{16}O, ^{20}Ne, which have an even, and equal, number of protons and neutrons, are particularly stable and their ground state could be described in terms of geometric arrangements of α particles known as α-clusters [2]. However, these so called α-conjugate nuclei are not found in ground states, but they are observed as excited states close to the decay threshold into clusters. This can be understood, as suggested by Ikeda and co-workers [3] in the late sixties, if we consider that in such light nuclei excitation energy has to be provided in order to permit the nucleus to undergo α-decay, while heavy nuclei can spontaneously experience α-decay. The threshold energy necessary for α-decay is precisely the same energy that is required to pre-form the α-particle inside the parent nucleus. This view is summarized in the Ikeda diagram, which links the energy required to liberate the cluster constituents to the excitation energy at which the cluster structures prevail in the host nucleus.

The possibility exists that valence particles, typically neutrons, may be exchanged between the α particle cores, similarly to the exchange of electrons in atomic molecules. In the nuclear case, these covalent neutrons stabilize the unstable multi-cluster states, giving rise to nuclear structures that can be described by molecular concepts. A new threshold diagram, the extended Ikeda diagram [4], is required in order to describe the structure of non-alpha conjugate nuclei.

Recently, nuclear clustering and the study of nuclear states built on clusters bound by valence neutrons in their molecular configurations, have gained large interest. In particular, clustering becomes important at the drip-line, because weakly bound systems prevail and clustering might actually be the preferred structural mode, especially in the case of light nuclei. Presently, these structures are mainly described by theory and must be experimentally verified at the new generation of radioactive beam facilities. In this regards, the evidence of alpha-clustering effects is proposed through the search of non-traditional signatures, that can bring new information on cluster formation processes.

2. Previous studies

In the past, a measurement campaign on the system ^{16}O + ^{116}Sn at various bombarding energies (E/A = 8 ÷ 16 AMeV), has been performed with the aim to identify possible projectile cluster structure effects on the de-excitation mechanism, especially in the energy range where pre-equilibrium emission is expected. To this end, the experimental spectra of protons and α particles have been compared with calculations obtained with the Hybrid Exciton Model [5,6]. The code used is a modified version of the statistical code PACE, where the main change is the insertion of a non-equilibrium stage in the fusion reaction before thermalization. The relaxation processes occurring during the fusion reaction is accounted for by the exciton model, based on the Griffin model [7], in which still one of the most intricate questions is the description of the angular distributions of secondary particles emitted in the non-equilibrium stage of the reaction [8]. The main parameter to be set is the initial number of excitons (n_o=$n_{particles}$+n_{holes}) in the projectile, that can be estimated from the empirical trend obtained in the work of N. Cindro et al. [9]. In the case of ^{16}O this number is n_o = 17 (16p+1h).

A general good agreement has been found between the experimental data and the model in the case of protons at all the energies over the measured angular range. On the contrary, an enhanced production of α particles has been observed at forward angles, which cannot be explained by the predicted pre-equilibrium emission contribution. A possible explanation of this significant increase of alpha particles in the pre-equilibrium part of the spectra might be related to the α-cluster structure in the ^{16}O projectile.

Therefore, the effect of the clustering structure in the projectile nucleus has been introduced in the model in terms of pre-formation probability of clusters. A second starting configuration is considered in which, with some probability, the ^{16}O projectile is supposed to be divided in a ^{12}C plus a α particle. This probability is the parameter to be determined. With the inclusion of a sizeable probability of α-clustering pre-formation, the model better describes the experimental data.

In order to obtain, in a model independent way, a confirmation that the projectile α-cluster structure can be responsible of the observed extra production, fusion reactions induced by clustered (^{16}O) and not clustered projectiles (^{19}F) are measured and their light charged particle production and spectra are compared, in an energy range where fast emission is also predicted.

2. The Experiment

With this goal, we have studied the two systems ^{16}O + ^{65}Cu and ^{19}F + ^{62}Ni, leading to the same compound nucleus ^{81}Rb*. The same bombarding energy per nucleon (16 AMeV) was chosen, since the pre-equilibrium emission is expected to be mostly dependent on the projectile velocity [10]. In this situation the non–equilibrium process are predicted to be almost the same for both reactions, while some little differences may appear in the evaporative part of the emitted particle spectra due to the different initial excitation energies of the compound nucleus (E*=209 MeV and E*=240 MeV respectively).

The inclusion of clustering effects in the model would suggest an over production of alpha particles at the forward angles only for the case of the ^{16}O induced reaction. Therefore, the observation of any difference in the experimental spectra, for the two reactions, can be interpreted as a model-independent way to establish the influence of the projectile α-cluster structure. This is especially true in the high energy region, which is more related to the fast emission.

The experiment has been performed at the Laboratori Nazionali di Legnaro (Italy), with the ^{16}O and ^{19}F beams provided by the TANDEM-ALPI acceleration system. The used experimental setup is the GARFIELD detection array implemented with the Ring Counter (RCo), at the forward angles, fully equipped with digital electronics [11].

The GARFIELD apparatus consists of two large volume gas detectors employing micro-strip gas chambers (MSGC) as ΔE stage, followed by CsI(Tl) scintillators as residual energy detectors, for fragment and light charged particle identification in an angular region from θ = 29^{o} to 151^{o}.

The Ring Counter is a three-stage annular detector, covering the $\theta = 5^o$ - 17^o angular range. The first stage is an ionization chamber (IC), followed by reverse mounted nTD silicon strip detectors (Si) and CsI(Tl) scintillators.

The coupled GARFIELD and RCo apparatus is able to perform high quality charged particle identification (Z and A) and energy determination, in a nearly 4π coverage (θ=5^o–151^o), for light charged particles and, in the forward direction (θ=5^o–17^o), for fragments with charge up to Z=14.

4. Preliminary Results

In the present experiment, light charged particles, detected in GARFIELD and RCo, have been measured in coincidence with Evaporation Residues (ER).

The ER have been selected setting gates in the ΔE-E energy spectra (IC vs Si) of the RCo, in an angular range from $\theta = 8.6^o$ and 17^o (just beyond the grazing angles).

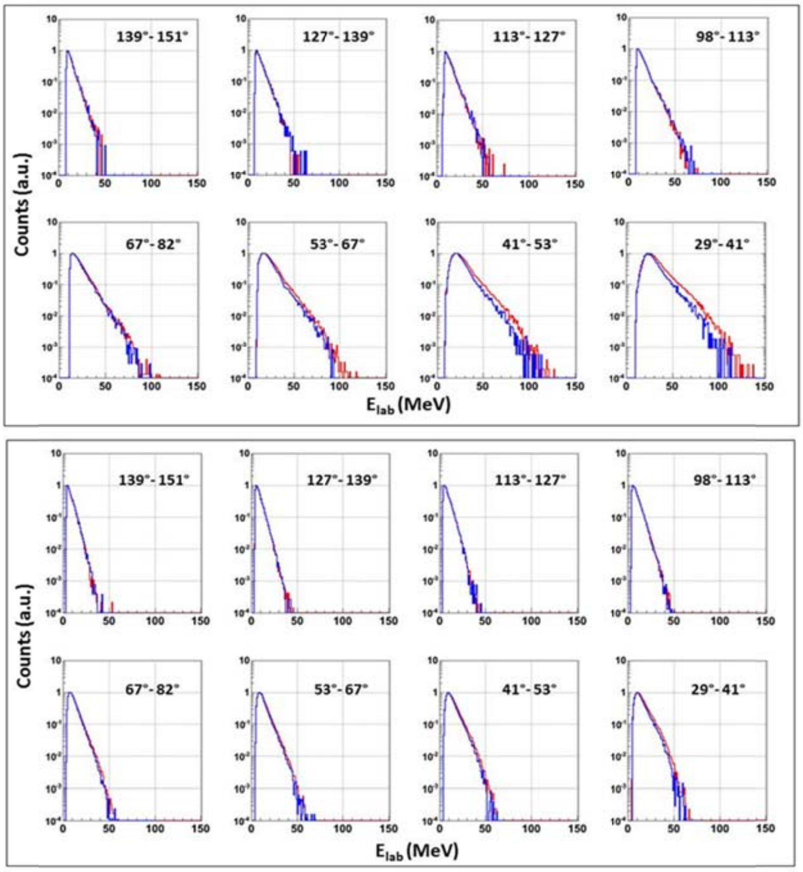

Figure 1. *Experimental energy spectra in the laboratory frame for α particles (upper panel) and for protons (lower panel) for the two reactions 256 MeV* ^{16}O + ^{65}Cu *(blue line) and 304 MeV* ^{19}F + ^{62}Ni *(red line) at different angles from* 29^o *to* 151^o.

In Fig. 1 the energy spectra in the laboratory frame of α particles (upper panel) and protons (lower panel) detected in coincidence with ER, are presented for the two reactions and for all the GARFIELD detection angles. The proton spectra for the two systems are very similar at almost all angles, a part from a small difference at the most forward angles. This may be mainly associated to the major excitation energy available for the ^{19}F case, since for these particles the pre-equilibrium contribution seems quasi-negligible for both systems. Even the alpha spectra are quite similar, but much larger differences are evident at the most forward angles and, in this case, the fast emission contribution is more evident. In particular, the over production of α particles evidenced in the case of the ^{19}F + ^{62}Ni reaction is in contrast to what is expected from model predictions as shown in Fig.2.

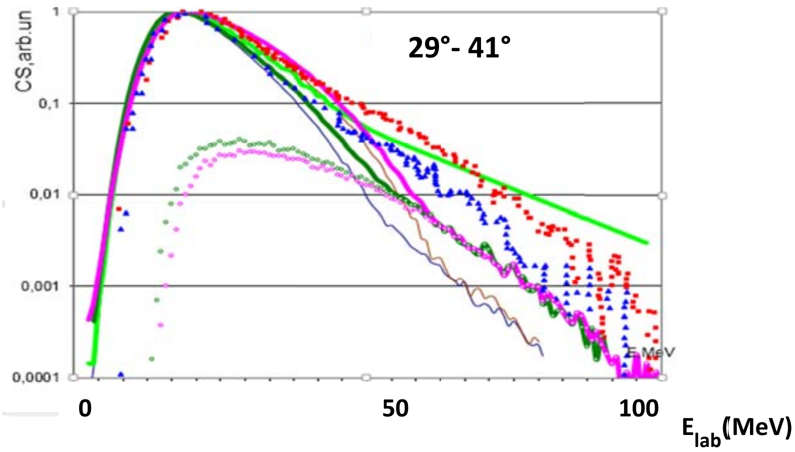

Figure 2. Comparison of experimental laboratory energy spectra of α particles for the two systems (red F+Ni; blu O+Cu) with Hybrid Model Calculation with (light green line for O+Cu) and without (pink line F+Ni; dark green line O+Cu) a-cluster preformation. The pre-equilibrium emission contribution is also shown (pink circles F+Ni; dark green circles O+Cu) together with the evaporative part (brown thin line F+Ni; blue thin line O+Cu).

This trend is confirmed by the comparison of the experimental spectra, normalized to the solid angles, to the standard statistical model code PACE4 prediction, which takes into account only the emission from a thermalized source, as shown in Fig. 3 (orange dots). In order to evaluate the contribution from the fast emission source, the experimental data were compared with the predictions of the Hybrid Exciton Model, in which both evaporation (green line) and pre-equilibrium (blue line) contributions are considered.

In particular, Fig. 3 shows the comparison of these preliminary calculations with the experimental alpha (left panel) and proton (right panel) energy spectra in the laboratory frame for the system ^{16}O + ^{65}Cu. For both particles the calculations were performed with an initial number of excitons n_o = 17 (16p+1h).

The model calculations seem to reasonably reproduce the alpha spectra with some exceptions at forward angles, which still have to be understood. On the contrary, using the same initial parameters, the model strongly overestimates the pre-equilibrium part of the proton spectra.

The same comparison was done for the system ^{19}F + ^{62}Ni with an initial number of excitons n_o = 20 (19p+1h). As shown in Fig. 4, the overproduction of alpha particles at the most forward angles is more evident than in the ^{16}O case, while, even in this system, the protons are largely overestimated.

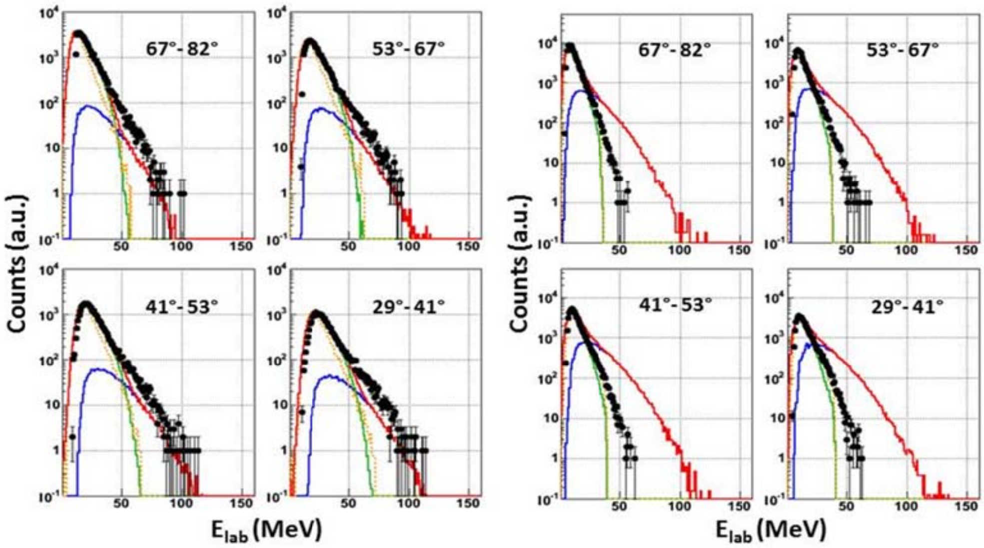

***Figure 3**. Comparison of experimental laboratory energy spectra of α particles (left panel) and protons (right panel) of the system ^{16}O + ^{65}Cu with preliminary calculations of Hybrid Exciton Model (red line). The Model evaporative (green line) and pre-equilibrium (blue line) contributions are shown. PACE4 calculations (orange dots) are also reported.*

By decreasing the starting parameters in the Hybrid Exciton Model, that is the number n_o of initial excitons, the predicted spectra tend, in general, to a better agreement with the experimental data in the case of alpha particles. On the contrary, for the protons the agreement is getting worse and worse.

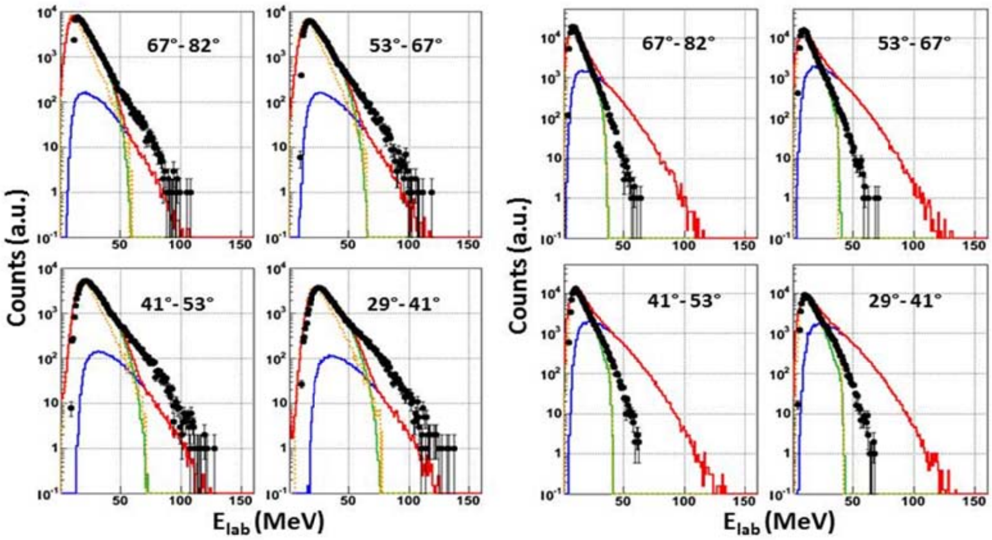

***Figure 4**. Same as Figure 3 for the system ^{19}F + ^{62}Ni.*

5. Conclusions

We have studied the secondary particles emission from the systems 256 MeV ^{16}O + ^{65}Cu and 304 MeV ^{19}F + ^{62}Ni, with the aim to probe α-clustering effects in nuclei. The preliminary results presented seem not to confirm the expected difference of the pre-equilibrium α particles spectra, due to the α–cluster structure of the ^{16}O projectile, since we observe a major α particle emission in the ^{19}F induced reaction.

We have compared the experimental particle spectra with the results obtained by the Hybrid Exciton Model code, proposed by O.V. Fotina et al. [5, 6]. The preliminary calculations, starting from an initial exciton number estimated from the empirical trend [9], reasonably describe the α energy spectra for both systems, but completely fail to reproduce the protons. In the same way, in our previous study of the system ^{16}O + ^{116}Sn the same model was not able to describe, with the same initial parameter, both the protons, and the α spectra. However, in that case, for protons the agreement was achieved with $n_o = 17$, while it was necessary to introduce some α-cluster pre-formation probability in the ^{16}O projectile to approach the experimental α spectra behavior in the forward angles.

As a consequence, more investigations have to be performed to understand if there exist a coherent set of model parameters capable to describe, at the same time, protons and α particles spectra for all the different studied systems. This means that the competition between protons and α emission has to be taken into account correctly, eventually even with the introduction of α-cluster pre-formation.

To this end, the analysis is still in progress in order to get information for all the light charged particles (p, d, t, ^{3}He, α), even at the most forward angle in the Ring Counter allowing an extension of the comparison with models.

References

[1] L.R. Hafstad , E. Teller, Phys. Rev. **54** (1938) 681.

[2] M. Freer, Rep. Prog. Phys. **70** (2007) 2149.

[3] K. Ikeda, N. Tagikawa, H. Horiuchi, Prog. Theor. Phys. 464 (Suppl.) (1968).

[4] W. von Oertzen et al., Phys. Rep. **432** (2006) 43.

[5] O. V. Fotina et al., Int. Journ. Mod. Phys. **E 19** (2010) 1134.

[6] O. V. Fotina et al., Phys. Atom. Nucl. **73** (2010) 1317.

[7] J. J. Griffin, Phys. Rev. Lett. **17** (1966) 478.

[8] M. Blann, M.B. Chadwick, Phys. Rev. **C 62** (2000) 034604.

[9] N. Cindro et al., Phys. Rev. Lett**. 66** (1991) 868.

[10] J. Cabrera et al., Phys. Rev. **C 68** (2003) 034613.

[11] M. Bruno et al., Eur. Phys. J. A. **49** (2013) 128 and ref. therein.