PRE-EQUILIBRIUM PARTICLES EMISSION AND ITS POSSIBLE RELATION TO α-CLUSTERING IN NUCLEI*

D. Fabris[a], F. Gramegna[b], T. Marchi[b], M. Degerlier[c]
O.V. Fotina[d], V.L. Kravchuk[e], M. D'Agostino[f], L. Morelli[f]
S. Appannababu[b], G. Baiocco[f], S. Barlini[g], M. Bini[g], A. Brondi[h]
M. Bruno[f], G. Casini[g], M. Cinausero[b], N. Gelli[g], R. Moro[h]
A. Olmi[g], G. Pasquali[g], S. Piantelli[g], G. Poggi[g]
S. Valdré[g], E. Vardaci[i]

[a]INFN, Sezione di Padova, 35131 Padova, Italy
[b]INFN, Laboratori Nazionali di Legnaro, 35020 Legnaro, Italy
[c]Nevsehir Haci Bektas Univ., Phys. Dep., Nevsehir, Turkey
[d]Skobeltsyn Inst. of Nucl. Phys., Lomonosov Moscow St. Univ., Moscow, Russia
[e]National Research Center "Kurchatov Institute", Moscow, Russia
[f]Dip. di Fisica, Univ. di Bologna and INFN Bologna, 40126 Bologna, Italy
[g]Dip. di Fisica, Univ. di Firenze and INFN Firenze, 50019 Firenze, Italy
[h]Dip. di Fisica, Univ. di Napoli and INFN Napoli, 80138 Napoli, Italy
[i]Dip. di Fisica, Univ. di Caserta and INFN Napoli, 80138 Napoli, Italy

(Received January 12, 2015)

The search for cluster structure effects in nuclei have been studied looking to the pre-equilibrium particles emitted in two different reactions at the same beam velocity (16 A MeV): ^{16}O + ^{65}Cu and ^{19}F + ^{62}Ni, leading to the same ^{81}Rb* compound nucleus. The GARFIELD + RCo multi-detection system operating at LNL has been used. The preliminary data analysis results and the first theoretical model calculations are presented.

DOI:10.5506/APhysPolB.46.447
PACS numbers: 25.70.Jj

1. Introduction

Nuclear clustering has been studied since a long time. It was originally proposed by Hafstad and Teller in 1938 [1] for light α-conjugate nuclei, which are observed as excited states close to the decay threshold into clusters, as summarized in the Ikeda diagram [2]. In neutron-rich systems, neutrons may act as valence particles which can be exchanged between the α-particle

* Presented at the Zakopane Conference on Nuclear Physics "Extremes of the Nuclear Landscape", Zakopane, Poland, August 31–September 7, 2014.

cores, as suggested in the extended Ikeda diagram. Recently, nuclear clustering has gained large interest 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 [3]. Presently, these structures are mainly described by theory since the low intensity of the exotic beams available prevents the experimental accessibility to such exotic structures. In this regards, waiting for the availability of the new generation of radioactive beam facilities like SPES, HIE-ISOLDE and SPIRAL2 [4], it is of particular interest to search for α-clustering effects looking to non-traditional observables, like those deriving from pre-equilibrium process studies, which may bring new information on the cluster formation process.

2. Previous studies

In the past, the system ^{16}O + ^{116}Sn at different bombarding energies has been studied with the aim to identify the amount of pre-equilibrium emission in asymmetric entrance channel reactions, comparing protons and α-particles experimental spectra with the Hybrid Exciton Model predictions [5]. The model uses a modified PACE2 code and the relaxation process is accounted for by the exciton model, based on the Griffin model [6]. The main parameter to be set is the initial number of excitation ($n_0 = n_{\rm particles} + n_{\rm holes}$), mainly related to the projectile properties, that can be estimated from the empirical trend described in the work of Cindro *et al.* [7]. The model described quite well the protons spectra at all the incident energies measured. On the contrary, an enhanced fast α-particle production was observed at forward angles. A possible explanation of this increase of α particles might be related to the α-cluster structure of the ^{16}O projectile [8]. To take into account this effect, a pre-formation cluster probability has been introduced in the model, considering a second starting configuration 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 configuration is the free parameter to be determined from the comparison with the experiment. While the shape of the energy spectra have been better reproduced with a quite sizeable probability (up to 50%) of α-cluster probability, still there are problems to reproduce the multiplicity of light charged particles. This fact has to be understood and may be studied changing the parameters of the statistical-model, like it was performed in the past works on similar subject [9, 10].

3. Experimental details and preliminary results

In order to obtain, in a model independent way, a confirmation of possible effects of α-cluster structure in the projectile, two fusion reactions ^{16}O + ^{65}Cu and ^{19}F + ^{62}Ni have been studied at 16 A MeV incident energy. The same projectile velocity was chosen since the pre-equilibrium emission is expected to be mostly dependent on this parameter [11], as a consequence, the fast emission process is predicted to be almost the same for both systems. The experiment has been performed at the Laboratori Nazionali di Legnaro, with the beams provided by the TANDEM-ALPI acceleration system. The experimental setup used is the GARFIELD array implemented with the Ring Counter (RCo), at forward angles, fully equipped with digital electronics [12]. Fully identified light charged particles, detected in GARFIELD and RCo, have been measured in coincidence with Evaporation Residues (ER) detected in RCo in an angular range $\theta = 8.6°–17°$. The first comparison between the two reactions shows very similar experimental 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. The predictions of the evaporative code PACE4, which takes into account the difference in the compound nucleus excitation energies, confirm that the purely statistical emission spectra should be very similar for the two systems, supporting the idea that a second fast emission source for both systems is needed.

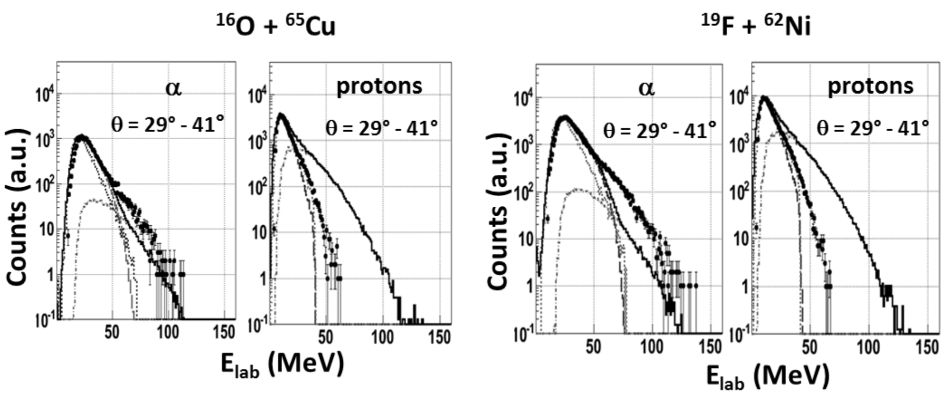

Fig. 1. Comparison of laboratory energy spectra (black dots) of a particles and protons for the systems ^{16}O + ^{65}Cu (left panels) and ^{19}F + ^{62}Ni (right panels) with preliminary calculations from Hybrid Exciton Model (black line). Evaporative (dashed line) and pre-equilibrium (dot-dashed line) Model contributions are shown together with PACE4 calculations (dotted line). The distributions have been normalized to the total area.

Waiting for the data sorting and calibration procedure to be completed, for a first estimate of the expected fast emission in the two cases, the data have been compared with the predictions of the Hybrid Exciton Model, as shown in Fig. 1. For the system ^{16}O + ^{65}Cu, with an initial exciton number of $n_0 = 17$ $(16p + 1h)$, the calculations reasonably describe the shape of the α-particle spectra, except for an underestimation at the forward angles in

GARFIELD. On the contrary, with the same initial n_0, the model strongly overestimates the proton pre-equilibrium emission. In the case of ^{19}F + ^{62}Ni, with an initial $n_0 = 20$ $(19p + 1h)$, the overproduction of fast α particles is even larger than in the previous reaction, while even in this case the protons are largely overestimated. A possible explanation for the larger production of fast α particles may be the lower energy needed to break up the ^{19}F nucleus into α + ^{15}N (4.01 MeV) with respect to the ^{16}O to be divided into α + ^{12}C (7.2 MeV).

4. Conclusions

We have studied the secondary particle emission from the reactions 265 MeV ^{16}O + ^{65}Cu and 304 MeV ^{19}F + ^{62}Ni in order to probe α-clustering effects in nuclei. From the preliminary comparison between the two systems, a difference in the fast α-decay channel has been evidenced, which can be related to the difference in the projectile structure. In the meanwhile the data sorting will be completed, the first comparison with the Hybrid Exciton Model has shown that the shape of the α-particle spectra are reasonably reproduced. On the contrary, using the same initial parameters, the fast emitted protons are largely overestimated. The fact that the model is not able to reproduce protons and α particles, with the same starting parameters, was already seen in our study of the system ^{16}O + ^{116}Sn. In that case, introducing some pre-formation probability in the projectile a better description of the α spectra was obtained, even if there were still problems to reproduce the particles multiplicities. As a consequence, a more complete analysis is needed to understand the process, looking to all different light charged particles and taking advantage of the large angular range in which the particles have been identified. This will permit to better disentangle the pre-equilibrium emission. For this purpose, a complete analysis, like the one reported in previous paper on similar systems [13, 14], will be performed, able to correlate the velocity and angular ranges of the heavy fragments and light charged particles. From the theoretical point of view, on the one hand, the Hybrid Exciton Model needs to be upgraded including all possible decay channels. On the other hand, it is under study the use of other theoretical approaches like the Antisymmetrized Molecular Dynamics (AMD) code [15].

REFERENCES

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

[2] K. Ikeda *et al.*, *Prog. Theor. Phys. Suppl.* **E68**, 464 (1968).

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

[4] `web.infn.it/spes`; `hie-isolde.web.cern.ch`; `www.ganil-spiral2.eu/spiral`
[5] O.V. Fotina *et al.*, *Int. J. Mod. Phys.* **E19**, 1134 (2010).
[6] J.J. Griffin, *Phys. Rev. Lett.* **17**, 478 (1966).
[7] N. Cindro *et al.*, *Phys. Rev. Lett.* **66**, 868 (1991).
[8] O.V. Fotina *et al.*, *EPJ Web Conf.* **66**, 03028 (2014).
[9] C. Bhattacharya *et al.*, *Phys. Rev.* **C65**, 014611 (2001).
[10] M. Rousseau *et al.*, *Phys. Rev.* **C66**, 034612 (2002).
[11] J. Cabrera *et al.*, *Phys. Rev.* **C68**, 034613 (2003).
[12] M. Bruno *et al.*, *Eur. Phys. J.* **A49**, 128 (2013) and references therein.
[13] C. Beck *et al.*, *Phys. Rev.* **C39**, 2202 (1989).
[14] D. Mahboub *et al.*, *Phys. Rev.* **C69**, 034616 (2004).
[15] A. Ono, *EPJ Web Conf.* **31**, 00023 (2012).