EPJ Web of Conferences **88**, 00026 (2015)
DOI: 10.1051/epjconf/20158800026

Cluster correlation effects in ^{12}C+^{12}C and ^{14}N+^{10}B fusion-evaporation reactions

L. Morelli[1], G. Baiocco[2], M. D'Agostino[1], F. Gulminelli[3], M. Bruno[1], M. Cinausero[4], M. Degerlier[5], D. Fabris[6], F. Gramegna[4], T. Marchi[4], S. Barlini[7], M. Bini[7], G. Casini[7], N. Gelli[7], A. Olmi[7], G. Pasquali[7], S. Piantelli[7], S. Valdré[7]

[1] Dipartimento di Fisica e Astronomia, Università di Bologna and INFN, Sezione di Bologna, Italy
[2] Dipartimento di Fisica, Università di Pavia and INFN, Sezione di Pavia, Italy
[3] CNRS, LPC, Caen and ENSICAEN, Caen, France
[4] INFN-Laboratori Nazionali di Legnaro, Legnaro (PD), Italy
[5] Physics Department, University of Nevsehir, Nevsehir, Turkey
[6] INFN, Sezione di Padova, Padova, Italy
[7] Dipartimento di Fisica e Astronomia, Università di Firenze and INFN, Sezione di Firenze, Italy

Abstract

The decay of highly excited states of ^{24}Mg is studied in fusion evaporation events completely detected in charge in the reactions ^{12}C+^{12}C and ^{14}N+^{10}B at 95 and 80 MeV incident energy respectively. The comparison of light charged particles measured spectra with statistical model predictions suggests that the dominant reaction mechanism is compound nucleus (CN) formation and decay. However, in both reactions, a discrepancy with statistical expectations is found for α particles detected in coincidence with Carbon, Oxigen and Neon residues. The comparison between the two reactions shows that this discrepancy is only partly explained by an entrance channel effect. Evidence for cluster correlations in excited ^{24}Mg CN is suggested by the comparison between the measured and calculated branching ratios for the channels involving α particles.

1 Introduction

The statistical decay of hot nuclei and nuclear clustering are very active research topics in nuclear physics [1]. The accurate study of the fusion-evaporation channel in light nuclei (A$\sim$30,Z$\sim$15) reactions allows to strongly constrain the level density in a mass and excitation energy region where few data exist, altogether coming from rather inclusive measurements. In addition, nuclear structure signatures are especially evident in light nuclei, even at high excitation energy. By carefully selecting the various decay channels and using a highly constrained statistical code, it is possible to put in evidence deviations from a statistical behaviour in the decay of the hot CN. Indeed there exist evidences in this mass region for some excited states with pronounced cluster features. These correlations may persist in the ground state along some selected isotopic chains, as shown by sophisticated ab-initio calculations [2]; according to the Ikeda diagrams [3] α-clustered excited states are expected at high excitation energies close to the multi-alpha decay threshold in all even-even N = Z nuclei. Such effects can be experimentally seen as an excess of cluster production with respect to the prediction of the statistical model, provided that the ingredients of the latter are sufficiently constrained via experimental data.

In this respect, the NUCL-EX collaboration carried on several exclusive measurements of fusion-evaporation reactions with light nuclei as interacting partners. We report here on the two system ^{12}C+^{12}C and ^{14}N + ^{10}B which were measured in order to study the decay of the ^{24}Mg compound nucleus, populated at the same excitation energy $\varepsilon^* = 2.6$ A.MeV but through different entrance channels.

2 The experiments

The experiments were performed at the LNL (Laboratori Nazionali di Legnaro), with ^{12}C and ^{14}N beams provided by the XTU TANDEM accelerator. The experimental setup [4] is composed of the GARFIELD apparatus and the Ring-Counter (RCo) annular detector, now fully equipped with digital electronics [5]. The combination of the two devices allows a nearly-4π coverage, which, combined with a high granularity, allows to measure the charge, the energy and the emission angles of nearly all the charged reaction products, with an excellent discrimination of the different reaction mechanisms. The set-up also provides information on the mass of the charged products in a wide range of energy and type. The GARFIELD detector, efficiently covering the polar range from 30° to 150°, is a two detection stage device, made by a microstrip gaseous drift chamber (μSGC), filled with CF_4 gas at low pressure (about 50 mbar), and CsI(Tl) scintillation detectors lodged in the same gas volume. The RCo detector is a forward-angle array of three-stage telescopes with truncated cone shape. The first stage is an ionization chamber (IC), the second a 300 μm reverse-mounted Si(nTD) strip detector, and the last a set of CsI(Tl) scintillators. It has azimuthal symmetry, with 8 sectors, and covers, with eight strips, the polar region from $6° \leq \theta \leq 18°$, with an angular resolution $\Delta\theta \approx 0.7°$ and an energy resolution of 0.3% (silicon strips) and 2-3% (CsI (Tl)).

3 Results

The fusion-evaporation events are selected setting conditions on the total detected charge and on the coincidence between a residue at forward angles (when $Z_{res} <12$) (RCo) and light charged particles (LCP) detected in GARFIELD. Only complete events where the total charge of the entrance channel ($Z_{det} = 12$) is detected are retained for this analysis.
Experimental data are compared to the predictions of a Monte Carlo Hauser-Feshbach code (HFℓ) [6, 7] for the evaporation of the compound nucleus ^{24}Mg, at $\varepsilon^* = 2.6$ A.MeV, corresponding to a complete fusion source, and filtered through a software replica of the experimental set-up. For both reactions the best reproduction of the systematics of the fusion cross sections is obtained assuming two different maximum value (J_{0max}) for the angular momentum distribution of the hot fused source [8]. In particular we use J_{0max}=18 $\hbar$ for ^{12}C+^{12}C reaction and J_{0max}=15 $\hbar$ for ^{14}N + ^{10}B reaction and we adopt the same diffusiveness parameter $\Delta J = 2$ for both reactions. Moreover, only even values of J_0 are allowed for the ^{12}C+^{12}C case, respecting parity conservation. The difference between theoretical predictions of the HFℓ code for the two reactions are therefore only due to the different angular momentum distribution of the decaying CN. As expected, this difference affects in a minor way observables as multiplicity distributions and energy spectra summed over different channels, while shows up more clearly in correlations and single channel observables. Therefore, for the observables presented hereafter in Fig. 1 and 2 we only show for simplicity filtered HFℓ calculations for the ^{12}C+^{12}C reaction.
The inclusive charge and α multiplicity distributions are reported for both reactions, in Fig. 1.

The two experimental charge distributions are globally well-reproduced

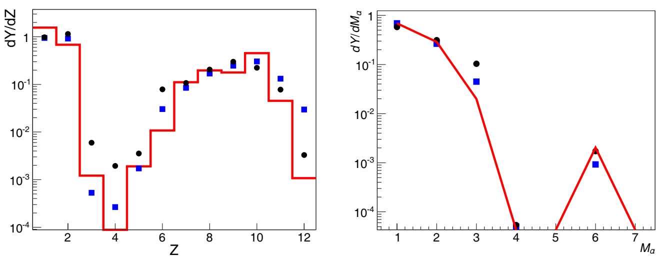

Figure 1: Inclusive charge distribution (left part) and alpha particle multiplicity (right part) of events completely detected in charge. Experimental data (dots and square for ^{12}C+^{12}C and ^{14}N+^{10}B respectively) are compared to filtered HFℓ calculations (line) for ^{12}C+^{12}C (see text for details).

by the theoretical calculation and their overall shape is typical of fusion-evaporation reactions. A detailed quantitative comparison of the single element cross section reveals discrepancies between data and calculation. First, light residue (Z=3,4) yield is systematically underestimated. This is an expected result, because of the absence of the break-up channel in the model. Second, Z=6 and Z=12 are also underestimated. The Z=12 yield strongly depends on the trigger condition. Concerning Z=6, the experimental excess could be attributed to the entrance channel of the reaction. A partial confirmation of this hypothesis comes from the reduced Carbon yield measured in the ^{14}N reaction, although the Carbon yield is in any case underpredicted by the HFℓ model.

Concerning the α-multiplicity distribution, reported in the right part of Fig. 1, the model reproduces the data quite well. The largest observed deviation is the underestimation of 3-α coincidences in both reactions: this is cleary linked to the underproduction of the Carbon residue. The good reproduction achieved for several global observables suggests anyway that the dominant reaction mechanism is the compound nucleus formation and decay.

This can be concluded also from Fig. 2, in which the energy spectra for protons and α particles detected at GARFIELD angles are plotted, for residues of different charge, for the ^{14}N reaction, and compared to HFℓ [6] calculations and to data for the ^{12}C+^{12}C reaction. For both reactions, a good reproduction of proton and α energy spectra is achieved in all channels except in events with an Oxygen residue, where the energy tails for α particles are not reproduced by the model.

For the ^{12}C+^{12}C reaction it has been already shown in [7, 9] that this discrepancy is mostly due to the an extra experimental cross section for

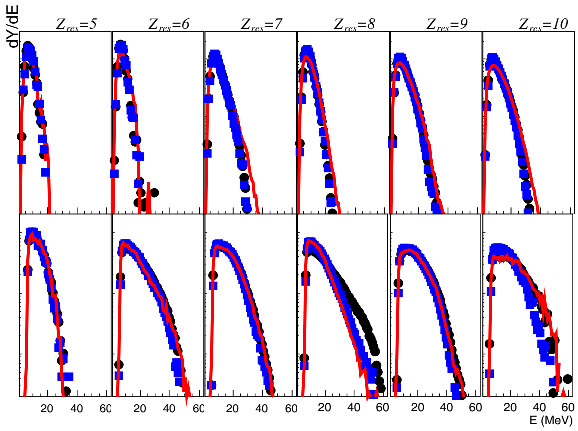

Figure 2: Proton (upper part) and α (lower part) energy spectra in complete Z_{det}=12 events detected in coincidence with a residue of charge Z_{res}, indicated in each figure column. Data (dots and square for ^{12}C+^{12}C and ^{14}N+^{10}B respectively) are compared to model calculations (lines) for ^{12}C+^{12}C (see text for details). All distributions are normalized to unitary area.

channels of the type (2α, $^{16}O^{gs/*}$). Such outgoing channels populated in the ^{12}C+^{12}C collisions can be attributed to an entrance channel effect, given the α-like structure of reaction partners and produced fragments. However, this seems not to exhaust the total discrepancy with HFℓ calculations, as we infer from the energy spectrum of α particles in coincidence with Oxygen for the ^{14}N reaction. Thanks to the completeness of event reconstruction, a Q-value distribution [10] can be built to further investigate the (2α, ^{A}O) channel in both reactions: $Q_{kin} = \sum_{i=1}^{2} E_{\alpha_i} + E_O - E_{beam}$, where E_{α_i} and E_O are, respectively, the laboratory energy of α particles and Oxygen, and E_{beam} is the energy of the incident projectile. Fig. 3 displays the obtained Q_{kin} distributions for ^{12}C+^{12}C (left panel) and ^{14}N+^{10}B (right panel) reactions. We can see that the two spectra show a common structure, with two narrow peaks and a broader region. In the statistical model interpretation, the two peaks correspond to α-decay chains, starting from the ^{24}Mg* compound nucleus and leaving a ^{16}O residue either in its ground state or in one of its excited bound states. The Q-values $Q_{kin} = -15.78$ MeV for ^{12}C and $Q_{kin} = -0.8$ MeV for ^{14}N reactions correspond to the opening of the 4-body channel ^{15}O$+n+\alpha+\alpha$. We will therefore call less (more) dissipative the events characterized by a Q_{kin} value greater (smaller) than such threshold values. Neutrons are not detected in the experiments, and the broader distribution observed for lower Q_{kin} values is due to events in which neutron(s)

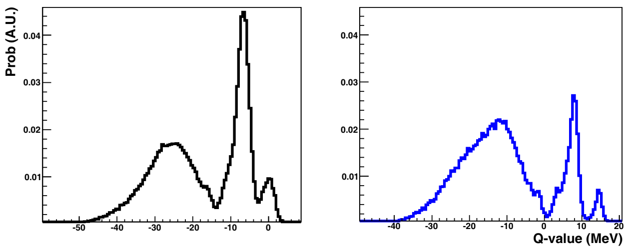

Figure 3: Q-values distribution of the channel ^{A}O + α + α for ^{12}C+^{12}C (left) and ^{14}N+^{10}B (right). For more details see text.

emission has taken place, and their kinetic energy has not been collected. A difference in the relative population of less dissipative events is evident between the ^{12}C+^{12}C (left panel) and ^{14}N+^{10}B (right panel) reactions in Fig. 3. In particular, a much higher percentage of (2α,^{16}O) events populates the less dissipative Q-value region in the ^{12}C experimental sample. This difference between the two data-sets confirms the possible contribution of direct reactions for the ^{12}C+^{12}C experiment. Since a residual deviation is observed in Fig. 2 for α's emitted in coincidence with an Oxygen in the ^{14}N reaction, we turn now to an estimation of the possible α clustering effects for both reactions, both in the entrance channel and in the excited ^{24}Mg. This can be achieved through the definition of a new variable R$_{clust}$, obtained for each residue as a difference between experimental and expected probability for the maximum α multiplicity channel:

$$R_{clust}(Z) = \frac{Y_{exp}(Z; n_Z\alpha)}{Y_{exp}(Z)} - \frac{Y_{HF\ell}(Z; n_Z\alpha)}{Y_{HF\ell}(Z)} \tag{1}$$

Where $Y(Z; n_Z\alpha)$ ($Y(Z)$) indicates coincident (inclusive) yields; $n_Z\alpha = (12-Z)/2$ is the maximum α multiplicity associated to the residue of charge Z and the subscripts "exp" and "HFℓ" refer to experimental and theoretical yields, respectively. The extra probability of α emission defined by (1) is plotted in Fig. 4.

The evaporation chains leading to a final Carbon or Oxygen or Neon residue show a preferential α decay in both reactions. A possible interpretation of this α excess could be the presence of residual α correlations in the excited ^{24}Mg or in its daughter nucleus ^{20}Ne, populated irrespective of the entrance channel of the reaction.

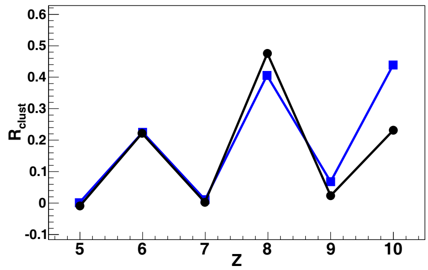

Figure 4: Branching ratio excess (Eq. 3.1 in the text) for α decay as a function of the charge of the final residue. Dots:^{12}C+^{12}C. Square:^{14}N+^{10}B.

4 Conclusions

In this work we discussed preliminary results for the ^{14}N+^{10}B reaction at 80 MeV beam energy, measured at LNL-INFN with the GARFIELD+RCo experimental set-up. Using the same selection described in Ref. [7, 9] we have compared experimental data to the ^{12}C+^{12}C reaction and to HFℓ statistical model calculations for the decay of the ^{24}Mg* source. The selected sample is compatible with the expected behavior of a complete fusion-evaporation reaction, with some exception of specific channels corresponding to the emission of two or three α particles in coincidence with a Oxygen or Carbon residue. The experimental branching ratio excess for α particle emission has been quantified for both reactions, putting in evidence an effect due to the cluster nature of projectile and target in ^{12}C+^{12}C reaction but, at the same time, an indication of the persistence of cluster correlations also in the hot fused ^{24}Mg, as suggested by data from ^{14}N+^{10}B collisions.

References

[1] W Von Oertzen 2010 Clusters in Nuclei, Lecture Notes in Physics 818 109-127.

[2] R. B. Wiringa; Phys. Rev. C 62 014001.

[3] K. Ikeda, Prog. Theor. Phys. (Suppl.) extra number, 464 (1968).

[4] M. Bruno et al., Eur. Phys. Journ. A 49 (2013) 128.

[5] G. Pasquali et al., Nucl. Instr. And Meth., A 570 (2007) 126.

[6] G. Baiocco, Ph.D. thesis, University of Bologna, Italy 2012.

[7] L. Morelli et al., J. Phys. G: Nucl. Part. Phys. 41 (2014) 075107.

[8] Ortiz M E et al 1982 Phys. Rev. C 25 1436.

[9] G. Baiocco et al., Phys. Rev. C 87,054614 (2013)

[10] L. Morelli et al., J. Phys. G: Nucl. Part. Phys. 41 (2014) 075108.