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α-clustering effects in ^{12}C +^{12}C and ^{14}N +^{10}B fusion reactions at 2.6 A.MeV excitation energy.

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The analysis of exclusive events completely reconstructed in charge for the two reactions ^{12}C+^{12}C and ^{14}N+^{10}B at 95 and 80 MeV incident energy respectively, is presented. The comparison of light charged particles energy spectra with dedicated Hauser-Feshbach calculations 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 a Carbon and an Oxigen residue. The comparison between the two reactions shows that this discrepancy is only partly explained by an entrance channel effect. The ratio of experimental to predicted branching ratios for different channels involving α emission finally suggests the persistency of cluster correlations in the hot fused ^{24}Mg source, at excitation energy well above the 6-α decay threshold.

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1. Introduction

The statistical theory of Compound Nucleus decay is the only way to access the fundamental quantity nuclear Level Density at energies higher than the threshold for particle decay. Despite the interest of this issue, few studies, mainly based on inclusive experiments, exist on the evaporation of very light nuclei (A $\sim$ 20 region) at high excitation energy ($\varepsilon^{*} \approx 3$ A.MeV).
The NUCL-EX collaboration has recently proposed an experimental campaign of exclusive measurements of fusion-evaporation reactions with light nuclei as interacting partners. The aim is to progress in the understanding of statistical properties of the decay of light nuclei at excitation energies above particle emission thresholds and to measure observables linked to the presence of cluster structures in nuclear excited levels.
The interest on this mass - excitation energy region is easily justified: from the experimental point of view, measuring light nuclei means low multiplicity events, which, together with a high detection coverage and high energy and angular resolution, leads to the possibility of achieving a complete event reconstruction, thus having a global control on the reaction mechanism.

Moreover some excited states of different nuclei in this mass region are known to present pronounced cluster structures; these correlations may persist in the ground state along some selected isotopic chains [1]; according to the Ikeda diagrams [2] α-clustered excited states are expected at high excitation energies close to the multi-α decay threshold in all even-even N = Z nuclei. Evidence for cluster structures comes from decay widths and branching ratios, meaning that we should measure a preferential decay to α-structures in daughter nuclei. For such light systems, signatures of cluster structure in the reactions are therefore expected to be more evident even at high excitation energy.
In the framework of this campaign, the ^{12}C+^{12}C and ^{14}N + ^{10}B reactions have been measured in order to study the decay of the same ^{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 [3] is composed of the GARFIELD [4] apparatus and the Ring-Counter (RCo) annular detector [5], now fully equipped with digital electronics [6]. The combination of the two devices allows a nearly-4π coverage of the solid angle, 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. They also provide information on the mass of the emitted charged products in a wide range of particle energy and type.
The GARFIELD detector, covering almost completely the polar range of angles 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 realized in a 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 the polar region from $6^\circ \leq \theta \leq 18^\circ$, with an angular resolution $\Delta\theta \approx 0.7^\circ$ and an energy resolution of 0.3% (silicon strips) and 2-3% (CsI (Tl)).

Due to the reverse mounting of the nTD Silicon detector it has been possible to identify the charge of stopped fragments via pulse shape analysis (PSA) with digital electronics, according to the results obtained in the R&D of the FAZIA detectors [7]. It is also possible obtain the isotopic separation via PSA in silicon detector for fragments with charge up to Z = 14 [3].

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 (RCo) ($6^\circ \leq \theta \leq 18^\circ$) and light charged particles (LCP) detected in GARFIELD ($\theta_{lab} \geq 30^\circ$). 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) [8, 9] 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.

The inclusive charge and α multiplicity distributions are presented, for both reactions, in Fig. 1 in comparison with the filtered HFℓ calculations.

The two experimental charge distributions are globally well-reproduced by the theoretical calculation and their overall shape is typical of fusion-evaporation reactions. However, a few discrepancies can be observed. Notably, lightest fragments (Z=3,4,5) are underestimated in the HFℓ prediction for the ^{12}C+^{12}C experimental sample. This could be interpreted as the presence of a break-up contribution in the data which is not treated by the calculation, which takes into account only light particle evaporation.

Another discrepancy between the two data samples and HFℓ calculations concerns the Z = 6 yield

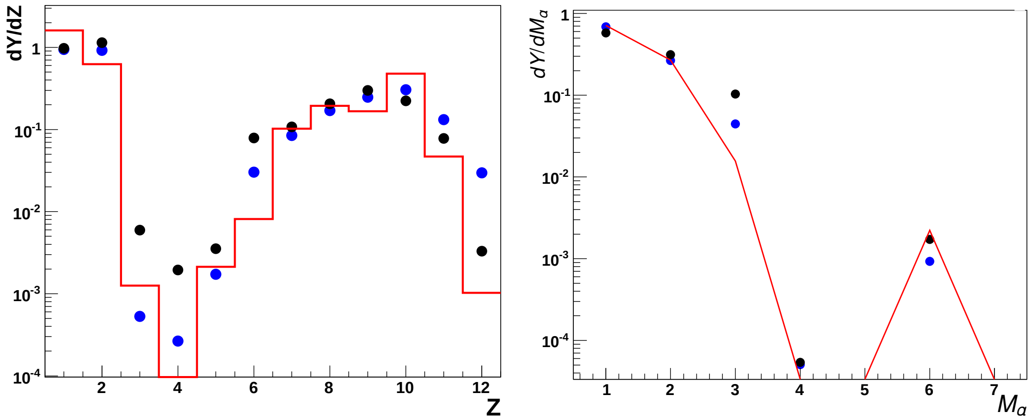

Figure 1: (Color online) Left part: Inclusive charge distribution of events completely detected in charge. Right part: alpha particle multiplicity distribution for the same data set. Experimental data (black and blue dots for ^{12}C+^{12}C and ^{14}N+^{10}B respectively) are compared to filtered HFℓ calculations (red line). All distributions are normalized to the total number of events.

which is underestimated by the model for both reactions. In the ^{12}C+^{12}C experiment, the Carbon 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, althought the Carbon experimental cross section is found again to disagree to with HFℓ calculations. 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. 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 calculations [8] and to data for the ^{12}C+^{12}C reaction.

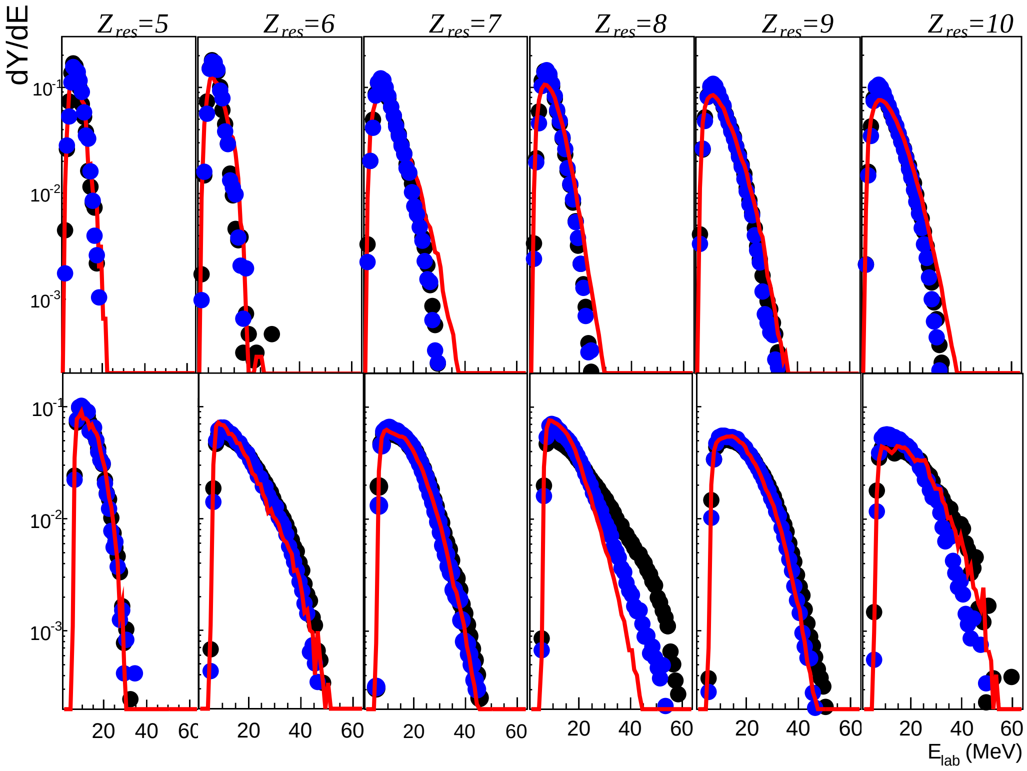

Figure 2: (Color online) Proton (upper part) and α (lower part) energy spectra in complete Z_{det}=12 events detected in coincidence with a residue of charge Z_{res}, indicated in each figure column. Data (black and blue dots for ^{12}C+^{12}C and ^{14}N+^{10}B respectively) are compared to model calculations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

For both reactions, a good reproduction of proton and α energy spectra is achieved in all channels but 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 [9, 10] that this discrepancy is mostly due to the an extra experimental cross section for 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 global 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 [11] 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.

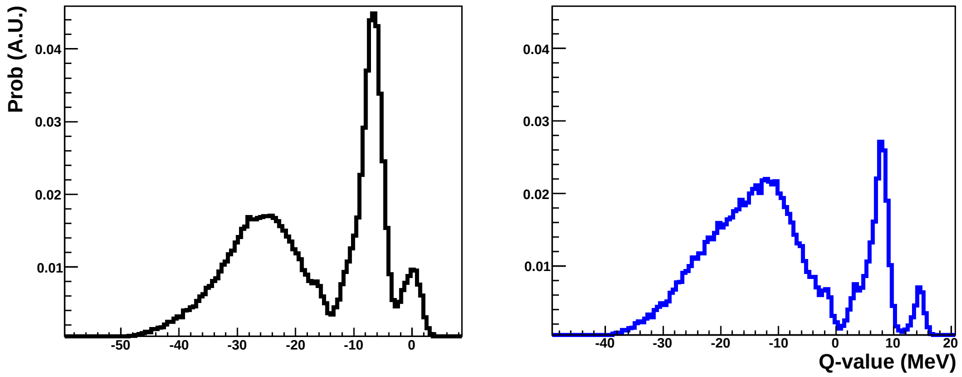

Figure 3: Q-values distribution of the channel ^{A}O + α + α for ^{12}C+^{12}C (left) and ^{14}N+^{10}B (right). For more details see text.

We can see that the two spectra show a common structure, with two narrow peaks and a broader region extending up to a high energy shortage. 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, which are not resolved in the experiment. 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) emission has taken place, and their kinetic energy has not been collected.

Besides the common pattern observed for the Q-value distributions, 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-set confirms the possible contamination 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 hot fused ^{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:

$$R_{clust}(Z) = \frac{Y_{exp}(Z;n_Z\alpha)}{Y_{exp}(Z)} - \frac{Y_{HF\ell}(Z;n_Z\alpha)}{Y_{HF\ell}(Z)} \tag{3.1}$$

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 data and theoretical predictions, respectively. The extra probability of α emission defined by (3.1) is plotted in Fig. 4.

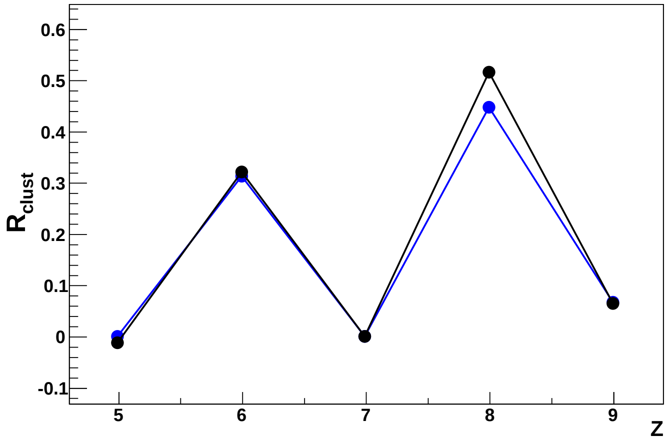

Figure 4: (Color online)Branching ratio excess (Eq. 3.1 in the text) for α decay as a function of the charge of the final residue. Black lines:^{12}C+^{12}C. Blue line:^{14}N+^{10}B.

The evaporation chains leading to a final Carbon or Oxygen residue show a preferential α decay in both reactions. The relatively small difference in the Oxygen case is due to entrance channel effect in the ^{12}C+^{12}C reaction, which, as also inferred from Fig. 2, does not exhaust the global discrepancy with statistical expectations.

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.

4. Conclusions

In this work we have presented 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. [9, 10] 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 the exception of a 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 fused hot ^{24}Mg as suggested by the data of the ^{14}N+^{10}B collisions.

The ensemble of these observations tends to indicate the persistence of cluster correlations for

^{24}Mg and/or its daughter nucleus ^{20}Ne, at excitation energies well above the threshold energy for full disintegration into α's.

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