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Investigation of precisely selected evaporation chains in the decay of ^{24,25}Mg

A. Camaiani(1)(2), G. Casini(2), L. Morelli(3), S. Barlini(1)(2), S. Piantelli(2), G. Baiocco(6), M. Bini(1)(2), M. Bruno(4)(5), A. Buccola(1)(2), C. Ciampi(1)(2), M. Cicerchia(7)(8), M. Cinausero(7), M. D'Agostino(4)(5), D. Fabris(9), C. Frosin(1)(2), F. Gramegna(7), N. Gelli(2), F. Gulminelli(10), I. Lombardo(11), G. Mantovani(7)(8), T. Marchi(7), A. Olmi(1)(2), P. Ottanelli(1)(2), G. Pasquali(1)(2), G. Pastore(1)(2), S. Valdré(2), G. Verde(11) and B. Schütrumpf(12)(13)

(1) *Dipartimento di Fisica, Università di Firenze - Firenze, Italy*
(2) *INFN, Sezione di Firenze - Firenze, Italy*
(3) *GANIL, CEA/DRFCNRS/IN2P3 - Bvd. Henri Becquerel, 14076 Caen, France*
(4) *Dipartimento di Fisica, Università di Bologna - Bologna, Italy*
(5) *INFN, Sezione di Bologna - Bologna, Italy*
(6) *Dipartimento di Fisica, Università di Pavia - Pavia, Italy*
(7) *INFN, Laboratori Nazionali di Legnaro - Legnaro, Italy*
(8) *Dipartimento di Fisica, Università di Padova - Padova, Italy*
(9) *INFN, Sezione di Padova - Padova, Italy*
(10) *Normandie Université, ENSICAEN, UNICAEN, CNRS/IN2P3, LPC Caen - F-14000 Caen, France*
(11) *INFN, Sezione di Catania - Catania, Italy*
(12) *Institut für Kerphysik, Technische Universität Darmstadt - Schlossgartenstraße 2, 64289 Darmstadt, Germany*
(13) *GSI Helmholzzentrum für Schwerionenforschung - Planckstraße 1, 64291 Darmstadt, Germany*

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Summary. — In this proceeding an overview on the NUCLEX scientific campaign aimed at studying the decays of light excited nuclei is presented. After an introduction on the physics case and a description of the adopted experimental strategy, the main results related to the decays of the ^{24}Mg and ^{25}Mg are reported. On both systems, an excess in the fusion-evaporation branching ratios of the channels where only α particles can be emitted has been observed. A possible explanation of the observed non-statistical effects is suggested within a recent application of nuclear time-dependent density functional theory.

1. – The NUCLEX scientific campaign on light nuclei

Since 2013 the INFN NUCLEX collaboration [1] has carried out a scientific campaign aimed at investigating the decay of light nuclei formed in fusion reactions [2-7]. Indeed, light nuclei (A$\leq$40), especially α-conjugated, manifest clusterization effects in their low-lying states, which can survive with increasing excitation. In fusion reactions forming Compound Nucleus (CN) at excitation energies well above the particle energy threshold, these effects can manifest in the CN decays as a deviation with respect to a pure statistical model: for instance an alpha overproduction has been observed [8] as well as an excess of CN break-up events involving α-conjugated nuclei [9]. Very recently, it has been suggested by a modern application of nuclear time-dependent density functional theory (TDDFT) that these non-statistical effects can raise from the pre-compound phase, where the systems can pass through clustered configurations [10], which can influence the de-excitation channels.

The NUCLEX scientific campaign fits within this context, dedicating many efforts two the analysis of the CN decays, from Mg up to Ar ions; in this proceeding some results related to the decay of ^{24,25}Mg at 61 and 65 MeV excitation energy are shown, formed in ^{12}C+^{12,13}C fusion reaction at 95 MeV. A full description of the analysis can be found in [3,4] and in [7] for ^{24}Mg and ^{25}Mg, respectively. Preliminary results for the heavier systems like ^{28}Si and ^{36}Ar cases are described in [11] and [12], respectively.

1˙1. *Experimental techniques.* – In order to investigate these phenomena the NUCLEX collaboration exploits two powerful tools, on both the experimental and theoretical side. The experimental apparatus is GARFIELD+ Ring Counter [13], located at the INFN Laboratori Nazionali di Legnaro (LNL): it is a large acceptance detector (approximately 70% of the solid angle is covered) with 488 detection channels; fragments (Z$\geq$3) emitted between 7° and 17° in the laboratory frame can be identified in charge up to the calcium region, while light charged particles (LCPs) are isotopically resolved in the whole covered solid angle. These features allow the detection of events completely described in charge, which, adding the request of total momentum conservation to remove residual spurious coincidence events, constitute a high quality data set for fusion-evaporation events.

To compare the exclusive dataset with reliable model predictions, a MonteCarlo code has been developed by the NUCLEX collaboration. This code, labelled as HFℓ, is a pure statistical model, based on the Hauser-Feshbach formalism including all the known single levels and keeping into account their populations during the decays. More details on the model can be found elsewhere [2,3].

Survival of non-statistical effects can manifest as discrepancies with respect to the pure statistical predictions. Thus, the adopted strategy is a tight comparison between the experimental data and the HFℓ results, starting from inclusive observables (for instance the charge or LPCs kinetic energy distributions) up to more exclusive ones for selected decay channels.

2. – Results on ^{24,25}Mg decays

In the ^{24,25}Mg fusion-evaporation processes, the experimental data are globally in agreement with the HFℓ predictions. In particular the kinematics of the decays is well reproduced by the model, both in the angular and in the kinetic energy distribution of the evaporation residues (ERs) and LPCs, as well as the charge distributions [3,7]. However, deviations are visible looking at the branching ratios (BRs) of specific decay channels as

TABLE I. – *BRs of the most probable decay channel with maximum number of α particles emitted for ^{24}Mg and ^{25}Mg case. Experimental and* HFℓ *comparison. All the values are normalized to the number of event for each Z_{ER}.*

Z$_{ER}$	Channel	^{24}Mg EXP [%]	HFℓ [%]	^{25}Mg EXP [%]	HFℓ [%]
10	$^{20,21-x}$Ne+xn+α	26±1	4	29±1	3.2
9	$^{19,20-x}$F+xn+p+α	92±3	84	86±3	84
8	$^{16,17-x}$O+xn+2α	63±3	14	69±3	30
7	$^{14,15-x}$N+xn+p+2α	91±3	95	83±3	90
6	$^{12,13-x}$C+xn+3α	98±4	67	97±4	79

shown in Tab.I. In particular the BR for the most probable channel with the maximum number of alpha emitted are shown, for each ER charge (Z$_{ER}$). Each BR is normalized to the total number of complete events with the same Z$_{ER}$; errors on the experimental data are due to identification contamination between ^{3}He and α while statistical errors are negligible. Some observation can be made looking at the values. In both systems, the HFℓ predictions are close to the experimental Fluorine and Nitrogen BR, but the code completely misses BRs for the Neon, Oxygen or Carbon, where only α particles are emitted (plus neutrons). This can be a sign of non-statistical processes which are effective in the experimental data. Moreover, it is also relevant that the α overproduction is of the same order in both systems; thus, the added neutron does not seems to modify the ^{25}Mg decays with respect to ^{24}Mg ones, at least at these high excitation energies.

A qualitative suggestion to interpret these effects can be found in the aforementioned theoretical paper in the context of refined TDDFT calculations [10]. There it is shown that, in fusion reactions between α-conjugated nuclei, during the pre-compound phase the systems could pass through cluster configurations whose presence might influence the α emission following fusion. The details of the calculation are beyond the aim of this proceeding. In short, the authors use a localization function (C_α) to reveal the occurrence of cluster configurations during the collisions. The first results of this calculation for our system ^{12}C+^{12}C at 95 MeV is shown in fig. 1. Here C_α plots are shown in the x-z plane for a central collision, at different times after the contact (which occurs at t=0 fm/c). The time evolution of the systems, taking snapshots at t=120, 160, 240 and 300 fm/c, is shown with the cluster configuration evidenced at each time. As visible in the panels of

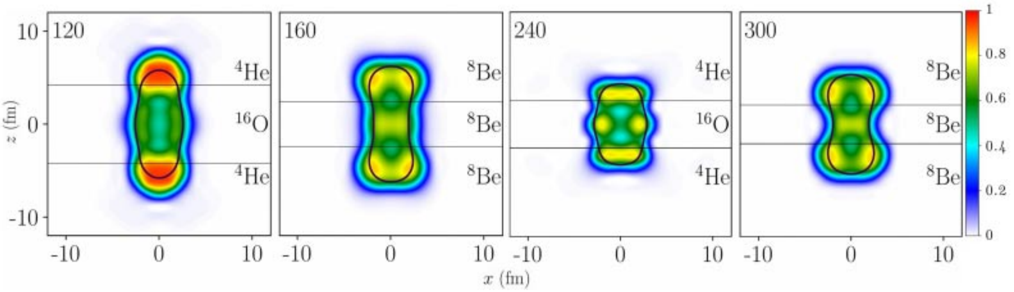

Fig. 1. – TDDFT results for the central ^{12}C+^{12}C collision at 95 MeV. Snapshots at t=120, 160, 240 and 300 fm/c are shown. In each panel the recognized cluster configuration is shown [14].

fig. 1, the pre-compound nucleus oscillates between two structures, α-^{16}O-α (t=120 and 240 fm/c) and ^{8}Be-^{8}Be-^{8}Be (t=160 and 300 fm/c): the probability of these configurations are the 20% and the 16% up to 300 fm/c, respectively.

The effects on the measured BRs (Tab. I) can therefore be consequences of these pre-compound effects shown in fig. 1. Indeed, the O+2α excess could be directly related to the α emission from the α-^{16}O-α configuration; moreover, also the Ne+α case could find an explanation, since one of the two α particles can be emitted, while the second is re-absorbed by the ^{16}O, forming a ^{20}Ne as ER. However, these are just speculations since this model is not capable to predict cluster (or α) emission probabilities, so far. These results are although an interesting starting point and a new way to look at the decays of these light systems.

3. – Conclusions

We presented the results coming from the investigation of the ^{24,25}Mg decays, formed through ^{12}C + ^{12,13}C fusion reactions at 95 MeV bombarding energy. Both systems present a similar behavior: indeed both are globally in agreement with the predictions of a pure statistical model but some deviations appear. In particular, some discrepancies have been found looking at the BRs of the decay channels: an excess in the channels Ne+α, O+2α and C+3α has been found, both in the ^{24}Mg and ^{25}Mg case. This α overproduction can be related to some surviving clustering effects in the fused systems: indeed, for instance, as suggested by TDDFT calculations, during the pre-compound phase some clustered configurations appear and they could influence the decay of the evolving systems. Unfortunately, within the model, no information can be inferred regarding the decay channels. Strategies for coupling TDDFT predictions to the successive decay of clustered configurations are currently being studied.

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