Towards a Reconstruction of Thermal Properties of Light Nuclei from Fusion-Evaporation Reactions

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Abstract

An experimental campaign has been proposed at *Laboratori Nazionali di Legnaro* - INFN, in order to progress in our understanding of statistical properties of light nuclei at excitation energies above particle emission thresholds. Exclusive measurements from fusion-evaporation reactions are used. Light nuclei are interesting probes for high temperature nuclear thermodynamics and the role of structure effects in their decay is a subject of great interest. A first reaction: ^{12}C+^{12}C at 95 MeV beam energy has been measured using the GARFIELD+Ring Counter(RCo) apparatuses. A theoretical study of the system, performed with a dedicated Monte-Carlo Hauser-Feshbach code, will be shown, together with results of the data analysis. Constraints on the nuclear level density at high excitation energy for systems ranging from $\sim$C to Mg are given, and out-of-equilibrium effects, possibly favoured by α-structure, are put in evidence.

1 Introduction

Dissipative nuclear reactions are a tool to investigate nuclear properties at finite temperature, notably including the excitation energy dependence of the nucleon effective mass, symmetry energy and pairing correlations. A general concern is associated with such experimental studies: the final inclusive yields represent integrated contributions and, because of that, the information they bear on specific excitation energy (temperature) regions of the nuclei explored during the reaction may be model dependent. The experimental challenge is therefore to perform a highly exclusive detection of reaction products, in order to backtrace their origin, with the final aim of constraining nuclear properties at finite temperature [1]. An additional challenge comes into play in modelization: because of the strong interplay of nuclear structure and reactions, statistical (and dynamical) codes should be highly constrained by available nuclear data on ground state properties and information on low excitation energies, with the aim of gaining a better predictive power on finite temperature observables.

In this spirit, the NUCL-EX collaboration has recently proposed an experimental campaign, whose aim is to progress in the understanding of statistical properties of light nuclei at excitation energies above

particle emission thresholds, by measuring exclusive fusion-evaporation data.
The choice of investigating light systems is easily explained in the light of our preliminary remarks: the low expected multiplicity of fragments produced in light nuclei collisions (combined with a high detection coverage) increases the probability of achieving a quasi-complete recontruction of the event.
Furthermore, the high energy and angular resolution of the chosen GARFIELD+RCo [2] experimental setup allows the measurement of kinematic correlations among fragments, thus obtaining a global control on the decay mechanism.
The study of the fusion-evaporation channel is the only way to access the fundamental quantity governing the thermal behaviour of any nuclear property, *i.e.* the nuclear Level Density (LD), above the thresholds for particle decay, through the theory of compound nucleus decay (CN). For light nuclei reactions, the reproduction of the features of accurately selected events by means of statistical model calculations allows to strongly constrain the level density in a mass and excitation energy region where few data exist, altogether coming from rather inclusive measurements. Available data in the A$\sim 10 \div 20$ and $E^* \sim 2 \div 3$ A·MeV point indeed to the persistence of the compound nucleus description, provided that the level density parameter is correctly renormalized and deformation is included at high angular momentum [3]. These findings are also consistent with qualitative expectations from surface effects and excitation energy dependence of the effective mass [4], and with theoretical and experimental studies [5] pointing to a limiting nuclear temperature increasing with decreasing compound mass.
Nevertheless, it is especially for light nuclei that signatures of nuclear structure in the reactions are expected to be more evident even at high excitation energy. Thanks to the exclusive channel selection and to the accurate comparison with a highly constrained statistical code, we might therefore find evidence of possible deviations from a statistical behaviour in the decay of the hot fused source formed in the collision.

The first measurement of this campaign: ^{12}C+^{12}C at 95 MeV beam energy, has been measured using the GARFIELD + Ring Counter (RCo) [2] apparatuses at *Laboratori Nazionali di Legnaro* LNL - INFN, Italy. Preliminary results of this study are presented in the following.

2 The ^{12}C+ ^{12}C Experiment

The reaction: ^{12}C+ ^{12}C at 95 MeV has been measured using the GARFIELD + Ring Counter (RCo) [2] apparatuses at LNL - INFN, Italy. Some details on this setup are given in the following.
Exclusive data for the fusion-evaporation channel have been compared to the predictions of a dedicated Monte Carlo Hauser-Feshbach (HF) code for the decay of the compound nucleus [6], explicitly including all the experimentally measured particle unstable levels from the archive NUDAT2 (*http://www.nndc.bnl.gov/nudat2/*). A realistic parameterization for the nuclear level density from Ref. [7] has been implemented in the code, and other statistical model ingredients are optimized for the description of light nuclei.
In the measured reaction, the compound nucleus issued in case of complete fusion is ^{24}Mg, at $E^* = 2.6$ A·MeV and with even values of the initial angular momentum J_0, extracted from a triangular distribution with $J_{0\ max} = 12\ \hbar$ (PACE4).

2.1 Inclusive energy spectra

The fusion-evaporation channel can be selected at first thanks to static conditions on the total detected charge (in this case, $\geq 80\%$ of the charge available in the entrance channel) and on the coincidence between a residue at forward angles (RCo) ($5° \leq \theta_{lab} \leq 17°$) and light charged particles (LCP) detected in GARFIELD ($\theta_{lab} \geq 30°$). Under these conditions, global observables as the charge distribution or LCP multiplicities, known to be less sensitive to the nuclear LD, are well reproduced by model calculations. In what concerns the comparison of LCP energy distributions to model predictions, as it is evident from the first two panels of Fig.1, a very good reproduction of the proton energy spectrum can be achieved, allowing us to constrain the level density model, while the same parameters choice cannot reproduce the energy spectrum of α particles. This deviation from a statistical behaviour could be attributed to out-of-equilibrium α emission, possibly favoured because of the α cluster-like nature of the ^{12}C projectile and target in the entrance channel [10]. This suggests that a contamination from other reaction mechanisms is present in the subset of events selected for the analysis.

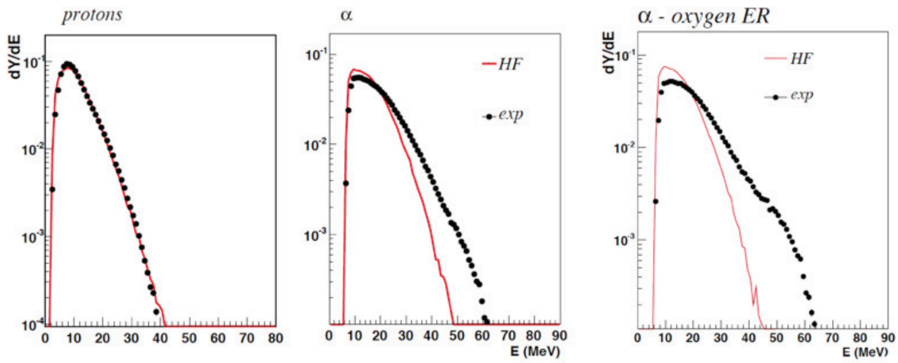

Fig. 1: From left to right, for the reaction ^{12}C (@95 MeV) + ^{12}C: in the angular range covered by GARFIELD, experimental data (dots) and filtered HF calculations (lines) for the laboratory energy spectra of protons and α particles in coincidence with any fragment at RCo angles, and for α in coincidence with a Z=8 fragment in the RCo, always under the condition of completeness of detection ($Z_{det} \geq 10$). In all spectra, normalization is to the total yield for p and α respectively.

2.2 The ^{12}C+^{12}C $\rightarrow$ ^{x}O+α + ... channel

In order to understand where the deviation from the maxwellian shape of the α energy spectrum stems from, we can investigate in more detail outgoing reaction channels in which α particles are detected. In particular, it is found that in the selected set of events, the largest cross section is related to the ^{12}C+^{12}C $\rightarrow$ ^{x}O+α + ... channel (Fig.1, third panel). The kinematic correlation between the oxygen fragment and the α particle(s) in this channel can be built, and it is shown in the top left panel of Fig.2. In the bottom left panel, the same correlation is shown for the Z=8 fragment and α particle(s) resulting from the decay of the ^{24}Mg CN, according to our HF calculations. As it is evident from the figure, there exists a locus of events in the experimental E(O) vs. E(α) matrix showing a strong correlation, which reminds of a not dissipative reaction kinematics. Such events are not easily attributed to the fusion-evaporation channel, but they have not been eliminated from the selected dataset, since they satisfy both requests on the completeness of detection and on the coincidence between a high Z fragment at forward angles and a particle at GARFIELD angles. It is also evident that even a discrimination of the reaction mechanism based on the velocity (or energy) of the "residue" [11] would not be enough to completely isolate such correlated events.

On the contrary, by building the correlation matrix of Fig.2, this discrimination can be easily performed, and the energy spectrum of α particles from events falling in the non-correlated region (delimited by the graphical cut) is shown in the left part of Fig.2 (full dots), together with the corresponding code calculation for the same channel (line). As a reference, also the inclusive energy distribution of α particles detected in coincidence with an oxygen is plotted again (empty dots). The cut used to separate the correlated from the uncorrelated region corresponds to the locus: E(^{16}O) vs. E(α), which can be calculated on the basis of kinematic arguments for the 3-body decay channel ^{16}O+2α, with a Q-value of $\sim$ -15 MeV, corresponding to the opening of 4-body channels (see next section for more details). As it is evident from the figure, the agreement between experimental data and calculations is greatly improved by excluding 3-body decay channels, which are identified as the source of the largest discrepancy.

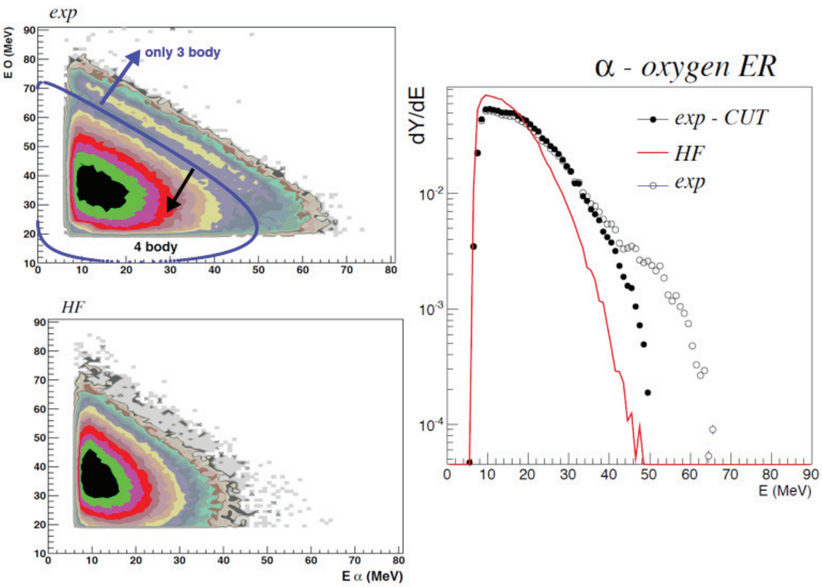

Fig. 2: Analysis of the ^{12}C+^{12}C $\rightarrow$ ^{x}O+α + .. reaction channel: on the left, top panel: experimental kinematic correlation between the oxygen (detected in the RCo) and the α particle(s) in GARFIELD; bottom panel: the same kinematic correlation as predicted by our HF calculations for the decay of the ^{24}Mg CN. On the right, full dots: energy distribution of α particles from dissipative events falling in the region identified by the kinematical cut in the experimental E(O) vs. E(α) matrix; red line: corresponding HF code calculation; empty dots: all α particles in coincidence with an oxygen. All distributions are normalized to the corresponding α particle yield.

2.3 The ^{12}C+^{12}C $\rightarrow$ ^{x}O+2α + ... channel

The ^{x}O+2α channel can be on turn investigated in more detail, even if a reduced statistics is available, due to the very stringent request on the complete charge reconstruction. For this latter case, the Q-value spectrum can be built, where:

$$Q = \sum_{i}^{mult} E_i - E_{beam} \tag{1}$$

and the sum of kinetic energies runs over all detected reaction products. The experimental distribution, plotted in the left panel of Fig.3, shows the same structure as the theoretical one on the right side, with two narrow peaks in the low Q-value region, and a broad distribution extending up to a high amount of energy shortage. By looking at model events, we can easily interpret such spectrum: the two narrow peaks correspond to decay chains in which the ^{16}O is produced either in its ground state (for the peak centered at Q $\sim$ 0.5 MeV), or in one of its first closely spaced excited states below the threshold for α particle emission (Q $\sim$ -6 MeV). The broad bump region corresponds to 4-body channels of the type ^{15}O$+2\alpha+n$, in which the missing energy is the kinetic energy of the emitted neutron. The Q-value at the opening of 4-body channels provides the best separation between the two regions, and it is used to calculate the kinematical cut in Fig.2. Despite the similarity in the structure of the two spectra, a clear discrepancy in the cross-sections for the population of the two regions is seen: in the experimental sample we have 30% of events falling in the narrow Q-value peaks region, while only $\sim$ 5% of model events fall in the same region according to the calculations. This discrepancy may be attributed to the contamination of direct reactions in the event selection, possibly favoured by the α-cluster like nature of projectile and target, which are expected to populated the same low Q-value region, without proceeding through a CN state. When enlarging the set of events to the $Z_{tot} \geq 10$ case (see previous section), this contamination cannot be totally excluded, since no real Q-value can be built for an incomplete charge detection. This might (at least partially) explain the persistence of a deviation from a statistical behaviour evident in the α energy spectrum of Fig.2.

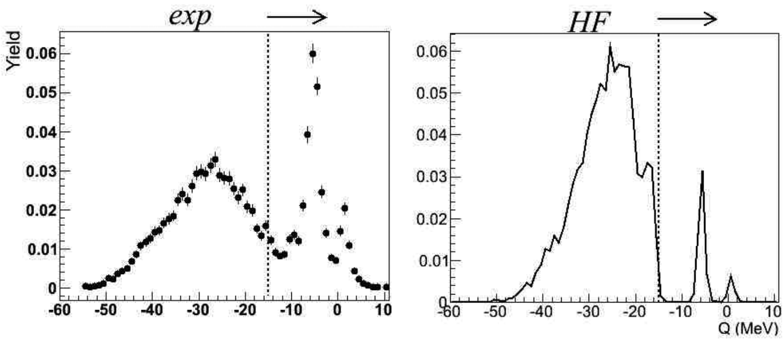

Fig. 3: For the ^{12}C+$^{12}C \rightarrow {}^{x}$O+$2\alpha +$ .. channel, experimental (left) and theoretical (right) Q-value distribution (eq.1). The experimental sample reduces here to 2.5% of the events considered in Fig.2. In both cases, the arrow identifies the region of 3 body exit channels (^{16}O$_{gs}$/^{16}O* $+ 2\alpha$), where a clear discrepancy in the measured and calculated population is observed. Normalization is to the number of events.

3 Conclusions and Perspectives

The results presented at this conference for the ^{12}C+^{12}C reaction have allowed us to put constraints to the level density of light nuclei in the A$\sim$ $10 \div 20$ and E* $\sim 2 \div 3$ A·MeV mass-excitation energy region, through the comparison with a dedicated Monte-Carlo Hauser-Feshbach code. An out-of-equilibrium component in α particle emission has been put in evidence, and tentatively attributed to the contamination of reaction mechanisms other than CN formation and decay, possibly favoured by the α structure of both projectile and target. The exclusive coincidence study for ^{12}C(^{12}C,^{x}O)(2)α discussed here in details will be extended by means of further analysis to other interesting decay channels in the same dataset. This will allow us to further refine the fusion-evaporation event selection, in order to understand if the contamination of non dissipative reaction mechanisms can be considered as the unique source of deviation from a statistical behaviour.

Within the same experimental campaign, a new measurement is already scheduled at LNL, with the same GARFIELD + RCo setup, concerning the ^{14}N (@ 80 MeV)+^{10}B reaction, leading in case of complete fusion of the two N$\neq$ Z reaction partners to the same ^{24}Mg compound nucleus at similar excitation energies. In the perspectives of this campaign, deviations from a statistical behaviour are used as a tool to get information on nuclear clustering, both in the ground-state for projectile and target and eventually in the hot source formed in the collision. A disentanglement of these two aspects and an insight on the persistence of cluster correlations at high excitation energy should be possible thanks to the comparison between the two reactions.

References

[1] M. D'Agostino *et al*., Nucl. Phys., A875 (2012) 139.

[2] F. Gramegna *et al.*, Nucl. Instr. and Meth., A389 (1997) 474;
A. Moroni et al., Nucl. Instr. and Meth., A556 (2006) 516,
M. Bruno *et al.*, in preparation;

[3] S. Adhikari *et al.*, Phys. Rev. C74 (2006) 024602.

[4] S. Shlomo and J.Natowitz, Phys. Rev. C44 (1991) 2878.

[5] J. B. Natowitz *et al.*, Phys. Rev. Lett. 89 (2002) 212701.

[6] G. Baiocco, Ph.D. thesis, Università di Bologna, Italy, and Université de Caen-Basse Normandie, France, 2012, *http://tel.archives-ouvertes.fr/lab/lpcc/*

[7] T. Von Egidy and D. Bucurescu, Phys. Rev., C72 (2005) 044311.

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

[9] V. L. Kravchuk *et al.*, EPJ Web of Conferences 2 (2010) 10006.

[10] V. L. Kravchuk *et al.*, IJMPE 20, 4 (2011) 1050 and proposal to LNL-PAC (2012).

[11] M. E. Ortiz *et al.* , Phys. Rev. C82 (1436) 1982.