Investigation of decay modes of Argon isotopes formed in fusion-evaporation reactions

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INTRODUCTION

The nucleus is a many-body quantum system which undergoes several configurations even with a fairly small excitation energy. A very well-known fact is that the density of a quantum mechanical state rises rapidly with excitation energy and becomes very large. As a result, the nucleus leaves the discrete region and enters the region of quasi-continuum and continuum. Because of this complexity, appropriate statistical models are crucial and a detailed knowledge of the nuclear level density (NLD), a key quantity in these models, is of fundamental importance to understanding reaction mechanisms [1]. The direct measurement of NLD from transfer reactions [2] is limited to a relatively low excitation energy domain. Above the thresholds for particle decay, the information about NLDs can only be accessed in fusion-evaporation reactions through the theory of compound nucleus decay [3]. While a wide collection of inclusive experimental data has been used to constrain this fundamental quantity, a very few data exists concerning the evaporation of light nuclei.

To make progress on this issue, the NUCL-EX collaboration has recently initiated an experimental campaign of exclusive measurements of fusion-evaporation reactions with light nuclei as interacting partners. In collisions involving light systems, the low expected multiplicity of fragments increases the probability of achieving a quasi-complete reconstruction of the event. In light α-like nuclei, clustering is observed as a general phenomenon at high excitation energy close to the α-decay thresholds. This exotic behavior has been perfectly illustrated by the Ikeda-diagram for even-even N=Z nuclei [4], and has been later extended by von Oertzen [5] for neutron-rich nuclei.

Very recently, the $^{12}$C (95 MeV) + $^{12}$C and $^{14}$N (80.7 MeV) + $^{10}$B reactions have been extensively investigated in order to study the decay pattern of the $^{24}$Mg compound nucleus, populated at the same excitation energy (~62 MeV) [3, 6, 7]. The fusion-evaporation mechanism was selected by considering a coincidence between light charged particles detected in GARFIELD and a residue detected at forward angles in the Ring Counter (RCo). This selection was reinforced by completeness conditions on the total detected charge and longitudinal momentum. The statistical character of the data sample was demonstrated by comparing inclusive and exclusive observables to model calculations. Despite a global agreement between experimental data and model calculations for both reactions, some discrepancies were evident when considering the α-decay channels leading to C, O and Ne residues. Particularly, the experimental and calculated particle energy-spectra shapes for both reactions were in reasonable agreement, except for α-emission events where an Oxygen residue was selected. While for the $^{12}$C+$^{14}$C reaction this out-of-equilibrium α emission has mainly been assigned to the α-cluster structure of reaction partners, such an assumption was not tenable for the $^{14}$N+$^{10}$B case. In studying the O+2α channel, for a deeper understanding of the reaction mechanisms, as a function of the dissipated energy, a much higher percentage of events was found to populate the less dissipative region in the experimental sample of $^{12}$C+$^{14}$C with respect to model predictions. This could be understood as a possible contamination of direct (α-transfer) reactions involving an excited $^{12}$C nucleus in competition with fusion-evaporation mechanism. However, the $^{14}$N+$^{10}$B dataset was also observed to show a similar trend in the dissipated-energy distribution as in $^{12}$C+$^{14}$C. To estimate the α-clustering effects for both reactions coming either from entrance channels or in the excited $^{24}$Mg, a new variable quantifying the experimental branching ratio excess for α-emission was introduced. In this way, preferential α-particle emissions in connection with C, O and Ne with respect to the theoretical expectations were observed. This was linked to a possible presence of residual α correlations in the excited $^{24}$Mg or in its daughter $^{20}$Ne. Hence, these findings have stimulated the need for more detailed exclusive measurements on different light hot systems.

For the reasons given above, we have proposed to study the formation and decay modes of excited Argon isotopes. Two different reactions, $^{24}$Mg (161 MeV)+$^{12}$C and $^{24}$Mg
(142 MeV)$^{13}$C, have been used to produce fused systems with nearly the same mass and excitation energy (∼70 MeV). The second system was chosen in order to investigate the influence of the structure of the reaction partners on the decay mode of the fused system. In this way, clustering aspects in light nuclei with neutron excess, as proposed in the extended Ikeda diagram, are investigated. In fact, it is expected that the extra neutron in the entrance channel would lead to a larger contribution in the more dissipative region of α-decay channels, in which at least one neutron is emitted together with α-particle(s) and a residue. This approach will, hopefully, help to eliminate uncertainties connected to a specific reaction mechanism.

EXPERIMENTAL DETAILS AND CALCULATIONS

The experiment was performed at INFN, Laboratori Nazionali di Legnaro, Italy. The beams of $^{24}$Mg, impinging on thin self-supporting carbon $^{12,13}$C targets (∼100 μg/cm²), were delivered by the TANDEM-ALPI accelerator. The experimental setup is composed of RCo coupled to GARFIELD for a total of 488 detecting cells with nearly 4π geometrical coverage, fully equipped with digital electronics. A detailed description of the apparatus can be found in Refs. [8, 9].

The experiment was conducted during the fall 2015. Beam intensities varied from 0.3 pnA to 0.6 pnA and we have collected data with a sufficient number of evaporation residues (ERs), necessary for intended correlation studies. During the experiment we have also performed some runs with a $^{197}$Au target using both beams in order to have a reference point for the energy calibration of the detectors given by the elastically scattered projectiles.

The particle identification and energy calibration are in progress. Typical examples of ΔE-E and fast-slow matrices used to identify particles and fragments, detected respectively in RCo and GARFIELD are shown in Figs. 1 and 2.

As the present work deals with the investigation of fusion-evaporation channels, we have used the GEMINI code [1] to simulate fusion-evaporation events which were filtered through a software replica of the experimental setup, taking into account the geometry, the energy thresholds, the energy resolution and the solid angle for each detector. In Fig. 3, one clearly sees the effect of the filter on the Z-distribution of ERs. This translates into the efficiency of RCo in detecting ERs and also its angular coverage. The dynamical part of the reaction is currently under study through the Antisymmetrized Molecular Dynamics (AMD) code [10]. Moreover, the Stochastic Mean Field (SMF) code [11] will also be used for comparison, followed by an afterburner stage to take into account the de-excitation of the system. Typically the GEMINI code will be used for this purpose which will be compared to the Monte Carlo Hauser-Feshbach (HF) code [6].