PRECISE STUDY OF SELECTED EVAPORATION CHAINS IN FUSION REACTIONS BETWEEN LIGHT NUCLEI*

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Evaporation chains in the fusion reaction ^{13}C+^{12}C at 95 MeV have been measured. Events complete in charge have been detected with the large acceptance GARFIELD+RCo apparatus at INFN-LNL and the features of the decay of the excited ^{25}Mg compound nuclei have been compared with predictions of statistical models. Some deviations from these predictions have been found, especially for the chains mainly containing α particles.

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1. Introduction

Reactions between light nuclei have been studied since decades. Recently, there have been impressive developments of the models in describing

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these quantum systems in a more fundamental way and also strong experimental progresses in measuring fine details of their behavior (for a recent review on the subject, see, for instance, Ref. [1]). Therefore, interesting new insights and perspectives have been published. This study is in this context and the idea was to produce fusion reactions with even $N = Z$ (or almost autoconjugate) nuclei to verify whether the underlying α-cluster nature of the system can play a role in the evolution towards fusion or during the evaporative decay. Such a role could manifest in a more abundant α emission than predicted by statistical models not including such α structures. Indeed, evidences of an excess of α multiplicities (or differences in their spectral shape) with respect to model predictions have been signaled, also recently [2, 3]. Moreover, preferential production of α-cluster fragments in break-up channels of hot compound nuclei (CN) has been reported in the fusion of $N = Z$ nuclei [4]. Our group initiated the experiments on this subject via fusion reactions producing CN of ^{24}Mg [5], either using autoconjugate colliding nuclei or not. Here, we shortly discuss recent findings on the decay of excited ^{25}Mg nuclei, just adding only one neutron in the system, in order to see whether some differences with respect to statistical models, as found in the $N = Z$ system, would survive (and to what extent) for ^{25}Mg nuclei, populated with comparable excitation energies ($E^{*} \approx 60$ MeV) and spins. The detailed description of this study is published elsewhere [6].

2. Experiment and results

The experiments are carried out at INFN-LNL with the GARFIELD+RCo setup capable of detecting with high efficiency most charged products (geometrical efficiency of around 70% of the solid angle with around 300 electronic channels). In practice, a statistically good set of central events complete in charge can be collected, with full charge identification from protons to evaporation residues (ER), up to Na ions in our case, and isotopic separation of H and He species (light charged particles, LCP). Fusion–evaporation events have been carefully selected, with specific software cuts to reject the various backgrounds and other types of reaction mechanisms. The (minority) break-up like events after fusion, with two coincident intermediate fragments both heavier than lithium have been discarded in this analysis. The measured features of the fusion–evaporation chains have been compared with statistical model predictions. We used two versions of the model, the well known Gemini++ [7] code and a MonteCarlo, labeled HFℓ [8], purposely developed by our group to better describe the decay of light-nuclei; HFℓ bases on the standard Hauser–Feshbach formalism but it includes the nuclear structure information available for light nuclides from scientific databases. By analyzing the events complete in charge, we can investigate different types of evaporation chains, disentangling the various paths that, for instance, bring to the various ERs. This accurate selection permits stringent tests on the model predictions because one can perform comparisons on very exclusive observables.

For the sake of brevity, among the main findings reported elsewhere [6], we here underline two main results.

Similarly to the ^{24}Mg fusion cases, also for this reaction, we found that the observed ER+LCP events are essentially consistent with the statistical decay of a hot CN ^{25}Mg source. Indeed, the charge and velocity distributions of the ER and the main characteristics of LCP are well-reproduced by models. However, when selecting specific chains, especially those ending with even-Z_{ER} and, therefore, reachable also via the emission of only α, we could detect some slight differences. The latter are basically associated with the incorrect mixing, in the models, of the various chains bringing to a given final ER. This is shown in Table I and it is the first remarkable result that we like to underline. One observes that for odd-Z_{ER}, the probabilities for chains also containing protons are correctly accounted for by the model. Instead, for most even-Z_{ER} ending decays, HFℓ sizably underestimates the data. As said, these discrepancies are at the origin of the small differences found when comparing data and model at a less exclusive level (see *e.g.* Fig. 9 of Ref. [5] or Fig. 3 of Ref [6]). A very similar mismatch has been previously found in the ^{12}C+^{12}C system [5], so one could wonder whether the additional neutron in the present ^{25}Mg case does not perturb so much the microscopic process (the fusion and the further decay), thus allowing some α-related effect to survive in the entrance channel and/or in the evaporative paths.

TABLE I

Branching ratios for some channels mainly considering chains with the maximum possible α multiplicities. Measured and calculated (by HFℓ) values are compared. Experimental errors include also systematic ^{3}He–α bad mixing (around 4%). The quoted ranges for the model are due to the uncertain knowledge of the CN spin distribution. Statistical errors are negligible in all cases. All values are normalized to the number of events for each Z_{ER}.

Z_{ER}	Chain	EXP [%]	HFℓ [%]
6	$^{13-x}$C$+xn+3\alpha$	97±4	79÷83
7	$^{15-x}$N$+xn+p+2\alpha$	83±3	90÷92
8	$^{17-x}$O$+xn+2\alpha$	69±3	30÷32
9	$^{20-x}$F$+xn+p+\alpha$	86±3	84÷86
10	$^{21-x}$Ne$+xn+\alpha$	29±1	3.2÷3.8
11	$^{24-x}$Na$+xn+p$	83±2	92

This argument motivated our further analysis exploiting the Jacobi coordinates for specific decay chains with three charged products (plus possible neutrons). We focused on ^{17,16}O$+2\alpha$ events (accompanied by zero or one neutron) in order to assess or at least get some indication about the emission order of the α particles and of the neutron. ^{17}O$+2\alpha$ and ^{16}O$+2\alpha+n$ events were selected with cuts on the Q-value distribution, according to the 1-, 2-neutron separation energies. Then the angular Jacobi coordinate θ_k was studied, while we here discard the Jacobi energy coordinate which appears to be less sensitive for our purposes. θ_k is the angle between the versor of the relative motion of the two α particles and that of the oxygen momentum with respect to the α-pair center of mass. We compare the experimental $\cos(\theta_k)$ distribution with model predictions, under the hypothesis that it is affected by the emission order of the neutron, in the case of "false" 3-body events ending up at ^{16}O. First, we verified that the HFℓ model well reproduces the $\cos(\theta_k)$ shape for events without neutrons ("true" 3-body events). Having checked the model reliability, we then compared the $\cos(\theta_k)$ spectra for the ^{16}O and this is reported in Fig. 1.

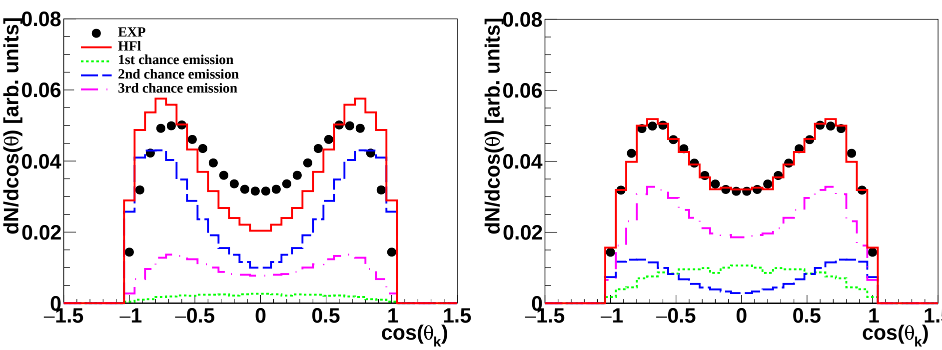

Fig. 1. (Color online) Experimental (points) and simulated (solid/red line) Jacobi angle distributions. Left: direct model predictions. Right: model output after fitting the weights for the best shape reproduction. See the text for more details.

The curves are normalized to the integral and the various emission order contributions (see colors in the legend) are drawn for the model where they can be easily recognized. On this basis, assuming as good the shape corresponding to each order ranking, we attempted a rescaling of the weights of the three order emission cases by a fit on the experimental data (right panel in the figure). It has been found that, at variance with the original model predictions, data suggest a preferential emission of α particles in close pairs $(\alpha+\alpha+n)$ or $(n+\alpha+\alpha)$. These two chances sum up to 80% of total, while the original HFℓ prediction is 25%. This is the second relevant result that we stress here. It could be connected to very recent TDHF [9, 10] calculations where, restricting to fusion between even–even nuclei, one shows that the system evolves in time developing bilobate α structures which, qualitatively, could act as doorway states to precompound emission of pairs of α towards the fusion.

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