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Deviations from Hauser-Feshbach behaviour in evaporation chains in light heavy-ion collisions

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Summary. — In the framework of the INFN NUCL-Ex experiment, we extended the investigation on the decay of light nuclei at excitation energies above particle emission thresholds, by performing exclusive fusion-evaporation measurements. The $^{16}O + ^{12}C$ reaction was investigated at three different bombarding energies, 90.5, 110 and 130 MeV. For complete fusion, such reactions lead to a fused $^{28}Si^*$ compound nucleus respectively at 55, 63 and 72 MeV excitation energy. By investigating this autoconjugate system we put into evidence the role of non-statistical effects, also clearly observed in our previous studies in lighter systems.

1. – Introduction

The statistical decay model, based on the Hauser-Feshbach formalism [1], is a well known theory used for describing the fusion-evaporation mechanism of the compound nucleus formed in central collisions. The detailed output and the decay channels of the reaction are predicted based on the knowledge of the level densities and trasmission coefficients. Nevertheless, nuclear structure signatures are especially evident in light nuclei, even at high excitation energy. In particular, according to the Ikeda diagrams [2], α-clustered excited states are expected at excitation energies close to the multi-alpha decay threshold in even-even N = Z nuclei.

By using an exclusive channel selection and a highly constrained statistical code, it is possible to put into evidence deviations from the statistical behaviour in the decay of the hot fused source formed in the collision. For this purpose we employed two statistical decay Monte-Carlo codes. The first is Hauser-Feshbach light ($HF\ell$) [3], a dedicated code designed by the collaboration where the statistical ingredients are optimized for the description of light nuclei ($A < 40$). The code explicitly includes all the experimentally measured excited levels from the archive NUDAT2. The second one is Gemini++ [4], a standard code employed in nuclear physics for describing the decay of hot nuclei.

2. – The experiment

The experiment was performed at the LNL (Laboratori Nazionali di Legnaro) using a pulsed beam of ^{16}O delivered by the XTU TANDEM accelerator at 90.5, 110 and 130 MeV. The employed apparatus is composed of the coupling of two detectors, namely GARFIELD and RingCounter (RCo). Hereafter, we will recall a few main features of the apparatus while a detailed description is given in [5]. GARFIELD is a two stage detector which covers the polar region $30° < \theta < 170°$. It is made of an ionization drift chamber and CsI(Tl) scintillators. Light reaction particles can be identified in charge and mass with a threshold around 1 AMeV and the energy can be determined up to a few percent accuracy [5]. The RCo is an array of three telescopes made by an ionization chamber (IC), silicon strips (Si) and CsI(Tl) scintillators which covers the most forward angles ($5° < \theta < 17°$). The charged particle and fragment identification is performed through the ΔE-E technique in IC-Si with a threshold of around 0.8÷1 AMeV. Mass identification for the light particles in also possible through either ΔE-E in Si-CsI and/or pulse shape analysis in the CsI with a threshold of 6 AMeV [5]. The combination of the two devices allows a nearly-4π coverage (around 70%), which permits to perform complete charge detection of the events and to discriminate the different reaction mechanisms.

3. – Results

Experimentally, the selection of the fusion-evaporation mechanism is based on the coincidence between light charged particles (LCP) and a fragment (evaporation residue) detected at forward angles by RCo. Moreover, we imposed charge and longitudinal momentum conservation which characterizes the complete detection of fusion events. We compared the predictions of the Monte-Carlo codes, filtered through a software replica of the apparatus, to the experimental data. In the first part of the analysis we focused on inclusive observable which describe the general behaviour of the reaction and then we proceeded to investigate more exclusive observables by selecting the various decay channels. The statistical models are generally able to reproduce globally the experimental data but clear differences can be noticed for more exclusive observables such as the α-particle energy spectra detected in coincidence with even-Z residues shown in fig.1. One can observe for example the $Z_{res} = 10$ (Neon) case where the energy tails for α-particles are not reproduced by the models for all three energy cases and also for $Z_{res} = 8$ (Oxygen) at 130 MeV. In order to understand better these differences, we discriminated further the

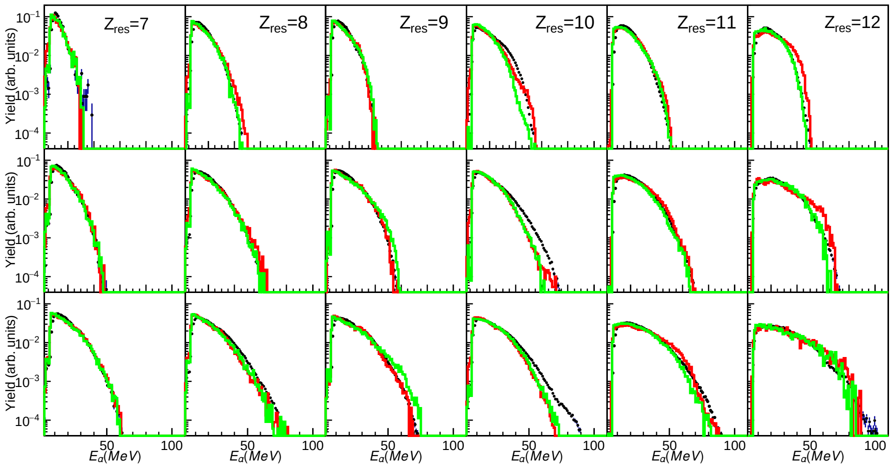

Fig. 1. – Laboratory energy spectra for α-particles detected in coincidence with a residue of charge Z_{res}, indicated in each pad, for 90.5 (top), 110 (middle) and 130 (bottom) MeV . Black dots represent the experimental data while the red and green line are the predictions of HFℓ and Gemini++, respectively. In each panel the distributions are normalized to unitary area for a better shape comparison.

different channels which contribute to each Z_{res} spectra. Table I contains the branching ratio for the channels containing the maximum number of allowed α-particles for the selected Z_{res}. Since the excitation energy of the CN is large compared to the neutron/s emission threshold, the decay channels are shown with the possible number "xn" of emitted neutrons. The obtained values are in agreement with the statistical predictions for odd-Z residues, with the exception of $^{23-xn}Na+\alpha+p+xn$ channel at 130 MeV, while even-Z are clearly underestimated by both models for most of the studied energies and

Table I. – *For Z_{res} from Nitrogen to Magnesium, the branching ratio for the channels containing the maximum number of allowed α-particles are reported. Measured values are compared, for each bombarding energy, to model calculations (HFℓ and Gemini++). Errors on the experimental values (about 5%) take into account both statistical error and the systematics due to the uncorrect particle identification.*

		90.5 MeV(%)			**110 MeV(%)**			**130 MeV(%)**		
$\mathbf{Z}_{res}$	**Channels**	Exp	HFℓ	Gem	Exp	HFℓ	Gem	Exp	HFℓ	Gem
7	$^{15-xn}$N+xn+p+3α	100	100	94	98	99	96	95	97	95
8	$^{16-xn}$O+xn+3α	100	99	91	99	87	63	88	43	31
9	$^{19-xn}$F+xn+p+2α	99	99	99	93	93	96	88	89	83
10	$^{20-xn}$Ne+xn+2α	74	17	13	45	6	9	29	2	4
11	$^{23-xn}$Na+xn+p+α	95	95	91	93	87	85	88	55	61
12	$^{24-xn}$Mg+xn+α	53	11	18	35	5	8	28	3	3

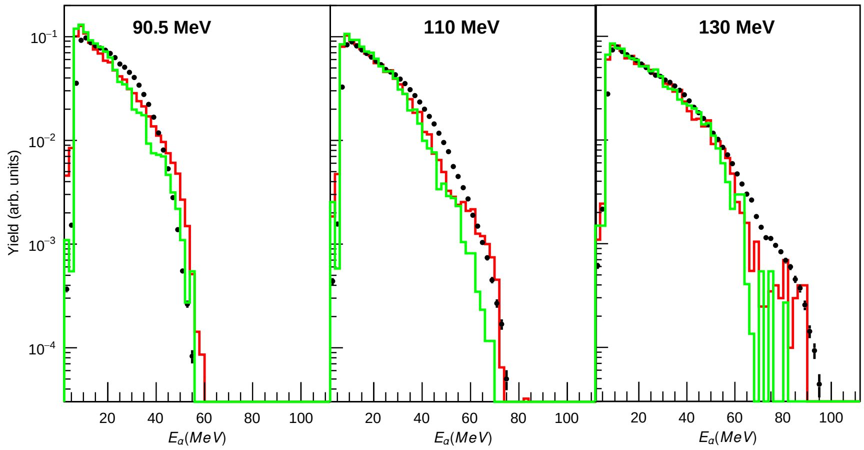

Fig. 2. – Laboratory energy spectra for α-particles detected in the $^{20-xn}Ne + 2\alpha + xn$ channel. Black empty dots represent the experimental data while the red and green line are the predictions of HFℓ and Gemini++, respectively. In each panel the distributions are normalized to unitary area for a better shape comparison.

Z_{res}. For these cases, in principle one can think of the shape differences in fig.1 as due to the different evaluation of the branching ratios in the experimental data and by the statistical decay models. In fact, one can look at the single α-particles energy spectra for the specific channels of table I. In fig.2, the case of $^{20-xn}Ne + 2\alpha + xn$ is shown as an example at the three energies. One can notice that the shape still presents clear differences with respect to the statistical models which are more evident at the highest energy. This means that the kinematics of the decay, for these specific channels, needs to be further studied in order to determine if non-statistical correlations are involved.

4. – Conclusions

We have compared experimental data for the ^{16}O+^{12}C reaction at 90.5, 110 and 130 MeV with the results of two Hauser-Feshbach statistical calculations for the decay of the ^{28}Si* compound nucleus. The measured data are compatible with the expected behavior of a complete fusion-evaporation reaction. For specific channels, corresponding to the emission of α-particles in coincidence with an even-Z residue, a higher branching ratio was measured with respect to the statistical decay models. These preliminary results, in analogy to the findings of [6, 7], can suggest that alpha correlations can play a role in the reaction stage or in the further evaporative decay.

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