Evaporation residue as a dominant exit channel at high thermal energies in ^{3}He + Ag reactions*

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Abstract

In the reaction ^{3}He (1.8 GeV) + ^{nat}Ag, events are observed with a heavy fragment (HF), A $\geq$ 10, in coincidence with charged particles detected over 70% of 4π solid angle. Calorimetric measurements show high thermal excitation energies of the target primary fragment: 6-8 MeV per nucleon for HF mass $\gtrsim$ 45. For these excitation energies, the probability for having an evaporative residue is shown to be unexpectedly high when compared with current multifragmentation models. This result is interpreted as linked to the use of light ion projectiles at relatively low incident energy.

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Motivation. One of the main objectives of heavy ion physics is the determination of bulk properties of nuclear matter versus temperature and/or density. Since nuclei are small entities, a more direct and perhaps more appropriate question is: what happens to a nucleus when it is heated, i.e. when it is given internal randomized excitation energy $E^{\star}_{\rm th}$? This question has been addressed theoretically by many authors [1–6]. Perhaps the most detailed answer in terms of possible final states is provided by the approaches of Bondorf *et al.* [4] and Gross *et al.* [5], who calculate the probability of the possible partitions of the system, basically in a canonical statistical model, for given volume and temperature (or excitation energy $E^{\star}_{\rm th}$). At low $E^{\star}_{\rm th}$, evaporation dominates, characterized by a heavy residue. As $E^{\star}_{\rm th}$ approaches the total binding energy, evaporation gives way to pseudo-fission and multi-fragmentation; at still higher values, vaporisation may occur [7]. In these calculations, the "effective thresholds" are however functions of the average density of the system. In particular, multifragmentation appears at lower $E^{\star}_{\rm th}$, when the density is diminishing. In fact, one is led in the Gross model, to assume the statistical decay to occur at reduced nuclear density around $\rho \approx \rho_0/3$, where ρ_0 is the normal density, in order to achieve a good representation of the heavy ion data [5,8]. This is generally interpreted as due to the expansion of the system, driven by the accumulation of compressional energy in the first stage of the collision. Friedman [9], who explicitly incorporated such an expansion in a statistical model, arrived at similar conclusions. An interesting aspect of the models [4,5] is that they predict the compound nucleus survival probability $W_{\rm comp}$ for excitation energies accessible in both heavy and light ion induced reactions.

The possible determination of these effective thresholds by heavy ion experiments raises a difficulty; the formation of an ideally thermalized source in the course of the collision can hardly be established. Would it be the case, the separation of effects related to the heating process (as pre-equilibrium emission) from those associated with the evolution of the equilibrated system itself, is not obvious, not to speak of the mixing of several sources in some situations. Using light ions offers, as it is largely believed [10–12], many advantages in this respect: formation of a single source, small angular momentum, minimal compression, etc, and this up to the GeV range according to a recent investigation by Colonna *et al.* and others [13,14] of ^{3}He-induced reactions.

Motivated by these considerations, an experiment has been performed at the Laboratoire National Saturne, Saclay, France, using a ^{3}He beam at 1.8, 3.6 and 4.8 GeV incident energies, a ^{nat}Ag target (of thickness 1.08 mg/cm^2) and a detector system, to be described below, allowing the detection of events with a heavy residue as well as of multifragmentation events. In previous publications [15–19], the emphasis was put on the latter. For the lowest incident energy, the evaluated cross-section for multifragmentation is low: $\sim$ 10 mb. In this paper we report on a complementary study, restricting to this incident energy. More specifically, we address the question of the compound nucleus survival by directly detecting a single heavy fragment (HF) and its accompanying charged debris. Events with excitation energies reaching 80% of the binding energy are characterized by a coupled Intra Nuclear Cascade and classical evaporation code. Also the extracted experimental $W_{\rm comp}$ values are compared to multifragmentation model predictions.

The experiment. The experimental set-up, consisted of three parts: (i) An annular hodoscope, DELTA, was employed to detect HF's, which included 30 high-field Si detectors about 140 μm thick. DELTA covered angles between 5 to 10° and the target-detector flight path was approximately 60 cm. (ii) The array ISiS [20], containing 162 triple detector telescopes in a spherical geometry, in which light charged particles(LCP), (Z=1,2), and intermediate mass fragments (IMF), (3 $\leq$ Z $\leq$ 20), were detected. The angular coverage ranges between 14° to 86.5° and 93.5° to 166°. Each telescope is composed of a gas ionisation chamber, a 500 μm ion-implanted silicon detector and a 28 mm CsI(Tℓ) crystal. The geometrical acceptance is approximately 70% and the energy thresholds are lower than 1. A MeV. Unit charge resolution is obtained up to Z=20. Mass resolution is obtained for those particles which punch through the Si counters (Z $\leq$ 2). (iii) An active beam collimator was used [18].

A noteworthy feature of this experiment is the possibility of detecting a recoiling HF in DELTA in coincidence with charged particles in ISiS. The mass, $m_{\rm HF}$, and velocity, $v_{\rm HF}$, of the HF were determined from the time between DELTA and ISiS and energy measurements. Corrections for time delay [21] and energy defect [22] are included. The latter was completed in a separate measurement through a coincident set-up using slowed down fission fragments from a ^{252}Cf source. Velocity and energy thresholds are lower than 0.3 cm/ns and 2.5 MeV, respectively.

Calorimetry. All theoretical investigations of nucleon- and light ion-nucleus interaction point to a rapid (~30-40 fm/c) thermalisation process with a net energy loss through the emission of pre-equilibrium nucleons, pions, and to a lesser extent, composite particles, producing an excited, basically thermalized, primary target residue which subsequently de-excites by emission of lower energy particles LCP's and IMF's. Adopting this scenario as the basic premise of our analysis, we can extract the mass number $A_{\rm th}$, the charge $Z_{\rm th}$ and "thermal energy", $E^{\star}_{\rm th}$, of the primary fragment, event by event, by standard calorimetric methods. We give a few details.

We consider two classes of events with a minimum bias in ISiS: those with a HF ($m_{\rm HF} \geq 10$) in DELTA (denoted class I), and those with no HF detected in DELTA (class II). The quantity $E^{\star}_{\rm th}$ for class I events is evaluated as follows; (i) we account for the detector acceptance, which includes the efficiency as a function of charge and mass for low energy particles. Efficiency corrections were established with the aid of an event generator INC+EVAP+FILTER, which consists of an intranuclear cascade code [10], an evaporation code [23] and a filtering routine accounting for angular acceptance, energy thresholds, energy losses, as well as for the angular straggling of the HF in the target. (ii) The primary charge $Z_{\rm th}$ is obtained by summing all charges, after efficiency corrections. If necessary, the mass of IMF's and HF's is deduced from their charge (or vice-versa) by reading off a correspondence table built from the simulation. The mass number $A_{\rm th}$ is determined from $Z_{\rm th}$ by assuming a $Z_{\rm th}/A_{\rm th}$ ratio in the valley of stability. (iii) Subtracting the efficiency corrected total mass of the detected particles from $A_{\rm th}$ yields the number of neutrons N_n. The mean neutron energies $\langle {\rm K}_n \rangle$ were evaluated using the codes EVAP [23] and LILITA [24]. (iv) The quantity $E^\star_{\rm th}$ is computed from the sum $E^\star_{\rm th}={\rm N_n}\langle {\rm K}_n \rangle+\sum_{\rm i}{\rm K_i}+{\rm Q}$, over thermal particles [16], corrected for the efficiency, and including Q-values. For LCP's the sum is extended over particles with kinetic energies, $\rm K_i$, which are below 25, 32, 39, 54 and 61 MeV for p, d, t, ^{3}He and ^{4}He, respectively. These values correspond to rather well-defined changes of slope in the particle spectra[1]. This procedure is partly justified by pre-equilibrium calculations, at least for the nucleon-nucleus case [25]. It is worth mentioning that the largest correction to the observed energy comes from the neutrons. On the average, about 50% of $E^\star_{\rm th}$ is directly observed. We estimate the uncertainty on $E^\star_{\rm th}/A_{\rm th}$ to be smaller than $\sim$0.5 MeV/nucleon.

The analysis yields a nearly constant $A_{\rm th}\approx$ 92 for $E^\star_{\rm th}\geq$ $250MeV$, which is also the prediction of the INC model itself. This observation re-inforces the validity of the procedure. This led us to develop a second method where $A_{\rm th}$ and $Z_{\rm th}$ are assumed and given by the INC model. The missing mass, charge and corresponding energies were assumed to arise only from LCP's and IMF's in the same proportion as the detected particles in the event. In both formulations, the average $E^\star_{\rm th}$ comes out to be the same. Events with characteristics of fission have been identified; their relative proportion is negligible.

A similar analysis was performed for class II events using the second method and including the efficiency corrections. To test the validity of this prescription, class I events were analyzed by ignoring the HF information in DELTA. The event-by-event comparison shows that the reconstructed HF mass, $\tilde{m}_{\rm HF}$, and energy, $\tilde{E}^\star_{\rm th}$, agree reasonably with the measured $m_{\rm HF}$ and $E^\star_{\rm th}$ values. Therefore class II events, where the HF is lost, can still be considered, with good confidence, as containing a single heavy fragment.

Results. Fig. 1 shows, for class I events, the joint distribution of $m_{\rm HF}$ and $\epsilon_{\rm th}=E^\star_{\rm th}/A_{\rm th}$

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[1]These values are relatively low, compared to Ref. [16] and therefore give a thermal energy value which is rather conservative.

for IMF multiplicity, $N_{\rm IMF} = 0$. The highest yield is for events with $m_{\rm HF} \approx 65$. Note that a similar plot is obtained for class II events for $E^{\star}_{\rm th} \gtrsim 250$ MeV, but with somewhat narrower widths. Due to the 70% geometrical efficiency of ISiS, not all events are true $N_{\rm IMF} = 0$ events. Using FILTER and the experimental $N_{\rm IMF}$ distribution, we find that 16% of these events correspond in fact to $N_{\rm IMF} > 0$. Given that the IMF Z-distribution decreases rapidly with increasing Z, this shows that the loss of mass from the HF by IMF emission is not significant. Further, the same plot as Fig.1 but with condition $N_{\rm IMF} = 1$ or 2 shows essentially the same trend but with decreasing statistics and a shift to lower residual mass with increasing $N_{\rm IMF}$. No shift to higher $\epsilon_{\rm th}$ is apparent.

In light-ion-induced reactions the highest yield of HF is expected for mass values close to that of the target [26], which is not the case in Fig.1. The failure to observe these HF's results from the fact that primary residues with low excitation energy have also suffered a small momentum transfer; their low velocity, conjugated with the energy losses in the target and the energy thresholds in DELTA, makes their detection difficult. Primary residues with high excitation energy have a larger velocity and are less affected by losses and thresholds, but they give rise to HF's with smaller mass. For our apparatus, these effects give a rather uniform DELTA efficiency of 60% for $m_{HF} \lesssim 55$.

The striking feature of Fig.1 is the high values of $\epsilon_{\rm th}$ still compatible with the existence of a heavy residue. This interpretation is supported by the correlation with the recoil velocity. The latter is more or less consistent with the transfer of a fraction of the incident momentum equal to the ratio of the excitation energy to the incident kinetic energy, except for the $\epsilon_{\rm th}$ ~ 9 MeV/nucleon events. The latter are incomplete events. Putting a constraint of 80% on the total charge detected, removes this part of Fig.1, leaving the shape of the rest of the distribution basically unchanged. Thus, Fig.1 suggests that, within statistics, the upper limit for observed $\epsilon_{\rm th}$ is ≈ 8 MeV/nucleon giving residual masses of $m_{HF} = 45 - 50$. In this mass window, the $\epsilon_{\rm th}$ spectrum is displayed in Fig.2. The mean value corresponds to $E^{\star}_{\rm th}/B_{\rm tot} \sim 0.8$, B_{tot} being the total binding energy of the primary residue. Comparing this value with systematics for the maximum excitation energy at which heavy fragment is still observed in heavy ion reactions [27,28] indicates that the present result is significantly higher, by 20% or so. This result corroborates the conclusion of the works of Refs. [29,30], using also ^{3}He as a projectile, but determining $\epsilon_{\rm th}$ by an indirect method.

Survival probability. To obtain a measure of the (survival) probability $W_{\rm comp}$ [31] for having a "compound nucleus", i.e. a primary residue that emits slow light particles only, two approaches were followed. The first one considers class I+II events (disregarding the HF information in DELTA for class I events to homogenize the sample). It assumes that vaporization is negligible [7] and that these events with $N_{\rm IMF}=0$ conditioned by the reconstructed $\tilde{m}_{\rm HF}\geq 45$ are representative of $W_{\rm comp}$. Let N_0 be the number of the selected events and N, the number of events for the same $\tilde{\epsilon}_{\rm th}$ with no restriction on $N_{\rm IMF}$ and $\tilde{m}_{\rm HF}$. The values of $W_{\rm comp}=N_0/N$, after correction for the acceptance of ISiS, are given by the full circles in Fig.3, for intervals of $\tilde{\epsilon}_{\rm th}$ between 4 and 6.5 MeV. The corrections include the effects due to the widths in the $\tilde{\epsilon}_{\rm th}$ determination. For the highest bin in $\tilde{\epsilon}_{\rm th}$, N_0 corresponds to a cross-section of $\sim$5 mb, evaluated using the results of ref. [33] as normalization. Performing the same analysis but with $N_{\rm IMF}\ \leq 1$ (emission of one IMF at $E^{\star}_{\rm th}/B_{\rm tot}$=0.7-0.8 is sometimes recognized as an evaporative process [9,31]) increases the $W_{\rm comp}$ values as shown by the open circles in Fig.3. The second approach deals with class I events only, thus including HF information. This time we have to extrapolate for the HF angular distribution outside DELTA, using INC+EVAP+FILTER. The extracted value, $W_{\rm comp}\sim 0.22$, for a high $\tilde{\epsilon}_{\rm th}$ interval and $N_{IMF}=0$ is displayed by the square in Fig.3. The difference with the first method is attributed principally to the uncertainties in the target and threshold corrections that are difficult to estimate for low velocity, high Z ions. The systematic error on the $W_{\rm comp}$ determination can be estimated from the difference between the two extracted values at $\tilde{\epsilon}_{\rm th}\sim 6$ MeV/nucleon.

We compare the present results with calculations by Gross *et al.* [5] and Botvina *et al.* [4,31]. The calculations of Gross are done for Xe and show that for $E^{\star}_{\rm th}/B_{\rm tot}=0.8$ the evaporative channel consisting of events with a single HF with $m_{\rm HF} \geq 10$ have a vanishingly small probability. Even if pseudo-fission (channel F in ref. [5]) is included, the probability is less than 0.1. Botvina *et al.* calculated $W_{\rm comp}$ for Ag with different parameters of their model. At the highest considered excitation energy ($\epsilon_{\rm th}$= 4.75 MeV/nucleon) they show values of $W_{\rm comp}$ below 0.01 for the considered range of parameters [2]. Comparing these results with the measured values for $N_{\rm IMF} = 0$ shows that the models significantly underestimate the data. Larger discrepancies are to be obtained by considering a higher theoretical value for $m_{\rm HF}$ (Gross *et al.*) or $\epsilon_{\rm th}$ (Botvina *et al.*). This suggests that hot nuclei, at least those formed by ^{3}He or similar light particles, are considerably more stable to multifragmentation than expected theoretically. The present experimental finding is consistent with the measurements of Refs. [29,30], for ^{3}He and of Ref. [34] for antiprotons. It is also consistent with the measurements for ^{3}He, over the 0.48-4.8 GeV energy range [33,35,16], which show that below 2 GeV the expansion is negligible and that multifragmentation of Ag is not a significant mechanism. This process becomes important above 2 GeV incident energy [16,36]. Preliminary analyses [36] of $W_{\rm comp}$ at 4.8 GeV show a decrease, by a factor ~ 2.

Comparison with INC+evaporation. Although our main objective in this work was to determine W_{comp} at high excitation energy, it is interesting to compare the data with a two-step model which encompasses the production and the decay of a hot residue. This is indeed the main hypothesis of our analysis. To perform such a comparison, we couple, event-by-event, an INC calculation with an evaporative code. Details of the INC model can be found in Ref. [10]. The cascade is stopped at 30 fm/c [14] and the characteristics of the primary residue are introduced in the evaporation code EVAP [23], similar to that of Charity *et al.* [37]. The level density parameter was set at A/13 MeV^{-1}. Of course, events

[2]Note that $W_{\rm comp}$ in [4] represents only multiplicity one events (all nucleons in the big fragment); however including other events with one big residue surviving multifragmentation would increase that value by less that one order of magnitude [32].

are filtered (code FILTER) before comparing with the data. Although the same model is used for reconstructing the mass of the primary fragment and to evaluate the efficiency corrections, the comparison is nevertheless meaningful, as we explain below.

The theoretical model reproduces the trend of the data shown in Fig.1; the ridge of the theoretical joint distribution is displayed by the heavy line in Fig.1. We stress that this result is not trivial. In the theoretical model, it comes from the subsequent evolution of the joint distribution (in mass and excitation energy E^*) relative to the primary residue. What is thus only imposed in the procedure explained above is the average value of the mass of this primary residue for the events detected, i.e. the average vertical position of this distribution would have in the graph of Fig.1. We mention that, for $E^*/A \gtrsim 2$ MeV/nucleon, the theoretical mass spectrum of the primary residue is practically independent[3] of E^* and shows a mean value of ~ 92 with a width of ~ 7. From Fig.1, we can thus infer that the energy removed from the primary fragment is ~ 14 MeV per lost nucleon.

Fig.2 shows the comparison with the theoretical model for the distribution of $\epsilon_{\rm th}$, a feature that is independent of the constraint of the theoretical model on the analysis above. We see that the agreement is rather good. The same is true for the IMF multiplicity distribution for large excitation energy (not shown). This suggests that IMF's are basically produced in the evaporative part of a two-step scenario. Other features, as the energy spectra of emitted composite particles, except of course for the small pre-equilibrium component in the forward direction (see Fig.5 of [18]), are also reasonably well described by the theoretical model. Further, the extracted $W_{\rm comp}$ values are compared to the INC+EVAP predictions (stars in Fig.3). At low $\epsilon_{\rm th}$ values the predictions are reasonably good but overestimate the data by 30-60% at 6 MeV/nucleon. Nevertheless, an overall satisfactory agreement with the data

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[3]This can be understood as coming from the fact that larger and larger excitation energy requires a larger and larger number of nucleon-nucleon collisions: participant nucleons are therefore less and less energetic and can escape less and less easily [38].

emerges and provides a convincing support of the validity of a two-step scenario, with a basically thermalised primary residue produced at the end of the first step. In contrast to the heavy ion induced reaction case, where an external compression could exist, the present agreement could mean that, even if the thermal pressure gives rise to expansion after the hard collisions, the nucleus can return close to normal density with moderate losses of excitation energy and mass.

Discussion and conclusion. We have reported on an experimental study of the ^{3}He (1.8 GeV) + ^{nat}Ag system in which HF's are detected in coincidence with charged particles. The LCP's and the IMF's were detected with 70% of 4π coverage and low energy thresholds. On the whole the data are well described by a two-step INC+evaporation model, giving some confidence in the characterization of the primary residue. Our analysis shows that the latter can sustain excitation (thermal) energy up to 80% of the total binding energy without apparently losing its cohesion, as its decay proceeds through an evaporative process. An estimate, at this excitation energy, of the survival probability of these heavy primary fragments (A$\sim$90) against multifragmentation is as large as 20-40 percent, in the most conservative estimate. This value is considerably larger than the theoretical expectations, based on the statistical models of Refs. [4,5]. This disagreement is not too surprising as both theoretical works [4,5,31] assume that all fragmentation partitions (including kinetic energy) are populated according to the final phase space density and neglect the path taken to reach them. The data show that there is some hindrance in that path, which can, perhaps, be viewed as due to barrier penetration in the multidimensional potential in the “direction” of multifragmentation.

The discrepancies between the experimental $W_{\rm comp}$ values and those calculated by the multifragmentation models could alternatively be accounted for by introducing the possible thermal expansion of the system. One could consider that the expansion gives rise to substantial losses of mass and excitation energy such that the multifragmentation is reduced. This is partly examplified in [39] where the INC predictions for masses and E* are adjusted for expansion before injecting these parameters in the multifragmentation model [4,31]. These modifications give a lowering of the mean $N_{\rm IMF}$ and a decrease of the multifragmentation decay mode. We conjecture that under strong hypotheses on the expansion, the latter could reduce the discrepancy on $W_{\rm comp}$. It is important to note that the adjustment in [39] is justified by results from the Expanding Emitting Source model [9]. However more complete calculations are required to clarify the present issue.

Whatever the explanation, our results reveal a high resistance against multifragmentation of nuclei heated by light ion induced reactions in the studied incident energy range. It is also of interest to underline that the survival probability is apparently (a careful analysis is still lacking in this case) smaller when the primary residue is formed by heavy ion reactions, with the same excitation energy per particle [4]. This is in keeping with the conjecture that compression/expansion effects are more at work in this case, allowing the excited primary fragment to reach conditions (smaller density primarily) which are more favourable to multifragmentation.

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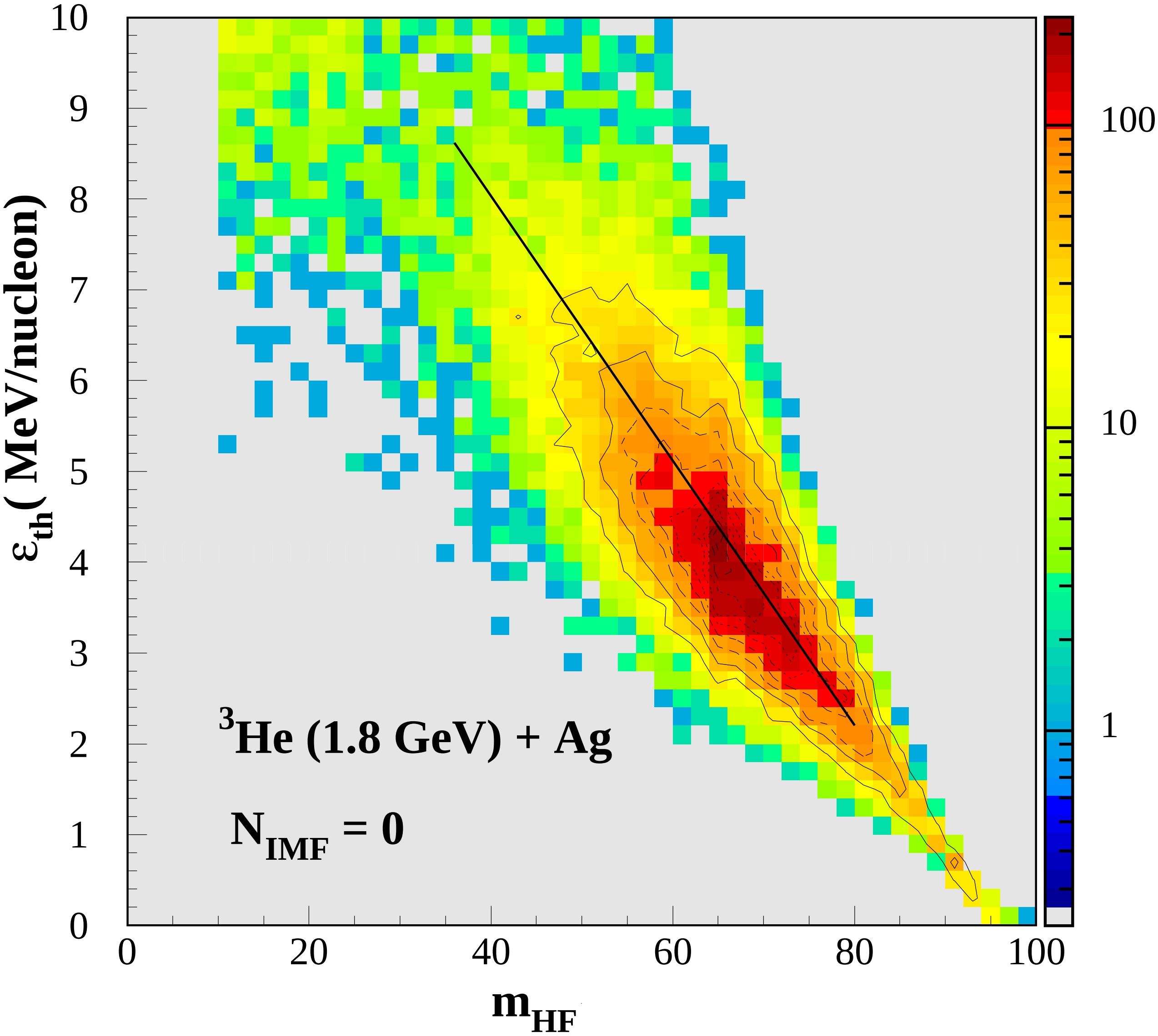
FIGURES

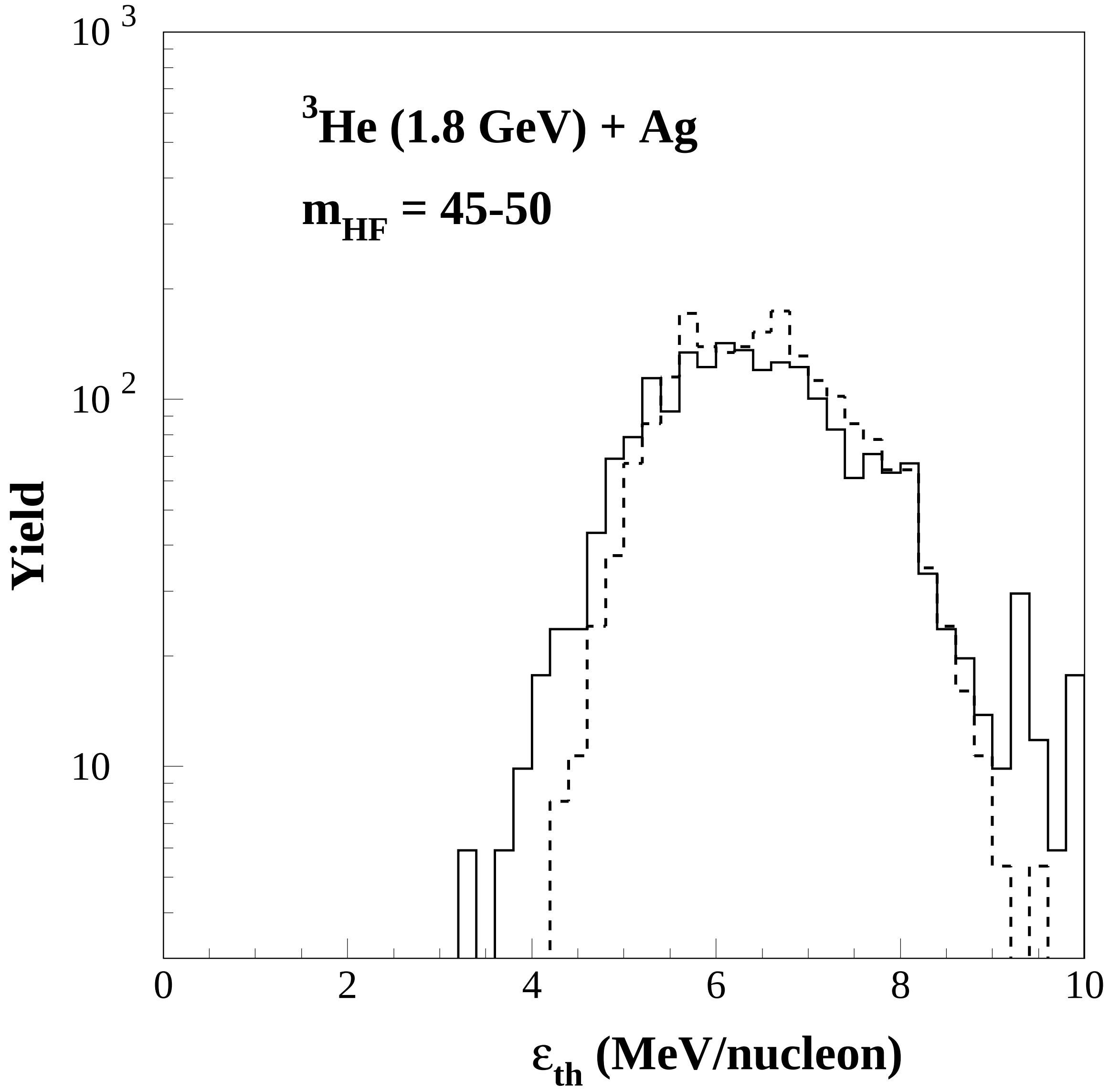
FIG. 1. Experimental $\epsilon_{\rm th}$-residual mass joint distribution for class I events (see text). Correspondence between color levels and counts is given on the right. Level contours equidistant in the logarithmic of the counts are drawn to guide the eye. The solid line represents the mean trend in the model calculations.

FIG. 2. Experimental $\epsilon_{\rm th}$ spectrum with the indicated mass window (solid histogram). The dashed curve represents the results of the model calculations. The two yields are arbitrarily normalised in order to compare the shapes.

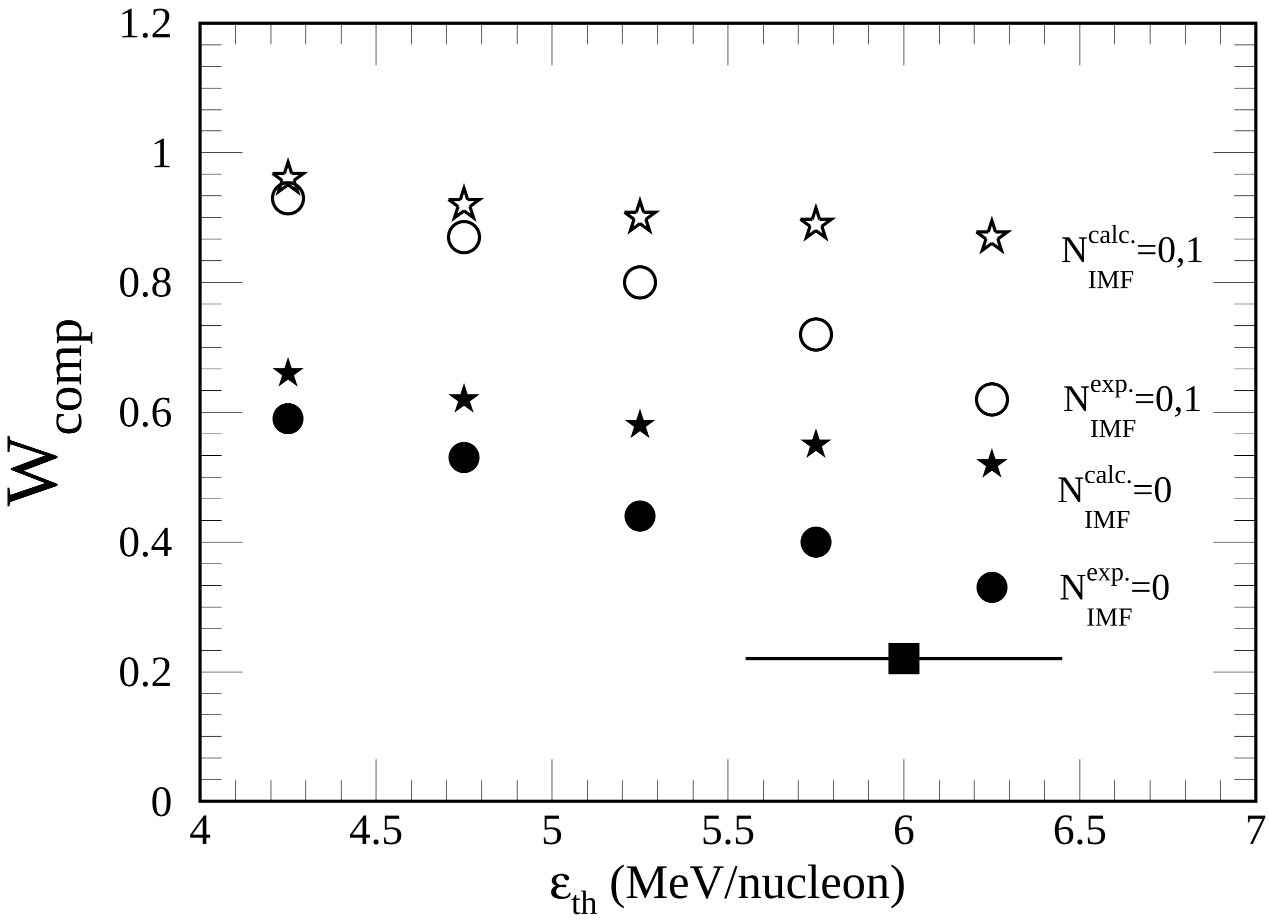
FIG. 3. Value of the probability W_{comp} for having an evaporative residue, as a function of $\epsilon_{\rm th}$ (averaged over intervals of 0.5 MeV) for $\tilde{m}_{\rm HF} \geq 45$ with the conditions $N_{\rm IMF} = 0$ and $N_{\rm IMF} \leq 1$ (full and open circles respectively). The full and open stars are the predictions from the INC+EVAP model with the same conditions. The square is obtained using the second procedure and $N_{\rm IMF} = 0$. See text for details. The horizontal bar indicates the variance σ of the $\epsilon_{\rm th}$ distribution from the INC+EVAP+FILTER calculations.



10
9
8
7
6
5
4
3
2
1
0
ε_{th}(MeV/nucleon)
0
20
40
60
80
100
m_{HF}
100
10
1
^{3}He (1.8 GeV) + Ag
N_{IMF} = 0



^{3}He (1.8 GeV) + Ag
m_{HF} = 45-50
Yield
ε_{th} (MeV/nucleon)
10^3
10^2
10
0
2
4
6
8
10



W_{comp}
1.2
1
0.8
0.6
0.4
0.2
0
4
4.5
5
5.5
6
6.5
7
ε_{th} (MeV/nucleon)
$N^{calc.}_{IMF}$=0,1
$N^{exp.}_{IMF}$=0,1
$N^{calc.}_{IMF}$=0
$N^{exp.}_{IMF}$=0