Isobar correlations bearing information on the properties of hot disassembling nuclear sources

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Two-particle correlations based on the multiplicity of selected isobars are found to be sensitive to the parametrization of the fragments' binding energies and the breakup volume assumed in the model calculations. The properties of these correlations have been examined in the framework of the statistical multifragmentation model as a function of the breakup temperature. The model calculations suggest that the maxima of these correlation functions occur at well-separated temperatures as the breakup volumes used in the model vary from 3 to 6 times that at normal density. These volumes are within the range assumed in most statistical calculations and supported by experiments. Besides their position, the height and width of the maxima are also found to be sensitive to the parametrization of the fragments' binding energy. The magnitude of all these effects also depends on the isobars considered in the correlations. We found that, due to an interplay between the symmetry energy and the volume dependent terms of the Helmholtz free energy, in the case of nearly symmetric sources, correlations involving light mirror nuclei seem to enhance these effects. We suggest that the proposed correlation functions could be used to extract information on the fragments' energies and on the breakup volume of nuclear sources.

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I. INTRODUCTION

Nuclear matter at the extreme conditions found in different stages of stellar evolution [1–5] may be recreated in experiments involving central and midcentral collisions between heavy ions at energies well above the Coulomb barrier [6–10]. Such reactions provide, in this way, means to study the properties of nuclear matter far from the equilibrium configuration, i.e., its equation of state (EOS). In this context, many studies have been carried out over the last decades [6,7,10–12] and big efforts have been made in order to determine such properties, as the symmetry energy EOS [10,13–22] and the nuclear caloric curve [23–33], for instance.

The scenario in which matter quickly expands, after attaining a compressed configuration in the initial stages of the collision, is supported by different models and experiments [8–14,34–38]. In one of the possible pictures, the system reaches a freeze-out configuration, at which thermal and chemical equilibrium are attained and multifragment production takes place [10,14,36–38]. As an alternative view, a continuous fragment production, during a short time span in the expansion phase, is suggested by other dynamical calculations [12,39]. These two frameworks have also been merged into a hybrid treatment [40,41] in which excited fragments are created in a prompt breakup within a breakup volume. They slowly de-excite as they travel away from each other due to the Coulomb repulsion among them and also their initial thermal and (possibly) flow velocities.

The volume occupied by the system in the freeze-out configuration, i.e., the breakup volume, is an important input information to some of the calculations mentioned above, besides the temperature and source's isotopic composition. Furthermore, its determination is key to the study of the nuclear EOS. Therefore, experimental efforts to determine this quantity have been devoted by different groups [10,14,36–38,42–45]. Such studies suggest that freeze-out is attained at densities ranging from $1/3$ to $1/10$ of the normal nuclear matter value. This is compatible with the assumptions made in different statistical models [46,47] and also found in dynamical calculations [34].

In this work we propose an observable which is fairly sensitive to the breakup volume assumed in the statistical calculations: correlations based on the multiplicities of light isobars. In the framework of the statistical multifragmentation model (SMM) [48–50], we examine the behavior of this quantity as a function of the breakup temperature, assuming different isotopic compositions for the disassembling source. We suggest that this observable may help narrow the uncertainty on the breakup density. These correlations also turn out to be sensitive to the assumptions made regarding the fragments' binding energy. Thus, they may provide information on this respect.

The remainder of this paper is organized as follows. A brief description of the model is made in Sec. II, where we derive the expressions used in Sec. III, which is devoted to the presentation and discussion of the main results. Concluding remarks are drawn in Sec. IV.

II. THEORETICAL FRAMEWORK

The SMM [48–50] assumes that a source of mass and atomic numbers A_0 and Z_0, respectively, is formed in a breakup volume V. This source undergoes a prompt decay, producing fragments whose abundances are dictated by their corresponding statistical weights. Mass and charge are strictly conserved. We adopt the canonical version of the model, so that the source is also assumed to be formed at temperature T. In this way, the statistical weight associated with a source (A_0, Z_0) is given by

$$\Omega_{A_0,Z_0} = \sum_{f\in F_0} \prod_{i\in f} \frac{\omega_i^{n_i}}{n_i!} \;, \tag{1}$$

where n_i symbolizes the multiplicity of the species 'i' with mass and atomic numbers a_i and z_i, respectively, and f corresponds to a set of species so that

$$\sum_{i\in f} n_i z_i = Z_0 \;\; \text{and} \;\; \sum_{i\in f} n_i a_i = A_0 \;. \tag{2}$$

In the previous expression, F_0 represents the set of all partitions f consistent with the constraint given by Eq. (2) and

$$\omega_i = \left(\frac{g_i V_f}{\lambda_T^3} A_i^{3/2}\right) \exp\left(-\mathcal{F}_i/T\right), \tag{3}$$

where $V_f = V - V_0$ is the free volume, V_0 is that at normal nuclear density, $\lambda_T = \sqrt{2\pi\hbar^2/mT}$, and m is the nucleon mass. The Helmholtz free energy $\mathcal{F}_i$, associated with species i, has contributions from the fragment internal energy, besides those associated with the Wigner-Seitz corrections [48] to the Coulomb energy. One should note that the term corresponding to the homogeneous charged sphere of the Wigner-Seitz approximation does not play a role in the canonical formulation of the model, being a phase that cancels out in the relevant expressions and is, therefore, omitted. Then, $\mathcal{F}_i$ reads

$$\mathcal{F}_i = \mathcal{F}_i^* - B_i - a_{\rm Coul} \frac{z_i^2}{a_i^{1/3}} \left(\frac{V_0}{V}\right)^{1/3}, \tag{4}$$

where $a_{\rm Coul}$ is a model parameter associated with the Coulomb energy of the fragment, B_i denotes its binding energy and $\mathcal{F}_i^*$ represents its internal Helmholtz free energy. The parameters entering in Eq. (4) are given in Refs. [51,52] and we adopted the standard values for the parameters of $\mathcal{F}_i^*$, listed in [52]. As two different parametrizations for B_i are used in this work, we state in the next section the values adopted in each case.

The traditional SMM implementation employs a Monte Carlo sampling of the relevant partitions in order to calculate different observables. In Refs. [53,54], Das Gupta and Mekjian derived recurrence relations which allow a very efficient evaluation of the statistical weights:

$$\Omega_{A_0,Z_0} = \sum_{i\in f_0} \frac{a_i}{A_0} \omega_i \, \Omega_{A_0-a_i,Z_0-z_i} \tag{5}$$

and f_0 represents the set of all possible species which may be produced. From this expression, many observables, e.g., the average species multiplicities may be calculated exactly in the framework of the model.

Let us consider events in which fragments of species i and j appear only once within each partition. From Eq. (1), the probability of observing such partitions is

$$Y_{i,j} = \frac{1}{\Omega_{A_0,Z_0}} \sum_{f\in F_0} \omega_i \delta_{n_i,1} \, \omega_j \delta_{n_j,1} \prod_{\substack{k\,\in\, f \\ k\,\neq\, i,\,j}} \frac{\omega_k^{n_k}}{n_k!} \tag{6}$$

where $\delta_{\alpha,\beta}$ is the usual Kronecker delta. The above expression may be rewritten as

$$Y_{i,j} = \omega_i \omega_j \frac{\Omega^{(i,j)}_{A_0-a_i-a_j,Z_0-z_i-z_j}}{\Omega_{A_0,Z_0}} \;, \tag{7}$$

where

$$\Omega^{(i,j)}_{A_0-a,Z_0-z} \equiv \sum_{f\in F_{i,j}} \prod_{\substack{k\,\in\, f \\ k\,\neq\, i,\,j}} \frac{\omega_k^{n_k}}{n_k!} \tag{8}$$

and $F_{i,j}$ represents the set of partitions which fulfill the constraint expressed by Eq. (2), for $A_0 \rightarrow A_0 - a$ and $Z_0 \rightarrow Z_0 - z$, subject to the further constraint that fragments of species i and j appear only once. The weight $\Omega^{(i,j)}_{A_0-a,Z_0-z}$ may be calculated using Eq. (5) if one suppresses the species i and j in that expression.

In the same vein, the probability of observing partitions which have a single fragment of species i (j) and none of species j (i) is given by

$$Y_\alpha = \sum_{f\in F_0} \frac{\omega_\alpha \delta_{n_\alpha,1}}{\Omega_{A_0,Z_0}} \prod_{\substack{k\,\in\, f \\ k\,\neq\, i,\,j}} \frac{\omega_k^{n_k}}{n_k!} \; = \omega_\alpha \frac{\Omega^{(i,j)}_{A_0-a_\alpha,Z_0-z_\alpha}}{\Omega_{A_0,Z_0}}, \tag{9}$$

$\alpha = i$ or j. One should note that, although the above expression resembles the average multiplicity of species α, as given by Eq. (4) of Ref. [55], the fact that species i and j are excluded in the statistical weight $\Omega^{(i,j)}_{A_0-a_\alpha,Z_0-z_\alpha}$, but are included in the cited formula, gives completely different meanings to these expressions. Actually, the above equation coincides with the probability of observing species α given by Eq. (9) of Ref. [55], making $n = 1$ in the latter expression. Equation (7) corresponds to a generalisation to the case of two species.

From these probabilities, we may define the correlation between the yields of two selected species as

$$C_{i,j} \equiv \frac{Y_{i,j}}{Y_i Y_j} = \Omega_{A_0,Z_0} \frac{\Omega^{(i,j)}_{A_0-a_i-a_j,Z_0-z_i-z_j}}{\Omega^{(i,j)}_{A_0-a_i,Z_0-z_i} \, \Omega^{(i,j)}_{A_0-a_j,Z_0-z_j}} \;. \tag{10}$$

This formula shows that, except for the global factor Ω_{A_0,Z_0}, which is independent of the selected species, this correlation, as defined, does not depend directly on the properties of the species i and j. They were included through ω_i and ω_j, which canceled out when we took the ratio in Eq. (10). The correlations originate in the characteristics of the partition functions $\Omega^{(i,j)}_{A_0-a,Z_0-z}$ appearing in Eq. (10), whose properties are determined by the composition of the fragmentation modes, after the removal of species i and j.

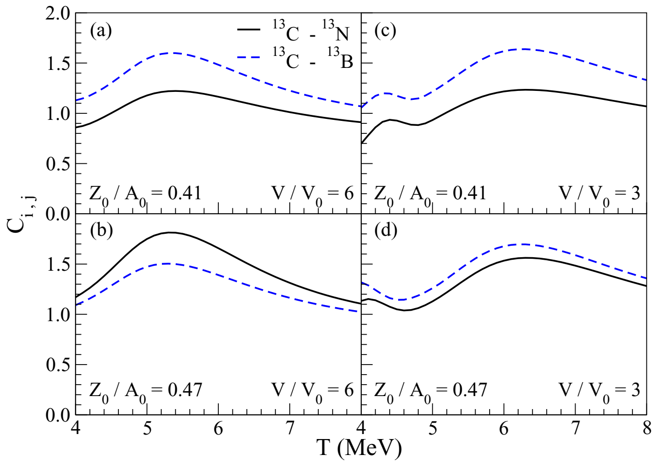

FIG. 1. Two-particle correlations as a function of the breakup temperature for a system of mass number $A_0 = 189$. In frames (a) and (c) the atomic number of the source is $Z_0 = 77$, in frames (b) and (d) $Z_0 = 89$. The breakup volume used in the calculations shown in frames (a) and (b) is $V = 6V_0$, in frames (c) and (d) $V = 3V_0$. For details, see the text.

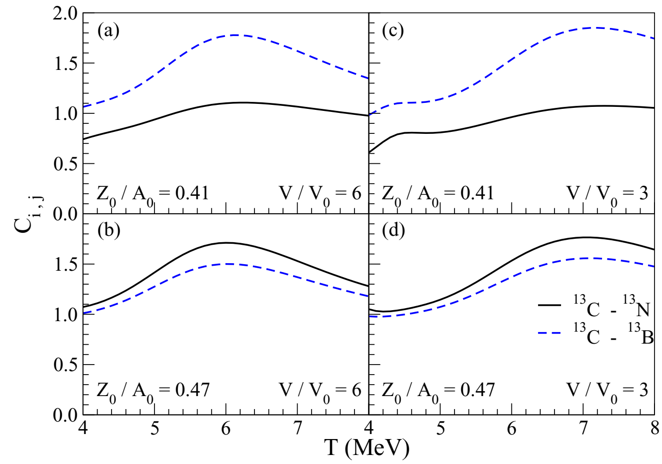

FIG. 2. Same as Fig. 1 for the mass formula used in Ref. [46]. For details, see the text.

III. RESULTS

We apply the correlation defined in the previous section to study the properties of the sources of mass number $A_0 = 189$ and atomic numbers $Z_0 = 77$ and $Z_0 = 89$. These sources have been selected because $A_0 = 189$ corresponds to 80% of the $^{124}\text{Xe} + ^{112}\text{Sn}$ system, recently studied in Ref. [56]. The different Z_0 values are intended to simulate neutron rich and nearly symmetric sources, which allow us to investigate the sensitivity of $C_{i,j}$ to the isotopic composition of the source. The parametrization for the fragments' binding energies developed in Ref. [52] is adopted, except where stated otherwise.

Figure 1 shows $C_{i,j}$ for two pairs of fragments: ^{13}C–^{13}N and ^{13}C–^{13}B. In panels (a) and (b), a breakup volume six times larger than V_0 is used. The isotopic composition of the sources is different in panels (a) and (b). In the former, a neutron rich source is adopted whereas a nearly symmetric one is assumed in the latter. One sees that the position of the peak of $C_{i,j}$, which occurs at $T \approx 5.3$ MeV, is fairly insensitive to the species considered and to the isotopic composition of the source. However, in the case of the neutron rich source, the peak height is much larger for the ^{13}C–^{13}B pair than for the mirror nuclei pair ^{13}C–^{13}N. The opposite happens in the case of the nearly symmetric source. Since the isotopic composition of the source affects the statistical weight $\Omega^{i,j}_{A_0-a,Z_0-a}$ only through the species composition within the partitions,[1] this effect is due to the interplay between the symmetry energy of the fragments and the volume terms of the Helmholtz free energy. This is illustrated in frames (c) and (d) of Fig. 1 which exhibits $C_{i,j}$ obtained with the same parameters as in frames (a) and (b), except for the breakup volume which is $V/V_0 = 3$, as indicated in the frames. One sees that, at the smaller breakup volume, the difference between the $C_{i,j}$ values for the two systems still decreases when the source's asymmetry is reduced. However, owing to the smaller breakup volume, the changes in the Helmholtz free energy are not large enough to lead to an inversion as the one observed in panels (a) and (b).

On the other hand, it clearly shows that the position of the peak moves to a larger temperature value, being now placed at $T \approx 6.3$ MeV. Although it is difficult to predict the position at which the peak will occur, our results clearly show that it is fairly sensitive to the breakup volume due to the important functional dependence of the Helmholtz free energy on this quantity. Therefore, it may be used to obtain information on the freeze-out density. It should be mentioned that no attempt has been made to introduce a temperature/excitation energy dependence on the breakup volume. Although this is certainly possible, as is done in Ref. [49], for instance, adding further assumptions could blur the main point of the present study, which consists in pointing out that the magnitude of the sensitivity of the proposed correlation-function to the freeze-out volume may provide relevant information on it. For this reason, we simply used two representative values in the range adopted in different theoretical studies [34,46,47,49] and suggested by experimental observations [10,14,36–38,42–45].

In order to examine the sensitivity of $C_{i,j}$ to the mass formula employed to describe the fragments' binding energies, we have also carried out the calculations with that traditionally employed in the SMM [46]. The results are displayed in Fig. 2, which have been obtained using the same parameters adopted in the previous calculations, except for the mass formula. The qualitative features observed previously are also present in Fig. 2. The noticeable differences are on the quantitative level. The peaks of $C_{i,j}$ calculated with mirror nuclei are broader, being almost flat for neutron rich sources. The differences between the results obtained using non-mirror and mirror nuclei are much larger in the present case. The sensitivity to the isotopic composition of the source is also much stronger if one adopts this mass formula. The positions of the peaks are also appreciably affected by the fragments'

[1]One should recall that, as discussed in Sec. II, the Wigner-Seitz term associated with the homogeneous sphere does not play any role in the canonical formulation.

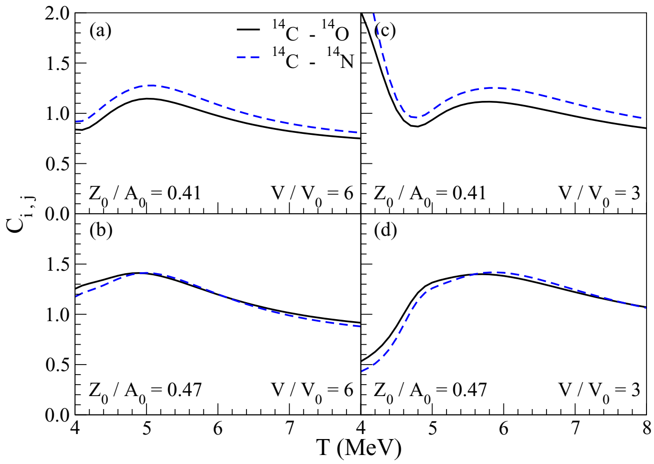

FIG. 3. Same as Fig. 1 for sources of mass number $A_0 = 122$ and atomic numbers $Z_0 = 50$ and $Z_0 = 57$. For details, see the text.

binding energy. Now, they are found at $T \approx 6.1$ MeV, for $V/V_0 = 6$ and at $T \approx 7.1$ MeV for $V/V_0 = 3$, i.e., about 0.8 MeV higher than for the previous mass formula.

Similar conclusions hold for different isobar pairs and smaller source's sizes. To illustrate this point, Fig. 3 displays $C_{i,j}$ for the ^{14}C–^{14}O and ^{14}C–^{14}N pairs, produced in the breakup of sources of mass number $A_0 = 122$ and atomic numbers $Z_0 = 50$ and $Z_0 = 57$. We return to the binding energy prescription developed in Ref. [52] and adopted in the calculations shown in Fig. 1. As anticipated, the same trends discussed above are observed in the present case, but the magnitude of the isospin effects are much smaller. This is associated with the smaller sources' volumes. Furthermore, the peaks occur at $T \approx 5.0$ MeV and at $T \approx 5.8$ MeV for $V/V_0 = 6$ and $V/V_0 = 3$, respectively, which are fairly close to the values obtained for the larger systems and different isobar pairs used in Fig. 1.

Therefore, our results suggest that the two-particle correlations studied in this work may provide valuable information on the breakup density of hot nuclear sources.

IV. CONCLUSIONS

We have studied the behavior of a two-particle correlation function, $C_{i,j}$, based on the yields of selected isobar pairs produced in the breakup of a hot nuclear source. Fast recursive formulas to evaluate it have been derived in the framework of the SMM in the spirit proposed in Refs. [53,54]. They have been applied to sources of different isotopic compositions and sizes. The sensitivity of $C_{i,j}$ to the breakup volume assumed in the statistical calculations has been investigated within the range experimentally bracketed [10,14,36–38,42–45] as a function of the temperature. The correlations turned out to be sensitive to the freeze-out density and, therefore, our results suggest that they may provide valuable information on this quantity. Furthermore, as the fragments' energies also affect the properties of $C_{i,j}$, this correlation function may be used to obtain information on them, since their properties, e.g., the symmetry energy coefficient, are affected by the finite temperature of the system [10,13–22]. We thus suggest that $C_{i,j}$ may be an useful tool to help improve our knowledge of the freeze-out configuration of a multifragmenting system.

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