Study of entropy production employing different stability criteria in secondary algorithm for fragment structures

Shivani and Rohit Kumar*
Department of Physics, Panjab University, Chandigarh - 160 014, India

Introduction

One of the most challenging observables in heavy ion collisions is the multifragmentation of heavy-ions [1]. The many-body correlations are preserved in the n-body transport/molecular dynamics model and thus used widely to study multifragmentation. One of the widely used secondary algorithms after the transport model calculations is based on spatial constraints [1] and this is dubbed as minimum spanning tree (MST) method. The use of this algorithm was widely questioned due to inability of this method to check the stability of the fragments. Later on, this conventional approach of constructing fragments was modified by putting constant binding energy or mass-dependent binding energy constraint [1] to the stability of fragments formed using conventional MST approach. At the same time, one realizes that in the literature large number of different binding energy formulae are available. We, in particular, use the formulae derived by Bethe-Weizsäcker (labeled as LDM) [2], LDM1 [3], LDM2 [4], LDM3 [5] and Modified Bethe-Weizsäcker (labeled as LDM4) [6] which though yield similar binding energy for higher masses, but show significant deviation for the lighter masses [2–6]. One, therefore, wonders whether various binding energy formulae will have effect on the production of lighter fragments or not and how do they affect associated phenomena.

One of the most important state variable which depends on the ratios of the lighter charged particles and does stay constant during expansion stage is the entropy per nucleon. The study of entropy can shed light on the early dynamics of the heavy-ion collisions. It was suggested by Kapusta *et al* [7] that entropy can be deduced from the observed ratios of deuterons to protons during the early stage of reactions by the following relation;

$$S_N = 3.945 - \ln R_{dp}, \quad (1)$$

where R_{dp} is the ratio of deuterons to protons. Later on, Bertsch and Cugnon [8] proposed that for the exact information of the entropy one should also include the other light composite particles viz. t, ^{3}He and $\alpha-$particles. So they proposed that the entropy is related to light particles as;

$$S_N = 3.945 - \ln x, \quad (2)$$

where,

$$x = d_{like}/p_{like} = \frac{d + \frac{3}{2}t + \frac{3}{2}^3He + 3\alpha}{p + d + t + 2^3He + 2\alpha}, \quad (3)$$

here, quantity 'x' measures the multiplicity ratios of

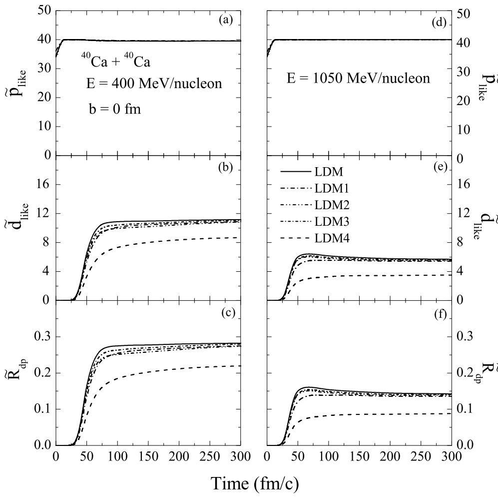

FIG. 1: The time evolution of the $\tilde{p}_{like}$, $\tilde{d}_{like}$ and their ratio $\tilde{R}_{dp}$ for the central collisions of ^{40}Ca+^{40}Ca at 400 MeV/nucleon (left panels) and 1050 MeV/nucleon (right) at b = 0 fm. The solid, dashed, dotted, dash-dotted and dash double-dotted lines represent results using LDM, LDM1, LDM2, LDM3 and LDM4, respectively.

*Electronic address: `rohitksharma.pu@gmail.com`

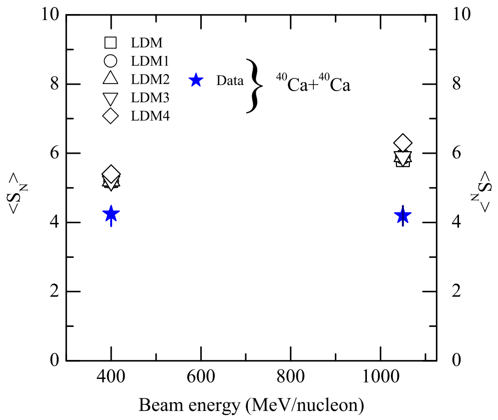

FIG. 2: The baryonic entropy $< S_N >$ as a function of beam energy for the central collisions of ^{40}Ca+^{40}Ca. The experimental results (stars) extracted using Kapusta's method [7, 9] are also displayed. Different symbols represent results obtained using various binding energy formulae.

deuteron-like to proton-like fragments. The ratio of deuteron-like ($\tilde{d}_{like}$) and proton-like ($\tilde{p}_{like}$) particles can be defined by the following expression [8];

$$\tilde{R_{dp}} = \frac{Y(n=2) + \frac{3}{2}Y(n=3) + 3Y(n=4)}{\tilde{p}_{like}}; \quad (4)$$

Here Y(n) stands for number of clusters with mass 'n' in one event and $\tilde{p}_{like}$ is defined as:

$$\tilde{p}_{like} = \left[\frac{Z_P + Z_T}{A_P + A_T}\right] \times [Y(n=1) + 2Y(n=2) + 3Y(n=3) + 4Y(n=4)], (5)$$

where $Z_P + Z_T$ and $A_P + A_T$ define the total charge and mass of the colliding heavy ions.

Results and discussions

We simulate the reactions of ^{40}Ca+^{40}Ca at incident energies of 400 and 1050 MeV/nucleon for the central collisions. For the present calculations we use Quantum Molecular Dynamics (QMD) model [1] with a soft equation of state and reactions are followed till 300 fm/c.

In fig. 1, we display the time evolution of the multiplicities of $\tilde{p}_{like}$, $\tilde{d}_{like}$ and their corresponding ratios $\tilde{R}_{dp}$. All the quantities saturates at ~ 75 fm/c. Here $\tilde{p}_{like}$ clusters are observed to be insensitive to the binding energy formula used in analysis. This is due to the formulation used to identify the $\tilde{p}_{like}$ particles and the structure of the cluster identifier which will treat nucleons of a fragment free, if fragment fails to fulfill binding energy criteria. For example, if one fragment with $A_f = 4$ fails to fulfill the binding energy constraint, then multiplicity of $A_f = 4$ fragment will decrease by one unit whereas free nucleons will increase by 4 units. On the other hand, for the calculation of $\tilde{d}_{like}$, free nucleons are not included, therefore, if one fragment with $A_f = 4$ fails the stability check, the multiplicity of $\tilde{d}_{like}$ fragments will decrease by one unit only. Therefore, the different binding energies do show difference in the results for $\tilde{d}_{like}$ fragments. The difference seen in the $\tilde{R}_{dp}$ ratio is only due to the difference in the multiplicities of $\tilde{d}_{like}$ fragments. In Fig 2, the comparison of our theoretical calculations and experimental data [9] for entropy production is presented for the central collisions of ^{40}Ca+^{40}Ca at 400 and 1050 MeV/nucleon. The comparison clearly shows that even though the individual multiplicities of the fragments used to extract the entropy changes with binding energy criteria, the entropy shows insignificant difference toward different binding energy formulae. We also notice that our theoretical values of the entropy over estimate the experimental ones which may be due to other various parameters like Gaussian width etc.

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