Bimodality from transport model calculations for intermediate energy heavy ion reactions

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The bimodal behaviour of the order parameter is an important signature of first order phase transition [1]. Phase transitions occur in very large systems but practical calculations (and experiments with heavy ions) need to be done with finite systems. The largest cluster is an important order parameter for studying nuclear liquid gas phase transition in intermediate energy heavy ion reactions. It has been recently proposed [2] that the double humped distribution (hence the name bimodality) of the largest cluster probability in nuclear multifragmentation is also a measurable signature of nuclear liquid gas phase transition.

The standard methods of theoretical studies of bimodality assume that because of two body collisions, nucleons equilibrate and then multifragmentation occurs either at constant volume (most prevalent assumption) or at constant pressure. But the acceptability of either of these assumptions is a debatable issue. The objective of this work is to investigate if bimodality emerges from a transport model calculation as it bypasses all such assumptions.

Boltzmann-Uehling-Uhlenbeck (BUU) transport model [3] is very successful in studying intermediate energy heavy ion collisions. The standard BUU model describes the properties of the average of all events. But to get the largest cluster probability distribution from transport model calculation one needs an event by event description, not just the average of all events. In order to do that a simplified yet accurate method of transport model is developed [4] which allows calculation of fluctuations in systems much larger than what was considered feasible in a well-known and already existing model [5].

To study bimodal behaviour, central collision reactions between projectile of mass $A_p = 40$ and target of mass $A_t = 40$ are simulated at different projectile energies (E_{beam}). As we are interested in phase transition under the influence of nuclear force, Coulomb effects are switched off. For 40 on 40 reaction the largest cluster probability distribution is plotted in Fig. 1 for $E_{beam} = 20$, 42.5 and 100 MeV/nucleon. At each energy, 1000 events are taken and for each event calculation is done up to $t = 300$ fm/c. The results shown are averages for graphs of 2 consecutive mass number at t=300 fm/c. At projectile beam energy (E_{beam})=20 MeV/nucleon, the $P_m(k)$ is peaked at around mass 60 which represents liquid phase where as at E_{beam}=100 MeV/nucleon, the probability distribution peaks at very low mass i.e. it suggests the system is in the gas phase. In between these two extremes, at E_{beam}=42.5 MeV/nucleon the largest cluster probability distribution shows the bimodal behaviour where the height of the two peaks are almost same [6].

A phase transition like behaviour emerges more directly from our calculations. This is quite revealing. For 40 on 40 reaction we do our calculation as a function of beam energy (from 20 MeV/nucleon to 120 MeV/nucleon). For each beam energy 1000 events were generated. From these events we compute the average total energy E_{tot}, the average kinetic energy E_k and the average potential energy E_p per particle. Let us plot the total energy E_{tot} in the centre of mass frame. This will of course increase in

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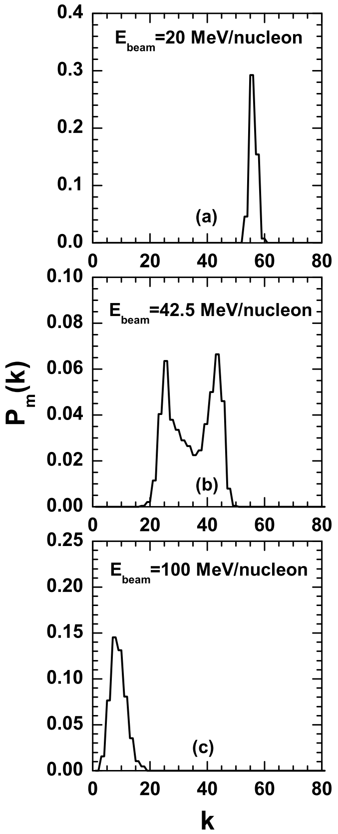

FIG. 1: Largest cluster probability distribution for $A_p = 40$ on $A_t = 40$ reaction at beam energies (a) 20 MeV/nucleon, (b) 42.5 MeV/nucleon and (c) 100 MeV/nucleon. The average value of 2 mass units are shown. At each energy 1000 events are chosen. The results shown in this figure are calculated at t=300 fm/c

value as E_{beam} (MeV/nucleon) increases. This energy E_{tot} is the sum of kinetic energy E_k and potential energy E_p. The origin of E_k is more complicated. It arises from Fermi motion of the test particles and also the cm kinetic energy of each cluster. The quantity E_p is more straightforward. It arises from the potential energy of the clusters. An insight is obtained by examining the derivative dE_p/dE_{tot}. A sudden change in the derivative dE_p/dE_{tot} occurs at the point where bimodality is observed. This type of break in the first derivative is typical of first order phase transition. This is shown in Fig. 2. We might consider this break to be an additional signature of a first order phase transition [6].

Therefore we can conclude that the

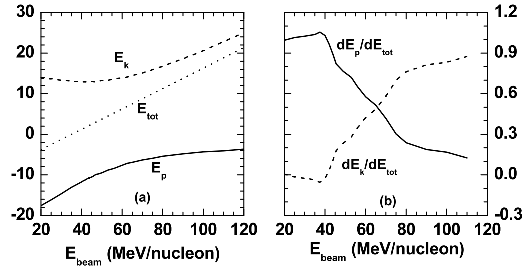

FIG. 2: Left panel: Dependence of kinetic energy per nucleon (dashed), potential energy per nucleon (solid) and total energy per nucleon (dotted) for $A_p = 40$ on $A_t = 40$ reaction on the projectile beam energy per nucleon.
Right panel: Dependence of first order derivatives of kinetic energy (dashed) and potential energy (solid) with respect to total energy on total energy per nucleon.

bimodal behavior of the largest cluster probability is clearly obtained from the BUU transport model calculation. In addition to that, a sudden change in the first order derivative of potential energy with respect to total energy ensures the occurrence of first order nuclear liquid gas phase transition.

References

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