Dynamical and statistical bimodality in nuclear fragmentation reactions at intermediate energies

S. Mallik[1],* G. Chaudhuri[1], and F. Gulminelli[2]
[1] Physics Group, Variable Energy Cyclotron Centre, 1/AF Bidhan Nagar, Kolkata700064,India
[2] LPC Caen IN2P3-CNRS/EnsiCaen et Universite, Caen, France

The phenomenon of liquid-gas phase transition occurring in heavy ion collisions at intermediate energies is a subject of contemporary interest in recent years [1]. The largest cluster is an important order parameter for studying nuclear liquid gas phase transition in intermediate energy heavy ion reactions. It has been proposed [2] that the double humped distribution (hence the name bimodality) of the largest cluster probability in nuclear multifragmentation is a measurable signature of nuclear liquid gas phase transition. But the origin of the experimentally observed bimodality is still not clear. Some recent work shows that it is due to presence of memory effect of entrance channel where thermal equilibrium is not achieved in this energy domain. The signal was interpreted in these studies as a dynamical bifurcation of reaction mechanism, induced by fluctuation of collision rate, which leads to fluctuations of collective momentum distribution [3]. Other successive studies establish the equilibrium scenario of bimodality, which would rather point towards a thermal phase transition [4]. This work focuses on the combined effect of entrance channel and exit channel on bimodality.

In order to study that theoretically, we concentrate on a single light symmetric system $^{40}Ca+^{40}Ca$ with projectile beam energy 100 MeV/nucleon at different impact parameters by switching off the Coulomb interaction. This does not allow yet to make quantitative comparisons with experimental data, which are left for future work. The dynamical stage is simulated by recently developed fluctuation added Boltzmann-Uehling-Uhlenbeck (BUU) transport model [5]. Freeze-out condition is identified (175 fm/c for 100 MeV/nucleon reaction) in transport simulation from the isotropy of momentum distribution and maxima of the average size of second largest cluster [6]. Finally the transport dynamics at freeze-out is coupled to Canonical Thermodynamical model (CTM) [7] for completing the de-excitation phase.

The largest cluster probability distribution is shown in Fig. 1 for four different impact parameters at freeze-out time where we have decided to stop the dynamical calculation. For central collision (b=0 fm), two peaks are seen which can be interpreted as dynamical bimodality very similar to the phenomenon described in [3]. Fluctuations in the collision rates lead to fluctuations in the momentum distribution, that is in the degree of stopping of the reaction. We have fixed a mass cut of A_{cut} = 37 to distinguish the two event

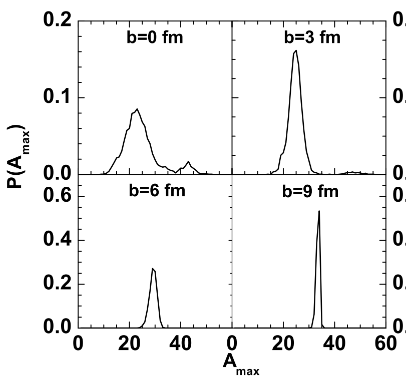

FIG. 1: Largest cluster probability distribution $P(A_{max})$ from BUU model at freeze-out.

*Electronic address: swagato@vecc.gov.in

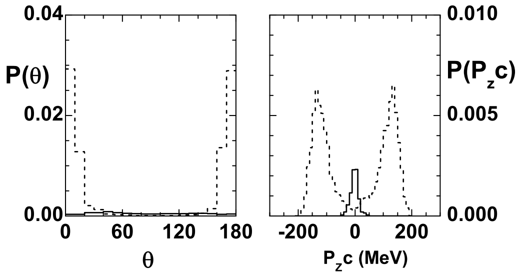

FIG. 2: Scattering angle (left panel) and momentum (right panel) probability distribution for fragments with $A_{max} \geq A_{cut}$ (solid lines) and $A_{max} < A_{cut}$ (dashed lines) for b =0 fm.

classes as it corresponds to the minimum between the two peaks. Fragments with $A_{max} \geq A_{cut}$ represent stopped events having nearly zero z-component (beam direction) of momentum and scattered isotropically in the centre of mass frame where as fragments with $A_{max} < A_{cut}$ represent crossed events having high z-component of momentum and scattered either in the forward direction (projectile like fragments) or backward direction (target like fragments). This is shown in Fig. 2. For non-central cases only liquid phase is present (crossed events).

The distribution plotted in Fig. 1 can be defined as freeze-out distribution and can still evolve in subsequent time because of

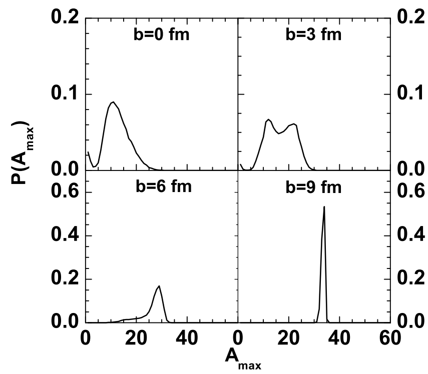

FIG. 3: Final largest cluster probability distribution after CTM calculation.

secondary decay which have been calculated by switching over to the CTM from the transport one. In Fig. 3, we have plotted the probability distribution of the largest cluster for these four impact parameters. The ones at b=0 fm are structuresless and typical of multifragmentation reactions: the average excitation energy is so high in this case that both fully stopped and incompletely stopped events undergo multiple decay. As a consequence, the bimodality signal observed in Fig. 1 disappears. At mid-central collision, the situation is reversed. The probability distribution of the largest cluster now shows a bimodal behaviour which is indicative of existence of two phases simultaneously.

This however strongly depends on the entrance channel conditions. In particular, central collisions at lower bombarding energy (40 MeV/nucleon) leads to a situation where the freeze-out distribution is not distorted by secondary decay and bimodal behaviour can be observed both after transport calculation, and after the statistical model calculation [6].

Therefore we can conclude that, depending on the incident energy and impact parameter of the reaction, both entrance channel and exit channel effects can be at the origin of the observed bimodal behavior. Specifically, fluctuations in the reaction mechanism induced by fluctuations in the collision rate, as well as thermal bimodality directly linked to the nuclear liquid-gas phase transition are observed in our simulations [6].

References

[1] P. J. Siemens, Nature, **305**, 410 (1983).
[2] Ph. Chomaz, F. Gulminelli and V. Duflot, Phys. Rev. E **64**, 046114 (2001).
[3] A.Le Fevre et al., Phys. Rev. Lett. **100**, 042701 (2008).
[4] E.Bonnet, et al., Phys. Rev. Lett. **103**, 072701 (2009).
[5] S. Mallik, S. Das Gupta and G. Chaudhuri, Phys. Rev. **C 91**, 034616 (2015).
[6] S.Mallik, G.Chaudhuri and F.Gulminelli, Phys. Rev. **C 97**, 024606 (2018).
[7] C. B. Das, S. Das Gupta et al., Phys. Rep **406**, 1 (2005).