Net-Proton Evolution in Heavy Ion Collisions

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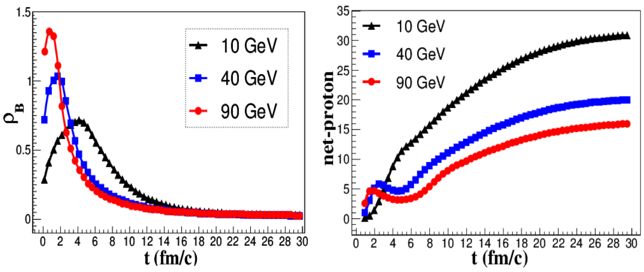
The exploration of the Quantum ChromoDynamics (QCD) phase diagram of strongly interacting matter is a major field of modern high-energy physics. Of particular interest is the transition from hadrons to partonic degrees of freedom which is expected to occur at high temperatures or high baryon densities. These phases play an important role in the early universe and in the core of neutron stars. Heavy ion collisions are used to create new form of matter at high energy/baryonic densities depending upon the incident beam energy. At FAIR energies (10 - 45 AGeV) matter at high baryonic density and moderate temperature is expected to be created. CBM (Compressed Baryonic Matter) experiment at FAIR will search for the critical point, the first order deconfinement phase transition from the hadronic matter to the partonic matter and the equation-of-state of dense baryonic matter.

Observables like fluctuations of conserved quantities (baryon number, electric charge and strangeness) are generally considered to be sensitive indicators of the phase transition and more important to the critical point[1]. Higher moments of distributions of conserved quantities, which measure the deviations from a Gaussian, are argued to have a sensitivity to critical point (CP) fluctuations due to a stronger dependence on correlation length (ξ) [2, 3].

Conserved quantities and their fluctuations are measured at freeze-out by the experiments. For heavy-ion collisions at relatively lower energy, likely to be accessible at FAIR, extreme density region created in the collision might result in large fluctuations of specific quantities as the density also fluctuates event by event. It will be useful to study the propagation of these fluctuations in terms of their survival at freeze-out.

Recently at RHIC, measurements have been done of the products of moments like $k\sigma^2$ and $S\sigma$ of net-proton multiplicity distributions and results have been compared with the lattice QCD. Near the Critical Point, susceptibilities are expected to diverge, causing these two observables to have non-monotonic variations with N_{part} and/or $\sqrt{S_{NN}}$.

We have used UrQMD3.3 version to study the space-time evolution of the fluctuations in Au-Au collisions at Lab energies ranging from 10 GeV/A to 90 GeV/A. UrQMD is one of the models being used widely in describing the results of high energy heavy-ion collisions. The initial version of the model was based on the use of transportation of hadrons with the implementation of various intermediate phenomena in the model. The model includes transportation of various degrees of freedom (e.g. baryons and mesons) and the production of new particles and their interaction. It treats the production of particles via fragmentation of strings made of valence quarks of the original colliding hadrons [5, 6, 7]. In the conventional UrQMD (hadronic version), time scans have been performed from t=1 fm/c till t=30 fm/c. We have used 8 million events of UrQMD default version taking particles of similar acceptance as of STAR (η cut of $\pm$ 0.5 and p_T region of 0.4 to 0.8). Particles are said to be finally frozen out and streams freely to the detector at 100 fm/c after the start of the collision. It should be noted that there is no phase transition implemented in this version. The temporal variation of the fluctuation is due to the evolution of the hadronic medium as created by the transport model. In this model, no explicit implementations have been made for chemical or thermal equilibrium.



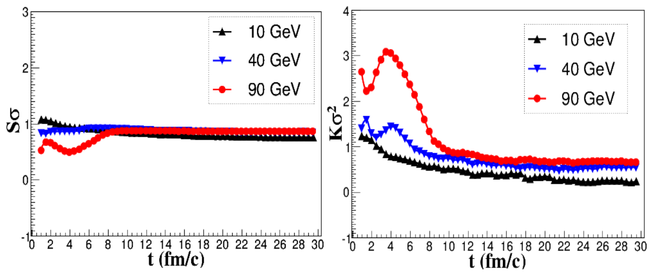
(a) (b)

Figure 1: (a) Evolution of baryon density with time elapsed after collision. (b) Time evolution of the mean of net-proton at different collision energies.

Fig. 1a shows the time evolution of the net-baryon density at three different incident energies. The flat top varies with the incident energy being longer-lived at lower energy. The density reaches a value up to 10 times the nuclear matter density suitable for a transition to a non-hadronic state. Fig. 1a, which shows the variation of net baryon density with time at different collision energies, demonstrates the importance of heavy-ion collisions at FAIR energies that generate high density matter. As expected from the time required for two nuclei to pass each other, the peak density is achieved faster at higher beam energy. It will therefore be very interesting to study the variation of net-proton with time and its correlation with the net-baryon density. It should be mentioned that, the time of reaching the peak net-baryon density might not coincide with the equilibration time especially at lower collision energy. A high density matter undergoing a transition to a partonic state at the highest net-baryon density might undergo rescattering to reach equilibration at a later time. The signal like fluctuation of specific quantities might then undergo evolution to reach the freeze-out stage via equilibration. The main aim of this work is to study this effect.

As a candidate of net-baryon numbers, results have been presented for net-proton distributions by several experiments. We have therefore extracted the time evolution of the net-proton and its fluctuation measured in terms of two widely used observables which represent the susceptibilities i.e., Kσ^2 and Sσ, where K, S and σ^2 represent kurtosis, skewness and variance of the distributions. Here we have taken the same coverage and kinematic cuts as that of STAR published results [4], i.e. pseudo-rapidity of 0.5 around mid-rapidity and p_T in the range of 0.4 - 0.8 (GeV/c), for the comparison of the results at freeze-out. It has been shown that these combinations of variables could be compared directly with the lattice simulation results.

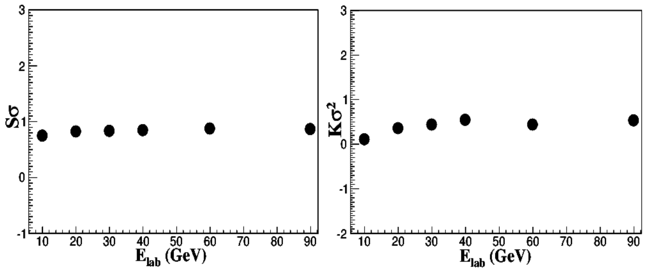
Fig. 1b represents the time evolution of net-proton at different collision energies. Starting from early times there is an in-flow of protons into the reaction zone scattering into the rapidity and pT interval- this inflow, aided by multiple rescattering last for the entire time evolution of the heavy ion reaction. In addition, at later times there we have resonance decays that populate protons (because a lot of baryons initially are being excited to Delta and N* resonances, that subsequently decay). It is clearly seen that net proton shows a peak at around the time of overlap of two colliding nuclei. While at E$_{lab}$=10 GeV net-proton evolution shows a smooth structure due to hadronic rescattering playing more dominant role.



(a) (b)

Figure 2: (a) Time evolution of Sσ, and (b) Kσ^2 for net-proton at different collision energies

Fig. 2 shows the time evolution of Sσ and Kσ^2, two widely used variables consisting of the combinations of the higher order moments for net proton. It is seen that $S\sigma$ is nearly flat with time except initially where it shows structure more prominent at higher energies which then grows to smooth value. Kσ^2 however reduces from higher values with time. It is interesting that the initial energy dependence in Kσ^2 gets washed out at 30 fm/c. Like other fluctuation measures, these two observables as measured at freeze-out is a result of significant dilution. In the study of fluctuation, we look for break from monotonous behavior of the fluctuation measures. In recent beam energy scan results from STAR, $\sqrt{s}$ dependence of these quantities have been shown and some interesting structure at around 19 GeV have been mentioned about. It is evident from the present study that the values measured at freeze-out does not contain the structures which might have been present during the evolution. We therefore would like to see the fate of the energy dependence of the structures at FAIR energies. Fig. 3 is showing the energy dependence of Sσ



(a) (b)

Figure 3: (a) Beam energy dependence of Sσ, and (b) Kσ^2 for net-proton at freeze-out

and Kσ^2 at freeze-out. There is no non-monotonous dependence with E_{lab} at FAIR-energy when calculated within the same coverage as of STAR. Even though the energy dependence at detection looks flat, there were structures present at the beginning of the collision.

Conclusion

In conclusion we have seen from the transport models that the net baryon density reaches maximum for a short time during the overlap of two nuclei. During this time, net-proton also shows peak and then slowly through the evolution reaches a near-saturated values at freeze-out. During this evolution, fluctuations of net-proton measured by Sσ and Kσ^2 show structures consisting of peaks at high baryonic density region which then smoothen out during the evolution. It therefore suggests that there is considerable modification of the early fluctuation signals.

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