A SIMULATION STUDY OF COLLECTIVE BEHAVIOUR OF HADRONIC MATTER AT FAIR ENERGIES

ABSTRACT

We investigate collective behaviour of hadronic matter produced in high-energy heavy-ion collisions in the framework of microscopic transport models and in the context of upcoming Compressed Baryonic Matter (CBM) experiment to be held at the Facility for Antiproton and Ion Research (FAIR). One of the major objectives to study nucleus-nucleus (AB) collisions at high-energies is to produce a color deconfined state like the Quark-gluon Plasma (QGP), composed of strongly interacting quarks and gluons, under extreme conditions of temperature and/or pressure. The properties of QGP are guided by the rules of quantum chromodynamics (QCD), the non-abelian color gauge theory of strong interaction. It is quite intriguing to see how macroscopic and collective properties develop in the QGP from interactions among quarks and gluons, taking place within a system of a few hundred (or thousand) fm^3 in volume and an average lifetime of about 10^{-22} sec. These simulated results are going to give us an opportunity to examine the collective behaviour of hadronic matter at high baryon density and moderate temperature.

In **Chapter One** we qualitatively review various aspects of high-energy AB collisions. At the very beginning we underline the salient features of QCD. The cosmological and astrophysical relevance of AB collisions are briefly mentioned. The heavy-ion accelerator facilities that existed in the past, operating at present and are going to come up in near future, are summarily reviewed. Some general physical characteristics of the QGP state created in the LHC experiments are listed. The space-time evolution of an AB collision is sequentially described with and without taking the QGP formation into account. Apart from the QGP, several other states of strongly interacting objects are allowed in nature. The QCD phase-diagram that gives us a summary of all such states and the demarcation lines separating one phase from the others, is qualitatively described. The thermodynamics and hydrodynamics of AB collisions have been discussed in the framework of Fermi's model, MIT bag model, Landau's hydrodynamic model and Bjorken's hydrodynamic model. In order to identify QGP formation, one must set appropriate signals that survive the vigor of AB collisions. The experimental status of several such signatures are summarily described. As the present investigation deals mainly with the simulation study of collective flow, we have discussed its experimental status with a little more details. A brief outline of the CBM-FAIR experiment has been discussed thereafter. To conclude this introductory chapter, we highlight the major objectives of the present investigation.

In **Chapter Two** we qualitatively describe the event generators used in this simulation based investigation. Salient features of the Ultra-relativistic Quantum Molecular Dynamics (UrQMD), A Multi Phase Transport (AMPT) model, both in its default and string melting (SM) configuration, and the Monte-Carlo Glauber (MCG) model are discussed. MCG code is used to determine the initial state geometry and centrality of AB collisions. Some global aspects of multiparticle emission are discussed by using Au+Au event samples simulated at different incident beam energies ($E_{\rm lab}$) expected at the FAIR. We observe that the charge hadron yield in the central particle producing region follows a power law dependence on the number of participating nucleons. Longitudinal scaling is observed in the pseudorapidity (η) distributions of charged hadrons and their average transverse momentum (p_T). The transverse mass spectra of different hadron species are used to determine the kinetic freeze out temperature and velocity of radial expansion. First indication of collective radial expansion is found from this analysis.

In **Chapter Three** we present our simulation results on elliptic (v_2) and triangular (v_3) flow parameters derived from the azimuthal distributions of charged hadrons in Au+Au events generated by the UrQMD and AMPT model(s) at $E_{\rm lab} = (10-40)A$ GeV. Event-by-event fluctuations of the collision geometry has been taken into account while determining the initial space asymmetries associated with the overlapping parts of the collision systems. The centrality dependence of eccentricity (ε_2), triangularity (ε_3), v_2 and v_3 are studied. The v_2-measures are found to be relatively small in the peripheral and extreme central collisions, but they peak around mid-central collisions. As ε_2 is scaled out from v_2, these maxima shift towards higher centrality. Our AMPT (SM) results on v_2 at $E_{\rm lab} = 30A$ GeV match with those of the STAR experiment on Au+Au collision at $\sqrt{s}_{NN} = 7.7$ GeV. Our v_2 results are also consistent with a universal scaling with respect to the transverse particle density. v_3 originates only from event-by-event fluctuations, and it is weaker than v_2 by more than an order of magnitude. UrQMD does not produce any v_3 at all. When ε_3 is scaled out of v_3, a linear rise with centrality is observed. This indicates an entropy driven multiplicity scaling, a characteristic feature of soft-hadron production. Both the flow parameters rise approximately linearly with p_T, a behaviour that is not quite influenced by the spatial asymmetries. It appears that at higher p_T particles are producing a higher amount of flow. Mass ordering of the flow parameters at low-p_T and a scaling with the number of constituent quarks are also observed. AMPT (SM) turns out to be the best option to describe the collective flow effects at FAIR energies. The cumulant technique has also been employed to estimate v_2 and its fluctuations, which reveals that significant contribution to the fluctuations is coming from the initial state distributions of the participant nucleons.

In **Chapter Four** we have studied the dependence of v_2 and v_3 on parton scattering cross-section (σ) in Au+Au events at $E_{\rm lab} = 30A$ GeV generated by the AMPT (SM). The

σ-dependences of charged hadron yield and average-p_T are examined too. Both the flow parameters and average-p_T are found to increase with increasing σ. The particle yield decreases marginally with increasing σ. The changes in observables however are not proportional to the changes in σ, and can at the best be called moderate. The STAR results seem to be better matching with our AMPT (SM) prediction for $\sigma = 1.5\,(3.0)$ mb. A longitudinal scaling with respect to the σ-variation has been observed in the η-distribution of v_2, which is not found in v_3.

A system-size dependence of the directed flow (v_1), v_2 and v_3 of charged hadrons produced in AB collisions is investigated in **Chapter Five**. AMPT (SM) has been used to generate ^{28}Si+^{28}Si, ^{59}Ni+^{59}Ni, ^{115}In+^{115}In and ^{197}Au+^{197}Au events at $E_{\rm lab} = 30A$ GeV. The distributions of flow parameters, their centrality and p_T-dependence are examined. η-distribution of v_1 is also presented. The centrality dependence of ε_2 and ε_3 are shown. All three flow parameters are found to be normally distributed. In comparison with v_2 and v_3, the distributions of v_1 are much more sharply peaked. The distributions of ε_2 and ε_3 are however slightly right skewed. They do not exactly coincide with the corresponding v_2 and v_3-distributions, indicating deviation from a one to one linear dependence. The η-dependence of v_1 wiggles around the zero line, a feature typically observed also in experiments. In cascade models this wiggle is explained in terms of a space-momentum correlation and different amount of rapidity loss in different regions. All other distributions behave more or less similarly as described in Chapter Three. In general a moderate amount of system-size dependence has been observed in the behaviour of all three flow parameters. Most of our simulation based results however can be interpreted in terms of geometrical effects and/or multiplicity scaling.

In order to explore the collective radial flow of charged hadrons, in **Chapter Six** the azimuthal distributions of their multiplicity values, total radial velocity (V_T) and mean transverse velocity (v_T) are compared with each other using Au+Au events generated by the AMPT (SM) model at $E_{\rm lab} = 10A$ and $40A$ GeV. v_T seems to be a good choice for studying the radial expansion. While the anisotropic part of each distribution indicates a collective radial expansion, its isotropic part characterizes a thermal motion. We have studied the centrality and p_T-dependence of both the anisotropic and isotropic parts. Our results on centrality dependence suggest that v_2 associated with V_T is strongest, which predominantly is due to the contribution coming from azimuthal anisotropy in the charged hadron multiplicity distributions. v_2 associated with v_T has been found to be rather weak. The isotropic component on the other hand is found to be strongest for the multiplicity distribution, a characteristic feature of soft-hadron production. In contrast, the p_T-dependence of v_2 shows that variations are more or less similar (linearly dependent) for all three observables, a feature that again is not quite unexpected. Higher p_T corresponds to a higher v_T. As a

result, the linear dependence between v_2 and p_T is directly mapped into a similar $v_2 - v_T$ dependence. Our study on p_T-dependence also suggests that at FAIR energies the isotropic component dominates the radial expansion. However, perhaps an analysis for different hadron species is required to better understand these observations.

In **Chapter Seven** we have used transverse sphericity (S_T), a unique event shape variable, to classify AB events into isotropic and jetty categories. A systematic study is presented on the p_T-spectra, particle yield and collective flow parameters of different charged hadrons for these two categories of Au+Au events generated once again at $E_{\rm lab} = 30A$ GeV by the AMPT (SM). The p_T-spectra of charged hadrons obtained for the isotropic and jetty events themselves provide an indication of the onset of collective behaviour. v_2 for the jetty events are found to be much higher in magnitude than those obtained from both the isotropic and S_T-integrated class of events. However, no such dependence on S_T is noticed for v_3.

The present thesis concludes with a brief and critical discussion on our results, that would help us to understand the early stage dynamics of the compressed QCD matter and set a reference baseline to the real experiments to be conducted at FAIR. However, there is an appendix at the end, where the kinematics of two-body interaction is discussed.