THEORETICAL MODELS FOR RELATIVISTIC HEAVY ION COLLISIONS

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The successes and limitations of theoretical models that have been used in understanding the signals of the quark-gluon plasm formed in nuclear collisions at the Relativistic Heavy Ion Collider (RHIC) are briefly reviewed.

1 Introduction

Since it was realized that matter formed during initial stage of relativistic heavy ion collisions might be hot and dense enough to produce a deconfined plasma of quarks and gluons, many observables have been proposed as possible signals for its existence. These include enhanced production of dileptons of intermediate invariant masses [1] and baryons made of multi-strange quarks [2], extracted long emission duration from pion interferometry [3,4], suppressed production of charmonia [5], large anisotropic flows of hadrons [6], quenching of minijets with large transverse momenta [7], fluctuations in net baryon [8] and charge [9] numbers as well as in total baryon number [10], and scaling of hadron elliptic flows according to their constituent quark content [11]. Most of these observables have been studied during past few years in experiments at RHIC involving Au+Au collisions at center-of-mass energies of 130A and 200A GeV. Through quantitative studies of these signals using various theoretical models, convincing evidence for the formation of the quark-gluon plasma in these collisions has been established [12]. In this talk, these models and their roles in interpreting the experimental observations are briefly discussed.

2 The statistical model

The simplest model for describing relativistic heavy ion collisions is to assume that observed hadrons and resonances are emitted from a thermally and chemically equilibrated non-interacting system. Such a statistical description [13,14] has been very successful in explaining measured ratios of stable hadrons, including those of multi-strange baryons, if these particles are assumed to be produced from a hot dense matter with properties expected for an almost baryon free quark-gluon plasma, i.e., having temperature $T \simeq 175$ MeV and baryon chemical potential $\mu_B \simeq 30-40$ MeV. Including also a collective velocity field, the resulting blast wave model [15] can further describe measured hadron transverse momentum spectra and their anisotropic flows. On the other hand, the statistical model does not describe very well the yield of resonances. This may not be surprising as their properties are expected to be modified in hot dense matter, which is needed to understand the enhanced production of low-mass dileptons seen in heavy ion collisions at SPS [16,17,18,19].

3 The hydrodynamic model

To generate the collective flow in the blast wave model, hydrodynamic model based on local thermal equilibrium has been introduced [20,21,22]. Using this model, it has been found that observed large hadron elliptic flows [23], which measure the asymmetry of particle momentum distributions in the plane perpendicular to the beam direction and are generated by the anisotropic pressure gradient in the initial hot dense matter in non-central heavy ion collisions, requires an initial temperature of about 340 MeV and energy density of about 25 GeV/fm^3. These values, which are similar to those predicted by the Color Glass Condensate model based on geometrical saturation of initial gluon distributions in the colliding nuclei [24], are significantly larger than predicted critical temperature and energy density from the lattice QCD for formation of the quark gluon plasma [25] Furthermore, the hydrodynamic model can reproduce observed inverted ordering of hadron elliptic flows with respect to their masses. However, except at low transverse momenta, the hydrodynamic model over-predicts hadron elliptic flows, indicating that high transverse momentum particles do not reach thermal equilibrium during collisions. Furthermore, elliptic flows of identified hadrons at intermediate transverse momenta are seen experimentally to follow approximately a quark number scaling[26], i.e., momentum dependence of their elliptic flows (with the exception of pions) becomes similar if both elliptic flow and momentum are divided by the number of constituent quarks in a hadron.

4 The transport model

To take into account non-equilibrium dynamics of relativistic heavy ion collisions, transport models, that have been extensively used in studying heavy ion collisions from SIS to SPS energies, can be employed [27,28,29,30]. With a multi-phase transport (AMPT) model [31], that includes both initial partonic and final hadronic interactions as well as the transition between these two phases of matters, measured large hadron elliptic flows can be explained by a parton scattering cross section that is an order of magnitude larger than that expected from the perturbative QCD. Such a large cross section may be due to the existence of quasi-bound states in the quark-gluon plasma as shown in both the strongly coupled gauged theory [32] and the lattice QCD calculations [33]. Because of the appreciable parton higher-order anisotropic flows generated during initial stage of collisions [34], the AMPT model can also reproduce the higher-order anisotropic flows of charged hadrons measured in experiments [35]. The AMPT model has further been used to study pion interferometry in heavy ion collisions at RHIC [36], and a good description of measured two-pion correlation function is obtained with same large parton cross section. The emission source from the model is found to be non-Gaussian with a large halo due to explosive expansion and resonance decays, a shift in the out direction along the total transverse momentum of the two pions, and a strong positive correlation between the out position and emission time. The latter is in contrast with the negative correlation generated by the inward moving freezeout surface in the hydrodynamic model. The non-Gaussian emission source also makes it questionable to use a Gaussian parameterization for extracting source size from measured two-pion correlation functions [37,38].

5 The quark coalescence model

Although parton elliptic flow in the AMPT mode is smaller than that from the hydrodynamic model, which has also been seen in other parton cascade study [39], large hadron elliptic flows can, however, be obtained if hadronization of the partonic matter is via coalescence or recombination of quarks and antiquarks. The quark coalescence model can also explain observed large baryon to meson ratio and quark number scaling of hadron elliptic flows at intermediate transverse momenta [40,41,42,43,44]. Deviation of the pion elliptic flow from the scaling behavior can be attributed to effects from resonance decay contribution to pion production in the coalescence model [45,46]. Resonance production also helps to maintain entropy conservation when hadronization proceeds through quark coalescence. In these studies, the large local parton directed flow has, however, been overlooked [47]. How to explain observed quark number scaling of hadron elliptic flows in the presence of this effect has not been resolved.

6 Jet quenching in dense matter

In some coalescence model studies [40,41], intermediate transverse momentum hadrons are dominantly produced from coalescence of thermal partons in the quark-gluon plasma with minijet partons produced from initial hard scattering between colliding nucleons, and this is consistent with the experimental observation that these hadrons are jet-like [48,49]. Minijets are, however, quenched in central relativistic heavy ion collisions at RHIC as shown by suppressed production of high transverse momentum hadrons [50,51]. Because of medium-induced gluon bremsstrahlung, minijet partons are found to have a mean energy loss that depends quadratically on the size of the quark-gluon plasma [52,53], unlike the linear dependence in a non-Abelian plasma. Fitting to observed suppression of high transverse momentum hadrons leads to the extraction of an initial energy density of about 20 GeV/fm^3 in heavy ion collisions at RHIC, similar to that determined from the hydrodynamic model fit to hadron spectra and elliptic flows as well as that given by the non-equilibrium transport model.

7 Conclusions

To understand relativistic heavy ion collisions at RHIC, theoretical models ranging from simple statistical model to microscopic transport model have been developed. These models have made it possible to examine quantitatively many of proposed signals of the quark-gluon plasma. Results from this comprehensive analysis have all pointed to the conclusion that the energy density of the initial matter produced in these collisions is order of magnitude higher than the critical energy density for the formation of the quark-gluon plasma. The requirement of initial thermalization in the hydrodynamic model and of large parton scattering cross sections in the transport model further indicates that this dense matter is non-perturbative. Next generation experiments on more penetrating probes such as photons and dileptons as well as hadrons made of heavy charm and bottom quarks will provide the possibility to study more directly the properties of this matter. The theoretical models described in this talk are expected to continue to play important roles in achieving this goal.

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