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Working group report: Heavy ion physics

Coordinator: JAN-E ALAM[1]

Contributors: K Assamagan[2], S Chattopadhyay[1], R Gavai[3], Sourendu Gupta[3], B Layek[4], S Mukherjee[3], R Ray[3], Pradip K Roy[5] and A Srivastava[4]
[1]Variable Energy Cyclotron Centre, 1/AF Bidhan Nagar, Kolkata 700 064, India
[2]Brookhaven National Laboratory, Upton, New York 11973-5000, USA
[3]Tata Institute of Fundamental Research, Homi Bhabha Road, Mumbai 400 005, India
[4]Institute of Physics, Sachivalaya Marg, Bhubaneswar 751 005, India
[5]Saha Institute of Nuclear Physics, 1/AF Bidhan Nagar, Kolkata 700 064, India
E-mail: jane@veccal.ernet.in

Abstract. The 8th workshop on high energy physics phenomenology (WHEPP-8) was held at the Indian Institute of Technology, Mumbai, India during January 5–16, 2004. One of the four working groups, group III was dedicated to QCD and heavy ion physics (HIC). The present manuscript gives a summary of the activities of group III during the workshop (see also [1] for completeness). The activities of group III were focused to understand the collective behaviours of the system formed after the collisions of two nuclei at ultra-relativistic energies from the interactions of the elementary degrees of freedom, i.e. quarks and gluons, governed by non-abelian gauge theory, i.e. QCD. This was initiated by two plenary talks on experimental overview of heavy ion collisions and lattice QCD and several working group talks and discussions.

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1. Introduction

The QCD renormalization group calculations predict that strongly interacting systems at very high temperature and/or density are composed of weakly interacting quarks and gluons [2] due to asymptotic freedom and the Debye screening of colour charge. At low temperature and density the quarks and gluons are confined within the hadrons. Therefore, a phase transition is expected to take place at an intermediate value of temperature and/or density (figure 1). A thermalized system where the properties of the system are governed by the quarks and gluons degrees of freedom is called quark gluon plasma (QGP). Lattice QCD calculations predict that nuclear matter undergoes a phase transition (or a cross over?) to a deconfined state of quarks and gluons at a temperature $T_{\mathrm{c}} \sim 170$ MeV for a baryon-free system.

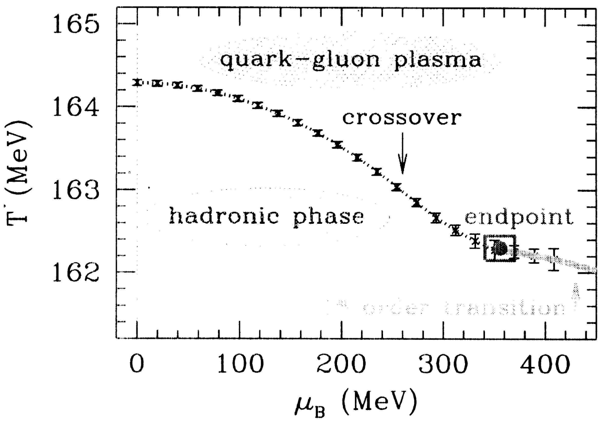

Figure 1. The QCD phase diagram from recent lattice calculations taken from ref. [5].

At large baryon density and low temperature the value of transition temperature and density is uncertain. One expects that ultra-relativistic heavy ion collisions (URHIC) at CERN/SPS, BNL/RHIC and CERN/LHC might create conditions conducive for the formation and study of QGP. Chattopadhyay [3] reviewed the results from various experimental groups working at BNL-RHIC. He pointed out that the jet quenching at high momentum is one of the most exciting results. This means that the pion spectra from Au + Au collisions is suppressed compared to that from $p + p$ collisions at RHIC energies at high transverse momentum region (p_{T}). This may be understood in the framework of perturbative QCD if one assumes partons produced from the initial hard collisions of the partons in the colliding nuclei lose energy due to radiation when they propagate through a hot and dense partonic (thermalized) medium before hadronization. The recent theoretical results from lattice QCD were reviewed by Gupta [4] in a plenary talk. He indicated how the results from lattice QCD can be used as inputs to understand the experimental data available at different colliding energies. Apart from these two plenary talks there were four working group talks on physics of URHIC. K Assamagan presented the overview of heavy ion program of ATLAS Collaboration at CERN-LHC. He claimed that with help of the ATLAS detector it will be possible to reconstruct very high energy jets from heavy ion collisions more efficiently than ever before. A Srivastava discussed various issues related to the fluctuations in QCD phase transitions. He argued that if the values of baryonic chemical potential and the temperature at the freeze-out are close to the boundary of the QCD phase transition then by studying the fluctuations in various thermodynamical quantities at different phase space region at different beam energies it will be possible to locate the critical point of transition. S Gupta in a working group discussions deliberated on the velocity of sound and susceptibilities from lattice QCD. J Alam indicated the effects of EOS on various experimental observables.

As mentioned above, one review talk was on the first principle theory (lattice QCD) and another was on experimental data. Therefore, the theme of the working group III (heavy ion physics) was set to establish a link between the subject matter of those two plenary talks. In the next few sections of this write-up we will concentrate on some of the problems discussed in the working groups.

2. Systematic studies of the rapidity dependence of chemical freeze-out temperature (T_{ch}), baryonic (μ_{B}) and strangeness (μ_{s}) chemical potentials

The ratios of the densities of different hadrons measured experimentally may be used to understand the properties of the system formed after heavy ion collisions at ultra-relativistic energies. These ratios vary in rapidity because the valance and the sea quarks inside the nucleons of the colliding nuclei have very different rapidity (y) distributions. More specifically, the valance quarks which carry the baryon number of the nucleons have harder momentum distributions, and hence their abundance at the central rapidity region ($y = 0$) will be smaller. The $y = 0$ region will be dominated by gluons because of their softer momentum distributions and larger interaction cross-sections. Therefore, the baryonic chemical potential at $y = 0$ will be smaller compared to $y \neq 0$ region, i.e. μ_{B} will be a function of y and so will be other thermodynamic variables. It will be very useful to analyse the experimental data on particle densities at different rapidities for different colliding energies and extract $T_{\mathrm{ch}}(y)$, $\mu_{\mathrm{B}}(y)$ etc. Recently the existence of a critical point in QCD phase diagram has been predicted at a temperature $T \sim 162$ MeV and baryonic chemical potential $\mu_{\mathrm{B}} \sim 360$ MeV [5]. (These values of T_{ch} and μ_{B} are not yet fully settled [4].) It will be interesting to see what are the values of T and μ_{B} that have been achieved at various rapidities and colliding energies, whether it is close to the critical point. It is important to mention here that at the critical point the fluctuations in the density of particles will be very large, a phenomenon similar to critical opalescence in condensed matter physics. Analysis of the experimental data for particle densities and fluctuations will be very useful to locate the point where the phenomenon of critical opalescence occurs at the QCD phase diagram.

The rapidity distribution, $\mathrm{d}N_H/\mathrm{d}y$ for thermal hadrons, H originating from an expanding fireball is given by

$$\frac{\mathrm{d}N_{\mathrm{H}}}{\mathrm{d}y} = \frac{g_{\mathrm{H}} V T_{\mathrm{ch}}^3}{(2\pi)^2} \sum_{n=1}^{\infty} (\pm 1)^{n+1} \int_{\eta_{\min}}^{\eta_{\max}} \mathrm{d}\eta\, \mathrm{e}^{-n m_{\mathrm{H}} x / T_{\mathrm{ch}}}\, \mathrm{e}^{n\,(\mu_{\mathrm{B}} B + \mu_{\mathrm{s}} S)/T_{\mathrm{ch}}} \times \left[\frac{m_{\mathrm{H}}^2}{n T_{\mathrm{ch}}^2} + \frac{2 m_{\mathrm{H}}}{n^2 T_{\mathrm{ch}} x} + \frac{2}{n^3 x^2} \right], \tag{1}$$

where V is the volume of the system at the chemical freeze-out point, g_H is the statistical degeneracy, B is the baryon number, S is the strangeness of the hadron H under consideration, η is the space-time rapidity and $x = \cosh(y - \eta)$.

Hadrons H originating from the decays of various resonances should also be included. The transverse momentum distribution of H originating from the (two body) decay of resonance R is given by [6]

$$\frac{\mathrm{d}N_{\mathrm{H}}}{\mathrm{d}y \mathrm{d}m_{\mathrm{TH}}^2} = \frac{m_{\mathrm{R}} b}{4\pi |p_{\mathrm{H}}^*|} \int_{y_{\mathrm{R}}^-}^{y_{\mathrm{R}}^+} \frac{\mathrm{d}y_{\mathrm{R}}}{f(y_{\mathrm{R}})} \int_{m_{\mathrm{TR}}^{2-}}^{m_{\mathrm{TR}}^{2+}} \mathrm{d}m_{\mathrm{TR}}^2 \frac{1}{g(m_{\mathrm{TR}}, y_{\mathrm{R}})} \frac{\mathrm{d}N_{\mathrm{R}}}{\mathrm{d}y_{\mathrm{R}} \mathrm{d}m_{\mathrm{TR}}^2}, \tag{2}$$

where b is the branching ratio of the decay $R \to H + X$, $m_{\rm R}$ is the mass of the resonance, $p^*_{\rm H}$ is the momentum of H in the rest frame of R,

$$y^{\pm}_{\rm R} = y_{\rm H} \pm \ln\left(\frac{\sqrt{E^{*2}_{\rm H} + p^2_{\rm TH}} + |p^*_{\rm H}|}{m_{\rm TH}}\right) \quad (3)$$

and the quantities $m^{\pm}_{\rm TR}$ is given by

$$m^{\pm}_{\rm TR} = \frac{m_{\rm R}[E^*_{\rm H} m_{\rm TH}\cosh(y_{\rm H} - y_{\rm R}) \pm p_{\rm TH}\sqrt{E^{*2}_{\rm H} + p^2_{\rm TH} - m^2_{\rm TH}\cosh^2(y_{\rm H} - y_{\rm R})}]}{m^2_{\rm TH}\cosh^2(y_h - y_{\rm R}) - p^2_{\rm TH}}. \quad (4)$$

The functions $f(y_{\rm R})$ and $g(m_{\rm TR}, y_{\rm R})$ in eq. (2) are given by

$$f(y_{\rm R}) = \sqrt{m^2_{\rm TH}\cosh^2(y_{\rm H} - y_{\rm R}) - p^2_{\rm TH}} \quad (5)$$

$$g(m_{\rm TR}, y_{\rm R}) = \sqrt{(m^+_{\rm TR} - m_{\rm TR})(m_{\rm TR} - m^-_{\rm TR})}. \quad (6)$$

Contributions from eqs (1) and (2) have to be added and the resultant should be compared with the experimental yields to extract various thermodynamic quantities like $T_{\rm ch}$ and $\mu_{\rm B}$. If the thermalization of the system is established then one can study the fluctuations of various thermodynamical quantities at different rapidities. The fluctuations in Θ can be written as

$$\Delta\Theta = \langle\Theta^2\rangle - \langle\Theta\rangle^2 = T_{\rm ch}\frac{\partial\Theta}{\partial\mu_\Theta}, \quad (7)$$

where μ_Θ is the chemical potential corresponding to the conserved quantity Θ.

Lattice calculations indicate a hierarchy of susceptibilities (i.e. fluctuations) in baryon number ($\chi_{\rm B}$), strangeness ($\chi_{\rm s}$) and electric charge (χ_Q) as follows [7]:

$$\chi_{\rm B} < \chi_Q < \chi_{\rm s} \quad (T > T_{\rm c}), \quad \chi_{\rm B} > \chi_Q > \chi_{\rm s} \quad (T < T_{\rm c}). \quad (8)$$

This indicate that the inversion of hierarchy as the temperature of the system crosses $T_{\rm c}$ may be a signal of QCD phase transition. It will be interesting to check these findings with experimental data at different colliding energies.

The fluctuations in net baryon numbers for AGS, SPS and RHIC energies at central rapidity are: $\Delta N^2_{\rm B}/(VT) \sim 11, 1.0$ and 0.4 respectively, indicating that the fluctuations in net baryon number increase with decrease in beam energies.

3. Sensitivity of elliptic flow velocity (v_2) and Hanbury, Brown and Twiss (HBT) radii on EOS

As mentioned before, collisions of nuclei at ultra-relativistic energies are expected to produce a hot and dense system of deconfined matter of quarks and gluons. The outward push of this matter decides the magnitude of the flow velocity. The space-time evolution of such a system (governed by relativistic hydrodynamics) crucially depends on the EOS. The momentum distribution of hadrons emitted from this system, the elliptic flow velocity [8], HBT radii of the system etc. are some of the quantities which are sensitive to the EOS.

Transverse mass spectrum of hadrons is given by

$$\frac{\mathrm{d}N}{m_{\mathrm{TH}}\mathrm{d}m_{\mathrm{TH}}\mathrm{d}y\mathrm{d}\psi} = \frac{g}{(2\pi)^3}\int_{\mathrm{f.o.}} r\mathrm{d}r\tau_{\mathrm{F}}\mathrm{d}\eta\mathrm{d}\phi\left[\gamma_{\mathrm{r}}\{e_y - q_{\mathrm{T}}\} - p_{\mathrm{TH}}\frac{\partial\tau}{\partial r}\right] \times\sum_{n=1}^{\infty}(\pm 1)^{n+1}\,\mathrm{e}^{-n[\gamma_{\mathrm{r}}\{e_y-q_{\mathrm{T}}\}/T_{\mathrm{F}}}\,\mathrm{e}^{n\mu_{\mathrm{B}}/T_{\mathrm{F}}}, \tag{9}$$

where $m_{\mathrm{TH}} = \sqrt{p_{\mathrm{TH}}^2 + m_{\mathrm{H}}^2}$ is the transverse mass, p_{TH} is the transverse momentum, v_{r} is the radial flow velocity, γ_{r} is the corresponding Lorentz factor, $e_y = m_{\mathrm{TH}}\cosh(y-\eta)$, $q_{\mathrm{T}} = v_{\mathrm{r}}p_{\mathrm{TH}}\cos(\phi-\psi)$ and T_{F} is the freeze-out temperature. Integration in eq. (9) has to be carried over the freeze-out surface. The elliptic flow velocity v_2 is defined as

$$v_2(p_{\mathrm{T}}, y) = \frac{\int_{-\pi}^{\pi}\mathrm{d}\psi\cos(2\psi)\frac{\mathrm{d}N}{m_{\mathrm{T}}\mathrm{d}m_{\mathrm{T}}\mathrm{d}y\mathrm{d}\psi}}{\int_{-\pi}^{\pi}\mathrm{d}\psi\,\frac{\mathrm{d}N}{m_{\mathrm{T}}\mathrm{d}m_{\mathrm{T}}\mathrm{d}y\mathrm{d}\psi}}. \tag{10}$$

Two-particle intensity interferometry along with the analysis of single-particle spectra have been widely used for a quantitative characterization of the hot zone [9]. One of the major limitations of carrying out the correlation studies with hadrons appearing at the final state is that, the information about the possible early dense state of matter is diluted or lost through re-scattering. In this respect correlation study with electromagnetically interacting particles is a better choice, although the experimental measurement is difficult. There are good scope of the analysis of the experiment data from RHIC on pion interferometry.

The two-particle correlations C_2 is defined as

$$C_2 = \frac{\mathcal{P}_2(p_1, p_2)}{\mathcal{P}_1(p_1)\mathcal{P}_1(p_2)}, \tag{11}$$

where $\mathcal{P}_1$ and $\mathcal{P}_2$ are one- and two-particle Lorentz invariant particle distributions respectively defined as

$$\mathcal{P}_1 = E_1\frac{\mathrm{d}^3N}{\mathrm{d}^3p_1} \tag{12}$$

and

$$\mathcal{P}_2 = E_1E_2\frac{\mathrm{d}^6N}{\mathrm{d}^3p_1\mathrm{d}^3p_2}. \tag{13}$$

A systematic study of these quantities with inputs from first principle theory, i.e. lattice QCD is an important problem which needs careful attention.

4. Spectral change of hadrons at non-zero density and temperature

The change of spectral functions of hadrons (i.e. their masses and widths) at $T \neq 0$ and $\mu_{\rm B} \neq 0$ is a very active field of research [10]. It is expected that penetrating probes, e.g. photons and dileptons are the most suitable tools to study such changes. However, particle ratios which are sensitive to their masses should reflect the possible changes in the spectral functions. It has been claimed that the particle ratios are determined at temperature close to the transition temperature [11], i.e. when $T_{\rm ch} \sim T_{\rm c}$. If so then it should bring the information on the change of hadronic masses efficiently as it is expected that the change will be maximum near the transition temperature. A huge amount of theoretical work has been done to calculate the effective masses and widths of hadrons within the ambit of effective interactions among the hadrons. For consistency the same interactions should be taken into account in the EOS. However, in most of the analyses of experimental data these effects were not taken into account, and hence these issues need to be addressed carefully.

5. How accurately can the heavy-ion collisions pin down the speed of sound?

Under the assumption of local thermal equilibrium, the EOS is the functional relation between pressure (P) and the energy density (ϵ), where P and ϵ are related through the velocity of sound $c_{\rm s}$ which is defined as $c_{\rm s}^2 = (\partial P/\partial \epsilon)_{\rm isentropic}$. For a massless, non-interacting gas, $c_{\rm s}^2 = 1/3$ (ideal gas limit). The velocity of sound plays a crucial role in the hydrodynamical evolution of the matter created in heavy-ion collision and affect almost all the observables originating from the fire ball. Consider a situation where quark gluon plasma (QGP) is formed at the initial state. In such a scenario, the matter evolves from an initial QGP state to the hadronic phase via an intermediate mixed phase of QGP and hadrons due to the expansion (hence cooling) of the system in a first-order phase transition scenario. Finally the system disassembles to hadrons (mainly pions) at the freeze-out where the interaction among the particles become too weak to maintain the equilibrium. The velocity of sound is very different in the three stages of expansion mentioned above reflecting the interaction among the constituents of the matter in the three stages. While in the QGP phase, it should in principle approach the ideal gas limit, in the mixed phase it should reduce to zero due to vanishing pressure gradient, indicating 'softness' of the EOS. Then below the critical temperature, it should have a value that reflects the presence of interacting hadrons in the system.

Relativistic hydrodynamical models proposed in refs [12] and [13] have routinely been used to evaluate the multiplicity distributions and transverse mass of hadrons produced in nuclear collisions. In all these calculations the velocity of sound is one of the most important inputs, which should be taken from lattice QCD. It will be interesting to see how the spectra are affected in a second-order phase transitions/cross-over scenario.

The velocity of sound can also be extracted from the measured fluctuations in multiplicity (or entropy) [14] from the relation,

$$\frac{\partial S}{S}\bigg/\frac{\partial E}{E} = \left[1 + \frac{c_{\rm s}^2}{1 + c_{\rm s}^2 \phi}\right]^{-2}, \tag{14}$$

where $\phi = {\rm d}\ln V/{\rm d}\ln T$, E is the energy, V is the volume of the system.

6. Jet quenching

It has been observed experimentally in Au + Au collisions that the scaled (by number of binary collisions) pion spectra at large transverse momenta are suppressed compared to the pion spectra obtained in $p+p$ collisions at $\sqrt{s} = 200$ A GeV, i.e.

$$R_{AA} = {\rm d}N_\pi^{\rm AuAu}/{\rm d}^2 p_{\rm T}{\rm d}y/(n_{\rm coll}^{\rm binary}{\rm d}N_\pi^{pp}/{\rm d}^2 p_{\rm T}{\rm d}y) \; < 1 \tag{15}$$

for $p_{\rm T} > 4$ GeV. Here ${\rm d}^{XY}N_\pi/{\rm d}^2 p_{\rm T}{\rm d}y$ is the invariant pion distribution originating from $X+Y$ collisions, $n_{\rm coll}^{\rm binary}$ is the number of binary nucleon–nucleon collisions in Au + Au collision. The high $p_{\rm T}$ pions are produced from the fragmentations (hadronizations) of the partons created from the initial hard collisions among the partons of the colliding nuclei. Hard partons are produced well before the (possible) formation of the quark gluon plasma (or dense hadronic medium) in high energy nuclear collisions. These hard partons then propagate through the dense medium (hadronic or partonic) and lose energy due to radiation before fragmentations into hadrons. This energy loss will be reflected in the suppression of the hadronic $p_{\rm T}$ spectra in Au + Au collisions. In $p+p$ collision there is no possibility of such energy loss. Hence at high $p_{\rm T}$ the ratio mentioned above is suppressed (figure 2). In almost all the works done so far it has been assumed that the partonic medium is thermalized. It will be interesting to estimate the energy loss per unit length when partonic system is away from equilibrium.

7. Strangeness production

It is possible to experimentally test the prediction of lattice QCD on the strangeness yield, parametrized through the Wrobleski parameter, $\lambda_{\rm s}(= 2\chi_{ss}/(\chi_{uu} + \chi_{dd})$ in heavy-ion collisions [4]. In a scenario where QGP is formed after the nuclear collisions, the production of strangeness will be enhanced because of larger production cross-sections, lower production threshold and larger phase space available in QGP phase compared to the hadronic phase. Therefore, strangeness enhancement will indicate the formation of QGP. A systematic microscopic study of the strangeness production at various beam energies is underway [16].

8. Summary

Some of the problems discussed above are under active considerations, results will be available in the near future. Theoretical understanding of the problems discussed above requires various inputs, some of those, e.g. EOS, value of the transition

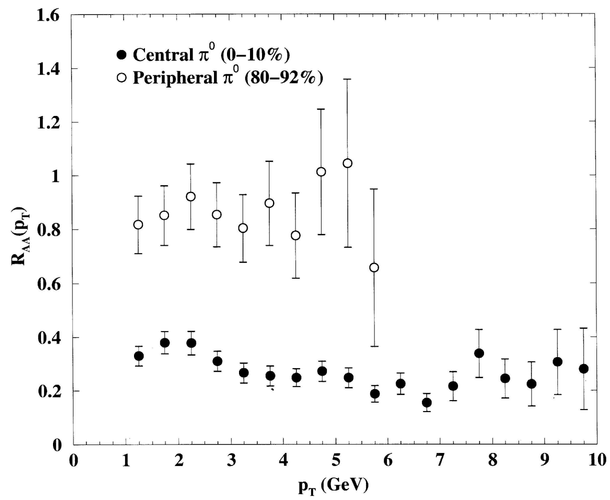

Figure 2. Variation of $R_{AA}(p_{\rm T})$ with $p_{\rm T}$ for central and peripheral collisions taken from ref. [15].

temperature etc. may be available from lattice QCD. However, other inputs, e.g. initial thermalization time, initial temperature etc. cannot be obtained from first principle. Therefore, these quantities may be treated as parameters of the model to describe the data. In many cases the background of QGP signal has to be estimated with the help of effective field theory for hadrons.

In spite of some of the remaining uncertainties, the progress in this field is remarkable, especially when one considers that not a large number of experiments to seek out QGP have been performed. Many of the ambiguities pertaining to the 'pre-data' theory have been removed by the experimental data from SPS and RHIC. We have all the reasons to look forward to more data from RHIC and LHC where the initial energy density will be so high that the formation of QGP is almost inevitable.

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