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FROM THE GLASMA TO THE QCD PHASE BOUNDARY*

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In this paper, I qualitatively discuss the matter formed in the fragmentation region of nuclear collisions at the highest energies. I argue that although the initial temperature and baryon number density can become very large, the ratio of initial baryon chemical potential to initial temperature, μ_{B}/T, is approximately independent of energy, when measured at a fixed rapidity measured from the end of the fragmentation region. This quantity is argued to be roughly invariant under expansion, and, therefore, the value measured at decoupling should be approximately the same as the initial value and largely independent of energy. The values of the initial temperature and initial baryon number are energy-dependent and become large as the center-of-mass collision energy increases.

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1. Introduction

The title of the talk was given to me by the organizers and force me to rethink what implications gluons saturation [1, 2] and the Glasma [3, 4] might have to do with the phase diagram of QCD in the region of high baryon number density. The problem I will address is what values of baryon number density and temperature are probed in the fragmentation region of nucleus–nucleus collisions at asymptotically high energy. I was, therefore, forced to go back and update the ideas found in the paper by Anishetty, Koehler and McLerran [5], and put them in a more modern context. This work is largely based on and stimulated by the considerations of Li and Kapusta [6]. This region was studied empirically based on experimental

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data in the classic work of Cleymans and Becattini [7]. I have attempted to simplify some of the arguments in these very nice papers, and address specifically the region of the phase diagram of QCD that one can study at asymptotic energies.

The result I find by very simple kinematic arguments is amusing: At asymptotically high energies and fixed rapidity as measured from the end of the fragmentation region, one makes a system initially at a very high temperature and a very high baryon number density. This temperature and baryon density grow as the collision energy increases. This can be much higher than the expected scale of the de-confinement or chiral symmetry restoration temperatures and densities. The ratio of the baryon chemical potential to temperature asymptotes to a constant. Since baryon number is conserved and the entropy is approximately conserved during expansion, the expansion dynamics should little change this ratio. Therefore, at late stages of the collision, one is probing the baryon-rich region of the phase diagram of QCD.

Although the experimental challenge to probe such a region is formidable, the theoretical advantage of studying such a region is that at a fixed temperature and baryon number density, the matter produced at high energy is more slowly expanding than at lower energy. This gives longer time for long-range correlations to grow. In addition, I believe we understand the dynamics of the early times better at high energy than we do at low energy.

2. Some phenomenological considerations

In Fig. 1, the values of baryon chemical potential and temperature extracted from fits to the spectra of produced particles at the top SPS and RHIC energies are shown. The ratio of μ_{B}/T for systems where the baryon number density is small compared to the temperatures is up to a constant the ratio of baryon number density to entropy

$$\mu_{\mathrm{B}}/T \sim N_B/S\,. \tag{1}$$

Since the baryon number is conserved during expansion and entropy is approximately conserved if the effects of viscosity are ignored, this ratio is an approximate invariant under expansion. If the system has initially a very high temperature, then the initial value of μ_{B} must be correspondingly increased. The advantage of studying systems that are initially very hot and dense is that by the time they reach low values of density and temperature, they are expanding more slowly than systems that started at lower temperatures and densities. This is because characteristic volumes and times are larger at fixed energy density for systems with higher initial densities.

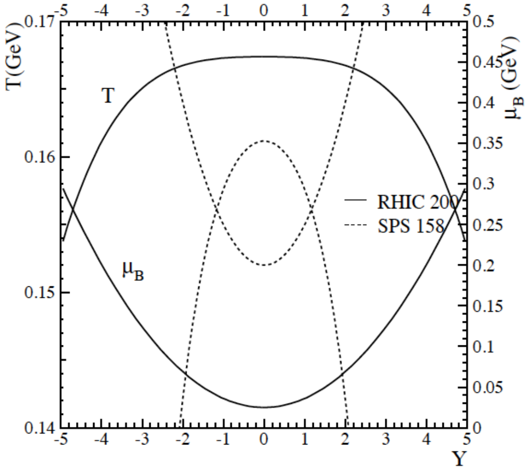

Fig. 1. Values of temperature and baryon number chemical potential as a function of rapidity for SPS and RHIC energies, from Ref. [7].

If there was limiting fragmentation for both baryons and pions, then we would expect that the rapidity distributions of these particles would be energy-independent when measured as a function of the rapidity distance from the kinematic limit for nucleon–nucleon scattering. Such limiting fragmentation has been observed at the RHIC energies.

The question we will address is how the initial energy density and baryon number density scale with energy, and how this independence of $\mu_{\rm B}/T$ arises.

3. Using saturation to estimate the early baryon density and temperatures

In the CGC description of the initial condition for ultra-relativistic heavy-ion collisions, the saturation momentum grows as a function of the rapidity distance from the fragmentation region as an exponential in rapidity (power law in $1/x$). If we sit in the fragmentation region of one heavy ion at some fixed rapidity difference from the beam rapidity, the density of partons in the beam nucleus does not grow. Let us call this rapidity difference Δy. The saturation momentum of the first nucleus is fixed at

$$Q_1^2 \sim Q_0^2 e^{\kappa\Delta y}\,, \tag{2}$$

where phenomenologically κ is a number of the order of $\kappa \sim 0.2$–0.3. The saturation momentum in the other nucleus grows as the beam energy like

$$Q_2^2 \sim Q_0^2 e^{\kappa(2y_{\rm cm}-\Delta y)}\,, \tag{3}$$

where $y_{\rm cm}$ is the center-of-mass rapidity.

At the saturation momentum of the first nucleus, the second nucleus is completely saturated and appears as a black disk. The collision will strip all of the partons from nucleus one up to a typical momentum scale of $Q_2^{\rm sat}$. In so far, as the parton distribution have little dependence upon the momentum scale of their measurement, the multiplicity will only very weakly depend upon $Q_2^{\rm sat}$ and, therefore, the beam energy. There is, therefore, approximate limiting fragmentation.

Let us estimate the density of produced particles in the fragmentation region of nucleus one. For the central collision of two nuclei of size R, multiplicity per unit area scales as

$$\frac{1}{\pi R^2}\frac{{\rm d}N}{{\rm d}y} \sim Q_1^2\,. \tag{4}$$

The initial time and initial longitudinal length scales as Q_2^{-1}, so that the initial entropy density is

$$\frac{S_{\rm initial}}{V} \sim Q_1^2 Q_2\,. \tag{5}$$

The initial baryon density is caused by compression of the target nucleon (nucleus 1) as the projectile (nucleus 2) passes through the target. This is easiest seen in the target rest frame. There the projectile is a thin disk striking a row of target nucleons, Fig. 2. The compression appears to be $1/(1-v)$, where v is the velocity of the projectile, but the struck nucleons are moving and the true compression is computed in the rest frame, which reduced the compression by a factor of $\gamma_{\rm comp}^{-1}$, resulting in a real compression factor of $\gamma_{\rm comp}$.

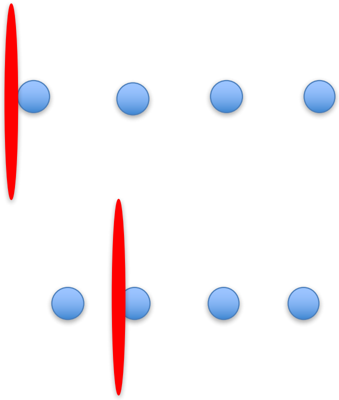

Fig. 2. The projectile nucleus passing through a target at rest.

Now, we need to determine the velocity associated with this compression. This is also simple to estimate since the longitudinal energy of fragments is trapped inside the nuclear fragmentation region so long as it is formed inside the target. This means that

$$\gamma_{\mathrm{comp}} \sim Q_2 R_1 \tag{6}$$

since the typical transverse mass scale for a particle is of the order of the saturation momentum of the projectile nucleus. We have therefore that

$$\frac{N_B}{V} \sim Q_2 R_1 \tag{7}$$

or that N_B/S is independent of the saturation momentum of nucleus 2 and is proportional to R_1/Q_1^2. This ratio has dependence on the rapidity difference from the kinematic endpoint, Δy, but is independent of R_1. These arguments are, of course too, crude to accurately resolve the rapidity dependence of this ratio. To do this properly requires a detailed simulation of the particle production and baryon compression factors.

4. Summary and conclusions

The simple conclusion from this analysis is that as one makes the collision energy asymptotically higher, then at some fixed distance away from the kinematic end point associated with the energy per nucleon in a heavy-ion collisions, the produced matter is initially hotter, denser and produced earlier. The entropy per baryon is roughly independent of energy, so that at late times at fixed energy density, the matter being studied is independent of beam energy. However, the dynamics of expansion will have changed and the matter is expanding more slowly as the energy changes. Therefore, from a theorists perspective, studying matter at finite baryon density is perhaps simpler as the energy is increased. Unfortunately, it gets much more difficult for experimentalists.

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