EPJ Web of Conferences will be set by the publisher
DOI: will be set by the publisher

De-Confinement in small systems: Clustering of color sources in high multiplicity $\bar{p}p$ collisions at $\sqrt{s}$= 1.8 TeV

L. J. Gutay[1,a]

[1] *Department of Physics and Astronomy, Purdue University, West Lafayette, IN-47907, USA*

Abstract. It is shown that de-confinement can be achieved in high multiplicity non jet $\bar{p}p$ collisions at $\sqrt{s}$= 1.8 TeV Fermi National Accelerator Laboratory(FNAL- E735) experiment. In this paper we have analyzed the transverse momentum spectrum in the frame-work of the clustering of color sources. This frame-work naturally predicts the reduction in the charged particle multiplicity with respect to the value expected from the number of independent strings. Results are presented for both thermodynamic and transport properties. The initial temperature and energy density are obtained from the data via the color reduction factor $F(\xi)$ and the associated string density parameter ξ. The results for he trace anomaly Δ and shear viscosity to entropy density ratio(η/s) are presented. These results confirm our earlier observation that the de-confined state of matter was created in high multiplicity events in $\bar{p}p$ collisions at $\sqrt{s}$=1.8 TeV.

1 Introduction

The observation of high total multiplicity, high transverse energy, non-jet, isotropic events led Van Hove [1] and Bjorken [2] to conclude that high energy density events are produced in high energy $\bar{p}p$ collisions [3]. These events have a far greater cross section than the jet production. In these events the transverse energy is proportional to the number of low transverse momentum particles. This basic correspondence can be explored over a wide range of the charged particle pseudorapidity density $\langle dN_c/d\eta\rangle$ in $\bar{p}p$ collisions at center of mass energy $\sqrt{s}$ = 1.8 TeV. In our earlier work, published in 2002, the evidence of hadronic de-confinement in $\bar{p}p$ collisions at $\sqrt{s}$ = 1.8 TeV was presented [4].

The objective of this work is to further analyze the published E735 data on the transverse momentum spectra of charged particles in the framework of Color String Percolation Model(CSPM). CSPM has been successfully applied to heavy ion data for thermodynamics and transport coefficients [5–9].

2 Color Strings and Percolation

Multiparticle production at high energies is currently described in terms of color strings stretched between the projectile and target. Hadronizing these strings produce the observed hadrons. The individual strings act as independent color sources of particles through the creation of $q\bar{q}$ pairs from the sea. At low energies only valence quarks of nucleons form strings that then hadronize. The number of strings grows with the energy and with the number of nucleons of participating nuclei. Color strings

[a] e-mail: gutay@purdue.edu

may be viewed as small discs in the transverse space filled with the color field created by colliding partons. Particles are produced by the Schwinger mechanisms [10]. With growing energy and size of the colliding nuclei the number of strings grow and start to overlap and interact to form clusters [11, 12].

We assume that a cluster of n strings behaves as a single string with an energy-momentum that corresponds to the sum of energy-momenta of the individual strings and with a higher color field, corresponding to the vectorial sum of the color field of each individual string [11, 12]. One can obtain the multiplicity μ and the mean transverse momentum squared $\langle p_t^2 \rangle$ of the particles produced by a cluster of n strings [12]

$$\mu_n = \sqrt{\frac{nS_n}{S_1}}\mu_0; \qquad \langle p_t^2 \rangle = \sqrt{\frac{nS_1}{S_n}}\langle p_t^2 \rangle_1, \tag{1}$$

where μ_0 and $\langle p_t^2 \rangle_1$ are the mean multiplicity and $\langle p_t^2 \rangle$ of particles produced from a single string with a transverse area $S_1 = \pi r_0^2$. In the limit of high string density, one obtains [11, 12]

$$\langle \frac{nS_1}{S_n} \rangle = \frac{\xi}{1 - e^{-\xi}} \equiv \frac{1}{F(\xi)^2}, \tag{2}$$

where $F(\xi)$ is the color suppression factor. $F(\xi)$ is related to the ξ

$$F(\xi) = \sqrt{\frac{1 - e^{-\xi}}{\xi}}. \tag{3}$$

The net effect due to $F(\xi)$ is the reduction in hadron multiplicity and increase in the average transverse momentum of particles. The CSPM model calculation for hadron multiplicities and momentum spectra for pp and AA collisions at RHIC and LHC energies were found to be in excellent agreement with the experiments [8, 9].

3 E735 Experiment

Experiment E735 was run during the 1988-1989 Tevatron running period, primarily collecting data triggered to enrich high multiplicity events in $\bar{p}p$ collisions at $\sqrt{s}$ = 1.8 TeV [13]. The multiplicity dependence of the transverse momentum p_t spectra was measured. The invariant p_t spectra was fitted with a power law $A/(p_0 + p_t)^n$ [14]. The power law function is the QCD inspired function which goes asymptotically to p_t^{-n} at large p_t and approximates an exponential at small p_t.

4 Color Suppression Factor and Temperature

The suppression factor is determined by comparing the charged particle spectra for $0.1 < p_t < 1.5$ GeV/c for minimum bias events from pp collisions and high multiplicity transverse momentum spectra from $\bar{p}$p. To evaluate the initial value of ξ from data a parameterization of pp events at $\sqrt{s}$ = 200 GeV is used to compute the p_t distribution

$$dN_c/dp_t^2 = a/(p_0 + p_t)^n, \tag{4}$$

where a is the normalization factor. $p_0 = 1.98$ and $n = 12.88$ are parameters used to fit the data [5]. A modified parameterization is used for high multiplicity events in $\bar{p}$p collisions at $\sqrt{s}$ = 1.8 TeV to take into account the interactions of the strings [12].

$$dN_c/dp_t^2 = \frac{a'}{(p_0\sqrt{F(\xi_{\bar{p}p})_{HM}/F(\xi_{pp})} + p_t)^n}, \tag{5}$$

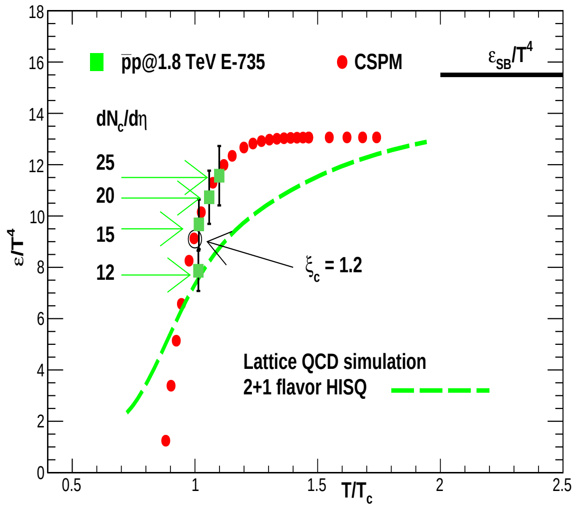

Figure 1. ε/T^4 as a function of T/T_c. Solid green squares are from $\bar{p}p$ collisions at $\sqrt{s}$ = 1.8 TeV. The lattice QCD calculation is shown as dotted green line [22]. CSPM for Au+Au at $\sqrt{s_{NN}}$ = 200 GeV are red solid circles [7].

where $F(\xi_{\bar{p}p})_{HM}$ is the color suppression factor in high multiplicity events in $\bar{\rm p}$p collisions at $\sqrt{s}$ = 1.8 TeV. In pp collisions $F(\xi_{pp}) \sim 1$ at $\sqrt{s}$ = 200 GeV due to the low string overlap probability [5].

The connection between the measured $F(\xi)$ and the temperature $T(\xi)$ involves the Schwinger mechanism (SM) for particle production. The Schwinger distribution for massless particles is expressed in terms of p_t^2 [10, 15]

$$dn/dp_t^2 \sim e^{-\pi p_t^2/x^2}, \tag{6}$$

where the average value of the string tension is $\langle x^2 \rangle$. The tension of the macroscopic cluster fluctuates around its mean value because the chromo-electric field is not constant. Quadratic fluctuations lead to a Gaussian distribution of the string tension for the cluster, which gives rise to the thermal distribution [5, 16, 17]

$$dn/dp_t^2 \sim e^{(-p_t\sqrt{\frac{2\pi}{\langle x^2 \rangle}})}, \tag{7}$$

with $\langle x^2 \rangle = \pi \langle p_t^2 \rangle_1 / F(\xi)$. The initial temperature is expressed as

$$T(\xi) = \sqrt{\frac{\langle p_t^2 \rangle_1}{2F(\xi)}}, \tag{8}$$

where $\langle p_t^2 \rangle_1$ is the average transverse momentum squared of particles produced from a single string and is evaluated using Eq. (8). At the percolation transition $\xi_c = 1.2$ the temperature $T_c = 167 \pm 2.6$ MeV as obtained from the statistical model analysis of data, which is the universal chemical freeze-out temperature and is a good measure of the phase transition temperature [18, 19]. This determines $\sqrt{\langle p_t^2 \rangle_1} = 207 \pm 3.3$ MeV [5] which calibrates the temperature.

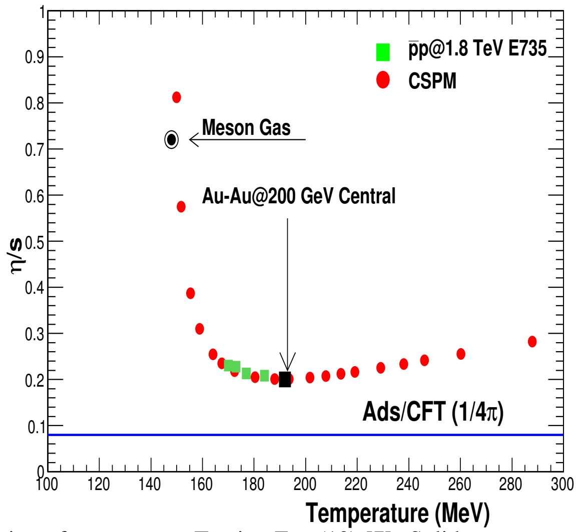

Figure 2. η/s as a function of temperature T using Eq. (10) [7]. Solid green squares are from $\bar{p}p$ collisions at $\sqrt{s}$ = 1.8 TeV. CSPM results for Au+Au at $\sqrt{s_{NN}}$ = 200 GeV are shown as solid red circles [7]. The meson gas value for $\eta/s \sim 0.7$ is shown as solid black circle at T ~ 150 MeV [23]. The lower bound shown is given by the AdS/CFT [24].

5 Energy Density

The QGP according to CSPM is born in local thermal equilibrium because the temperature is determined at the string level. After the initial temperature $T > T_c$ the CSPM is described as a perfect fluid and may expand according to Bjorken boost invariant 1D hydrodynamics [20]

$$\varepsilon = \frac{3}{2}\frac{\frac{dN_c}{dy}\langle m_t\rangle}{S_\perp \tau_{pro}}, \tag{9}$$

where ε is the energy density, $\langle m_t\rangle$ the average transverse mass, $S_\perp$ the transverse overlap area of the colliding nucleons, and τ_{pro} the proper time. Above the critical temperature only massless particles are present in CSPM. In Schwinger model τ_{pro} is the formation time for gluon production and is given by $\tau_{pro} = \frac{2.405\hbar}{\langle m_t\rangle}$ [10]. With the determination of T and ε one can compare the energy density expressed as ε/T^4 with the available lattice QCD results [21, 22]. Figure 1 shows a plot of ε/T^4 as a function of T/T_c. The error on ε/T^4 is 8-11% mainly due to the uncertainty in temperature. The LQCD results are from the HotQCD Collaboration [22]. It is observed that for highest multiplicity $\langle dN_c/d\eta\rangle \sim 27$, ε/T^4 from $\bar{p}p$ collisions is close to the value obtained for Au+Au at 200 GeV. This result strongly supports the formation of the QGP above the phase transition temperature in high multiplicity events in $\bar{p}p$ interactions at $\sqrt{s}$ = 1.8 TeV. This emphasizes that high string densities determines the initial energy density and temperature.

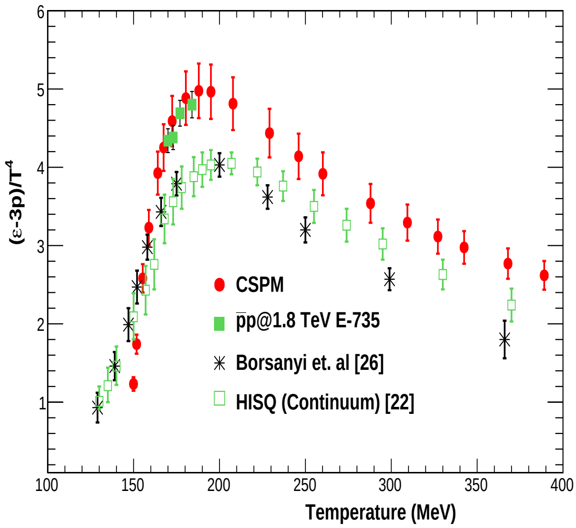

Figure 3. The trace anomaly $\Delta = (\varepsilon - 3p)/T^4$ vs temperature. Solid green squares are from $\bar{p}p$ collisions at $\sqrt{s}$ = 1.8 TeV. Green open squares are from HotQCD Collaboration [22]. Black stars are from Borsanyi et al. [26].

6 Shear viscosity to entropy density ratio η/s

Shear viscosity to entropy density ratio η/s was obtained in the framework of kinetic theory and the string percolation [7] and is given by

$$\frac{\eta}{s} = \frac{TL}{5(1 - e^{-\xi})}, \tag{10}$$

where T is the temperature and L is the longitudinal extension of the source ~ 1 fm. Fig. 2 shows η/s as a function of the temperature [7]. The error on η/s is driven by the error on temperature which is ~ 2.5-3.5%. The lower bound shown in Fig. 2 is given by the AdS/CFT conjecture [24]. It is seen that for $\langle dN_c/d\eta \rangle \sim 25$ the η/s is equal to the value from the most central collisions in Au+Au at $\sqrt{s_{NN}}$ = 200 GeV.

7 Trace anomaly Δ

The trace anomaly Δ is the expectation value of the trace of the energy-momentum tensor, $\langle \Theta^{\mu}_{\mu} \rangle = (\varepsilon - 3p)$, which measures the deviation from conformal behavior and thus identifies the interaction still present in the medium [25]. We find that the reciprocal of η/s is in numerical quantitative agreement with the dimensionless ratio $(\varepsilon - 3p)/T^4$ from LQCD over a wide range of temperatures [6, 8]. Fig. 3 shows Δ for $\bar{p}p$ along with the CSPM calculation and LQCD simulations. The minimum in $\eta/s \sim 0.20$ determines the peak of the interaction measure ~ 5 in agreement with the recent HotQCD values [22]. The maximum in Δ corresponds to the minimum in η/s. This is true for the highest multiplicity events in $\bar{p}p$ collisions.

8 Summary

The $\bar{p}p$ collisions at $\sqrt{s}$ = 1.8 TeV from the E735 experiment have been re-analyzed in using the clustering of color sources data based phenomenology. The results for temperature T, energy density ε and shear viscosity to entropy density ratio η/s have been extracted for high multiplicity events. The trace anomaly is also obtained and compared with the LQCD results. These results strongly argue that even in small systems at high energy and high multiplicity events QGP formation is possible as seen in $\bar{p}p$ collisions at $\sqrt{s}$ = 1.8 TeV.

9 Acknowledgment

This research was supported by the Office of Nuclear Physics within the U.S. Department of Energy Office of Science under Grant No. DE-FG02-88ER40412. Author is grateful to A. S. Hirsch, R. P. Scharenberg and B. K. Srivastava for useful and simulating discussions.

References

[1] L. Van Hove, Phys. Lett. B **118**, 138 (1982).
[2] J. D. Bjorken, Fermilab Pub. 82/44-THY (1982).
[3] L. McLerran, Rev. Mod. Phys. **58**, 1021 (1986).
[4] T. Alexopoulos et al. (E735 Collaboration), Phys. Lett. B **528**, 43 (2002).
[5] R. P. Scharenberg, B. K. Srivastava and A. S. Hirsch, Eur. Phys. J. C **71**, 1510 (2011).
[6] R. P. Scharenberg, PoS (CPOD 2013), **017** (2013).
[7] J. Dias de Deus, A. S. Hirsch, C. Pajares, R. P. Scharenberg and B. K. Srivastava, Eur. Phys. J. C **72**, 2123 (2012).
[8] B. K. Srivastava, Nucl. Phys. A **926**, 142 (2014).
[9] M. A. Braun, J. Dias de Deus, A. S. Hirsch, C. Pajares, R. P. Scharenberg and B. K. Srivastava, Phys. Rep. **599**, 1 (2015).
[10] J. Schwinger, Phys. Rev. **128**, 2425 (1962).
[11] M. A. Braun and C. Pajares, Eur. Phys. J. C **16**, 349 (2000).
[12] M. A. Braun, F. del Moral and C. Pajares, Phys. Rev. C **65**, 024907 (2002).
[13] T. Alexopoulos et al. (E735 Collaboration), Phys. Rev. D **48**, 984 (1993).
[14] C. Albajar et al. (UA1 Collaboration), Nucl. Phys. B **335**, 261 (1990).
[15] C. Y. Wong , *Introduction to high energy heavy ion collisions* (World Scintific, 1994).
[16] A. Bialas, Phys. Lett. B **466**, 301 (1999).
[17] J. Dias de Deus and C. Pajares, Phys. Lett. **642**, 455 (2006).
[18] P. Braun-Munzinger, J. Stachel and C. Wetterich, Phys. Lett. B **596**, 61 (2004).
[19] F. Becattini, P. Castorina, A. Milov and H. Satz, Eur. Phys. J. C **66**, 377 (2010).
[20] J. D. Bjorken, Phys. Rev. D **27**, 140 (1983).
[21] A. Bazavov et al., Phys. Rev. D **80**, 014504 (2009).
[22] A. Bazavov et al., Phys. Rev. D **90**, 094503 (2014).
[23] M. Prakash, M. Prakash, R. Venugopalan and G. Wleke, Phys. Rep. **227**, 321 (1993).
[24] P. K. Kovtun, D. T. Son and A. O. Starinets, Phys. Rev. Lett. **94**, 111601 (2005).
[25] M. Cheng et al., Phys. Rev. D **81**, 054504 (2010).
[26] S. Borsanyi et al., Phys. Lett. **730**, 99 (2014).