Dissipative properties of the matter formed at the Large Hadron Collider energies using Color String Percolation Model

D. Sahu[1*] and R. Sahoo[1,2†]
[1]*Department of Physics, Indian Institute of Technology Indore, Simrol, Indore 453552, India and*
[2]*CERN, CH 1211, Geneva 23, Switzerland*

1. Introduction

Recently, there has been a lot of interest to understand the behavior of the newly known state of matter called Quark-Gluon Plasma (QGP), which is expected to be formed in the ultra-relativistic heavy-ion collisions at the Large Hadron Collider (LHC). Properties such as shear viscosity to entropy density ratio (η/s) and bulk viscosity to entropy density ratio (ζ/s) shed light on the dissipative nature of the fluid formed in such collisions. Study of η/s and ζ/s can indicate a possible critical point where the transition from hadron gas to deconfined quark matter occurs. Also, as predicted by several effective models, the change in behavior of (ζ/s) is expected near QCD critical temperature (T_c), where conformal symmetry breaking might be significant. On the other hand, the squared speed of sound (c_s^2) can define the equation of state of the system. In our work [1], we have studied these observables for various collision systems at the LHC energies within the Color String Percolation Model (CSPM), which is a well established theoretical model.

2. Forrmulation

In CSPM, we assume that color strings are stretched between the partons of the colliding nuclei, and the hadronization of these strings forms the final state particles. The strings occupy a finite area in the transverse space. The number of colliding partons increases with the increase in collision energy, making the number of strings grow. The strings then start overlapping, forming clusters in the transverse space. After a certain critical string density (ξ_c), a macroscopic cluster appears, marking the percolation phase transition. The dimensionless string density parameter is expressed as, $\xi = \frac{N_s S_1}{S_N}$, where N_s is the number of overlapping strings, S_1 and S_N being the transverse area a single string and the transverse area occupied by the overlapping strings, respectively. In the thermodynamic limit, the color suppression factor $F(\xi)$ and the percolation density parameter ξ are related as [2],

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

To obatin $F(\xi)$, we fit the following function to the $p_{\rm T}$ spectra within the $p_{\rm T}$ range 0.15-1.0 GeV/c of pp, p-Pb, Xe-Xe and Pb-Pb collision systems at the LHC energies [1].

$$\frac{d^2N_{ch}}{dp_T^2} = \frac{a}{(p_0\sqrt{F(\xi)_{pp,\sqrt{s}=200\ \rm GeV}/F(\xi)_{pp,pA,AA}} + p_{\rm T})^{\alpha}}$$

The initial percolation temperature can be defined in terms of $F(\xi)$ as [2],

$$T(\xi) = \sqrt{\frac{\langle p_T^2\rangle_1}{2F(\xi)}}. \tag{2}$$

Here, $\langle p_{\rm T}^2\rangle_1$ is the single-string squared average momentum and $\sqrt{\langle p_{\rm T}^2\rangle_1} = 207.2 \pm 3.3$ MeV. Now, with the help of the parameters ξ and T obtained from the above formulation, we can calculate the required observables within CSPM.

The shear viscosity to entropy density ratio in CSPM can be estimated from the expression [1],

$$\eta/s = \frac{TL}{5(1-e^{-\xi})}, \tag{3}$$

where, $L \simeq 1$ fm is the length of a string. Furthermore, the squared speed of sound can be expressed as [1],

$$c_s^2 = (-0.33)\left(\frac{\xi e^{-\xi}}{1-e^{-\xi}} - 1\right)$$
$$+0.0191(\Delta/3)\left(\frac{\xi e^{-\xi}}{(1-e^{-\xi})^2} - \frac{1}{1-e^{-\xi}}\right), \tag{4}$$

where, Δ is the trace anomaly.

Finally, the bulk viscosity to entropy density ratio can be written as [1],

$$\zeta/s = 15\frac{\eta}{s}\left(\frac{1}{3} - c_{\rm s}^2\right)^2. \tag{5}$$

*Electronic address: `Dushmanta.Sahu@cern.ch`
†Electronic address: `Raghunath.Sahoo@cern.ch`

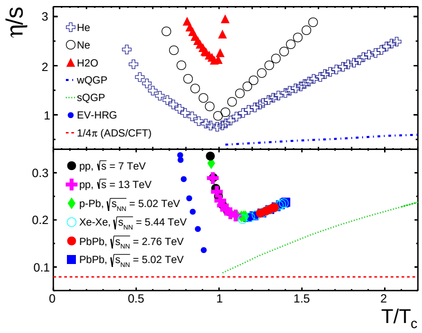

FIG. 1: Shear viscosity to entropy density ratio as a function of initial percolation temperature normalized by critical temperature (for *pp* collisions at $\sqrt{s}$ = 7 and 13 TeV, *p*-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV, Xe-Xe collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.44 TeV, Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 and 5.02 TeV) [1].

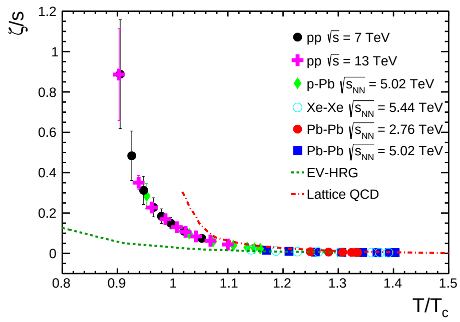

FIG. 2: Bulk viscosity to entropy density as a function of initial percolation temperature normalized by critical temperature (for *pp* collisions at $\sqrt{s}$ = 7 and 13 TeV, *p*-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV, Xe-Xe collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.44 TeV, Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 and 5.02 TeV) [1].

3. Results and Discussions

The shear viscosity to entropy density ratio as a function of initial temperature normalized by T_c is plotted in Fig.1. We can see that at a certain temperature, the η/s is minimum. After this, the trend again starts to increase, which indicates the QGP phase. It is observed that the minimum point of η/s for the matter produced in the high-energy collision is the smallest when compared to any other known fluid. It is also close to the predictions from strongly interacting (sQGP) coupled QCD plasma. Furthermore, the results are close to the minimum value of AdS/CFT conjecture. This makes the matter produced in high-multiplicity high-energy collisions to be the closest perfect fluid found in nature.

Figure 2 shows the variation of bulk viscosity to entropy density ratio as a function of initial percolation temperature normalized by T_{c}. As we go from low temperature to high-temperature regime, we observe a critical behavior at a certain temperature, after which ζ/s becomes almost zero. Our results from CSPM agree to a reasonable extent with the predictions from the lattice QCD model.

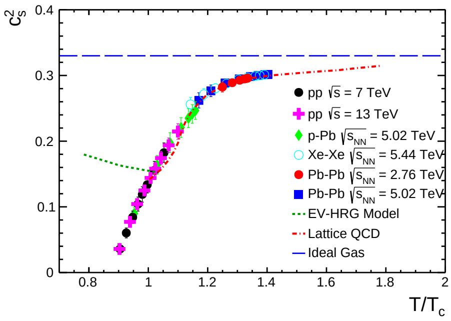

FIG. 3: Speed of sound as a function of initial percolation temperature normalized by critical temperature (for *pp* collisions at $\sqrt{s}$ = 7 and 13 TeV, *p*-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV, Xe-Xe collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.44 TeV, Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 2.76 and 5.02 TeV) [1].

In Fig. 3, we have plotted the squared speed of sound as a function of initial percolation temperature normalized by T_{c}. For *pp* collisions, the value of c_{s}^2 is low, and it increases with an increase in temperature. For most central heavy-ion collisions, the squared speed of sound approaches to the value of c_{s}^2 of ideal massless gas. Here also, our obtained results agree with the predictions from lattice QCD.

4. Summary

In summary, high-multiplicity *pp* collisions and heavy-ion collisions showing similar values of η/s indicate a strongly coupled QGP being formed in such collisions. The matter formed in these collisions is closest to a perfect fluid. In addition, the result from CSPM agrees with that of lattice QCD results to a reasonable extent.

The detailed results on other transport coefficients and thermodynamic variables for all the collision species at the LHC will be presented.

References

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