Density fluctuations near the QCD critical point in presence of a magnetic field

Mahfuzur Rahaman

Darjeeling Government College

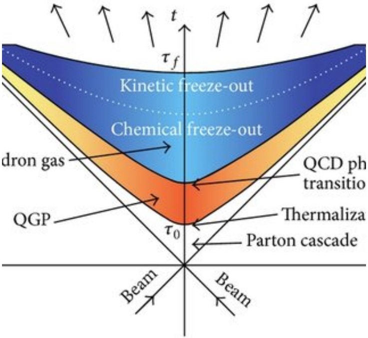
based on **arXiv 2306.06905** *(MR, Md Hasanujjaman, Golam Sarwar, Abhijit Bhattacharyya, Jan-e Alam)*

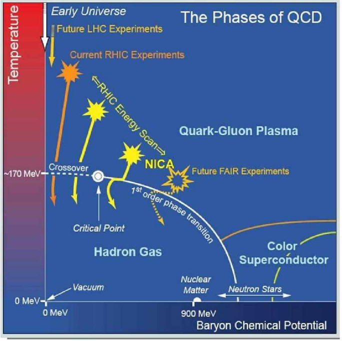
Meeting on the physics of ALICE, CBM and STAR (MPACS), 29-30 January

Outline

Introduction

The collisions at LHC, RHIC create a matter, called **quark-gluon plasma**.





- An anticipated critical end point (CEP) at finite μ_B
- We want to investigate if the evolution of the QGP pass through the critical region.

Introduction

- Relativistic Hydrodynamics
- Ideal Hydro: Euler's Equation
- Navier-Stokes **acausal, unstable** **Hiscock,Ann.Phys151,466**
- Israel-Stewart Hydrodynamics: **causal, stable** **Israel, Stewart Ann.Phys.118,341(1979)**

$$T^{\lambda\mu} = \epsilon u^{\lambda} u^{\mu} + P\triangle^{\lambda\mu} + q^{\lambda} u^{\mu} + q^{\mu} u^{\lambda} + \tau^{\lambda\mu} \ , \ N^{\mu} = n u^{\mu} + n^{\mu}$$

Conservation equations: $\partial_\mu T^{\mu\lambda} = 0, \quad \partial_\mu N^{\mu} = 0$

$$\begin{aligned} \Pi &= -\zeta[\partial_\mu u^\mu + \beta_0 D\Pi - \alpha_0 \partial_\mu q^\mu] \\ \pi^{\lambda\mu} &= -2\eta[\Delta^{\lambda\mu\alpha\beta}\partial_\alpha u_\beta + \beta_2 D\pi_{\alpha\beta} - \alpha_1 \partial_\alpha q_\beta] \\ q^\lambda &= \chi T \Delta^{\lambda\mu}[-\frac{1}{T}\partial_\mu T - Du_\mu - \beta_1 D q_\mu + \alpha_0 \partial_\mu \Pi + \alpha_1 \partial_\nu \pi^\nu_\mu] \end{aligned}$$

Relativistic magneto-hydrodynamics

Non-central collisions $\Rightarrow$ strong magnetic field, $eB \approx 10^{18}$ Gauss! **Skokov,et.al. IJMPA 24,5925**
For very large σ, the electric field will approach zero.
Constant magnetic field $\Rightarrow$ modify energy-momentum tensor: **Gedalin,PRE 51,4901(1995)**

$$T^{\mu\nu}_{em} = \frac{B^2}{2}\left(u^\mu u^\nu - \Delta^{\mu\nu} - 2b^\mu b^\nu\right), \quad B^\mu B_\mu = -B^2, \quad b^\mu = \frac{B^\mu}{B}$$

For ideal fluid, the total EMT:

$$T^{\mu\nu}_{em\ (0)} = \left(\epsilon + \frac{B^2}{2}\right) u^\mu u^\nu - \left(P + \frac{B^2}{2}\right) \Delta^{\mu\nu} - B^2 b^\mu b^\nu$$

In the presence of polarization (or non-zero magnetization):

$$T^{\mu\nu}_{em\ (0)} = (\epsilon + P - MB)u^\mu u^\nu - (P - MB + \frac{1}{2}B^2)g^{\mu\nu} + (MB - B^2)b^\mu b^\nu$$

Total EMT:

$$T^{\mu\nu}_{tot} = T^{\mu\nu}_{em\ (0)} - \Pi\Delta^{\mu\nu} + q^\mu u^\nu + q^\nu u^\mu + \pi^{\mu\nu}$$

Modified equations:

$$\partial_\mu T^{\mu\nu}_{tot} = 0 \ , \ \partial_\mu N^\mu = 0$$

Linearised equations

$$
\begin{aligned}
0 &= \frac{\partial \delta n}{\partial t} + n_0 \vec{\nabla}.\delta\vec{v}\,, \\
0 &= n_0 \frac{\partial \delta s}{\partial t} + \frac{1}{T_0}\vec{\nabla}.\delta\vec{q} - \frac{1}{n_0\, T_0}(B^2 - M\,B)\frac{\partial \delta n}{\partial t}\,, \\
0 &= (h_0 + B^2 - M\,B)\frac{\partial \delta v}{\partial t} + \nabla(\delta P + \delta\Pi) + \frac{\partial \delta q}{\partial t} + \vec{\nabla}.\delta\vec{\pi}\,, \\
0 &= \delta\Pi + \zeta\left[\vec{\nabla}.\delta\vec{v} + \beta_0 \frac{\partial \delta\Pi}{\partial t} - \alpha_0 \vec{\nabla}.\delta\vec{q}\right], \\
0 &= \delta\pi^{ij} - \eta\left[\partial^i\delta v^j + \partial^j\delta v^i - \frac{2}{3}g^{ij}\vec{\nabla}.\delta\vec{v} - 2\beta_2\frac{\partial \delta\pi^{ij}}{\partial t} - \alpha_1(\partial^i\delta q^j + \partial^j\delta q^i - \frac{2}{3}g^{ij}\vec{\nabla}.\delta\vec{q})\right], \\
0 &= \delta q - \kappa T_0\left[-\frac{\nabla\delta T}{T_0} - \frac{\partial \delta v}{\partial t} - \beta_1\frac{\partial \delta q}{\partial t} + \alpha_0\nabla\delta\Pi + \alpha_1\vec{\nabla}.\delta\vec{\pi}\right].
\end{aligned}
$$

Correlation between Q_i and Q_j is

$$\left\langle \delta Q_i(\vec{k},\omega)\delta Q_j(\vec{k},0)\right\rangle$$

The dynamic density factor:

$$\mathcal{S}_{nn}(\vec{k},\omega) = \frac{\left\langle \delta n(\vec{k},\omega)\delta n(\vec{k},0)\right\rangle}{\left\langle \delta n(\vec{k},0)\delta n(\vec{k},0)\right\rangle}$$

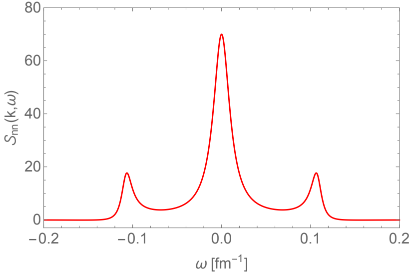


Figure: Away from CEP

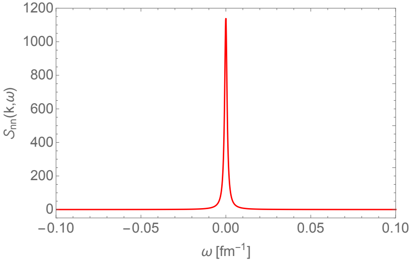


Figure: Near CEP

Dynamic density fluctuation: magnetic field case

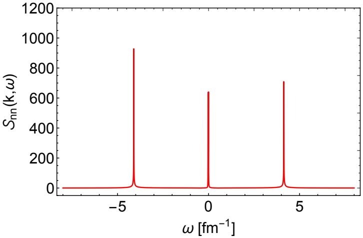


Figure: $eB = m_\pi^2$

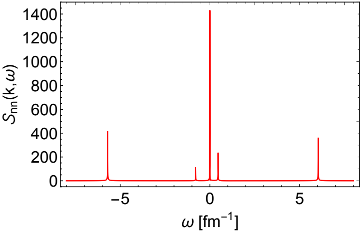
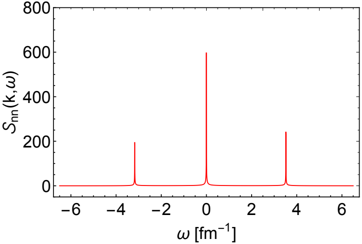


Figure: $eB = 3\, m_\pi^2$



Dynamic density fluctuation: CEP and magnetic field

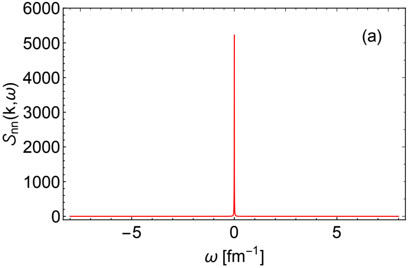


Figure: Near CEP with $B = m_\pi^2 < B_{th}$

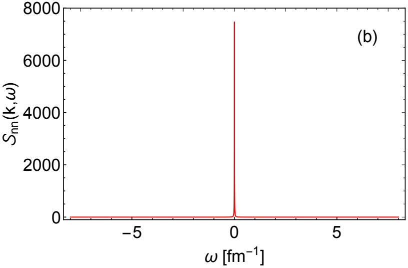


Figure: Near CEP with $B = 3\, m_\pi^2 \geq B_{th}$.

Summary, Conclusions and Outlook

- Without B, the $\mathcal{S}_{nn}(\vec{k}, \omega)$ admits a Rayleigh peak and two Brillouin peaks.
- In B, two extra peaks appearing closer to the R-peak, identified as the B-peaks due to the adiabatic transverse pressure fluctuation.
- The extra B-peaks (near side) exclusively appear beyond a threshold value of the magnetic field.
- The away side and the near side B-peaks are caused by the pressure fluctuation in longitudinal and transverse direction respectively due to pressure difference $P_\perp = P - MB$ and longitudinal, $P_L = P$ components.
- This inherent pressure anisotropy will subsequently influence the flow harmonics.
- The $\mathcal{S}_{nn}(\vec{k}, \omega)$ for Navier-Stokes reveals near side B-peaks are absent but away side B peaks are present although their position and magnitude differs. It suggests that near side B peaks appear due to coupling between B and the coupling and relaxation coefficients of 2nd order theory.

Thank You