# QCD matter under rotation and magnetic field

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## Introduction and motivation

In this thesis, I explore the confluence of rotation and magnetic field in hot and dense (baryon-rich) QCD matter and the consequences this can have in present-day collider physics and cosmology. QCD matter under extreme conditions prevailed in the microseconds-old universe and is created in ultra-relativistic heavy-ion collisions (HIC). In a generic non-central high-energy nucleus-nucleus collision the overlap region transforms into a fireball of quark-gluon plasma (QGP) that sustains strong vorticity due to the finite impact parameter arising from the geometry of the collision and the resultant deposition of angular momentum. This QGP droplet may also be embedded in very powerful magnetic fields sourced initially by the spectator protons of the colliding nuclei and likely sustained or reinforced due to the conductivity and swirling charges of the QGP medium. This motivates the extension of the conventional $T$–$\mu_b$ planar phase diagram for QCD matter by extending it to a multi-dimensional domain spanned by temperature $T$, baryon chemical potential $\mu_b$, external magnetic field $B$ and angular velocity $\omega$. Not only is this relevant for the HIC experiments at lab facilities such as LHC, RHIC and FAIR, NICA, etc. (upcoming), but the vorticity and magnetic fields may also impact the cosmic fluid filling the early universe at the very early quark-hadron epochs. This is studied in preliminary form in the final part of the thesis.

This thesis also includes a rotating HRG model calculation of conserved charge susceptibilities and correlations that relate to experimentally accessible fluctuation properties extracted from HIC data. This should serve to generate a theoretical baseline from which experimental deviations might be measured if the HIC fireball system passes through or near the QCD critical point. Freeze-out data from particle yields and ratios measurements are usually interpreted, using the statistical thermal model, to demarcate a so-called freeze-out curve on the $T$–$\mu_b$ planar phase diagram and thus collider experiments are already used as thermometer and baryometer to probe a part of the phase diagram that is at or near the QCD phase transitions for small $\mu_b$.

Finally I discuss the possible presence of gyromagnetic conditions such as vorticity from fluid turbulence and seed cosmological magnetic fields in the primordial plasma would probably cause modifications to the quark-hadron transition and the cosmic equation of state in statistically distributed patches of the universe. This could be relevant for the formation of primordial black holes and gravitational waves during the QCD epoch. It is interesting to follow this line of research to study the implications of our findings for the hadronizing baby universe and possible observable artefacts of the QCD confinement-deconfinement transition.

## Theoretical model and formalism

We consider HRG rigidly rotating with angular velocity $\overrightarrow{\omega}$ and embedded in a uniform and parallel magnetic field $\overrightarrow{B}$. In such a system composed of both charged as well as neutral particles the former couple with the background magnetic field while the latter do not.

The introduction of a rigid, global rotation necessitates us to confine the system in the transverse direction and a causality bound appears in conjunction with the magnetic limit, $1/\sqrt{|QB|} \ll R \leqslant 1/\omega$.

Obeying the above constraints, free energy density [1, 3] for all charged baryons and mesons under simultaneous and parallel $\overrightarrow{\omega}$ and $\overrightarrow{B}$ is given by the formula $f_{i,c}^{b/m} = \mp\frac{T}{\pi R^2}\int\frac{dp_z}{2\pi}\sum_{n=0}^{\infty}\sum_{l=-n}^{N-n} \times\sum_{s_z=-s_i}^{s_i}\ln(1 \pm e^{-(\varepsilon_{i,c}-q_i\omega(l+s_z)-\mu_i)/T})$ where the Landau levels are $\varepsilon_{i,c} = \sqrt{p_z^2+m_i^2+|Q_iB|(2n-2s_z+1)}$. Here $Q_i$, $q_i = Q_i/|Q_i| = sign(Q_i)$, $s_i$ and $m_i$ are the charge, sign of charge, spin and mass of the $i^{th}$ hadron and the subscripts $c$ refers to charged particles. The upper (lower) signs correspond to the baryons (mesons).

In the same situation the free energy density for neutral particles (or all particles when $eB = 0$) assumes the form that is valid for just uniform rotation [2, 4]. The energy dispersion is accordingly different $\varepsilon_{i,n} = \sqrt{p_r^2+p_z^2+m_i^2}$.

## Results, discussion and outlook

The squared speed of sound is defined as $c_s^2 = \frac{\partial p}{\partial \epsilon}|_{(\mu_B,\omega,eB)} = s/C_V$. The dip in $c_s^2$ provides an estimate for the deconfinement or pseudo-critical temperature $T_C$ because the specific heat blows up. The Hagedorn limiting temperature argument and the so-called universal freeze-out criteria from scaled entropy density provide an independent estimate as well. See Fig. 1 from [1].

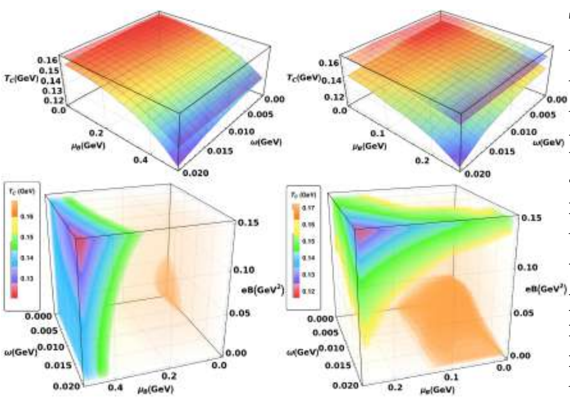


FIG. 1: Top: [3-D plots] Deconfinement transition surfaces showing $T_C(\mu_b,\ \omega)$ for $eB = 0$ (upper surface) and $eB = 0.15$ GeV$^2$ (lower surface); Bottom: [4-D plots] Fully augmented phase space showing $T_C(\mu_b,\ \omega,\ eB)$; Left plots obtained from $s/T^3 = 5.5$; Right plots obtained from the minima of $c_s^2$.

The simultaneous turning on of both the $eB$ and $\omega$ appears to significantly amplify the drop in $T_C$, by close to 40 to 50 MeV. The framework of statistical hadronization was implemented to achieve a consistent and robust prediction for $T_C(\mu_b, \omega, eB)$. An augmented phase diagram was thus constructed. Strategies to apply this knowledge to trace out freeze-out curves in the higher dimensional phase space and probe HIC fireballs as 'anemometer' and 'magnetometer' were explained.

The rotating HRG model was then used to compute conserved charge susceptibilities [2]. These quantities provide a baseline prediction for HIC. The results indicate that the individual impact of either the vorticity or the magnetic field alone may be experimentally negligible for the practically feasible magnitudes studied but the combination of gyromagnetic effects is likely to be much stronger and potentially detectable in experiments. In this sense the non-trivial net contribution of vorticity, magnetic field and baryon chemical potential gives rise to a situation where the whole is greater than the sum of its parts.

I also draw some cosmological implications. The QCD phase transition has been argued to have a uniquely important impact on both the formation of primordial black holes and the primordial gravitational wave background. Primordial vorticity and magnetic fields have also been hypothesized. It would be exciting to understand the gyromagnetic effects on these important exotic phenomena of the early universe. The primordial cosmic fluid comprising the quarks, leptons and gauge bosons may present us with a system that is even more non-trivial as one adds into the mix vorticity and magnetic fields. Open problems and questions abound. Definitive answers are yet to come.

## References


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