An Augmented QCD Phase Portrait: Mapping the Quark-Hadron Deconfinement Transition for Hot, Dense, Rotating Matter under Magnetic Field

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Introduction

The beginning of this century marks the first experimental production and detection of quark-gluon plasma, an extreme phase of QCD matter that is believed to have filled the early universe in its first microseconds after the Big Bang. The same substance comes into existence in ultra-relativistic heavy ion collisions, artificially actualized at facilities like RHIC and LHC, and in the future, NICA and FAIR. Apart from very high temperatures and densities, the femtoscopic system may also sustain significant rotation and a strong magnetic field background within the droplet produced in a typical off-central heavy ion collision. Thus a comprehensive treatment should include variables like angular velocity and magnetic field as additional parameters characterizing hot and dense QCD matter. The present work aims to advance in this direction focusing on the rich phase structure that manifests in this multi-dimensional parameter space.

Statistical hadronization model with rotation and magnetic field

Our sought modifications to the standard Hadron Resonace Gas (HRG) model adapted to the scenario incorporating a uniform external magnetic field as well as a parallel global rotation have been deduced and the entropy density for charged baryons and mesons is then given by

$$s_{i,c}^{B/M} = \frac{1}{\pi R^2}\int \frac{dp_z}{2\pi} \sum_{n=0}^{\infty}\sum_{l=-n}^{N-n}\sum_{s_z=-s}^{s} \frac{E_{i,c}}{T(e^{E_{i,c}/T}\pm 1)} \pm ln(1\pm e^{-\frac{E_{i,c}}{T}})$$

while the corresponding entropy density of neutral hadrons of spin S_i is given by

$$s_{i,n}^{B/M} = \frac{1}{8\pi^2}\int dp_r^2 \int dp_z \sum_{l=-\infty}^{\infty}\sum_{\nu=l}^{l+2S_i} J_\nu^2(p_r r)[\frac{E_{i,n}}{T(e^{E_{i,n}/T}\pm 1)} \pm ln(1\pm e^{-\frac{E_{i,n}}{T}})]$$

where the dispersion relations provide the required energy spectra given by the rotation-modified (Landau, for non-zero magnetic fields) levels:

$$E_{i,c} = \sqrt{p_z^2 + m_i^2 + |q_i B_z|(2n - 2s_z + 1)} + \frac{q_i}{|q_i|}\omega(l + s_z) - \mu_i,$$

$$E_{i,n} = \sqrt{k_r^2 + k_z^2 + m_i^2} - (l + S_i)\omega - \mu_i.$$

The above forms are extracted from field theoretical calculations as reported in [1], [2], [3] and we have combined the results as suitable for our augmented HRG model.

We neglect anomalous magnetic moments and zero-point quantum fluctuations without significant consequences.

Results and Discussion

The working criterion we use to localize the deconfinement zone in the phase diagram is a

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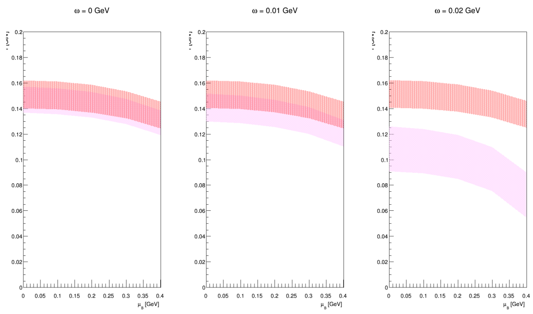

FIG. 1: Phase diagram showing T_C, deconfinement temperature bands as defined in the text, upper red band for $eB = 0$ and lower pink band for $eB = 0.25GeV^2$

reflection of both the theoretical argument for a rapid rise of thermodynamic quantities like the entropy density [4] and the experimentally supported universal freezeout condition that serves as a close proxy specially at small to medium values of the baryon chemical potential. The obtained bands as depicted in Fig.1 are bounded below by the locus of all points for which $s/T^3 = 3.3$ and above by $s/T^3 = 5$. We observe a lowering of the deconfinement crossover zone due to finite magnetic field for each of the three distinct values of ω. The trend is clear across the span of these external parameters: the dip in T_C is amplified substantially when both the magnetic field and the angular velocity take on high values and at the baryon chemical potential of around 0.4 GeV the drop reaches a nadir of around 0.09 GeV. This is remarkable since at zero magnetic field the effect of rotation with ω rising from 0 to 0.02 GeV is extremely slight within the range considered here. However the simultaneous imposition of an external magnetic field over and above the rotation leads to nearly the same drop in the deconfinement temperature at $\omega \sim 0.02$ GeV as that estimated at extremely large values of $\omega \sim 0.3$ GeV when there is no magnetic field present at all [2]. This would suggest that although the latter (pure, $eB = 0$) rapid rotation scenario might not be experimentally feasible in HIC, a similar effective downward shift of the deconfinement region may nevertheless still apply if the realistic situation sustains a strong enough magnetic field accompanying the more modest but also more plausible ω values as in the case of the former. In Fig.2 we depict the comprehensive portrait that may be called an augmented QCD phase diagram. The drop of the deconfinement temperature as one moves away from the origin to the diagonally opposite corners is colour-coded and visualized in 3-D (using Mathematica) after taking the average value between the boundaries of the deconfinement bands from Fig.1 that were meant to represent the approximate location of the continuous but rapid quark-hadron crossover region.

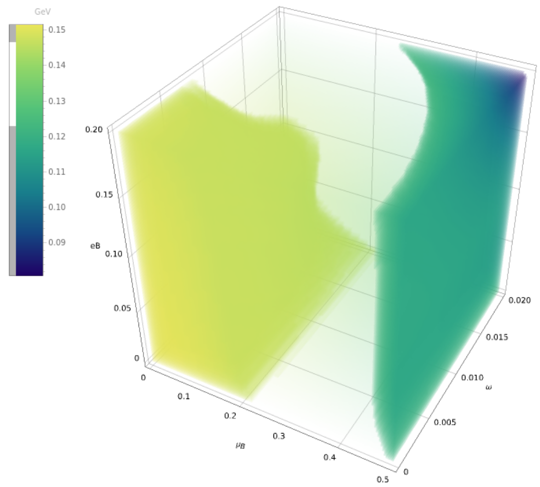

FIG. 2: Augmented phase diagram showing T_C, the deconfinement temperature (color coded) as a field or heatmap in the space of the three external parameters

References

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