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A rotation/magnetism analogy for the quark–gluon plasma

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Abstract

In peripheral heavy ion collisions, the Quark–Gluon Plasma that may be formed often has a large angular momentum per unit energy. This angular momentum may take the form of (local) rotation. In many physical systems, rotation can have effects analogous to those produced by a magnetic field; thus, there is a risk that the effects of local rotation in the QGP might be mistaken for those of the large genuine magnetic fields which are also known to arise in these systems. Here we use the gauge-gravity duality to investigate this, and we find indeed that, with realistic parameter values, local rotation has effects on the QGP (at high values of the baryonic chemical potential) which are not only of the same kind as those produced by magnetic fields, but which can in fact be substantially larger. Furthermore, the combined effect of rotation and magnetism is to change the shape of the main quark matter phase transition line in an interesting way, reducing the magnitude of its curvature; again, local rotation contributes to this phenomenon at least as strongly as magnetism.

1. Rotation/magnetism and the quark–gluon plasma

It has often been observed that, in many physical systems, local rotation (or vorticity) plays a role analogous to that of a magnetic field: to take but one of many examples, this “rotation/magnetism analogy” is important in the study of the quantum Hall effect [1].

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As is now well known [2–5], huge magnetic fields can be present in the quark–gluon plasma (QGP) produced by peripheral heavy-ion collisions [6–10], and these can give rise to a number of remarkable effects. In particular, various computations suggest that *strong magnetic fields tend to lower the temperature* at which various phenomena are otherwise expected to occur. For example, lattice computations [11] indicate the existence of a very remarkable "inverse magnetic catalysis" effect, in which the presence of a strong magnetic field lowers the temperature of the chiral transition (and, presumably—but see [12]—also the pseudo-critical temperature): see [13, 14].

On the other hand, it has recently become clear that local rotation might *also* be important in these systems, and this might manifest itself in the form of such phenomena as the "chiral vortical effect": see [15] for a review. Now the large magnetic fields in the QGP mentioned above are in fact closely associated with very large angular momentum densities [16–24]; see [25,26] for recent in-depth analyses. The angular momentum arises in the same way as the magnetic field, and the corresponding vectors are (to a good approximation) parallel [26] (that is, perpendicular to the reaction plane).

This prompts the question: could the rotation/magnetism analogy be valid for the QGP? Might, for example, local rotation directly affect temperatures, just as magnetism apparently does? If this is so, then *ignoring the effects of local rotation could lead to serious errors* in estimating the effects of the magnetic field on the behaviour of the plasma.

For example, suppose that one has a calculation, for example lattice-based, of the likely location of the quark matter critical endpoint (see for example [27–32]) in the quark matter phase diagram. For the QGP produced in peripheral collisions, it is thought that the corresponding magnetic field lowers the temperature and the baryonic chemical potential, μ_B, at that point (with fixed values of the other parameters), relative to the values expected in the absence of a magnetic field—that is, in a central collision. (See [31,32] and references therein for recent discussions of this.) But if there is a rotation/magnetism analogy, the local rotation generated by a peripheral collision could have an independent effect which might significantly strengthen (*or even weaken*) this important phenomenon. (Note that rotation itself may play a useful role [33] in locating the critical endpoint, underlining the importance of understanding its effects.)

To take another, related example: the quark matter critical endpoint, if it exists, is associated with a *phase transition line*, and investigating this line (see Fig. 1) is a prime objective of the beam energy scan experiments such as RHIC, GSI-FAIR and NICA, among others [34–39]. The line[1] bends down into the region of lower temperature and higher μ_B, that is, into the region of higher net particle density. From a theoretical point of view, one hopes ultimately to compute not just the location of the critical endpoint but also the *curvature* of this line. Now, strong magnetic fields might affect not just the location but also the shape of the phase line. In other words, there could be a non-trivial interaction between increased net particle density and magnetism. However, if there is indeed a local rotation/magnetism analogy, there will be a corresponding interaction between the rotational angular momentum and the net particle density.[2] Again, if this is indeed so, then ignoring local rotation could lead to erroneous predictions regarding this entire region of the phase diagram, for quark matter produced in peripheral collisions.

In short, if a local rotation/magnetism analogy exists, it must be taken into account in theoretical studies related to the high-μ_B experiments currently under way or projected: it is quite

[1] There may of course be other phase transition lines, as shown in Fig. 1, but we will not consider them here.

[2] This could be related to the recent suggestion of a possible "rotation/density" analogy [40].