Chapter 1
Strongly Interacting Matter in Magnetic Fields: A Guide to This Volume

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1.1 Introduction

Electromagnetic probes have proved to be extremely important for understanding strongly interacting matter—for example, the discovery of Bjorken scaling in deep-inelastic scattering (DIS) has allowed to establish quarks as the constituents of the proton, and has opened the path towards Quantum Chromodynamics (QCD) and the discovery of asymptotic freedom. The development of QCD has quickly led to the realization that the dynamics of extended field configurations is crucial for understanding non-perturbative phenomena, including spontaneous breaking of chiral symmetry and confinement that define the properties of our world. The challenge

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of understanding the collective dynamics in QCD calls for the study of response of strongly interacting matter to intense coherent electromagnetic fields. Such fields induce a host of interesting phenomena in QCD matter, and understanding them brings us closer to the ultimate goal of understanding QCD. Some of these phenomena (e.g. Magnetic Catalysis of chiral symmetry breaking [1],[1] and Inverse Magnetic Catalysis [2]) exist in a static equilibrium ground state, and affect the phase diagram of QCD matter in a magnetic field. About one half of this volume addresses such equilibrium phenomena, mostly in the context of QCD [3–6], and we give an overview over this part in Sect. 1.3. The other half addresses mainly anomaly-induced transport phenomena and is summarized in Sect. 1.2. These phenomena include the Chiral Magnetic and Chiral Vortical effects (reviewed in [7–14]) which require the existence of a chirality imbalance induced by the topological transitions in matter or the presence of vorticity.

Experimental access to the study of QCD plasma in very intense magnetic fields with magnitude $eB \sim m_\pi^2$ (or $\sim 10^{18}$ G) is provided by collisions of relativistic heavy ions at nonzero impact parameter. They create a magnetic field which is (on average) aligned perpendicular to the reaction plane. Somewhat weaker magnetic fields $\sim 10^{15}$ G exist on the surface of magnetars. They are possibly much larger in the interior of the star, where they may affect the properties of cold dense quark matter as reviewed in [15].

1.2 Chiral Magnetic Effect and Anomaly-Induced Transport

The Chiral Magnetic Effect (CME) is the phenomenon of electric charge separation along an external magnetic field that is induced by a chirality imbalance. In QCD matter, the source of chirality imbalance are the transitions between the topologically distinct states—the index theorem and the axial anomaly relate the resulting change in topological number to the chirality of fermion zero modes. The CME is thus a topological effect: it results from an interplay of topology of the zero mode of a charged fermion in an external Abelian magnetic field, and of the non-Abelian

[1] In this introduction we refer only to the contributions in the volume, and provide the corresponding arXiv references when available; many more references can be found in these individual contributions. If you would like to cite one of the contributions on a specific topic, please refer to them directly (instead of citing the entire volume), e.g.

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If you would like to refer to a broad review representing the collective work of the authors, you can refer to the entire volume as

Strongly Interacting Matter in Magnetic Fields, ed. by D. Kharzeev, K. Landsteiner, A. Schmitt, H.-U. Yee. Lect. Notes Phys. **871**, 1 (2013). arXiv:1211.6245 topology of the gluon field configurations. Because of this, the CME current is topologically protected (not sensitive to local perturbations) and non-dissipative.

At weak coupling, the quasi-particle picture is appropriate, and allows to understand the phenomenon in a very simple and intuitive way, as we now explain. An external magnetic field aligns the spins of the positive and negative fermions at the lowest Landau level in opposite directions (only the lowest Landau level matters for the CME, as the contributions of all excited levels cancel out—see [8] for details). Therefore, the electric charge, chirality and momentum of the fermion are correlated—for example, a positively charged right-handed fermion propagates along the direction of magnetic field, and a negative right-handed fermion propagates in the opposite direction. This creates an electric current, which however is usually compensated by the left-handed fermions that propagate in the opposite direction.

Let us however imagine that the fermions, apart from the Abelian $U(1)$ charge, are also charged under a non-Abelian group—for us, the most important example is provided by quarks, which carry both electric and color charges. The non-Abelian gauge theories possess a rich spectrum of topological solutions, and the axial anomaly links the topology of gauge fields to the chirality of fermions. Therefore, in a topologically non-trivial non-Abelian background, the numbers of left- and right-handed fermions will in general differ—because of this, their contributions to the electric current will no longer cancel. As a result, an external magnetic field will induce an electric current along its direction—an effect that is absent in Maxwell electrodynamics.

The absence of CME in conventional electrodynamics follows already from symmetry considerations—the magnetic field is a (parity-even) pseudo-vector, and the electric current is a (parity-odd) vector. Therefore, CME signals the violation of parity—indeed, as we discussed above, its presence requires the asymmetry between the left and right fermions.

It is well known that there are no perturbative corrections to the axial anomaly, so the CME expressions for the electric current and electric dipole moment are exact (at the operator level). Moreover, because the origin of CME is topological, it appears that the CME current at zero frequency remains the same even in the limit of strong coupling, that is accessible theoretically through the holographic correspondence—see [12, 16]. A phenomenon similar to CME arises when instead of a magnetic field there is an angular momentum (vorticity) present—this is the so-called Chiral Vortical Effect (CVE). The CVE is also caused by the quantum anomaly, but by the gravitational one [16]. In a holographic setup, this is described through a mixed gauge-gravitational Chern-Simons term.

In the absence of external charge, magnetic field in the framework of AdS/CFT correspondence induces an RG flow to an infrared $AdS_2 \times \mathbb{R}^2$ geometry [17]. This theory is the holographic description of the dimensionally reduced 2d conformal field theory describing the strongly coupled fermions on lowest Landau levels. In general, the dimensional reduction proves very beneficial to treating the CME and related phenomena—see [9] for review. In particular, in the limit of strong magnetic field one can construct an explicit solution describing the QCD instanton in magnetic background [9]—since the instanton induces an asymmetry between left- and right-handed fermions, this solution has been found to possess electric dipole moment, in accord with CME expectations. It is of great interest to investigate the dynamics of CME by considering the decay of topological objects in magnetic backgrounds—see [11] for a review.

The persistence of CME at strong coupling and small frequencies makes the hydrodynamical description of the effect possible, as reviewed in [10]. The quantum anomalies in general have been found to modify hydrodynamics in a significant way. This has a profound importance for transport, as the anomalies make it possible to transport currents without dissipation—this follows from the P-odd and T-even nature of the corresponding transport coefficients. The existence of CME and CVE in hydrodynamics is interesting also for the following reason—usually, in the framework of quantum field theory one thinks about quantum anomalies as of UV phenomena arising from the regularization of loop diagrams. However, we now see that the anomalies also modify the large distance, low frequency, response of relativistic fluids. This is because the anomalies link the chirality of fermion zero modes to the global topology of gauge fields.

The CME can be studied numerically from first principles on Euclidean spacetime lattices, see [13, 14] for reviews. On the lattice, one can measure the fluctuations of electric charge asymmetry induced by the dynamical topological fluctuations in QCD vacuum and plasma in a magnetic background [13]. Alternatively, one can introduce the chiral chemical potential, and measure the CME current explicitly, testing the relation between the current, magnetic field, and the chiral chemical potential—this approach is reviewed in [14]. Note that the chiral chemical potential (unlike the baryon one) does not lead to the determinant "sign problem" and thus does not prevent one from performing lattice QCD simulations.

From the experimental viewpoint, CME makes it possible (at least in principle) to observe directly the fluctuations of topological charge in heavy ion collisions—indeed, these fluctuations in magnetic field induce the asymmetry of electric charge distributions with respect to the reaction plane. Such a study has to carefully separate the CME effects from all possible backgrounds, as reviewed in [18]. One of the CME tests discussed in [18] is the collision of two Uranium ions where the deformation of the Uranium nucleus allows to separate the CME from the backgrounds, as we now explain.

The main idea behind the UU measurement is the following: all possible backgrounds to CME should, on symmetry grounds, be proportional to the elliptic flow of hadrons. The elliptic flow stems from the ellipticity of the initial fireball produced in heavy ion collisions, and so it exists only in non-central collisions, just like the magnetic field that drives the CME. This complicates the separation of CME from possible background effects [18]. However, since the Uranium nucleus is strongly deformed, even most central UU collisions (where there is no magnetic field) produce a deformed fireball and hence a sizable elliptical flow of hadrons. Thus, if the charge separation persists in most central UU collisions, the observed effect is most likely due to background, and vice versa. Very recently, the RHIC result on UU collisions has been presented at the Quark Matter 2012 Conference by the STAR Collaboration. The presented result indicates that the signal vanishes in the absence of a magnetic field, providing a strong support for the CME interpretation.

1.3 Phase Structure in a Magnetic Field

Equilibrium properties of matter can be changed significantly by the presence of a background magnetic field. This is true even for non-interacting matter. Consider for example a Fermi sphere of charged, non-interacting fermions, say at zero temperature, that is subject to a static and homogeneous magnetic field. Instead of a continuous spectrum with respect to all three momentum directions, the system will develop discrete energy levels with respect to the momentum directions transverse to the magnetic field. Only the longitudinal momentum remains continuous. If the magnetic field is large enough, i.e. of the order of the Fermi momentum squared, the discretization of the energy levels, called Landau levels, will have an important effect on the properties of the system. For instance, upon increasing the magnetic field, the distance between the energy levels increases and as these levels "pass" the given Fermi energy, the observable quantities such as the number density change. Eventually, for sufficiently large magnetic fields, all fermions reside in the lowest Landau level, where only one spin polarization is allowed. The system has become fully polarized.

A more challenging question is how the equilibrium properties of *strongly interacting* matter are affected by a magnetic field. One might for instance ask whether there are still Landau levels or whether this description becomes incorrect. One might also wonder about the phase transitions induced by magnetic field—do we enter genuinely different phases upon increasing a background magnetic field in a given, strongly-interacting, system? If yes, what are the order parameters, what is the order of these phase transitions, and what are the critical magnetic fields? Or, ultimately, what is the phase diagram of a given system with one of the axes corresponding to the magnetic field? A well-studied example from condensed-matter physics is the phase diagram of Helium-3. Due to the nontrivial structure of the order parameter with respect to spin and orbital angular momentum, Helium-3 has more than one superfluid phase, and an externally applied magnetic field can induce phase transitions between different superfluid phases.

1.3.1 Phases of QCD in a Magnetic Field

In these Lecture Notes, the term "strongly interacting matter" mostly refers to the matter governed by QCD, although some chapters address questions from "ordinary" condensed-matter systems [17, 19, 20], see also the discussion about graphene in Sect. 3.3 of Ref. [1]. Usually, "the phase diagram of QCD" is drawn in the plane spanned by the temperature T and the baryon chemical potential μ. But various additional directions, i.e., higher-dimensional versions of the phase diagram, are of interest as well. First, one can imagine to change the parameters of QCD by hand, for example by adding an axis for the quark mass(es) or for the number of colors N_c to the phase diagram. The purpose of such a theoretical manipulation can be to enter a more tractable regime and/or to put the QCD phase structure into a wider context, with the ultimate goal to understand better the phase structure of real-world QCD. Second, there are external parameters of direct phenomenological interest that reflect the characteristics of matter, such as the baryon and isospin chemical potentials that become important in the context of neutron stars. A (uniform) magnetic field is both: it is of phenomenological interest but also a theoretically useful "knob" by which interesting and rich physics can be introduced which may help us to deepen our understanding of strongly interacting systems. (This volume mostly addresses the effects of a magnetic field from ordinary $U(1)$ electromagnetism; the effects of chromomagnetic fields are briefly discussed in [6].)

Phase transitions in QCD can be expected to occur at energy scales comparable to the QCD scale $\Lambda_{\rm QCD} \sim 200$ MeV. As a consequence, we are interested in magnetic field strengths of the order of $B \sim (200\text{ MeV})^2 \simeq 2 \times 10^{18}$ G. As mentioned above, such strong magnetic fields indeed exist in non-central heavy-ion collisions [18] (at least temporarily), and possibly in the interior of compact stars, then called magnetars [15]. These two instances are (together with the early universe) the only systems with which we can reach out "experimentally" also into the μ-T plane of the QCD phase diagram and thus probe the phase structure of QCD. Most notably, we are interested in the nonperturbative phenomena of confinement and chiral symmetry breaking. Both heavy-ion collisions and compact stars are expected to "live" in a region of the phase diagram where the transitions to deconfined and/or chirally restored matter occur and thus it is relevant to discuss the location and the nature of these transitions in magnetized QCD matter.

The various chapters addressing the phase structure of QCD in magnetic fields [1–6, 15, 21] make use of different theoretical tools. At asymptotically large energies, methods from perturbative QCD can be applied, see parts of [1, 15]. For moderate energies, however, first-principle QCD calculations can only be done on the lattice and are restricted to vanishing (vector) chemical potentials [6]. These results from QCD are complemented by model calculations, which may differ (and, judging from the results presented here, *do* differ) in important aspects from actual QCD. Nevertheless, they may be useful to get an idea about some of the physical mechanisms behind the phase structure. The models discussed here are the Nambu-Jona-Lasinio (NJL) model, including different variants with respect to the interaction terms and extensions to incorporate confinement (PNJL) [1–3, 5], the MIT bag model [4], and a quark-meson model [3, 4]. Additionally, we employ the gauge/gravity duality [2, 21] which provides us with a reliable tool for the physics in the strongly coupled limit, albeit for theories that differ more or less—depending on the model at hand—from real QCD.

The holographic calculations presented here make use of two different setups. Firstly, based on the original AdS/CFT correspondence, a background geometry given by D3-branes is discussed, where D7-branes, corresponding to fundamental (as opposed to adjoint) degrees of freedom, are introduced as probe branes [21]. And secondly, we use the Sakai-Sugimoto model, where "chiral" D8-branes are embedded into a background of D4-branes, which includes a compact extra dimension that serves to break supersymmetry completely [2, 21].

The picture that emerges from these studies is, concerning QCD, a preliminary one at best, and many questions are still open—and, in fact, are raised by these studies. Nevertheless, let us try to summarize the current picture. Before one addresses the question of how a magnetic field affects a hot and dense medium, one might ask whether and how the vacuum changes in a magnetic field. A very important part of the answer to this question—since it is of very general nature and thus not only relevant for QCD—is "magnetic catalysis", which is reviewed in great detail in Ref. [1]. This effect has been confirmed in numerous model calculations, as well as in QED-like theories and—at least at zero temperature—in QCD lattice calculations. In simple words, it says that a magnetic field favors chiral symmetry breaking. A more precise version, for instance employing the mean-field approximation of the NJL model, is as follows. For $\mu = T = 0$ and vanishing magnetic field, there is a critical coupling strength above which a chiral condensate forms, i.e., there is a phase transition from the chirally restored to the chirally broken phase as one increases the (attractive) coupling of the four-fermion interaction. In the presence of a background magnetic field, however, there is a chiral condensate for *arbitrarily small* coupling. Thus, the magnetic field has a profound qualitative effect on chiral symmetry breaking. One way to understand the physics behind magnetic catalysis is the analogy to BCS Cooper pairing. In both cases, the dynamics of the system becomes effectively $1+1$ dimensional at weak coupling, in the case of Cooper pairing because of the presence of the Fermi surface, in the case of chiral condensation because of the magnetic field. As a consequence, an infrared divergence occurs which is cured by a nonvanishing mass gap that shows precisely the same exponential, nonperturbative behavior in both cases.

Another possible effect of an ultra-strong magnetic field on the QCD vacuum is the condensation of ρ mesons [5]. In a weak-coupling picture, this condensation is suggested from the Landau-level structure of spin-1 bosons. Since ρ mesons are electrically charged, their condensation implies electric superconductivity. The details of this interesting idea are reviewed in Ref. [5].

How does magnetic catalysis manifest itself in the QCD phase diagram? A straightforward, but, as we now know, too naive, expectation is that the phase space region of the chirally broken phase should get larger with the magnetic field. The current picture is more complicated and can be summarized as follows.

- *Hot medium*, $\mu = 0$. Lattice studies with physical quark masses suggest that the (pseudo-)critical temperature T_c for the chiral crossover *decreases* [6], whereas the results of all above mentioned model calculations (as well as lattice results for unphysically large quark masses [6]) show a monotonically *increasing* T_c. While it is clear that none of the models can capture all features of QCD, the physical mechanism behind the lattice result is still under discussion, see for instance Sec. 3.2 in Ref. [1]. There are also slight differences in the behavior of T_c in the different models: for instance, while T_c saturates at a finite value for asymptotically large magnetic fields in the holographic Sakai-Sugimoto model [2, 21], no such saturation can be seen in the NJL-like models [2, 3].
- *Dense medium*, $T = 0$. In this case, there are currently no lattice results due to the sign problem. In the model calculations we see an interesting nontrivial effect,

termed "inverse magnetic catalysis" [2]. At strong coupling, the critical chemical potential can *decrease* with the magnetic field, which is in apparent conflict with magnetic catalysis. In contrast to the $\mu = 0$ result on the lattice, a physical explanation for this behavior is known. It can be traced back to the cost in free energy that has to be paid for chiral condensation at nonzero μ. Crucially, this cost is not independent of B and competes with the gain from condensation which, due to magnetic catalysis, increases with B.

We know that the QCD phase structure at large densities can be very rich due to various color-superconducting phases. Model calculations at nonzero B including two-flavor color superconductivity seem to confirm the effect of inverse magnetic catalysis. From first principles we know that at asymptotically large densities, the ground state of three-flavor quark matter is the color-flavor locked (CFL) phase. The CFL order parameter is invariant under a certain combination of generators of the color and electromagnetic gauge groups, resulting in a massless gauge boson (which is predominantly the original photon, with a small admixture from one of the gluons). As a consequence, the CFL phase is a color superconductor (all gluons become massive), but not an electromagnetic superconductor. An ordinary magnetic field can thus penetrate this phase. Depending on the strength of the magnetic field, certain variants of the CFL phase become favored. These phases as well as their possible astrophysical relevance are discussed in [15].

For the deconfinement crossover in a magnetic field, the results on the lattice are similar to the chiral crossover [6]. Again, with physical quark masses the temperature for the crossover seems to decrease. This behavior is not reproduced by the PNJL model, where confinement is mimicked by including the expectation value of the Polyakov loop by hand. Depending on the details of the interactions within the model, the deconfinement and chiral phase transitions do or do not split in a magnetic field, but in any case the critical temperature of both transitions seems to increase monotonically with the magnetic field [3]. This is also the case in a quark-meson model [4]. Within the MIT bag model, however, with the confined phase simply being modelled by a noninteracting pion gas, the deconfinement transition decreases with the magnetic field, in qualitative agreement with the lattice results [4]. These studies show that the mechanism behind the behavior of the deconfinement transition—just like for the chiral transition—in a magnetic field is not yet understood, and further analyses that clarify this picture are necessary.

1.3.2 Condensed Matter Systems in a Magnetic Field via AdS/CFT

The gauge-gravity or AdS/CFT correspondence plays an important role in the above mentioned studies of the phase structure of QCD. This is quite natural since in general the gauge-gravity correspondence relates a non-Abelian gauge theory at strong coupling and large N to a weakly coupled (super)gravity background with asymptotic AdS boundary conditions. The idea that strongly coupled phases of quantum field theories can be described by a gravity dual is however more general than that. In particular it has been applied to “tabletop“ laboratory condensed matter systems that inherently involve strongly correlated electrons and are conjectured to be governed by an underlying quantum critical phase such as high Tc superconductors or the so called strange metals. Many condensed-matter systems are supposed to undergo a quantum phase transition at zero temperature upon varying a parameter such as the doping in a high-T_c superconductor, the pressure or the applied magnetic field. At the phase transition the system is at a quantum critical point which often turns out to be in a strongly coupled regime with an emergent Lorentz (or more generally Lifschytz) invariance. In the vicinity of the quantum critical point, e.g. at finite temperature the dynamics of the system is still governed by the degrees of freedom relevant at the critical point. One might hope that such strongly coupled quantum critical points can be described by a gravity dual just as QCD in its strongly coupled regime might be described by e.g. the Sakai-Sugimoto model. At the very least one can expect that the gauge-gravity duality helps to develop interesting toy models of quantum critical points that can lead to a better understanding of qualitative or even quantitative behavior of condensed matter systems whose theoretical description is otherwise rather elusive due to their strongly coupled nature.

A central role is played by charged asymptotically AdS black holes. Due to the underlying scaling symmetry two regimes can naturally be distinguished, one in which the temperature T is much larger than the chemical potential μ. This is the hydrodynamic regime and the gauge gravity duality allows to compute transport coefficients such as viscosities or conductivities. The other regime of interest is the opposite with $\mu \gg T$. Here the black hole is near extremality. At precisely $T = 0$ the black hole horizon becomes degenerate with profound implications for the dual field theory physics. It turns out that the entropy of an extremal charged AdS black hole is macroscopically large, scaling with some positive power of the number of the underlying microscopic degrees of freedom N. This feature is generally interpreted as pointing towards an inherent instability of such black holes. Indeed many such instabilities are known to arise upon adding additional fields, e.g. scalars (even uncharged ones) tend to condense near extremality leading to a superconducting phase transition. The charge that was hidden behind the horizon is pulled outside and the scalarfield forms the (symmetry breaking) condensate. If one replaces the scalar with a fermion a similar transition occurs where the black hole is replaced by a geometry without horizon and the charge is carried by the fermions forming an “electron star” in asymptotically AdS. The field theory interpretation of this transition is one between a “fractionalized” phase and a “mesonic” phase. This is in one-to-one correspondence to the deconfined/confined phases of non-Abelian gauge theory, only that in condensed matter it is often the mesonic or confined phase that appears as the more fundamental one. Real world fractionalization occurs for example in the separation of spin and charge degrees of freedom of electrons or the appearance of quasiparticles carrying fractions of the electron’s charge. Such gravity duals of fractionalized/mesonic phases in the presence of a magnetic field are the subject of [19]. A crucial role is played by the presence of a dilaton which allows to find a rich structure of solutions including partially fractionalized phases.

The quantum critical behavior of four dimensional field theories described by a gravity dual including a $U(1)$ gauge field with an additional Chern-Simons term in a magnetic field is the subject of [17]. The authors find a quantum phase transition for large enough magnetic field beyond which the charge is completely expelled outside the horizon and the background geometry has zero entropy.

Another important theme in the condensed matter applications of the gauge gravity correspondence is the spectrum of fermions in asymptotically AdS black holes. Fermions in the gravity dual obeying a Dirac equation dual to gauge invariant fermionic operators in the field theory. One can study the holographic fermionic two point function and in particular look out for poles that identify the presence of Fermi surfaces. It is indeed well known by now that such probe fermions can show behavior consistent with Landau's theory of Fermi liquids but also more exotic possibilities such as marginal Fermi liquids in which the residue of the corresponding pole vanishes or completely non-Landau Fermi liquid behavior are realized. The Fermi level structure of such probe fermions in a four dimensional dyonic, i.e. including a magnetic field, asymptotically AdS black hole is the subject of [20]. For strong magnetic field the Fermi surface vanishes and the authors associate this with a metal to strange metal phase transition.

To summarize, this volume of Lecture Notes presents a review of the current research of strongly interacting matter in magnetic fields. Most of the applications considered here concern QCD matter, but a number of important cases from condensed matter physics is considered as well. The focus of the volume is on the theoretical results; however these results have a direct significance for experiment, in particular for heavy ion collisions that are currently under intense study at RHIC and LHC. While most of the contributions in this volume reflect the work done very recently, the field is evolving so rapidly that we expect to see a significant progress already in the near future. Because of this, we do not expect this volume to express a "final word" in any sense; instead, we view it as a snapshot of the exciting work that is being done right now. A large number of open questions has emerged as a result of this work; some of them have been mentioned in this brief overview, but we encourage the reader to read the individual contributions for an in-depth exposure. We hope that this volume will convince the reader that strongly interacting matter in a magnetic field is a rich and vibrant research area, and many more discoveries and surprises can be fully expected.

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