論文の内容の要旨

Chirality Generation under Strong Electromagnetic Fields and the Schwinger Mechanism
(強電磁場中でのカイラリティ生成とシュウィンガー機構に関する研究)

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Anomalies are ubiquitous and of the utmost importance in our understanding of the behavior of quantum field theories (QFT). An anomaly occurs when a symmetry that might be classically conserved is broken by quantum effects [1]. A noteworthy example and basis of this work is the chiral symmetry. Massless theories, it seems, ought to decouple into left and right-handed parts–classically. However due to the anomaly, the chiral symmetry is broken and leads to the generation of mass predicting the bulk of the visible mass in the universe [2, 3]. There exists indirect evidence of the chiral anomaly in QCD through the large pseudoscalar meson mass, however, direct evidence is lacking. And, an important manifestation of the chiral anomaly that might be directly observable is the chiral magnetic effect [4].

The chiral magnetic effect (CME) is the generation of an electromagnetic current in the presence of and parallel to an external magnetic field due to a chirality imbalance. Simply stated in special parity-violating backgrounds the chiral anomaly dictates a non-conservation of chirality. Then the chirality imbalance–for approximately massless fermions–elicits a net current in the direction of the magnetic field due to a polarization effect of the strong field.

The strong magnetic field for the CME is, in fact, a key feature in heavy-ion collisions and hence the CME and anomalous effects should be observable there. Identifying the CME in colliders is a challenging task, however. A relativistic fermionic dispersion relation is producible in condensed matter environments such as Weyl and Dirac semimetals. And, in fact, in such analog environments, the electromagnetic current associated with the CME has been directly observed, such as for a Dirac semimetal [5]. Then it becomes an essential task to verify the CME's existence in QCD. However, in contrast to the condensed matter system, there are theoretical shortcomings that should be addressed first. These are the CME's behavior under a finite mass and in and out-of-equilibrium. Furthermore, how might a chirality imbalance be generated in the first place?

An essential feature of the CME is a finite generation of a net chirality. The CME is typically described with a chiral chemical potential, in essence, an insertion of chirality imbalance by hand into the theory. However, it would be desirable to have a chirality imbalance emerge organically. This is critical especially for heavy-ion collisions, as globally there is no net chirality in a collision event. However, locally this may not be the case [6]. The insertion of a chiral chemical potential is likened to an insertion of an out-of-equilibrium quantity into an equilibrated system.

Considering the transient nature of the CME in colliders, it too would be essential to acquire an out-of-equilibrium description of the CME. Moreover, how might one characterize the observables related to the anomalous generation of chirality in and out-of-equilibrium? In colliders, a dense gluonic state forms called the glasma [7, 8], which is thought to give rise to chromo-electromagnetic flux tubes thought to encase parity-violating configuration responsible for the CME [9]. And indeed, the glasma is highly un-equilibrated.

A final issue with the CME in QCD is that quarks have a finite mass, even though small. This has observable consequences we will find out. It is important to address the significance of the fermion mass in applications to the anomaly as well in high-energy applications. Frequently, in fact, the fermion mass is dropped in anomalous physics studies; we will later show that this dismissal is not so trivial.

An answer to the above problems we find can be furnished with a vacuum instability called the Schwinger mechanism. Unstable QFTs have a rich history whose physics underlie significant achievements in the field, including but not limited to spontaneous symmetry breaking [10], Hawking radiation [11], and the topic of this thesis, the Schwinger mechanism [12]. The Schwinger mechanism predicts a spontaneous generation of particle anti-particle pairs from the QFT vacuum due to a vacuum instability in an external electric field. In brief, the electric field of the Schwinger mechanism, from an intuitive classical perspective, is thought to pull apart virtual particle anti-particle pairs, allowing tunneling from the Dirac sea to the QFT continuum. In QCD the process is thought to occur in chromo-electric flux tube breaking leading to hadronization [13].

How then might one foresee a net chirality from the Schwinger mechanism? This occurs with a strong magnetic field parallel to the electric field. When a particle anti-particle pair are produced due to the strong magnetic field, the pairs' spins will become polarized, in essence setting up a net chirality [9].

A concrete means of calculating the effects of the anomaly with mass effects stemming from the Schwinger mechanism relies on the use of, an exact at the operator level, axial Ward identity [14, 15]. The axial Ward identity predicts a chirality non-conservation not only due to the chiral anomaly but also due to a mass-dependent pseudoscalar term. While the axial Ward identity is well known at the operator level, how it behaves under expectation values is unknown–particularly the case for the Schwinger mechanism. However, a straightforward calculation using traditional QFT methods predicts no effects from the Schwinger mechanism. Moreover, it also predicts a conservation of chirality, in other words, no anomaly! This is, however, in disagreement with the heuristically motivated picture just presented and it has remained a mystery how to reconcile the heuristic picture with expectation values. Furthermore, as the traditional QFT methods are a valid observable, what is it that they are observing?

The solutions to the above-presented problems, we find, are through the identification of vacuum states of the expectation values [16]. In-out or in-in expectation values yield completely different physical outcomes, the former we argue represents a scenario of Euclidean equilibrium and the latter an out-of-equilibrium scenario.

An in-out expectation value represents one found using traditional QFT methods, which describe a matrix element of a scattering state. So long as the in vacuum equal the out vacuum, then the in-

in and in-out values would coincide, however, this is not the case for the Schwinger mechanism. We find for the pseudoscalar, and hence axial Ward identity, and CME current using in-out expectation values

$$\langle out|\,\bar{\psi}i\gamma^5\psi\,|in\rangle = -\frac{e^2EB}{4m\pi^2} \tag{1}$$

$$\partial_\mu\,\langle out|\,\bar{\psi}\gamma^5\gamma^\mu\psi\,|in\rangle = 0 \tag{2}$$

$$\langle out|\,\bar{\psi}\gamma^\mu\psi\,|in\rangle = 0\,. \tag{3}$$

There are no effects coming from the anomaly. We can understand this in that the Wick rotated QFT Lagrangian represents a Euclidean one in equilibrium. Thus the anomaly and hence CME does not exist in equilibrium. In other words, the above expectation values simply represent a scenario where no particles are produced in the out state. This is not the case, however, for in-in expectation values. Even so, the above cancellation has profound implications for the study of the anomaly and CME in that we see out-of-equilibrium methods are necessitated.

The anomaly and CME do, however, exist out-of-equilibrium. And one can reliably find out-of-equilibrium expectation values using in-in vacuum states–this is also the same as a Schwinger-Keldysh contour. A characteristic exponential mass indicative of the Schwinger mechanism is found for such cases. We find (in comparison to the in-out case above)

$$\langle in|\,\bar{\psi}i\gamma^5\psi\,|in\rangle = -\frac{e^2EB}{4m\pi^2}\left[1-\exp\left(-\frac{m^2\pi}{eE}\right)\right] \tag{4}$$

$$\partial_\mu\,\langle in|\,\bar{\psi}\gamma^5\gamma^\mu\psi\,|in\rangle = \frac{e^2EB}{2\pi^2}\exp\left(-\frac{m^2\pi}{eE}\right) \tag{5}$$

$$\langle in|\,\bar{\psi}\gamma^\mu\psi\,|in\rangle = \frac{e^2EBt}{2\pi^2}\coth\left(\frac{B}{E}\pi\right)\exp\left(-\frac{\pi m^2}{eE}\right). \tag{6}$$

We find with the inclusion of the Schwinger mechanism in-in observables give rise to the anomaly and CME. What is more, is the exponential suppression of the Schwinger mechanism is indeed strong. This has implications for theories that rely on the anomaly. It is, for example, important for theories of baryogenesis or in heavy-ion colliders.

In light of the new knowledge of the anomaly out-of-equilibrium with mass effects, we also examine related applications such as the chiral condensate, chiral fluctuations, and inhomogeneous parity-violating fields.

In analogy to cooper pairing in a superconductor, the breaking of the chiral symmetry in QCD can be characterized through a non-zero chiral condensate–even for massless QCD. Then, it becomes a natural question to ask what else might give rise to a non-zero condensate. Actually, a background magnetic field can do this; and is referred to as magnetic catalysis [17–19]. While the chiral condensate is well-known under a magnetic field how it behaves under an electric field and with effects stemming from the Schwinger mechanism is unknown. We find an electric fields acts, opposite to the magnetic field, to oppose the formation of condensate–in effect separating it. The emergence of the Schwinger produced pairs can even negate the condensate all together. The melting of the chiral condensate could be impactful in the study of chiral symmetry breaking in QCD.

During the formation of flux tubes in the early stages of heavy-ion collision, a net chirality via the Schwinger mechanism may be producible. However, in the final state of a collision event, one ought to expect a (global) net chirality of zero. Even so, locally this is thought not to be the case. [6, 20]. A measure for the local formation of chirality imbalance is provided through the calculation of chiral density fluctuations. Therefore, it is important that such chiral density fluctuations be addressed using our in-out and in-in formalisms. We, indeed, find in support of other chiral related observables a similar exponential suppression indicative of the Schwinger mechanism. Both the equilibrated and out-of-equilibrium chiral density fluctuations are finite; however, as expected only real-time dependence was seen for the out-of-equilibrium in-in case. Given the highly transient nature of heavy-ion collision events, it is also important to address more relevant inhomogeneous background fields in the generation of chirality due to the Schwinger mechanism.

Inhomogeneous fields are not only important for realistic backgrounds but, in fact, they can also considerably reduce the threshold for Schwinger pair production. Then it would be instructive to apply our above ideas of the generation of chirality in more advanced field types. So that we still have parity-violating fields, we explore the case of temporally inhomogeneous electric fields along with spatially inhomogeneous magnetic fields. The former is well known to reduce the threshold for pair production, culminating in "dynamically assisted electric fields [21]." However, we find, additionally, spatially inhomogeneous magnetic fields may enhance the Schwinger mechanism [22]. This proceeds by a lowering of the excited Landau levels for a Sauter-like pulsed magnetic field.

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