Chiral magnetic effect and the evolution of magnetic helicity in relativistic fluids

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Summary

For systems with charged chiral fermions, the imbalance of chirality in the presence of magnetic field generates an electric current - this is the Chiral Magnetic Effect (CME). I will describe the recent discovery of CME in experiments with Dirac semimetals, and an evidence for the effect in relativistic heavy ion collisions at RHIC and LHC. The CME stems from the chiral anomaly, and is thus linked to the topology of the gauge field – in particular, it provides a mechanism for the dynamical real-time evolution of magnetic helicity. I will present the recent finding that the chiral anomaly induces the inverse cascade of magnetic helicity towards the large distances, and that at late times this cascade becomes self-similar, with universal exponents. We also find that in terms of gauge field topology the inverse cascade represents the transition from linked electric and magnetic fields (Hopfions) to the knotted configuration of magnetic field (Chandrasekhar-Kendall states). The magnetic reconnections are accompanied by the pulses of the CME current directed along the magnetic field lines.

The anomaly-induced transport of charge in systems with chiral fermions has attracted a significant interest recently. This interest stems from the possibility to study a new kind of a macroscopic quantum dynamics. While the macroscopic manifestations of quantum mechanics are well known (for example, superfluids, superconductors and Bose-Einstein condensates), so far they have been mostly limited to systems with broken symmetries characterized by a local order parameter, e.g. the density of Cooper pairs in superconductors. The effects induced by quantum anomalies in systems with chiral fermions are of different nature.

Let us consider as an example the Chiral Magnetic Effect (CME) in systems with charged chiral fermions – the generation of electric current in an external magnetic field induced by the chirality imbalance [1], see [2] for a review and references. The experimental observation of CME in a Dirac semimetal $ZrTe_5$ has been reported recently [3]. In this case, no symmetry has to be broken, and the system is in its normal state. However the chirality imbalance is linked by the Atiyah-Singer theorem to the non-trivial global topology of the gauge field. Since the global topology of the gauge field cannot be determined by a local measurement, there is no corresponding local order parameter, and we deal with "topological order".

This has very interesting implications for the real-time dynamics of a system composed by charged chiral fermions and a dynamical electromagnetic field. Indeed, let us initialize the system by creating a lump of chirality imbalance localized within a magnetic flux that forms a closed loop. Magnetic field will induce the CME current flowing along the lines of magnetic field $\mathbf{B}$ (note that this effect is absent in Maxwell electromagnetism). Because the vector CME current acts as a source for the magnetic field, the current flowing along $\mathbf{B}$ will twist the magnetic flux and induce a non-zero expectation value for the *magnetic helicity* known since Gauss's work in XIX century and introduced in magnetohydrodynamics by Woltjer [4] and Moffatt [5], see also [6]:

$$h_m \equiv \int d^3x \; \mathbf{A} \cdot \mathbf{B} \,. \tag{1}$$

Magnetic helicity is a topological invariant (Chern-Simons three-form) characterizing the global topology of the gauge field. It is mathematically related to the knot invariant, and measures the chirality of the knot formed by the lines of magnetic field. Because of this, the generation of magnetic helicity will create the chiral knot out of the closed loop of magnetic flux – so the topology of magnetic flux will change. In a recent paper [7] we have quantified this statement, and studied how the topology of magnetic flux changes in real time. We have found that as a consequence of chiral anomaly and the CME, the magnetic field evolves to the self-linked Chandrasekhar - Kendall states. During the evolution, the size of the knot of magnetic flux increases. Moreover, at late times this evolution becomes self-similar, and is characterized by universal exponents.

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