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Non-stationary measurements of Chiral Magnetic Effect

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HIGHLIGHTS

- Asymmetry in the response function for vector currents of massless fermions in the magnetic field is computed.
- Asymmetry caused by axial chemical potential is practically indistinguishable from the one caused by non-stationarity.
- The CME current is non-dissipative in the stationary case and dissipative in the non-stationary case.
- Importance of studies of P-odd signatures in central collisions is emphasized.

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ABSTRACT

We discuss the Chiral Magnetic Effect from the quantum theory of measurements point of view for non-stationary measurements. The effect of anisotropy for fluctuations of electric currents in a magnetic field is addressed. It is shown that anisotropy caused by nonzero axial chemical potential is indistinguishable in this framework from anisotropy caused by finite measurement time or finite lifetime of the magnetic field, and in all cases it is related to abelian triangle anomaly. Possible P-odd effects in central heavy-ion collisions (where the Chiral Magnetic Effect is absent) are discussed in this context. This paper is dedicated to the memory of Professor Mikhail Polikarpov (1952–2013).

1. Introduction

The behavior of matter in magnetic fields stays of interest since the discovery of magnetism and plenty of outstanding results in condensed matter physics have been obtained in this way. In recent years considerable attention has been paid to a particular case of chiral fermions in an external magnetic field. The examples range from gapless quasiparticle excitations like the ones in graphene to almost massless quarks deconfined for the very short time during heavy-ion collision. While the

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magnetic field in the former case is applied (and artificially varied) by the experimenter, the latter system is always under the influence of the magnetic field for non-central collisions created by the debris of the colliding ions. The magnitude of this field is fixed by geometry and kinematics of the problem. An important part of heavy-ion experimental programs of RHIC at BNL and of LHC at CERN is devoted to the studies of possible physical effects caused by this strong magnetic field [1–6].

The most interesting effect discussed in this context is the so-called Chiral Magnetic Effect (CME) [7–16]. From a theoretical side, it corresponds to the fact that the chirally asymmetric medium of charged massless fermions under an external magnetic field conducts electric current given by the following expression:

$$\mathbf{J} = \langle \bar{\psi} \boldsymbol{\gamma} \psi \rangle = \frac{e\mathbf{B}}{2\pi^2} \mu_5 \tag{1}$$

where $\mu_5 = (\mu_R - \mu_L)/2$ is the axial chemical potential and μ_L, μ_R are chemical potentials for right- and left-handed chiral fermions, respectively. The expression (1) can be derived in many complementary ways and from the theoretical side is a robust result. It has got support from the lattice [17,18]. On the other hand, the question about clear experimental manifestations of CME is far from being simple. Perhaps the most important reason for that is an obvious discrepancy between the stationary character of (1) and highly non-stationary dynamics of heavy-ion collisions. In particular, the magnetic field B of high enough magnitude exists for $0.1 \div 0.2$ Fm/c and decays with time in a very fast way.

As is advocated in [19,20] the crucial feature of the CME which gives a chance for the corresponding effects to be experimentally observable is the classicalization of some degrees of freedom. The necessity for that can be roughly explained as follows. At a classical level, originally there is no nonzero axial chemical potential in the problem. Quantum-mechanically one could have some superposition of states with different values of μ_5, for a given collision event. However there is no quantum mechanical current (1) in such a state, $\langle \mathbf{J} \rangle = 0$, because state vectors with positive and negative μ_5 have equal weights. To get nonzero measured current (1) in a particular event, this superposition must be projected to a state with definite and nonzero μ_5. This projection takes place in the course of measurement, i.e., the interaction of the quantum system under consideration with the classical measuring device. Taking into account that typical heavy-ion collision process is characterized by huge energy density and particle multiplicity it is natural to assume that the role of such measuring device is played by the medium itself. All that has clear links to Color Glass Condensate idea [21] and even earlier studies of the subject [22].

There exist various theoretical frameworks taking into account quantum-to-classical transition. Quantum measurement theory is among well studied ones. The basic idea is to couple some artificial system ("the detector") with the quantum field in question and study the response of the former. There are in general two groups of factors, having effect on the detector's response: external conditions (fields, temperature, etc.) and geometric form of the detector's world-line embedded in bulk space–time. In most cases discussed in the literature one's main interest is to compare an inertial detector under some external factor in the Minkowski space–time with the response of a non-inertial detector. The best known example is the celebrated Unruh result [23] about correspondence between an inertial detector in thermal bath and a non-inertial detector at constant acceleration. Of much interest is the application of this theory in the condensed matter context [24]. In the present paper (like in [20]) the attitude is different: the detector is supposed to be at rest and attention is focused on the dependence of the detector's response on external conditions.

In [20] the finite temperature case is considered. In the present paper we deal with the chiral fermions at finite chemical potential. The effects of finiteness of the measurement interval are discussed. In the last section the problem of P-odd signatures at central collisions is also briefly addressed.

2. Finite chemical potentials

For the reader's convenience let us remind basic steps of quantum measurement procedure ([25,26]; see also [27] in the context of vector current measurements). The Hamiltonian describing