論文審査の結果の要旨

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There are 9 chapters in this thesis. Chapter 1 gives a general introduction and research motivations on the chiral magnetic effect (CME) and the Schwinger mechanism. Chapter 2 further shows the backgrounds and the detailed history of the CME and Schwinger mechanism, as well as their relations to condensed matter physics, heavy-ion collisions, and high powered lasers. Chapter 3 presents in detail the "in-in" formalism by the Schwinger-Keldysh closed time path, which is a way to calculate the real-time expectation values of the systems out of equilibrium. Chapter 4 further highlights the differences between the "in-in" formalism and the "in-out" formalism, which is a conventional method representing a scenario of Euclidean equilibrium. From Chapter 5 to Chapter 8, the different results by the equilibrium in-out formalism and the out-of-equilibrium in-in formalism for the axial Ward identity, CME, chiral density fluctuations, and dynamical chiral condensate are obtained and compared. Finally, Chapter 9 gives the summary and conclusions.

Generally speaking, an anomaly occurs when a symmetry that might be classically conserved is broken by quantum effects. Anomalies are ubiquitous and of the utmost importance in understanding the behavior of quantum field theories. In this thesis, based on the Euclidean equilibrium in-out formalism and the Schwinger-Keldysh out-of-equilibrium in-in formalism, the primary new finding is the importance of asymptotic vacuum states for the determination of expectation values related to the chiral anomaly. This is an essential finding, because it not only paints a new picture of the chiral anomaly in and out of equilibrium, but also establishes the anomaly dependence on the vacuum instability, i.e., the Schwinger mechanism.

The most important results of this thesis are summarized in Table 9.1. Significant new derivations and understandings are obtained for the properties of chiral condensate in equilibrium as well as the properties of pseudo-scalar, axial Ward identity, and chiral current out of equilibrium. Moreover, entirely new results are obtained for the properties of axial Ward identity, chiral current, and chiral fluctuations in equilibrium as well as chiral fluctuations and condensate out of equilibrium. Parts of the results have been published in *Phys. Rev. Lett.* **117**, 081603 (2016) and *Phys. Rev. Lett.* **121**, 261602 (2018).

Even some part in the thesis, e.g., Chapter 5, contains the parts created jointly with Kenji Fukushima and Shi Pu, it is admitted that the author of the present thesis played the leading role in the relevant research.

したがって、博士 (理学) の学位を授与できると認める。