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Macroscopic manifestations of quantum anomalies in hydrodynamics (Mini-review)

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It is well known that systems of chiral fermions exhibit a set of transport phenomena – chiral effects – which are closely tied with the axial anomaly of the underlying quantum field theory (QFT). These effects can considerably influence dynamics of a variety of systems from quark-gluon plasma to Weyl and Dirac semimetals, see [1, 2] for a review. A recent renaissance of interest in chiral effects resonated with the discovery of the quark-gluon plasma (QGP) at the RHIC accelerator. Chiral fermions are thought of as light quarks in that case. One of the most remarkable properties of the QGP is that its η/s ratio (where η is the viscosity and s is the entropy density) is the lowest known for any fluid, which allows to think of it as a (nearly) ideal fluid.

Nowadays, the chiral effects represent a whole branch of theoretical physics. In this review we focus on the macroscopic manifestations of the chiral quantum anomalies in hydrodynamics of an ideal fluid. The crucial observation, made first in the seminal paper [3] is that within the standard hydrodynamic approach one can rederive the chiral effects in the strong-coupling limit of the dissipation-free fluid. The anomaly then enter the analysis through modified conservation of the axial current. An important point for our consideration is the existence of the additional conservation laws in the ideal limit, which turn out to be related to the chiral anomaly in the underlying theory. The origin of these laws is purely dynamical and is related to the certain boundary conditions, which distinguishes them form the local microscopic conservation laws which follow from some symmetry of the system. The simplest way to see these new conservation laws is what we refer to as the dual field theory, which is nothing but the introduction of the effective interaction which shifts the gauge field. The vertices generated by this substitution correspond exactly to the chiral effects. The conservation laws are then implied by the Adler–Bardeen theorem as this effective interaction should leave the anomalous divergence intact. This, in turn, introduces some non-local restrictions on the dynamics of the ideal fluid.

We also discuss the recent developments in the study of chiral effects in the external gravitational field. In linear order the effects of turning on the gravitational field can be recovered using the equivalence principle. One particular example of using this approach that we discuss is the so-called gravimagnetic anomaly. Surprisingly, despite the fact that the nature of this anomaly seems to be gauge dependent, its value is actually fixed by the same equivalence principle. Another topic that we discuss is the possible connection between the mixed gauge-gravitational anomaly and the thermal vortical effect. Namely, we review recently proposed mechanism of such a connection [4] for the fermions and its generalization for the systems of particles of higher spin.

Finally, we review the mechanism of generating CVE in the pionic superfluid as a particular example that allows to understand the origin of the chiral effects on the microscopic level. The vorticity in that case is realized by the linear defects and the chiral vortical effect is generated by the fermionic zero modes propagating on these defects. The final result for the current can be obtained after thermodynamical averaging over the vortices. The simplicity of the setup allow for the explicit microscopic calculation of the effect and the comparison with the results provided by the calculation of the triangle diagrams with effective vertices, which are absent in the microscopic theory.

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