Annual report
Ph.D. in Physics and Nanoscience

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1 Research activity: Hydrodynamics

The main focus of my research has been the theory of hydrodynamics.

Hydrodynamics is a low-energy effective field theory that describes the dynamics of many-body thermal systems close to thermodynamic equilibrium. The working assumption is that the time scale associated with the interaction of the fluid constituents is the shortest scale in the system, thus the fluid thermalizes quickly in each fluid volume and the relevant degrees of freedom that survive the coarse-graining procedure are the conserved charges (energy, momentum, electric charge) and eventually other slow modes (e.g. an order parameter near the critical point or a Goldstone mode).

It is than clear that strongly-coupled phases of matter, in which the quasi-particles interact frequently, are systems where the hydrodynamic regime is strongly enhanced. In particular, hydrodynamic behaviour has been observed in certain condensed matter systems such as graphene, Dirac or Weyl semimetals.

During this last year I mostly investigated two aspects of hydrodynamics: quasi-hydrodynamics and anomalous hydrodynamics, in order to describe the transport properties of Weyl semimetals.

1.1 Quasi-hydrodynamics

The equations of hydrodynamics are the conservation equation for energy, momentum and other charges. However, in many cases, these conservation laws are not exact: in condensed matter the electron fluid can interact with impurities and phonons and lose momentum, or the symmetry associated to the conservation law might only be approximate, as in the case of axial charge conservation in Weyl semimetals. These effects can be modeled by an effective decay term that spoils the conservation of the relevant charge.

During this last year I studied such quasi-hydrodynamic systems under different perspective. First, in *Non-dissipative electrically driven fluids*, we investigated whether a fluid can achieve a steady state with a non-zero velocity, even in the presence of momentum relaxation, which typically tends to bring the equilibrium velocity to zero. Indeed, we found that by considering a system without boost symmetry, we could balance the effect of momentum relaxation with an externally applied electric field, reaching a stationary state. Because in hydrodynamics stationary states are used as a basic step to add dissipative corrections, this study implies that in the presence of momentum relaxation the constitutive relations of hydrodynamics must be modified.

Later, in *Restoring time-reversal covariance in relaxed hydrodynamics*, we investigated a more general set of relaxations. Hydrodynamics can be used to compute response functions by linearising around a given background and solving the equations of motion. However, this becomes difficult to do in the presence of relaxations, which always ruin some of the symmetries needed to obtain the full set of correlators. To analyze the issue, we considered all the possible relaxations consistent with symmetries in the linearised equations of hydrodynamics and obtained a set of constraints that these terms must obey in order for the theory to show time-reversal invariance, linear stability and positivity of entropy production. Then, we showed how to obtain the full set of correlators for such quasi-hydrodynamic theory from a variational approach.

1.2 Anomalous hydrodynamics

Hydrodynamics receives corrections in the presence of QFT anomalies. In particular, the chiral/axial anomaly induces extra terms in the constitutive relations, that give rise to known macroscopic phenomenological effects such as the Chiral Magnetic Effect or the Chiral Vortical Effect.

Anomalous hydrodynamics is particularly relevant to study the dynamics of the quark-gluon-plasma created in heavy-ion collisions, but also to describe the transport properties of Weyl semimetals. These are 3D topological materials in which the band structure is such that the quasi-particles are chiral and have a linear dispersion relations, thus the low-energy excitations of Weyl semimetals are Weyl fermions. Weyl semimetals have many interesting properties, but one of the most interesting is their negative longitudinal magneto-resistance, i.e. due to the axial anomaly the electric conductivity grows with the applied magnetic field.

We can then use anomalous hydrodynamics to study the magneto-resistance of Weyl semimetals, however older studies in the literature incorrectly claimed a magnetic-field dependence of the conductivity from order-one hydrodynamics. In *Leading order magnetic field dependence of conductivities in anomalous hydrodynamics* we discuss this problem and suggest a solution to obtain the negative magneto-resistance from anomalous hydrodynamics: namely one should take the magnetic field to be order zero in derivatives, so that it enters the equilibrium thermodynamics.

There is however one last problem that we addressed in *Relaxation terms for anomalous hydrodynamic transport in Weyl semimetals from kinetic theory*: the conductivities obtained from anomalous hydrodynamics diverge in DC, which means that they cannot be used to describe real materials. One possible way to obtain finite conductivities is to use the generalised relaxations of *Restoring time-reversal covariance in relaxed hydrodynamics*, which allow us to describe a system with many desirable features (finite DC conductivity, time-reversal invariance, conservation of electric charge). Finally, we show that these generalised relaxations can be obtained from kinetic theory under very general ground, simply considering energy-dependent scatterings with impurities and phonons.

2 Courses and exams

During this last year I gave the last exam

- Non-abelian gauge theories (Maggiore) – Algebraic renormalization of Yang-Mills

3 Conferences and Visitings

- *Visiting period*: I spent three months (October to December 2022) at the Université Libre de Bruxelles, working with Prof. Riccardo Argurio on gauge theories and fractons.
- *Seminar*: I gave a talk at the Université Libre de Bruxelles on *A new class of hydrostatic theories* – 8/11/2022, Bruxelles
- *Workshop*: I joined a Workshop on *Holographic perspectives on chiral transport* organized by the European Center for Theoretical Studies in Nuclear Physics and Related Areas (ETC*) – from 13 to 17/03/2023, Trento.
- *Conference*: I gave a talk at the joint conference CMD30-FisMat2023 on *On Frames and Magneto-Transport in Anomalous Hydrodynamics* – from 4 to 9/09/2023, Milan.
- *Workshop*: I got accepted to the Workshop *Hydrodynamics at all scales* organized by Nordic Institute for Theoretical Physics (Nordita) – from 17 to 23/09/2023, Stockholm

4 Publications

- *Non-dissipative electrically driven fluids*
  A. Amoretti, D.K. Brattan, L. Martinoia, I. Matthaiakakis
  Journal of High Energy Physics, 05 (2023) 218
- *Leading order magnetic field dependence of conductivities in anomalous hydrodynamics*
  A. Amoretti, D.K. Brattan, L. Martinoia, I. Matthaiakakis
  Physical Review D, 108.1 016003 (2023)
- *Restoring time-reversal covariance in relaxed hydrodynamics*
  A. Amoretti, D.K. Brattan, L. Martinoia, I. Matthaiakakis
  Physical Review D, 108.5 056003 (2023)
- *Relaxation terms for anomalous hydrodynamic transport in Weyl semimetals from kinetic theory*
  A. Amoretti, D.K. Brattan, L. Martinoia, I. Matthaiakakis, J. Rongen
  arXiv preprint [hep-th]: 2309.05692