Annual report
Ph.D. in Physics and Nanoscience

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Ph.D. cycle: XXXVI, second year

1 Research activity: field theory methods for condensed matter

1.1 Superconductivity in thin films

It is a common lore in the scientific community that static external electric fields should have almost no effects on bulk superconductors: this is because standard BCS superconductors still contain many free charges that reorganize in order to screen the electric field (as it happens in normal metals).

Recently, however, it has been reported that a static electric field can be used to control the value of the supercurrent in thin films BCS superconductors. In particular for large enough electric field $E \approx 10^8 \mathrm{V\,m^{-1}}$ a transition to the normal metallic phase has been observed, this effect is called Superconductive Field Effect (SFE). In these thin films the screening length $\lambda_E \approx 1$nm is much smaller then the thickness of the film, that is about the same size of the coherence length $L \sim \xi \approx 100$nm, so naively the external electric field should have no effect in the bulk. Furthermore it was observed that increasing the thickness of the sample completely suppresses the SFE and no transition to the metal phase happens.

During the first half of the year we worked on a possible solution to the problem, specifically we discussed a modification to the standard phenomenological Ginzburg-Landau free energy by considering two extra coupling terms between the external electric field and the order parameter (the superconducting gap). We numerically solved the equations of motion for the order parameter and obtained the value of the extra couplings by fitting the experimental data.

With only these two free parameters we managed to correctly reproduce the dependence of the critical supercurrent with respect to the applied electric field and the suppression of the SFE by increasing the thickness to great accuracy. Finally, we also suggested a tabletop experiment based on a superconductor-superconductor junction for which our model gives a specific prediction.

We are now also working on trying to obtain the new phenomenological parameters from a microscopic BCS theory. To do so we are considering the standard approach by Gor'kov, but modified to also include the effect of the electric field on the mean-field Ginzburg-Landau free energy.

1.2 Hydrodynamics

Throughout all the year I also worked on other projects related to my main topic of expertise, the theory of hydrodynamics. Generally speaking hydrodynamics is a many-body effective field theory that describes the dynamics of the conserved charges near thermal equilibrium. It finds many application in the context of strongly interacting systems, e.g. Weyl semimetals, graphene and High temperature superconductors in condensed matter.

1.2.1 Hydrodynamics with background electric field and momentum relaxation

Standard hydrodynamics, in which momentum is perfectly conserved, predicts an infinite DC electrical conductivity, because the electric field accelerates the fluid without bound. To overcome this problem a relaxation term Γ that breaks momentum conservation is usually considered, thus obtaining a coherent Drude-like conductivity that is finite in DC.

As an effective field theory, hydrodynamics is based on a derivative expansion approach, hence to all fields (dynamical or not) is assigned a specific derivative counting and higher order derivatives terms are less important than lower order ones. From this point of view, usually both the electric field and the momentum relaxation term are assumed to be order one in derivatives.

Our idea was to describe a fluid for which the momentum relaxation opposes the electric field producing a fluid that moves with constant velocity and reaches a steady state. To do so we considered both the electric field and the relaxation term to be order zero in derivatives, furthermore, since the global thermodynamic equilibrium now explicitly depends on the velocity of the fluid, such system breaks boost invariance.

We studied such a system including many possible relaxation and dampening terms and computing all the hydrostatic transport coefficients up to order one in derivatives. We discussed bounds due to stability and found relations between these new terms.

1.2.2 Anomalous hydrodynamics

Relativistic hydrodynamics receives corrections in the presence of quantum anomalies. In particular the chiral anomaly for a $U(1)$ abelian symmetry is relevant for the description of Weyl semimetals in condensed matter, in these systems the axial anomaly is responsible for the observed large magneto-resistivity.

However there are still issues in the theory of anomalous hydrodynamics, in particular using different hydrodynamic frame (these are ambiguity in the definitions of the hydrodynamic field, so all frames should carry the same physical information) to compute physical observables (such as the conductivities) gives different results. Furthermore the conductivities obtained are never Onsager reciprocal (a symmetry of the transport coefficients due to microscopic time-reversal invariance) and it is not clear why this is the case.

I proposed a possible solution to the first problem: if we consider the magnetic field order zero in derivatives then the conductivities do not depend on the choice of the hydrodynamic frame anymore. This intuition also has effects on other hydrodynamic theories, such as parity-violating hydrodynamics. I also suggested a solution to the problem of Onsager relations, by noticing that the anomalous part of the fluid is dissipationless and should be considered separately when relaxing the charges.

2 Courses and exams

During my second year I followed the classes below, with the respective seminars at the end of the course:

- Conformal Field Theory (Magnoli) – Perturbative corrections of the critical Ising model in a magnetic field
- Non-abelian gauge theories (Maggiore)

I also joined (virtually) an International Workshop *Emergent Hydrodynamics in Condensed Matter and High-energy Physics* 2 - 6 May 2022 Max Planck Institute for the Physics of Complex Systems, Dresden, Germany

3 Publications

- *Destroying superconductivity in thin films with an electric field*
  A. Amoretti, D.K. Brattan, N. Magnoli, L. Martinoia, I. Matthaiakakis and P. Solinas
  accepted for publication by Physical Review Research – arXiv:2202.00687