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FELLOWSHIP FINAL REPORT

Chiral matter: theory and applications

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ABSTRACT

Chirality is a recurring cross-disciplinary theme in modern science, from particle physics to biology. In quantum physics, the chirality of fermions is linked to the topology of gauge fields by the chiral anomaly. While the chiral anomaly is usually associated with the short-distance behavior in field theory, recently, it has been realized that it also affects the macroscopic behavior of chiral matter. In particular, the local imbalance between left- and right-handed fermions in the presence of a magnetic field induces non-dissipative transport of electric charge ("the Chiral Magnetic Effect", CME). Recently, the CME has been discovered in Dirac and Weyl semimetals possessing chiral quasi-particles. Here we report on the investigation of related phenomena in non-centrosymmetric superconductors and Josephson junctions and discuss their potential applications in quantum computing.

1- Introduction

In 1874, Louis Pasteur wrote: ``The universe is asymmetric, and I am persuaded that life, as it is known to us, is a direct result of the asymmetry of the universe or of its indirect consequences." Life *is* asymmetric, and the concept of chirality is quite literally ingrained in our DNA.

In quantum physics, the chirality of fermions appears through the projection of the fermion spin onto its momentum (with a minus sign for antifermions). For massless fermions, chirality is conserved in the interactions with gauge fields on the classical level - so a left-handed fermion will always stay left-handed. However, quantum chiral anomaly allows for a chirality transmutation - a left-handed fermion can become right-handed if it interacts with a chiral configuration of the gauge field.

In the presence of an external magnetic field, such chiral configurations of gauge field can thus decay into charged fermions and produce an electric current along the direction of the magnetic field. This is the essence of the ``chiral magnetic effect” (CME) currently under investigation in quark-gluon plasma produced in relativistic heavy ion collisions at Brookhaven National Laboratory and European Laboratory for Particle Physics, CERN.

While the search for the CME in high-energy nuclear physics is still ongoing, the effect has already been discovered in experiments with a new class of materials that support the chiral quasi-particle excitations – Dirac and Weyl semimetals.

In our investigation [1,2], we have extended the studies of the chiral effects for a particular class of superconductors that break parity – the symmetry between the left and right.

As discussed in more detail below, we found that a direct analog of CME appears in the Josephson junction consisting of two non-centrosymmetric superconductors (NCSs) connected by a uniaxial ferromagnet [1]. We argued that the resulting "Chiral magnetic Josephson (CMJ) junction" is protected from noise caused by fluctuations in magnetization. This feature of CMJ junctions makes them potentially suitable for superconducting quantum processors.

Extending our study of chiral effects in NCSs, we discovered that parity violation in these materials leads to very unusual properties of magnetic vortices [2]. In particular, vortices can exhibit an inversion of the magnetic field at a certain distance from the vortex core. In stark contrast to conventional superconducting vortices, the magnetic-field reversal in the parity-broken superconductor leads to non-monotonic intervortex forces and, as a consequence, to the exotic properties of the vortex matter such as the formation of vortex bound states, vortex clusters, and the appearance of metastable vortex/anti-vortex bound states.

2- Theoretical methods

Theoretical methods used by us for the investigation of chiral matter reflect the cross-disciplinary nature of this field and range from analytical computations in quantum field theory to numerical studies of the effective Ginzburg-Landau action describing superconductors.

In NCSs, the violation of parity results in a term describing the coupling of the magnetic field to electric current. We have found that this term significantly affects the tunneling of Cooper pairs across the magnetized weak link in the junction between two NCSs [1]. Moreover, the same term in the effective action ultimately leads to the novel vortex structure and dynamics in NCSs [2].

3- Results and discussion

The results of our investigations can be summarized as follows. For the case of the "Chiral magnetic Josephson junction", i.e. the junction between two non-centrosymmetric superconductors (NCSs) connected by a uniaxial ferromagnet, we have found that the current across the junction is a direct analog of the chiral magnetic effect [1]. Namely, for short junctions, the electric current is proportional to the product of magnetization and of the parameter describing the parity violation in the NCS.

We have proposed to use this Chiral Magnetic Josephson junction as an element of a qubit with parameters tunable by the ferromagnet's magnetization [1]. The resulting Chiral Magnetic Qubit is protected from noise caused by fluctuations in magnetization and does not require an external magnetic flux, allowing for a simpler and more robust architecture of a quantum processor based on it. The practical realization of our proposal requires further research into the parity-odd response of NCSs and their interfaces and opens opportunities for future cross-disciplinary research.

This motivated our study of the response of NCSs to the magnetic field and the formation of vortices [2]. Here, we have demonstrated, within a Ginzburg-Landau framework describing NCSs with O point group symmetry, that vortices can exhibit an inversion of the magnetic field at a certain distance from the vortex core. In stark contrast to conventional superconducting vortices, the magnetic-field reversal in the parity-broken superconductor leads to non-monotonic intervortex forces and, consequently, to the exotic properties of the vortex matter such as the formation of vortex bound states, vortex clusters, and the appearance of metastable vortex/anti-vortex bound states [2].

4- Perspectives of future collaborations with the host laboratory

The research described above naturally leads to the continuation and extension of cross-disciplinary collaborations within the host laboratory. The reported research has been carried out in collaboration with Dr. Julien Garaud, who has become a permanent member of the Institut Denis Poisson (IDP) during the reported period. One should stress that the successful collaboration within this Le Studium program has decisively promoted the selection of our co-author for the Professor position at the University of Tours.

The support of Le Studium Institute was crucially important in stimulating this collaboration and developing the careers of young researchers at the host laboratory. In particular, the success of this Le Studium program has been one of the crucial reasons for organizing the new master's course at the University of Tours, the new CMI in Quantum Technologies (cursus master en ingénierie en Technologies Quantiques, “TechQu”). This initiative, which started within the reported period, unifies the researchers and professors from GREMAN and IDP, as well as members of other faculties of the University of Tours. In December 2022, the CMI was officially approved by the Réseau Figure and listed in the national platform of French higher education. The program in quantum computing at the IDP/GREMAN is projected to be started officially in 2024.

Our research has also stimulated productive interactions with condensed matter physics groups at Tours University and at GREMAN, which can lead to future collaboration in the study of the parity-odd response of NCSs and their use in superconducting quantum processors. In addition to the existing reported publications, a few papers are now in the stage of preparation and finalization.

Quantum computing can also be used as a novel tool in the study of the real-time, non-equilibrium response of chiral matter. We start to collaborate on quantum simulations of real-time dynamics of chiral matter and plan to organize a Le Studium conference on the topic in July of 2023 in Tours.

5- Articles published in the framework of the fellowship

[1] M.N.Chernodub, J. Garaud and D.E.Kharzeev, Universe 8 (2022) 12, 657; e-print: arXiv:1908.00392

[2] M.N.Chernodub, J. Garaud and D.E.Kharzeev, Phys. Rev. B 102 (2020) 18, 184516; e-print: arXiv: 2003.10917

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