Dislocations in stripes and lattice Dirac fermions

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SUMMARY

Tangible pieces of material, that share the length and time scales of humans, possess an amazing range of physical behavior and often surprising properties. These we can use to build better and new technologies, but also to study fundamental theoretical questions in a novel way. The phenomenological richness of such materials comes from the fact that a collection of very many microscopic particles, like fundamental electrons, can behave radically different than the particles themselves. We can only observe their collective response when we probe the system using small energies and impulses. The system is then characterized by an *effective* theory, which might describe previously unknown effective particles, and can even mimic a theory of various fundamental particles in Nature.

The different phases in which the macroscopic system can be found are usually distinguished by different space-time, or internal, symmetries that are observed. The effective theory can in such cases describe the behavior of a physical *order parameter*, a quantity which locally measures the breaking of the given symmetry, and thereby characterizes the state of the system. A special role is then played by *topological defects*. In two dimensional systems, as the ones studied in this thesis, a topological defect is a configuration in which the order parameter is forced to vanish at a point, the core of the defect, because its values on a loop around the core “twist” in a way that cannot be smoothly “untwisted” as the loop shrinks around the core. The topological defects are therefore stable and robust configurations that fundamentally destroy the ordered phase of the system.

In this thesis we study two different types of systems which exhibit topological defects called *dislocations*. Lattice dislocations locally destroy the crystal lattice ordering by restoring the translational symmetry of free space — whenever we count lattice steps along any path going around the dislocation, there is always a fixed number of steps missing. In Chapters 2 through 5 we study the effects of dislocations on *graphene* and two-dimensional *topological insulators*, systems where the effective theory of non-interacting electrons happens to describe fundamental Dirac fermions. In Chapters 6 and 7 we study an effective theory of strongly interacting electrons in the high critical temperature (high-T_c) copper superconductors, called “cuprates”, which describes the local patterns of translational and rotational symmetry breaking. A prominent role is played by *stripe dislocations*, topological dislocational defects in stacks of parallel lines of charge known as “stripes”.

In Chapter 2 we explore the connection between the electrons in graphene with topological defects, and the fundamental theory of Dirac fermions in curved spaces. We study both disclinations (topological defects restoring the rotational symmetry of free space), and dislocations, which correspond to a space-time carrying curvature and torsion, respectively. We demonstrate that electrons in defected graphene are transported in the same way as fundamental Dirac fermions in such a non-trivial 2+1-dimensional space-time, with the proviso that the former remember the lattice constant through the finite Fermi momentum associated with the existence of the graphene lattice. We find that the extra lattice constant effect corresponds to modified Euclidean symmetry generators of the underlying space.

In Chapter 3 we explore the observables connected to the graphene electron Berry phase caused by the topological action of lattice dislocations. An elementary scale consideration of a graphene Aharonov-Bohm ring leads to an apparent violation of the basic law of linear transport that magnetoconductance is even in the applied flux. We discuss this discrepancy in the Feynman path picture of dephasing when addressing the transition from quantum to classical dissipative transport. We also investigate this device accounting for the effects of dephasing by the Büttiker dephasing voltage probe-type model, where the magnetoconductance remains even in the flux, also when different dephasing times are allowed for the individual, time-reversal connected, electron modes.

In Chapter 4 we study grain boundaries in graphene, the extended defect structures that form on the boundary between two graphene grains with different orientations. We introduce a model for amorphous grain boundaries, and find that stable structures along the boundary are responsible for local density of states enhancements identified in scanning tunneling spectroscopy measurements. We also consider the continuum theory of arrays of dislocations in graphene and show that it predicts localized zero energy states, similar to the ones found experimentally. Taking further into account the lattice scale effects, we analyze stable dislocation cores and show that they indeed carry zero energy states.

In Chapter 5 the physical system in focus are the two-dimensional topological insulators. We show that lattice dislocations induce spin currents on the system edges. Using this fact, we propose an experiment for identifying the elusive Majorana fermion states, which are believed to form on topological insulator — superconductor — ferromagnet junctions, and whose identification is important for quantum computing applications. Our proposal consists of a simple two terminal conductance measurement in an interferometer formed by two edge point contacts, which reveals the nature of Majorana states through the dislocation induced spin currents.

In Chapter 6 we study the electron-phonon coupling effects in cuprates, when electrons show a strong static stripe ordering. We demonstrate that the strong anomalies in the high frequency LO-phonon spectrum can be explained by the enhanced electronic polarizability associated with the one-dimensionality of metallic stripes. Contrary to models of transversal stripe fluctuations, the anomaly should occur at momenta parallel to the stripes. We explain the doping dependence of the anomaly, and predict that the phonon linewidth, as well as the spread of the anomaly in the transverse momentum decrease with increasing temperature, while high resolution measurements should reveal a characteristic substructure to the anomaly.

In Chapter 7 we study the interplay of local patterns of symmetry breaking observed in cuprates, including stripes (translational) and inter-unit-cell nematic (orientational) orderings. We demonstrate how to observe stripe dislocations in scanning tunneling microscopy data. We then argue on general grounds that they leave a distinct non-destructive footprint in nematic order and observe this footprint directly in measurements of the local nematic order parameter.