

Electrons are particles smaller than an atom, responsible for conducting electricity. In conventional materials (such as copper, aluminum or silicon), these particles act like billiards. They move inside electrical wires, effectively delivering the energy we need for everyday use. Such as billiards, electrons constantly bump into each other and against atoms in their way. This causes them to move slowly, in a disordered fashion. In the macroscopic scale, this translates into losses in the form of heat - due the existence of intrinsic electrical resistances.

In certain materials, however, electrons behave like photons – or light waves. These are known as Dirac systems. Examples include graphite, bismuth and antimony. In these systems, electrons travel faster, covering longer distances before bumping into each other and into atoms in their paths. This odd behavior causes electrons to lose less energy and to exhibit electrical properties not usually seen in their billiard-like counterparts. In particular, when exposed to magnetic fields, these materials can be tuned into metals or insulators, depending on the strength of the magnetic field applied.

Such conversion of an insulator into a metal without modifying the spatial structure or chemistry of the material is the foundation of our current silicon-based electronics. Differently from silicon, however, Dirac systems possess the advantage of having light-like electrons, making them viable candidates to integrate the next generation of high-speed, energy-efficient electronic devices. However, the metal-insulator modulation found in Dirac systems happens in the presence of magnetic fields - as opposed to electric fields in conventional semiconductors. The physical reasons for such modulation are still not fully understood, with different competing theories trying to explain the phenomenon. Hence, before Dirac materials can find place in industrial applications, a better grasp of their underlying physics is crucial.

In addition, it is experimentally observed that, at low temperatures, virtually all Dirac systems can present a phenomenon known as superconductivity. In it, electrons transmit energy with zero loss when certain conditions are met. Such phenomenon is apparently triggered in Dirac systems when the materials undergo some disturbances from their pristine state (such as the creation of defects in the material structure, or its doping with chemical elements). The reason for such observations are not yet understood. A careful study is necessary to verify the role that light-like electrons and disorder have in inducing superconductivity in these systems.

For these reasons, in this project, we propose to investigate the fundamental properties of Dirac systems through a comparative study on the electrical and magnetic properties of different materials. In particular, we propose to understand the origin of the metal-insulator modulation seen in Dirac systems, as well as the role of light-like electrons and disorder in triggering superconductivity. In order to achieve our goals, several Dirac systems (such as graphite, bismuth and antimony) will have their electrical and magnetic properties carefully characterized and compared. We expect our results to be invaluable for making Dirac systems compatible with the existing semiconducting technology, as well as to improve the current understanding on the origin of superconductivity in this class of materials. Our research should enable the development of more power efficient technologies, helping to shape the future of the electronic industry.