Mesoscopic studies of Topological Insulators and Superconductors

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Background

Topological Insulators (TIs) are a new form of matter that have robust conducting metallic surface states while the bulk is an insulator. The surface is so vastly different from the bulk, that it can be seen as a playground of new properties never seen before. One such novel property is that the surface is host to Dirac Fermions which behave relativistically and massless-like. Such particle behavior was predicted by Paul Dirac. The first experiment that demonstrated this prediction was done on graphene, a very similar cousin to the TI. These particles are identified as Dirac Fermions because they obey the Dirac equation which models relativistic (near speed of light) particles. These massless relativistic Fermions, demonstrate a direct linear relationship between the energy (E) and their quantized momentum (k), $E = \pm\hbar vk$. This peculiar energy relationship is uncommon in materials.

Previous work

I have published two papers with my advisor, Erhai Zhao and one accepted paper with Ming Tian (see CV). In the first paper, "Mott scattering at the interface between a metal and a topological insulator", I studied the ability to control the spin of an electron by reflecting it off the surface of a topological insulator (TI). The results of this study show that there is a very strong possibility of using TIs for spintronics. Spintronics uses the electron spin for in information processing. In the paper it was shown that there is a clear ability to cause a spin flip on the electron, depending on the angle of reflection and the energy of the electron. This result is analogous to the classical Brewster's law, which predicts the angle that (spin) polarized light reflects. For example this effect is used in polarized sunglasses where this ability reduces reflection from surfaces such as glass and water.

In the second paper, "Microscopic simulation of superconductor/topological insulator proximity structures", we calculated the effect of a superconductor on a TI as well as the effect the TI on the superconductor. A main result was that the low energies in this system are well described by the Fu-Kane model. It was also shown that the surface could potentially host Majorana particles. Majorana particles are fundamentally important because of their Anyon (non-Abelian statistics) behavior which is drastically different from Bosons (such as photons) and Fermions (such as electrons). Such Anyons are also important from a practical point of view because they can provide a means for topological quantum computing, a robust method of quantum computing. These particles are yet to be experimentally found.

The third paper involves a calculation takes a clever approach to manipulate a quantum system and compares it to a traditional approach of quantum control. The paper shows that the new approach is more robust to systematic and random errors than the traditional approach using a quantitative metric called quantum fidelity. Such a result has great implications in quantum control and in turn quantum computing, the holy grail of information science.

Current Work

In continuation of my previous work, I have studied superconductors in close proximity to TIs. As stated in the previous section, the implications are vast and many interesting experiments can be performed to understand new physics with such a class of materials. Currently there are three projects that are near completion. The first project is the study of the proximity effect on the surface of the TI and a superconductor. This project differs greatly from the second paper because in the second paper, the primary focus was not directed at the surface but rather, the inner bulk of the TI. Material-wise we model Bi_2Se_3. One key result from this is the local density of states (LDOS) (figure b.) shows a second smaller bump forming due to the TI, which is an anomalous effect when compared to traditional superconductors (see high peak red plot in figure b.). This second bump is an important signature of a new type of superconductivity that is unconventional.

The second project is the Josephson π junction on the surface of the TI. This setup was predicted to host Majorana particles but no one has performed a realistic, self consistent simulation. The results provide information about the zero-energy Majorana. Figure a.shows the zero-energy crossings that are the signatures of the Majorana. The TI surface, when in contact with a superconductor, can host the elusive Majorana particle. One of the signatures of the Majorana is the zero energy, which can be seen in figure a. where the graph has intersection points at E=0.

The third project involves calculating the conductance of a TI and superconductor junction where the results differ greatly from the traditional Blonder-Tinkham-Klapwijk theory for conductance.

Future Work

Once these projects are complete, there are many interesting directions to go in this world of TIs. Experiments are currently being conducted at many universities to study the many aspects of the TI. Much collaboration is available to present a lot of new physics.

The Jiang research group at Georgia Institute of Technology has conducted a few Andreev spectroscopy experiments in superconductor-TI heterostructures and reached out to us for collaboration to understand some results of their experiments. Additionally, we will study non-equilibrium physics of TIs, by modeling the TIs with an additional driving force, such as a magnetic field, an optical laser or voltage bias. There has been work in achieving a creation of a topological state similar to a TI through the use of similar driving forces. This work can give much insight into the new topological nature of matter. Lastly, I have been in talks with Qiliang Li of the Electrical and Computer Engineering department at GMU about doing calculations on a possible device built from a TI that could be used as a new form of memory. The possibility of this stems from the uncommon current-voltage relationship that the TI has. Such a device would improve efficiency in storage devices such as flash memory and essentially be a new device to complement or even replace silicon.

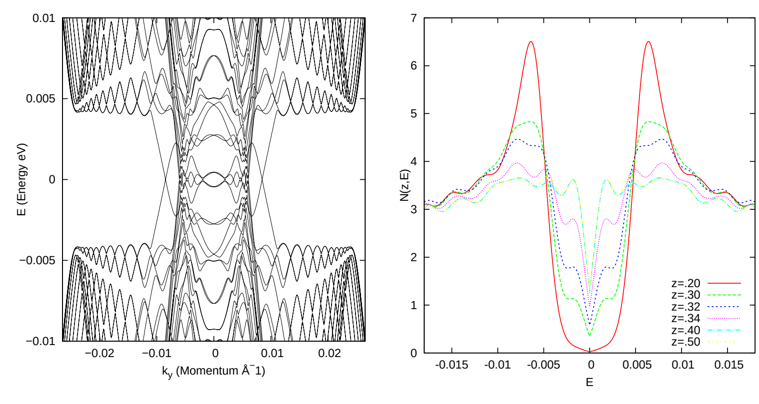

Figure 1: (color electronic version) a. Plotted are energies of S-TI-S Josephson π junction on the surface. The zero-energy crossings in the plot represent possible Majorana particle states. b. Plotted is the local density of states of a S-TI-S zero-phase surface as a function of energy and position along the surface.