Warsaw, 23 August 2023

EFFECT OF EXCITONS IN QUANTUM SPIN HALL EFFECT

Abstract

A quantum spin Hall insulator is a two-dimensional insulator with an insulating bulk and conducting edges. They belong to an entirely new class of materials which cannot be adiabatically connected to usual (topologically trivial) insulators and semiconductors. Much like the quantum Hall and quantum anomalous Hall effects, the quantum spin Hall effect also finds connection to topology to explain its many interesting features. After establishing key concepts related to topological materials in general and quantum spin Hall effect in particular, this thesis begins an investigation into electron-hole correlations in the quantum spin Hall effect of band-inverted electron-hole bilayers. The Coulomb interactions favors the formation of excitons, a pair of electron and hole from the conduction and valence bands, respectively, that condense to form a highly coherent phase. Excitonic correlations enrich the topological phase diagram of quantum spin Hall insulators by inducing an insulating phase with spontaneously broken time-reversal symmetry between the trivial and quantum spin Hall phases. One of the paradigmatic features of topological phase transitions in correlation-free topological insulators is the bulk-gap closing. However, the presence of excitons lead to a transition where the bulk-gap does not close. This could be interpreted as an effort by the system to minimise energy during the topological transition. There are multiple, recent experimental observations pointing out the existence of excitons in these systems but so far the spontaneous time-reversal symmetry breaking has not been directly observed. In the original work carried out for this thesis, we propose an experimental set-up to observe this time-reversal symmetry broken phase. Numerical experiments of transport in a Corbino disc measure bulk and edge conductances and confirm that the topological phase transition manifests without bulk-gap closing. Moreover, we also propose to utilize the system in its broken time-reversal symmetry state, together with an s-wave superconductor, to create, probe and manipulate the appearance of Majorana zero modes. We find, both numerically and analytically, the existence of Majorana zero modes at the interface of an s-wave superconductor and a time-reversal symmetry broken insulator. We provide an experimental configuration of a superconductor/TRS broken insulator/superconductor Josephson junction to observe 4π Josephson current, which is indicative of the Majorana zero modes residing at the interface. Finally, we also propose how to manipulate the quantum information stored in the Majorana zero modes and read out the state of the topological qubit.

Tania Paul