# NOVEL BOUND STATES AND THEIR MANIPULATIONS IN SUPERCONDUCTOR/DILUTED MAGNETIC SEMICONDUCTOR HYBRIDS AND MESOSCOPIC SUPERCONDUCTORS

Abstract

by

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Superconductors, diluted magnetic semiconductors, and ferromagnets have dramatically different properties, particularly in the way they respond to an external magnetic field. By using modern molecular beam epitaxy or lithography techniques, hybrid materials with above mentioned constituents can be fabricated. These composite materials show novel, emergent properties which do not exist in any of the homogeneous, single-phase components. In this thesis I investigated diluted magnetic semiconductor/superconductor hybrids, as well as ferromagnet/superconductor hybrid systems. Besides hybrid samples, single-phase material with mesoscopic size can also harbor novel states that are vastly different from bulk states. In contrast to the hybrid materials, where the proximity of the other phase provides confinement, in mesoscopic superconducting samples, the geometric confinement plays the role of the ingredient that causes emergent behavior. Motivated by the similarity between hybrid and mesoscopic systems, in this thesis I study mesoscopic superconductors as well. We discovered that mesoscale superconductivity can host not only regular vortex matter, built up by singly quantized vortices, but also exotic phases

containing giant vortices with vorticity greater than one. Such exotic phases cannot be found in bulk superconductors.

I studied the diluted magnetic semiconductor/superconductor hybrid system that can host and allow for the manipulation of spin-polarized bound states. In particular, I investigated the effects of impurities on such spin-polarized states. My results have important experimental implications as they predict robust spin textures even for less than ideal samples.

I will also present a study of a ferromagnet/superconductor hybrid system. It turns out, that one can tailor how a nearby ferromagnet suppresses the superconductivity, by changing the sample geometry and the external magnetic field. These parameters allow us to "design" the superconductign order parameter landscape with an unprecedented control. In particular, I investigated a superconductor film with a nanometer-sized ferromagnetic disc on top of it. The ferromagnetic disc creates a sombrero-shaped superconducting order parameter landscape. I show that in this geometry the Andreev bound states are trapped in a ring. Furthermore, I show that the quantum mechanical problem of Andreev bound states in such a potential can be mapped onto a the well-known problem of a quantum rotor. If a transport current is applied, the quantum rotor is exposed to an effective gravity and becomes a quantum pendulum. For pulsed current, the problem can be mapped onto a kicked rotor. I also show that the pendulum can also be driven with an external $AC$ magnetic field, and that a quantum inverted pendulum can be stabilized.

For the mesoscopic superconductor, I investigate how the density of states evolution for a multi-to-giant-vortex transition. Accordingly, I propose that the transition can be detected using high precision calorimetry and magnetometry measurements. Our results provide a clear prediction and are immediately relevant to the currently available experimental techniques.

The overarching theme presented in this thesis can therefore be formulated as follows: $(a)$ I am exploring the conditions (such as geometric confinement and the proximity of another ordered state) leads to exotic vortex phases and order parameter landscape, and $(b)$ provide a detailed quantum mechanical description of the electronic states hosted by the novel vortex matter.