Spin and charge Josephson oscillations

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State of the Art

Whereas electronics is the foundation for modern technology, the field of spintronics has in the recent decades proven to hold a real potential for generating technological advancements that may not only complement, but even replace conventional semiconductor-transistor based devices. The giantmagnetoresistance (GMR) effect is one of the most well-known direct implementation of spintronics in everyday appliances, in this particular case pertaining to harddrive technology and magnetic random access memory.

The general objective of spintronics is to find ways to generate, manipulate, and detect spin flow. At first glance, spintronics might seem completely incompatible with superconducting order since superconductors in general expel magnetic fields and are comprised of spinless Cooper pairs as the fundamental building block. Remarkably, it turns out that superconductivity can adapt to the presence of magnetic order by creating an unusual type of superconductivity known as odd-frequency pairing. This type of pairing is robust not only toward impurity scattering, but also toward the paramagnetic limitation of a magnetic field. Such unusual superconductivity may be generated in bilayers consisting of a superconductor attached to a ferromagnet.

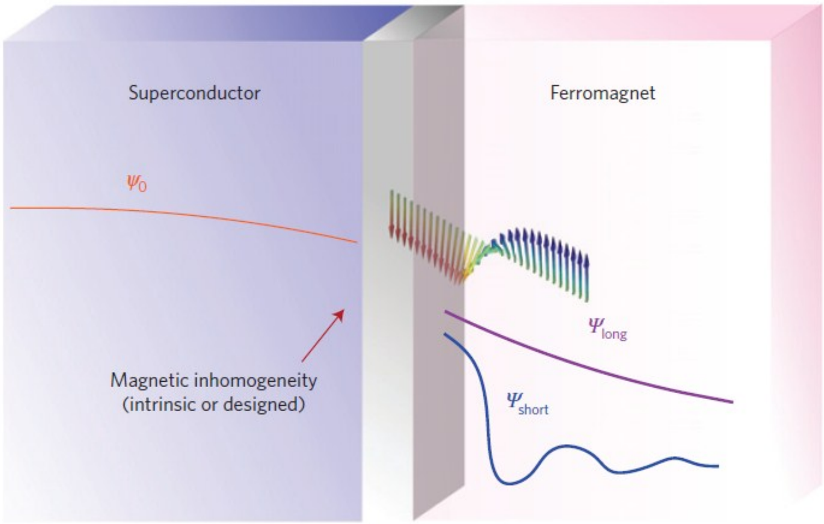

Figure Caption: *Starting out with a conventional superconductor that proximity couples a homogeneous ferromagnet, the superconducting correlations rapidly decay in an oscillatory way in the ferromagnet. In the presence of a magnetic inhomogeneity at the interface, spin-polarized triplet Cooper pairs emerge which can penetrate a long distance into the ferromagnet.*

Traditional studies that combine spintronics and superconductivity have mainly focused on the injection of spin-polarized quasiparticles into superconducting materials. However, a complete synergy between superconducting and magnetic orders turns out to be possible through the creation of odd-frequency spin-triplet Cooper pairs, as described above, which are generated at carefully engineered superconductor interfaces with ferromagnetic materials. Currently, there is intense activity focused on identifying materials combinations that merge superconductivity and spintronics to enhance device functionality and performance. The results look promising: it has been shown, for example, that superconducting order can greatly enhance central effects in spintronics such as spin injection, magnetoresistance, spin Hall effect, and even cause giant thermoelectric effects.

The intersection between superconductivity and magnetism represents an exciting research arena. On the one hand, it hosts very rich fundamental quantum physics - on the other hand, it also holds the potential for creating low-temperature nanoscale devices with improved functionality compared to using *e.g.* conventional transition metal ferromagnets. We believe that it is both timely and of importance to expand the knowledge on superconducting spintronics, exploring new physics and determining to which extent it is possible to achieve new types of functionality based on the spin degree of freedom.

Objective

The main objective of this master thesis is to study the quantum phenomenon of Josephson oscillations and to determine how not only charge, but also spin supercurrent oscillations can be controlled.

Josephson oscillations take place in a superconductor/weak link/superconductor junction where the weak link can be for instance a normal metal. When a voltage is applied to such a system, an oscillating supercurrent emerges. However, little is known about what happens when one incorporates magnetic elements (possibly inhomogeneous, such as domain walls) in such a system in terms of the Josephson oscillations. Is it possible to obtain a controllable **AC spin Josephson effect?** What are the quantum mechanical signatures of the spin-polarization in the supercurrent? These questions and more will be answered through this thesis work.

Timeline

During the autumn of 2016, the candidate will:

- Learn the fundamental theory of superconductivity, with particular emphasis on quantum transport.
- Become familiar with the technical framework used to describe such structures in the ballistic limit: the Blonder-Tinkham-Klapwijk framework.

During the spring of 2017, the candidate will

- Conduct a research project on a novel research topic involving AC spin Josephson effects.

Relevant introductory literature

Besides the introductory articles listed below, the candidate should read up on how to work with

- 2nd quantized Hamiltonians
- The fundamental theory of superconductivity and the Josephson effect
- Basic quantum field theory

This material can be found in conventional textbooks. Also, the curriculum and material (see webpage) in the course “Quantum theory for many-particle systems” TFY4210 at NTNU is highly relevant, which includes the topics listed above. Below is a suggested literature list, in recommended order:

1. Superconductivity: Physics and Applications (A. Sudbø and K. Fossheim).
   - Chapter 1
   - Chapter 2.1, 2.2
   - Chapter 3
   - Chapter 4.1-4.5

2. Review describing why spin-polarized supercurrents are of interest in spintronics. M. Eschrig, Physics Today **64**, 43 (2011).

3. The original article describing superconducting transport in hybrid structures. G. E. Blonder et al., Phys. Rev. B **25**, 4515 (1982).

4. How to compute AC supercurrents with the BTK-formalism. M. Hurd et al., Phys. Rev. B **56**, 11232 (1997).