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# SUMMARY

This thesis explores the phenomenon of triplet superconductivity, which refers to a condensate of equal-spin Cooper pairs (pairs of electrons with equal spin). While exceptionally rare in nature, triplet pairing of electrons can occur if either the temporal or spatial component of the superconducting wavefunction can be represented by an odd function. These are often referred to as odd-frequency and odd-parity triplets, respectively. We use hybrid magnetic devices to study the former, while the latter is investigated in mesoscopic structures of strontium ruthenate ($Sr_2RuO_4$).

### TRIPLET CORRELATIONS IN MAGNETIC HYBRIDS

While odd-frequency (even parity) triplet superconductivity has not yet been found by itself in nature, long-range triplet correlations can be generated in carefully engineered superconductor-ferromagnet hybrids. These spin-polarized Cooper pairs have become the centrepiece of the newly emerging field of *superconducting spintronics*, a new generation of technology that consumes little power and dissipates little heat, with applications in a wide range of subjects including state-of-the-art sensors, superconducting logic circuits, quantum computing and non-volatile cryogenic memories. Usually the focus is on the spin-polarization of the triplets, which can potentially enable low-dissipation magnetization switching. However, the fundamental mechanism for generating triplet correlations can also provide an exceptional level of control over superconductivity. We demonstrate this by combining state-of-the-art micromagnetic simulations with transport experiments in mesoscopic devices. In Chapter 4 we describe how to design and fabricate Josephson junctions in which the pathway of spin-triplet supercurrents through the junction can be controlled. This is demonstrated using a disk-shaped Josephson junction, where the barrier is a cobalt layer which contains a magnetic vortex with a core in the centre. We show how the supercurrent pathways can be regulated by moving the vortex with an applied magnetic field.

Generating long-range triplet correlations in a ferromagnet requires some form of magnetic inhomogeneity at the interface with a superconductor; and so far this has been realised with the use of multiple (at least two) ferromagnetic layers which have non-collinear magnetization. In Chapter 4 this was done with nickel contacts on top of the cobalt layer. Controlling the magnetization of individual layers however is a highly challenging task. A simpler method would be to use the spin texture of a single ferromagnet to realise the necessary magnetic inhomogeneity for generating triplets. This type of device, which we call the spin-textured Josephson junction, is described in Chapter 5, where we demonstrate how the triplet currents can be generated by the in-plane exchange field gradient of a ferromagnetic vortex in a cobalt disk. The devices show a remarkable capacity to control the phase, amplitude and spatial distribution of triplet supercurrent in a dynamic fashion.

The spin-textured junctions also have a promising potential as non-volatile superconducting memory elements. In this case, the maximum supercurrent which our junctions can sustain before leaving the zero-resistance state (also known as the critical current of the junction) depends on the configuration of the transport channels, which is determined by the position of the ferromagnetic vortex or vortices in the cobalt disk. In the absence of magnetic fields, there are a number of stable magnetic states in which the system can be prepared, each yielding a different value for the critical current (ranging from maximum to zero). We can therefore consider the value of zero-field critical current as a “bit”, which the junction can store (e.g. 0 for minimum critical current and 1 for maximum). While it is necessary for the device to be in the superconducting state to access (or “read”) the bit, the information is not lost when the system is warmed up to room temperature for extended periods of time.

### ODD-PARITY IN $Sr_2RuO_4$

$Sr_2RuO_4$ is one the handful materials known to exhibit odd-parity triplet superconductivity. In this particular case the superconducting wavefunction is expected to have a non-zero orbital angular momentum ($L = \pm 1$), which can be thought of as the electrons of the Cooper pair having a relative orbital motion, rotating either clockwise or anticlockwise. This orbital motion results in a handedness or “chirality”, where the two winding directions (left or right) constitute a twofold degenerate ground state for the superconducting condensate. An interesting consequence of this would be the emergence of chiral superconducting domains in the bulk $Sr_2RuO_4$ crystal, where the chiral states are segregated in space. Despite the efforts of the past two decades, a direct observation of such chiral domains is still lacking. In Chapter 7 we present a new approach to this, using transport experiments on high-quality mesoscopic structures of $Sr_2RuO_4$, where the domain configuration could be controlled by well-defined geometries, as shown by the theoretical simulations of the order parameter. In particular, we focus on the boundary between adjacent domains (the chiral domain wall), which acts as an unconventional Josephson junction due to the local suppression of the condensate. Chapter 7 examines this, using a mesoscopic ring prepared by structuring a single $Sr_2RuO_4$ crystal. Order parameter simulations predict this system to a have multi-domain ground state, with a domain wall crossing the arms of the ring, where it forms a pair of parallel Josephson junctions.

This is examined by our transport experiments, where we find distinct critical current oscillations when applying an axial magnetic field, similar to that of a DC SQUID with two symmetric Josephson junction.

One of the most fascinating aspects of a chiral domain wall junction is its Josephson energy profile as function of the phase difference of the condensate on both sides of the junction. Contrary to conventional junctions, the Josephson potential of a chiral domain wall has *two* minima with different energies as function of the phase difference $\varphi$ , resulting in one stable ($\varphi_0$) and one metastable ($\varphi'$) Josephson phase. Here $\varphi_0$ and $\varphi'$ are determined by the orientation of the domain wall, and can take on *any* values between 0 and $\pi$. We describe how this multi-minima Josephson potential would manifest itself as a multistage current-voltage characteristic, similar to the ones in our transport measurements.

In addition to making a compelling case for the existence of chiral domains in $Sr_2RuO_4$, this study presents a new outlook on the potential use of chiral domain walls as Josephson junctions with adjustable ground state energy. The current across a Josephson junction is driven by the phase difference between the leads, mentioned above. Usually, the ground state of a junction has a phase of 0 or $\pi$, both of which correspond to zero transport across the junction. In a chiral domain wall however, the ground state of the junction can be offset by a phase that is different from zero or $\pi$. This provides the conditions for an anomalous supercurrent to flow from one lead to another (at zero bias), which would make this one of the very few cases where both time-reversal and chiral symmetries are broken. In addition to the promise of rich physics, such systems are highly desirable for their potential as superconducting phase batteries, rectifiers, and future applications in quantum computing.