MSc project: Josephson radiation measurements

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Summary

Your task will be to investigate the presence of gapless Majorana bound states in topologically non-trivial Josephson junctions by measuring the junctions Josephson radiation. This will be realized using a radiofrequency pick up and amplification setup. Using a spectrum analyzer we identify frequency components of the amplified signal.
Topological Josephson junctions host Majorana zero modes whose non-abelian exchange statistics can be utilized in fault-tolerant topological quantum computation schemes. In Josephson junctions with topological insulator (TI) weak links (as schematically shown in Fig. 1 a)), they manifest as electron-hole bound states with a 4π-periodic energy phase relation. They become zero-energy states, when the phase difference of the superconducting leads equals $\varphi = \pi$ (see Fig. 1 b)). Conventional Andreev bound states are gapped at $\varphi = \pi$ and have a typical 2π-periodic bound-state energy-phase relation. For our investigations we will initially focus on Josephson junctions with a 3D TI weak-link. If initial experiments are promising, a natural next step would be to investigate Josephson junctions with weak-link materials of other topologically non-trivial nature (e.g. Quantum Anomalous Hall Insulators) or to investigate 3D TI nanowire/nanoribbon geometry Josephson junctions.

Keywords: **Josephson Junctions, Josephson Radiation, Andreev Bound states, Topological Insulator, Majorana Bound States, Quantum Anomalous Hall Insulator, radiofrequency detection and amplification**

Project Description

Before turning our attention to the investigation of topologically non-trivial Josephson junctions we will have to install, test and calibrate our experimental setup.

Installation: The experimental setup is schematically depicted in Fig. 1 c). The power of the emitted radiation is very small and needs to be amplified both at cryogenic temperatures (InP HEMT/LNF-LNC0.3 14B or LNF-LNC4 8F installed at 4K) as well as at room temperature. The radiofrequency signal is separated from the d.c. potential applied using a bias-T (QMC-BIASTEE-0.218SMA). The bias-T comprises a single input, two outputs passive device. One output is equipped with an in-line capacitance, for high-frequency components of the signal to pass, while blocking low frequency components. On the other hand, the second output port has an in-line inductance for low frequency components to pass only. Within the amplification chain of the high frequency components of the signal the circuit is equipped with a single (or two series) isolator. The isolator is a passive device that will let a signal pass in one direction while it mostly reflects any high-frequency noise from the other side. Additionally, in order to avoid high-frequency noise from entering the system als good filtering of the lines carrying the d.c. voltage bias has to be implemented. Therefore we use a filter cascade of homemade pi-filter elements at room temperature as well as RC- (lowpass-)filter and silver matrix microwave filters (Basel Precision Instruments microwave filter/thermalizer) at cryogenic temperatures.

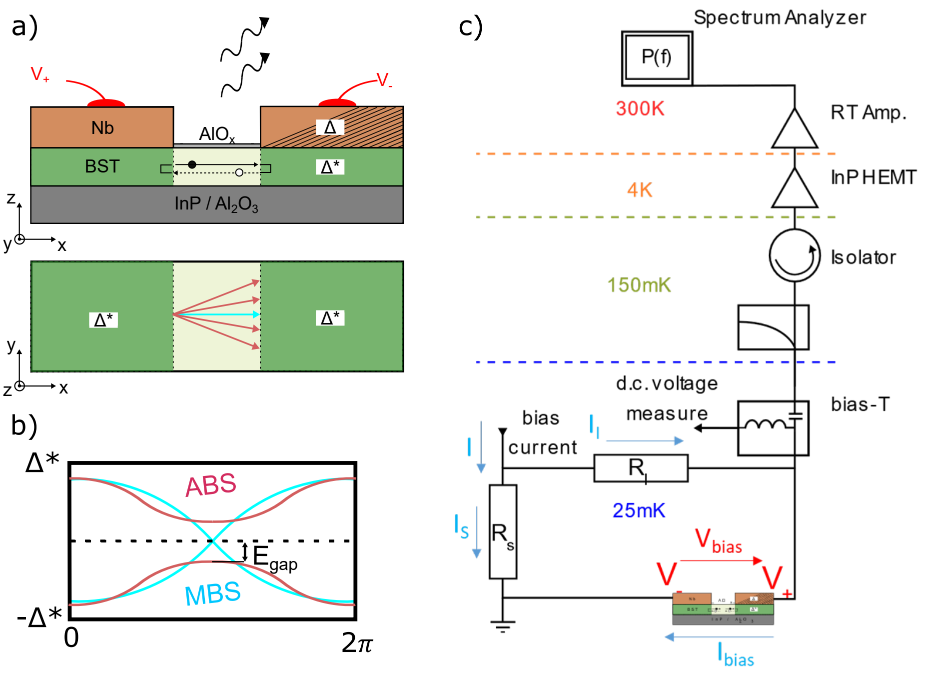

Figure 1: **Josephson emission experiment** a) Devices under test are lateral topological insulator Josephson junctions comprised of two superconducting contacts (Nb) on top of a MBE grown topological insulator thin film (BST, $(Bi,Sb)_2Te_3$). b) The bound state spectrum in the junctions is comprised of gapped Andreev bound states (red) and gapless Majorana bound states (cyan). c) Josephson emission measurement setup. The junction is voltage biased using a shunt resistor R_s and the d.c. current is measured through resistor R_I. The d.c. component of the signal is used to determine the junctions IV-characteristics and separated from the Josephson emission signal at the bias-T. The low power microwave signal is amplified, once at 4 K and again at room temperature before fed to a spectrum analyzer.

Room Temperature Testing: After installation of the measurement setup we have to test the components installed. Therefore we use a vector network analyzer (VNA) that can measure the frequency dependent transmission and reflection properties of the setup.

Calibration at cryogenic teperatures: Josephson radiation measurements on conventional Al/AlO$_x$/Al tunnel junctions could be useful as control experiments in order to calibrate our experiment. Experiments in the Ando lab have recently shown that in tunnel junctions, higher-order Josephson terms (e.g. $\cos 2\varphi$) are not negligible and could be investigated in more detail here. The critical current of these tunnel junctions is comparably large and the power of the radiofrequency pick up should be sufficiently large. At the same time, Al/AlO$_x$/Al tunnel junctions clearly do not host Majorana bound states.

Research Background

Topological insulators have, compared to trivial insulators, an inverted band structure due to a strong spin-orbit interaction of charges within p-orbitals energetically closest to the Fermi energy (*1*). Well-known examples are the heavy-element binary compounds Bi_2Te_3 (BT), Bi_2Se_3 (BS), Sb_2Te_3 (ST) as well as ternary $(Bi_xSb_{1-x})_2Te_3$ (BST) and quaternary $(Bi_xSb_{1-x})_2(Te_ySe_{1-y})_3$ (BSTS) alloys of these chalcogenide V-VI compounds. The topologically non-trivial band ordering evokes gapless surface states at the interface towards a topologically trivial insulator as bands of the same parity need to connect. This gives rise to metallic surface states with linear Dirac dispersion at the interface of a TI towards a trivial insulator. Due to the strong spin orbit interaction on atomic level, the spin of charges in TI thin-films is also found to be dependent on the charges momentum within the crystal. In three dimensions the band dispersion of the surface states resembles a Dirac cone as schematically depicted on the left side of Fig. 2.

Just recently the **quantum anomalous Hall state** (quantum Hall state with intrinsic magnetic moment) has been experimentally verified in magnetically doped topological insulator materials. These materials include Cr- and V-doped $(Bi,Sb)_2Te_3$ (BST). When magnetised below the Curie

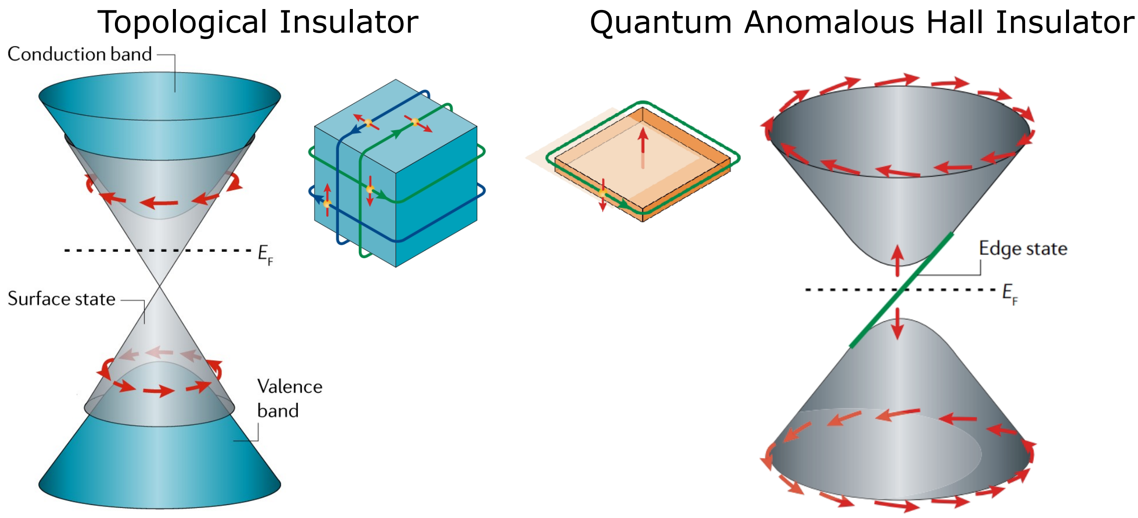

Figure 2: Schematic representation of the surface and bulk state dispersion in topological insulators (TI, left) and the surface and edge state dispersion in quantum anomalous Hall insulators (QAHI, right), adapted from (*7*). The surface state dispersion of the TI is represented by the Dirac cone shown in grey, highlighting the helical spin dispersion of surface charges. Due to a magnetic exchange interaction in magnetically doped TIs an energetic gap in the surface state spectrum around small momenta at the Dirac point established. Within the magnetic gap chiral QAH edge states arise (green).

temperature (20-30 K) the magnetization of the magnetic dopants within Cr-/V-BST perpendicular to the surface will open an exchange gap around small momenta at the Dirac point of the topologial insulator surface states. Within the exchange gap chiral anomalous Hall edge states give rise to a quantized Hall resistance of h/e^2. The surface state dispersion including the magnetic exchange gap are schematically depicted in Fig 2 (right side).

The bound-state periodicity of Josephson junctions can and has previously also been probed in **Shapiro step measurements**, where the junctions response at finite voltage biases under microwave radiation is measured. The external microwave bias can be applied using a microwave source connected to the directional coupler within the microwave detection setup. When the junctions frequency within the finite-bias state is in resonance with the external microwave drive, Shapiro steps occur at $V_0 = i \cdot hf/2e$, where $i = 1, 2, 3, ...$ for conventional Andreev bound states and $i = 2, 4, 6, ...$ for Majorana bound states. Missing odd-order Shapiro steps have been reported in a multitude of topologically non-trivial systems, which mostly reported a single missing odd-order Shapiro step. Beside the presence of Majorana bound states Landau-Zener transitions (*2*) and self-heating near the superconducting switching current (*3*) have early been suggested to mimic 4π-periodic bound states or hinder the observation of low-order Shapiro steps, respectively. Recent experiments suggests that Shapiro step measurements with even higher order missing odd steps are not an unambiguous evidence for Majorana bound states in the respective Josephson junctions as they have as well been identified in topologically trivial systems (*4*, *5*). Reasons are due to the strongly non-linear response of a Josephson junction when subject to a microwave excitation. Compared to Shapiro steps, measuring the Josephson emission within the finite bias state of the junctions directly (*6*) is a more reliable passive probe of the bound state periodicity, without the additional complexity of an external oscillating drive.

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