Measuring Andreev Reflection in Nb/Cu and Nb/Ni Quantum Point Contacts

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We measured the energy spectrum of a quantum point contact made from a niobium wire tip on two foil samples, copper and nickel, in order to detect Andreev Reflection. By measuring the differential conductance at 4.2K, we effectively obtain the density of states in our system. We observed in both samples an increase in density of states at zero energy within the superconducting gap, indicating Andreev Reflection. Since nickel is a ferromagnetic material, we expect its spin polarization to produce less Andreev Reflection states than copper, which is non-ferromagnetic. We confirm that the Andreev states are indeed reduced in the nickel sample by the normalized conductance of the two samples. By fitting our spectra to the Blonder-Tinkham-Klapwijk (BTK) model, we determine a superconducting gap energy of $\Delta = 1.23 \pm 0.05$ meV for copper. We calculated the effective barrier height parameter Z to be -0.04±0.05 for copper. The electron state lifetimes were estimated to be 615± 38 fs.

I. BACKGROUND

Andreev Reflection is a charge transfer process where normal current in a metal is converted to supercurrent in a superconductor. It is a process that contributes to the density of states at energies below the superconducting gap. The reflection occurs when an electron from the normal metal incident on the superconductor causes a Cooper Pair to form within the superconductor. By charge conservation, a hole is reflected back in the normal metal. This process of reflection thus transfers a total charge of $2e$ across the two materials.

Andreev Reflection can be induced when a fine superconducting tip is placed into contact with a normal metal. At low temperatures, the density of states approaches the conductance of the point contact, thus by measuring the differential conductance while scanning through a range of energies, we obtain the energy spectrum of the system. We attempt to measure the energy spectrum due to Andreev Reflection with this method.

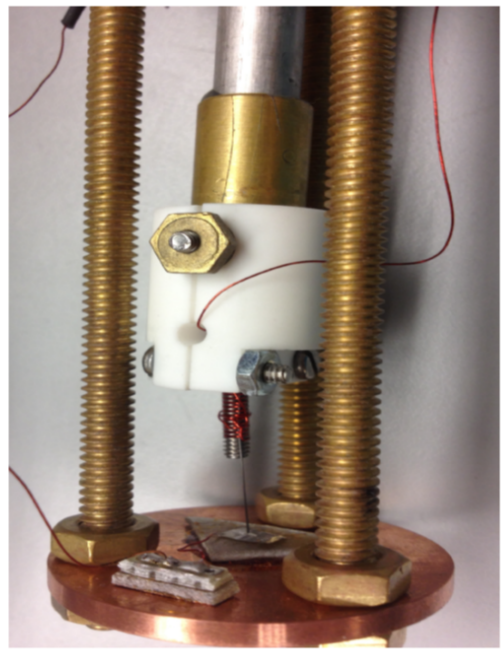

Figure 1: *Mechanical setup of the quantum point contact*

BTK MODEL

In a superconductor-normal metal point contact, transmission, reflection and Andreev reflection occur at the tunneling junction. Reflection can occur at every energy, and transmission only occurs at energies above the superconducting gap. However, if the tunneling barrier is low enough (less than superconducting gap size), Andreev reflection can occur through the formation of Cooper Pairs. In the case of non-spin polarized materials, the energy spectrum can be modeled with the BTK theory, which accounts for the density of states for electron spins. The formulation for solving the Bogoliubov-de Gennes (BdG) equations is given in a previous paper [4]. The solution yields the density of states as a function of electron energy. At low temperatures, the density of states approaches the conductance, so we can measure the conductance experimentally to determine the density of states. The differential conductance G is the derivative of the voltage response V with respect to current I, and can be written as

$$G_{\mathrm{NS}} = \left.\frac{dI_{\mathrm{NS}}}{dV}\right|_{T=0} = \alpha\left(1 + A[E] - B[E]\right) \qquad (1)$$

where A and B coefficients are given in a previous paper [4]. This model has four experimental parameters. The first is the proportionality constant α. The second is Γ, which indicates the inverse of the lifetime of the electronic state,

$$\Gamma = \frac{\hbar}{\tau} \quad (2)$$

Delta is the superconducting gap size. Z is the ratio between barrier height, H, and the fermi velocity of the electrons in the sample, $v_{\mathrm{F_s}}$. That is to say,

$$Z = \frac{H}{\hbar v_{\mathrm{F_s}}} \quad (3)$$

At low temperatures, the density of states approaches the conductance, so we can measure the conductance experimentally to determine the density of states. Using these four fitting factors, we can obtain an estimate of the electronic state lifetime, barrier height and superconducting gap size. However, for spin-polarized materials, the overlap between spin up and spin down bands at zero energy is reduced [3], thus there are fewer states available for Cooper Pair formation at zero energy, so we expect less Andreev reflection.

METHODS

We chose niobium (Tc 9.3K) as our superconducting tip with copper and nickel as our non-superconducting samples. We created the contact by applying a voltage across the niobium tip and metal sample. The tip and sample were then gradually brought into contact with a Newport DM-13 micrometer, as shown in fig.1. The measurements were made with a niobium-copper contact and a niobium-nickel contact. The niobium tip was fabricated by cutting a niobium wire at an angle with pruning shears. The niobium wire was 0.25 mm in diameter, with 99.99% purity. The metal samples were fabricated from copper and nickel foil of unknown purity. Details on the construction of our apparatus can be found in the supplementary material.

To measure differential conductivity as a function of applied voltage, we used a lock-in amplifier with a low amplitude sine wave modulation to measure $\frac{dV}{dI_{\mathrm{NS}}} I_{\mathrm{NS}}$, and then scanned through a range of voltages using a low frequency triangle wave to change the applied voltage. We used a 4 terminal measurement to reduce the effect of resistance due to wiring on the measurement of $\frac{dV}{dI_{\mathrm{NS}}}$. By placing the 4 terminal junction near the sample-to-tip contact region, we were able to simultaneously apply current and measure voltage across the sample with a minimal voltage drop between the two. We add a 4kHz lock-in amplifier sine wave modulation to a 1Hz triangle wave using a unity gain summing amplifier. Then we applied the resulting waveform across a voltage divider with our sample as the load resistance. The voltage drop across the sample is then measured with the lock-in amplifier. Accounting for the voltage divider, we can determine $\frac{dV}{dI_{\mathrm{NS}}}$. To quantify the relationship between $\frac{dV}{dI_{\mathrm{NS}}}$ and V, we measured the voltage across the sample and the lock-in output simultaneously using an oscilloscope. To improve the signal strength and to reduce the feedback between the lock-in amplifiers input and the rest of the circuit, a lock-in preamplifier/follower was inserted between the voltage divider and the lock-in itself. We also used 0.2MHz low-pass RC filters to reduce high frequency noise. Moreover, to prevent high frequency cross-talk between the lock-in preamplifier and the oscilloscope, separate filters are applied to each. See fig. 2 for a circuit schematic.

RESULTS

We plot the differential conductance of our point contact with respect to electron energy in fig. 3a) and 3b). For the copper sample, the contact resistance was around 5.8Ω. We observe a peak at zero energy with a +22% height difference from the conductance at high energy. For the nickel sample, the contact resistance was around 2.6Ω. We also observed peak at zero energy, this time with a smaller height of +8% of the conductance at high energy. Since the conductance is related to the density of states by equation (1), we fit our data with the BTK model with fitting parameters Γ, Δ and Z, as expressed in equation (1), (2), (3). The increased density of states at zero energy suggests the presence of Andreev reflection. The fitting parameters are listed in Table 1. From equation (3), the electronic state lifetime in the copper-niobium contact is estimated to be 615±38fs. Although the niobium-nickel contact cannot be modeled by simple BTK theory, as it involves spin polarization not accounted for by the BTK model, we show what the BTK model would have produced in the niobium-nickel contact for reference. As observed, the indicator of the effective barrier height Z is indeed low enough to be in the Andreev regime [4].

When we normalize the conductances of the two experiments with respect to the conductance at high

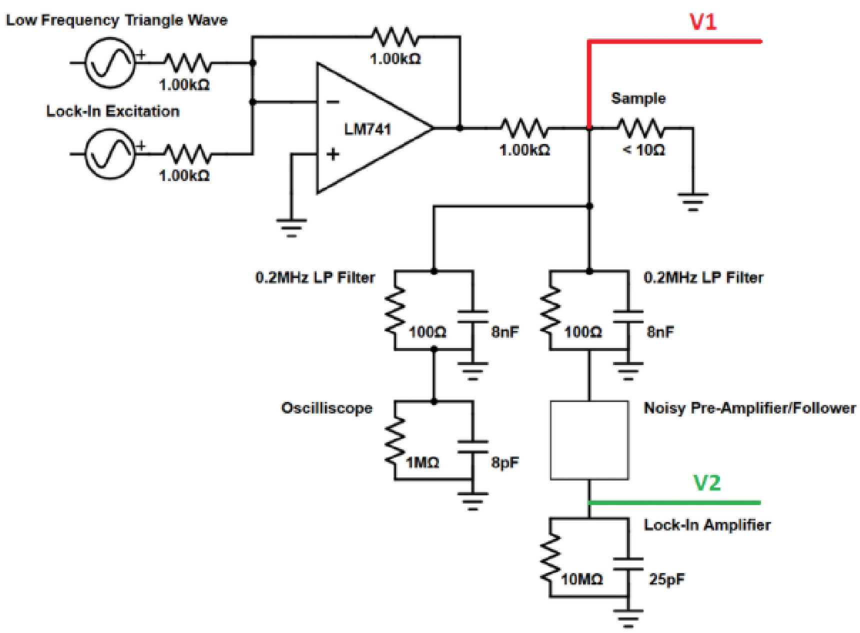

Figure 2: *Electronic setup of the point contact measurement: An oscilloscope was used to measure the output voltage from the sample,V1, simultaneously with the output of the lock-in, V2.*

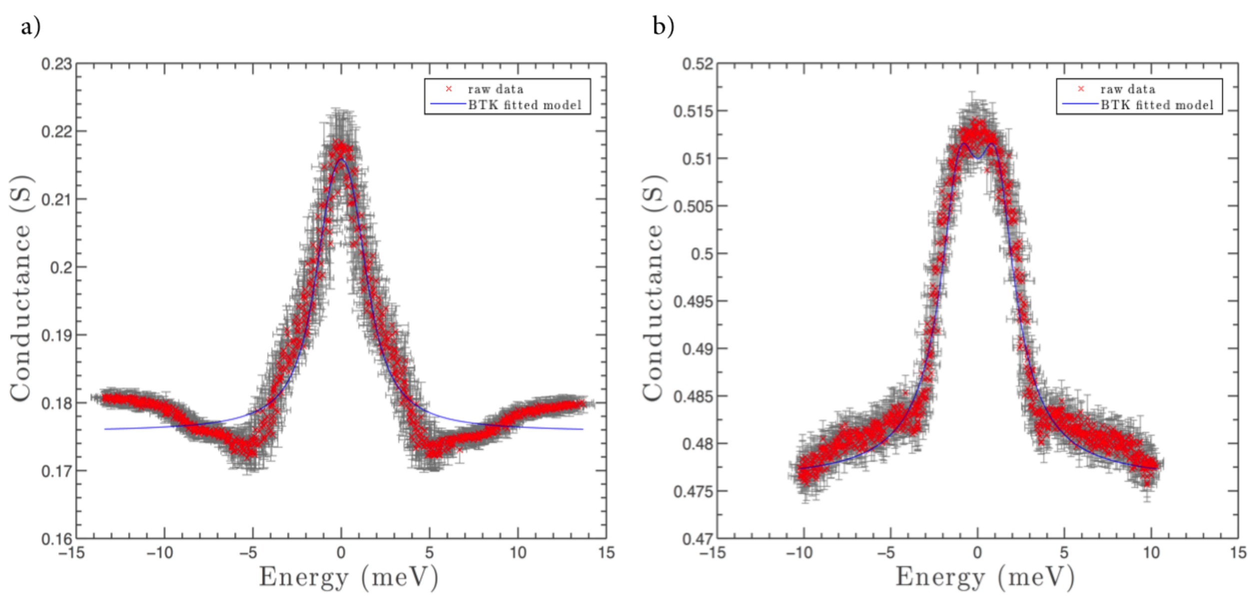

Figure 3: *a) Differential Conductance of Nb on Cu: A peak at zero energy is observed in a superconducting gap. b) Differential Conductance of Nb on Ni: A peak at zero energy is also observed, with smaller amplitude.*

	Cu	Ni
Γ (meV)	1.07± 0.07	1.07± 0.02
Δ (meV)	1.23± 0.05	1.2± 0.01
Z	-0.04± 0.06	0.4± 0.005
α	0.176± 0.001	0.526± 0.001

Table I: *Fitting parameters for the copper and nickel sample*

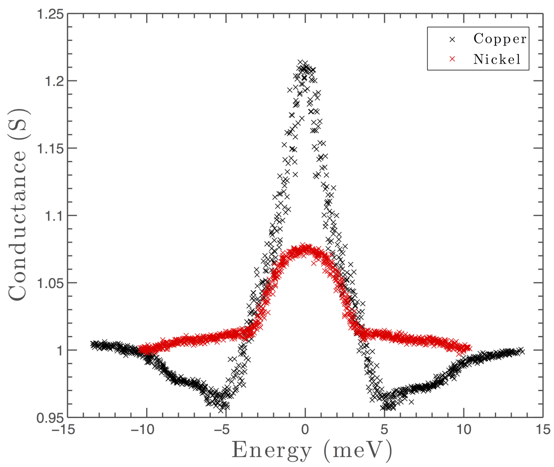

Figure 4: *Normalized conductance of copper and nickel.*

energy, we observe that copper has a stronger peak at zero energy than nickel, indicating stronger Andreev reflection, as shown in fig. 4. This was expected because nickel has 40% spin polarization, while copper is 0% spin-polarized, which allows more overlap of up and down spin electron energy bands at zero energy. This facilitates cooper pair formation and hence increases Andreev reflection. Lastly, we can also resolve finer features of the conductance curves, which is not captured by the BTK model. These features are due to the band structure of the niobium tip and metal samples.

CONCLUSION

We observed Andreev Reflection in the energy spectrum of niobium-copper and niobium-nickel quantum point contacts. By fitting our data with the BTK model, we measured a superconducting gap energy of $\Delta = 1.23 \pm 0.05$ meV for copper. We calculated the effective barrier height parameter Z to be -0.04±0.05 for copper, which puts us well in the Andreev Reflection regime, and we estimated the electron state lifetime to be 615±38 fs. by comparing the spectrum of copper and nickel, we found Andreev reflection to be attenuated in nickel, confirming that spin polarization reduces Andreev reflection states.

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