Superconducting Tunnel Junctions

Guide : Prof. Sangita Bose, CBS
Co-guide : Prof. Pratap Raychaudhuri, TIFR

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मौलिक विज्ञान प्रकर्ष केन्द्र

PPr801 Presentation
Gaurav Agarwal
P181211

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Trajectory

- BCS theory and the band gap.
- Tunnel junctions and their importance
- Experimental setup and techniques
- Data Analysis

Theoretical Backing

- **BCS Theory (1957)** [1]
  - Motivation
    - Experimentally T_c depended on atomic weight : connection of phonons and electrons.
    - Presence of critical temperature and magnetic field : Some thresholds/energy gaps.
    - Electrons seemed to occupy ground states - somewhat bosonic behaviour.
  - Proposed ‘**Cooper pairs’** : Electrons with opposite spins that pair up due to an attractive potential. These electrons are mathematically dealt with as ‘quasiparticles’. The pair leads to the somewhat bosonic behaviour.
  - The pair is unlocalised and interaction happens with phonons in the lattice.
  - Energy required to break these pairs gives rise to the **band gap (Δ)** and critical temperature (T_c).

[1] Bardeen, Cooper, and Schrieffer, ‘Theory of Superconductivity’ 1957

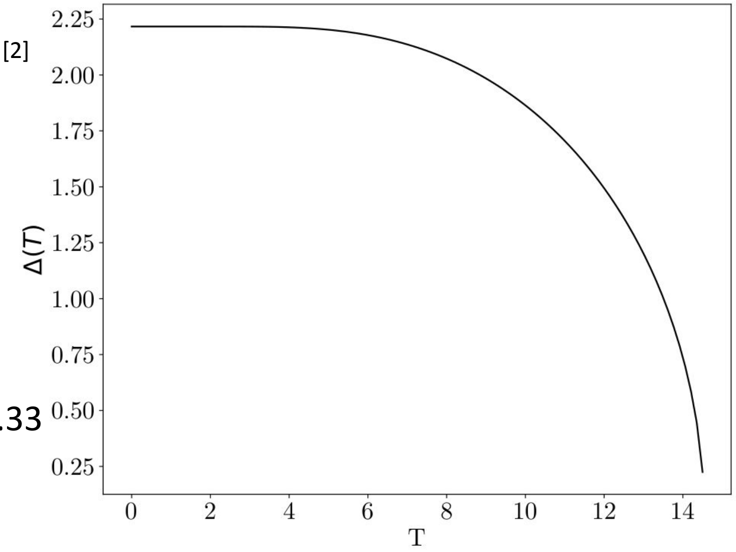
Theoretical Backing

- **BCS Theory (1957)** [1]
  - The band gap Δ depends on the temperature as:[2]

$$\frac{1}{N(0)V} = \int_0^{\hbar\omega_c} \frac{\tanh \frac{1}{2}\beta\left(\xi^2 + \Delta^2\right)^{1/2}}{\left(\xi^2 + \Delta^2\right)^{1/2}} d\xi$$

$$kT_c = \beta_c^{-1} = 1.13\hbar\omega_c e^{-1/N(0)V}$$

  - N(0)V is the inverse interaction strength set as 0.33 for weakly coupled superconductors.



[1] Bardeen, Cooper, and Schrieffer 1957
[2] Michael Tinkham. Introduction to superconductivity.

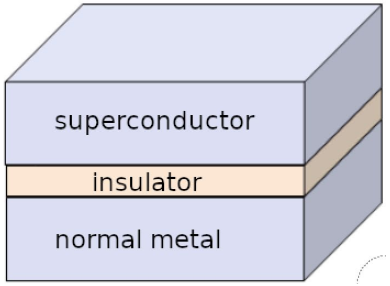
Tunnel Junctions

What they are:

- Sandwich of normal metal-insulator-superconductor (in our case).

Working:

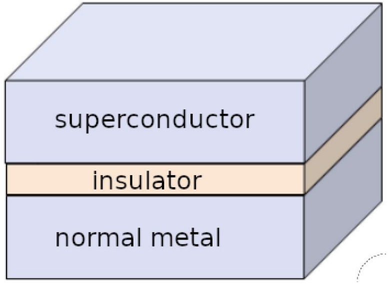
- Electrons quantum mechanically tunnel through the insulator and form a tunneling current.
- This tunneling current can be made directional by applying a potential difference.
- Presence of superconductivity introduces new physics.

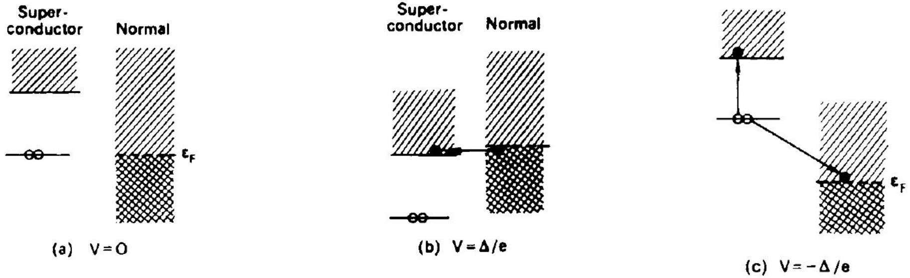


Tunnel Junctions

Use Case:

- Band gap prohibits the existence of any electrons up till a certain energy level.
- Electron cannot jump from normal metal to superconductor unless it has the band gap energy.
- Since we are adjusting relative potential difference across the tunnel junction, we can **measure the band gap**![1]





[1] Ivar Giaever. Physical Review Letters 5.4 (Aug. 1960)

Tunnel Junctions

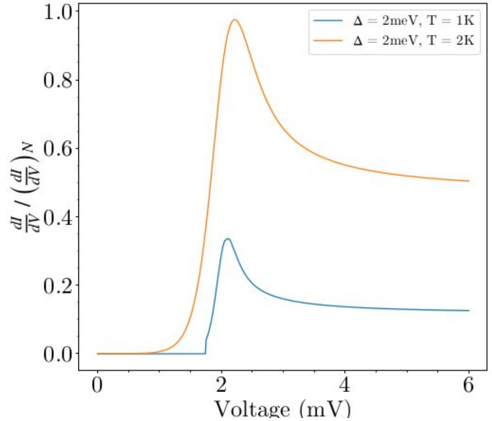
The tunneling current across the N-I-S junction is given by [1]:

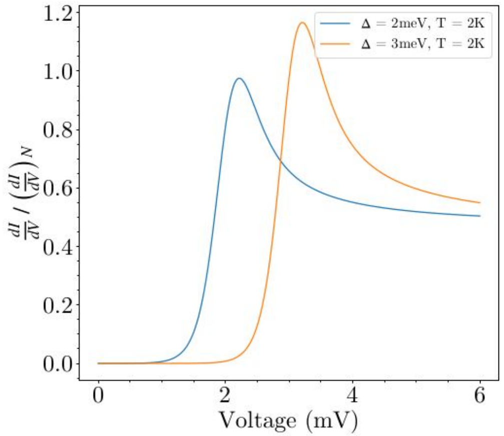
$$I_{ns} = A|T|^2 N_1(0) \int_{-\infty}^{\infty} N_{2s}(E)[f(E) - f(E+eV)]dE$$
$$= \frac{G_{nn}}{e} \int_{-\infty}^{\infty} \frac{N_{2s}(E)}{N_2(0)}[f(E) - f(E+eV)]dE$$

$$\frac{dI}{dV} = G_{nn} \int_{-\infty}^{\infty} \frac{N_{2s}(E)}{N_2(0)} f'(E+eV)dE$$

The curve broadening with temperature is due to finite-lifetime effects of the quasi-particles, and is phenomenologically dealt with[2]:

$$\frac{N_s(E)}{N(0)} = \begin{cases} \mathrm{Re}\left[\frac{Abs[E+i\Gamma]}{\sqrt{[E+i\Gamma]^2-\Delta^2}}\right], & (|E| > \Delta) \\ 0 & ,(|E| < \Delta) \end{cases}$$





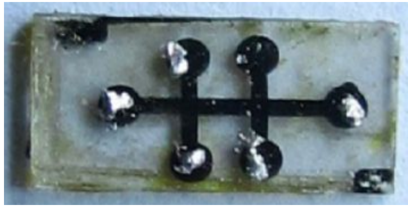
[1] Rose-Innes. Introduction to superconductivity.Oxford Pergamon Press, 1994.
[2] R. C. Dynes et al. “Direct Measurement of Quasiparticle-Lifetime Broadening in a Strong-Coupled Superconductor”. PRL 41.21 1978

Experimental Setup

Requirements: Fabrication, cryostats and instruments for measurement.

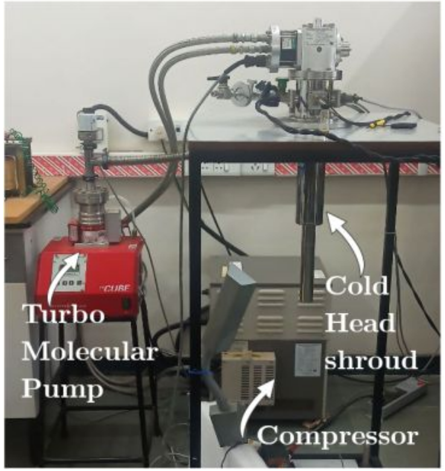
Fabrication:

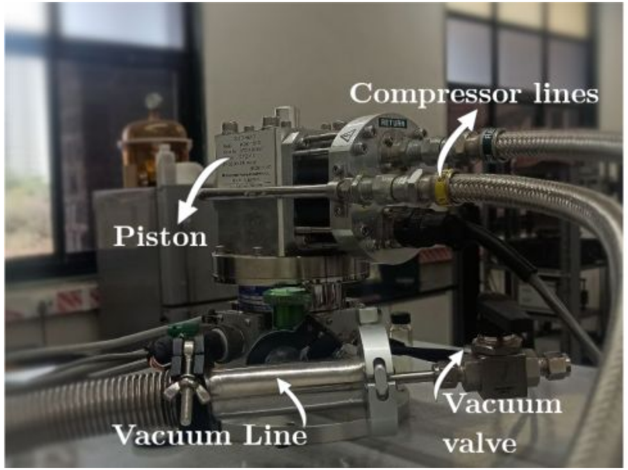
- ➢ Sputtering NbN on a MgO substrate at $600^{o}C$ and 7 mTorr $Ar+N_2$.
- ➢ Cooling to $250^{o}C$ and oxidation for 60 minutes.
- ➢ Deposition of Ag in an evaporation chamber.

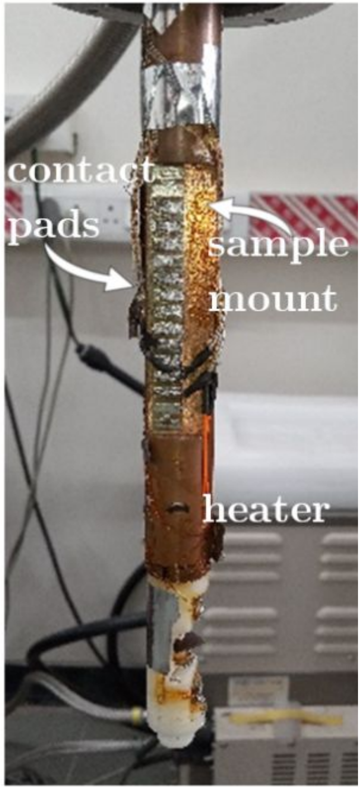


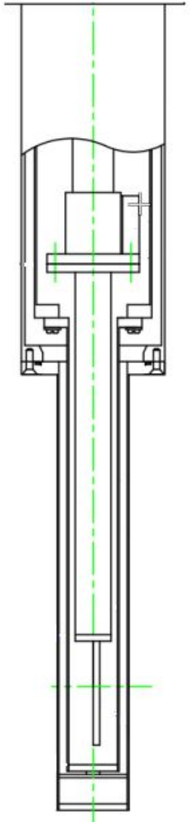
Experimental Setup

Cryostats: Two used - Dry and Wet systems.
Dry:







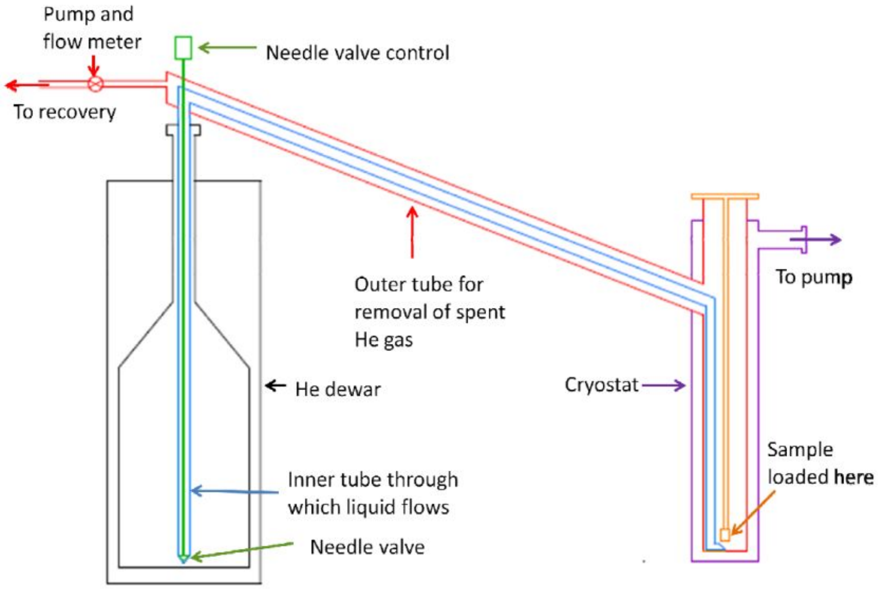


Vacuum achieved : 10^{-6} mbar.
Temperature achieved : 2.7 Kelvin.

Experimental Setup

Cryostats: Two used - Dry and Wet systems.

Wet:



Coolant : He4

Temperature achieved : 2.2 Kelvin

Electrical equipment and techniques used:

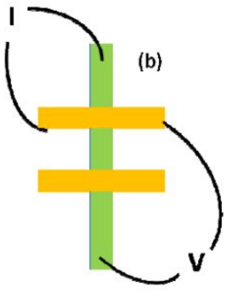
Soldering: We use In-Ag wire for soldering onto contact points.

Four-Probe Measurements: All Voltage measurements are done using the four probe technique for eliminating contact resistance.

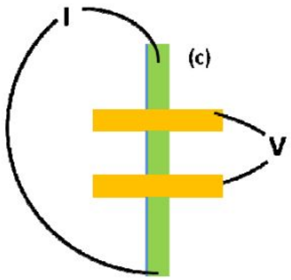
RT Measurements: Four probe measurement with constant current (~ 5 µA) and varying temperature done on the heating cycle. Telemetry includes resistance, temperature, current and potential drop. Used to determine T_C.

IV Measurements: Four Probe current v/s voltage measurement at constant temperature. ~ 30 readings are averaged for one data point.

Equipment used: PID based 335 Lakeshore temperature controller, and Keithley 2400 current source meters (measure l.c. 5µV, source l.c. 1µA).

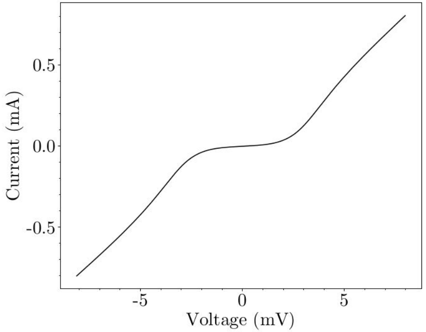


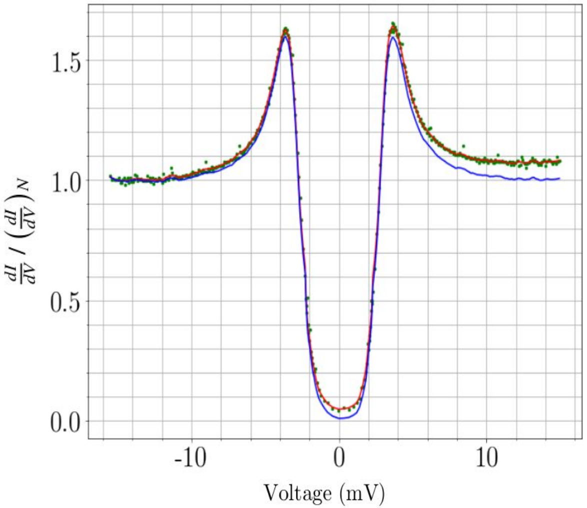
IV Measurement

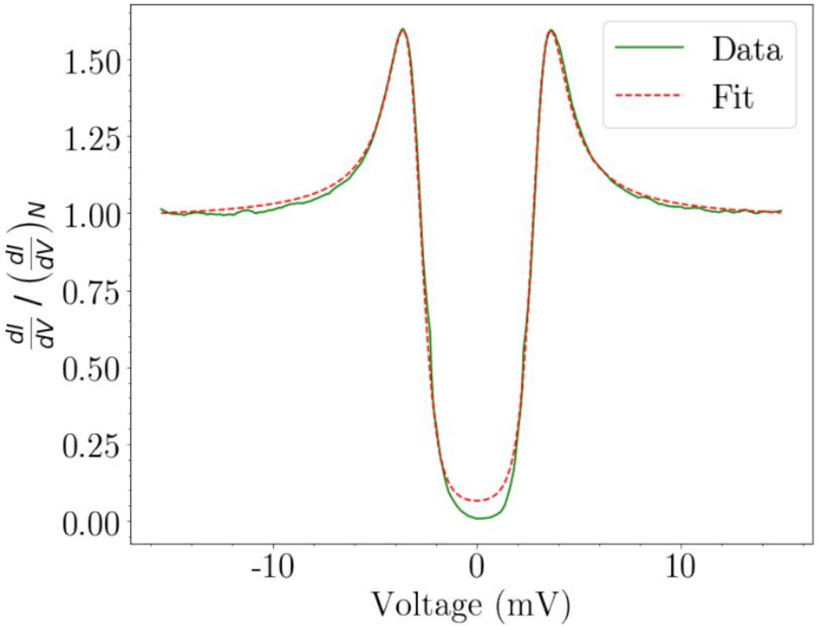


RT Measurement

Data Analysis - Example

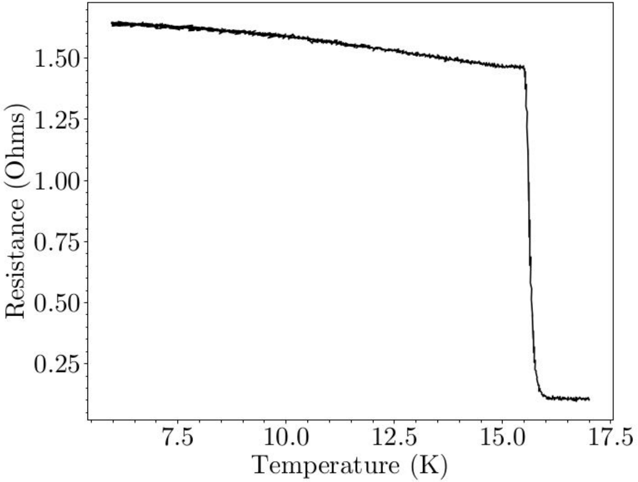






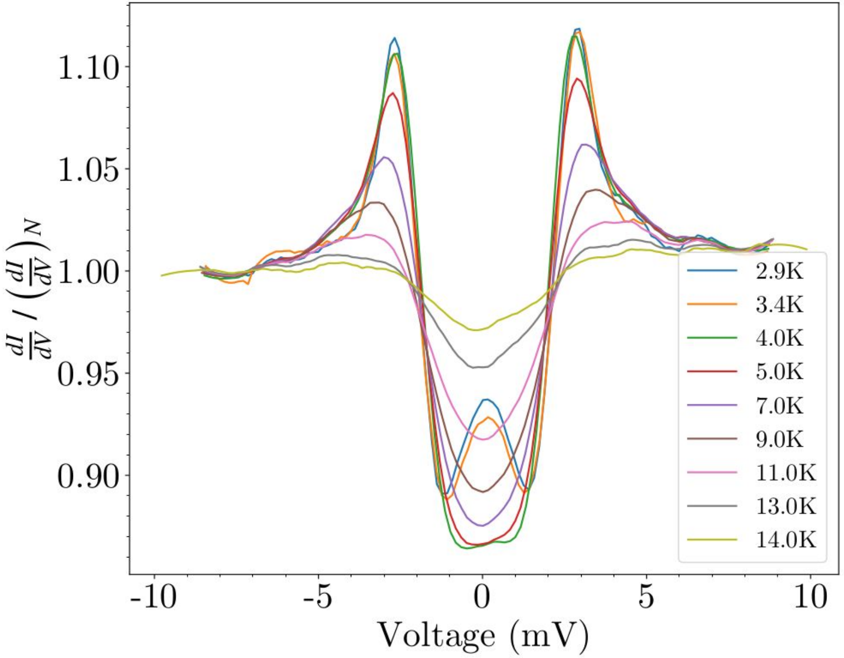
Data taken at 4 Kelvin.
Parameters Extracted:
Δ = 3.061 +/-0.171 meV
Γ = 0.004 +/-0.003 meV

Data Analysis - Tunnel junction #1



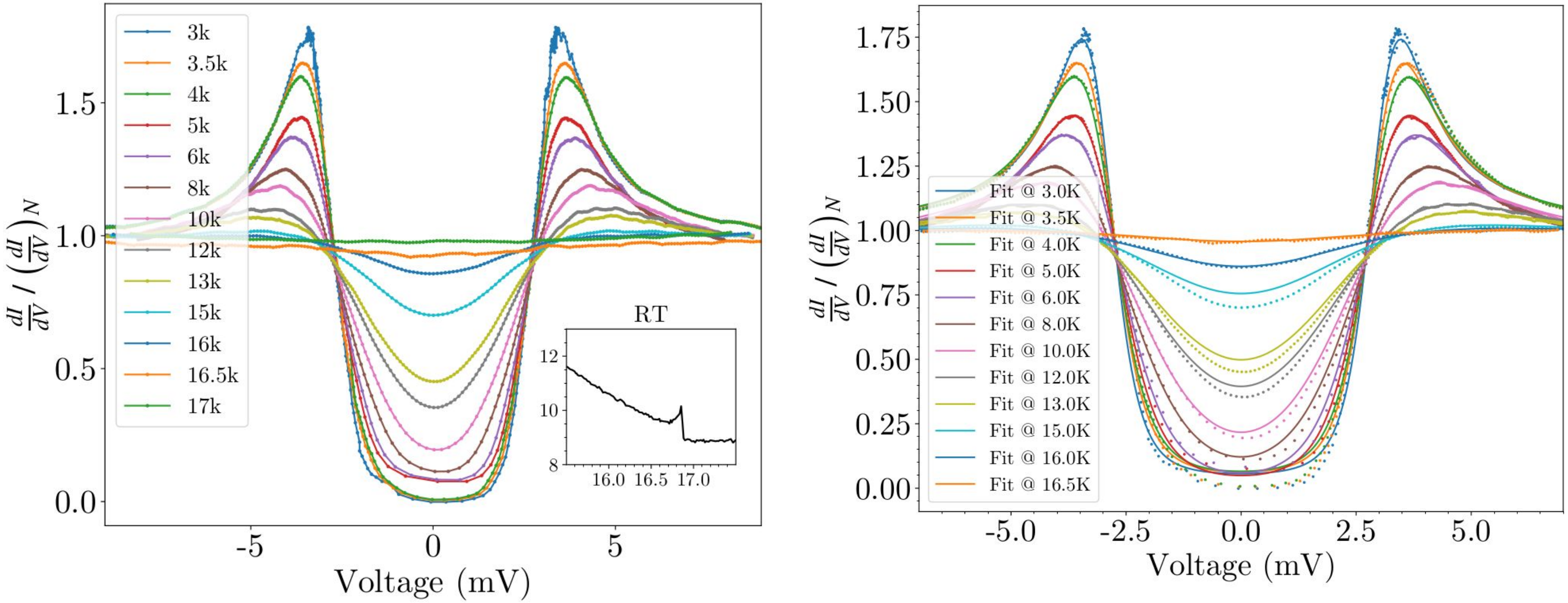
The resistance of the tunnel junction drops as soon as the NbN transitions to the normal state.

The Tc is found to be 15.8 Kelvin.

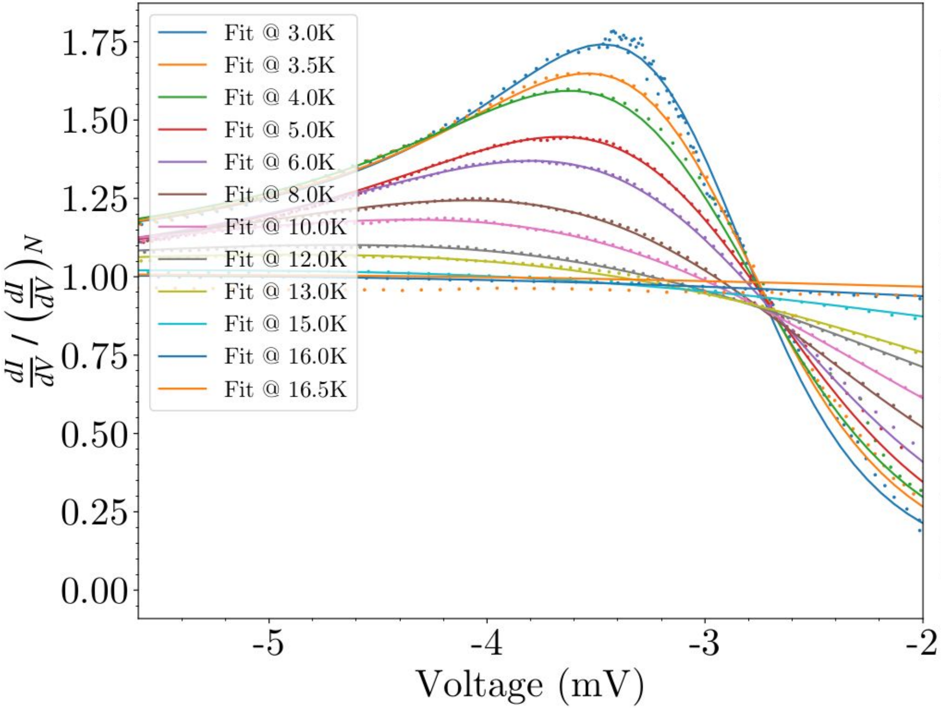


- Needs more smoothening
- Andreev reflections. Punctured oxide layer.

Data Analysis - Tunnel junction #2



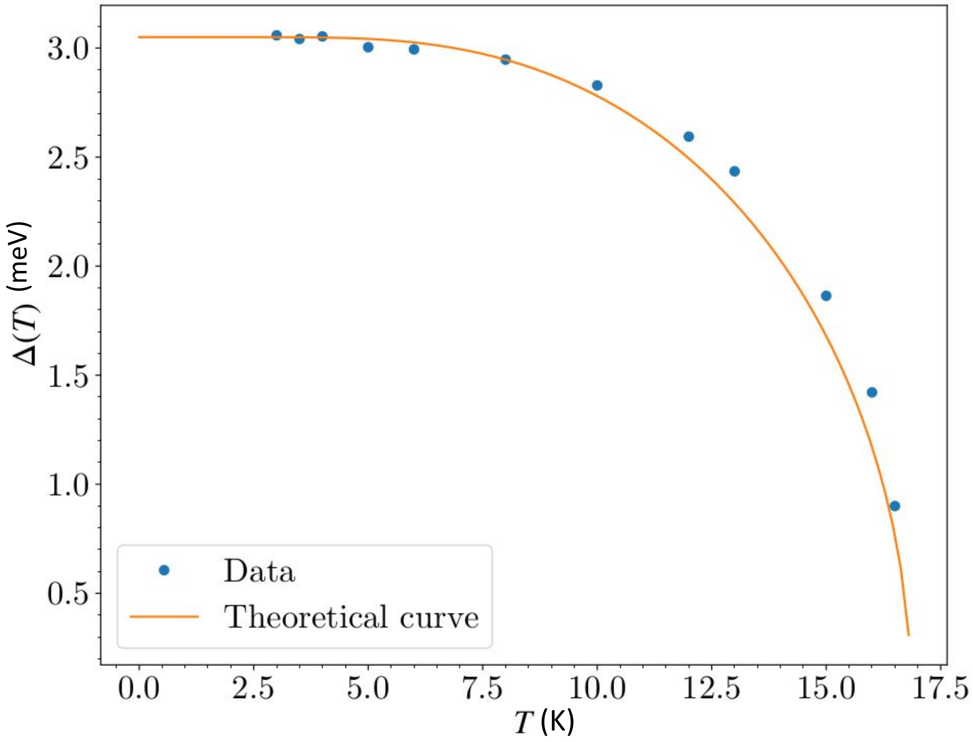
Data Analysis - Tunnel junction #2



Temperature (K)	Γ (meV)	$\pm\Gamma$	Δ(meV)	$\pm\Delta$
3	0.168	0.004	3.050	0.004
3.5	0.186	0.005	3.045	0.005
4	0.186	0.004	3.061	0.004
5	0.123	0.003	3.002	0.003
6	0.114	0.003	2.991	0.003
8	0.131	0.003	2.942	0.004
10	0.130	0.004	2.830	0.005
12	0.259	0.005	2.594	0.006
13	0.358	0.008	2.435	0.008
15	0.761	0.029	1.871	0.021
16	1.008	0.062	1.420	0.016
16.5	1.520	0.344	0.902	0.055

At temperature close to the critical temperature, Γ (quasiparticle lifetimes) blows up.

Data Analysis - Tunnel junction #2



Our analysis strongly agrees with the experiments we performed!

Tunnel Junctions

On the introduction of a magnetic field H, the quasiparticle energy becomes $E = (\epsilon_k^2 + \Delta^2)^{1/2} \pm \mu H$

Introduction of spin-polarisation in materials leads to[1]:

$$dI/dV \propto N_\uparrow |M_\uparrow|^2 \int_{-\infty}^{\infty} \rho_\uparrow(E,H) f'(E+eV)dE + N_\downarrow |M_\downarrow|^2 \int_{-\infty}^{\infty} \rho_\downarrow(E,H) f'(E+eV)dE$$

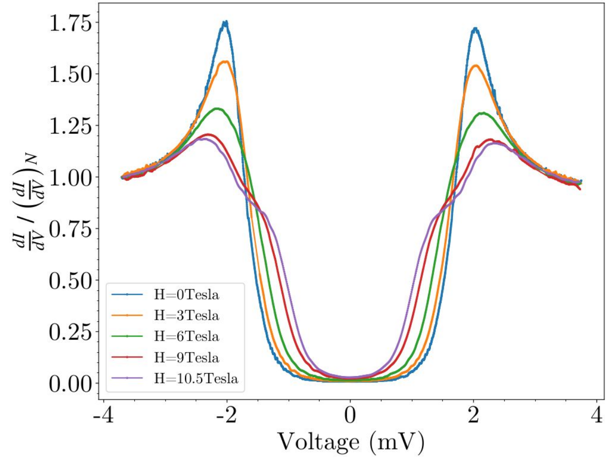
$$\rho_{\downarrow\uparrow}(E) = \frac{\rho(0)}{2} \operatorname{sgn}(E) \operatorname{Re}\left(\frac{u_\pm}{(u_\pm^2 - 1)^{1/2}}\right)$$

$$u_\pm = \frac{E \mp \mu H}{\Delta} + \frac{\zeta u_\pm}{(1-u_\pm^2)^{1/2}} + b\left(\frac{u_\mp - u_\pm}{(1-u_\mp^2)^{1/2}}\right)$$

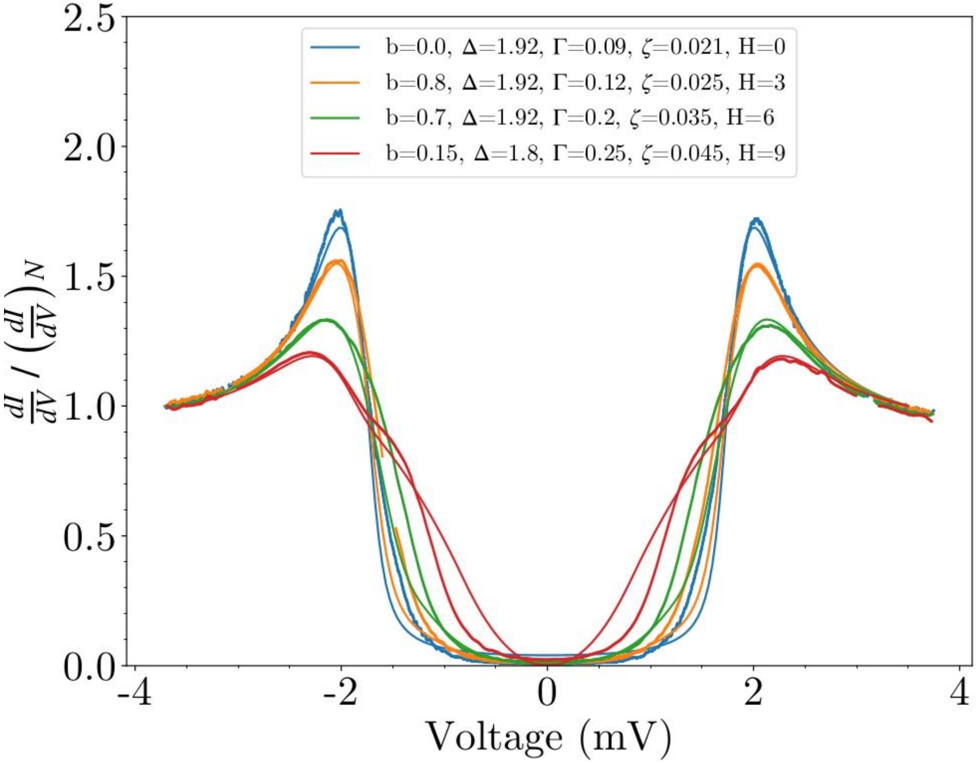
ζ is the orbital depairing parameter, and b is the spin-orbit scattering parameter.

[1] R. Meservey and P.M. Tedrow. “Spin-polarized electron tunneling”. 1994
[2] D. C. Worledge and T. H. Geballe. “Maki analysis of spin-polarized tunneling in an oxide ferromagnet”. 2000

Data Analysis - Magnetic Field

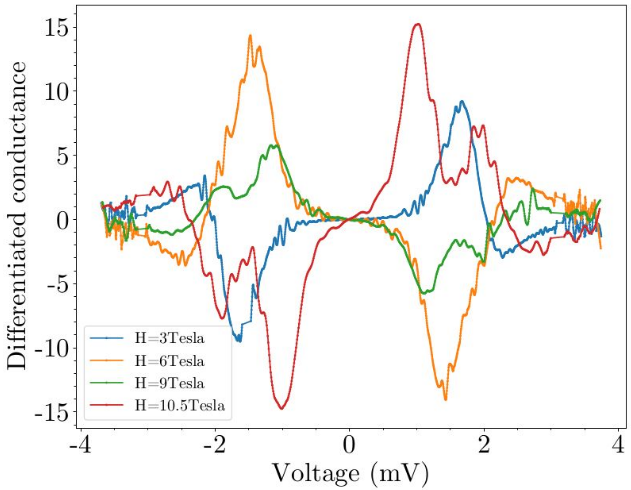


Data acquired at 0.4 Kelvin.[1]



[1] By Pritam Das, TIFR.

Data Analysis - Magnetic Field



The Zeeman splitting was found to be:
3 Tesla : 0.64mV
6 Tesla : 1.07mV
9 Tesla : 0.77mV
10.5 Tesla : 0.94mV

Conclusion

- Tunneling spectroscopy is important to study in superconductors.
- Demonstrated electron tunneling in NIS junctions.
- Extracted band gap energy Δ and quasi-particle lifetimes Γ in zero field.
- Band gap v/s T in perfect agreement with BCS.
- Used Maki theory to extract orbital depairing (ζ), spin-orbit scattering (b) and zeeman splitting.

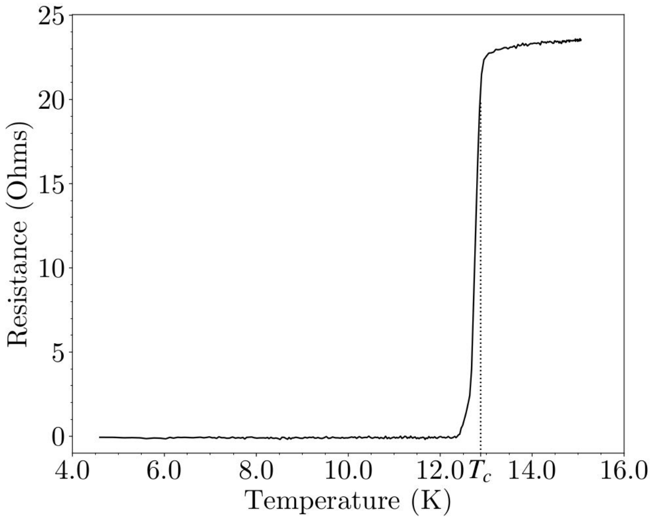
Future directions

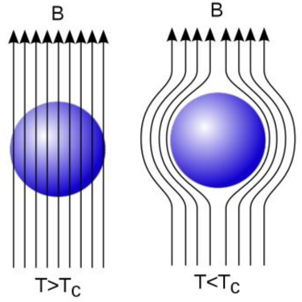
This analysis will further be applied to spin polarized tunneling, with ferromagnetic materials (Co) in place of normal metal (Ag).

Thank You!

Superconductivity

- Phenomenon of '**zero resistance**' below a certain temperature.[1]
- The temperature is called **critical temperature**, depicted as T_c.
- The sample admits **'perfect diamagnetism'**. It expels all the magnetic fields. Penetration depth λ is observed as the field decays inside.
- Cooling in the presence of magnetic field also leads to expulsion. It is called the **Meissner Effect.**





[1] H. K. Onnes, Commun. Phys. Lab.12,120, (1911)