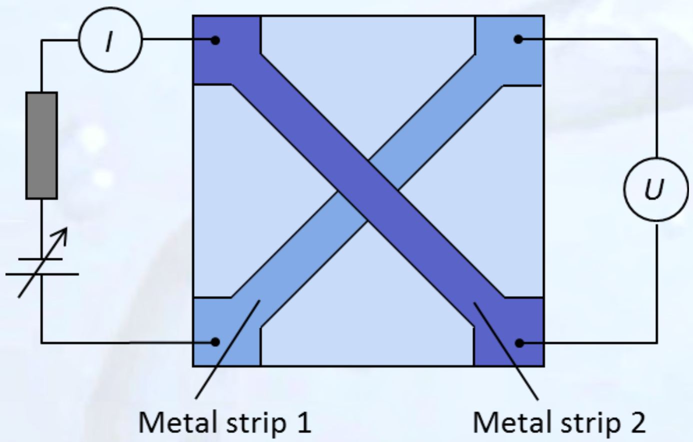
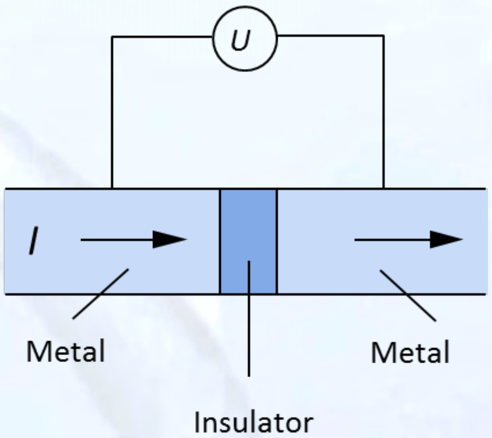
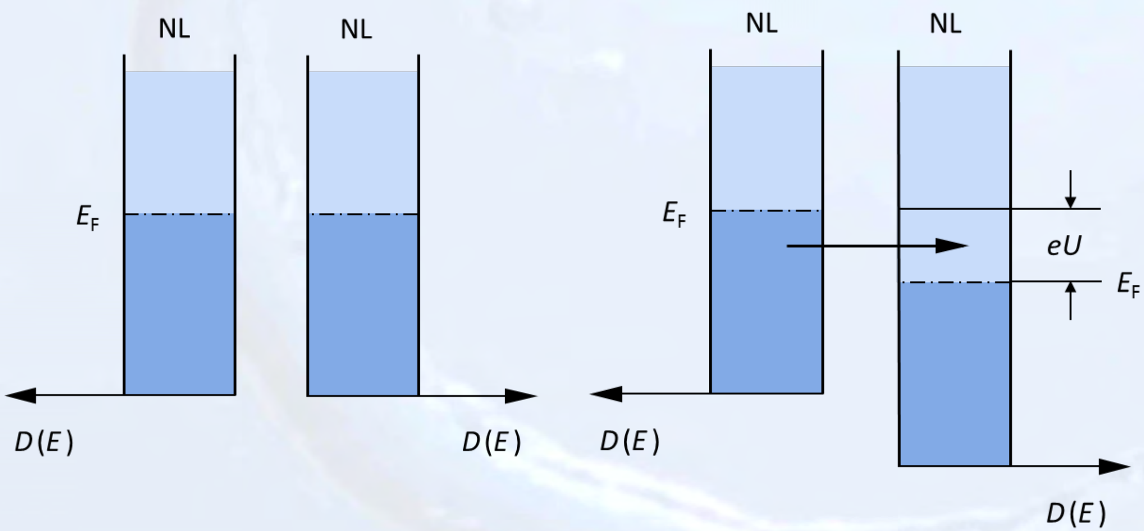
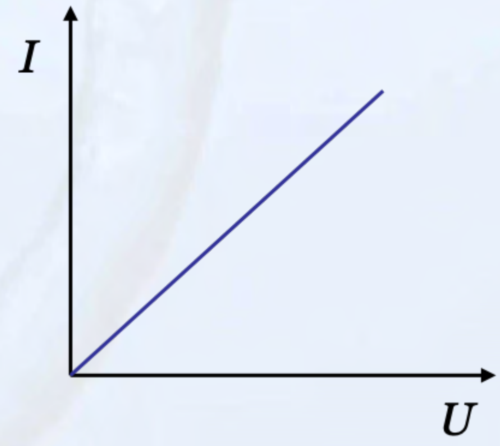
MVCMP-Tunneling Experiments - Normal Conductors



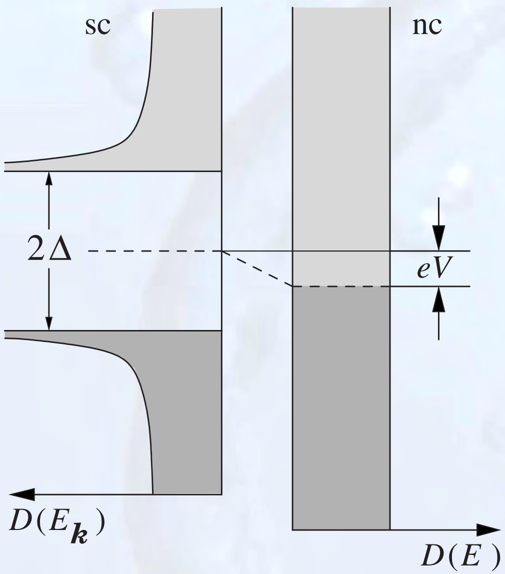




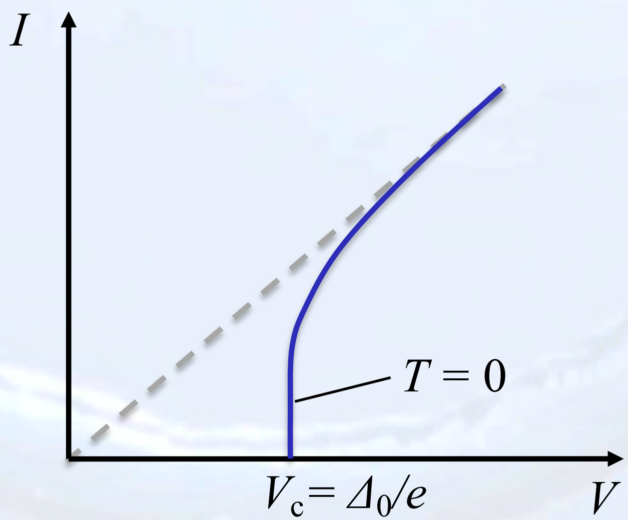


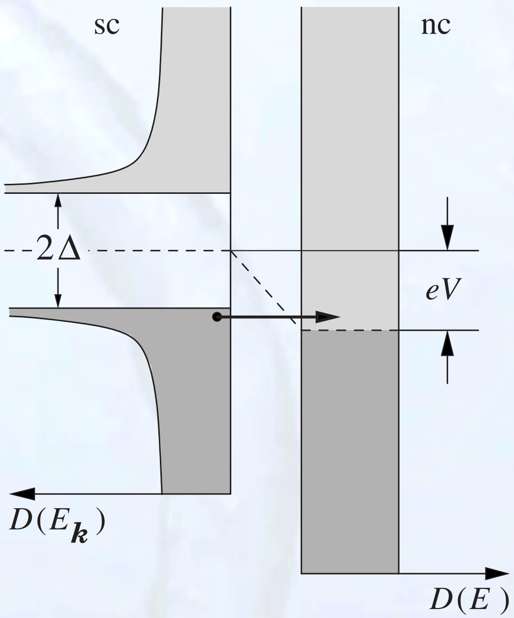
S-I-N Junction, $T = 0$

One-particle representation



$V < V_c = \Delta_0/e$

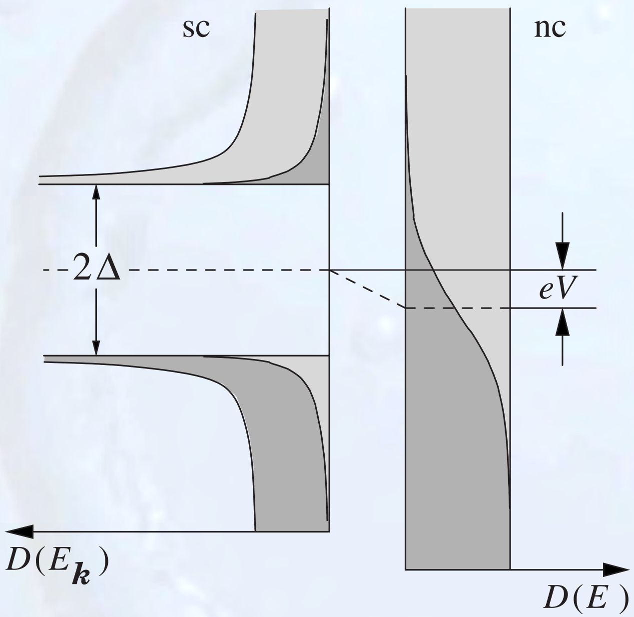


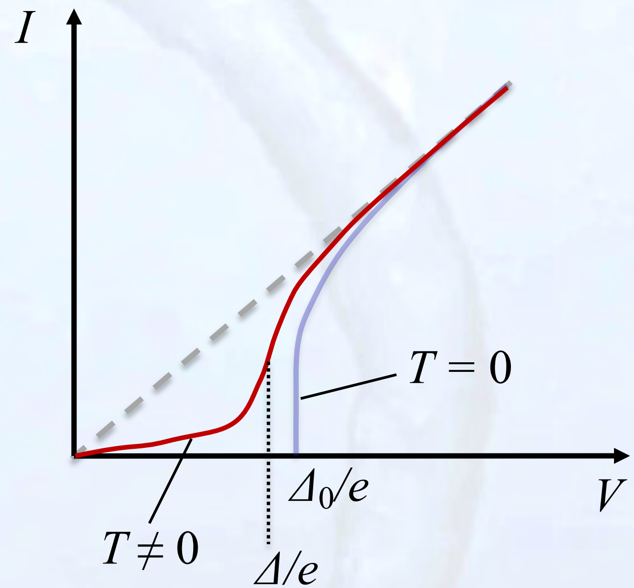


$V > V_c = \Delta_0/e$

S-I-N Junction, $T \neq 0$

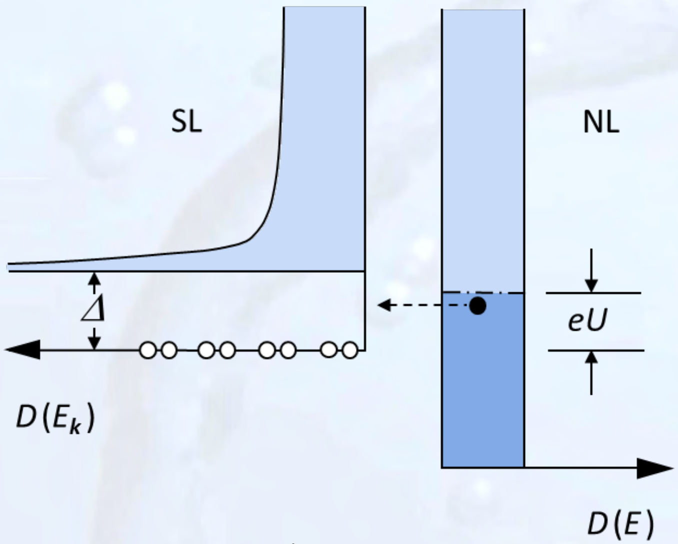
One-particle representation



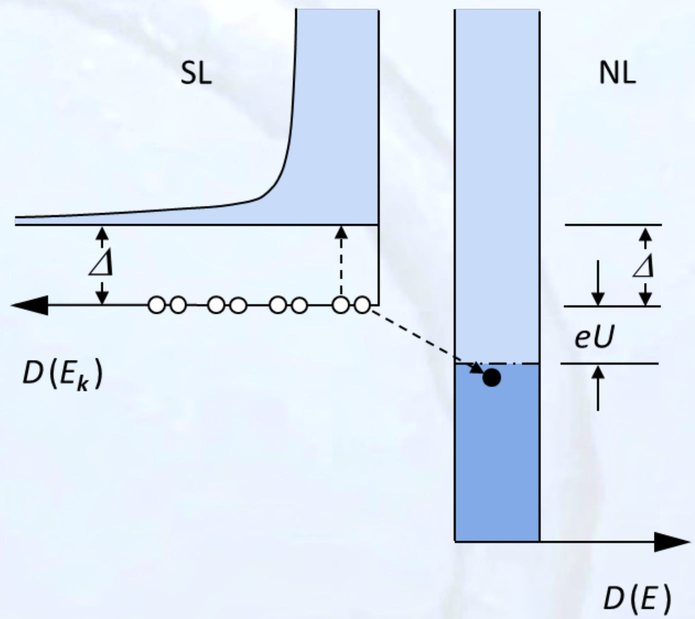


S-I-N Junction, $T = 0$

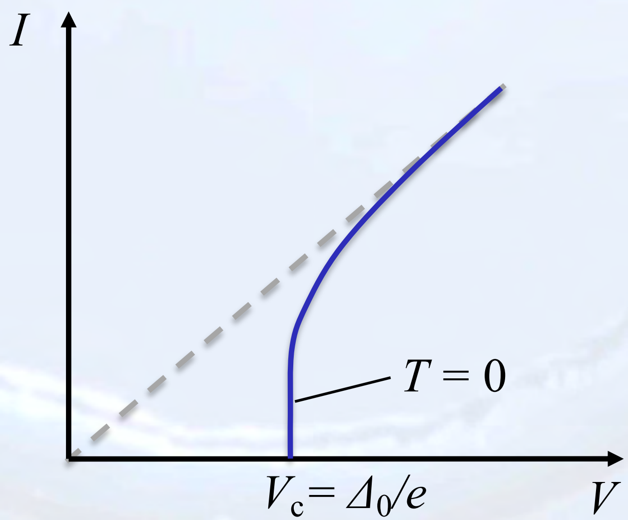
Two-particle representation



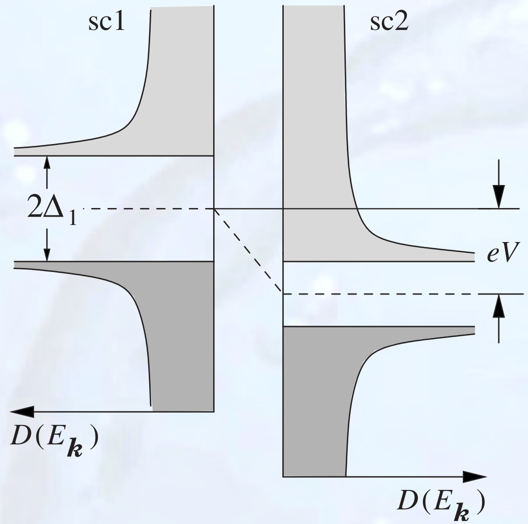
$V < V_c = \Delta_0/e$

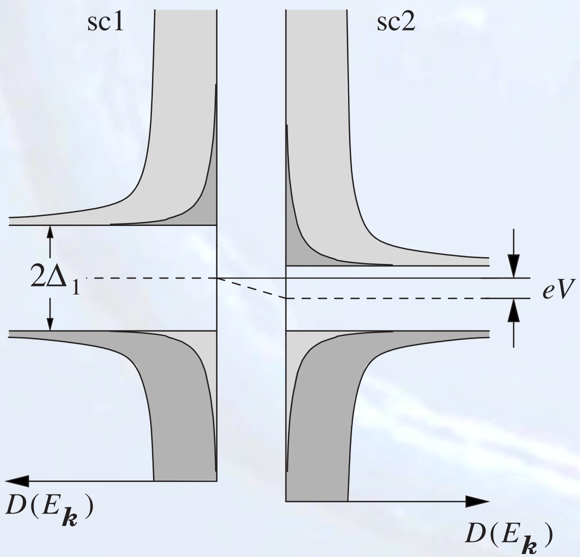


$V > V_c = \Delta_0/e$

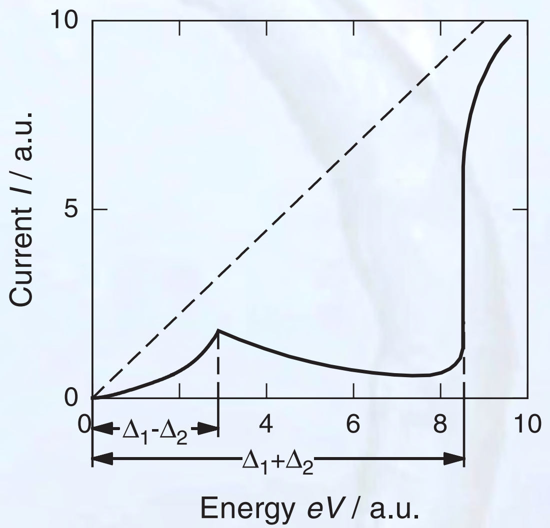


S-I-S Junction



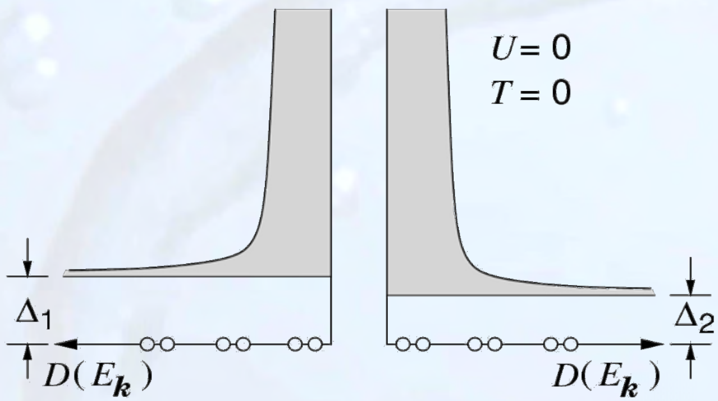


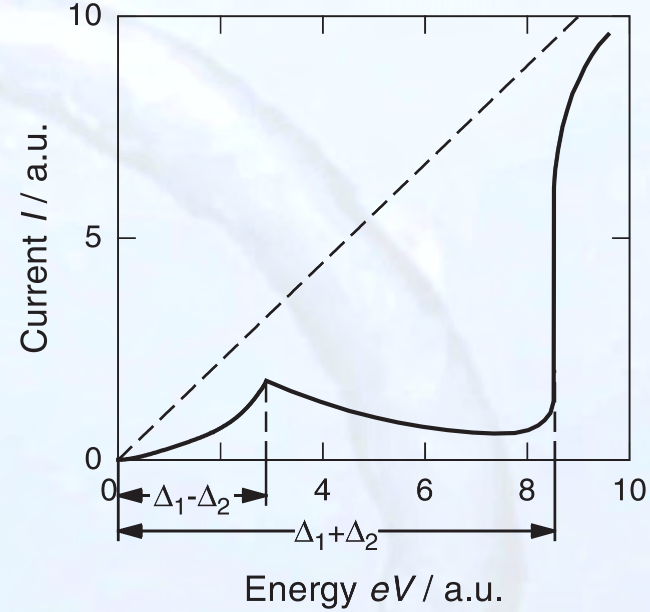
Two-particle representation

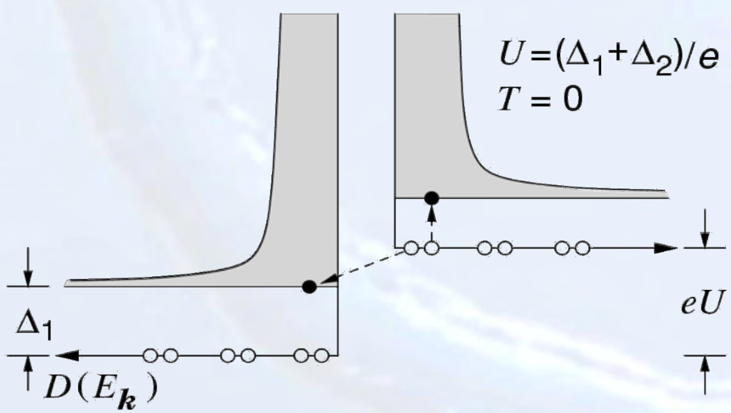


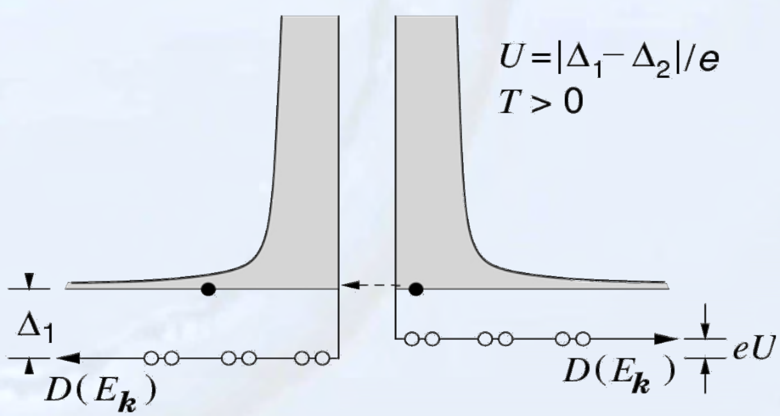
S-I-S Junction

Two-particle representation

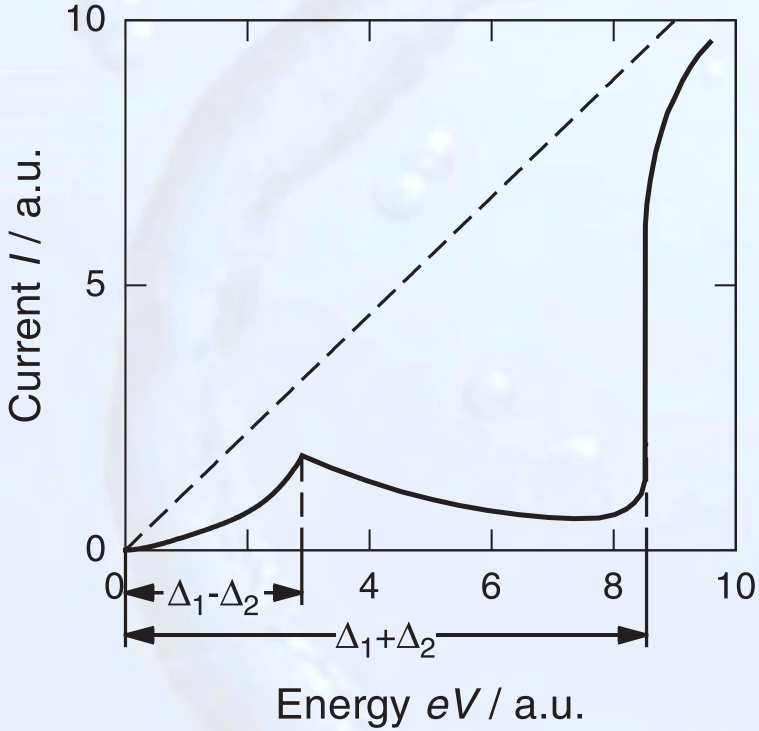


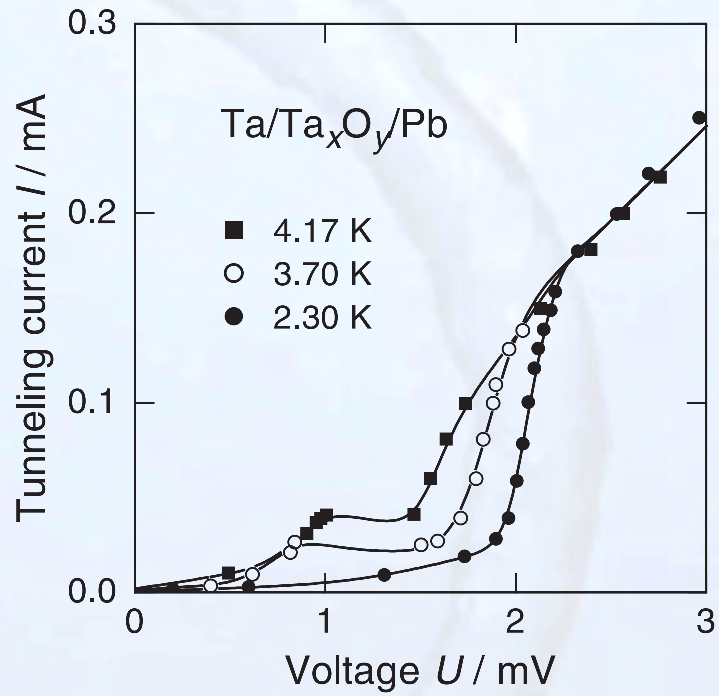






S-I-S Junction





10.3 Macroscopic Quantum State

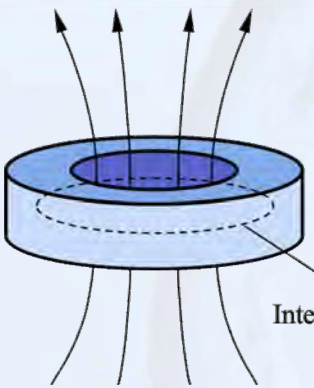
Macroscopic wave function $\Psi = \Psi_0 \, \mathrm{e}^{\mathrm{i}\varphi(\boldsymbol{r})}$ → flux quantization, Josephson effect

$|\Psi_0|^2 = n_\mathrm{s}$

a) flux quantization

phase $\varphi(\boldsymbol{r})$ is well defined in entire superconducting system

consider superconducting ring in magnetic field



phase difference along a path $\Delta\varphi = \int_1^2 \mathrm{grad}\,\varphi(\boldsymbol{r}) \cdot \mathrm{d}\boldsymbol{s}$

closed loop $\boldsymbol{r}_1 = \boldsymbol{r}_2 \longrightarrow \Delta\varphi = 2\pi p$

quantum mechanical current density $\boldsymbol{j} = \mathrm{i}\frac{\hbar q}{2M}\left(\Psi^\star \nabla \Psi - \Psi \nabla \Psi^\star\right) - \frac{q^2}{M}\boldsymbol{A}\,\Psi^\star\Psi$

with $q = -2e$ and $M = 2m$ $\longrightarrow \mu_0 \lambda_\mathrm{L}^2 \boldsymbol{j} = \left(\frac{\hbar}{e}\nabla\varphi - 2\boldsymbol{A}\right)$

integration along closed contour line L

$$\mu_0 \lambda_\mathrm{L}^2 \oint_L \boldsymbol{j} \cdot \mathrm{d}\boldsymbol{s} = \frac{\hbar}{e}\oint_L \nabla\varphi \cdot \mathrm{d}\boldsymbol{s} - 2\underbrace{\oint_L \boldsymbol{A} \cdot \mathrm{d}\boldsymbol{s}}_{\int_\Sigma \boldsymbol{B} \cdot d\boldsymbol{f} = \Phi}$$

$\boldsymbol{j} = 0$

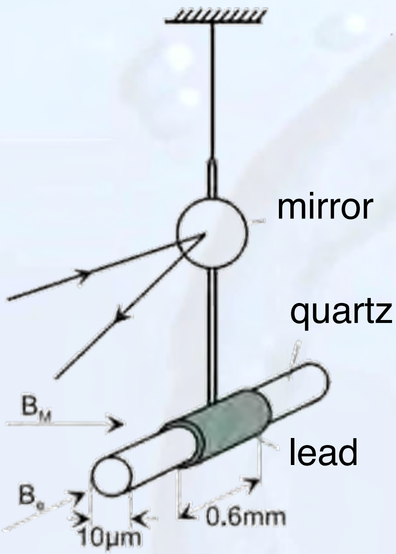
Stokes theorem

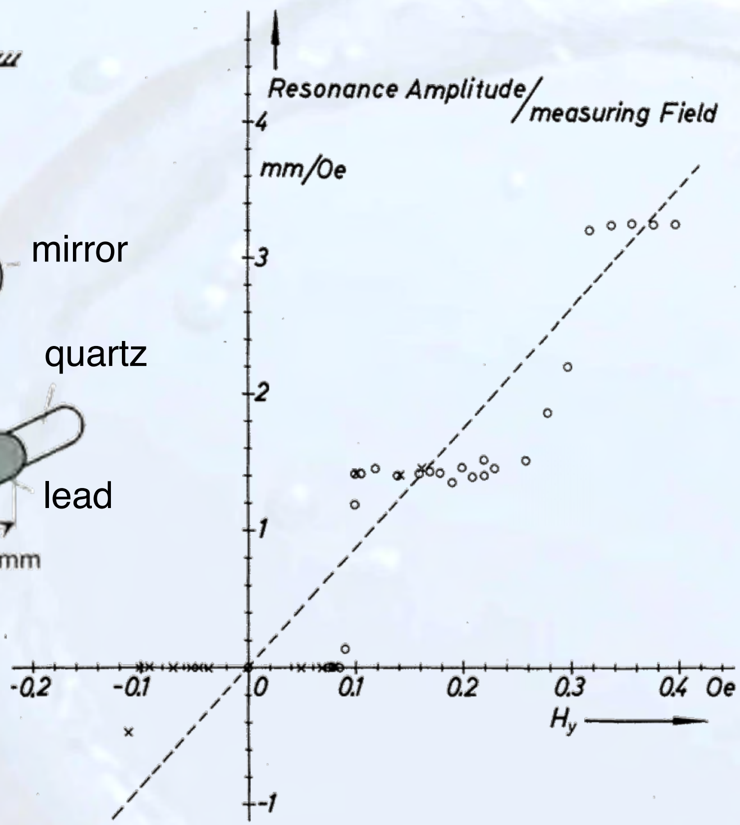
$$\boxed{\Phi = p\,\frac{h}{2e} = p\,\Phi_0}$$

magnetic flux enclosed by the ring is quantized

10.3 Macroscopic Quantum State

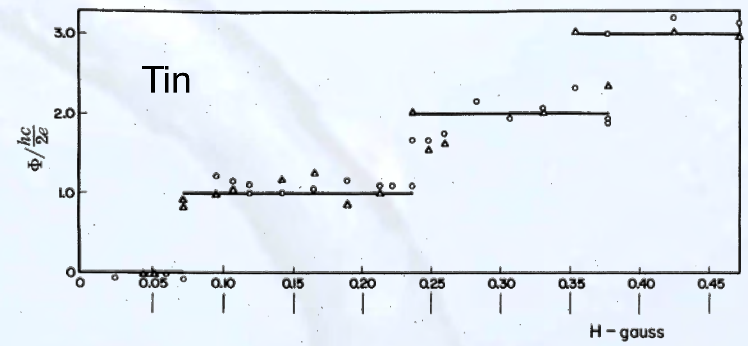
Experimental observation of flux quantization 1961



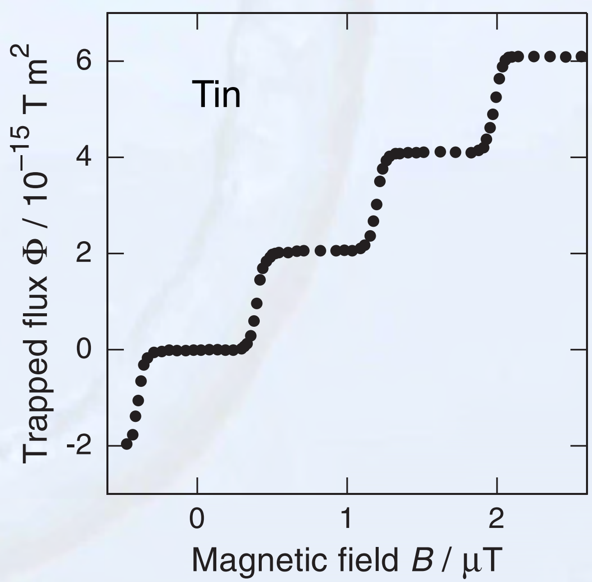


Doll and Näbauer

Deaver and Fairbank

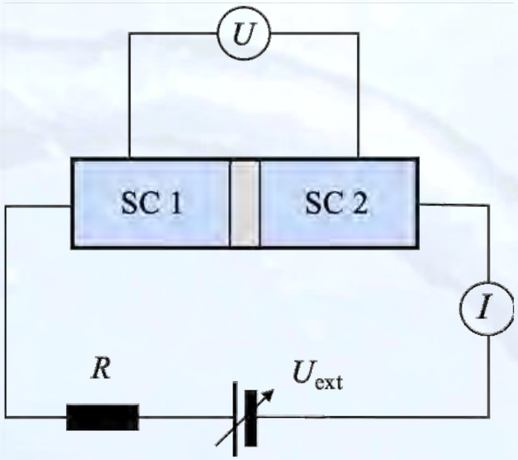


modern measurement



10.3 Macroscopic Quantum State

Josephson effects (1962)



Brain Josephson

Schrödinger equations

$$i\hbar\dot{\Psi}_1 = \mu_1\Psi_1 + \mathcal{K}\Psi_2$$

$$i\hbar\dot{\Psi}_2 = \mu_2\Psi_2 + \mathcal{K}\Psi_1$$

chemical potential   coupling strength

ansatz $\Psi_1 = \sqrt{n_{s1}}\mathrm{e}^{\varphi_1}$ and $\Psi_2 = \sqrt{n_{s2}}\mathrm{e}^{\varphi_2}$

with $n_s = n_{s1} = n_{s2}$

Josephson equations

$$\boxed{\begin{aligned} \dot{n}_{s1} &= \frac{2\mathcal{K}}{\hbar} n_s \sin(\varphi_2 - \varphi_1) = -\dot{n}_{s2} \\ \hbar(\dot{\varphi}_2 - \dot{\varphi}_1) &= -(\mu_2 - \mu_1) = 2eV \end{aligned}}$$

$V = 0 \longrightarrow \mu_1 = \mu_2 \longrightarrow I_s = I_c \sin(\varphi_2 - \varphi_1)$ dc Josephson effect

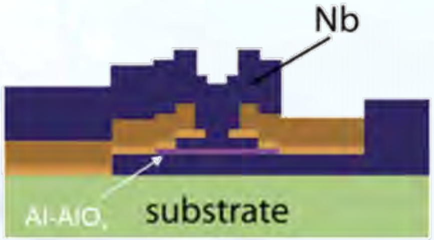
$V \neq 0 \longrightarrow \mu_2 - \mu_1 = -2eV \longrightarrow I_s = I_c \sin(\omega_J t + \varphi_0)$ ac Josephson effect

$\omega_J = 2eV/\hbar$

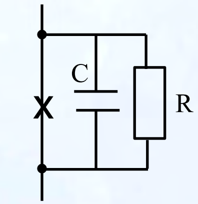
10.3 Macroscopic Quantum State

Experimental observation of dc Josephson effect

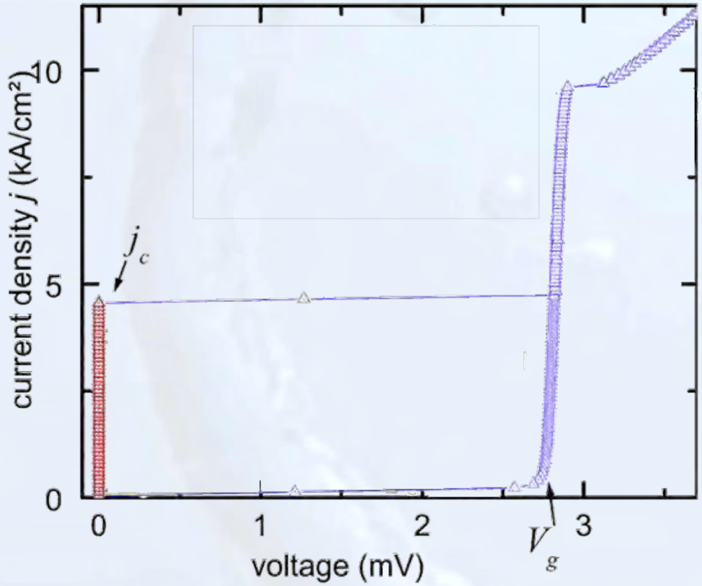
hysteresis parameter: $\beta_c = 2\pi I_c R^2 C/\Phi_0$



Josephson junction

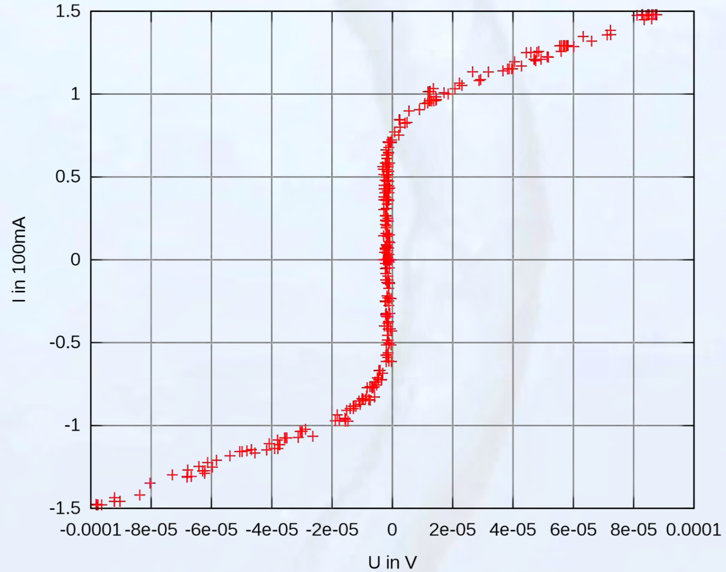


underdamped junction (large *R* and *C*)



- hysteretic Josephson junction
- for $I < I_c$ current is determined by current source
- for $I > I_c$ super current breaks down

overdamped junction (small *R* and *C*)



- non-hysteretic Josephson junction
- for $I > I_c$ super current breaks down