Direct Observation of the Transition from the Conventional Superconducting State to the π State in a Controllable Josephson Junction

J.J.A. Baselmans, T.T. Heikkilä, B.J. van Wees, T.M. Klapwijk

Phys. Rev. Lett. **89**, 207002 (2002)

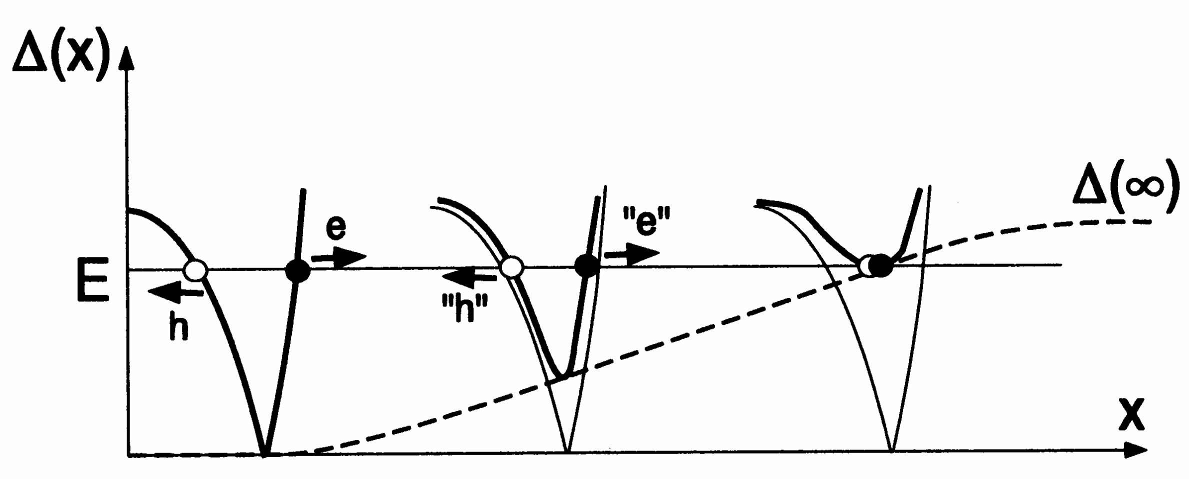
Overview

- Supercurrent through SNS junctions: Andreev Reflection
- Experimental setup: Controllable π-SQUID
- Measured data: Periodicity of CΦR doubles
- Quasiclasical Theory: energy distribution in the N part
- Conclusion

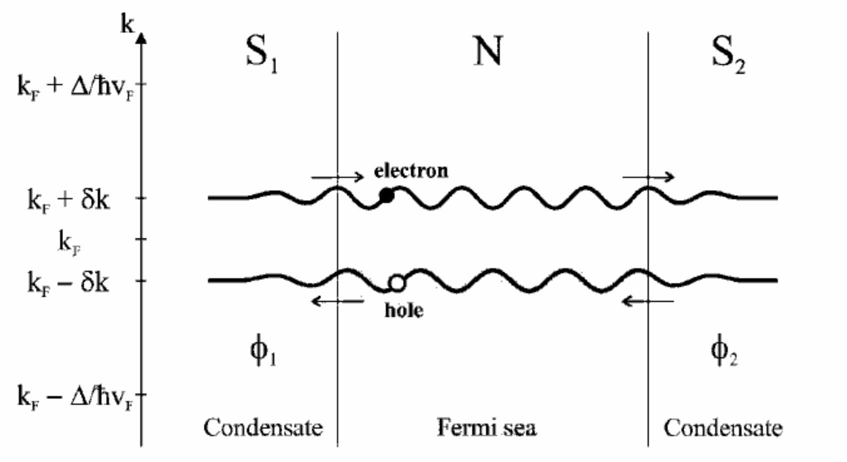
Andreev Reflection

How can subgap quasiparticles cross the N→S interface?

➡ Order parameter Δ varies slowly over interface (proximity effect)



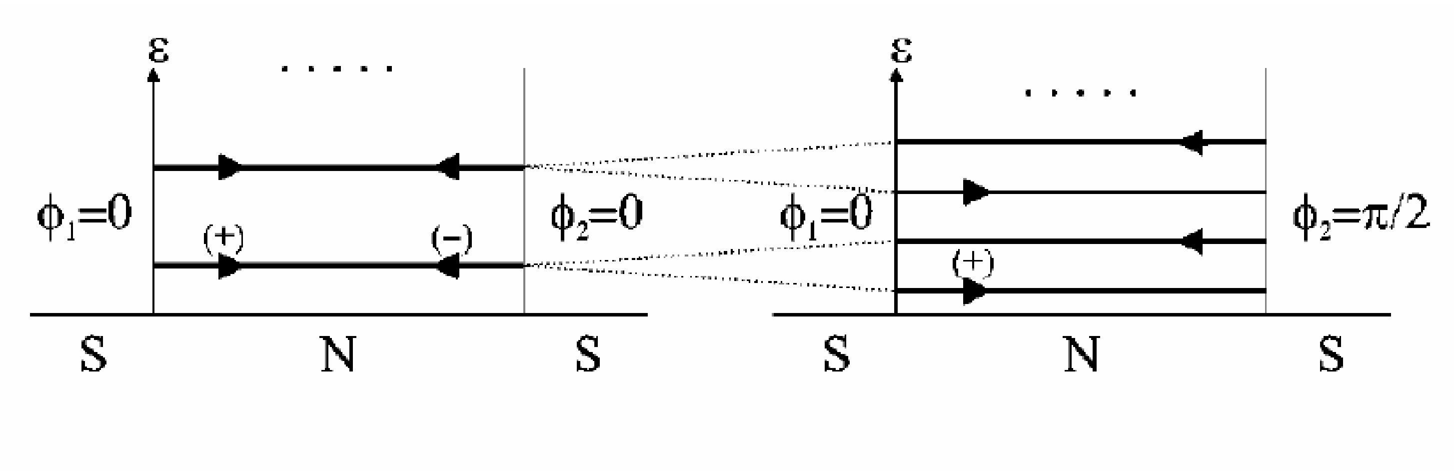
Andreev bound states



bound state: wavefunctions satisfy the boundary conditions imposed by the superconducting phases

$$\Delta\varphi = 2\frac{\epsilon_n}{\hbar v_F} d = \pm\phi + 2\arccos\frac{\epsilon_n}{\Delta} + 2\pi n .$$

where $\Delta\varphi = 2\,\delta k\, d$ is the relative phase change of the pair and $\delta k = \epsilon/\hbar v_F$



Junction critical current I_c determined by:

- energy spectrum of the Andreev bound states
- occupation of these states

π-junction: zero current state at $\Phi=\pi$

central question:

How does the transition occur from the 0 to the π state ?

Does the minimum at $\varphi=\pi$ start to develop while the one at $\varphi=0$ ist still present?

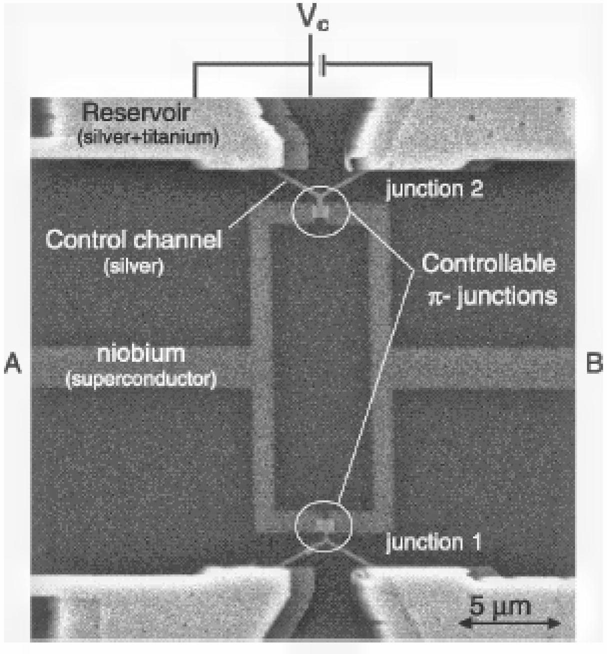
Free energy of the junction:

$$W(\varphi) = \frac{\phi_0}{2\pi}\int_0^{\varphi} I_{sc}(\varphi')\,d\varphi$$

Double mimimum in free energy implies doubling in periodicity of the supercurrent-physe-relation:

$$I_{sc} = I_c \sin(\varphi) \quad \rightarrow I_{sc} = I_c \sin(2\varphi)$$

experimental setup



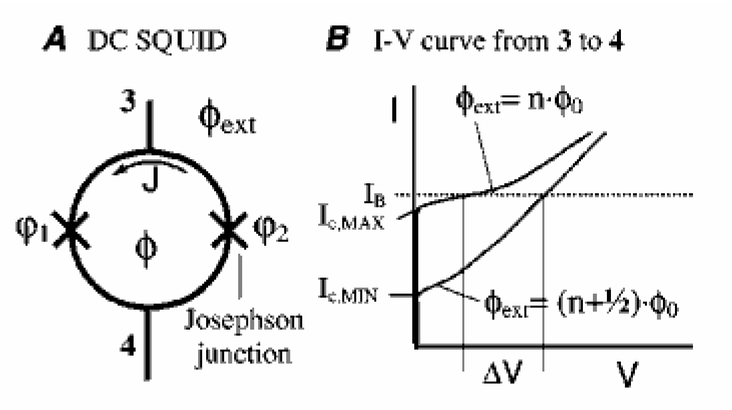
- Nb/Ag/Nb junctions
- $E_T = 27\mu eV$
- Thickness 50nm
- Loop surface area $70\mu m^2$
- Control channel length ≈ 5µm
- $I_c = 11\mu A \quad (V_c = 0)$

Controllable π SQUID:
control voltage V_c creates non-thermal energy distribution in N

⇨ reduction of I_c and subsequent transition to π state

SQUID geometry

measurement of $I_{sc}(\varphi)$ over entire range of phase φ over one of the SNS junctions:



$$\Phi = \Phi_{ext} + LI$$

$$\varphi_1 = 2\pi\,\Phi/\,\Phi_0 - \varphi_2$$

$$I_{c,SQUID} = \max\left|I_{sc1}(\varphi_1) + I_{sc2}(\varphi_2)\right|$$

Negligible self-inductance: $2\pi L I_c' < 1 \;\Rightarrow\; \Phi = \Phi_{ext}$

Via control voltage: $I_{c1} \gg I_{c2}$

$$I_{c,SQUID}(\Phi_{ext}) = I_{c1} + I_{sc2}(\varphi_2)$$

SQUID biased with current slightly larger than I_c

$\Rightarrow I_{c,SQUID}(\Phi_{ext})$ transferred into voltage signal

measured data:

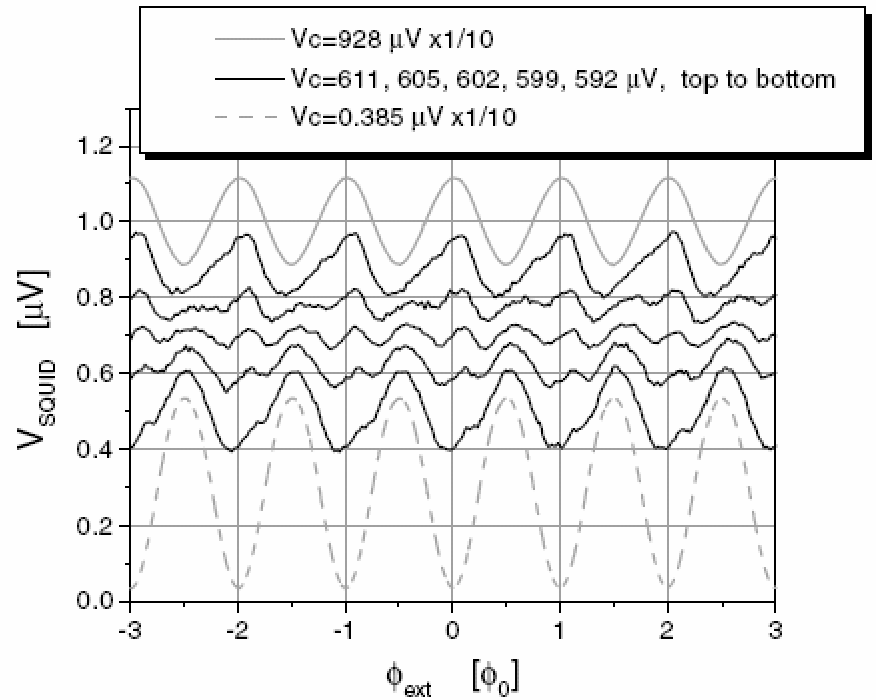
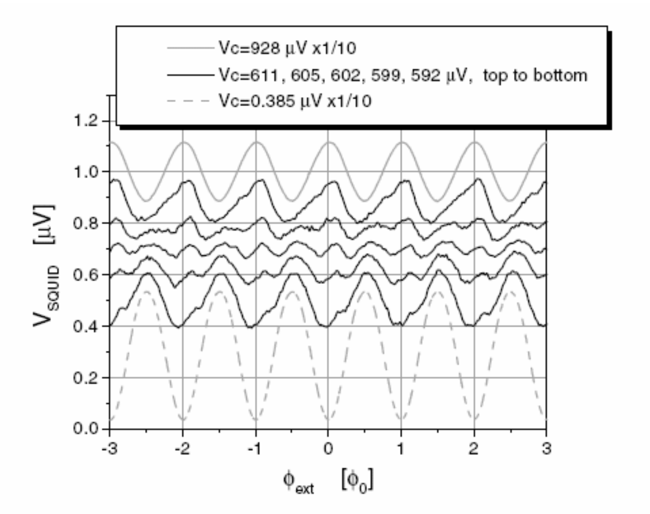
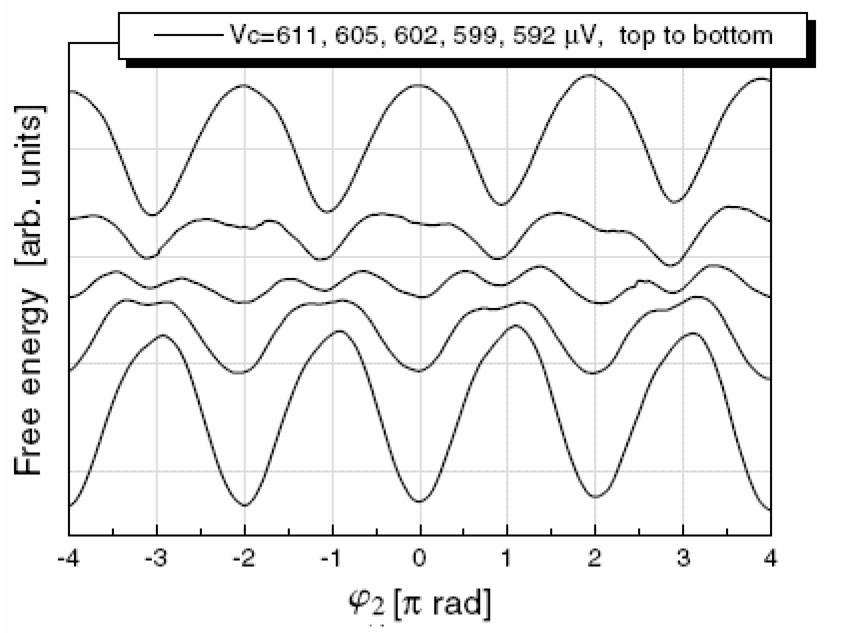


FIG. 2. Voltage over the SQUID (from contacts A to B in Fig. 1) at a bias current slightly larger than $I_{c,\mathrm{SQUID}}$ as a function of the ϕ_{ext} for different values of V_c. The amplitudes of the two grey curves are multiplied by $1/10$. Around $V_{c,\mathrm{critical}} = 602\ \mu\mathrm{V}$, a doubling in periodicity of the voltage oscillations is observed.

experimental free energy:

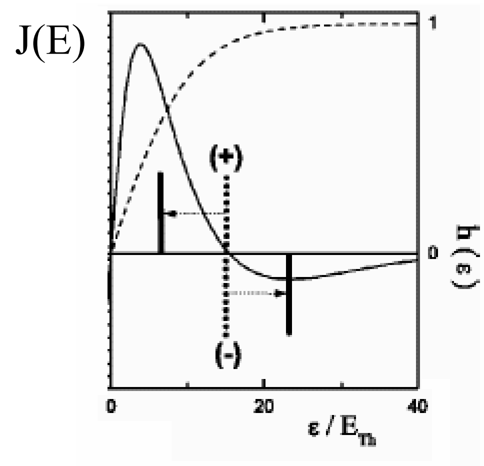


via $$W(\varphi) = \frac{\phi_0}{2\pi}\int_0^{\varphi} I_{sc}(\varphi')\,d\varphi$$



Quasiclassical theory

in the diffusive regime, the ABS have a continuous energy spectrum J(E):

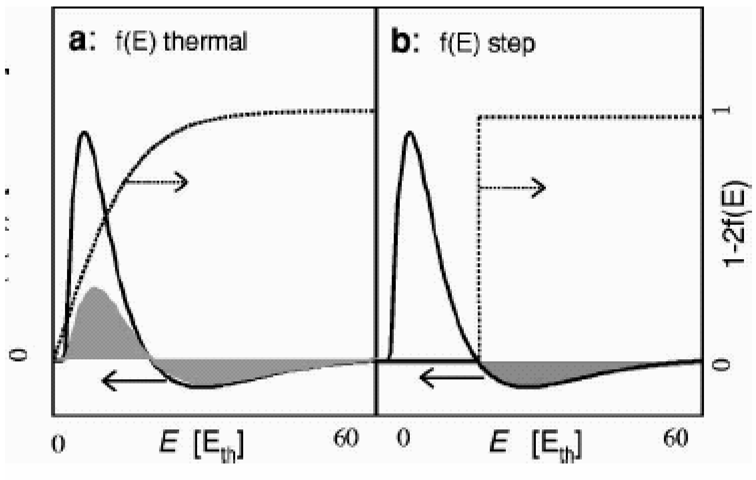


net supercurrent by integrating over e and h excitation of all + and – states:

$$I_{sc} \sim e \int_0^\infty dE[f(E)k_+(E) - (1-f(E))k_-(E)](\nu_+(E) - \nu_-(E))$$

$$\boxed{I_{sc}(V_c, \varphi) = \frac{1}{2R_n} \int_{-\infty}^{\infty} dE[1 - 2f(E, V_c)]J(E, \varphi)}$$

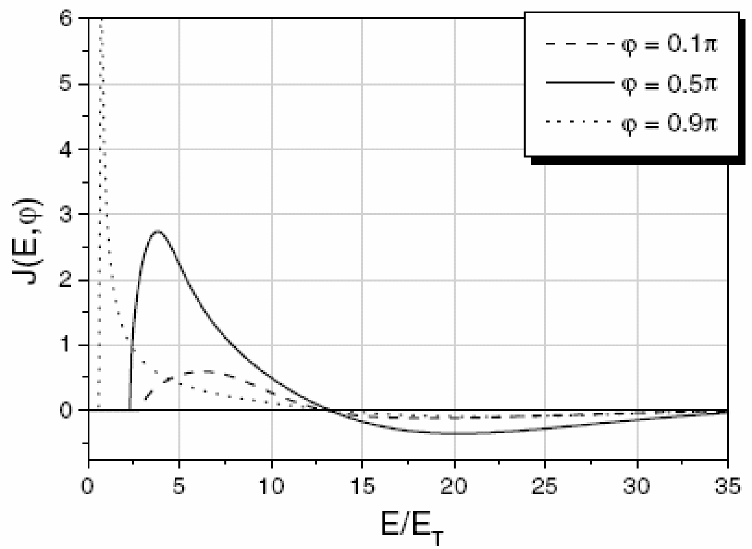
at $V_{c,critical}$ step distribution will block all positive contributions of J(E):



➡ Reversal in direction of I_{sc}

= π state

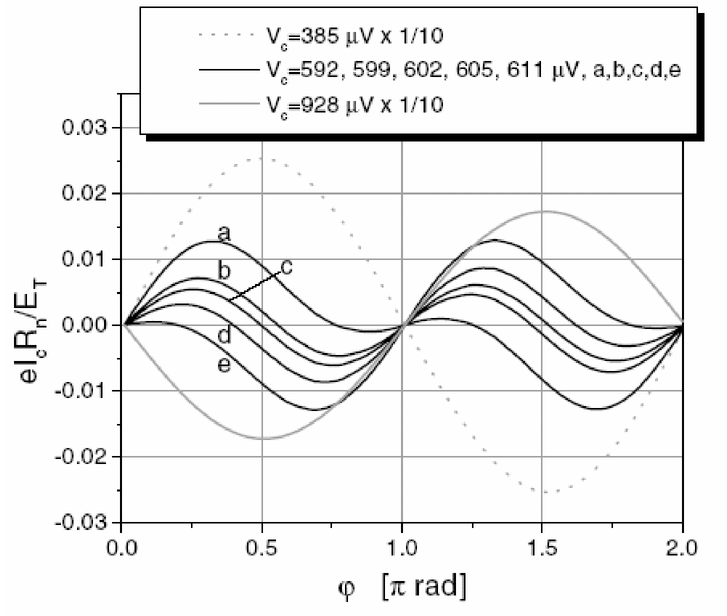
Supercurrent carrying density of states for different values of the macroscopic phase difference:



From theoretical calculation of $J(E,\varphi)$ and $f(E,V_c)$

using E_T and equilibrium I_c as fit parameters

Calculate $I_{sc2}(V_{c,} \varphi_2)$:



in good agreement with experimental data!

Conclusions

- Andreev reflection enables supercurrent transport in SNS junctions
- $I_{sc}(\varphi)$ dependence measured with controllable π SQUID
- arount transition from 0 to π state: periodicity of CΦR doubles
- energy distribution of quasiparticles in N manipulated by control voltage
- experimental results in good agreement with quasiclassical theory

The End.