Quantum fluctuations in superconducting nanostructures

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Outline

1. Introduction
   Fluctuations in quasi-1D superconductors
   Quantum Phase Slip concept

2. Applications
   Junctionless Cooper pair transistor
   Quantum standard of electric current

3. Conclusions
R(T) transition

H. K. Onnes,
Commun. Phys. Lab. 12, 120, (1911)
Fluctuations vs. system dimensionality

For a superconductor dimensionality is set by the temperature-dependent coherence length $\xi(T)$.

3D

2D

1D

S inclusions reduce the total system resistance $\rightarrow$

rounded top

$\sigma_{\text{FLUCT}} \sim (T-T_c)^{-(2-D/2)}$

(Aslamazov – Larkin)

no contribution of N inclusions: normal current is shunted by supercurrent $\rightarrow$

abrupt bottom

N inclusions block the supercurrent $\rightarrow$

rounded bottom

(Langer – Ambegaokar)

Topic of the talk

R

$T$

R

$T$

N

normal metal

S

superconductor
Fluctuations in a 1D superconductor

Long 1D wire of cross section $\sigma$

If the wire is infinitely long, there is always a finite probability that in some fragment(s) the magnitude of the order parameter instantly becomes zero and the phase changes by $2\pi$.

The minimum length the superconductivity can be destroyed is the coherence length $\xi(T)$.

The minimum energy corresponds to destruction of superconductivity in a volume $\xi(T) \sigma$:

$$\Delta F = B_c^2 \xi(T) \sigma,$$

where $B_c(T)$ is the critical field.

In the limit rare events the probability of the process $P(T) \sim \exp (- \Delta F / \mathcal{E})$.

Thermal activation: $\mathcal{E} \sim k_B T$. Important at $T \to T_c$.

Quantum: $\mathcal{E} \sim \Delta$. Weak temperature dependence, exist even at $T \to 0$.

In current state the particular manifestation of a quantum fluctuation when magnitude of the order parameter momentary nulls and phase changes by $\pm 2\pi$ is often called “phase slip”.

$\xi(T)$

$\forall \sigma \leq \xi(T) \ll L$
Phase of the superconducting order parameter

$$\Psi = |\Psi| e^{i\phi}$$

The initial and final states have different energy $\rightarrow$ dissipation in a superconductor
**Manifestation of QPS: broadening of R(T) transition**

Dashed lines: thermally activated fluctuations (LAHM) at $T \sim T_c$
Solid lines: quantum fluctuations (Golubev – Zaikin) model at $T << T_c$

- Aluminium
- Titanium

$\sigma^{12} = 11 \text{ nm} \pm 2 \text{ nm}$
$\sigma^{12} = 12 \text{ nm} \pm 2 \text{ nm}$
$\sigma^{12} = 13 \text{ nm} \pm 2 \text{ nm}$

Al-Cu126-3
$I = 5 \text{ nA AC}$

Nanowire 1
- $d = 29 \text{ nm}$
- $d = 35 \text{ nm}$
- $d = 50 \text{ nm}$
- $d = 54 \text{ nm}$
- $d = 58 \text{ nm}$

LAHM
QPS

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Persistent currents in nanorings
Amplitude and period of oscillations as function of the loop linewidth (aluminium)

**Wide wire: classic limit**

110 nm x 75 nm wire, 
$T_{bath}=65 \pm 5$ mK, $\sigma_{fit}^{1/2}=90.8$ nm

**Intermediate regime:**

$T_{bath}=52 \pm 5$ mK. Solid line: $\sigma_{fit}^{1/2}=12.49$ nm and $\Delta \Phi/\Phi_0=3$ period, dashed line - calculated $\Delta \Phi/\Phi_0=1$ oscillations in a slightly narrower loop $\sigma_{fit}^{1/2}=12.37$ nm

**QPS limit:**

same sample as in (b) further gently sputtered at $T_{bath}=54 \pm 5$ mK
Solid line - calculations in the QPS limit with $\sigma_{fit}^{1/2}=12.15$ nm
Fluctuations of the superconducting gap amplitude
Fluctuations of the order parameter

$$\Delta = \Delta_0 \exp(i\varphi)$$

T. Rantala, MSc thesis, University of Jyvaskyla, 2013
Direct determination of the fluctuating energy gap

\[ \delta|\Delta| / |\Delta| \sim (S_{QPS})^{-1} \]

Superconducting gap can be associated with E/M radiation absorption threshold

Characteristic scale

\[ \Delta(\text{Al}) \sim 80 \text{ to } 100 \text{ GHz}, \quad \Delta(\text{Ti}) \sim 15 \text{ to } 25 \text{ GHz}. \]

\[ \delta \Delta / \Delta \text{ can reach } 30\% \text{ in sufficiently thin nanowires} \]
SIS I(V) at various diameters of nanowires

\[ \Delta_1 - \Delta_2 \] features and Coulomb blockade and/or Josephson current (?)

The smaller the nanowire diameter (1) the smaller the average value \(<\Delta>\) and (2) the larger the gap smearing \(\delta\Delta\).
Conclusions on physics

Quantum fluctuations in narrow superconducting nanowires suppress ‘basic’ superconducting attributes manifesting as:

• Broadening of the R(T) transition. In thinnest samples zero resistance is not reached even at T→0.
• Suppression of persistent currents in nanorings.
• Smearing of the superconducting gap edge.
Applications
Superconducting horse-shoe, shortened by a QPS nanowire

Spectroscopy of the system across a wide range of flux and frequency.

J. E. Mooij and C. J. P. M. Harmans

Coulomb Effects

Thick (conventional) superconducting wire

Thin wire and low-$\Omega$ environment

Very thin wire and high-$\Omega$ environment: Coulomb blockade
Quantum duality between JJ and QPS junctions

Hamiltonian of a superconducting nanowire in the regime of quantum fluctuations:

\[ \hat{H} = \frac{E_L}{(2\pi)^2} \phi^2 - E_{QPS} \cos(2\pi q) + \hat{H}_{coup} + \hat{H}_{env} \]

is dual to the corresponding Hamiltonian of a Josephson junction:

\[ \hat{H} = E_C \phi^2 - E_J \cos(\phi) + \hat{H}_{coup} + \hat{H}_{env} \]

with the accuracy of substitution: \( E_C \leftrightarrow E_L, E_J \leftrightarrow E_{QPS}, \phi \leftrightarrow \pi q / 2e \)

\( E_L, E_C, E_J \) and \( E_{QPS} \) are the inductive, charging, Josephson coupling and QPS energies, \( \phi \) is phase and \( q \) is quasicharge.

The extensively developed physics for Josephson systems can be ‘mapped’ on the superconducting nanowires in the regime of quantum fluctuations.

Let us consider the simplest case of a QPS Copper pair box: \[
\hat{H}_{QPS_{box}} = E_c \left( \hat{Q} - \frac{q}{2e} \right)^2 + E_1\hat{\phi}^2 - E_{QPS}\cos(2\pi \hat{Q})
\]

First two terms correspond to linear LC oscillator. If to shift the charge variable by \(q/2e\), the induced charge disappears from the oscillator part, while the QPS amplitudes acquire the phase factors:

\[
\hat{H}_{QPS}\psi(\phi) = -E_{QPS}e^{-\frac{ieq}{e}}\psi(\phi + 2\pi) - E_{QPS}e^{\frac{ieq}{e}}\psi(\phi - 2\pi)
\]

The charge sensitivity is purely due to the coherent QPS term: the induced charge \(q/2e\) affects the interference of the phase slips with two opposite directions \(\pm 2\pi\).

The mandatory requirement for the charge effects observation is the high impedance of the environment: current bias \(\rightarrow\) charge is a ‘good’ quantum number.

QPS is a dynamic equivalent of a conventional (static) tunnel junction.
High-Ohmic environment

Purely dissipative environment:
high-Ohmic normal metal probes with $R_{\text{probe}}$ up to 10 MOhm
24 nm titanium nanowire, 10 MΩ contacts

All three neighboring parts of the same multiterminal structure demonstrate the same value of the Coulomb gap. The effect disappears above $T_c$ and/or $H_c$. 
Magnetic field dependencies

At a given (low) temperature the Coulomb gap and the gate modulation disappear above certain magnetic field (the $B_c$ of Ti?).
Electron transport in a Cooper pair transistor is a **periodic** process corresponding to cyclic charging/discharging of the central island by $2e$. Synchronisation of the process with external drive should lead to resonance.

**Josephson junction:** critical current

**QPS wire:** critical voltage

**Josephson junction:** voltage steps (Shapiro effect)

**QPS wire:** current steps
Hybrid high impedance environment

High-Ohmic electrodes

Ti-AlOx-Ti SQUIDs

Ti - nanowires

island

High-Ohmic normal metal probes with $R_{\text{probe}}$ up to 500 KOhm and 1D array of SQUIDs.
dV/dI at $f_{RF}=350$ MHz and amplitude $100$ mV. Current is normalized by $(2e) \times f_{RF}$. One can distinguish steps with quantum number $n \leq 8$.

Universal relation $I(n) = (2e) * n * f_{RF}$
Red symbols correspond to Bloch steps (2e), blue – single electron (e), black – 1st subharmonic of single electron oscillations.

Proof-of-principle demonstration of a quantum standard for electric current.
Width of the Bloch step

T = 70 mK
f_{RF} = 3.12 GHz
I_{mod} = 0.5 pA rms

Demonstrated accuracy is +/- 2%.
Further accuracy improvement is mandatory for practical metrology.
Digest on Coulomb effects in QPS

• Quantum phase slip and Josephson tunneling are the phenomena described by identical Hamiltonians: the quantum dynamics is indistinguishable.

• Superconducting nanowire (homogeneous!), in the regime of QPS, is the dynamic equivalent of a Josephson junction.

• Containing no static (in space and time) junctions, QPS nanowire can sustain much higher currents and has no undesired two-level ’fluctuators’ present in tunnel contacts.

• All phenomena, observable in Josephson systems, can be observed in QPS nanowires.
Thank you!
Summer University in Moscow

Quantum Technologies

"Quantum Technologies" program provides the unique opportunity to get introduction to the quickly developing interdisciplinary topics of quantum solid state physics, quantum photonics and nanotechnology. The program includes both the introductory and the rather advanced courses at the very frontier of modern science. The invited lecturers are the world-class leading experts in corresponding fields. The training is addressed to students of bachelor / magister level who have affinity with physics, electronics, IT and computer sciences. The courses might appear attractive also to researchers in natural sciences such as chemistry and biology who wish to advance their knowledge in various phenomena related to nanoscience. The program at the Summer University is the pilot project announcing the new English-speaking full-scale MSc program "Quantum Information Technologies (iQT)" to start at Higher School of Economics in 2017. The objective of that program is to train specialists of the highest qualification in the field of transmission, storage and processing of information using the most advanced methods of quantum physics and quantum communication. The announced courses of Summer University-2016 have been prepared by the core lecturers of the upcoming iQT program, and represent the selected and shortened versions of MSc training in quantum communication.

https://www.hse.ru/international/summer/quantum