Transport through Andreev Bound States in a Superconductor-Quantum Dot-Graphene System

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Outline

• Tunneling spectroscopy with a superconducting probe
• Fabrication of SC-QD-graphene system
• Data: Superconducting tunneling into QD-graphene system
• Analysis: Spectroscopy of Andreev bound states
Graphene electronics

Dirac Cones in momentum space

linear dispersion around Dirac point

\[ E_{\pm}(p) = \pm v_F \sqrt{p_x^2 + p_y^2} = \pm v_F p \]

\[ E_{\pm}(p, m) = \pm \sqrt{m^2 v_F^4 + v_F^2 p^2} \quad \text{with} \quad m = 0 \]

\[ v_F = \frac{3ta}{2} \approx \frac{c}{300} \]

→ Simple devices show a large variety of electronic behavior:
* room temperature quantum Hall effect
* transistors
* relativistic Klein tunneling

Often, high-mobility, low-density of states, & gate-tunability more important than Dirac spectrum (surface accessible 2DEG)
Superconductivity in graphene

Bipolar supercurrent (Heersche et al, Nature 2007)

Andreev billiards (Miao et al, Science 2007)

Current-phase relation (Chialvo et al, arXiv 2011)
→ Tunneling spectroscopy with a superconducting probe on graphene:

- Sharp DOS of superconductor can “map out” features of graphene

- Use subgap conductance to study Andreev reflections & proximity effect
Tunneling spectroscopy with a superconducting probe:

- Previously, spectroscopy of carbon nanotubes
- Non-equilibrium tunneling → electron interactions in carbon nanotubes

Chen et al, PRL (2009)
Tunneling spectroscopy with a superconducting probe:

- Measure proximity effect

Blonder, Tinkham, Klapwijk (BTK), PRB (1982)

\[ Z=0, \text{ perfect transmission } \rightarrow \text{ enhanced conductance below gap } (\Delta) \]

\[ Z \text{ large, tunnel barrier } \rightarrow \text{ suppressed conductance below } \Delta \]
→ Tunneling spectroscopy with a superconducting probe:

- **Surface Andreev bound states in d-wave superconductors**

→ Nodal, d-wave nature of high-Tc

See Deutscher, RMP (2005)

→ Can superconducting tunneling spectroscopy be used to measure Andreev bound states in graphene-based system?
Can superconducting tunneling spectroscopy be used to measure Andreev bound states in graphene-based system?

Andreev Reflections

Andreev Bound States (ABS)

Standing waves → ABS of discrete energies

- Similar ABS in S-N systems if normal metal confined (e.g., superconductor-quantum dot systems)

- In long superconducting junctions, supercurrent carried by ABS

Relevant for characterizing & understanding long Josephson junctions, SNS systems; applications such as SC-SETs, qubits, etc
Can superconducting tunneling spectroscopy be used to measure Andreev bound states in graphene-based system?

Andreev Reflections  Andreev Bound States (ABS)

Standing waves $\rightarrow$ ABS of discrete energies

Renewed interest in utilizing ABS:

Andreev Level Qubit

A. Zazunov,¹ V. S. Shumeiko,¹ E. N. Bratus,² J. Lantz,¹ and G. Wendin¹
Sharp spectra of individual Andreev bound states are difficult to measure:

- In transport, ABS observed as supercurrent, measure contributions from many modes
- In point-contact tunneling, ABS seen as zero-bias anomalies
- Spectra of ABS in SNS systems not measured

ABS can be measured via quantum dot coupled to a superconductor:

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Self-consistent description of Andreev bound states in Josephson quantum dot devices

Tobias Meng and Serge Florens
Institut Néel, CNRS and Université Joseph Fourier, 25 Avenue des Martyrs, 38042 Grenoble, France

Pascal Simon
Laboratoire de Physique et Modélisation des Milieux Condensés, CNRS and Université Joseph Fourier.
ABS can be measured via quantum dot coupled to a superconductor:

Tunneling Spectroscopy of Andreev Energy Levels in a Quantum Dot Coupled to a Superconductor


QD is “normal” when occupied by single particle

ABS form on quantum dot energy levels

Subgap features for Au-QD-Al system

→ need N lead to be weakly coupled to reduce smearing
Can superconducting tunneling spectroscopy be used to measure Andreev bound states in graphene-based system?

In Superconductor-graphene system:
- Tunneling to obtain spectroscopy
- Low density of states leads → few carriers, sharp spectra
- Possibility of gate-tuning energy levels
- ABS confined in quantum dot coupled to graphene and superconductor
Device fabrication

- SC tunnel probe
- Thin tunnel barrier
- graphene
- contact
- SiO$_2$
- Si
- Cr/Au
- PbO$_x$
- AlO$_x$ nanoparticle

Circuit diagram:
- V
- G
- S

Contact layers and electrode:
- SiO$_2$
- Si (gate electrode)
Device fabrication

1) Exfoliate graphene onto Si/SiO2

- Exfoliate with tape

Diagram:
- SC tunnel probe (Pb)
- AlOx nanoparticle
- Cr/Au
- SiO₂
- Si (gate electrode)
- PbOx

Scale bars: 5 μm and 10 μm
Device fabrication

1) Exfoliate graphene onto Si/SiO2
2) Cr/Au (2nm/50nm) contacts to ends
3) Deposit 1 nm AlOx via atomic layer deposition

- nanoparticles form at graphene edges and defects
Device fabrication

4) Pb probes
   → capped with In
   → ~ 200x200 nm² overlap with graphene edge; covers a few nanoparticles
   → oxidize Pb to attain desired tunnel resistance

Room temperature resistances:

\[ R_{\text{ends}} = 500 \, \Omega \quad R_{\text{tunnel}} = 100-500 \, k\Omega \]
Measurement Setup

![Measurement Setup Diagram](Image)
Tunnel Conductance for Pb-AlOx-Graphene

Similar data seen for 6 different samples, both single layer and multilayer graphene
Oscillations above the gap …
Oscillations above the gap: geometric resonances

\[ \alpha V_{\text{gate}} - V_{\text{bias}} = \pi n v_F / L \]

For \( L = 3.5 \mu \text{m}, \quad v_F \sim 6 \text{ evÅ} \)

\[ \pi v_F / L \sim 0.5 \text{ meV} \]

"particles in a (graphene) box"
Oscillations above the gap: geometric resonances

“particles in a (graphene) box”

\[ \alpha V_{\text{gate}} - V_{\text{bias}} = \pi n v_F / L \]

\[ G \mu \text{S} \]

\[ V_{\text{tunnel}} \text{(mV)} \]

\[ 0.4 \text{ meV} \]

\[ \rightarrow \text{extracted value of } \alpha \text{ consistent with other measurements} \]
Oscillations above the gap: geometric resonances

“particles in a (graphene) box”

\[ \alpha V_{\text{gate}} - V_{\text{bias}} = \pi n v_F/L \]

Simulations of geometric resonances consistent with data

(coupling to discrete QD levels allows cavity energy levels to be observed)
Two low-energy peaks appear inside the gap (ABS) …
Subgap peaks have strong gate-voltage dependence …
Data nearly identical to simulation of Andreev reflections in a superconductor-quantum dot-graphene system …

Behavior similar to recent work on Andreev reflections and bound states in quantum dots ...
Behavior similar to recent work on Andreev reflections and bound states in quantum dots …

Andreev bound states in supercurrent-carrying carbon nanotubes revealed

J-D. Pillet¹, C. H. L. Quay¹, P. Morfin², C. Bena³,⁴, A. Levy Yeyati⁵ and P. Joyez¹*
Robust against temperature, magnetic field
ABS only seen when AlOx deposited on graphene …

→ QD states likely due to AlOx nanoparticles hybridizing with dangling bonds at graphene edge or defect sites
Transport through Andreev bound states in a superconductor-quantum dot-graphene system!

Gate-tunable, sharp bound states

To be discussed:
- How do bound states form?
- Can data be explained by spectra of bound states?
How do ABS form?

“normal” quantum dot: single electron transport, separated by charging energy (even/odd spin filling for levels)

Quantum dot coupled to superconductor: no single-particle states, electron and hole (Andreev) levels
How do ABS form?

solid: electron-like
dashed: hole-like

ABS form on energy levels

Resonant conduction when level within $V_b$ of Fermi energy

Levels can shift with gate voltage

Discrete level $\rightarrow$ possibility of isolating individual ABS!

Only resolve ABS as subgap peaks for charging energy $U > \Delta$
If $U < \Delta$, form Cooper pairs on levels within gap; conductance suppressed (BTK-like)
How do ABS form?

- solid: electron-like
- dashed: hole-like

ABS form on energy levels

Resonant conduction when level within $V_b$ of Fermi energy

Levels can shift with gate voltage

Discrete level $\rightarrow$ possibility of isolating individual ABS!

Role of graphene?

- Low density lead $\rightarrow$ sharp spectra
- Large range of gate tunability for QD
- Single particle QD state from hybrid of AlOx & graphene
Spectroscopy of Andreev Bound States ...

\[ H = (\varepsilon_\uparrow - E_{\text{shift}}) c_\uparrow\dagger c_\uparrow + (\varepsilon_\uparrow + U - E_{\text{shift}}) c_\downarrow\dagger c_\downarrow + \Delta_{\text{eff}} c_\uparrow\dagger c_\uparrow + \Delta_{\text{eff}}^* c_\uparrow c_\uparrow \]

\[ \varepsilon \sim \text{QD single-particle energy (\uparrow or \downarrow)}, \ E_{\text{shift}} = \alpha(\Delta V_{\text{gate}}), \ U \sim e^2/\kappa C, \]

ABS Energy as function of gate voltage:

\[ E_{\pm} = \frac{1}{2} \left( \pm U + \sqrt{4\Delta_{\text{eff}}^2 + (2\varepsilon_\uparrow - 2E_{\text{shift}} + U)^2} \right) \]
Spectroscopy of Andreev Bound States …
Spectroscopy of Andreev Bound States:

**Ongoing Work:** Correlate ABS spectra with number and size of QDs under superconducting probe

1 nm ALD AlOx

0.5 nm thermally evaporated Al
Spectroscopy of Andreev Bound States:

**Ongoing Work**: Correlate ABS spectra with number and size of QDs under superconducting probe

Simulation of ABS for 2 coupled dots
Spectroscopy of Andreev Bound States:

**Ongoing Work:** Correlate ABS spectra with number and size of QDs under superconducting probe

Simulation of ABS for 3 coupled dots

- Controlled multiple-dot spectroscopy, systems of coupled ABS
- Patterning QDs by patterning defects in graphene
Summary

“Transport through Andreev bound states in a superconductor-graphene quantum dot system”

In superconductor-insulator-graphene-normal metal system:

- Geometric resonances \(\rightarrow\) conductance oscillations
- Quantum dot formed, likely due to nanoparticle-graphene hybridization
- Sharp, gate-tunable Andreev bound states formed in quantum dot

*Superconducting tunneling spectroscopy fertile technique
*Lots of new physics in hybrid superconducting systems

*See Nat. Phys. 7, 386
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Difficult to experimentally verify quantum dot (work in progress) ..

- Pillet et al find no evidence of Coulomb blockade when leads normal

- We also find no evidence of Coulomb blockade when leads normal

→ Quantum dot can be well-coupled to leads, or in “open” regime, as long as charging energy significant
Effect of end-to-end bias
Tunneling spectroscopy with a superconducting probe:

- Measure weak tunneling signals in quantum dots
- Enhanced conductance signals in carbon nanotube quantum dots

Dirks et al, APL (2009)
Sharp spectra of individual Andreev bound states are difficult to measure:

In transport, ABS observed as supercurrent - measure contributions from many modes
In point-contact tunneling, ABS seen as zero-bias anomalies

➔ Can couple a superconductor to a quantum dot for individual states
➔ Create tunnel junction to obtain spectra
➔ Make S-QD-N junction to avoid other superconducting resonances
➔ Use low density of states leads to get sharp spectra
➔ Tuning QD energy levels with gate or bias tunes ABS

S-QD-graphene system works well!
How does one get conductance inside a superconducting gap?

- Leaky tunnel barrier \( X \)
- Kondo \( X \)
- Andreev reflections

But, according to BTK, these should be exponentially suppressed inside gap for a tunnel barrier!

(and don’t see periodicity of MAR)
Oscillations above the gap: geometric resonances

\[ \alpha V_{\text{gate}} - V_{\text{bias}} = \pi n v_F/L \]

“particles in a (graphene) box”

Coupling to discrete QD levels allows cavity energy levels to be observed
\[ \Rightarrow \text{Spectroscopy of low-energy resonant states!} \]