Subgap Density of States in Ultrathin Superconductor-Normal Metal Bilayers

Zhenyi Long, Michael Stewart, Taejoon Kouh, and Jim Valles

Subgap States in SN Bilayers

• Quest for a metallic state in 2D

• Is there a superconductor to metal transition in superconductor-normal metal bilayers?

• We observe subgap states that give the tunneling density of states a hybrid superconductor/metal appearance
  - The subgap quasiparticles are weakly coupled to the superconductor or quasi-trapped in the N layer
  - The fraction of subgap quasiparticles grows as $T_c$ decreases
Mike, Zhenyi, Por, TJ

Subgap DOS in Pb/Ag Bilayers

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SC Grain Embedded in Metal

- $R_N \rightarrow \infty$
  - $R_S > \xi_s$ then SC
  - $R_S < \xi_s$ then normal
  (DeGennes)

- Quantum fluctuations in order parameter
  (Spivak)

Subgap DOS in Pb/Ag Bilayers

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Superconductor to Metal*

\[ T_{co} = 0 \]

\[ T_{co} > 0 \]

\( N_{sc} < N_{sc}^* \)
Anomalous MR
Pseudogap in DOS

\( N_{sc} > N_{sc}^* \)
Anomalous \( H_c \)
QP’s in ground state

Ultrathin Pb/Ag Bilayers

Subgap DOS in Pb/Ag Bilayers
Quench Condensed Pb/Ag Films

- $1.5 \text{ nm} < d_{\text{Pb}} < 6 \text{ nm}$
- $d_{\text{Ag}} < 20 \text{ nm}$
- $\xi > 60 \text{ nm}$
- Measure \textit{in situ}

For tunneling:

Subgap DOS in Pb/Ag Bilayers
SIT compared to SMT

Homogeneous film SIT

Pb/Ag bilayer films SMT(?)

Subgap DOS in Pb/Ag Bilayers

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Proximity Effect Theory: Cooper Limit

(Cooper, Degennes, Usadel)

\[ T_c = T_o \exp\left(-\frac{1}{\lambda_{eff}}\right) \]

\[ \Rightarrow T_c \propto \exp(-\alpha d_N) \]

e\(^{-}\)'s Andreev scatter from interface many times in
\[ \frac{h}{k_B T_c} \]

Volume average the coupling constant

\[ \lambda_{eff} = \lambda_s \left[ \frac{d_S}{d_S + \beta d_N} \right] \]

Subgap DOS in Pb/Ag Bilayers

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Reduction of $T_{co}$

Agreement with MFT
- thickest Pb film
- over a decade

Deviations from MFT
- in thinner Pb films
- at low $T_{co}$
- tend toward metal

Lines: $T_{co} = T_o \exp[-(d_{pb} + \beta d_{Ag})/\left(\lambda_{pb} d_{pb} + \beta \lambda_{Ag} d_{Ag}\right)]$

$\lambda_{pb} = 0.757$, $\lambda_{Ag} = -0.017$, $\beta = 0.366$, and $T_o = 21.5K$, 27.6K, 30.1K for $d_{pb} = 1.5$, 2.2, and 3.0 nm, respectively.

Subgap DOS in Pb/Ag Bilayers

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Tunneling Density of States

Junction conductance $\propto N(eV-E_F)$ at low $T$

Subgap DOS in Pb/Ag Bilayers

$N_s(E) = \frac{E}{\sqrt{E^2 - \Delta^2}}$

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**DOS in the Cooper Limit**

(Cooper, Degennes, Usadel)

\[ \Delta_0 \propto \exp(-\alpha d_N) \]

Subgap DOS in Pb/Ag Bilayers

\[ N_s(E) = \frac{E}{\sqrt{E^2 - \Delta^2}} \]

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$d_{\text{Pb}} = 4.1 \text{ nm}, \quad d_{\text{Ag}} = 4.2$

Subgap DOS in Pb/Ag Bilayers

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Subgap DOS in Pb/Ag Bilayers

\[ d_{\text{Pb}} = 4.1 \text{ nm}, \quad d_{\text{Ag}} = 4.2, 6.7, 9.1, 12.4, 15.6, 19.3 \text{ nm} \]
Peaks are too broad

Subgap DOS in Pb/Ag Bilayers
Subgap DOS in Pb/Ag Bilayers

Subgap States!
Gap Fills as $T_c \to 0$
$2\Delta /kT_c < 3.5$!
Subgap DOS in Pb/Ag Bilayers

Reversing the Trend

*add S atop SN layer*

Peaks move out
Peaks sharpen
$G_j(0)$ decreases
Subgap DOS in Pb/Ag Bilayers

Subgap DOS Grows as $T_c$ decreases
- Linear $E$ dependence
- Finite DOS @ $E_F$

Deviation from BCS

Broad Peaks
- Broader as $T_c$ decreases
- Shorter as $T_c$ decreases

Voltage (mV)
-0.6  -0.3  0.0  0.3  0.6

$G_j$
0.0  0.1  0.2  0.3

Voltage (mV)
-1.0  -0.5  0.0  0.5  1.0

$G_j$
0  1  2

$T = 0.06 \text{ K}$
Broadened Peaks

\[
\Delta \propto \Delta_0 \exp \left( -a \frac{d_N}{d_S} \right)
\]

\[\Delta \propto \Delta_0 \exp \left( -a \frac{d_N}{d_S} \right)\]

Gap Distribution

DOS with log normal distribution of \(\Delta\)

\[
\tilde{N}_s^\sigma (E) = \frac{1}{\sqrt{2\pi}k\sigma} \int_0^{\Delta_0} \tilde{N}_s^{BCS} (E, \Delta) \exp \left( -\frac{(\ln(\Delta/\Delta))^2}{2(k\sigma)^2} \right) \frac{d\Delta}{\Delta}
\]

Subgap DOS in Pb/Ag Bilayers

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Fitting the DOS

Peaks fit broadened BCS

(∼10-20% thickness variation)

Subgap States not fit by broadened BCS

Subgap DOS in Pb/Ag Bilayers

Brown University
Fitting the DOS

Peaks fit broadened BCS

(~10-20% thickness variation)

Subgap DOS requires

\[ N_{\text{subgap}}(E) = \alpha E + \beta \]
Subgap Quasiparticle Origins

• Proximity Effect Theories:

Subgap states for \( \tau_{AS} > \frac{h}{k_B T_c} \)

• Need \( d_N < \xi \) or “trapped” quasiparticles

Bilayers too thin

Billiard Models
Induced superconductivity distinguishes chaotic from integrable billiards

J. A. Melsen, P. W. Brouwer, K. M. Frahm and C. W. J. Beenakker

Instituut-Lorentz, University of Leiden
P.O. Box 9506, 2300 RA Leiden, The Netherlands

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PACS. 05.45+b – Theory and models of chaotic systems.
PACS. 74.50+r – Proximity effects, weak links, tunneling phenomena, and Josephson effects.
PACS. 74.80Fp – Point contacts; SN and SNS junctions.

Abstract. – Random matrix theory is used to show that the proximity to a superconductor opens a gap in the excitation spectrum of an electron gas confined to a billiard with a chaotic classical dynamics. In contrast, a gapless spectrum is obtained for a non-chaotic rectangular billiard, and it is argued that this is generic for integrable systems.
Soft Gap Prediction

Chaotic billiard

*Chaotic, untrapped trajectories*

*Hard gap*

Rectangular billiard

*Integrable trapped trajectories*

*Subgap DOS*

*Subgap DOS in Pb/Ag Bilayers*

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Linear Subgap DOS!

Rectangular billiard

\[ N_{\text{subgap}}(E) \sim \frac{E}{E_{\text{Th}}} \]

where \( E_{\text{Th}} \) is the Thouless energy

Mixed Integrable and Chaotic Phase Space

\[ N_{\text{subgap}}(E) \sim \frac{E}{E_{\text{Th}}} + \beta \]

where \( \beta \) is a constant (Schomerus and Beenakker)

Subgap DOS in Pb/Ag Bilayers

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Linear Subgap DOS

Experiment
\[ \alpha \sim d_N^3 \]

Theory
\[ \alpha \sim E_{Th}^{-1} \sim d_N^2 \]

Difference due to a \( T_c \) dependence?

Subgap DOS in Pb/Ag Bilayers

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SN Bilayers = Mixed Phase Space

 qp’s with nearly integrable trajectories
 Trapped in N layer

 qp’s on chaotic trajectories
 Visit both S and N layers

Subgap DOS in Pb/Ag Bilayers
• Subgap states give DOS a hybrid metal-superconductor appearance
• DOS becomes more metallic as $T_c$ decreases
  – Sign of an approaching SMT?

• Growing fraction of qp’s decouple from superconductor as $T_c$ decreases –
  – *is this spontaneous phase separation?*

• Route to a gapless superconductor without time reversal symmetry breaking