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Conference on Superconductor-Insulator Transitions

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Spin effects near the superconductor-insulator transition in ultra-thin A1 and Be films

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Spin Effects Near the Superconductor-Insulator Transition in Ultra-Thin Al and Be Films

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Outline:

1. Superconductivity and Magnetic Fields
2. The Spin-Paramagnetic Transition
3. Incoherent pairing in film with $R << R_Q$
4. Quantum Metallicity in films with $R > R_Q$
5. Summary and Future Research

Collaborators:

- Yimin Xiong
- Gianluigi Catelani

Wenhao Wu

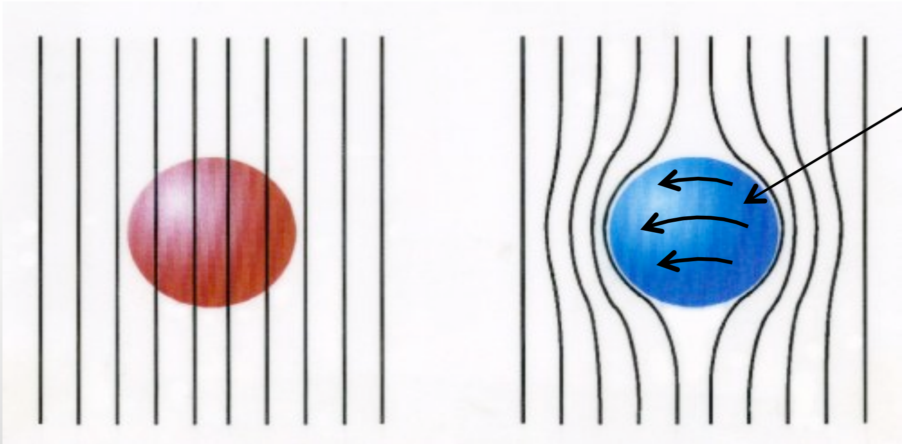
Vladimir Butko

Hank Wu

Orbital Response of a Superconductor to a Magnetic Field

Bulk Superconducting Systems

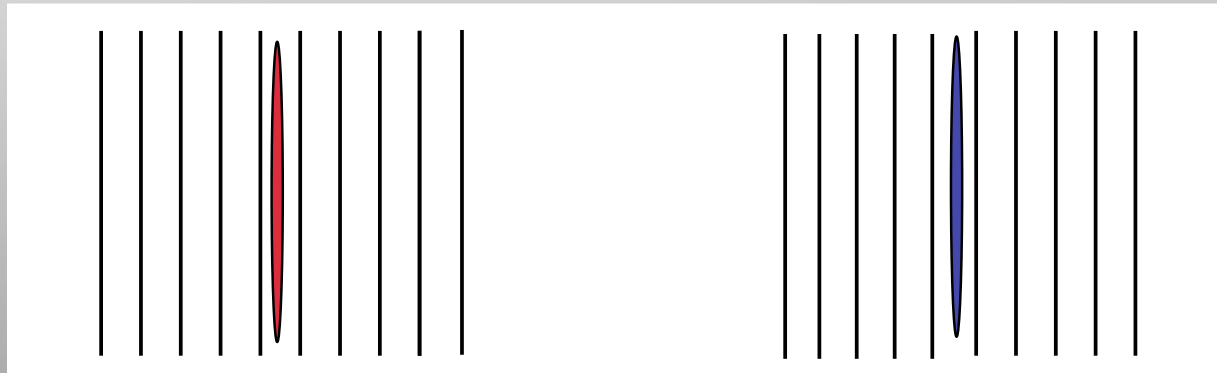
Normal State



Screening currents

Superconducting State
(Meissner Effect)

Disk with width << ξ in a parallel field

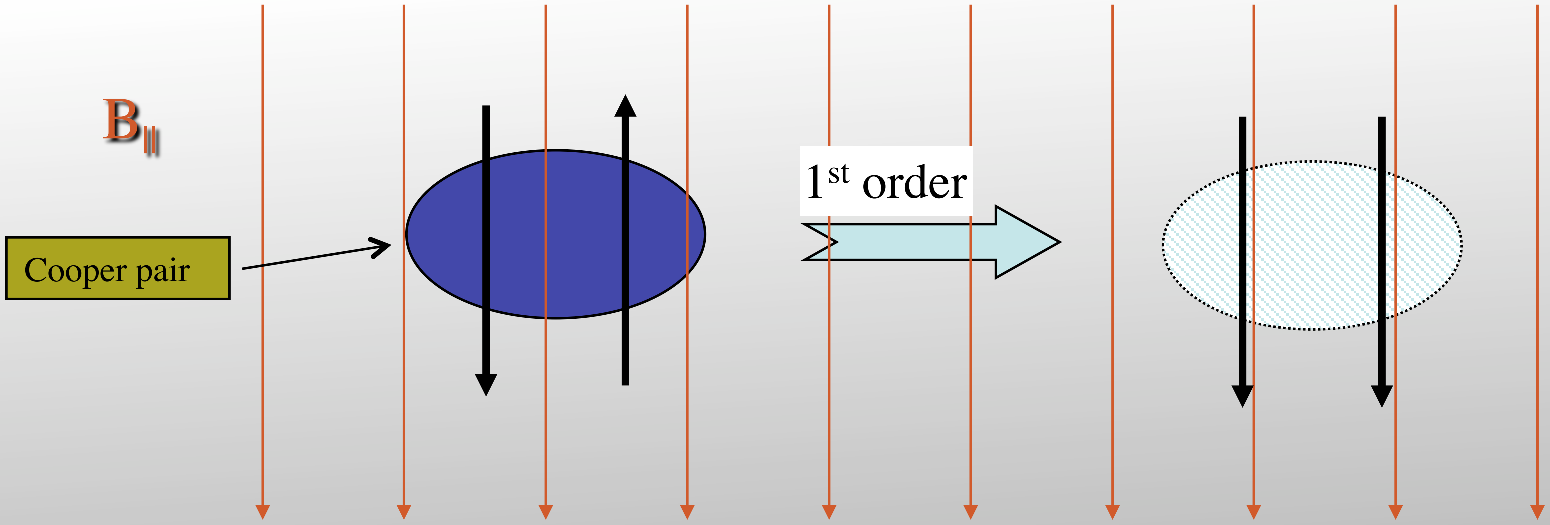


Normal State

Superconducting State
(no screening currents)

Thin Film Superconductivity in High Parallel Magnetic Fields

Assume magnetic field oriented parallel to superconducting film of thickness $d < \xi_o$ so that there can be no significant orbital response to the applied field.



Energy: Δ $2\mu_B B_{||}$

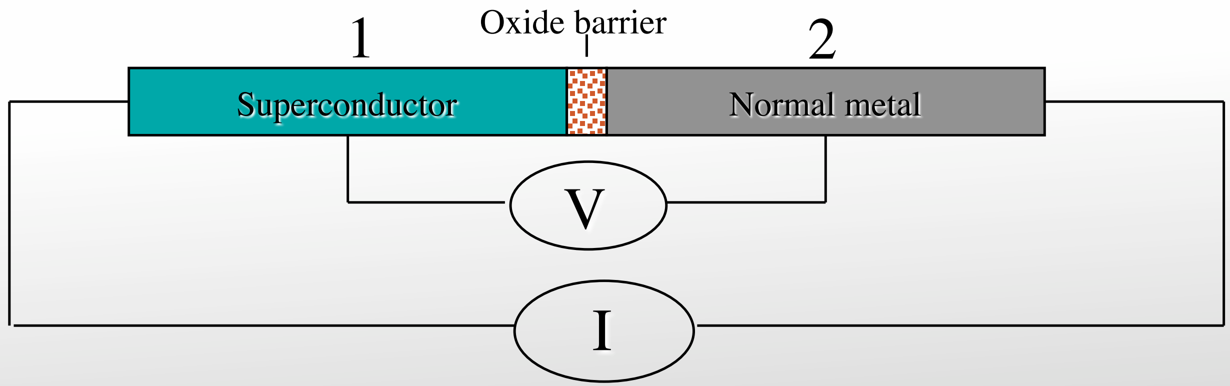
S-P Transition:

(Spin-Paramagnetic)

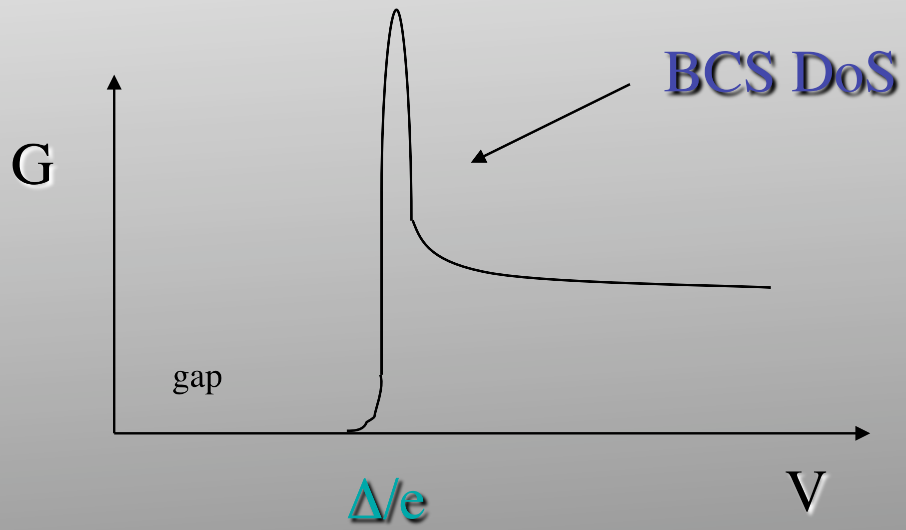
$$B_{c||} \approx \frac{\Delta}{\sqrt{2}\mu_B}$$

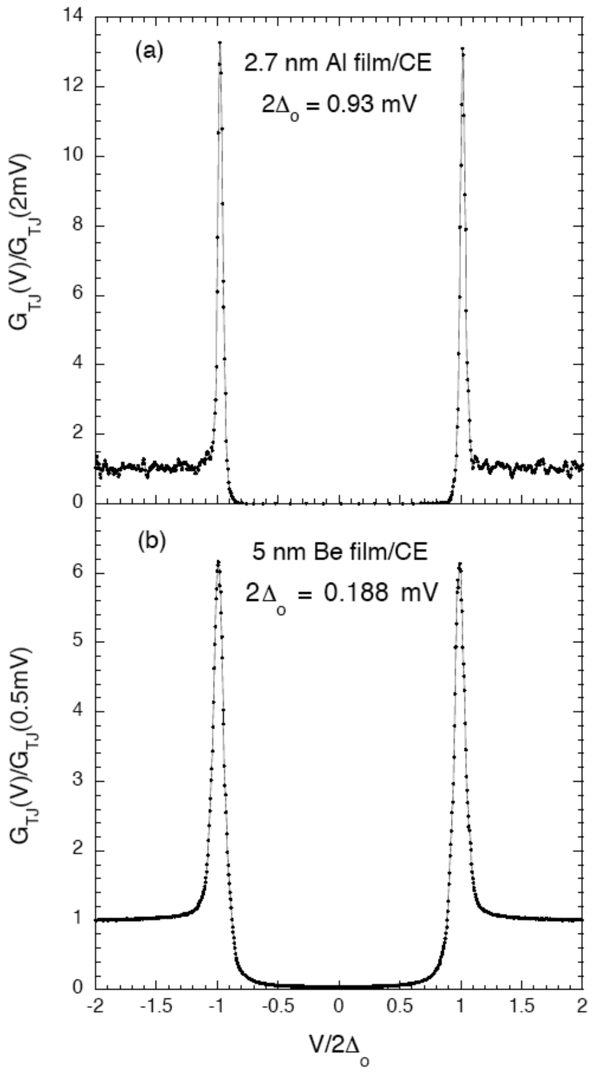
$(g_L = 2)$

Electron Tunneling and the DOS



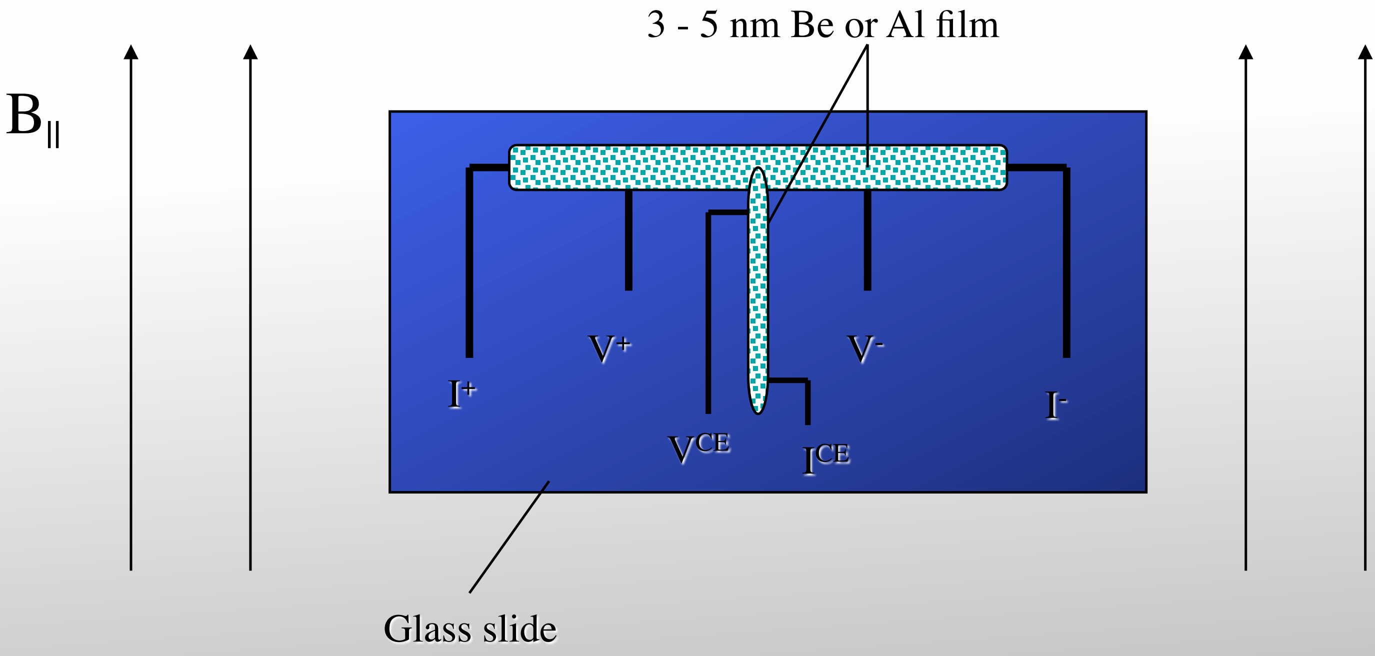
Tunneling Conductance: $G(V) \propto N_1 N_2 \quad (kT << eV, \Delta)$





(a)
2.7 nm Al film/CE
2Δo = 0.93 mV
G_TJ(V)/G_TJ(2mV)
(b)
5 nm Be film/CE
2Δo = 0.188 mV
G_TJ(V)/G_TJ(0.5mV)
V/2Δo

Sample Geometry



Be:

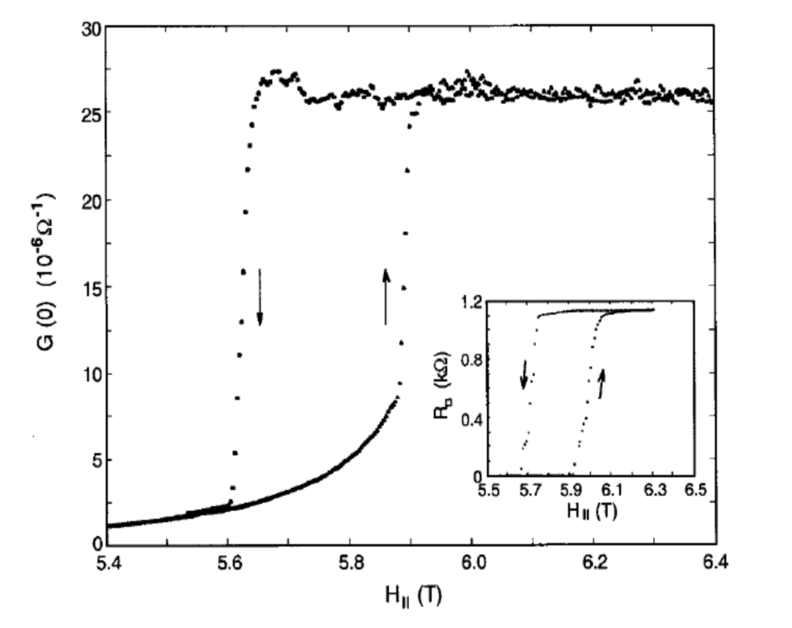
T_c = 0.026 K (bulk)
T_c ~ 0.6 K (quenched film)
barrier type oxide BeO
g-factor=2; $E_z = 2\mu_B B_{\parallel}$

Al:

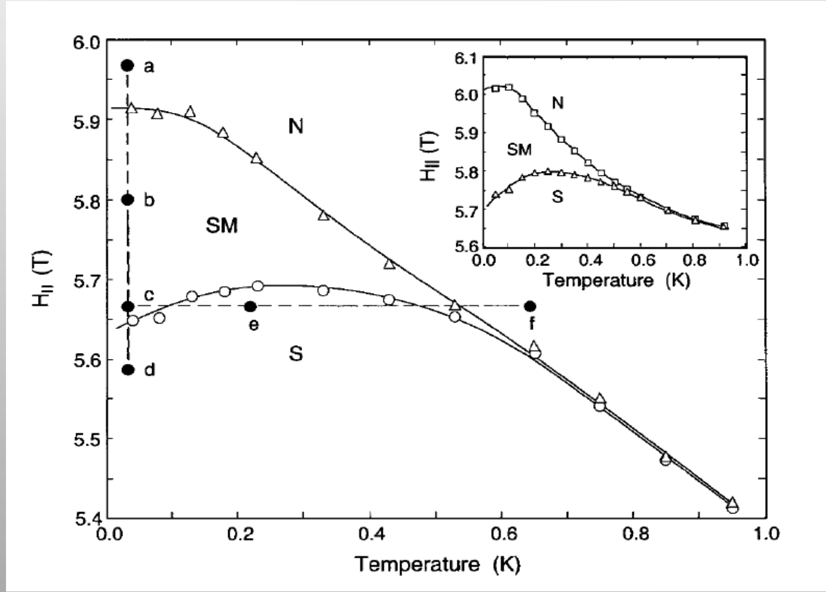
T_c = 1.1 K (bulk)
T_c = 2.7 K (quenched film)
barrier type oxide Al_2O_3
g-factor ~ 1.8^*; $E_z \sim 1.8\ \mu_B B_{\parallel}$

Spin Paramagnetic Phase Diagram in Al Films

DoS at Fermi Energy

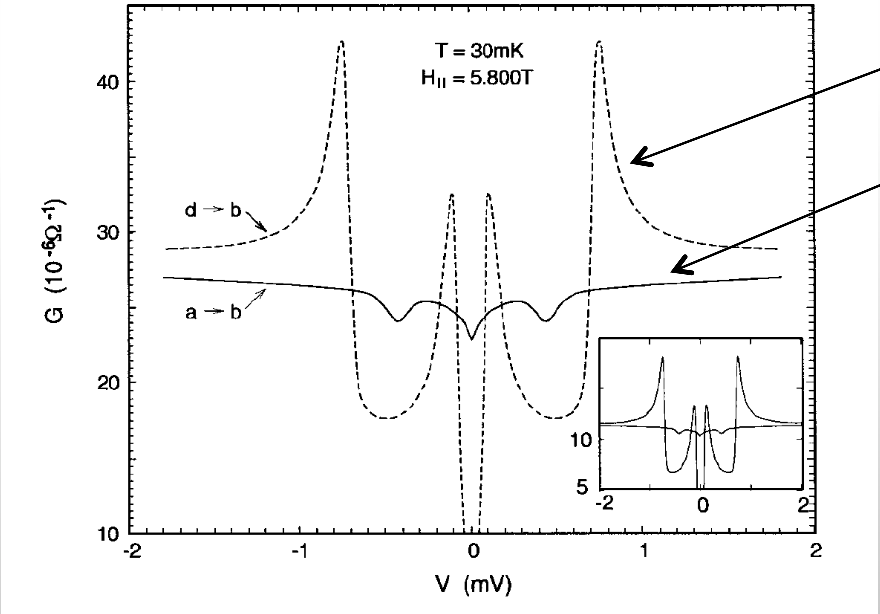


Phase Diagram



N: normal state
SM: state memory coexistance
S: superconducting phase

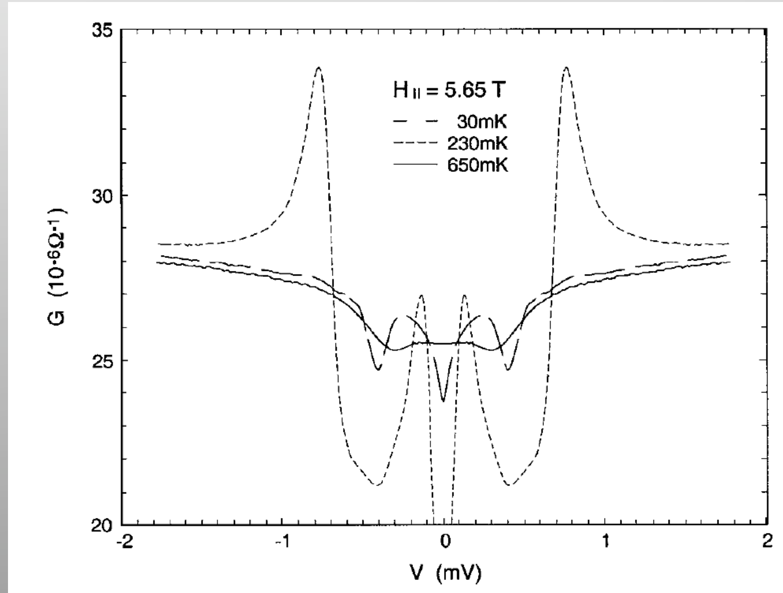
State Memory: two curves taken at same $H_{||}$ and T



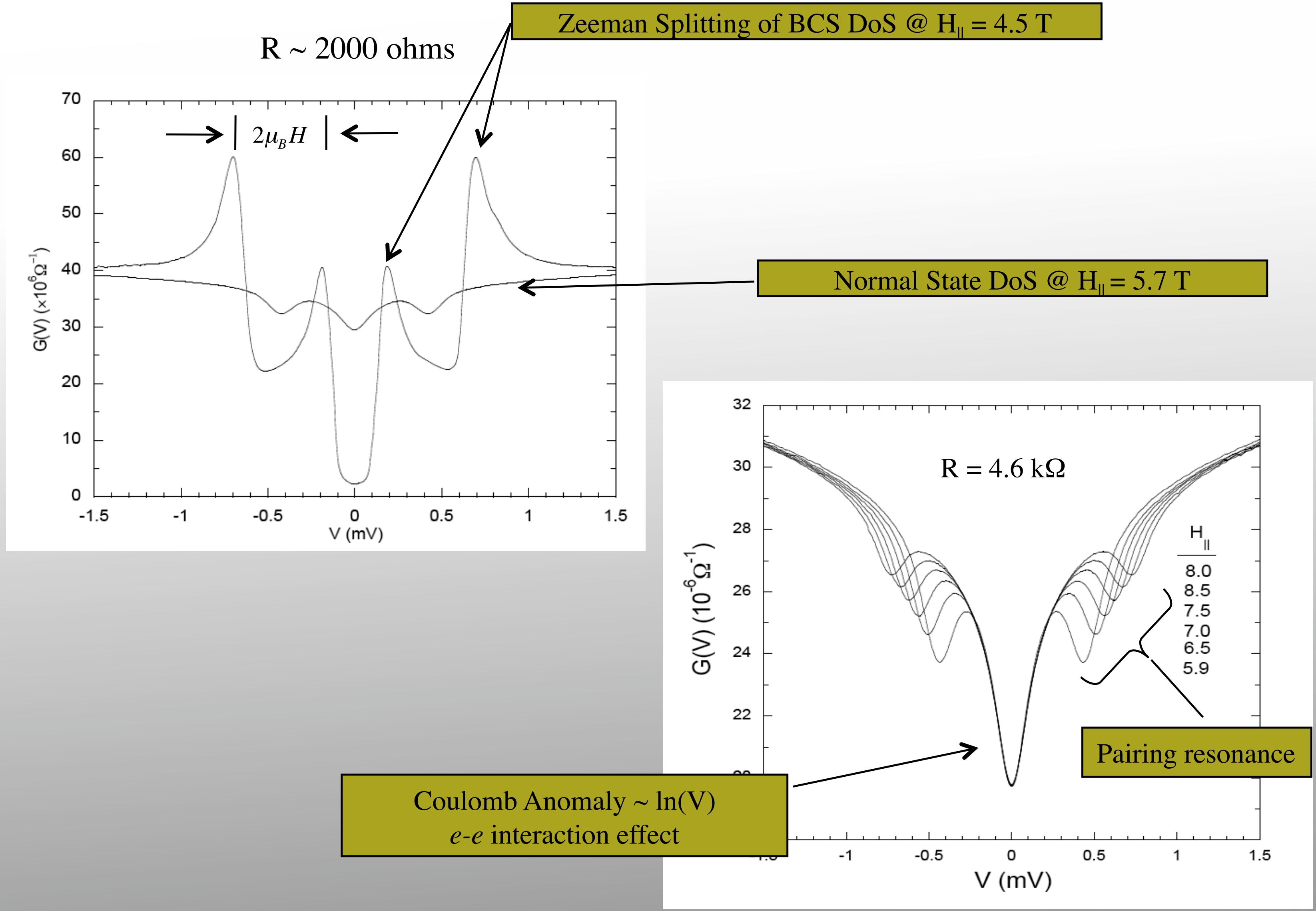
Superconducting spectrum

"Normal state" spectrum

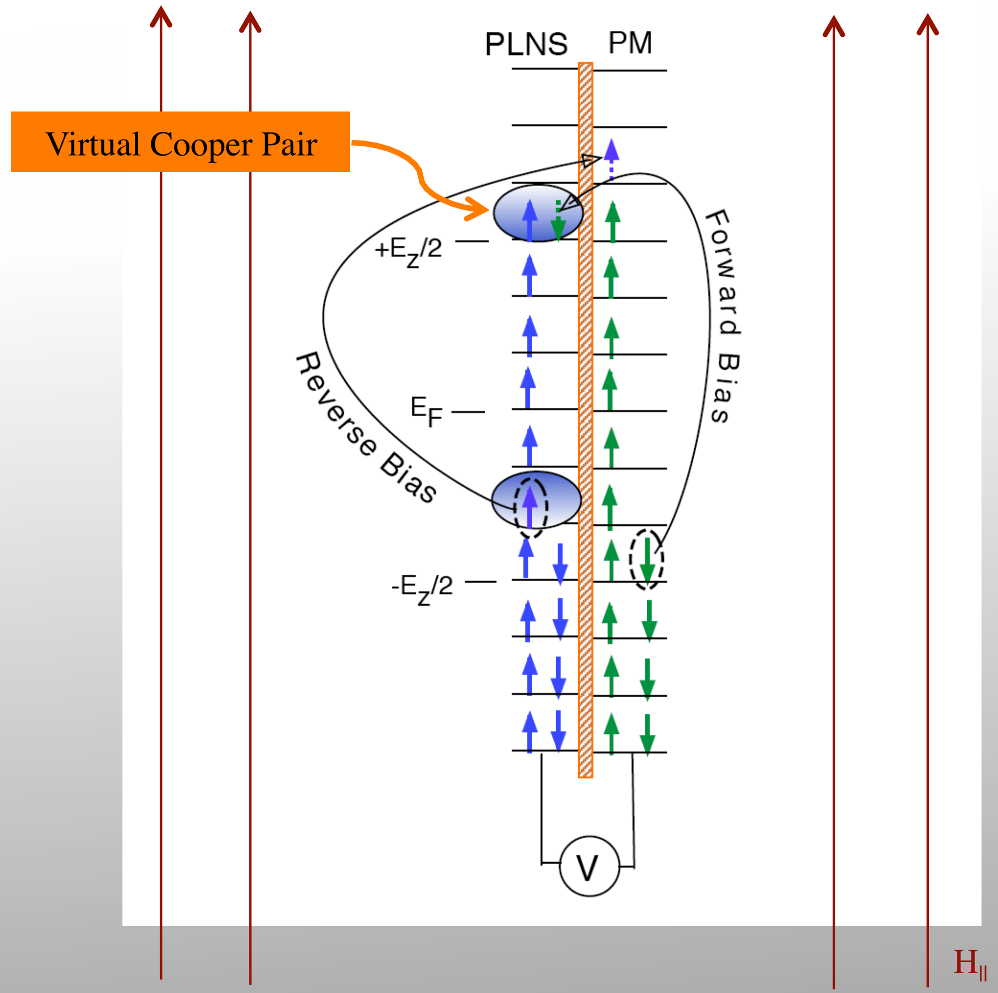
Reentrance in Tunneling DoS



Pairing Resonance



Origin of the Resonance

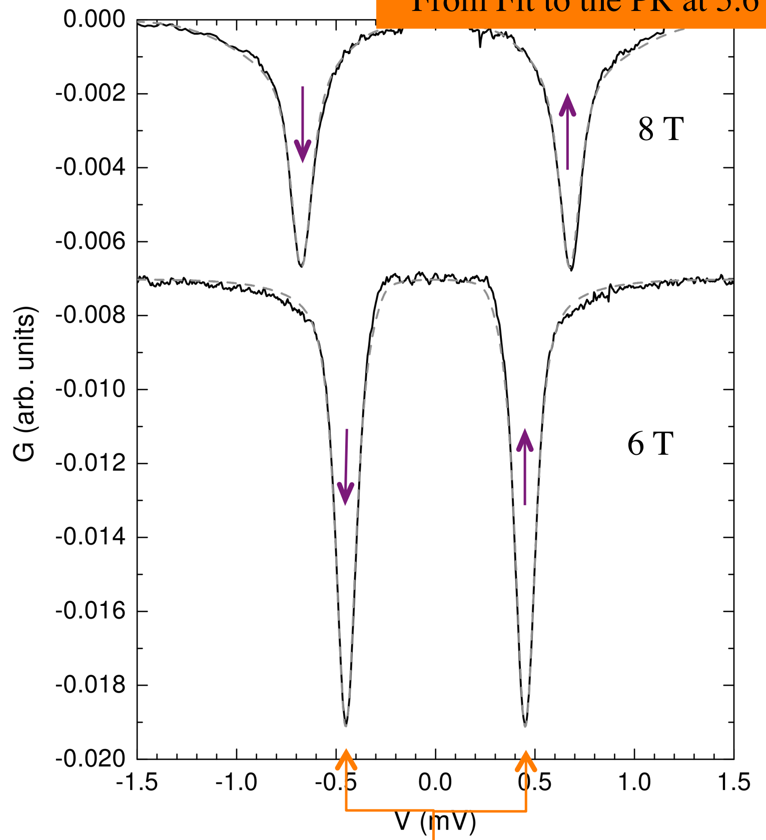


Aleiner and Altshuler, PRL 79, 4242 (1997)

Extracting Superconducting Parameters From PR

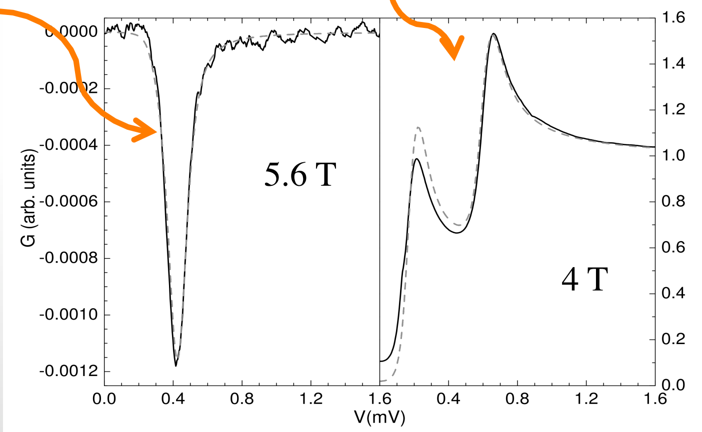
Al-PM Tunnel Junction

SC Parameters Extracted From Fit to the PR at 5.6 T



$$eV^* = \tfrac{1}{2}\left[eV_z + \sqrt{(eV_z)^2 - \Delta_o^2}\right]$$

Predicted DoS at 4 T



<u>Parameters Extracted From PR Fits</u>

Gap: Δ_o

SO: $b = \dfrac{\hbar}{3\tau_{so}\Delta_o}$

Orbital: $c = \dfrac{De^2t^3\Delta_o}{8l_o\mu_B^2\hbar}$

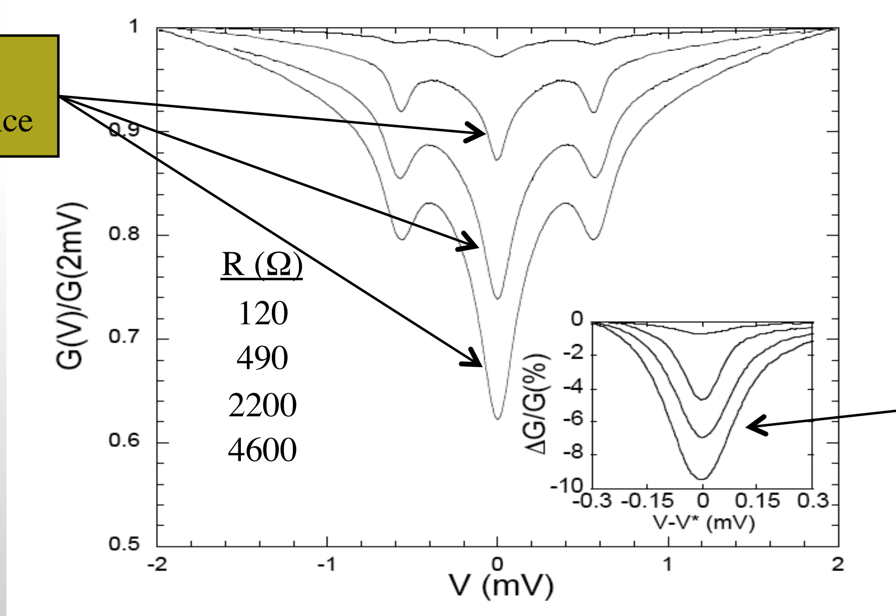
FL Parameter: G^0

Note: $E_z = \dfrac{2\mu_B H}{1+G^0}$ $H_c^{CC} = \dfrac{\Delta_o\sqrt{1+G^o}}{\sqrt{2}\mu_B}$

Catelani et al., arXiv:0905.2414v1

S-I Insulator Transition from the perspective of the PR

ZBA grows rapidly
with increasing sheet resistance

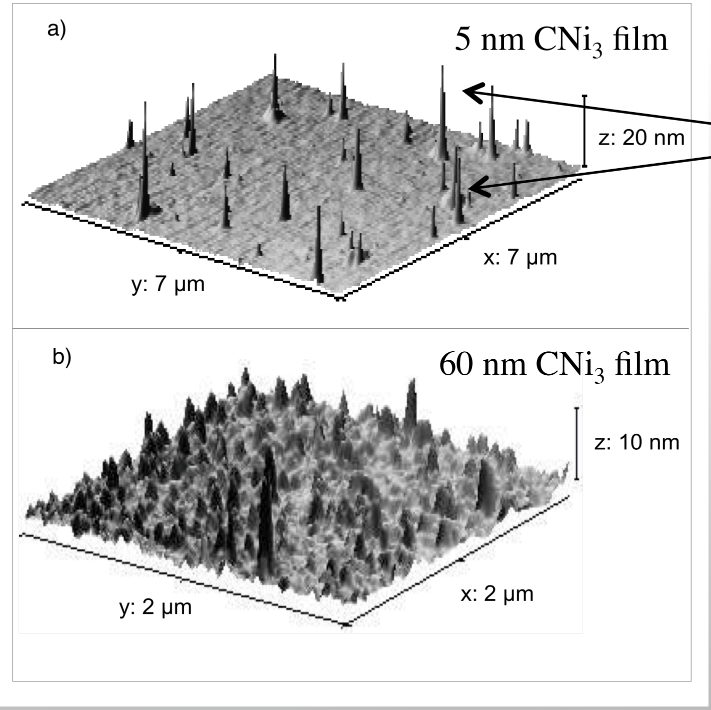


The PR also deepens
with increasing sheet
resistance.

Can the PR survive the zero-field S-I transition, and, if so,
does film morphology matter?

Al/AlO$_x$/FM Tunnel Junctions and Electron Polarization

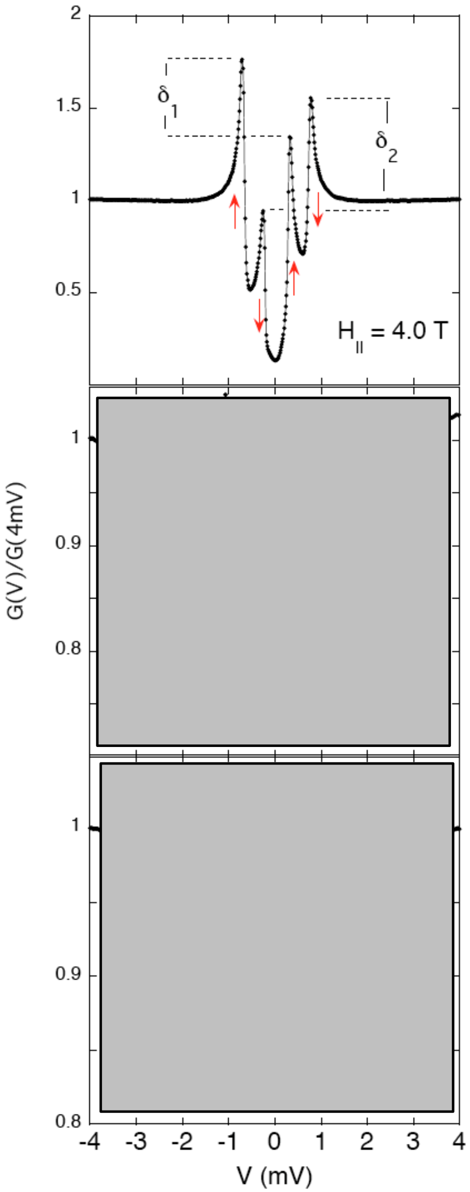
Ferromagnetic Carbides: CNi_3, CCo_3, CFe_3



Multi-wall carbon nanotubes

The magnetic properties of these films are very similar to that of pure Ni, Co, and Fe films.

Al-CNi_3 Tunneling Spectra



SC phase

$$P = \frac{|\delta_1 - \delta_2|}{|\delta_1 + \delta_2|}$$

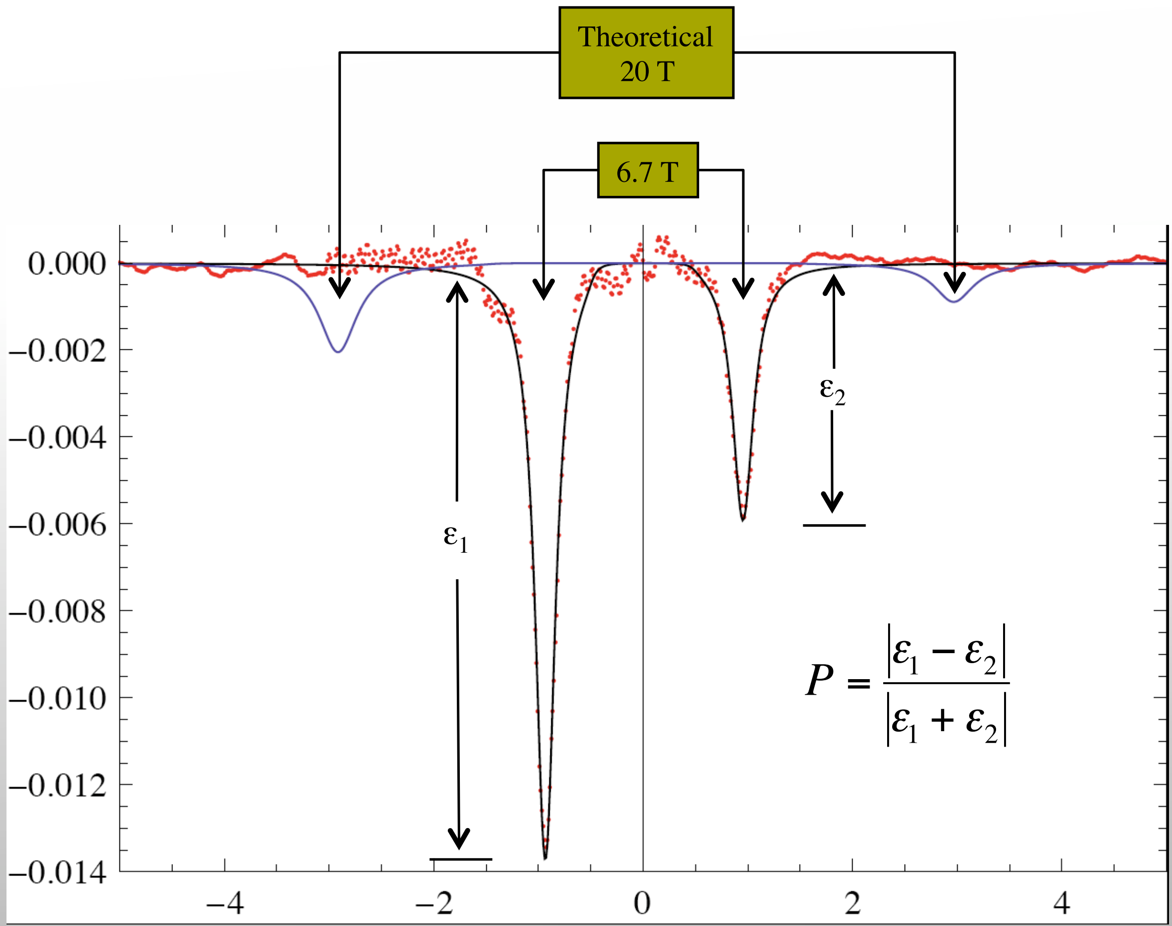
Tedrow and Meservey,
PRL 26, 192 (1971)

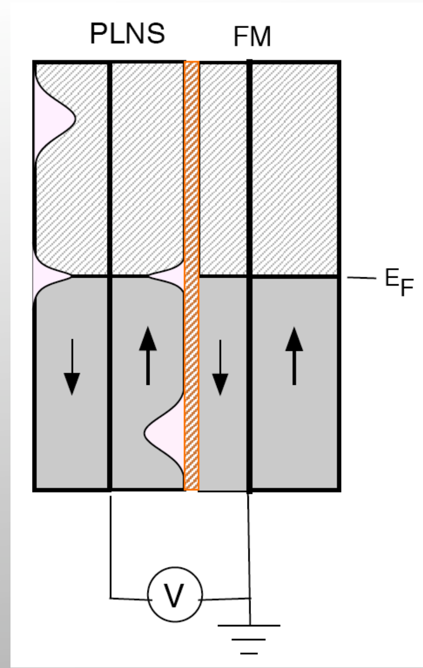
Coexistence region

$H_{c||} \sim 6.9$ T

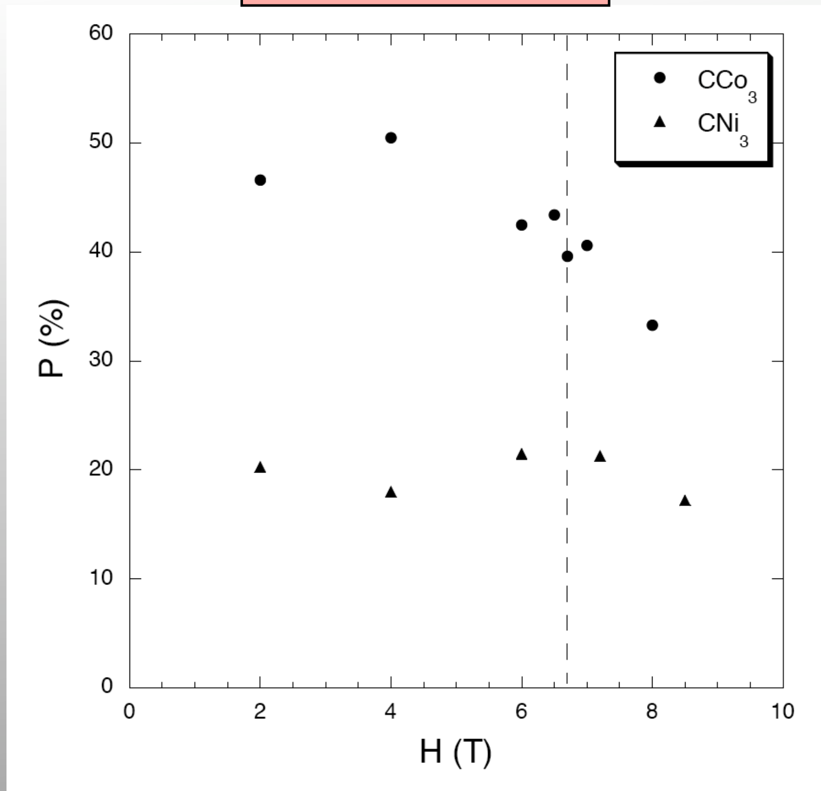
Pauli-limited Normal State

Polarization in a CCo_3 Film

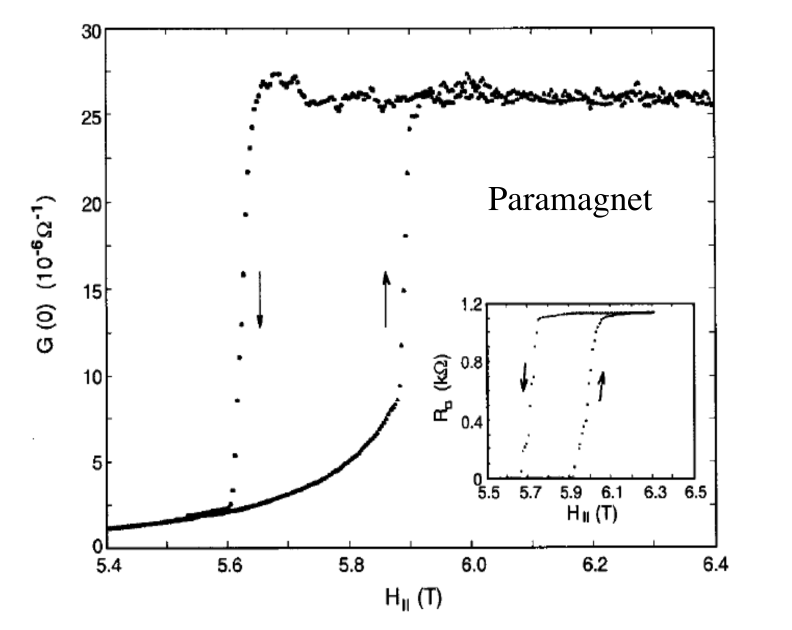


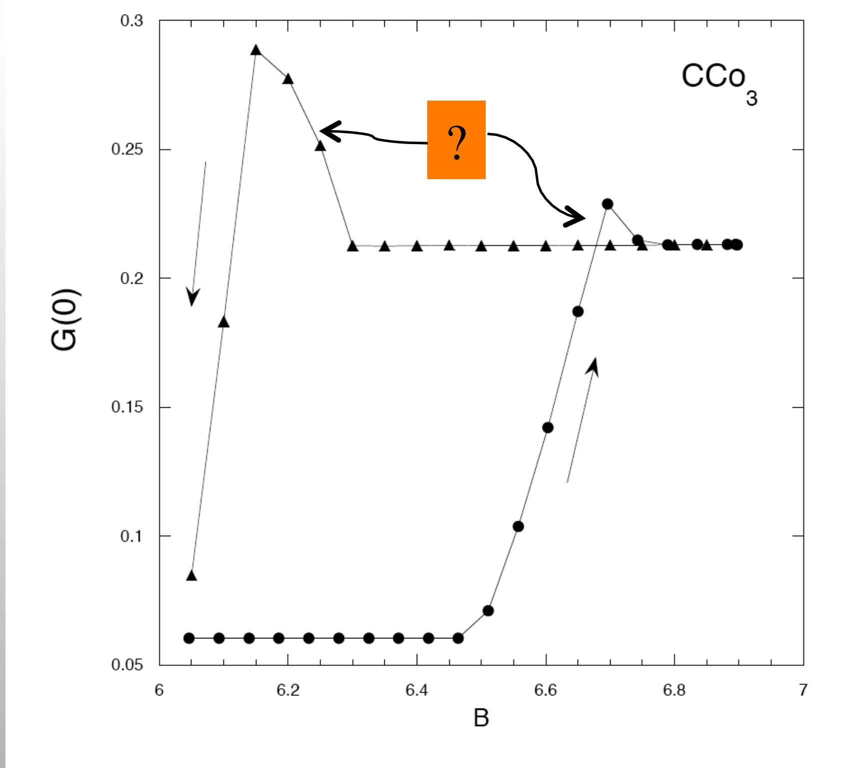


Measured Polarizations

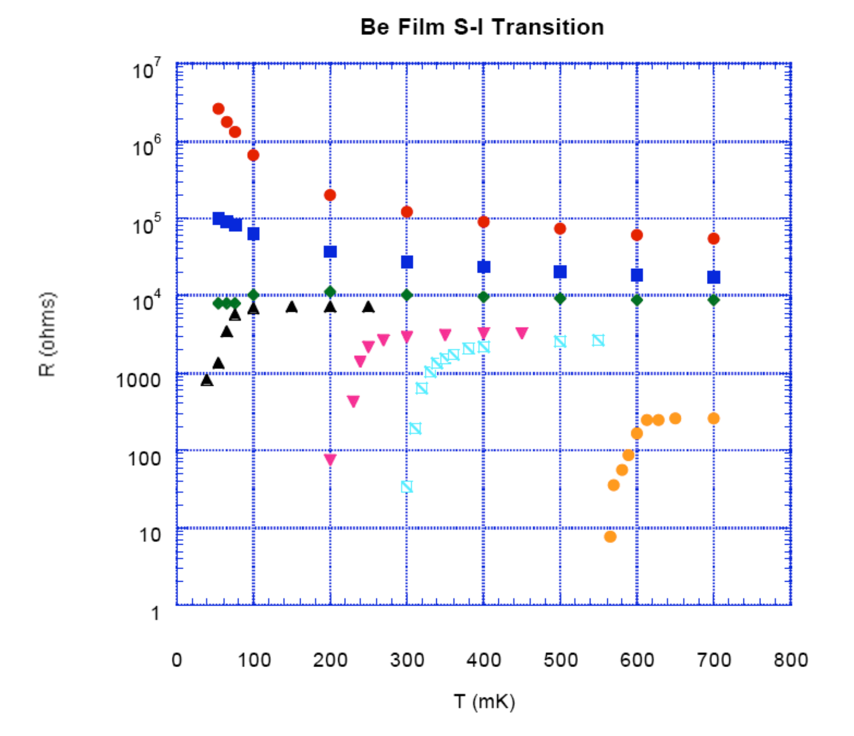


DoS @ Fermi Energy

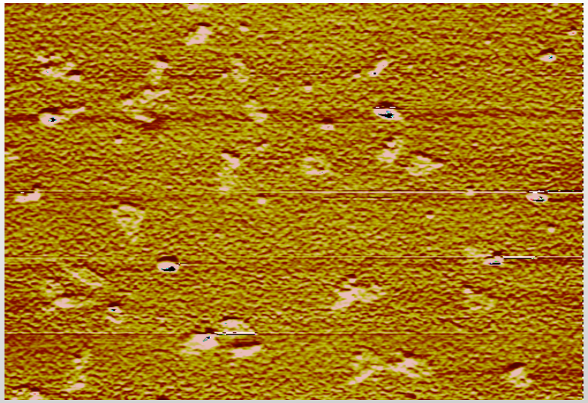




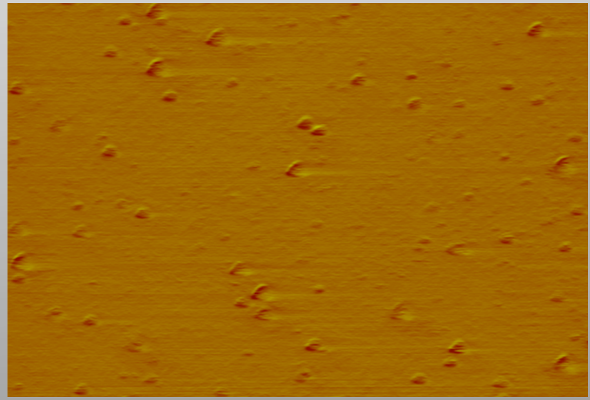
Quantum Metallicity in Insulating Be Films



AFM Micrographs of 3 nm films
0.1 x 0.1 nm



Al

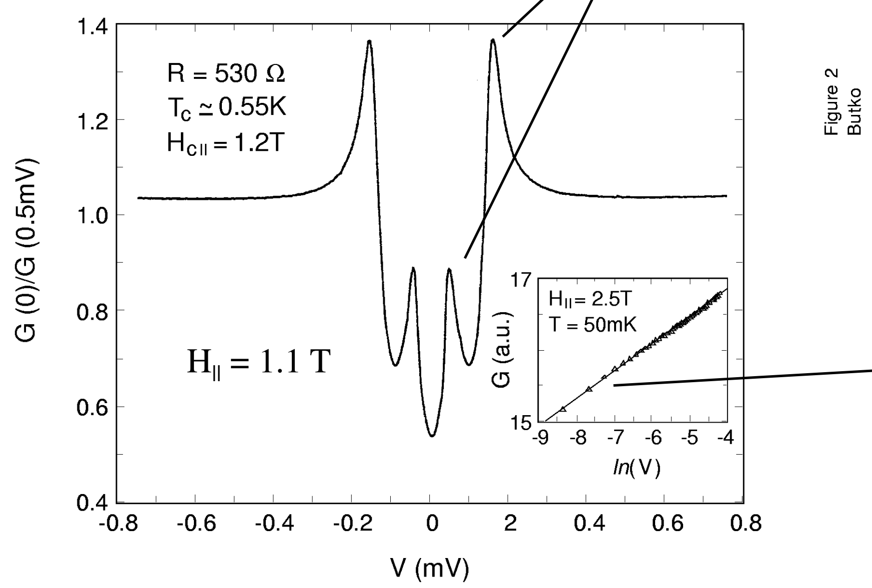


Be

Coulomb Gap in High Resistance Be Films

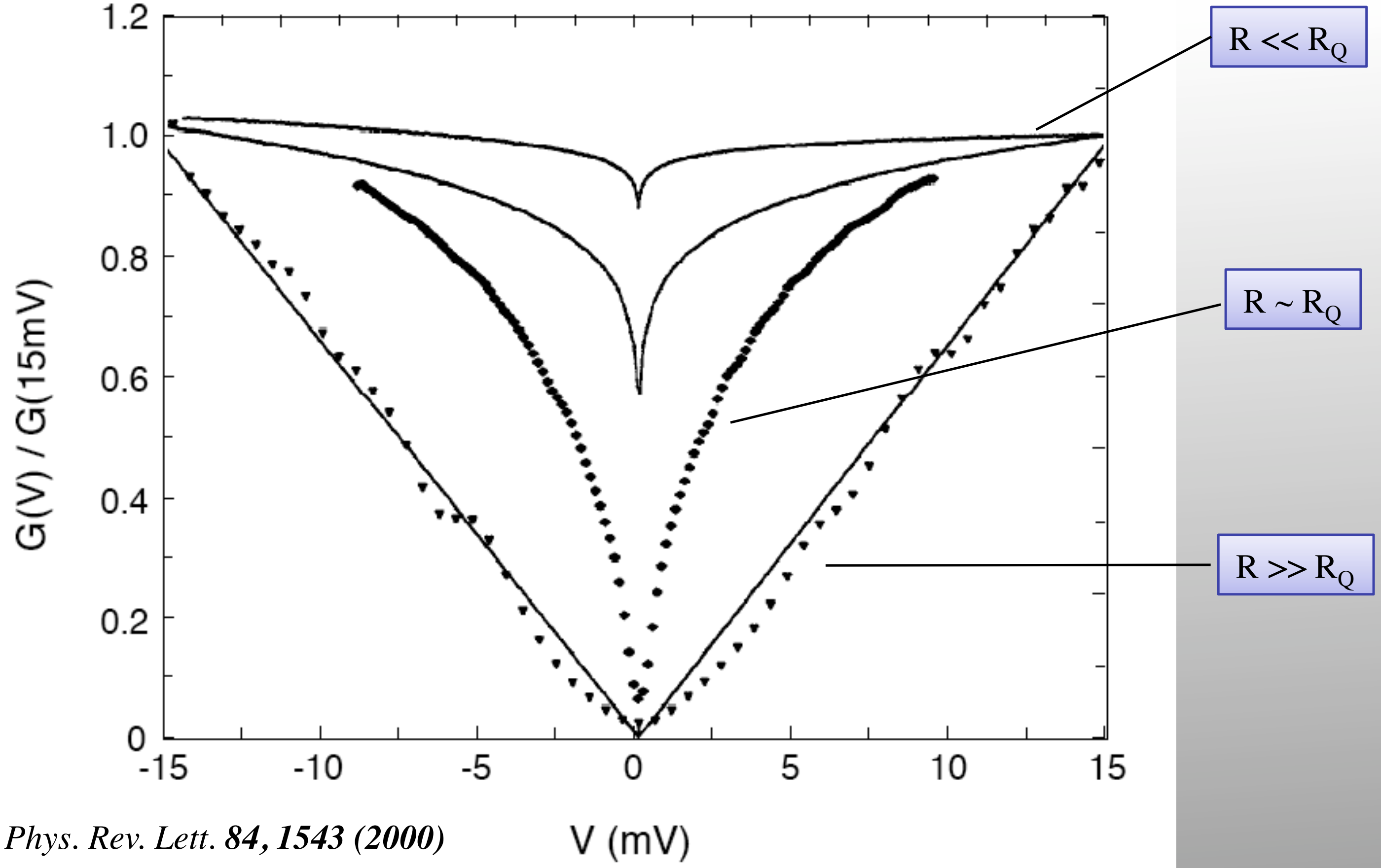
Superconducting Phase of a 3 nm Be Film with $R << R_Q$

Zeeman splitting of BCS peaks



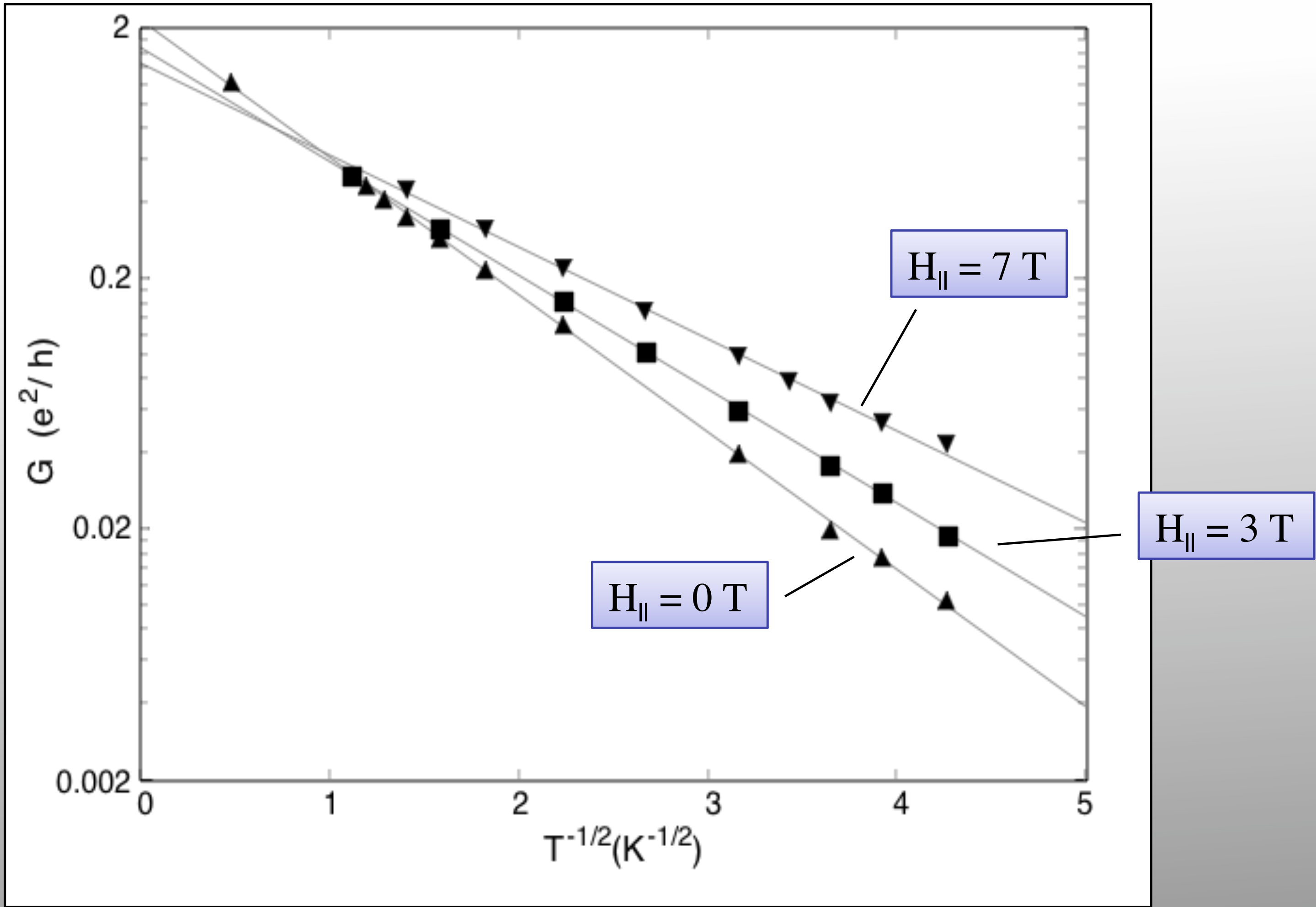
Zero bias anomaly

Evolution of Tunneling Density of States with Increasing R



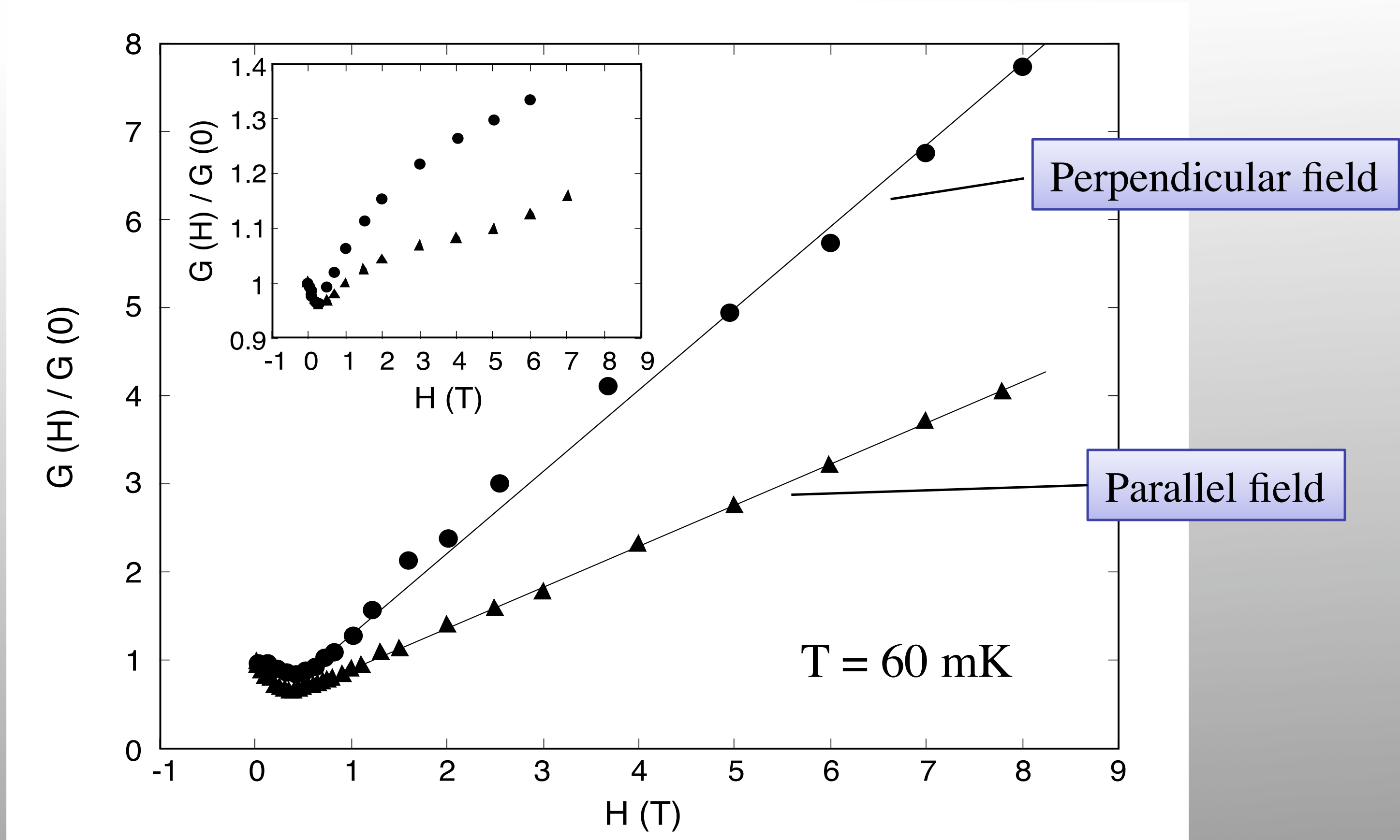
Phys. Rev. Lett. ***84, 1543 (2000)***

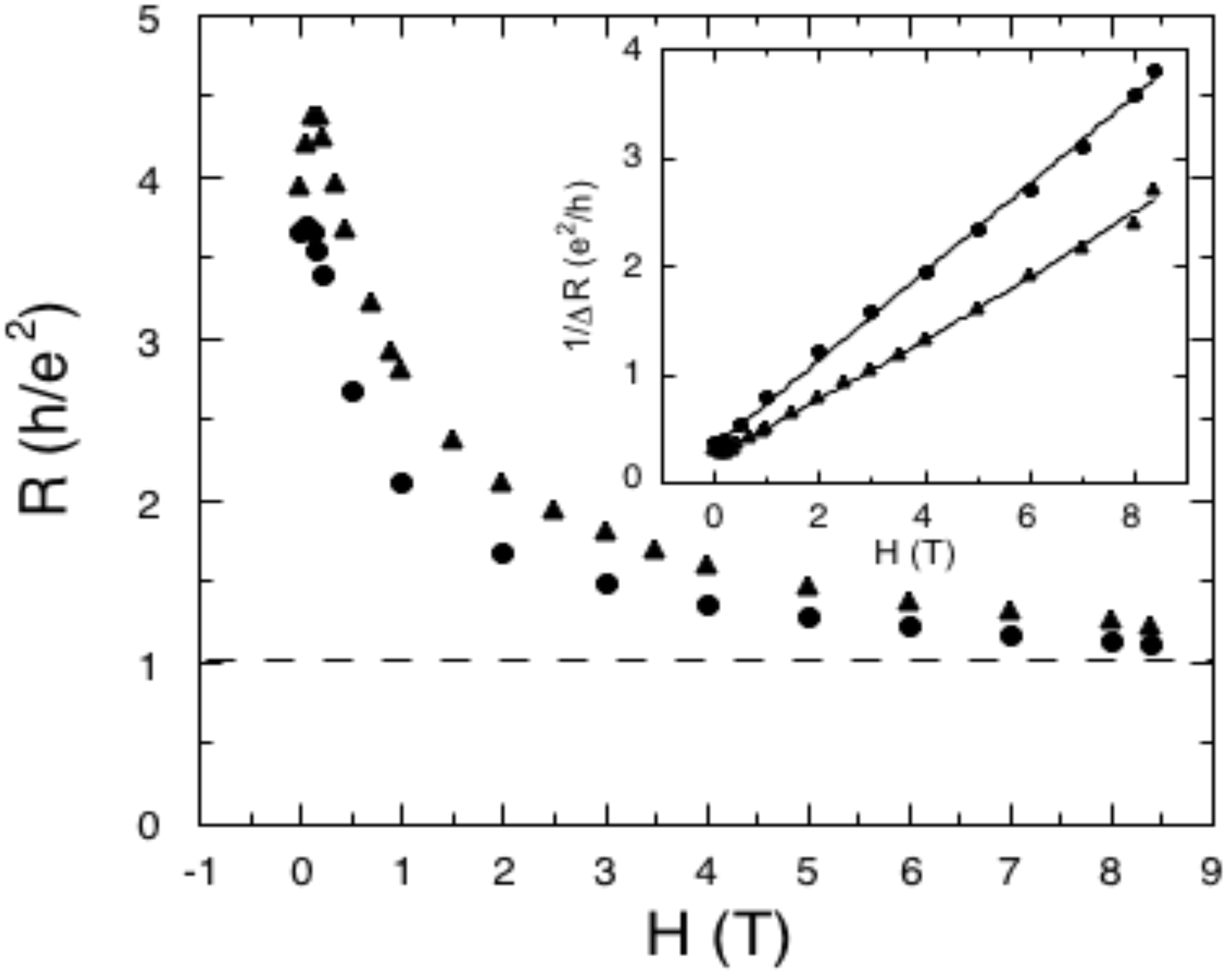
VRH in Film Conductance



Extraordinary MC in VRH Regime

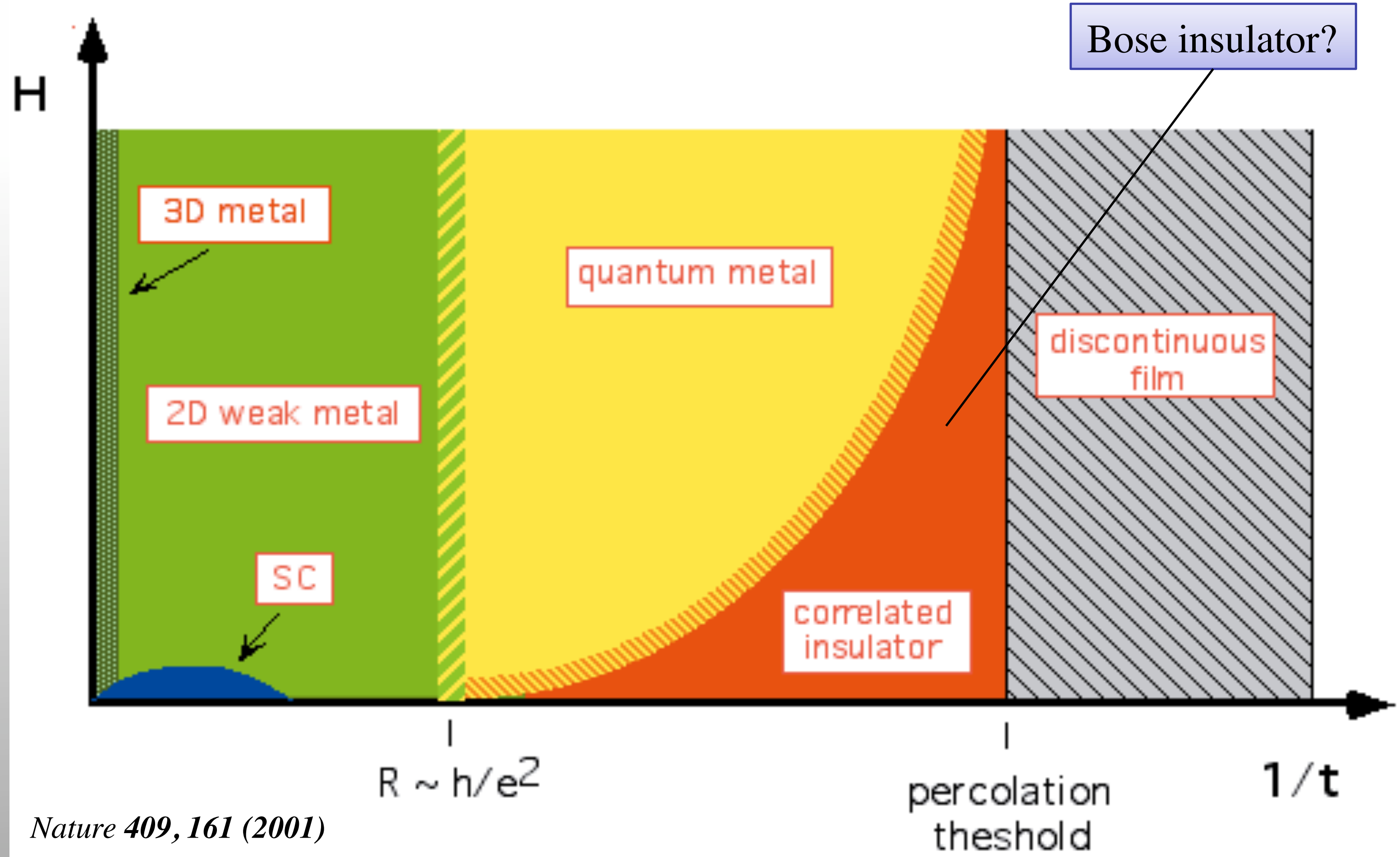
99061a eh/lb





R (h/e^2)
H (T)
1/ΔR (e^2/h)
H (T)

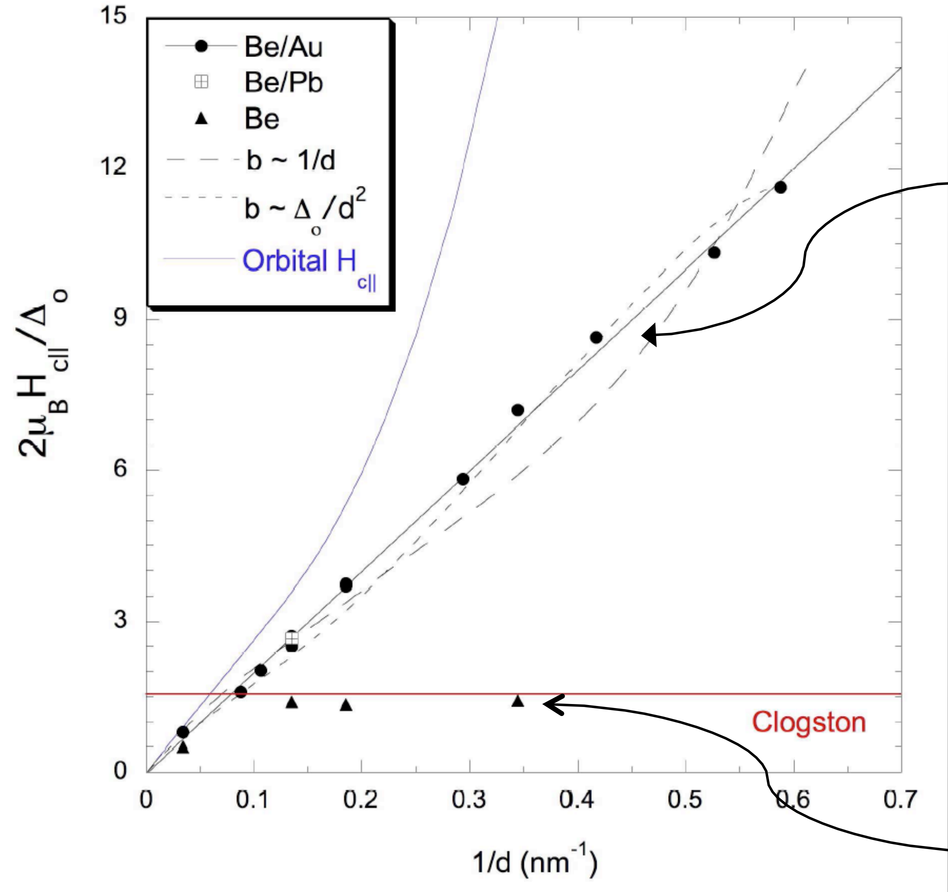
Phase Diagram Assuming No Spin-Orbit



Nature ***409*, *161* (2001)**

Inducing Spin-Orbit by Dusting with Au

Reduced Critical Field as a Function of Be Thickness

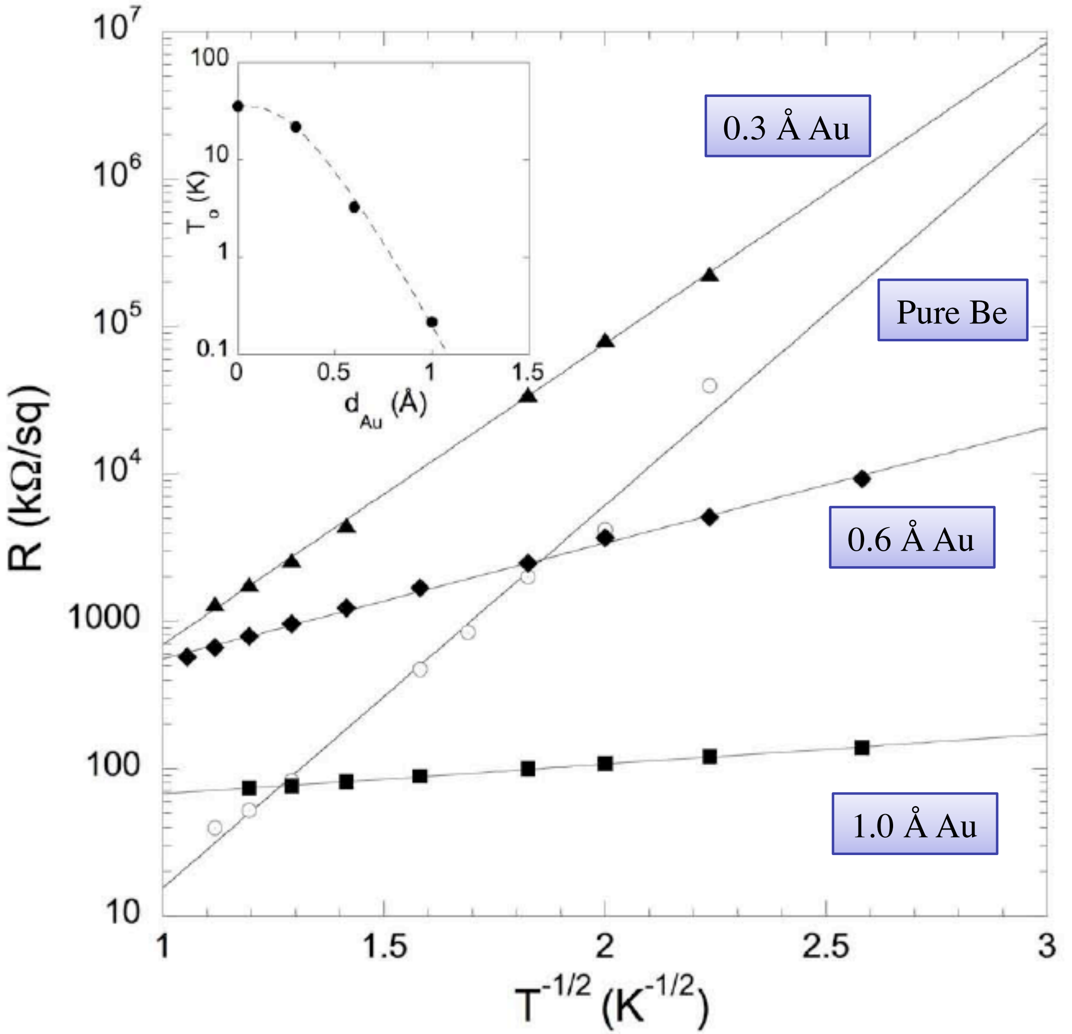


Be films coated with 5 Å of Au.

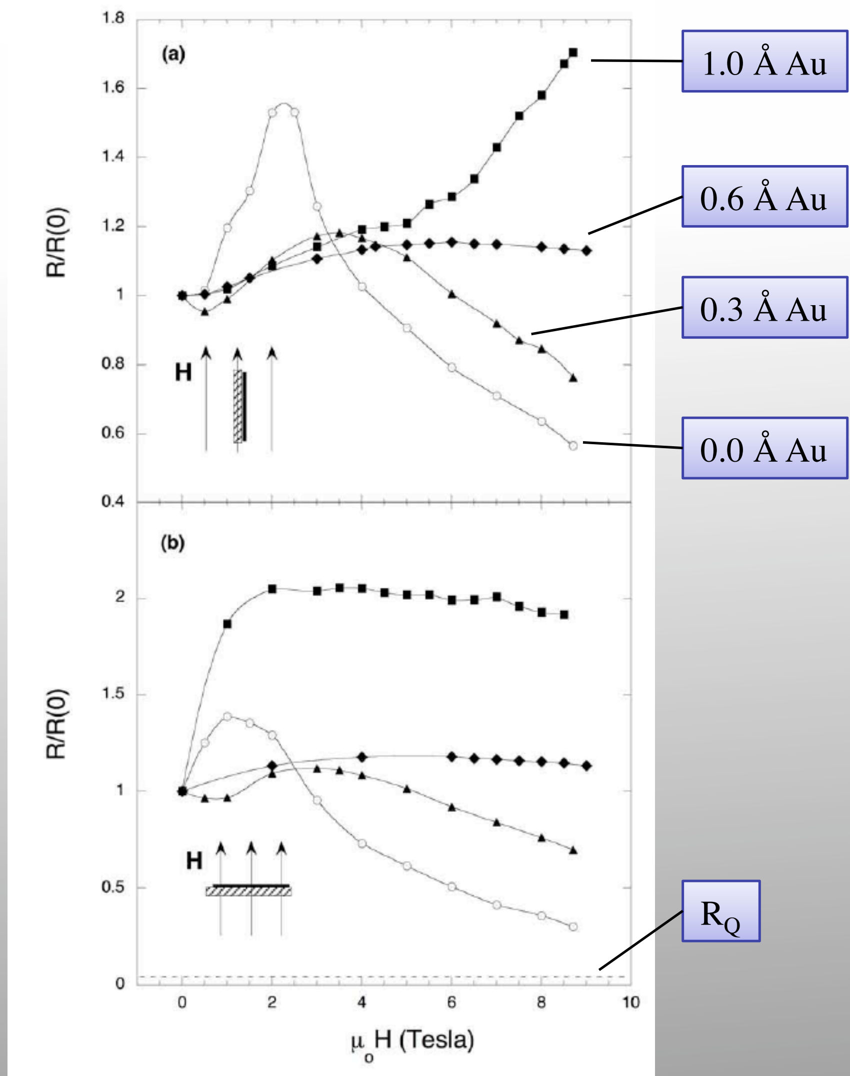
Pristine Be films.

Assuming that the films are sufficiently thin so that the Zeeman coupling dominates the critical field behavior, we expect

$$\frac{2\mu_B H_{c\parallel}}{\Delta_o} = \sqrt{3b/\Delta_o}$$

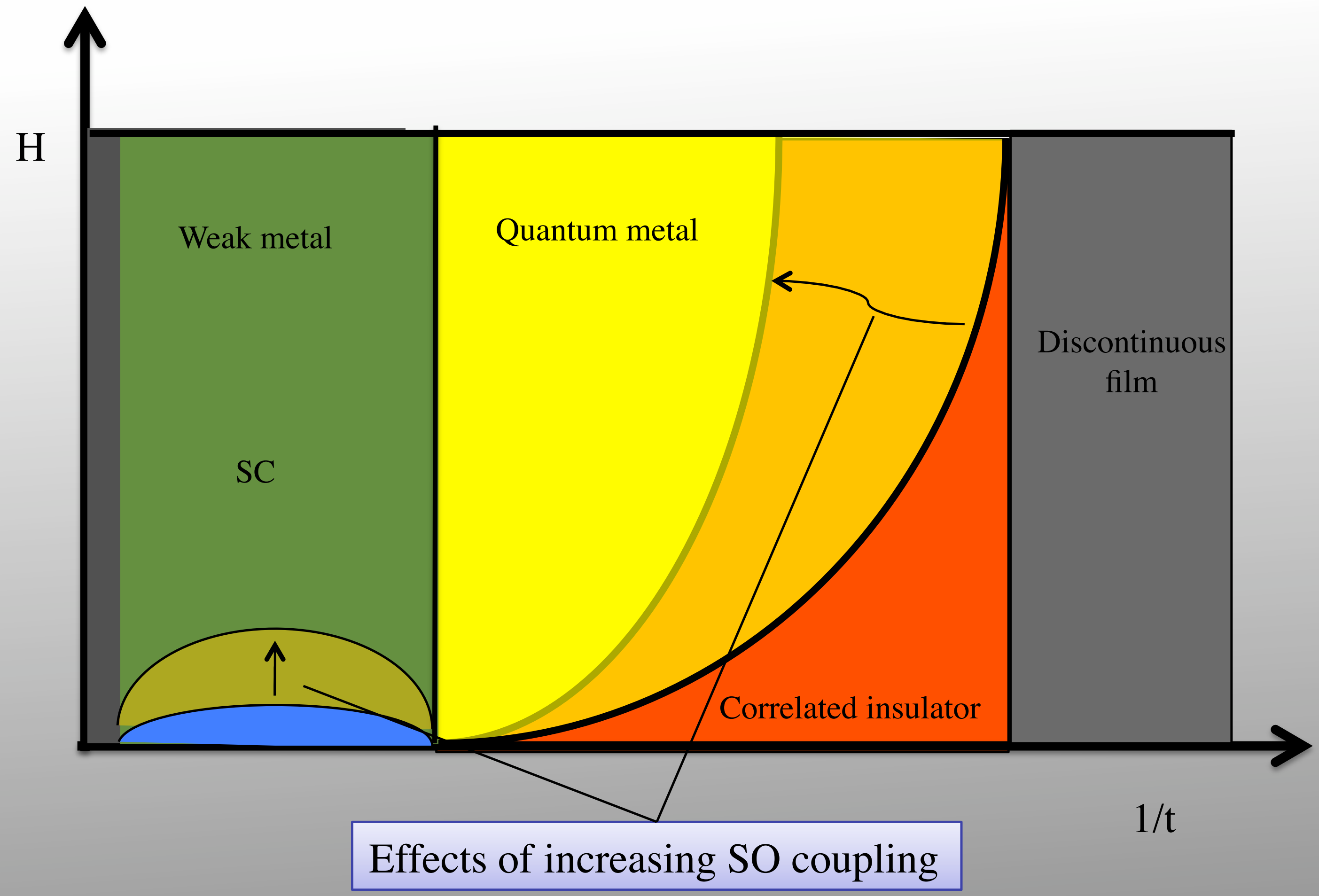


0.3 Å Au
Pure Be
0.6 Å Au
1.0 Å Au
R (kΩ/sq)
$T^{-1/2}$ ($K^{-1/2}$)
T_o (K)
d_{Au} (Å)



(a)
(b)
R/R(0)
H
μₒH (Tesla)
1.0 Å Au
0.6 Å Au
0.3 Å Au
0.0 Å Au
R_Q

Phase Diagram With Spin-Orbit



Summary

- We observe incoherent Cooper pairs in high-field tunneling spectroscopy.
- By fitting PR feature to theory we can determine the gap, the spin-orbit scattering rate, orbital pair breaking parameter, and the anti-symmetric FL parameter G^0.
- The PR can also be used to determine spin polarization in ferromagnetic films at fields well beyond the parallel critical field.
- High field saturation of MR to R_Q observed in Be, InO_x, and TiN films, all of which undergo a S-I transition.
- The effect of spin-orbit scattering is to greatly increase the characteristic field scale of the quantum metal phase.
- Naively, if localized Cooper pairs exists then spin-orbit scattering will dramatically increase their Zeeman critical field.