Planar Tunneling and Andreev Reflection: Powerful probes of the superconducting order parameter

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Outline:

Lecture 1 (Tunneling spectroscopy on HTS):

- **Promo**: Grand statement / DoE-BES report / new SCs
- **Broken symmetries** (gauge, reflection and time-reversal)
- **Tunneling** and order parameter (OP) symmetry
- **Andreev reflection** (AR)
- **Tunneling** into Andreev bound states: Broken symmetries

Lecture 2 (Andreev reflection spectroscopy on HFs):

- Point Contact Andreev Reflection Spectroscopy (PCARS)
- Blonder-Tinkham-Klapwijk (BTK) theory and it's ext. to d-wave
- Definition of the issues (AR at HFSs and spectroscopy of HFs)
- CeCoIn5 and related HFs
- Describe data with a
  - two-fluid model and
  - Fano resonance in an energy-dependent DoS

Collaborators

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Zack Fisk	(UC Irvine)

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Dozens of undergraduates, NSF, and DoE.

**in memory*

Group Seminar, Monday September 15, 2008

Introduction to Blonder-Tinkham-Klapwijk Theory and Point-Contact Spectroscopy

Wan Kyu Park

Outline

- ❑ Tunneling and Andreev reflection
- ❑ Blonder-Tinkham-Klapwijk theory
- ❑ Point-contact Spectroscopy
- ❑ Examples: Nb and MgB_2
- ❑ PCS of heavy fermions: CeCoIn5 and related)
- ❑ PCS of graphite

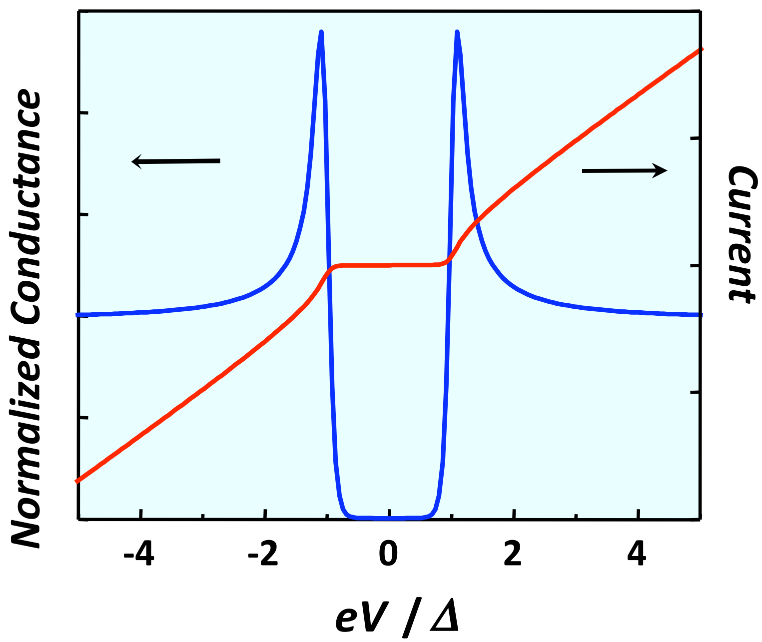
Electron Tunneling Spectroscopy (last lecture)

Tunnel Current: $I(V) = A|T|^2 eN_n(0)\int_{-\infty}^{\infty} N_s(E)\left[f(E-eV)-f(E)\right]dE$

Tunnel Conductance: $G(V) \equiv \dfrac{dI}{dV} = A|T|^2 e^2 N_n(0)\int_{-\infty}^{\infty} N_s(E)\dfrac{\partial f(E-eV)}{\partial(eV)}dE$

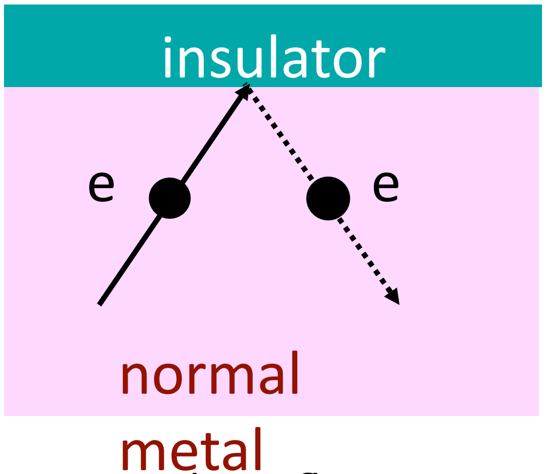
$For\ T=0,\ \dfrac{\partial f(E-eV)}{\partial(eV)} = \delta(E-eV) \Rightarrow G(V) \propto N_s(eV).$

$For\ T>0,\ G(V)\ is\ given\ as\ a\ Convolution\ of\ SC\ DOS\ w.r.t.\ Derivative\ of\ Fermi\ Function.$



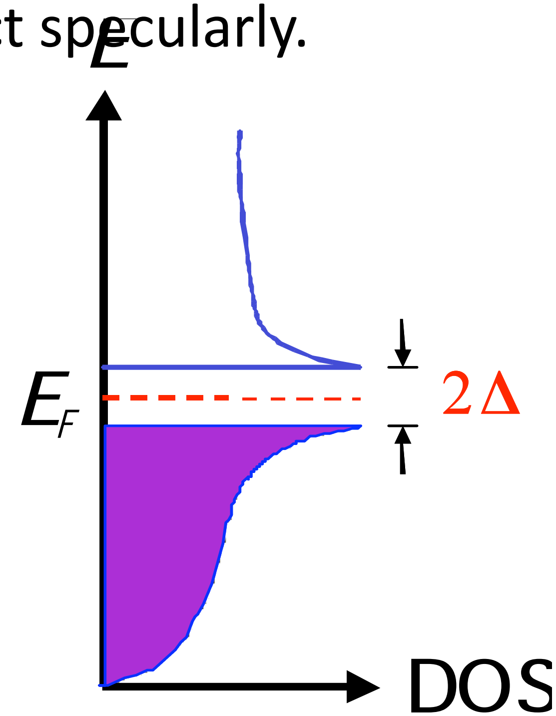
- Bias dependence of tunneling conductance directly probes DOS. ⇒ well established to probe SC gap.
- E. L. Wolf, *Electron tunneling spectroscopy*

What will happen to an electron with $E < \Delta$ if $\exists$ no tunnel barrier?



specular reflection

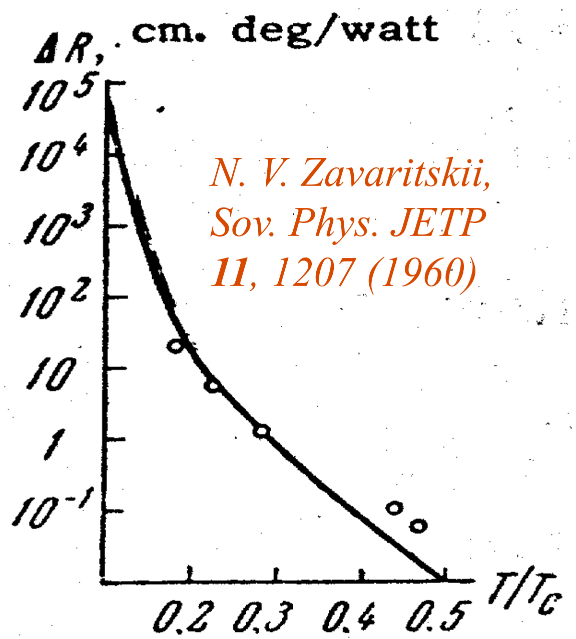
cf. At an interface with huge potential barrier that is translationally invariant along the transverse direction, incoming electrons reflect specularly.



- No QP states available, no single particles are allowed to enter S.
- Will a NS system be less conductive that a single S?

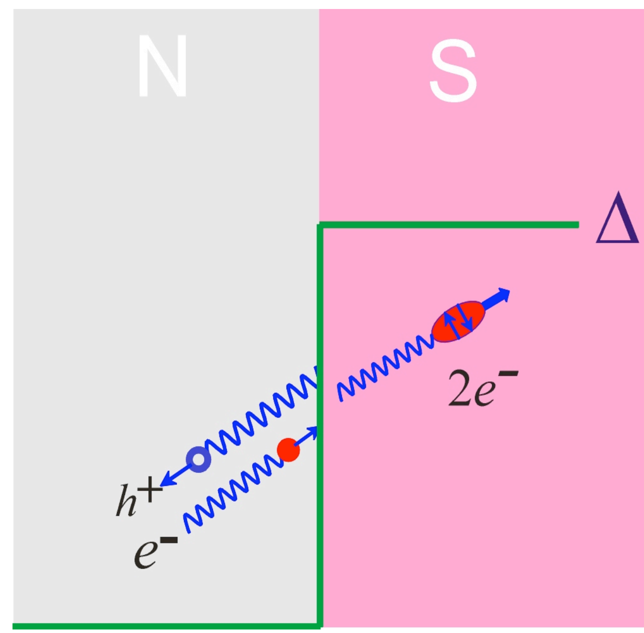
- No!

Andreev Reflection (I)

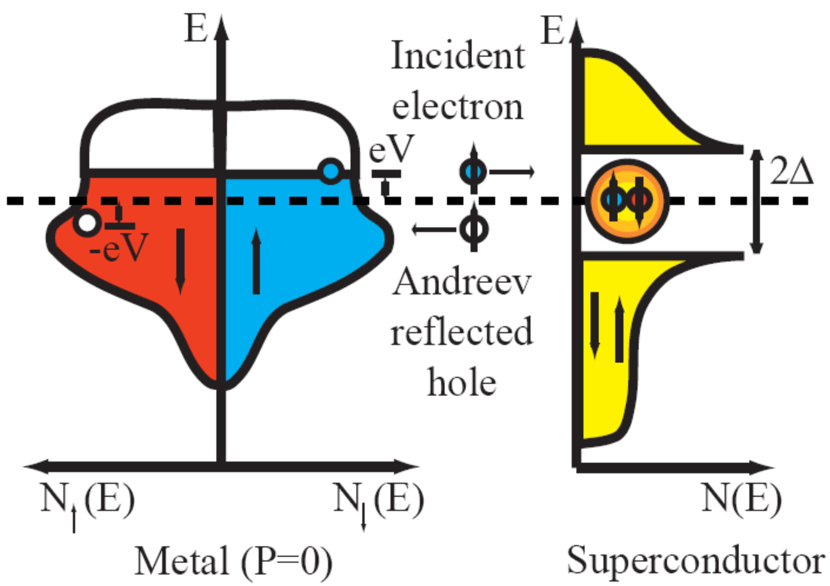


- While trying to explain the rapid increase of thermal resistance of Sn in the intermediate state, Andreev discovered that an additional scattering must be involved. *A. F. Andreev, Sov. Phys. JETP* ***19****, 1228 (1964)*

- QM scattering off SC pair potential near N/S
- Particle-hole conversion process
  multi-particle (AR) vs. single particle (tunneling)
- Retro-reflection $\mathbf{v}_h = -\mathbf{v}_e$



Andreev Reflection (II)

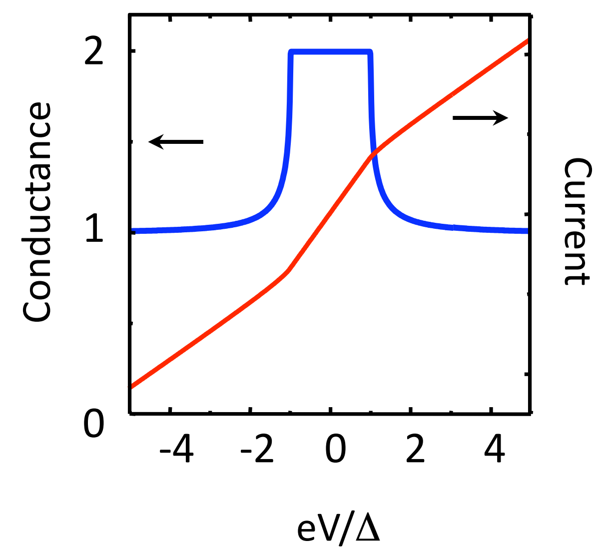


- Conserved quantities
  - Energy (E)
  - Momentum ($\hbar k$) ($\Delta \ll E_F$)
  - Spin (S)
  - Charge inc. Cooper pairs

- Sub-gap conductance is doubled.

- Andreev reflected hole carries information on the phase of electron state and macroscopic phase of SC. phase change = Φ + arccos (ε/Δ)

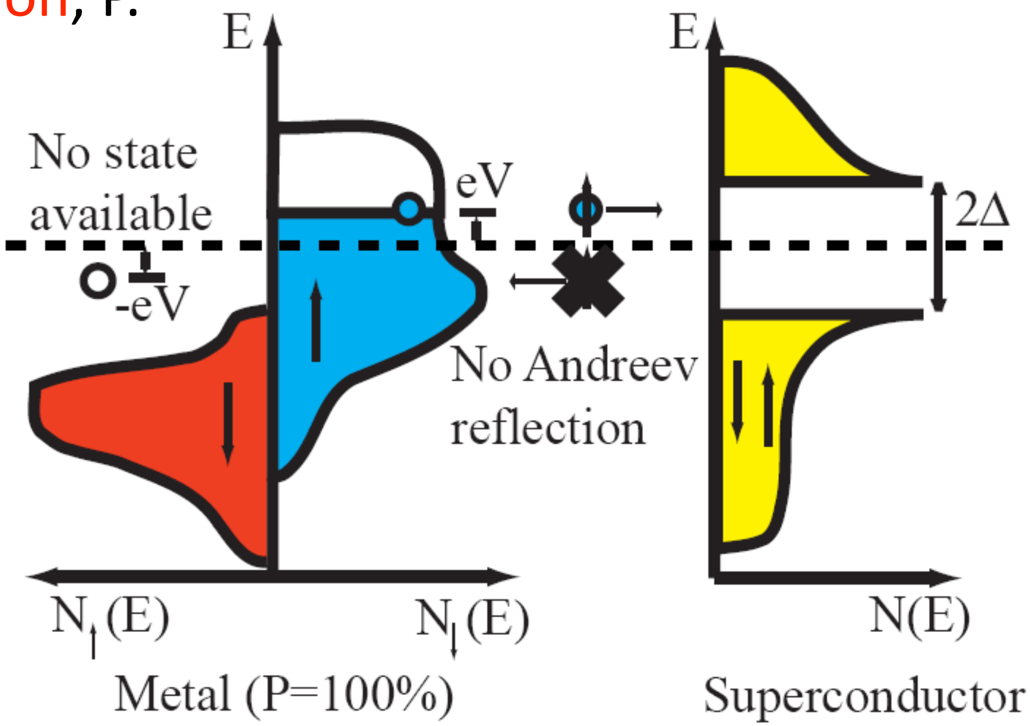
- Inverse process (S $\Rightarrow$ N): AR of a hole or
  - emission of a Cooper pair ("Andreev pairs"): proximity effect



Andreev Reflection (III)

• If a metal electrode has unequal number of spin up and spin-down electrons as in ferromagnets or half metals, Andreev reflection is suppressed.

• Measuring conductance of FM/S junction gives information on spin polarization, P.

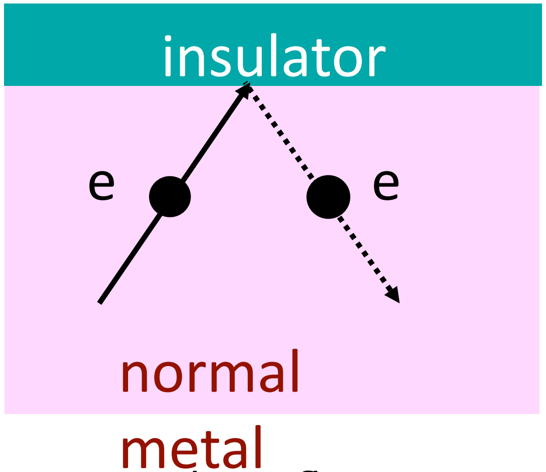


Andreev Reflection (IV)

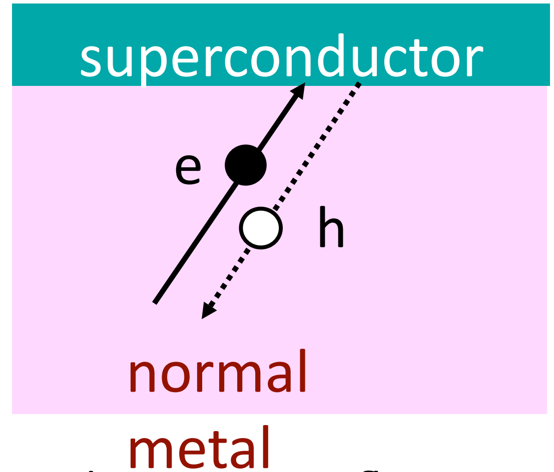
- Proximity effects: S/N, S/N/S (Josephson junction)
- Subharmonic gap structure: S/N/S (MAR, KBT & Octavio 1982-3)
- Reentrant behavior: mesoscopic S/N (vs. conjugated mirror)
- Reflectionless tunneling: S/I/DN (enhanced AR prob, ZBCP.)
- Andreev bound states: nodal surfaces of *p*- and *d*-wave SC
- Andreev interferometer
- Andreev billiard
- Crossed (or nonlocal) AR
- Kondo QD coupled to SC: interplay between AR & Kondo effect

Andreev reflection is an interesting and fascinating phenomenon, having various applications to superconducting devices, AND NORMAL STATE PROPERTIES !

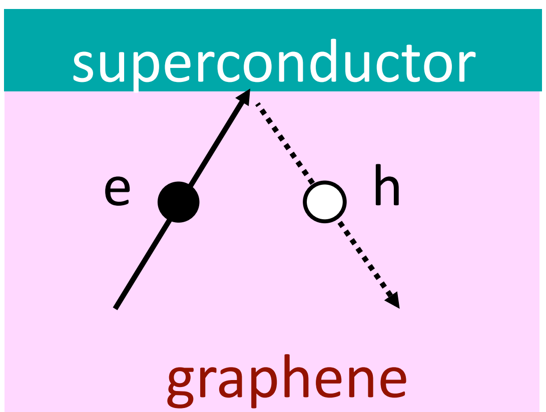
Various Quasiparticle Reflections at Interfaces



specular reflection

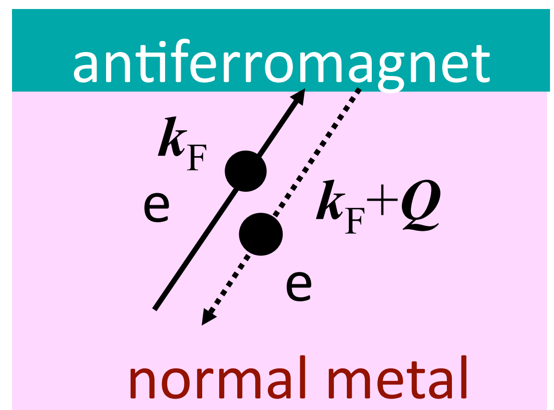


Andreev retro-reflection



specular Andreev reflection

Beenakker, PRL (2006)



spin-dependent Q-reflection

Bobkova et al., PRL (2005)

Elementary QP Excitations in a SC

$$i\hbar\frac{\partial f}{\partial t} = \left[-\frac{\hbar^2}{2m}\nabla^2 - \mu(x) + V(x)\right] f(x,t) + \Delta(x) g(x,t)$$

$$i\hbar\frac{\partial g}{\partial t} = -\left[-\frac{\hbar^2}{2m}\nabla^2 - \mu(x) + V(x)\right] g(x,t) + \Delta(x) f(x,t)$$

Bogoliubov – de Gennes (BdG) Equations

Assume $\mu(x) = \mu$, $V(x) = 0$, $\Delta(x) = \Delta$.

Plane wave solutions

$$f = \tilde{u}e^{ikx - iEt/\hbar}$$

$$g = \tilde{v}e^{ikx - iEt/\hbar}$$

$$\begin{bmatrix} \left(\frac{\hbar^2 k^2}{2m} - \mu\right) & \Delta \\ \Delta & -\left(\frac{\hbar^2 k^2}{2m} - \mu\right) \end{bmatrix} \begin{bmatrix} \tilde{u} \\ \tilde{v} \end{bmatrix} = E \begin{bmatrix} \tilde{u} \\ \tilde{v} \end{bmatrix}$$

BCS Quasiparticle: Bogoliubon

Solving for $E, \tilde{u}, \tilde{v}$,

$$E^2 = \left(\frac{\hbar^2 k^2}{2m} - \mu\right)^2 + \Delta^2$$

$$\hbar k^\pm = \sqrt{2m\mu}\sqrt{1 \pm \frac{\sqrt{E^2 - \Delta^2}}{\mu}}$$

$$\hbar q^\pm = \sqrt{2m}\sqrt{\mu \pm E} \text{ for N } (\Delta = 0)$$

$$\tilde{u}^2 = \frac{1}{2}\left(1 \pm \frac{\sqrt{E^2 - \Delta^2}}{E}\right) = 1 - \tilde{v}^2$$

$$u_0^2 \equiv \frac{1}{2}\left(1 + \frac{\sqrt{E^2 - \Delta^2}}{E}\right) \equiv 1 - v_0^2$$

$(u_0 > v_0)$

Four types of QP waves for a given E

$$\text{Defining } \psi = \begin{pmatrix} f(x) \\ g(x) \end{pmatrix},$$

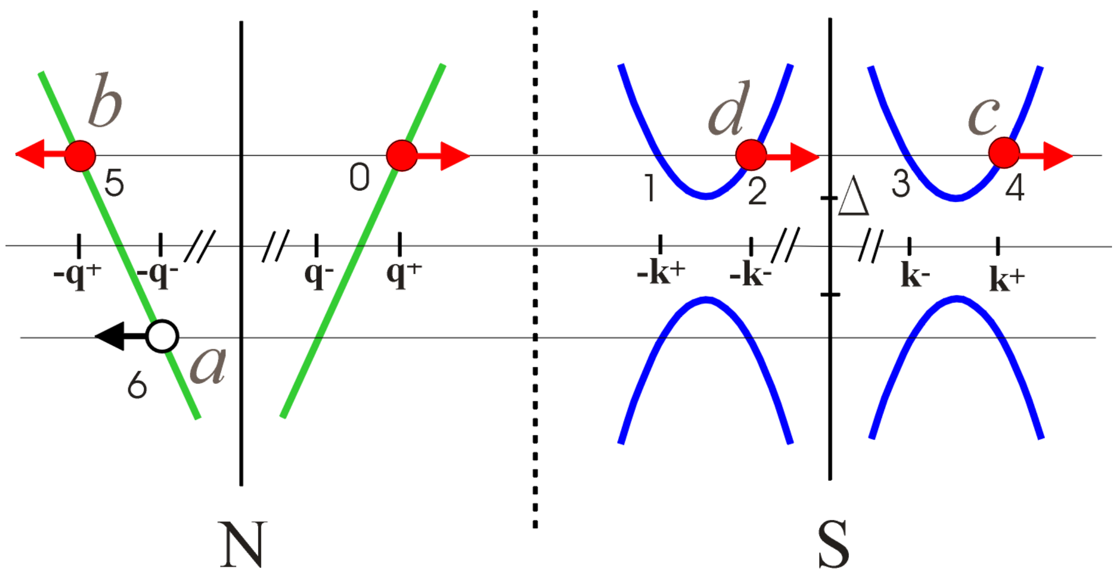
$$\psi_{\pm k^+} = \begin{pmatrix} u_0 \\ v_0 \end{pmatrix} e^{\pm i k^+ x}, \quad \psi_{\pm k^-} = \begin{pmatrix} v_0 \\ u_0 \end{pmatrix} e^{\pm i k^- x}$$

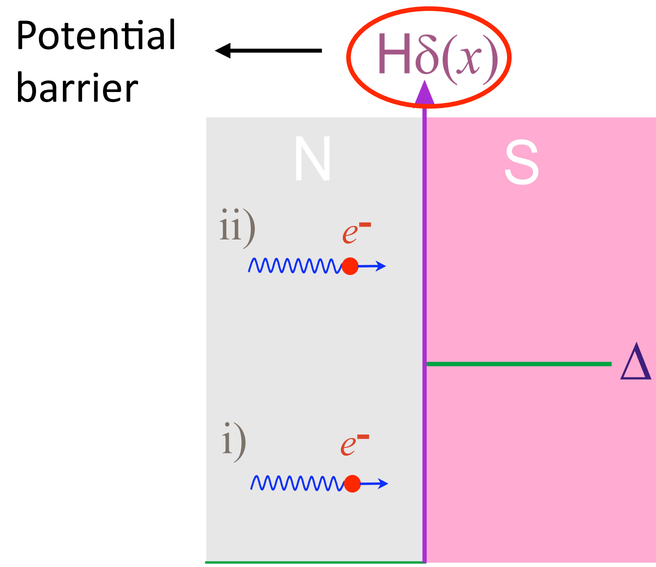
Bogoliubon: QP – a coherent combination of an electron-like and hole-like excitations

Blonder-Tinkham-Klapwijk Model

PRB ***25****, 4515 (1982), cf. Klapwijk for history, J. Supercond.* ***17****, 593 (2004)*

What is the fate of an electron approaching an N/S interface?





Four trajectories are possible.

a : Andreev reflection

b : Normal reflection

c : Transmission without branch-crossing

d : Transmission with branch-crossing

Boundary Condition Problem

Boundary Conditions

i) $\psi_S(0) = \psi_N(0) \equiv \psi(0)$

ii) $\frac{\hbar}{2m}\left(\psi_S' - \psi_N'\right) = H\psi(0)$

iii) wave directions are defined

by group velocities

Trial Wave Functions

$$\psi_{inc} = \begin{pmatrix} 1 \\ 0 \end{pmatrix} e^{iq^+x},$$

$$\psi_{refl} = a\begin{pmatrix} 0 \\ 1 \end{pmatrix} e^{iq^-x} + b\begin{pmatrix} 1 \\ 0 \end{pmatrix} e^{-iq^+x},$$

$$\psi_{trans} = c\begin{pmatrix} u_0 \\ v_0 \end{pmatrix} e^{ik^+x} + d\begin{pmatrix} v_0 \\ u_0 \end{pmatrix} e^{-ik^-x}$$

$$A = aa^*, \qquad a = \frac{u_0 v_0}{\gamma}$$

$$B = bb^*, \qquad b = -\frac{u_0^2 - v_0^2}{\gamma}\left(Z^2 + iZ\right)$$

$$C = cc^*, \qquad c = \frac{u_0\left(1 - iZ\right)}{\gamma}$$

$$D = dd^*, \qquad d = \frac{iv_0 Z}{\gamma}$$

$$\gamma = u_0^2 + \left(u_0^2 - v_0^2\right)Z^2$$

$$u_0^2 = 1 - v_0^2 = \tfrac{1}{2}\left\{1 + \left(E^2 - \Delta^2\right)^{1/2} / E\right\}$$

$$Z = \frac{mH}{\hbar^2 k_F} = H / \hbar v_F$$: barrier strength

$$Z_{eff} = \sqrt{Z^2 + \frac{(1-r)^2}{4r}}, \quad r \equiv v_{FN} / v_{FS}$$

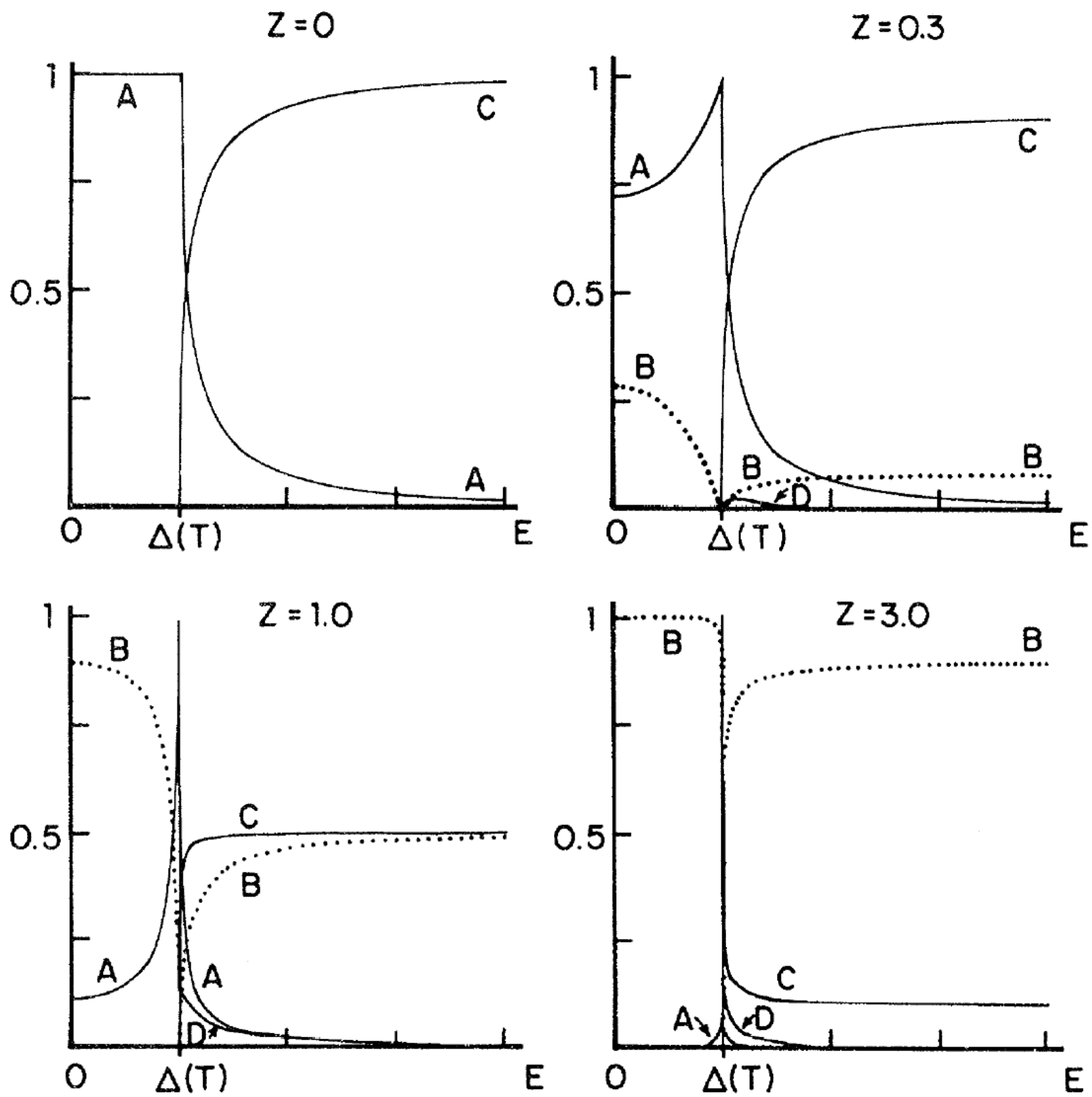
Reflection and Transmission Probabilities

	A	B	C	D
Normal state	0	$\dfrac{Z^2}{1+Z^2}$	$\dfrac{1}{1+Z^2}$	0
General form				
$E<\Delta$	$\dfrac{\Delta^2}{E^2+(\Delta^2-E^2)(1+2Z^2)^2}$	$1-A$	0	0
$E>\Delta$	$\dfrac{u_0^2 v_0^2}{\gamma^2}$	$\dfrac{(u_0^2-v_0^2)^2 Z^2(1+Z^2)}{\gamma^2}$	$\dfrac{u_0^2(u_0^2-v_0^2)(1+Z^2)}{\gamma^2}$	$\dfrac{v_0^2(u_0^2-v_0^2)Z^2}{\gamma^2}$
No barrier $(Z=0)$				
$E<\Delta$	1	0	0	0
$E>\Delta$	v_0^2/u_0^2	0	$1-A$	0
Strong barrier $[Z^2(u^2-v^2)>>1]$				
$E<\Delta$	$\dfrac{\Delta^2}{4Z^2(\Delta^2-E^2)}$	$1-A$	0	0
$E>\Delta$	$\dfrac{u_0^2 v_0^2}{Z^4(u_0^2-v_0^2)^2}$	$1-\dfrac{1}{Z^2(u_0^2-v_0^2)}$	$\dfrac{u_0^2}{Z^2(u_0^2-v_0^2)}$	$\dfrac{v_0^2}{Z^2(u_0^2-v_0^2)}$

A = AR, *B* = NR, *C* = TM w/ branch crossing (BC), *D* = TM w / BC

A+*B*+*C*+*D*=1

Probabilities (Cont'd)



- $A(E)$ peaks at Δ for Z > 0. $\Rightarrow$ double peaks in dI/dV vs. V curve
- At $E = \Delta$, $A = 1$, $B = C = D = 0$, independent of Z.

I-V & *dI/dV-V* Formulas

$$I(V) = S\,J$$

$$= 2N(0)ev_F S\int_{-\infty}^{\infty} dE\left[f_{\rightarrow}(E) - f_{\leftarrow}(E)\right]$$

$$= 2N(0)ev_F S\int_{-\infty}^{\infty} dE\left[f_0(E-eV) - f_0(E)\right]\left[1 + A(E) - B(E)\right]$$

$$= 2N(0)ev_F S\int_{-\infty}^{\infty} dE\left(\frac{1}{1+\exp\left(\frac{E-eV}{kT}\right)} - \frac{1}{1+\exp\left(\frac{E}{kT}\right)}\right)\left[1 + A(E) - B(E)\right]$$

$$\frac{dI}{dV}(V) = 2N(0)ev_F S\int_{-\infty}^{\infty} \frac{\partial f_0(E-eV)}{\partial(eV)}\left[1 + A(E) - B(E)\right]dE$$

$$= 2N(0)e^2 v_F S\int_{-\infty}^{\infty} dE\,\frac{\exp\left(\frac{E-eV}{kT}\right)}{kT\left[1+\exp\left(\frac{E-eV}{kT}\right)\right]^2}\left[1 + A(E) - B(E)\right]$$

How to Calculate BTK Conductance?

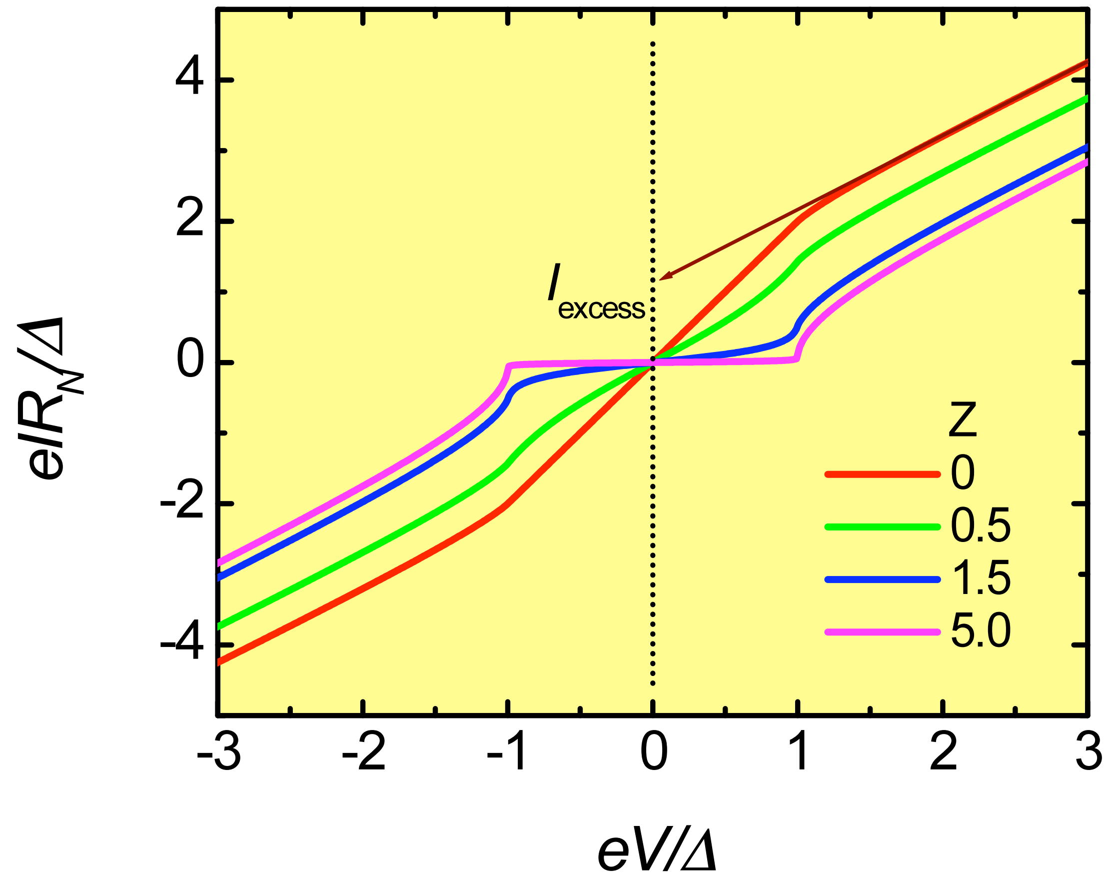
- Numerical integration using MATLAB®
- Original BTK kernel
  - singular points of the integrand
  - different formulas for E < Δ and E > Δ.
- To fit exp. data, use three fitting parameters

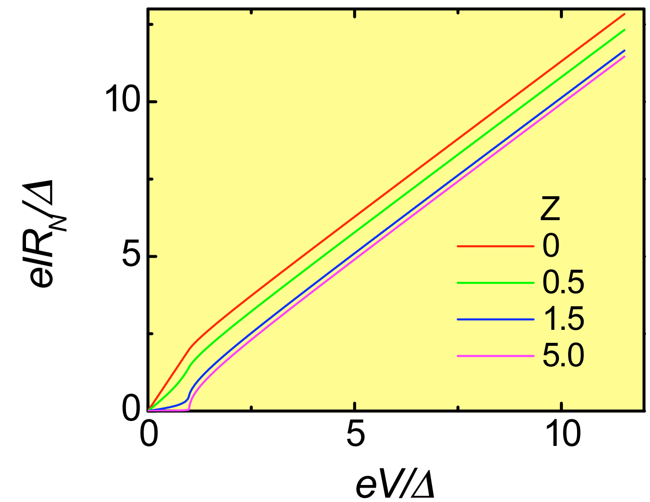
  Z: dimensionless barrier strength (0: metallic, ~5: tunnel limit)

  Δ: energy gap (peak position)

  Γ: (Dynes) QP lifetime broadening factor, $\Gamma = h/2\pi\tau$
- How to incorporate Γ?
  - replace $E \rightarrow E - i\Gamma$ in a, b, & calculate $A = aa^*$, $B=bb^*$
  - very complicated to do this!
- d-wave BTK Kernel developed by Tanaka & Kashiwaya gives the same results for *s*-wave SC but much more convenient to use.

Current vs. Voltage Characteristics (Z-dep.)



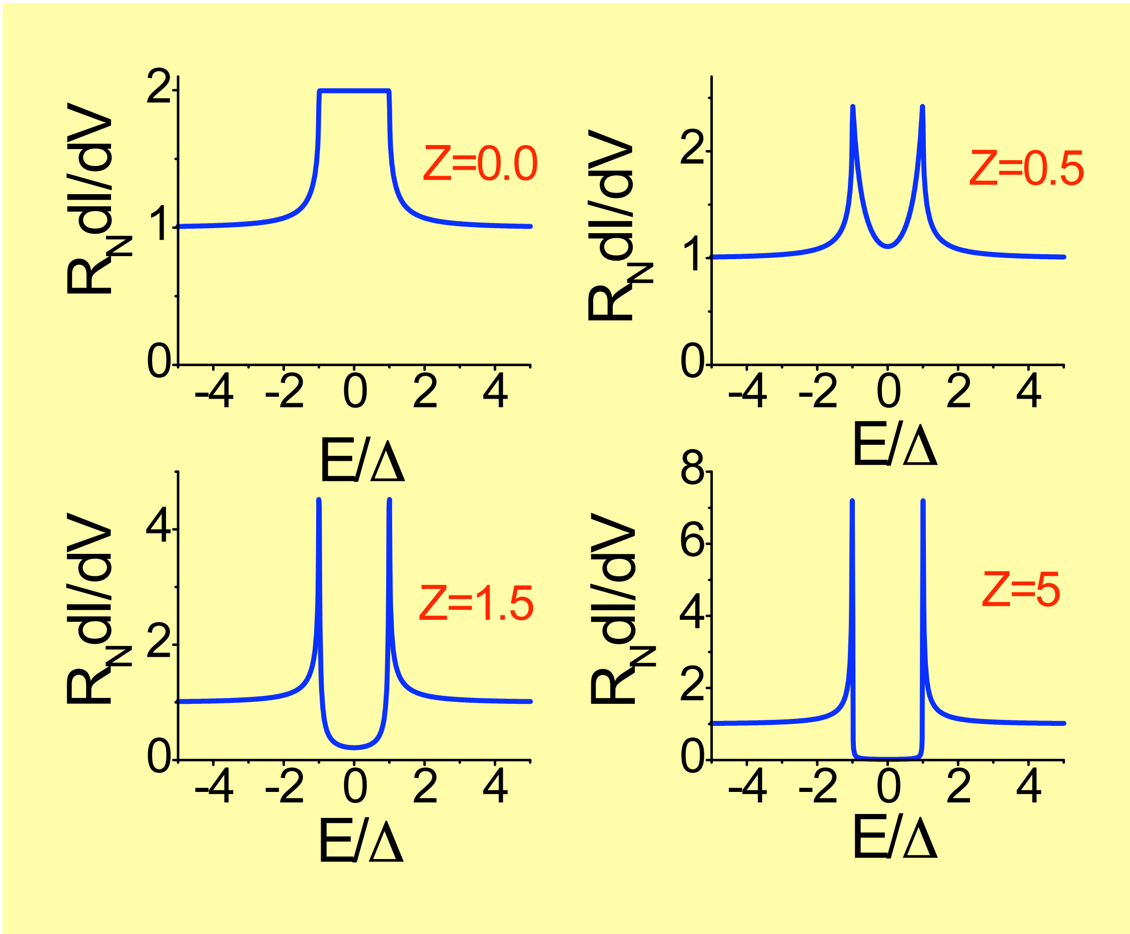


Excess current

$$I_{exc} \equiv (I_{NS} - I_{NN})\,|_{eV>>\Delta}$$

$$I_{exc}(V) = (4\Delta / 3eR_N)\tanh(eV / 2kT), \quad \Delta << T$$

Conductance vs. Voltage Characteristics (Z-dep.)



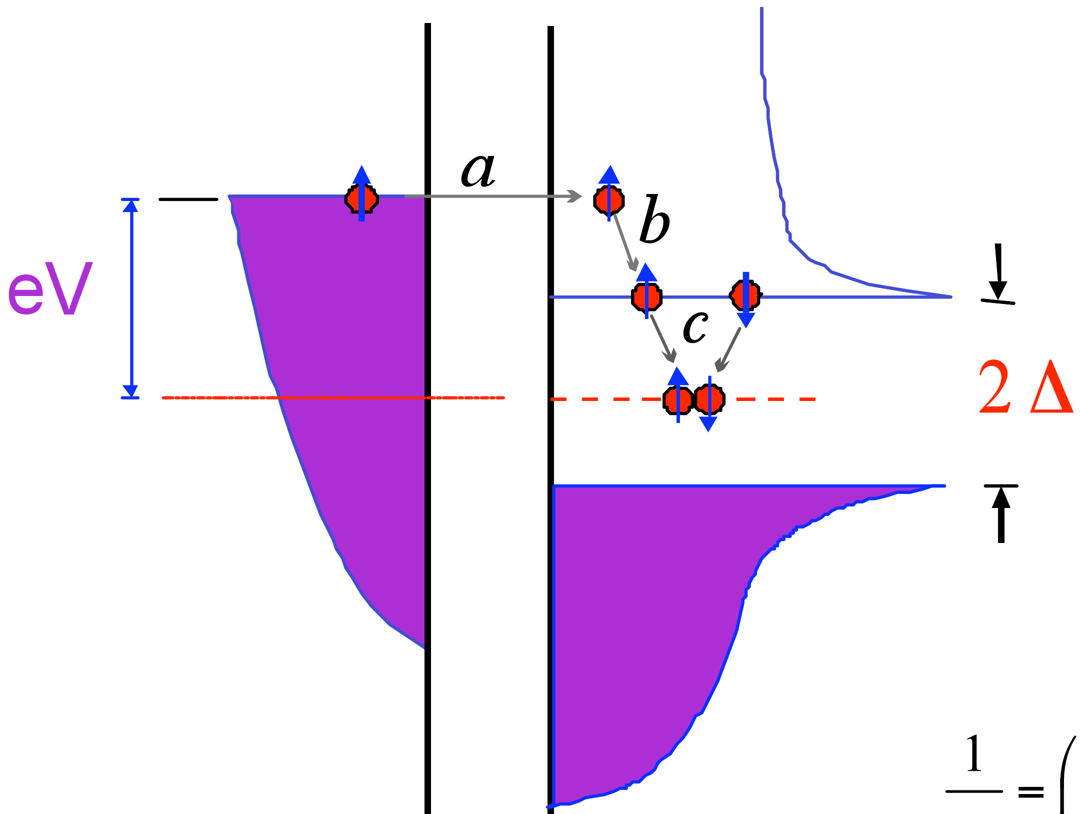
With increasing Z,
AR $\longrightarrow$
Tunneling

$$Z = \sqrt{Z_0^{\,2} + \frac{(1-r)^2}{4r}},\ r \equiv {}^{v_{FN}}\!/_{v_{FS}}$$

Is AR observable in heavy fermions?

Quasiparticle Lifetime

Consider, e.g., tunneling processes in a N/I/S junction.

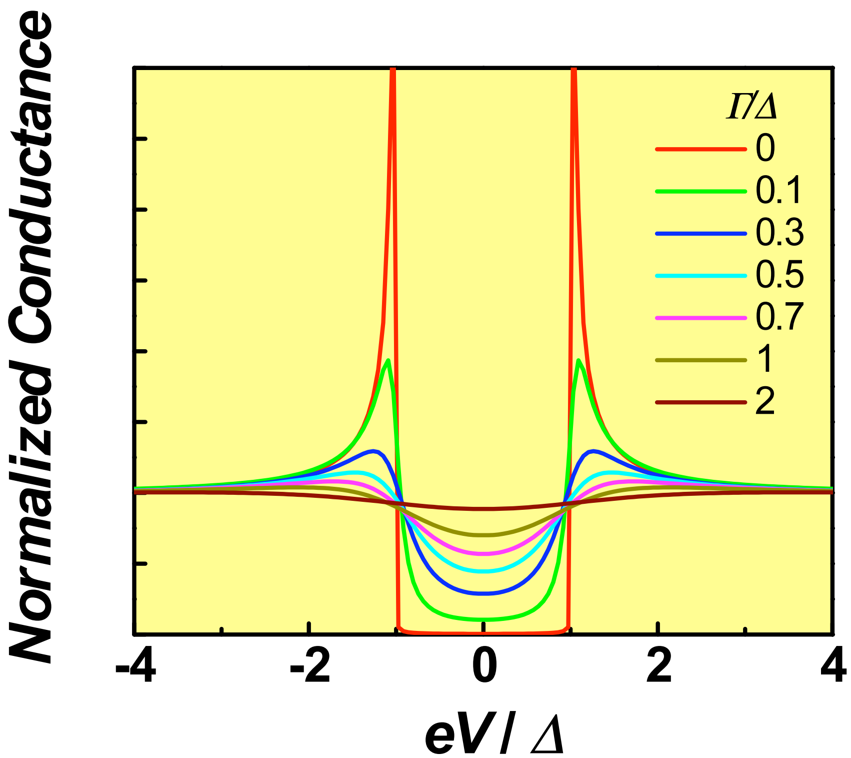


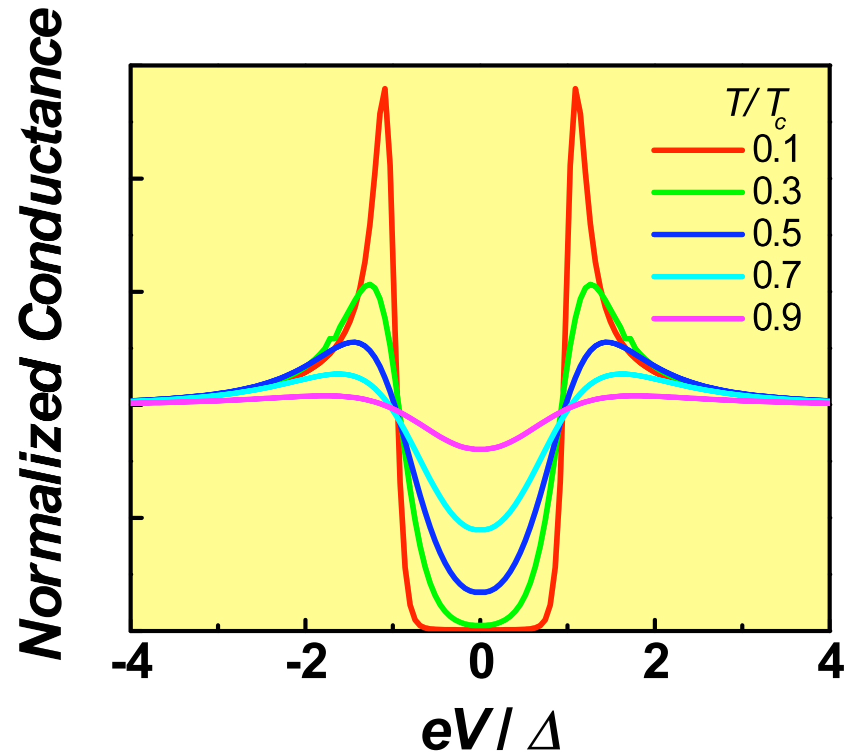
a : tunneling
b : relaxation
c : recombination (τ_R)

$$\frac{1}{\tau_R} = \left(\frac{T}{\Delta}\right)^{1/2} \frac{1}{\tau_0} e^{-\Delta/kT}$$

(Dynes et al., PRL 41 1509, 1978)

Quasiparticle vs. Thermal Smearing (Large Z)





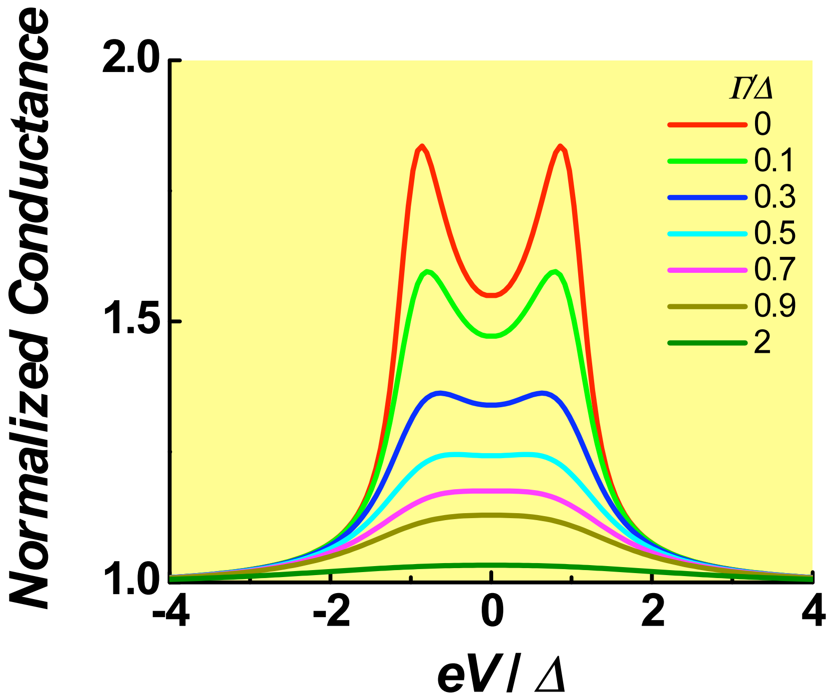
Z = 10, T = 0

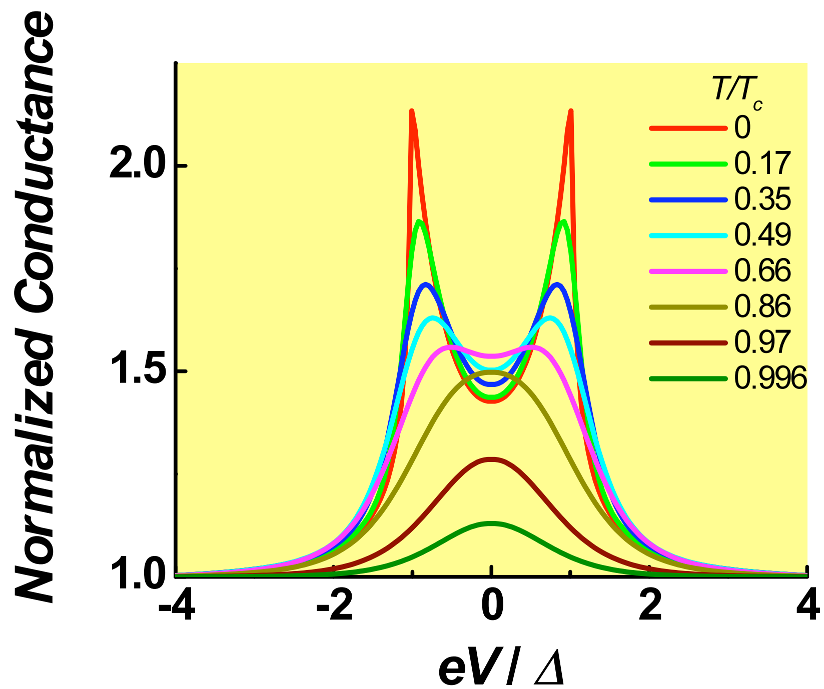
Smearing due to finite lifetime of transferred QP

Z = 10, Γ = 0

Smearing due to broadening of Fermi function

Quasiparticle vs. Thermal Smearing (Small Z)





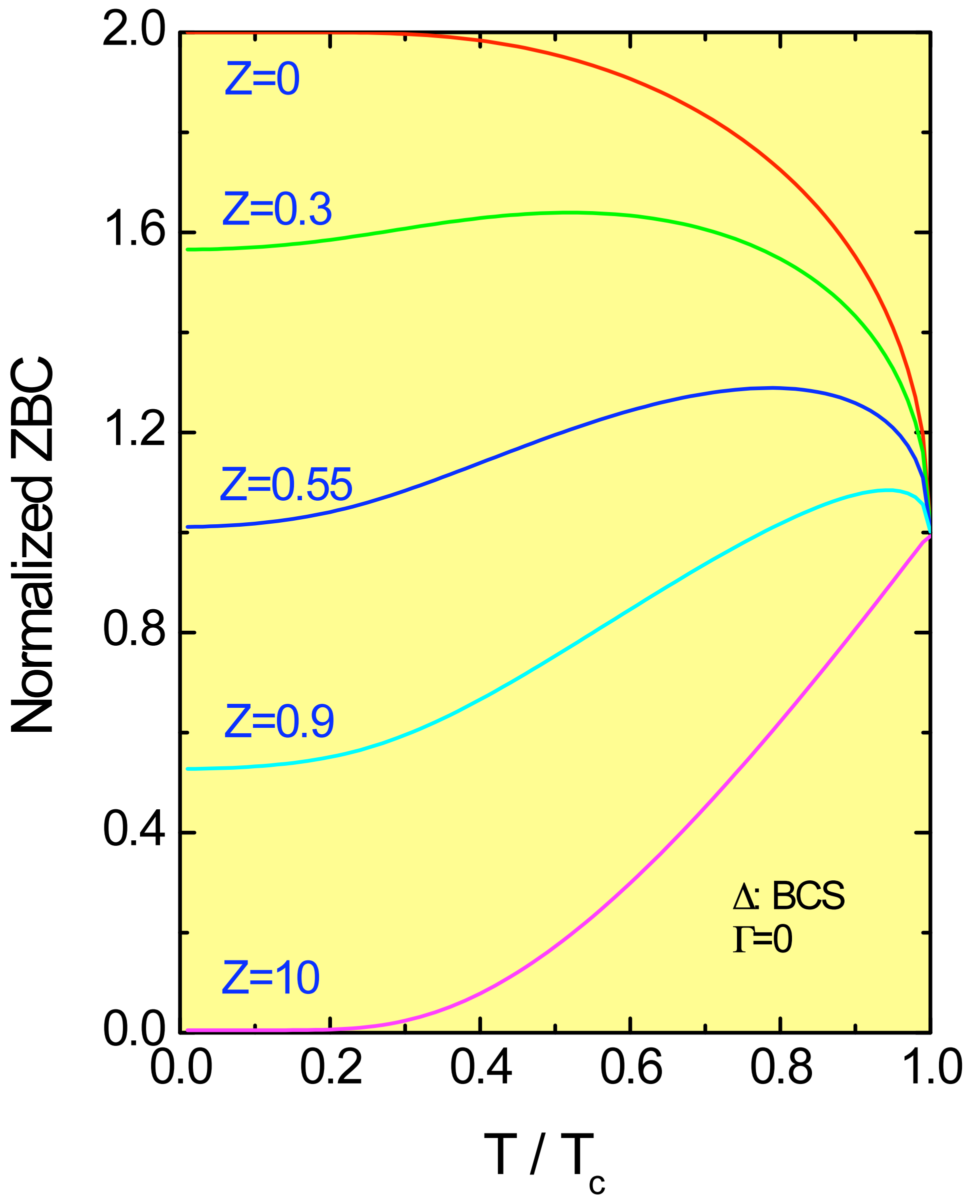
Z = 0.308, T = 0

Smearing due to finite "lifetime" of transferred QP

Z = 0.35, Γ = 0

Smearing due to broadening of Fermi function

Zero-bias Conductance vs. Temperature (Z-dep.)



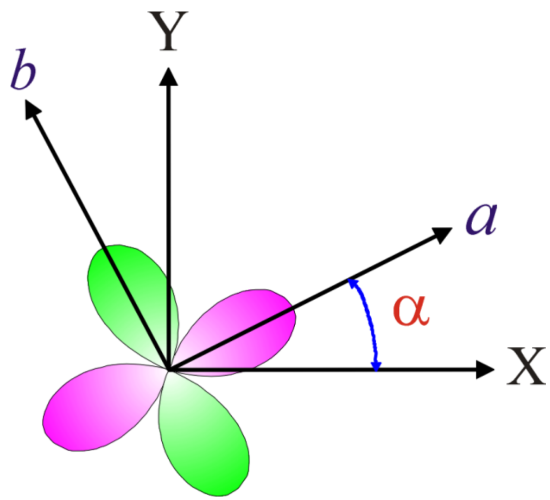
- ZBC vs. Temp. w/ inc. Z

  AR ⟶ Tunneling

- Useful to characterize the type of N/S junction
- Could be used to estimate local T_c

Extended BTK theory (to d-wave)

*S. Kashiwaya et al., PRB **53**, 2667 (1996)*



c-axis junction of d-wave superconductor

$$\Delta(T,\phi)=\Delta(T)\cos 2\phi$$

$$\Delta_+=\Delta_-,\ \varphi_+=\varphi_-,\ \Gamma_+=\Gamma_-=\frac{E-\sqrt{E^2-|\Delta|^2}}{|\Delta|}$$

The conductance is given by

the integration over the half space of momentum

$$\sigma_S(E)=1+|a(E)|^2-|b(E)|^2$$

$$=\sigma_N\frac{1+\sigma_N|\Gamma_+|^2+(\sigma_N-1)|\Gamma_+\Gamma_-|^2}{|1+(\sigma_N-1)\Gamma_+\Gamma_-\exp(i\varphi_--i\varphi_+)|^2}$$

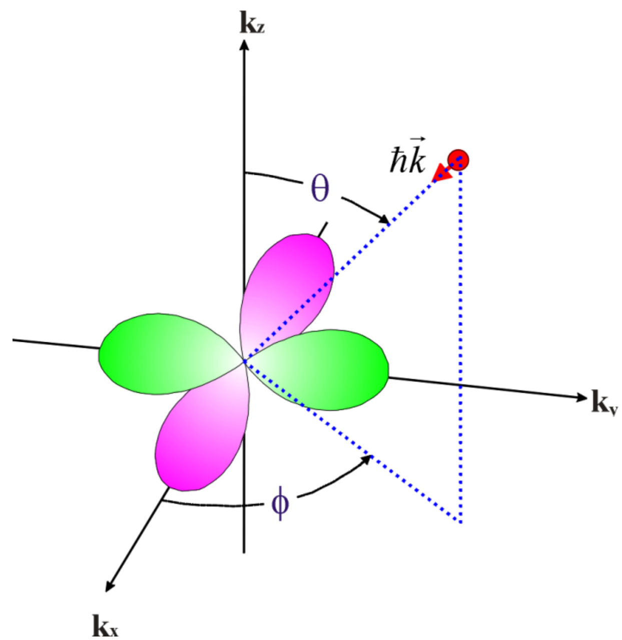
$$\Gamma_\pm=\frac{E-\Omega_\pm}{|\Delta_\pm|},\ \Omega_\pm=\sqrt{E^2-|\Delta_\pm|^2},\ \Delta_\pm\equiv\Delta\left(\pm \mathrm{k}_{FS}^{\pm}/k_{FS}\right)=|\Delta_\pm|\exp(i\varphi_\pm)$$

$$\lambda=\lambda_0\frac{\cos\theta_S}{\cos\theta_N},\ \lambda_0\equiv\frac{k_{FS}}{k_{FN}},\ k_{FS}\sin\theta_S=k_{FN}\sin\theta_N$$

$$Z=\frac{Z_0}{\cos\theta_N},\ Z_0\equiv\frac{mH}{\hbar^2 k_{FN}}$$

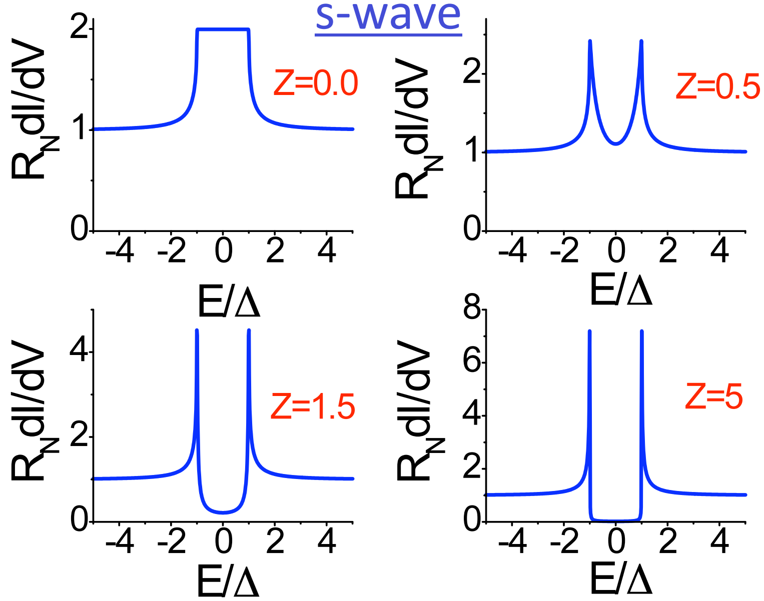
$$\sigma_N\equiv\frac{4\lambda}{(1+\lambda)^2+4Z^2}$$

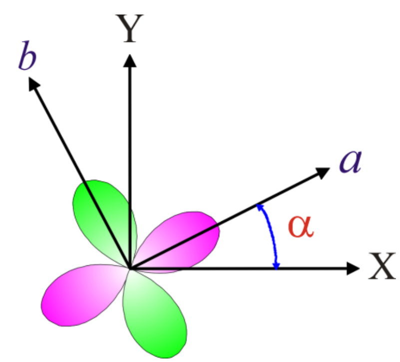
$$E'=E-i\Gamma,\ \Gamma=\hbar/\tau$$

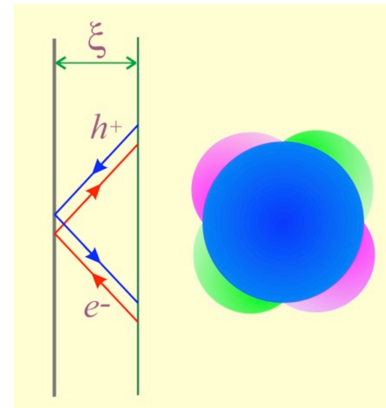


BTK Model for *s-wave and extended to d-wave.*

s-wave

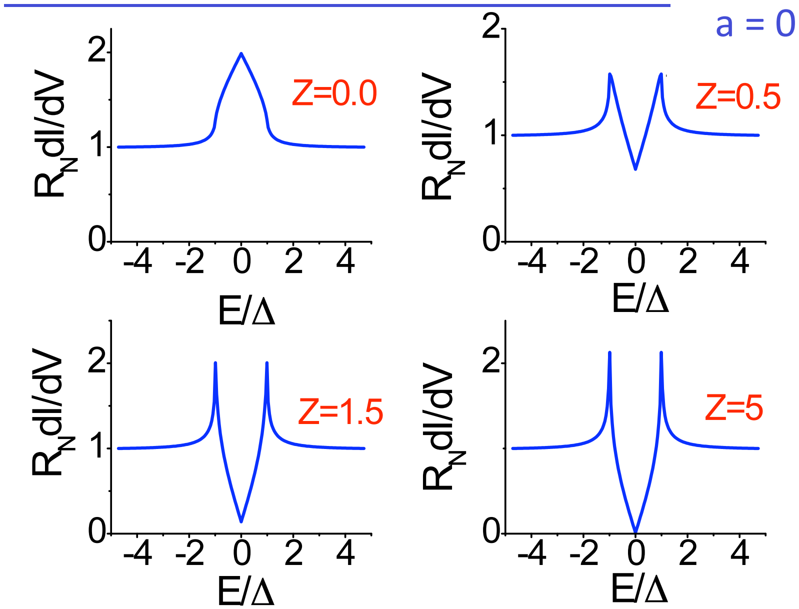






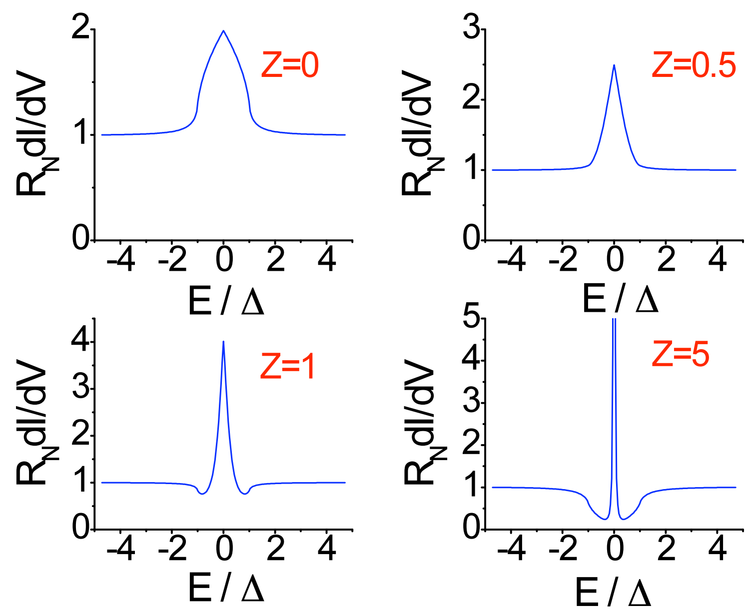
d-wave: c-axis or lobe direction

a = 0



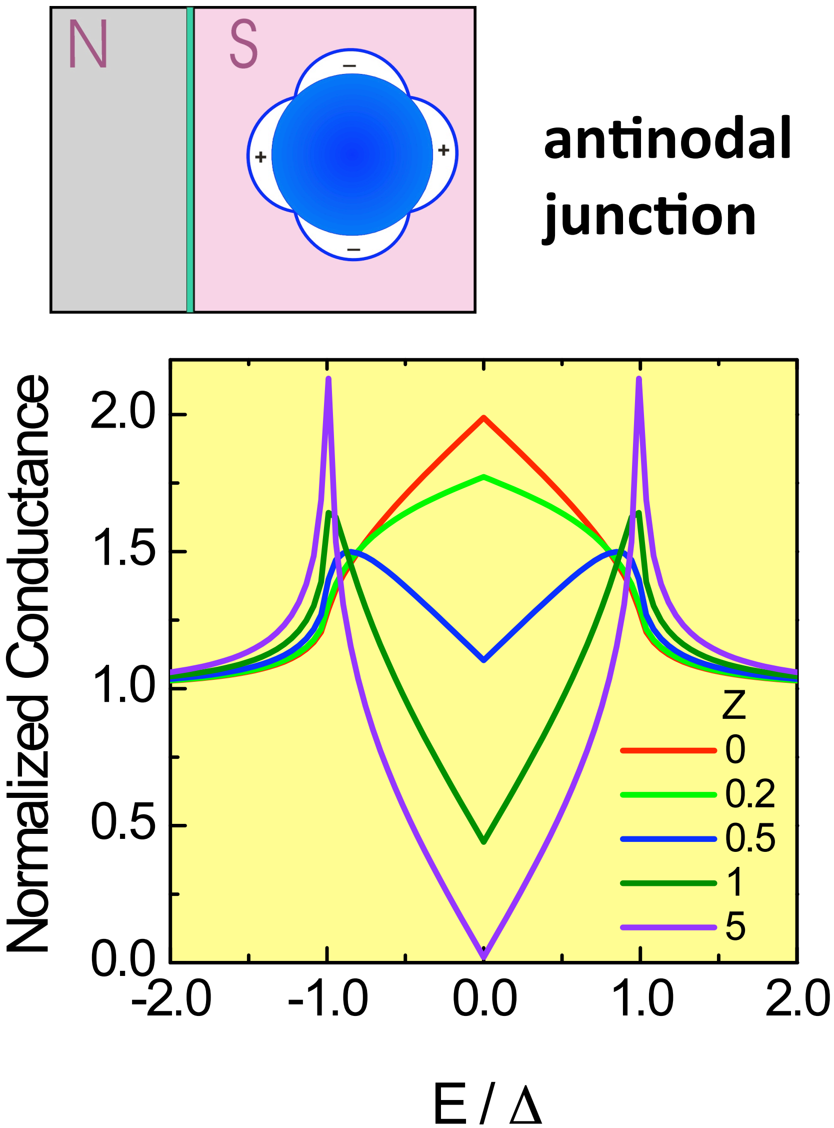
a = π/4

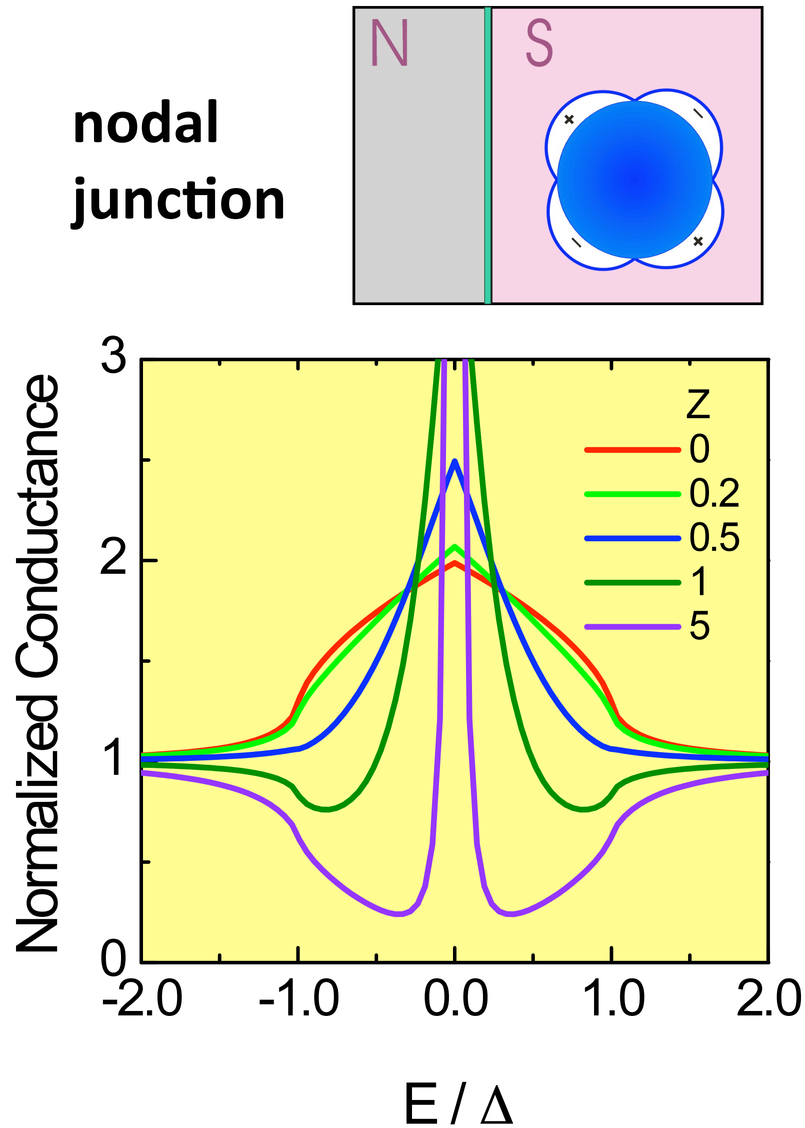
d-wave: nodal direction



YET AGAIN: d-wave BTK Model

Y. Tanaka et al. (PRL,1995) S. Kashiwaya et al. (PRB,1996)





ABS Tunneling Spectroscopy of High-T_c Cuprates

VOLUME 79, NUMBER 2 PHYSICAL REVIEW LETTERS 14 JULY 1997

Observation of Surface-Induced Broken Time-Reversal Symmetry in $YBa_2Cu_3O_7$ Tunnel Junctions

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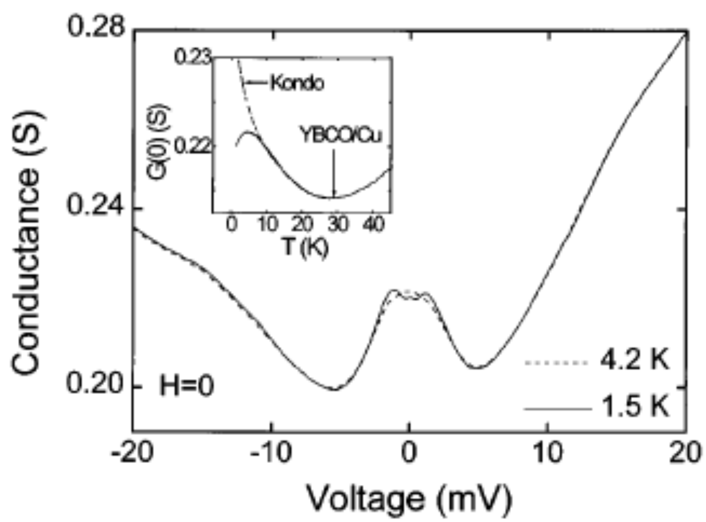
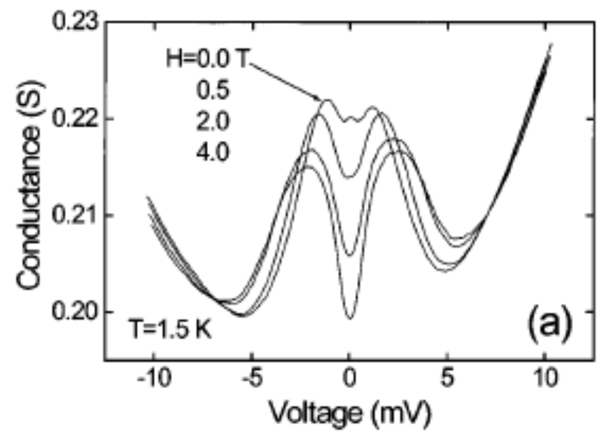
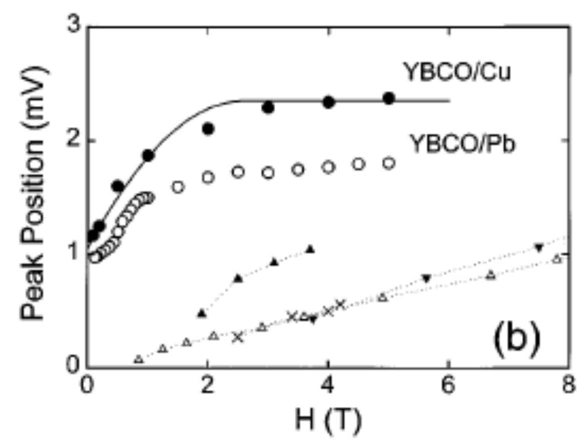
Department of Physics, University of Illinois at Urbana-Champaign, Urbana, Illinois 61801

F. Xu, J. Zhu, and C. A. Mirkin
Department of Chemistry, Northwestern University, Evanston, Illinois 60208
(Received 6 March 1997)







- ZBCP due to ABS splits under magnetic field (Doppler shift).

Further Extensions of BTK Model

- Mismatch in Fermi surface parameters

  - Fermi velocity $\Rightarrow$ enhance Z_{eff}

  - Effective mass, Fermi wave vector $\Rightarrow$ renormalized version of BTK

  - Fermi energy: breakdown of Andreev approximation ($\Delta << E_F$)

    $\Rightarrow$ Imperfect retro-reflection

- Tunneling cone effect

  Transmission Factor

$$D = A\exp(-2\kappa d/\cos\theta) = \exp\left(-\frac{\cos\theta_c}{\cos\theta_c - 1}\frac{\cos\theta - 1}{\cos\theta}\right) \qquad \kappa = \left(\frac{2m}{\hbar^2}\right)^{1/2}[U-E]^{1/2}$$

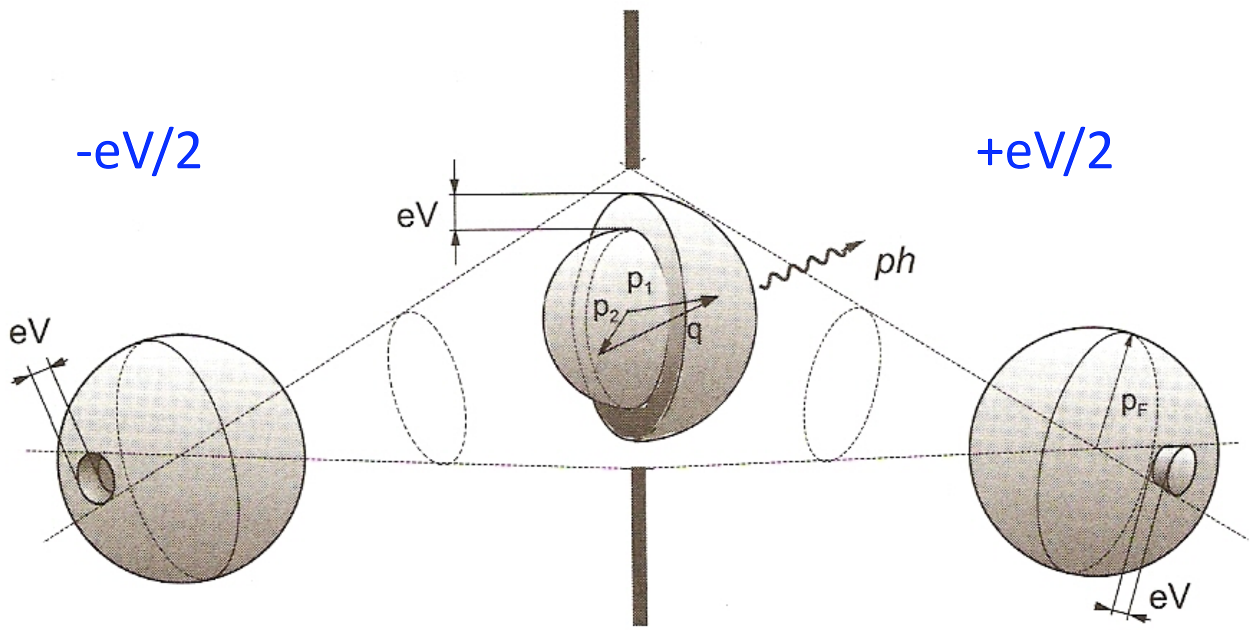
$$\theta_c = \cos^{-1}\left(\frac{2\kappa d}{1+2\kappa d}\right) = \cos^{-1}\left(\frac{1}{1+\frac{1}{2\kappa d}}\right) = \cos^{-1}\left(\frac{1}{1+\frac{1}{\sqrt{16\pi Z\frac{d}{\lambda_F}}}}\right)$$

$$Z = \frac{mH}{\hbar^2 k_F} = H/\hbar v_F$$

$$Z = \frac{m\cdot U\cdot d}{\hbar^2 k_F} = \frac{2m\cdot U}{\hbar^2}\frac{d}{2k_F} = \kappa^2\frac{d}{2k_F}$$

$$\Rightarrow \kappa = \sqrt{\frac{2k_F Z}{d}}, \kappa d = \sqrt{2k_F dZ} = \sqrt{4\pi Z\frac{d}{\lambda_F}}$$

What is Point-Contact Spectroscopy (PCS) ?



• If two bulk metals are in contact with each other and the contact size is smaller than electronic mean free paths, quasiparticle energy gain/loss mostly occurs at the constriction.

• Nolinearities in current-voltage characteristics reflect energy-dependent quasiparticle scatterings in the contact region.

Junction Size Matters in PCS!

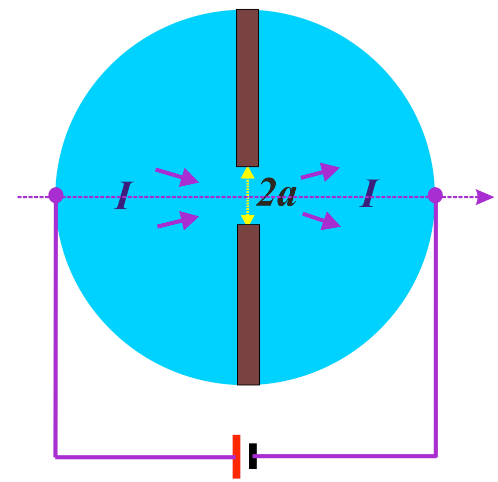
Wexler's formula

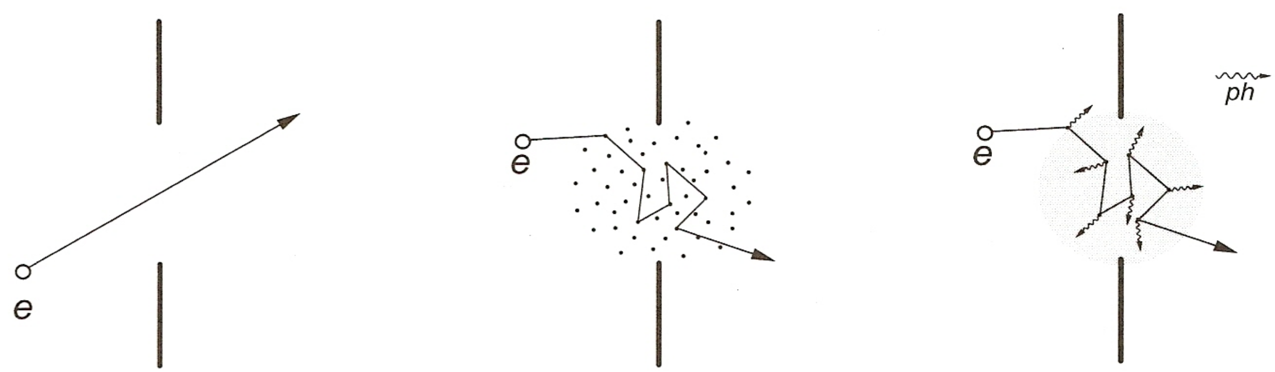
G. Wexler, Proc. Phys. Soc. London **89**, 927 (1966)

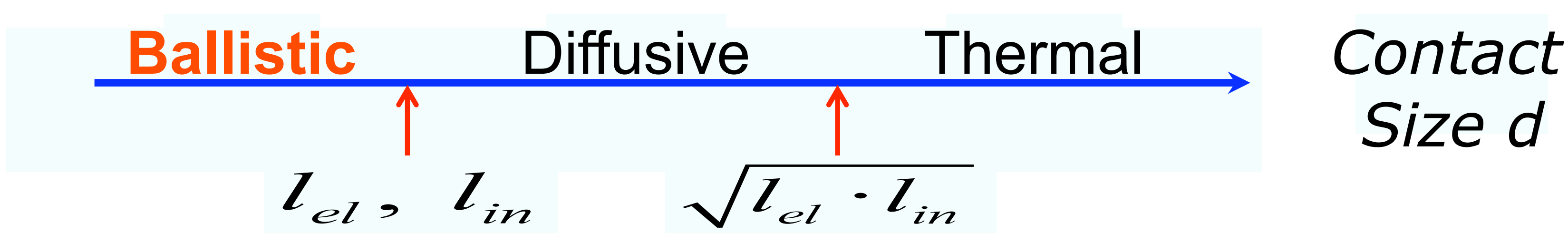
$$R_0 = \frac{4\rho l_{el}}{3\pi a^2}\left\{1+\frac{3\pi}{8K}\gamma(K)\right\},\ K \equiv l_{el}/a,\ \text{Knudsen ratio}$$

$$i)\ K >> 1,\ \gamma(K) \rightarrow 0.694,\ R_0 = \frac{4\rho l_{el}}{3\pi a^2},\ \text{Sharvin limit}$$

$$ii)\ K \rightarrow 0,\ \gamma(K) \rightarrow 1,\ R_0 = \frac{\rho}{2a},\ \text{Maxwell limit}$$







Point Contact Techniques

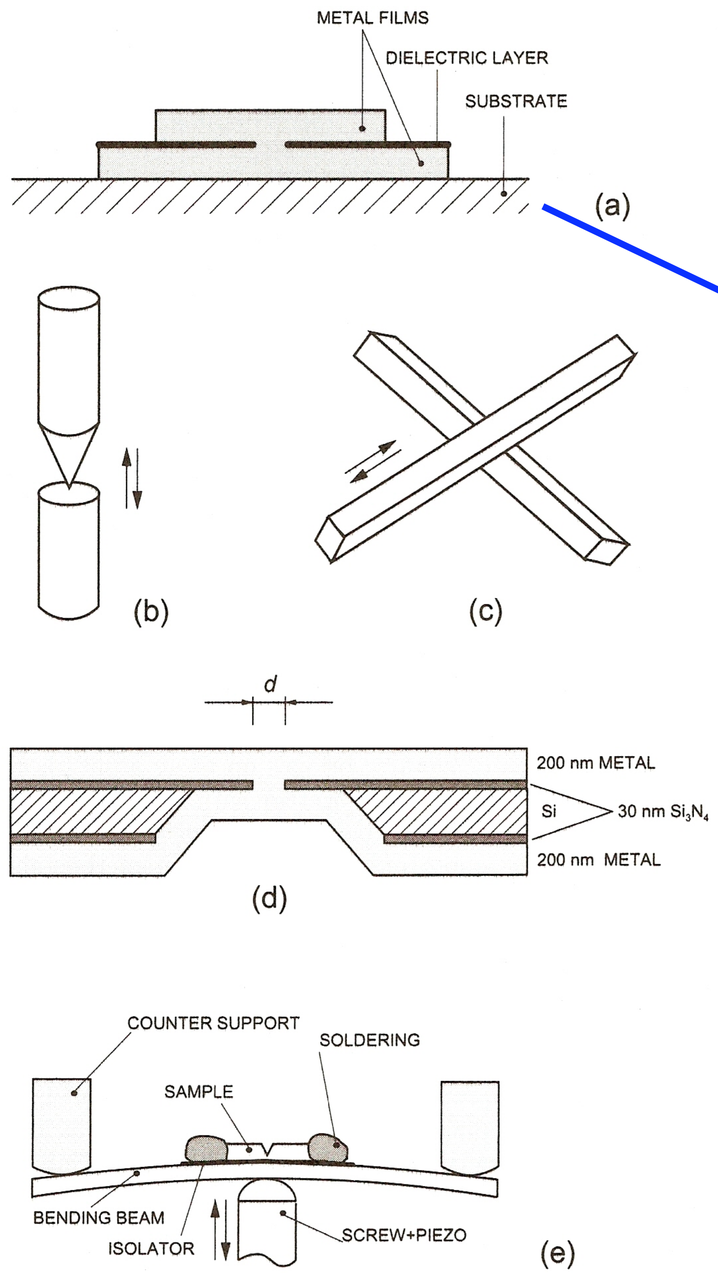
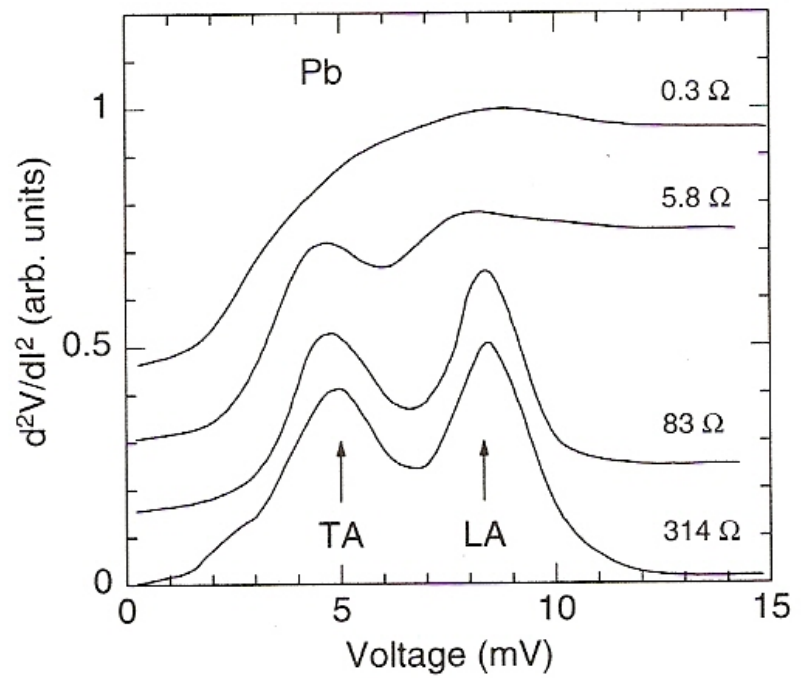


Fig. 4.1. Schematic view of different methods of point-contact formation: (a) thin films, (b) needle-anvil, (c) shear, (d) lithography, and (e) break-junction (see text for details).

I K Yanson

Sov. Phys. JETP **39**, 506 (1974)



$$\frac{d^2V}{dI^2} \propto \alpha(\omega)^2 F(\omega)$$

Similar to tunneling results by McMillan and Rowell (1965)

Needle-anvil tech. developed by A.G.M. Jansen *et al.*

Example (I): Au/Nb

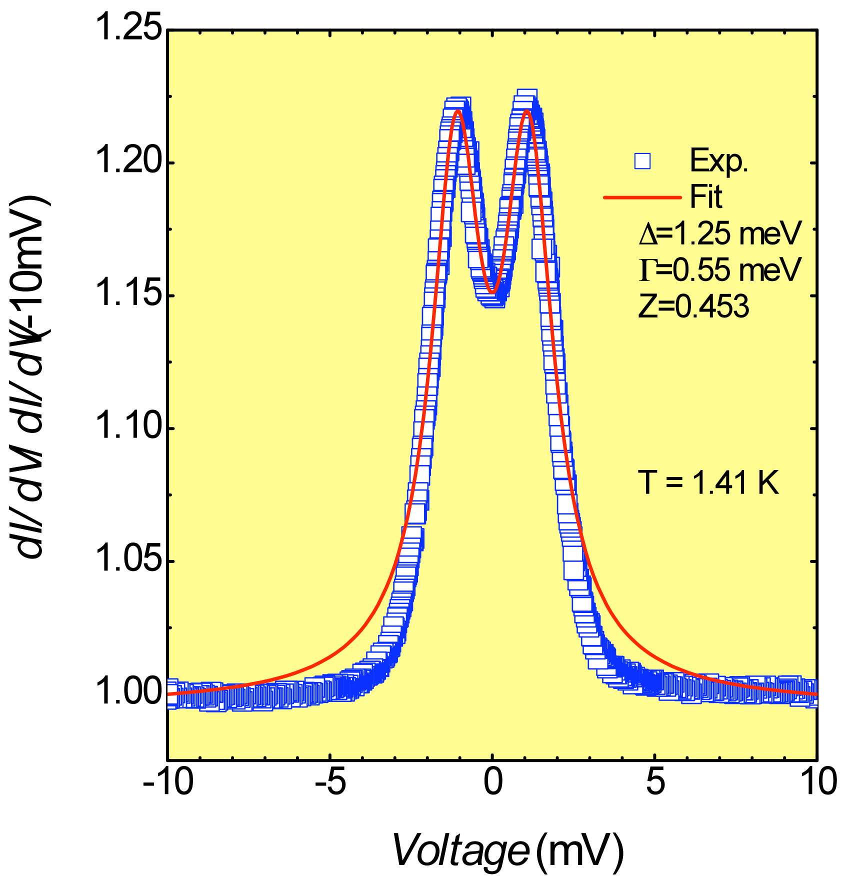
Park & Greene, *Rev. Sci. Instum.* **77**, 023905 (2006)

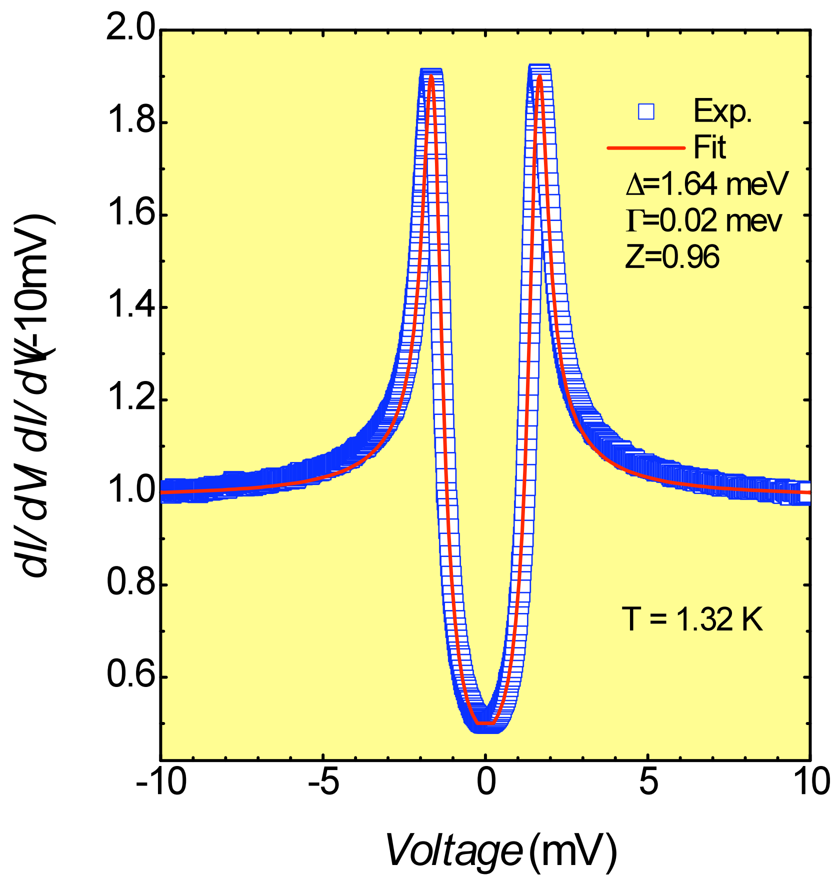
$$\frac{dI}{dV} \propto \int_{-\infty}^{\infty} \frac{\partial f\left(E-eV\right)}{\partial\left(eV\right)}\left[1+aa^{*}-bb^{*}\right]dE$$

Δ : Energy gap

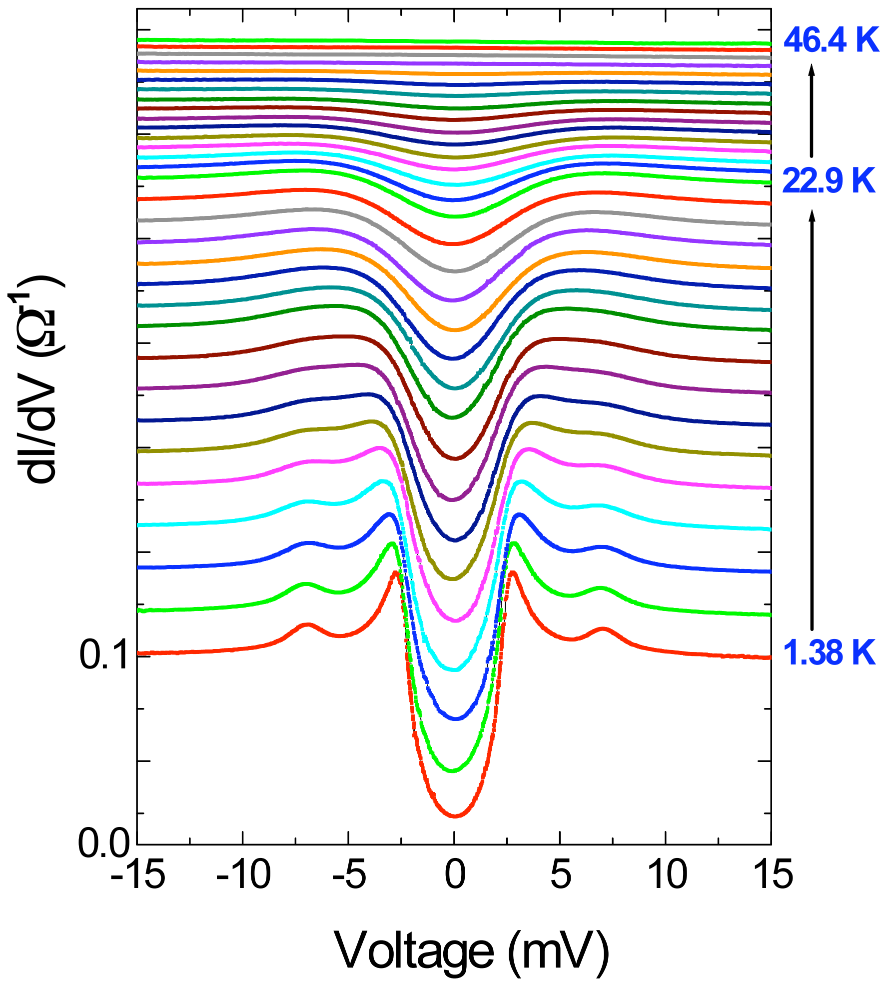
Γ : Quasiparticle smearing

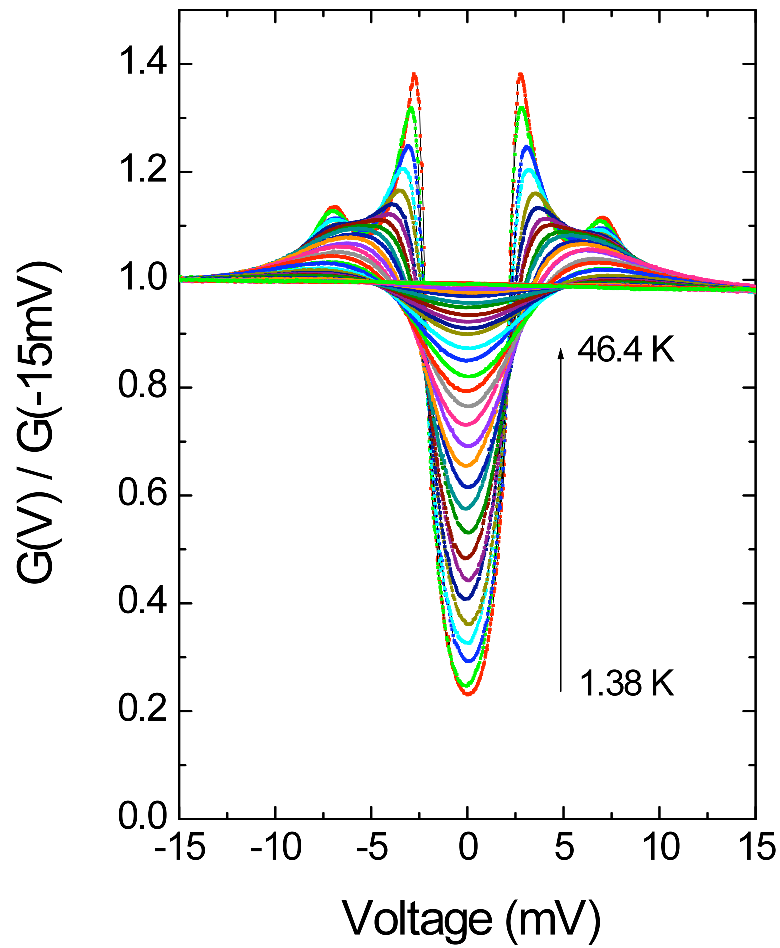
Z : Tunnel barrier strength



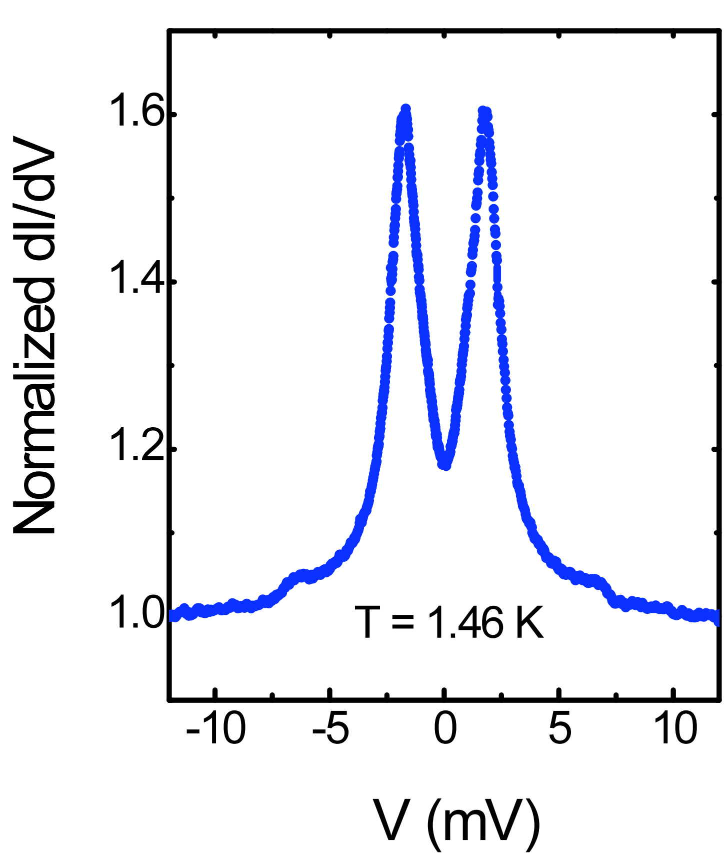


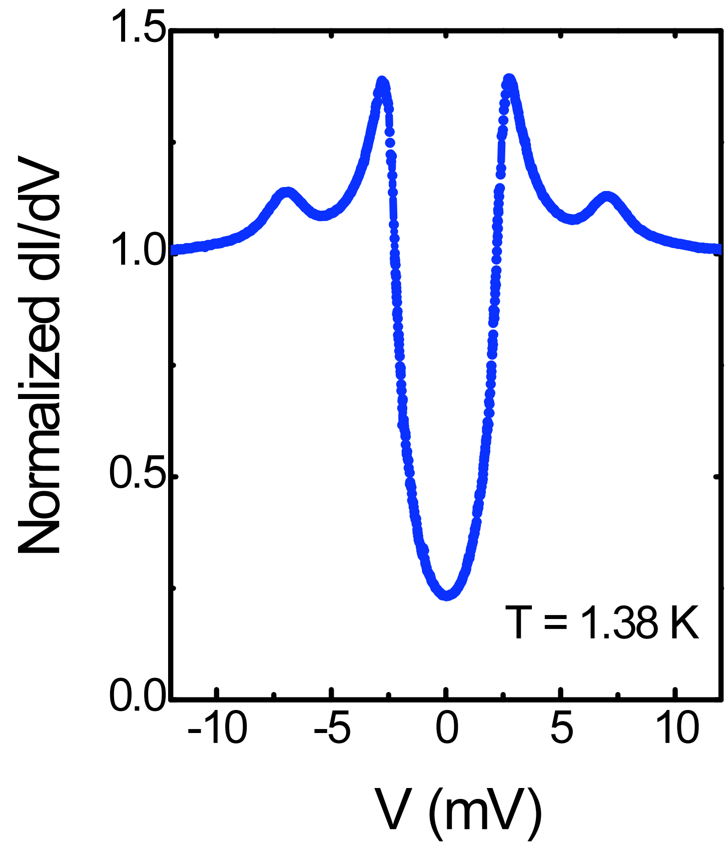
Example (II): Au/MgB_2





Two types of conductance curves from MgB_2/Au



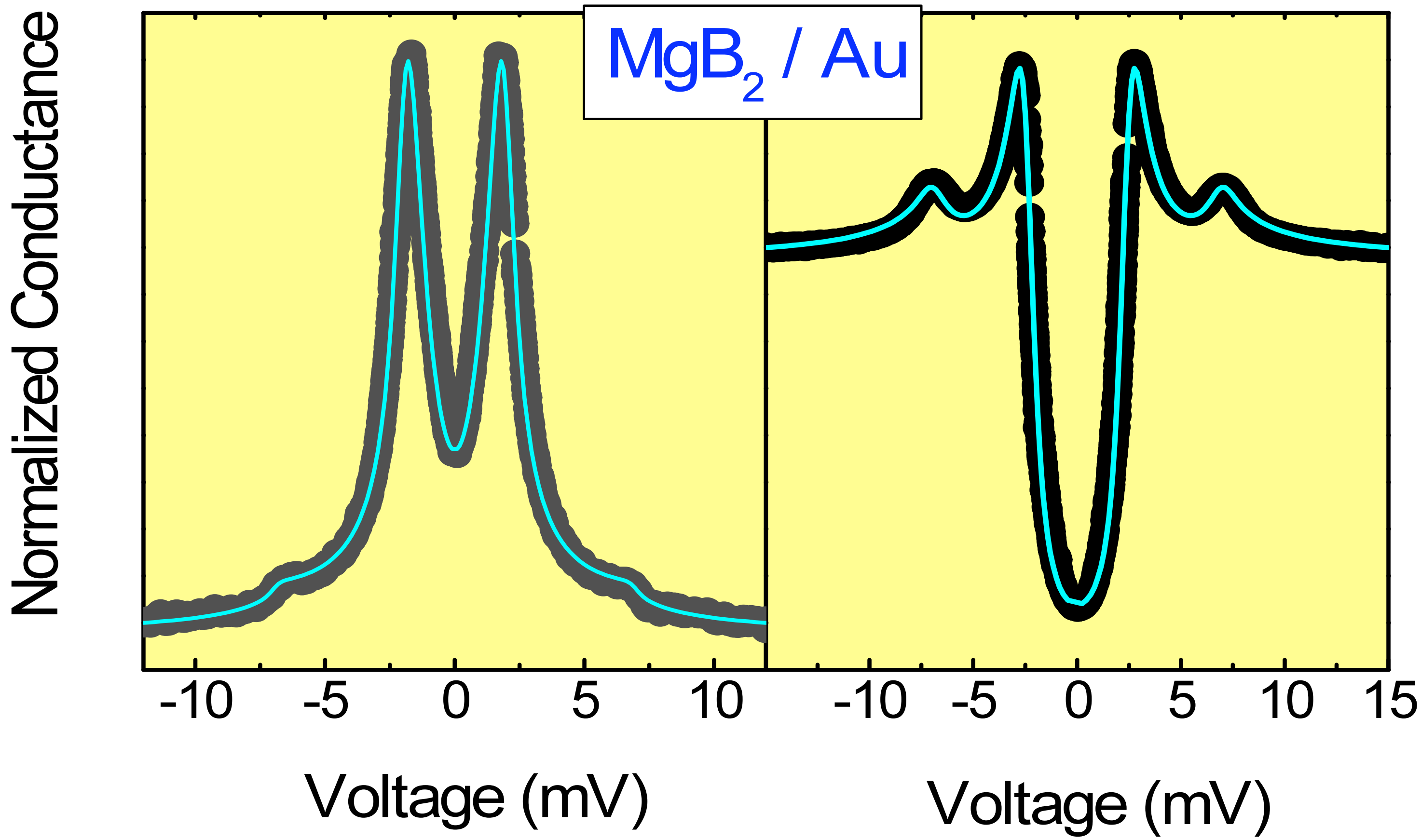


Two-band BTK model

$$\frac{dI}{dV} = \omega_\pi \left.\frac{dI}{dV}\right|_\pi + (1-\omega_\pi)\left.\frac{dI}{dV}\right|_\sigma$$

$$\left.\frac{dI}{dV}\right|_i = \int_{-\infty}^{\infty} dE\left[1 + A(E,\Gamma,Z) - B(E,\Gamma,Z)\right]\frac{\partial f(E-eV,T)}{\partial(eV)}$$

Park & Greene, *Rev. Sci. Instum.* **77**, 023905 (2006)



Δ = 1.97, 6.90 meV

Γ = 0.18, 0.01 meV

Z = 0.47, 0.25

ω_π = 0.972

Δ = 2.43, 7.00 meV

Γ = 0.41, 0.45 meV

Z = 2.5, 0.9

ω_π = 0.90

Conclusions for for BTK Model

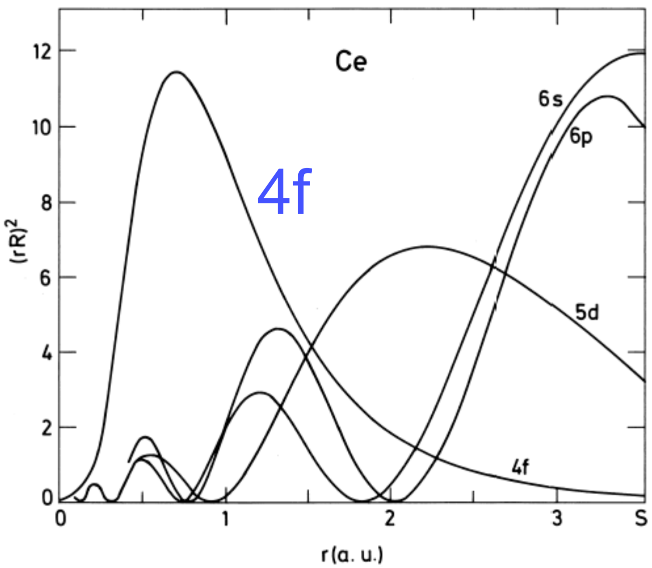
- Blonder-Tinkham-Klapwijk (BTK) theory can explain the transitional behavior from Andreev reflection to Tunneling using a single parameter, the effective barrier strength (Z).

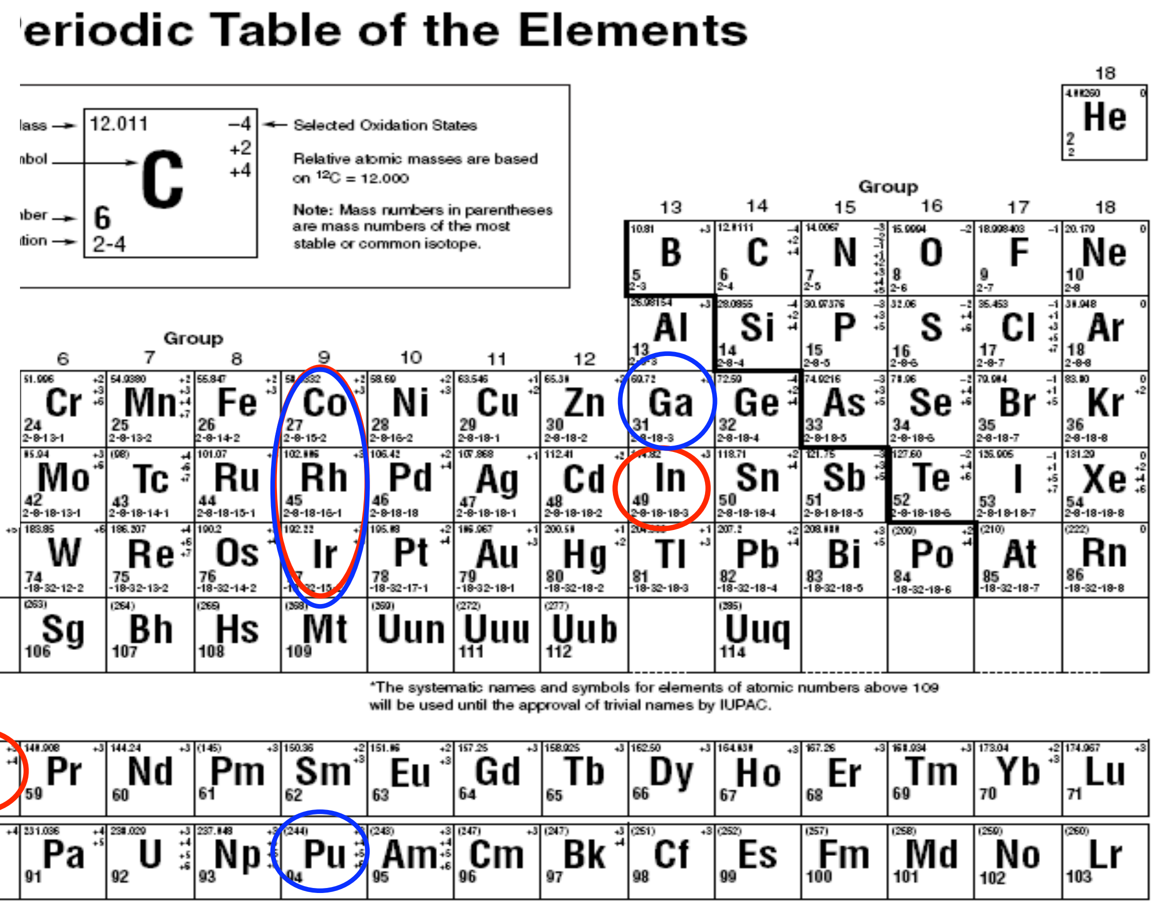
- BTK and extended BTK theories provide a useful framework to understand charge transport phenomena in various types of N/S hetero-structures.

- To analyze PCS data on a superconductor using BTK theory, three fitting parameters: Z, Δ, Γ

- BTK theory has been successfully applied to analyze our PCS data for Nb and MgB_2.

1-1-5 Heavy-Fermion Compounds





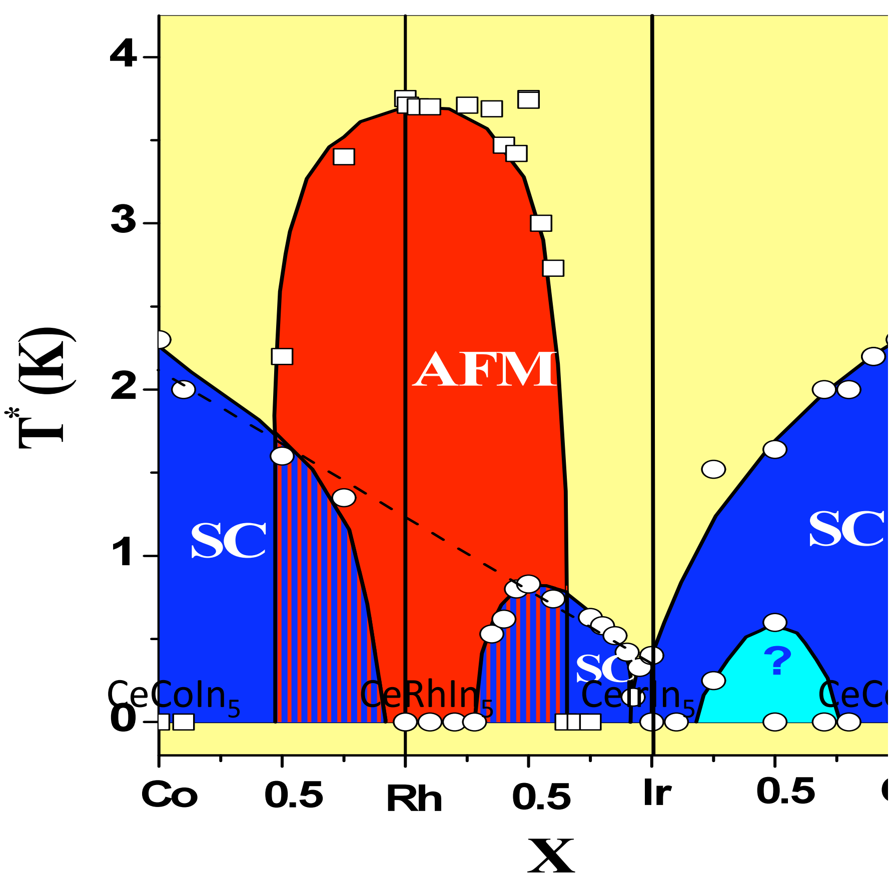
4*f* or 5*f* electrons

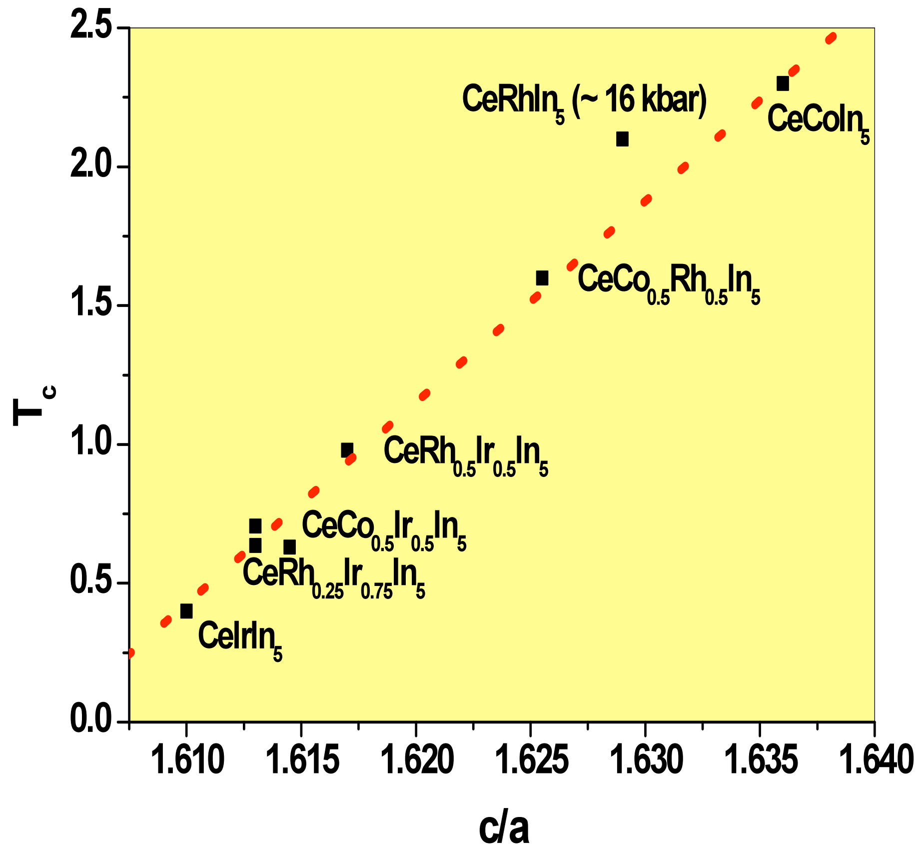
$CeMIn_5$ — $CeCoIn_5$ (T_c=2.3 K, g_{el}=290 $mJmol^{-1}K^{-2}$)

$PuMGa_5$ — $PuCoGa_5$ (T_c=18.5 K, g_{el}=77 $mJmol^{-1}K^{-2}$)

The Heavy Fermion Superconductor $CeCoIn_5$:

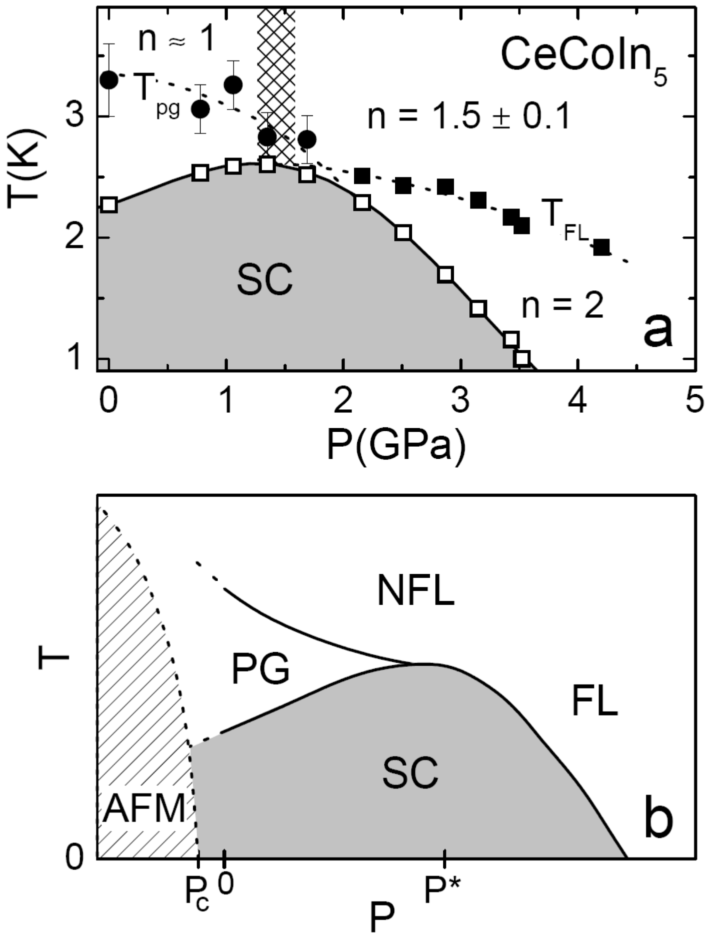
Phase diagram of series Ce M In_5 (M = Co, Rh, In)





Pagliuso et al., Phys. Rev. B 64 (2001) 100503(R)

The heavy-fermion Superconductor $CeCoIn_5$: Some interesting properties



*V. A. Sidorov et al., PRL **89**, 157004 (2002)*

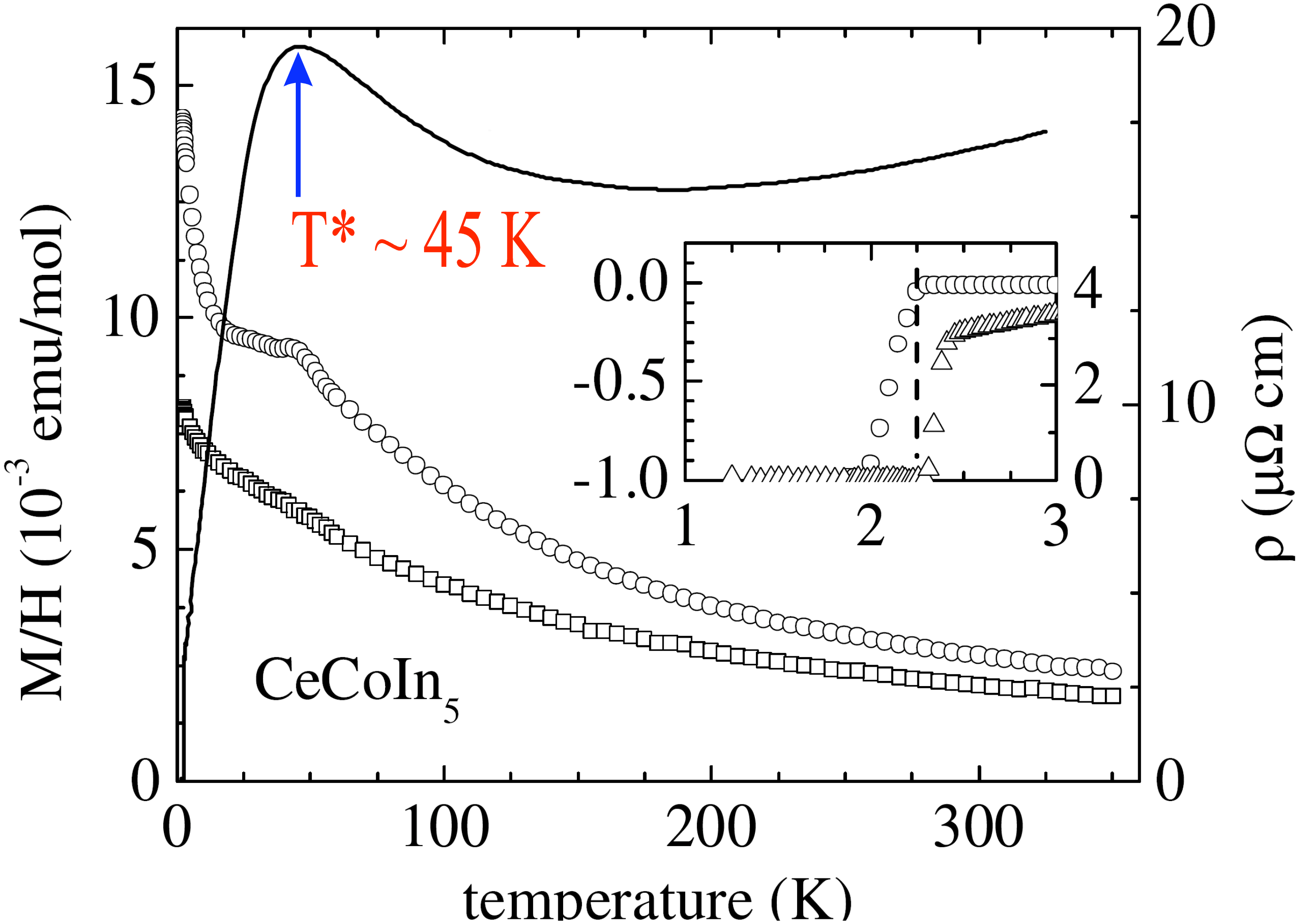
- **Quantum Phase Transition**
  with chemical substitution,
  hydrostatic pressure,
  magnetic field ,
  (similar to cuprates)
- **FFLO Phase Transition**

> - **Anisotropic type-II SC**
> - **Heavy-fermion liquid**
>
> $m_{eff} = 83 m_0$
>
> $T^* \sim 45$ K
> - **Non-Fermi liquid**
>
> $\rho \sim T^{1.0 \pm 0.1}$,
>
> $C_{en} / T \sim -\ln T$,
>
> $1 / T_1 T \sim T^{-3/4}$

The Heavy-Fermion Superconductor $CeCoIn_5$

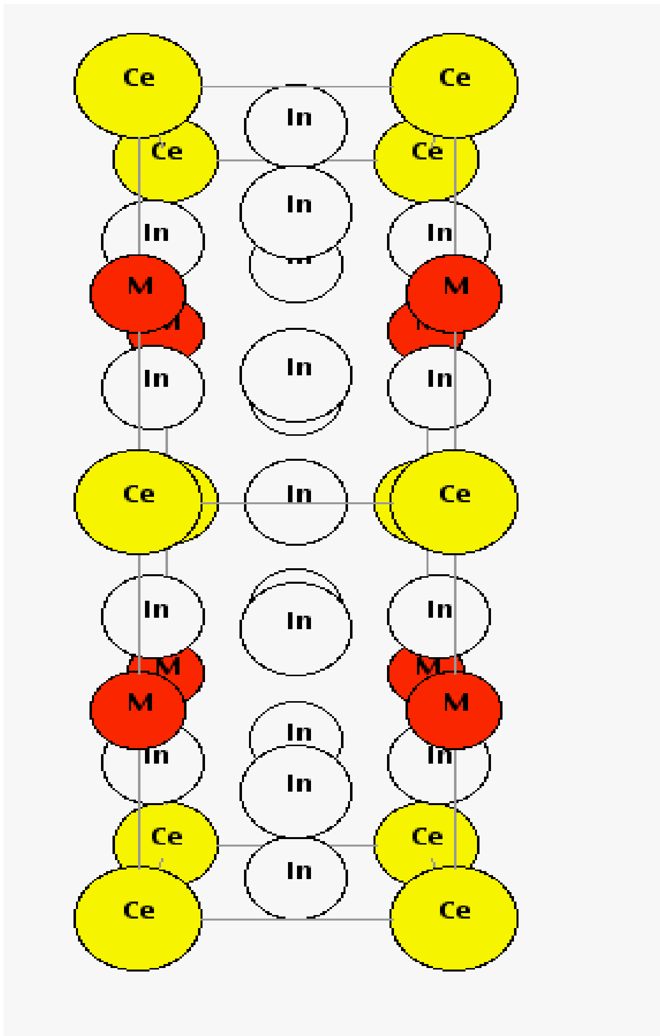
Why it is <u>our</u> HFS of choice (ideal for PCS):

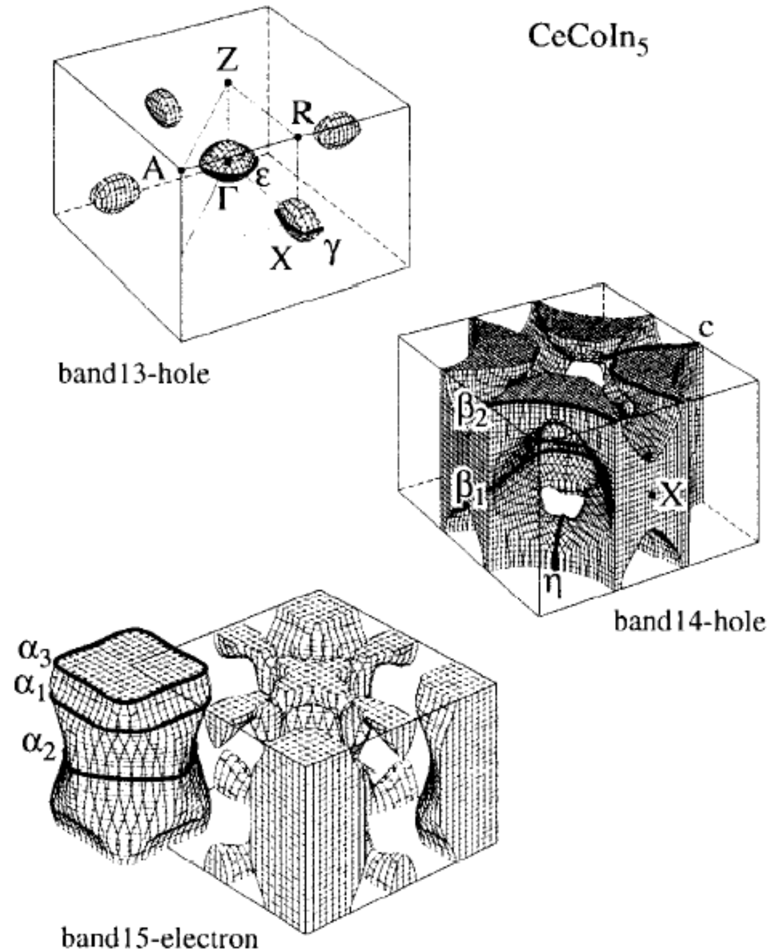
- T_c = 2.3K (high for HFS)
- Superconductivity in clean limit (*mfp* = 810Å >> ξ_0)



*C. Petrovic et al., J. Phys.: Condens. Matter **13**, L337 (2001)*

Crystal Structure and Fermi Surface: Quasi 2-dimensional





R. Settai et al., JPCM **13**, L627 (2001)

BTK model has worked well for a wide range of materials, but as we will see, NOT for heavy-fermion superconductor / normal metal (HFS/N) interfaces

The Fermi velocity mismatch is so great at the HFS/N interface that **Andreev reflection (AR) should never occur** ($Z>5$ → expect the extreme tunneling limit).

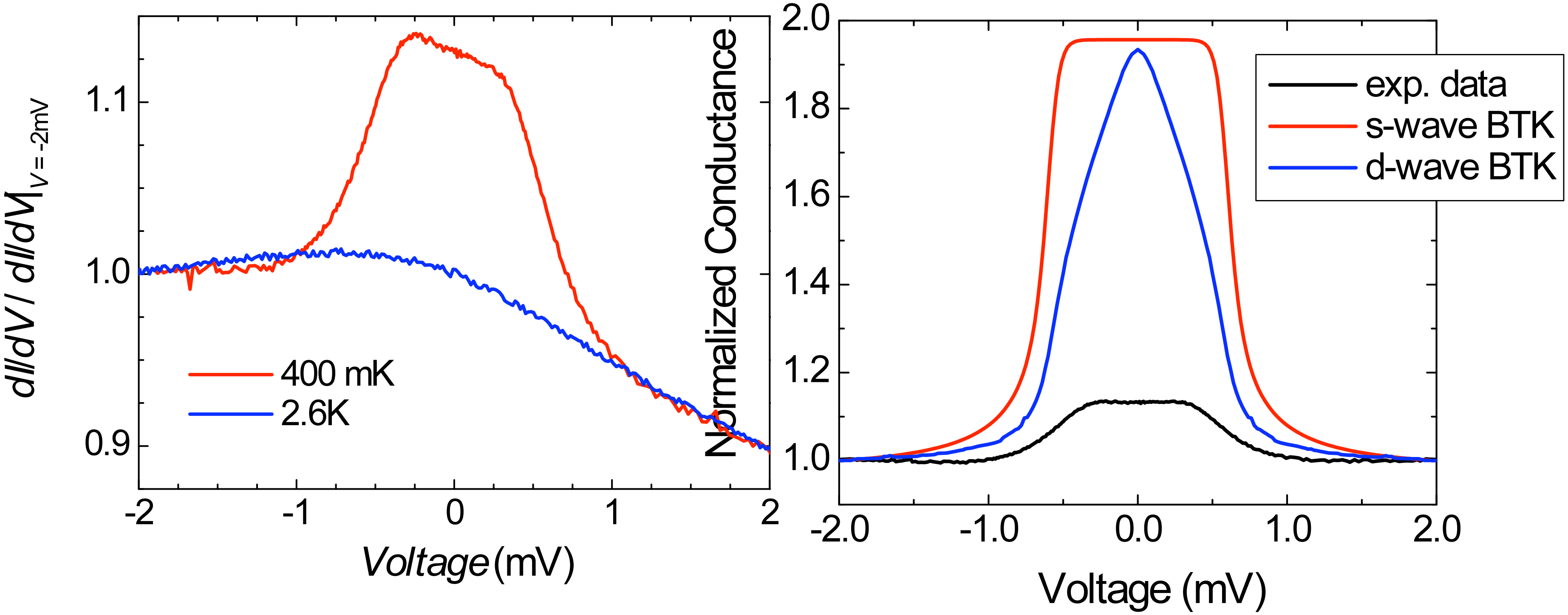
Recall effective barrier strength:

$$Z_{eff} = \sqrt{Z^2 + \frac{(1-r)^2}{4r}}, \quad r \equiv v_{FN} / v_{FS}$$

However, AR is routinely measured at the N/HFS interface, albeit suppressed compared to N/conventional-S.

Andreev reflection at the N/HFS interface cannot be explained by existing theories

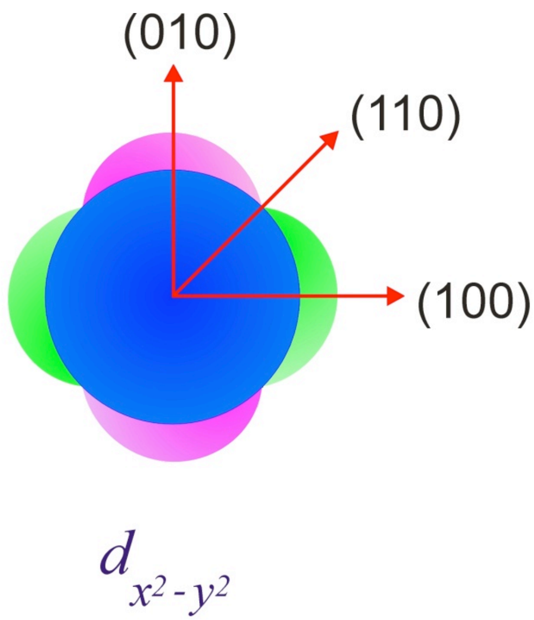
Definition of the issues

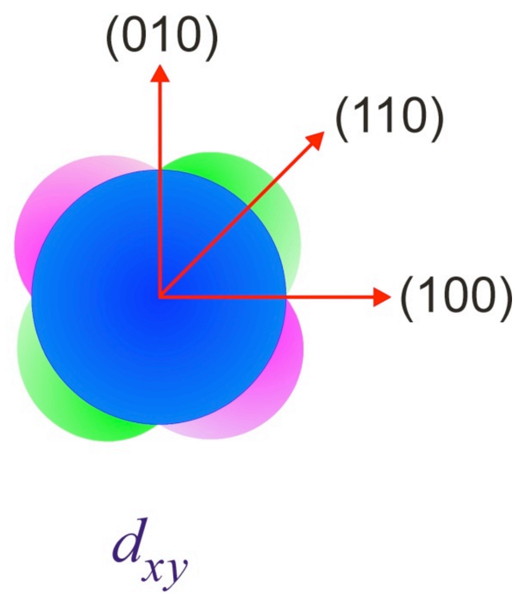


1. **Understanding charge transport across HF interface**
   Existing models cannot account for
   Andreev reflection at the HFS/N interface
2. **Spectroscopic studies of $CeCoIn_5$** (OP symmetry, mechanism,…)
   The "Rosetta stone for heavy fermions"

$CeCoIn_5$: Superconducting Order Parameter Symmetry:
Previous work

- Evidence for the existence of line nodes:
  Power law dep: $C_{en} / T \sim T$, $\kappa \sim T^{3.37}$, $1/T_1 \sim T^{3+\varepsilon}$, $\lambda \sim T^{1.5}$
- Four-fold symmetry of field-angle dep in thermal cond.:
  small angle neutron scattering $\Rightarrow d_{x^2-y^2}$
  specific heat $\Rightarrow d_{xy}$
- Spectroscopic evidence was lacking to determine the locations of line nodes: (110) or (100) i.e. d_{xy} or $d_{x^2-y^2}$?



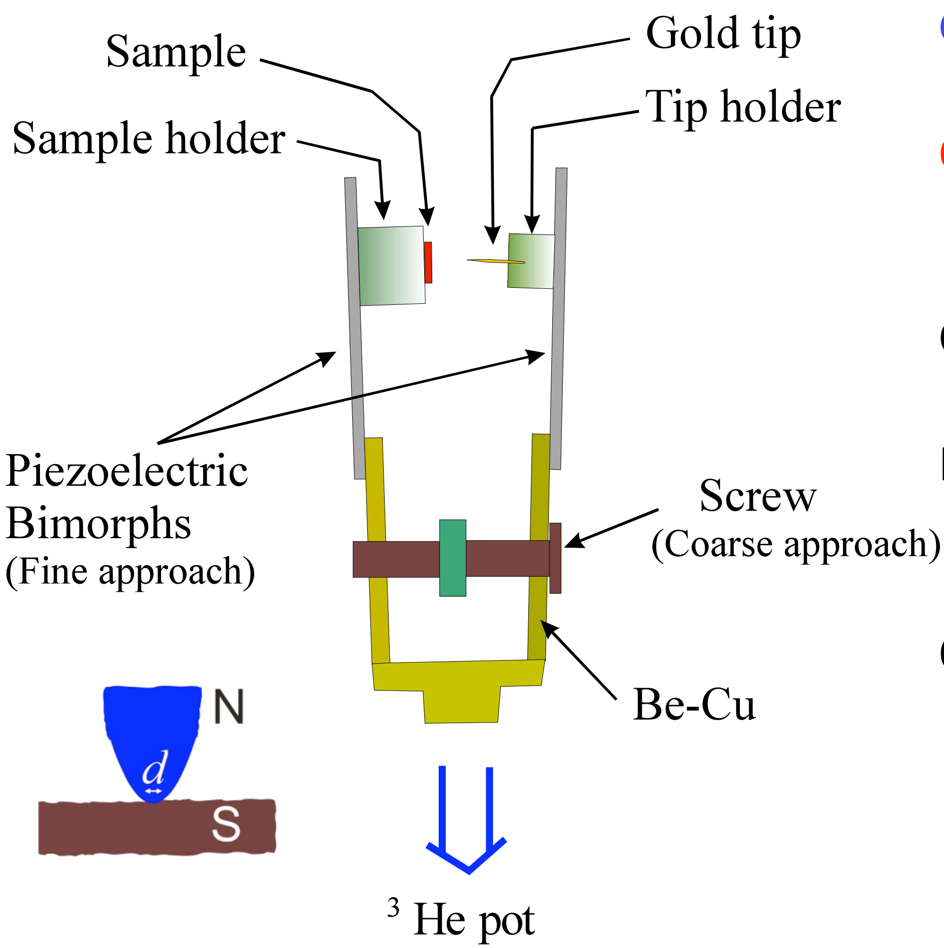


Our Experiments:

Point Contact Andreev Reflection Spectroscopy (**PCARS**)

1) Cantilever-Andreev-Tunneling (**CAT**) Rig

W.K. Park, LHG, RSI (06).



Gold tip

- electrochemically etched

$CeCoIn_5$ single crystal

- *(001), (110) and (100)* oriented
- etch-cleaned using H_3PO_4

Coarse approach

- done before inserting probe

Fine approach

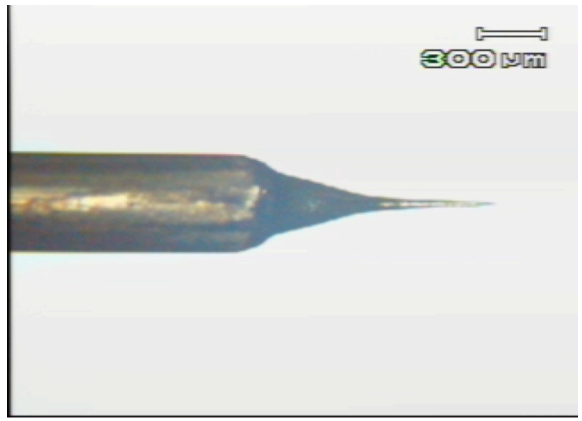
- done during cool down
- piezo driven by computer control

Operation range

- Temperature : down to 300mK
- Magnetic Field : up to 12T

Basics of PCS: Tip production

The sharp gold tip is electrochemically etched in hydrochloric acid



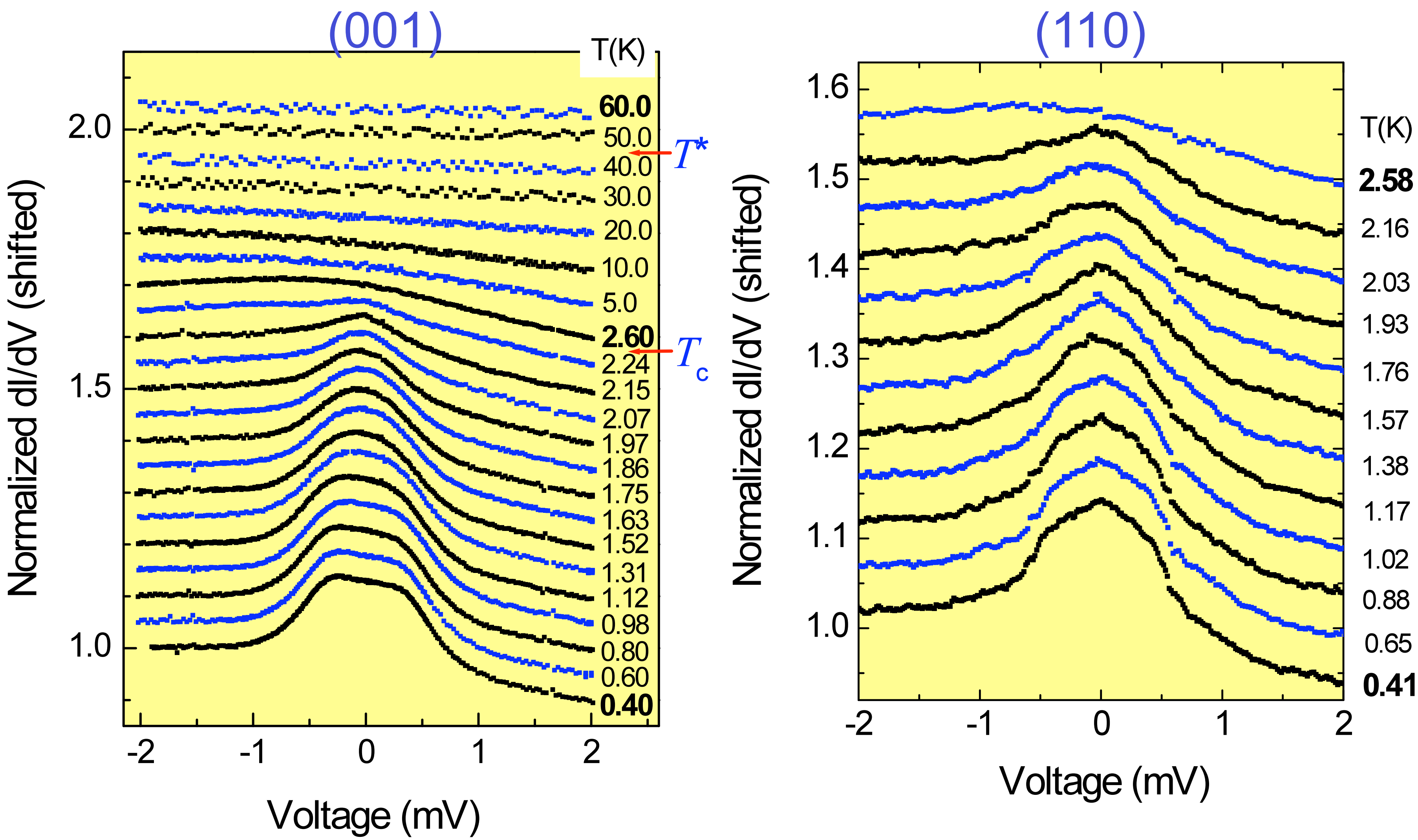
For our experiment (R_N = 1-4 Ω) and **<u>not T-dep</u>**:

* Upper limit of 2a = 46 nm

* l_{el} at T_c= is 81 nm (from thermal conductivity), and increases with decreasing T, to 4-5 μm at 400mK.

Our experiments are in the Sharvin Limit, <u>and</u> are reproducible.

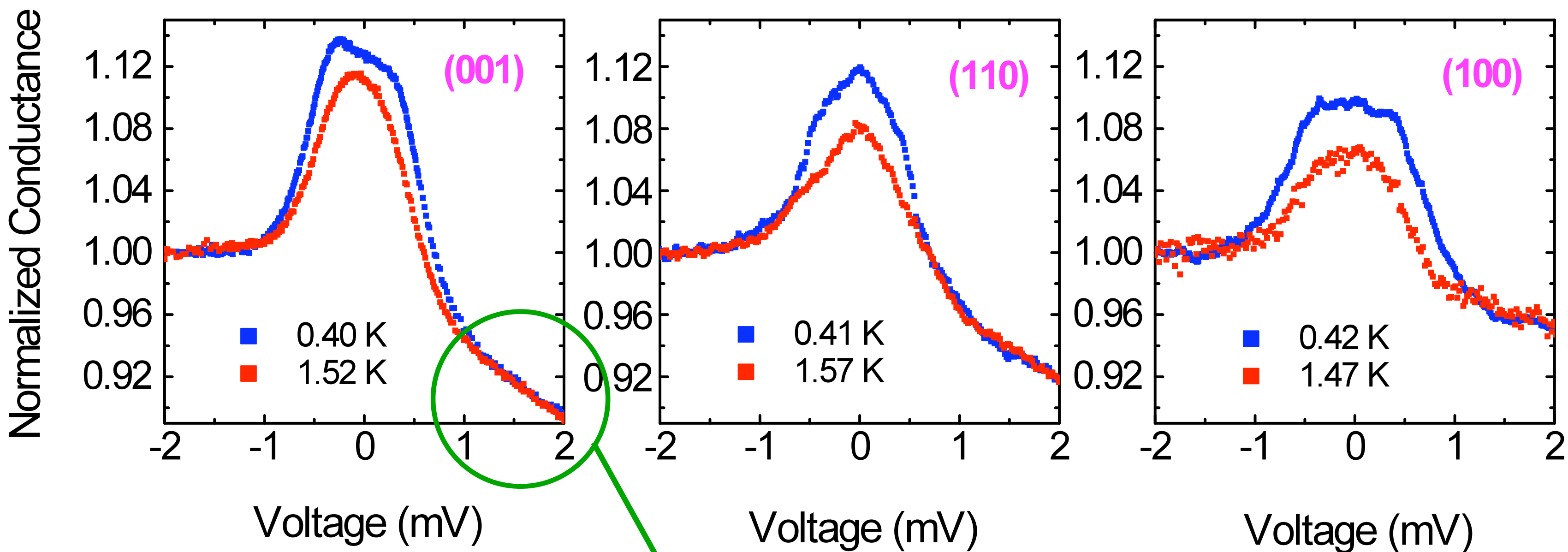
Andreev Reflection Conductance of Au/CeCoIn$_5$



Conductance asymmetry begins at T^* and saturates below T_c

Consistency Along Three Orientations

- Conductance magnitude (AR)
- Conductance width (Δ)
- Background asymmetry (2-fluid & DoS peak ?)

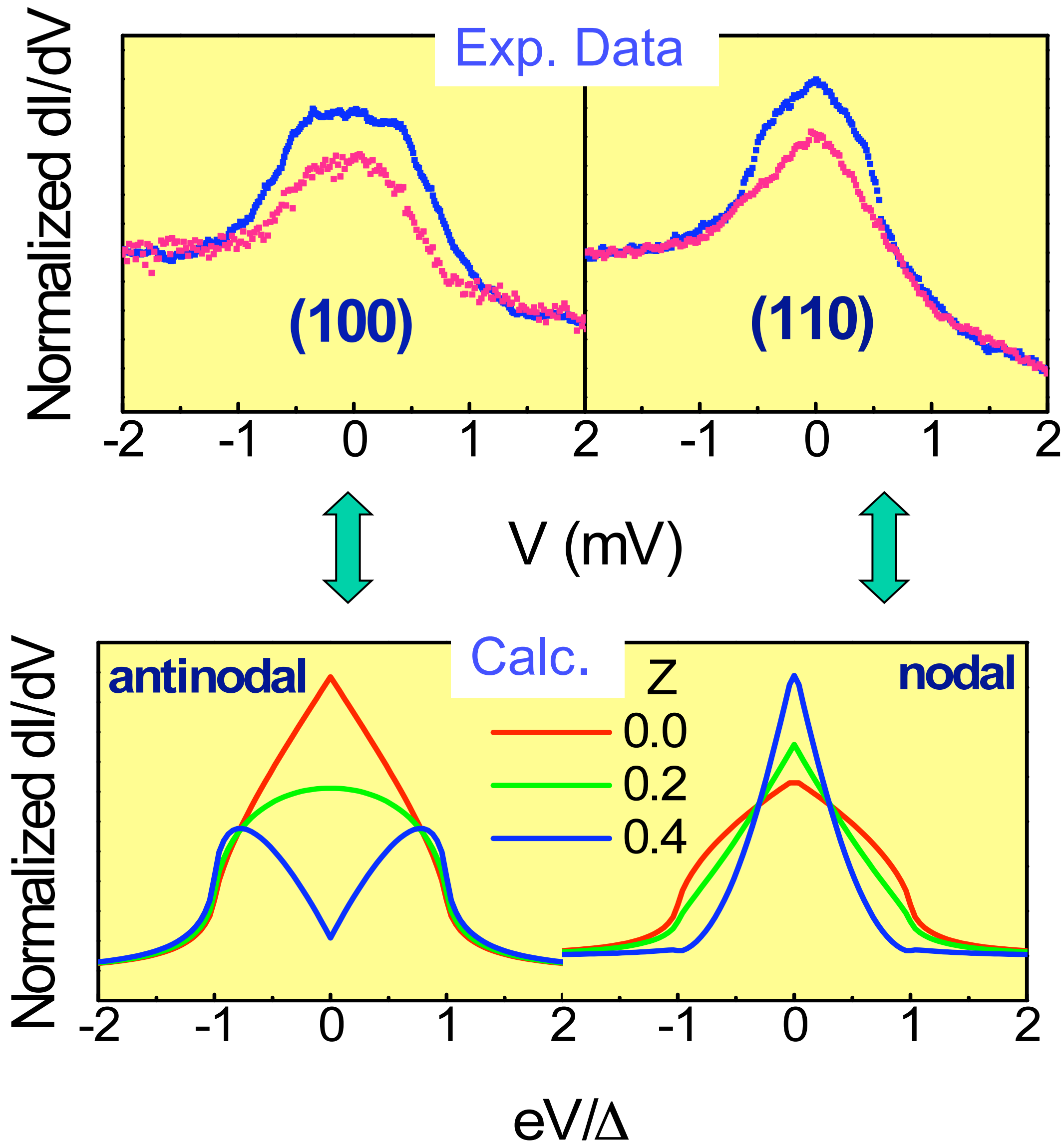


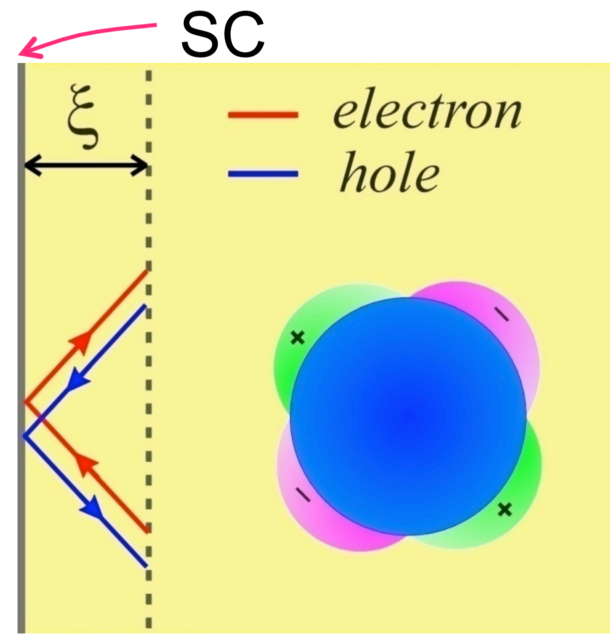
(+) $CeCoIn_5$; (−) Au

=> Adding electrons to $CeCoIn_5$ above the Fermi energy is more difficult than removing them

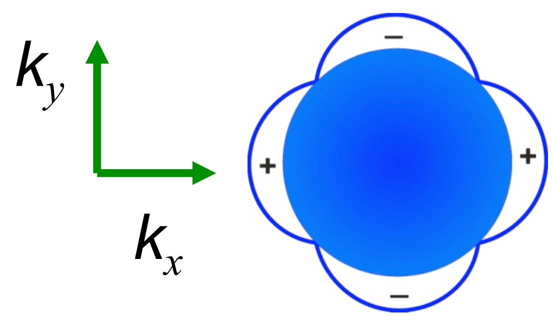
Note the shapes of the conductance curves

Spectroscopic Evidence for $d_{x^2\text{-}y^2}$ Symmetry



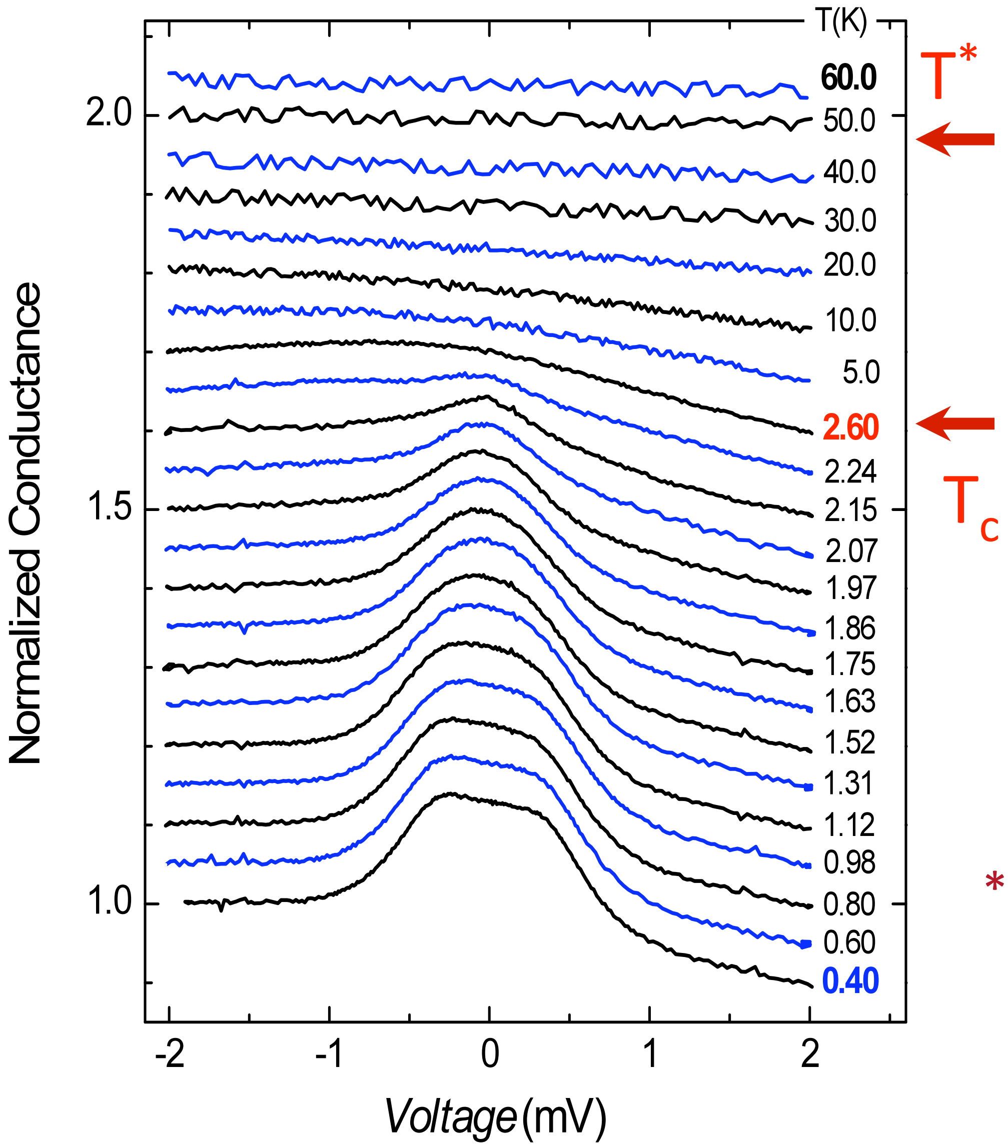


Andreev Bound States (ABS)



WKP et al., PRL **100**, 177001 (2008)

Background Conductance Asymmetry of Au/$CeCoIn_5$

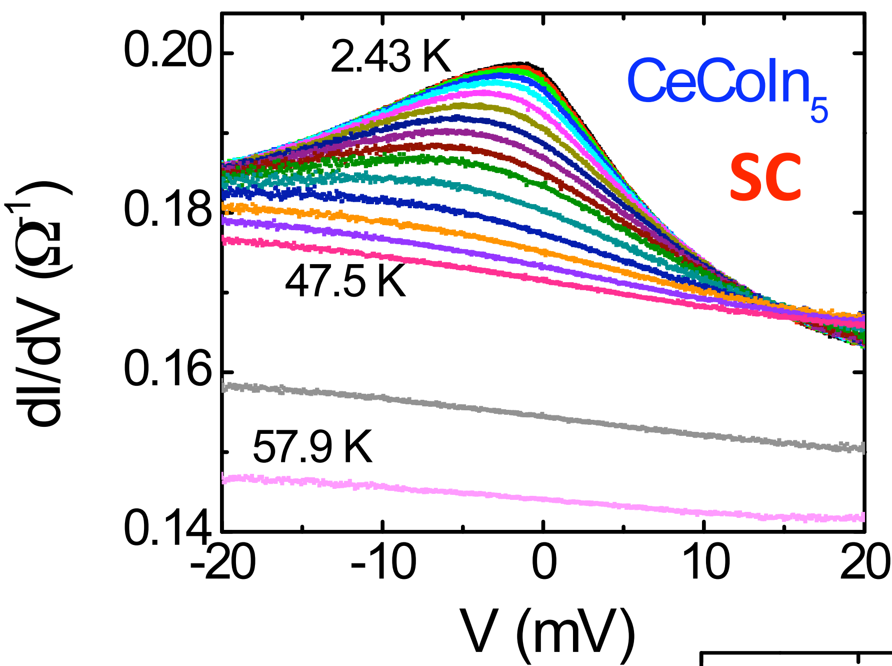


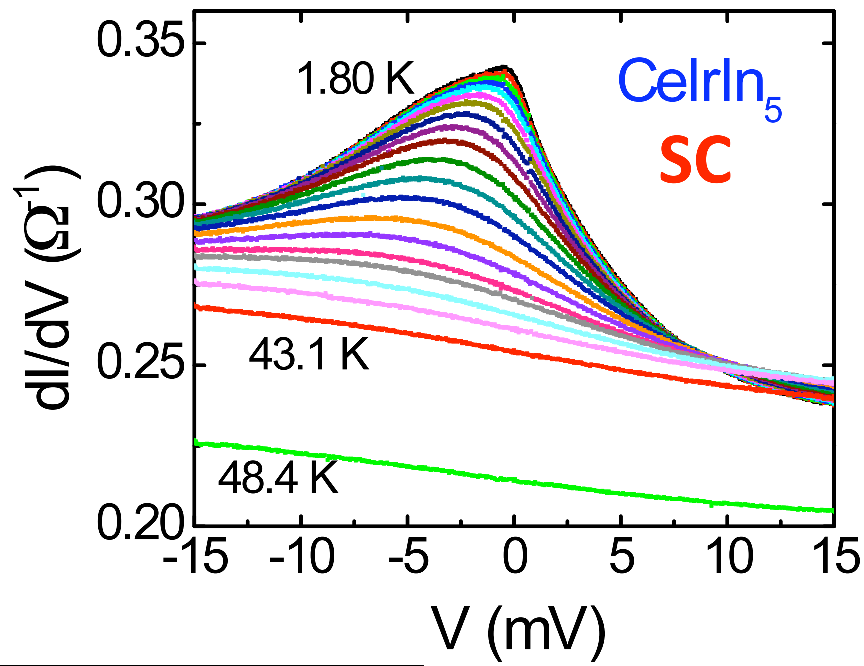
Background develops an asymmetry* at the heavy-fermion liquid coherence temperature,
$T^* \sim 45$ K.

This asymmetry gradually increases with decreasing temperature until the onset of superconducting coherence,
$T_c = 2.3$ K.

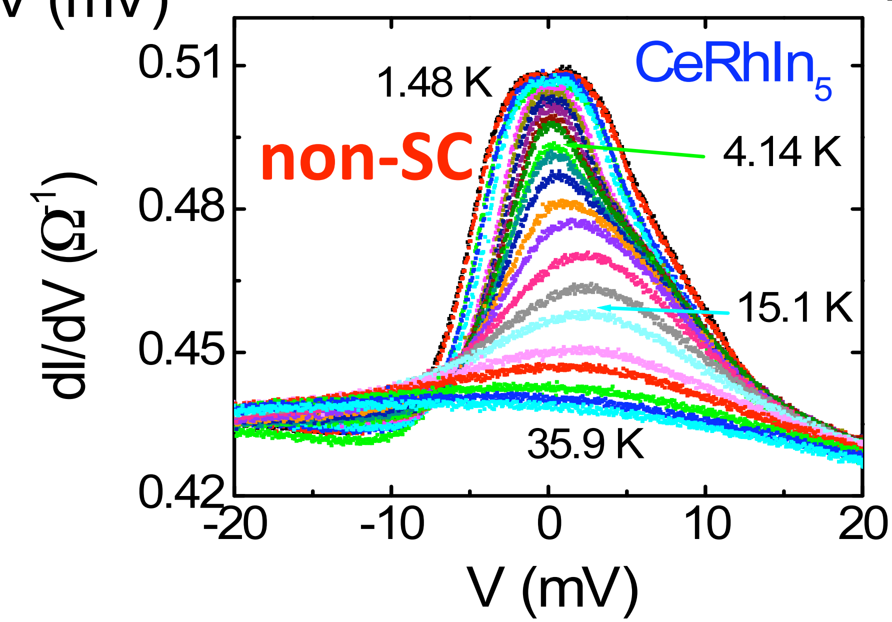
* el-h asymmetry described by Nakatsuji, Pines & Fisk, PRL **92**, 016401 (2004)

Background Conductance Asymmetry of Au/CeMIn$_5$





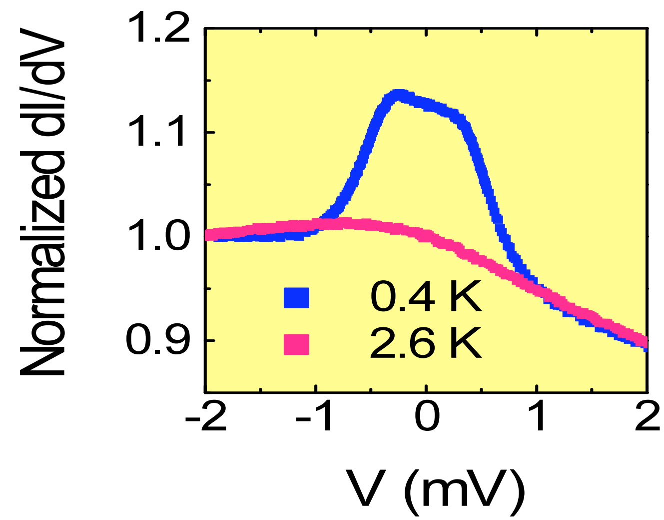
- **Co- & Ir-115: qualitatively similar**



- Rh-115: additional structure due to AFM (also, in Cd-doped Co-115)

Why is the conductance asymmetric?

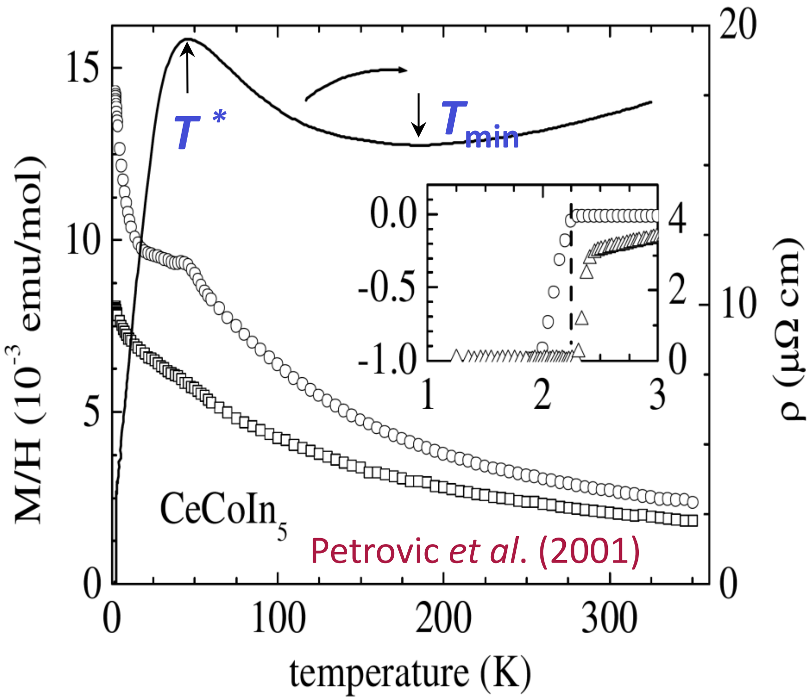
• Asymmetry is reproducible; conductance is always smaller when HFs are biased positively for the two SC 115s.



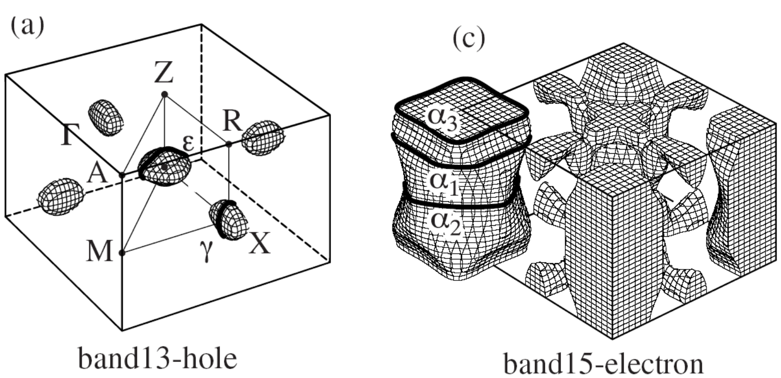
Relevance of Proposed Models

- Competing order (Hu & Seo, PRB 2006)
  - Does not explain STS data on UD-Bi2212, nor our $CeIrIn_5$ data.
- Non-Fermi liquid behavior (Shaginyan, Phys. Lett. A 2005)
  - Asymmetry is still seen in field-induced Fermi liquid regime.
- Large Seebeck effect in HF + thermal regime (Itskovich-Kulik-Shekhter, Sov. JLTP 1985): asymmetry persists in SC states.
- Energy-dependent QP scattering (Anders & Gloos, Physica B 1997)
  - Explains both reduced signal & asymmetry, but unclear origins.
- Strongly energy-dependent DOS (Nowack & Klug, LT Phys. 1992)

Two-fluid picture of heavy fermions

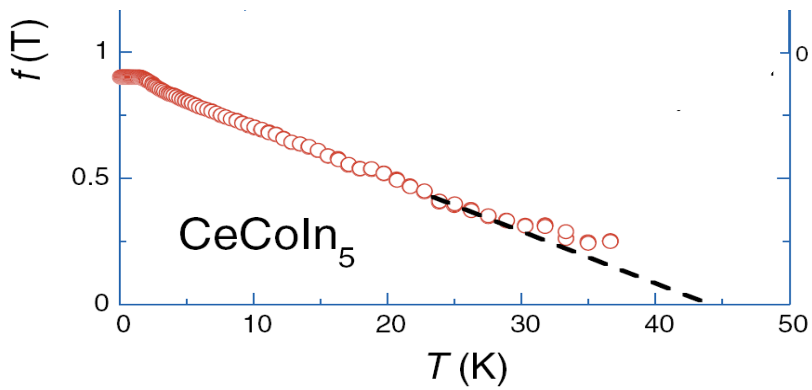


Petrovic *et al.* (2001)



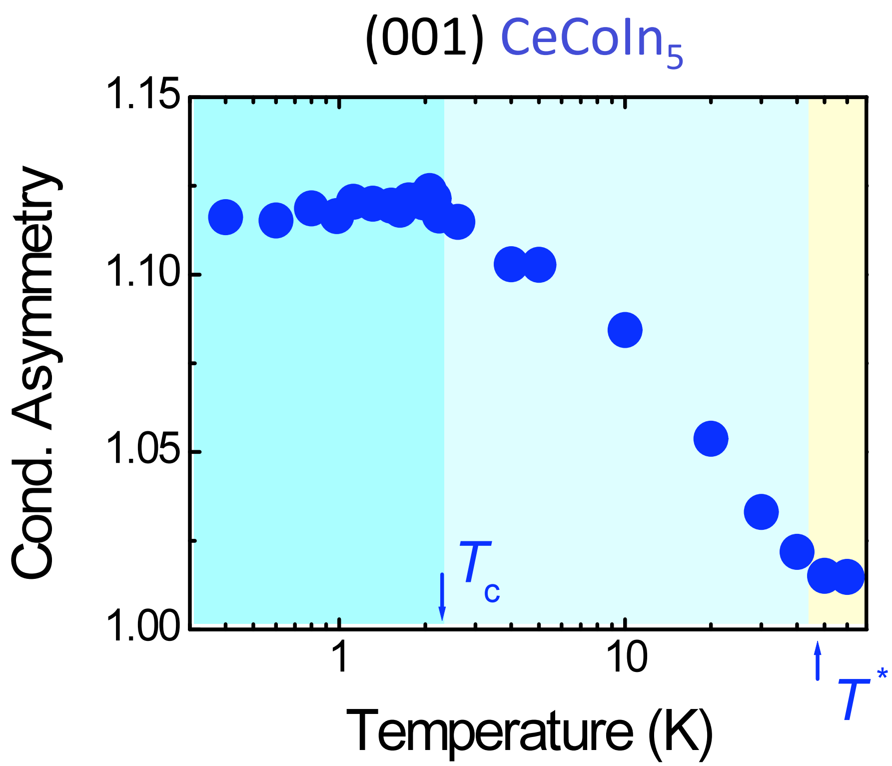
Shishido *et al.* (2002)

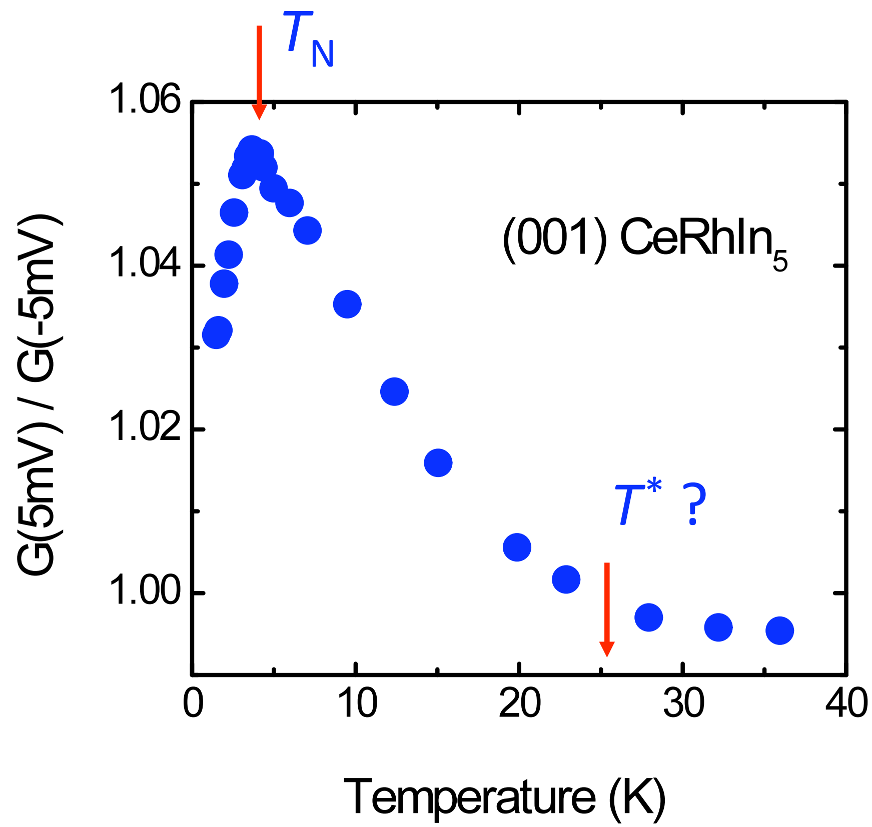
- Emerging heavy fermions in Kondo lattice systems below a coherence temperature, T^* (~ 45 K in $CeCoIn_5$).
- *f* (T) : relative weight of heavy-fermion liquid, increases with decreasing *T* and saturated below 2 K. Nakatsuji, Pines, Fisk, PRL **92**, 016401 (2004).



- This two-fluid picture appears valid in other heavy-fermion systems. Curro *et al.*, PRB **70**, 235117 (2004).
- "Heavy electrons superconduct but light electrons don't." Tanatar *et el.*, PRL **95**, 067002 (2005).

Conductance Asymmetry vs. Two-Fluid Behavior



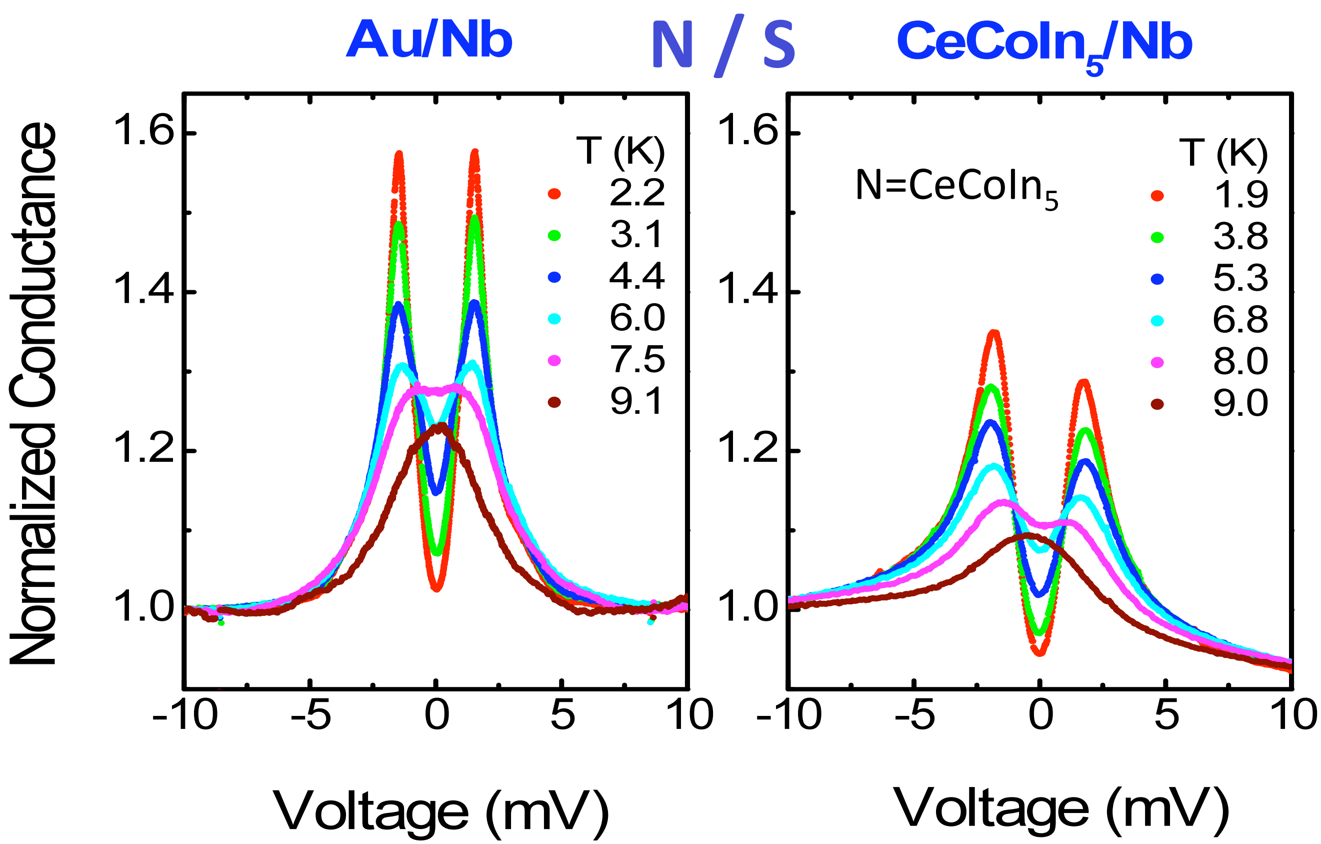


- Asymmetry follows HF spectral weight qualitatively.
- Saturation or decrease below SC or AFM transition.
- $NdRhIn_5$ (non-HF AFM) show no asymmetry.

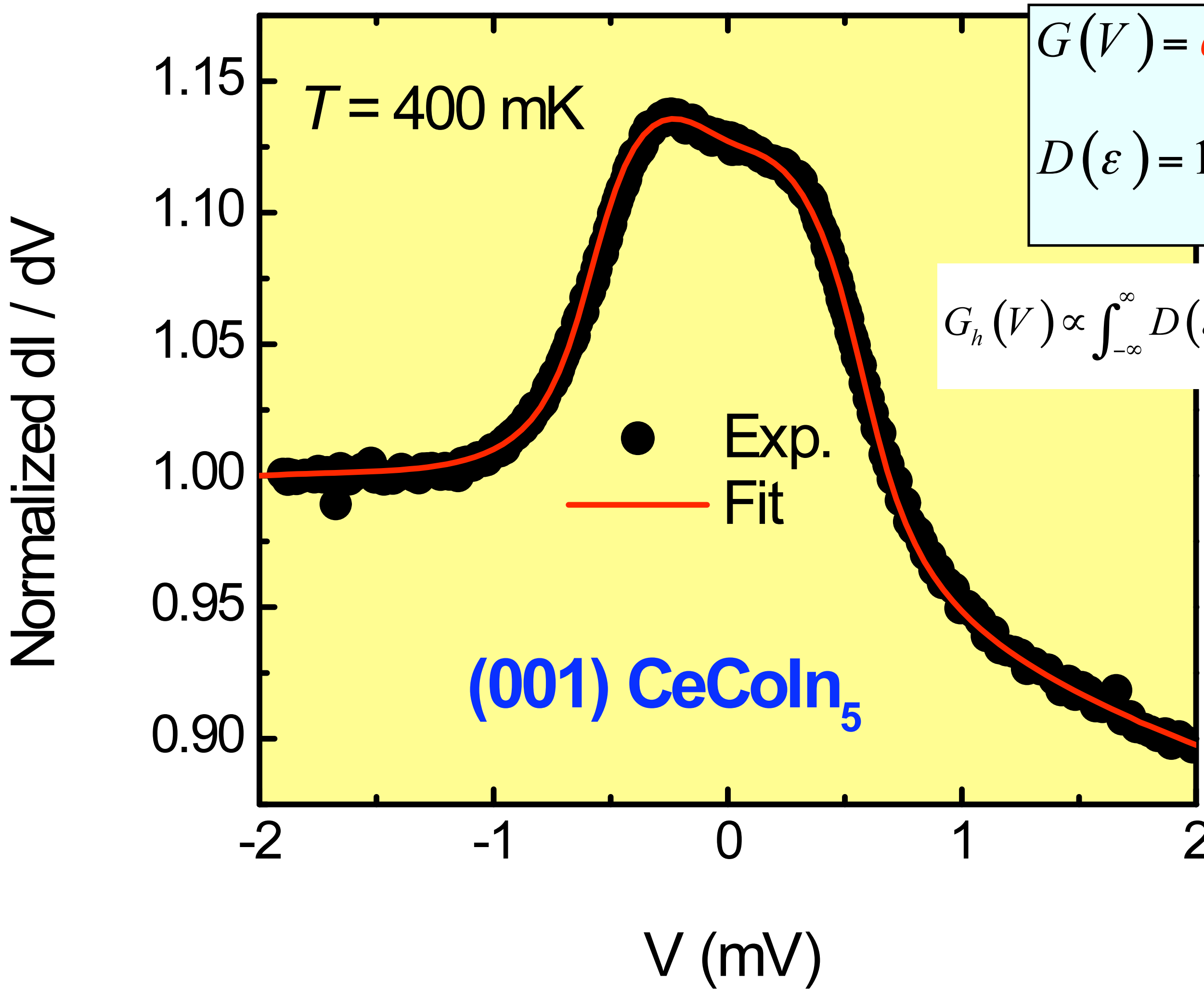
More support for 2-fluid model in $CeCoIn_5$

PCARTS for both N/S junctions of Au/Nb & $CeCoIn_5$/Nb are comparable, where there is no 2-fluid model for S Nb so all the Cooper pairs participate in the AR.

Recall for N/S Au/$CeCoIn_5$ is greatly reduced and we argue that "one of the 2 fluids does not participate in the AR"



Two-channel Model Based on Lorentzian DOS



SC heavy el.   Non-SC light el.

$$G(V) = \omega_h G_h(V) + \omega_l G_l(V)$$

$$D(\varepsilon) = 1 + \sigma \frac{\Gamma^2}{\Gamma^2 + (\varepsilon - \varepsilon_0)^2}$$

$$G_h(V) \propto \int_{-\infty}^{\infty} D(\varepsilon) \frac{\partial f(\varepsilon - eV)}{\partial (eV)} \left[1 + aa^* - bb^*\right] d\varepsilon$$

fitting parameters

ω_h = 0.51

$\sigma = 1$, $\Gamma = 5$ meV

$\varepsilon_0 = -2.1$ meV

$Z = 0.28$

$\Gamma_{\mathrm{Dynes}} = 95\ \mu\mathrm{eV}$

$\Delta = 600\ \mu\mathrm{eV}$

***cf.* 1-channel BTK fit**

$\Gamma_{\mathrm{Dynes}} = 218\ \mu\mathrm{eV}$

$\Delta = 460\ \mu\mathrm{eV}$

WKP *et al.*, PRL **100**, 177001 (2008) fitting parameters

$\omega_h = 0.51$

$\Gamma_{\text{Dynes}} = 95\ \mu\text{eV}$

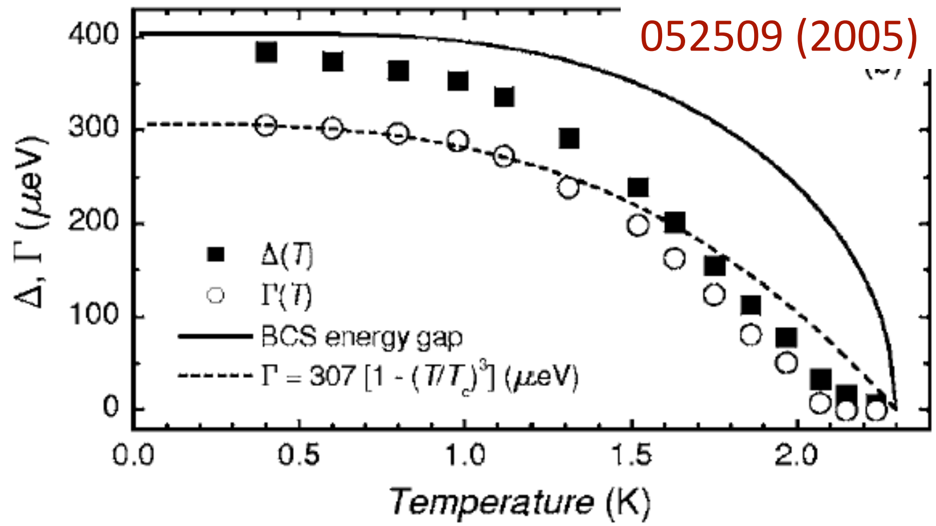
$\Delta = 600\ \mu\text{eV}$

cf. 1-channel BTK fit

$\Gamma_{\text{Dynes}} = 218\ \mu\text{eV}$

$\Delta = 460\ \mu\text{eV}$

WKP *et al.*, PRB **72**, 052509 (2005)



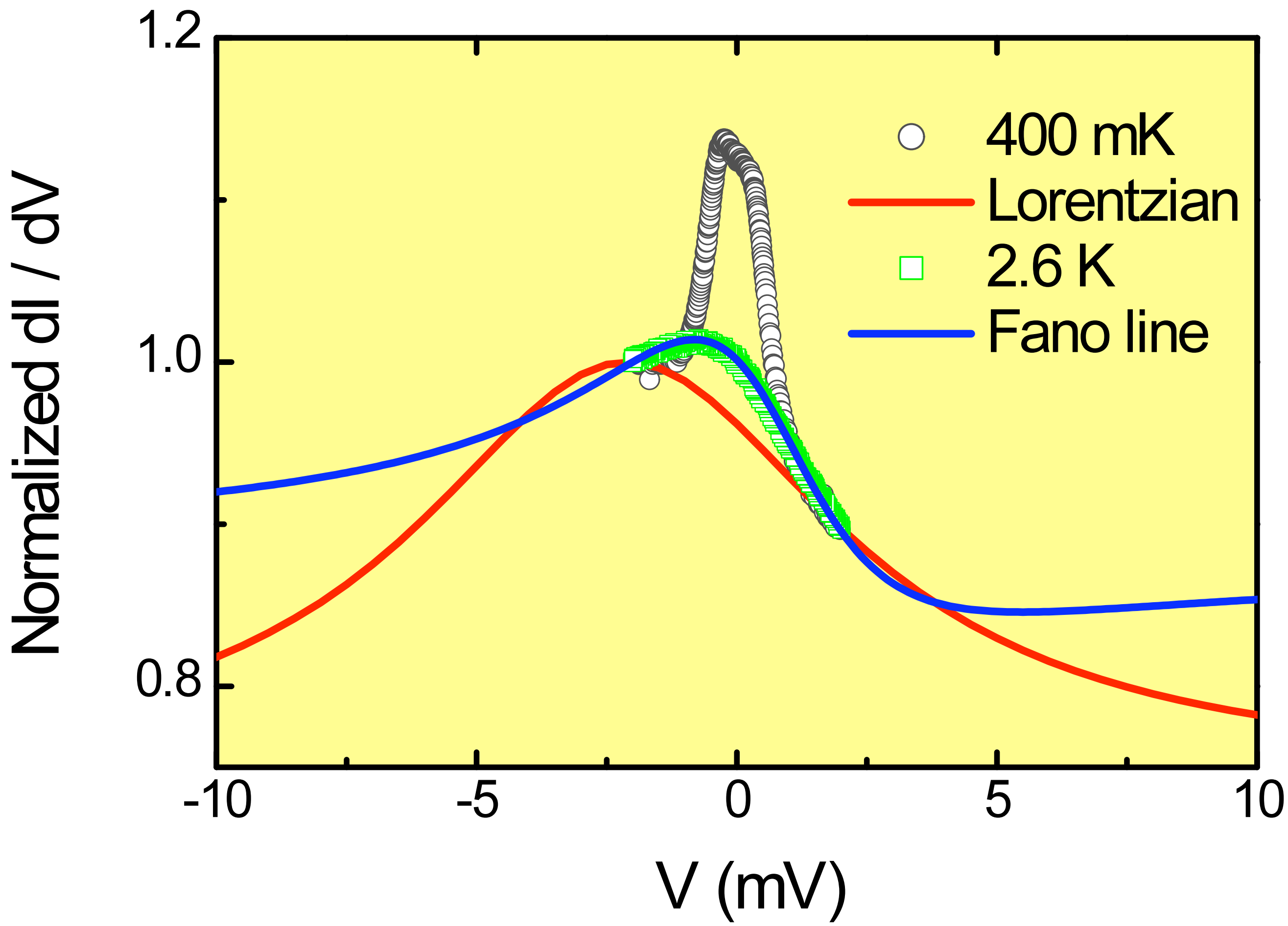
- Quality of the fit is sensitive to ω_h.

- Much smaller Γ_{Dynes} than that obtained from one-channel BTK fit → Fit does not suffer from unphysical temp. dependence of Γ_{Dynes}.

- Generality of two-fluid behavior (Curro et al., Yang & Pines) and reduced AR & cond. Asymmetry → Our model may be generally applicable to other HFS.

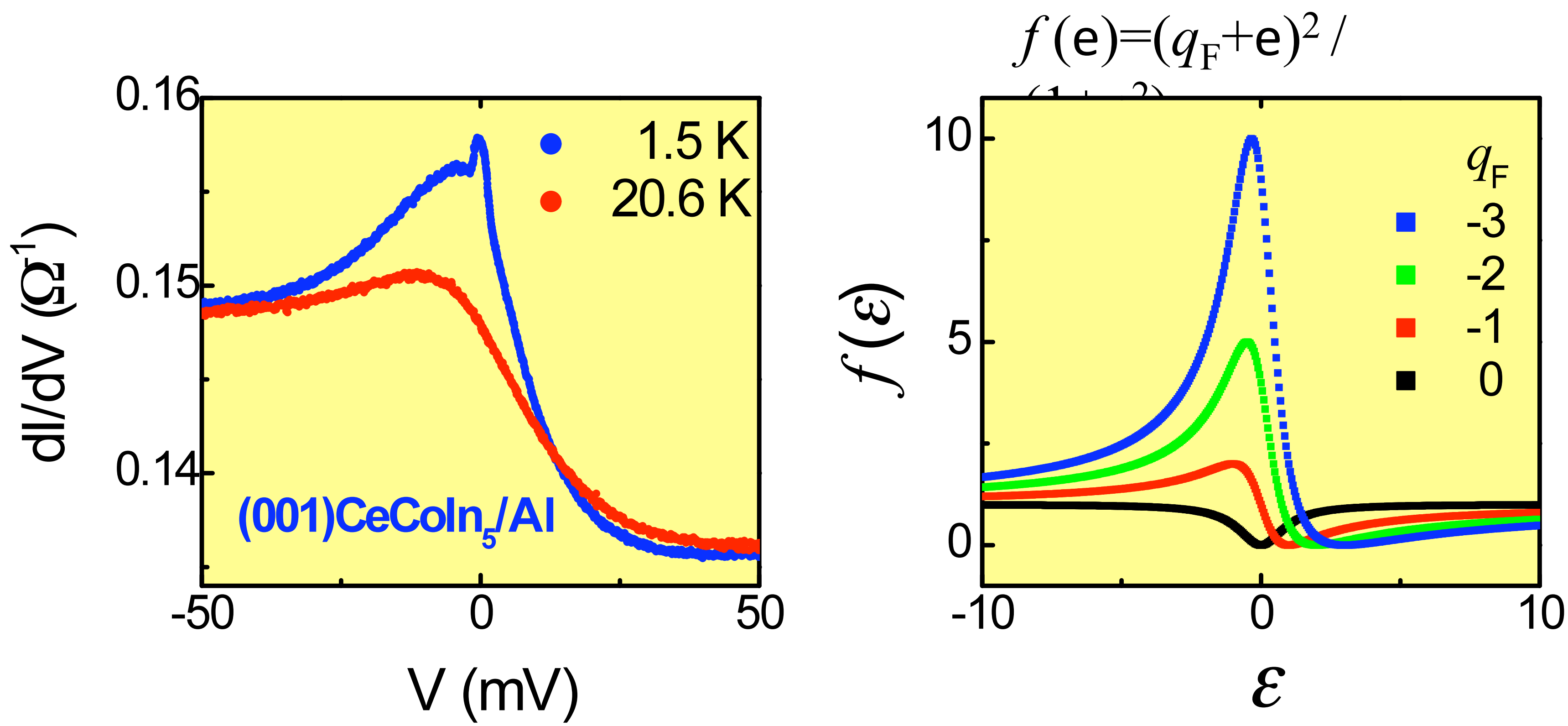
- BTK-like calculation based on two-fluid picture (Araujo & Sacramento, PRB 77, 134519 (2008)): claim both channels should be put implicitly into kernel (interference), but no account for asymmetry

High-Temperature Deviation



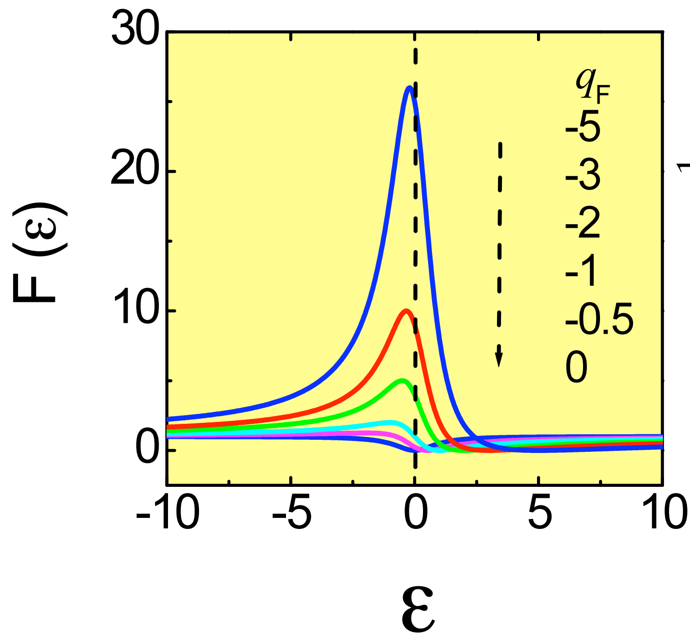
- Do not fit to a Lorentzian but to a Fano line-shape.

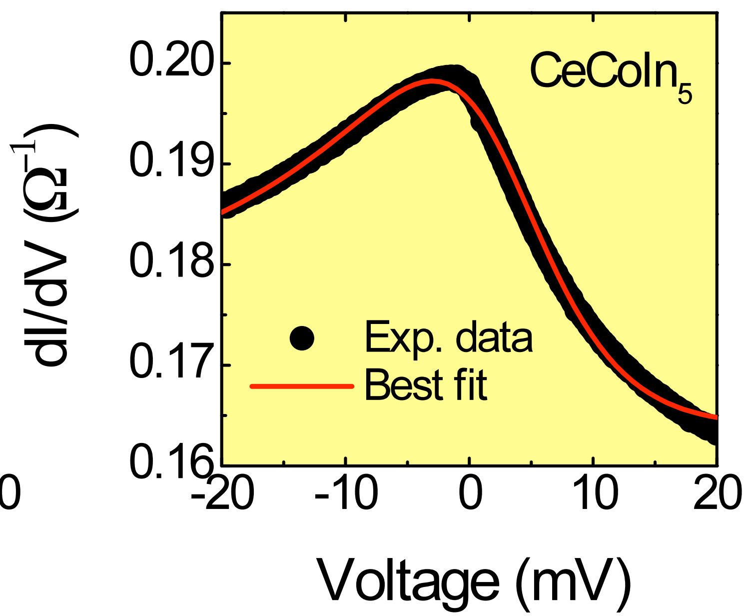
Fano Effect in Kondo Lattice?



- Conjecture: Fano interference effect between two conduction channels: heavy-electron band and conduction electron band.
- Fano factor can have negative value (interference), and peak position below Fermi level can mean the Kondo resonance above Fermi level.
- Underlying microscopic picture is being investigated, which should provide valuable insight into the Kondo lattice physics.

Conductance Model based on Fano Formula





$$F(\varepsilon) = (q_F+\varepsilon)^2 / (1+\varepsilon^2),\ \varepsilon \equiv (E-E_0)/(\Gamma/2),\ \ dI/dV = C\cdot F(\varepsilon)+G_0$$

- q_F=-2.14, E_0=2.23 meV, $\Gamma/2$=11.13 meV, C=0.0061 Ω^{-1}, G_0=0.164 Ω^{-1}
- negative q_F value - interference; positive E_0 - Kondo resonance above E_F; large G_0 - large portion is not involved in interference.
- Fano interference effect between two conduction channels, into heavy-electron band and conduction electron band.

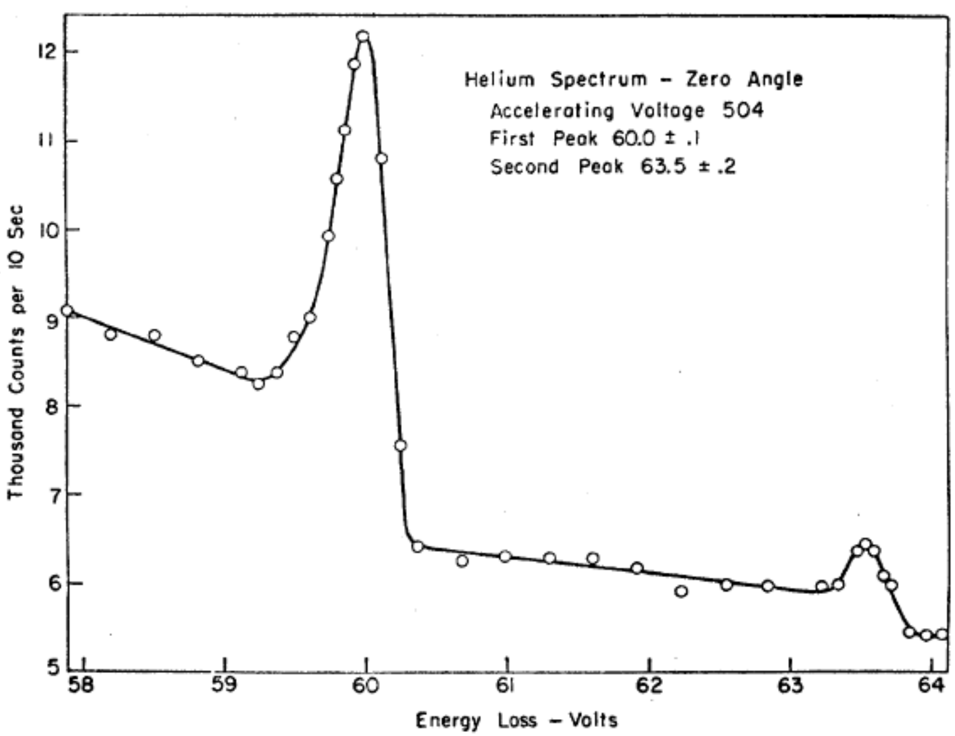
Fano Resonance

PHYSICAL REVIEW VOLUME 124, NUMBER 6 DECEMBER 15, 1961

Effects of Configuration Interaction on Intensities and Phase Shifts*

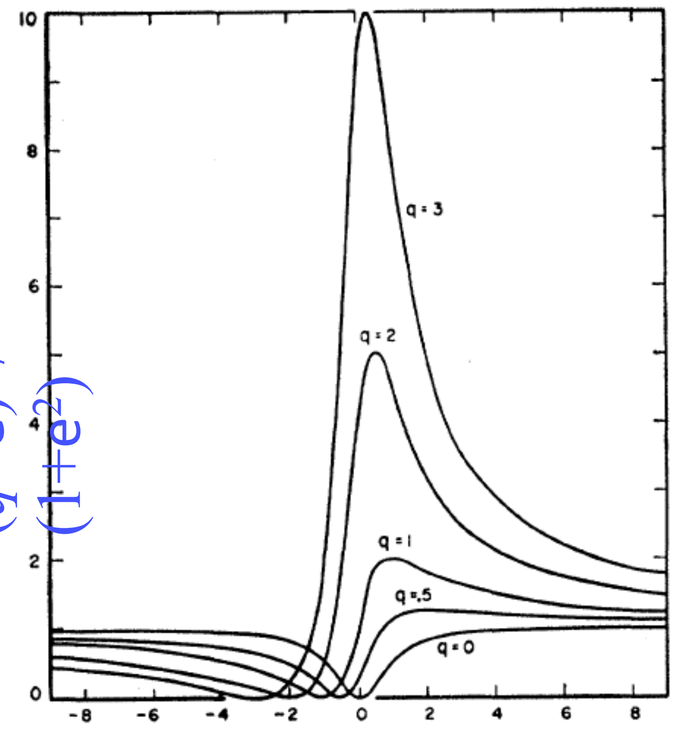
U. Fano
National Bureau of Standards, Washington, D. C.
(Received July 14, 1961)

Electron-Helium inelastic scattering



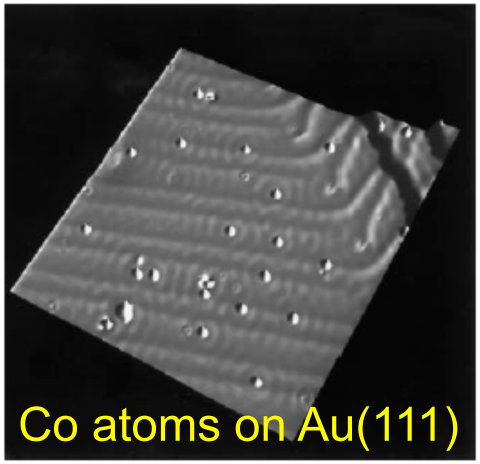
Probability ratio for transition to discrete and continuum

$(q+e)^2 / (1+e^2)$



e, relative to e_{res}

Fano / Kondo Resonance in Single Impurities



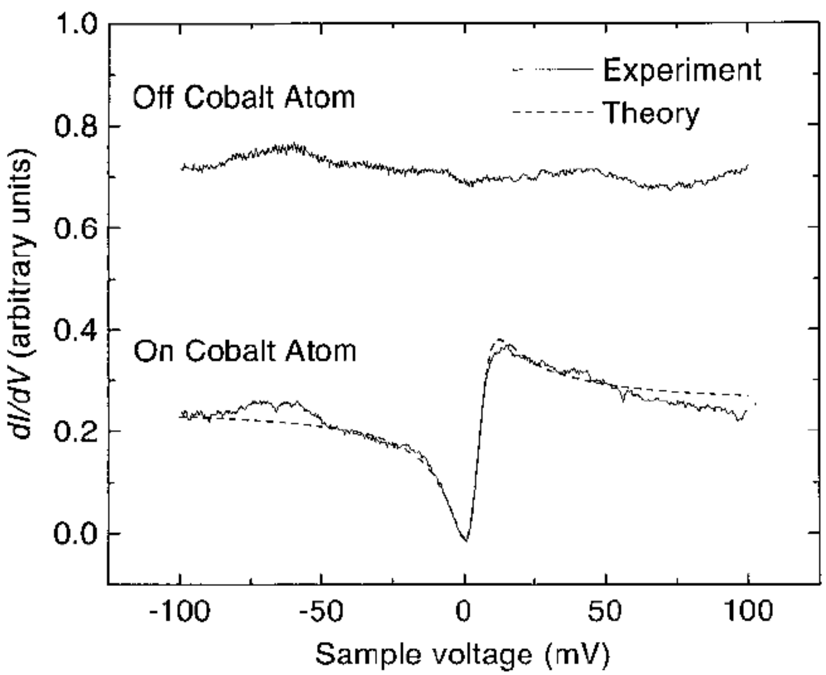
V. Madhavan et al., Science 280, 567 (1998)

$$\frac{dI}{dV}(V)=\frac{4e^2}{\hbar}\rho_{\text{tip}}\left[\pi\sum_k |\hat{M}_{tk}|^2\delta(eV-\varepsilon_k)\right]\frac{(\varepsilon'+q)^2}{1+\varepsilon'^2}+C$$

$$qe^{i\theta}=\frac{A}{B}$$

$$A(\varepsilon)=M_{at}+\sum_k M_{kt}V_{ak}P\left(\frac{1}{\varepsilon-\varepsilon_k}\right)$$

$$B(\varepsilon)=\pi\sum_k M_{kt}V_{ak}\delta(\varepsilon-\varepsilon_k).$$



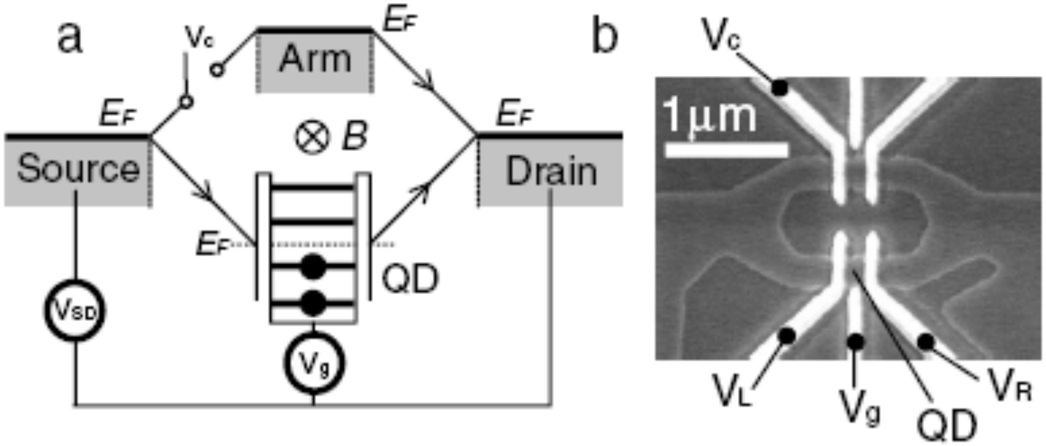
A: coupling to atomic orbital, direct or indirect via virtual transitions involving band electrons

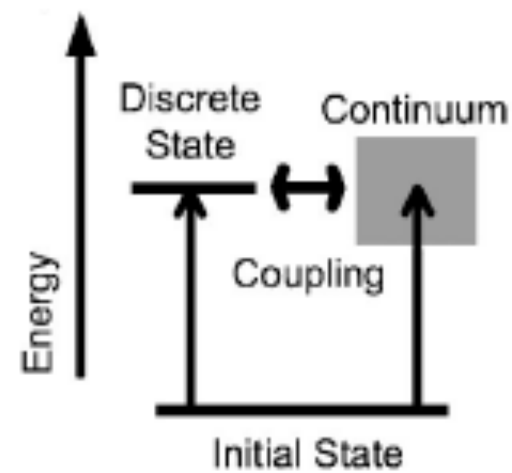
B: coupling to conduction electron continuum

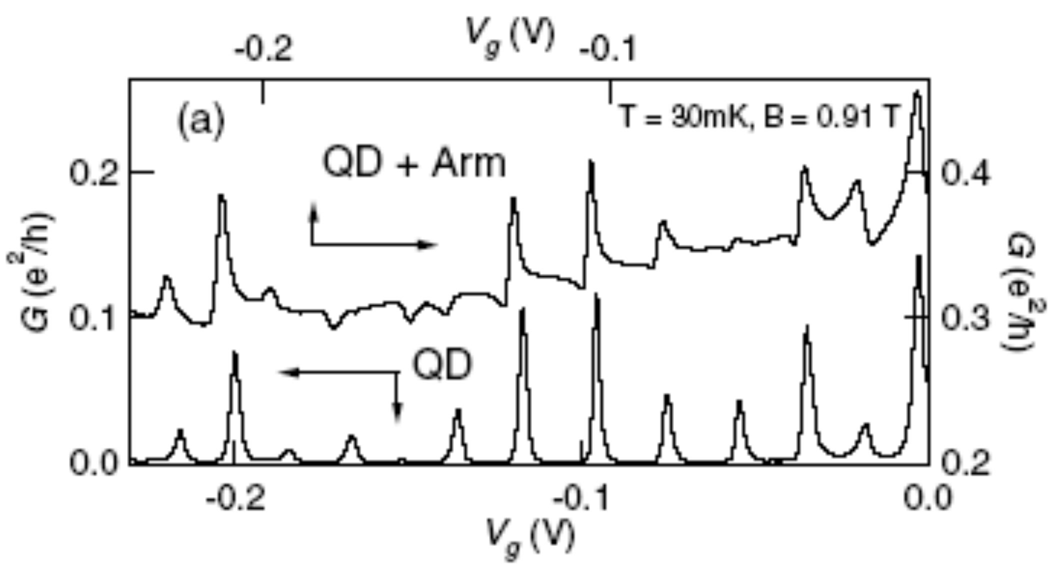
Other groups: Schneider, Eigler, Lieber, Kern, Zhao, Berndt, …

Fano Resonance in Quantum Dots

K. Kobayashi et al., PRL 88, 256806 (2002)







“The Fano effect is essentially a single-impurity problem describing how a localized state embedded in the continuum acquires itinerancy over the system.”

Conclusions

- **Strength of the PCARS method**
  - First spectroscopic demonstration of d_{x2-y2} symmetry in $CeCoIn_5$
  - Density of states effects measured! (energy-dependent DoS; peak)

- **Kondo Lattice Properties:**
  - Two-fluid model
  - Energy-dependent DoS given by a Fano resonance possibly due to the interference of the f-electrons with the conduction electrons.