The effect of quasiparticle-self-energy on $Cd_2Re_2O_7$ superconductor

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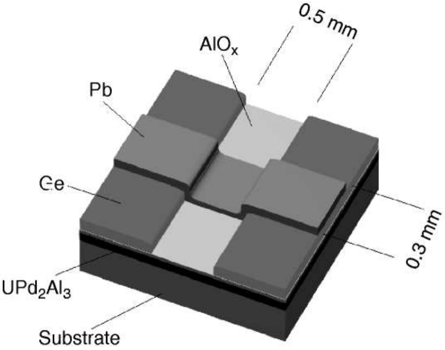
Outline

- Tunneling junction spectroscopy and point-contact spectroscopy of superconductors
- Blonder-Tinkham-Klapwijk (BTK) theory of point-contacts
- Previous attempts to include the quasiparticle lifetime effects in the BTK theory
- BTK theory with self-energy effects
- Application to point-contact spectroscopy of $Cd_2Re_2O_7$

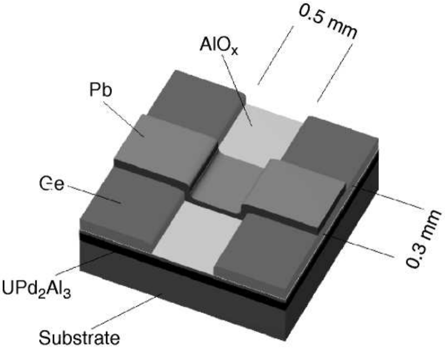
Co-Investigators

- Yousef Rohanizadegan, Brock (MSc Thesis)
- F. Razavi, M. Hajialamdari and M. Reedyk, Brock
- R. Kremer, MPI & Brock

Tunneling junction spectroscopy

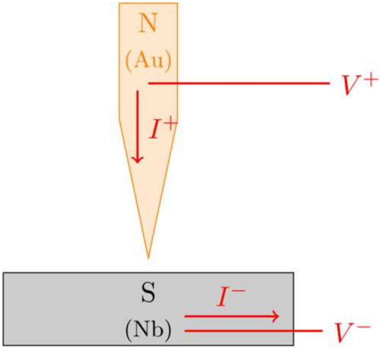


Tunneling junction spectroscopy



Problems: It is difficult to make good tunneling junctions with superconductors which have complicated structure and a short coherence length.

Point-contact spectroscopy



BTK theory

The BTK theory is based on:

1. Bogoliubov equations

$$\begin{pmatrix} -\frac{\hbar^2}{2m}\frac{d^2}{dx^2} - \mu + V(x) & \Delta \\ \Delta & \frac{\hbar^2}{2m}\frac{d^2}{dx^2} + \mu - V(x) \end{pmatrix} \begin{pmatrix} u \\ v \end{pmatrix} = i\hbar\frac{\partial}{\partial t}\begin{pmatrix} u \\ v \end{pmatrix}$$

Δ=0 in N, $\Delta \neq$0 in S

2. Demers-Griffin model for the N-S interface: $V(x) = H\delta(x)$

BTK theory

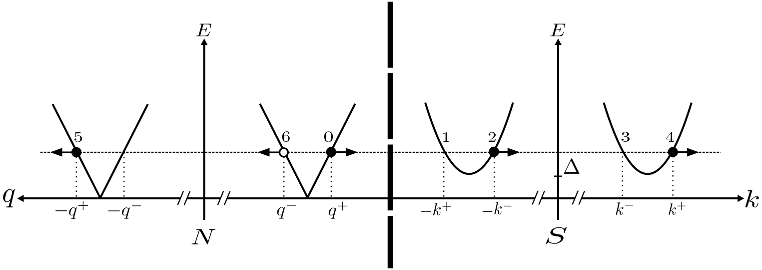
Stationary plane wave solutions $\begin{pmatrix} u(x,t) \\ v(x,t) \end{pmatrix} = \begin{pmatrix} u_0 \\ v_0 \end{pmatrix} e^{\hbar kx - Et/\hbar}$

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

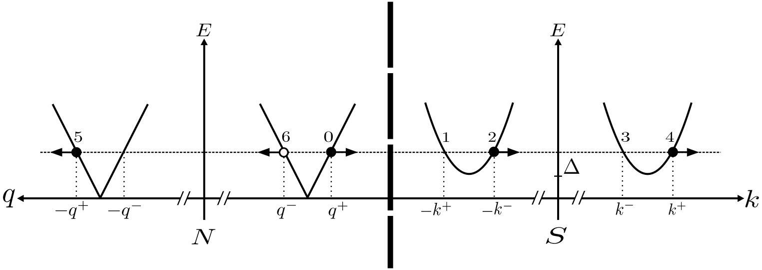
$$u_0^2 = \frac{1}{2}\left[1 + \frac{\sqrt{E^2 - \Delta^2}}{E}\right] = 1 - v_0^2$$

Density of states $N(E) = \mathrm{Re}\left[(u_0^2 - v_0^2)^{-1}\right] = \mathrm{Re}\frac{E}{\sqrt{E^2 - \Delta^2}}$

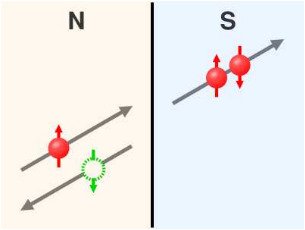
BTK theory



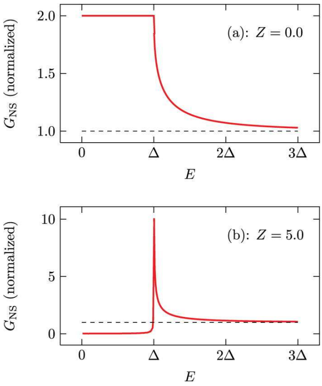
BTK theory



6: Andreev reflection



BTK theory



$$Z = \frac{H}{\hbar v_F}$$

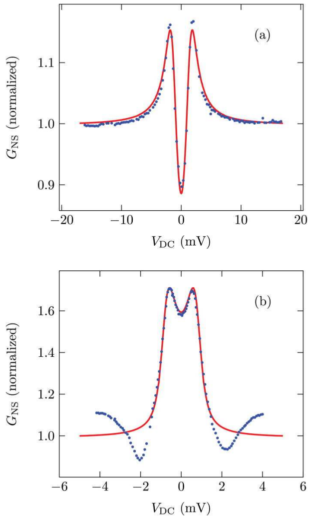
metallic contact: Z=0

tunneling regime: $Z \geq$5

$$G_{NS} = \frac{dI_{NS}}{dV} = 2N(0)ev_F\mathcal{A}\int_{-\infty}^{+\infty} dE \frac{df(E-eV)}{dV}[1 + A(E) - R(E)]$$

Fit parameters: Δ and Z

Experiments



Au-Nb point contact

(a) 10-Ω contact resistance

(b) 3-Ω contact resistance

Note: Experimental curves are broadened BTK curves

Dynes formula and phenomenological extention of the BTK theory

Dynes formula (PRL **41**, 1509 (1978)):

$$N_D(E) = \mathrm{Re}\frac{E - i\Gamma}{\sqrt{(E - i\Gamma)^2 - \Delta^2}}$$

Eliashberg theory:

$$N(E) = \mathrm{Re}\frac{E}{\sqrt{E^2 - \Delta^2(E)}}, \quad \Delta(E) = \Delta_1(E) + i\Delta_2(E)$$

Mitrović & Rosema (J. Phys.: Condens. Matter **20**, 015215 (2008)):

quasiparticle lifetime $\Gamma = -\mathrm{Im}\Delta(E = \Delta_0)$

When $\Gamma, \Delta_2 \ll \Delta$ $N_D(E)$ and $N(E)$ give nearly identical results (except near E=0). Nevertheless $N_D(E)$ is wrong!

Dynes formula and phenomenological extention of the BTK theory

Phenomenological extension of the BTK theory to include finite quasiparticle lifetime:

$$\begin{pmatrix} u(x,t) \\ v(x,t) \end{pmatrix} = \begin{pmatrix} u_0 \\ v_0 \end{pmatrix} e^{\hbar kx-(E-i\Gamma)t/\hbar}$$

The resulting theory is identical to the BTK theory but with the density of states given by the Dynes formula.

Fit parameters: Δ, Z and Γ

(Plecenník et al., PRB **49**, 10016 (1994); de Wilde et al., Physica B **218**, 165 (1996))

BTK theory with self-energy in S

McMillan, Phys. Rev. **175**, 559 (1968): Eliashberg version of Bogoliubov Equations

$$\{[-\frac{\hbar^2}{2m}\frac{d^2}{dx^2} - \mu]\tau_3 + \Sigma(x,E)\} \begin{pmatrix} u(x,E) \\ v(x,E) \end{pmatrix} = E \begin{pmatrix} u(x,E) \\ v(x,E) \end{pmatrix}$$

$$\Sigma(x,E) = (1 - z(x,E))\tau_0 + \phi(x,E)\tau_1 \ , \quad \Delta(x,E) = \frac{\phi(x,E)}{z(x,E)}$$

BTK theory with self-energy in S

The resulting theory is identical to the BTK theory but with complex and energy dependent gap $\Delta(E)$

$$G_{NS} = \frac{dI_{NS}}{dV} = 2N(0)ev_F\mathcal{A}\int_{-\infty}^{+\infty} dE\frac{df(E-eV)}{dV}[1+A(E)-R(E)]$$

$$\begin{aligned}
A(E) &= \frac{|u|^2|v|^2}{|\gamma|^2} \\
R(E) &= \frac{[|u|^4+|v|^4-2\,\mathrm{Re}(u^2v^2)]z^2(z^2+1)}{|\gamma|^2} \\
\gamma &= u^2+(u^2-v^2)z^2 \\
u &= \frac{1}{\sqrt{2}}\sqrt{1+\sqrt{E^2-\Delta^2(E)}/E} \\
v &= \frac{1}{\sqrt{2}}\sqrt{1-\sqrt{E^2-\Delta^2(E)}/E}\,.
\end{aligned}$$

(Y. Rohanizadegan, MSc. Thesis, Brock University (2013))

BTK theory with self-energy in S

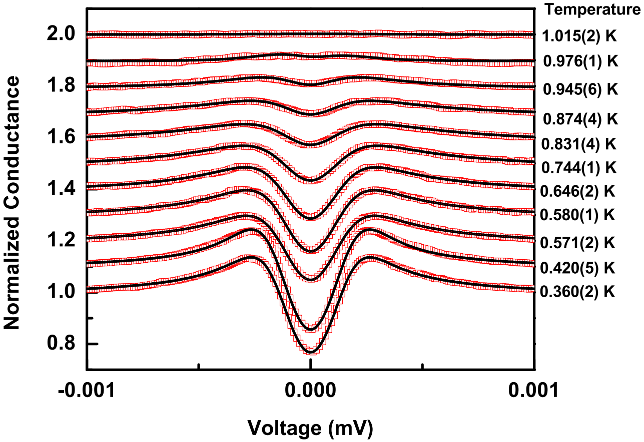
For the energies close to the gap edge Δ the fit parameters are:

Δ, Z and Δ_2–the imaginary part of gap at the gap edge

Note: The temperature enters via Δ and Δ_2

Application to $Cd_2Re_2O_7$

Razavi, Rohanizadegan, Hajialamdari, Reedyk, Kremer, and Mitrović, Canadian Journal of Physics, 2015, **93**(12), pp. 1646-1650 – **Canadian Journal of Physics Best Paper Award, 2015**.

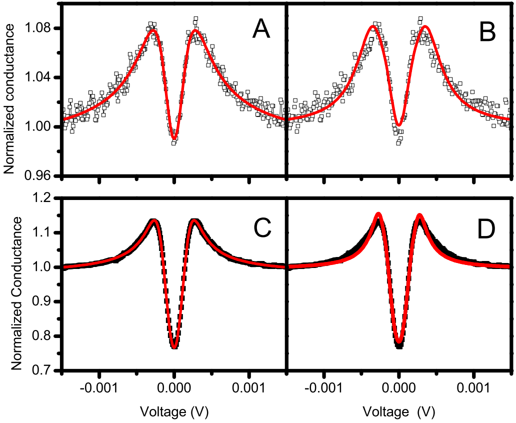


Application to $Cd_2Re_2O_7$

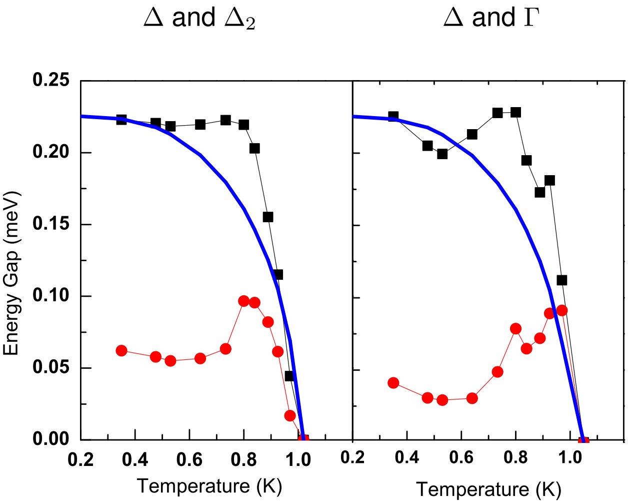
Fits:

T=0.831 K: A–with Δ_2, B–with Γ

T=0.360 K: C–with Δ_2, D–with Γ



Application to $Cd_2Re_2O_7$



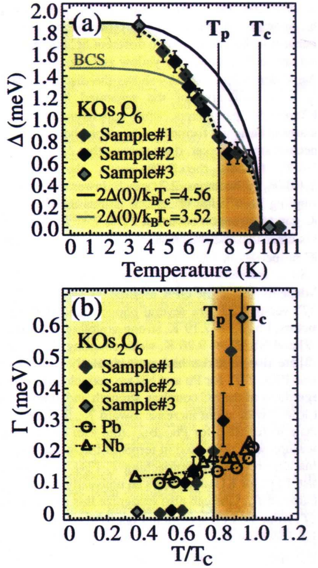
$$\frac{2\Delta}{k_B T_c} = 5.0(1) \qquad T_c = 1.02 \text{ K}$$

KOs_2O_6 (Photoemission Spectroscopy)

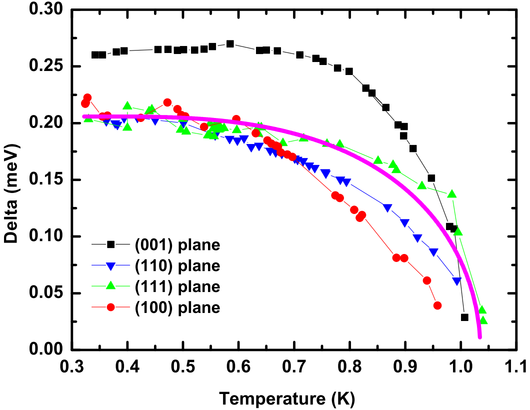
Shimojima et al. PRL **99**, 117003 (2007), using Dynes formula:

$$\frac{2\Delta}{k_B T_c} \geq 4.56$$

T_c=9.6 K



$\Delta(T)$ of $Cd_2Re_2O_7$ for different crystallographic planes



The solid line is the BCS prediction with measured T_c and $\Delta(0)$.

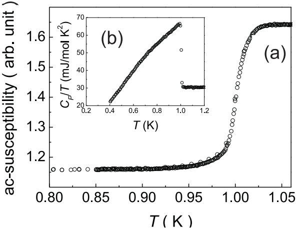
Comparison with other experiments

Specific heat:

Hiroi & Hanawa, J. Phys. Chem. Solids **63**, 1021 (2002):

$$\frac{\gamma \text{exp}}{\gamma \text{band}} = 2.63 \Rightarrow \lambda = 1.63$$

Razavi et al., CJP **93**, 1646 (2015)



$$\frac{\Delta C_e}{\gamma T_c} = 1.15 < \text{the BCS value of } 1.43$$

$\Downarrow$

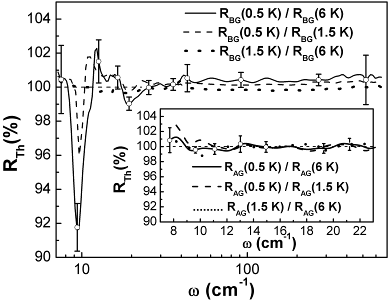
anisotropic/multiband supercond. (?)

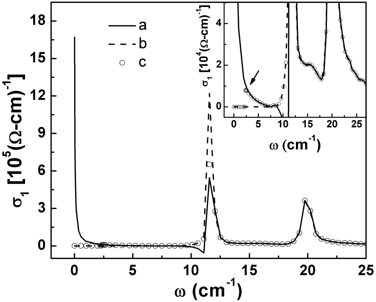
Note:
There is a kink at $T = 80\ \%\ T_c$!

Comparison with other experiments

Far-IR:

Hajialamdari et al., J. Phys.: Condens. Matter **24**, 505701 (2012)





New peaks appear in the superconducting state at T =0.5 K ($<$ 0.8 K)!

Possible scenario

There is a structural transition in $Cd_2Re_2O_7$ below T_c (at 0.8 K) similar to the transition in KOs_2O_6. The new low frequency phonon modes appear which couple strongly to the electrons leading to a large low temperature Δ.