Intrinsic tunnelling data for Bi-2212 mesa structures and implications for other properties.

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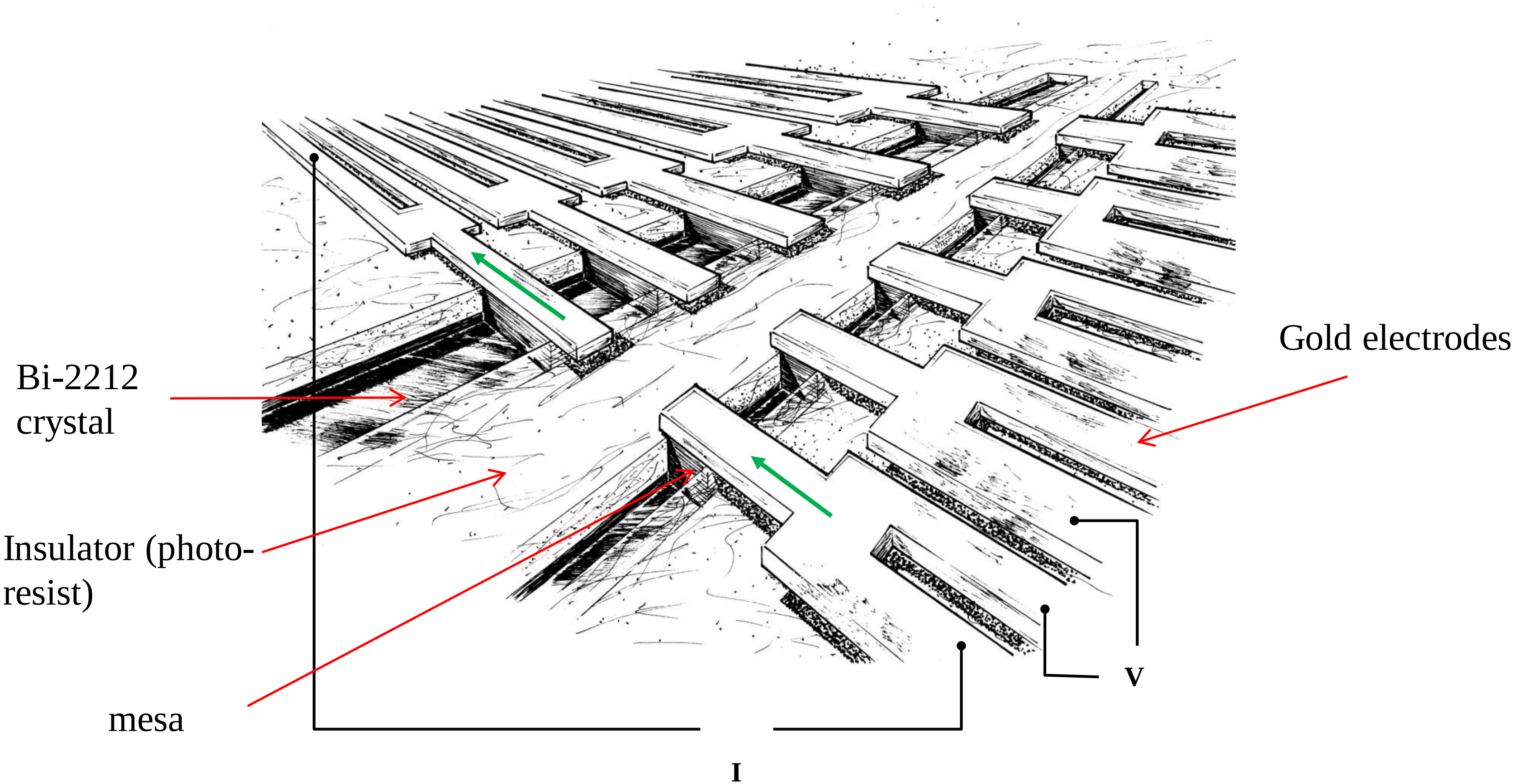
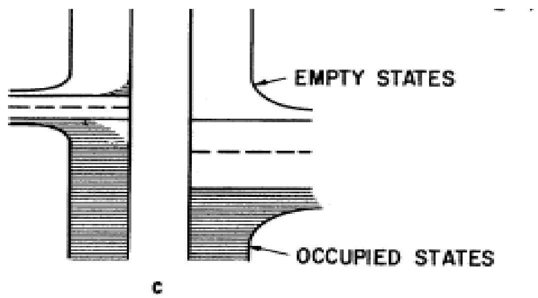


Multi-step process using photo-lithography and wet chemical etching

Measure *I* vs. *V* and *dI/dV* vs. *V*

Details given in T.M. Benseman PhD thesis. University of Cambridge 2007.

Original motivation: look for structure in *dI/dV* vs. *V* above gap edge which could be associated with the pairing boson.
E.g., McMillan and Rowell in the 1960’s for Pb. Phonon density of states from neutron scattering and analysis using Eliashberg theory.
Provides the clearest evidence for superconductivity induced by electron-phonon coupling in classical superconductors.

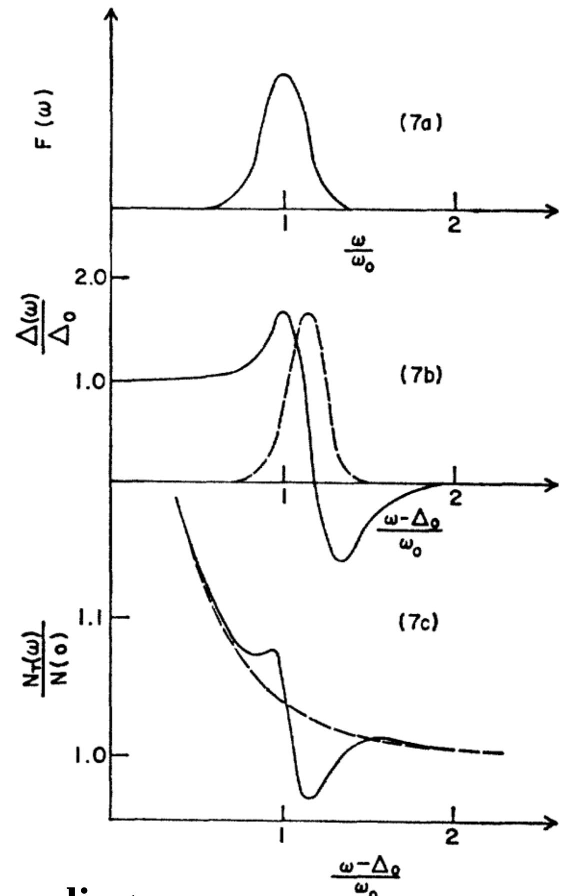


$$I = C_N \int_{-\infty}^{\infty} \rho(E)\rho(E+V)[f(E) - f(E+V)]dE,$$

$$\rho(E) = \mathrm{Re}[|E|/(E^2 - \Delta^2)^{1/2}]$$

$$\rho(E,\Gamma) = (E - i\Gamma)/[(E - i\Gamma)^2 - \Delta^2]^{1/2},$$

Dynes formula Γ is quasi-particle recombination rate or inverse lifetime – valid for $|E| \leq \Delta$



DOS single Boson mode

Energy dependent complex gap parameter

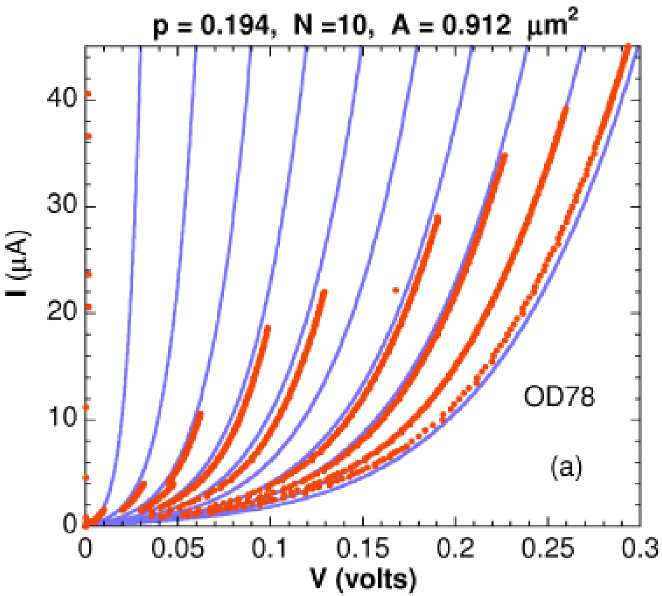
Structure in quasi-particle DOS

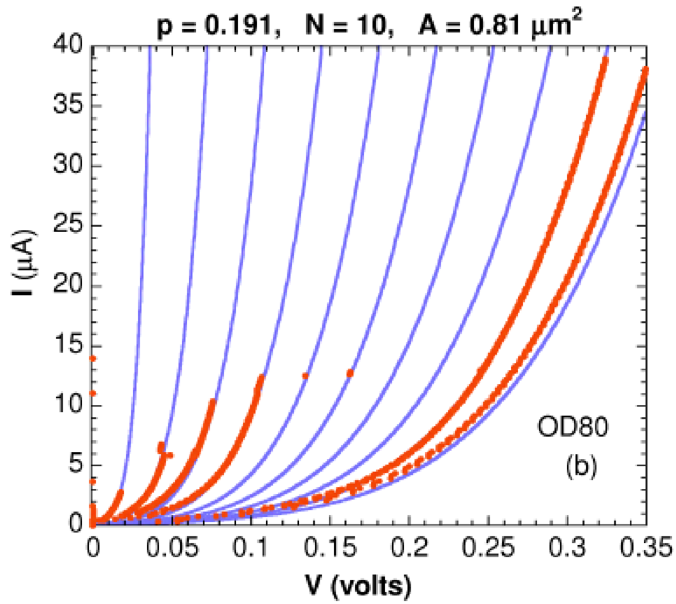
Important concept for classical strong-coupling s/cs: Virtual el-phonon processes give pairing, real inelastic el-phonon scattering is pair-breaking.

Preprint -T.M. Benseman, JRC and G. Balakrishnan - arXiv:1503.00335v2 [cond-mat.supr-con] 16 Mar 2015
Do see "dip-hump" structure above gap edge (previously seen via STM -Davis group and "break junction" tunnelling, Mandrus et al. and Zasadzinski group) and a further dip at higher voltages. Hope this will be analysed by theorists* using Eliashberg – type theory and candidate pairing bosons, especially the "*S*=1" resonance excitation seen by neutron scattering (see e.g. M. Eschrig, Adv. Phys. 55, 47-183, 2007)
Surprising new results: Structure rapidly washed out both by magnetic fields // c axis and with increasing temperature.
Here will focus more on evidence for pair-breaking by comparing measured data at various temperatures with data taken at 1.4 K that have been "thermally broadened" numerically. Procedure also suggests that low energy bosons may be more important than previously thought.

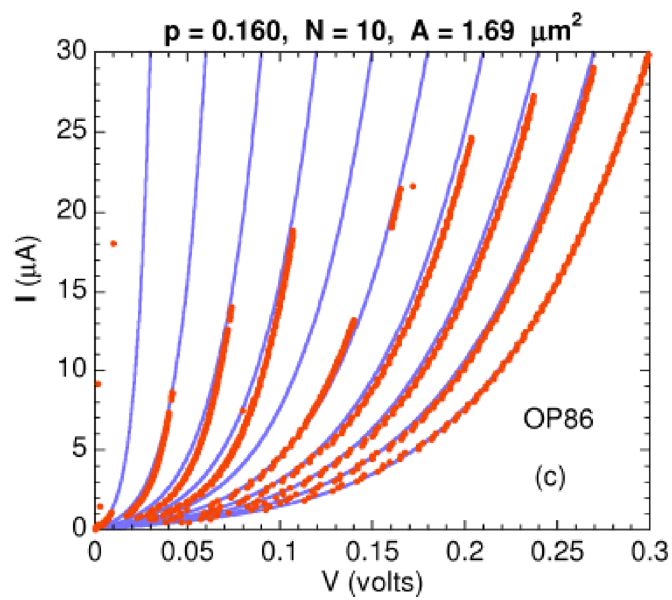
*More complicated
- d-wave gap varies around FS
- SIS analysis not as straightforward as SIN
- Probable conservation of in-plane momentum ($\mathbf{k}_{//}$)
- Variation of inter-plane hopping matrix element with $\mathbf{k}_{//}$
- Pseudogap for p<0.19
- Residual DOS of unknown origin

But
Planar geometry (cf. break junction and STM)
Bulk probe (cf. STM and ARPES)
Measurements of field and temperature dependence relatively straightforward

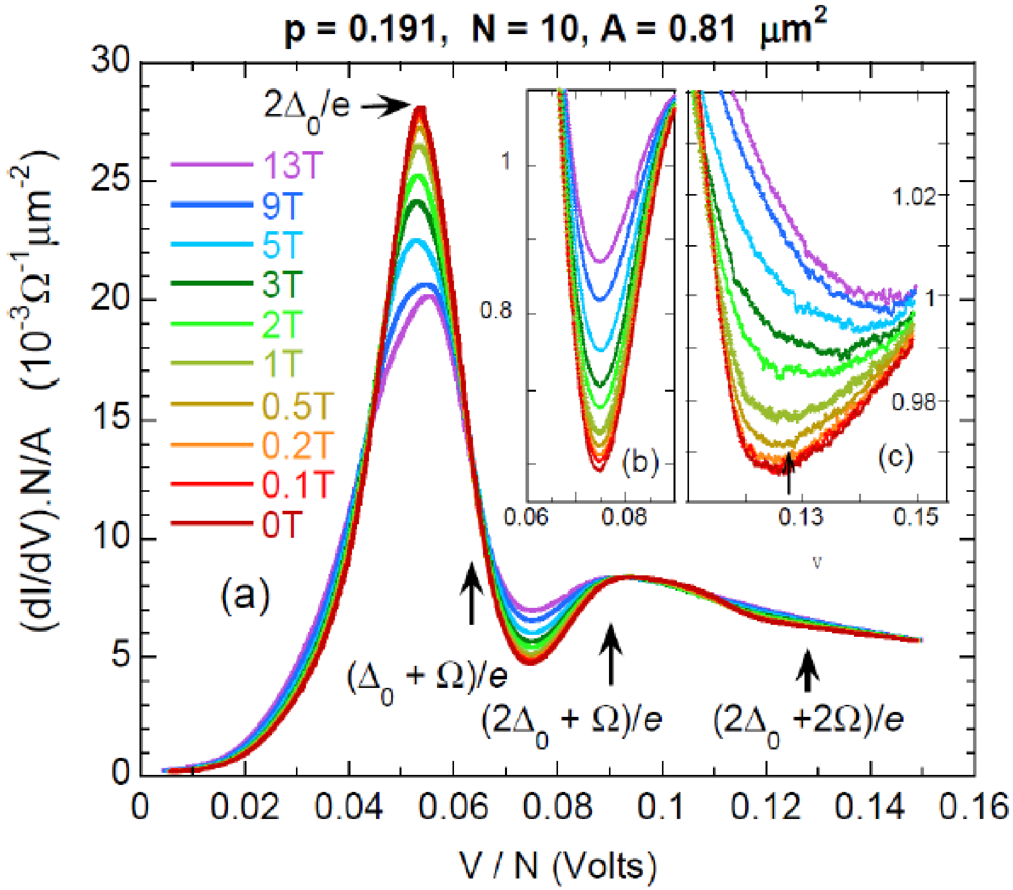




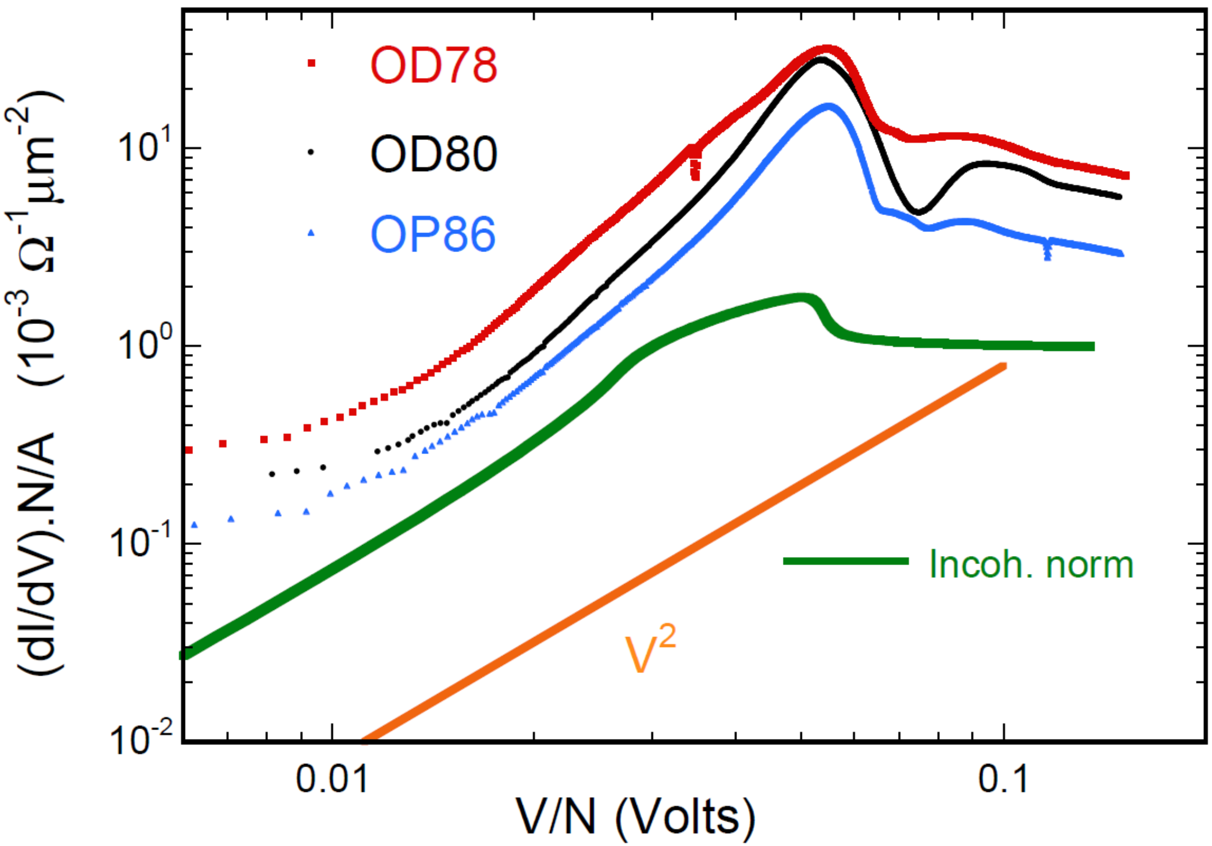
Typically 10 *S*-*I*-*S* junctions in series. Suppress Josephson effects by taking data on downward current sweeps. When there is a non-zero voltage across an *S*-*I*-*S* junction average Josephson current is zero.



I-*V* curves for 3 mesas. Red points data taken while sweeping *I* up, then down to a finite value after a "switch", and up again until finally the right hand red curve is obtained. Blue curves show the same polynomial fitted to the (N-1) th curve and then scaled by n/(N-1) where n<=N and N are integers. *dI/dV* data are taken on downward *I* sweep (to suppress Josephson currents) using a modulation method.



dI/dV at 1.4 K for mesa OD80 with various fields applied perpendicular to the CuO_2 planes. Ω is energy of *S*=1 resonant excitation ($5.4k_BT_c$). For s-wave incoherent *SIS* tunnelling would expect structure at $2\Delta_0 + \Omega$ and possibly also at $2\Delta_0 + 2\Omega$

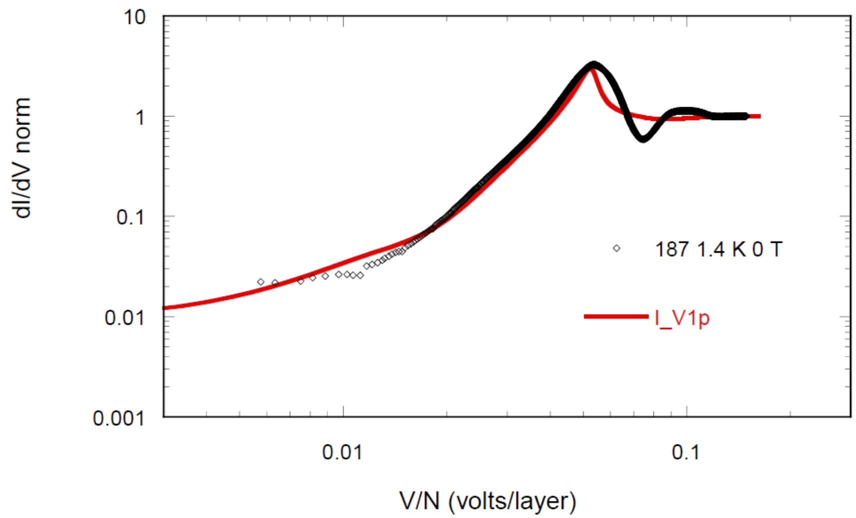


OD78
OD80
OP86
Incoh. norm
V^2
$(dI/dV).N/A \quad (10^{-3}\ \Omega^{-1}\mu m^{-2})$
10^1
10^0
10^{-1}
10^{-2}
0.01
0.1
V/N (Volts)

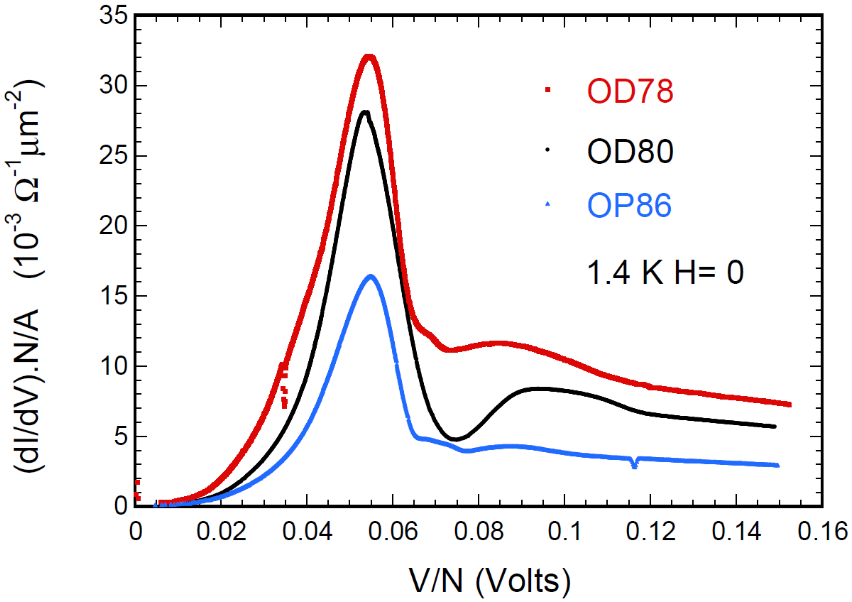
$$I(V) = \int_0^{2\pi}\int_0^{2\pi}\int_{-\infty}^{\infty} M_{\theta_1\theta_2}^2 N(E,\theta_1)\, N(E-eV,\theta_2)\,[f(E-eV)-f(E)]\, dE d\theta_1 d\theta_2$$

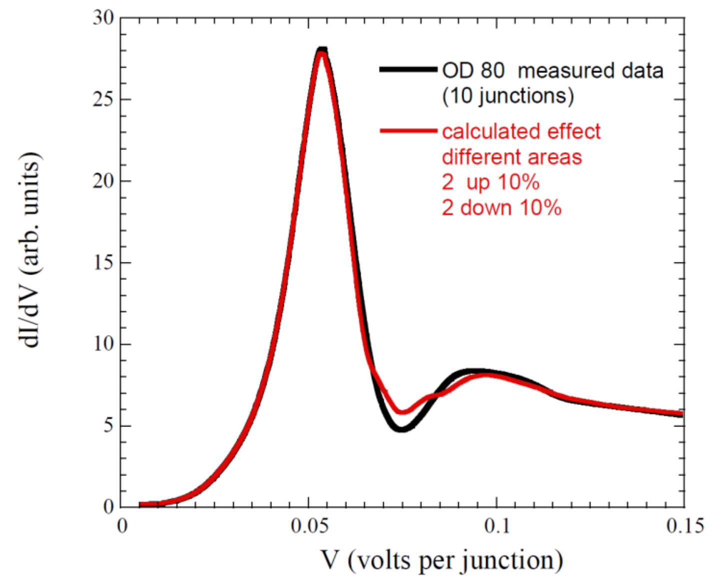
Incoherent, M^2 independent of θ do not worry about *k//* conservation (as in classical tunnel junctions)

Coherent, k// conserved $M^2 = C\delta(\theta_1 - \theta_2)/2\pi$
Also possibility of extra $sin^2(2\theta)$ *or* $sin^4(2\theta)$ term from angular dependence of t_c



Large amount of *k//* conservation

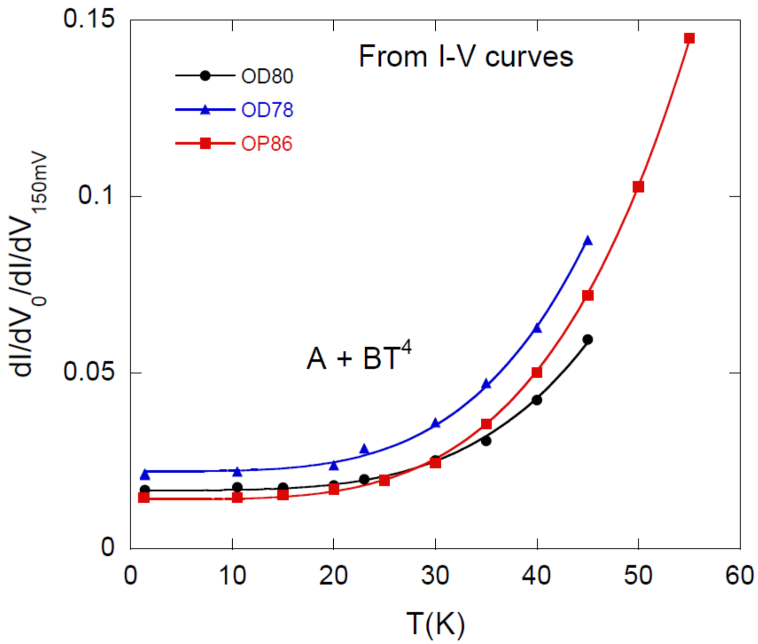


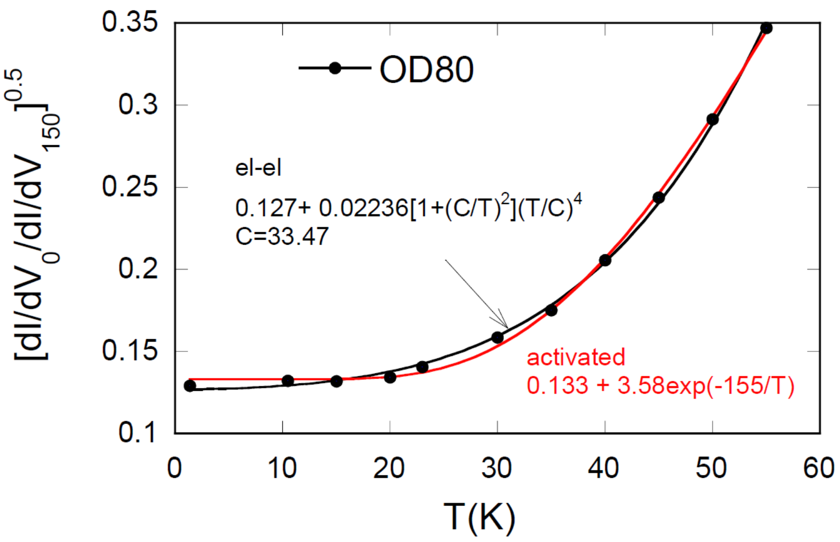


Reason for lack of reproducibility of dip-hump structure from one mesa to the next?

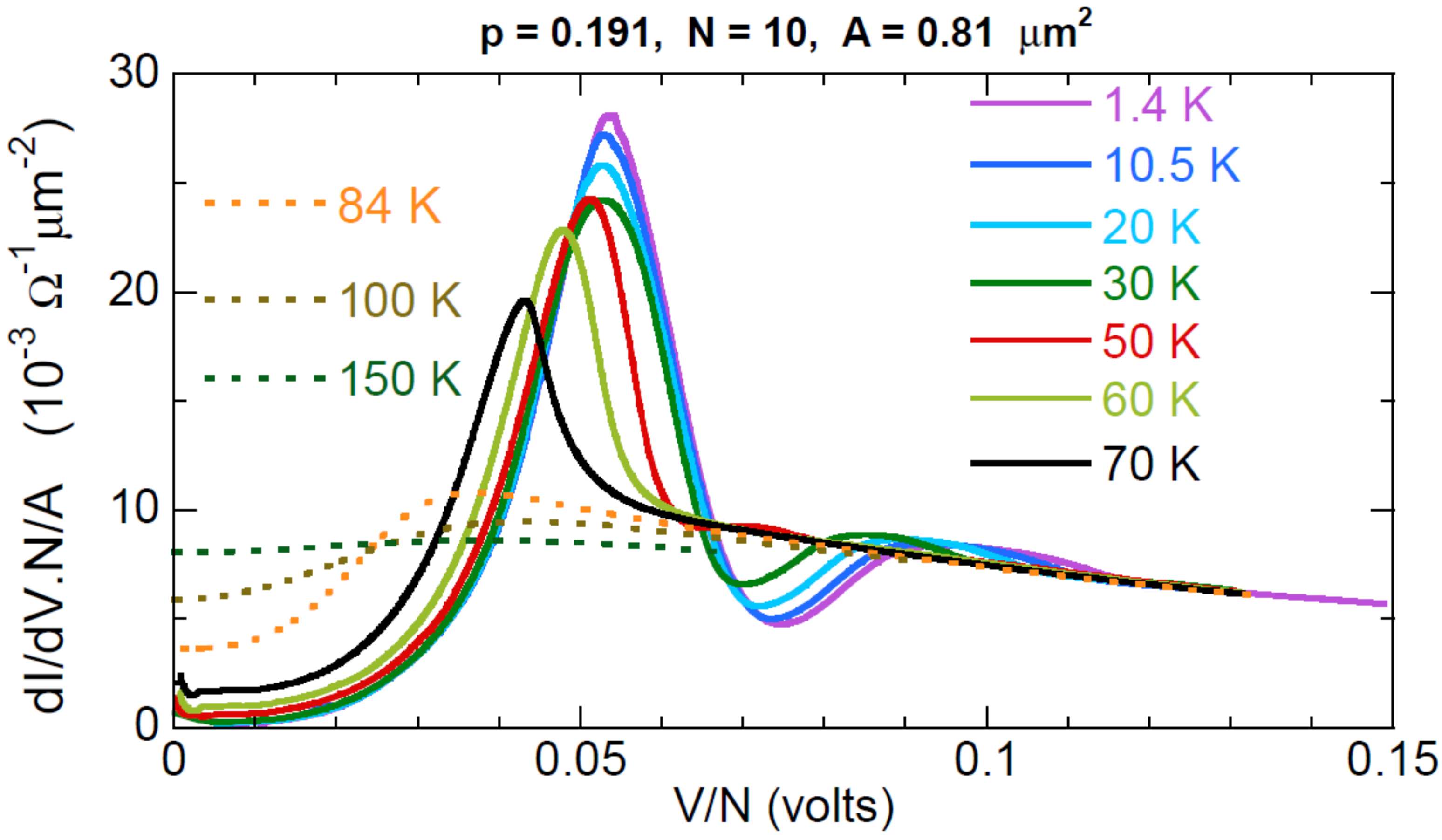
Non-uniformity of effective junction areas Or equivalently their resistance - very dependent on doping level *p*.

Analyse low voltage behaviour by differentiating *I(V)* curves – in preprint had small "jumps" in dI/dV_{AC} caused by Josephson currents.
Normalised values $(dI/dV_{V\to 0})/(dI/dV_{150\ mV})$ reproducible.
Simple model goes as $N_{res}(E_F)^2$. For s/c (Dynes formula) $N_{res}(E_F)$ ~ scattering rate Γ.

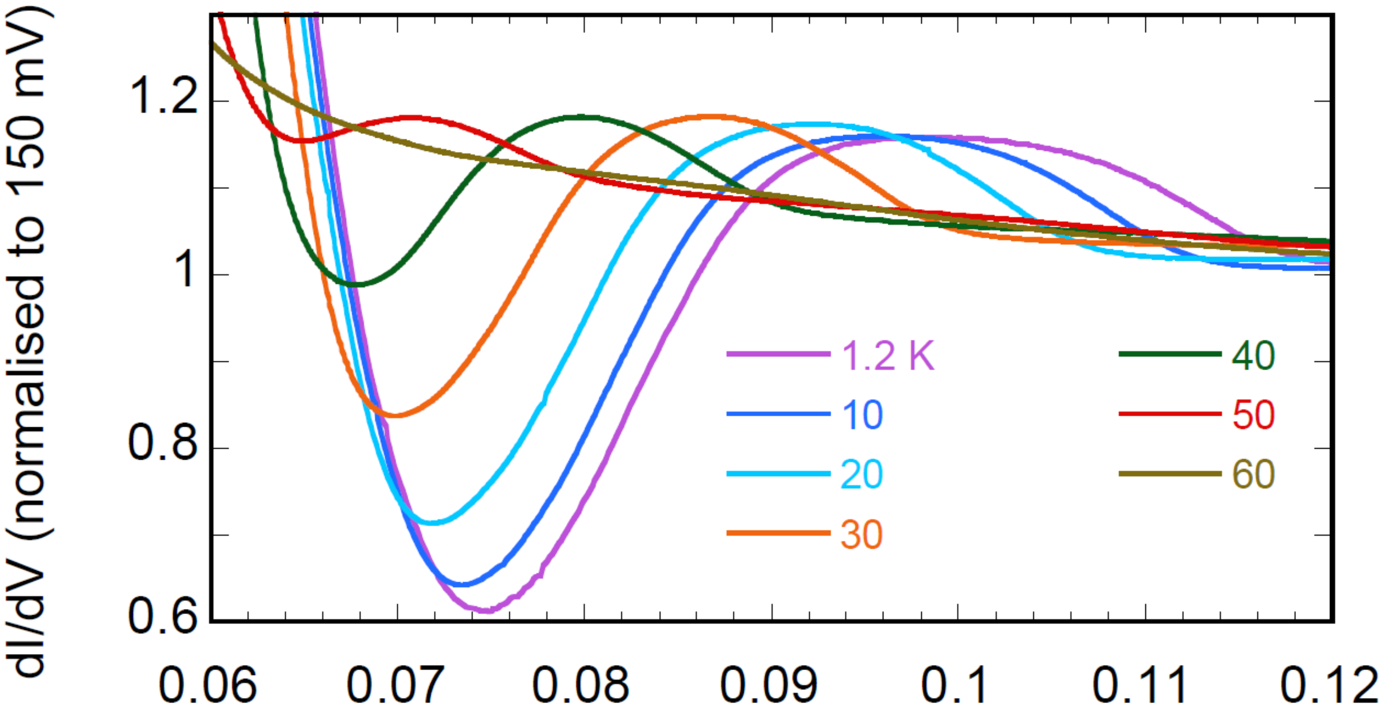




For 3 mesas find $N_{res}(E_F)/N_{norm}(E_F) = 0.132 \pm 0.015$ – agrees well with $(C/T)_{res}/\ (C/T)_{norm} = 0.14$ (A. Junod's group).
H dependence may help decide whether low lying states are near nodes or in other regions of k- space.
If $N(E)$ ~ const., el-el scattering rate ~ T^2, if $N(E)$ ~ E, el-el scattering rate ~ T^4.



dI/dV at selected temperatures for OD80.

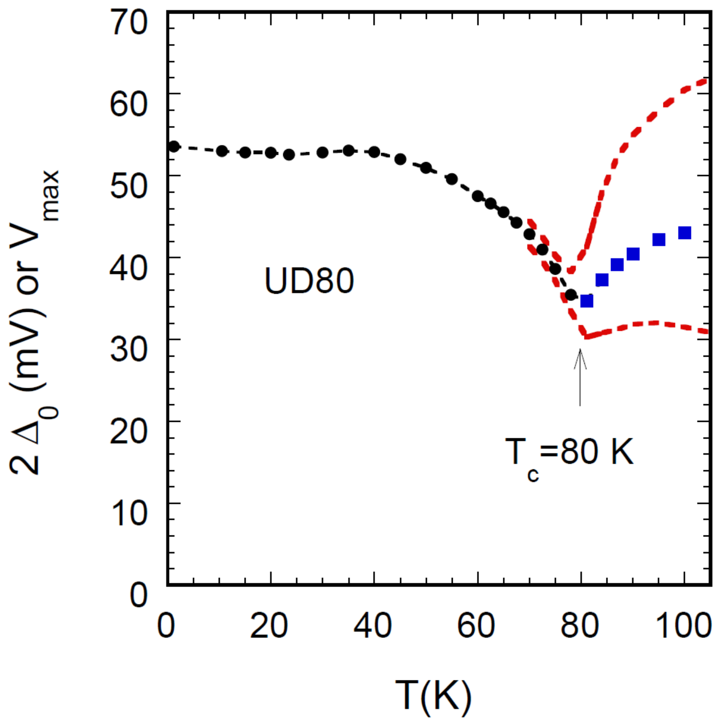


Zoom of data above gap edge for OD80.

Evolution with *T* between 1.4 and 10 K rules out both "trivial" heating, which depends on area of mesas, <u>and</u> possible electron heating effects which could be present even in the smallest mesas.

Strong shift to lower voltages as *T* is increased.

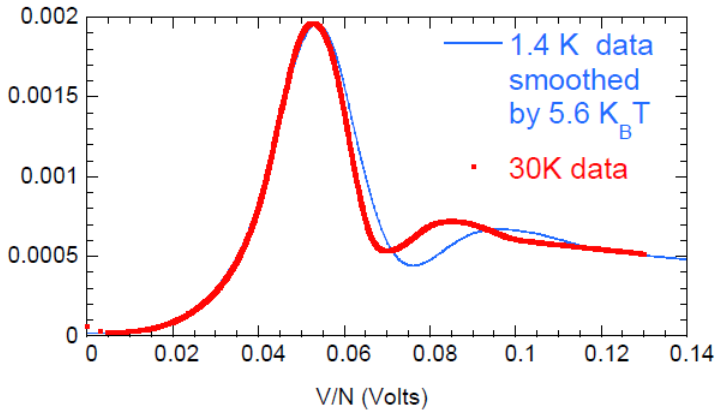
For the two OD mesas the amplitude of the "hump" is less *T*-dependent than the "dip".

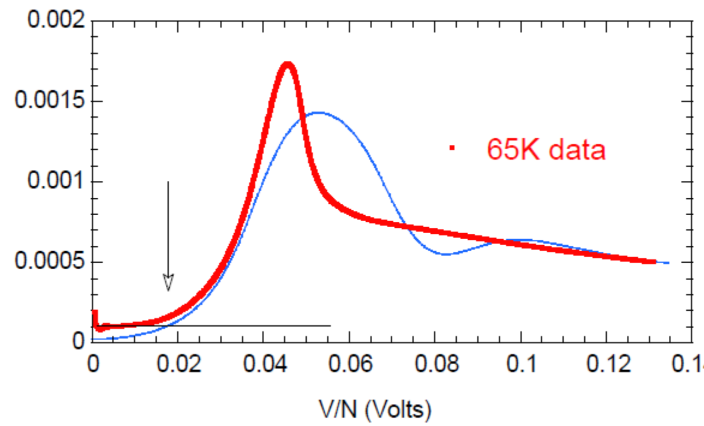


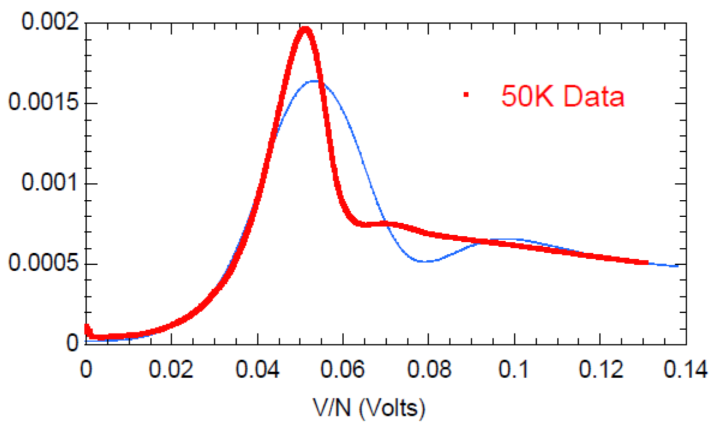
The gap is still large at T_c. (Approx. equal to the energy of the S=1 resonance mode ($5.4k_BT_c$). Is this a coincidence or not?)

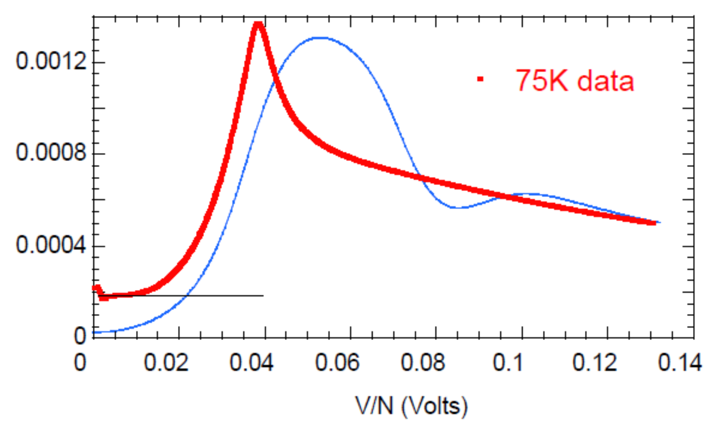
Believe there is enough accurate information in this data to test the possibility that the dip-hump structure arises from the S=1 resonant mode and possibly whether anti-ferromagnetic spin fluctuations provide the pairing mechanism.
But in view of caveats mentioned before it is quite a complicated theoretical problem.

Now use a simple method to discuss the temperature dependence. Compare the *dI/dV* curve at 1.4 K (smoothed over a voltage interval of 5.6 k_BT) with the measured curves at every temperature. Some examples:



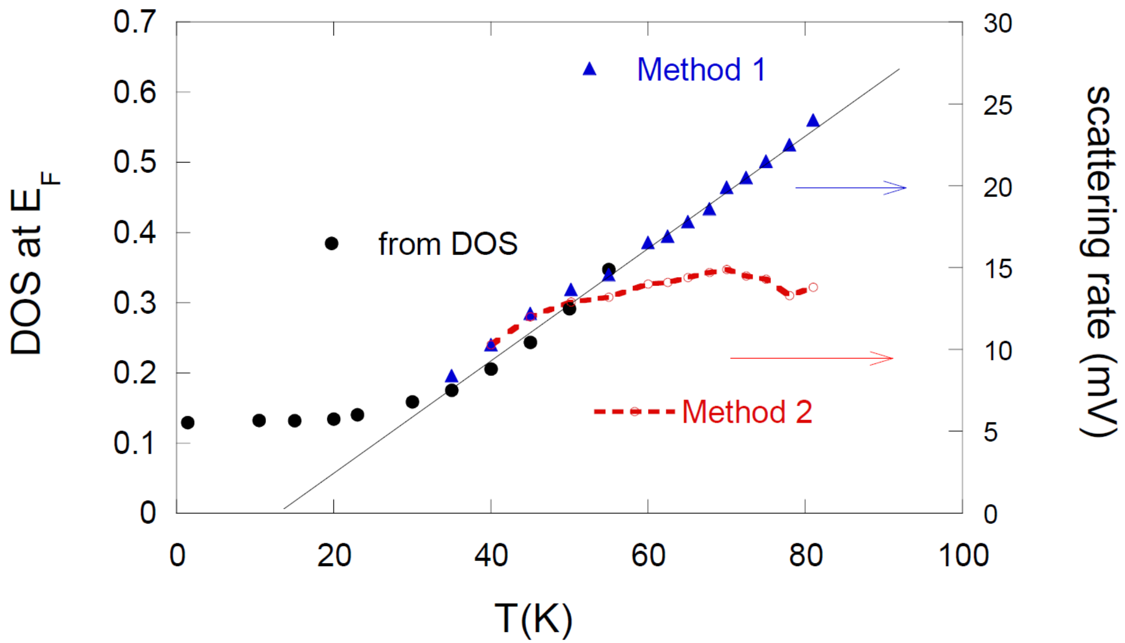






Looks as if there is T-dependent pair-breaking. Gives larger DOS at $V = 0$. Comes in at about 50 K where dip-hump structure goes away. Also high T curves narrower!

First thought (mentioned in 2015 preprint):
Real inelastic scattering processes: e.g. electron-electron scattering or electron-boson scattering cause pair-breaking. If true then can estimate scattering rate by drawing horizontal line across to thermally broadened 1.4 K curves. Two possible methods 1– ignore fall in Δ_0 with T or 2 - allow for it by scaling V and dI/dV. Method 1 –linear variation of $1/\tau$ with T and $\hbar/\tau = \Delta_0$ at T_c – method 2, $1/\tau$ flattens off .

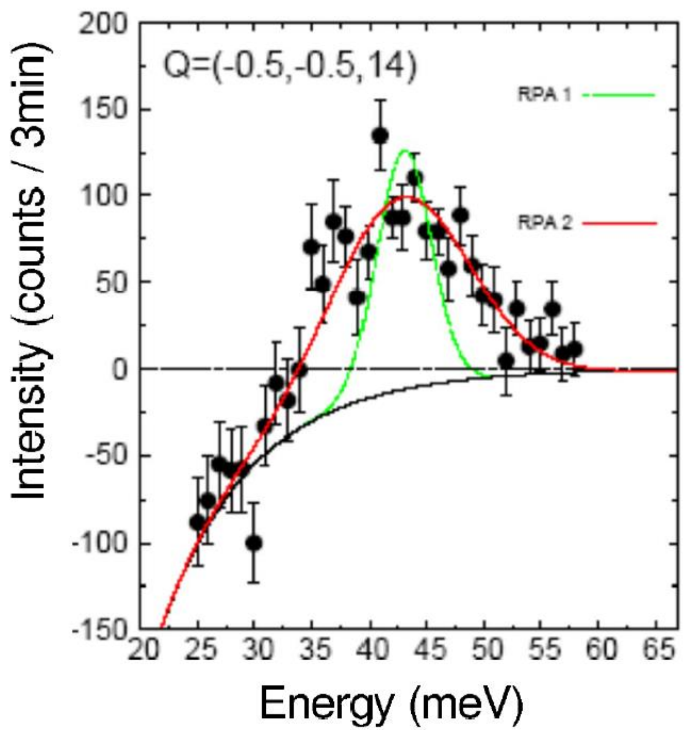


Compare above T_c e.g. Tl2201 OD60 know FS area and m^* from QO studies
Find in-plane resistivity $\rho(60)$ = 40 μΩ cm corresponds to 10 mV.

Possible cause of broadening of $2\Delta_0$ peaks at 30 K and below? Strong coupling to low frequency boson modes.

PHYSICAL REVIEW B **76**, 214512 (2007)

PRL **106**, 167005 (2011)



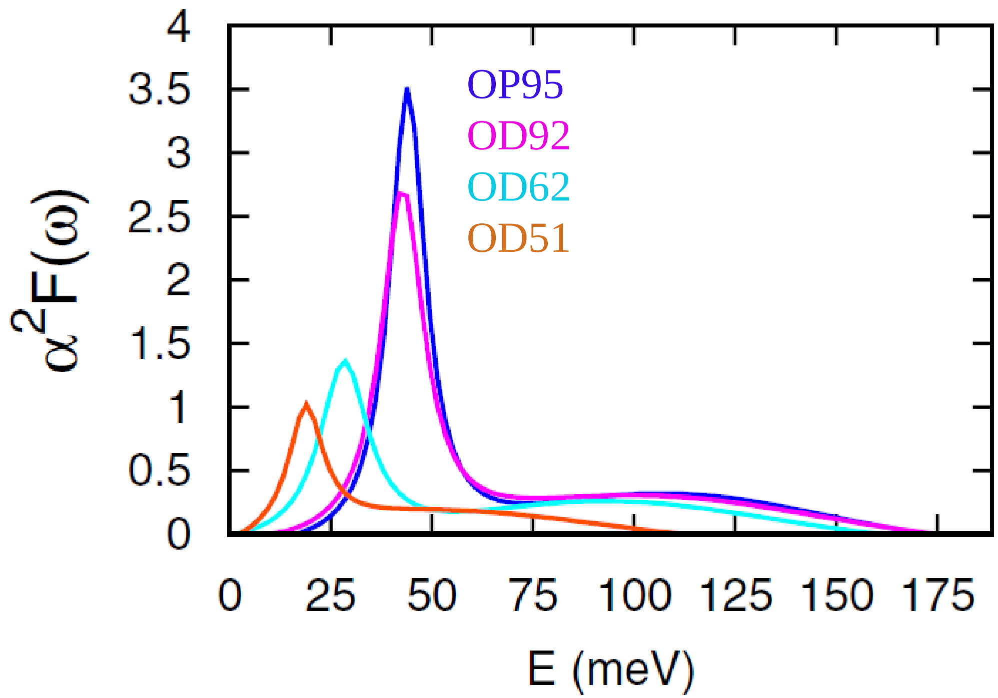


FIG. 7. (Color online) Resonant magnetic modes in nearly optimally doped $Bi_2Sr_2CaCu_2O_{8+\delta}$ (T_c=87 K) measured at **Q**

Ph. Bourges and B. Keimer groups S = 1 resonance from neutron scattering at 10 and 100 K FWHM ~15 *mV*.

Zasadzinski group: Eliashberg analysis of Bi2212 break junction data. (Did not get very good fits to data immediately above gap edge).

Conclusions

1. If accept this evidence for strong pair-breaking in s/c state then properties such as heat capacity and London penetration depth should be interpreted in a different way. In fact this has been done in a recent paper by J.G. Storey *New J. Phys. 19 (2017) 073026* who was inspired by recent ARPES work namely:

Kondo T, Malaeb W, Ishida Y, Sasagawa T, Sakamoto H, Takeuchi T, Tohyama T and Shin S (2015) Point nodes persisting far beyond T_c in Bi2212 *Nat. Commun. 6 7699*
and
Reber T J et al 2015 Pairing, pair-breaking, and their roles in setting the T_c of cuprate high temperature superconductors *arXiv:1508.06252*

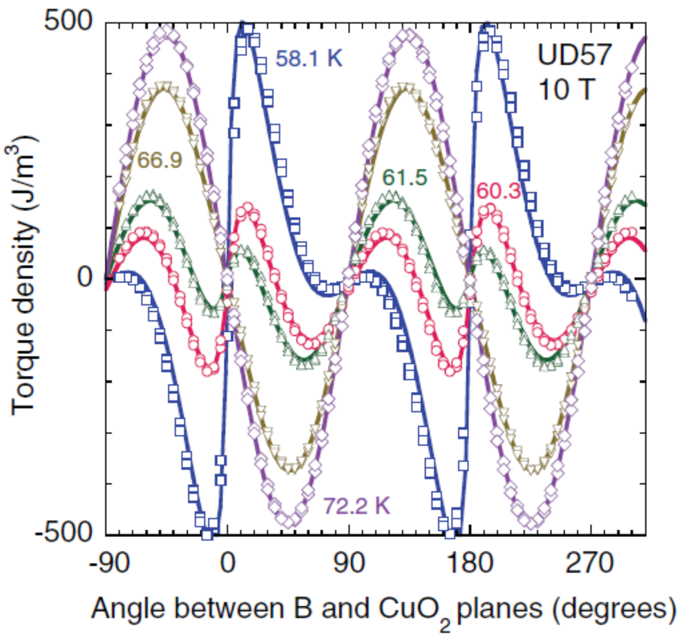
We have arrived at a similar conclusion independently when trying to understand our intrinsic tunnelling data in the semi-quantitative but model-independent way described in this talk and in our earlier preprint *T.M. Benseman, JRC and G. Balakrishnan - arXiv:1503.00335v2 [cond-mat.supr-con] 16 Mar 2015*

2. Tend to think that the broadening of the gap-edge peaks below 30 K highlighted here suggest that low frequency boson modes may be more important than currently recognised.

3. Another aspect of our work in the last few years has been studies of superconducting fluctuations above T_c as described briefly in the abstract.

Some time ago we showed that own Nernst effect data for various Zn and Ca YBCO crystalline films and published data for LSCO were consistent with theory for Gaussian superconducting fluctuations. *I. Kokanovic, JRC and M. Matusiak, PRL 102, 187002 (2009).*

More recently we reached the same conclusion for the diamagnetic susceptibility of YBCO crystals UD22, UD 57 and OP89 measured using torque magnetometry. *I. Kokanovic, D. J. Hills, M. L. Sutherland, R. Liang and JRC Phys. Rev. B 88 060505(R) (2013)*



At high T the torque density given by $(\chi_c - \chi_{ab}) B^2(\sin 2\theta)/2$ which is caused by the anisotropy in the spin susceptibility (via the g-factor anisotropy) where $\chi_c - \chi_{ab}$ ~10^{-4} emu/mole. As T_c is approached, s/c fluctuations cause χ_c to fall and eventually there are large deviations from $\sin 2\theta$.

By analogy with published work on the Nernst effect of Nb Si films, *A. Pourret, H. Aubin, J. Lesueur, C. A. Marrache-Kikuchi, L. Bergé, L. Dumoulin, and K. Behnia, Phys. Rev. B 76, 214504 (2007)* IK showed that these deviations occur when the magnetic length $(\phi_0/B)^{1/2}$ becomes comparable to the in-plane s/c coherence length $\xi_{ab}(T)$.

More formally in the 2D limit the theoretical expression for the Free energy contribution F from Gaussian fluctuations given in the textbook by Varlamov and Larkin is:

$$F = \frac{k_B T}{2\pi \xi_{ab}^2 s} \left\{ b \ln\left[\Gamma\left(\frac{1}{2} + \frac{\epsilon}{2b}\right) \Big/ \sqrt{2\pi} \right] + \frac{\epsilon}{2} \ln(b) \right\}$$

Here $\epsilon = \ln(T/T_c)$, $b = B/B_{c2}(0)$ with $B_{c2}(0) = \phi_0/(2\pi\, \xi_{ab}(0)^2)$, s is the CuO_2 bi-layer spacing, ϕ_0 is the flux quantum for pairs and Γ is a standard function. T_c is the mean field transition temperature in zero magnetic field. We showed that to within a few % the above formula for F leads to a magnetisation $M = -\partial F/\partial B$ for $0.01 < \epsilon < 1$ given by:

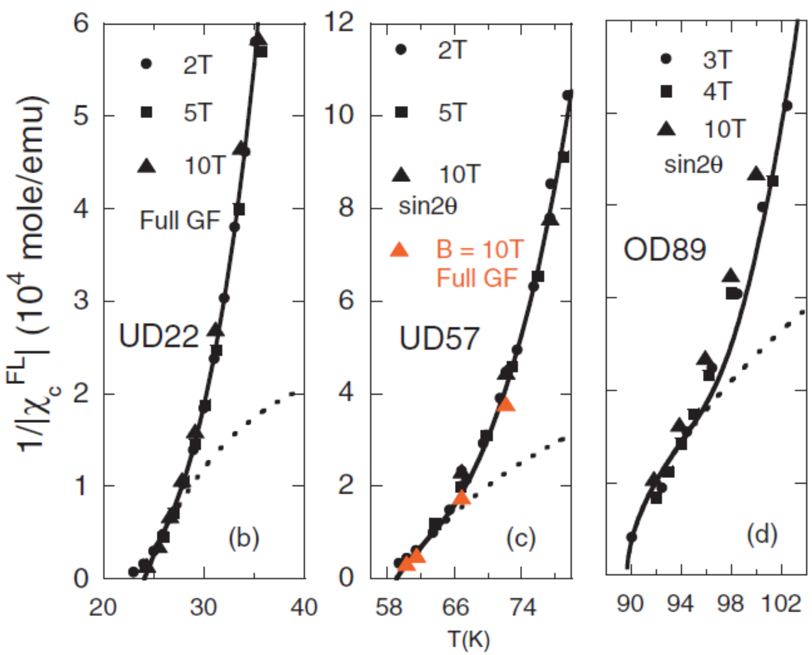
$M= -bk_BT/[\phi_0 s(3b+6\epsilon)]$

This only depends on T_c and $\xi_{ab}(0)$. In a fixed field it gives a torque proportional to:

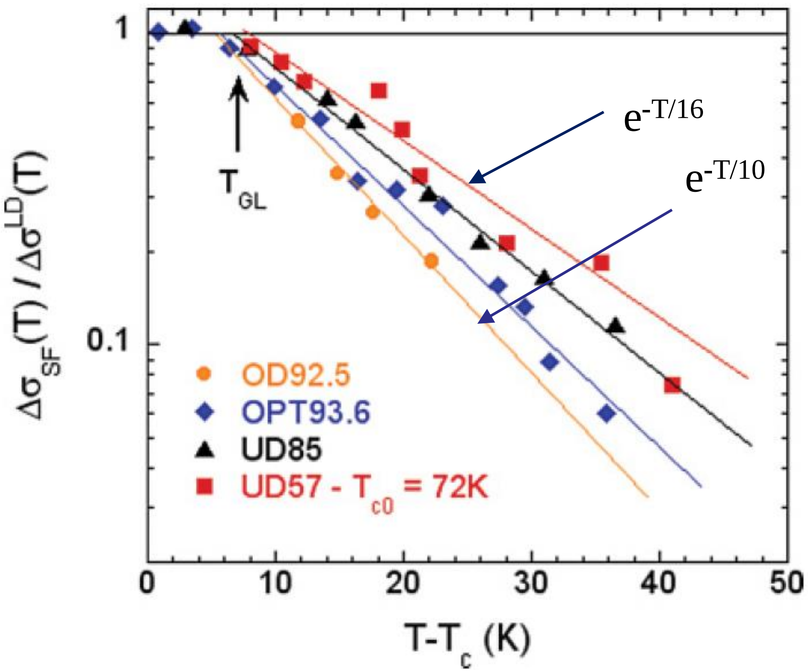
$a\ sin(2\theta)/[(1 + |c\ sin\theta|]$,

where θ is the angle between B and the CuO_2 planes, $a \sim B^2/\epsilon$ and $c \sim B/\epsilon$ with constants of proportionality that only depend on $\xi_{ab}(0)$. When c becomes comparable to unity (larger fields B or T closer to T_c) there are large deviations from $sin2\theta$ but the above formula still gives good fits to the experimental data, as shown in previous slide by the solid lines.

T_c can be a few degrees higher than the measured value because of departures from GF formula near T_c caused by critical fluctuations. Therefore we plot $1/a$ vs. T or equivalently the inverse of the fluctuation contribution to χ_c as shown below



Dashed lines show the GF fits which only hold for $T/T_c < 1.08$ - 1.1. Above that $|\chi_c^{FL}|$ decreases rapidly as $exp[-(T\text{-}1.1T_c)/T_0]$ with T_0 values of 8.7,12.3 and 7 K for OD89,UD57 and UD22 respectively. The corresponding increase in $1/|\chi_c^{FL}|$ is shown by solid lines



F. Rullier-Albenque, H. Alloul and G.Rikken, Phys. Rev. B **84**, 014522 (2011).

2D Aslamazov- Larkin

$\sigma_{2D}{}^{SF} = (e^2/16\hbar s)/ln(T/T_c)$

$\sigma_{MEAS} \quad = \quad \sigma_N + \quad \sigma_{2D}{}^{SF}$

σ_N from high magnetic field measurements.

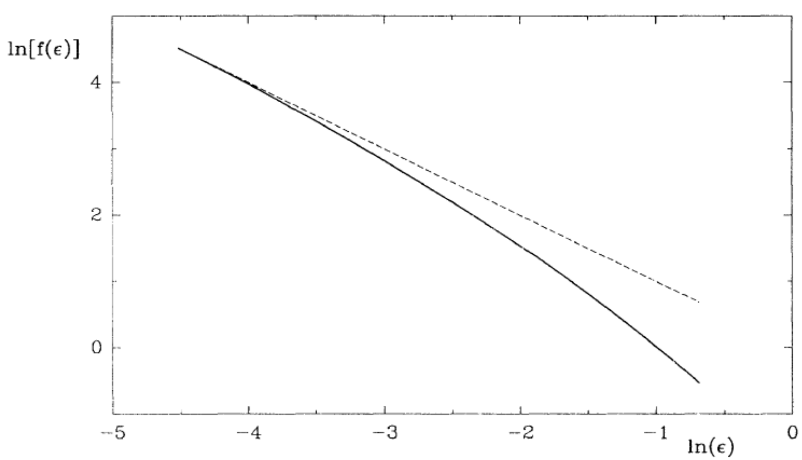


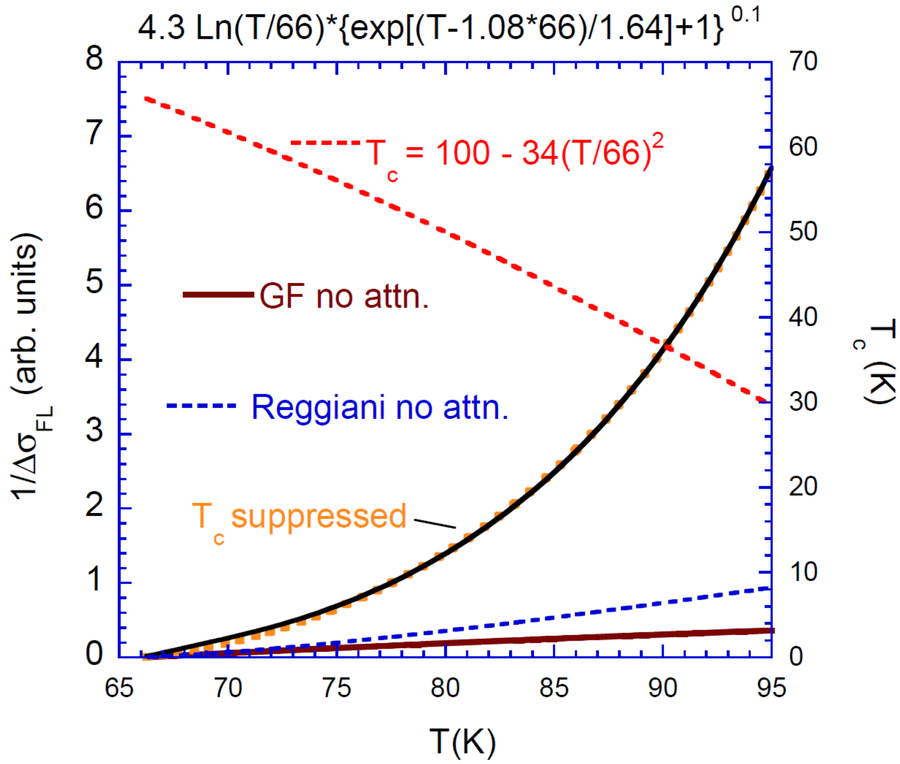
FIG. 5. Behavior of the function $f(\epsilon) = (16a/e^2)\sigma_{fl}(\epsilon)$ in a ln-ln scale (solid line). The dashed line is the Aslamazov-Larkin expression.

L. Reggiani, R. Vaglio and A. A. Varlamov Phys. Rev. B44, 9541 (1991)

$\epsilon = ln(T/T_c) >> 1, \ \sigma_{2D}{}^{SF} \sim 1/\epsilon^3$

No theory for effect of inelastic scattering on s/c fluctuations.

Here are results of a simple model in which inelastic scattering above T_c reduces the effective value $T_c(T)$ used in the Aslamazov-Larkin formula for the fluctuation conductivity.



Can get observed value of T_0 in *exp(-T/T*$_0$*)* attenuation factor. Formula and black curve correspond to T_0 = 16.4 K. But prefactor 4.3? Not whole story.