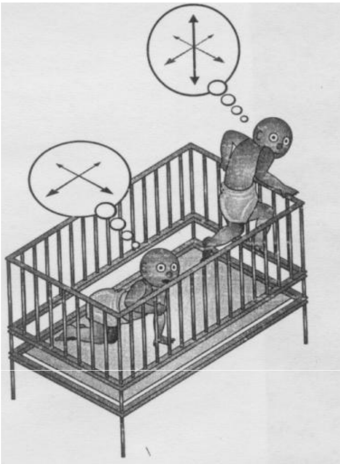
The Mysterious Metallic Phase in 2D Superconductors and the Resulting Phase Diagram



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Yoon's Group
Department of Physics
University of Virginia

Outline

1. Lab Tour.

2. Conventional Treatments of Electronic Transport in 2D Superconducting films.

3. Unexpected Metallic Phase in B-induced Suppression of Superconductivity. Is the Metallic Phase Real? What's the Origin?

4. Mapping the Phase Diagram in B-T-Disorder Space (Based on the Nonlinear Transport Characteristics). Fundamental Issues Related with the Phase Diagram.

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6. Conclusions

Properties of Tantalum

General: $^{181}_{73}Ta$, column 5B , transition metal, hard material, high melting point, slow oxidation in the air

Bulk: T_c=4.5K

Film: Excellent wetting on most of the substrates

Ta films are dc sputter deposited on Si substrates

1. Base pressure ~10^{-8} Torr before deposition.

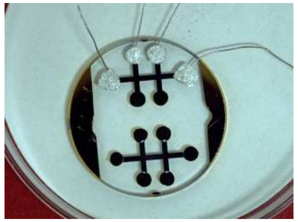
2. Clean the chamber and Ta source by presputtering.

3. Films are grown at a rate of ~0.05nm/s at an Ar pressure of 4 mTorr.

4. Films are patterned into a bridge for 4-leads measurement

5. Up to 12 films per batch

The Ta films we grown are highly amorphous, as demonstrated
(1) by the x-ray diffraction pattern (no sign of local atomic correlation)
(2) by the fact that Tc decreases with decreasing thickness



Helium: The Coolant

- Firstly created in the Big Bang; Then created as a result of the nuclear fusion of hydrogen in stars.
- Rare on earth; Mainly created by the radioactive decay of much heavier elements (alpha particles are helium nuclei).
- Trapped with natural gas in concentrations up to 7% by volume, from which it is extracted commercially by fractional distillation.

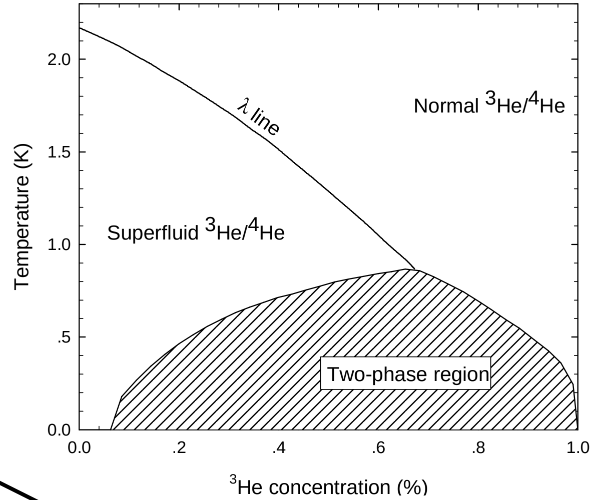
ScienceDaily (Jan.5, 2008)

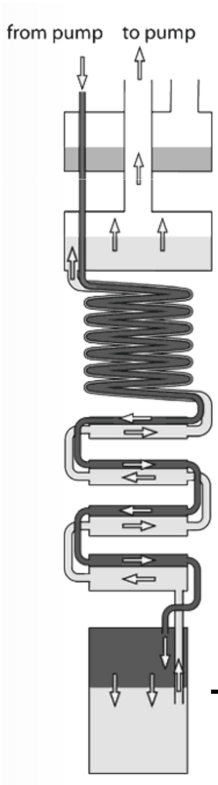
Helium Supplies Endangered, Threatening Science And Technology

The element that lifts things like balloons, spirits and voice ranges is being depleted so rapidly in the world's largest reserve, outside of Amarillo, Texas, that supplies are expected to be depleted there within the next eight years.

"All should make better efforts to recycle it."

Low temperature measurements are carried out in ^3He – ^4He Dilution Refrigerator





(Bath) 4.2K

(1K pot) 1.5K

(Still pot) 0.6K

(50mK/100mK stage) 0.1K

(Mixing chamber) 0.02K

Low temperature measurements are carried out in ^3He – ^4He Dilution Refrigerator

❑ For our Dilution Refrigerator

- Base Temperature (T_{min}) : 40mK
  (It takes ~12 hours to reach T_{min} from 600mK)

- Maximum Magnetic Field (B_{max}) : 9T
  Provided by superconducting magnets
  (It takes ~ 12 hours to reach B_{max} from 0T without apparent heating to the samples)

Caution

If you do it within 3 hours, heating effect is significant !

If you do it within 1 minute, a PHD (short for "Permanent Head Damage") may be produced !!

❑ Transport Measurements:

- T-dependence of resistance
- B-dependence of resistance
- V dependence of I
- dV/dI dependence of I

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Conventional Treatments for 2D Superconductors (Cooper Pairs)

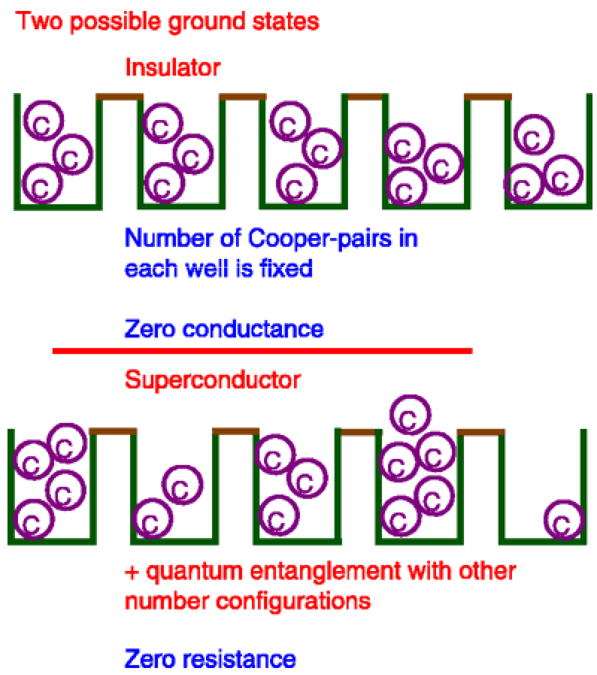
- At low temperatures, lattice-mediated attractive interactions between electrons produce a resistanceless state in which the charge carriers are electron pairs called **Cooper pairs** (charge 2e bosons).

- Superconducting state can be characterized by the complex order parameter $\boldsymbol{\Psi = \Psi_0 e^{i\Phi}}$.Here Ψ is a **macroscopic** wavefunction for the superconducting electrons.

- Superconductivity is destroyed by either **breaking the Cooper pairs or disrupting phase coherence**. An **insulating state** will obtain in either case.

- Phase and particle number are **conjugate variables**, so their simultaneous measurement is limited by the **Heisenberg uncertainty principle**.

- Bosons can either be in an **eigenstate** of **particle number** or **phase**: the eigenstate of phase is a superconductor and that of particle number is an insulator.



P. Phillips and D. Dalidovich, Science **302**, 243 (2003)

Conventional Treatments for 2D Superconductors (Vortices)

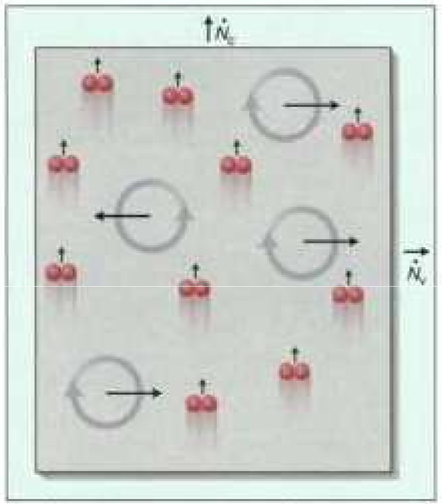
- For thin films, one can experimentally transform a superconductor into an insulator by either (1) decreasing the film thickness or (2) applying a perpendicular magnetic field.

  (1) Decreasing the thickness increases boundary scattering and hence disorder drives the transition.

  (2) In the application of a magnetic field, resistive topological excitations called **vortices** frustrate the onset of global phase coherence.

- If a Cooper pair moves around the vortex, the quantum phase of the system winds by $\pm 2\pi$. Associated with this gradient in the phase is a circulating current much like a whirlpool in an ordinary fluid.

- Vortices and Cooper Pairs are related by a duality transformation. In 2D superconductors this transformation interchanges Cooper Pairs and vortices and maps the insulating and superconducting phases onto each other.



Dual view. Superconductor containing Cooper pairs (red circles) and magnetic vortices (circulating arrows). The two are related by dual symmetry.

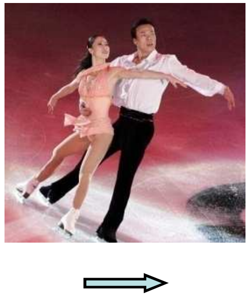
S.M.Girvin, Science **274**, 524 (1996)

Conventional Treatments for 2D Superconductors
(“Dirty Bosons” Model Proposed by M. P. A. Fisher)

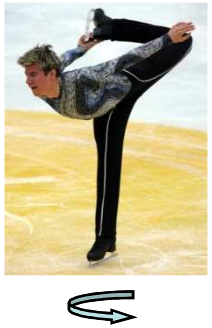
Superconducting Phase:

A condensate of Cooper pairs with localized vortices

free “Cooper pair”



localized “vortex”



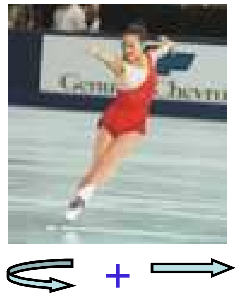
localized “antivortex”

Insulating Phase:

A condensate of vortices with localized Cooper pairs

localized “Cooper pair”

free “vortex”



free “antivortex”

Conventional Treatments for 2D Superconductors (General Conclusion)

Bosonic Picture: (For the strong disorder regime, where quantum fluctuations have the dominant effect)

M. P. A. Fisher, Phys. Rev. Lett. **65**, 923 (1990).
M. P. A. Fisher, G. Grinstein, and S. M. Girvin, Phys. Rev. Lett. **64**, 587 (1990).
A. Larkin, Ann. Phys. **8**, 785 (1999).

Fermionic Picture: (For the weak disorder regime, where the conductivity is mostly determined by the weakly decaying fermionic excitations)

A. Finkelshtein, JETP Lett. **45**, 46 (1987).
A. Larkin, Ann. Phys. **8**, 785 (1999).

General Conclusion

There is no true metallic behavior in 2D superconductors.
The suppression of the superconductivity leads to a direct SIT at T=0.

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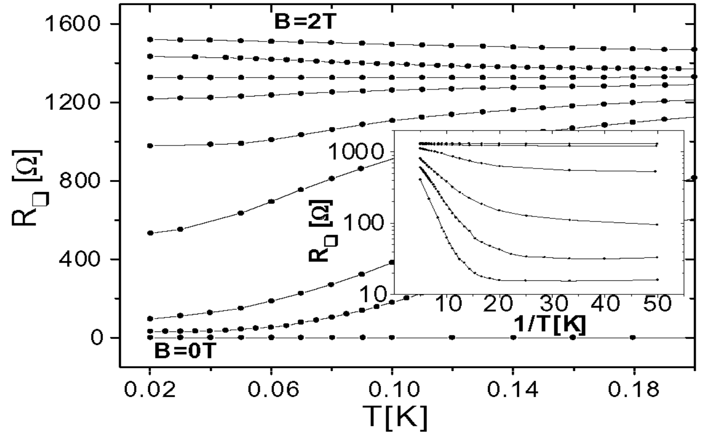
SIT vs. SMIT

Superconductor-Insulator Transition

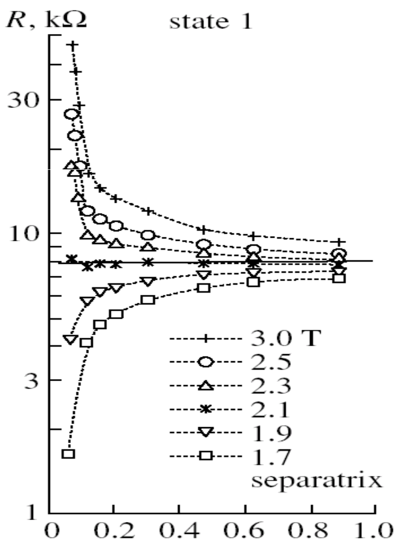
Superconductor-Metal-Insulator Transition

MoGe



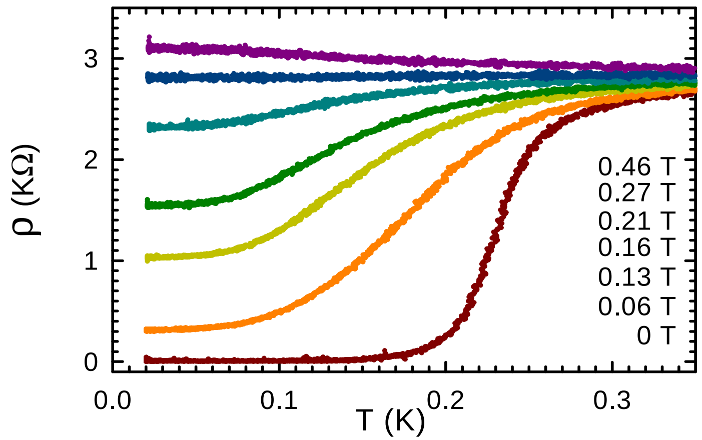
Mason and Kapitulnik, PRL **81**, 5342 (1999)

InO
(Bi, Be, MoSi, …)



V. F. Gantmakher et al, JETP **71**, 160 (2000)

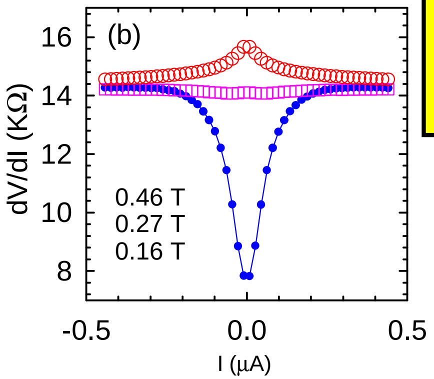
Ta



Y.Qin, C.Vicente, and J.Yoon, PRB **73**, 100505(R) (2006)

Nonlinear I-V Characteristics in Three Different Phases

M-I boundary



Insulating phase

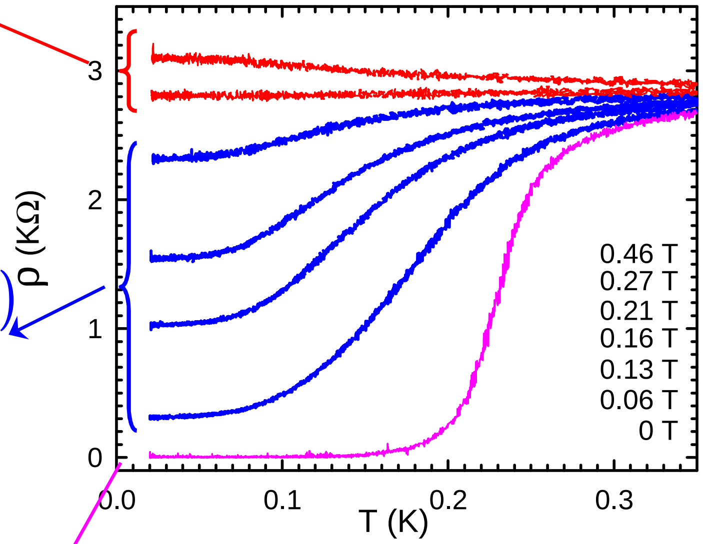
$$\frac{d^2V}{dI^2} < 0$$

$$\left(\frac{d\rho}{dT} < 0\right)$$

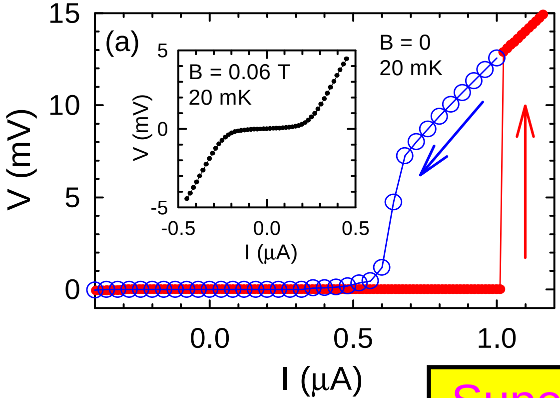
Metallic phase

$$\frac{d^2V}{dI^2} > 0$$

$$(\rho = finite)$$



S-M boundary



Superconducting phase

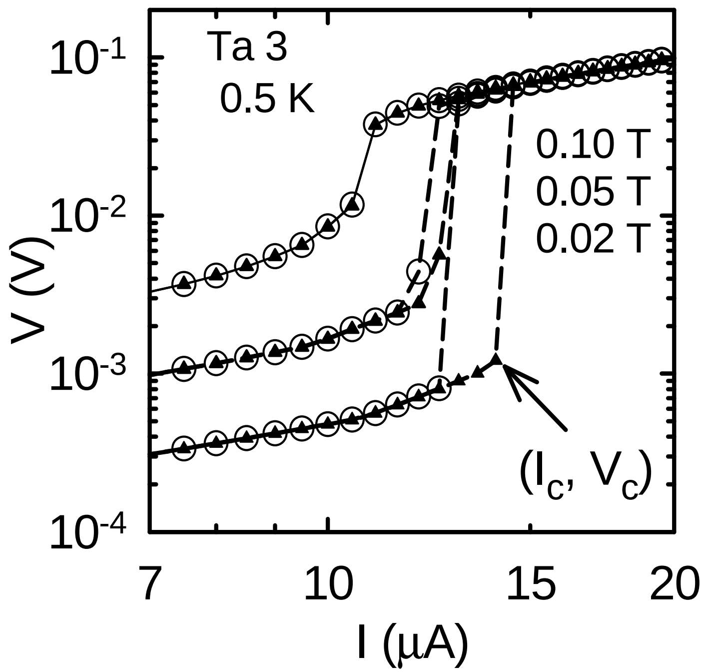
$$hysteretic \;\; I-V$$

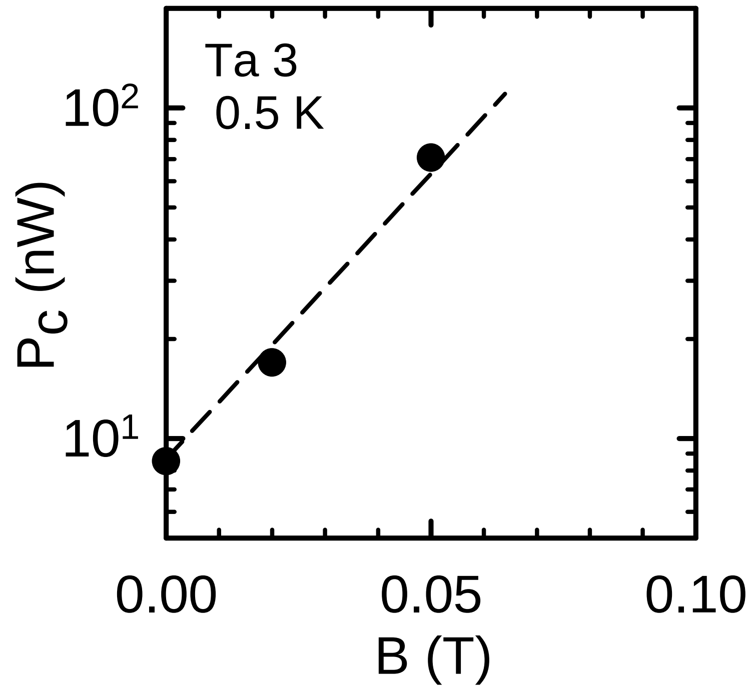
$$(\rho = 0)$$

Q: Is the metallic phase real? Can it be due to electron heating?

A: The Metallic Phase Is Real!

Strong increase of Pc
Smooth evolution across S-M boundary





Y. Seo, Y. Qin, C. Vicente, K. Choi and J. Yoon, Phys. Rev. Lett. **97**, 057005 (2006)

Proposed Origins for the Metallic Phase

- Bosonic interactions in the nonsuperconducting phase

D. Dalidovich and P. Phillips, Phys. Rev. B **64**, 052507 (2001)

D. Dalidovich and P. Phillips, Phys. Rev. Lett. **89**, 027001 (2002)

- Contribution of fermionic quasiparticles to the conduction

V. M. Galitski, G. Rafeal, M. P. A. Fisher, and T. Senthil, Phys. Rev. Lett. **95**, 077002 (2005)

- Quantum phase fluctuation

D. Das and S. Doniach, Phys. Rev. B **60**, 1261 (1999)

D. Das and S. Doniach, Phys. Rev. B **64**, 134511 (2001)

M. V. Feigelman and A. I. Larkin, Chem. Phys. **235**, 107 (1998)

B. Spivak, A. Zyuzin, and M. Hruska, Phys. Rev. B **64**, 132502 (2001)

An agreement is yet to be achieved!

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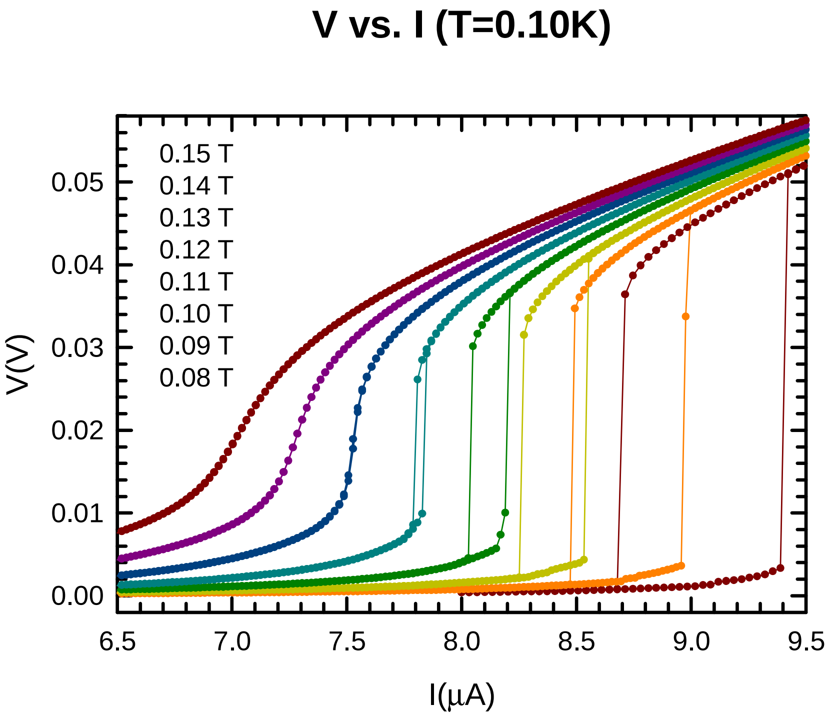
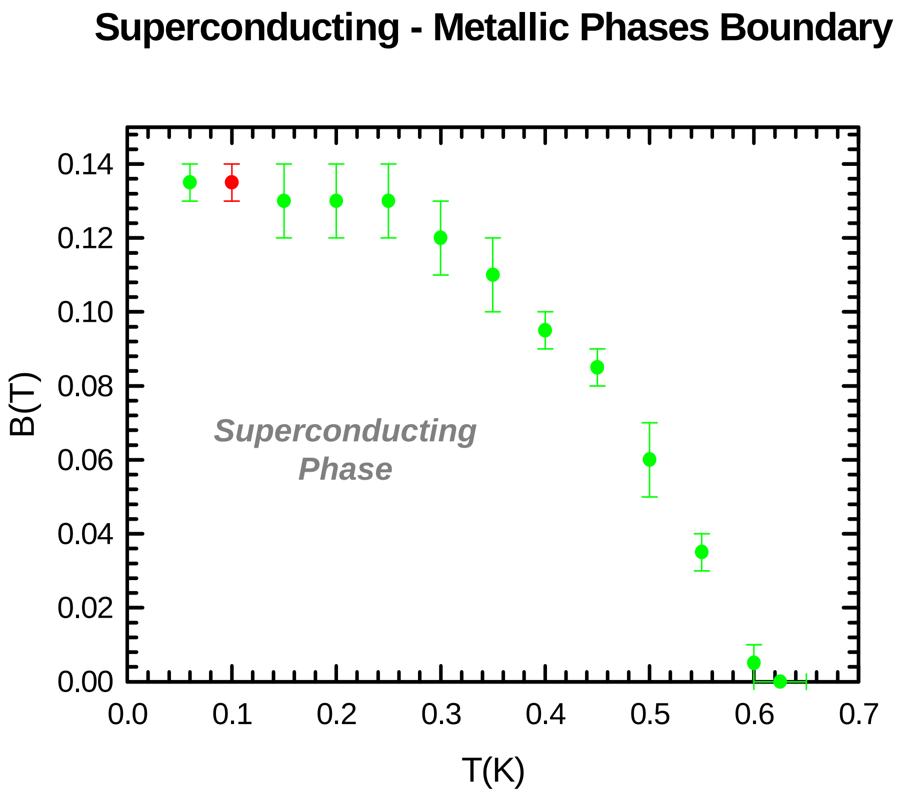
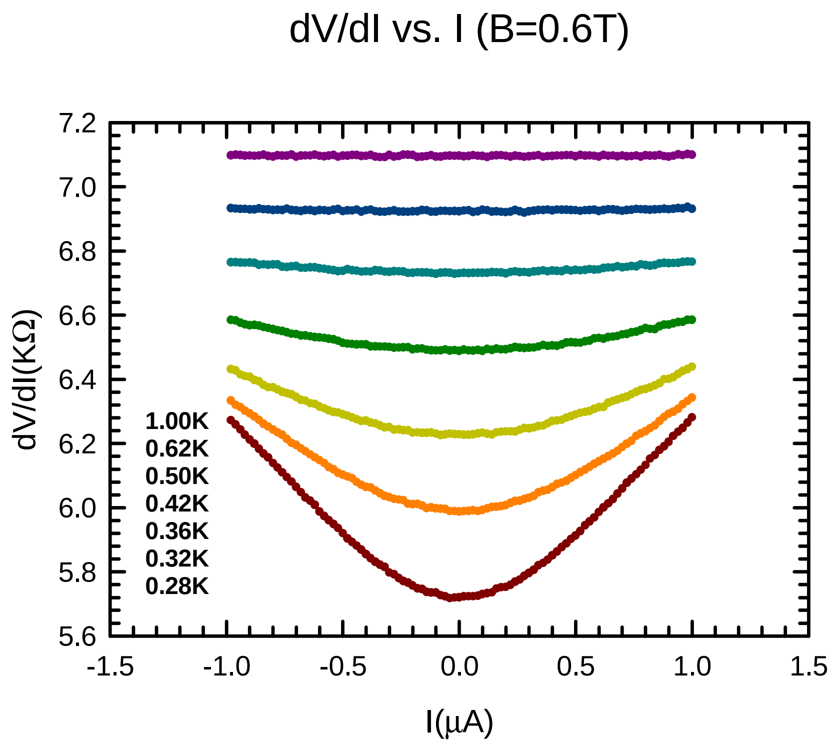
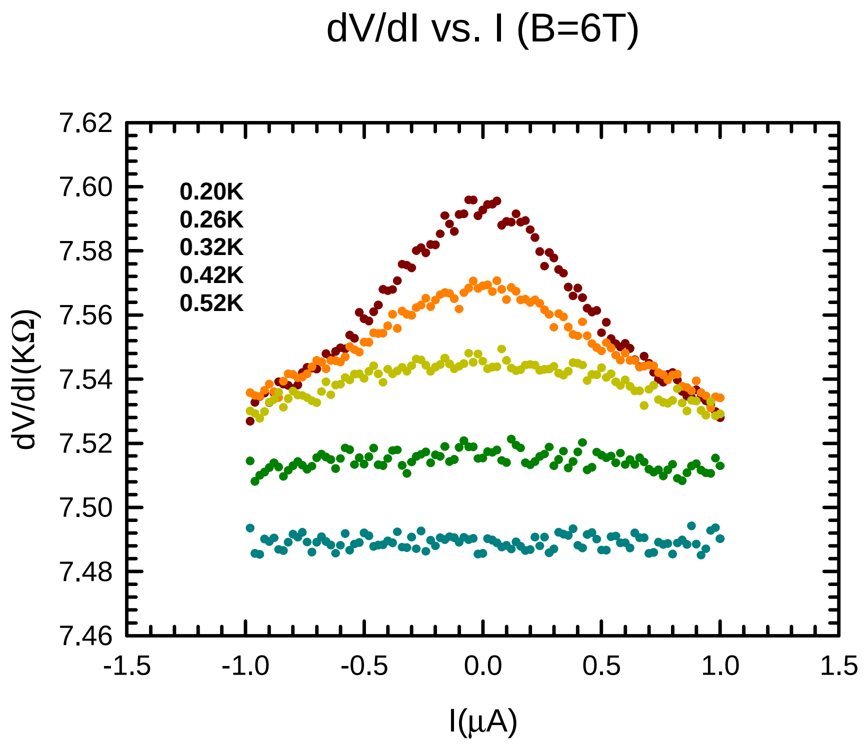
Superconducting-Metallic Phases Boundary





Quantum Metal, Insulator, and Normal Metal “Phases” Boundaries





Identifying the Boundaries Quantitatively

- We found that the measured differential IV can be fitted to a quadratic form,

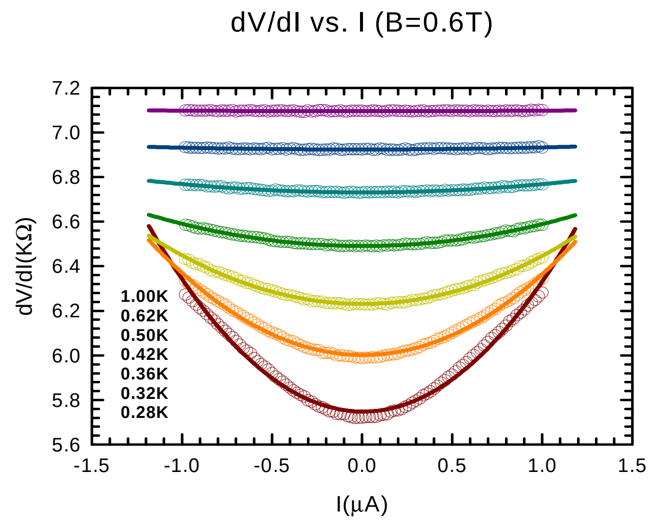
  $dV/dI = a(I-b)^2 + c$, where "a", "b" & "c" are fitting parameters.

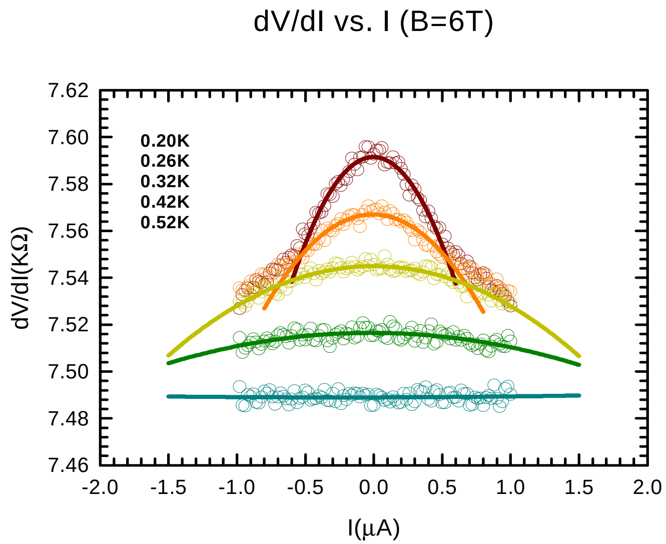
- The sign of parameter "a" can be used to identify phases:

  a>0: quantum metallic phase

  a<0: insulating phase

  a=0 (or a≈0): normal metal phase



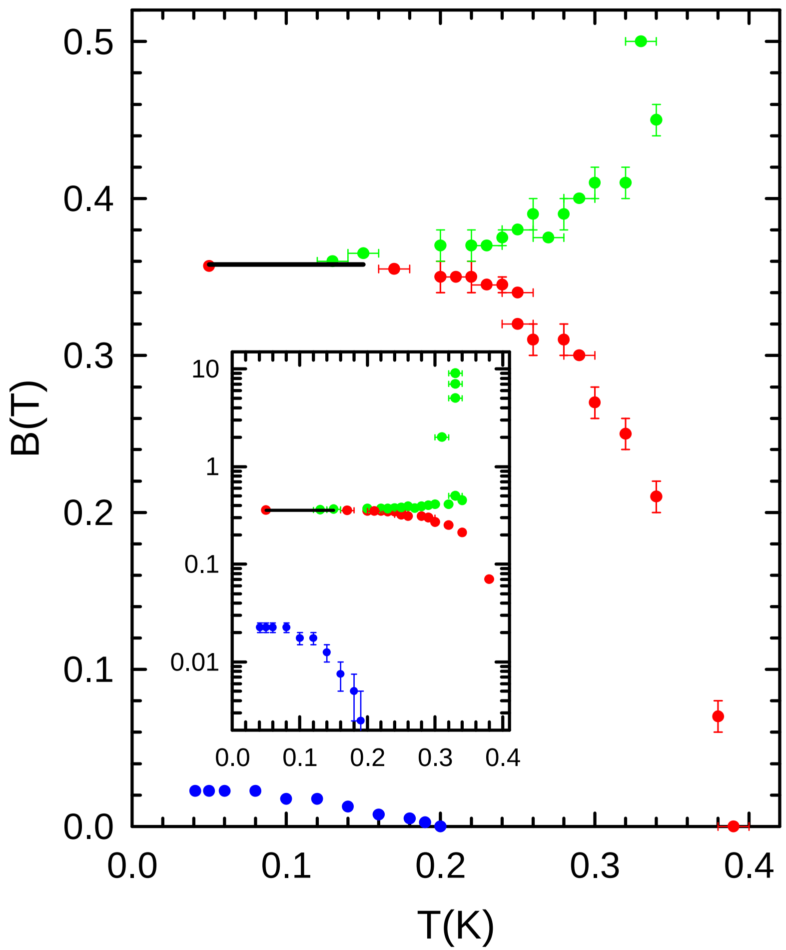


Stephanie's former Brute force approach on data analysis.

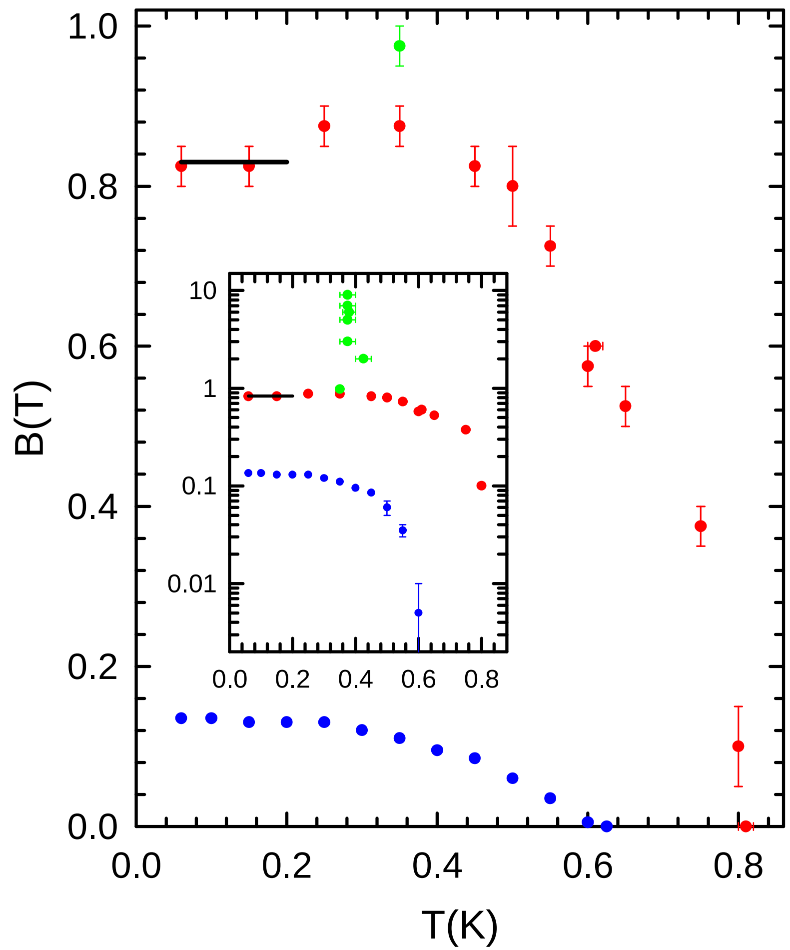
Stephanie's C program helps her to achieve unbelievable efficiency boost on data analysis && makes the analyzing process much more enjoyable.

Phase Diagrams on B-T plane

Sample 1 (high disorder)
Norminal film thickness : 4.1nm
Normal state sheet resistivity : 2.3KΩ
T_c (B=0) : 0.26K

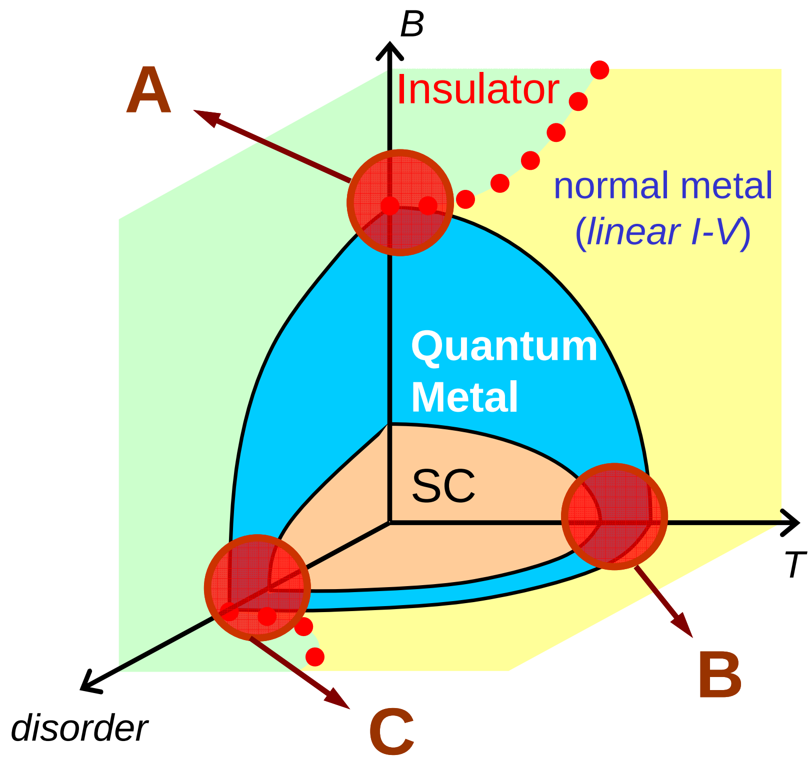


Sample 2 (low disorder)
Norminal film thickness: 5.6nm
Normal state sheet resistivity: 1.4KΩ
T_c (B=0) : 0.65K



Phase Diagram in B-T-Disorder Space

- Outstanding questions to be answered:
  - ***A. Nature of the Metal-Insulator Transition ?***
  - ***B. The Fate of Kosterlitz-Thouless Transition ?***
  - ***C. Is There Disorder-Induced Metallic Phase ?***



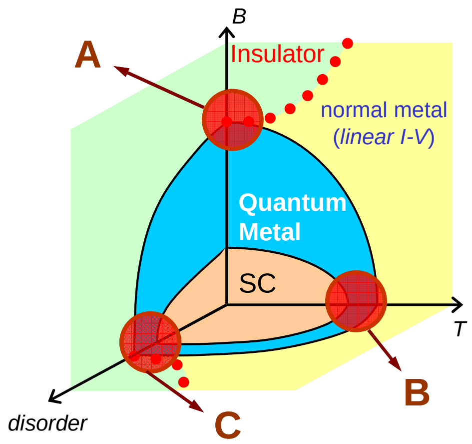
A. Nature of the Metal-Insulator Transition ?

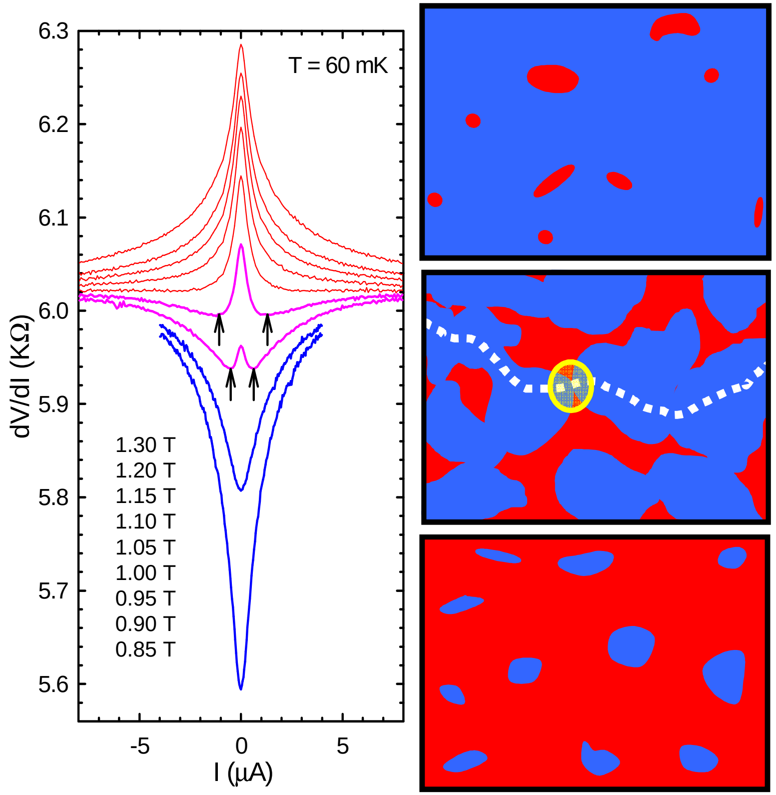
Percolation Type

At B < Bc, isolated insulating puddles exist in the background of the metallic region and $d^2V/dI^2 > 0$ at all currents.

At B ≳ Bc, the sign of d^2V/dI^2 changes with increasing bias current because of narrow insulating gaps in the current flow path.

At B >> Bc, where isolated puddles of metallic phase exist in the background of the insulating region, $d^2V/dI^2 < 0$ at all currents.

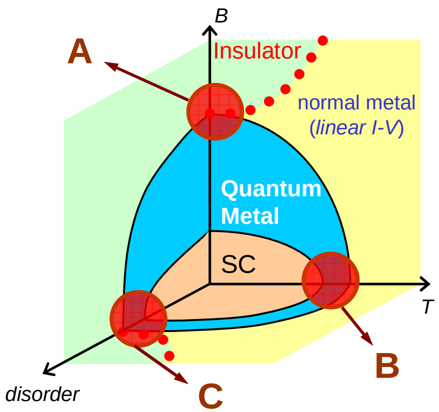


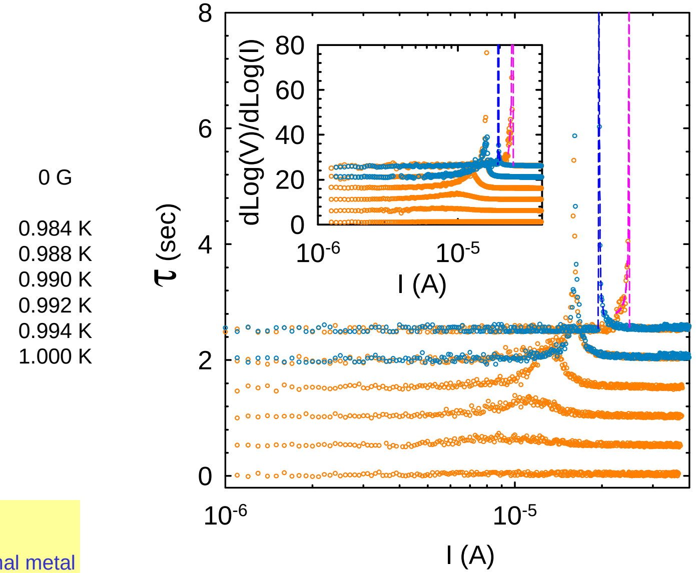


C.Vicente, Y.Qin, and J.Yoon, PRB **74**, 100507(R) (2006)

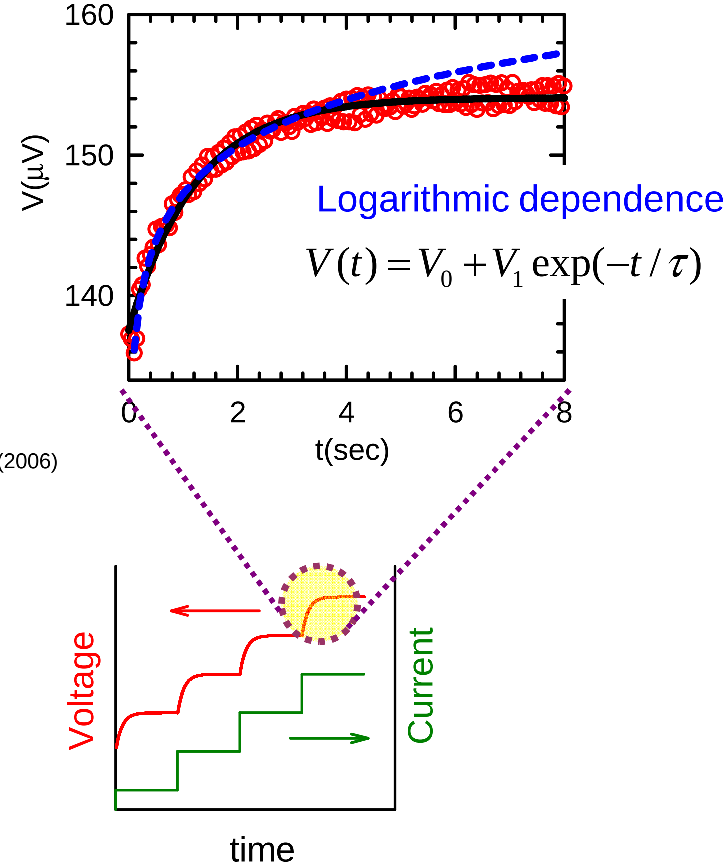
B. The Fate of Kosterlitz-Thouless Transition ?

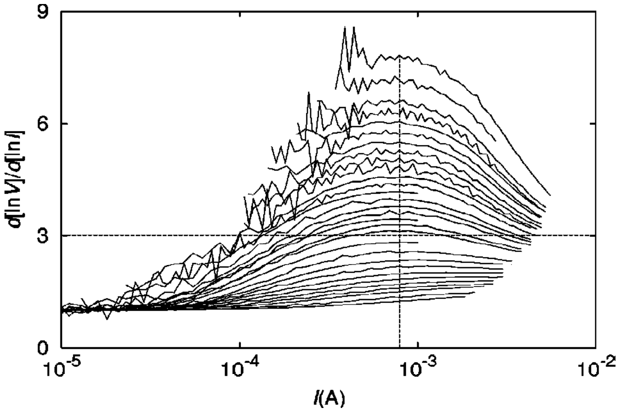
Vortex Pinning-Depinning Transition





Y. Seo, Y. Qin, C. Vicente, K. Choi and J. Yoon, PRL **97**, 057005 (2006)



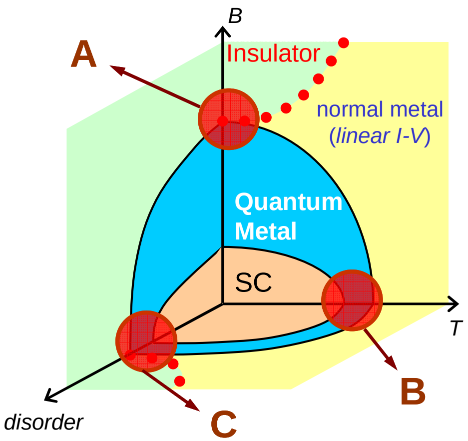


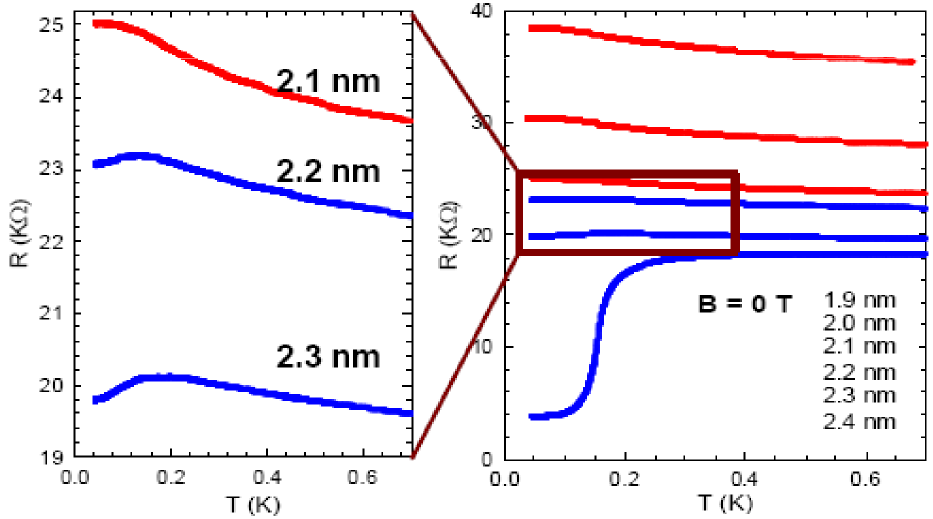
K. Medvedyeva, B. Kim, and P. Minnhagen, PRB 62, 14531 (2000)

C. Is There Disorder-Induced Metallic Phase ?

Probably Yes !

So far, the B=0 quantum metal phase, which is induced by disorder rather than B, has not been reported in amorphous superconducting films.





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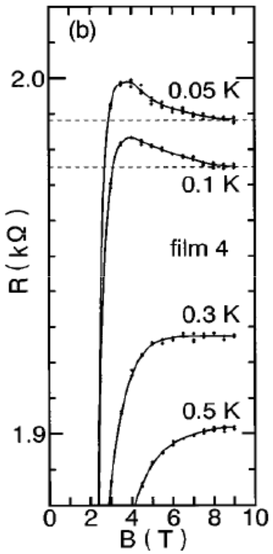
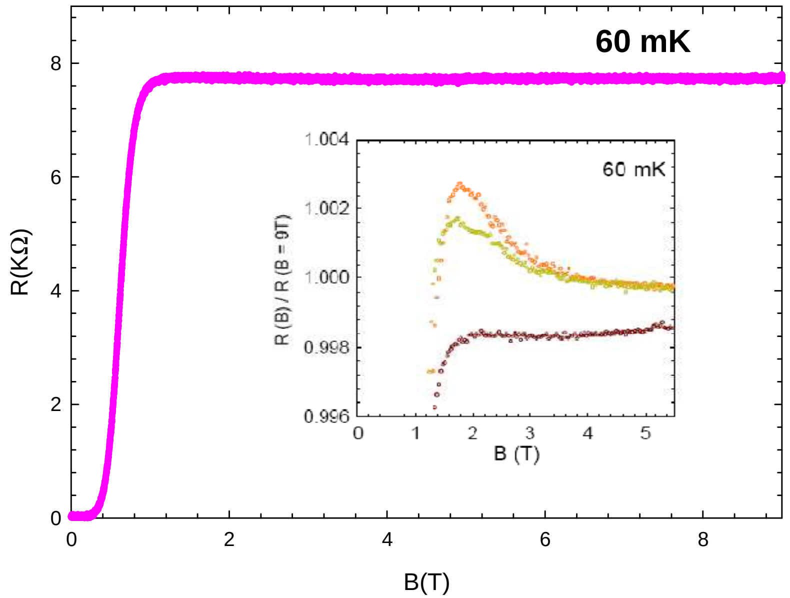
Magnetoresistance (MR) Measurements

MoSi
(InO, Bi)



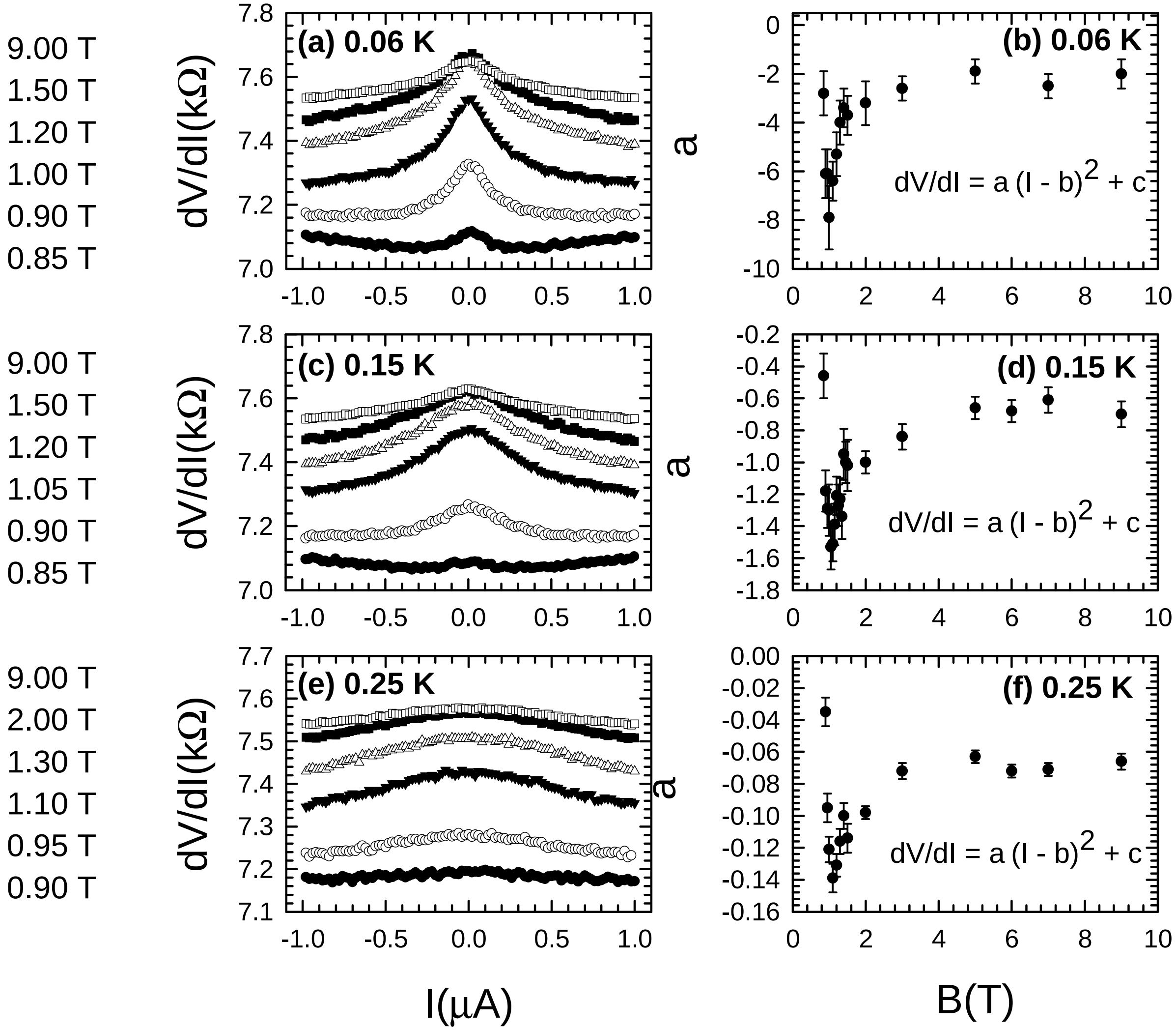
S. Okuma et al, PRB **58**, 2816 (1998)

Ta



Negative MR is not Sample – Independent.

The Peak Structure of Differential IV Traces in Insulating Phase Displays a Non-Monotonic Change as a Function of B



Voice of
"Localized Cooper Pair"

Conclusions

1. **Real metallic behavior is observed in amorphous Ta thin films.**

2. **Phase diagrams we have mapped for 2 samples indicate that the superconducting phase is completely surrounded by the metallic phase on B-T plane. By studying samples with various disorders, we can map out the 3D phase diagram in B-T-disorder space.**

3. **A sample – independent signature for the localized Cooper pairs in insulating phase might be in nonlinear transport characteristics, instead of in negative MR.**