Insulators, Metals, Superconductors and Quantum Critical Points: The Physics of Disordered Ultrathin Films

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University of Minnesota, September 19, 2001
Current and Recent Collaborators

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Outline

- Introduction
- Relevant Experimental Results
- Discussion
Introduction

The study of disordered superconductors is more than 60 years old -- Shal’nikov

Interest has been heightened recently by the possibility that the Superconductor-Insulator (SI) Transition is a Quantum Critical Point (QCP) (or that it is not)

For reviews see:

November 1998 Physics Today, Markovic and Goldman
January 1997 Reviews of Modern Physics, Colloquium, Sondhi et al.
S. Sachdev, “Quantum Phase Transitions”
Electrons in Two Dimensions

When electrons are confined to a plane, they are not expected to conduct electricity in the zero temperature limit. They are not supposed to be metals.

This is an important paradigm in contemporary Condensed Matter Physics, *Localization*.

*Exceptions* are dilute, ordered two-dimensional electron gases (2DEGs) – controlled by carrier concentration or magnetic field, and two-dimensional superconductivity – controlled by thickness or magnetic field.
History of the Disorder Problem in Superconductors

- Anderson’s Theorem: nonmagnetic impurities have no effect on superconductivity.
- Only relevant to systems with extended states.
- If disorder is such that the wavefunctions are localized, then-
- Weakening effects due to localization and Coulomb repulsion compete with pairing interaction
As disorder increases, states become localized.

Superconductivity disappears.

(There are scenarios for the persistence of superconductivity with localized states.)

(Graybeal and Beasley)/Finkel’shtein
Special Nature of Two Dimensions

- Superconducting Transition occurs as a Kosterlitz-Thouless-Berezinskii Transition. This means that the phase correlation function decays algebraically and the phase-coherent state is not at all robust. In fact there is resistance at any nonzero current.

- Weakly interacting electron systems in 2D are always localized, even for arbitrarily weak disorder.
Experimental Techniques

- Apparatus is a dilution refrigerator combined with an MBE system.
- Carry out repeated cycles of evaporation and measurement with evaporation onto substrates at helium temperatures.
**Schematic of Apparatus**

- Dilution refrigerator sits on top of an MBE chamber.
- Magnet configuration permits application of either parallel or perpendicular magnetic fields.
- Cryostat can be driven in and out of growth chamber and separated from it with a gate valve.
- There are radiation doors at 77K and 4K.
Crash!
ex situ AFM Images

50 Å thick Ga film
Grey scale 200 Å

18 Å thick Ga film
Grey scale 100 Å

18 Å thick Ga film
Grey scale 100 Å
Properties of Quench-Deposited Films

- Underlayer of Ge seems to prevent agglomeration of films into mesoscale clusters.
- Onset of conductance at thicknesses the order of a monolayer.
- Without underlayer-granular films result.
Evidence for an SI Transition

- Cyclic evaporation leads to evolution of superconductivity with thickness
- Clear separation between superconducting and insulating behavior
- Critical resistance close to $h/4e^2 = 6450 \, \Omega$
Quantum Phase Transitions (QPTs)

- Are at absolute zero and are controlled by a parameter in the Hamiltonian.
- Ground state changes when the critical point is crossed.
- In thermal transitions, although the order parameter is quantum mechanical, classical thermal fluctuations govern behavior at long wave-lengths.
- In QPTs, where \( T = 0 \), the fluctuations themselves are quantum mechanical.
QPTs Continued

- Have divergent correlation lengths, for the spatial, $\xi$, and for the temporal direction, $\xi_\tau$. The latter is associated with a vanishing energy scale $\xi \sim |\delta|^{-\nu}$, and $\xi_\tau \sim \xi^z$

- The correlation length exponent is $\nu$ and the dynamical critical exponent is $z$.

- Have interplay of dynamics and thermodynamics. $d$-dimensional quantum systems at finite temperature in the $T \to 0$ limit become classical with $d + 1$ dimensions. (Actually $d + z$ dimensional)
QPTs continued

- The finite extent of the system in the extra dimension being given by $-\hbar\beta$ in units of time.

- $\beta = 1/k_B T$. The extent of this extra dimension is divergent only in $T \to 0$ limit.

- Universality class of the QPT may be one studied extensively in some classical context.

- Have possibility of a computational treatment of the quantum mechanical problem using simulations of the $d+1$ dimensional classical problem.

- Effect of considering $T \neq 0$ in the statistical mechanics is to force the “temporal” dimension of the problem to be finite.
Simplest Realization: Josephson Junction Arrays
Integer Quantum Hall Effect
**Finite Size Scaling**

- The scaling form for resistance in two dimensions is
  \[ R_{\square} = R_c F(\delta/T^{1/\nu z}) \]
- The control parameter \( \delta = |t - t_c| \) or \( |H - H_c| \), where \( t \) is thickness, and \( H \) is magnetic field, and \( t_c \) and \( H_c \) are critical thickness and critical fields.
- Other parameters such as stress and charge density, or disorder at fixed thickness, might also be effective tuning parameters.
- Close enough to the transition it probably does not matter what tuning parameter is used.
\( R_{\square} = R_c F(\delta/T^{1/\nu z}) \)

\( \delta = |t - t_c| \text{ or } |H - H_c|, \)
Field Driven Transition  (Kapitulnik et al.)
Thickness Driven Transition in Different Magnetic Fields

(Markovic)
Phase Diagram in Field and Thickness
There is a proposed critical point at $\Delta_c$ and a line of critical points in the $T = 0$ plane dividing the vortex and electron glass phases. This is inferred from Hall effect studies.
Qualitative Understanding of the SI Transition in Disordered Systems

- Need to understand the many-body wave function
- It is a sum over components corresponding to different numbers of Cooper pairs.
- State is **rigid** with respect to Cooper pair scattering. This rigidity is the *phase coherence*.
- In a disordered system pairs move freely between spatially localized regions, and there is no information regarding their number in any region.
- Insulators lack phase coherence, and are characterized by fixed numbers of Cooper pairs in localized regions.
Superconductivity

- Order parameter $\Psi = \Psi_0 e^{i\phi}$, where the amplitude is $\Psi_0$ and the phase is $\phi$.
- Macroscopic wavefunction
- Zero resistance occurs when $\Psi$ is nonzero and phase time-independent.
- $\Psi_0 \neq 0$ and the resistance can be simultaneously nonzero in the presence of phase fluctuations.
- This is local superconductivity as contrasted with global superconductivity where $R = 0$. 
Phase and number uncertainties obey a generalized form of the Heisenberg Uncertainty Principle.

\[ \Delta \phi \Delta N \geq 1 \]

The Superconductor-Insulator Transition is governed by this Quantum Uncertainty.
“Dirty Bosons” (the original model for the SI transition)

- Bose particles in a random medium, originally considered in the context of helium, are called "dirty bosons."
- Model Cooper pairs by point-like, charge 2e bosons, interacting with a long range Coulomb force.
- Boson picture correctly describes critical behavior of superconductors.
- Boson density increased through the critical density results in a $T = 0$ transition from an insulating localized Bose-glass phase (localized Cooper pairs) to a superconducting phase.
Dirty Bosons continued

- Application of a magnetic field adds vortices, which interact with a logarithmic potential and behave as quantum point particles.
- As field is increased, the gas of point vortices can in principle Bose condense at some critical field. This results in an Bose insulator with localized Cooper pairs.
- Insulator at zero temperature is a Bose condensate of vortices with the original Bose particles being localized.
Duality

- Adding Cooper Pairs by increasing film thickness results in a Cooper pair condensate, and adding vortices by applying a perpendicular magnetic field leads to a vortex condensate.
- Vortices and charges are related by a duality transformation.
- Insulator at zero temperature is a Bose condensate of vortices with the original Bose particles being localized.
Conductance at Criticality

- At criticality, conductivity is a finite and metallic.
- Resistance per square at criticality is predicted to be universal, its value depending upon the universality class of the transition, and not on microscopic details.
- With self-duality, the resistance at criticality is $\hbar/4e^2$.
- Interaction potentials between charges and between vortices would have to be identical which is problematical for real films.
Self-Duality

\[ V = \left( \frac{h}{2e} \right) \dot{\vartheta} = \left( \frac{h}{2e} \right) \dot{n}_v \]

\[ I = 2e \dot{n}_c \]

\[ R = \frac{V}{I} = \frac{h}{(2e)^2} \left( \frac{\dot{n}_v}{\dot{n}_c} \right) \]

\[ \dot{n}_v = \dot{n}_c \]
Experimental Situation

- Tunneling studies suggest that there are amplitude fluctuations as well as phase fluctuations.
- Vanishing of energy gap in tunneling implies that there are no Cooper pairs on the insulating side.
- There is evidence of vorticity on the insulating side which would appear to contradict this.
- Issue of Universal Limiting Resistance - The fact that it is not, suggests that there is other physics.
Tunneling

Disappearance of gap is used to argue that transition is dominated by amplitude fluctuations. Curves correspond to different magnetic fields.
<table>
<thead>
<tr>
<th>Material</th>
<th>$R_0 (k\Omega)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MoC</td>
<td>3.2 ± 0.4</td>
</tr>
<tr>
<td>Bi on Ge</td>
<td>6.42 ± 0.2</td>
</tr>
<tr>
<td>Pb</td>
<td>6.75 ± 0.8</td>
</tr>
<tr>
<td>In-InO$_x$</td>
<td>6.97 ± 1.4</td>
</tr>
<tr>
<td>Ga on SiO</td>
<td>6</td>
</tr>
<tr>
<td>Bi on SiO</td>
<td>6</td>
</tr>
<tr>
<td>Pb on SiO</td>
<td>6</td>
</tr>
<tr>
<td>Nb</td>
<td>6.4</td>
</tr>
<tr>
<td>DyBaCuO</td>
<td>6.4</td>
</tr>
<tr>
<td>NdCeCuO</td>
<td>6.4</td>
</tr>
<tr>
<td>Pb on Ge</td>
<td>9.94 ± 0.4</td>
</tr>
<tr>
<td>Bi on Sb</td>
<td>10</td>
</tr>
<tr>
<td>Pb</td>
<td>15 ± 2</td>
</tr>
<tr>
<td>Al on Ge</td>
<td>18.6 ± 1.7</td>
</tr>
</tbody>
</table>
Spread in values may be in part extrinsic as there are morphological differences between films of different materials.

Material-specific features such as the strength of spin-orbit coupling could influence the universality class.

Data used to analyze the transition may not be from the critical regime of the $T = 0$ phase transition.

Possible coupling to fermionic channels leading to a dissipation-controlled transition.

Percolation effects.
Superconductor-Insulator or Metal-Insulator Transition?

Some data are consistent with the transition being from an insulator to a normal metal rather than to a superconductor, e.g., the data shown for DyBa$_2$Cu$_3$O$_{7-x}$. 
Other evidence of metallic phases in 2D

• Scaling theory of localization: NO 2D METAL [Abrahams et al. PRL 42, 673 (1979)]

• MIT of 2DEG in Si MOSFETS [Kravchenko et al. PRB 50, 8039 (1994)]

• Break down of scaling in amorphous MoGe [Mason and Kapitulnik, PRL 82, 5341 (1999)] (See figures at right)
Magnetic Field-Induced Metallic Phase

α-Be films have been studied by Butko and Adams. Application of a parallel magnetic field appears to eliminate hopping conduction.

The field also alters the electronic density of states.
Gallium Films without an $a$-Ge Underlayer
Bose Metal

D. Das and S. Doniach PRB 60, 1261 (1999), cond-mat/0102442.
• Assumes: Bose-Hubbard model
  High filling limit
  Two order parameters
• Includes: Josephson coupling
  Onsite and n.n. Coulomb interactions
• Bose metal (BM) = Cooper pairs and vorticies
  mobile but not condensed.
  Occurs when n.n. ~ onsite
  Stabilized by dissipation
  More than one point on phase diagram
• Resistivity of the metallic phase:

\[ R_{sq} \approx R_Q \left[ \frac{R_n}{R_c} - 1 \right]^{2\nu} \]
Bose Metal

D. Dalidovich and P. Phillips, cond-mat / 0005119
• Interaction induced Bose metal
• Cancellation: Exponentially small population of bosonic quasiparticles Exponentially long scattering time

T. Ng and D. Lee, PRB 63, 144509 (2001)
• No Bose metal at T=0
• Crossover regime at finite T
True Superconductivity?

Signature of Crossover leading to scaling may be illusory.

In experiments in MoGe in a field, crossover at relatively high temperatures is followed by a “true” superconducting transition.

There may be a similar problem in the QHE
Possibility that metallic phase results from coupling of the system to a dissipative bath.

Direct SI transition is still possible for very weak coupling, while for stronger coupling the system goes through a metallic phase.
Shimshoni et al - percolation

Insulator – activated tunneling of Cooper pairs between superconducting domains.

Superconductor-vortices tunnel from one insulating domain to another.

This approach can explain values of $\nu_z$. It turns out that an exponent product of 1.2 to 1.4 could correspond to percolation exponents.

This suggests that all or most of the experiments may be evidence of percolation.
Don’t Jump to Conclusions!

- Extrapolation to zero temperatures is risky - get colder.
- Scaling fits are far from perfect - do a lot better.
- Not clear that films are being cooled at all. (solve issues of thermal noise, external noise and heating by measuring current).
- Finite Size Scaling may not include data at either sufficiently low temperatures or with values of the tuning parameter close enough to criticality for the analysis to be valid.
- Films may not be homogeneous and ideal.
Kelvinox 400 Dilution Refrigerator (Hernandez)

0.004K limiting temperature

15T field
Evolution of Superconductivity with Thickness

Needs cooled filters to be certain that this is intrinsic.
A New Generation of Samples: Polyacene Crystals as Model 2D Superconductors

Schematic structure of an organic single crystal field-effect transistor.

Channel resistance of pentacene, tetracene and anthracene field-effect devices as a function of temperature. The electron density in each channel is approximately one electron per molecule.
Hole Doping of $C^{60}$