Bose metals as a disruption of the KT transition in thin films

D. Dalidovich
J. Wu
\[ \beta = \frac{d \ln g(L)}{d \ln L} = d - 2 \]

no metals for \( d \leq 2 \)

2D MIT

2D IST

Kravchenko 1995

unresolved?

Goldman 1989
insulator-superconductor transition

\[ \rho = \frac{h}{4e^2} \]

Hebard/Paalanen
phase-only critical bosons

\[ H = E_C \sum_i p^{2}_{\theta_i} + J \sum_{\langle ij \rangle} \cos(\theta_i - \theta_j) \]

\[ \frac{\partial}{\partial \theta_i} \longleftrightarrow \theta_i \]

\[ \langle n_i \rangle \neq 0 \quad \text{and} \quad \langle \theta_i \rangle \neq 0 \]

\[ g = E_C / J \]

vortex-particle duality
(MPAF 1990)

\[ \Delta \theta \Delta n \geq \hbar \]
insulator-superconductor transition

\[ \rho = \# \frac{\hbar}{4e^2} \]

\[ \# = \infty \]
\[ g_c \]
\[ \# = 1 \]
\[ \# = 0 \]

\[ \sigma = 0 \]
\[ g = \frac{E_C}{J} \]
\[ \rho = 0 \]

\[ G(k, \omega) = k^{d/2-\eta} F \left( \frac{\omega}{k^z} \right) \]
does this theory really work?
non-universality of $\rho_c$?
is a metallic phase for bosons possible?
activated region shifts to lower T as H increases

metal below $H_{c2}$

mason/kapitulnik (2000)
not a refrigeration artifact

bose metal

\[ \rho \propto (H - H_{\text{SM}})^\gamma \quad \gamma \approx 3 \]
phases disrupting superconductivity

**dissipation (Kapitulnik)**

**Bose-Hubbard model (disordered)**

**disorder-localised insulator (short-range hopping)**
Do Superconductors Have Zero Resistance in a Magnetic Field?

Center for Superconductivity Research, University of Maryland, College Park, Maryland 20742
(Received 31 October 2000; published 23 July 2001)

We show that dc voltage versus current measurements of a YBa$_2$Cu$_3$O$_{7-\delta}$ film in a magnetic field can be collapsed onto scaling functions proposed by Fisher et al. [Phys. Rev. B 43, 130 (1991)] as is widely reported in the literature. We find, however, that good data collapse is achieved for a wide range of critical exponents and temperatures. These results strongly suggest that agreement with scaling alone does not prove the existence of a phase transition. We propose a criterion to determine if the data collapse is valid, and thus if a phase transition occurs. To our knowledge, none of the data reported in the literature meet our criterion.

In this paper we have focused on the absence of a vanishing dc resistance—the popular definition of a superconductor. One can also use ac measurements [21] to probe an Ohmic to inductive transition in complex linear impedance [22]. However, we are not aware of ac measurements that demonstrate the Ohmic to inductive transition in both magnitude and phase, which is necessary for agreement with scaling. A critical comparison between dc and ac on the same sample would be important for this issue.

In conclusion, we have found that a data collapse is not sufficient evidence for a transition to zero resistance since the critical temperature at which this occurs is not uniquely determined. In addition to obeying scaling, $I$-$V$ data must also satisfy the opposite concavity signature we propose in order to determine a $T_c$ below which the resistance vanishes. Since our $I$-$V$ data plus many in the literature do not show this signature, a transition to zero resistance has not yet been demonstrated despite the fact that much of the data scales. Furthermore, this signature can be used as a criterion to judge future $I$-$V$ data in order to help settle the controversy surrounding critical phenomena in the high-temperature superconductors.
is a Bose metal possible?

\[ \sigma_{dc} = \lim_{T \to 0} \lim_{\omega \to 0} \sigma(\omega, T) \]

collision-dominated transport Damle/Sachdev (hydrodynamic regime)
\[ H = E_C \sum_i p_{\theta_i}^2 + J \sum_{\langle ij \rangle} \cos(\theta_i - \theta_j) \]
qp collisions

\[ n \propto e^{-m/T} \]

\[ \tau \propto e^{m/T} \]

\[ \sigma \propto n\tau \sim O(1) \]

\[ \sigma = \frac{2}{\pi} \frac{e^{*2}}{\hbar} \]
the insulator is a metal

but it is fragile

\[ \frac{1}{\tau} \rightarrow \frac{1}{\tau} + \eta \]

\[ \sigma \rightarrow 0 \]
\[ F[\psi] = \int d^2 r \int d\tau \left\{ \left[ \left( \nabla + \frac{ie^*}{\hbar} \vec{A}(\vec{r}, \tau) \right) \psi^*(\vec{r}, \tau) \right] \right. \\
\left. \cdot \left[ \left( \nabla - \frac{ie^*}{\hbar} \vec{A}(\vec{r}, \tau) \right) \psi(\vec{r}, \tau) \right] \right. \\
+ \kappa^2 |\partial_\tau \psi(\vec{r}, \tau)|^2 + m^2 |\psi(\vec{r}, \tau)|^2 \right\} + L_{\text{dis}} \\
L_{\text{dis}} = \eta \sum_{\vec{k}, \omega_n} |\omega_n| |\psi(\vec{k}, \omega_n)|^2 \]

\text{ohmic dissipation}
\[
\sigma(\omega) = \frac{(e^*)^2}{2\pi\hbar\omega} \int_0^\infty k^3 dk \int_{-\infty}^{\infty} \coth \frac{z}{2T} dz \left[ (G^R(z) - G^A(z)) \\
[G^R(z) + G^A(z) - G^R(z + \omega) - G^A(z - \omega)] \right].
\]

\[
G^{R(A)}(z) = (k^2 + m^2 - \kappa^2 z^2 \pm i\eta z)^{-1}
\]

\[
\sigma(\omega = 0) = \frac{(e^*)^2}{2\pi\hbar} \int_0^\infty k^3 dk \int_{-\infty}^{\infty} \frac{dx}{\sinh^2 x} \times \frac{8\eta^2 T^2 x^2}{[(\epsilon_k^2 - 4T^2\kappa^2 x^2)^2 + 4T^2\eta^2 x^2]^2}
\]

\[
\sigma = \frac{2e^2}{\pi\hbar} \frac{\pi\kappa^2 T}{\eta} \ln \frac{\kappa T}{m} \quad \eta/\kappa \ll m
\]
include interactions

\[ m = \kappa T \exp \left( -\frac{2\pi|\Delta|}{UT} \right) \quad |\Delta| \gg \kappa T \gg \eta/\kappa \]

\[ \Delta = \delta + U[\Lambda + O(\eta/\kappa)]/4\pi\kappa \]

\[ \sigma = \frac{2e^2}{\pi h} \frac{\pi\kappa^2 T}{\eta} \ln \frac{\kappa T}{m} \quad \eta/\kappa \ll m \]

\[ \sigma = \frac{4e^2}{h} \frac{\pi\kappa^2 |\Delta|}{\eta U} \quad \eta/\kappa < m \]

T-independent conductivity
but conductivity diverges at low $T$

$$\sigma = \frac{e^2}{h} \exp \left( \frac{4\pi |\Delta|}{UT} \right) \quad \kappa T < \eta/\kappa$$

dissipation alone is not enough
\[ H = -E_C \sum_i \left( \frac{\partial}{\partial \theta_i} \right)^2 - \sum_{\langle i, j \rangle} J_{ij} \cos(\theta_i - \theta_j) \]

\[ P(J_{ij}) = \frac{1}{\sqrt{2\pi J^2}} \exp \left( -\frac{(J_{ij} - J_0)^2}{2J^2} \right) \]

3-phases

- phase glass
- paramagnet
- superconductor
\[ \ln[Z] = \lim_{n \to 0} \left( [Z^n] - 1 \right)/n \]

\[ S_i = (\cos \theta_i, \sin \theta_i) \]

\[ Q^{ab}_{\mu \nu}(\vec{k}, \vec{k}', \tau, \tau') = \langle S^a_{\mu}(\vec{k}, \tau) S^b_{\nu}(\vec{k}', \tau') \rangle \]

\[ D(\tau - \tau') = \lim_{n \to 0} \frac{1}{Mn} \langle Q^{aa}_{\mu \mu}(\vec{k}, \vec{k}', \tau, \tau') \rangle \]

Edwards-Anderson
order parameter

\[ \Psi^a_{\mu}(\vec{k}, \tau) = \langle S^a_{\mu}(\vec{k}, \tau) \rangle \]

SC order
\[ \mathcal{F}[\Psi, Q] = \mathcal{F}_{SG}(Q) + \sum_{a, \mu, k, \omega_n} (k^2 + \omega_n^2 + m^2)|\Psi^a_\mu(k, \omega_n)|^2 \]

\[ -\frac{1}{\kappa t} \int d^d x \int d\tau_1 d\tau_2 \sum_{a, b, \mu, \nu} \Psi^a_\mu(x, \tau_1) \Psi^b_\nu(x, \tau_2) Q^{ab}_{\mu \nu}(x, \tau_1, \tau_2) \]

\[ + U \int d\tau \sum_{a, \mu} [\Psi^a_\mu(x, \tau) \Psi^a_\mu(x, \tau)]^2 \]

\[ Q^{ab}_{\mu \nu} (k, \omega_1, \omega_2) = \beta (2\pi)^d \delta^d(k) \delta_{\mu \nu} \left[ D(\omega_1) \delta_{\omega_1 + \omega_2, 0} \delta_{ab} + \beta \delta_{\omega_1, 0} \delta_{\omega_2, 0} q^{ab} \right]. \]

\[ D(\omega) = -|\omega|/\kappa \]

\[ z = 2 \]
\( \mathcal{F}_{\text{gauss}} = \sum_{a,k,\omega_n} (k^2 + \omega_n^2 + \eta|\omega_n| + m^2)|\psi^a(\vec{k},\omega_n)|^2 \)

\[-\beta q \sum_{a,b,k,\omega_n} \delta_{\omega_n,0} \psi^a(\vec{k},\omega_n)[\psi^b(\vec{k},\omega_n)]^* \]

new term propagator is replica off-diagonal

\( G_{ab}^{(0)}(\vec{k},\omega_n) = G_0(\vec{k},\omega_n)\delta_{ab} + \beta G_0^2(\vec{k},\omega_n)q\delta_{\omega_n,0} \)
conductivity

\[ \sigma(\omega = 0, T \to 0) = \frac{2}{3} \frac{\eta q_{\text{EA}} e^*}{m^4} \frac{e^*}{h} \quad z = 2 \]

\[ \propto (g - g_c)^{-2z
u} \]

experiments: \[ \rho \propto (H - H_{\text{SM}})^\gamma \quad \gamma \approx 3 \]
is a phase glass stiff?

\[ \Delta F \propto \rho_s k^2 ? \]
\[ \rho_s \neq 0 \]

\[ \rho_s = 0 \]
\[ \Delta E \propto L^\theta \]
\[ \theta < 0 \text{ no stiffness} \]

FIG. 3. Scaling plot of the root-mean-square current \( I_{\text{rms}} \) in two dimensions according to the form expected if \( T_c = 0 \), Eq. (10). We see acceptable scaling of the data at low temperatures. Deviations at higher \( T \) are presumably due to corrections to scaling. This plot is for \( \theta = -1/\nu = -0.39 \).

Numerical Study of Order in a Gauge Glass Model

J. M. Kosterlitz and N. Akino
Department of Physics, Brown University, Providence, Rhode Island 02912

FIG. 1. Size \( L \) dependence of domain wall energy in 2D. Both RT and BT measurements are shown. Solid lines are power-law fits. Error bars are not shown if smaller than symbol size.
Do Superconductors Have Zero Resistance in a Magnetic Field?


Center for Superconductivity Research, University of Maryland, College Park, Maryland 20742

(Received 31 October 2000; published 23 July 2001)

We show that dc voltage versus current measurements of a YBa$_2$Cu$_3$O$_{7-8}$ film in a magnetic field can be collapsed onto scaling functions proposed by Fisher et al. [Phys. Rev. B 43, 130 (1991)] as is widely reported in the literature. We find, however, that good data collapse is achieved for a wide range of critical exponents and temperatures. These results strongly suggest that agreement with scaling alone does not prove the existence of a phase transition. We propose a criterion to determine if the data collapse is valid, and thus if a phase transition occurs. To our knowledge, none of the data reported in the literature meet our criterion.
\[ F_{\text{gauss}} = \sum_{a, \vec{k}, \omega_n} (k^2 + \omega_n^2 + \eta |\omega_n| + m^2) |\psi^a(\vec{k}, \omega_n)|^2 \]

\[-\beta q \sum_{a, b, \vec{k}, \omega_n} \delta_{\omega_n, 0} \psi^a(\vec{k}, \omega_n)[\psi^b(\vec{k}, \omega_n)]^* \]

bose metal

is the ground state of bosons in a finite magnetic field?

is the vortex glass a metal?

glassy physics
experiments+
theory
indicate
yes
what is $z$ in the bose metal?

$z = 2$

bose metal has particle hole symmetry (phase glass)
\[ \rho_{xy} = 0 \quad \text{p-h symmetry} \]
vortex glass is a metal