

Magnetoresistance of granular superconductors at low temperatures

Igor Beloborodov

Materials Science Division, Argonne

University of Chicago

*Collaboration: K. Efetov, A.I. Larkin,
A. Lopatin, Ya. Fominov, V. Vinokur*

Rev Mod Phys 79, 469 (2007)



Argonne
NATIONAL
LABORATORY

... for a brighter future



U.S. Department
of Energy

UChicago ►
Argonne_{LLC}

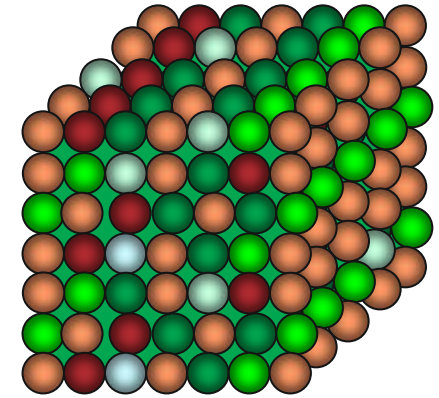


Office of
Science
U.S. DEPARTMENT OF ENERGY

A U.S. Department of Energy laboratory
managed by UChicago Argonne, LLC

Motivation:

New materials paradigm: Artificial Nanosolids



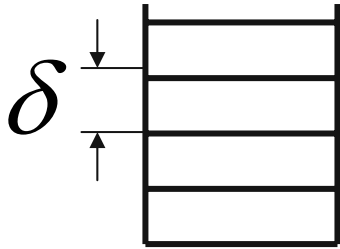
metals, semiconductors, **superconductors**,
ferromagnets, hybrid nanostructures

Fundamental physical parameters for nanosolids

- i) Nanograin sizes – ***electron confinement***
- ii) Coupling between grains – ***electron tunneling***
- iii) Electron interaction – ***Coulomb blockade***
- iv) Dimensionality – ***multiple tunneling pathways***

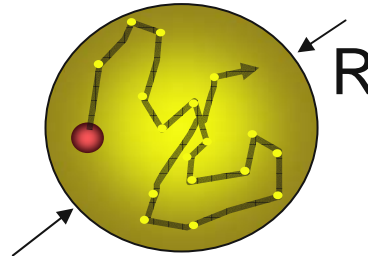
Properties of a single grain

confinement



mean energy
level spacing

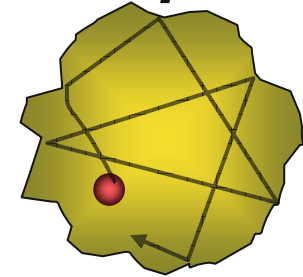
disorder in grain



diffusive

$$\tau = \frac{1}{E_T} = \frac{R^2}{D}$$

imperfect shape



ballistic

$$\tau = \frac{1}{E_T} = \frac{R}{v_F}$$

$g_0 = E_T / \delta$ - single grain conductance

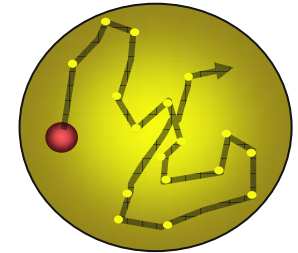
15 nm Al grain: $\delta \approx 0.1 \text{ meV}$ $E_T \approx 10 \text{ meV}$

Single superconducting grain

Focus on grain sizes > 7 nm

$$\Delta > \delta$$

*condition for
superconductivity
in a single grain*



Anderson'59

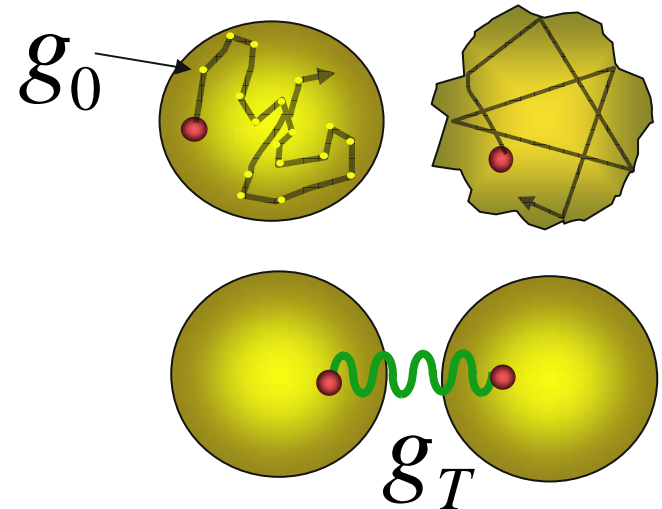
Δ - superconducting energy gap

$\Delta \sim \delta$ - big fluctuations of Δ destroy
superconductivity

Nanosolids characterized by two conductances

g_0 - *grain conductance*

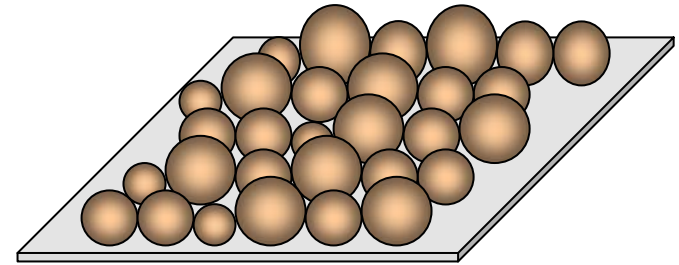
g_T - *tunneling conductance*



$g_0 > g_T$ - **granular**

$g_0 \approx g_T$ - **homogeneous**

Array of superconducting grains



Assumptions: $\delta < t, \Delta, E_C < E_T$
good metal \nearrow small grains ($R < \xi$)

R - single grain size

ξ - coherence length for corresponding bulk sample

Model Hamiltonian

$$\hat{H} = \hat{H}_{BCS} + \hat{H}_T$$

$$\hat{H}_{BCS} = \hat{H}_0 - |\lambda| \sum_{i,k,k'} a_{i,k}^+ a_{i,-k}^+ a_{i,-k} a_{i,k}$$

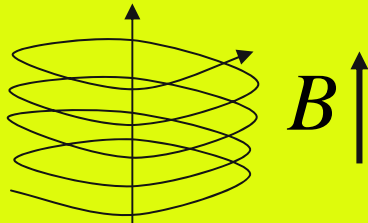
free e + disorder

e-e attraction

$$\hat{H}_T = \sum_{ij} t_{ij} a_i^+ a_j + c.c. \quad \leftarrow \quad \text{tunneling}$$

Effect of magnetic field on superconductivity

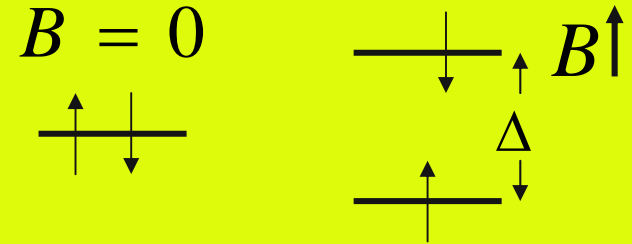
Orbital



bulk - $B_C^{or} \xi^2 \approx \Phi_0$
 grain - $B_C^{or} \xi R \approx \Phi_0$

$$\frac{B_C^{or}}{B_C^Z} \approx \frac{R_C}{R}$$

Zeeman



$$\mu_B B_C^Z \approx \Delta$$

$$R_C = \frac{\Phi_0}{\sqrt{D \Delta}} - \text{critical sample size}$$

diffusion coefficient

$R > R_C$ - orbital

$R < R_C$ - Zeeman

Magnetoresistance of granular superconductors

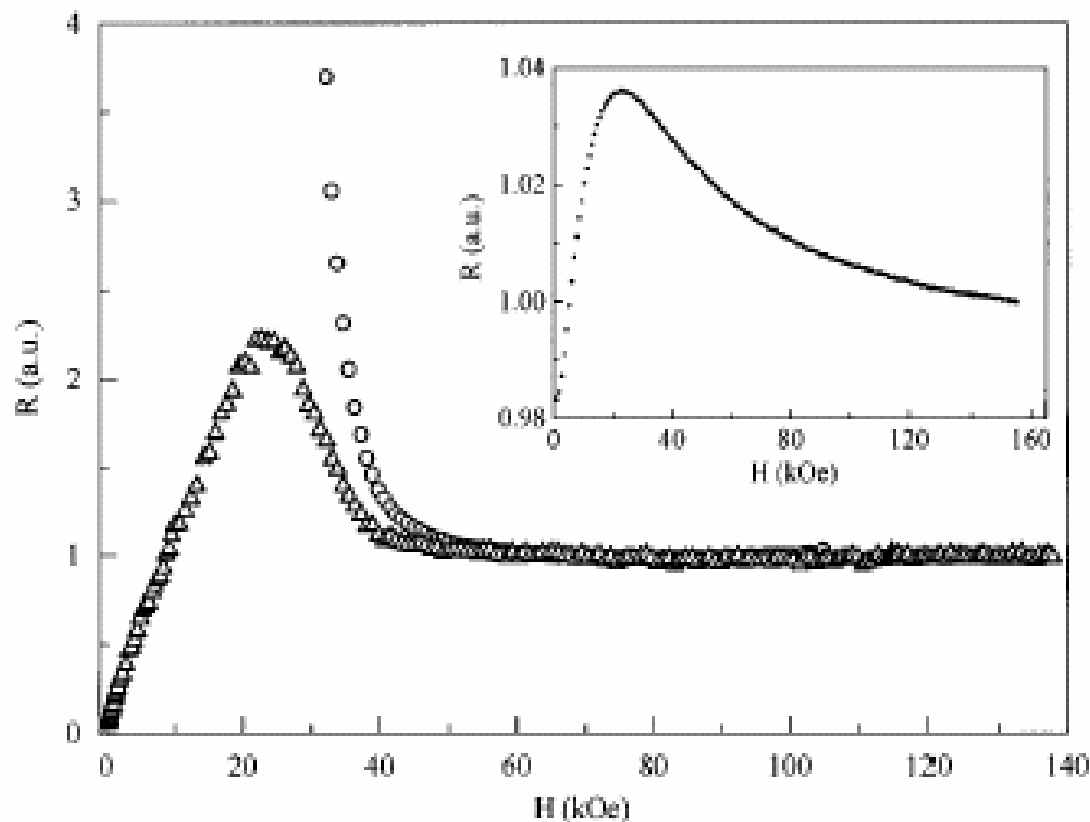
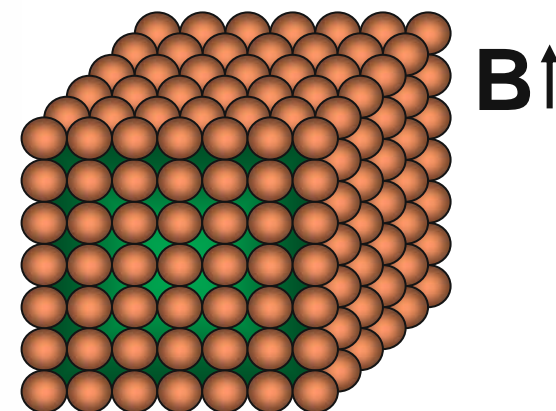


FIG. 4. Normalized resistances of sample 1 (open circles) and sample 2 (triangles) as a function of applied magnetic field measured at $T = 0.3$ K. Inset: magnetoresistance of sample 3 at $T = 2$ K normalized at $H = 160$ kOe.

Gerber et al' 97



Experiment

- grain size 120 Å
- B up to 17 T

$$T_C \approx 1.58 K \quad (B = 0)$$

Magnetoresistance of granular superconductors

$$\sigma = \sigma_1 + \sigma_2 + \sigma_3$$

single electron
tunneling

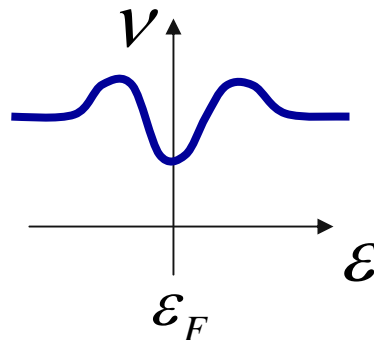
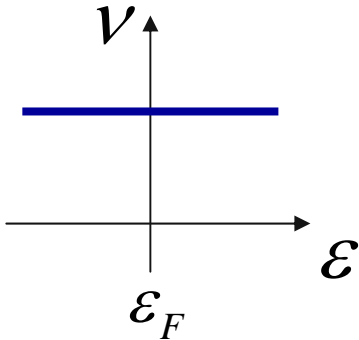
virtual Cooper
pair tunneling

interference

$$\sigma_1 \sim V_i(\varepsilon)V_j(\varepsilon)$$

$$\sigma_{2,3} \sim T^2 \text{ at } T \ll T_C$$

no interaction disorder & interaction



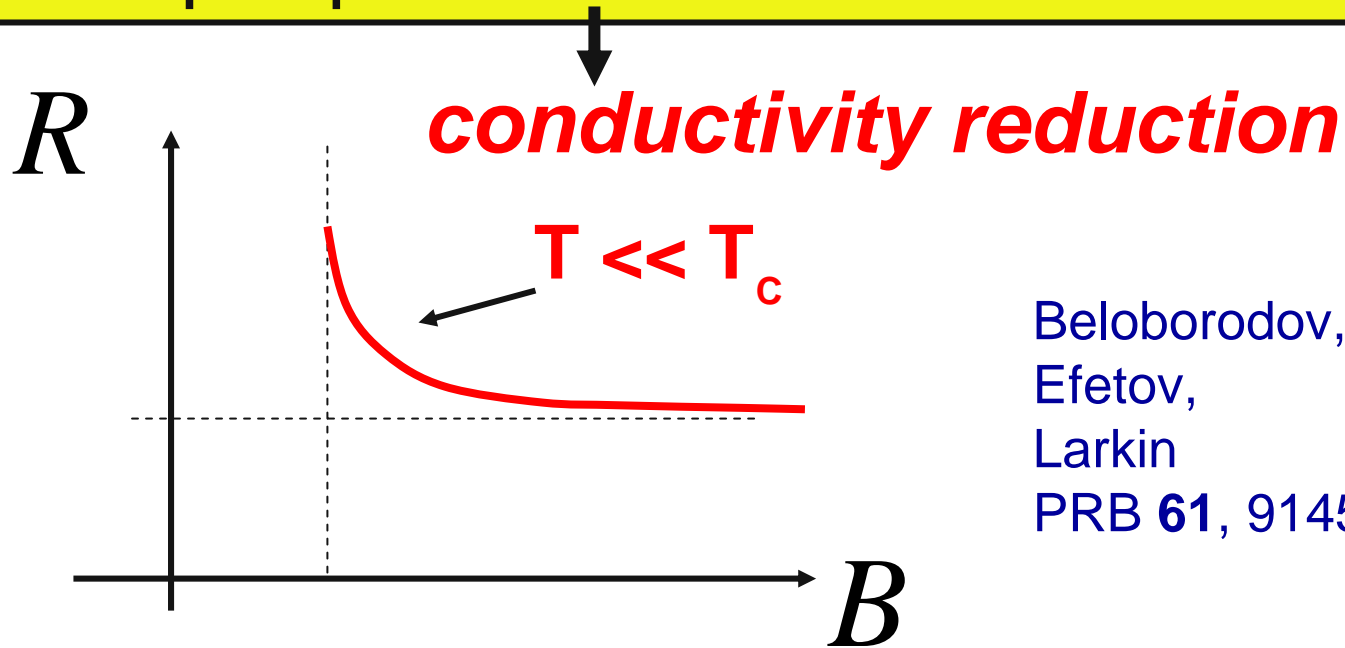
Cooper pairs localized

no current contribution

suppression of conductivity

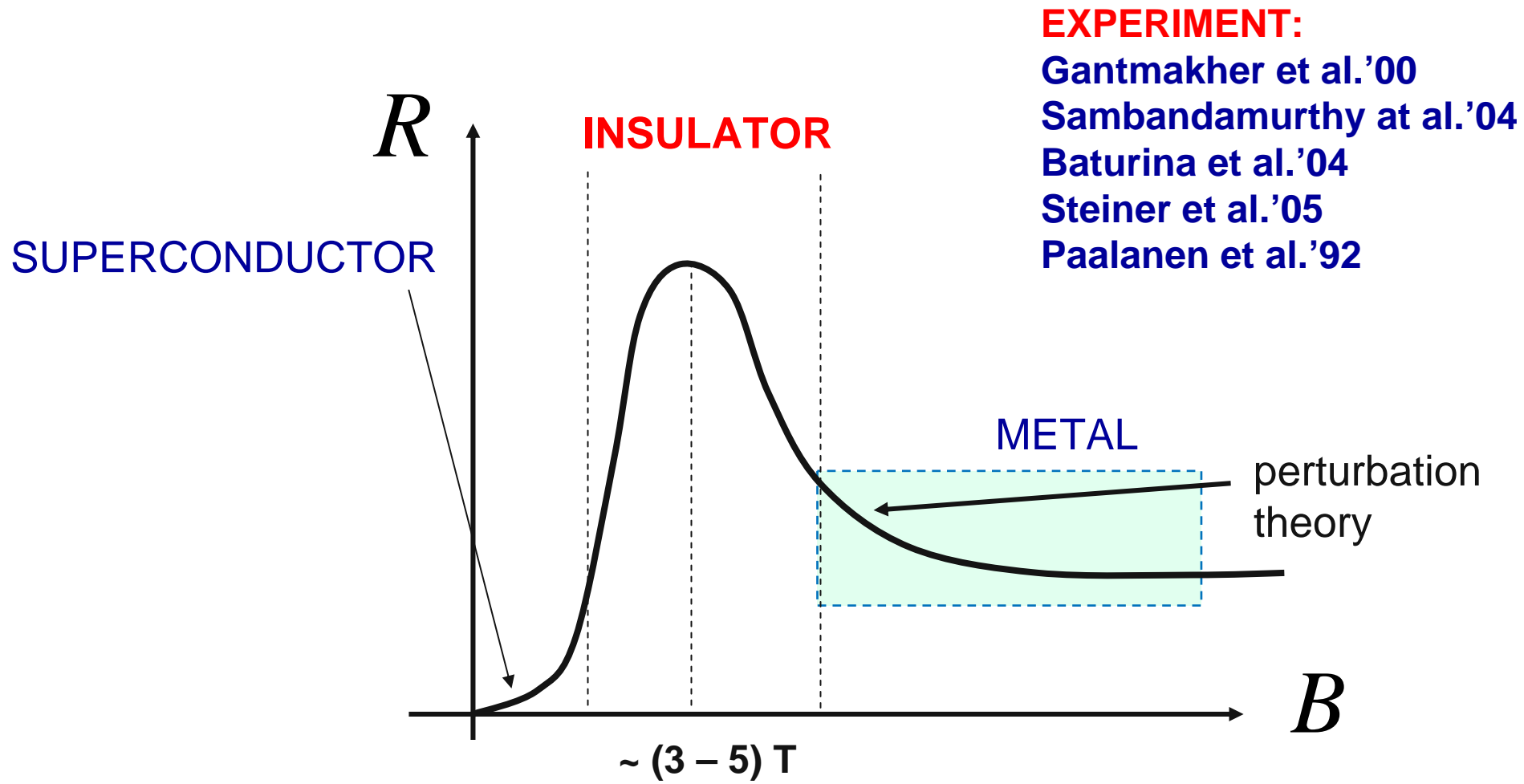
Magnetoresistance of granular superconductors

- 1) Superconducting fluctuations at **low temperatures** and **high magnetic fields** lead to density of states suppression
- 2) All Cooper pairs are localized



Beloborodov,
Efetov,
Larkin
PRB **61**, 9145 (2000)

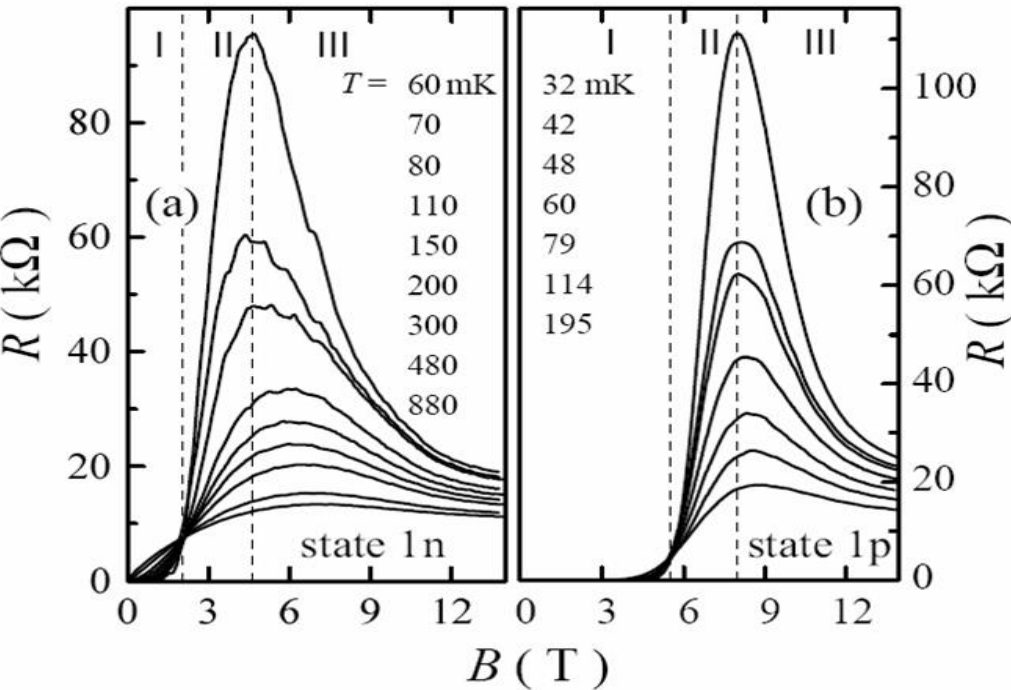
Insulating state of granular superconductors



Insulating state of granular superconductors

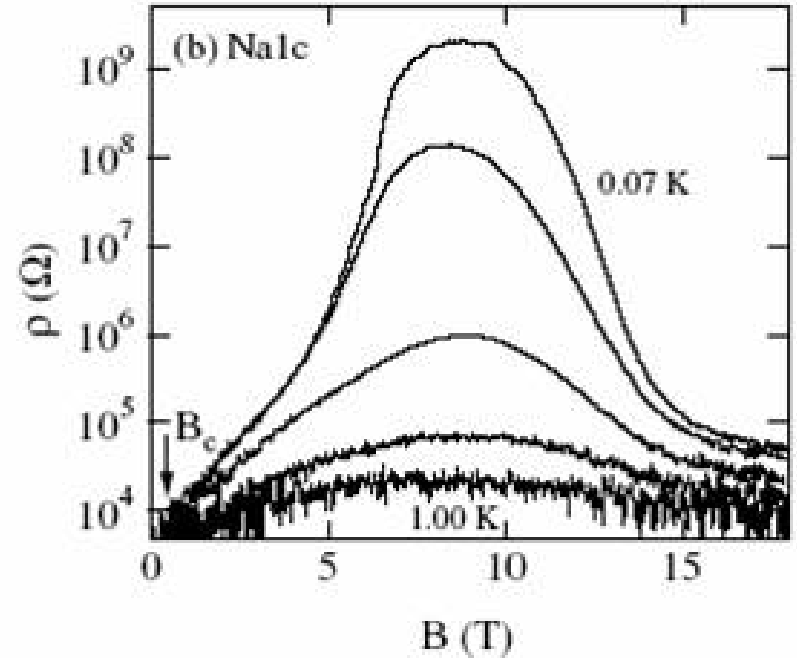
perpendicular

parallel



Gantmakher, et al ' 2000

In-O, perpendicular field



G. Sambandamurthy et el ' 2004

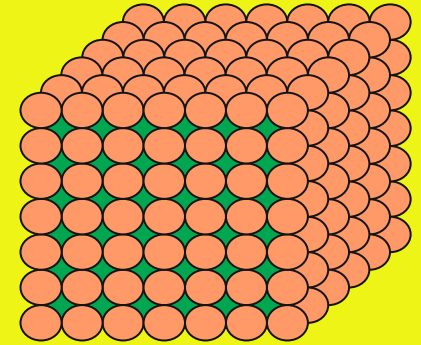
Experiment: strong grains coupling

Superconductor – Insulator transition in granular metals

Efetov ' 80

$$E_c \sim E_J - \text{SI transition}$$

Insulating state possible for $E_c > E_J$



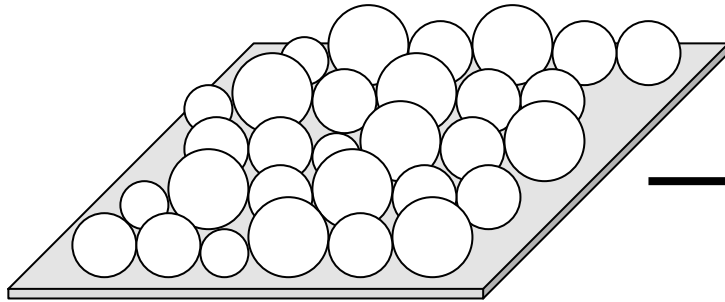
experiment: $g > 1$, $E_c \rightarrow E_c^{\text{eff}} \sim \Delta/g$

$E_J \sim g \Delta \gg E_c^{\text{eff}} \rightarrow$ superconducting state

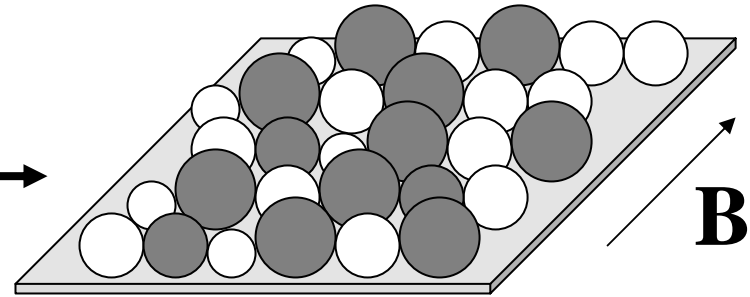
We need different model !

Insulating state of granular superconductors

no magnetic field



applied magnetic field



- *grains of slightly different sizes*
- *magnetic field \rightarrow change relative fraction of superconducting and normal grains*

In 2D exist concentrations of sites where simultaneously neither black no white sites percolate

Insulating state: theoretical description

$$g_{ns} \gg g_{nn}, g_{ss}$$

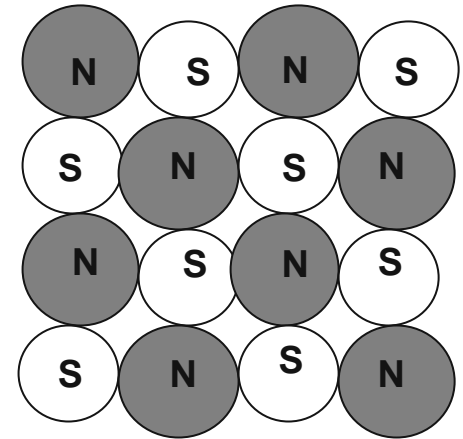
$$S = S_{c_i} + S_{ns}$$

for $g_{ns} \gg 1$

$$S \sim \int d\tau \int d^2q E_c(q) |\dot{\Phi}_q(\tau)|^2$$

$$E_c(q) = (E_c^{-1} + B[1 - E_q])^{-1},$$

Due to magnetic field :



$$B \sim g / \Delta_0,$$

$$E_q = \frac{1}{2} \sum_a \cos qa$$

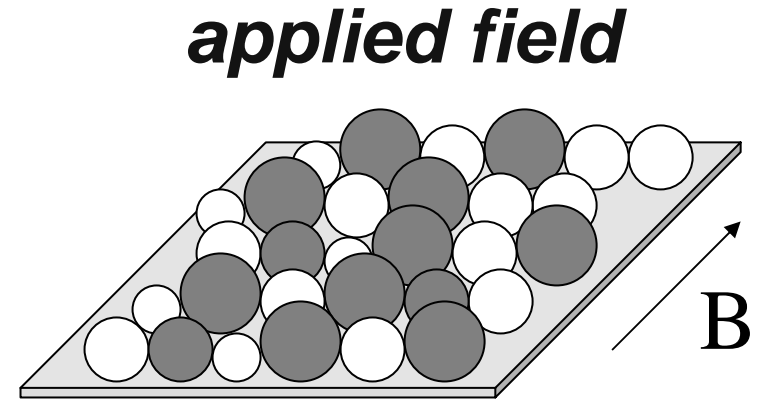
Insulating state of granular superconductors

gap in electron spectrum

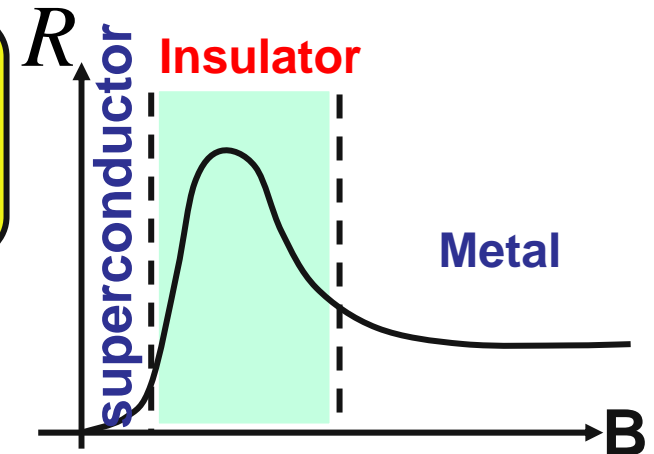
$$\Delta \sim (\Delta_0 / g) \ln (g E_C / \Delta_0)$$

Δ_0 - superconducting gap at $B=0$

g - tunneling conductance, E_C - charging energy



Conductivity : $\sigma \sim \exp(-\Delta/T)$

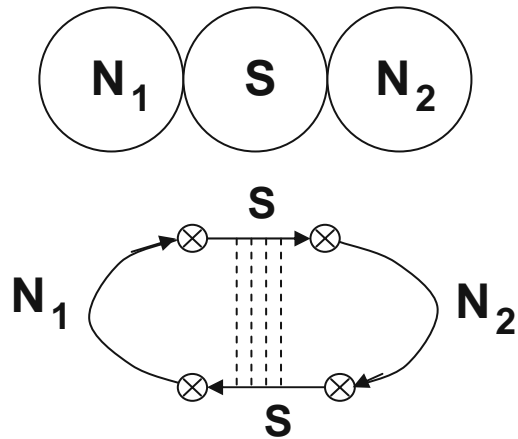


What is the applicability of this result ?

Stability of insulating state

with respect to formation of **normal** state

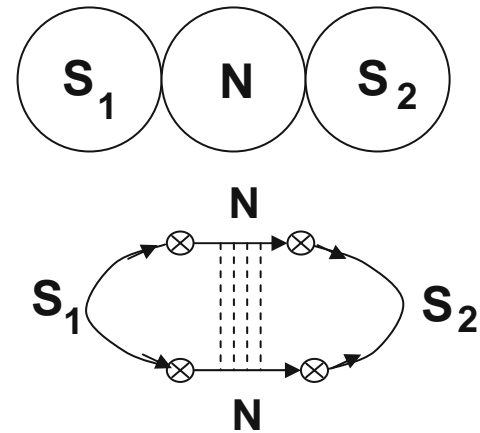
Electron tunneling via virtual state



small for $g < \sqrt{\Delta_0/\delta}$

with respect to formation of **superconducting** state

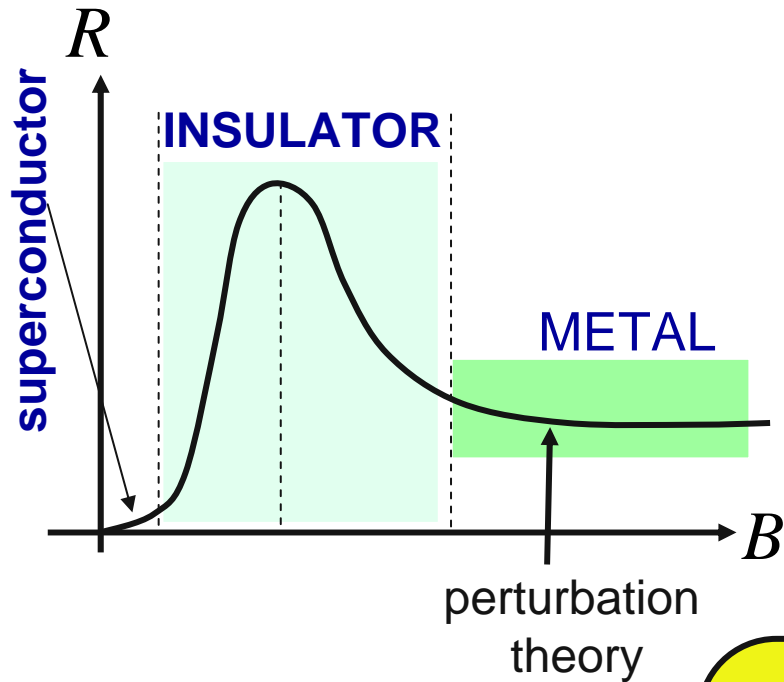
Cooper pair tunneling



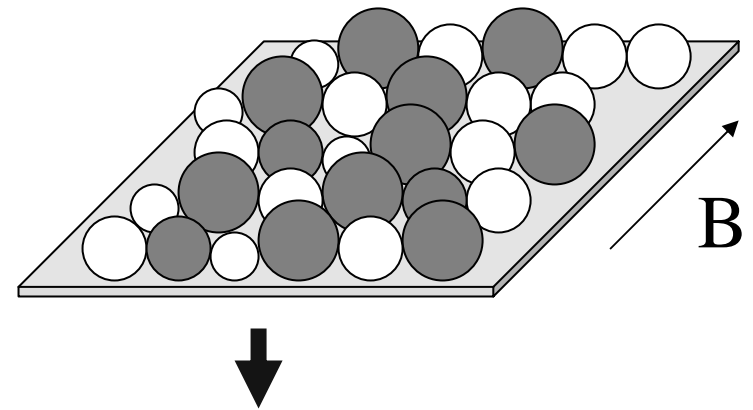
small for $g < (\Delta_0/\delta)^{1/3}$

Insulating state is stable for : $g < (\Delta_0/\delta)^{1/3}$

Summary



magnetic field



stable for :

$$g < (\Delta_0 / \delta)^{1/3} \quad \longleftrightarrow$$

$$\sigma \sim \exp(-\Delta/T)$$

$$\Delta \sim (\Delta_0/g) \ln(gE_C/\Delta_0)$$