Electrodynamics of granular aluminum from superconductor to insulator: observation of collective superconducting modes

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work done with

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Outline

- **Introduction**: collective superconducting modes
- **Optical spectroscopy** with superconducting resonator
- **Study of granular aluminum versus $\rho$**:
  - phase diagram SIT: $\Delta$, $T_c$, $J$, $E_c$
  - various sub-gap optical absorptions for $h\nu<2\Delta$
**Superconducting collective modes**

Superconductivity: condensate of electrons with a *unique* phase

\[
|\Psi| e^{i\theta}
\]

breaking the rotational U(1) symmetry.

| $|\Psi|$-fluctuation | $\theta$-fluctuation |
|----------------------|----------------------|
| “Higgs” mode         | “Goldstone” mode     |

at $q=0$

- $E=2\Delta$
- $E=0$ or $\omega_{\text{plasma}}^* \gg \Delta$

Both modes optically inactive in conventional superconductor

**BUT…**

*with Coulomb interaction*
Below $2\Delta$: Higgs or Goldstone mode?

Excess of optical absorption below $2\Delta$ interpreted as:

The Higgs mode in disordered superconductors close to a quantum phase transition


Optical signatures of the superconducting Goldstone mode in granular aluminum: experiments and theory

Below 2\(\Delta\): Higgs or Goldstone mode?

**Excitation modes in disordered superconductors:**

The Higgs mode is a Goldstone mode emerging at the superconductor-to-insulator transition (SIT). It is associated with a symmetry breaking that occurs in disordered systems.

**Experimental observation:**

In the current study, using a new optical spectroscopy technique, various resolved sub-gap optical absorptions have been observed. These absorptions were detected at 100mK, with an energy \(\Delta E \sim 1\)GHz = 4\(\mu\)eV = 0.04\(\text{cm}^{-1}\).

**Optical signatures:**

Optical signatures of the superconducting Goldstone mode in granular aluminum have been observed. The experiments and theory confirm the presence of this mode.

References:


Image captions:

- Optical signatures of the superconducting Goldstone mode in granular aluminum: experiments and theory.
- D. Sherman and colleagues.
KIDs

\( \text{hv} > 2\Delta \)

**RLC resonator:**

- **design and electrical measurement**
- **photonic detection principle:** \( \text{hv} > 2\Delta \)


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1. **feed-line:** Al

2. **superconducting resonator**

   thin film ~tens of nm substate=Si, MgO, Al\(_2\)O\(_3\),...

\[ f_0 = (LC)^{-1/2} \]

\( L \sim \text{kinetic inductance of the superfluid} \)

\( L \sim 1/n_s \)

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**N\text{\textael}**

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Optical spectroscopy with superconducting resonators

KIDs

\[ h \nu > 2 \Delta \]

RLC resonator:
design and electrical measurement


photon detection principle :
\[ h \nu > 2 \Delta \]

\[ f_0 = (LC)^{-1/2} \]

L \sim \text{kinetic inductance of the superfluid}
L \sim 1/n_s

|S_{21}| (dBm)

\[ \delta f \]

\[ \delta \nu \]

\[ f_0 \sim 1 \text{ GHz} \]

\[ f \]

\[ C \]

\[ L \]

\[ 1 \]

\[ \text{feed-line: Al} \]

\[ \text{superconducting resonator} \]

thin film \sim \text{tens of nm}
substrate=Si, MgO, Al_2O_3,..
Optical spectroscopy with superconducting resonators

KIDs

hv > 2Δ

RIH design and electrical measurement

= Kinetic Inductance Detector : KID detection hv > 2Δ through δf

f₀ = (LC)⁻¹/²

L ~ kinetic inductance of the superfluid
L ~ 1/nₘ

frequency shift: δf due to nₛ↓

Q-factor↓ due to dissipation↑
Optical spectroscopy with superconducting resonators

pure Al 20nm-thick

For bulk Al:
Tc = 1.2K, 2Δ = 85 GHz

hv > 2Δ

incident photon frequency [GHz]
Optical spectroscopy with superconducting resonators

$\hbar \nu < 2\Delta$

present a: $\text{InO}_x$:
$T_c \sim 2.8\text{K}, \ 2\Delta \sim 260\text{ GHz}$\(^1\)

\(^1\) Sacépé et al, PRB 91, 220508 (2015)

unpublished

$d$-STM and optical spectroscopy agreement
**Optical spectroscopy with superconducting resonators**

**SKIDs**

hv < 2Δ

**SKID :** Sub-gap Kinetic Inductance Detector (2017).

**detection through δf for a specific hv < 2Δ in**

\[ \frac{L}{\pi} \]

- hv-selection = resonance mode (or any collective mode?)
- hv-absorbed 
  - \( \rightarrow \) superfluid current density \( J \) increases
  - \( \rightarrow \) superfluid density \( n_s \) decreases
  - \( \rightarrow \) kinetic inductance \( L_k \sim 1/n_s \) increases
  - \( \rightarrow \) resonance frequency shift

\[
L(J) = L(0)[1 + J^2/J_*^2 + .]^{1,2} \quad J_* = 2/3^{3/2}J_c
\]

1 see any textbook on superconductivity (de Gennes, Tinkham)


**low Jc is a priori more adapted for sub-gap detection**
Optical spectroscopy with superconducting resonators

Tunable sub-gap radiation detection with superconducting resonators

- $\nu < 2\Delta$

$\nu$-selection = resonance mode (or any collective mode?)
$\nu$-absorbed -> superfluid current density $J$ increases
-> superfluid density $n_s$ decreases
-> kinetic inductance $L_k \sim 1/n_s$ increases
-> resonance frequency shift

$$L(J) = L(0)[1 + J^2/J_*^2 + ..]^{1,2}$$
$$J_* = 2/3^{3/2}J_c$$

1 see any textbook on superconductivity (de Gennes, Tinkham)

low $J_c$ is a priori more adapted for sub-gap detection
Granular Aluminium: resistivity

**FIG. 2:**

- **Superconductor left of $T_c$-dome**
  - $#A$
  - $#B$
  - $#C$
  - $#D$

- **Superconductor right of $T_c$-dome**
  - $#E$
  - $#F$
  - $#G$
  - $#H$

- **Insulator**
  - $#I$
  - $#J$

**Critical Temperature Evolution Close to the $T_c$-Dome**

- The superconductor to insulator transition is clearly visible on the resistivity measurements displayed on figure 2. The evolution of the superconducting gap determined theoretically for various samples is shown.

**Bottom:** resistivity (µΩ.cm) as a function of temperature for eight different samples.

**Temperature:**
- 100 K
- 250 K

**Room Temperature Resistivity**
- For samples #C to #H a semiconducting behavior is observed and superconductivity is confirmed by the dashed line that corresponds to critical temperatures obtained on samples prepared in different composition of superconducting granular aluminum, for increasing room temperature.

**Metals to Semiconducting Change of Behavior**

- The critical temperature dome shape is confirmed as the inflection point of the resistive transitions. Errors bars cover the distance to get a nulle resistance. Resistivity and temperature are in linear scales.

**Critical Temperatures Versus Resistivity**

- Figure 2 focuses on the superconducting transition. Temperature is in linear scale, $10^2K < T < 300 K$. The dashed line correspond to critical temperatures, black dot, correspond to the inflection point of the resistive transitions. Errors bars cover the distance to get a nulle resistance. Resistivity and temperature are in linear scales. Bottom: critical temperatures versus resistivity at different scales.

**Superconductor-Insulator Transition**

- The superconductor to insulator transition is clearly visible on the resistivity measurements displayed on figure 2. The evolution of the superconducting gap determined theoretically is shown for various samples.

**Critical Temperature Determination**

- In that context, the critical temperatures have been determined as the inflection point of the resistive transitions. Errors bars cover the distance to get a nulle resistance. Resistivity and temperature are in linear scales.

**Superconducting Gap Determination**

- The superconducting gap determined theoretically for various samples is shown.

**Temperature Scale**

- The temperature scale is linear, ranging from $10^2$ K to 300 K.

**Graphs**

- Graphs illustrate the resistivity as a function of temperature for different samples, demonstrating the superconductor-insulator transition.

**Samples**

- Samples #A to #H exhibit different behaviors, with #A showing metallic behavior, #B showing superconducting behavior, and others showing semiconducting behavior.

**Substrates**

- Different substrates (aluminum oxide) are used, with #A and #E on aluminum oxide, and others on a matrix of aluminum oxide.
Granular Aluminium: Tc dome shape
Granular Aluminium: optical spectroscopy with superconducting resonators

Samples

(a)

- Ground plane
- Feedline

1

2

21

22

(b)

- $f_1$
- $f_{22}$

$\sim 400\mu m$

325$\mu m$

12$\mu m$

212$\mu m$

Al

grAl

$\text{Al}_2\text{O}_3$

from Martin-Puplett spectrometer
Granular Aluminium: optical spectroscopy with superconducting resonators

Set-up

source = 300K black body
Fourier-Transform spectrometry
**Granular Aluminium: optical spectroscopy**

left of Tc-dome

- T_{mes} \approx 100 \text{ mK}
- T_{c} = 1.90 \text{ K}
- T_{c} = 2.04 \text{ K}
- T_{c} = 2.17 \text{ K}

right of Tc-dome

- T_{c} = 2.08 \text{ K}
- T_{c} = 2.03 \text{ K}
- T_{c} = 1.99 \text{ K}
- T_{c} = 1.91 \text{ K}
Granular Aluminium: optical spectroscopy

left of Tc-dome

right of Tc-dome

\( T_{\text{mes}} \approx 100 \, \text{mK} \)

\( 2\Delta, \omega_p, \omega_G \)

\( T_c = 1.90 \, \text{K} \)

\( T_c = 2.04 \, \text{K} \)

\( T_c = 2.17 \, \text{K} \)

\( T_c = 2.08 \, \text{K} \)

\( T_c = 2.03 \, \text{K} \)

\( T_c = 1.99 \, \text{K} \)

\( T_c = 1.91 \, \text{K} \)
Granular Aluminium: phase stiffness $J$

$$J = \frac{\hbar}{4e^2} \frac{\pi \Delta}{R_{sq}}$$

$\ll$

$$J = \frac{\hbar^2}{4e^2 L_s}$$

$\longrightarrow$

$J_\Delta$ from measurements

$L_s$ obtained by RF-simulation adjusting the actual resonance frequencies $f=(LC)^{-1/2}$
Granular Aluminium: Coulomb $E_c$

$$E_c = \frac{e^2}{4\pi\varepsilon_0\varepsilon_r d} \frac{s}{s + d/2}$$

$d = 3\text{nm}-6\text{nm} \quad s = 0.5\text{nm} \quad \varepsilon_r = 8.5$

$$E_c \sim 100+/- 50 \text{ K}$$
Granular Aluminium: phase diagram

interplay of J, $E_c$ and $\Delta$

- $J > E_c$: “metal”
  $\Delta/T_c \sim 1.78$

- $\Delta < J < E_c$: “non-metal”
  $\Delta/T_c \sim 2.10$
  sub-gap absorptions

- $J < \Delta$: insulator

agreement with Pracht and al, PRB 93, 100503(R) 2016.
Granular Aluminium: $\omega_p$

Scaling of $\omega_p$ with $\Delta$
Granular Aluminium: $\omega_G$

Scaling of $\omega_G$ with $J$ (?)
Granular Aluminium

- sub-gap optical absorption in agreement with literature but now resolved features
- onset when \( J \lesssim E_c \) suggest phase fluctuations
- literature explains 1 mode observation of 2 (or more?) modes
- \( \text{N. Maleeva and al, Nat. Com 9, 3889 (2018)} \)
  \( \omega_p = \text{saturation of 2D plasmon dispersion} \)
  quantitative agreement but for multipeaks
- \( \omega_G ? \ldots \)
Conclusion

• Sub-gap modes in (various) superconductors

• Origin(s) under debate

• Of interests for 3 communities:
  - astrophysics instrumentation (photon detection)
  - quantum engineering (high-\(L_K\) vs dissipation?)
  - fundamental studies
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THANK YOU