Workshop on Supersolid 2008

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Non-classical response of solid helium confined in porous media

E. Kim

KAIST, Republic of Korea
Superflow in solid helium

Eunseong Kim

KAIST, Republic of Korea
Outline

- Brief history on supersolid experiments
- $^3$He effects
- New experiments at KAIST
The first observation of superflow in solid helium & $^3$He effects at Penn State
Supersolid experiments at KAIST
Part 1

BRIEF HISTORY OF SUPERSOLID EXPERIMENTS

Observation of Non-Classical Rotational Inertia

E. Kim and M. Chan
Superfluidity & Bose Einstein Condensation

Superfluid $^4$He
Kapitza (1978)

Superfluid $^3$He
Lee, Osheroff, Richardson (1996)
Theory
Leggett (2003)

BEC in a bose gas
$= \text{Super-gas}$
Cornell, Ketterle, Wieman (2001)

Super-Solid $= \text{Solid with Superfluidity}$?
Overlap of wavefunctions ~ Exchange amplitude ~ nearly zero in classical solid

\[ T > T_O \]

\[ \lambda_{dB} \propto \sqrt{\frac{1}{T}} \ll a \]

Finite exchange amplitude

\[ T < T_O \]

→ Coherent exchange at very low temperature
Superfluidity in solid is not impossible!

If solid $^4$He can be described by a Jastraw-type wavefunction that is commonly used to describe liquid helium then crystalline order (with finite fraction of vacancies) and BEC can coexist.


Andreev and Lifshitz assume the specific scenario of zero-point vacancies and other defects (e.g. interstitial atoms) undergoing BEC and exhibit superfluidity.

No experimental evidence of superflow in solid helium prior to 2004.

- **Plastic flow measurement**

- **Torsional oscillator**

- **Mass flow**

- **\(P_v(T)\) measurement**

- **Ultra sound Measurements**
Ultrasound velocity and dissipation measurements in solid $^4$He with 27.5ppm of $^3$He

The results are interpreted by the authors as showing BEC of thermally activated vacancies above 200mK.


However, such a clear ‘anomaly’ was not seen in other ultrasound experiments of Goodkind.
Quantum exchange of particles arranged in an annulus under rotation leads to a measured moment of inertia that is smaller than the classical value

\[ I(T) = I_{\text{classical}} [1 - f_s(T)] \]

\( f_s(T) \) is the supersolid fraction. Its upper limit is estimated by different theorists to range from \( 10^{-6} \) to 0.4; Leggett: \( 10^{-4} \)
Ideal torsional oscillator

Torsion cell containing helium

Drive

Detection

Be-Cu Torsion rod
Ideal torsional oscillator

Torsion cell containing helium

Drive

Detection

Be-Cu Torsion rod
Ideal Torsional oscillator

\[ \tau_o = 2\pi \sqrt{\frac{I}{K}} \]

I : rotational inertia of torsion cell
K: torsion constant of the torsion Rod

Change of rotational inertia, \( I \), can be detected by increase (or decrease) of the resonant oscillation period, \( \tau_o \).

→ Detection of NCRI
Torsional Oscillator for solid helium confined in Vycor glass

Torsion cell with Vycor glass

Al shell

Vycor disk

Drive

5cm

Detect
Solidification of helium in Vycor

Vycor glass

Characteristic
Pore diameter = 7nm
Porosity = 30%

![Diagram of solidification phases](image)
Blocked Capillary methods: Solidification of helium

- Heat drain
- Solid blocks fill-line
- Be-Cu torsion rod and fill-line
- Gravity
Solid $^4$He at 62 bars in Vycor glass

Period shifted by 4260ns due to mass loading of solid helium

$\tau^* = 966,000\text{ns}$
Solid helium in Vycor glass

\[ f_0 = 1024\text{Hz} \]

- Pressure = 62 bar
- Total mass loading = 4260 ns
- Measured decoupling, \(-\Delta \tau_0 = 17\text{ns}\)
- NCRIF = 0.4%
Solid helium in Vycor glass

\[ f_0 = 1024 \text{Hz} \]

- Its viscosity should be smaller than \( 1.5 \times 10^{-11} \) Pa·s, which is \( 10^5 \) times smaller than that of normal liquid helium.
- Viscosity penetration depth \( \ll 7 \text{nm} \)

\( \tau^* = 971,000 \text{ns} \)
Strong velocity dependence

- For liquid film adsorbed on Vycor glass
  \[ v_c > 20 \text{ cm/s} \]

- For superflow in solid \(^4\text{He}\)
  \[ v_c < 30 \mu\text{m/s} \]
Weak Pressure Dependence from 40 to 65 bar

![Graphs showing weak pressure dependence from 40 to 65 bar]
Control experiment: solid (bcc)$^3$He
Effect of $^3$He impurities

Data shifted vertically for easy comparison

$\tau^* = 971,000\text{ns}$
Bulk solid helium in annulus

Torsion cell with helium in annulus

Torsion rod

Torsion cell

Detection

Drive

Filling line

Mg disk

Al shell

Solid helium in annular channel
Superflow in bulk solid helium

E. Kim and M. H. W. Chan,

- Resonant frequency = 912 Hz
- Sample pressure 51bar
- Total mass loading = 3012ns
- Mass decoupling, $-\Delta \tau_0 = 41$ns
- NCRIF = 1.4%
Non-Classical Rotational Inertia Fraction

\[ \rho_S / \rho \]

\[ |v|_{\text{max}} \]

\[ \tau_{\text{Total mass loading}} = 3012 \text{ns at 51 bars} \]

\[ NCRIF = \frac{\Delta \tau}{\text{total mass loading}} \]
Solid $^4$He at various pressures show similar temperature dependence, but the measured supersolid fraction shows scatter with no obvious pressure dependence.
Pressure dependence of NCRI

Blue data points were obtained by seeding the solid helium samples from the bottom of the annulus.

What are the causes of the scatter in NCRI?

Scatter in NCRI is larger in bulk than in Vycor!
Strong and ‘universal’ velocity dependence in all annular samples.

\[ \omega R v_C \sim 10 \mu m/s \]

\[ \int v_s \, dt = \frac{h}{m} \cdot n \]

\[ v_s = \frac{h}{2 \pi R m} \cdot n \]

For \( n = 1 \) the value is approximately 3.16 \( \mu m/s \).

Evidence of vortices? \( v_C \) is larger for cylindrical samples.
Control experiment: blocked annulus

With a barrier in the annulus, there is no simple superflow and the measured superfluid decoupling should be vastly reduced.

Torsion cell with helium in annulus

Channel
OD = 15mm
Width = 1.1mm

Filling line

Mg Disk

Mg barrier

Al shell

Solid helium in annular channel

Solid helium

Mg disk

Al shell
Irrotational Flow

- Superfluids exhibit potential (irrotational) flow
  - For our exact dimensions, NCRIF in the blocked cell should be about 1% that of the annulus*

\[ \psi = |\psi| e^{i\phi} \]

\[ -\frac{\hbar}{m} \nabla \phi = v_s \]

*E. Mueller, private communication.
Reversibly blocked annulus

Rittner & Reppy at Cornell

**Blocked cell**
- Solid inertia

**Open cell**
- Nonclassical rotational inertia

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**Graph:**
- **ΔPeriod [ns]** vs. **Temperature [K]**
- **Solid** line: Blocked annulus, gap 73 μm
- **Open** line: Open annulus, gap 73 μm
NCRI has been reproduced by

- Reppy group
  - Disorder & Supersolidity: annealing and confinement effect

- Shirahama group
  - NCRI in nano pores & 2D supersolid on Grafoil

- Kubota group
  - Solid helium under rotation: New vortex state?

- Kojima group
  - Frequency dependence & hysteresis

- Kim Group at KAIST
Recent experiments other than TO

- DC flow
  - NO pressure driven flow by Beamish group
  - $\Delta \mu$ driven flow at LS coexistence through liquid channel by Balibar group
  - Umass Sandwich by Hallock group
  - High P Liquid in Vycor – Solid – High P Liquid in Vycor

- Pressure measurements
  - No anomaly on L-S boundary at low temperature: $P \sim T^4$
  - Extra $T^2$ dependent term detected away from melting boundary

- Neutron scattering and X-ray diffraction
  - The resolution is marginal to see the effect

- Shear modulus measurement
  - Frequency, $^3$He impurity, temperature dependence, & hysteresis qualitatively similar to NCRI
Deviation from Debye solid $T^3$ dependence

Coincide with NCRI
Summary 1.

NCRI observed in solid helium below ~ 0.2K
Temperature dependence reproducible, 
but NCRI F varies by 3 orders of magnitude.

Strong velocity dependence observed

The addition of 3He impurities enhances the onset.
Part 2

\[ ^3 \text{HE EFFECTS} \]

Dislocations and NCRI

Kim, Xia, West, Xi, Clark, and Chan
\( ^3\text{He} \) Impurity effect (in Vycor)  

Two torsional oscillators for $^3$He dependence studies

<table>
<thead>
<tr>
<th></th>
<th>Open Cylinder TO1</th>
<th>Open cylinder TO2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Confining dimension</td>
<td>0.7cm</td>
<td>1 cm</td>
</tr>
<tr>
<td>A/V (cm$^2$/cc)</td>
<td>5.9</td>
<td>7.2</td>
</tr>
<tr>
<td>ResonantFrequency</td>
<td>783Hz</td>
<td>1298Hz</td>
</tr>
<tr>
<td>Covered $X_3$ concentration</td>
<td>47ppb - 30ppm</td>
<td>1ppb-100ppb</td>
</tr>
</tbody>
</table>
This work is done in the B/T facility of the high magnetic field lab. Dr. Xia (University of Florida)

Total mass loading due to solid helium
\[ \tau_{\text{He}} - \tau_{\text{empty}} = 3939 \text{ns} \]

Shift in the period
\[ \Delta \tau = 1 \text{ns} \]

Supersolid fraction
\[ \sim 1 \text{ns}/3939 \text{ns} \]
\[ \sim 0.025\% \]

Torsional oscillator
\[ f_0 = 1298 \text{Hz}, \quad Q \sim 1 \times 10^6 \]
Effects of $^3$He impurities
In bulk solid samples in cylindrical torsion cells

Kim et. al, PRL 100,065301 (2008)
Effects of $^3$He impurities

Addition of $^3$He
1) enhances the onset of NCRI
2) broadens transition (longer high temperature tale)

NCRI marches up to higher temperature with increasing $^3$He concentration.
Effect of $^3$He impurities in bulk samples
Onset T vs. $^3$He impurities

Kim et. al, PRL 100,065301 (2008)
Observations

Strong $^3$He impurity dependence
Only 1 ppb of $^3$He impurity introduces very dramatic change in the onset.

Addition of $^3$He enhances the onset temperature and broadens the transition

The characteristic behavior is very similar to the observed $^3$He impurity pinning (by condensation) of the dislocation line.
Dislocations

- Dislocation line is common defect in crystals
- Created by thermal and mechanical stresses

Two of the common types: edge & screw
Dislocations

- Dislocation line is a common defect in crystals
- Created by thermal and mechanical stresses

Dislocation density, $\Lambda$, : Total length of dislocation lines per unit volume. (cm$^{-2}$)

Dislocation lines form complicated networks and intersect at nodes which are localized.
Dislocations

- The density of dislocations in crystals determined by an analysis based on the vibrating string model of dislocation.

\[ \frac{\Delta v_d}{v_0} = R \int \frac{\Delta v(l)}{v_0} l N(l) \, dl \]

\[ \alpha = R \int \alpha(l) l N(l) \, dl \]
Dislocations

- Information on \( \Lambda \) comes mostly from ultrasound attenuation measurements between 5 to 50 MHz.

\[
\frac{\Delta v(l)}{v_0} = - \frac{4v_0^2}{\pi^3} \frac{\omega(l)^2 - \Omega^2}{[\omega(l)^2 - \Omega^2]^2 + (B\Omega/A)^2}
\]

\[
\alpha(l) = \frac{4v_0}{\pi^3} \frac{\Omega^2 B/A}{[\omega(l)^2 - \Omega^2]^2 + (B\Omega/A)^2}
\]

- Dislocation density in poor crystals \( \sim 10^9 \) per cm\(^2\)
- (constant volume\(^1\))
- Dislocation density in good crystals \( \sim 10^5 - 10^7 \) per cm\(^2\)
- (constant pressure\(^2\) or temperature\(^3\) above \( \sim 0.5\mathrm{K} \))
- Dislocation density in best crystals \( \sim 0 \) to 100
- (constant temperature\(^4\) growth below \( \sim 0.2\mathrm{K} \))

Granato-Lücke theory

Dislocations intersect on a characteristic length scale of \( L_N \sim 1 \rightarrow 5\mu m \)

\( ^3 \)He atoms also can be detached

Break-away of \( ^3 \)He impurities \( \rightarrow \) Reduces shear modulus
Dislocation pinning

- Dislocation density, $\Lambda = 5 \sim 10^{10} \text{ cm}^{-2}$
  Solid helium grown by a constant volume method; $\Lambda = 10^5$ to $10^9 \text{ cm}^{-2}$

- Dislocations intersect on a characteristic length scale of $L_N$
  (if $\Lambda \sim 10^5$ to $10^9 \text{ cm}^{-2}$)
  $0.1 < \Lambda L_N^2 < 0.3 \rightarrow L_N \sim 0.1$ to $10 \mu \text{m}$

- Dislocations can also be pinned by $^3$He impurities
  $L_{IP} \sim$ Distance between $^3$He atoms
$^3$He and dislocation

- Actual $^3$He concentration on dislocation line is thermally activated

\[ x_3 = x_0 \exp \left( \frac{W_0}{T} \right) \]
$^3\text{He}$ and dislocation

- Actual $^3\text{He}$ concentration on dislocation line is thermally activated

\[
x_3 = x_0 \exp\left(\frac{W_0}{T}\right)
\]

*Typical binding energy is very small, $W_0$ is 0.3K to 0.7K
$^3$He and dislocation

• Actual $^3$He concentration on dislocation line is thermally activated

$$x_3 = x_0 \exp\left[\frac{W_0}{T}\right]$$

*Typical binding energy is very small, $W_0$ is 0.3K to 0.7K

• Pinning length due to $^3$He impurity

$$L_{IP} = \left(4\mu\right)^{1/3} b^2 W_0^{-1/3} x_0^{-2/3} \exp\left[-\frac{2W_0}{3T}\right]$$
$^3$He-dislocations interaction

Line was drawn by considering $W_0=0.42$K and average $L_{IP}$ pinning length~ 1.9μm.

Smaller lengths are expected for larger dislocation densities.

$L_{IP}$ $^3$He pinning length, $\mu$, shear modulus, $b$, Burger’s vector.

$T_{IP} = -2W_0\left(\ln\left[\frac{x_3^2L_{IP}^3W_0}{4\mu b^6}\right]\right)^{-1}$

Line was drawn by considering $W_0=0.42K$ and average $L_{IP}$ pinning length $\approx 1.9\mu m$.

Smaller lengths are expected for larger dislocation densities

$\rightarrow$ cross-over from network pinning to $^3$He pinning

$T_{50} \sim T_P$ : Below this temperature dislocation network is pinned by impurity

Why no difference in Vycor?

Much smaller pinning length is expected in Vycor glass (most of all dislocations are pinned)

Porous media: no substantial shear stress applied due to tortuous structure and small pore.

Vycor glass 7nm pores at 20 μm/s: $\sigma \sim 10^{-6}$ dyne/cm$^2$ = $10^{-7}$ Pa

100,000 times smaller stress causes similar strain of dislocation?
With strong confinements?

The graph shows the relationship between $T_{50}$ [mK] and $x_3$ [ppb]. The data points are color-coded to represent different materials and configurations:

- Purple triangles: TOF
- Red squares: TOP
- Orange circles: Annulus [22]
- Blue diamonds: AgCu - BC [5]

Key features:
- $L_N \approx 180\text{nm}$
- $L_N \approx 7\text{nm}$

The graph indicates that with strong confinements, the temperature $T_{50}$ increases significantly as $x_3$ increases.
Elastic properties of solid helium

- Shear modulus change


Shear modulus stiffened from dislocation pinning

Similar T, drive, freq, $^3$He dependence with NCRI
Elastic stiffening of solid helium at low temperature make the mechanical response faster. Accordingly increase the resonant frequency of TO.

Nussinov et al PRB 76, 014530(2007)
Stiffening of solid helium responsible for NCRI? No

Clark et al PRB 77 184513(2008)

Stiffening of solid helium increase the resonant frequency of TO. However, observed 5-20% shear modulus increase is too small to explain the NCRI

Blocked annulus results cannot be explained by shear modulus change
Summary

- **Dramatic effect of $^3$He impurities on supersolid $^4$He.**
  The addition of $^3$He impurity broadens transition and enhances the onset temperature.

- **NCRI is not solely due to $^3$He impurities**

- **The effect is probably related with dislocation pinning by $^3$He.**

  After dislocation motion pinned by $^3$He impurities supersolid phase appears.

  He3 impurities pin down dislocation lines and help to appearance of NCRI
Part 3

New experiments at KAIST

2D SUPERSOLID & DYNAMIC RESPONSE STUDY
New LT Lab at KAIST
New LT Lab at KAIST
Interior

Pumping room (basement) vibration is isolated with double gymbal structures.
Search for the supersolidity in 2D

Motivation

The nonsuperfluid inter layer

\[ \rho_s(T = 0) = n_4 - n_0 \]

From the Lennard-Jones potential

\[ V(z) = \frac{4C_3^3}{27D^2} \frac{1}{z^9} - \frac{C_3}{z^3} \]

We can calculate the attractive force between the atoms of the substrate and the atoms in the film.

<table>
<thead>
<tr>
<th>Atomic layer</th>
<th>Pressure by van der Waals force</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st layer</td>
<td>306.0 atm</td>
</tr>
<tr>
<td>2nd layer</td>
<td>19.1 atm</td>
</tr>
<tr>
<td>3rd layer</td>
<td>11.3 atm</td>
</tr>
<tr>
<td>4th layer</td>
<td>4.8 atm</td>
</tr>
</tbody>
</table>

25 atm >
Helium films

- Helium films below the coverage for onset of superfluid can be a supersolid system.

Helium films

- Reentrant superfluid phase in the second layer of $^4$He adsorbed on grafoil.
- They discussed "possible 2D supersolid"
Reentrant superfluid phase in the second layer of $^4$He adsorbed on graphite.

M. Hieda and Moses made very interesting observation on 2D amorphous solid helium, so called inert layer. Resonant frequency of QCM increased at very low temperature.

NO clear velocity dependence
Search for the supersolidity in 2D

* Porous Vycor glass
* Mass loading: 458 ns/layer

Period change in the inert layer

Superfluid transition of He films
Quest for lower amplitude

Vycor tube glued by stycas1266

CuNi capillary for feeding helium

Resonant frequency 738 Hz, Q-factor 8 * 10^5
Amorphous solid helium film on Vycor

![Graph showing the relationship between period and temperature for different layer densities.](image)
Thermal history: Unusual long time constant

Typical equilibration time of TO due to very high mechanical Q-factor at low temperature: $\sim 1000\text{sec}$

Below 0.1K we observed unusually extended equilibration time. Not fitted well with exponential decay function only. After few thousands sec. logarithmic time dependence is dominant.
Thermal history dependence was carefully revisited. Clark et al PRB 77, 184513(2008)

Meta-stable state
Vortex pinning mechanism or elastic anomaly could explain hysteresis
Long dissipation (amplitude) relaxation in bulk solid helium

Long time constant observed upon the change of TO drive amplitude in bulk TO cell. Aoki et al PRL 100, 215303 (2008)

\[ v_r = v_0 + A \exp\left(-\frac{t}{\tau}\right) + B \ln[t + t_0] \]

The exponential dependence: The mobility of dislocation (and pinning by 3He impurities) and vortex liquid interpretation are discussed in their paper. They argue that long dissipation relaxation is likely due to vortex liquid in solid helium.
Solid $^4$He confined in porous gold

The motion of the shear modulus change in porous media is reduced by small confinements.

- Porous Gold
  - Pore size ~180nm
  - Porosity ~71%
  - Surface area 0.66m$^2$
Solid $^4$He confined in porous gold

- Tostional oscillator
- Resonant frequency
  $\sim 948$ Hz
- $Q \sim 3 \times 10^5$
- No bulk space

Superfluid $^4$He in the porous gold
Solid $^4$He confined in porous gold

- Solid Helium was prepared by the BC (blocked capillary) method
- Starting Pressure: 60 bar
- Measured Sample pressure: 53 bar
- Samples grown by quench cooling
  3K -> 1K for 15 min.
- $^3$He: 0.3 ppm

Graphs showing:
- 1/Q x 10^6 vs Temperature [K]
- NCRI [K] vs Temperature [K]
- 216 μm/s, 656 μm/s, 2084 μm/s
Response to drive change

Long relaxation of NCRI when drive increases.

NCRI change looks hysteretic according to the drive change.
Response to drive change

Long relaxation of NCRI when drive increases.

NCRI change looks hysteretic according to the drive change.
Thank you for your attention!