Workshop on Supersolid 2008

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Brief introduction to the field

M. Chan

Pennsylvania State University, USA
Superfluid and supersolid

An introduction at the ICTP
‘Supersolid 2008’ workshop

Moses Chan

The Pennsylvania State University

Supported by National Science Foundation
Where is Penn State University?

State College
The Pennsylvania State University

Old Main

American elm trees

Beaver Stadium
Outline

- Quantum mechanics at low temperatures: de-Broglie wave-packets, Bose-Einstein Condensation in vapor and liquid.
- Experimental principle for the observation of Superfluidity: Torsional Pendulum
- Observation of superflow in solid helium
The lowest possible temperature $0 \text{ K} = -273.15 \degree \text{C} = -459.7 \degree \text{F}$

$10^6 = 1,000,000; \ 10^{-6} = 0.000001$

<table>
<thead>
<tr>
<th>Temperature Scale (K)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting of iron</td>
<td>10^3</td>
</tr>
<tr>
<td>Melting of ice ($273\text{K}=0\degree\text{C}$)</td>
<td>$10^2$</td>
</tr>
<tr>
<td>Evaporation of $^4\text{He}$ (4.2K)</td>
<td>10</td>
</tr>
<tr>
<td>Cosmic background (3K)</td>
<td>$10^{-1}$</td>
</tr>
<tr>
<td>Superfluid (2.18K)</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>Dilution Fridge temperature 10mK</td>
<td>$10^{-3}$</td>
</tr>
<tr>
<td>Superfluid $^3\text{He}$ (2mK)</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>Nuclear Demag. 1µK</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>Mixing Chamber (10mK)</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>Still (0.7K)</td>
<td></td>
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<tr>
<td>1Kpot (1.2K)</td>
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</tbody>
</table>
Quantum Theory simplified: Thermal de Broglie Wavelength; \( \lambda_{dB} \)
(1924)

A particle, e.g., an atom, electron, elementary particles, and indeed all objects can behave like a wave.

\[ k_B T \] is a measure of “energy of motion”
Classical and Quantum pictures of an object (e.g. atom, electron, etc.)

Classical

Quantum

\[ \lambda_{dB} = \frac{h}{\sqrt{2\pi mk_B T}} \]

\( k_B = 1.38 \times 10^{-23} \text{ Joules-K: Boltzmann constant} \)
\( T : \text{ absolute temperature} \)
\( h = 6.626 \times 10^{-34} \text{ Joules-s: Planck constant} \)
\( m: \text{ mass of the object of interest} \)
Some $\lambda_{dB}$

1) $m=70\text{kg (human)}$ at $T=300\text{K}$
   $\lambda_{dB} = 8 \times 10^{-23}\text{cm}$
   $= 0.0000000000000000000008\text{cm}$

2) $m=9.1 \times 10^{-31}\text{kg (electron)}$ at $T=300\text{K}$
   $\lambda_{dB} = 4 \times 10^{-7}\text{cm} = 4\text{nm}$

3) $m=6.69 \times 10^{-27}\text{kg (}^4\text{He)}$ at $T=300\text{K}$
   $\lambda_{dB} = 5 \times 10^{-9}\text{cm} = 0.05\text{nm}$
   at $T=2\text{K}$ $\lambda_{dB} = 6 \times 10^{-8}\text{cm} = 0.6\text{nm}$
   at $T=0.2\text{K}$ $\lambda_{dB} = 2 \times 10^{-7}\text{cm} = 2\text{nm}$

4) $m=1.42 \times 10^{-25}\text{kg (Rubidium atom)}$ at $1\text{nK}$
   $\lambda_{dB} = 1 \times 10^{-3}\text{cm} = 10\mu\text{m}$
If the distance between the particles, $l$, is much larger than $\lambda_{dB}$ then the particles retain their individual identity and their behavior is governed by classical thermodynamics.
What if the temperature is reduced so that $\lambda_{dB}$ grows to be on the order or even larger than $l$, the inter-particle spacing?

Einstein, built on the idea of Bose, proposed in 1924 that these identical particles lose their individual identity and begin to behave as one single “giant atom”.

This is known as Bose-Einstein condensation (BEC).

Now we know that this prediction is correct only for bosons (with integer spins).
Collection of identical particles

Decreasing temperature increases $\lambda_{dB}$
As $T$ approaches zero, $\lambda_{dB} \gg l$

"One for all and all for one"

Particles behave coherently like a single "giant atom"
Bose-Einstein Condensation in the vapor phase (Supergases)

1) Introduce Rb vapor into a vacuum space
2) Cool the Rb atoms by colliding them with appropriate laser beam and other clever techniques so that their $\lambda_{dB}$ is larger than the separation of the atoms.
3) First accomplished by Carl Wieman and Eric Cornell in 1995 on Rb atoms
Bose-Einstein Condensation in the vapor phase

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Nobel Prize in 2001
BEC of Rubidium gases

JILA BEC group (1995)
Superfluidity in liquid $^4$He

- Superfluid helium film can flow up a wall
- Superfluid Fountain

T$_\lambda$ = 2.176K
Fritz London is the first person to recognize that superfluidity in liquid $^4\text{He}$ is a BEC phenomenon.

\[ \lambda_{dB} = \frac{h}{\sqrt{2\pi m k_B T}} \]

At 2K, $\lambda_{dB}$ of $^4\text{He}$ = 0.6nm, separation of $^4\text{He}$ atoms $l = 0.3$nm
Superfluidity in liquid $^4\text{He}$

- Superfluid helium film can flow up a wall
- Superfluid Fountain

![Graph showing superfluidity phase transition]

- Solid
- Normal Liquid ($^4\text{He}$)
- Superfluid ($^4\text{He}$ II)

$T_\lambda = 2.176 \text{K}$
Persistent current in superfluid

- Vanishing viscosity; “The viscosity of He II is at least 1500 times smaller than that of normal helium (He I)”
  Allen & Misener *Nature* 141, 75 (1938)

Persistent current can be created by stirring the liquid helium while cooling through $T_\lambda$. Superfluid will continue to rotate after the stirring is stopped. Conversely, if one starts from the superfluid state, the superfluid will stay still even if one try to stir it.
Particles behave coherently like a single “giant atom”

\[ \lambda_{dB} > > l \]

“One for all and all for one”

In the Bose-condensed state particles or atoms do not “run” into each other. Because they act as a single coherent entity they cannot easily lose or gain energy from the surroundings. Hence superfluidity is possible.
$\lambda_{dB} >> l$

$\psi = |\psi|e^{i\varphi}$
Superconductivity

The phenomenon of superconductivity is analogous to superfluidity. In superconductivity, electric current can flow with no resistance. A similar persistent current of electron pairs can be set up.

MRI uses magnet powered by superconducting current in the persistent mode. In this mode the current and therefore the magnetic field is extremely stable.

- Superfluidity and superconductivity are macroscopic quantum phenomenon
Principle for the observation of liquid helium behaving as a “Macroscopic Atom” : torsional pendulum

period of oscillation

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

When \( I \) decreases, Resonant period decreases
Torsional Pendulum

Period of Oscillation

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

What if we have a set of infinitely smooth ball bearings?
Torsional Pendulum

Period of Oscillation

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

The ring on the top remains stationary and decouples from the oscillation, \( I \) decreases and period decreases.
Torsional oscillator ideal for detection of superfluidity

Resolution

Resonant period \((\tau_o) \sim 1\ \text{ms}\)

Stability in \(\tau\) is 0.1ns

\[ \frac{\delta \tau}{\tau_o} = 5 \times 10^{-7} \]

Mass sensitivity \(\sim 10^{-7}g\)

\[ Q = \frac{f_0}{\Delta f} \sim 2 \times 10^6 \]

\[ \tau_o = 2\pi \sqrt{\frac{I}{K}} \]
Above 2.176K, liquid helium behaves as a normal fluid. It will oscillate with the disk if $d$ is smaller than the viscous penetration depth ($\delta$).

$\delta \sim 3\mu m$, if the oscillating frequency is $2\pi \times 1000$ rad/s

$d < \delta$ of normal fluid

In the normal fluid phase,

$I_{\text{total}} = I_{\text{cylinder}} + I_{\text{helium}}$

$\delta = \sqrt{\frac{2\eta}{\rho \omega}}$

$\eta$ : viscosity
As temperature is cooled below $T_\lambda$, Superfluid fraction stays still when the container is being oscillated we can measure the fraction of superfluid.

\[
\rho = \rho_s + \rho_n
\]

\[
\rho_s = \psi \ast \psi
\]

\[
I_{\text{total}} = I_{\text{cylinder}} + I_{\rho_n(T)};
\]

$I_{\text{total}} = I_{\text{cylinder}}$; at $T=0$, $\rho_n=0$

Non-Classical Rotational Inertia
Empty torsional cell

\[ I_{\text{total}} = I_{\text{torsion cell}} \]

\[ \tau^* = 1,723,000 \text{ns} \]

\[ \tau_o = 2\pi \sqrt{\frac{I_{\text{cell}}}{K}} \]
Helium is introduced into the cell

$\tau_o = 2\pi \sqrt{\frac{I_{cell} + I_{helium}}{K}}$

$\tau^* = 1,723,000$ns

$T [K]$

Period shifted by 2155ns due to mass loading of normal liquid helium

$I_{total} = I_{torsion\ cell} + I_{normal\ helium}$
Expected background if there is no superfluid transition

\[ \tau_o = 2\pi \sqrt{\frac{I_{cell} + I_{helium}}{K}} \]

\( \tau^* = 1,723,000 \text{ns} \)
A certain fraction of the liquid, known as superfluid fraction, decouples from the oscillation of the torsional cell and does not contribute to the rotational inertia.

\[ \tau_0 = 2\pi \sqrt{\frac{I_{\text{cell}} + I_{\text{normal fluid}}}{K}} \]

\[ \tau^* = 1,723,000 \text{ ns} \]
Superfluid fraction

\[ \rho = \rho_s + \rho_n \]; two fluid model of Tisza and Landau

\[ \rho_s = \psi \psi^* \]

Superfluid fraction

\[ \frac{\Delta \tau}{\text{total mass loading}} \]

At T=0K

100% superfluid
Does Bose-Einstein Condensation also occur in a solid?

1) In principle it is possible, however “conventional wisdom” said it is unlikely to happen or immeasurably small.

2) Early theoretical model emphasize the phenomenon may occur as a consequence of the condensation of zero point vacancies. (Chester, Andreev and Lifshitz, Reatto)

3) If it is going to occur, the likely candidate is solid $^4$He, the most quantum mechanical solid.
Search for the supersolid phase in solid $^4$He.

Be-Cu Torsion Rod

- OD = 2.2mm
- ID = 0.4mm

Torsion cell with helium in annulus

- Filling line

Mg disk

- Channel OD = 10mm
- Width = 0.63mm

Al shell

Solid helium in annulus channel

Detection

Drive

Eunseong Kim
Torsional Oscillator

- Torsion rod
- Torsion cell
- Detection
- Drive

3.5 cm
Solid $^4$He at 51 bars

A decrease in the resonant period, similar to that found in superfluid liquid helium, appears below 0.25K

$\tau_0 = 1,096,465$ns at 0 bar
$1,099,477$ns at 51 bars
(total mass loading=3012ns due to filling with helium)

The nonclassical rotational (NCRI) fraction is $\sim 1.3\%$

Nature, 425, 227 (2004); Solid helium in porous glass
Science 305, 1941 (2004); Bulk solid
Different Speed of Oscillation

4 µm/s is equivalent to oscillation amplitude of 7 Å
Supersolid fraction or nonclassical rotational (NCRI) fraction

The supersolid fraction at T=0K is on the order of 1.3%
Control experiment I: Solid $^3$He?
Control experiment II

- With a barrier in the annulus, there should be NO simple superflow and the measured superfluid decoupling should be vastly reduced.
The flow is irrotational like superfluid.
Phase Diagram of $^4$He
Open Questions

- Supersolid response found in high quality crystalline sample (disorder appears to enhance the measured magnitude of NCRI) but is it possible in a ‘perfect’ crystal?
- The most puzzling result is the large (3 orders of magnitude) variation in NCRIF in different torsional oscillator measurements.
- Effect of $^3$He impurity?
- 2D supersolid?