The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

1959-11

Workshop on Supersolid 2008

18 - 22 August 2008

Brief introduction to the field

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Superfluid and supersolid

An introduction at the ICTP
'Supersolid 2008' workshop

Moses Chan

The Pennsylvania State University

Supported by National Science Foundation

NSF

Where is Penn State University?

The Pennsylvania State University

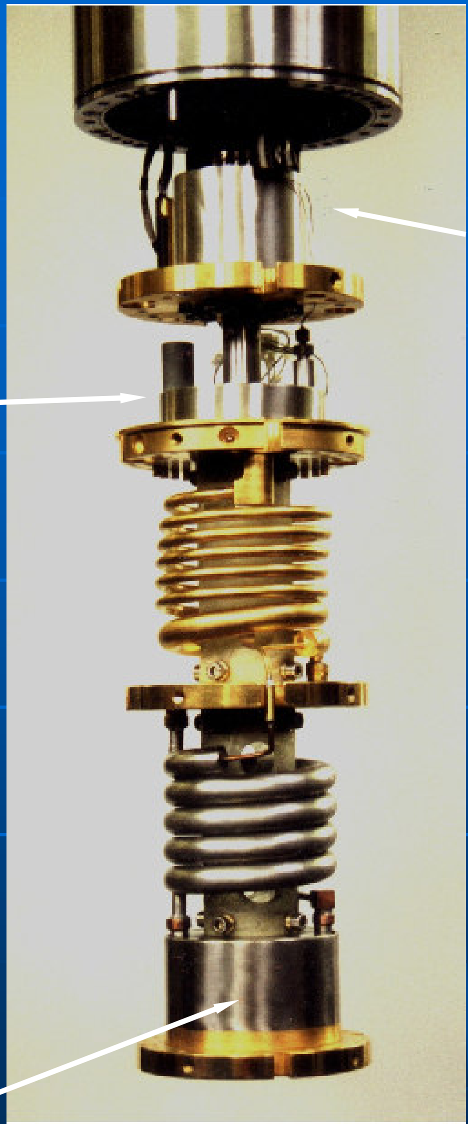
Old Main

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 of observation of Superfluidity: Torsional Pendulum
- Observation of superflow in solid helium



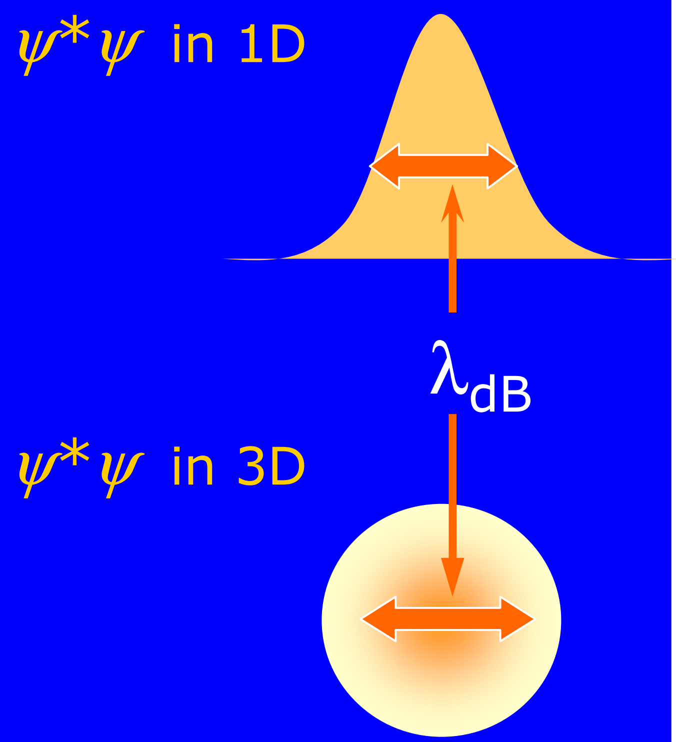
Temperature Scale (K)

Melting of iron	10^3
Melting of ice (273K=0°C)	10^2
	10
Evaporation of ^4He(4.2K)	
Cosmic background(3K)	
Superfluid (2.18K)	1
	10^{-1}
Dilution Fridge temperature 10mK	10^{-2}
Superfluid ^3He (2mK)	10^{-3}
	10^{-4}
	10^{-5}
Nuclear Demag. 1μK	10^{-6}

The lowest possible temperature 0 K=-273.15°C=-459.7°F

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

Quantum Theory simplified: Thermal de Broglie Wavelength; λ_{dB} (1924)



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

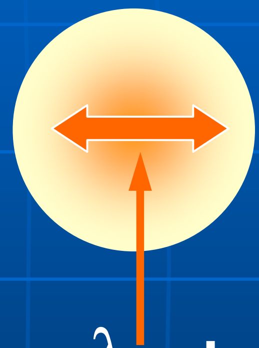
$k_B T$ is a measure of "energy of motion"

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

Classical and Quantum pictures of an object (*e.g.* atom, electron, etc.)

Classical

Quantum



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

λ_{dB}:
de Broglie wave length

k_B = 1.38×10^{-23} Joules-K: Boltzmann constant
T : absolute temperature
h = 6.626×10^{-34} *Joules-s*: Planck constant
m: mass of the object of interest

Some λ_{dB}

1) m=70kg (human) at T=300K

λ_{dB} = 8×10^{-23}cm

=0.000000000000000000000008cm

2) m=9.1×10^{-31}kg (electron) at T=300K

λ_{dB} = 4×10^{-7}cm = 4nm

3) m= 6.69×10^{-27}kg(^{4}He) at T=300K

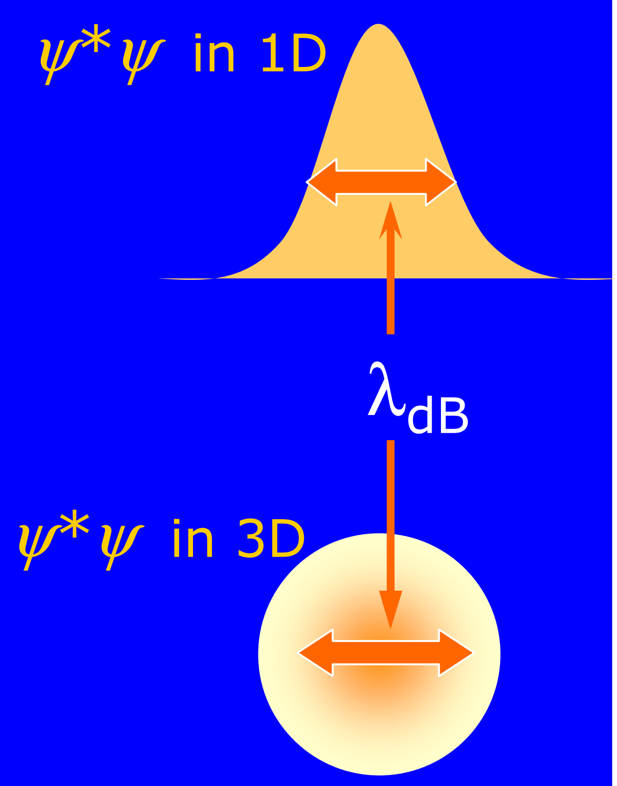
λ_{dB} = 5×10^{-9}cm=0.05nm

at T= 2K λ_{dB} = 6×10^{-8}cm = 0.6nm

at T=0.2K λ_{dB} = 2×10^{-7}cm = 2nm

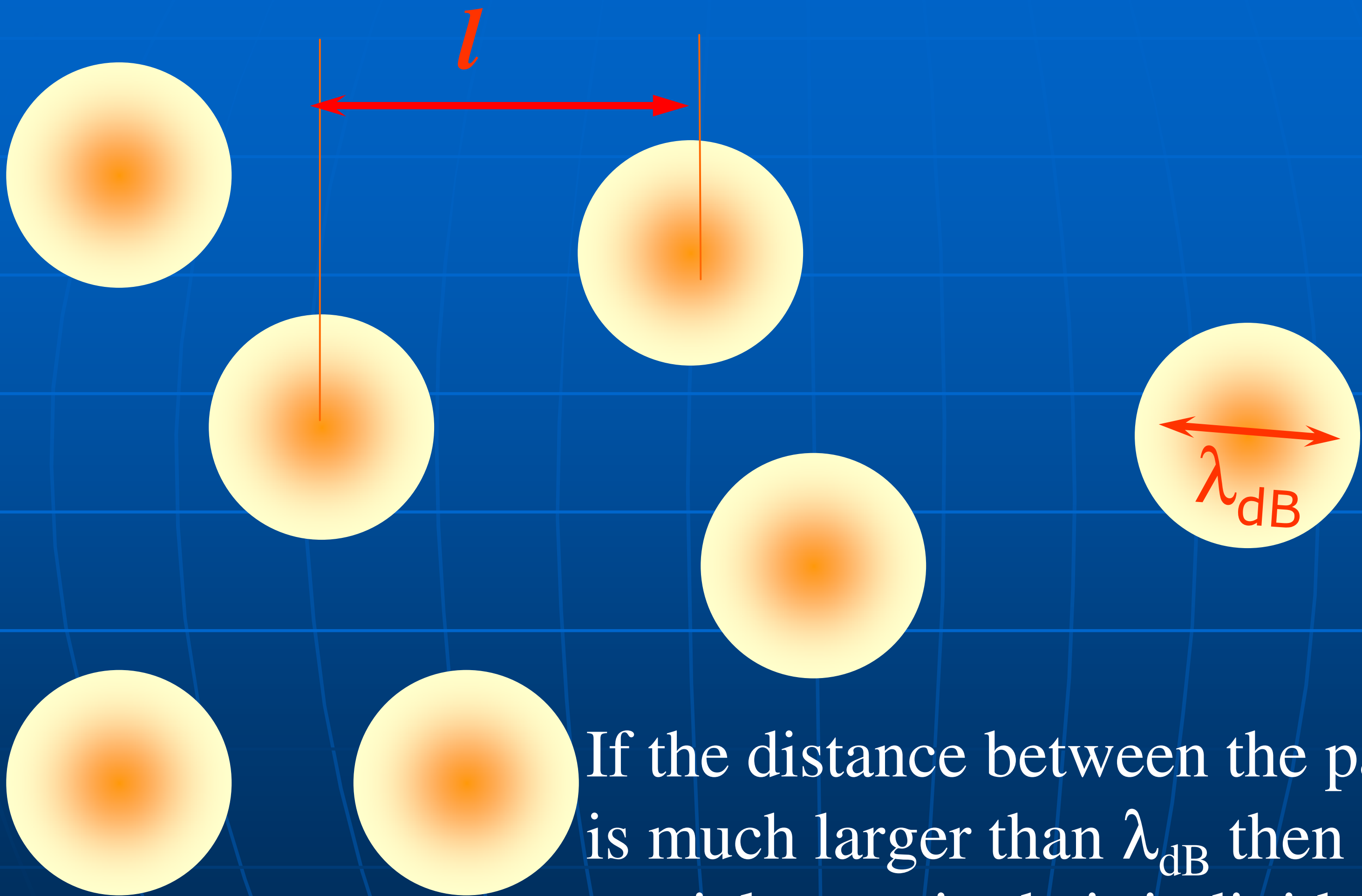
4) m=1.42×10^{-25}kg (Rubidium atom) at 1nK

λ_{dB} = 1×10^{-3}cm = 10μm



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

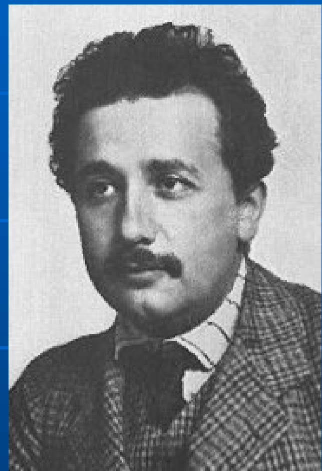
Collection of identical particles

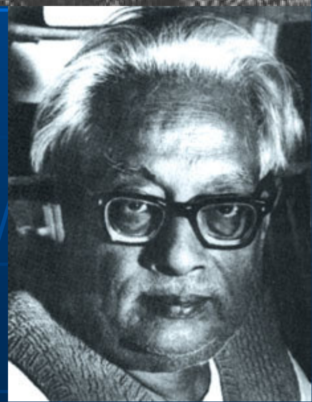


If the distance between the particles, l, is much larger than λ_{dB} then the particles retain their individual identity and their behavior is governed by classical thermodynamics

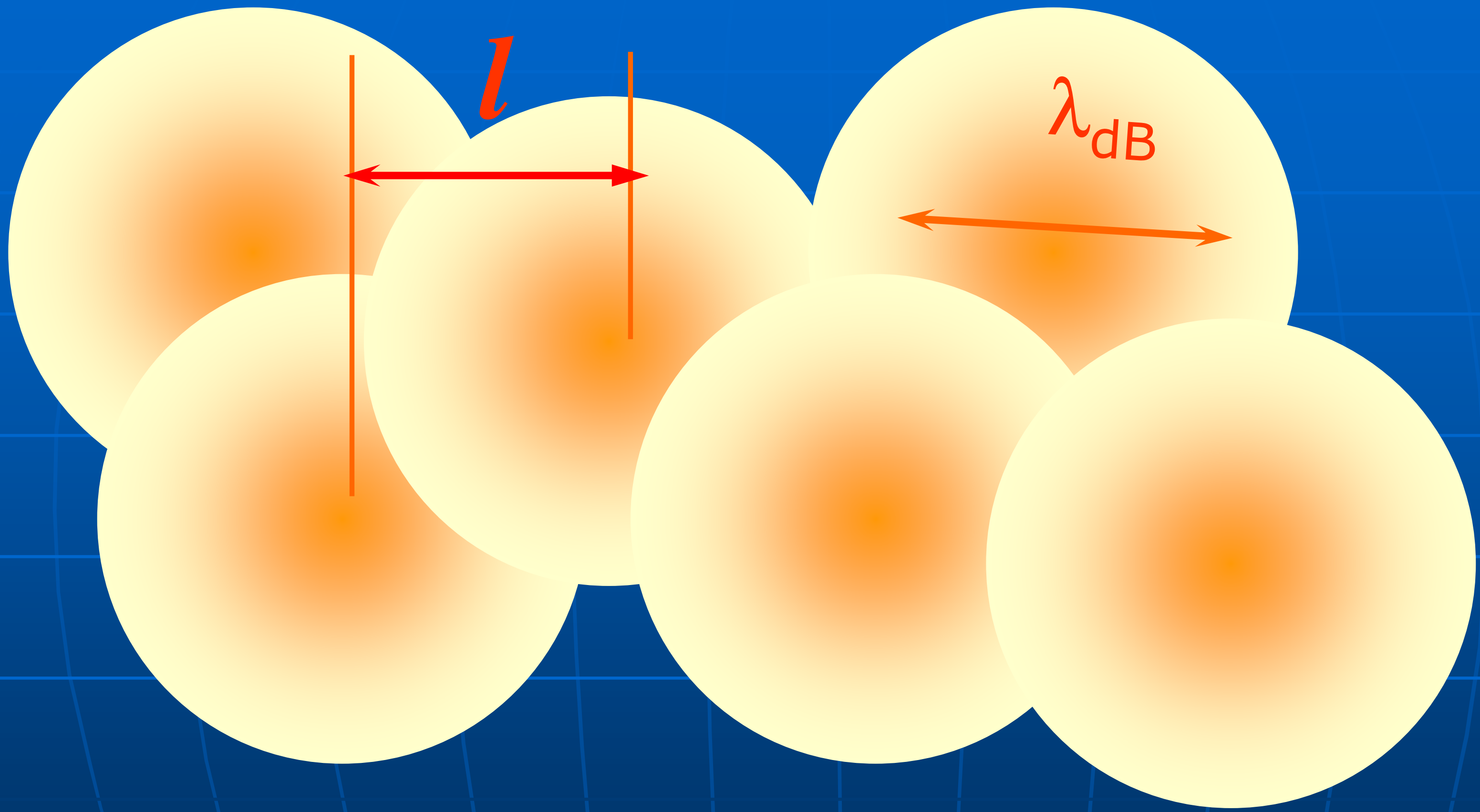
Bose-Einstein Condensation

- What if the temperature is reduced so that λ_{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)



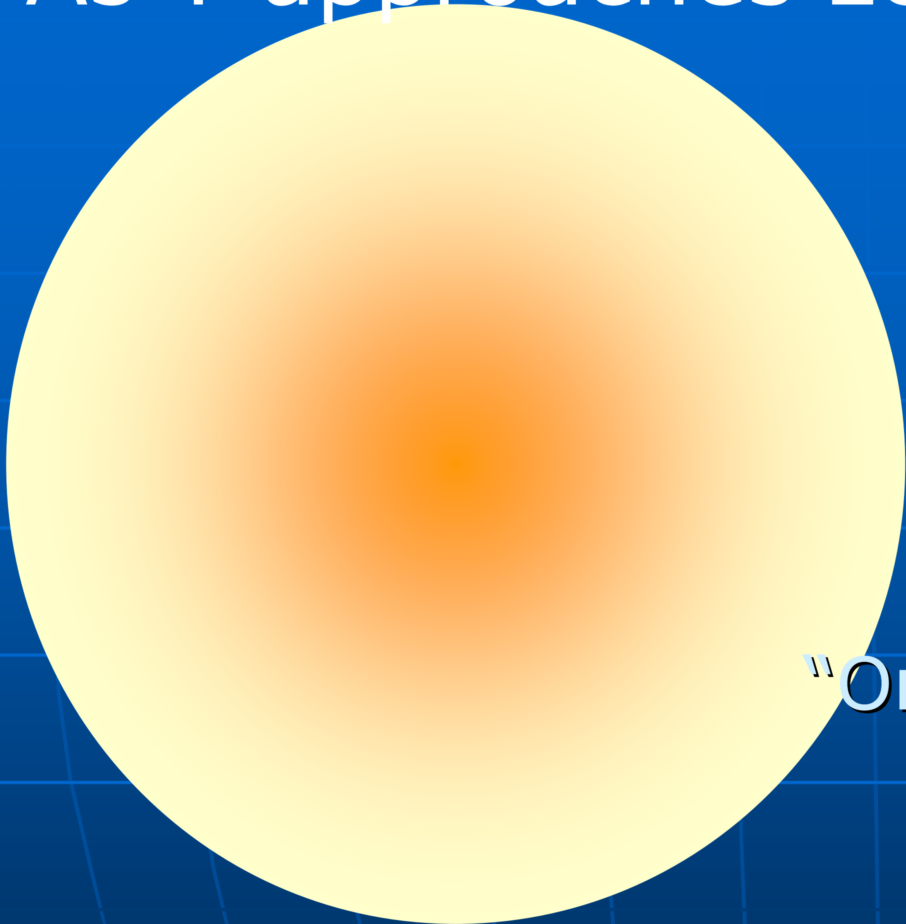


Collection of identical particles



Decreasing temperature increases λ_{dB}

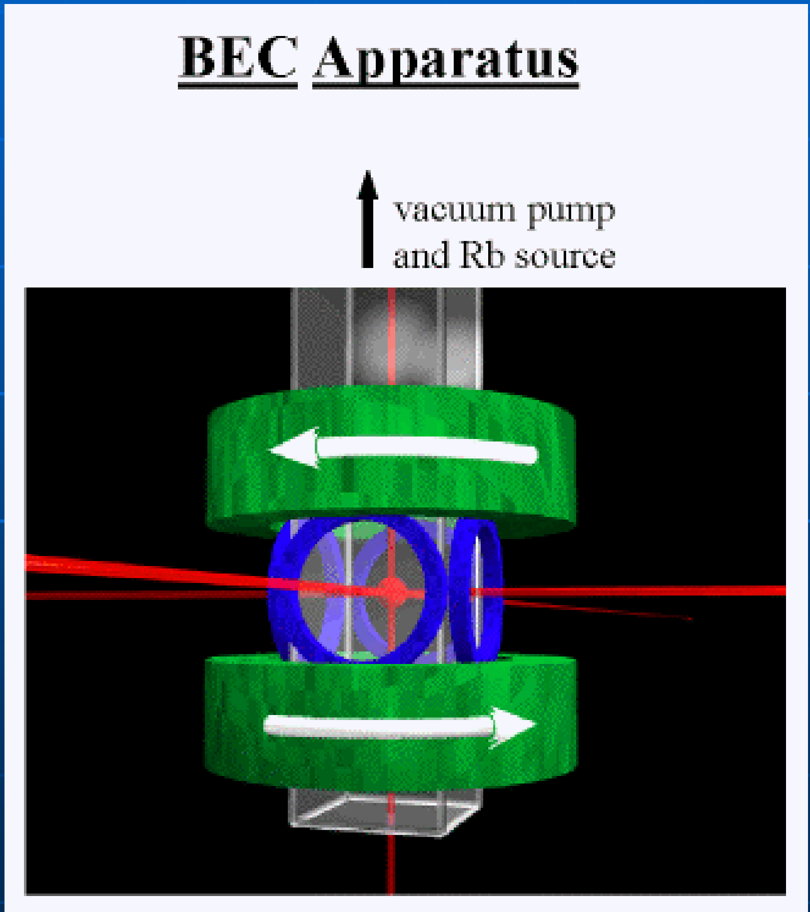
As T approaches zero $\lambda_{dB} >> l$



"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 λ_{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

Wieman

Cornell

Nobel Prize in 2001

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 λ_{dB} is larger than the separation of the atoms.
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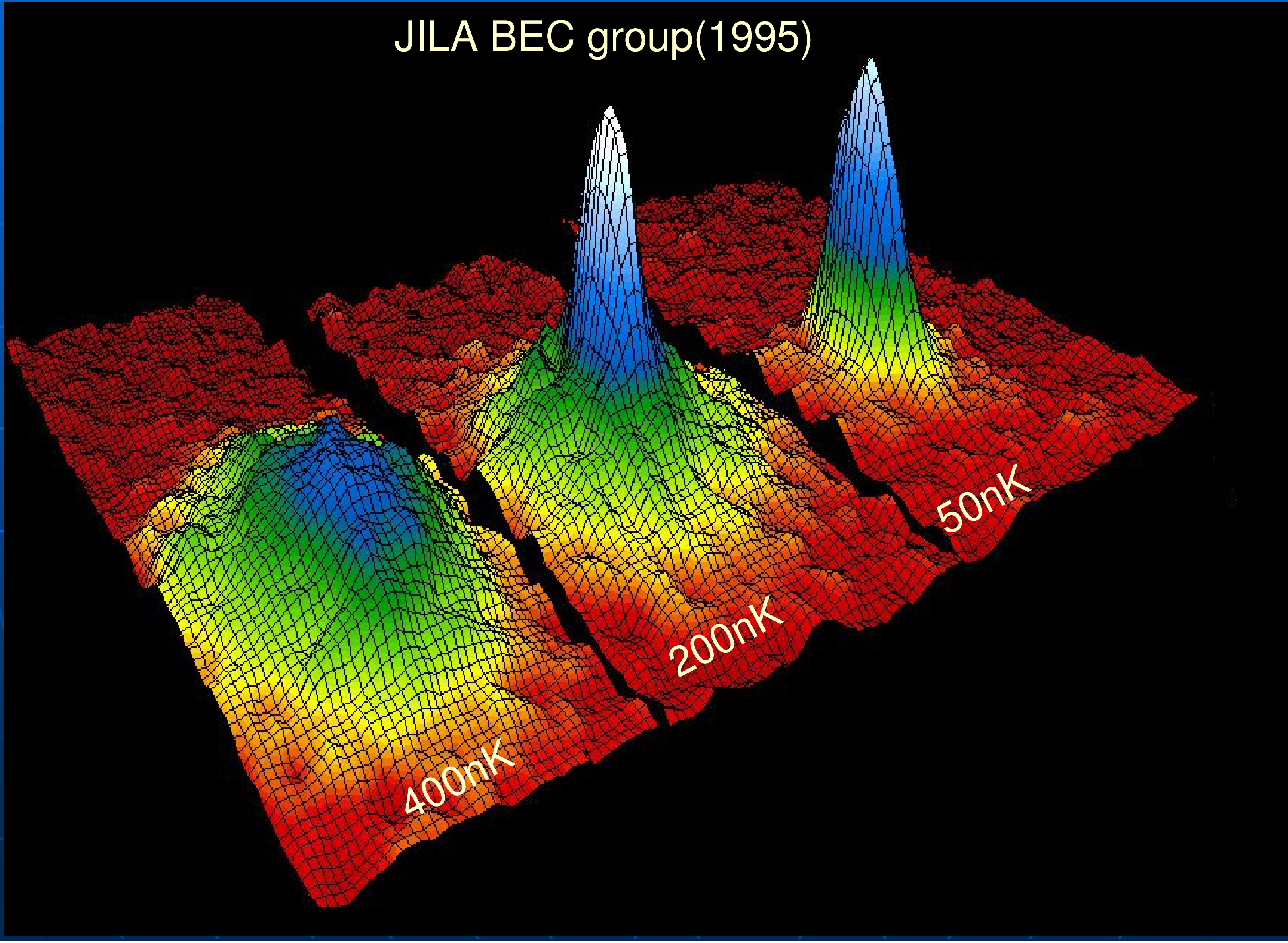
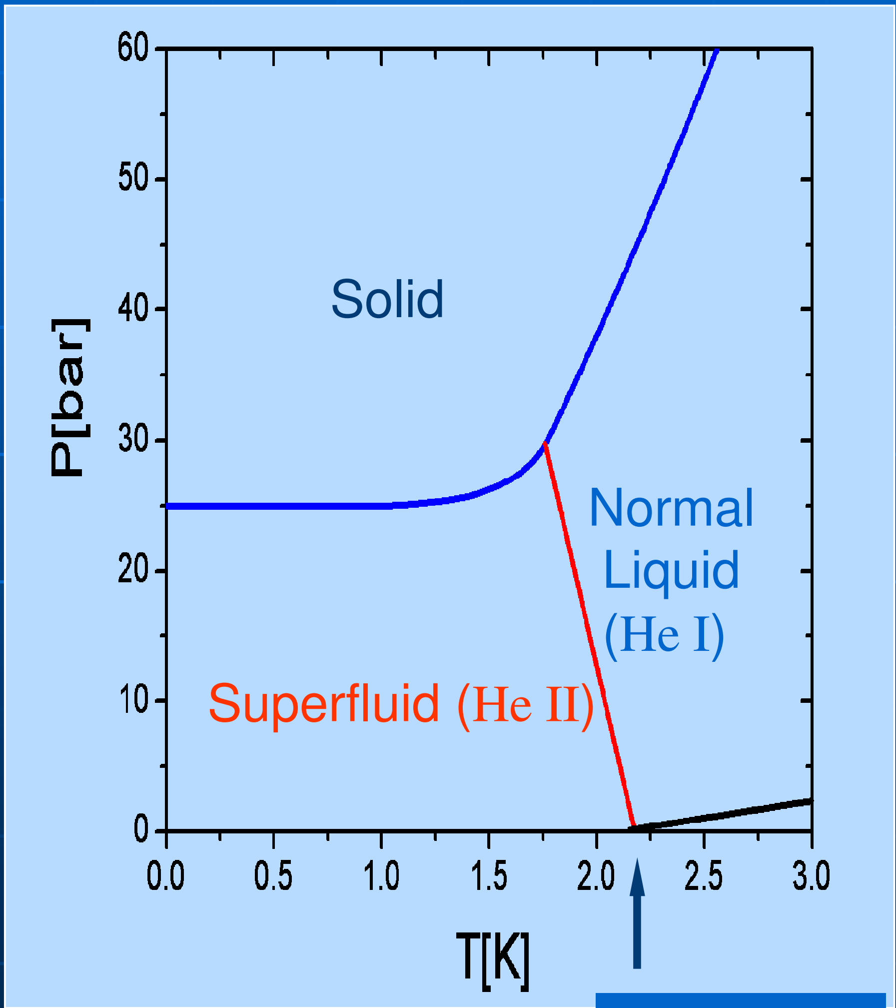
BEC of Rubidium gases

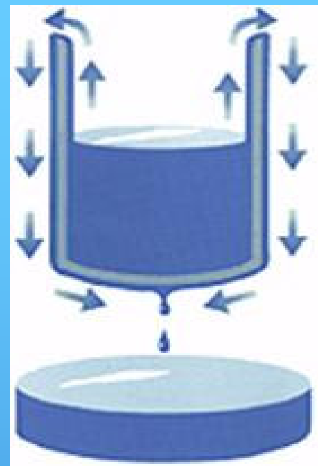


Superfluidity in liquid ^{4}He



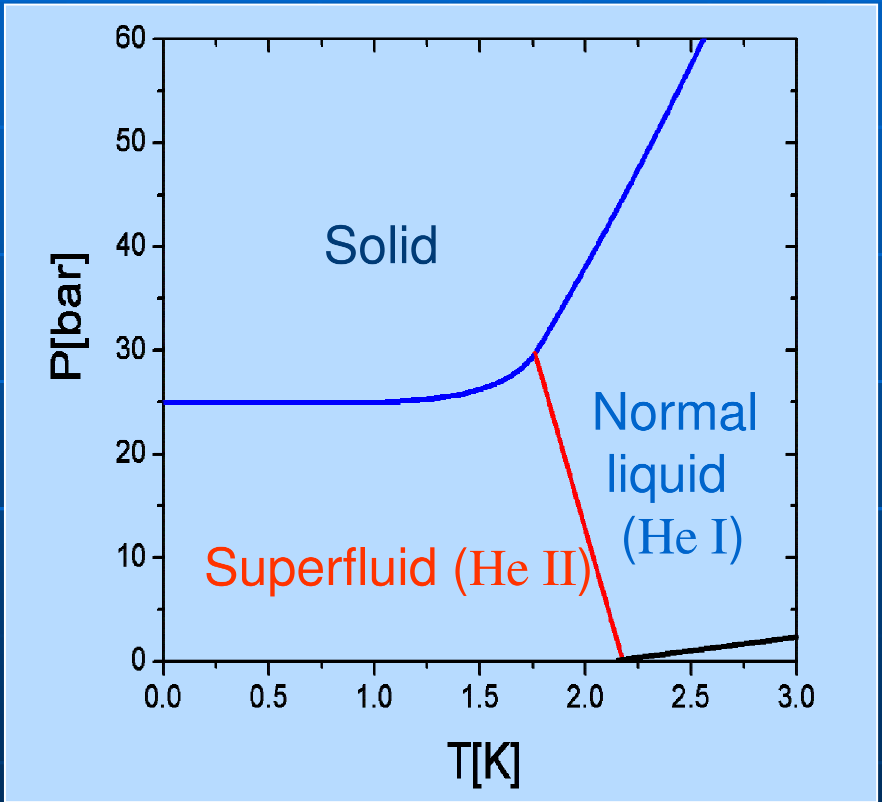
T_λ=2.176K

- Superfluid helium film can flow up a wall



- Superfluid Fountain

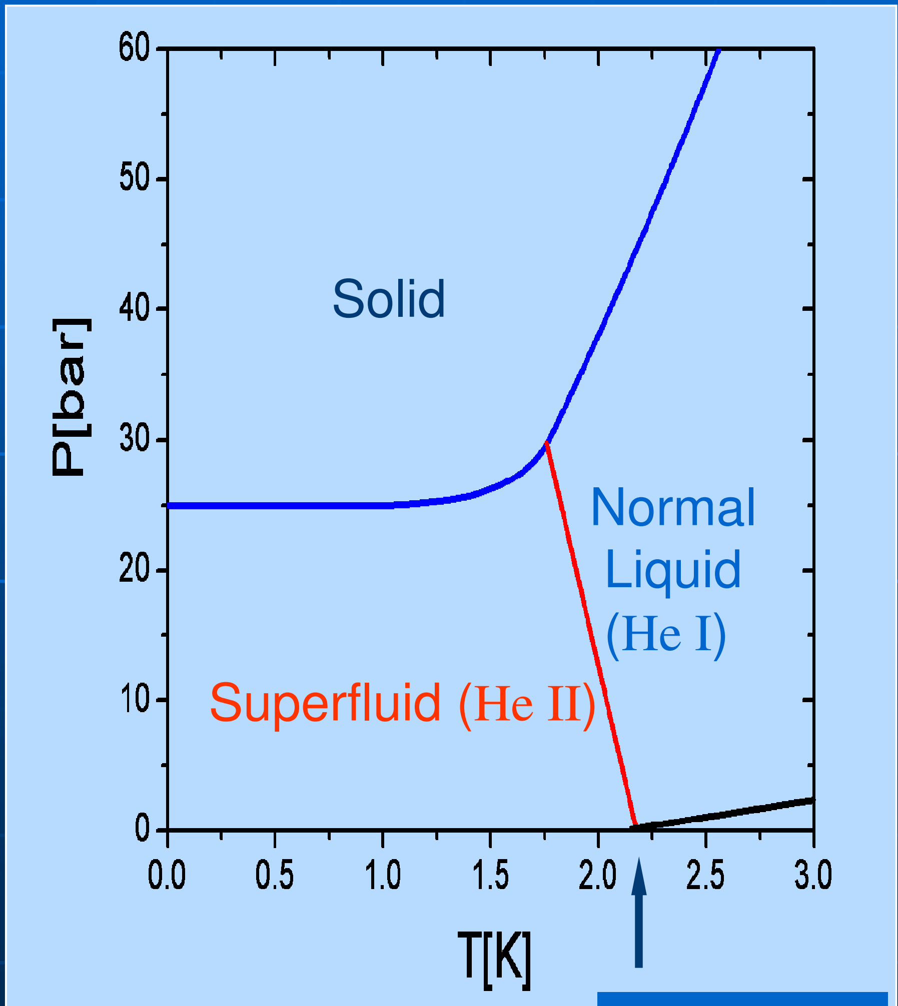
Fritz London is the first person to recognize that superfluidity in liquid ^{4}He is a BEC phenomenon.



$$\lambda_{dB} = \frac{h}{\sqrt{2\pi\, m\, k_B T}}$$

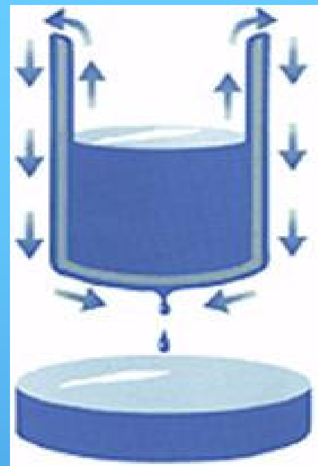
At 2K, λ_{dB} of ^{4}He = 0.6nm , separation of ^{4}He atoms l = 0.3nm

Superfluidity in liquid ^{4}He



T_λ=2.176K

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



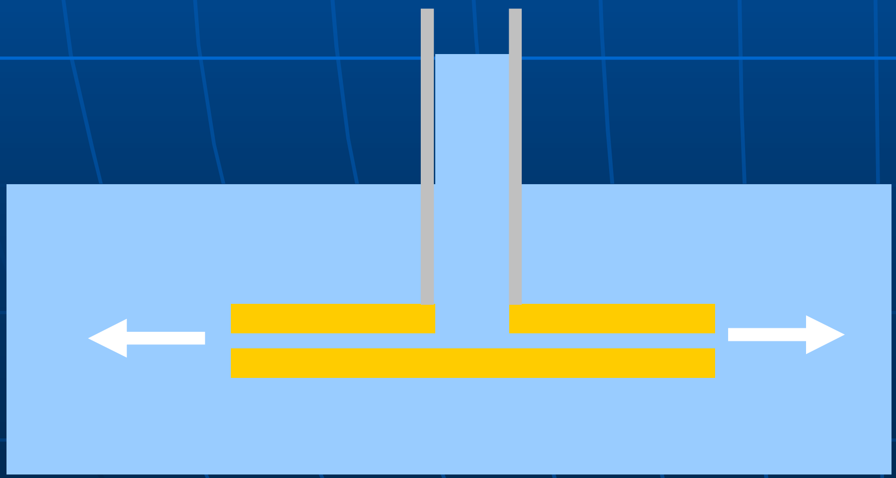
- Superfluid Fountain

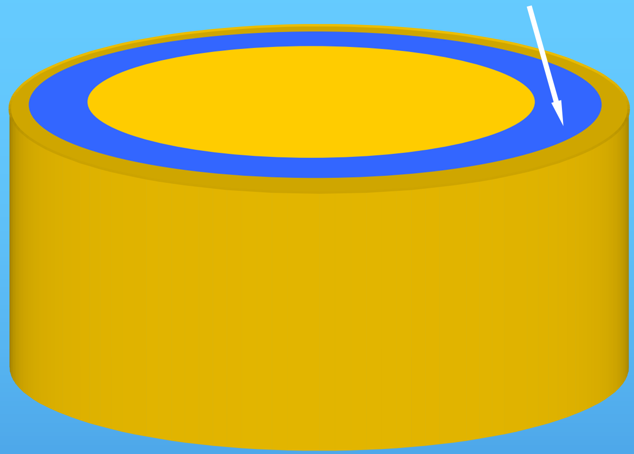
Persistent current in superfluid

- Vanishing viscosity; "The viscosity of He II is at least 1500 times smaller than that of normal helium (He I)"

  P. Kapitza, *Nature* **141**, 74 (1938)

  Allen & Misener *Nature* **141**,75 (1938)

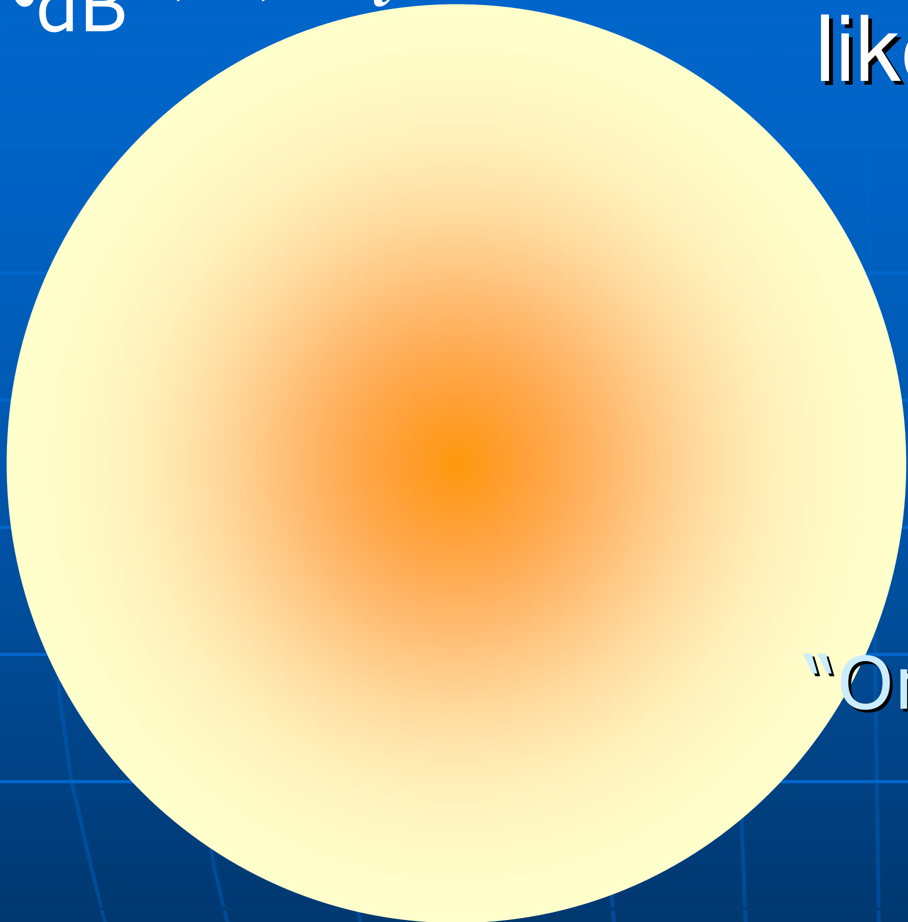




Persistent current can be created by stirring the liquid helium while cooling through T_λ. Superfluid will continue to rotate after the stirring is stopped. Conversely, if one starts from the superfluid state, the superfluid will stay still even if one try to stir it.

$\lambda_{dB} >> l$

Particles behave coherently like a single "giant atom"



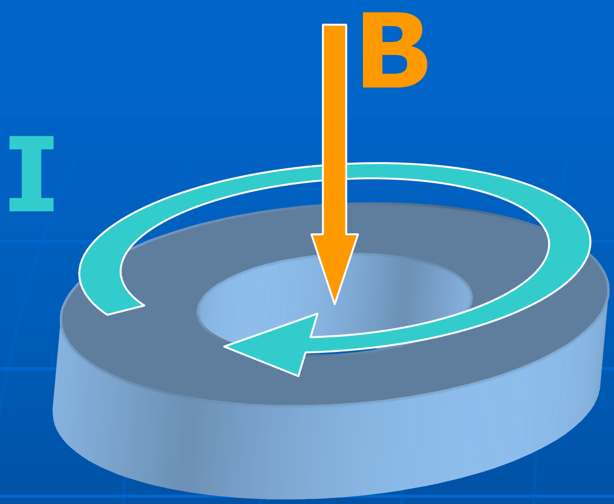
"One for all and all for one"

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

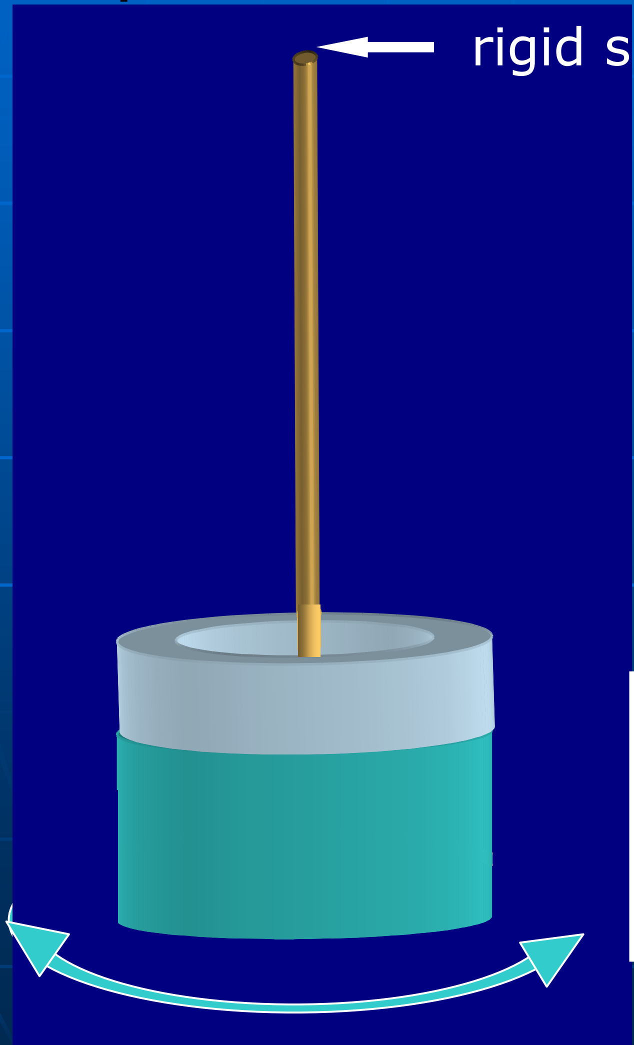


The phenomenon of superconductivity is analogous to superfluidity. In superconductivity, electric current can flow with no resistance. A similar persistent current of electron pairs can be set up.

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

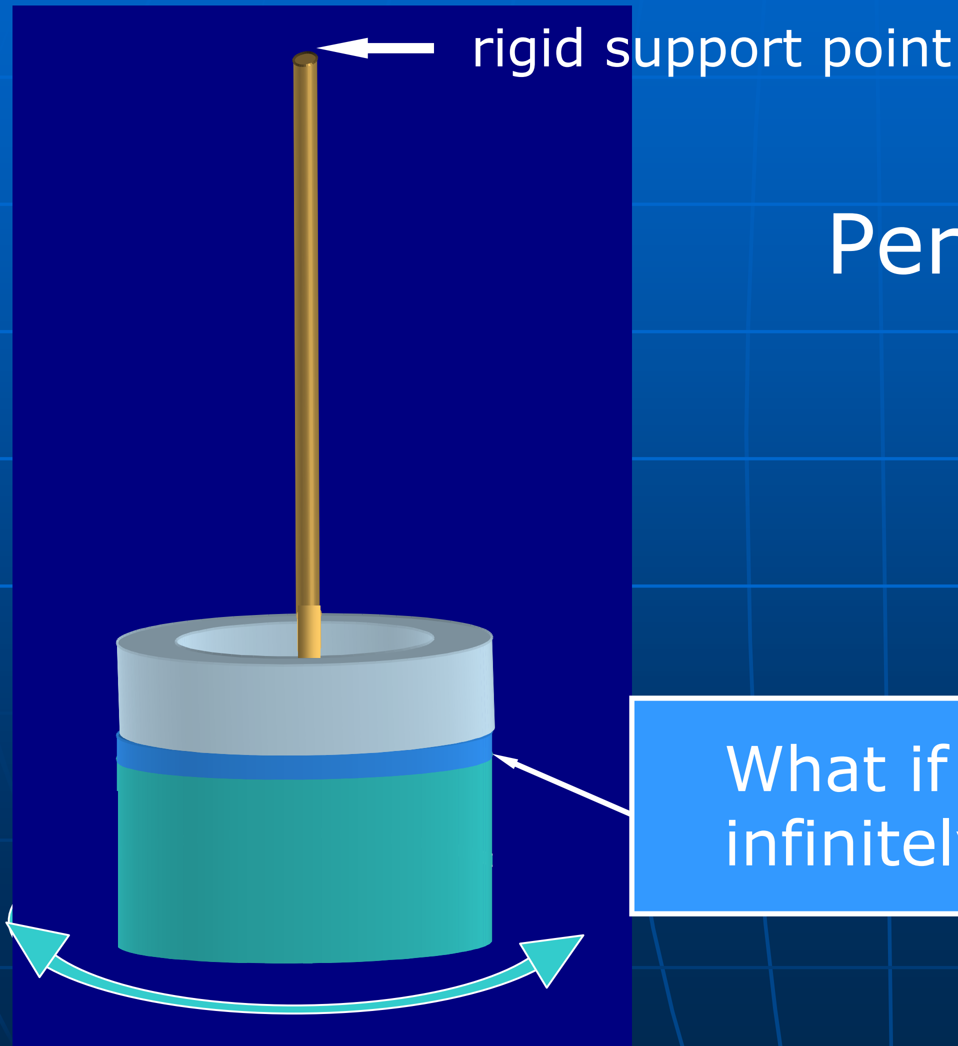


Period of Oscillation

$$\tau = 2\pi\sqrt{\frac{I}{K}}$$

When *I* decreases,
Resonant period decreases

Torsional Pendulum

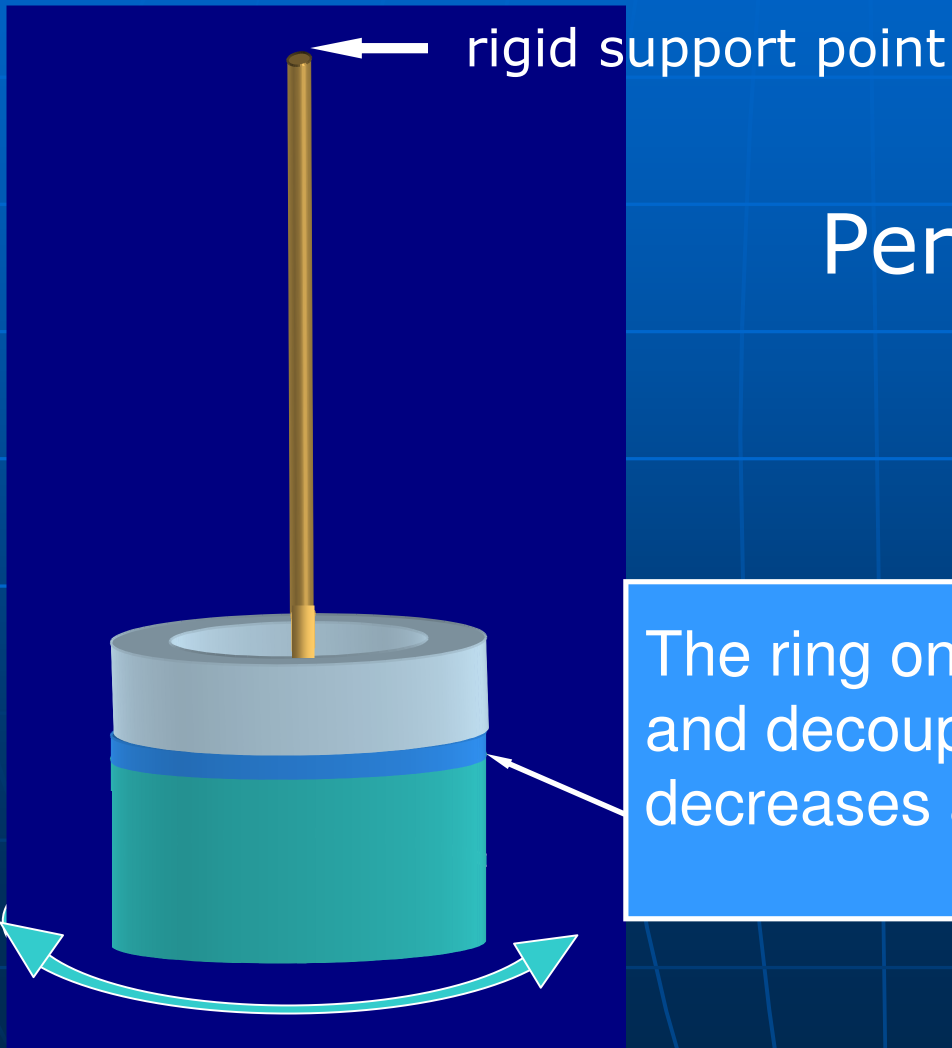


Period of Oscillation

$$\tau = 2\pi\sqrt{\frac{I}{K}}$$

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

Torsional Pendulum

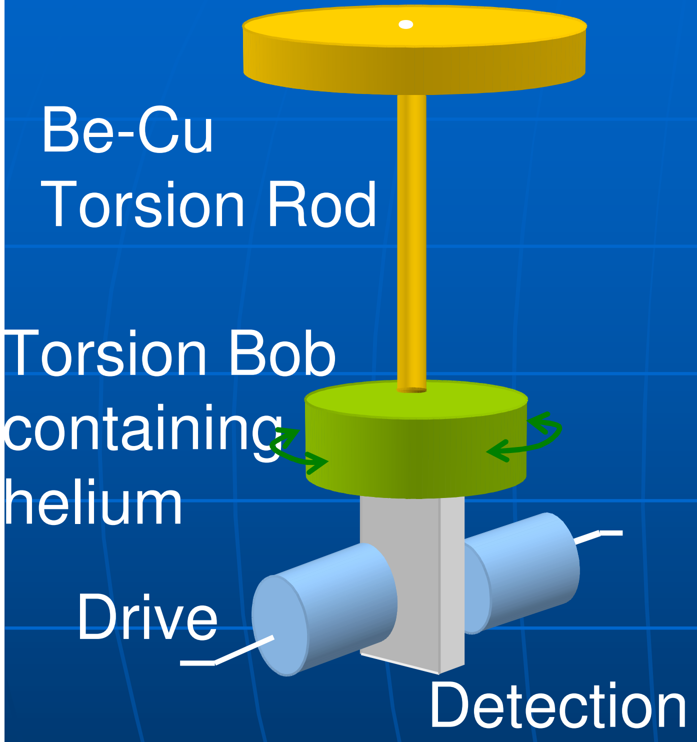


Period of Oscillation

$$\tau = 2\pi\sqrt{\frac{I}{K}}$$

The ring on the top remains stationary and decouples from the oscillation, I decreases and period decreases.

Torsional oscillator ideal for detection of superfluidity



$$\tau_o = 2\pi\sqrt{\frac{I}{K}}$$

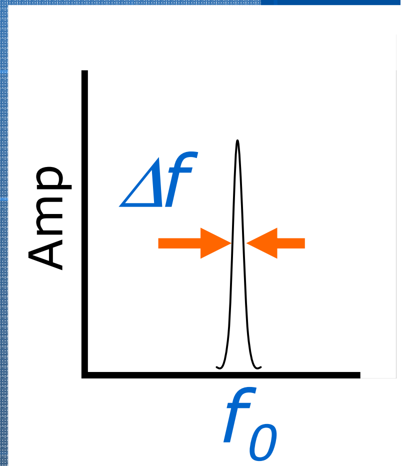
Resolution

Resonant period (τ_o) ~ 1 ms

stability in τ is 0.1ns

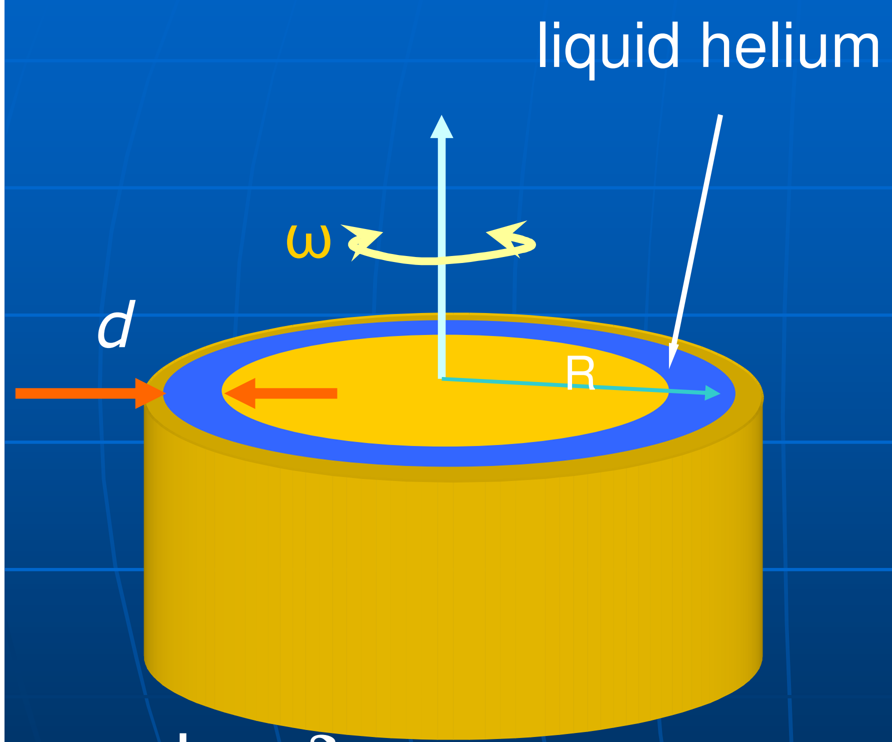
$\delta\tau/\tau_o = 5\times10^{-7}$

Mass sensitivity ~10^{-7}g



$Q = f_0/\Delta f \sim 2\times10^6$

Measurement of superfluidity



$d < \delta$ of normal fluid

In the normal fluid phase,

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

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 (δ).

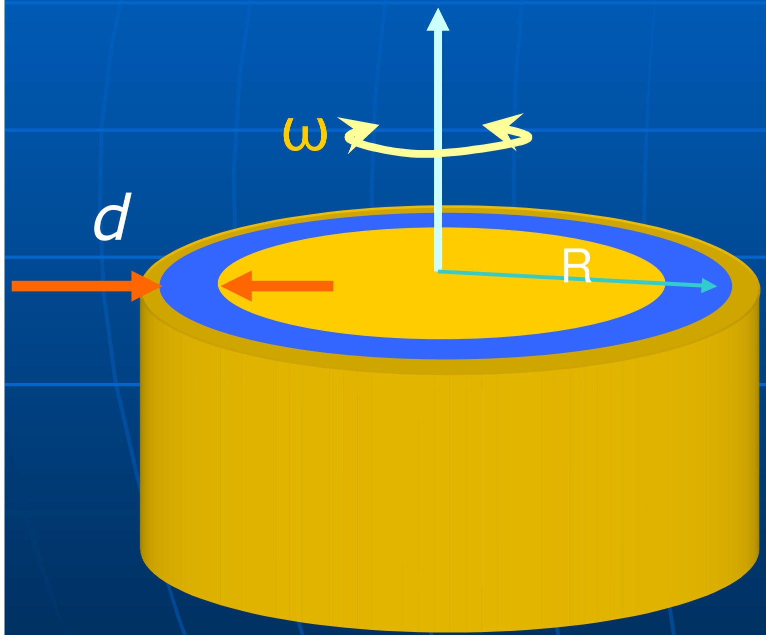
($\delta \sim 3\mu m$,
if the oscillating frequency is 2π*1000 rad/s)

$$\left(\delta = \sqrt{\frac{2\eta}{\rho\omega}} \right)$$

η : viscosity

As temperature is cooled below T_λ

Superfluid fraction stays still when the container is being oscillated we can measure the fraction of superfluid.



$$\rho = \rho_s + \rho_n$$

$$\rho_s = \psi^* \psi$$

$I_{total} = I_{cylinder} + I_{\rho_n}(T)$;

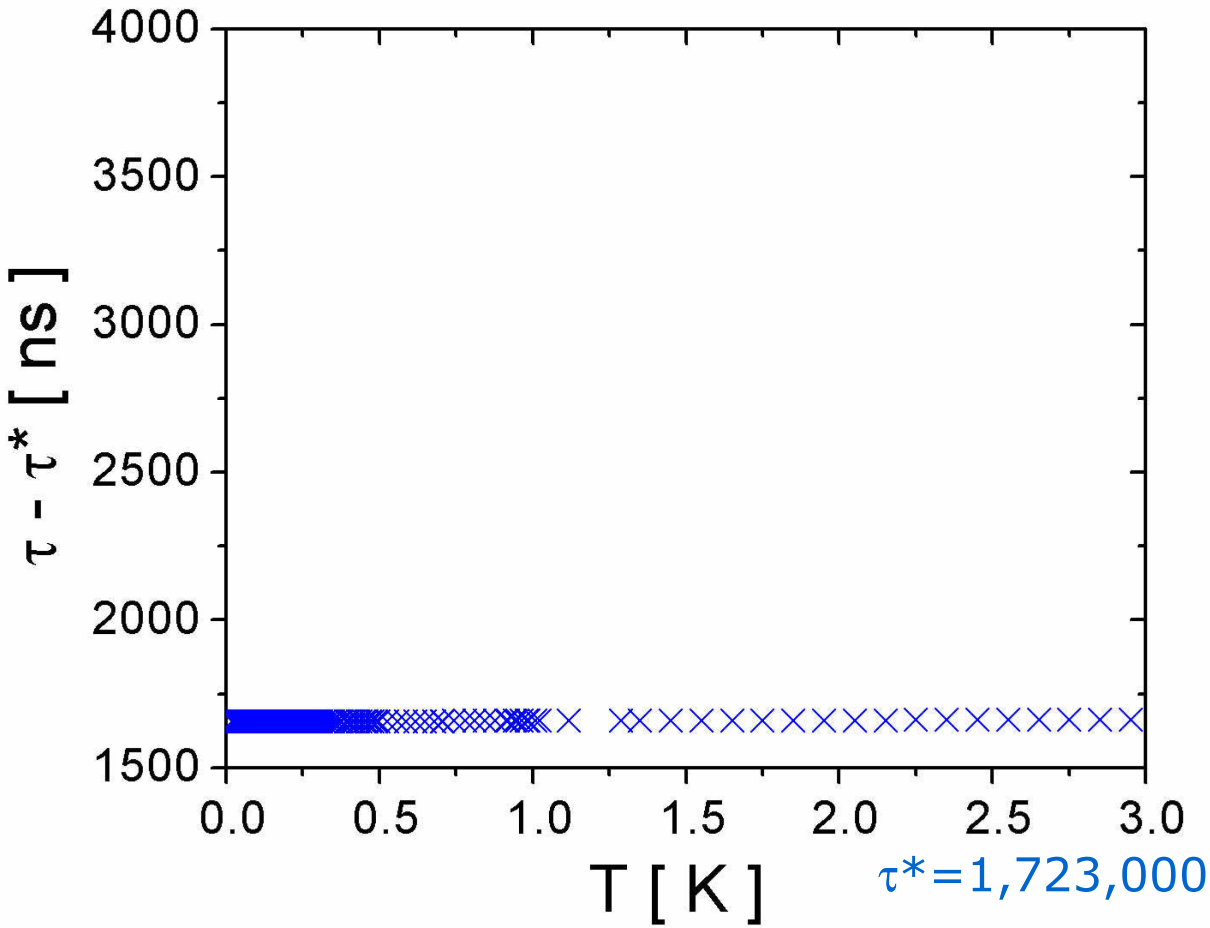
$I_{total} = I_{cylinder}$; at $T=0$, $\rho_n=0$

$d < \delta$ of normal fluid

Non-Classical Rotational Inertia

Empty torsional cell

$I_{total} = I_{torsion\ cell}$

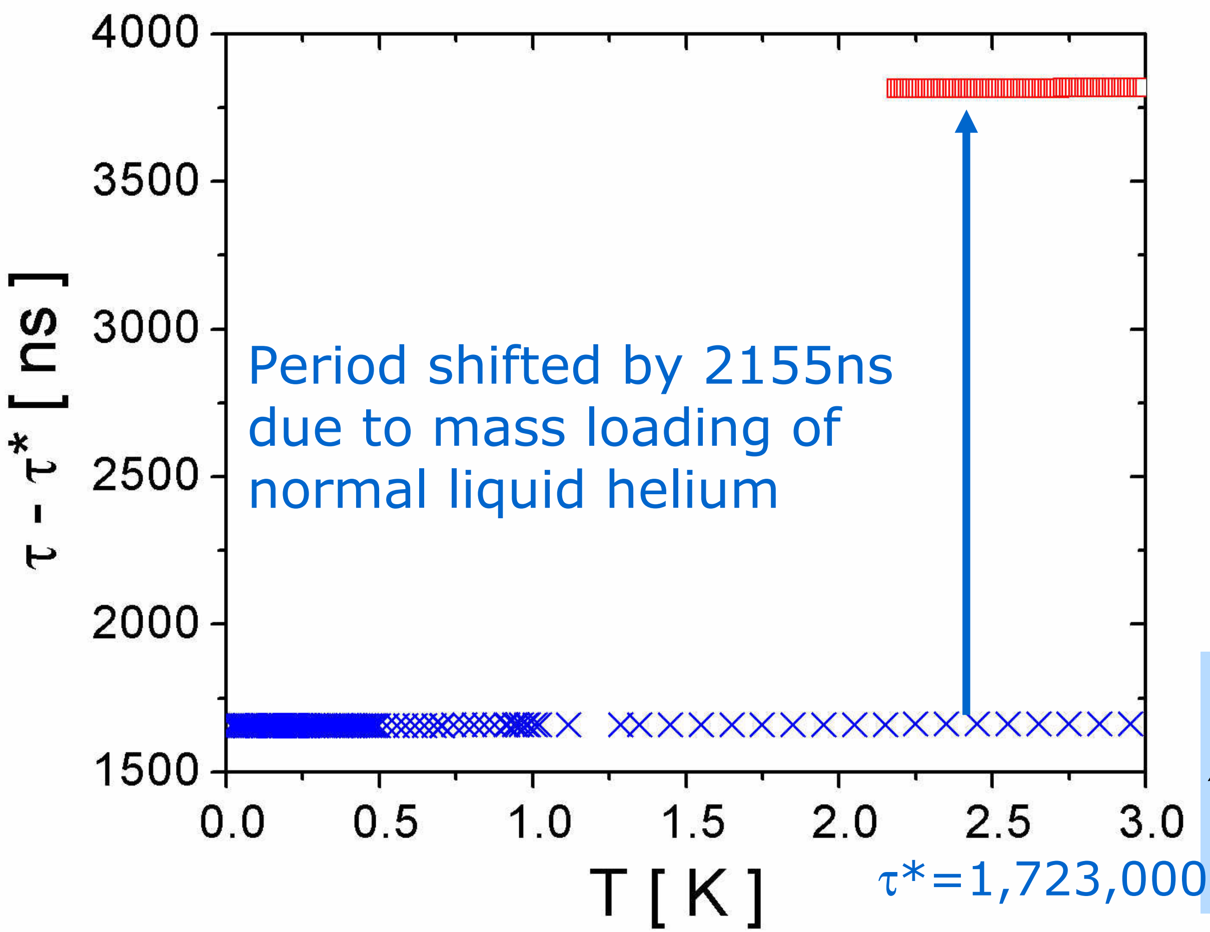


τ*=1,723,000ns

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

Helium is introduced into the cell

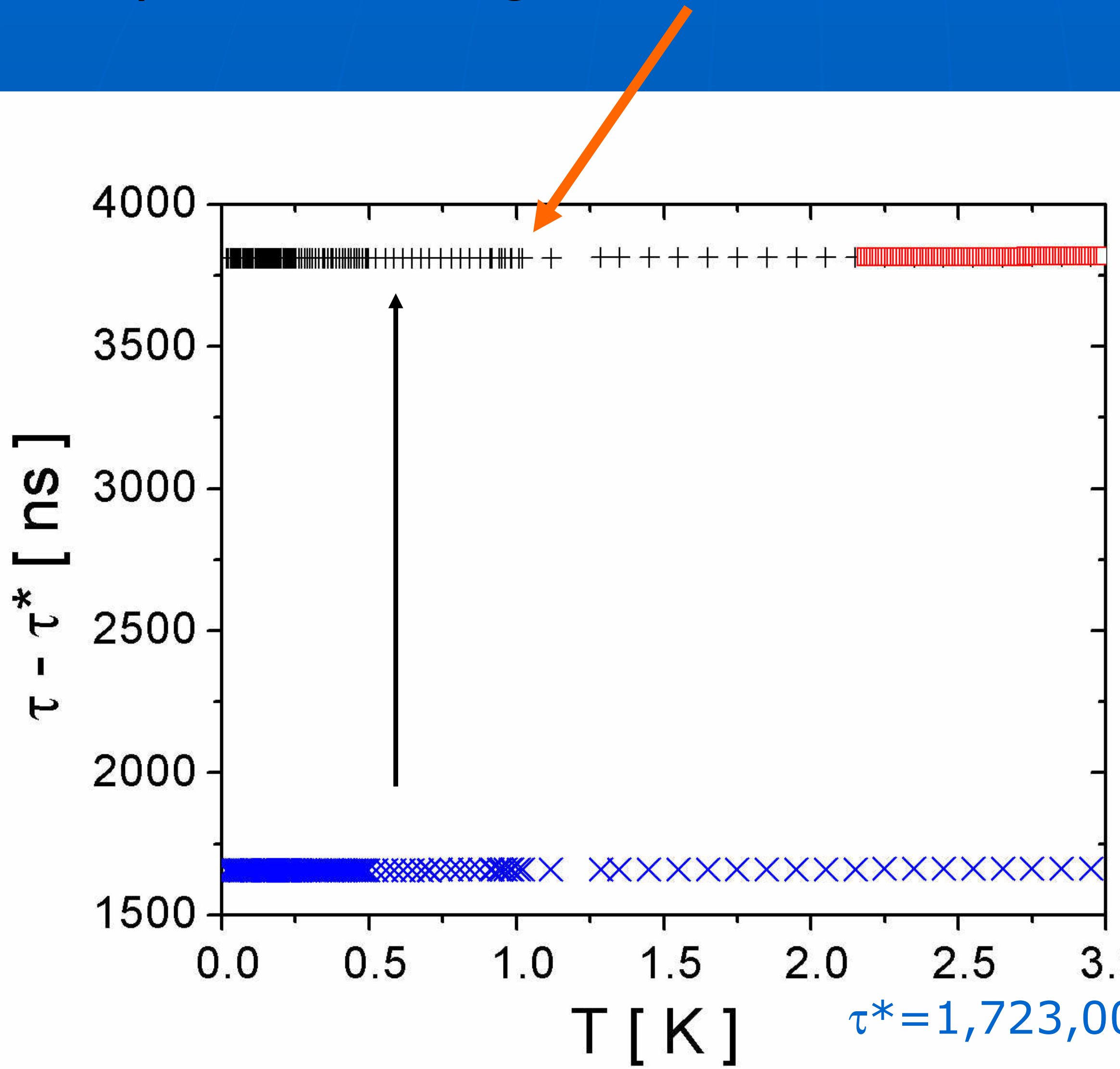
$$I_{total} = I_{torsion\ cell} + I_{normal\ helium}$$



τ*=1,723,000ns

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

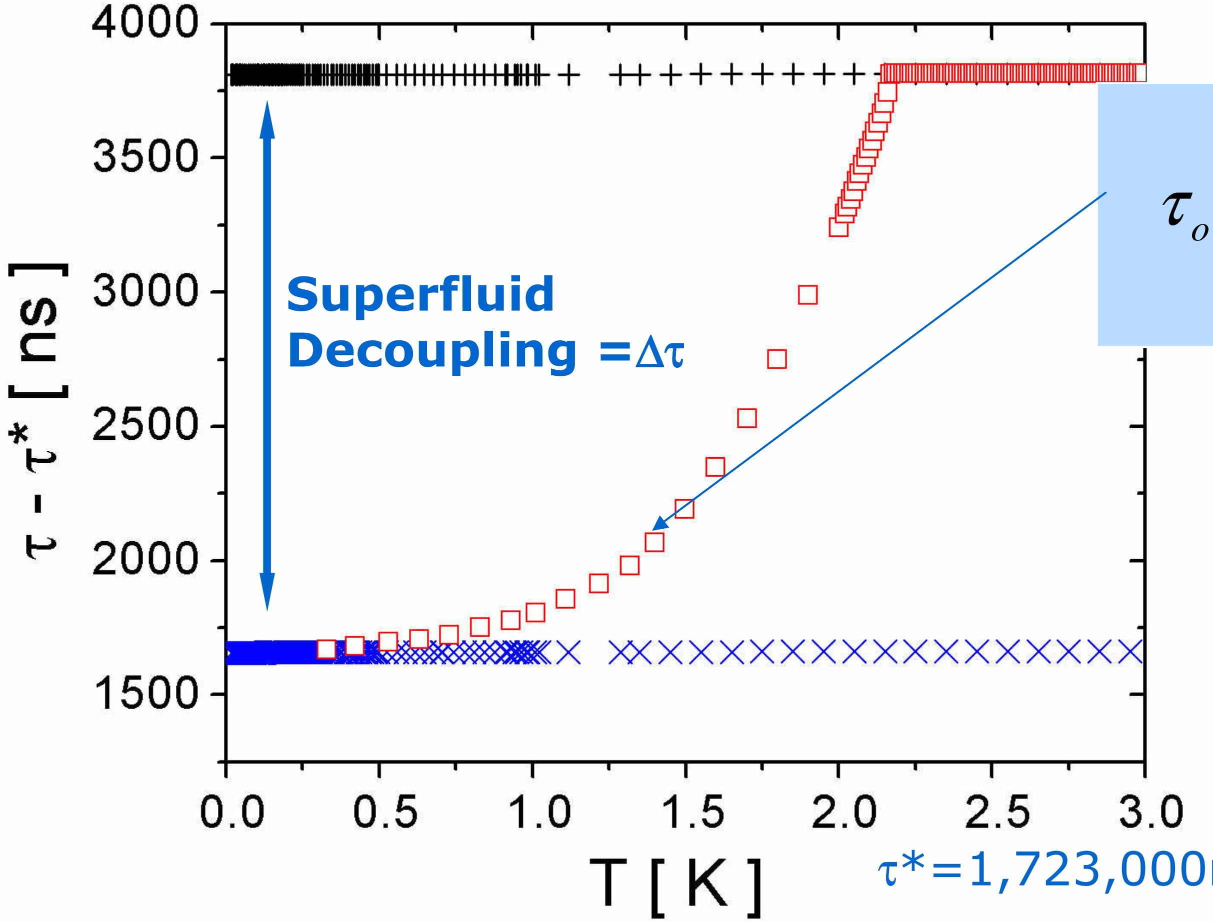
Expected background if there is no superfluid transition



τ*=1,723,000ns

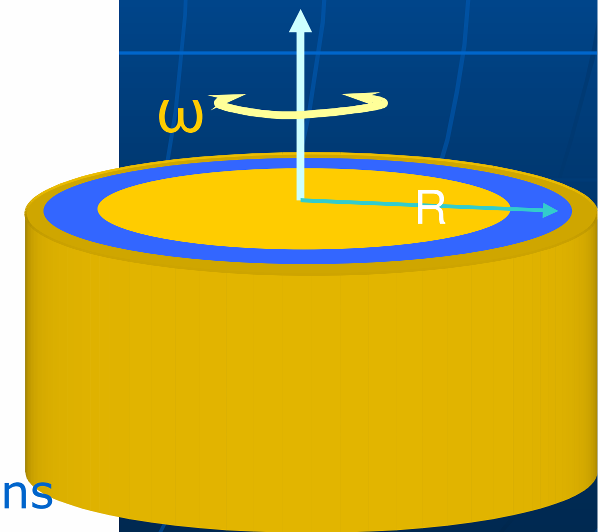
$$\tau_o = 2\pi\sqrt{\frac{I_{cell} + I_{helium}}{K}}$$

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



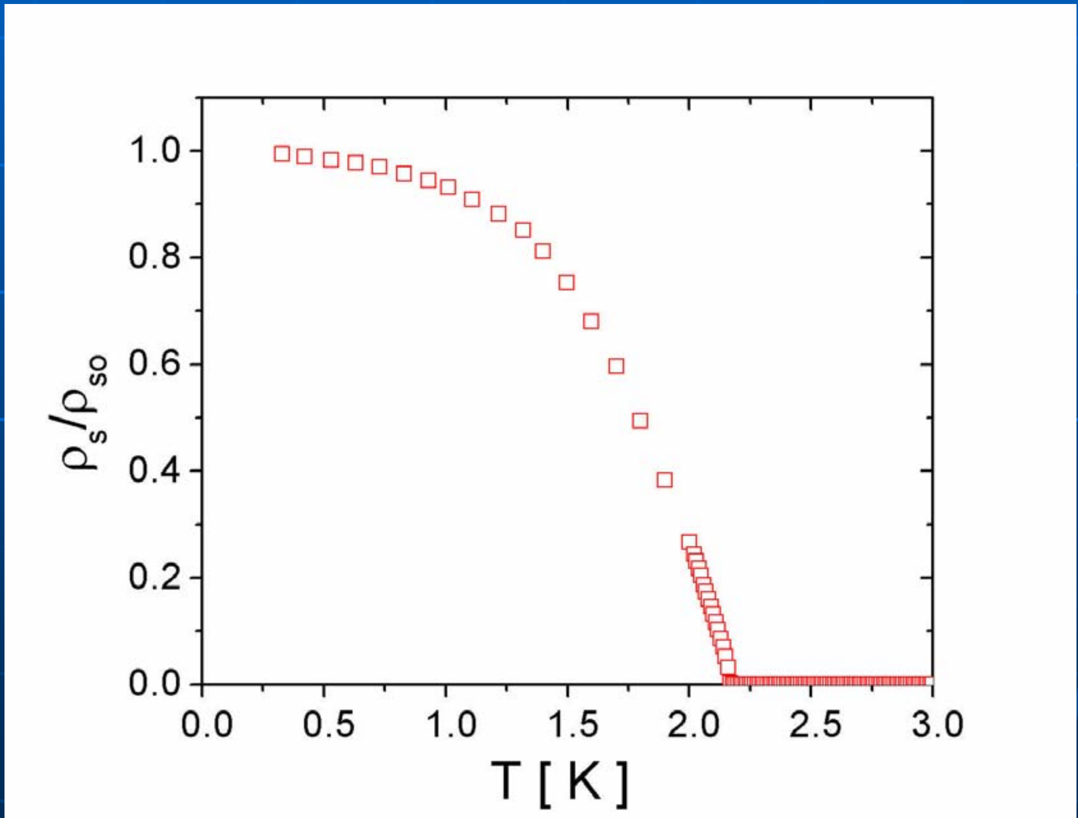
τ*=1,723,000ns

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



Superfluid fraction

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



$$\rho_s = \psi^* \psi$$

Superfluid fraction

$$= \frac{\Delta\tau}{\text{total mass loading}}$$

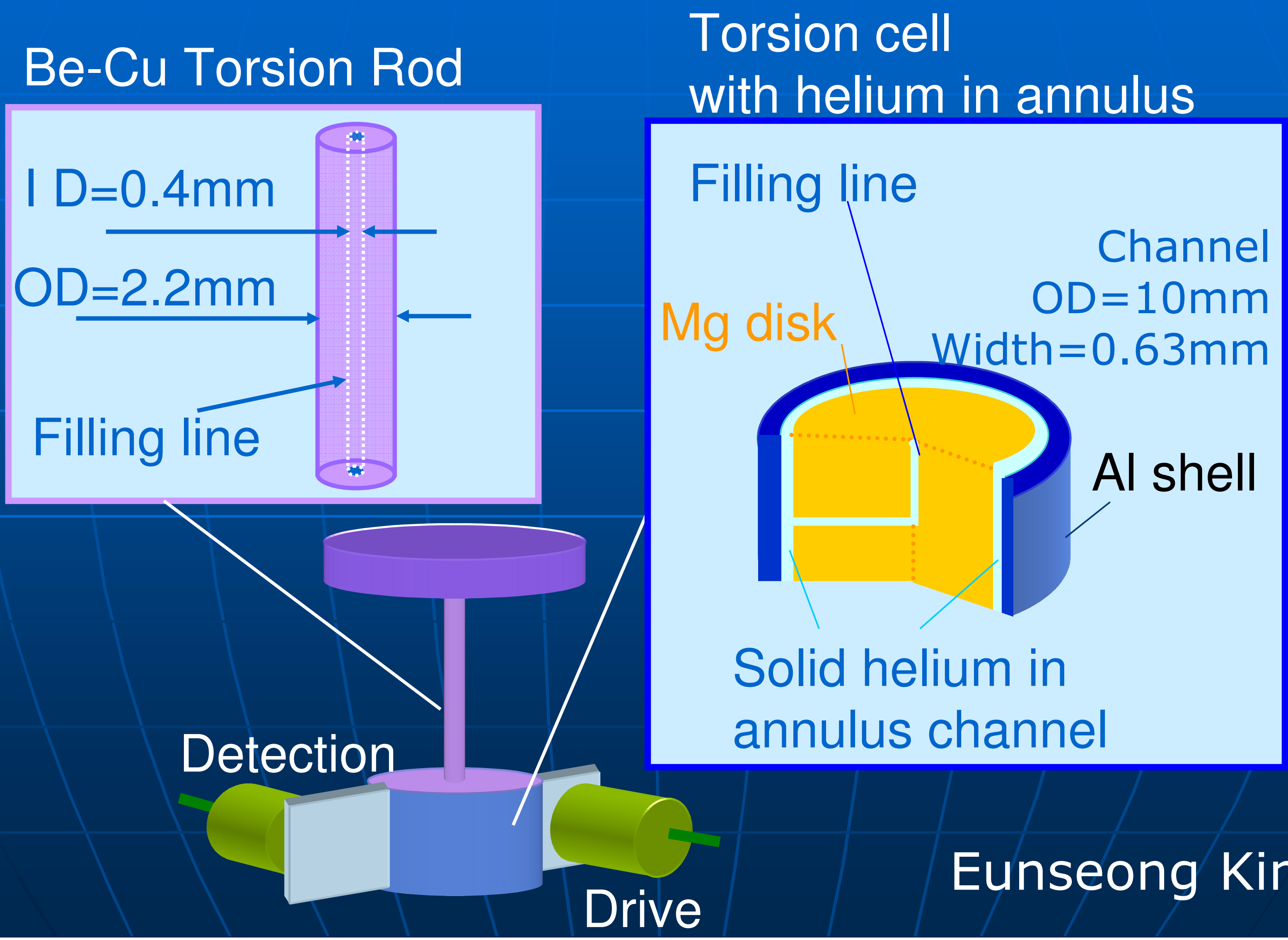
At T=0K
100% superfluid

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.

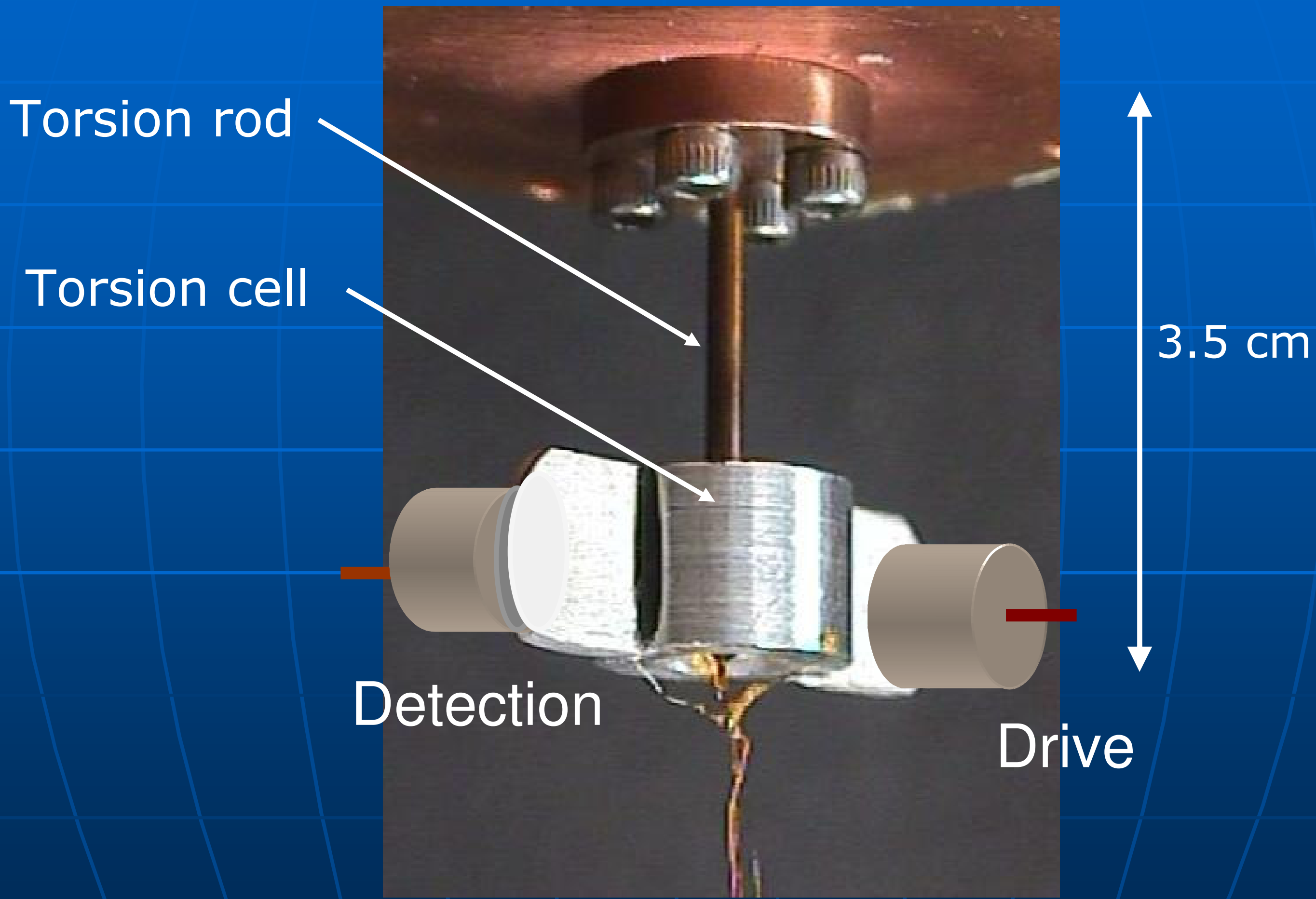
   (Chester, Andreev and Liftshitz, Reatto)
3) If it is going to occur, the likely candidate is solid ^4He, the most quantum mechanical solid.

Search for the supersolid phase in solid ^{4}He.

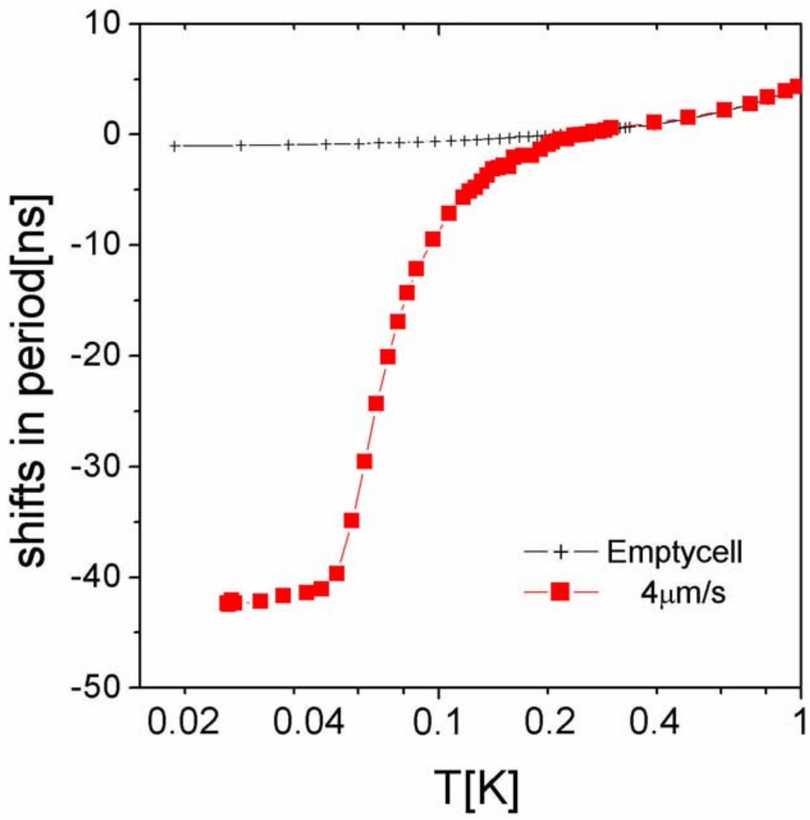


Eunseong Kim

Torsional Oscillator



Solid ^{4}He at 51 bars



Amplitude of oscillation is 7Å

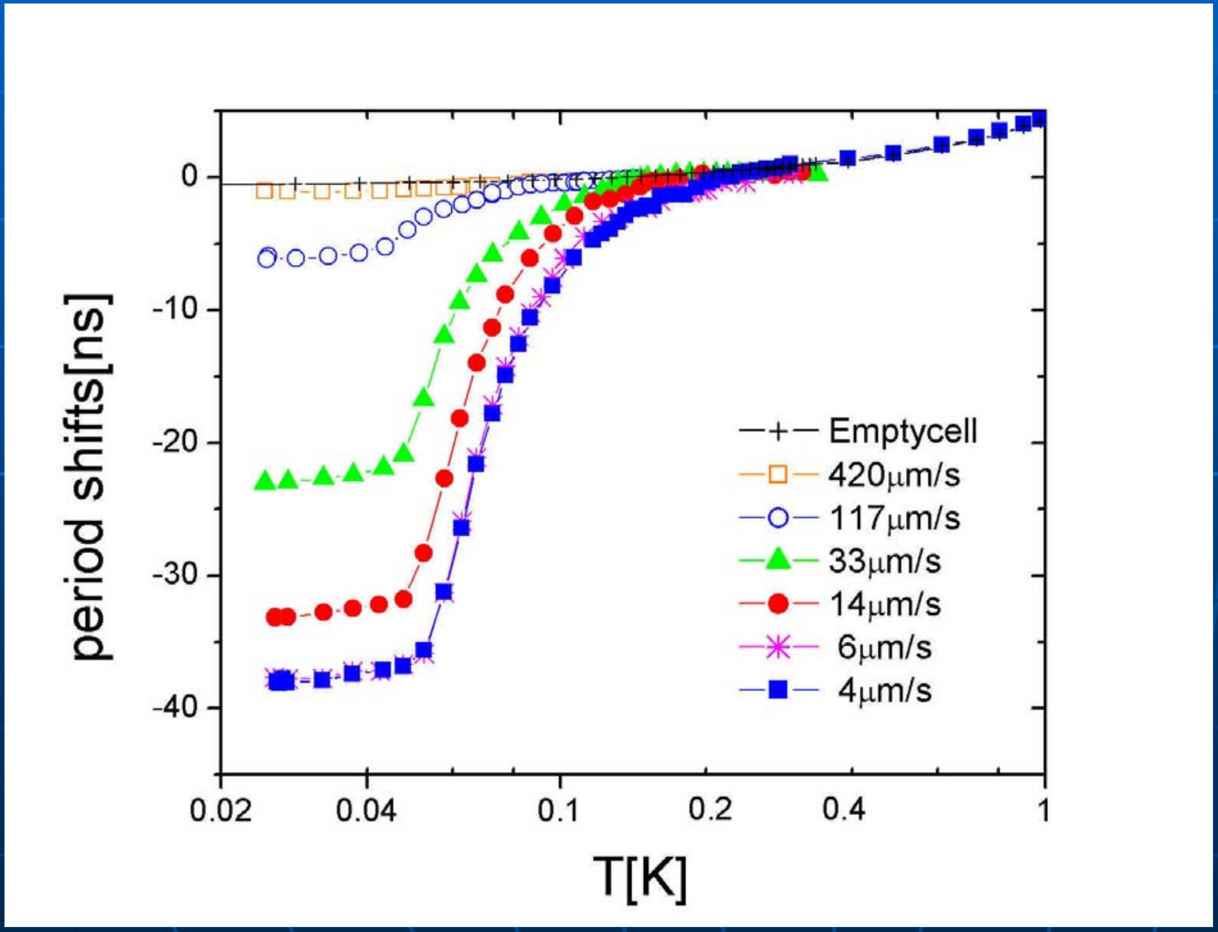
A decrease in the resonant period, similar to that found in superfluid liquid helium, appears below 0.25K

τ_0= 1,096,465ns at 0 bar
1,099,477ns at 51 bars
(total mass loading=3012ns due to filling with helium)

The nonclassical rotational (NCRI) fraction is ~1.3%

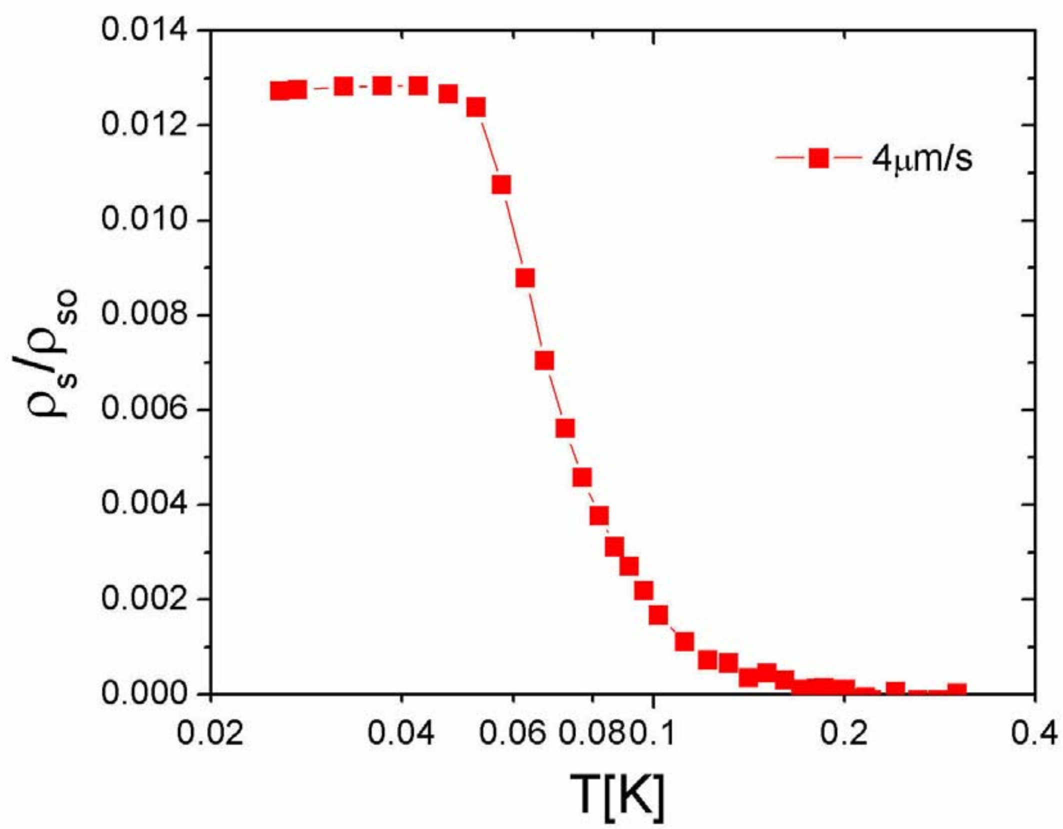
Nature, **425**, 227 (2004); Solid helium in porous glass
Science **305**, 1941 (2004); Bulk solid

Different Speed of Oscillation



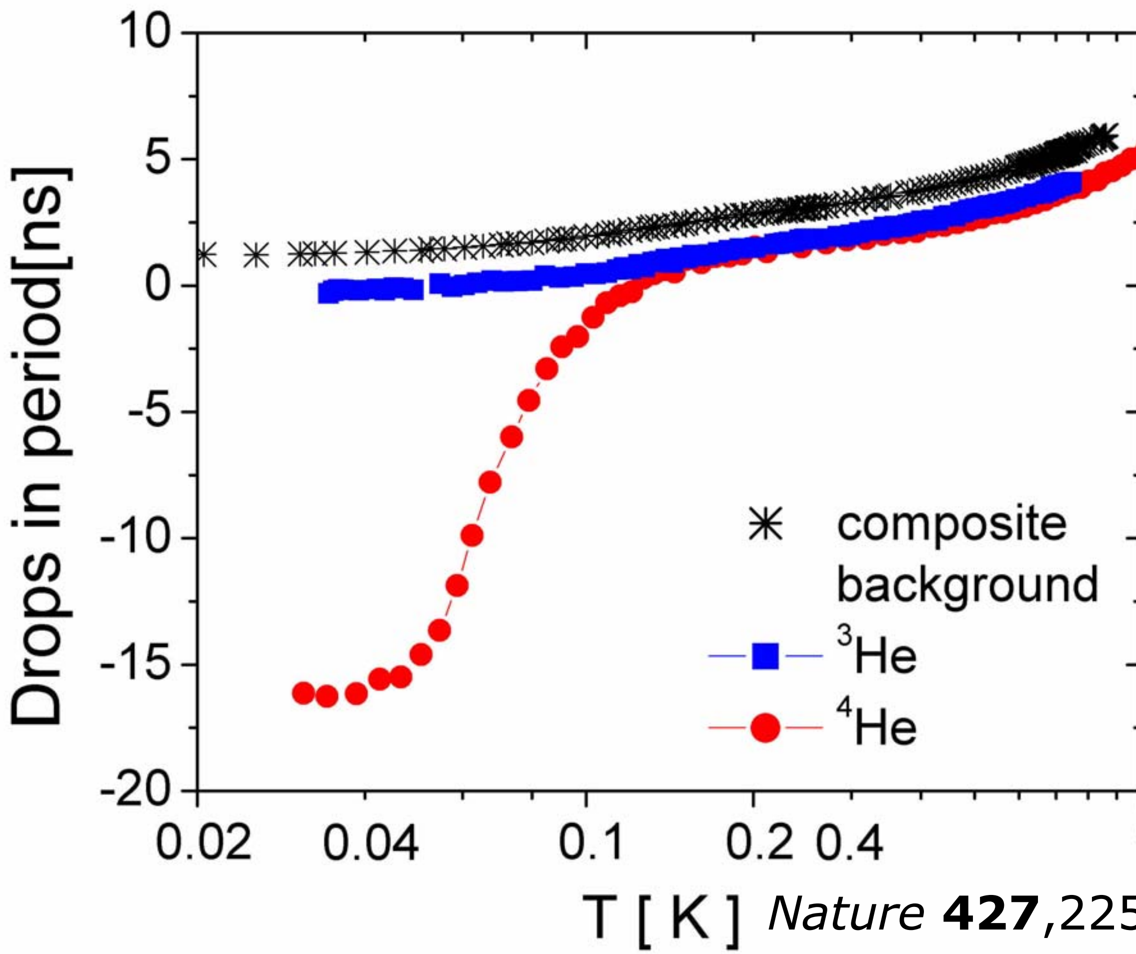
4μm/s is equivalent to oscillation amplitude of 7Å

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?

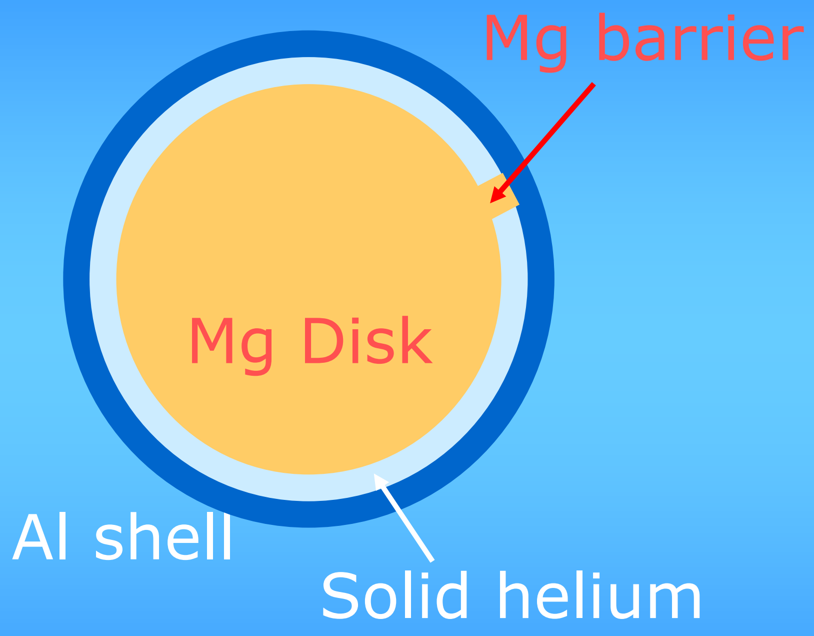


Nature **427**,225(2004)

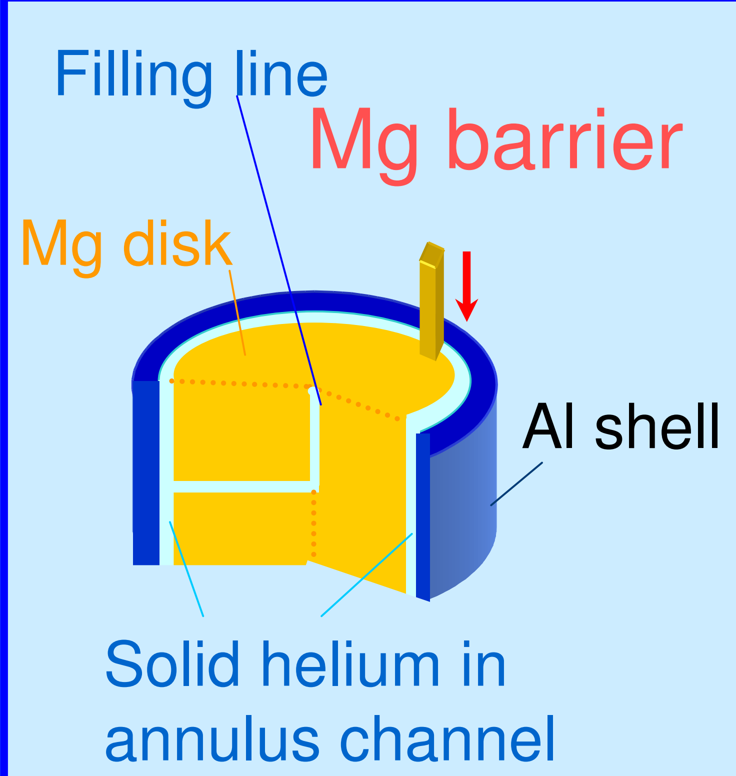
Control experiment II

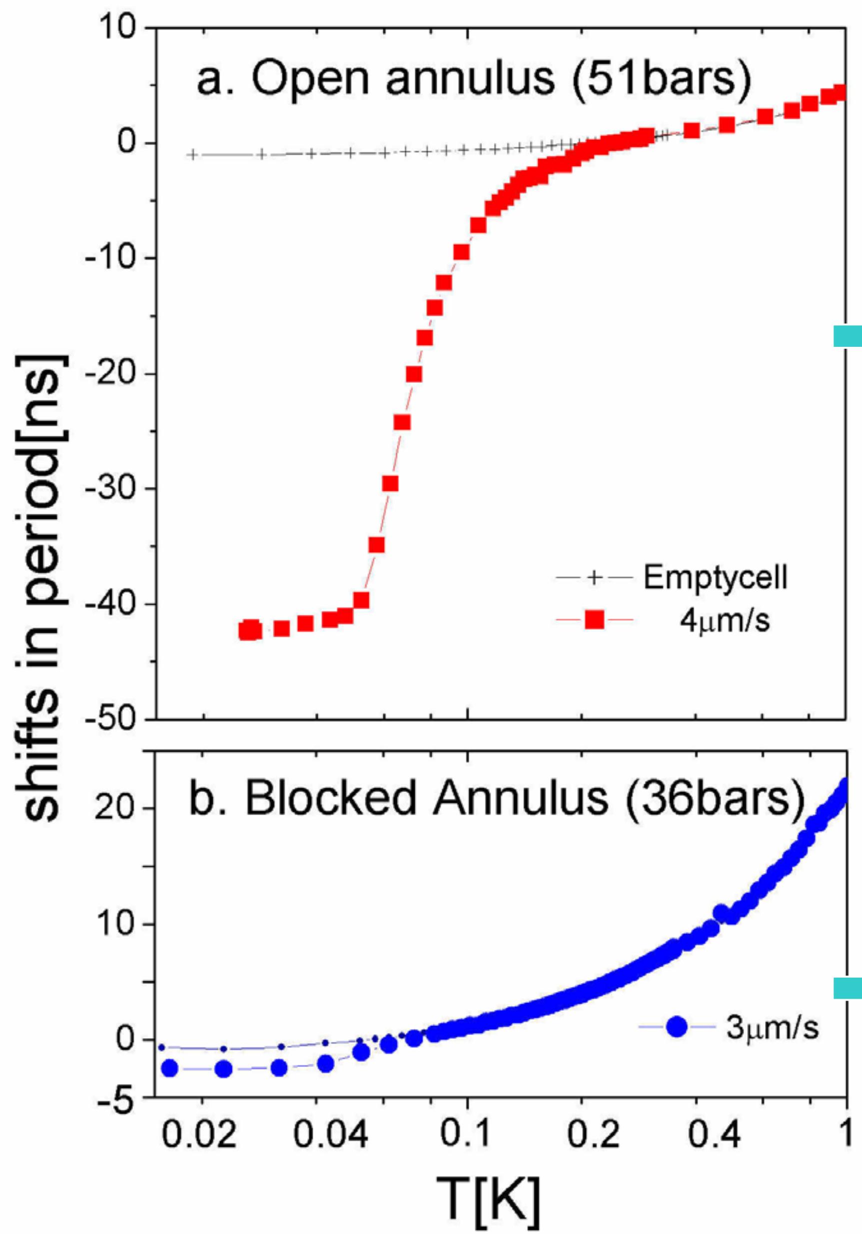
- With a barrier in the annulus, there should be NO simple superflow and the measured superfluid decoupling should be vastly reduced

Torsion cell with blocked annulus



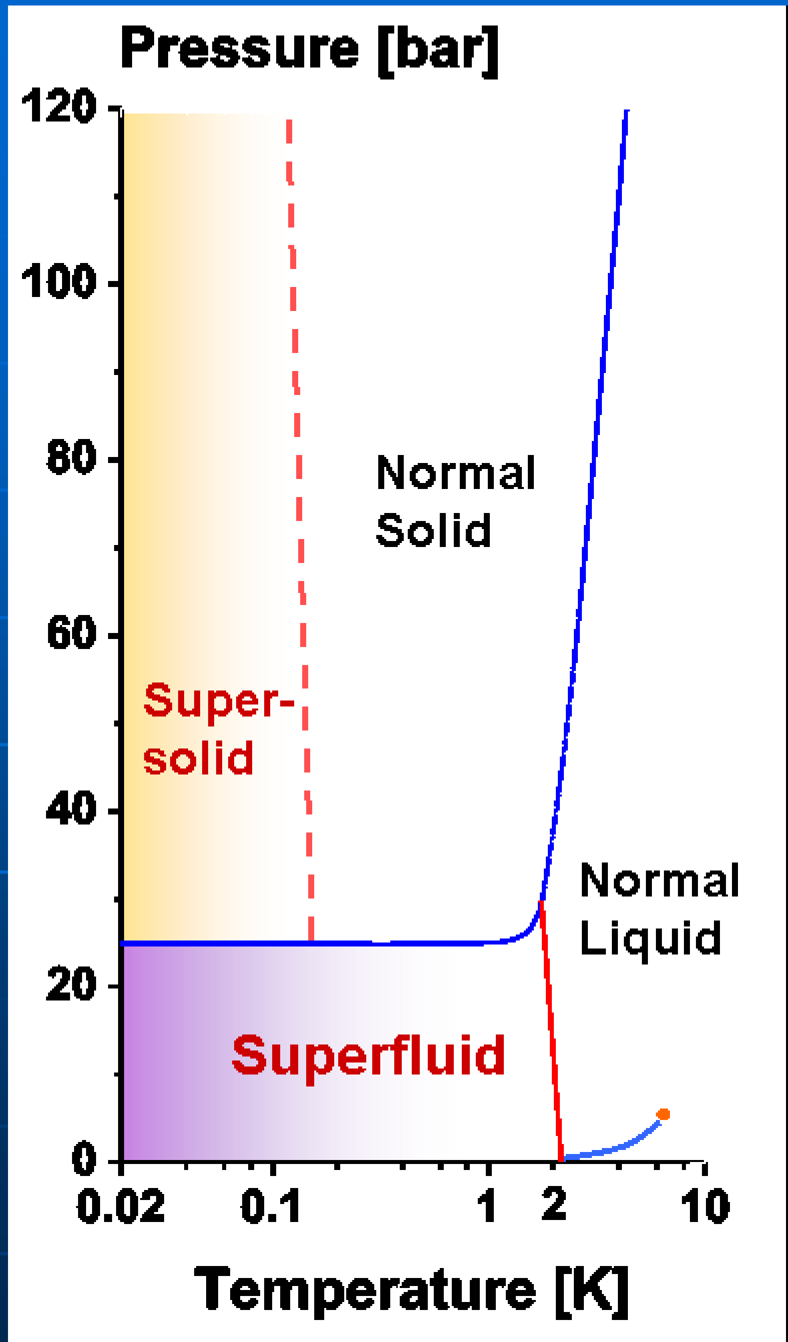
Channel OD=15mm
Width=1.5mm





The flow is irrotational like superfluid

Phase Diagram of ^4He



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.
- Are there other experimental signature? dc superflow? persistent current? second sound? direct evidence of quantum vortices? Specific heat peak! Shear modulus change!
- Effect of ^{3}He impurity?
- 2D supersolid?