PHYS4801

Superfluid Helium-3 in aerogel

Tsang Chun Wai, Tai Chuen Hei

Department of Physics

The Chinese University of Hong Kong

Content

- Superfluid He-4 and He-3
- Brief introduction of BCS theory and Cooper pair
- Introduce aerogel into He-3
- Identify the superfluid phase in aerogel

Superfluid!

- He4 is superfluid under $T_c = 2.1K$
- Discovered in 1937 by Pyotr Kapitsa, John F. Allen and Don Misener

Source: https://youtu.be/2Z6UJbwxBZI

Superfluid!

- $Viscosity \to 0$
- Can climb up wall and leaks!

Source: https://youtu.be/2Z6UJbwxBZI

Helium-4 is a boson…

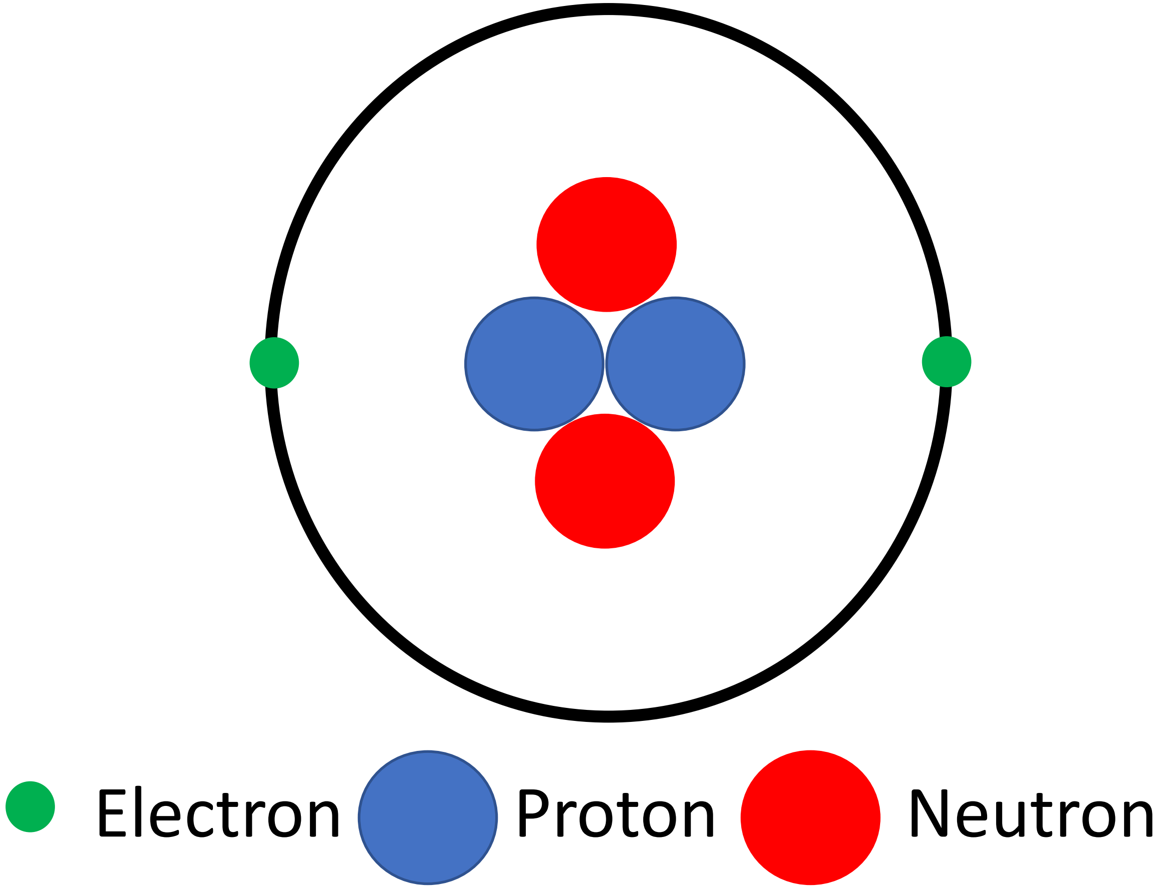


Fig. Helium-4 atom

- Electron, proton and neutron carries ½ spin (fermions)
- Integer net spin(1/2 * 6 = 3)
- Boson!
- Bose-Einstein statistics $\frac{1}{e^{\frac{\epsilon}{kT}}-1}$

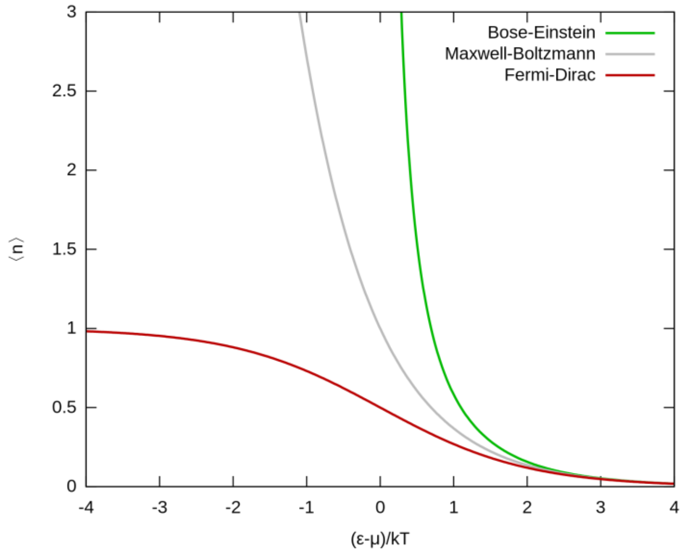
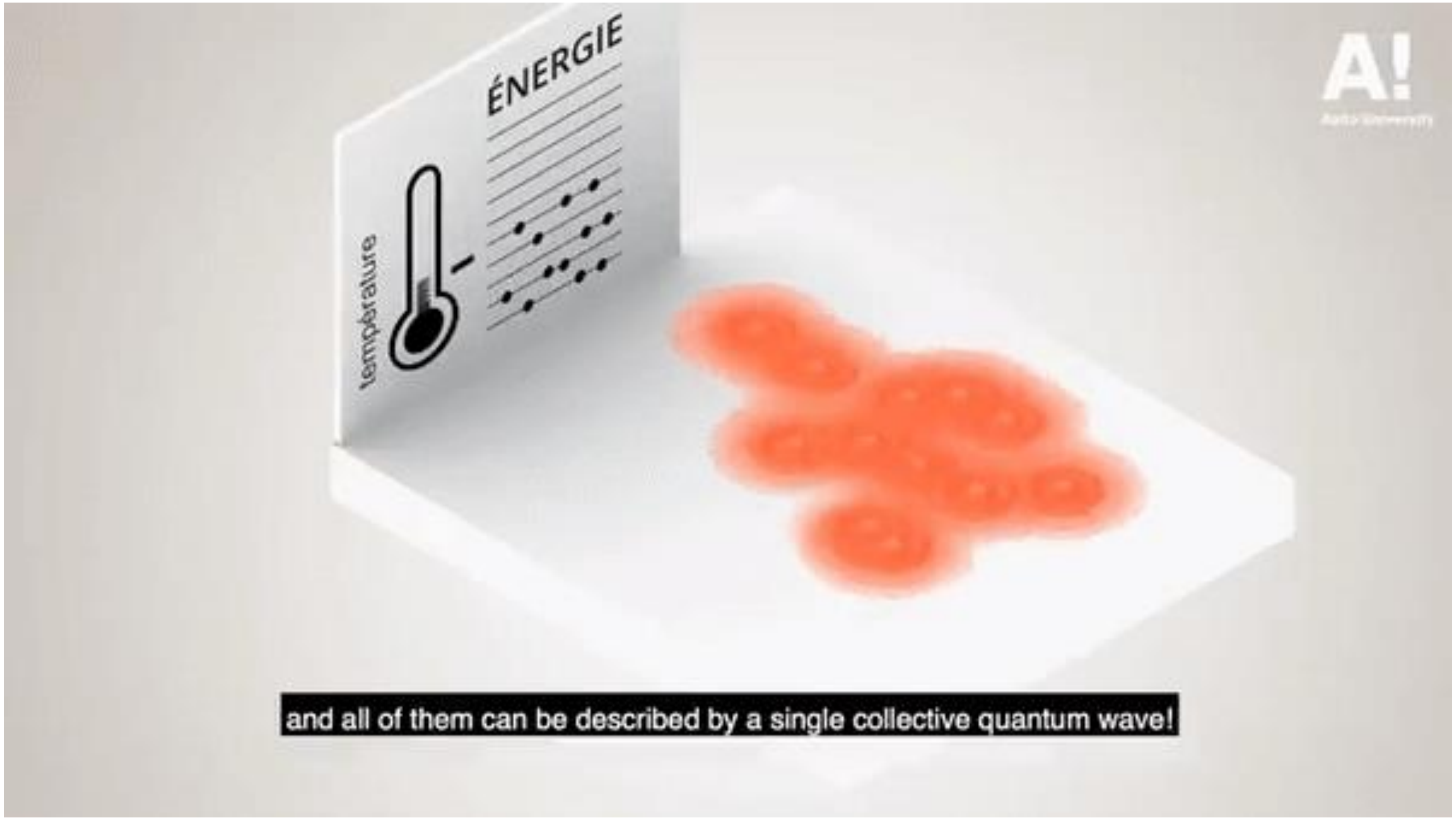


Fig. Bose-Einstein distribution By Victor Blacus - Victor Blacus, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=18645324

…so it forms Bose-Einstein Condensate

- Can stack at same energy level
- Behave like a giant single wavefunction



Source: https://youtu.be/okZmnB3Hhb4

But Helium-3 is a fermion, so it does not become superfluid...

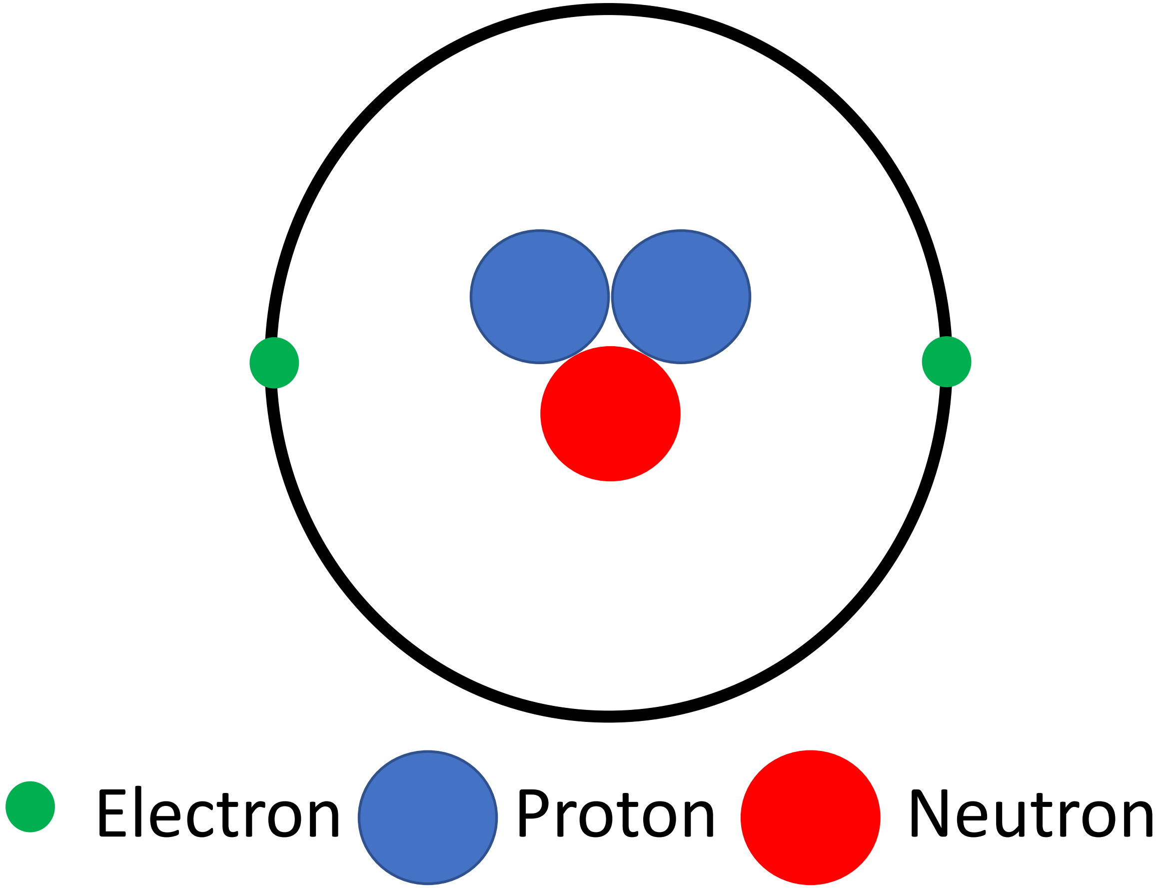


Fig. Helium-3 atom

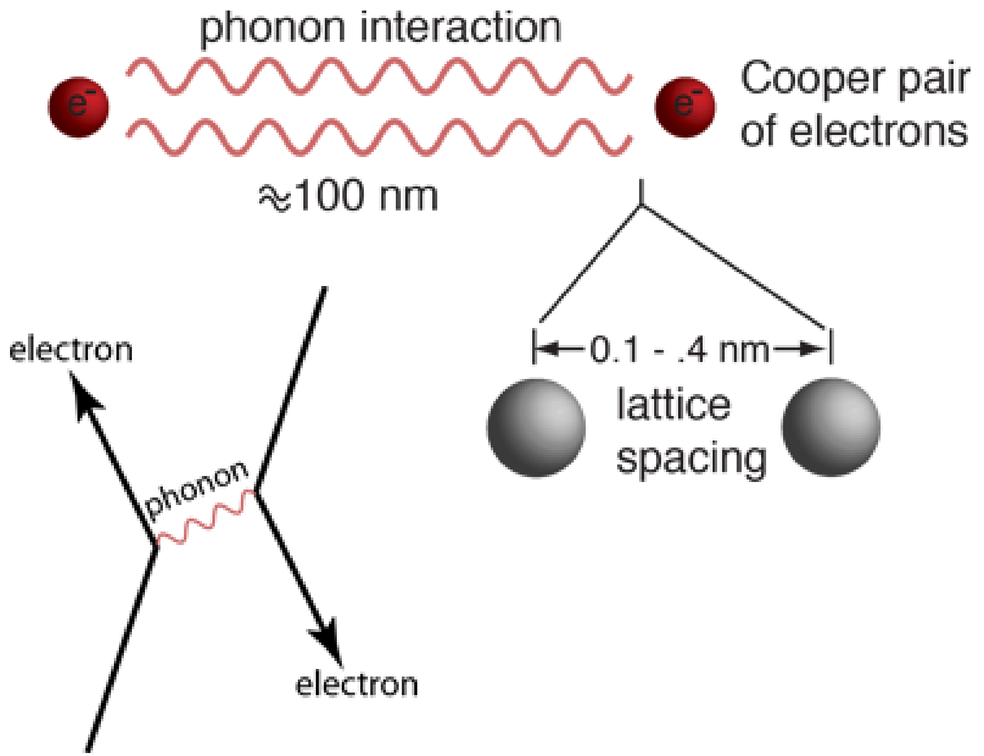
- Half integer net spin (1/2 * 5 = 5/2)
- Fermion
- Obey Pauli exclusion principle
- Cannot stack at same energy level

- So it does not form superfluid...

…Or Does it?

BCS theory

- Proposed by Bardeen, Cooper and Schrieffer in 1957
- Pair electrons form a bound state (Cooper pairs) via phonon-electron interaction
- Phonon: lattice vibration



Source:
[Cooper Pairs and the BCS Theory of Superconductivity (gsu.edu)]

BCS theory

- Coulomb force between electron and ion deform the lattice
- Creates a positive charge distribution
- Attracts another electron, forming Cooper pair
- (The figure is just an illustration! Don't take it too seriously)

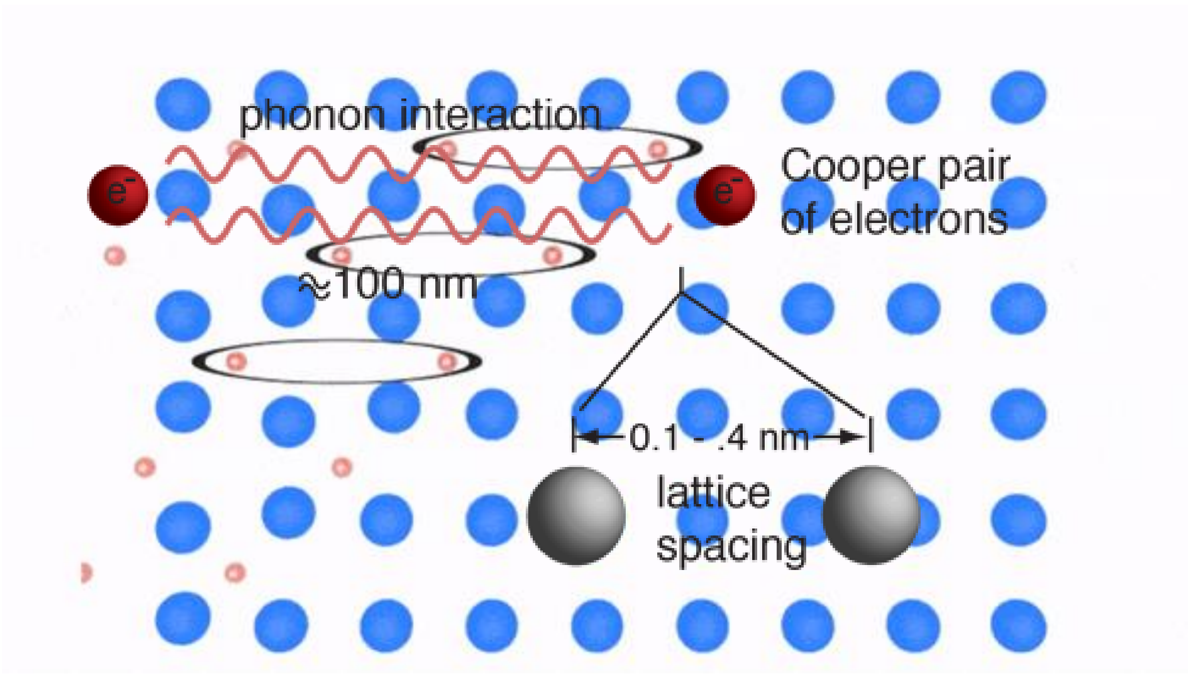
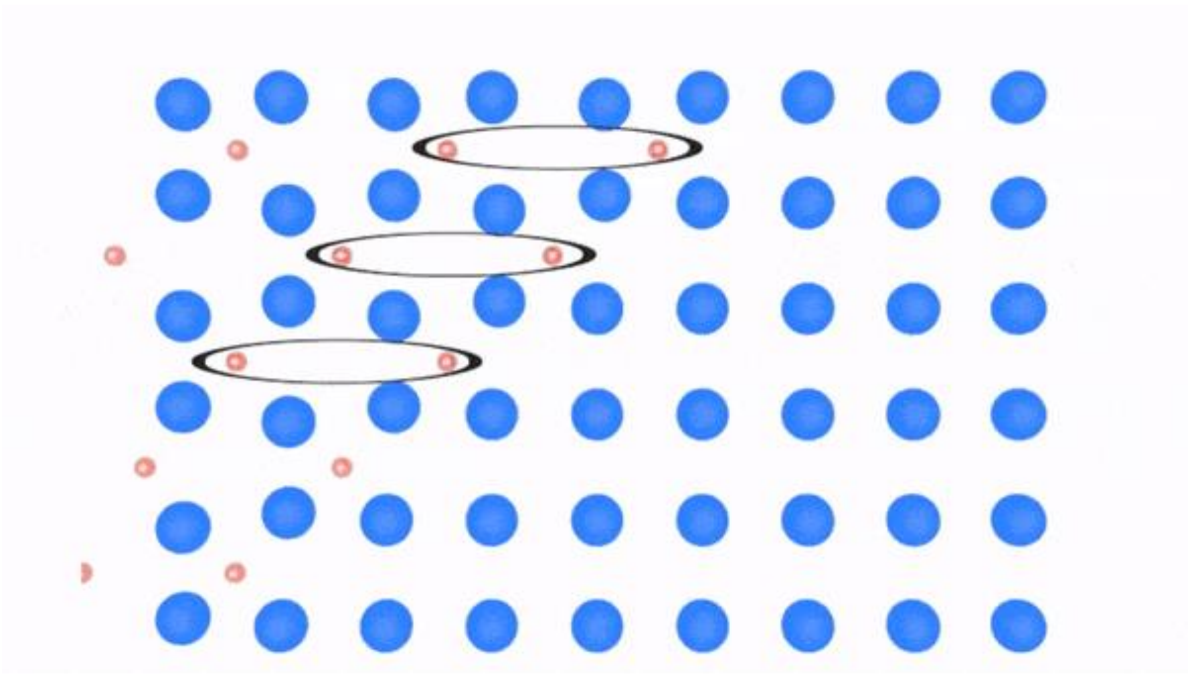


Fig. Illustration of electron-phonon interaction. Note that the direction is wrong! Just take it as an illustration.
Source: https://youtu.be/zGPb04wg_5o

BCS theory

- In general, any attractive force can induce pairing (can be other than electron-phonon)

- Cooper pair has integer net spin! Expect bosonic behavior



Source: https://youtu.be/zGPb04wg_5o

BCS-like pair condensation of He-3

- Van der Waals potential
- Attractive potential! Cooper pairs can form!
- Bosonic He-3 quasiparticle!
- Strong repulsive at small distance suggest non-zero orbital angular momentum! (Wave function vanish at zero distance)

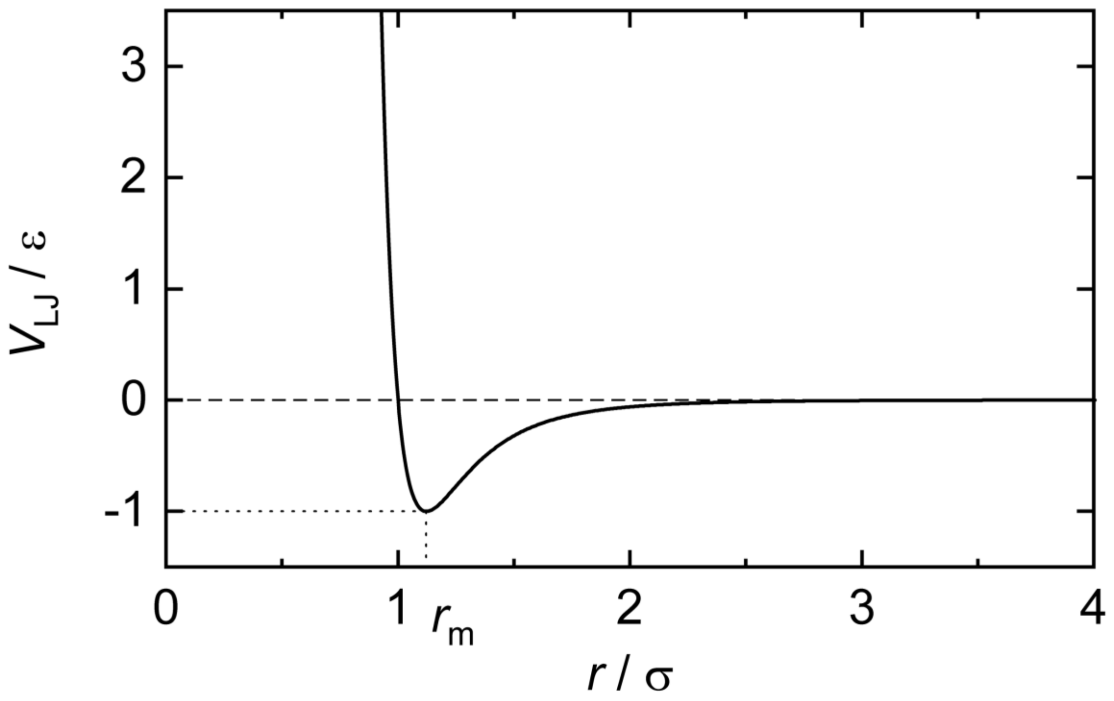
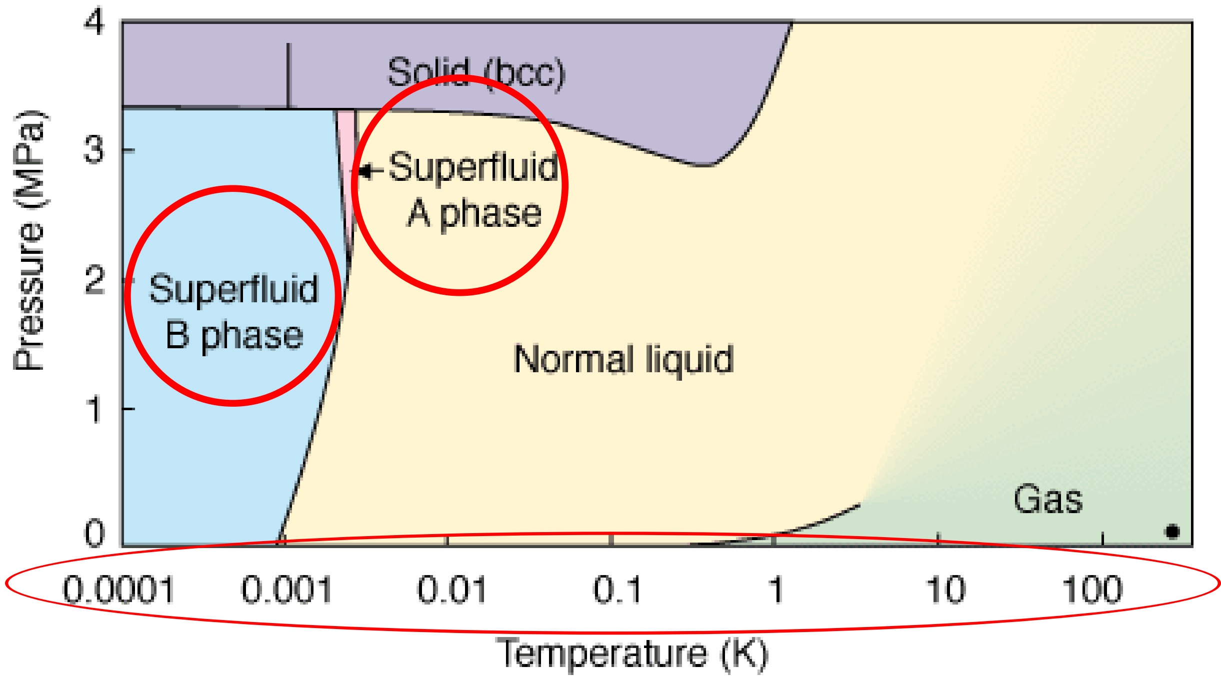


Fig. Illustration of the strong repulsive and weak attractive nature of van der Waals force. Note this figure shows the Lennard-Jones potential, which may not be a good description of the van der Waals force at low temperature limit.

…We finally have superfluid He-3!

- In 1972, superfluid helium-3 was discovered (35 years after superfluid helium-4!)
- $T_c = 0.0025K, \sim$1/1000 of He4!
- But…Why is He-3 more interesting?
- Note the two superfluid phases (He4 only has one). Why?



Source: *Erkki Thuneberg (2003),*Helium (tkk.fi)

Superfluid He-3 phases

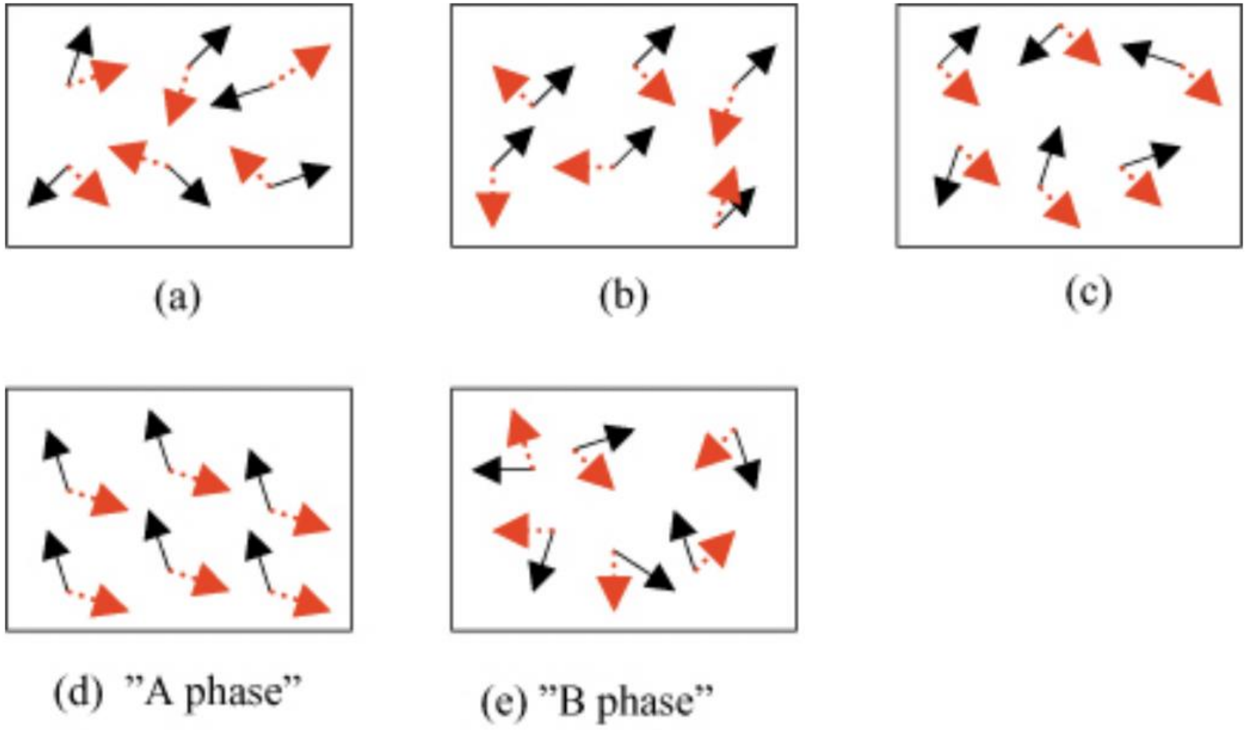


Fig. The possible states in a two-dimensional model liquid of particles with two internal degrees of freedom. Red: spin angular momentum, Black: orbital angular momentum
Source: Press release. NobelPrize.org. Nobel Prize Outreach AB 2022. Tue. 25 Oct 2022

- $spin\ s = 1$
- $orbital\ angular\ momentum\ l = 1$
- Two degrees of freedom!
- (a):invariant under rotations in spin and orbital space
- (b)-(e): different types of long range order -> broken symmetries
- (d): Rotational symmetries in spin and orbital space are broken
- (e): Relative orientation of the spin and orbital degrees of freedom is broken

- Richer behavior compared to He-4!

We are also interested at disorder!

- Want to know more about the superfluid behavior? Add impurities!
- Usually, very little impurities are enough to destroy the Cooper pairing.
- BUT superfluid He-3 exclude impurities (even He-4!)

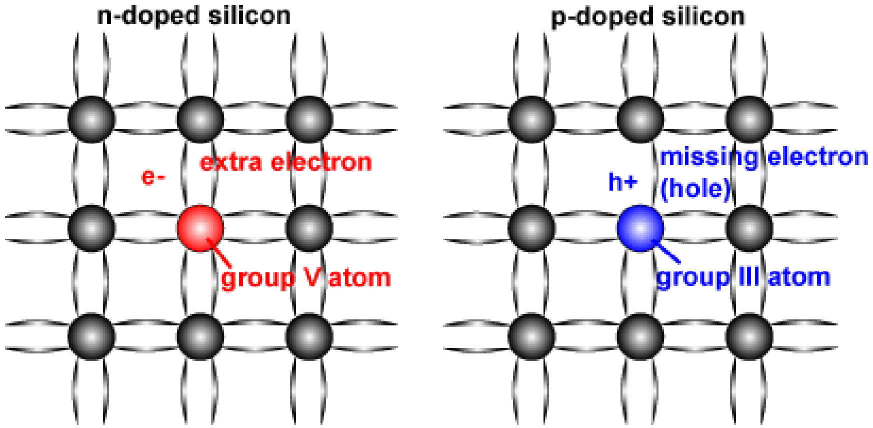


Fig. Doping in semiconductor as an analogy of impurity effect in superfluid.
Source: [Doping | PVEducation]

Aerogel as a game changer

- 98% porosity aerogel is used
  - ➢ silica is not evenly distributed

- He-3 quasiparticle scattering inside aerogel can break pairs

- Quasiparticle mean-free-path λ
- Correlation length ξ
  - ➢ New parameter $\frac{\xi}{\lambda}$ to control "lifetime" τ of Cooper pair
  - ➢ $\frac{\xi}{\lambda} \propto \frac{1}{\tau}$
- Higher τ, less easy to break pair, stronger superfluid state

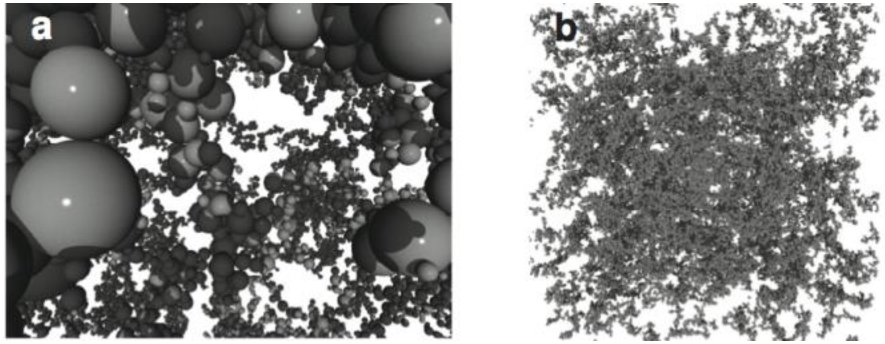


Fig. Aerogel Structure Simulation

How to make Aerogel

- Made of silica nanoparticle (SiO_2)
- ~ 3 nm in size

- Synthesized by catalytic reaction
- Aerogel with methanol is soaked in supercritical CO_2
- Slowly remove CO_2

- Details: NileRed - Making aerogel

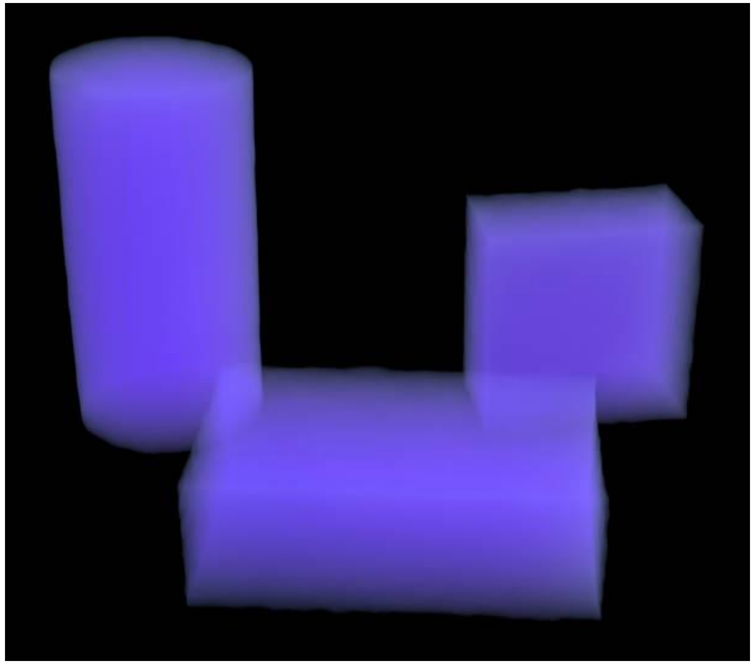


Fig. typical aerogel

Mean-free-path λ of aerogel

- Parameter of aerogel

- Mean distance travelled by quasiparticle (Cooper pair)
- ~180 nm

- Fixed by aerogel structure, independent of pressure

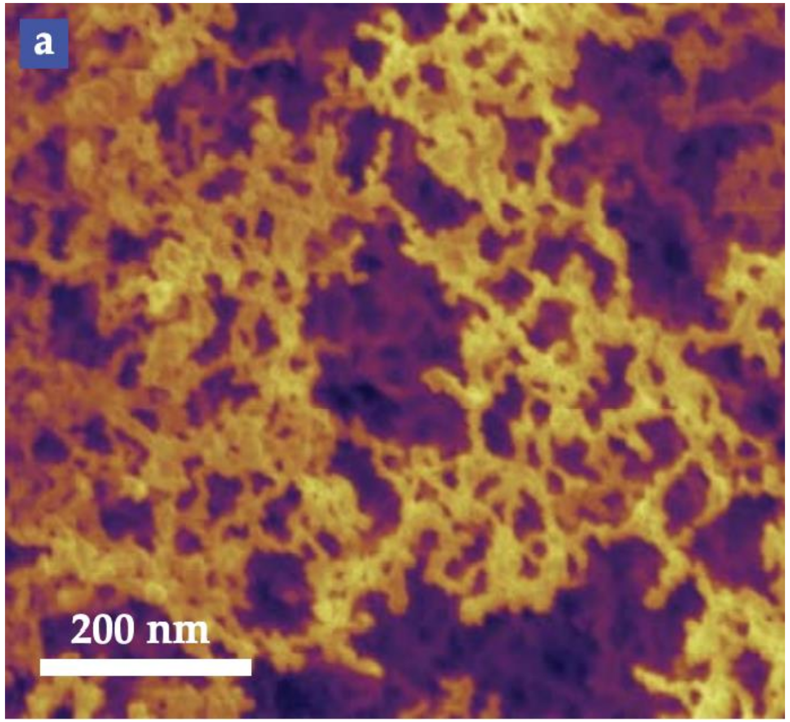


Fig. Aerogel Structure Simulation

Correlation length ξ of aerogel

- Another parameter of aerogel
- Largest void

- Controlled by pressure
- High pressure => ξ = 16 nm
- Zero pressure => ξ = 70 nm

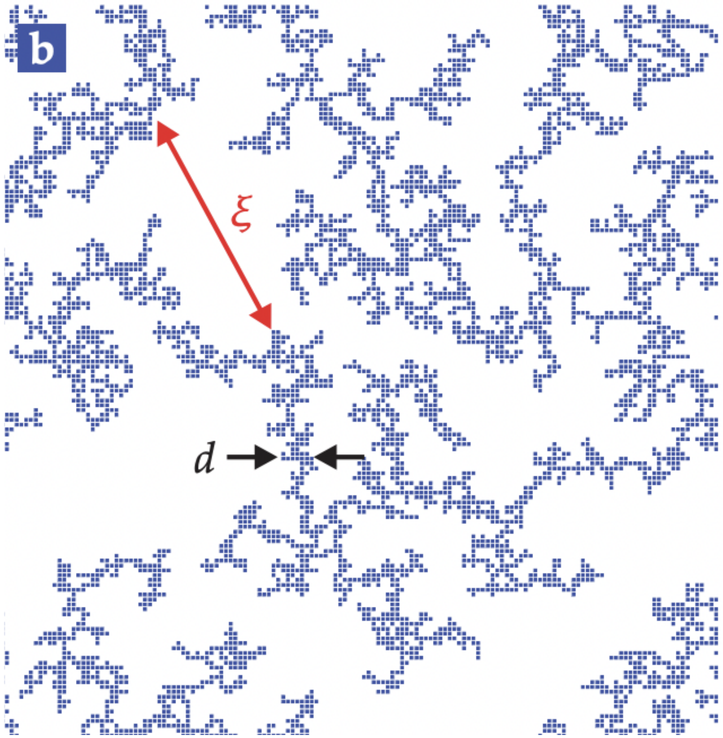


Fig. 2D view of a 3D simulation of the aerogel illustrates the strand size d and the correlation length ξ, the largest voids.

Torsion pendulum

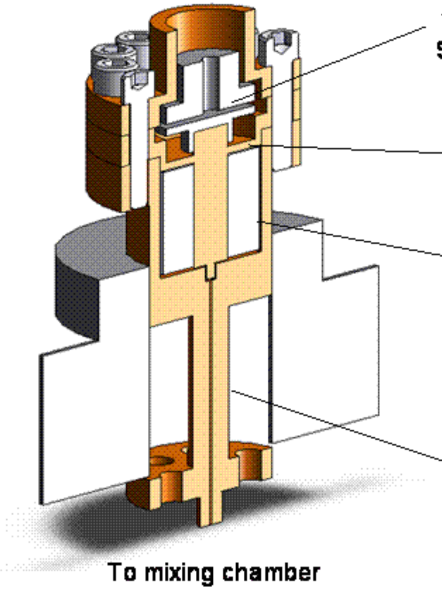


Fig. typical set-up for torsion pendulum

- Period $T = 2\pi\sqrt{\frac{I}{K}}$
- $I_{total} = I_{cylinder} + I_{helium,n}$

➢ Superfluid feels no friction (kind of)

➢ $Viscosity \rightarrow 0$

- Expectation: more superfluid, shorter T

- Superfluid fraction = $\frac{\rho_s}{\rho}$
- Can be calculated by the change of T

Torsion pendulum (Result)

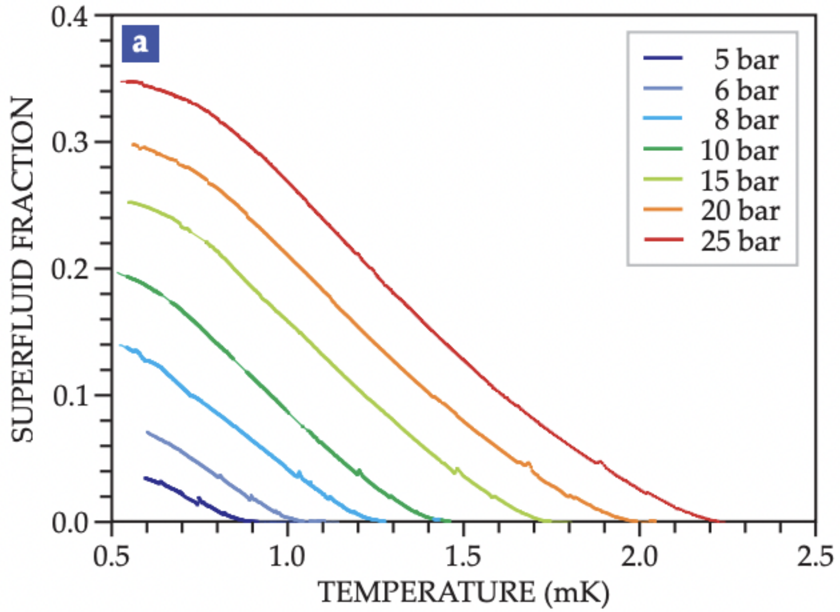


Fig. The superfluid fraction as a function of temperature and pressure

- Point to note:
  atmospheric pressure = 1.01 bar
- More pressure applied
  - $\xi \downarrow \Rightarrow \frac{\xi}{\lambda} \downarrow \Rightarrow \tau \uparrow$
- Higher superfluid fraction
- Higher Onset Temperature

In case you forget: ξ correlation length, λ mean-free-path, τ "lifetime" of pairs

NMR and frequency shift

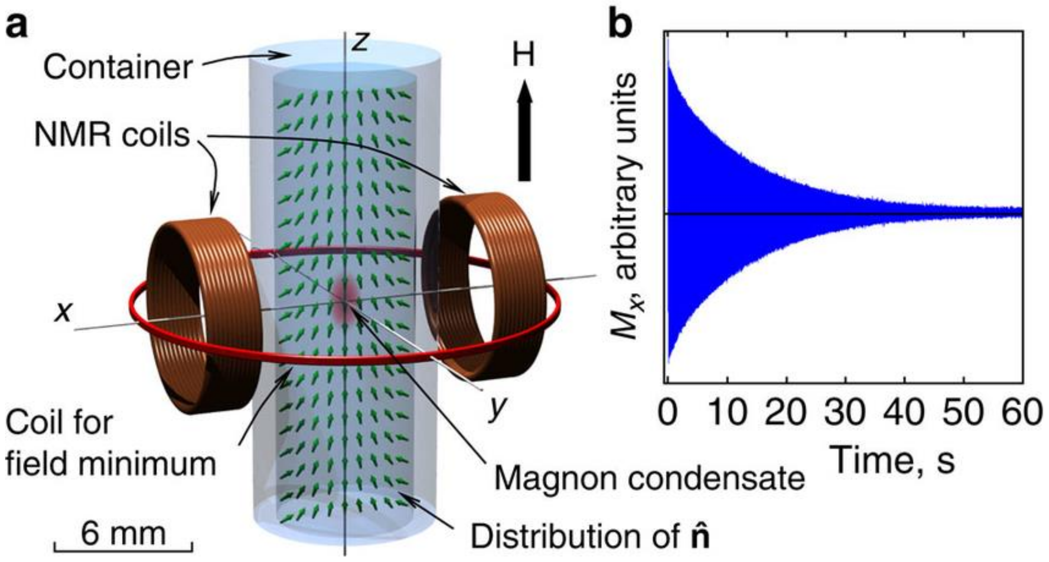


Fig. typical NMR experimental setup

- $\vec{\mu} = \gamma\vec{S}$
- Pair could have larger S than a single atom
- Recall:
- A phase (high P, 2.5 mK):
- |↑↑> + |↓↓>
- B phase (low P, 0.9 mK):
- |↑↑> + |↓↓> + |↑↓+↓↑>
- NMR measures the resonance frequency of the particle by a homogeneous B field

NMR result

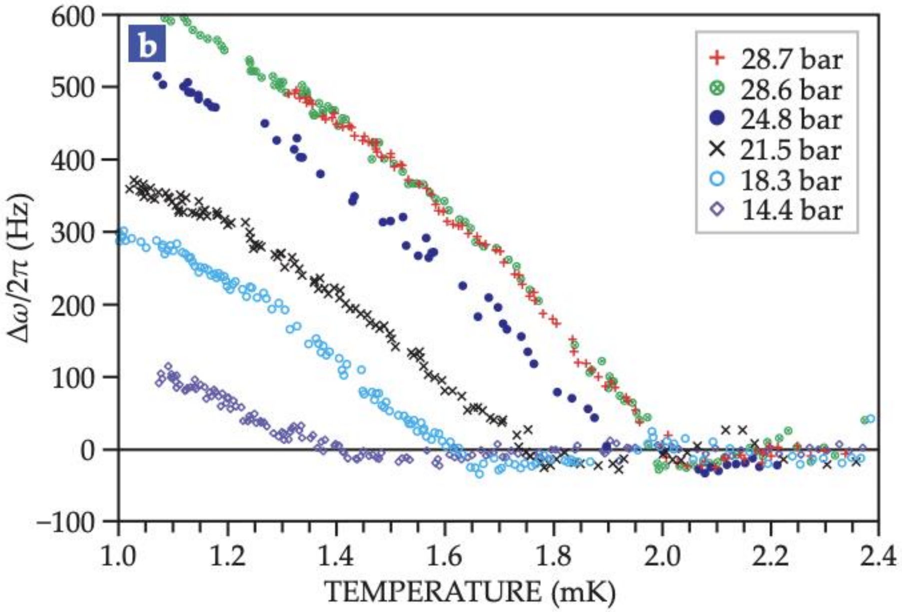


Fig. NMR frequency shift $\Delta\omega$ away from the value for a normal fluid

- Δω = frequency shift from normal state
- Higher pressure
  - More away from the normal state
- Confirm the result from torsion pendulum experiment

Comparison with theory

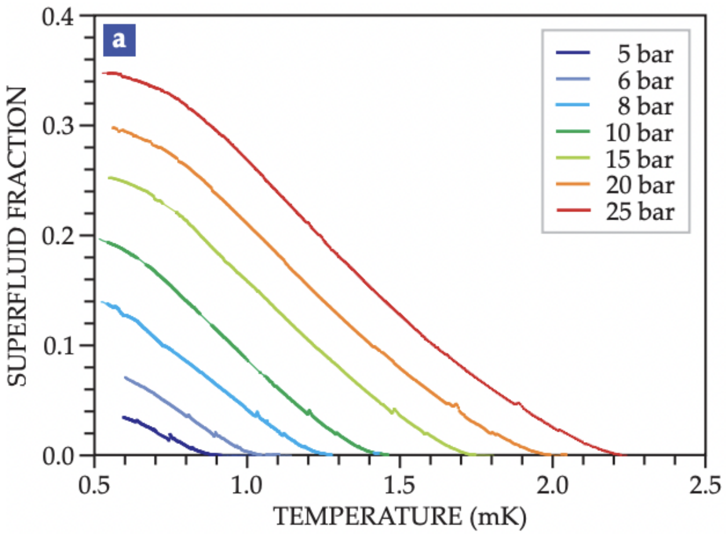


Fig. Pendulum result

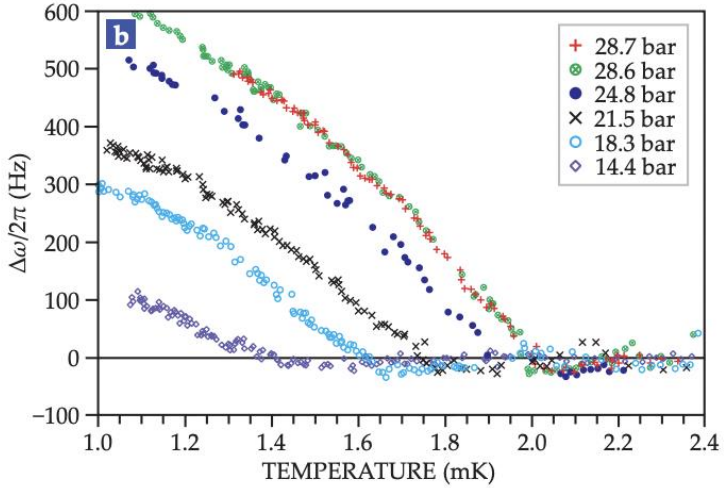


Fig. NMR result

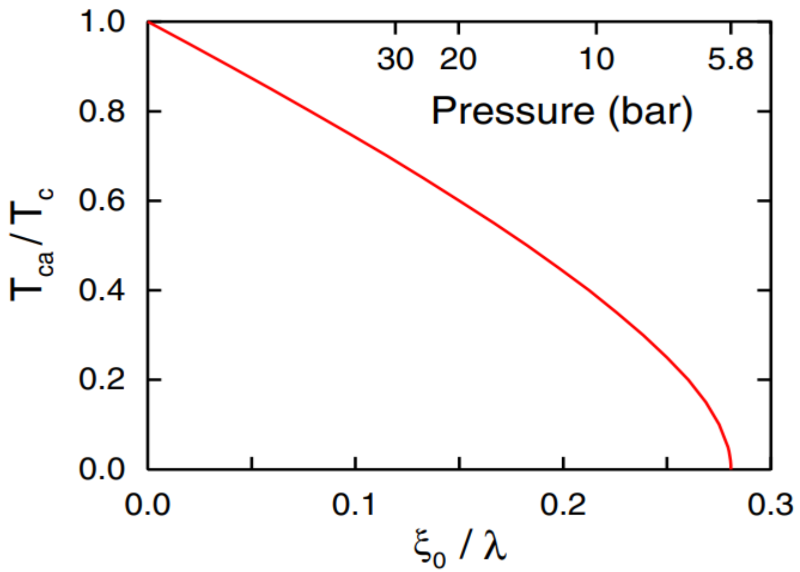


Fig. theoretical curve from Abrikosov-Gorkov theory with modifications

- 2 experiments obtain same result
- Imagine flipping the graph by 45^0

➢Similar to Abrikosov-Gorkov theory for superconductor

Note: different x-y axis in different graphs!!!

Relation to other fields

- Quantum amplifier
  - Weak interaction (e.g., nuclei dipole-dipole interaction) may reflect on macroscopic coherence
- Unconventional superconductors
  - Some are “heavy-fermion systems”, which can inherit the concepts developed for superfluid He-3

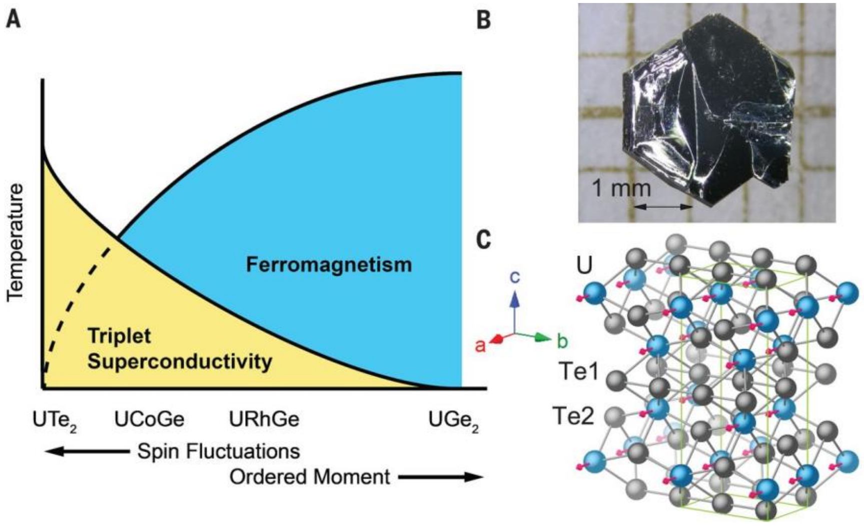


Fig. UTe2, a spin-triplet superconductor, also a heavy fermion superconductor

Reference

- Zhang-Yu Nie et al, “P-T phase diagram of a holographic s+p model from Gauss-Bonnet gravity”, Journal of High Energy Physics, 2015(10).
- W.P. Halperin, “Superfluid 3He in Aerogel”, Annual Review of Condensed Matter Physics, 2019(10).
- P. Halperin ,William and Choi ,Hyoungsoon and P. Davis ,John and Pollanen ,Johannes, “Impurity Effects of Aerogel in Superfluid 3He”, Journal of the Physical Society of Japan, 2008, DOI 10.1143/JPSJ.77.111002.
- William P. Halperin, Jeevak M. Parpia, and James A. Sauls. Superfluid helium-3 in confined quarters. Physics Today 71, 11, 30 (2018).https://doi.org/10.1063/PT.3.4067
- Moses Chan and Norbert Mulders and John Reppy. Helium in Aerogel. Physics Today 49, 8, 30 (1996). https://doi.org/10.1063/1.881509
- D. Vollhardt and P. Wölfle. Superfluid Helium 3: Link between Condensed Matter Physics and Particle Physics. Acta Phys.Polon. B31 (2000) 2837. https://doi.org/10.48550/arXiv.cond-mat/0012052
- Press release. NobelPrize.org. Nobel Prize Outreach AB 2022. Tue. 25 Oct 2022. https://www.nobelprize.org/prizes/physics/2003/press-release