Superfluid Helium

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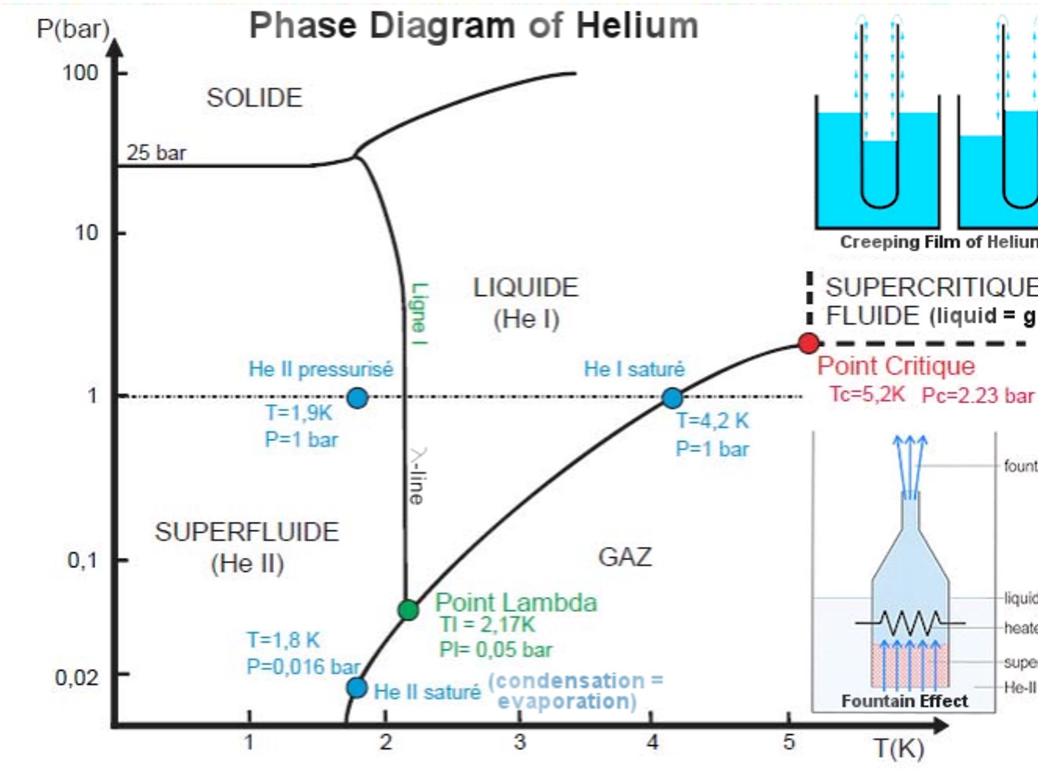
Outline

- Background of Superfluid Helium
- Experiment 1: Second Sound
- Experiment 2: Heat Capacity
- Implications/Takeaways

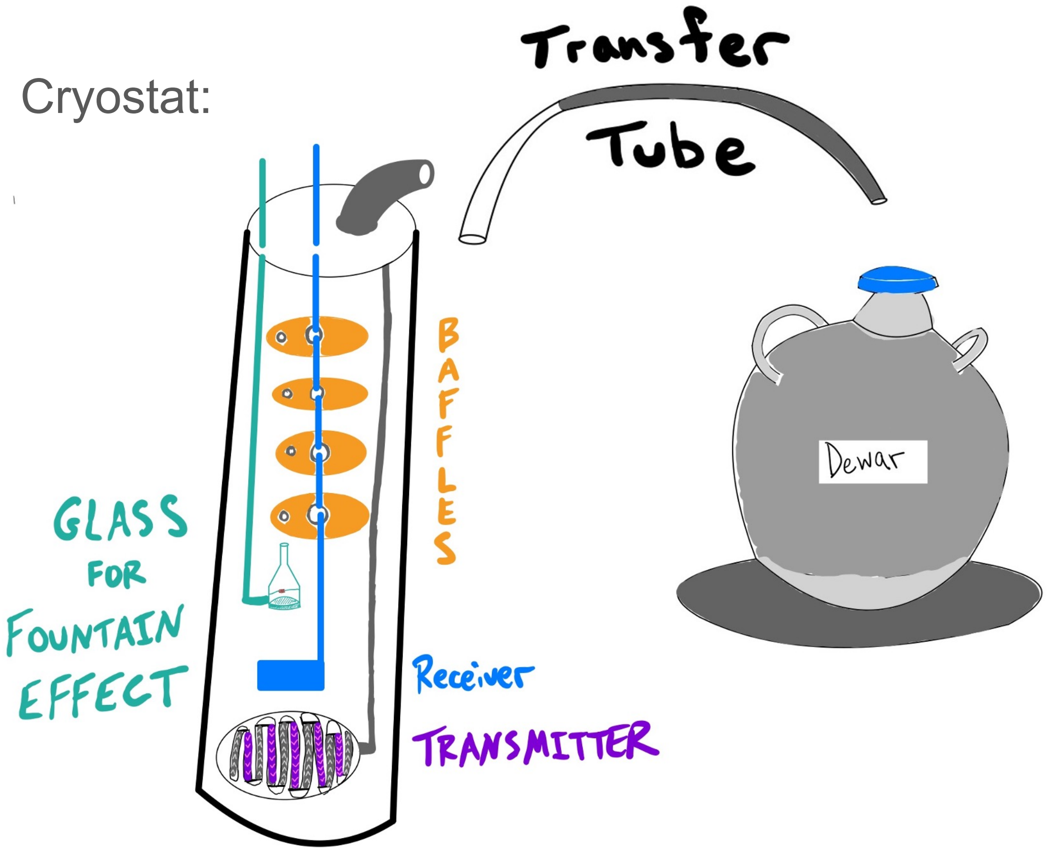
Background on Superfluid Helium

- At the lambda point, approx. A vapor pressure of 37 Torr or equivalently 2.17 K, liquid helium becomes superfluid helium
- Superfluid helium behaves as a fluid without viscosity
- Can propagate heat waves like sound waves
- Creeping film leading to the fountain effect



Cool Down Procedure

Cryostat:



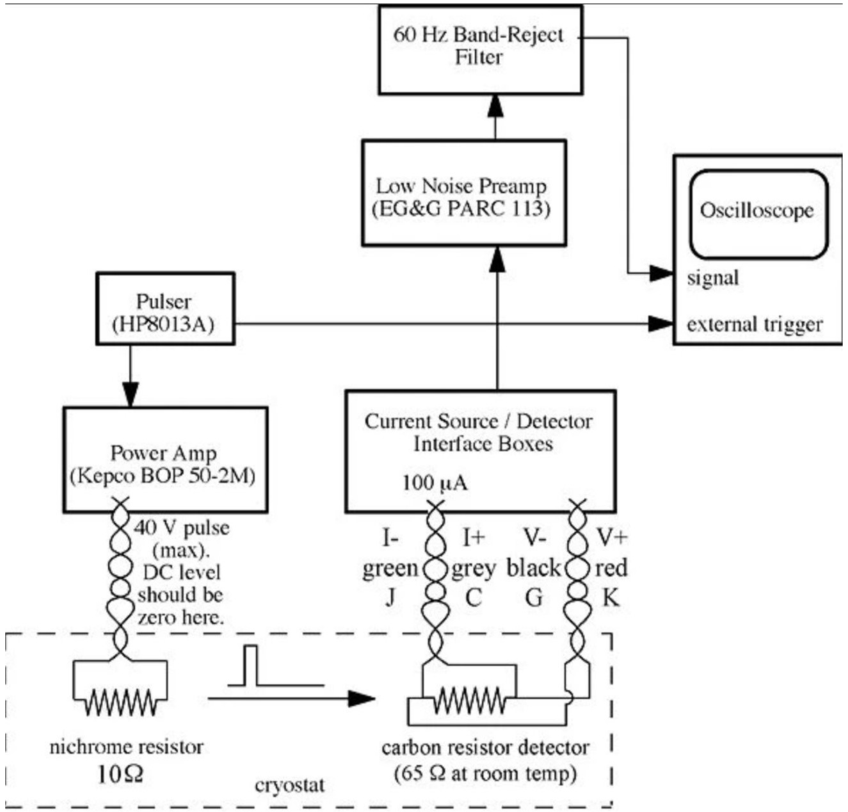
- First, we pre-cool with liquid nitrogen
- After removing the nitrogen, we pump in helium gas to repressurize the cryostat
- Next, we pump liquid helium in
- Finally, we achieve further cooling to the lambda point by lowering the pressure

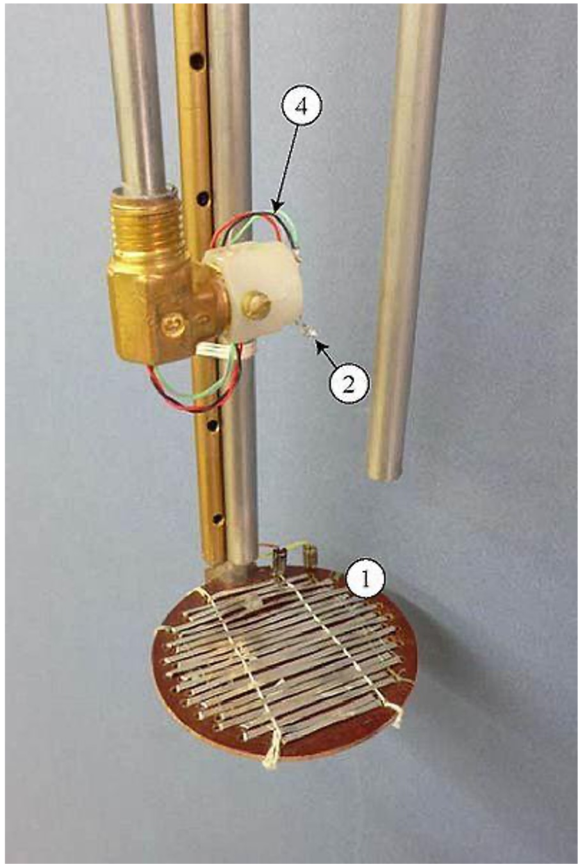
Second Sound Setup

We send a pulse through the bottom resistor (1) that dissipates heat

The detector (2) has another resistor whose resistivity changes as a function of temperature

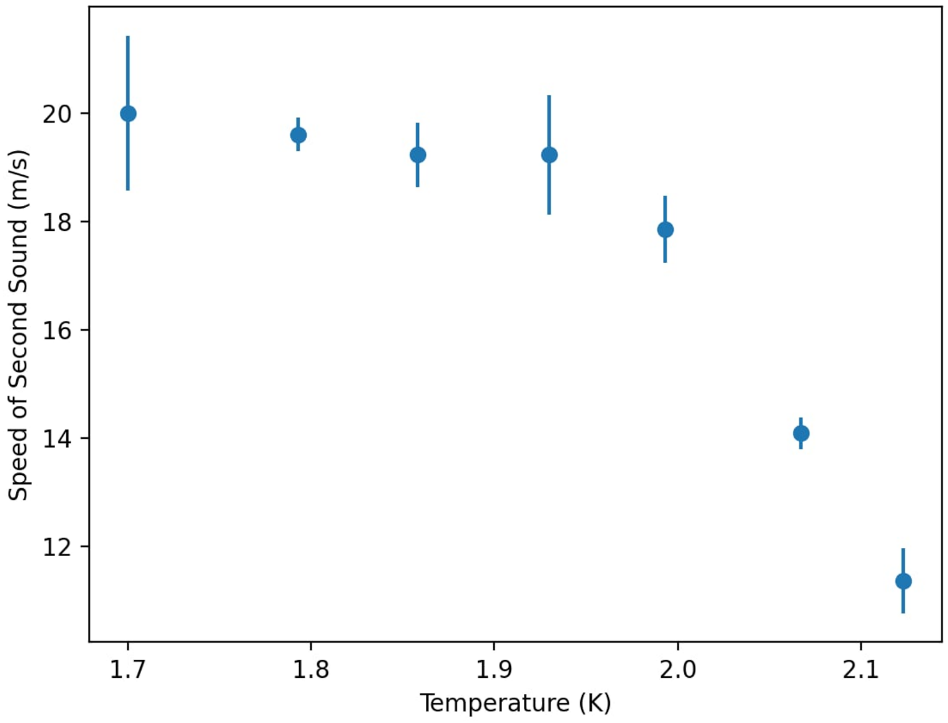
We find that resistance over time via a four-point measurement (4)

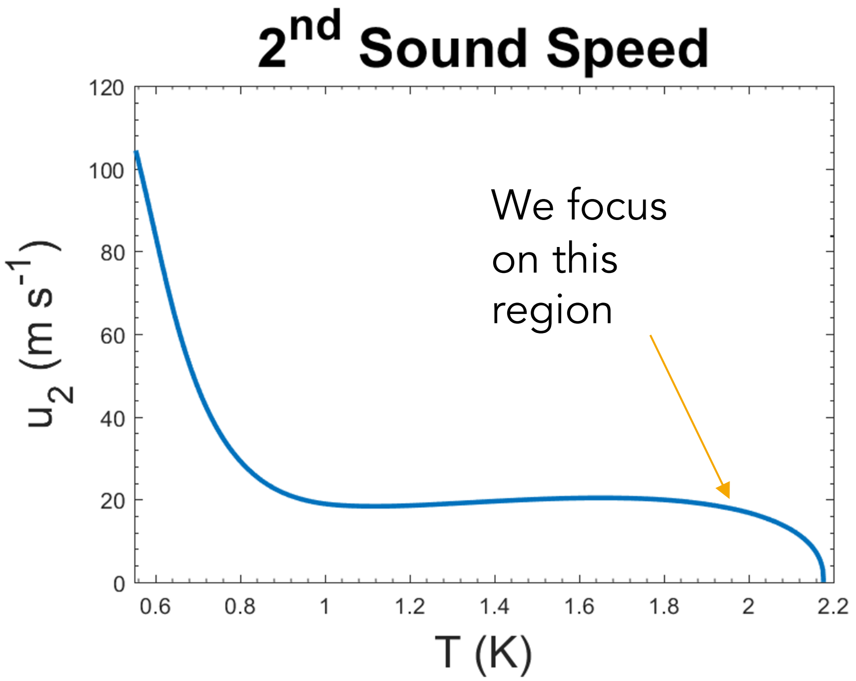




Second Sound Results

- Second sound speed plateaus at around 1.9 degrees Kelvin
- Our results line up closely with the literature

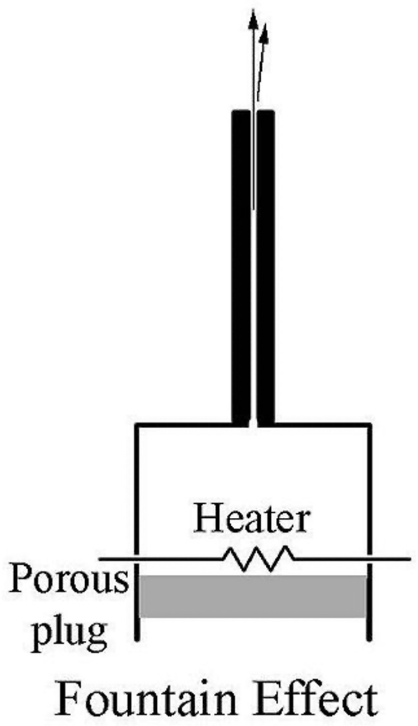




Fountain Effect

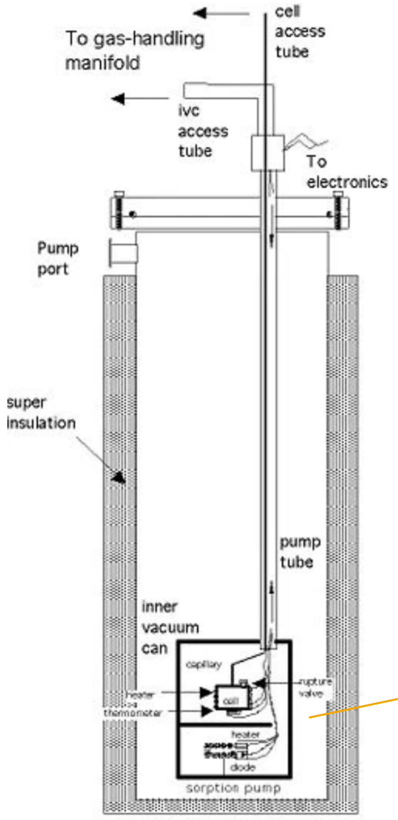
- When warmed, the superfluid's expansion creates a fountain at the surface of the liquid

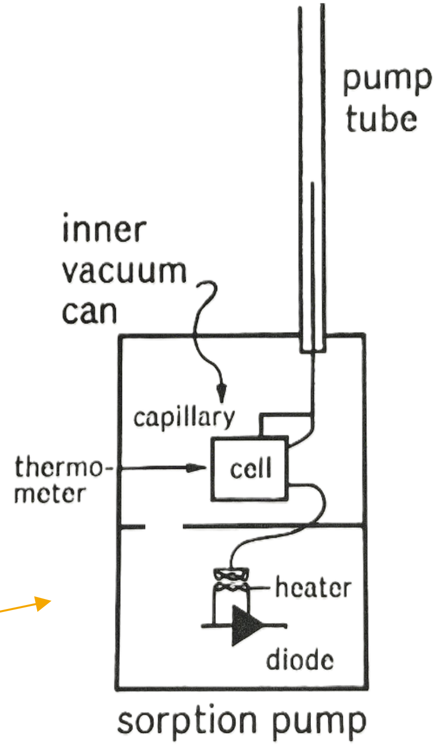
- The helium flows up the sides of the container, forming a small fountain



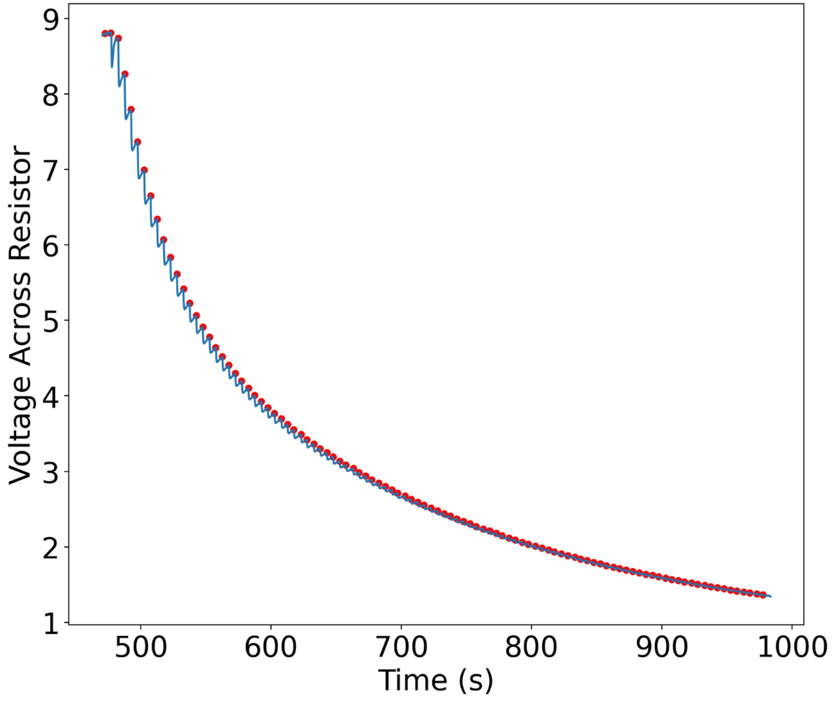
Heat Capacity Plan/Apparatus

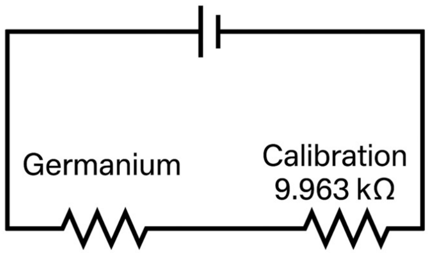
- The heat capacity experiment uses a similar concept: resistor power dissipation for heating
- We measure the change in temperature of the helium with a given injection of heat, where the temperature is calculated with a germanium resistor
- The helium is cooled post heating using a sorption pump





Temperature Measurement: Germanium Resistor Calibration



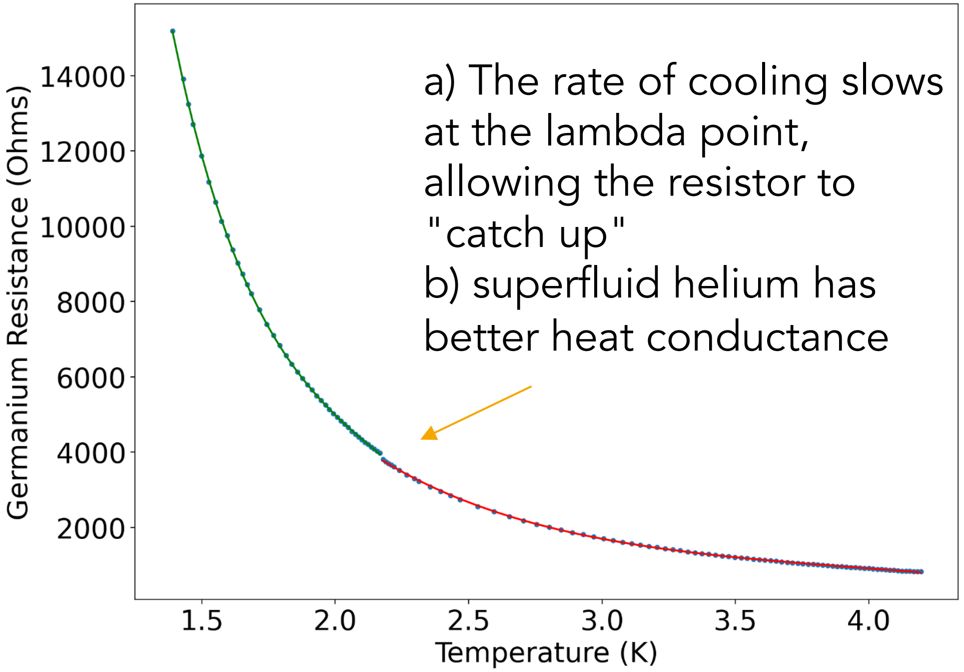


$$R_{cal} = 9963$$

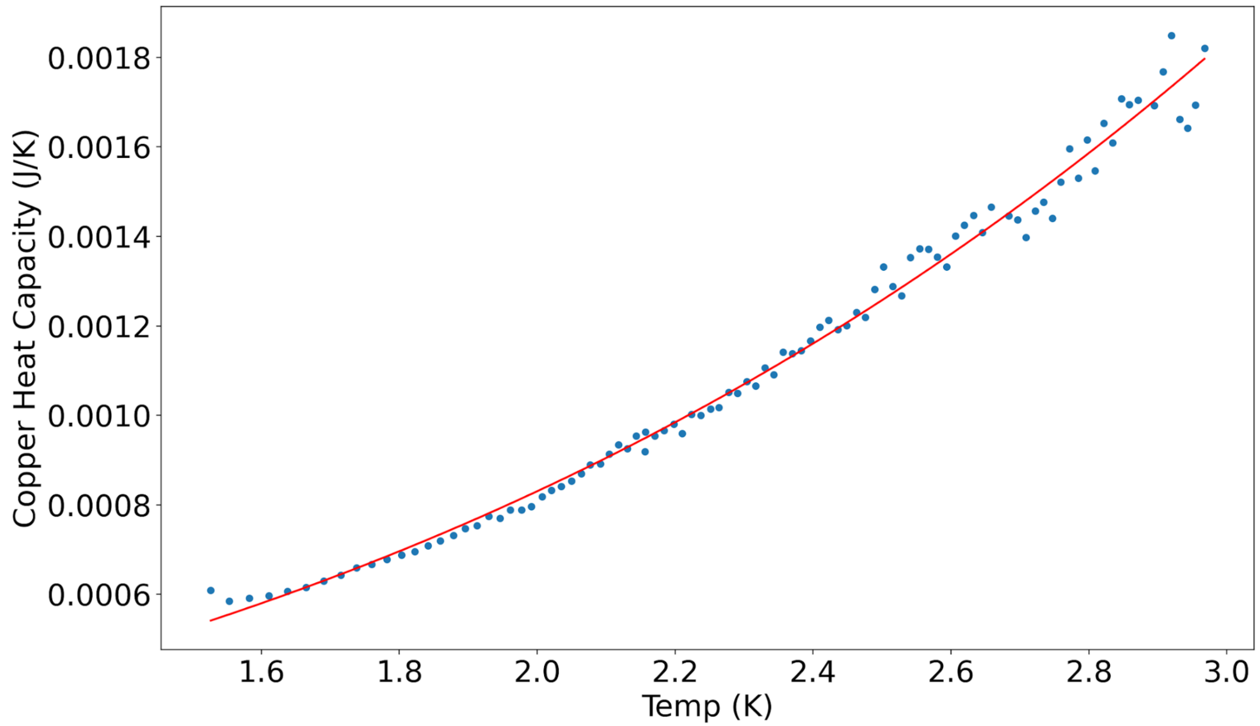
$$I = \frac{V_{cal}}{R_{cal}}$$

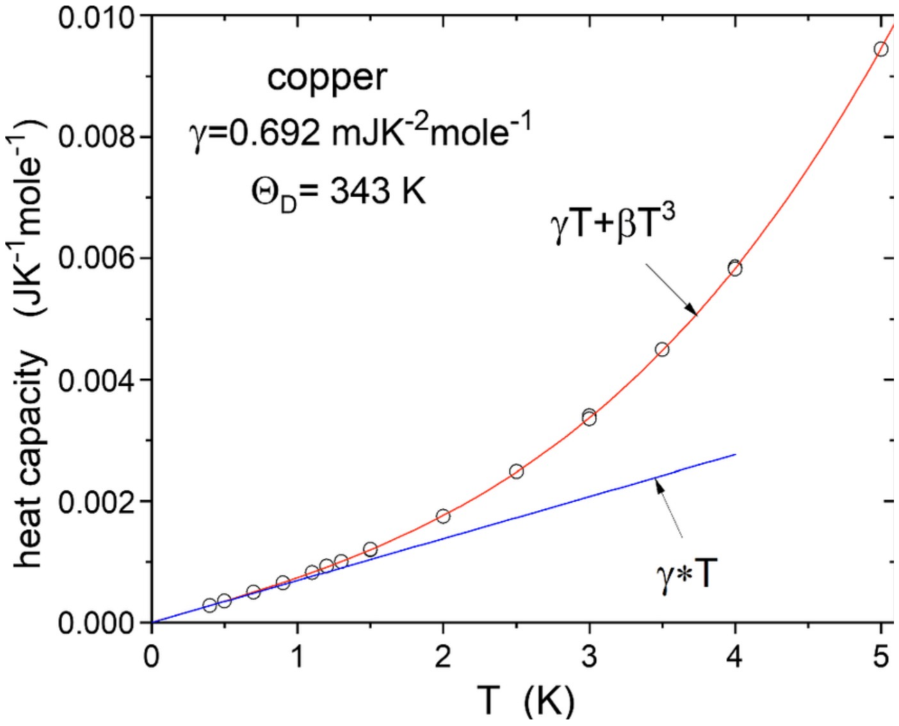
$$R_{ger} = \frac{V_{ger}}{IV_{cal}}$$

$$R_{ger} = \frac{9963 \cdot V_{ger}}{V_{cal}}$$



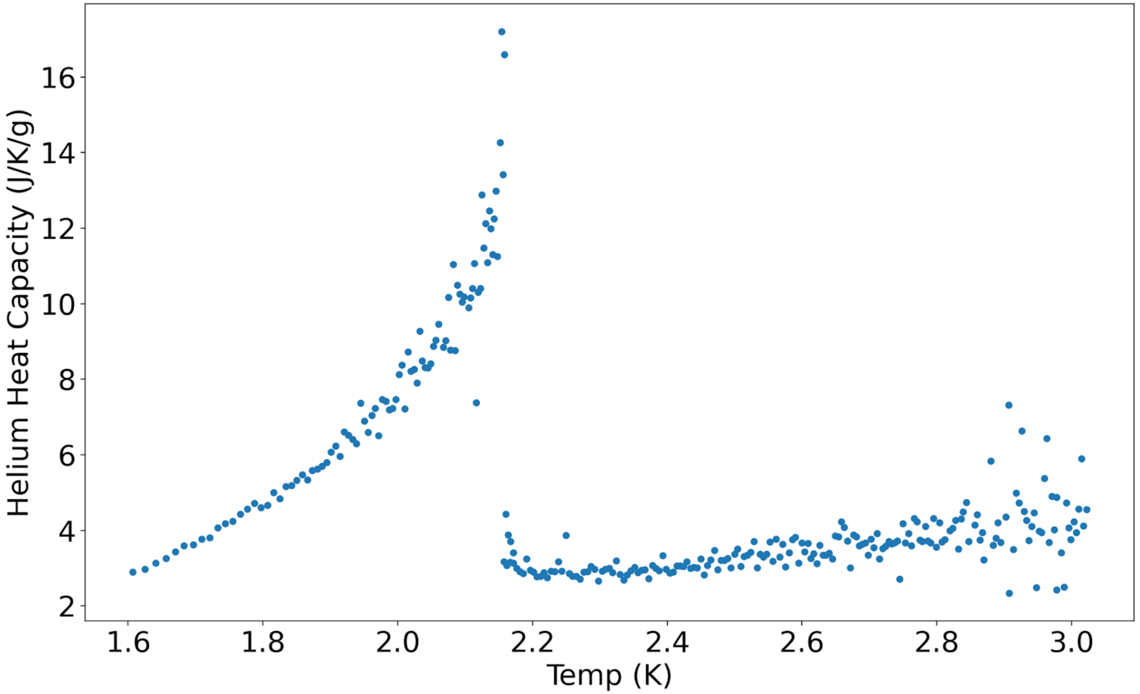
Empty Cell Heat Capacity

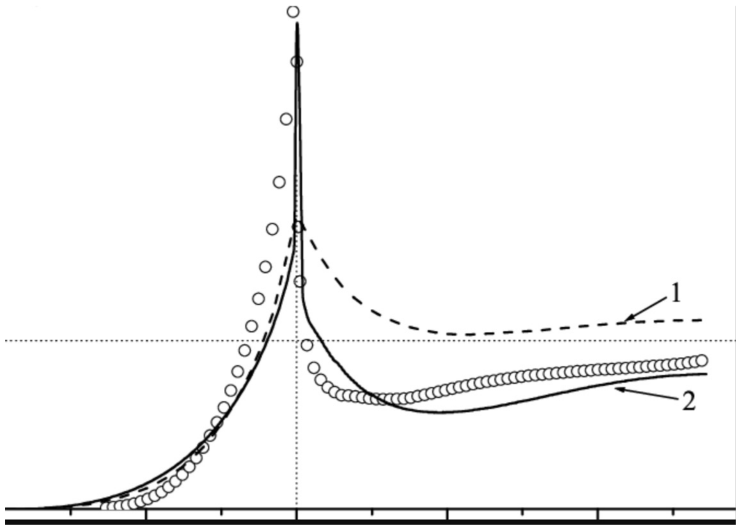




Helium Heat Capacity Results

- Heat capacity rises sharply near the lambda point
- It is roughly flat afterwards, with a mild upwards trajectory
- Results are in line with the literature

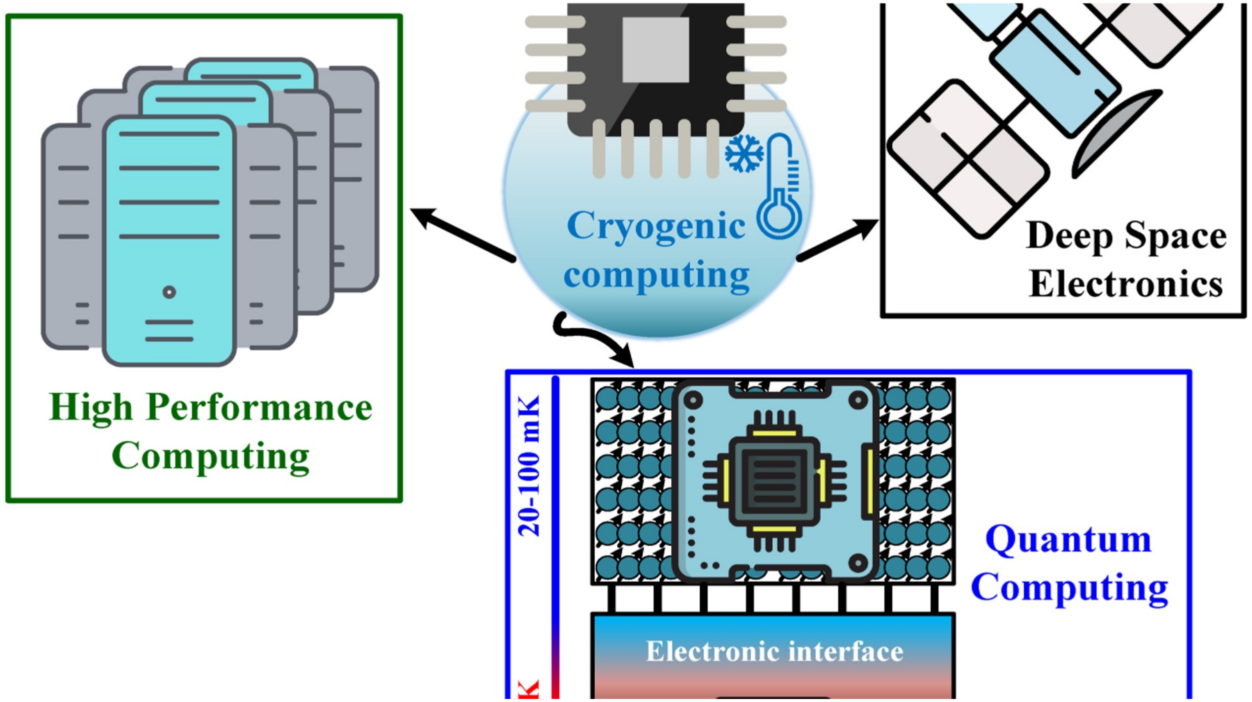




Accepted results

Implications

- The physics of liquid helium around the lambda point has many applications, such as cryogenic computing
- Superfluid helium can be used to develop techniques for cryocoolers to reach closer to absolute zero [7]
- Some quantum computers have an architecture based on superconducting qubits
- Ultraslow light propagation in BEC was experimentally realized by Prof. Hau [8]



Takeaways

1. Superfluid helium can propagate second sound heat waves as opposed to normal heat dispersion
2. There is a sharp discontinuity in liquid helium heat capacity around the lambda point
3. The physics of liquid helium has applications to high-efficiency computing

References

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- [4] Russell J. Donnelly, Carlo F. Barenghi; The Observed Properties of Liquid Helium at the Saturated Vapor Pressure. J. Phys. Chem. Ref. Data 1 November 1998; 27 (6): 1217–1274. https://doi.org/10.1063/1.556028
- [5] Nobel Prize Outreach. "The Nobel Prize in Physics 2001." NobelPrize.org. Accessed May 6, 2025. https://www.nobelprize.org/prizes/physics/2001/summary/.
- [6] London, F. "The λ-Phenomenon of Liquid Helium and the Bose-Einstein Degeneracy." Nature 141, no. 3571 (1938): 643–644. https://doi.org/10.1038/141643a0.
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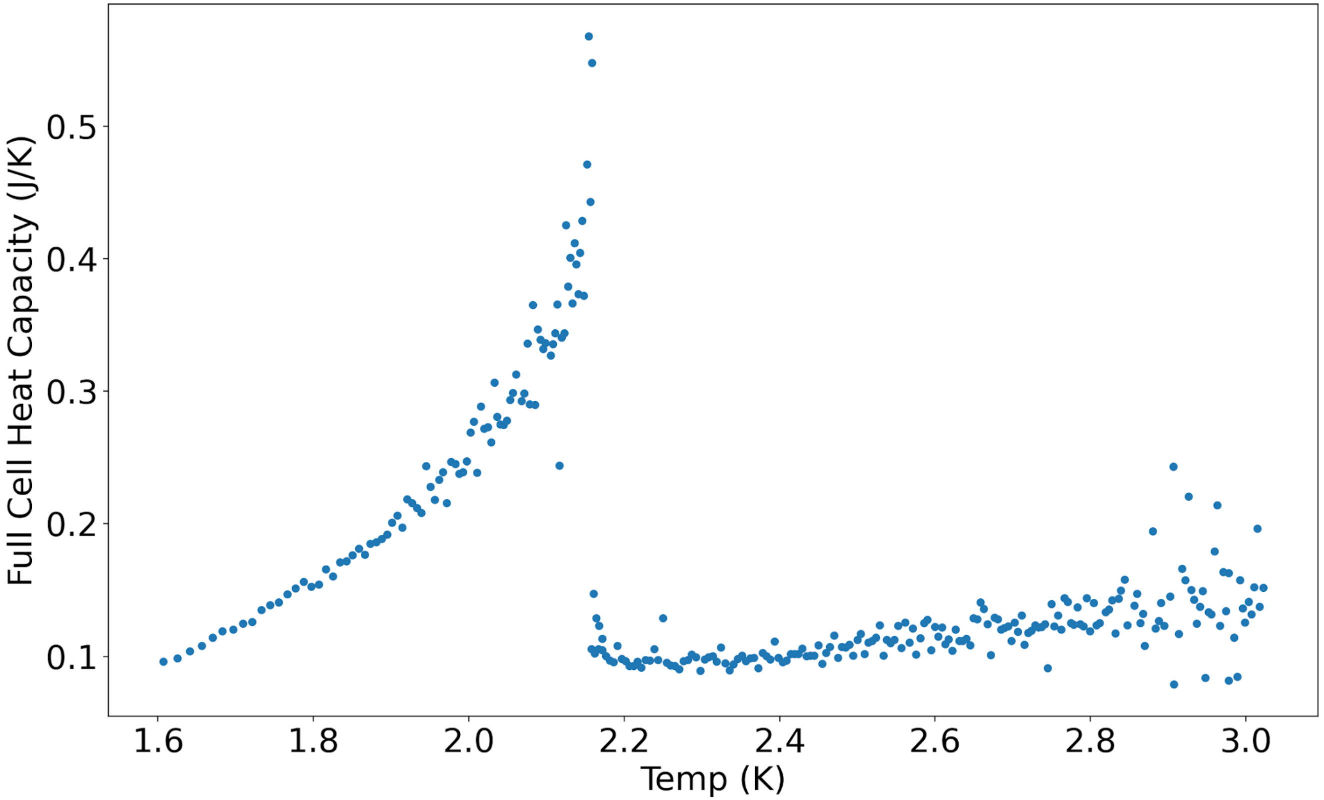
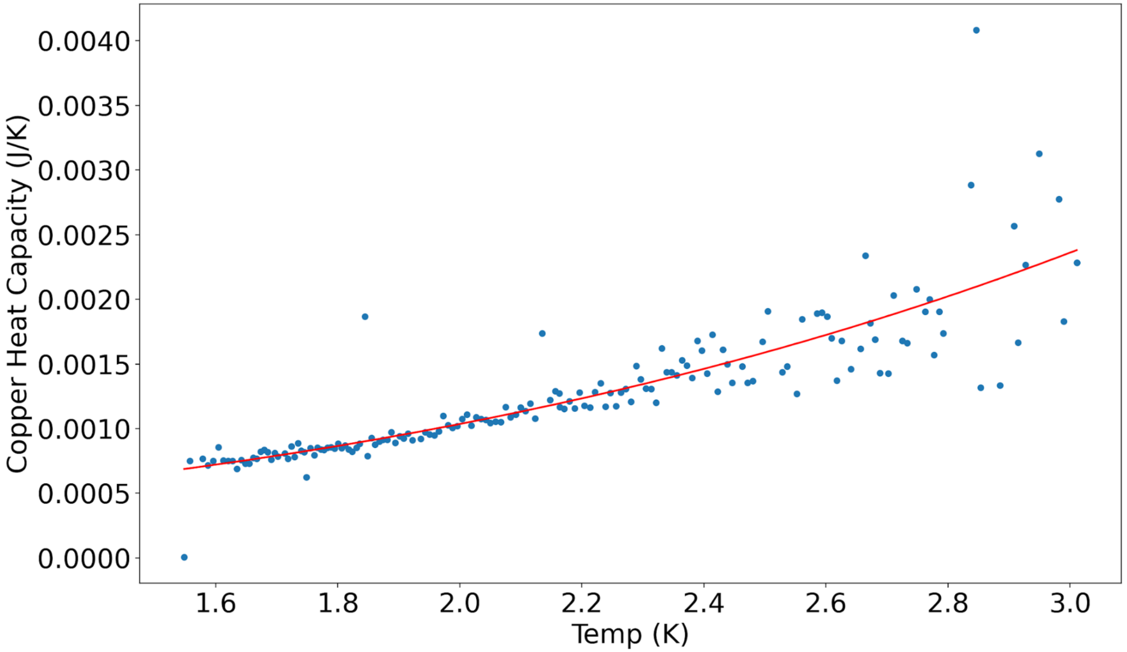
- [8] Ginsberg, Naomi S., Sean R. Garner, and Lene Vestergaard Hau. 2007. Coherent control of optical information with matter wave dynamics. Nature 445(7128): 623-626.

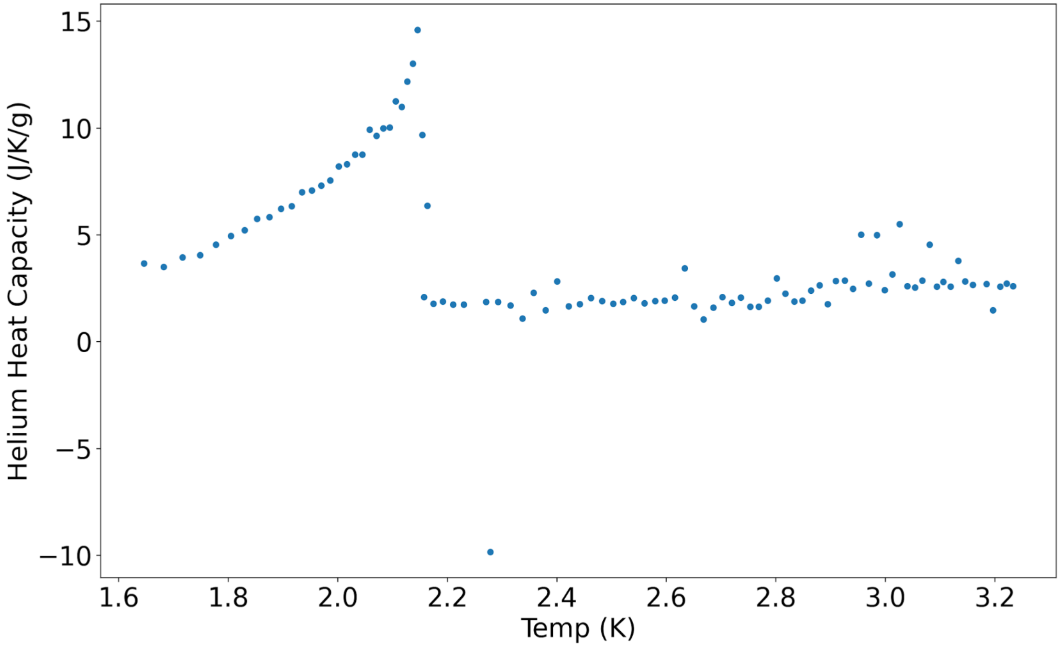
Questions?

Supplemental Graphs: Full Cell



Supplementary Graphs: Different Step Size





Theory Supplemental Slide

BEC condensation temperature for Helium treating it as a non-interacting boson gas: $T_E = \frac{\tau_E}{k_B} = \frac{1}{k_B}\frac{2\pi\hbar^2}{m}\left(\frac{n}{2.126}\right)^{2/3} \approx 3K.$ *

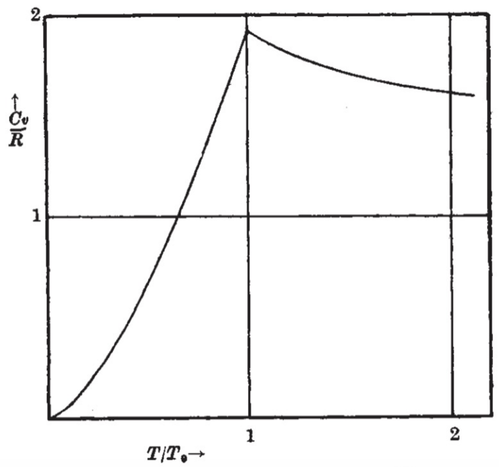
Actual lambda point was at 2.17 K, since Helium is weakly interacting

*Lecture 17 of Physics 181 taught by Prof. Girma Hailu

Theory Supplemental Slide

Excerpt of Fritz London's 1938 paper,* showing theoretical formula for specific heat of Bose Einstein gas:

(Specific heat)(mass of object)
= heat capacity of object



SPECIFIC HEAT OF AN IDEAL BOSE-EINSTEIN GAS.

heat (phase transition of third order). In the accompanying figure the specific heat (C_v) of an *ideal* Bose-Einstein gas is represented as a function of T/T_0 where

$$T_0 = \frac{h^2}{2\pi m^* k}\left(\frac{n}{2{,}615}\right)^{2/3}.$$

With m^* = the mass of a He atom and with the mol. volume $\frac{N_l}{n} = 27{\cdot}6$ cm.³ one obtains $T_0 = 3{\cdot}09°$. For $T \leqslant T_0$ the specific heat is given by

$$C_v = 1{\cdot}92\, R\, (T/T_0)^{3/2}$$

and for $T \geqslant T_0$ by

$$C_v = \frac{3}{2}\,\mathrm{R}\left[1 + 0{\cdot}231\left(\frac{T_0}{T}\right)^{3/2} + 0{\cdot}046\left(\frac{T_0}{T}\right)^{3} + \ldots\right]$$

The entropy at the transition point T_0 amounts to $1{\cdot}28\, R$ independently of T_0.

*London, F. “The λ-Phenomenon of Liquid Helium and the Bose-Einstein Degeneracy.” Nature 141, no. 3571 (1938): 643–644. https://doi.org/10.1038/141643a0.