Superfluids

Hope Johnson
Modern Physics 3305
November 30, 2017

Overview

- Superfluids first examined in capillary flow experiments
- Quantum mechanical phenomenon viewed at a macroscopic scale
- Coherent wave function throughout the volume leads to atoms forming a BEC
- He-3 vs He-4

Properties

Frictionless transport of atoms, no viscosity, loses no kinetic energy

Superfluid is a separate phase below a critical temperature. Above the critical temperature it behaves like a normal liquid, below the critical temperature it behaves like a superfluid. This temperature is identified by the lambda point.

High thermal conductivity at the lambda transition in the graph of heat capacity

Result of Bose Einstein Condensate and coherent wave function

Frictionless Flow

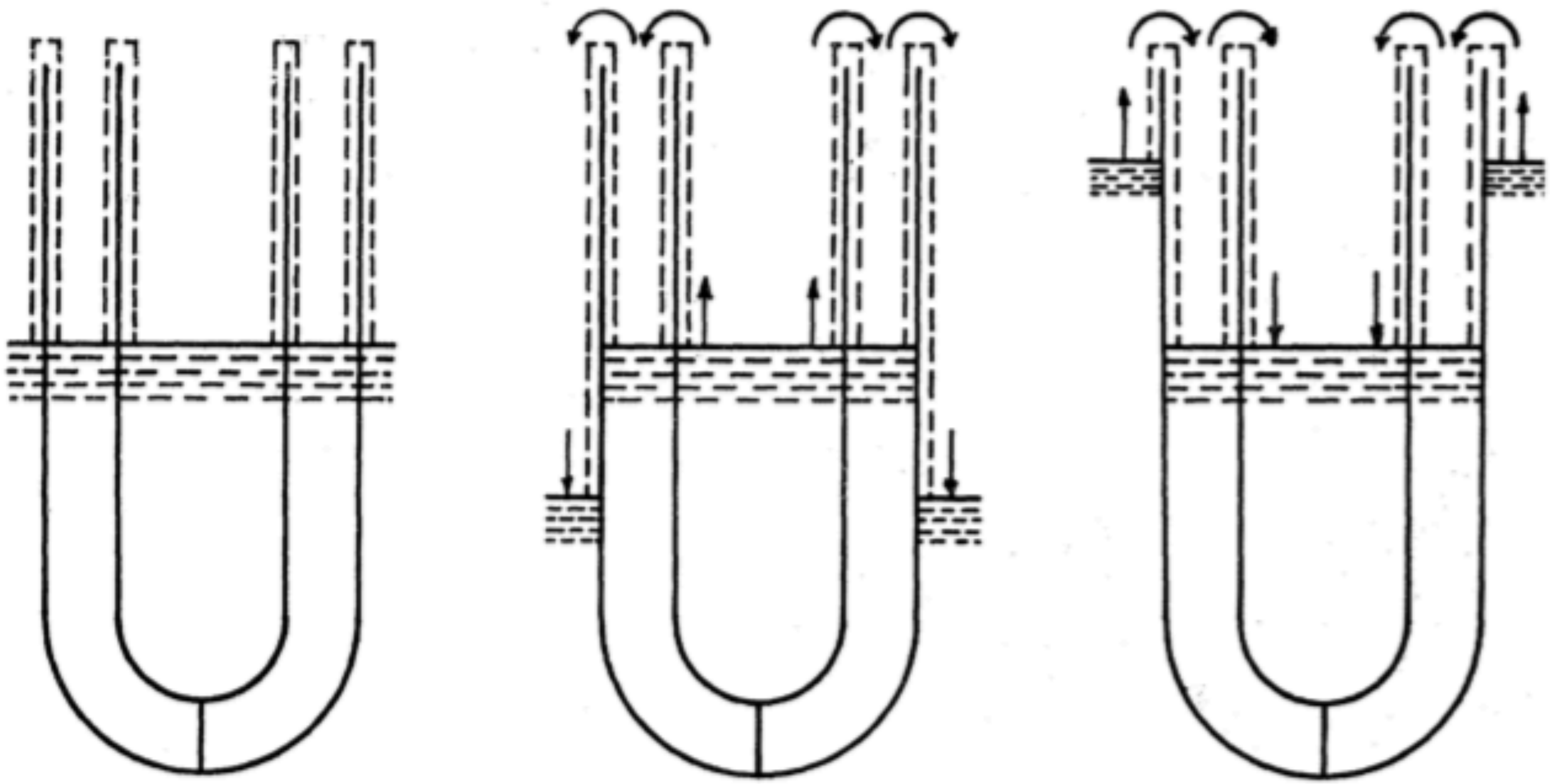


Fig. 15. Experimental demonstration of zero friction.

Superfluids. K. Mendelssohn.

Phase Diagrams

Phase Transition- abrupt change in properties of a system, especially heat capacity, with a small change in a thermodynamic variable (P,V,T)

Critical point- densities of phases converge and coexist

Why other elements freeze first?

- At low temperatures KE is solely from zero-point motion. The zero-point motion of He is large enough to prevent He from forming a solid.

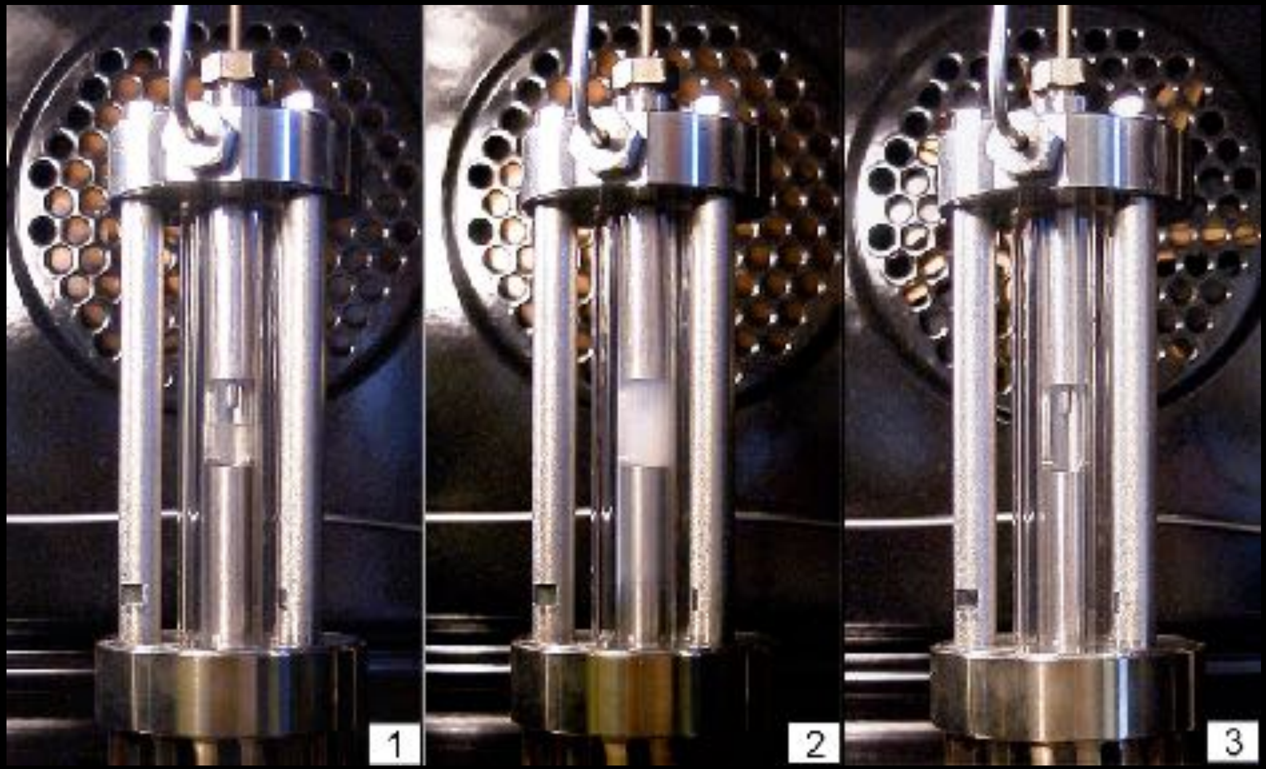
He will form a solid only under intense pressure

Critical Opalescence

- liquid ethane in the left vial, gaseous ethane in the right vial

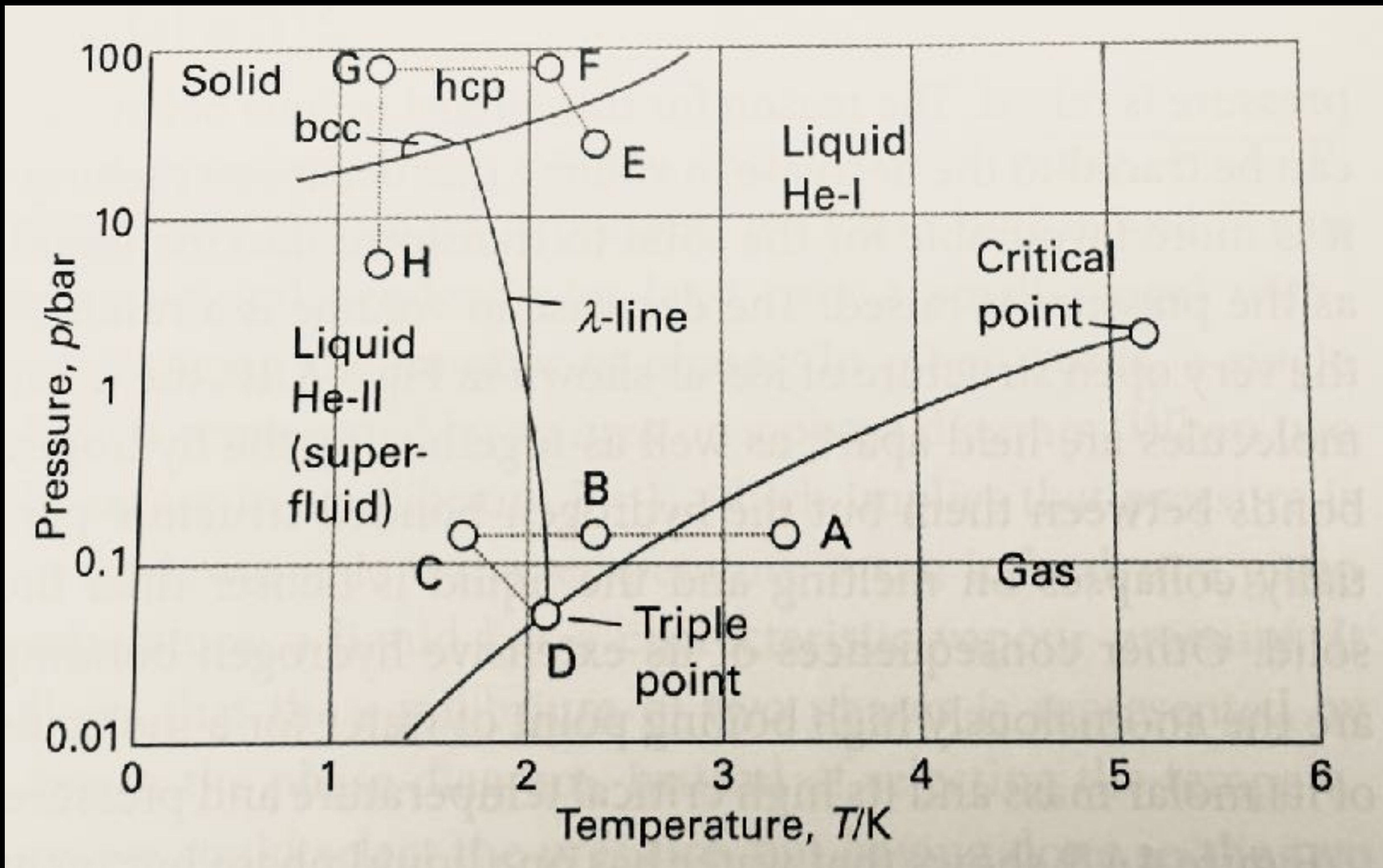
- at 2, the critical point, there are density fluctuations where the density of the liquid approaches the density of the gas

- this produces a milky appearing liquid because of the refraction of light



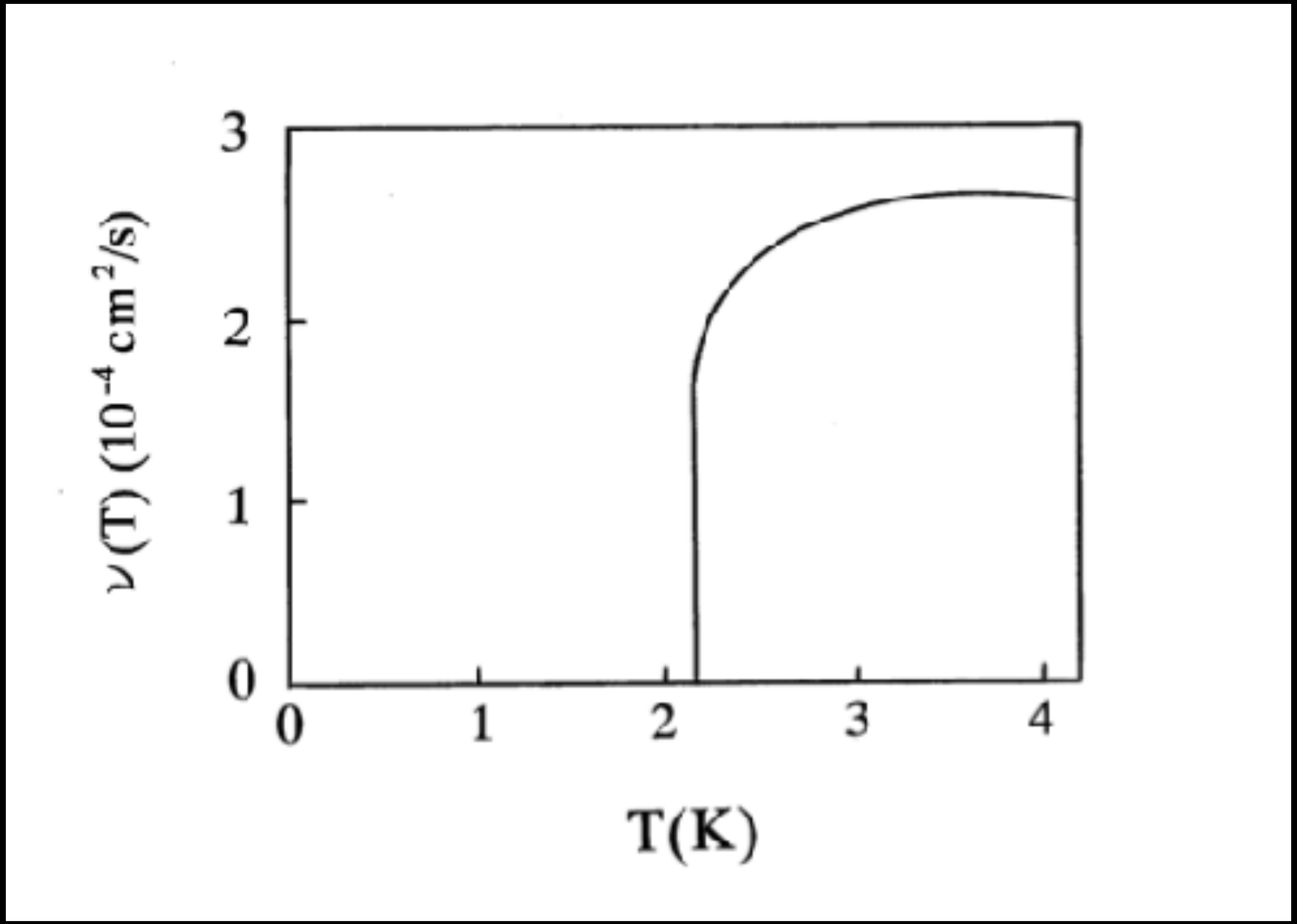
By Dr. Sven Horstmann - Persönlich übergeben von Sven Horstmann. In ähnlicher Form verwendet in: Horstmann S., "Theoretische und experimentelle Untersuchungen zum Hochdruckphasengleichgewichtsverhalten fluider Stoffgemische für die Erweiterung der PSRK-Gruppenbeitragszustandsgleichung", Doktorabeit, C.-v.-O. Universität Oldenburg, 2000, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=17691627

He-4 Phase Diagram



Physical Chemistry Thermodynamics, Structure, and Change. Ch 4, p 162. Peter Atkins.

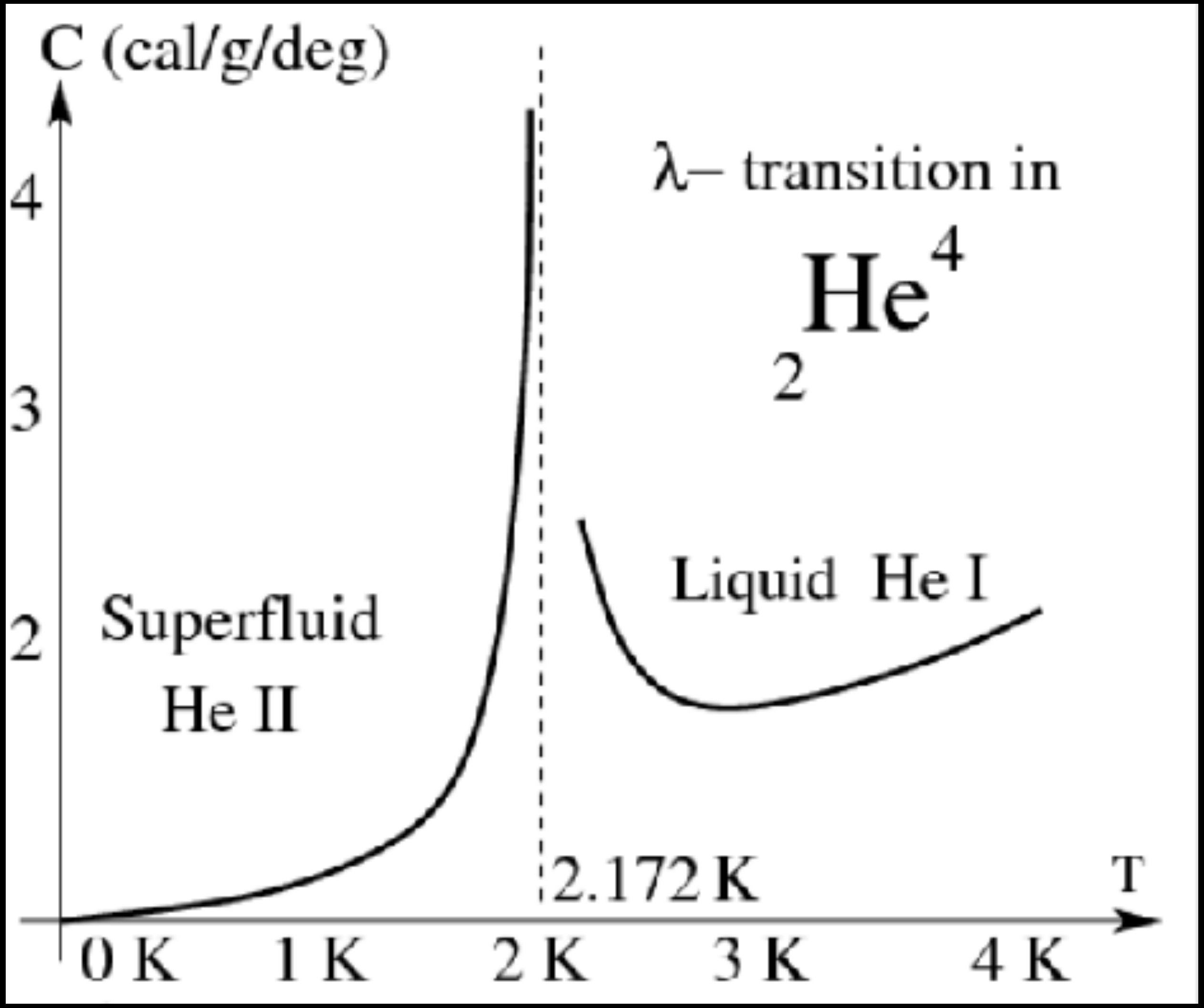
hcp- hexagonal close packing
bcc- body centered cubic packing



https://arxiv.org/pdf/0808.4030.pdf

- Heat capacity shows an infinite discontinuity at the lambda point at approximately 2.17 K

- As the temperature approaches 2.17 K there is a sharp drop where the viscosity of liquid He-4 is 0 and it enters the superfluid state



https://arxiv.org/abs/1402.6837

He-4

He-4 Bose Einstein condensate

Formed by cooling low density gas to low temperatures

He atom electrons are are allowed to share single quantum state, wave function nature becomes more apparent

Zero entropy state: represents the ordering of the 3 position and 3 momentum components

Two-fluid model: mixture of regular liquid and superfluid liquid. We can view the superfluid state independently of the regular liquid

He-3

He-3 is a fermion and also enters a superfluid, but at much lower temperature

Pauli exclusion principle makes it more difficult for fermions to occupy the same state (same four quantum numbers: principle quantum number, angular momentum, magnetic quantum number, spin quantum number)

Forms cooper pairs instead, similar to electrons in a superconductor. Once fermions in He-3 pair up, they are composite bosons and immediately turn to the superfluid state.

Classical fluid vs superfluid

- Imagine a classical liquid is set moving with an initial velocity V, eventually the atoms exchange enough energy with the container and reach thermal equilibrium. The average drift velocity, V, reaches 0.
- Imagine the same situation above, but for superfluids. There is a special velocity associated with the condensate from T=0 to the lambda point (T=2.17K)
- The condensate wave function has phase coherence through the entire volume of the system and represents the current under appropriate circumstances (momentum is not too fast and does not fluctuate too rapidly)
- Superfluid velocity field must be irrotational. Similar to classical ideal incompressible liquid, provided that it is initially irrotational and subject only to conservative forces.
- Macroscopic circulation is subject to quantization condition of n(h/m)

He-3 vs He-4

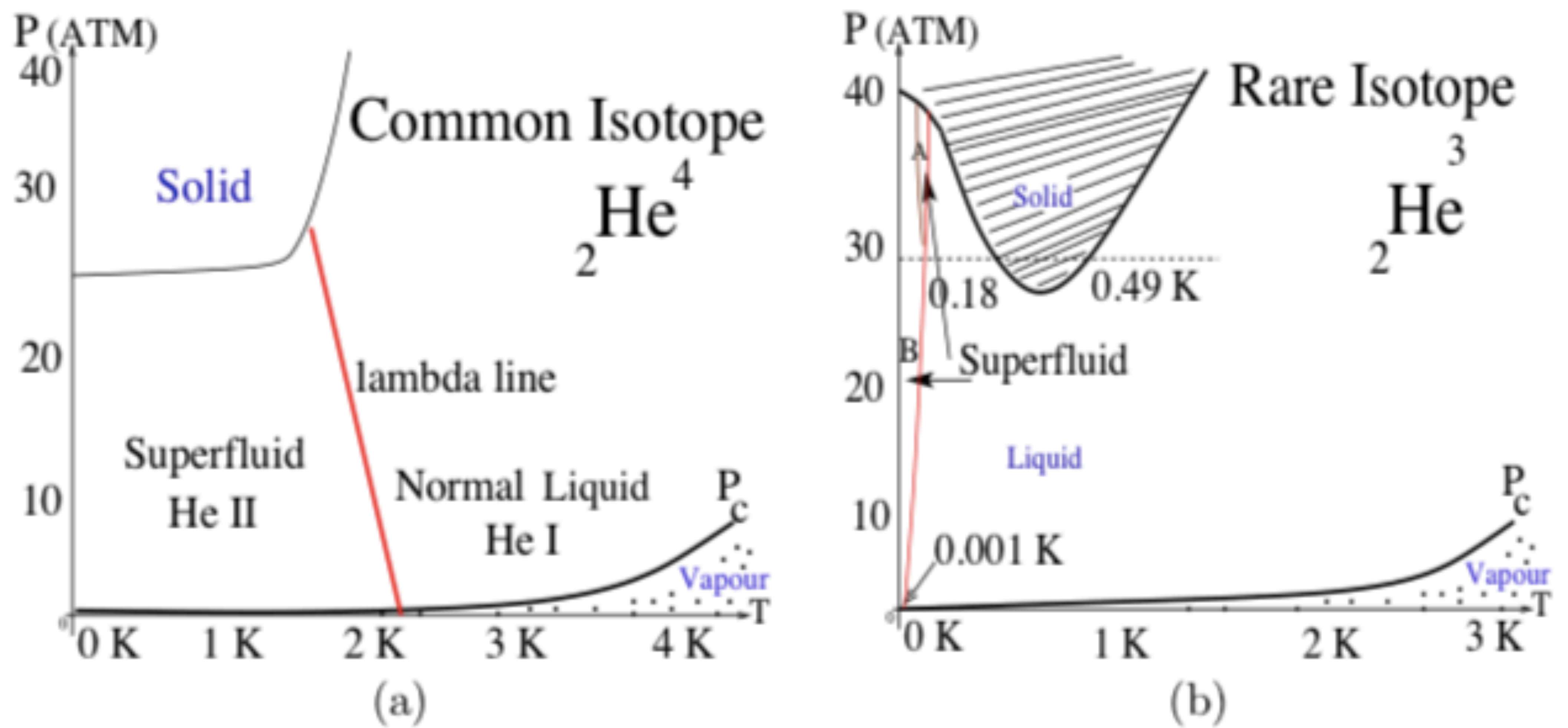


Figure 3: Phase transitions in Helium. (a) Common Isotope $_2He^4$, (b) The rare isotope $_2He^3$.

Applications

- Astronomy
  - By observing the thermal evolution of of neutron stars, we can identify superfluids in the interior
  - Phase transitions in He-3 serve as model for cosmological phase transitions that happened milliseconds after the Big Bang
- Defining the temperature scale at low temperatures using the Zeroth Law of Thermodynamics. No standard temperature scale below 83 K, so it is convenient for laboratories to calibrate relative to cooled gases
  - Zeroth Law of Thermodynamic states that if two systems, A &B, are in thermodynamic equilibrium with a third system, C, then all three systems are in thermodynamic equilibrium with each other. Objects in equilibrium have the same temperature.

Summary

- The wave-like nature of matter becomes apparent in superfluids when atoms are allowed to occupy the same quantum state

- Superfluidity is the result of a portion of the atoms condensing and occupying the lowest possible energy state

Citations

David Pacchioli. "The Critical Point." Penn State News. May 1, 2001. http://news.psu.edu/story/140624/2001/05/01/research/critical-point

D. O. Edwards and S. Balibar . "The Liquid and Solid 3He–4He Phase Diagram Revisited." Japanese Journal of Applied Physics. 1987. http://iopscience.iop.org/article/10.7567/JJAPS.26S3.37/pdf

Mendelssohn, K. "Superfluids." *Science*, vol. 127, no. 3292, 1958, pp. 215–221. *JSTOR*, JSTOR, www.jstor.org/stable/1756449.

Navinder Singh. "Thermodynamical Phase transitions, the mean-field theories, and the renormalization (semi)group: A pedagogical introduction." Feb 27, 2014. https://arxiv.org/abs/1402.6837

Peter Atkins. "Physical Chemistry Thermodynamics, Structure, and Change."

Shiladitya Chakraborty. "The superfluid phases of 3He." http://guava.physics.uiuc.edu/~nigel/courses/569/essays_f2004/files/chakraborty.pdf.

Shun-ichiro Koh. "The onset of superfluidity in capillary flow of liquid helium 4." Physics Division, Faculty of Education, Kochi University. https://arxiv.org/pdf/0808.4030.pdf.

W F Vinen. "Macroscopic Quantum Effects in Superfluids." *Reports on Progress in Physics*, vol. 31, no. 1, 1968, pp. 61–121.

W F Vinen. "THE PHYSICS OF SUPERFLUID HELIUM." School of Physics and Astronomy, University of Birmingham, Birmingham B15 2TT, UK. https://pdfs.semanticscholar.org/bb23/c04171209d6ebace1ad8ed2f3718620747c5.pdf