Characteristics of a cryogenic fluid

1. **Critical, normal boiling, and triple point temperatures of cryogenic fluids**
2. **Vapor pressure of liquids**
3. **Liquid Helium**
4. **Superfluids**

Critical, normal boiling, and triple point temperatures of cryogenic fluids

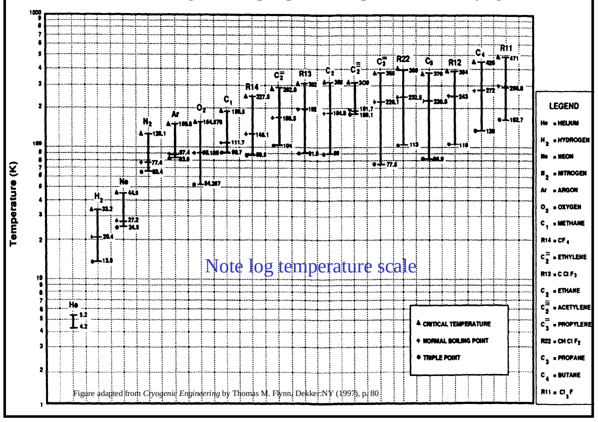


Figure adapted from *Cryogenic Engineering* by Thomas M. Flynn, Dekker:NY (1997), p. 80

Vapor pressure of liquids

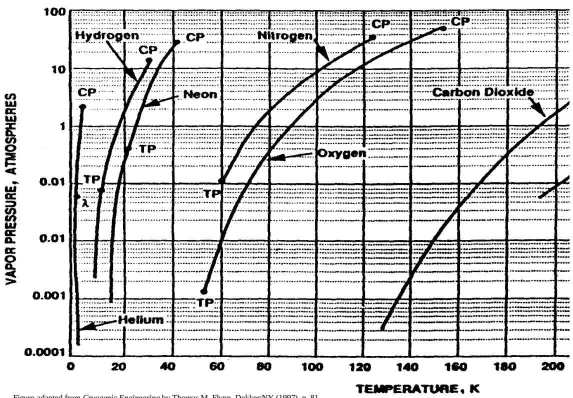


Figure adapted from *Cryogenic Engineering* by Thomas M. Flynn, Dekker:NY (1997), p. 81

Helium

- Spherical shape
- Two isotropic forms: ^{3}He and ^{4}He
- Low mass
- Van der Waals forces → low critical and boiling points
- Remains a liquid even at absolute zero (unless external pressure is applied)

Spelling Bee

How do you spell the word for making a gas into a liquid?

A. liquify
B. liquefy
C. liquafy
D. liquifi
E. liquiphy

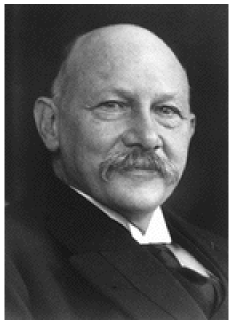
Name that man

In whose laboratory was helium first liquefied?

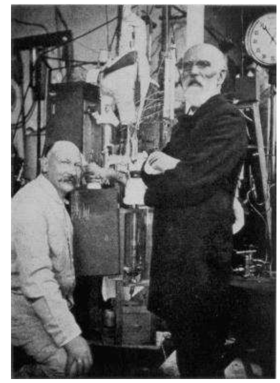
A. Sir James Dewar
B. Cailletet
C. Wroblewski
D. Onnes
E. Van der Waals

1882-Helium liquefied at Leiden University

H. Kamerlingh Onnes was one of the first professors in experimental physics at Leiden University. His lab first to liquefy helium (1908), for which he was awarded the Nobel prize in 1913, and he discovered superconductivity in 1911. He liquefied hydrogen to pre-cool the helium gas in his liquefier.

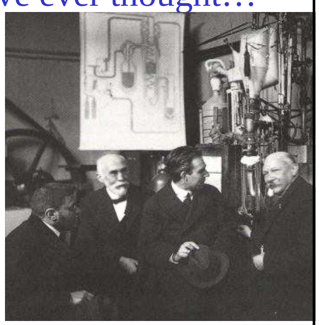


- In 1882, Onnes was appointed Professor of Experimental Physics at Leiden University. In 1895, he established Leiden Laboratory
- His researches were mainly based on the theories of J.D. van der Waals and H.A. Lorentz
- Was able to bring the temperature of helium down to 0.9 °K, justifying the saying that the coldest spot on earth was situated at Leiden.



Heike Kamerlingh Onnes (left) and Van der Waals in Leiden at the helium 'liquefactor' (1908)

Who would have ever thought…



Heike Kamerlingh Onnes, his stamp, and (*right*) showing his helium liquefier to passers-by: Niels Bohr (visiting from Kopenhagen), Hendrik Lorentz, and Paul Ehrenfest (*far left*).

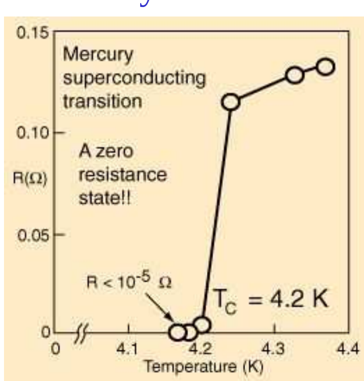
Why Not A Solid?

- Zero-Point Energy
- energy of a free particle in a small box
- E decreases as V increases → the effect of the Zero-Point to raise molar volume
- Kinetic energy exceeds the interaction potential energy

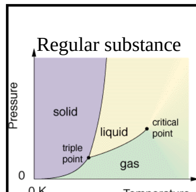
$$E = \frac{3h^2}{8mV^{\frac{2}{3}}}$$

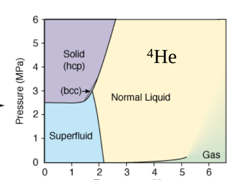
Superconductivity-1911

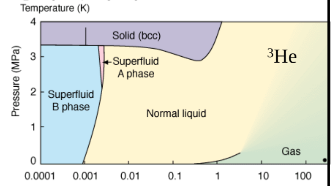
Heike Kamerlingh Onnes discovered superconductivity, the total lack of dc electrical resistance in certain materials when cooled to a temperature near absolute zero.



Phase Diagrams





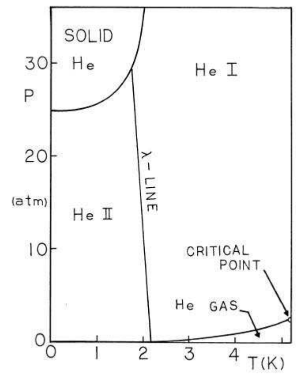


Why so low?

Superfluidity occurs in ^4He at about 4.2 K but only below about 0.002 K in ^3He. Why?

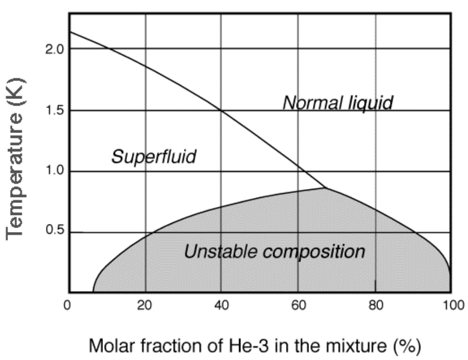
A. ^3He is rarer than ^4He in nature
B. ^3He is always in smaller containers than is ^4He
C. ^3He has different chemical properties than ^4He
D. ^4He superfluidity is an electronic process while ^3He superfluidity is a nuclear process
E. ^3He superfluidity is an electronic process while ^4He superfluidity is a nuclear process

Helium-4 Phase Diagram

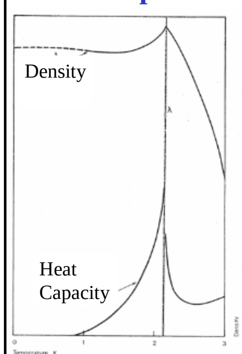


- At 2.17K ^4He undergoes a transition to the superfluid state
- The lambda line separates He I and He II
- ^3He does not become a superfluid until below 2mK

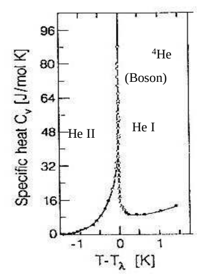
Helium Mixtures



1931: Keesom discovered lambda shaped-specific heat in helium at Leiden



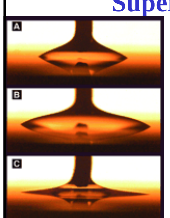
Allen and Misener and Kapitza (1939)



T_λ=2.17K

[Frank Pobell, 1992]

Superfluidity in Helium 4 in 1938



Science 24 October 1997: Vol. 278. no. 5338, pp. 664 - 666

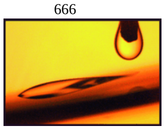


Fig. 2. (**A** through **C**) Microscope images showing an edge-on view of superfluid drops on a horizontal Cs substrate. The dark bar in the upper half of the image is the capillary tube. The pictures show the outline of the drop as well as its mirror image in the reflective substrate. As the volume of the drop increased from (A) to (B), the contact angle remained constant. When fluid was withdraw as in (C), the contact angle decreased but . the diameter remained constant

Figure 3. Microscope image of a superfluid drop on a Cs substrate inclined at 10° to the horizontal. A drop hanging off of the capillary is also seen in the upper right. The drop on the inclined substrate is stationary. The downhill edge of the drop has the same contact angle as shown in Fig. 2B, whereas the uphill edge has a vanishing contact angle.

- Superfluidity is a dramatic visible manifestation of quantum mechanics, being the result of Bose–Einstein condensation in which a macroscopic number of ^4He atoms occupy the same, single-particle quantum state. It was discovered simultaneously by Kapitza, Allen and Misener working separately, though only Kapitza received the Nobel prize. It is also amusing to note that Allen was a "classical physicist" at heart, who didn't much care for the subatomic world. He discovered superfluidity with a pen light.

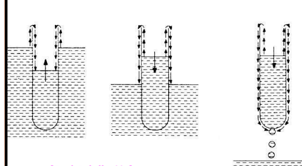
Superfluidity of the Quantum Fluid, ^4He

Thermal de Broglie wavelength of ^4He at 2K:

$$\lambda_T = \frac{h}{\sqrt{3mkT}} \approx 8.9Å$$

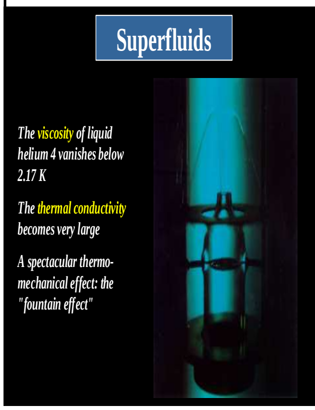
≥ mean interparticle distance of ^4He ≈ 3.6 Å

Breaker experiment:



[Frank Pobell, 1992]

The Fountain Effect-1938

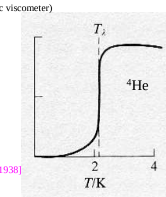


- In february 1938 J.F. Allen and H. Jones had found that when they heated superfluid helium on one side of a porous medium or a thin capillary, the pressure increased sufficiently to produce a fountain effect at the end of the tube which contained the liquid. The “fountain effect” was a spectacular phenomenon that was impossible to understand within classical thermodynamics.

Two Fluid Model– Landau in 1941

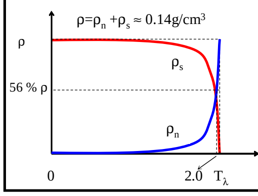
(oscillating disc viscometer)

Viscosity (μP)



[W.H. Keesom, 1938]

Fluid density



Two Fluid model		density	viscosity	entropy
Two fluids	Super-fluid	ρ_s	$\eta_s=0$	$S_s=0$
	normal fluid	ρ_n	$\eta=\eta_n$	$S_n=S_{He}$

Two-fluid equations for He II:

$$\frac{\partial \rho}{\partial t}+\vec{\nabla}\cdot\rho\vec{\upsilon}=0 \text{ (mass conservation)}$$

$$\frac{\partial \rho s}{\partial t}+\vec{\nabla}\cdot\rho s\vec{\upsilon}_n=0 \text{ (entropy conservation)}$$

$$\frac{D_s\vec{\upsilon}_s}{Dt}\equiv\frac{\partial \vec{\upsilon}_s}{\partial t}+(\vec{\upsilon}_s\cdot\vec{\nabla})\vec{\upsilon}_s=-\vec{\nabla}\mu$$

$$\frac{\partial J_i}{\partial t}+\frac{\partial P_{i\alpha}}{\partial r_\alpha}=0 \text{ (momentum conservation)}$$

stress tensor $P_{ij}=p\delta_{ij}+\rho_n\upsilon_{n,i}\upsilon_{n,j}+\rho_s\upsilon_{s,i}\upsilon_{s,j}$

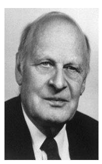
total mass flow $\vec{J}\equiv\rho\vec{\upsilon}=\rho_n\vec{\upsilon}_n+\rho_s\vec{\upsilon}_s$

[S.J. Putterman, 1974]

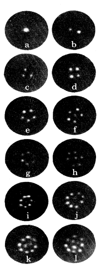
Quantization of Superfluid Circulation

Quantization of superfluid circulation:

$$\kappa=\oint\vec{\upsilon}_s\cdot d\vec{\ell}=\frac{nh}{m}\approx 9.97\times10^{-4}\, n\ cm^2/s$$



(postulated separately in 1955 by Onsager and Feynman)



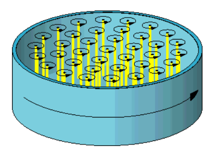
The angular velocity Ω is
(a) 0.30 /s, (b) 0.30 /s,
(c) 0.40 /s, (d) 0.37 /s,
(e) 0.45 /s, (f) 0.47 /s,
(g) 0.47 /s, (h) 0.45 /s,
(i) 0.86 /s, (j) 0.55 /s,
(k) 0.58 /s, (l) 0.59 /s.

[Yarmchuk, 1979]

All superfluid vortex lines align along the rotation axis with ordered array of areal density= length of quantized vortex line per unit volume= $\frac{2\Omega}{\kappa}=\frac{\vec{\nabla}\times\vec{\upsilon}_s}{\kappa}\approx 2000\Omega$ lines/cm^2

1. Circulation round any circular path of radius r concentric with the axis of rotation=$2\pi r^2\Omega$
2. Total circulation=$\pi r^2 n_0 h/m$ (n_0: # of lines per unit area)
3. $\therefore n_0=2\Omega m/h=2\Omega/\kappa$

Rotating bucket of Superfluid

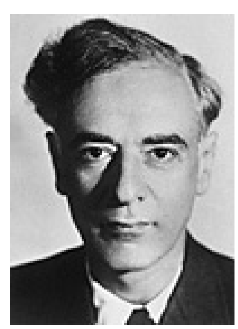


Properties of Superfluids

- All of their atoms are in the same quantum state → they have identical momentum; if one moves, they all move
- Ordinary Sound
- Second Sound (Temperature Waves)
- Third Sound (Surface Waves)
- Fourth Sound

1962 Nobel – Lev Landau

- Constructed the complete theory of quantum liquids at very low temperatures
- He developed theories on both the Bose and Fermi type liquids



http://www.nobel.se/physics/laureates/1962/index.html

1971 – Superfluidity discovered in 3He (US)

- Super fluidity was first discovered in helium-3 by American physicists David M. Lee, Douglas D. Osheroff, and Robert C. Richardson. It occurs at temperatures a few thousandths of a degree above absolute zero and is distinguished by either an A phase or a higher-pressure, lower-temperature B phase. Helium-3 is anisotropic, which means it displays different properties when measured in different directions, and as such, its study has become valuable to scientists in the fields of big-bang theory and superconductivity.

David M. Lee

Cornell University
Ithaca, NY, USA

Douglas D. Osheroff

Stanford University
Stanford, CA, USA

Robert C. Richardson

Cornell University
Ithaca, NY, USA

1972

Discovery of superfluidity in helium-3

Douglas D. Osheroff, David M. Lee, and Robert C. Richardson (US)

The experiment

In a cryostat, figure 1, a container of ^3He was cooled to about 2mK. While the ^3He was being slowly compressed at a constant rate, the inner pressure was measured and when 3.4 MPa was reached, the helium was allowed to expand.
As the volume decreased and then increased, small changes in the slope of the pressure curve were observed, and also small kinks. These observations were the first evidences of transitions to superfluid phases in ^3He. Two superfluid phases were discovered, "A" and "B", figure 2.

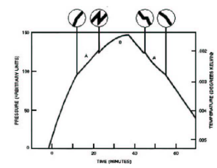


Figure 2. Pressure inside a sample containing a mixture of liquid ^3He and solid ^3He ice.

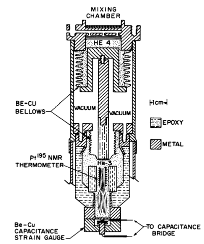


Figure 1. Schematic diagram of the Pomeranchuck cell used in the discovery.

MN-09/09/03

Pictures taken from:http://www.nobel.se/physics/laureates/1996/osheroff-lecture.pdf

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Ways to the Superfluid State

- ^4He (even number of elementary particles (6) each with intrinsic angular momentum ½ → integral angular momentum: BOSON; Bose Statistics
- 3He (odd number of elementary particles (5) → half-integral spin: FERMION; Fermi Statistics

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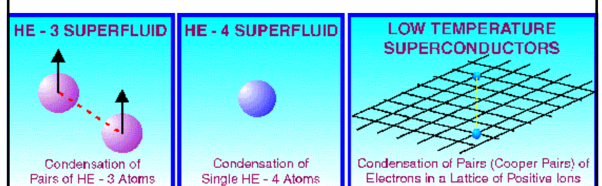
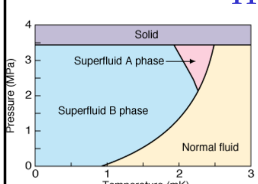
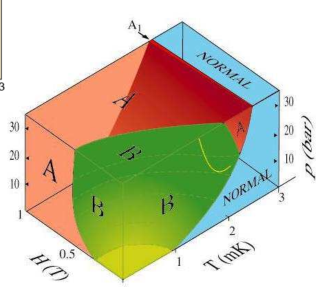
Microscopic Picture of Superconductivity



Helium 3





Length Scales in Superfluid ^3He