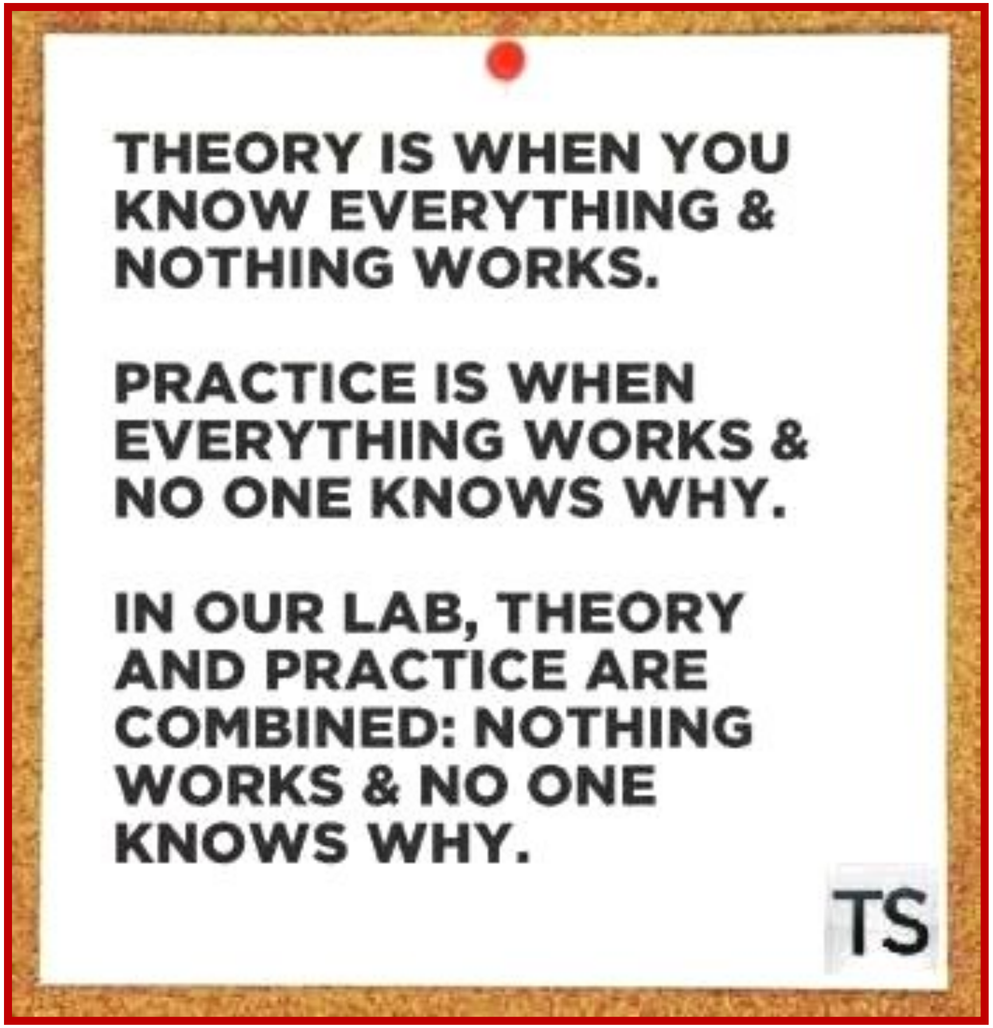
Superfluidity in Liquid Helium



THEORY IS WHEN YOU KNOW EVERYTHING & NOTHING WORKS.

PRACTICE IS WHEN EVERYTHING WORKS & NO ONE KNOWS WHY.

IN OUR LAB, THEORY AND PRACTICE ARE COMBINED: NOTHING WORKS & NO ONE KNOWS WHY.

TS

Boiling Points

- The *two helium isotopes have the lowest boiling points* of all known substances:

  3.2 K for ^{3}He and 4.2 K for ^{4}He.

- Both isotopes apparently remain liquid down to absolute zero. To solidify helium, **a pressure of about 25 atmospheres is required.**
- Lack of a solid phase for helium at all temperatures & at atmospheric pressure is due to two factors:

  1. **The low atomic mass.**
  2. **The extremely weak forces between atoms**

  (Van der Waals Forces)

- The low atomic mass means a high zero-point energy. This can be understood from the uncertainty principle.

Zero-point Energy

- The uncertainty in momentum of a particle in a cavity with characteristic dimension **R** is

$$\Delta p \sim h/R.$$

- So it's **zero-point energy** is:

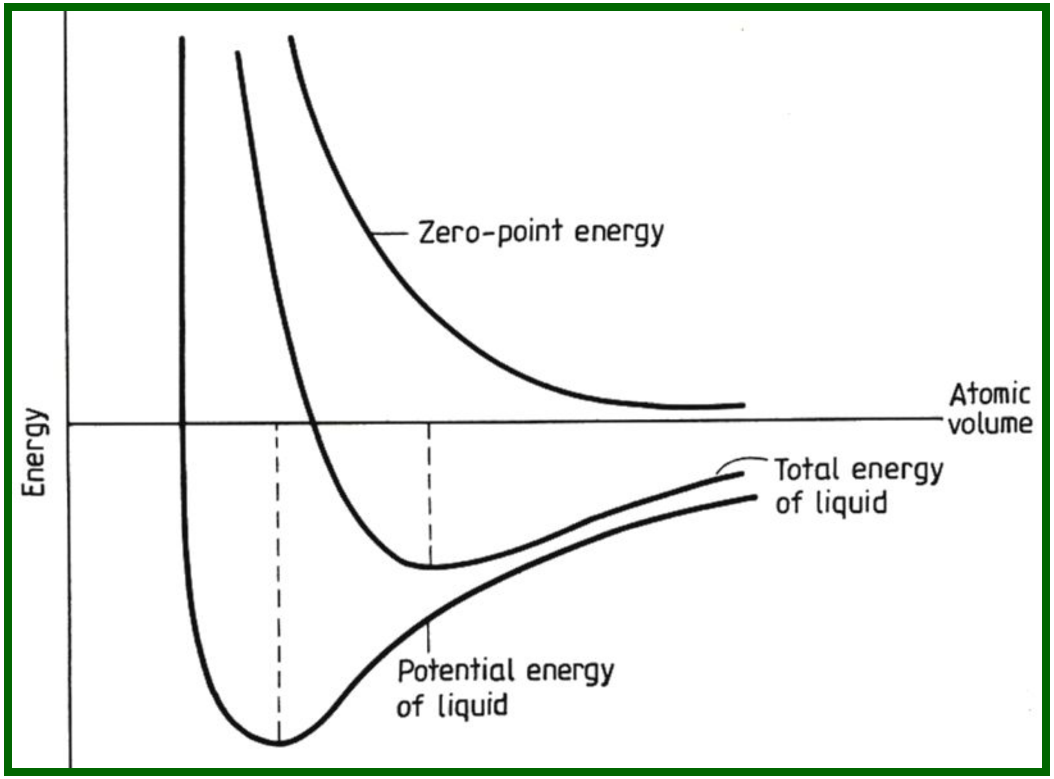
$$E_0 \sim (\Delta p)^2/2m$$

or

$$E_0 \sim h^2/2mR^2.$$

- This large zero-point energy must be added to the potential energy of the liquid to give the liquid's total energy.

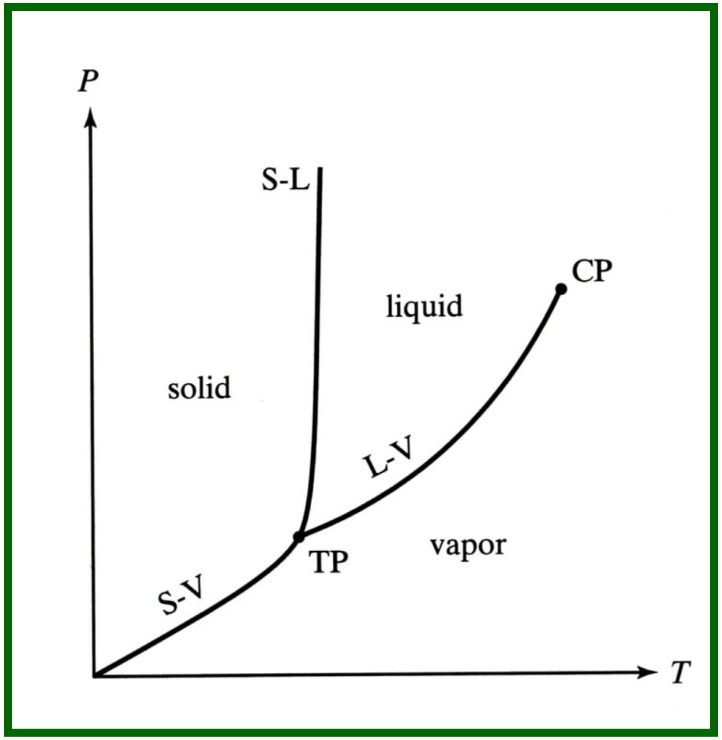
Zero-point Energy

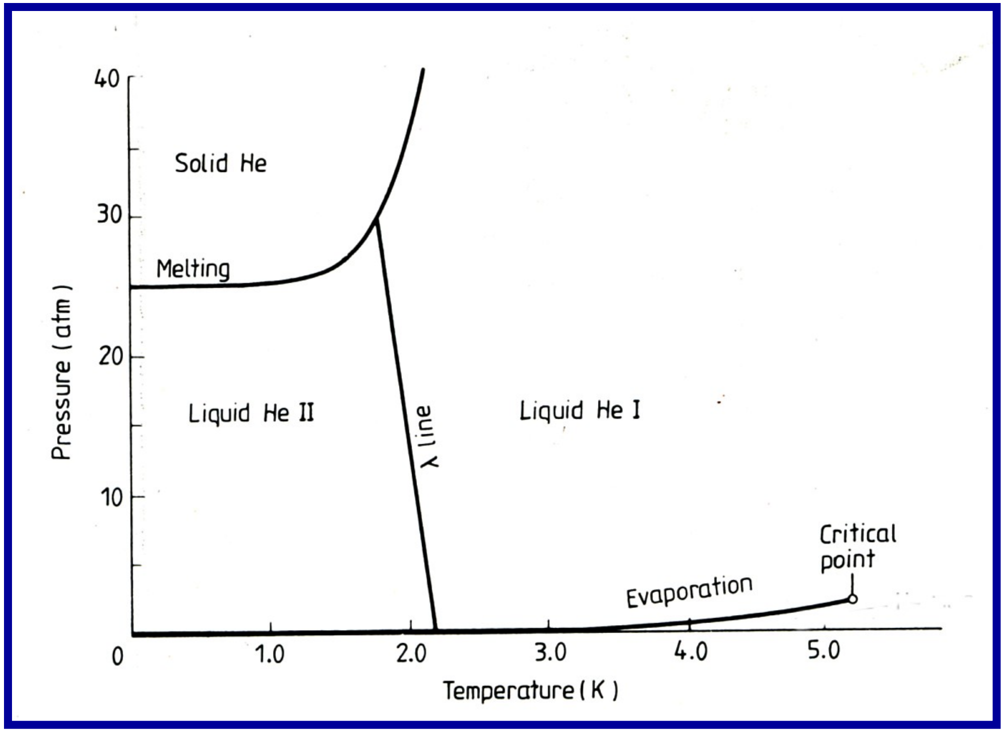


- Because **He atoms are so light**, **the zero-point Energy is comparable to the PE**, & the minimum of the total energy occurs at a high atomic volume.
- For other inert gas atoms, the zero-point energy is of negligible magnitude.

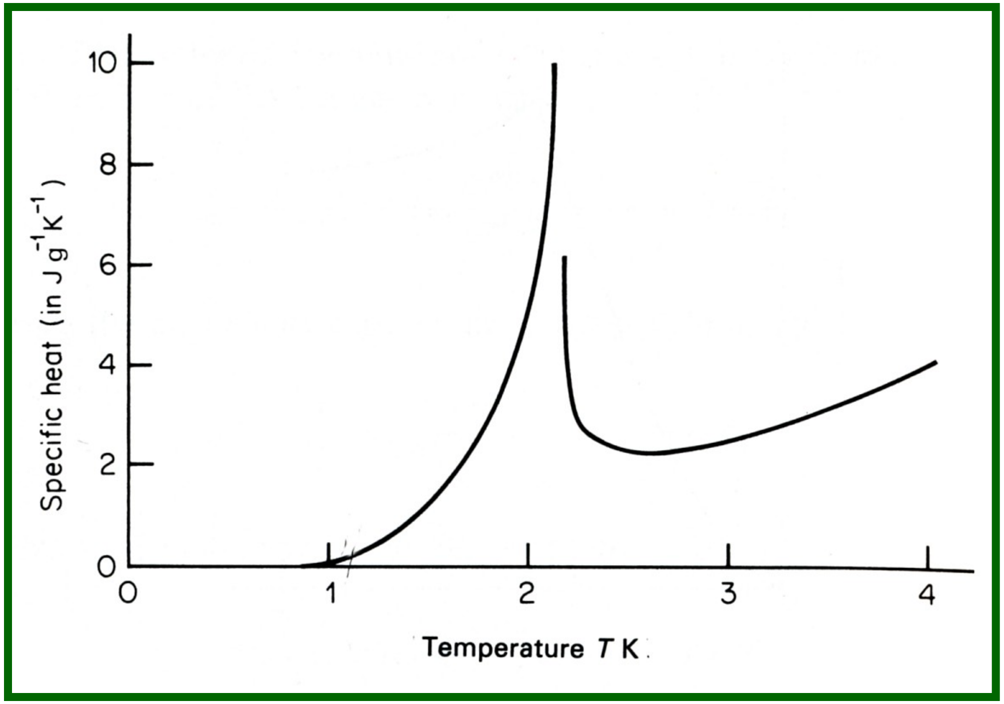
Phase Diagrams

- The large zero-point energy of the liquid eliminates the solid-vapor curve that is present for a normal material.
- **The λ line occurs only for ^{4}He,** and is associated with the ***λ-point*** **transition to superfluid behavior near 2 K.**





The λ Specific Heat Transition in Liquid ^{4}He



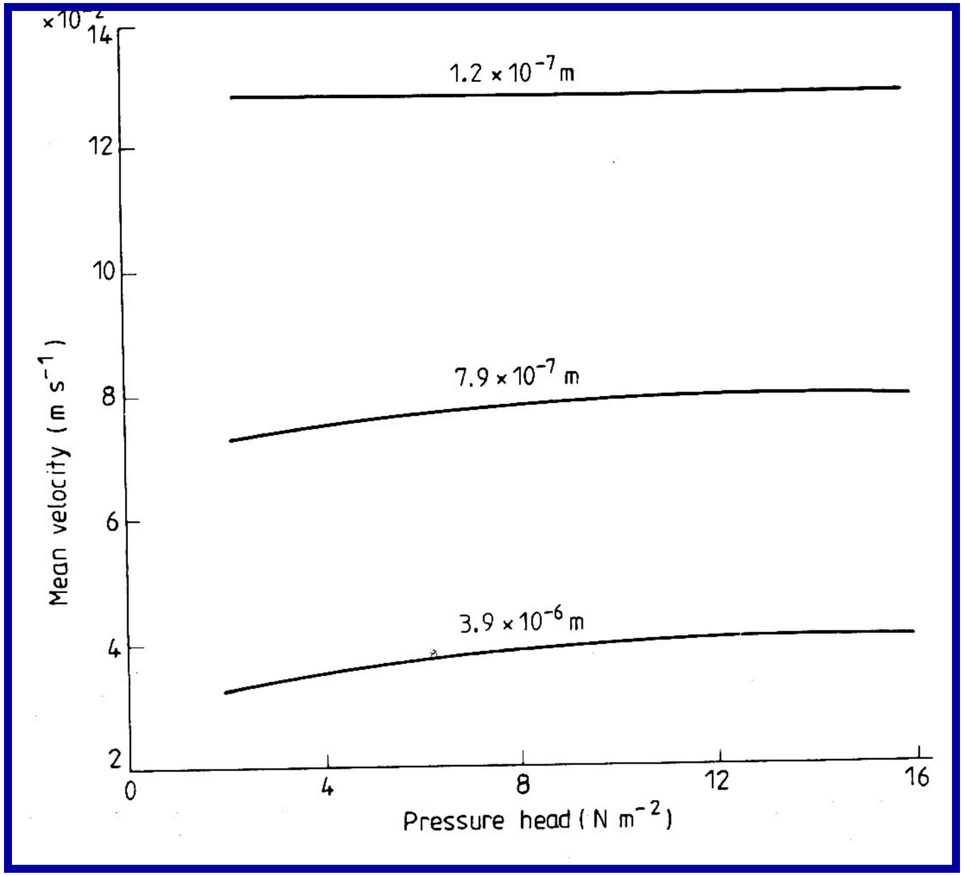
- If ^{4}**He, which liquifies below 4.2 K,** is cooled by lowering the pressure above it, bubbles of vapor form in the liquid, which boils vigorously.

- However, below **2.17 K, the λ point**, the liquid becomes very still, as the transition from a normal fluid (He I) to a superfluid (He II) occurs.
- **In ^{3}He, a transition to a superfluid occurs near 3 mK.**

Macroscopic Properties of Superfluid He II

Zero Viscosity

- Measurements showing zero resistance to flow of He II were first made in 1964.
- This was done by showing that the flow velocity through channels of widths between 0.1 μm and 4 μm were independent of the pressure gradient along the channel.

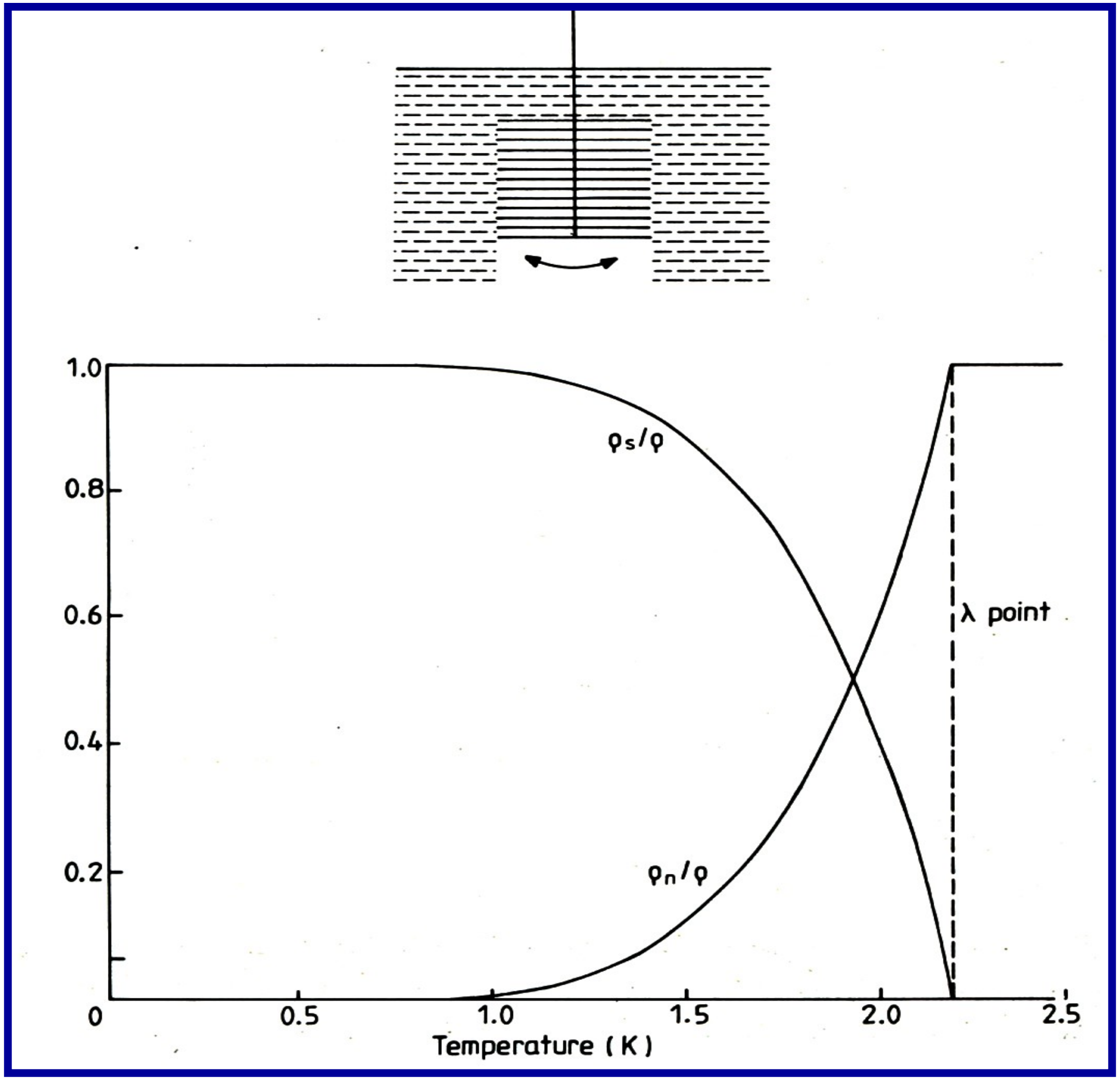


Two-fluid Model of He II

Zero viscosity

- Experiments showed an apparent contradiction, that He II was both viscous & non-viscous at the same time.
- This result was the source of the *two-fluid* model of He II, introduced by Tisza in 1938.
- This is a quantum effect; the liquid does not consist of two distinct fluids, one normal and the other a superfluid.
- In Andronikashvili's 1946 experiment, a series of equally spaced metal disks, suspended by a torsion fibre, were made to oscillate in liquid He.
- The results confirmed that He II consists of a normal viscous fluid of density ρ_n and a superfluid of density ρ_s, and allowed the ratios ρ_s/ρ and ρ_n/ρ to be measured as functions of temperature, where $\rho = \rho_n + \rho_s$.

Andronikashvili's Experiment



Macroscopic Properties of Superfluid He II

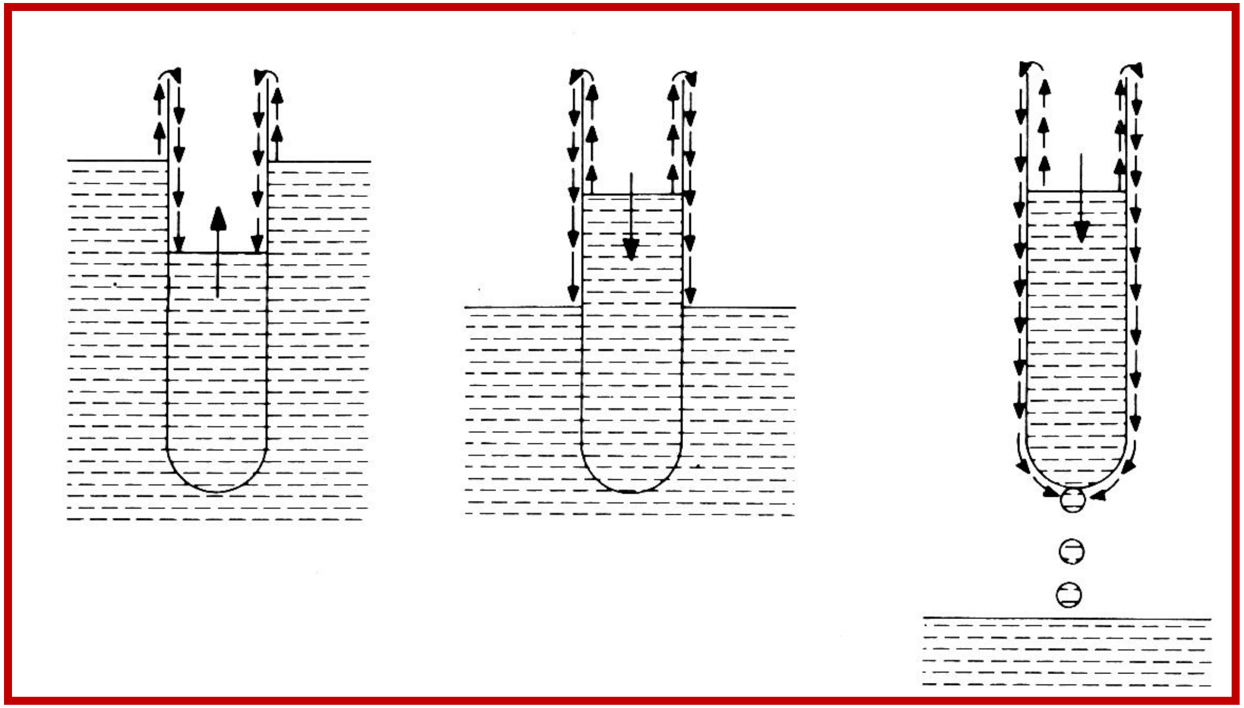
Infinite thermal conductivity

- This makes it impossible to establish a temperature gradient in a bulk liquid. In a normal liquid, bubbles are formed when the local temperature in a small region in the body of the liquid is higher than the surface temperature.

Unusually thick adsorption film

- The unusual flow properties of He II result in the covering of the exposed surface of a partially immersed object being covered with a film about 30 nm (or 100 atomic layers) thick, near the surface, and decreasing with height.

Flow of He II over Beaker Walls

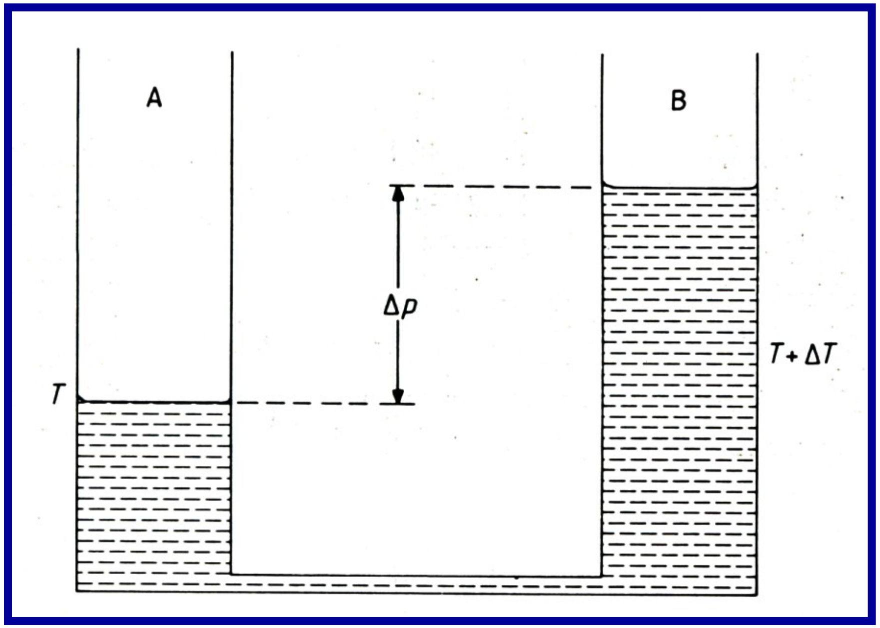


- The temperature is the same throughout the system, and the superfluid acts as a siphon, flowing through the film to equalize the levels in the two bulk liquids.
- By observing the rate at which the beaker level changes, the superfluid velocity has been found to be about 20 cm/s.

Thermomechanical Effect

- If a temperature gradient is set up between two bulk volumes connected by a ***superleak***, through which only the superfluid can flow, the superfluid flows to the higher temperature side, in order to reduce the temperature gradient.
- This is an example of the ***thermomechanical effect***. It shows that heat transfer and mass transfer cannot be separated in He II.

Thermomechanical Effect



- At equilibrium we have (Gibb’s Free Energies)

$$G_A = G_B;\ \text{i.e. } \Delta G = 0.$$

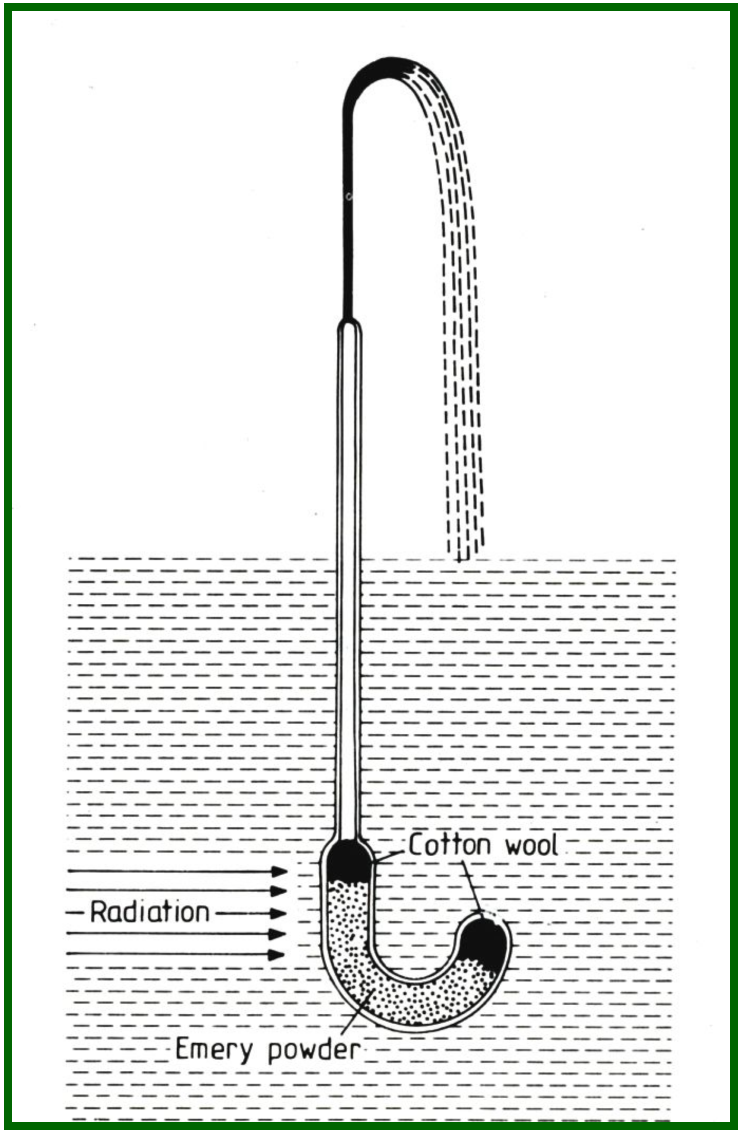
- Now, $dG = -S\,dT + V\,dP = 0$

$$\Delta P = (S/V)\,\Delta T = (s/v)\,\Delta T,$$

where s and v are the values per kg. $\rho = 1/v$, so that,

$$\Delta P = s\,\rho\,\Delta T.$$

The Fountain Effect



- In this famous experiment of Allen and Jones (1938), the superleak is heated by a flashlight.
- In order to equalize temperatures, the superfluid flows through the superleak with sufficient speed to produce a fountain rising 30 cm or more.
- According to Landau’s theory (1941), the normal fluid consists of the excited quantum states. The fine channels in the superleak filter out the excited states