CRYOGENIC ENGINEERING

Prof. Milind D. Atrey

Department of Mechanical Engineering,
IIT Bombay

Lecture No - 4

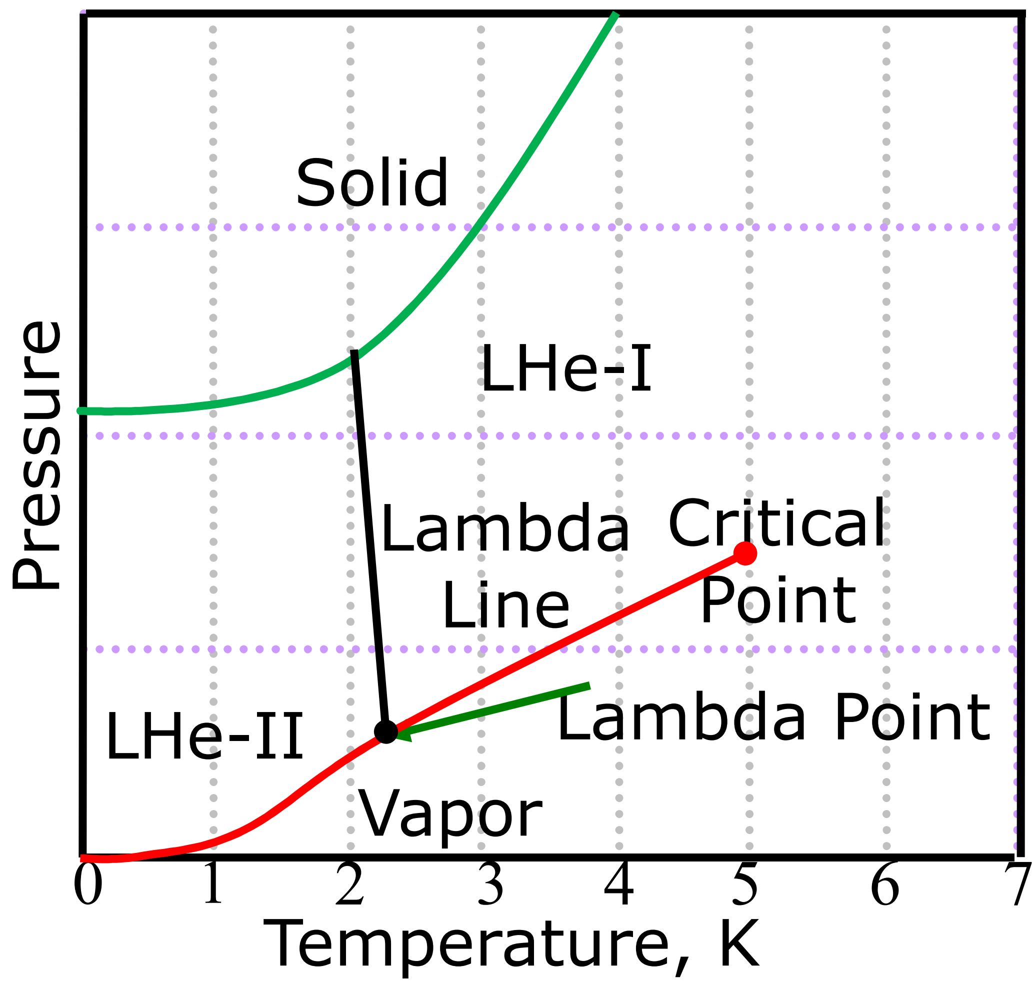
Overview of Earlier Lecture

- Hydrogen
- Helium
- Phase Diagram of Helium
- Super fluid Helium

Outline of the Lecture

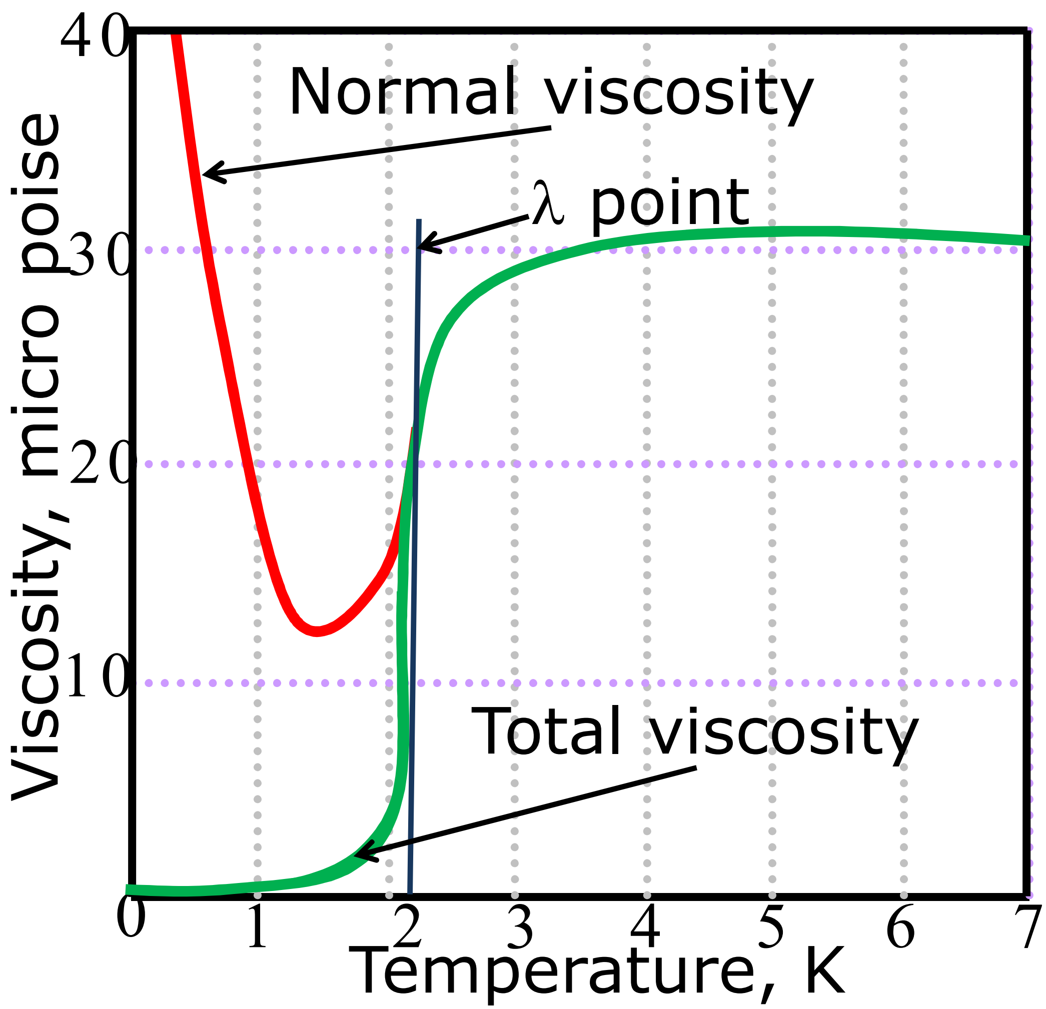
- Uses of Helium – 4
- Thermomechanical, Mechanocaloric, Fountain, Rollin Film Effects.
- Sound Propagation in Super fluid
- Helium – 3 and Phase Diagram
- Summary

Helium – 4 Phase Diagram



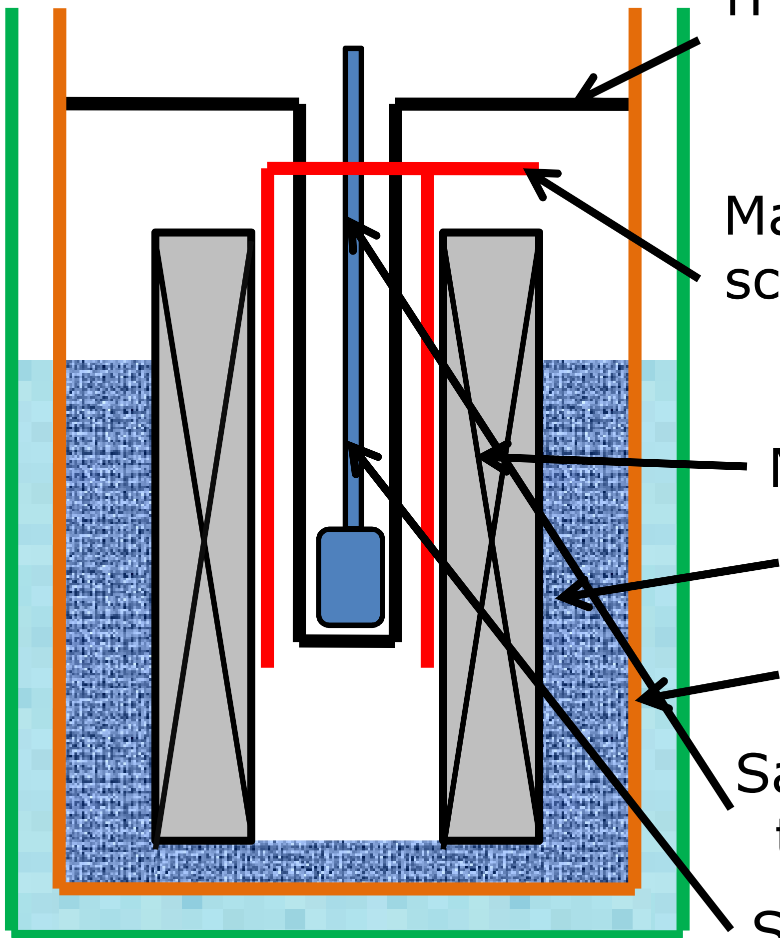
- LHe – II, called as super fluid, exhibits properties like zero viscosity and large thermal conductivity.
- It flows through narrow slits and channels very rapidly.

Helium – 4



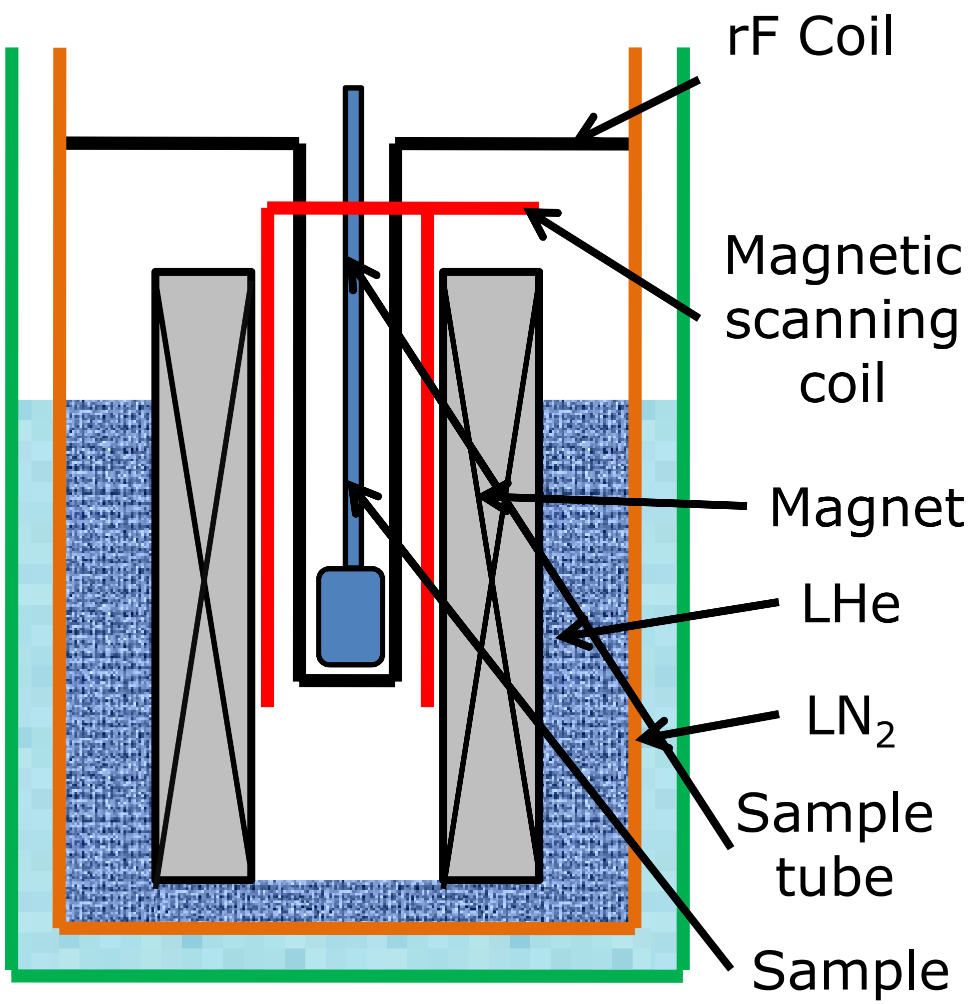
- Kapitza et al. stated that viscosity for flow through thin channels is independent of pressure drop and is only a function of temperature.

Uses of Helium – 4



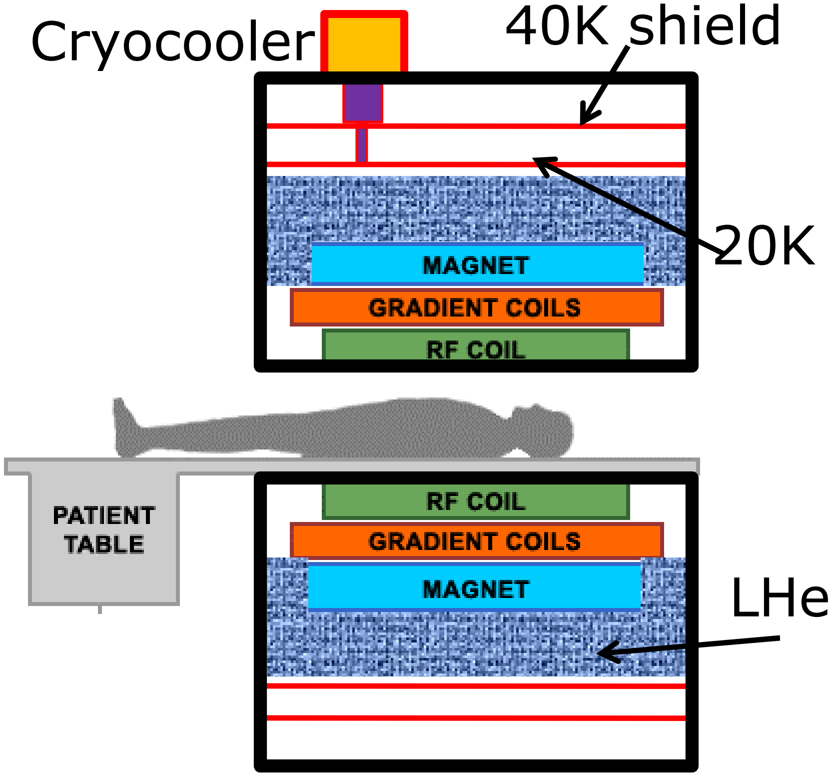
- The NMR (Nuclear Magnetic Resonance) is used by the pharmaceutical industry to study the molecular structure.

Uses of Helium – 4



- It has a superconducting (SC) magnet (10 T ~ 25 T) cooled by Liquid Helium bath.
- The accuracy of measurement increases with the field strength.

Uses of Helium – 4



- The MRI (Magnetic Resonance Imaging) machines are used for body scanning.
- The SC magnets for both NMR and MRI machines are cooled by Liquid Helium.

Uses of Helium – 4

- The Super conducting magnet systems at CERN spanning over 27 Km radius are kept at 1.9 K using the Liquid Helium.
- The low viscosity and high thermal conductivity of Liquid Helium makes the system more efficient.
- Also, the engineering project ITER has Superconducting magnets maintained at 4 K by Liquid Helium.

Uses of Helium – 4

- Helium being a thin and inert gas, is used in leak detection systems.

- It is used as a shielding gas in arc welding to provide an inert atmosphere.

Liquid Helium - II

- The peculiar properties of Liquid Helium – II give rise to interesting thermal and mechanical effects as listed below.

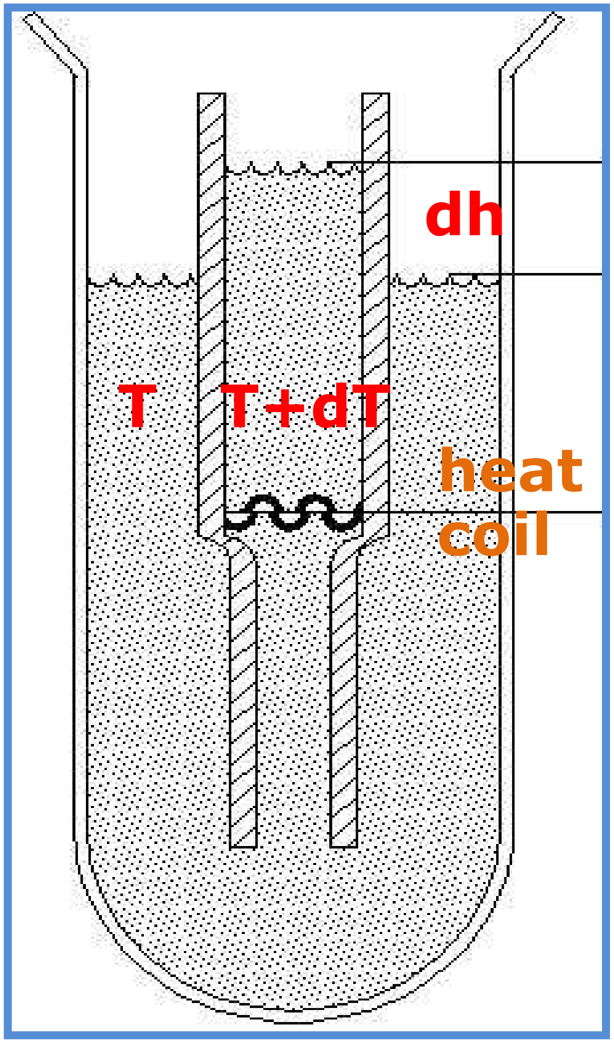
  - Thermomechanical Effect

  - Mechanocaloric Effect

  - Fountain Effect

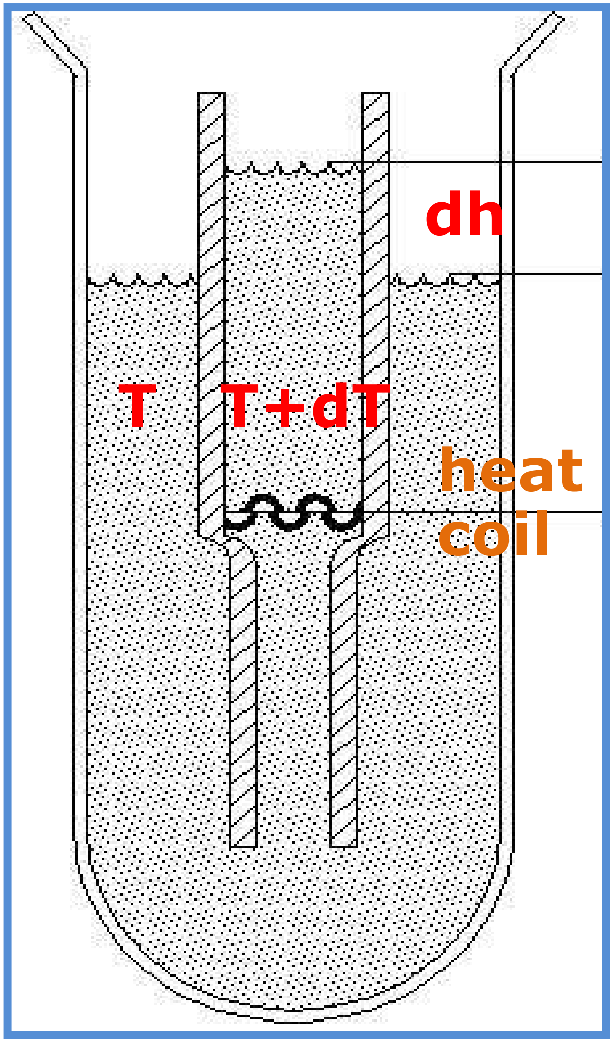
  - Rollin Film Effect

Thermomechanical Effect



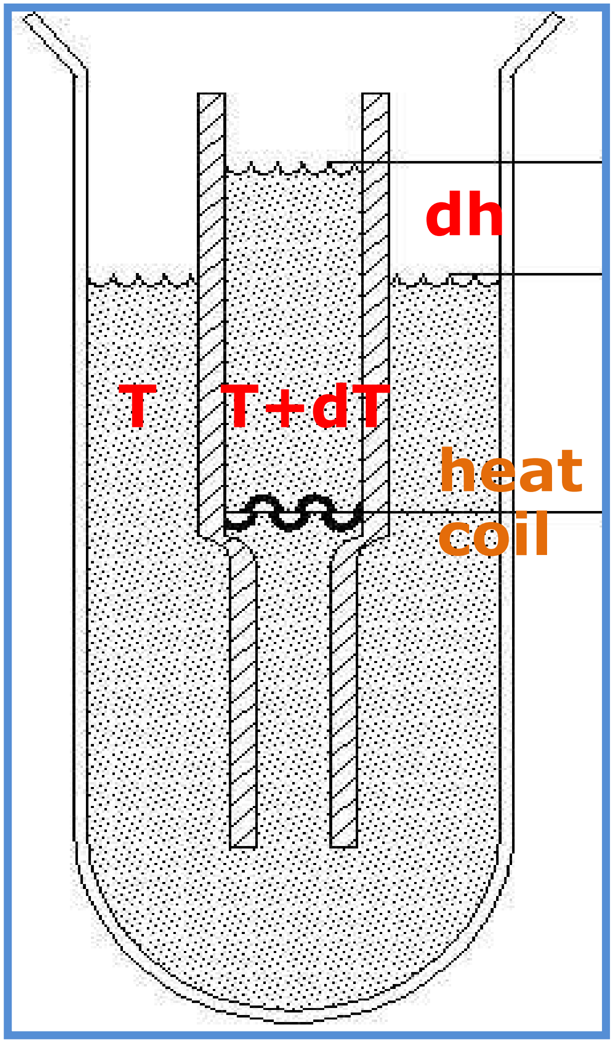
- This effect was discovered in the year 1938.
- Consider a flask filled with super fluid helium (LHe – II) and a heating coil placed inside a differential container as shown in the figure.
- When the heat is applied to the fluid in the inner container, the concentration of normal fluid increases.

Thermomechanical Effect



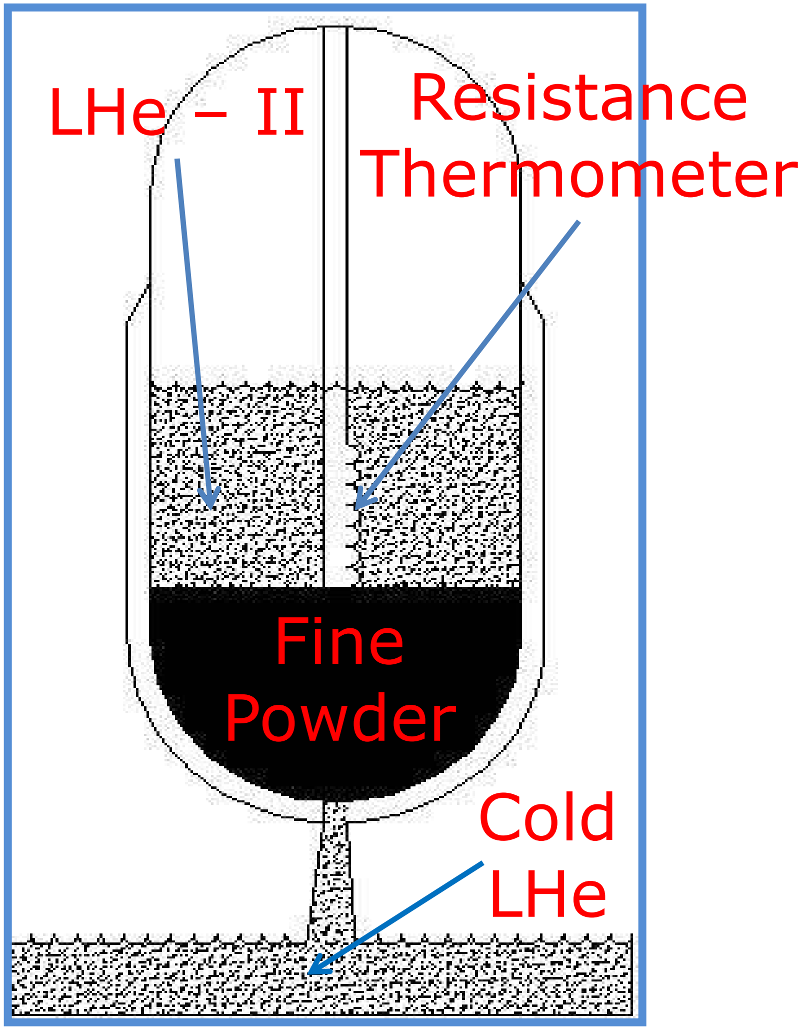
- The Super fluid component tends to move towards this region to equalize the concentration.
- Super fluid being less viscous, can flow rapidly through the narrow channel.
- Normal fluid being more viscous, its flow is impeded by the channel resistance.

Thermomechanical Effect



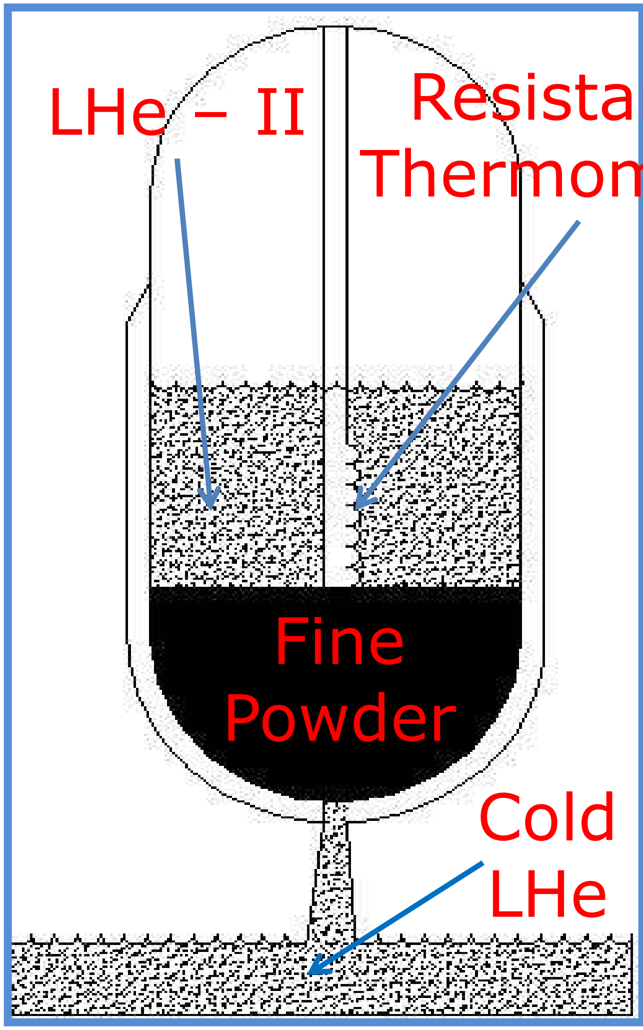
- As a result, due to the induced pressure difference, a pressure head called as Thermo Mechanical Pressure Head is developed.
- This head is proportionate to the temperature rise of ΔT in the fluid.

Mechanocaloric Effect



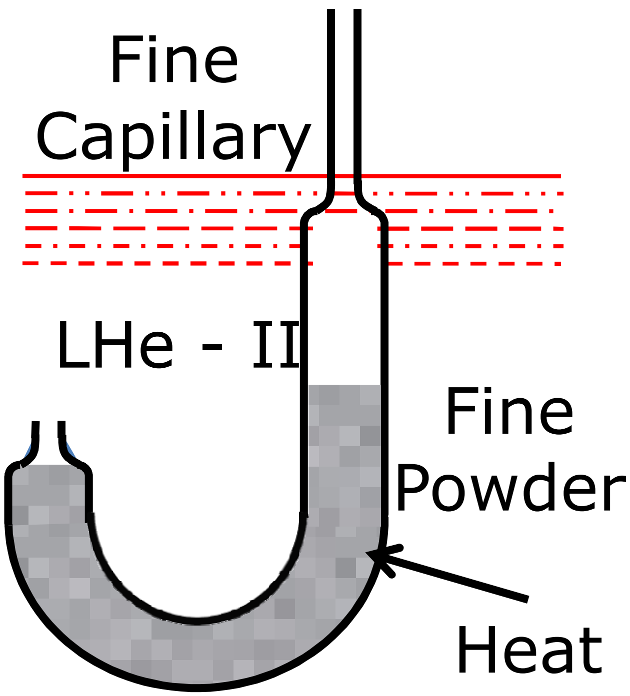
- It was discovered in the year 1939.
- The apparatus consists of a round flask filled with a fine powder and Super fluid Helium (LHe – II). The flask has an opening at the bottom.
- A resistance thermometer is mounted to detect the temperature changes, as shown in the figure.

Mechanocaloric Effect



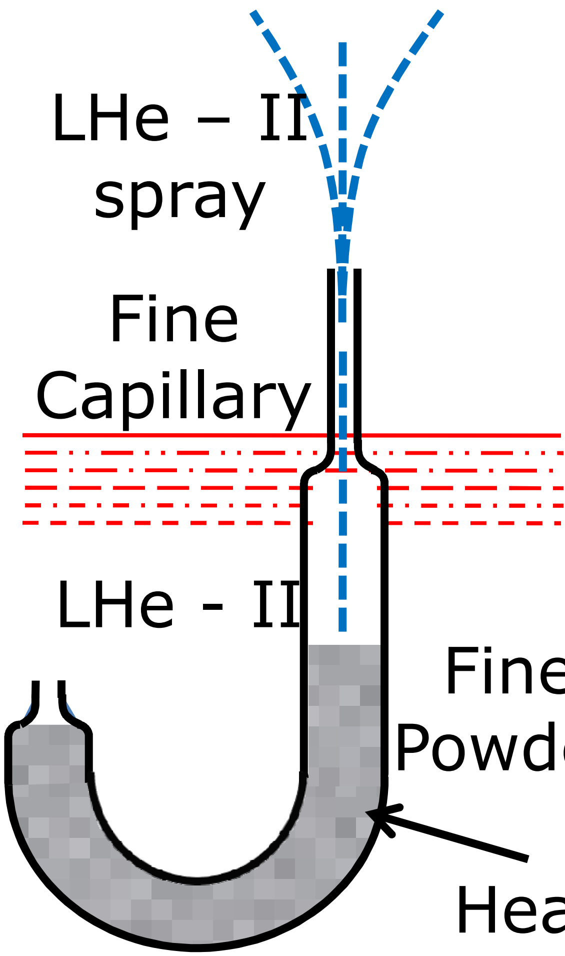
- The Super fluid Helium (LHe - II) being less viscous flows through the fine powder easily.
- As a result, the concentration of normal fluid increases above the powder.
- Hence, the temperature increases inside the flask, which is sensed by resistance thermometer.

Fountain Effect



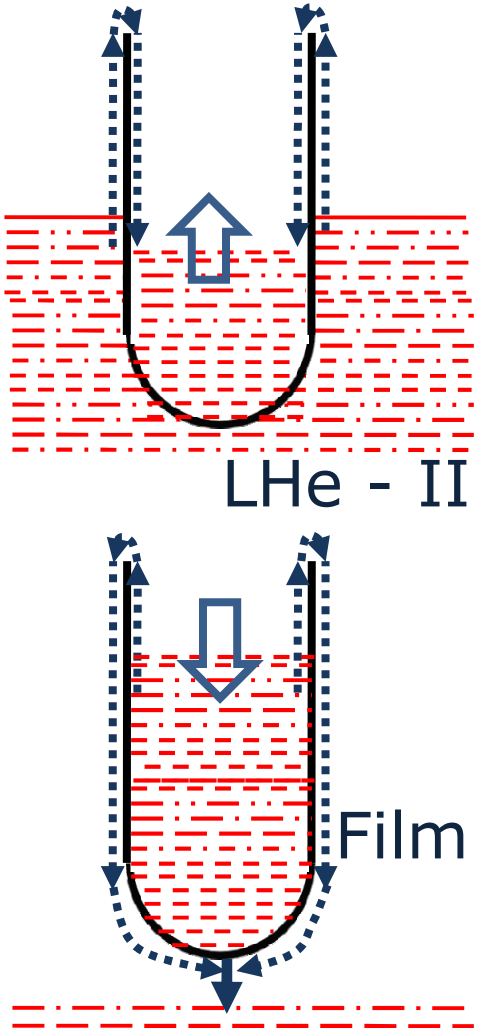
- Consider an U-tube with a fine capillary as shown in the figure.
- The U-tube is filled with a fine powder and is immersed in Super fluid Helium (LHe – II) bath.
- When heat is added to the powder, the concentration of normal fluid increases due to rise in the temperature.

Fountain Effect



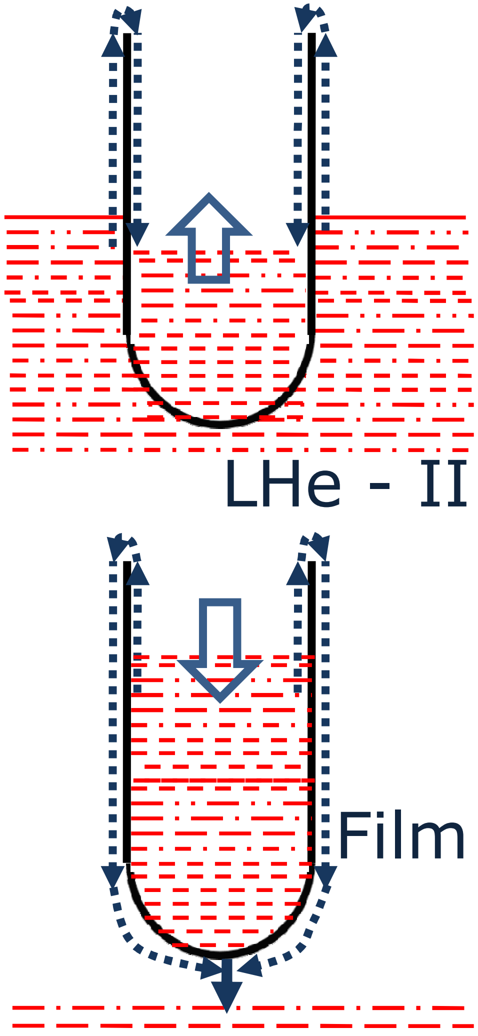
- As a result, the Super fluid rushes in, to equalize the concentration.
- Normal fluid, being more viscous cannot flow through the fine powder.
- The inflow of super fluid builds up with time and finally squirts out through the fine capillary opening at the top.

Rollin Effect



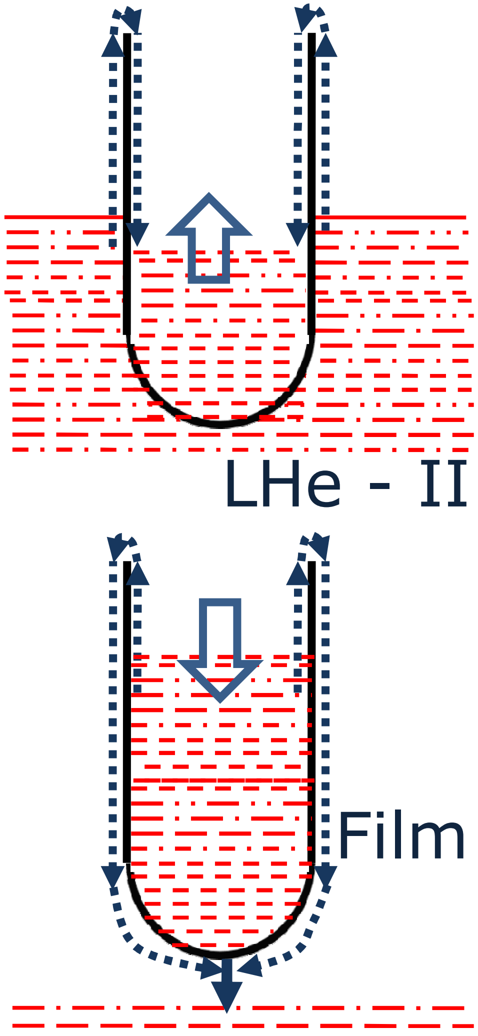
- This effect is named after Bernard V. Rollin in the year 1937.
- The Liquid Helium – II exhibits a property of clinging to the walls of the container called as Creeping effect.
- The thickness of the film is in the order of 30 nm.
- Consider a test tube filled with Liquid Helium – II as shown in the figure.

Rollin Effect



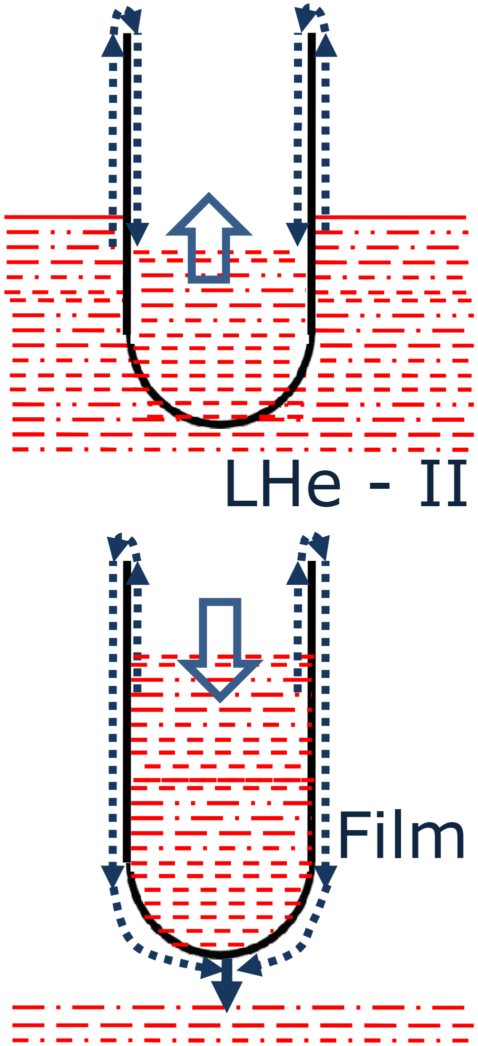
- When the test tube is lowered into the Liquid Helium - II bath, the Rollin film clings to the tube and gradually fills the tube.
- On the other hand, if the tube is raised above the bath level, it empties out slowly.
- The ability of the fluid to flow against gravity is called as Onnes effect.

Rollin Effect



- In these films, the capillary forces dominate the gravity and viscous forces.
- The rate of flow is independent of height of flow or barrier and difference in level. It increases with drop in temperature.
- It is zero at lambda point and becomes constant below 1.5 K.

Rollin Effect



- This creeping behaviour added to leaking ability of Helium – II, makes containment of LHe – II to an enclosure difficult.

- The enclosure or the container has to be designed properly otherwise Helium – II creeps to the warmer side through valves and openings and will evaporate.

Sound Propagation

- In LHe – II, at least three different mechanisms of sound can be propagated.
- For temperatures above and below lambda point, propagation of ordinary sound which is nothing but pressure and density oscillations occurs.
- This is called as First sound.

Sound Propagation

- Below the lambda point temperature, the Liquid Helium has LHe- I (normal fluid) and LHe – II (super fluid) components.
- Due to difference in concentrations of these fluids, there exists a temperature gradient. This gradient causes oscillations of Normal fluid and Super fluid which are called as Second sound.
- The velocity of Second sound varies from zero at lambda point to 239 m/s at near 0 K.

Sound Propagation

- In thin films, the LHe – I component clings to the walls due to the viscous effects.
- If only the super fluid component in Second sound oscillates, then it is called as Third sound.
- This wave motion appears as an oscillation in the thickness of the film. The velocity of propagation of Third sound is around 0.5 m/s.
- Another form of sound called as Zero sound has been detected recently. The research is on to study its characteristics.

Helium Nomenclature

Isotopes	Temp	
Helium – 4 →	λ	→ LHe – I → LHe – II
Helium – 3		

Helium – 3

Helium – 3

- It is a non radioactive isotope with two protons and one neutron.

Normal Boiling Point	K	3.19
Normal Freezing Point	K	-
Critical Pressure	MPa	0.117
Critical Temperature	K	3.32
Liquid He – 3 Density	kg/m^3	58.9
Latent Heat	kJ/kg	8.49

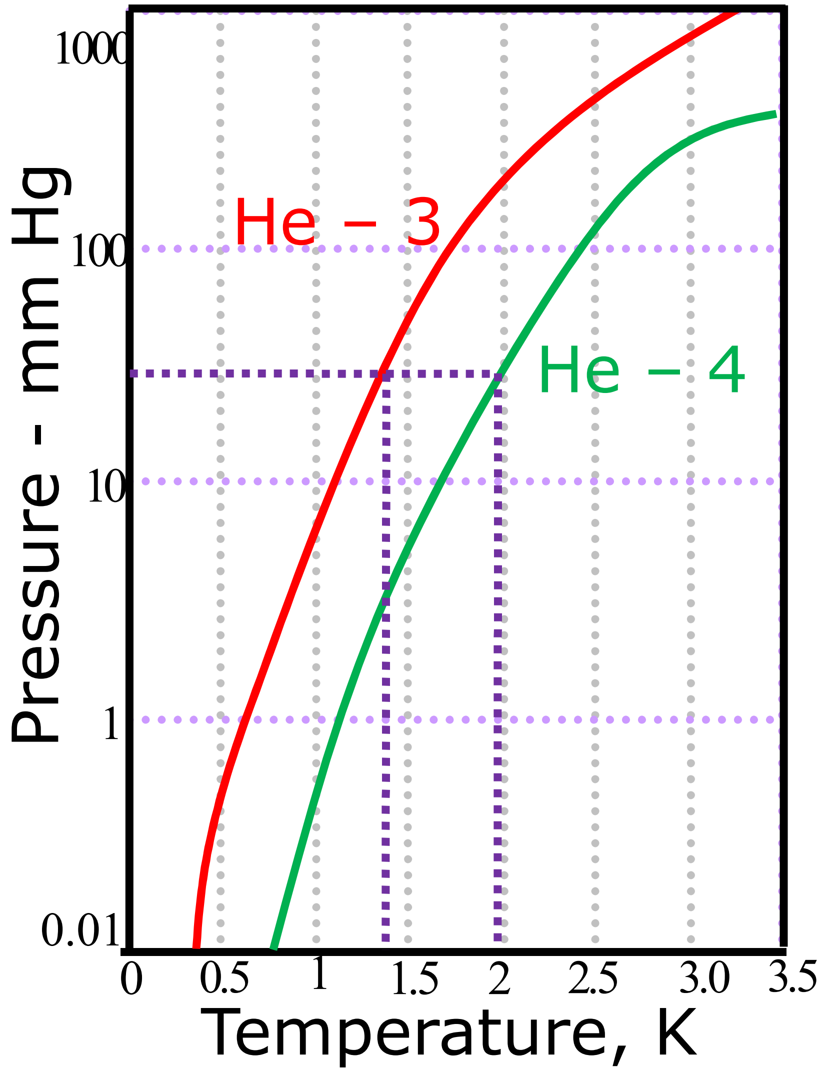
Helium – 3

- In 1920, Aston discovered another isotope of Helium, He^3. First liquefaction of Helium – 3 was achieved by Sydoriak et. al. in the year 1948.

- This isotope He - 3 is very rare and is difficult to isolate from He – 4.

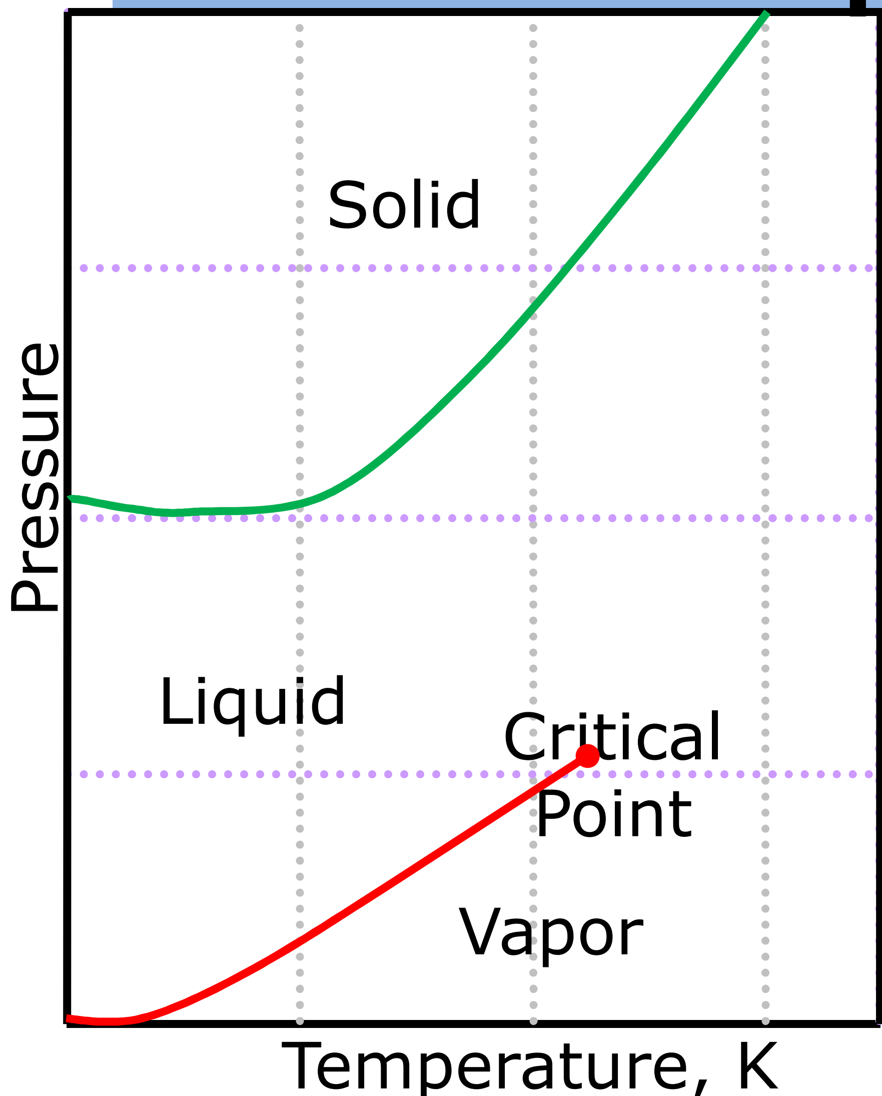
Isotope	Relative %
He – 4	~100
He – 3	1.3×10^{-4}

Helium – 3



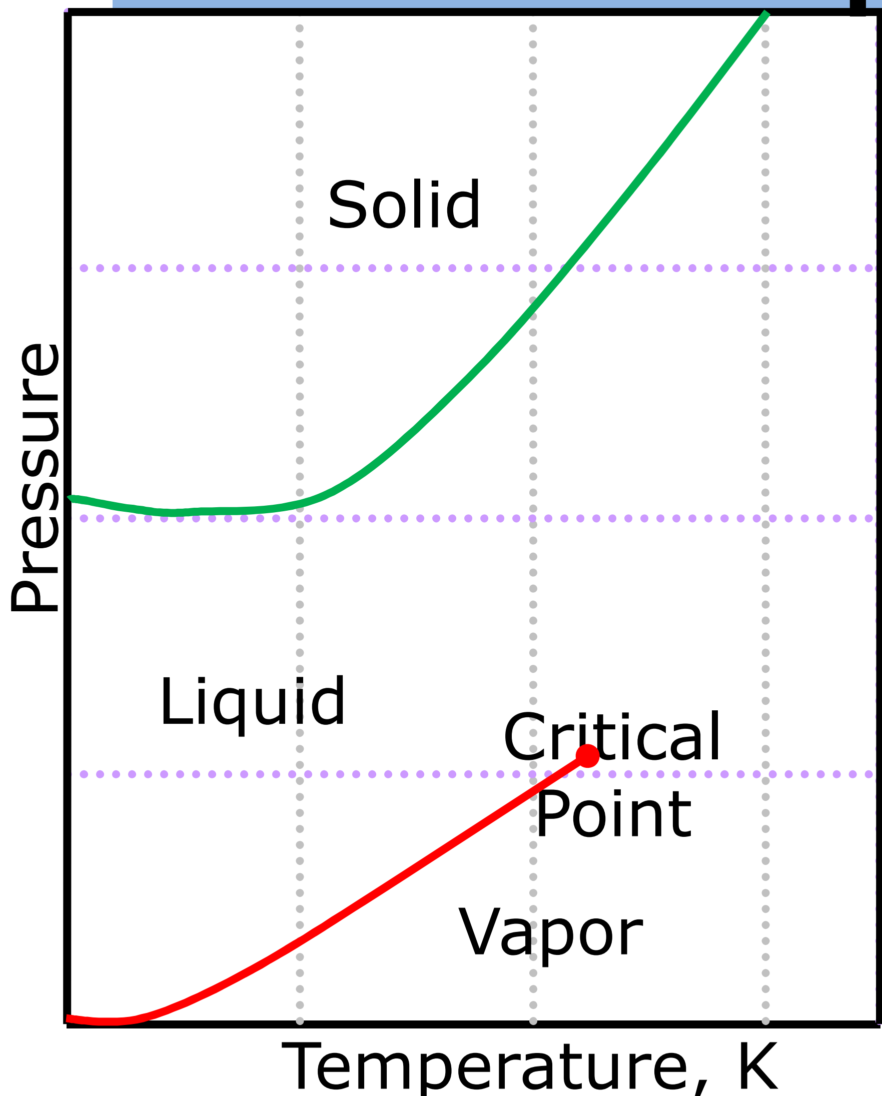
- From the adjacent figure, it is clear that for a given pressure Liquid He - 3 is more colder than Liquid He – 4.

Helium – 3 phase diagram



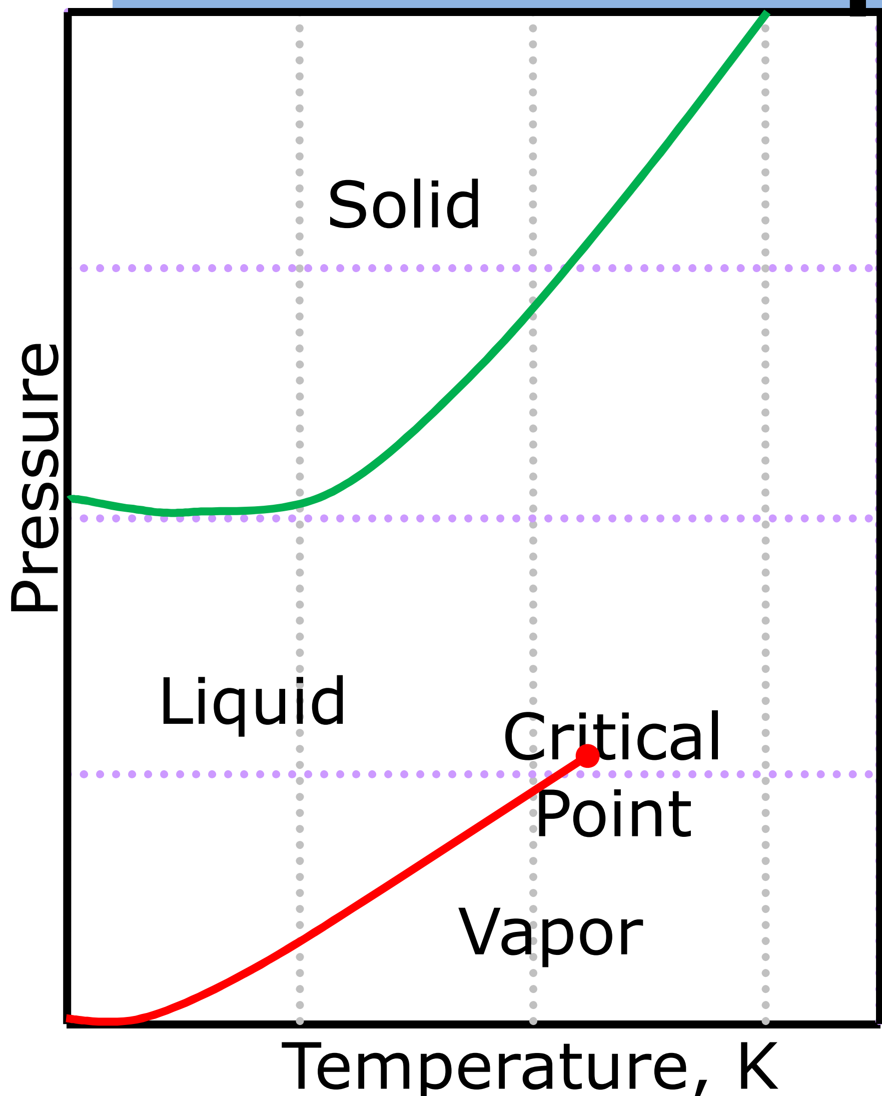
- From the adjacent figure
- Saturated solid line.
- Saturated vapor line.
- Critical point.

Helium – 3 phase diagram



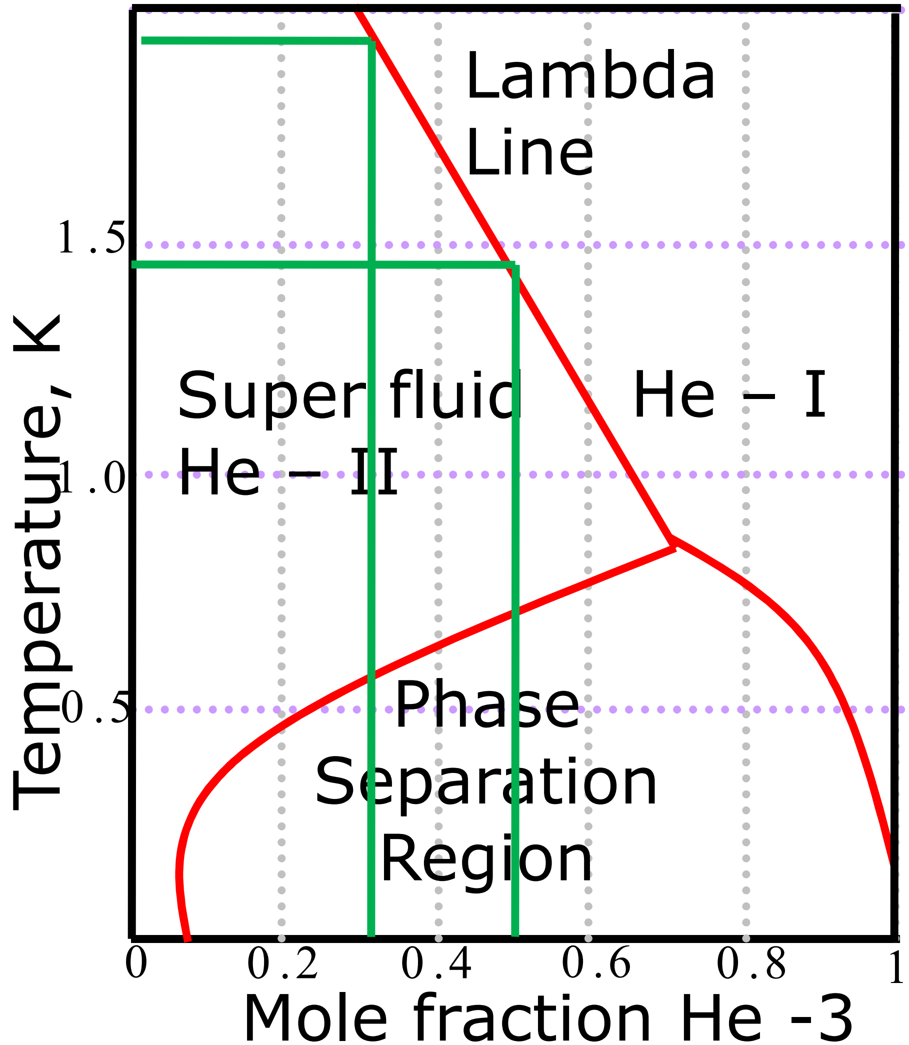
- LHe - 3 (like LHe - 4) remains liquid under its vapor pressure up to absolute zero.
- It must be compressed to 28.9 bar at 0.32 K to solidify.

Helium – 3 phase diagram



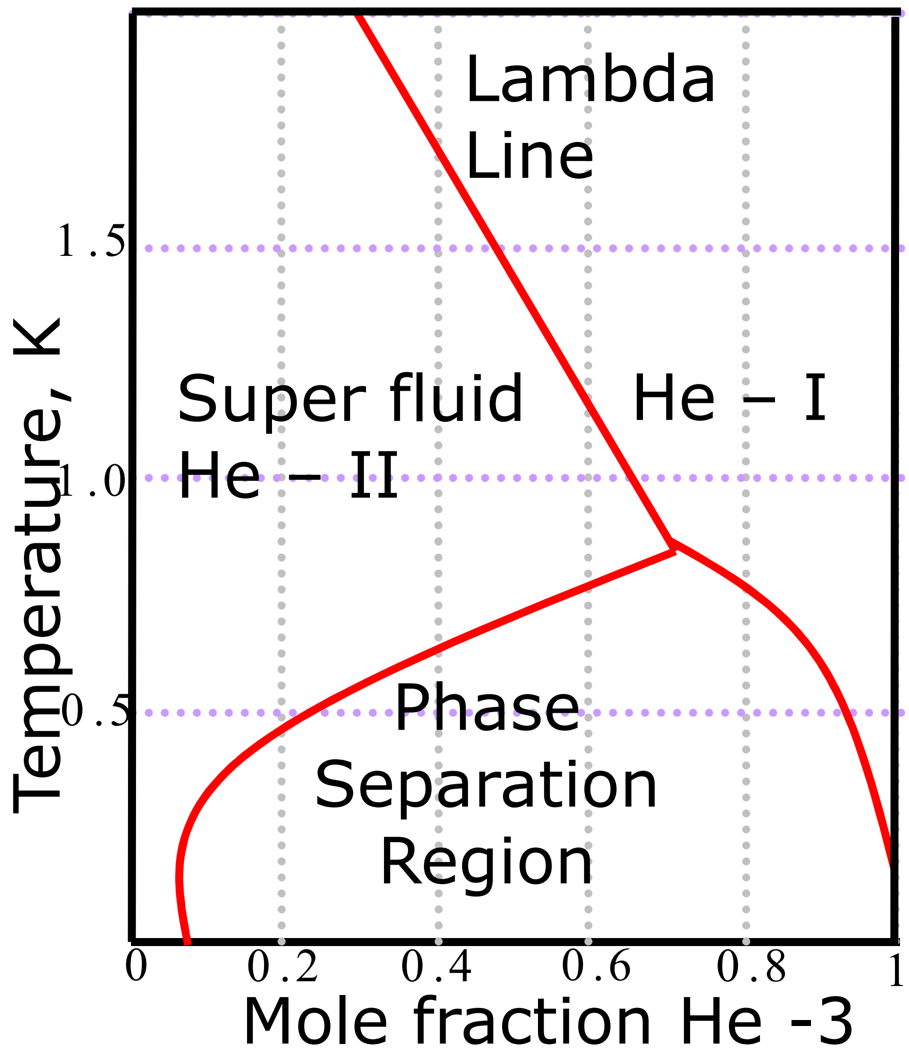
- Helium – 3 has no temperature and pressure at which solid - liquid – vapor can co-exist. It means that it has no triple point.
- Liquid He - 3 undergoes a different type of super fluid transition at approximately 3.2 mK.

He – 3 & He – 4 Mixture



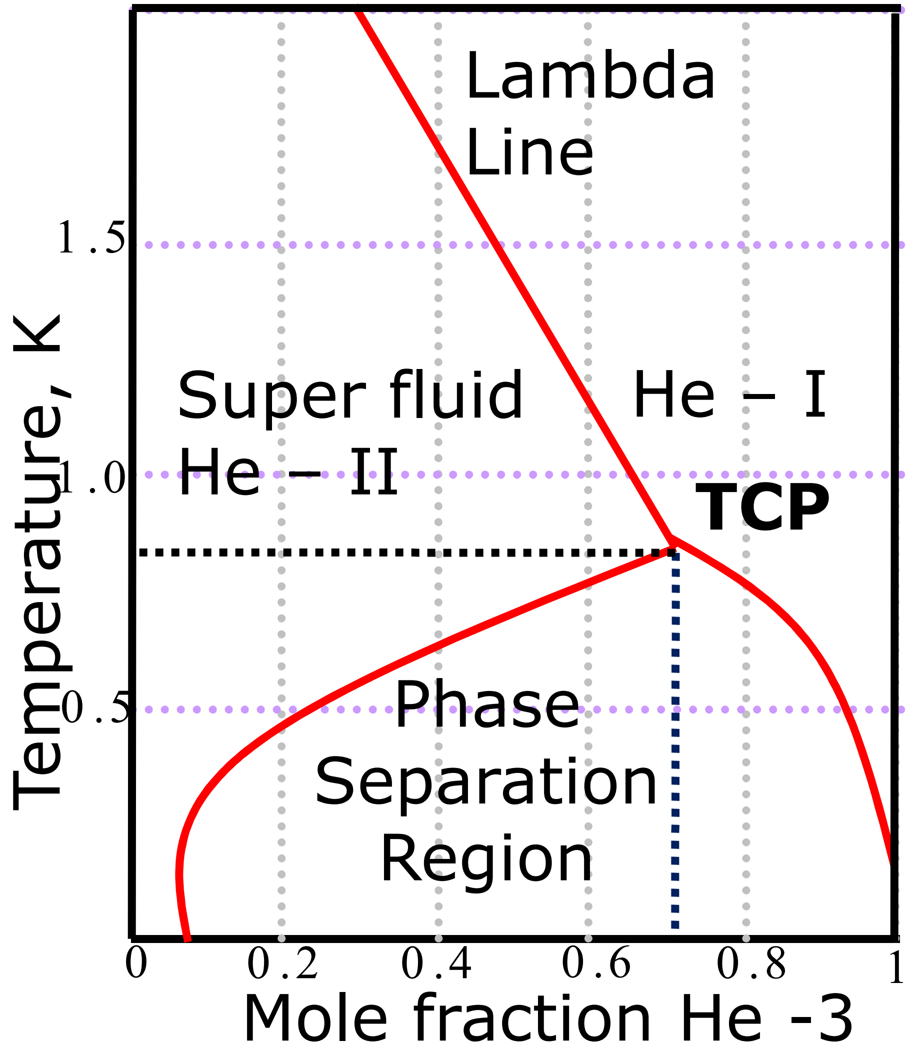
- The λ line shown in the adjacent figure is a function of concentration of He – 3.
- The λ point is depressed by addition of small amounts of He – 3.
- The mixture of He – 3 and He – 4 is not completely miscible at very low temperature.

He – 3 & He – 4 Mixture



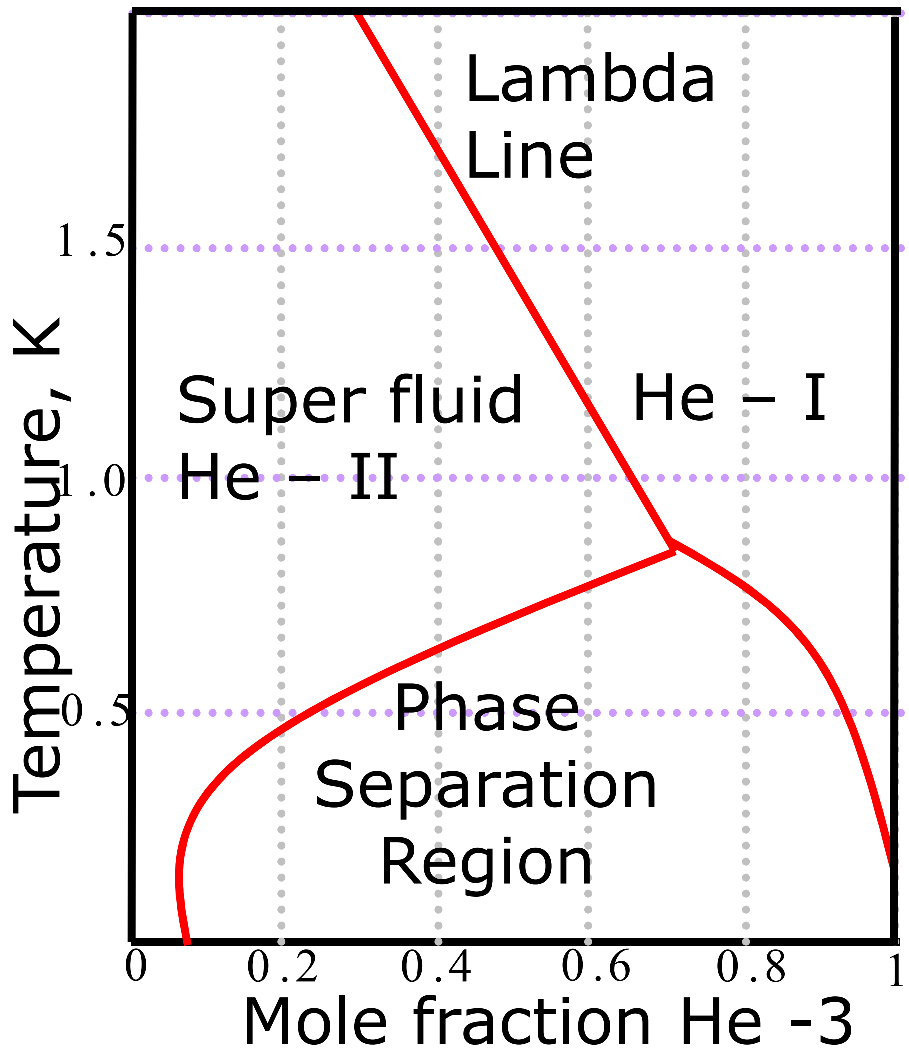
- The mixture of He – 3 and He – 4 separate below 1 K due to the differences in isotopic mass.
- Separation occurs into Super fluid (rich in He - 4) and Normal fluid (rich in He - 3).

He – 3 & He – 4 Mixture



- The point of intersection of Lambda line and phase separation region is called as Tricritical point (TCP).
- The TCP at 0.872 K and with a concentration of 0.669 of He – 3.

He – 3 & He – 4 Mixture



- This separation into two liquid phases and difference in vapor pressure forms the basis for Dilution Refrigerator.

Uses of Helium – 3

- It is mostly used in Dilution refrigerators to achieve low temperatures.
- It is also used as working fluid in Cryocoolers. Temperature close to 1 K are reported with Pulse Tube Cryocooler.
- The properties are of interest in relation to the theories of quantum statistical mechanics.
- It is an important isotope in instrumentation for neutron detection.

Summary

- The summary of the topics covered are
- Introduction to Cryogenics
- Properties of Cryogens, T – s Diagram
- Hydrogen
- Helium
- Super fluid Helium
- Helium - 3

- A self assessment exercise is given after this slide.

- Kindly asses yourself for this lecture.

Self Assessment

1. The pressure head in Mechanocaloric effect is proportional to ___________________.

2. In Thermomechanical effect, ____________ fluid flows out of fine powder.

3. The viscosity of Super fluid helium is __________ than normal fluid.

4. At a given pressure, the temperature of LHe – 3 is ___________ than LHe – 4.

Self Assessment

5. Boiling point of LHe – 3 is ________

6. Principle of Dilution Refrigerator is ___________

7. _____________ isotope of Helium is difficult to separate & also mention the temperature.

8. Second sound is due to the oscillations of ____________

9. The speed of Third sound in LHe – II is _________

Self Assessment

10. The thickness of Rollin film is in the order of ____________

11. The Tricritical point occurs at ___________ temperature.

12. Phase separation in He- 3 and He -4 Mixture occurs below _____________ Temperature.

Answers

1. Rise in temperature
2. Super fluid helium (LHe –II).
3. Greater
4. Lower
5. 3.19 K
6. The separation that occurs below 0.8 K.
7. He – 3
8. Normal fluid and Super fluid Helium
9. 0.5 m/s

Answers

10. 30 nm
11. 0.872 K
12. 1 K

Thank You!