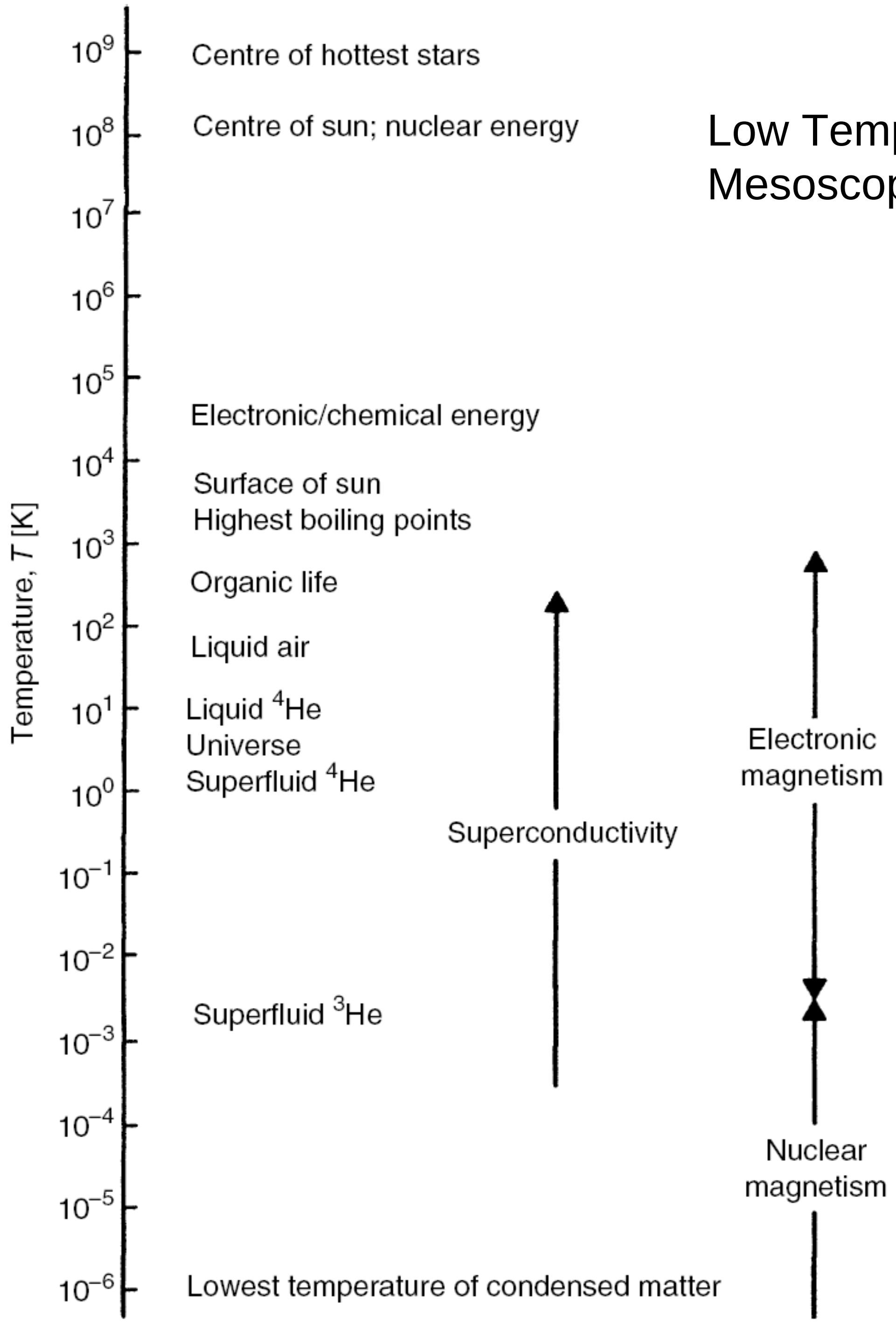
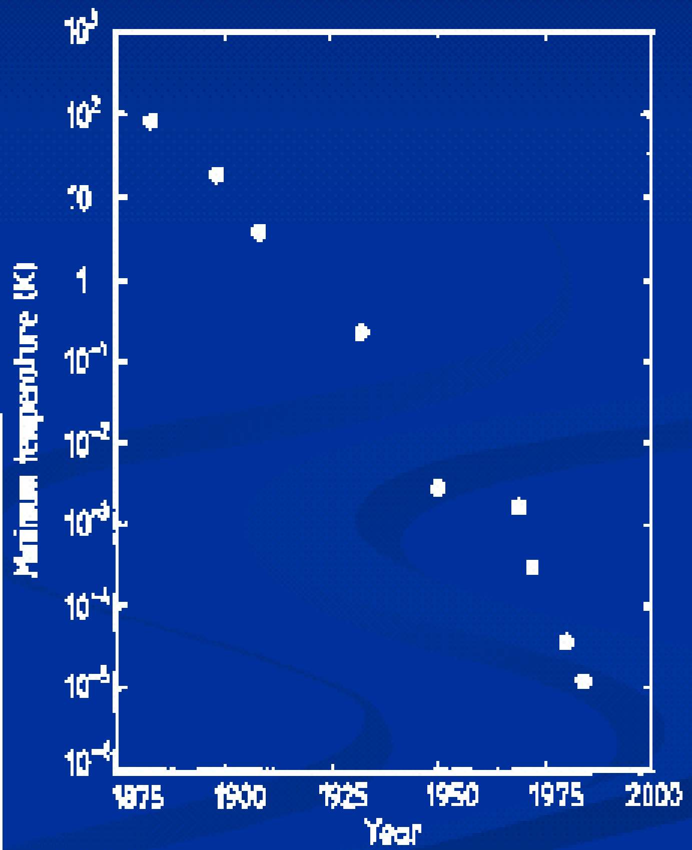
Low Temperature Methods in Mesoscopic Physics

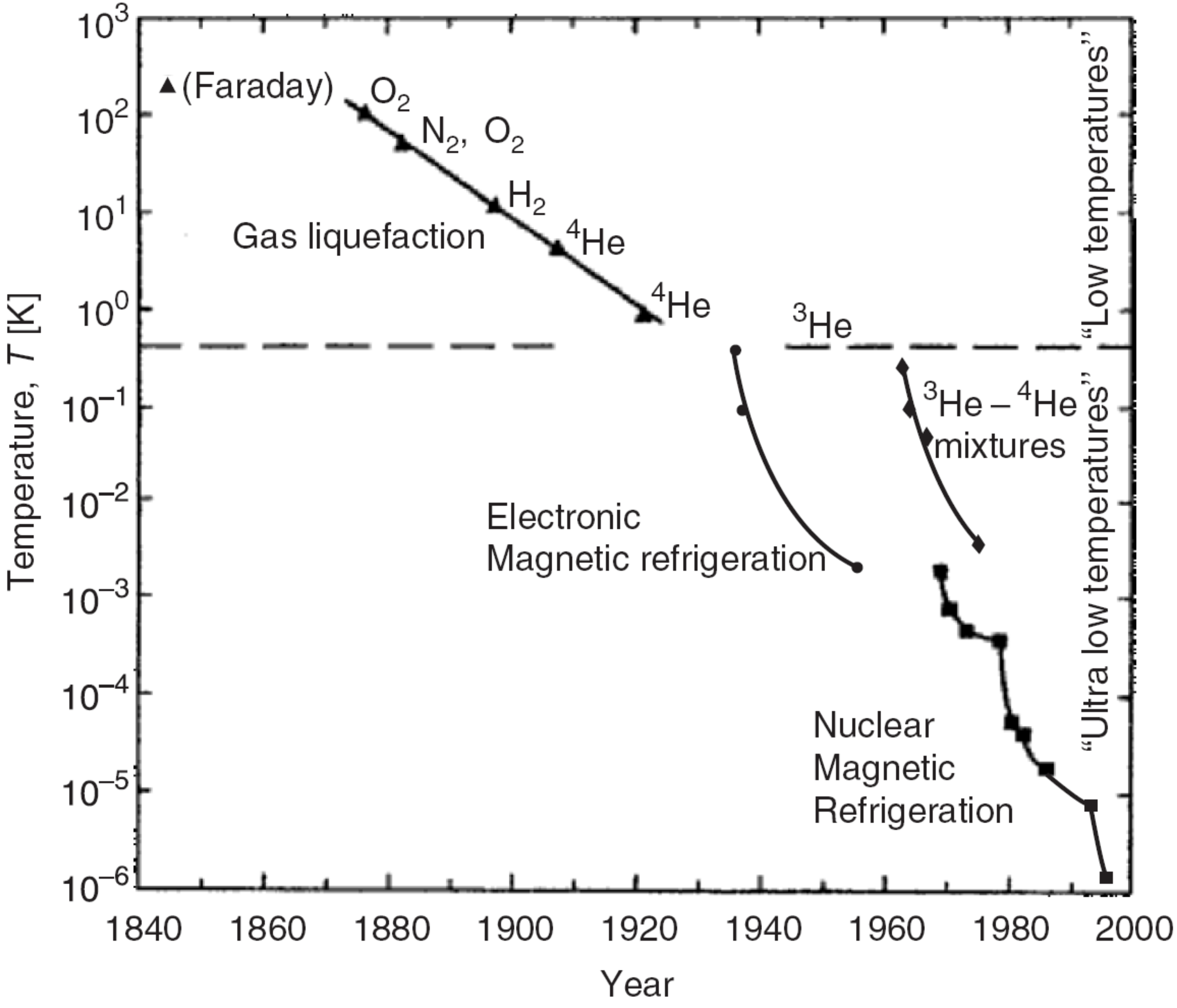


Historical Overview

1755	artificial ice by evaporating (Cullen)
19th cent.	Liquification of various gases
1848	Discovery of absolute zero (Thompson)
1877	„DRP1250 Kälteerzeugungsmaschine“ (Linde)
1908	Liquid Helium (Kammerling-Ones)

Temperature range		Refrigeration technique	Available since	Typical $T_{\min}$	Record $T_{\min}$
I	Kelvin	Universe			2.73 K
		Helium-4 evaporation	1908	1.3 K	0.7 K
		Helium-3 evaporation	1950	0.3 K	0.23 K
II	Milli-kelvin	**^{3}He–^{4}He dilution**	1965	10 mK	2 mK
		Pomeranchuk cooling	1965	3 mK	2 mK
		Electronic magnetic refrigeration	1934	3 mK	1 mK
III	Micro-kelvin	**Nuclear magnetic refrigeration**	1956	100 μK	1.5 μK[a]





(Faraday)
O_2
N_2, O_2
H_2
^{4}He
^{4}He
Gas liquefaction
^{3}He
^{3}He – ^{4}He mixtures
Electronic Magnetic refrigeration
Nuclear Magnetic Refrigeration
"Low temperatures"
"Ultra low temperatures"
Temperature, T [K]
Year
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
1840
1860
1880
1900
1920
1940
1960
1980
2000

subst.	T_b (K)	T_m (K)	T_{tr} (K)	P_{tr} (bar)	T_c (K)	P_c (bar)	lat. heat, L (kJ l^{-1})	vol% in air
H_2O	373.15	273.15	273.16	0.06*	647.3	220	2,252	–
Xe	165.1	161.3	161.4	0.82	289.8	58.9	303	0.1×10^{-4}
Kr	119.9	115.8	114.9	0.73	209.4	54.9	279	1.1×10^{-4}
O_2	90.1	54.4	54.36	0.015	154.6	50.4	243	20.9
Ar	87.2	83.8	83.81	0.69	150.7	48.6	224	0.93
N_2	77.2	63.3	63.15	0.13	126.2	34.0	161	78.1
Ne	27.1	24.5	24.56	0.43	44.5	26.8	103	18×10^{-4}
n-D_2	23.7	18.7	18.69	0.17	38.3	16.6	50	–
n-H_2	20.3	14.0	13.95	0.07	33.2	13.2	31.8	0.5×10^{-4}
^{4}He	4.21	–	–	–	5.20	2.28	2.56	5.2×10^{-4}
^{3}He	3.19	–	–	–	3.32	1.15	0.48	–

* The exact value is $P_{tr} = 61.1657\,\mathrm{mbar}$

Relevant Low Temperature Techniques

Properties of Liquid Helium	Helium-4	Helium 3
Critical Temperature	5.2 K	3.3 K
Boiling Point at 1 atm	4.2 K	3.2 K
Minimum melting pressure	25 atm	29 atm at 0.3 K
Superfluid transition temperature at saturated vapor pressure	2.17 K	1 mK in zero magnetic field
Type	Boson	Fermion

Table 2.3. Properties of liquid helium

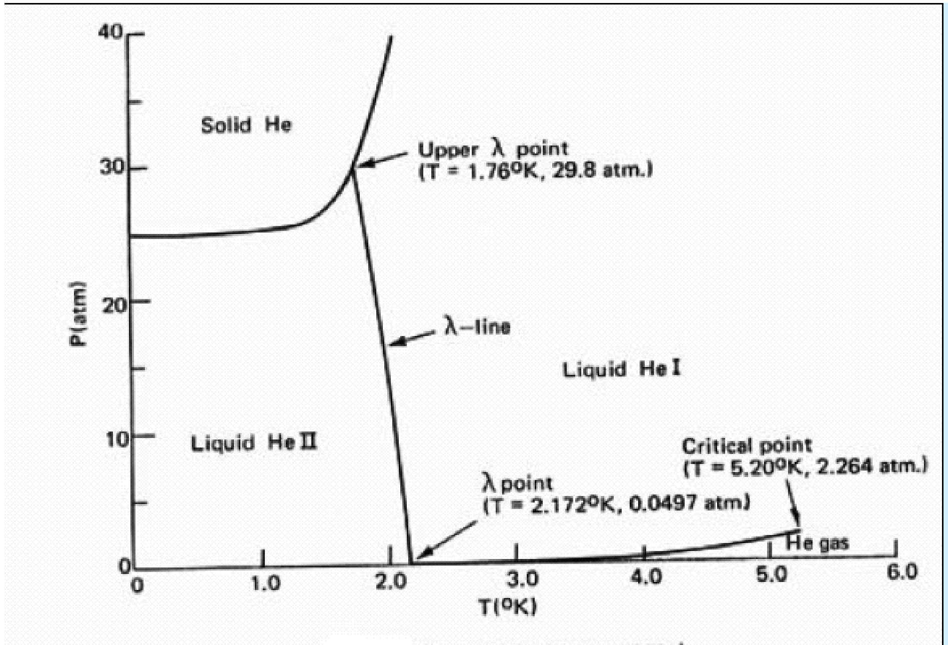
	^3He	^4He
Boiling point, T_b (K)	3.19	4.21
Critical temperature, T_c (K)	3.32	5.20
Maximum superfluid transition temperature, T_c (K)	0.0025	2.1768
Density[a], ρ ($g\,cm^{-3}$)	0.082	0.1451
Classical molar volume[a], V_m ($cm^3\,mol^{-1}$)	12	12
Actual molar volume[a], V_m ($cm^3\,mol^{-1}$)	36.84	27.58
Melting pressure[b], P_m (bar)	34.39	25.36
Minimum melting pressure, P_m (bar)	29.31	25.32
Gas-to-liquid volume ratio[c]	662	866

[a] At saturated vapour pressure and $T = 0\,K$.

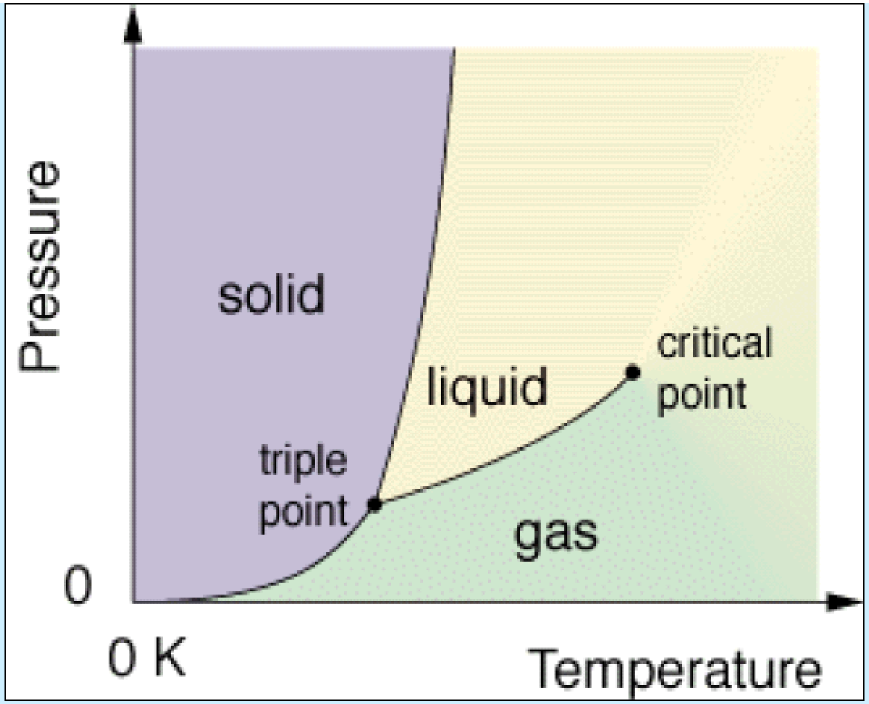
[b] At $T = 0\,K$.

[c] Liquid at 1 K, NTP gas (300 K, 1 bar).

^4He Phase Diagram



The phase diagram of He^4.

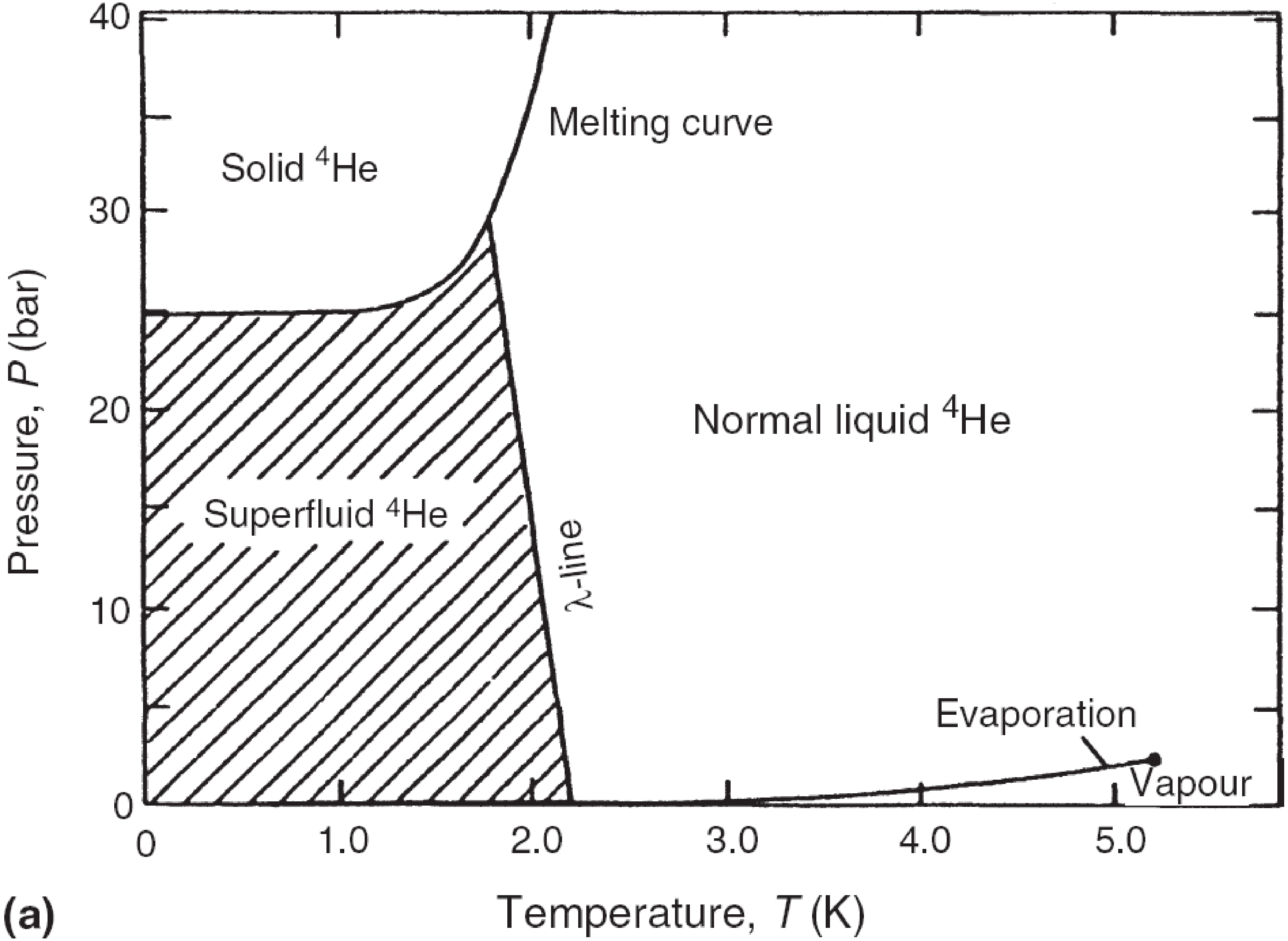


The critical point

$T_c = 5.20$ K

$P_c = 2.264$ atm

Typical phase diagram



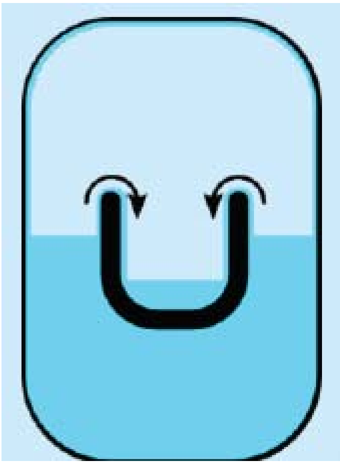
Solid ^{4}He
Melting curve
Normal liquid ^{4}He
Superfluid ^{4}He
λ-line
Evaporation
Vapour
Pressure, P (bar)
Temperature, T (K)
0
10
20
30
40
1.0
2.0
3.0
4.0
5.0

(a)

He II: Superfluid

Bose-Einstein condensate

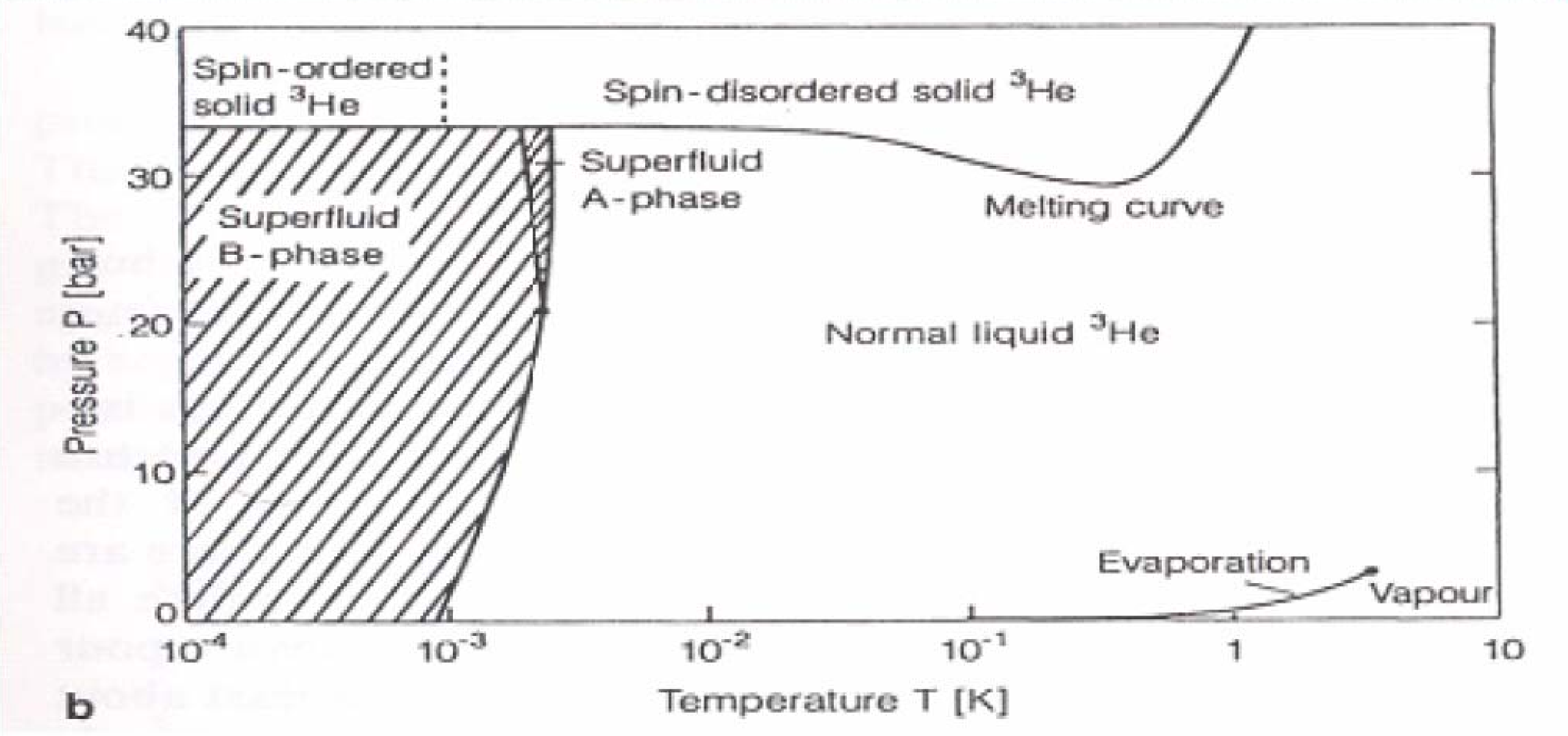
frictionless fluid



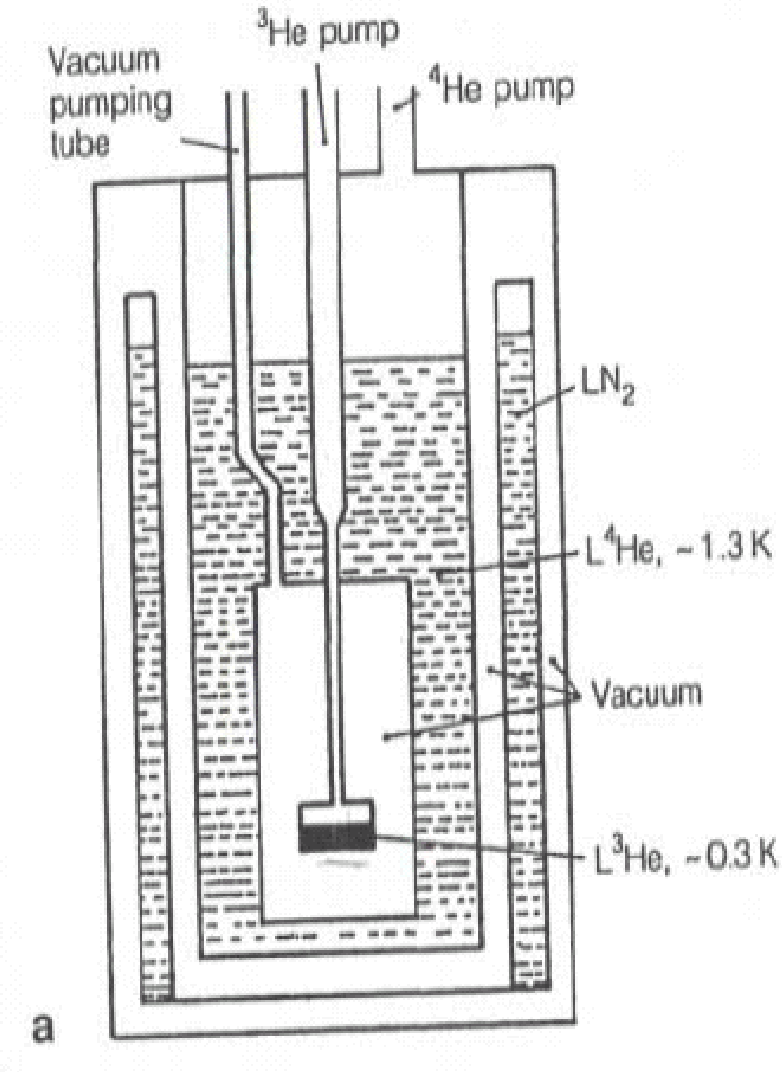
- will escape from a vessel that is not sealed by creeping along the sides until it reaches a warmer region where it evaporates
- moves in a 30 nm thick film Rollin film regardless of surface material.
- leaks rapidly through tiny openings

- **Production of He-3**
- Tritium Decay.
- D-D Fusion Reaction.
- The p+Li6 Reaction for Breeding He-3.

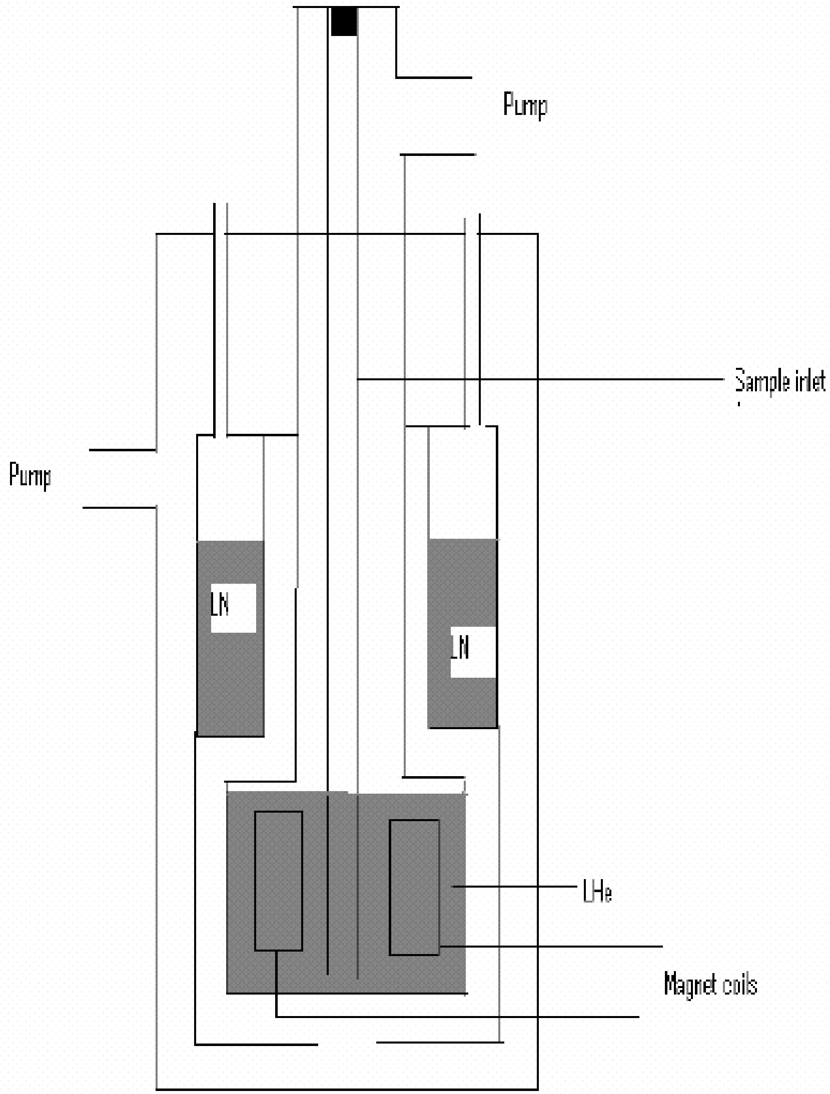
3He Phase Diagram



Cryostats



³He pump
Vacuum pumping tube
⁴He pump
LN₂
L⁴He, ~1.3 K
Vacuum
L³He, ~0.3 K
a



Pump
Sample inlet
Pump
LN
LN
LHe
Magnet coils

Evaporative Cooling

Clausius-Clapeyron-Equation

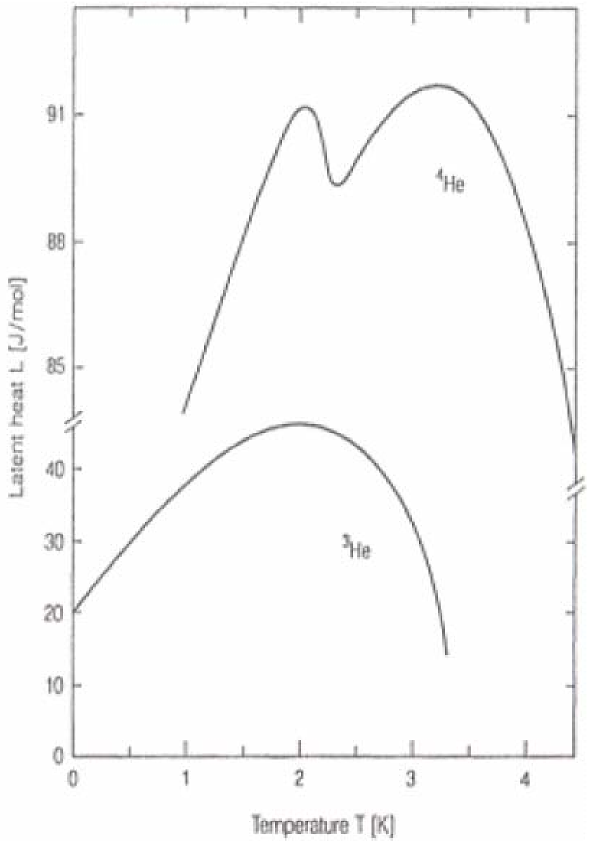
$$\left(\frac{\partial P}{\partial T}\right)_{vap} = \frac{S_{gas} - S_{liq}}{V_{mol,gas} - V_{mol,liq}}$$

with

$$S_{gas} - S_{liq} = \frac{L}{T}$$
$$V_{mol,gas} \gg V_{mol,liq}$$
$$V_{gas}P = RT$$
$$L \neq L(T)$$

The vapour pressure is

$$P_{vap} \sim \mathrm{e}^{-\frac{L}{RT}}$$

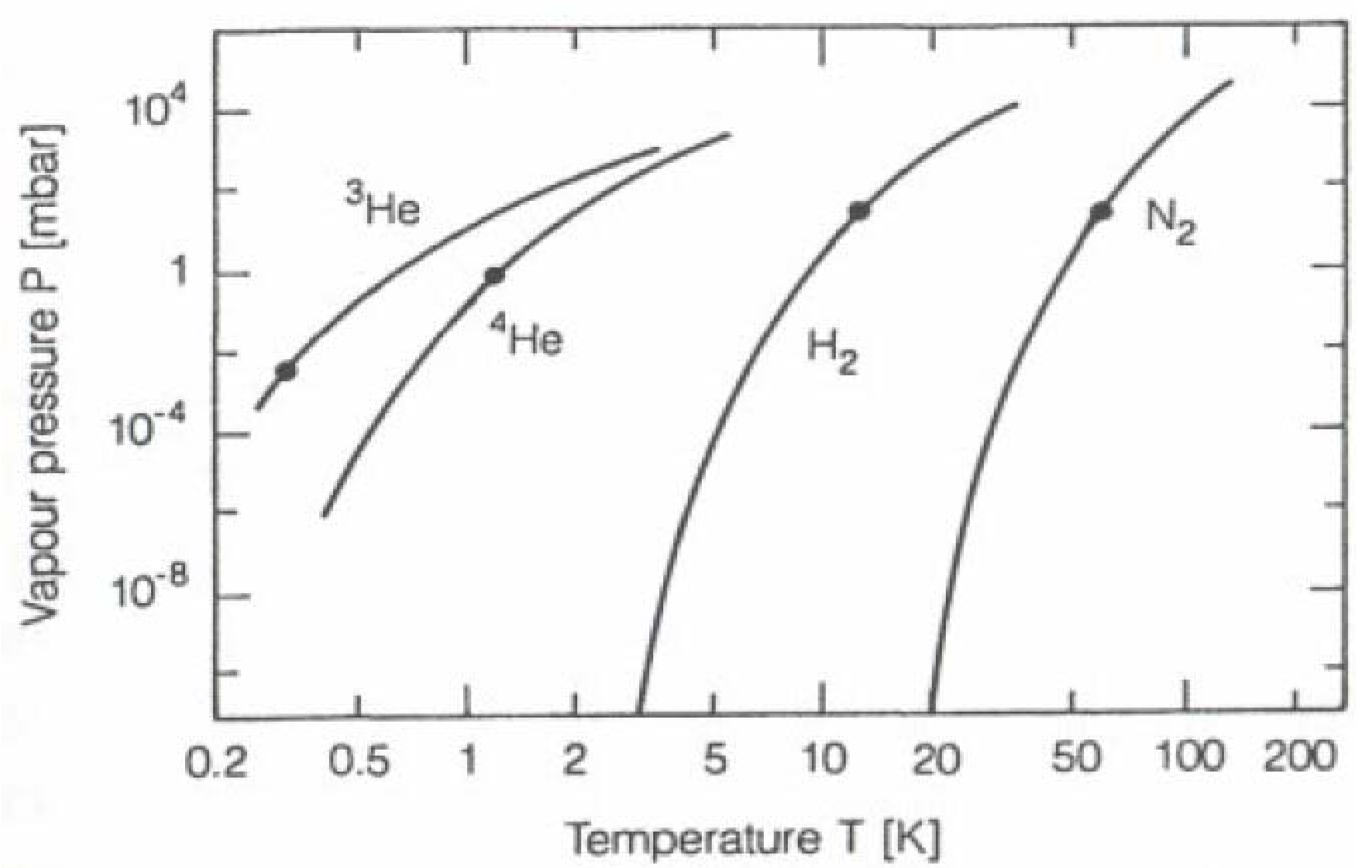


Resulting cooling power

$$\dot{Q} = \dot{n}L \sim LP_{vap} \sim \mathrm{e}^{-\frac{1}{T}}$$

Cooling Power proportional to Vapour Pressure

$$P \propto \exp\left(-\frac{L}{RT}\right)$$



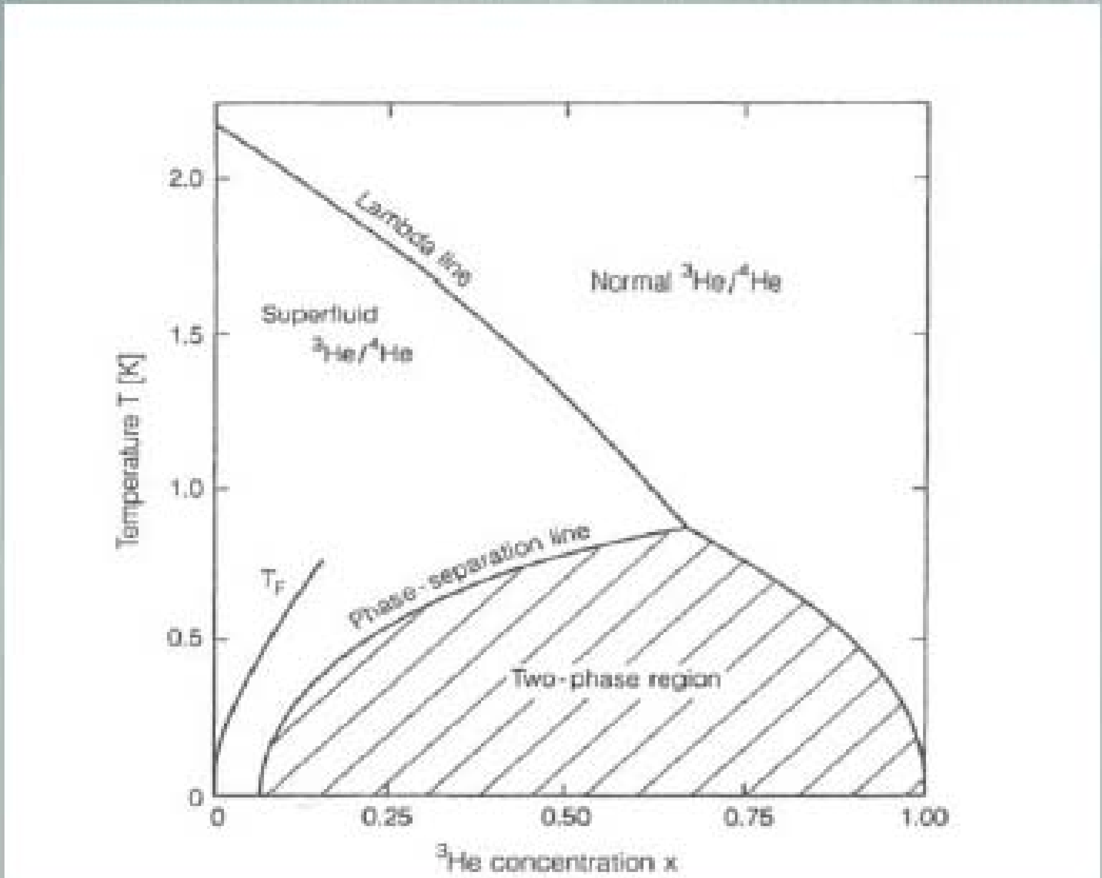
pumping on ^{4}He: ~ 1 K
pumping on ^{3}He: ~ 0.25 K

Dilution Refrigeration

He3-He4 mixture

the working fluid mixture of the dilution refrigerator:

Phase separation into ^{3}He rich and ^{3}He poor phase below T ~ 800 mK



Dilution Refrigeration

- **The Cooling Power:**
- The cooling capacity is the heat mixing of the two isotopes. The cooling power of an evaporating cryogenic liquid:

$$\dot{Q} = \dot{n}\,\Delta H = \dot{n}\,L$$

- Make use of the latent heat L of evaporation, pumping with a pump of constant volume rate $\dot{V}$ on He3 and He4 bath with vapour pressure P:

$$\dot{Q} = \dot{V}\,P(T)L(T)$$

- He3-He4 dilution refrigeration: Use the difference of the specific heats of the two phases (the enthalpy of mixing):

$$\Delta H \propto \int \Delta C\,dT$$

$$\Rightarrow \dot{Q} \propto x\Delta H \propto T^2$$

dilution refrigerator:
cooling power: ~ T^2

reaches temperature ~ few mK

Dilution Refrigeration: Working Principle

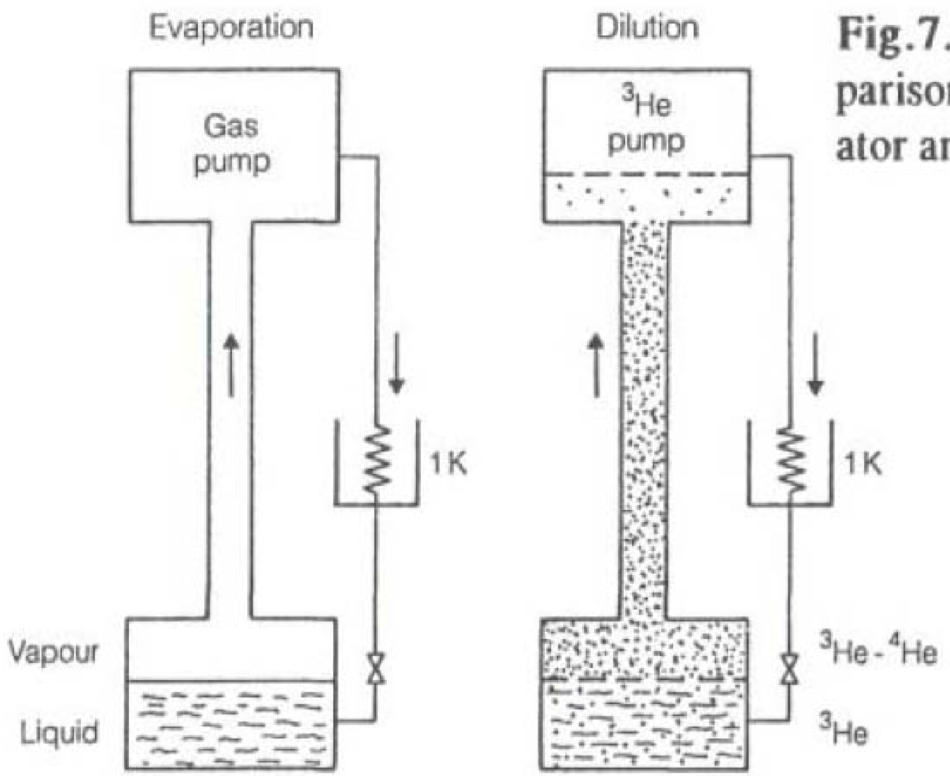


Fig.7.8
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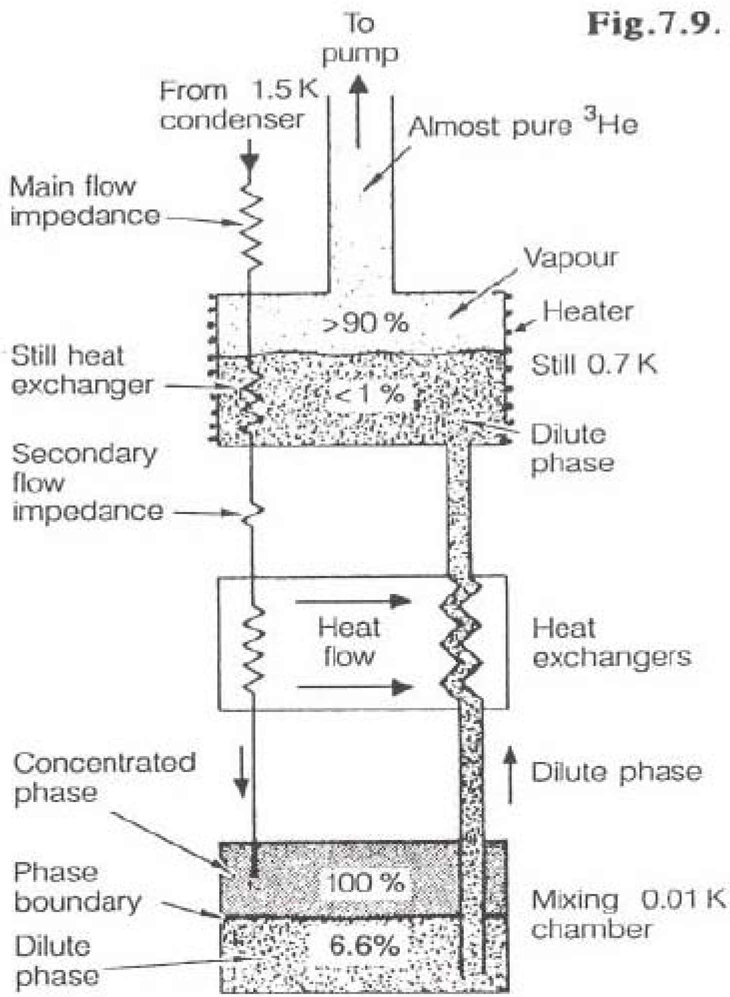

Fig.7.9. Sc

A Dilution Refridgerator

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