1.2 Phase Diagrams

Melting curve anomalies of ^{3}He and ^{4}He

Both isotopes show an unusual minimum in their melting curves for very different reasons

^{4}He: very shallow (hardly to see) minimum at 0.8 K because the phonon entropy is higher in the solid phase

^{3}He: pronounced minimum at 0.32 K because the nuclear spin entropy is higher in the solid phase

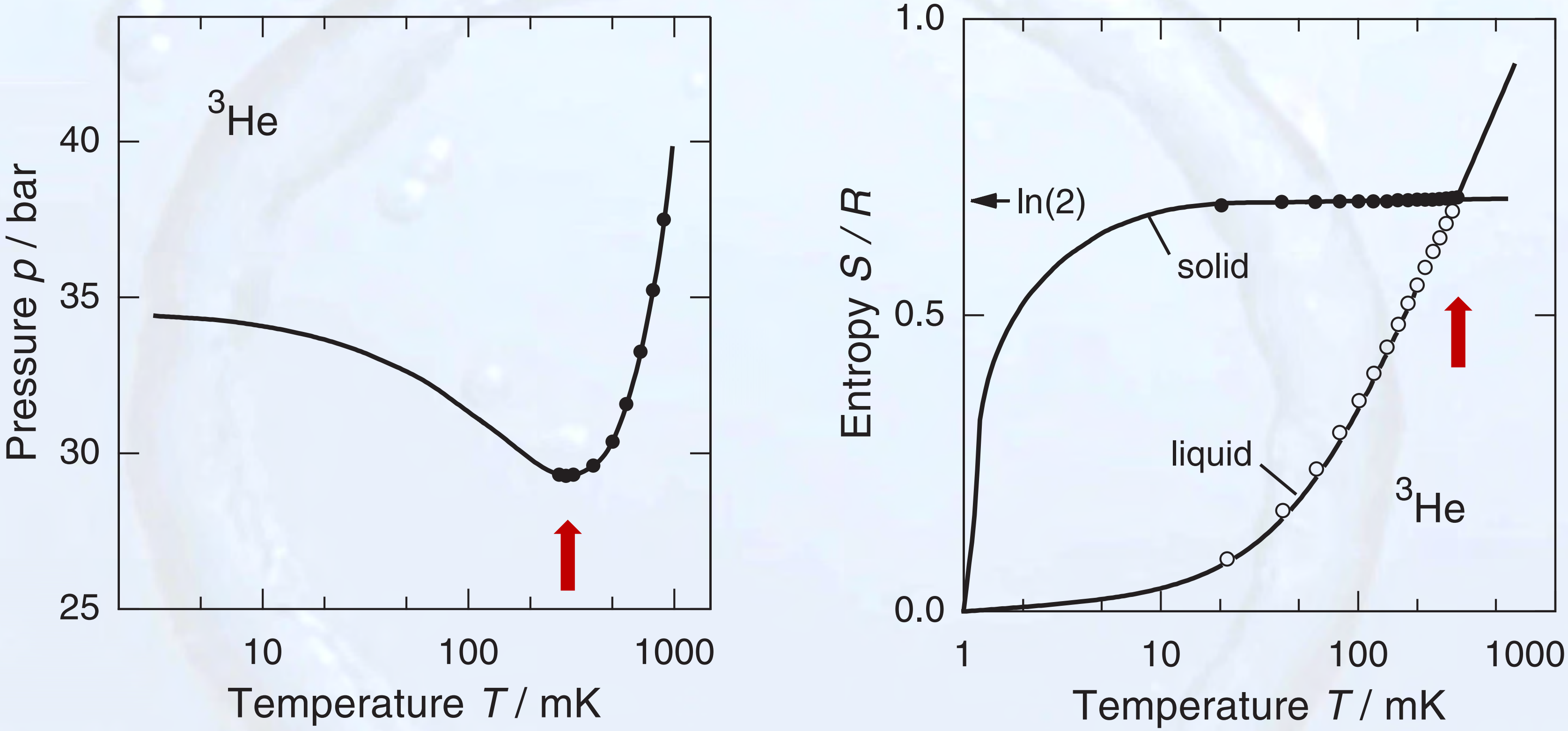
Clausius–Clapeyron equation

$$\left.\frac{\partial p}{\partial T}\right|_{\text{meltingcurve}} = \frac{S_\ell - S_\mathrm{s}}{V_\ell - V_\mathrm{s}}$$

If $V_\ell > V_\mathrm{s}$ and $S_\mathrm{s} > S_\ell$ the slope of the melting curve becomes negative

1.2 Phase Diagrams

Here the example of **^{3}He**



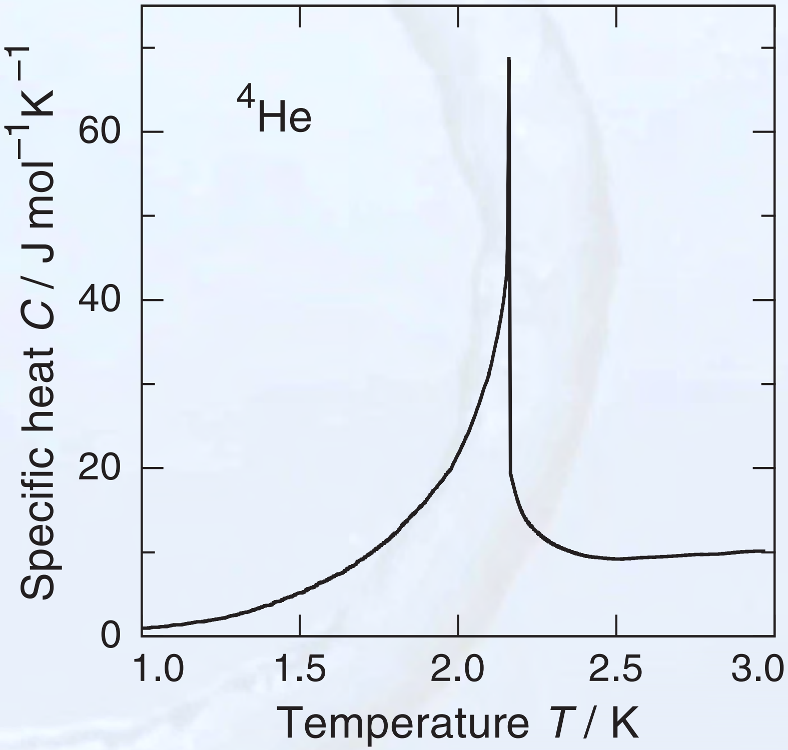
Liquid ^{3}He is a Landau liquid
more in Chapter 3

a) Specific heat

^{4}He: first measurements 1926 by Kamerlingh Onnes and Dana
(rise at T_λ neglected)
later Keesom and Clausius discovery of phase transition at T_λ at 2.17 K

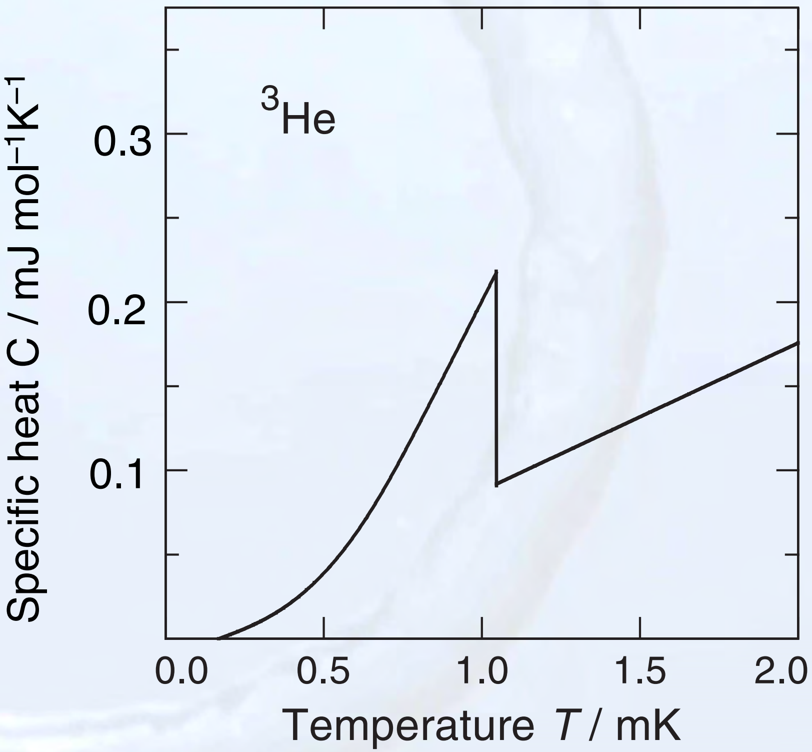
Explanation not before 1938:

first idea: new crystalline phase
Model of liquid crystal
but X-ray scattering results



1.3 Thermodynamic Properties

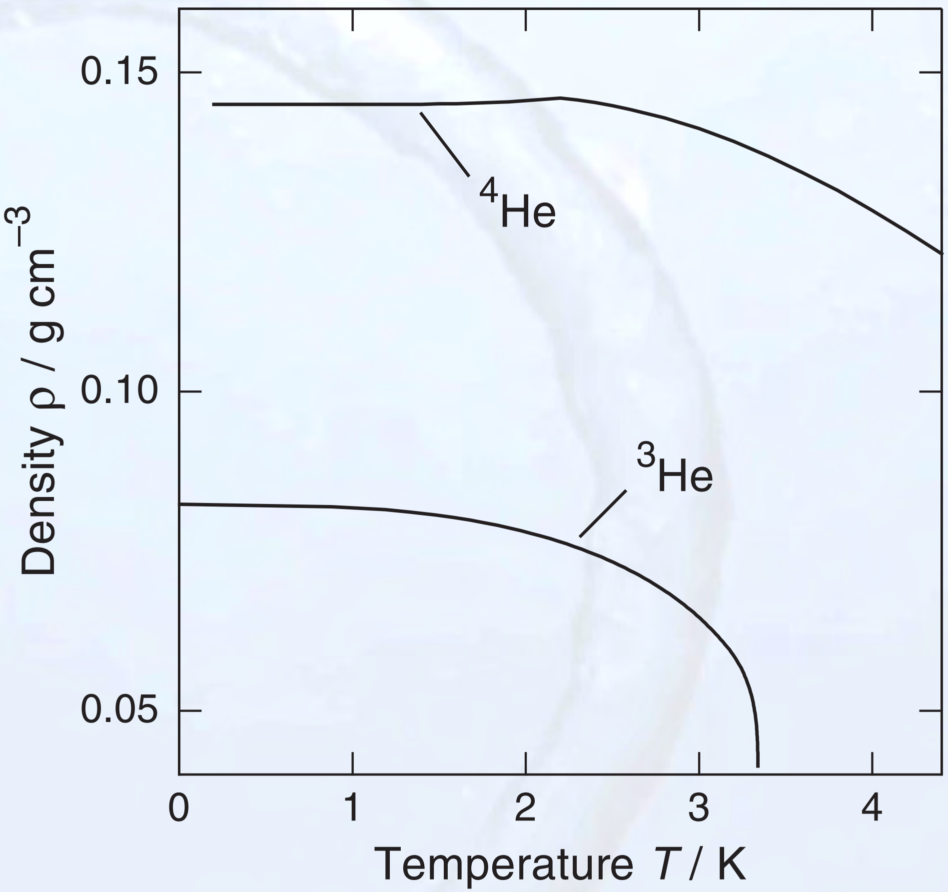
^{3}He: Discovery of phase transition with NMR by Richarson, Lee, Osheroff before specific heat measurements
(also wrong interpretation: phase transition in solid ^{3}He)



b) Density

^{4}He: maximum at T_λ

^{3}He: smooth monotone temperature dependence

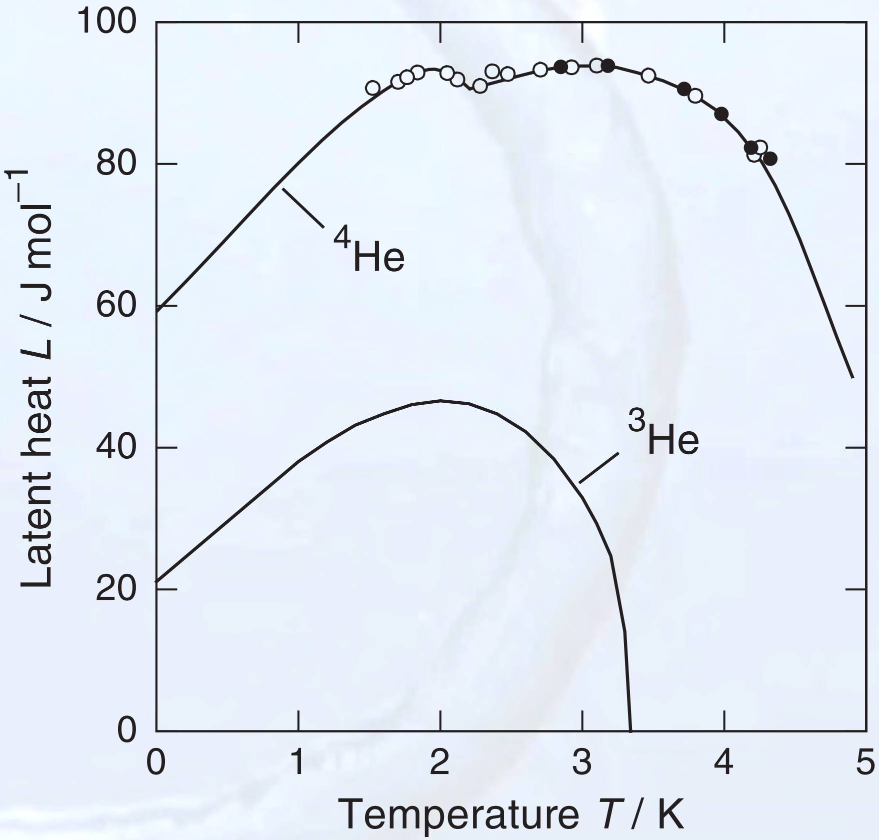


c) Latent heat

evaporation of helium
line: from vapor pressure measurement and Clausius-Claperyron equation

^{4}He: kink at T_λ

^{3}He: smooth temperature dependence



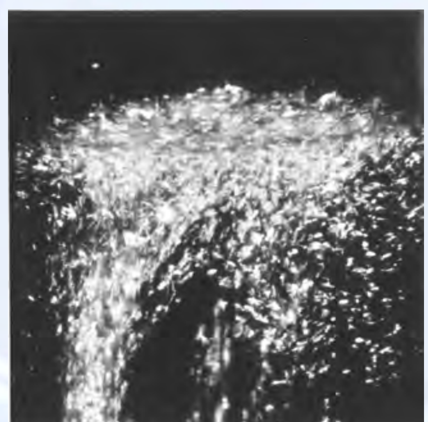
2.1 Experimental Observations

a) Boiling

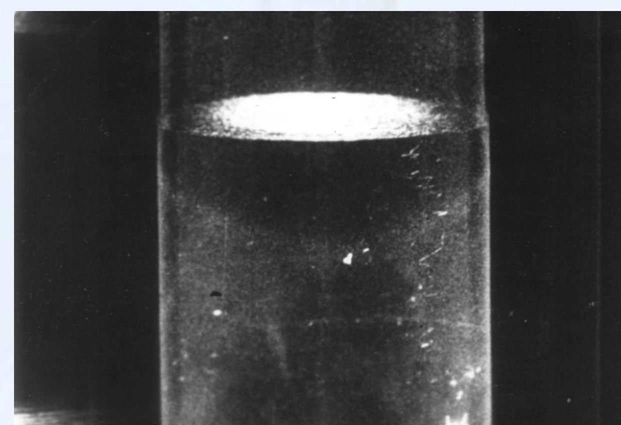
at boiling point: liquid ⟷ dense classical gas

at lambda point $T_\lambda = 2.17$ K boiling ceases abruptly!
transition from He-I to He-II

$T > T_\lambda$



$T \sim T_\lambda$

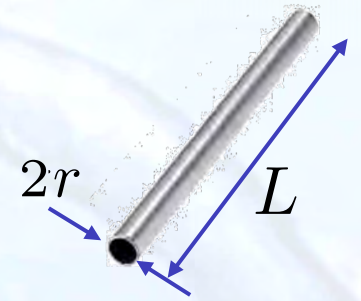


$T < T_\lambda$

2.1 Experimental Observations

b) Viscosity

measurement: flow through thin capillaries



Hagen-Poiseuille law

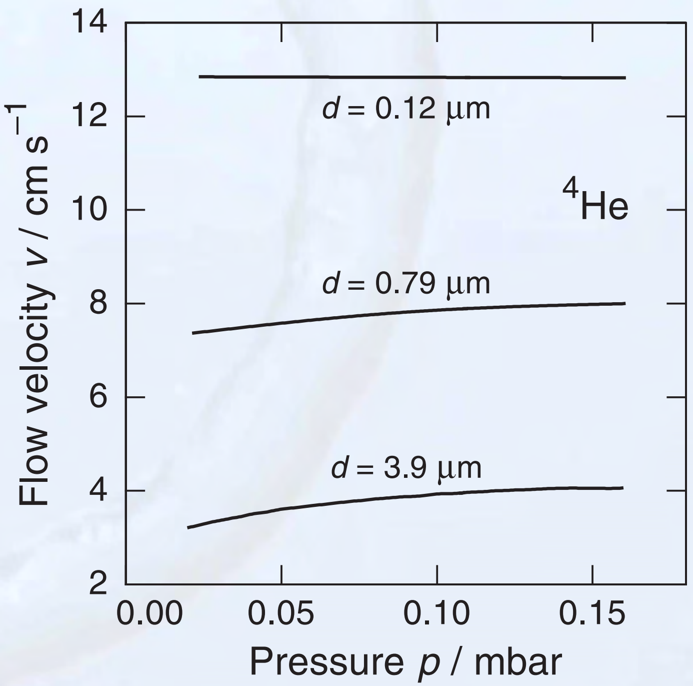
$$\dot{V} = \frac{\pi r^4}{8} \frac{1}{\eta} \frac{\Delta p}{L}$$

volume rate

viscosity

flow velocity $v = \dot{V}/(\pi r^2)$

$v \propto r^2 \Delta p$



Experimental results:

- ► v independent of pressure
- ► v increasing with decreasing diameter

Persistent Flow Experiments

Conclusion: $\eta_{\text{He-II}} < 10^{-3}\,\eta_{\text{He-I}} < 10^{-2}\,\eta_{H_2O}$

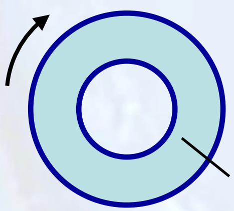
→ discovery of superfluidity 1938 — Kapitza; Allen, Misener

Question: $\eta_{\text{He-II}} = 0$?

→ persistent flow experiments 1965 — Reppy, Mehl; Zimmermann

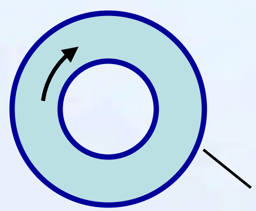
Torus with fine powder and He

$T > T_\lambda$ ⟶ $T < T_\lambda$



fine powder

rotation



slowly breaking, He-II rotates further

→ measurement of angular velocity

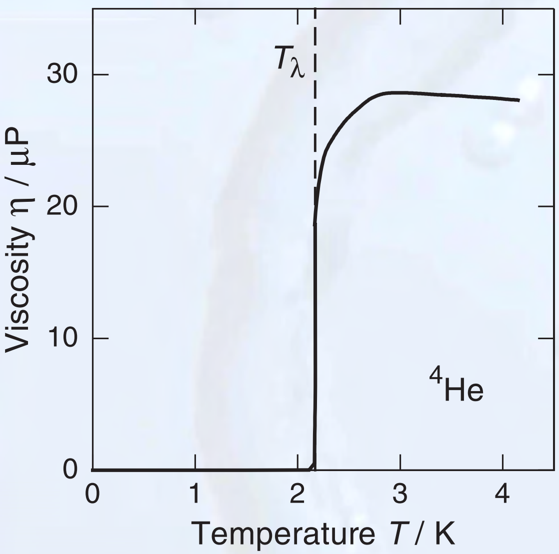
Results: angular velocity constant over many hours

$\eta_{\text{He-II}} < 10^{-11}\,\eta_{\text{He-I}}$ → $\eta_{\text{He-II}} \overset{!}{=} 0$ within measurement error

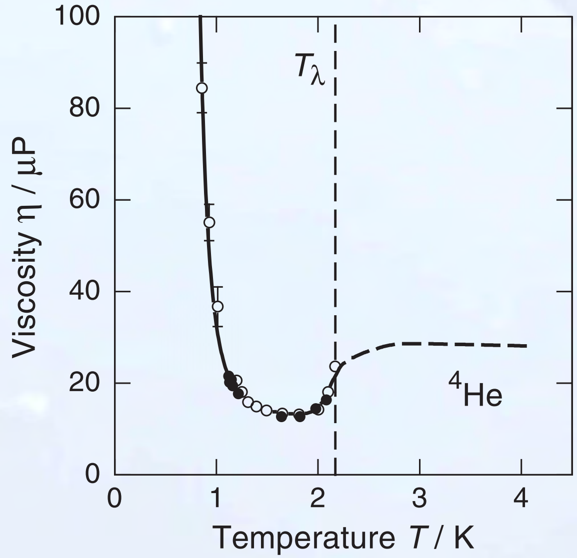
Temperature Dependence of Viscosity

Measurements with 3 standard methods

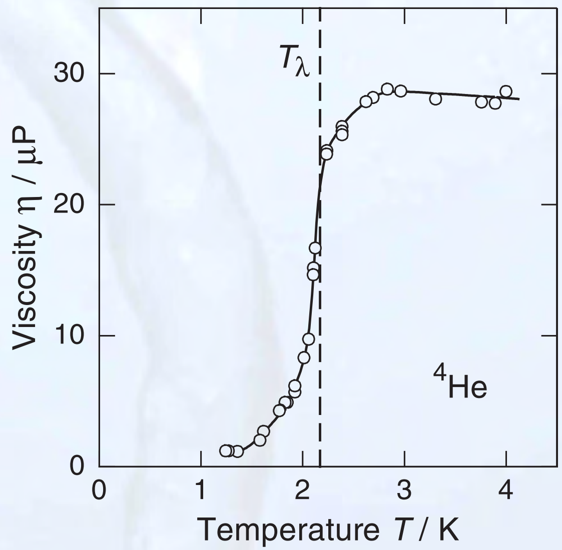
Capillaries, Slits



Rotary Viscosimeter



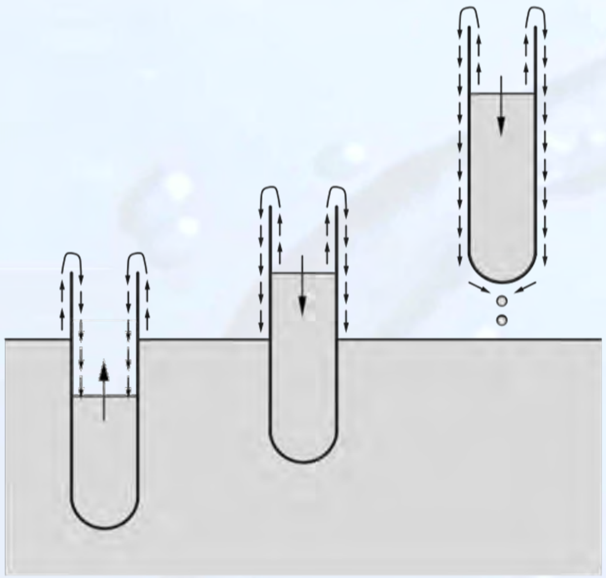
Oscillating Disc



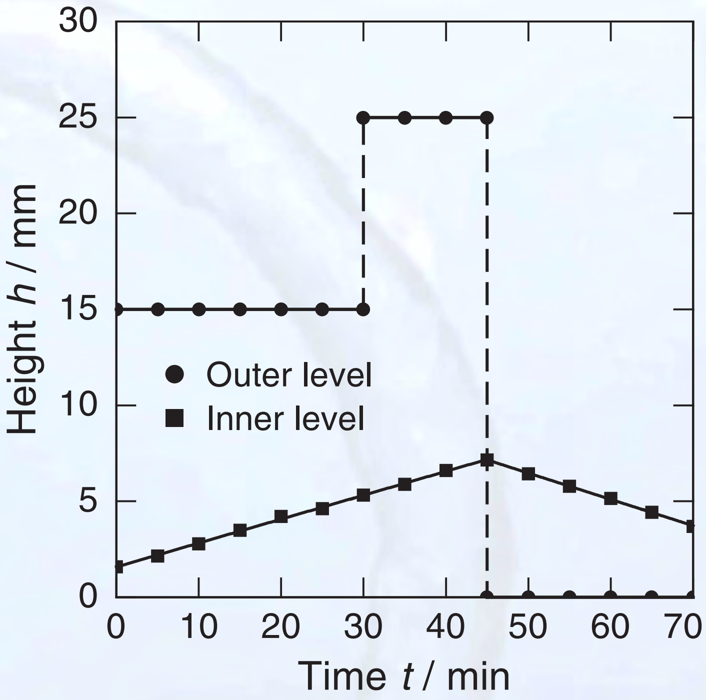
➡ results are seemingly completely inconsistent

1 Pa/s = 10 P (Poise)

c) Beaker Experiments

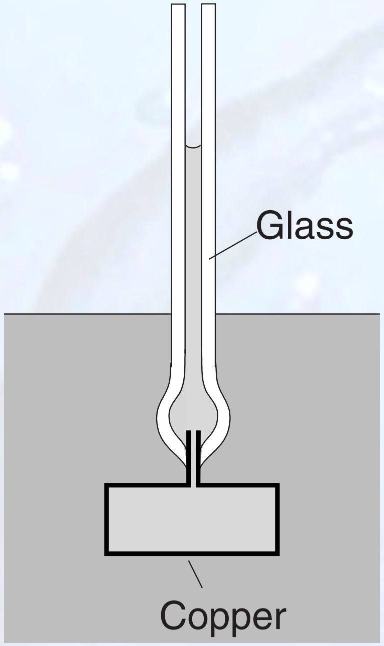


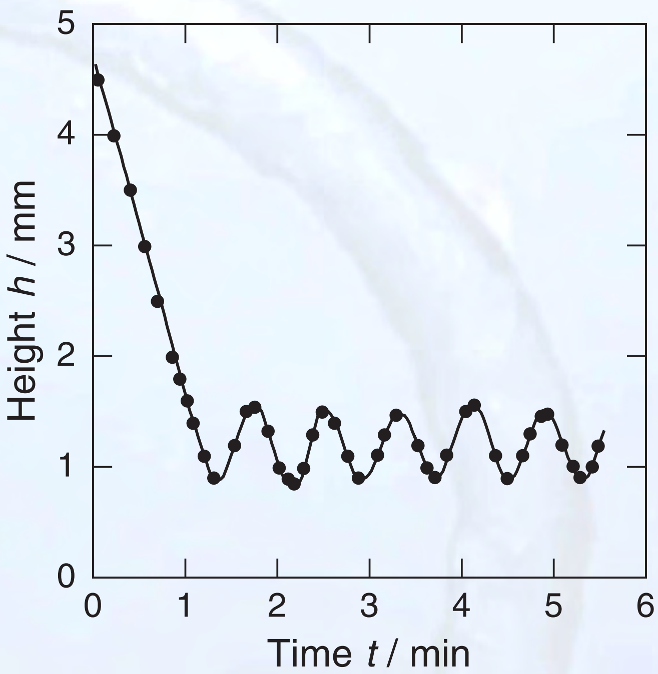
liquid level



- helium flows over the rim of beakers
- helium flows with constant rate independent of level difference
- flow can be reversed at equal rate

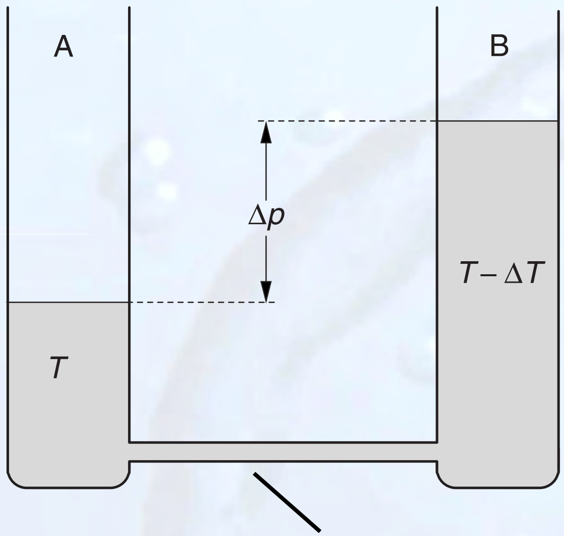
Detailed Beaker Experiments





- detailed measurement with thin neck ➡ small ΔV ➡ large Δh
- oscillations are observed when level equalizes ➡ not damped (in special cases)
  ➡ persistent flow

d) Thermomechanical Effect



Very thin capillary (super leak)

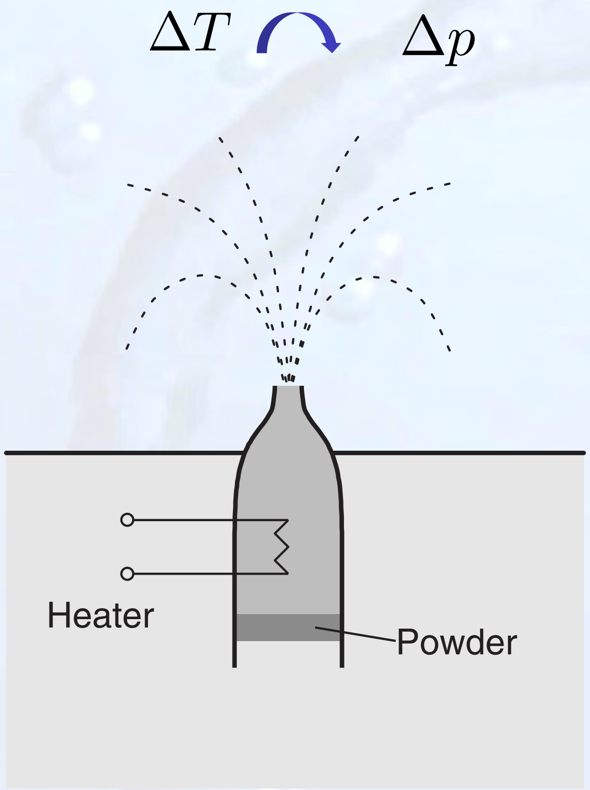
course of the experiment

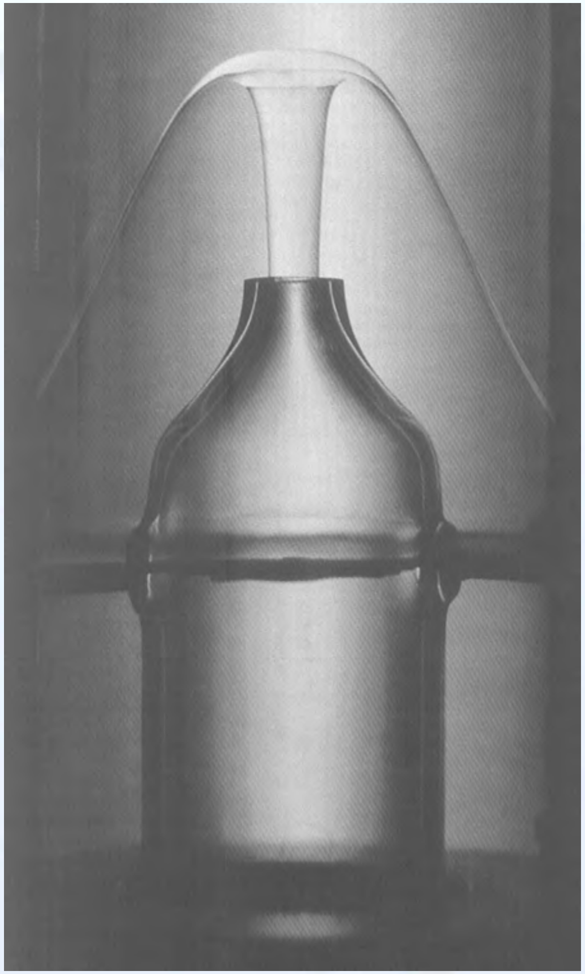
1. pressures and temperatures are equal
2. pressure increases in A
3. helium flows to B
4. temperature in A increases and drops in B

$$\rightarrow \Delta p \rightarrow T_A\uparrow, \; T_B\downarrow \rightarrow T_A > T_B$$

- ▶ Mass flow is connected with heat transport
- ▶ $\Delta p \curvearrowright \Delta T$, but heat flow is in opposite direction of mass flow

Reverse Experiment: Fountain-Effect





- heating of helium inside vessel ↷ helium shoots out at the top
- stationary heights up to 30 cm, have been observed!