Pressure-driven Flow in Solid ^{4}He

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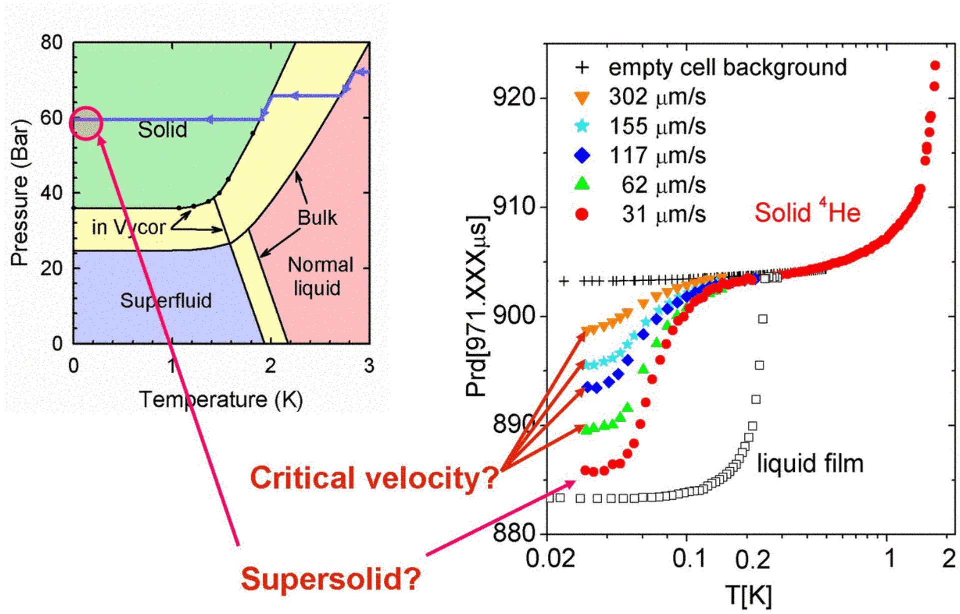
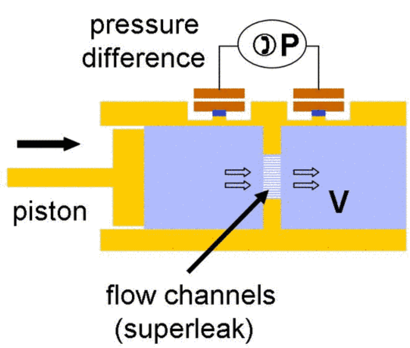
Outline

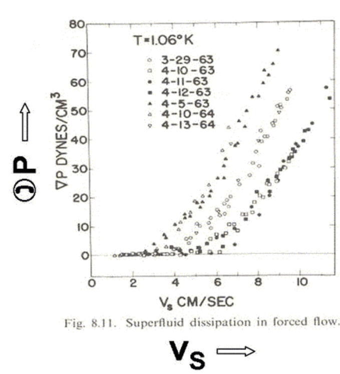
- solid ^{4}He in Vycor pores
- bulk solid ^{4}He
- deformation and annealing near T_m
- dislocations in solid helium

Kim and Chan: solid ^{4}He in Vycor



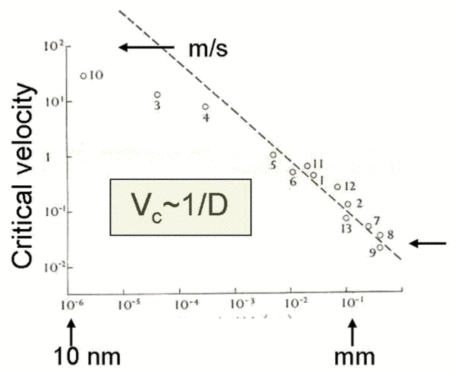
Pressure driven flow and critical velocity (superfluid)





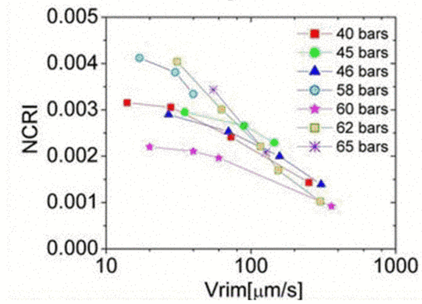
Critical velocities

Liquid ^4He



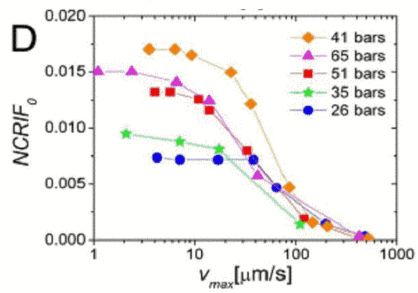
$V_c \sim 1/D$

Vycor



D~5 nm

Bulk solid ^4He



D~mm

$v_C \sim 10\ \mu m/s$ for both

Questions

^4He in Vycor:

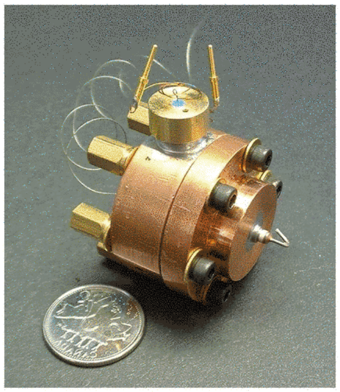
- Is all the helium frozen? Could the superfluidity be in a liquid layer?
- Could the torsional oscillator period change reflect a mass redistribution rather than superfluid decoupling?

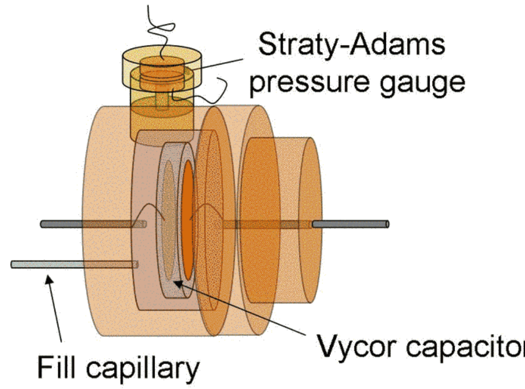
Bulk and confined ^4He:

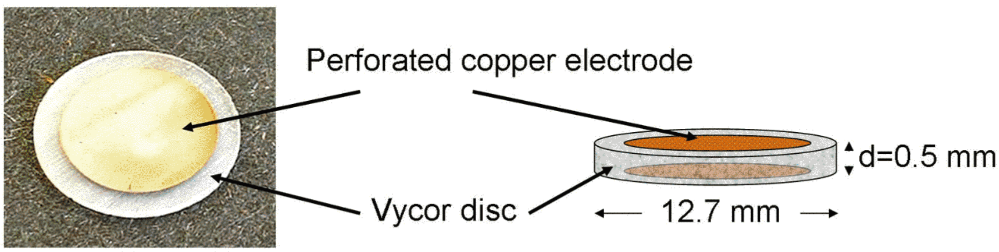
- How does solid helium flow in response to a pressure difference?
- Effects of ^3He impurities?
- Annealing and dislocations

Phys. Rev. Lett. **95** (2005): 035301
Phys. Rev Lett. (in press): condmat
LT24, ULT 2005

Vycor cell (solid ^4He density/pressure)







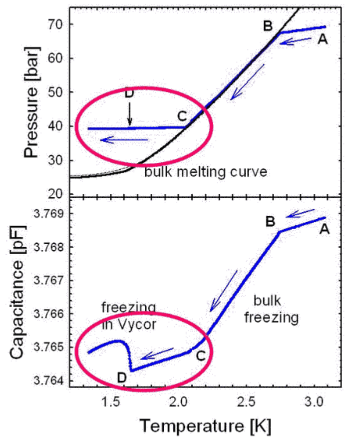
Capacitance as a Probe of Helium Density

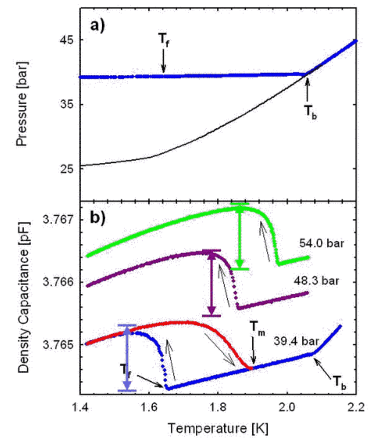
$$C_o = \varepsilon_o \frac{A}{d}$$ geometric capacitance

$$\Delta C = \phi(\varepsilon_{He} - 1)C_o$$ effect of helium in pores

$$(\varepsilon_{He} - 1) \propto \rho_{He} \quad \Rightarrow \quad \boxed{\Delta C \propto \rho_{He}}$$

Freezing at constant volume (blocked capillary)

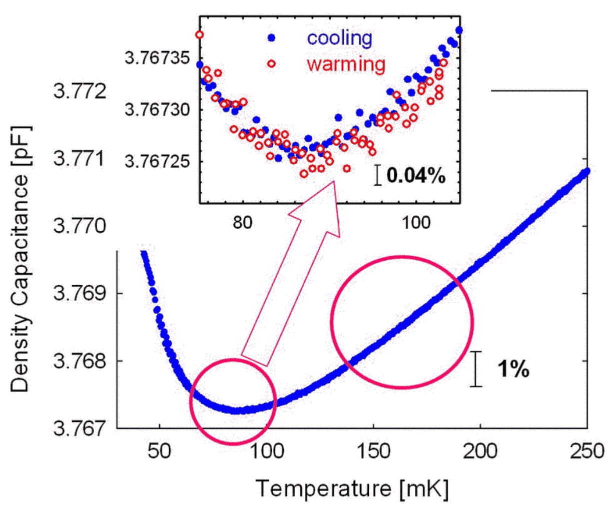




$\Delta\rho_{\textbf{liquid-solid}}$ ~ 2.8% (vs. 6% for bulk) ⇨ not all helium freezes?

$\Delta\rho$ independent of pressure (32 – 54 bar) ⇨ hard to freeze the rest? already solid?

Helium density change at low T?

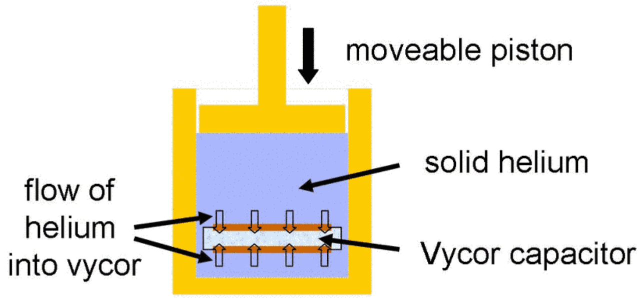


Density constant to < 0.04% (overnight cooling to 30 mK)

No sign of helium leaving the pores where torsional oscillator sees decoupling

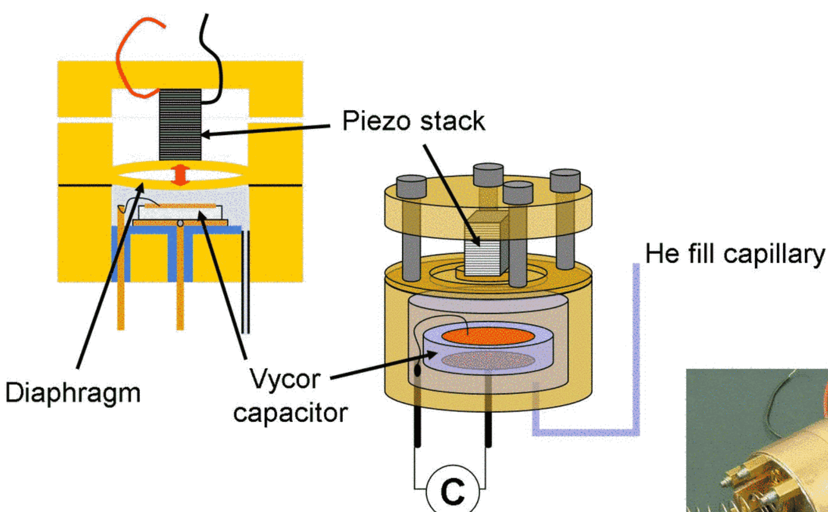
Torsional oscillator period shift **not** due to mass redistribution

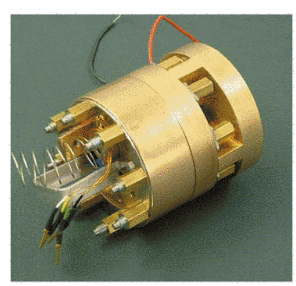
How does solid helium flow in Vycor?



1) Freeze helium in Vycor pores
2) Squeeze surrounding bulk solid helium
3) Look for flow into Vycor (change in helium density in pores)

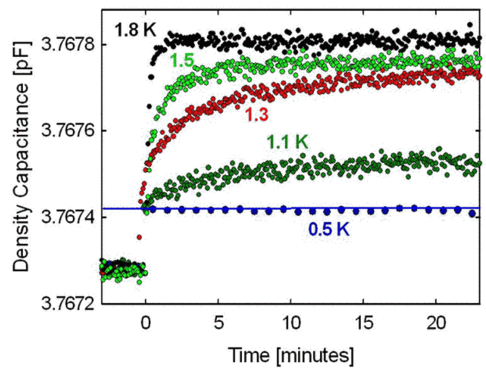
Vycor/solid He flow cell





Solid ^4He in Vycor (P=57 bar, T_F=2.05 K)

Response to a “squeeze” (~ bar)

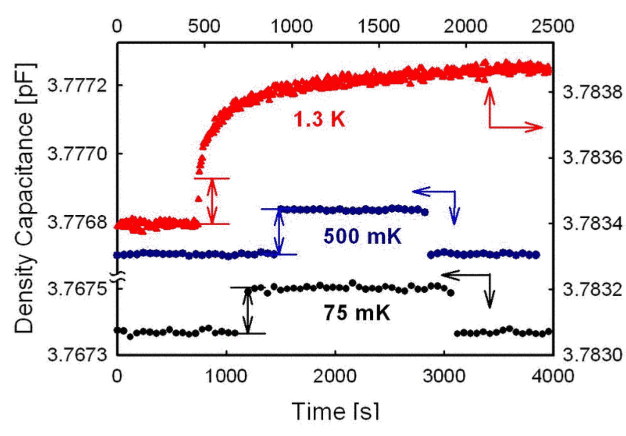


Immediate “elastic” C_V jump (~second) (compression of the Vycor)

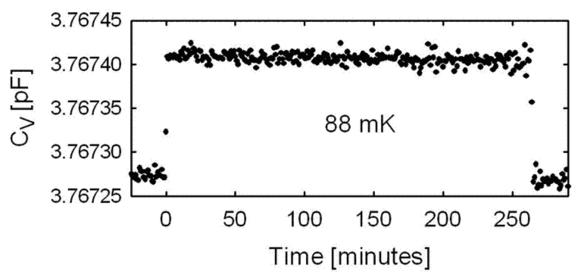
Subsequent slow (~seconds to hours) thermally activated flow ($U/k_B \sim 9$ K)

No flow (over hours) below ~700 mK

Is there any unusual flow below 200 mK (NCRI region)?



No flow down to 50 mK (just elastic compression)



Average flow: $v < 0.015$ nm/s

$v = (\rho_s/\rho)\, v_C \Rightarrow v_C < 3$ nm/s

(torsional oscillator $v_C \sim 10\ \mu$m/s)

Greywall solid ^4He flow experiment (1977)

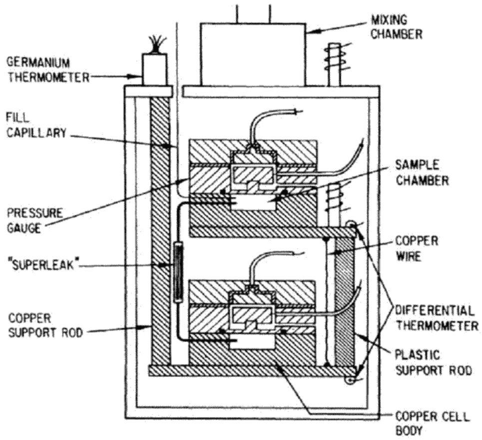


FIG. 1. Sample chambers.

25 capillaries (i.d. 200 μm)

pressure 25 – 50 bar

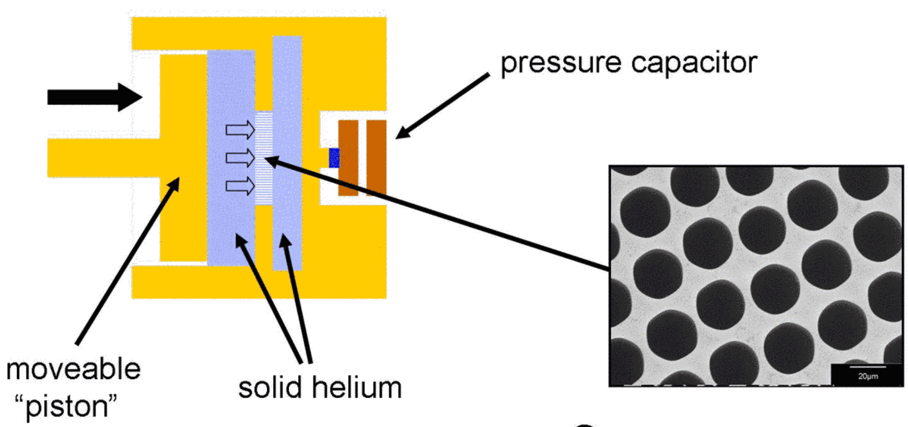
ΔP ~ bar (during freezing)

T > 30 mK

⇨ no flow (v < 0.025 nm/s)

⇨ $v_C = \left(\rho / \rho_S\right) v$ < 2.5 nm/s

Solid helium flow through capillaries



Glass **C**apillary **A**rray (GCA):

36,000 holes
25 μm diameter
3 mm long

Helium: natural composition (0.3 ppm ^3He)

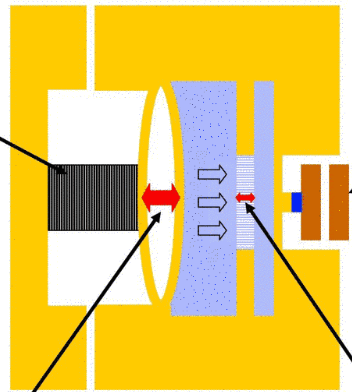
isotopically pure (**0.002 ppm ^3He**)

Solid helium flow cell

Analogous experiments by Dyumin, Grigor'ev et al. near melting (1990's)

PZT stack

pressure capacitor

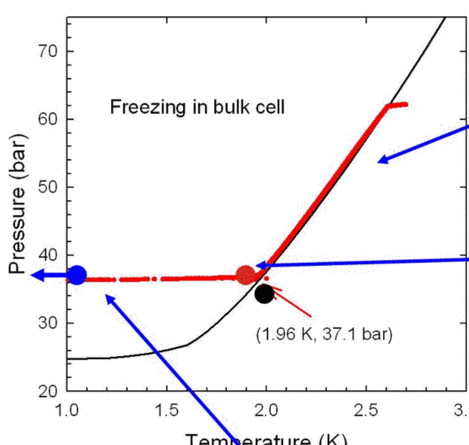


$\delta P \sim 0.2$ mbar ⇨ $\delta x \sim 0.3$ nm

Diaphragm (squeeze): $\Delta X \sim 1\ \mu m$ ⇨ $\Delta P \sim 0.1$ bar

GCA flex: $\Delta P \sim 0.1$ bar ⇨ $\Delta x \sim 30$ nm

Thermodynamic path for bulk freezing



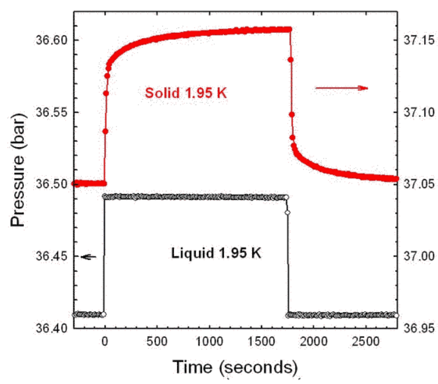
Freeze at constant volume (blocked capillary)

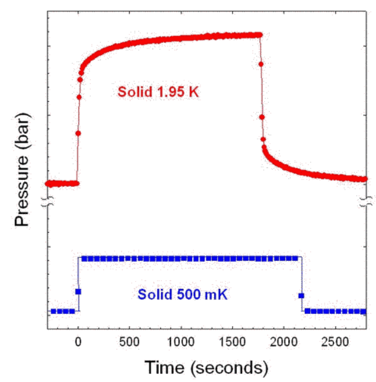
Anneal for a few hours just below freezing (T_m = 1.96 K)

Cool to low temperature (pressure 36.6 bar)

Squeezing ^4He through 25 μm channels

Squeeze: $\Delta x \sim 1$ μm ⇨ $\Delta P \sim 0.1$ bar ⇨ GCA flex: $\delta x \sim 30$ nm





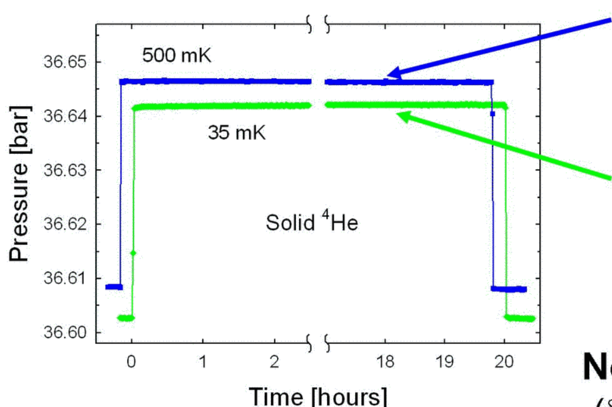
liquid flows "instantly"
(in fraction of a second)

near melting, solid flows easily
(in about half an hour)

no solid flow at T < 1 K

Does the solid flow in the supersolid phase?

Isotopically pure ^4He (0.002 ppm ^3He)

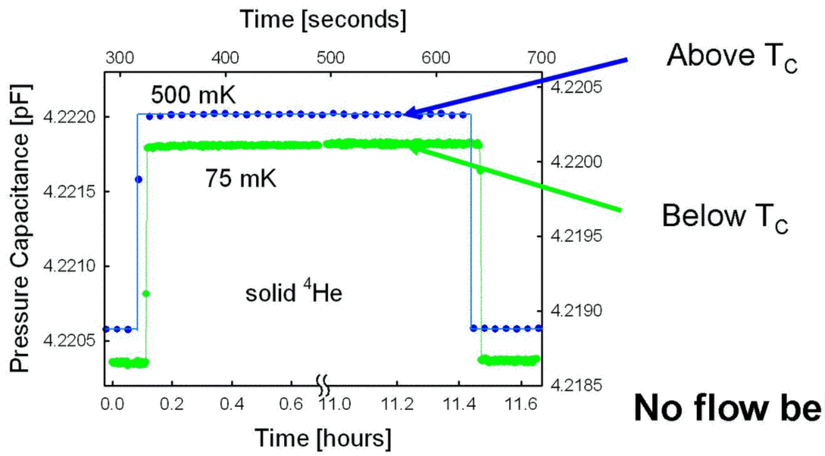


Above T_C

Below T_C

No onset of flow below T_C
($\delta x < 0.7$ nm in 20 hours)

Natural isotopic composition (0.3 ppm ^3He)

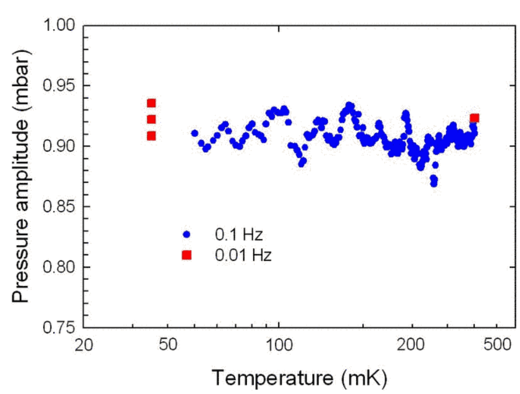


No flow below T_C

AC vs. DC flow?

frequency < 1 Hz

ΔP_{AC} ~ 4 mbar



no change in AC displacement

δx < 0.03 nm

no AC flow at low T

Pressure/flow measurements

DC ΔP (100 mbar) ⇨ no flow

Natural / isotopically pure ^4He ⇨ no flow

small ΔP (1 mbar) ⇨ no flow

AC ΔP (0.01 – 0.5 Hz) ⇨ no flow

Limits on flow of solid helium at low T

System	torsional oscillator		upper limits from flow	
	ρ_S/ρ	v_c	v	$v_C = \left(\rho/\rho_S\right) v$
^4He/Vycor	0.5%	~10 μ/s	<0.015 nm/s	< 3 nm/s
bulk ^4He	1.5%	~10 μ/s	$<10^{-5}$ nm/s	$< 10^{-3}$ nm/s

10^7

Solid ^{4}He at low temperatures does **not** respond to pressure the way a superfluid does

Questions:

- does a supersolid have to respond to pressure?
- are there “weak links” or blocks in our channels?
- role of crystal growth and annealing?
- role of ^{3}He impurities at ppb concentrations?

Does a supersolid have to respond to pressure?

Pressure difference $\Leftrightarrow$ chemical potential difference

Thermal vacancies flow in pressure gradient

(concentration gradient $\Rightarrow$ diffusion)

Gradient in commensurability (ZPV) $\Rightarrow$ flow?

Are there "weak links" or blocks in our channels?

Torsional oscillator ⇨ internally connected over ~ cm

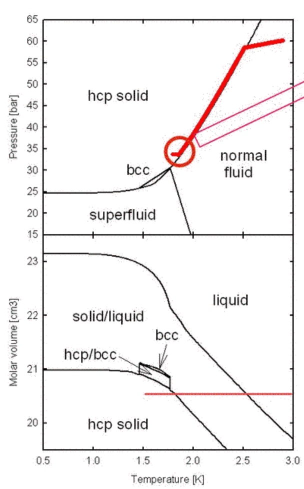
⇨ blocking at pore/channel ends?

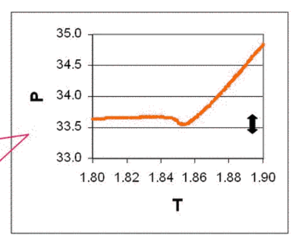
But: thermally activated flow occurs near T_m

25 µm channels are pretty macroscopic

Role of crystal growth and annealing?

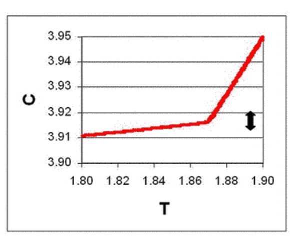
Blocked capillary





ΔP ~ 100 mbar

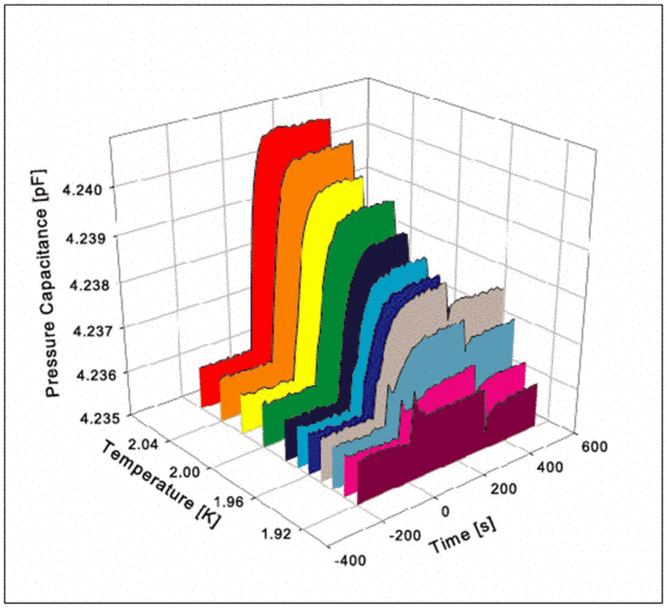
Initial freezing



ΔP < 10 mbar

Warming after annealing

Plastic deformation, annealing near melting (T_m = 2.06 K)



(T_m – T) ~ 20 mK

⇨ ΔP anneals

(T_m – T) ~ 100 mK

⇨ ΔP remains (~ 50 mbar)

⇨ response depends on history

Dislocations in helium

- created during growth or (in hcp ^{4}He) by plastic deformation
- **some** dislocations can be annealed at high T (e.g. by vacancy motion)
- dislocations form stable networks, pinned at nodes
- move easily in response to stresses (flow, sound …)
- slip system is edge dislocations gliding in basal plane of hcp lattice
- motion becomes undamped at low temperature ($B \sim T^3$)
- ^{3}He binding $E_B \sim 0.3 – 0.7$ K (impurities “evaporate” at high T)
- pinned by ^{3}He at ppm concentrations (even ppb?) at low T
- “stress-induced” breakaway from ^{3}He gives amplitude dependence

Dislocations in helium

Typical parameters: $\Lambda \sim 10^6$ /cm^2 (grown at constant pressure)

$\sim 10^9$ /cm^2 (near melting, or "bad" crystals)

L ~ 10 μm (f_c ~ Mhz)

^{3}He impurities: diffusion time (10 μm to dislocation) ~

1 ppb ^{3}He and $\Lambda = 10^6$ /cm^2 $\Rightarrow$ D ~ 0.3 nm