The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

1959-5

Workshop on Supersolid 2008

18 - 22 August 2008

Observation of mass flux through solid helium

R. Hallock

University of Massachusetts Amherst, USA

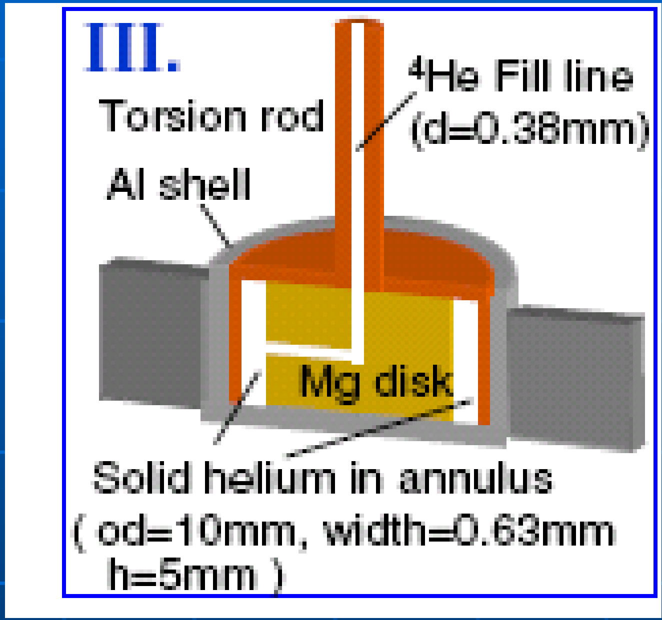
Observation of Mass Flux through Solid ^{4}He off the Melting Curve*.

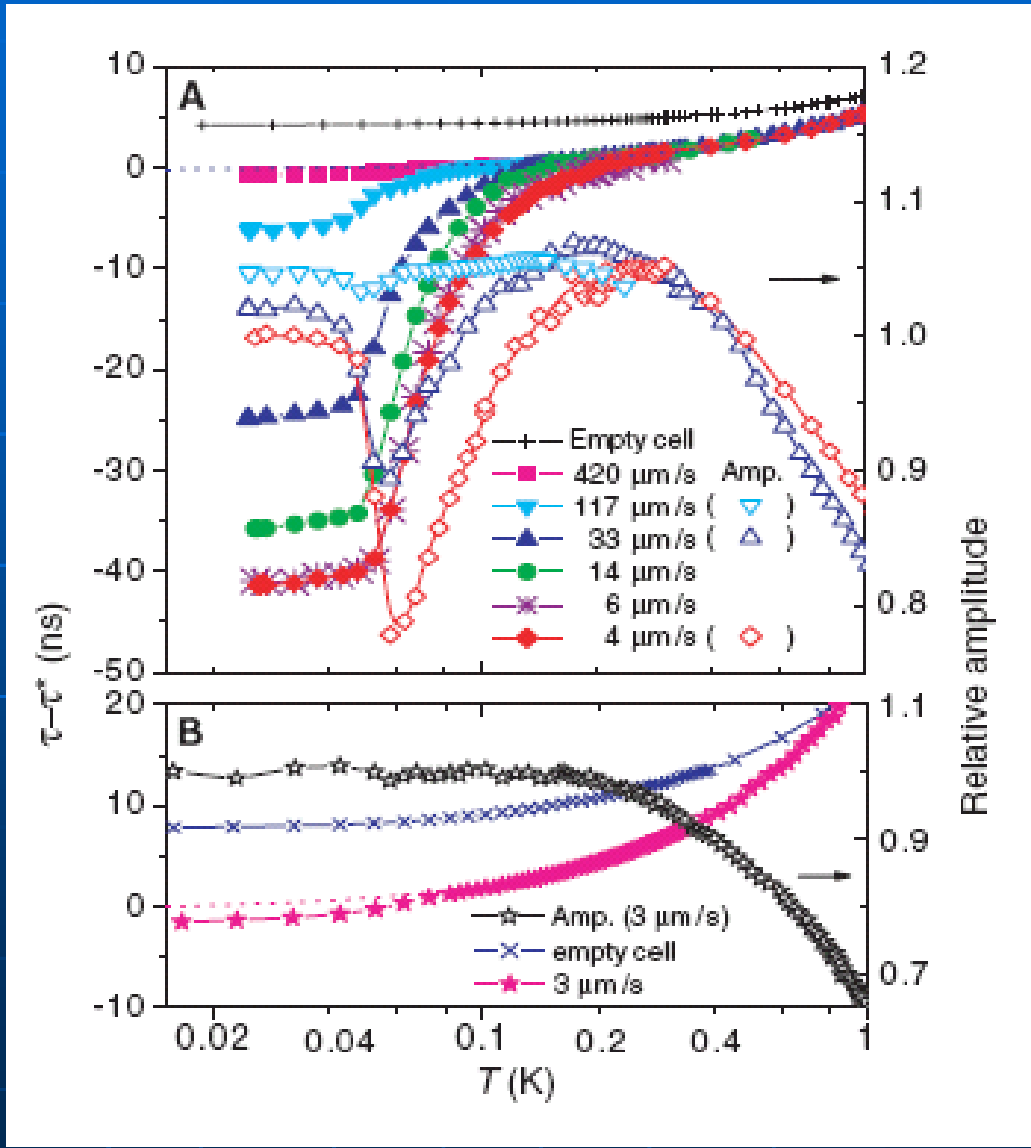
M.W. Ray and R.B. Hallock

Laboratory for Low Temperature Physics,
Department of Physics,
University of Massachusetts, Amherst, MA, USA

* Supported by the National Science Foundation, the CRDF and Research trust funds from the University of Massachusetts Amherst.

Following the work by John Goodkind's group, considerable renewed interest in solid ^{4}He was stimulated by Kim and Chan*.



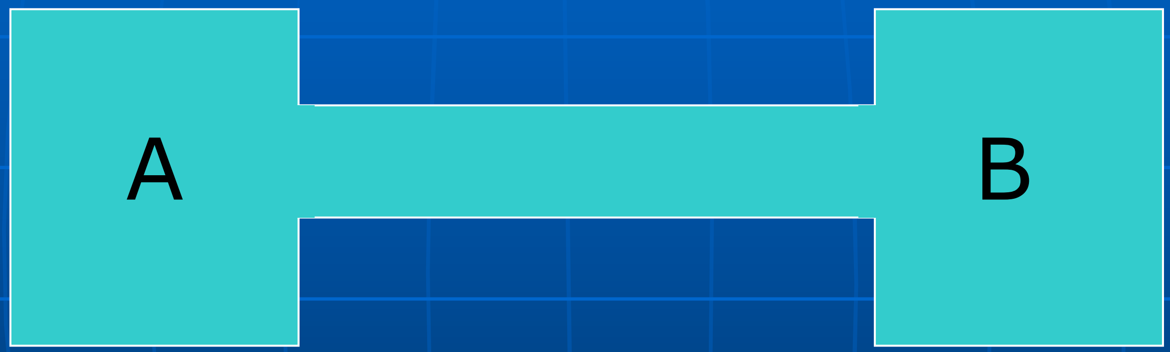


Observed period shift was interpreted as the observation of NCRI.

* Nature 427, 225 (2004); Science 305, 1941 (2004)

Is it possible to cause solid helium to flow?

The basic conceptual design of the experiments by Greywall (1977) and by Day and Beamish (2005,6)*:



Squeeze the solid directly (off the melting curve):
E.g., increase the pressure in A and see no change in B.

→ no flow.

*Greywall: Phys. Rev. B 16, 1291 (1977);
Beamish group: Phys. Rev. Lett. 95, 035301 (2005); Phys. Rev. Lett. 96, 105304 (2006)

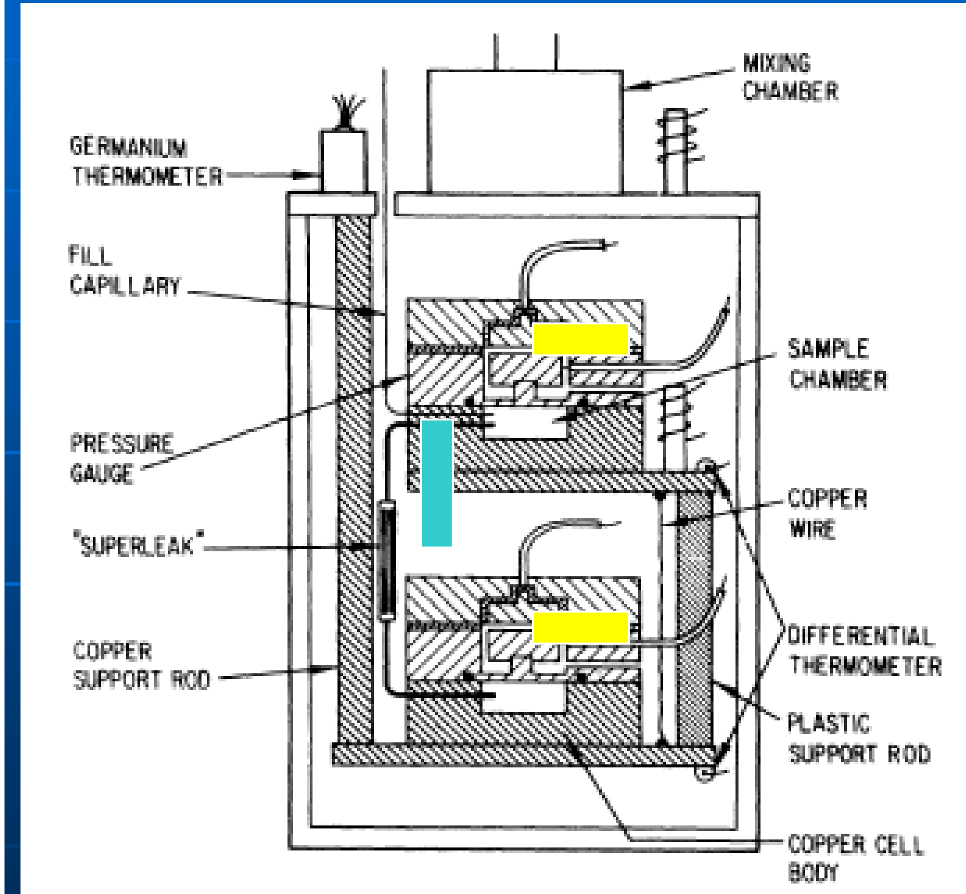
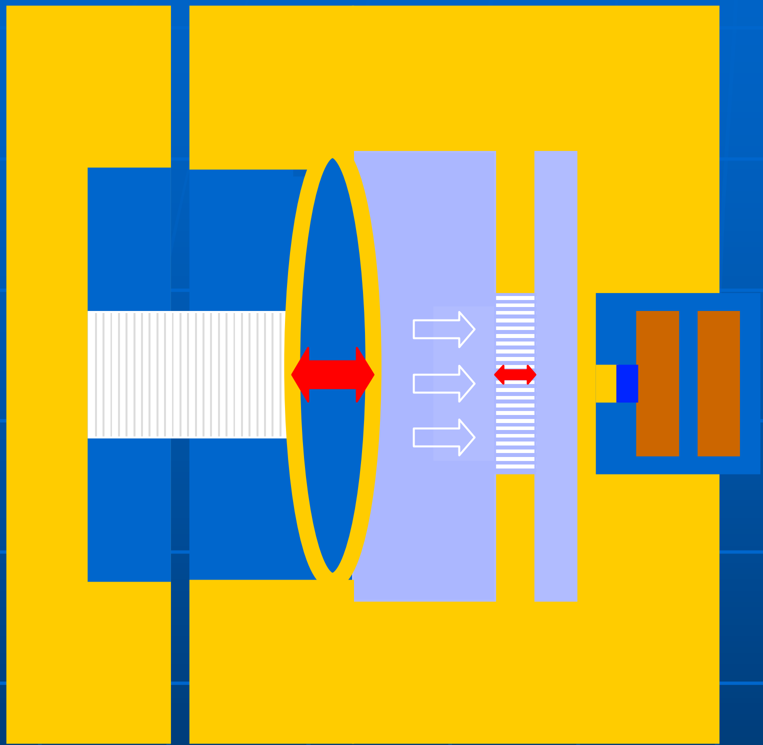
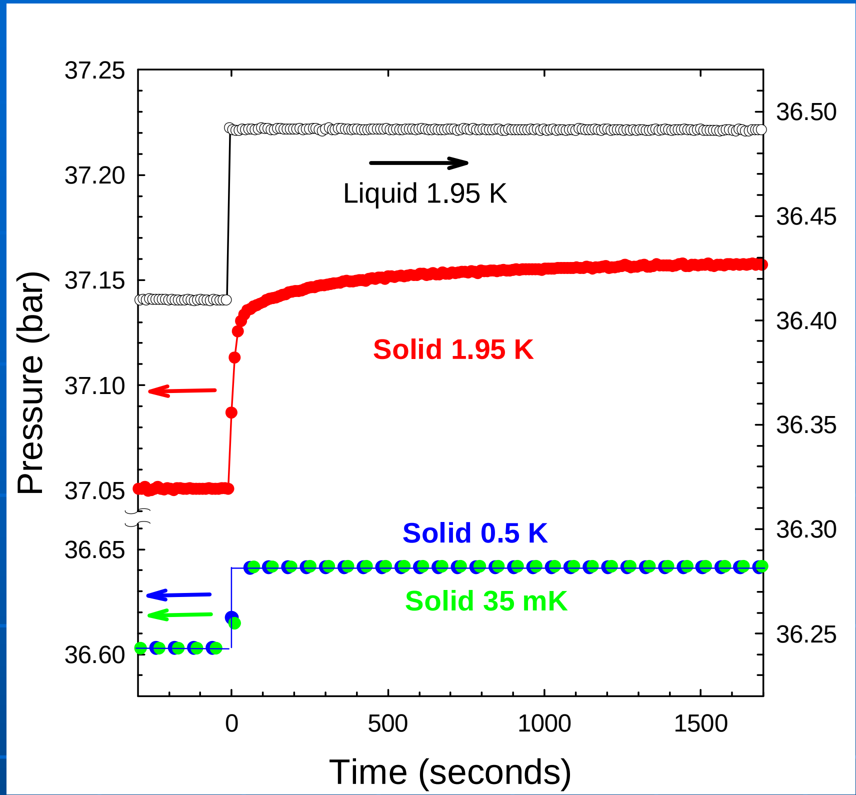


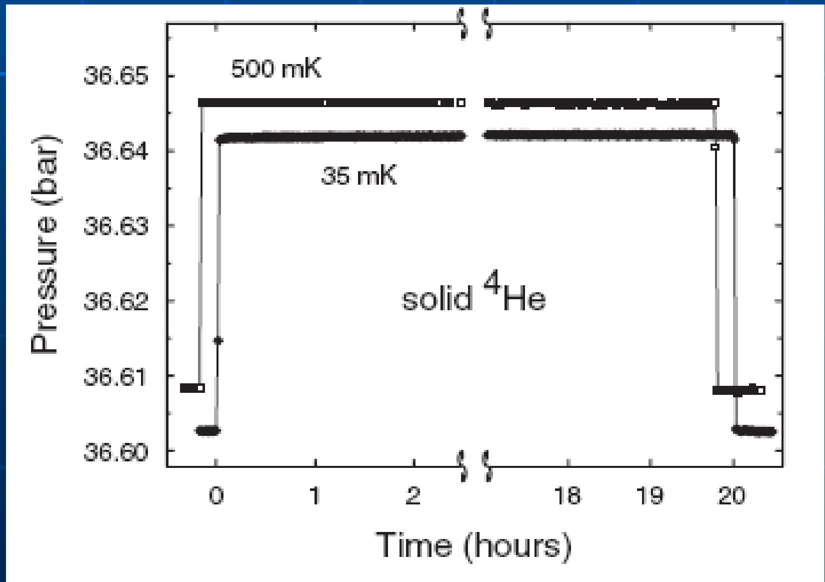
TABLE I. Pressure in the top and bottom cells for each of the five samples.

Sample	P_{bottom} (bar)	$P_{bottom}-P_{top}$ (bar)
1	25.77	−1.25
2	27.98	0.24
3	32.79	1.21
4	38.48	1.37
5	49.16	−2.12

Greywall, Phys. Rev. B 16 1291 (1977)

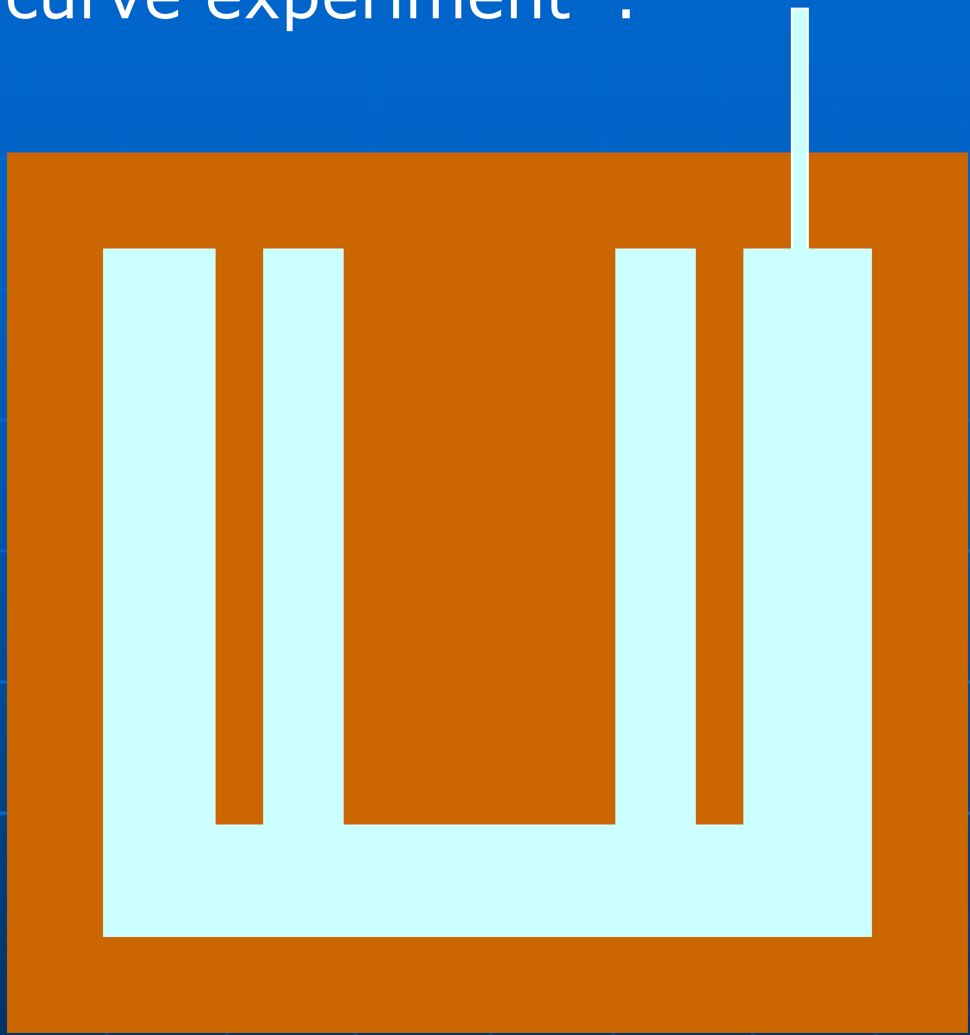




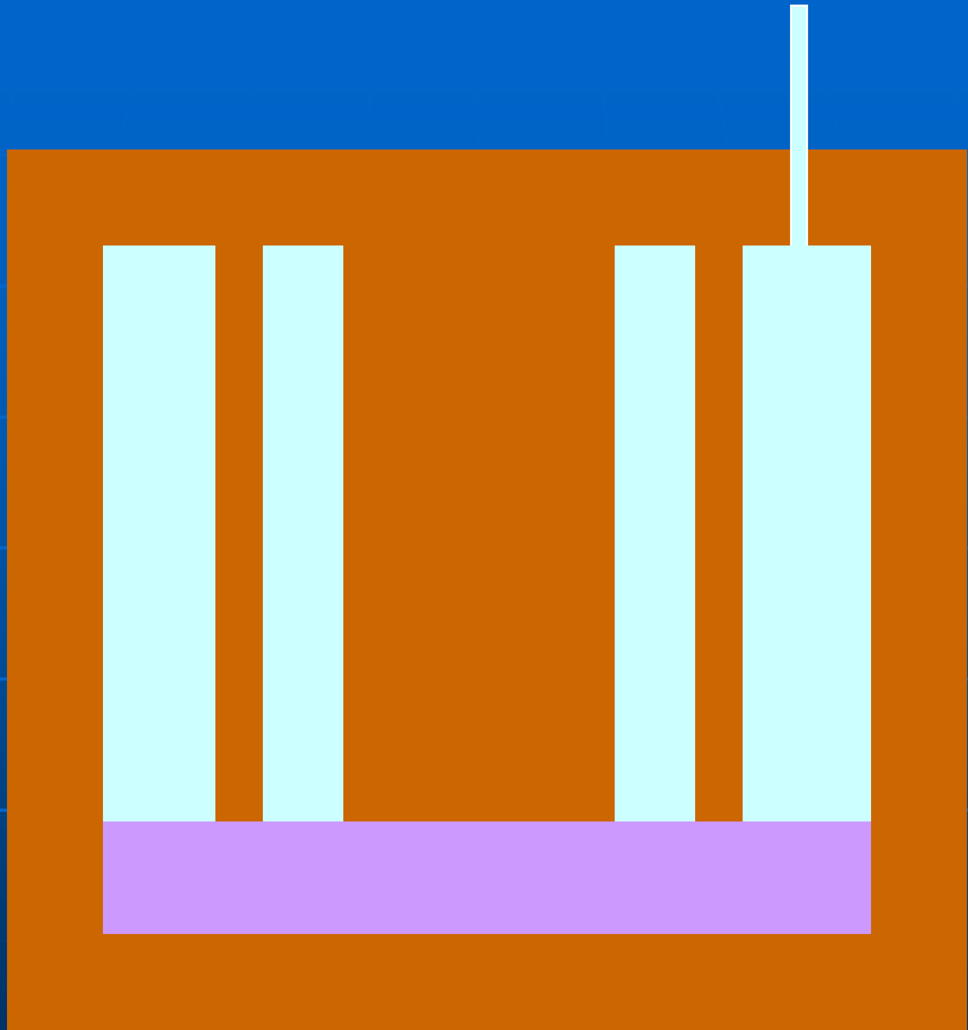


Images and data set provided, thanks to John Beamish (Minnesota Workshop, 2007)

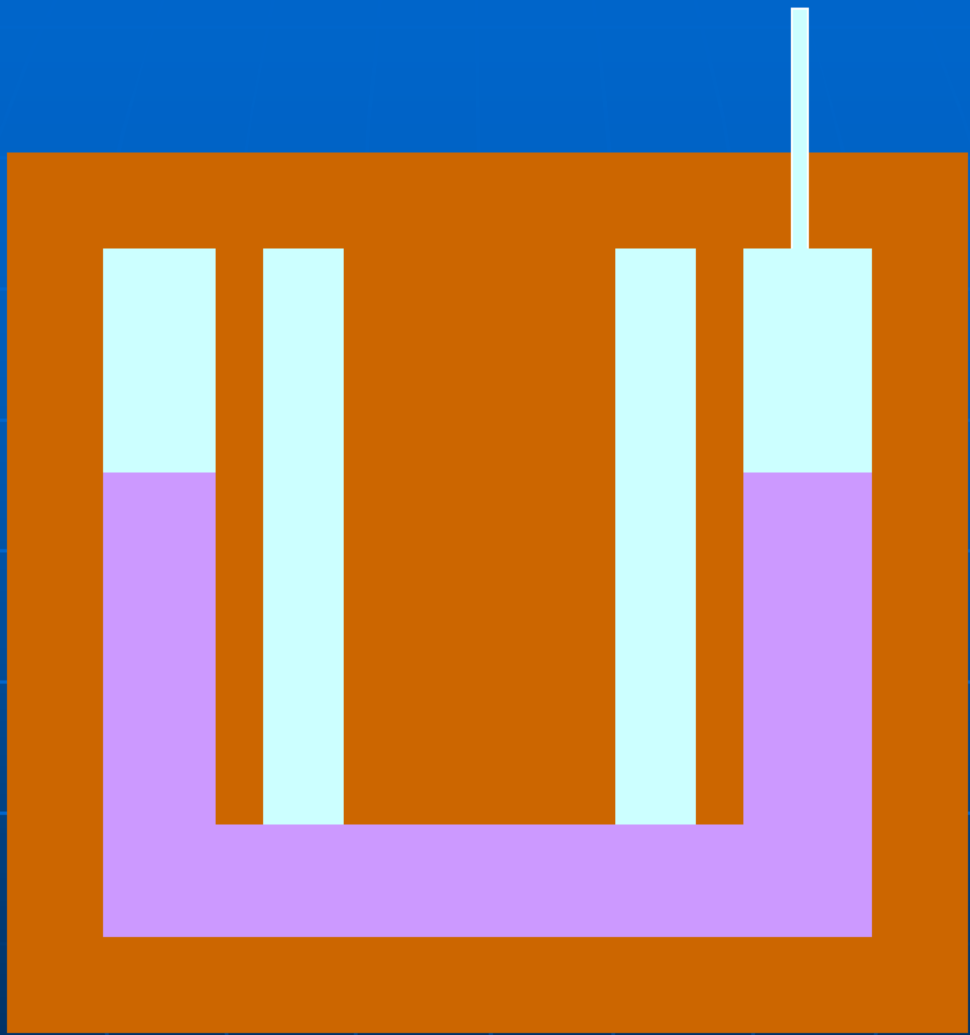
A melting curve experiment*:



*Bonfait et al., J. Phys (Paris) 50, 1997 (1989)



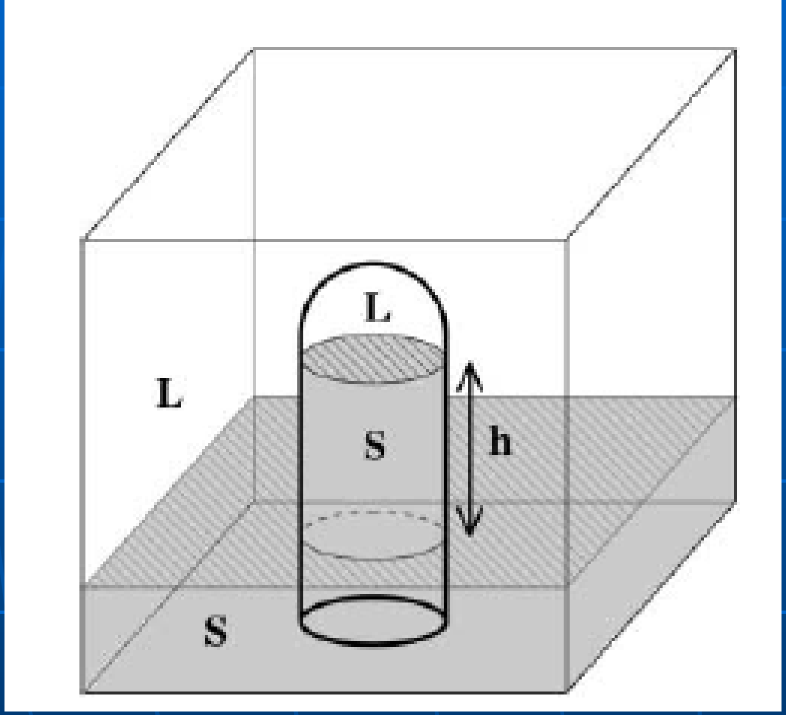
Bonfait et al., J. Phys (Paris) 50, 1997 (1989)

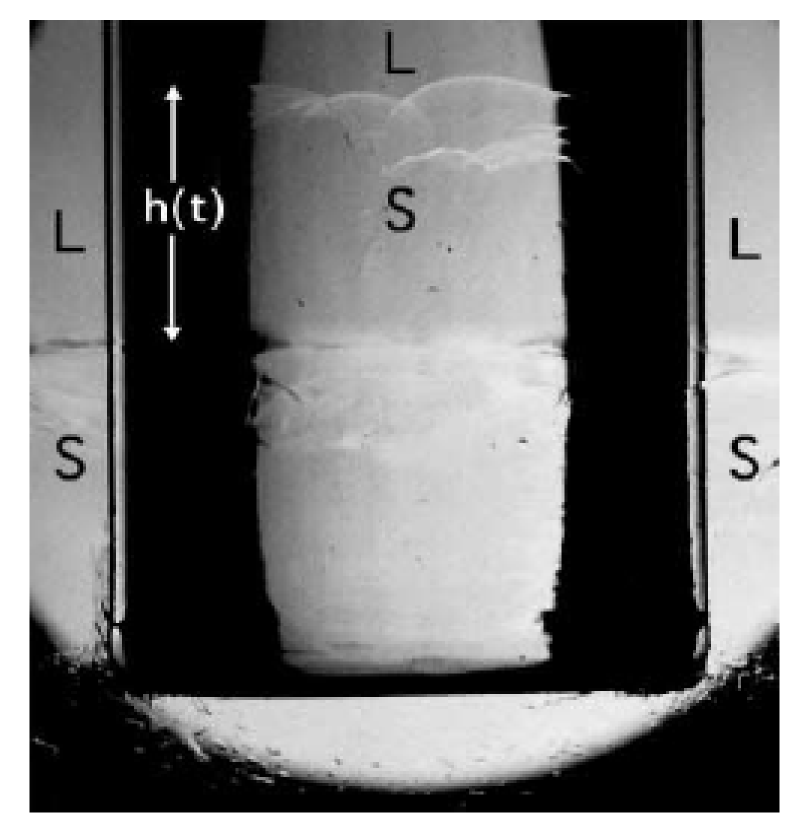


→ No Flow

Bonfait et al., J. Phys (Paris) 50, 1997 (1989)

Some more melting curve experiments*:





Flow observed,
but later interpreted as due to liquid channels.

*Sasaki, et al. Science 313, 1098 (2006); Phys. Rev. Lett. 99, 205302 (2007)

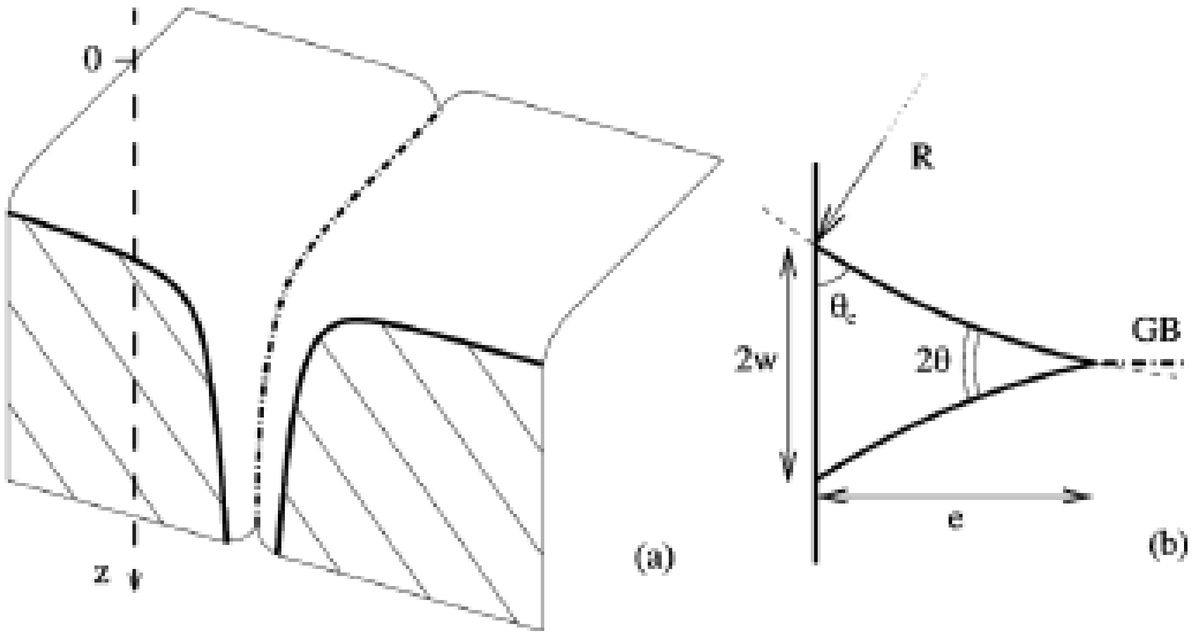
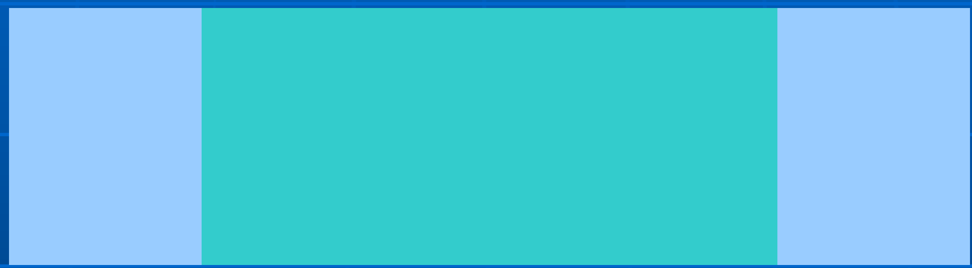


FIG. 3. (a) Three-dimensional view of the contact between a grain boundary (dash-dotted line) and a wall. The hatched area shows the contact of the wall with the solid. (b) Horizontal cross section of the liquid channel near the wall.

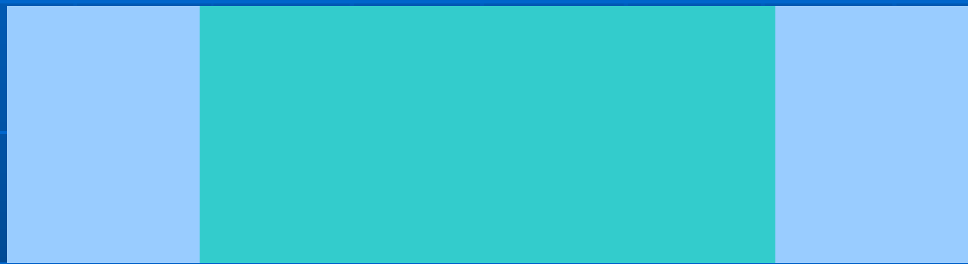
Grains may also meet in the absence of walls to form liquid channels.

Sasaki, et al. Phys. Rev. Lett. 99, 205302 (2007)

Our Conceptual Design: Do not squeeze the lattice, but, apply a chemical potential difference by applying pressure to superfluid helium in contact with the solid.



Our Conceptual Design: Do not squeeze the lattice, but, apply a chemical potential difference by applying pressure to superfluid helium in contact with the solid.



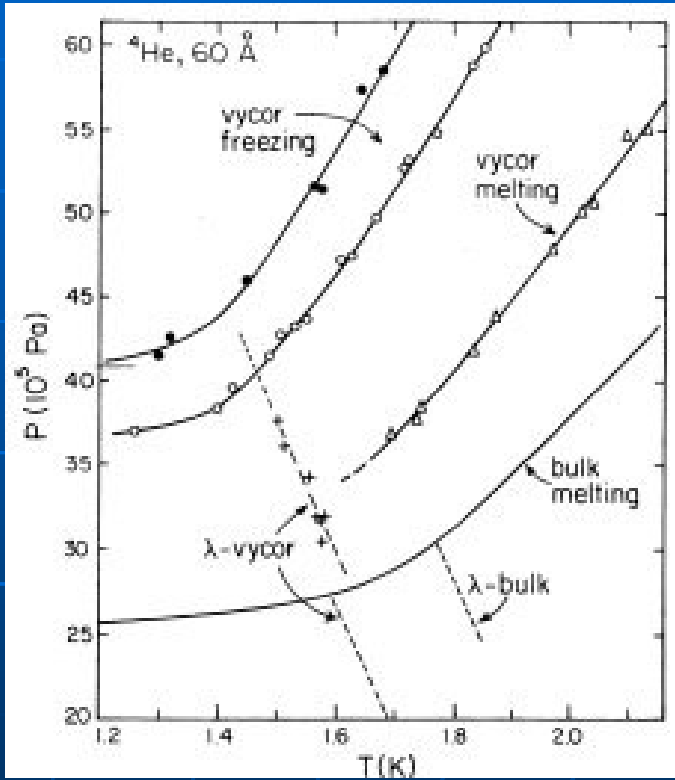
One needs a liquid-solid interface and so this can generally only be done on the melting curve, where liquid an solid coexist.

But, we wished to work off the melting curve.

Note: helium in a porous material remains liquid to a higher pressure than it does in bulk*.

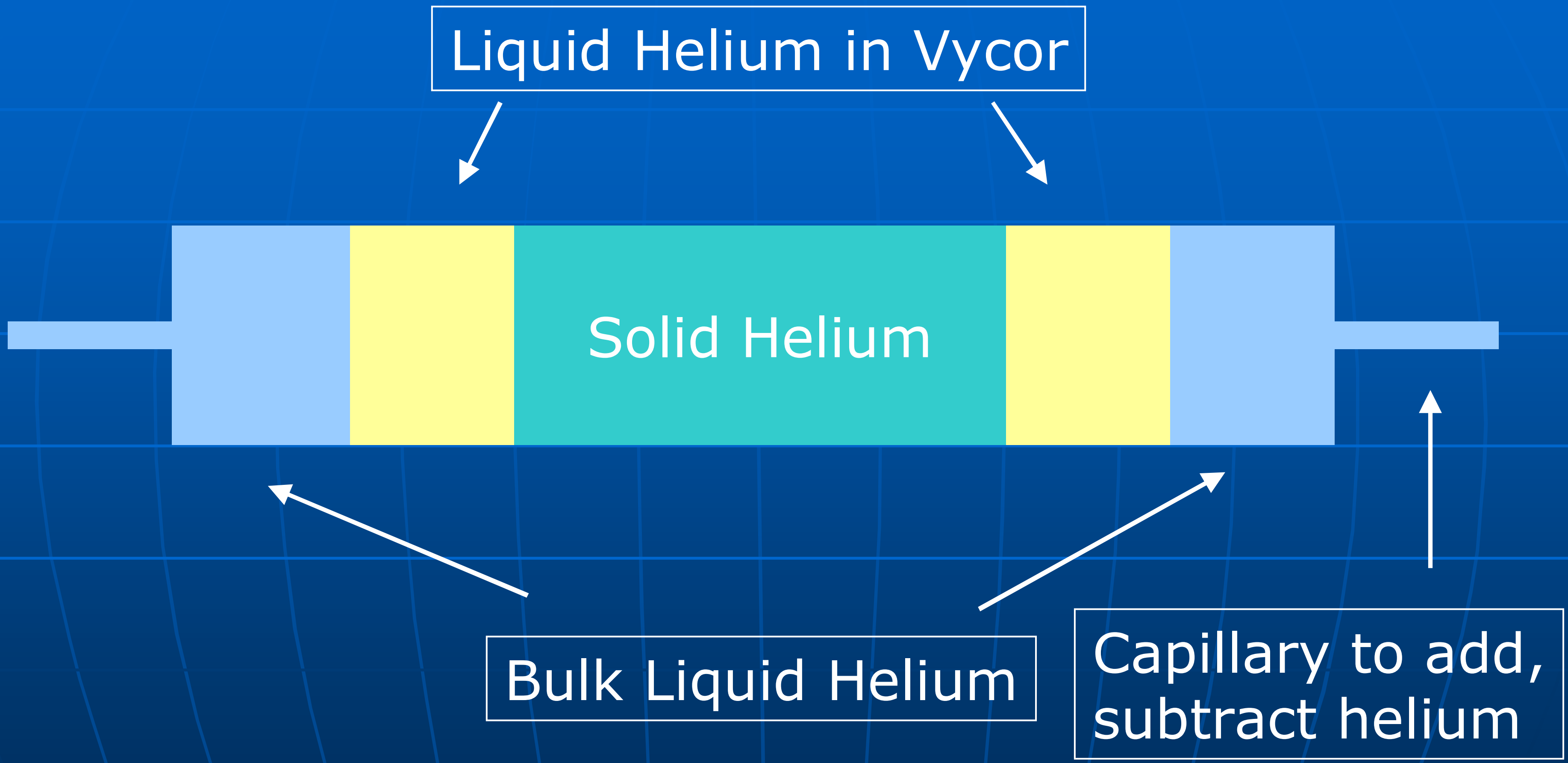
For example:

Vycor

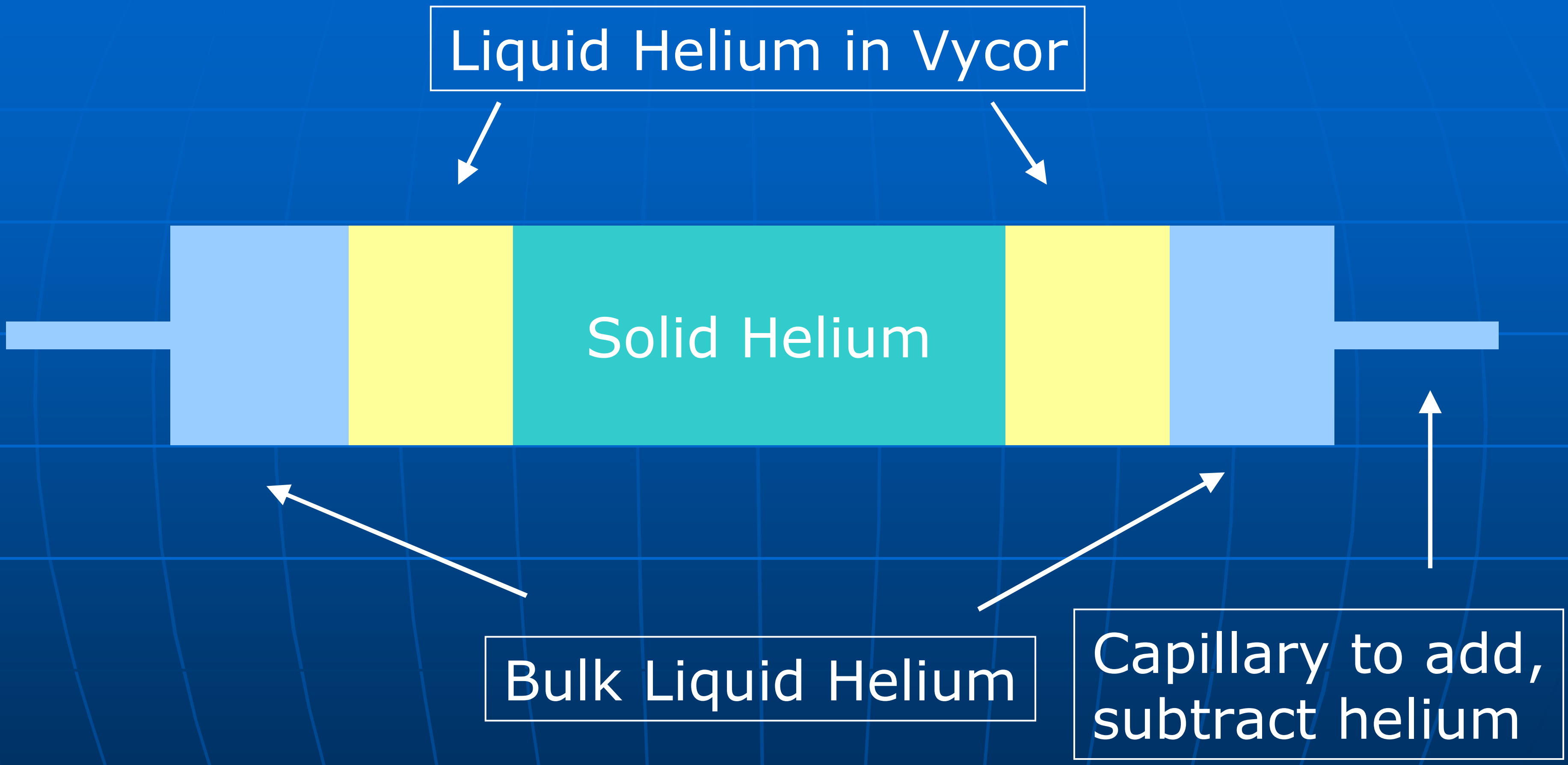


*Beamish et al., Phys. Rev. Lett. 50, 425 (1983);
Adams et al., J. Low Temp. Phys. 66, 85 (1987);
Lie-zaho et al., Phys. Rev. B 33, 106 (1986).

We utilize this fact and create a sandwich:

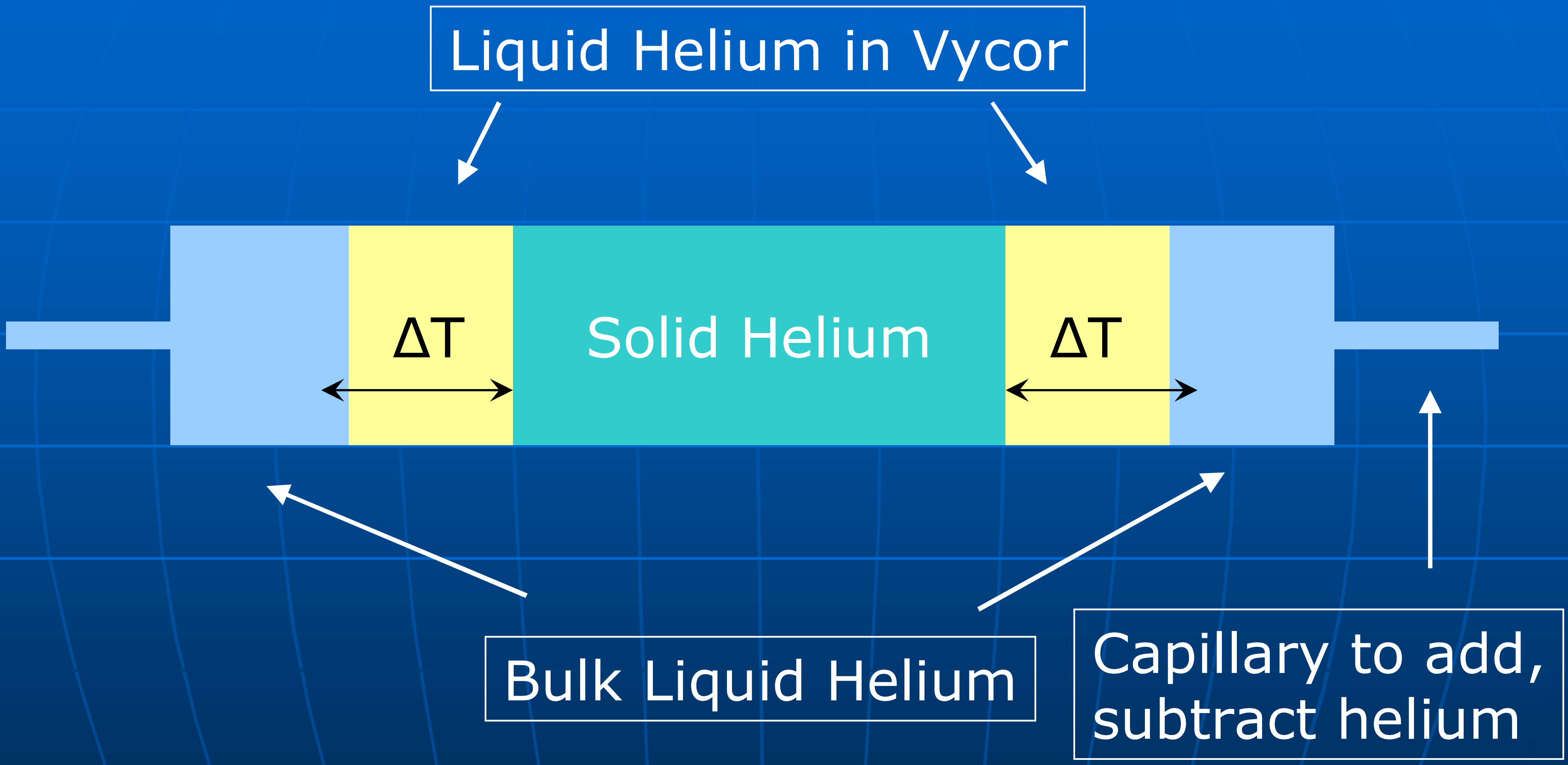


We utilize this fact and create a sandwich:

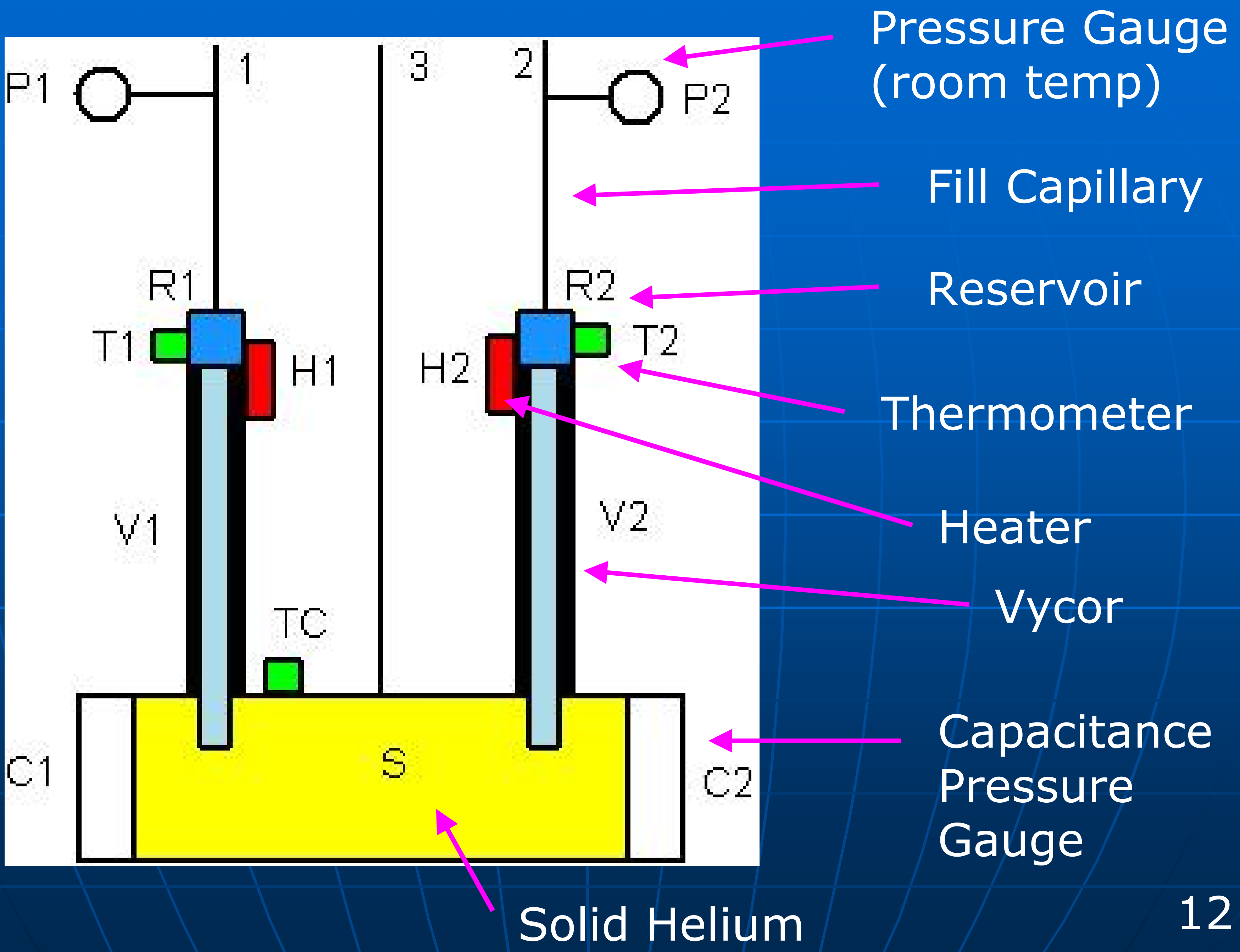


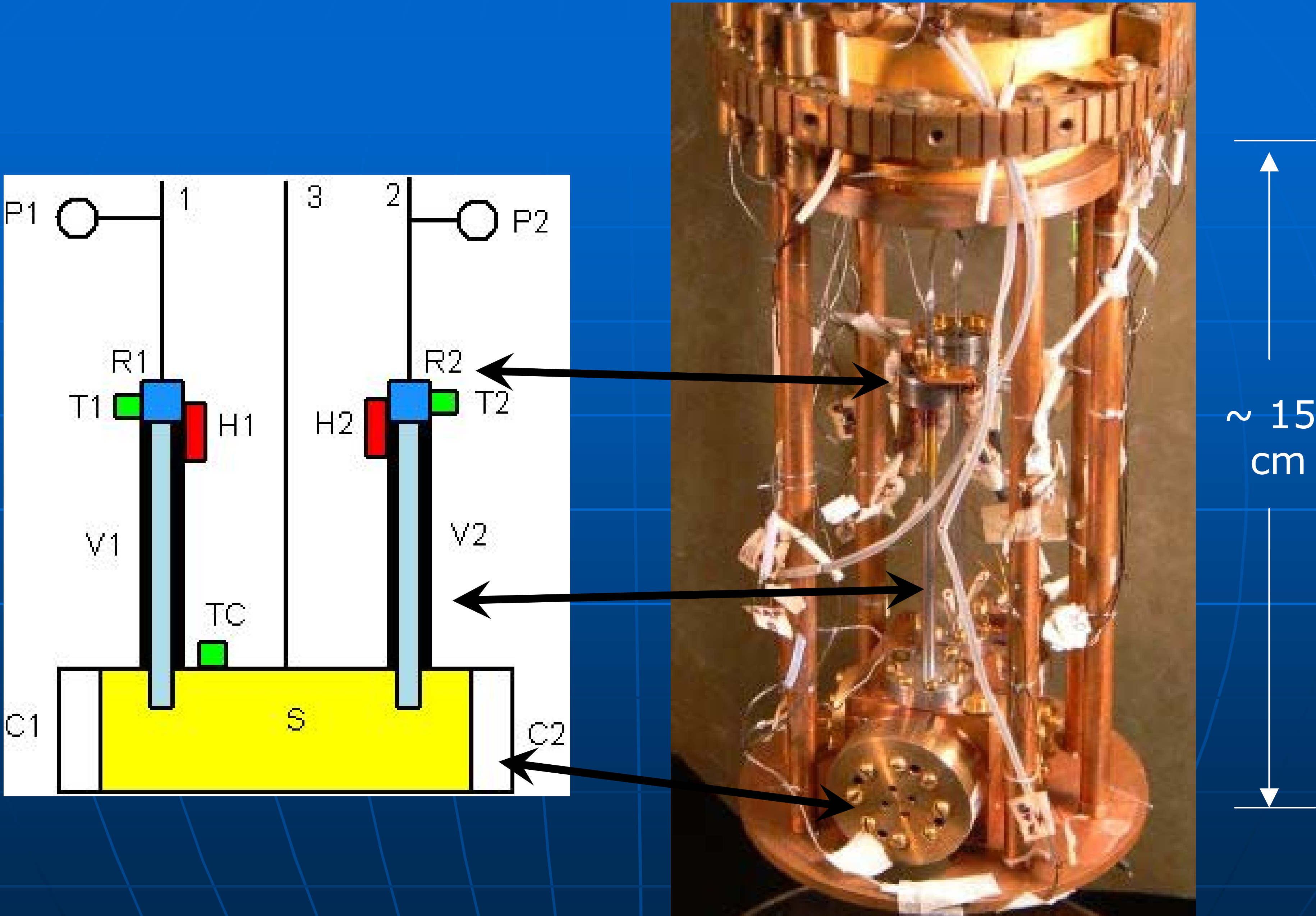
We must apply a temperature gradient across the Vycor sections for the solid to be off the melting curve.

We utilize this fact and create a sandwich:

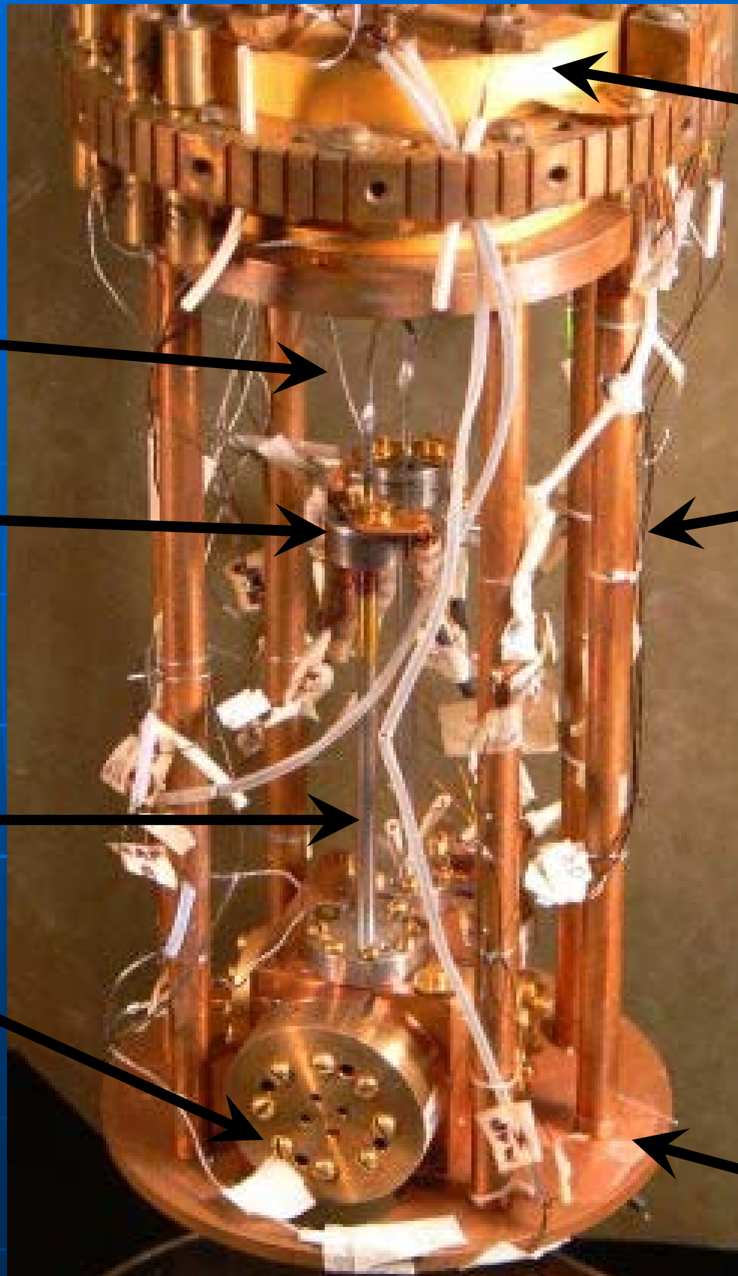


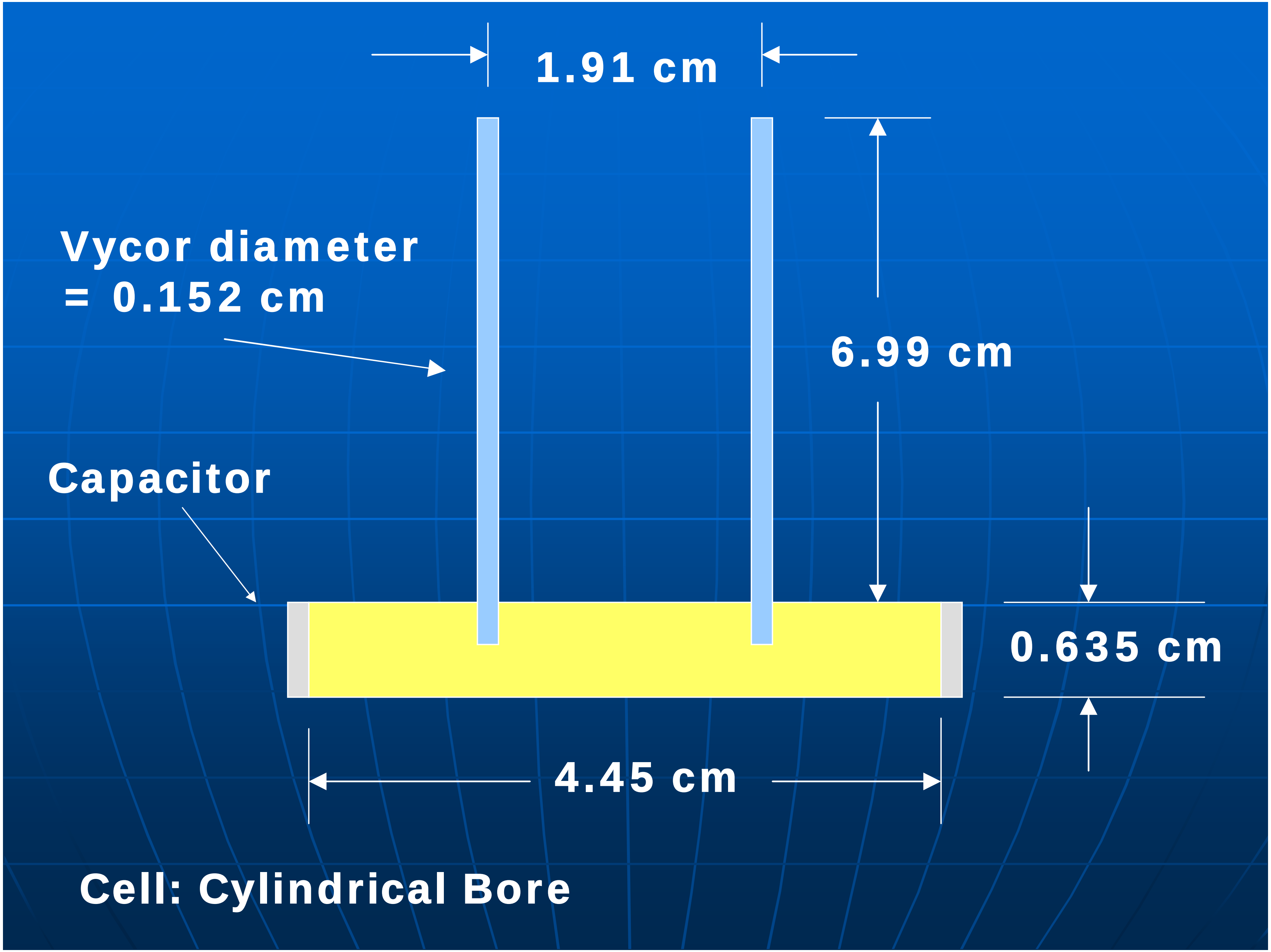
We must apply a temperature gradient across the Vycor sections for the solid to be off the melting curve.


P1
1
3
2
P2
R1
R2
T1
H1
H2
T2
V1
V2
TC
C1
S
C2
Pressure Gauge
(room temp)
Fill Capillary
Reservoir
Thermometer
Heater
Vycor
Capacitance
Pressure
Gauge
Solid Helium

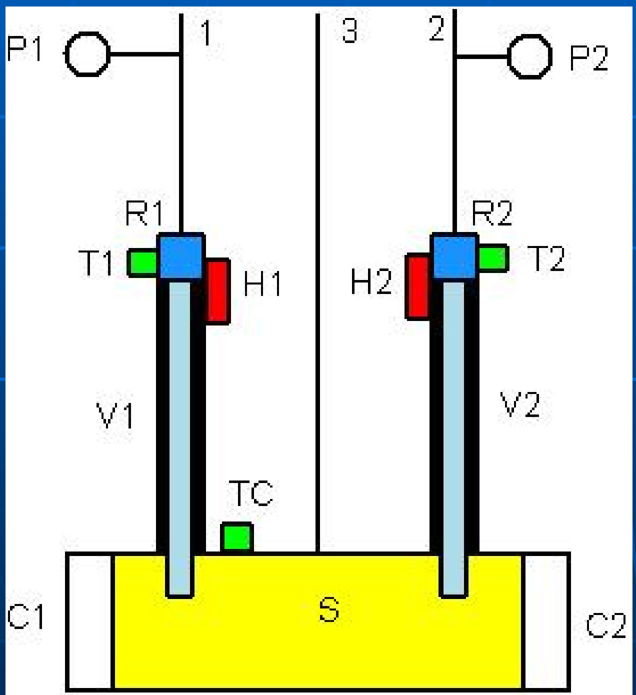


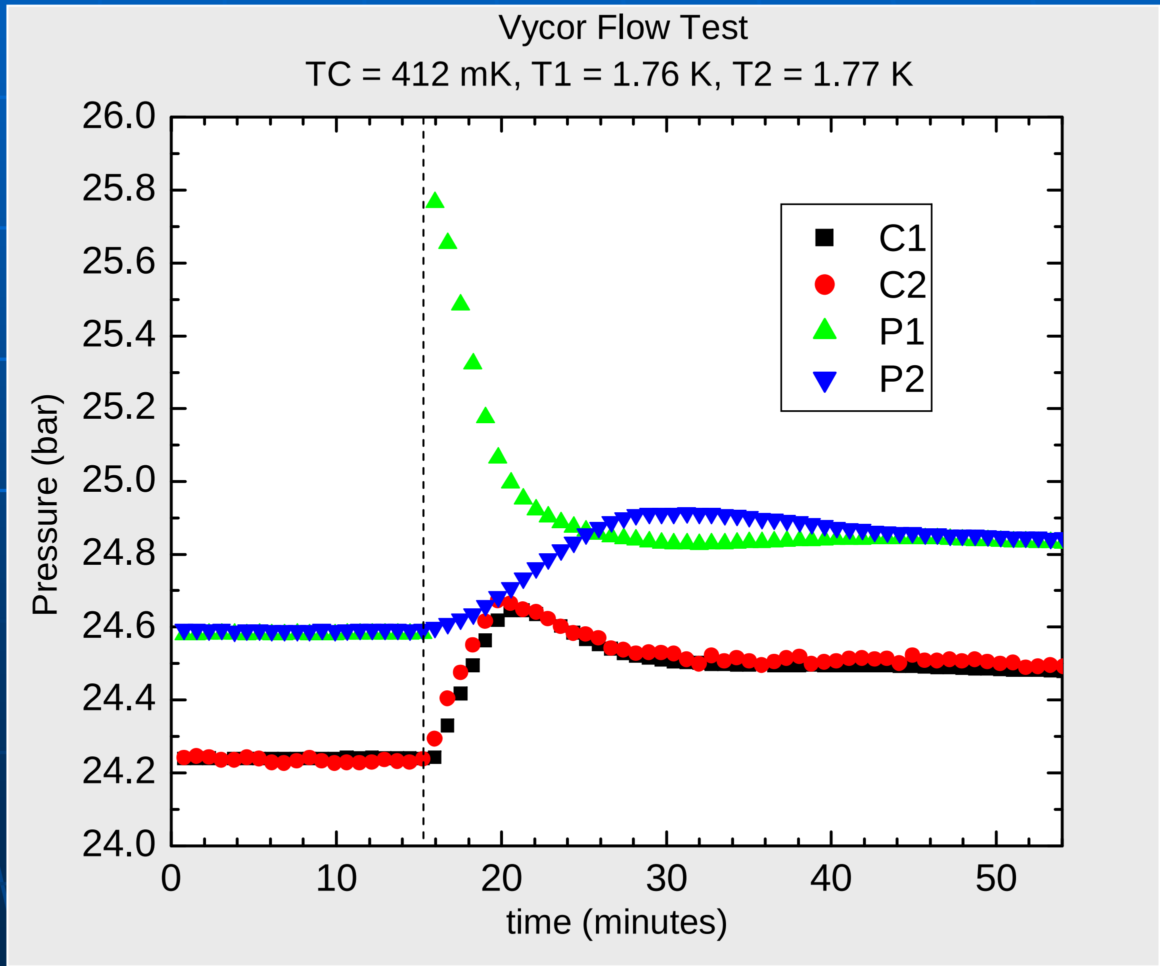
P1
1
3
2
P2
R1
R2
T1
H1
H2
T2
V1
V2
TC
C1
S
C2
~ 15
cm


Mixing Chamber
Fill Capillary
Copper
Bus Bars
Reservoir
Vycor Rod
Capacitor
Copper Base Plate

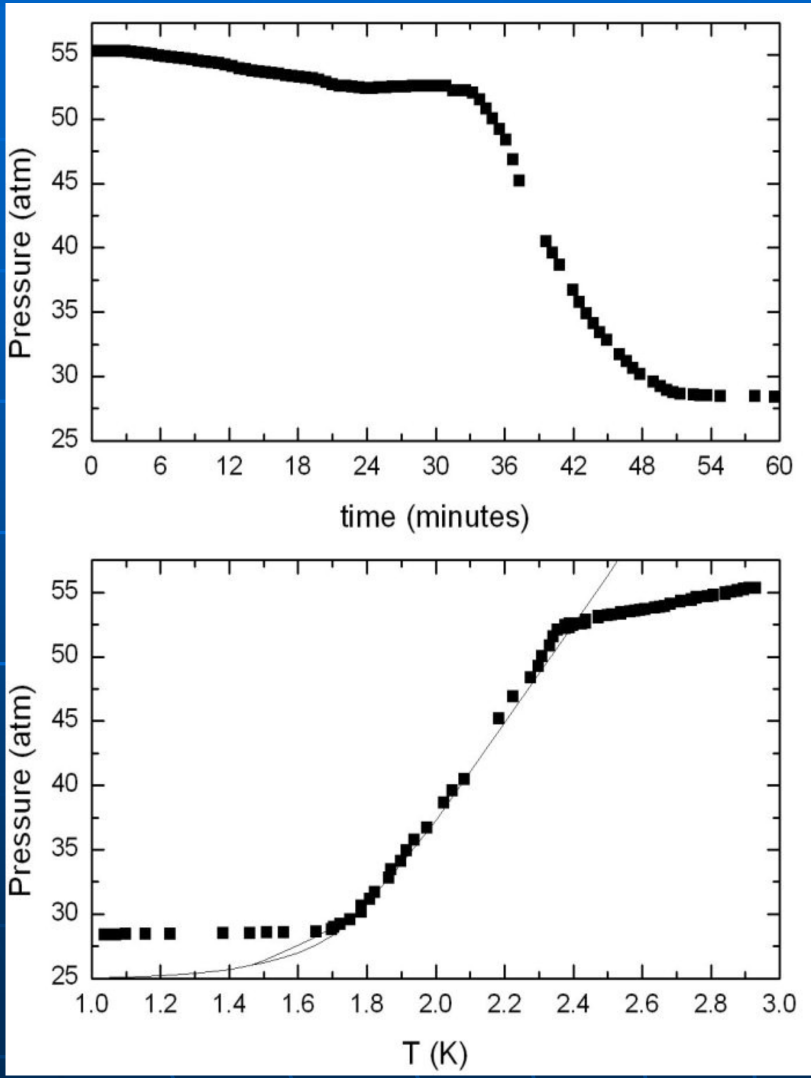

1.91 cm
Vycor diameter
= 0.152 cm
6.99 cm
Capacitor
0.635 cm
4.45 cm
Cell: Cylindrical Bore

We need to check the behavior of the Vycor to ensure that Vycor does not influence any flow measurement.

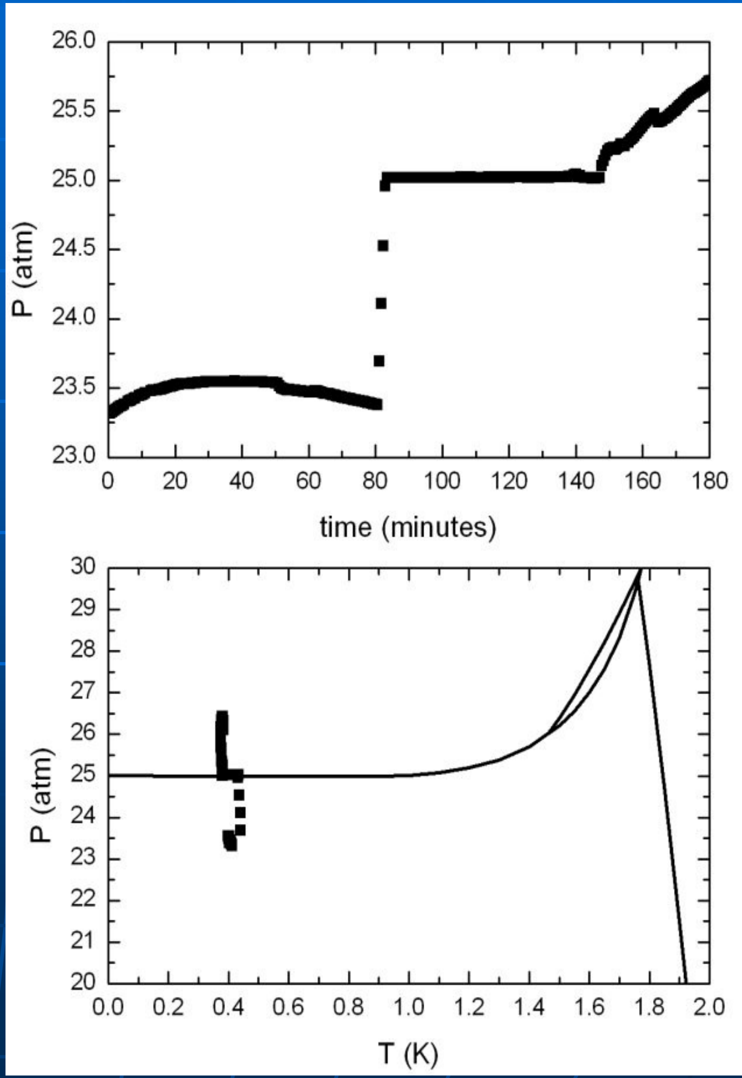




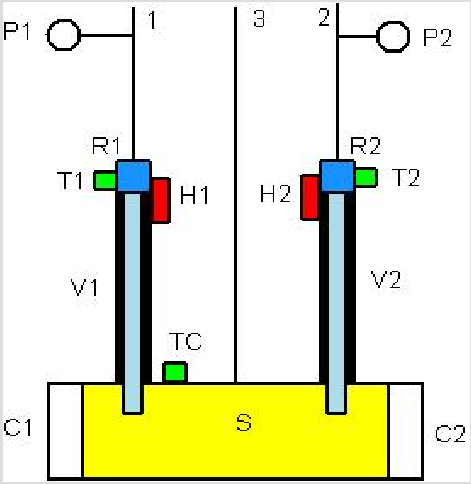
Growth curves for growth by blocked capillary.

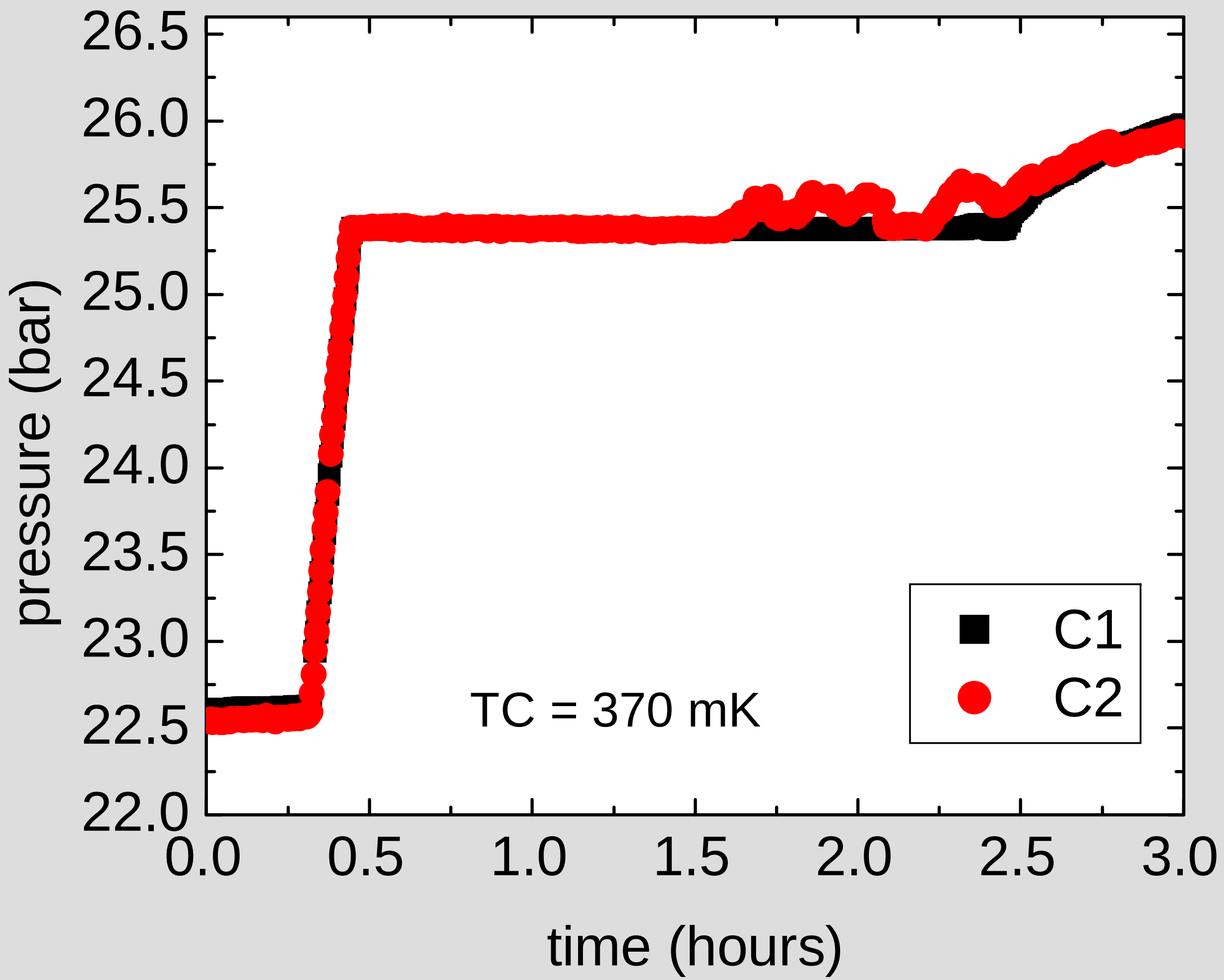


Growth curves for growth from superfluid.

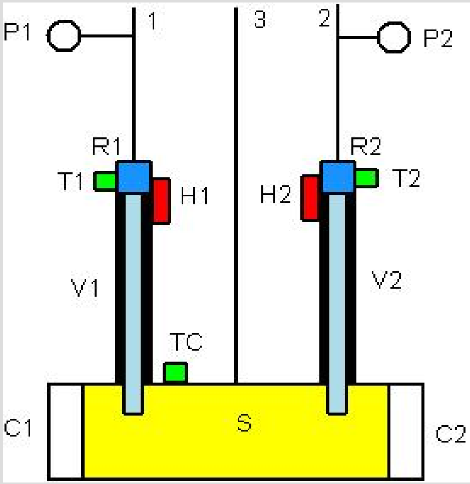


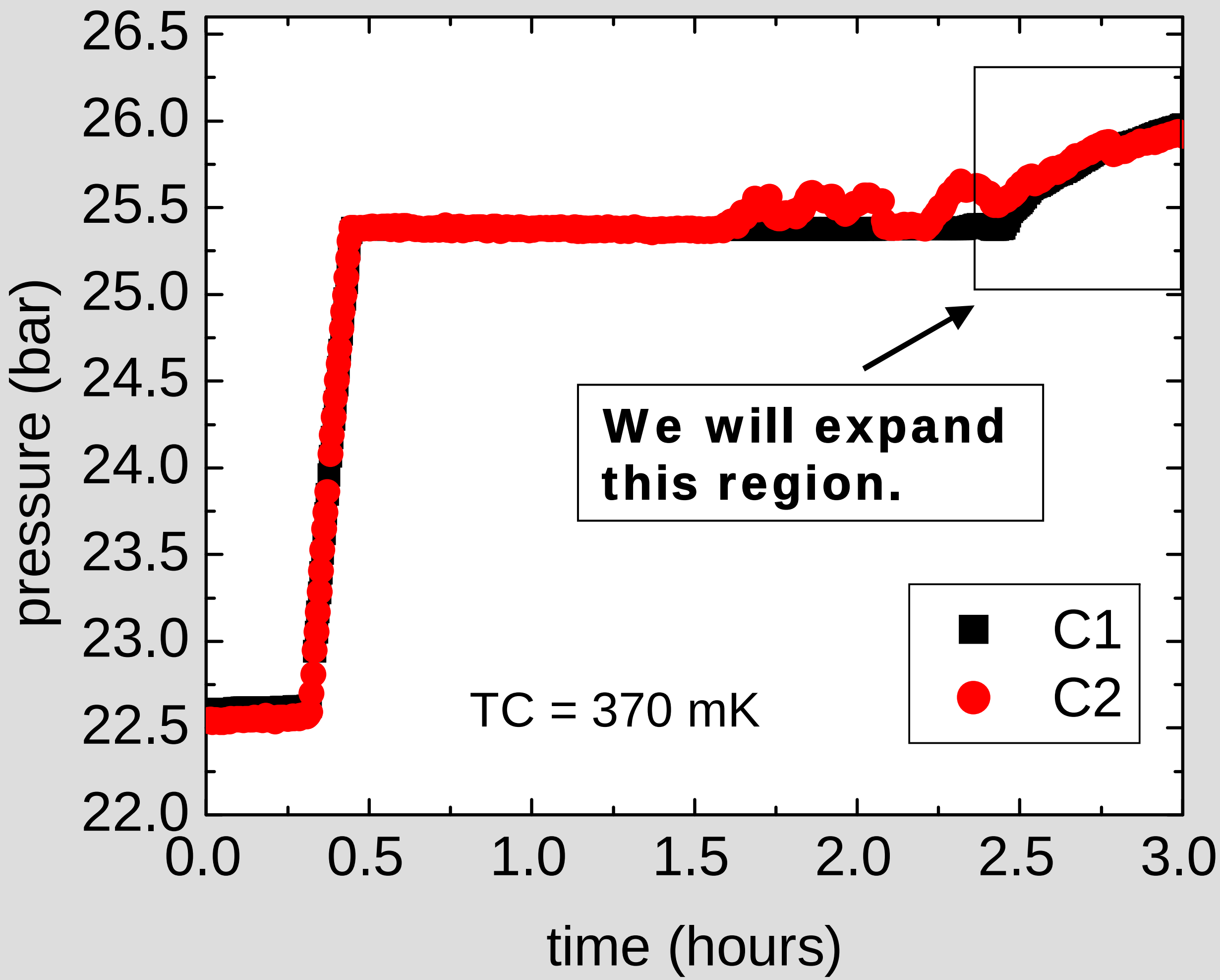
Increase pressure to line 1 and line 2: grow solid from the superfluid phase.



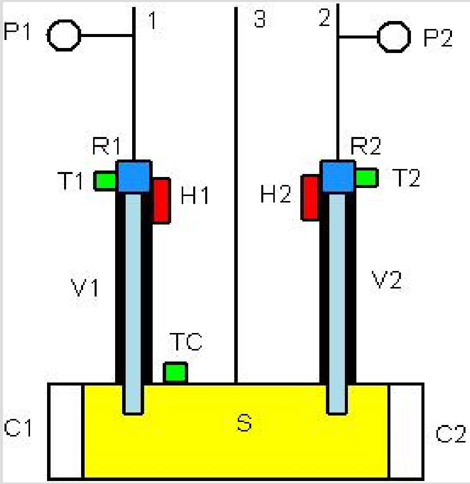


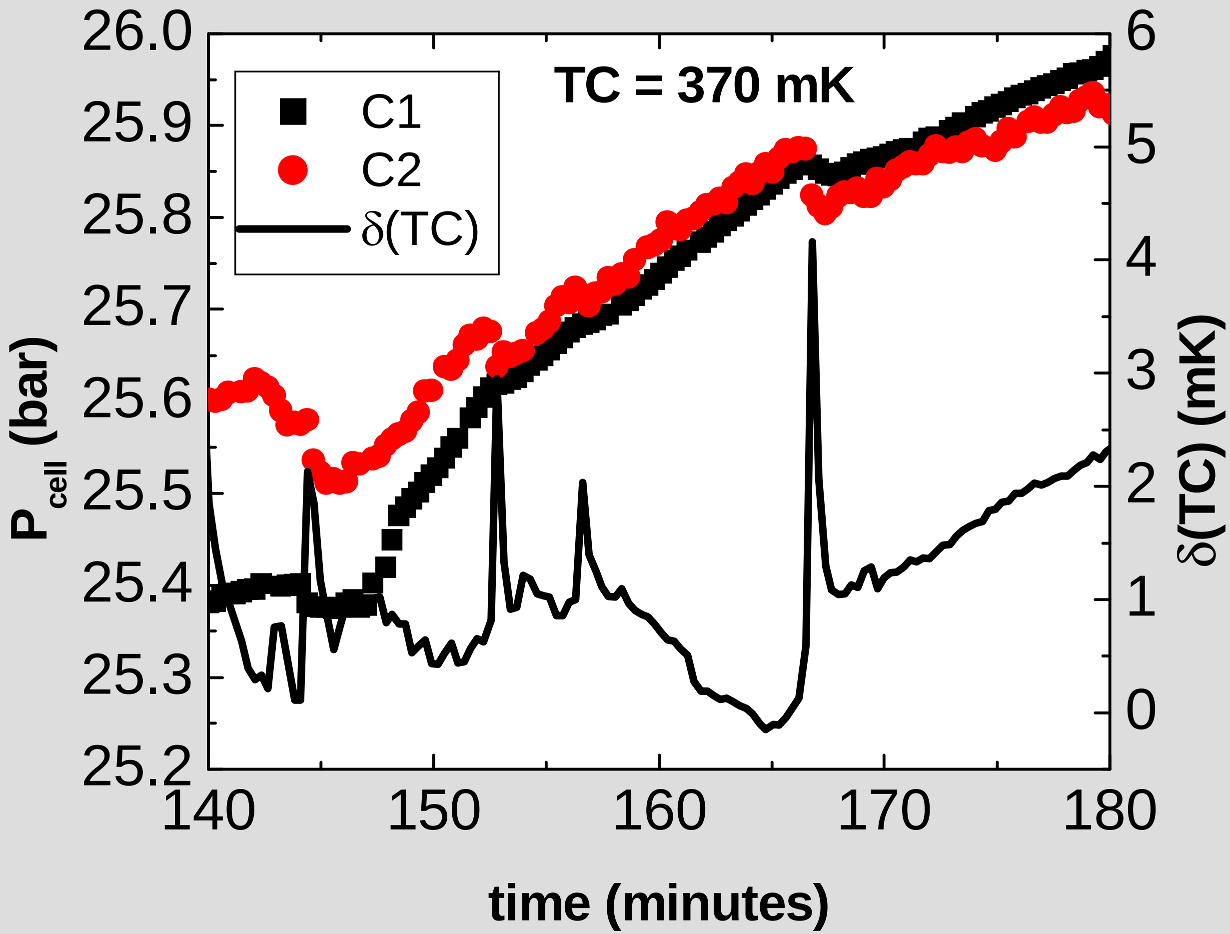
Increase pressure to line 1 and line 2: grow solid from the superfluid phase.





Expanded view.





Temperature spikes and pressure shifts on and very near to the melting curve.

Temperature transients: ~ 2 mK

Pressure drops: ~ 50 mbar

Liquid converting to solid?

Dislocations disappearing?

Grain boundaries disappearing?

Injection effect?

Temperature spikes and pressure shifts on and very near to the melting curve.

Temperature transients: ~ 2 mK

Pressure drops: ~ 50 mbar

Liquid converting to solid?

Melting curve slope is small: 300 – 750 mK yields 8 mbar drop.

Also work done as PdV.

Temperature spikes and pressure shifts on and very near to the melting curve.

Temperature transients: ~ 2 mK

Pressure drops: ~ 50 mbar

Dislocation: dia ~ 5 x 10^{-8} cm
Energy: 7.7 x 10^{-16} J/cm
Need: 4.5 x 10^{9} cm of dislocations

Dislocations disappearing?

Assume ~ 1 K/atom
Along a defect.

Grain boundaries disappearing?

Grain Boundary: thickness ~ 5 x 10^{-8} cm
Need: 175 cm^{2} of grain boundaries

Temperature spikes and pressure shifts on and very near to the melting curve.

Temperature transients: ~ 2 mK

Pressure drops: ~ 50 mbar

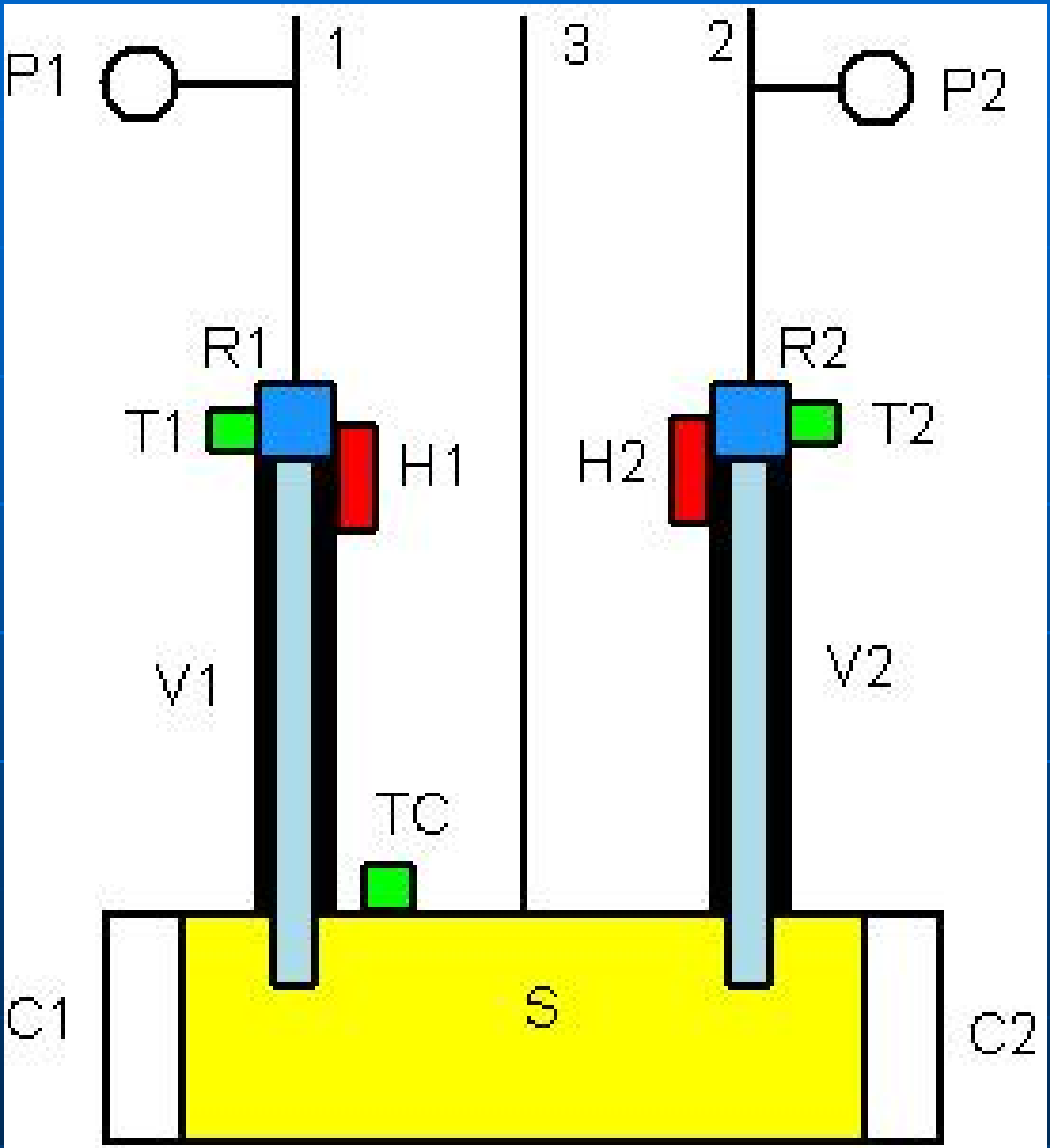
Liquid converting to solid?

Dislocations disappearing?

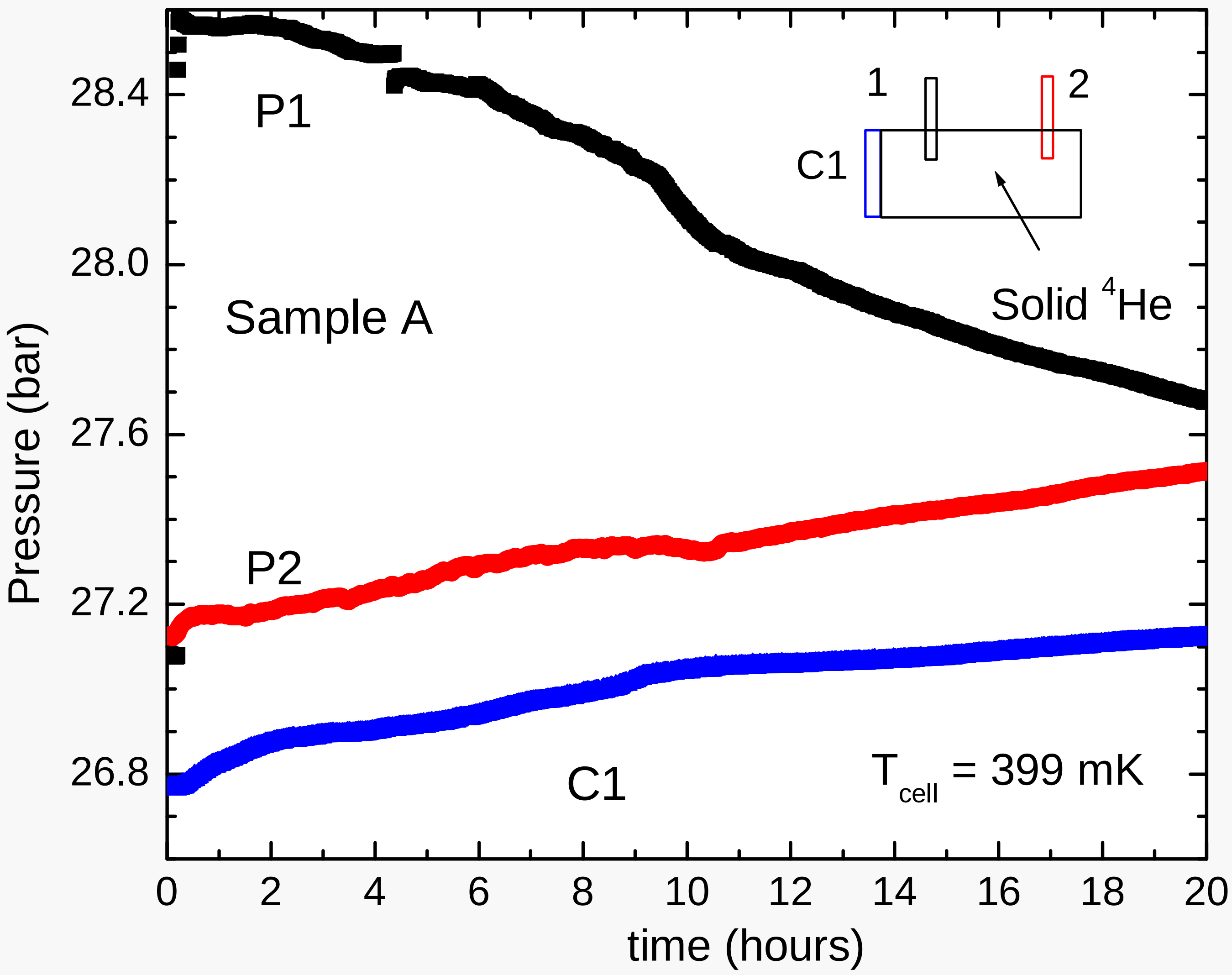
Grain boundaries disappearing?

Injection effect? Flow to places that solidify, heating, …

Add helium to line 1 and see what happens at P2.



The first sample we studied that showed evidence for flow:



Ray and Hallock, Phys. Rev. Letters 100, 235301 (2008)

Quantitative detail (Sample A)– full cross section conducts:

1×10^{-4} grams of ^{4}He moved from line 1 to line 2
(in 20 hours, which is 1.4×10^{-9} g/sec)
4.5×10^{-4} grams of ^{4}He joined the solid

$M/t = \xi\, \rho\, VXY$ = mass moved from 1 to 2 in time t

Assume full cross section is available:

$\xi\, VXY = 8 \times 10^{-9}\ \mathrm{cm}^3 / \mathrm{sec}$
$\xi\, V = 2.5 \times 10^{-8}\ \mathrm{cm} / \mathrm{sec}$

If $V = 100\ \mu\mathrm{m/sec}$, then $\xi = 2.5 \times 10^{-6}$

Quantitative detail – discrete structures conduct:

Either a line or a plane with one thickness, $x = 0.5$ nm

Then, $\xi\, VY = 0.16\ cm^2 / sec$

If $\xi = 1$, then $VY = 0.16\ cm^2/sec$

If $V = 200$ cm/sec, then $Y = 8 \times 10^{-4}$ cm

If structures are 0.5 nm x 0.5 nm, then we need
~ 1.6×10^4 pipe-like conduits.

This would be a density ~ $5.0 \times 10^4\ cm^{-2}$.

Quantitative detail – discrete structures conduct:

Either a line or a plane with one thickness, $x = 0.5$ nm

Then, $\xi VY = 0.16\ cm^2 / sec$

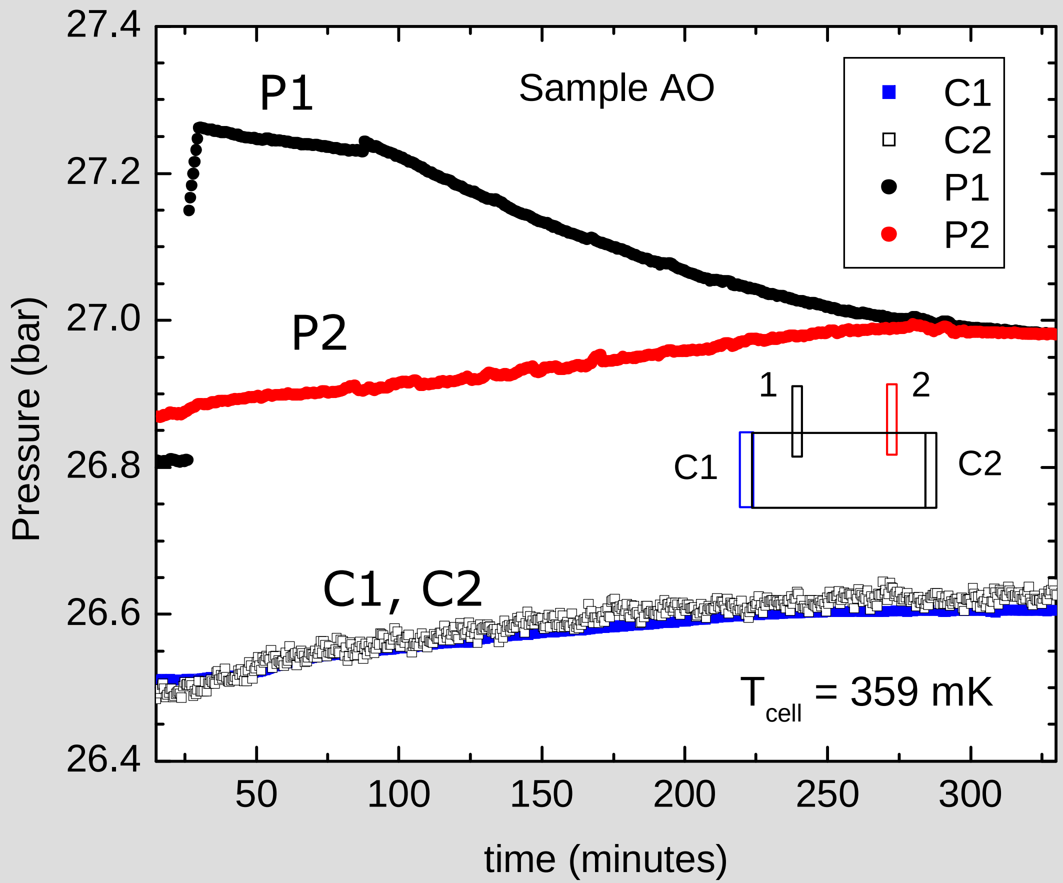
If $\xi = 1$, then $VY = 0.16\ cm^2/sec$

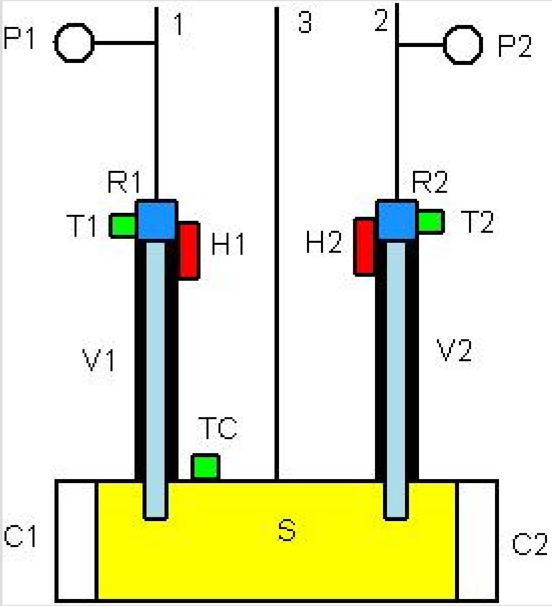
If $V = 200$ cm/sec, then $Y = 8 \times 10^{-4}$ cm
If $V = 100$ μm/sec, then $Y = 16$ cm

If structures are 0.5 nm x 0.5 nm, then we need
~ 1.6×10^4 (~ 3.2×10^8) pipe-like conduits.

This would be a density ~ $5.0 \times 10^4\ cm^{-2}$ (~ $1.0 \times 10^9\ cm^{-2}$).

Another Example Interpreted as Evidence for “Flow”





Quantitative detail (Sample AO)– full cross section conducts:

3.5×10^{-5} grams of ^4He moved from line 1 to line 2
(in 250 minutes, which is 2.4×10^{-9} g/sec)
1.1×10^{-4} grams of ^4He joined the solid

$M/t = \xi \rho VXY$ = mass moved from 1 to 2 in time t

Assume full cross section is available:

$\xi VXY = 1.3 \times 10^{-8}\ cm^3 / sec$
$\xi V = 4.1 \times 10^{-8}\ cm / sec$

If $V = 100\ \mu m/sec$, then $\xi = 4.1 \times 10^{-6}$

Quantitative detail – discrete structures conduct:

Either a line or a plane with one thickness, $X = 0.5$ nm

Then, $\xi VY = 0.26\ cm^2 / sec$

If $\xi = 1$, then $VY = 0.26\ cm^2/sec$

If $V = 200$ cm/sec, then $Y = 1.3 \times 10^{-3}$ cm

If structures are 0.5 nm x 0.5 nm, then we need
~ 2.6×10^4 pipe-like conduits.

This would be a density ~ $8.2 \times 10^4\ cm^{-2}$.

Quantitative detail – discrete structures conduct:

Either a line or a plane with one thickness, X = 0.5 nm

Then, ξ VY = 0.26 cm^2 / sec

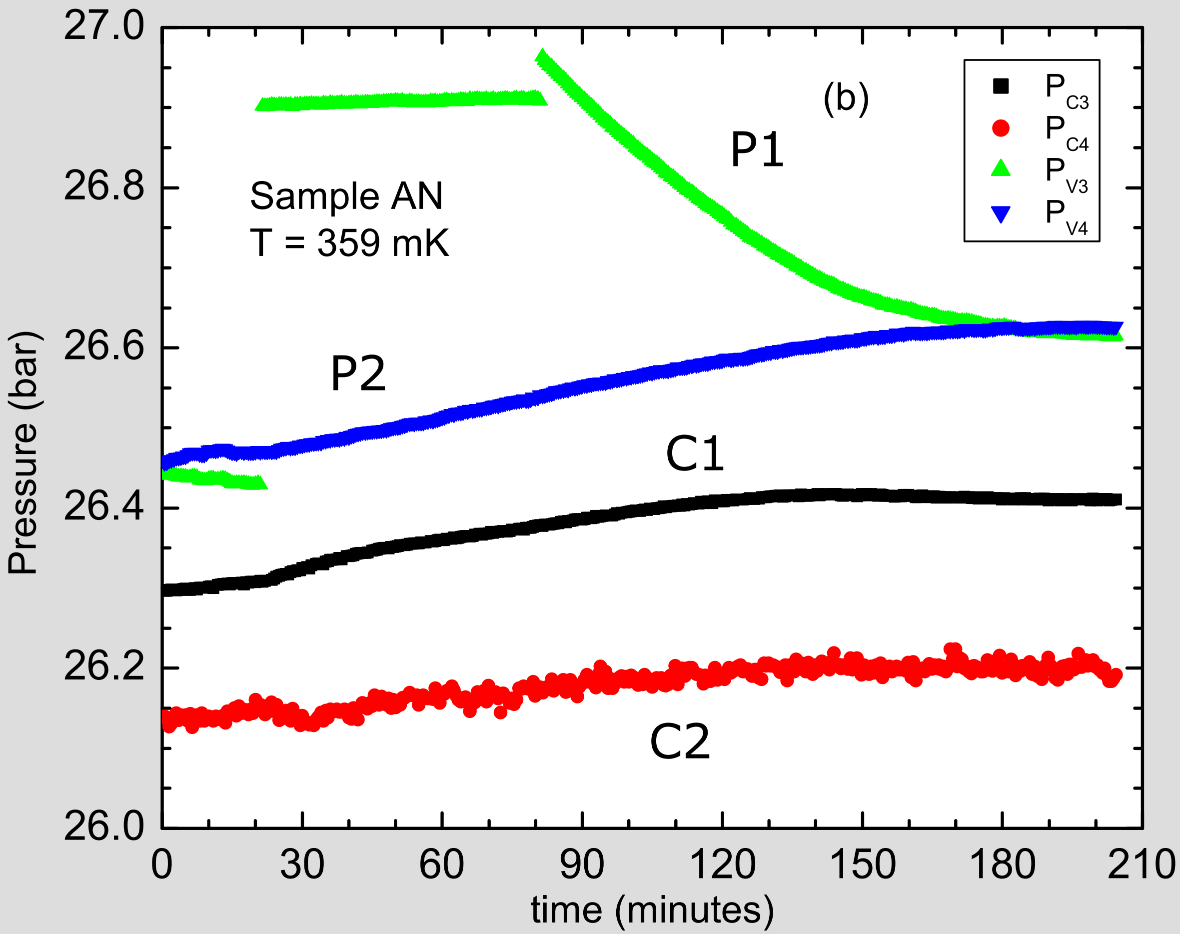
If ξ = 1, then VY = 0.26 cm^2/sec

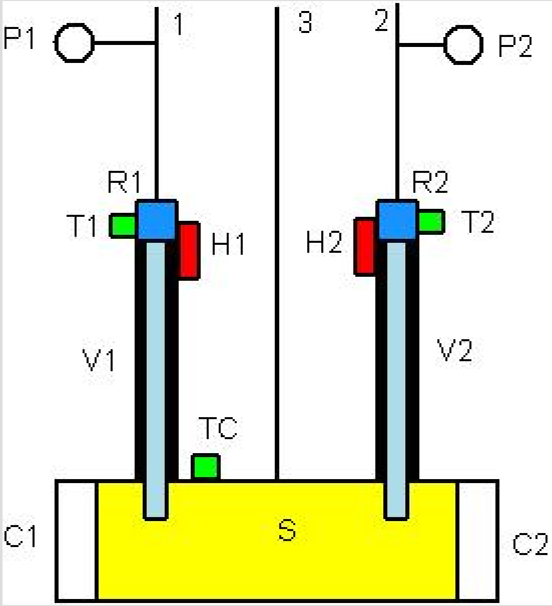
If V = 200 cm/sec, then Y = 1.3 x 10^{-3} cm
If V = 100 μm/sec, then Y = 26 cm

If structures are 0.5 nm x 0.5 nm, then we need
~ 2.6 x 10^4 (~ 5.2 x 10^8) pipe-like conduits.

This would be a density ~ 8.2 x 10^4 cm^{-2} (~ 1.6 x 10^9 cm^{-2}).

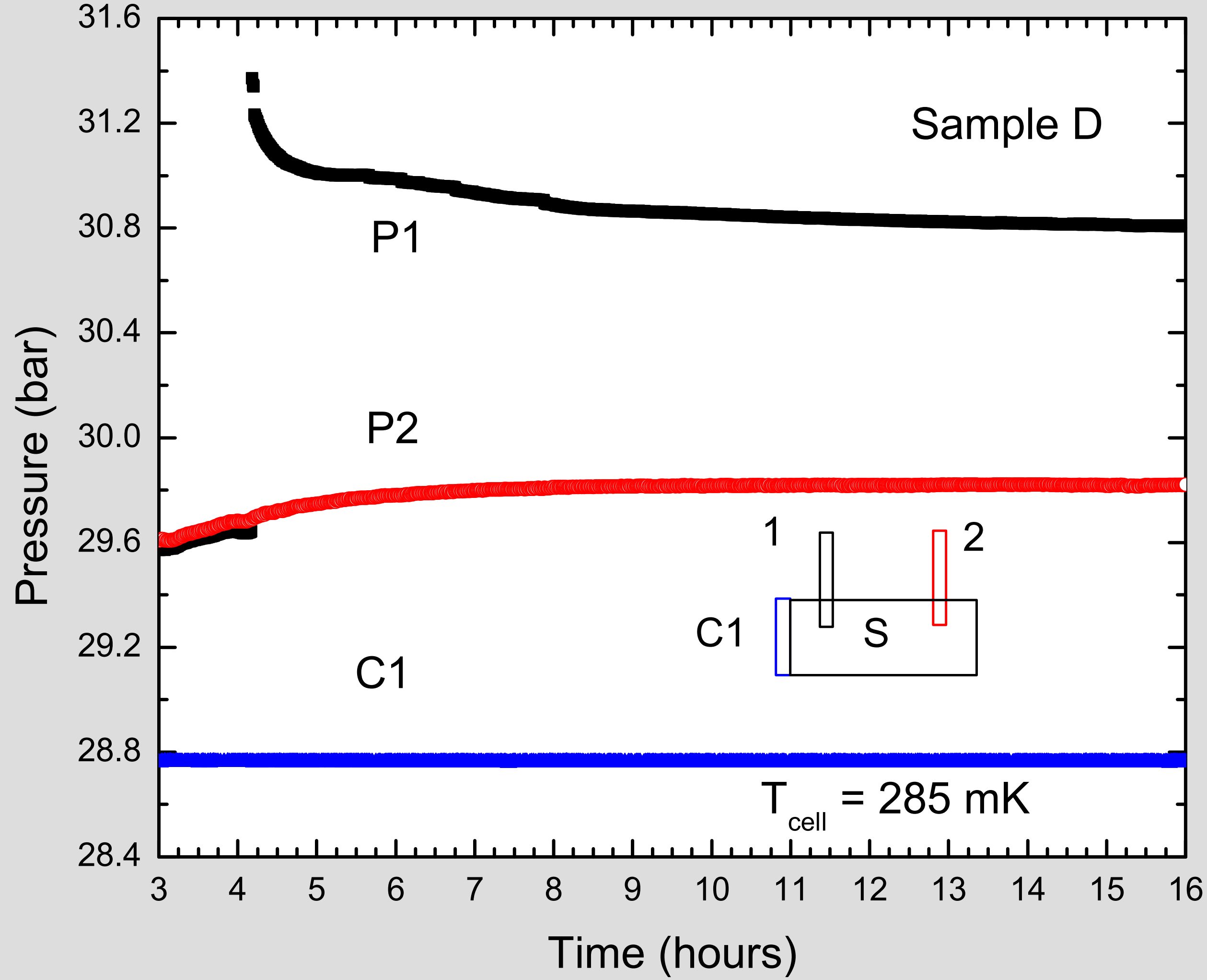
Another: Interpreted as Evidence for "Flow"



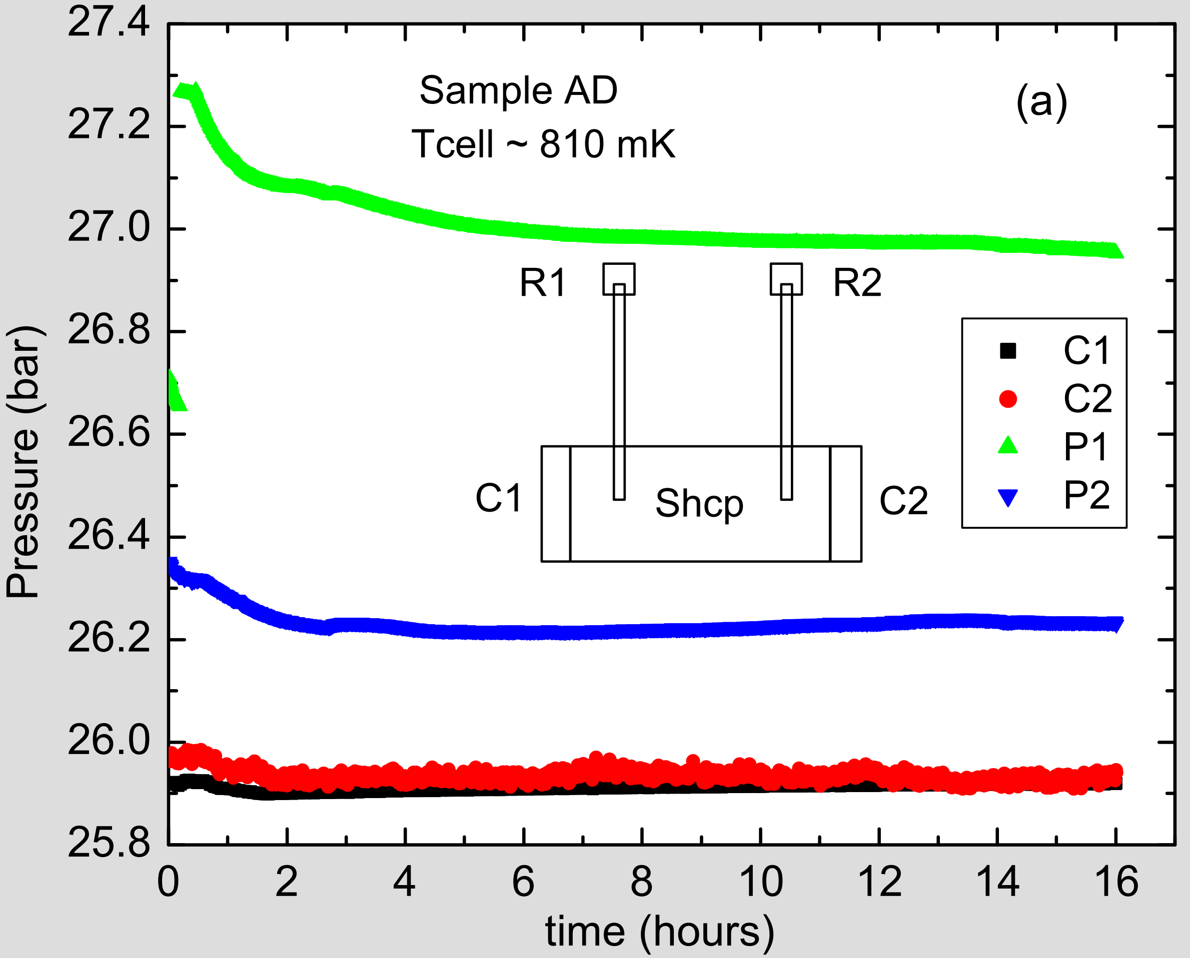


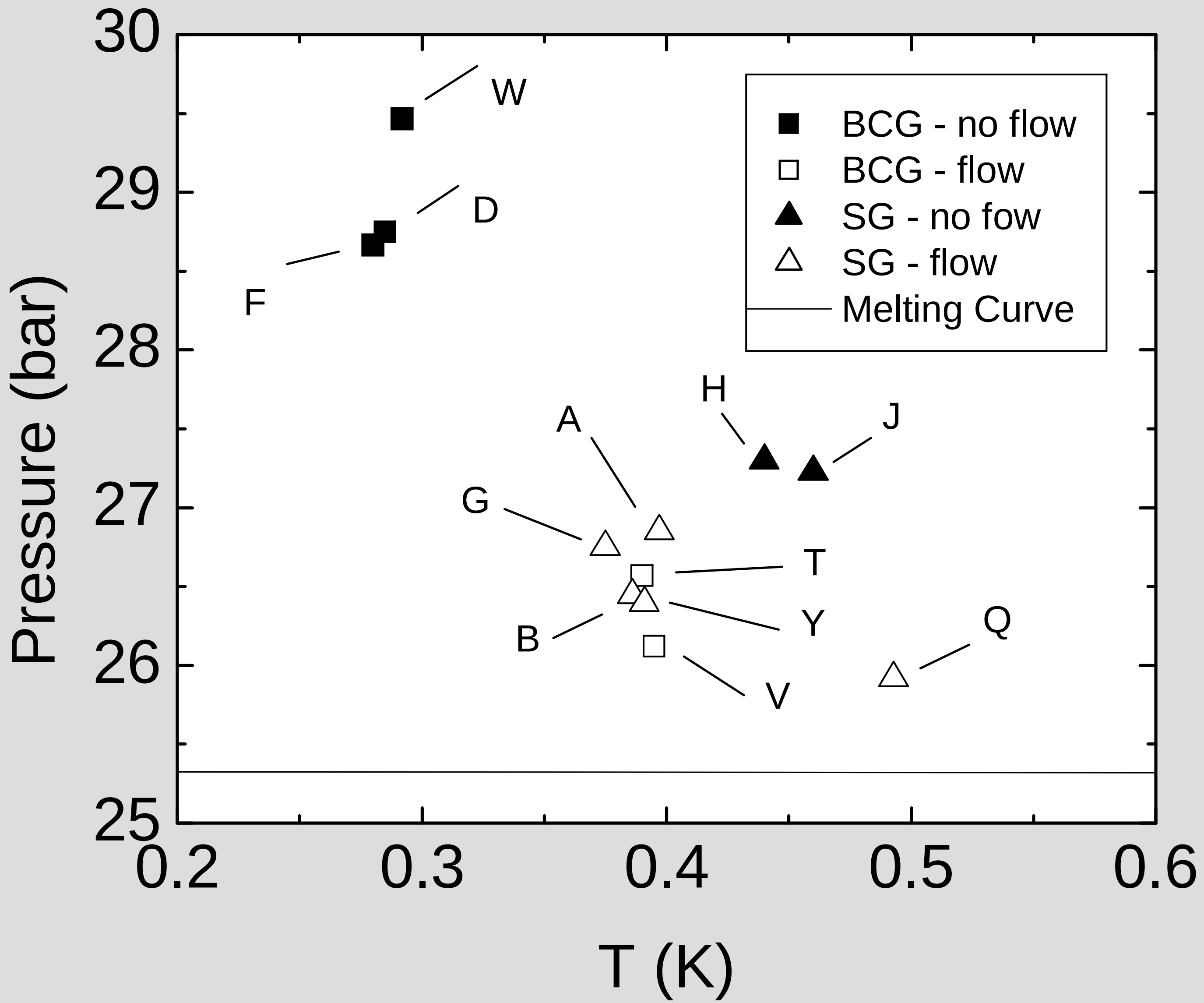
Note: Sometimes C1 and C2, like in this case, show a gradient is present in the cell.

An Example Interpreted as Long-term "No Flow"

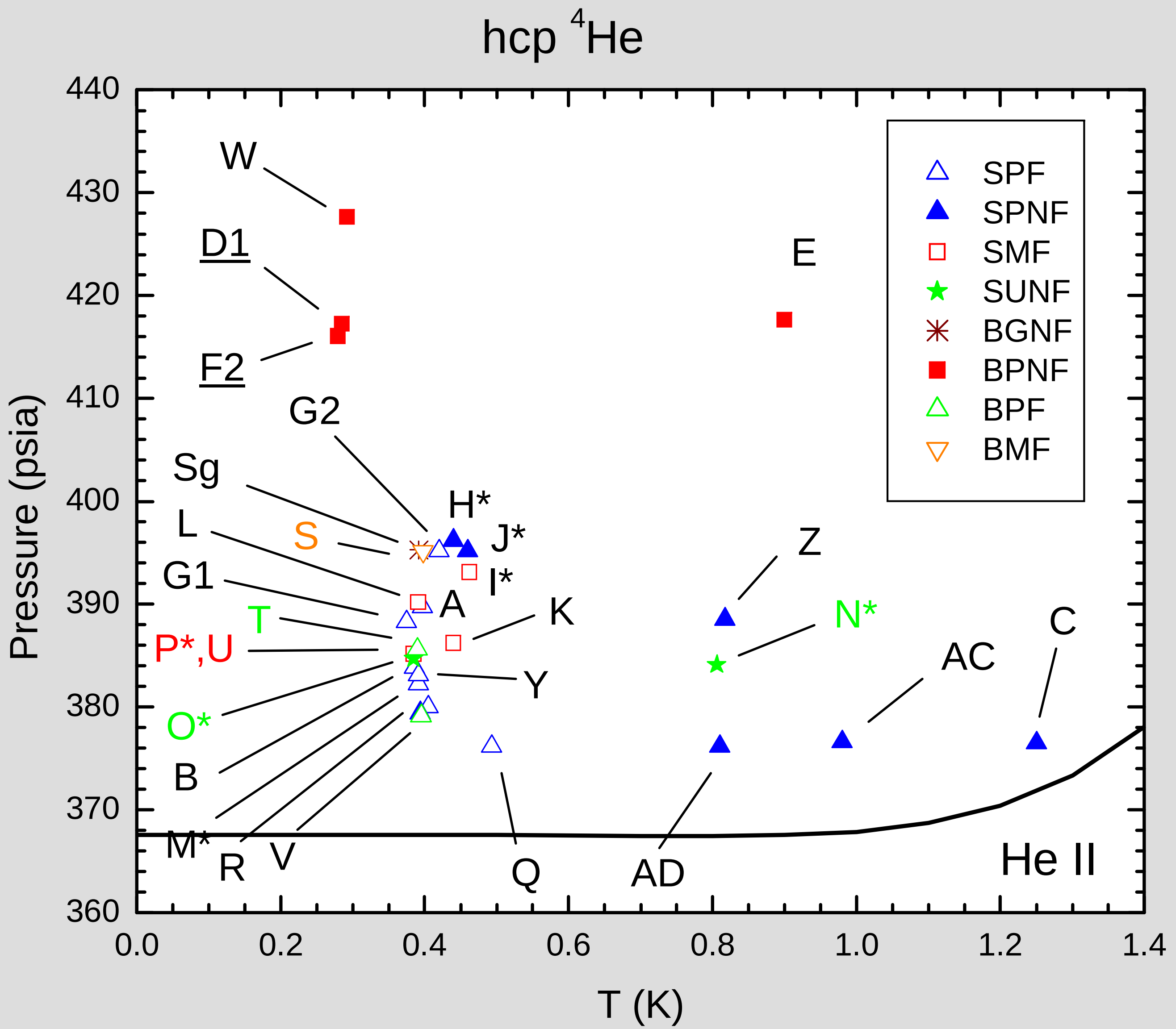


Another: Interpreted as Long-term "No Flow"



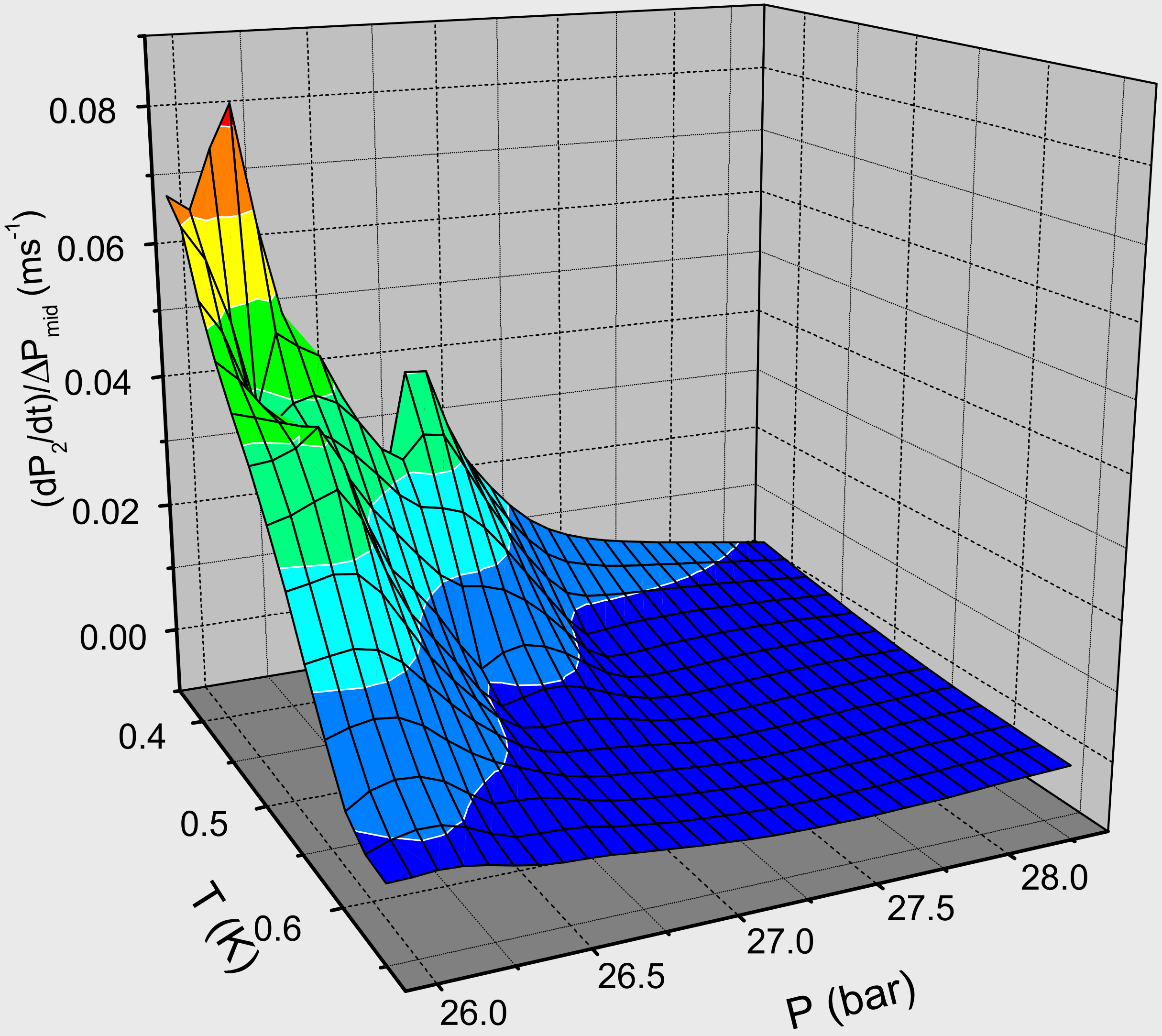


30
29
28
27
26
25
0.2
0.3
0.4
0.5
0.6
Pressure (bar)
T (K)
BCG - no flow
BCG - flow
SG - no fow
SG - flow
Melting Curve
W
D
F
H
J
A
G
T
B
Y
Q
V



hcp ^{4}He
Pressure (psia)
T (K)
SPF
SPNF
SMF
SUNF
BGNF
BPNF
BPF
BMF
W
D1
F2
G2
Sg
L
S
G1
T
P*,U
O*
B
M*
R
V
H*
J*
I*
A
K
Y
Q
AD
E
Z
N*
AC
C
He II

(dP2 / dt) / (P1 – P2) at midpoint of the flow vs. T and P



Recent work by Rittner and Reppy also is interpreted as evidence for flow.

Apparatus and approach similar to the Beamish group, but different geometry.

To date: low pressures studied, flow is present, but no temperature dependence is seen.

What causes the behavior we see?

Flow in Liquid channels?
Flow along dislocations, grain boundaries?
Some sort of plastic flow?
Something else?

Flow in Liquid channels?

Should remain above 1.5 K (presuming the Liquid channel does not anneal away)

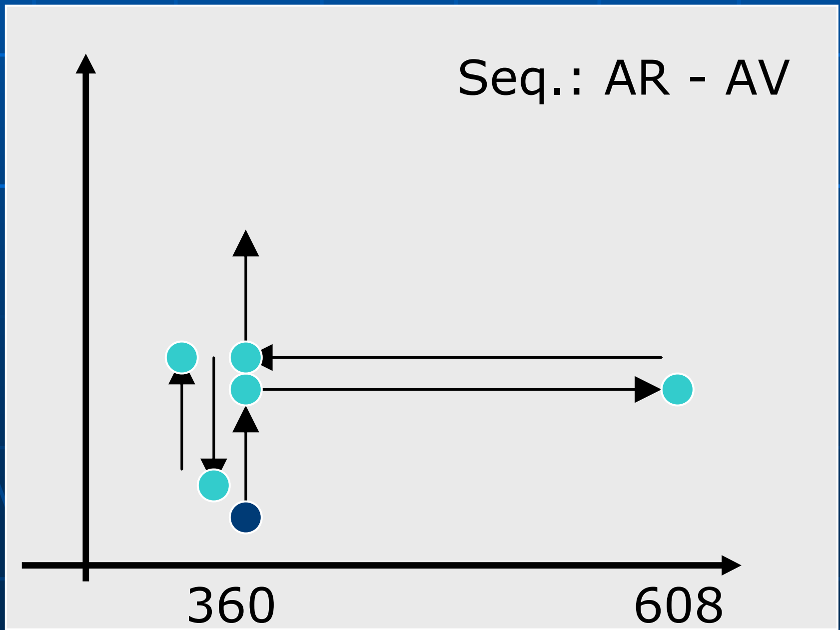
Should be pressure dependent.

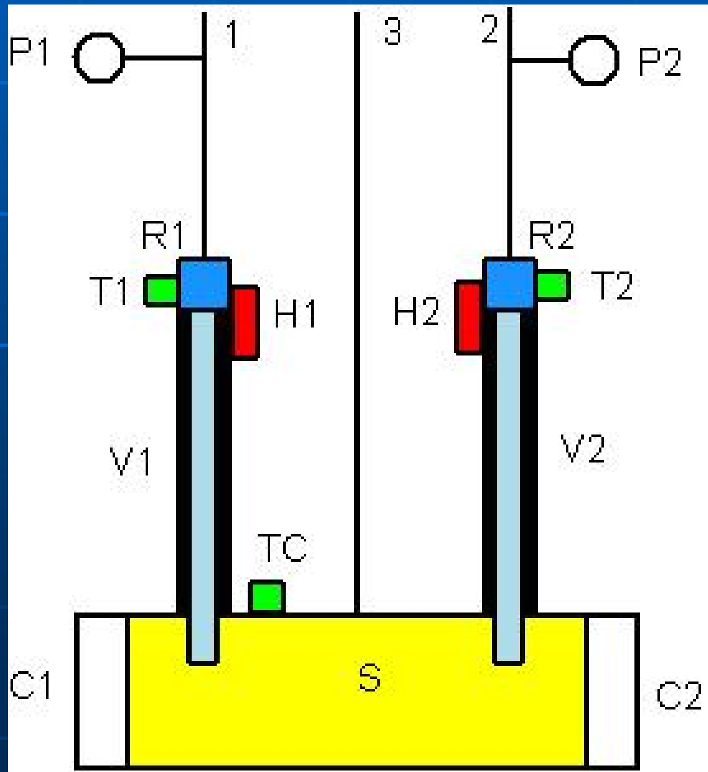
Flow along dislocations, grain boundaries?

May have a transition temperature that depends on pressure or temperature, or both.

Some sequential measurements:

Create sample at ~ 360 mK, 26.249 bar, push, see flow
Warm sample to ~ 608 mK, 26.373 bar, push, no flow
Cool to ~ 360 mK, 26.363 bar, push, no flow
At ~ 360 mK, pull, see flow
At ~ 360 mK, push, see flow.





New Sample: Create at 400 mK and repeat cycle with 800 mK instead of 600 mK yields the same result.

New Sample: Create at 400 mK and repeat cycle with 800 mK instead of 600 mK yields the same result.

Maybe the warming damages the flow path. So, create fresh samples at the higher temperatures.

New Sample: Create at 400 mK and repeat cycle with 800 mK instead of 600 mK yields the same result.

Next, create fresh samples at 600 mK, push, and observe no flow. Same result with fresh samples Created at 800 mK, no flow.

Also, at 600 mK, after push and no flow, also did a pull with the result of no flow.

➔ *Note that for samples near 400 mK, a pull always has resulted in a flow, even when a previous push did not.*

New Sample: Create at 400 mK and repeat cycle with 800 mK instead of 600 mK yields the same result.

Next, create fresh samples at 600 mK, push, and observe no flow.   Same result with fresh samples Created at 800 mK.

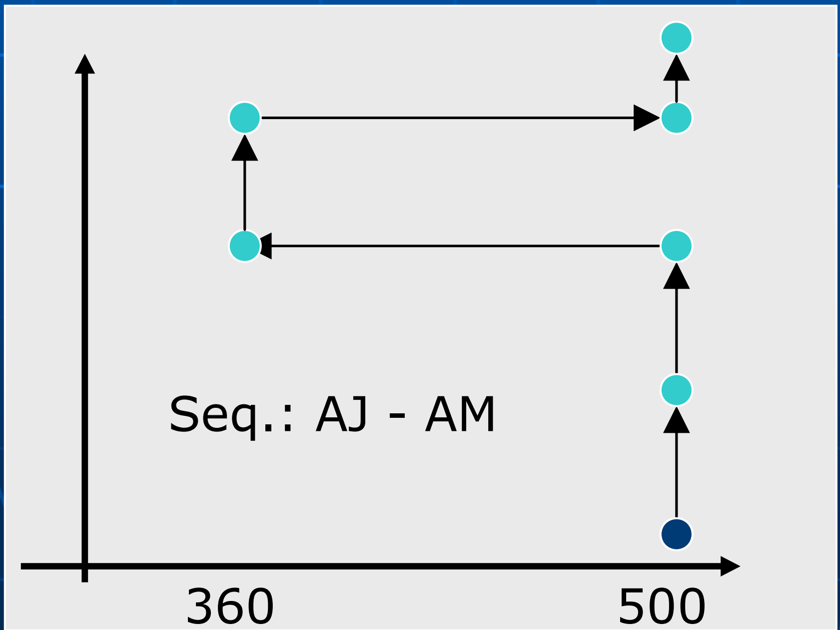
If what we see were due to Liquid channels, we believe that they should be created at 600 mK and at 800 mK and should conduct. We do not see such behavior.

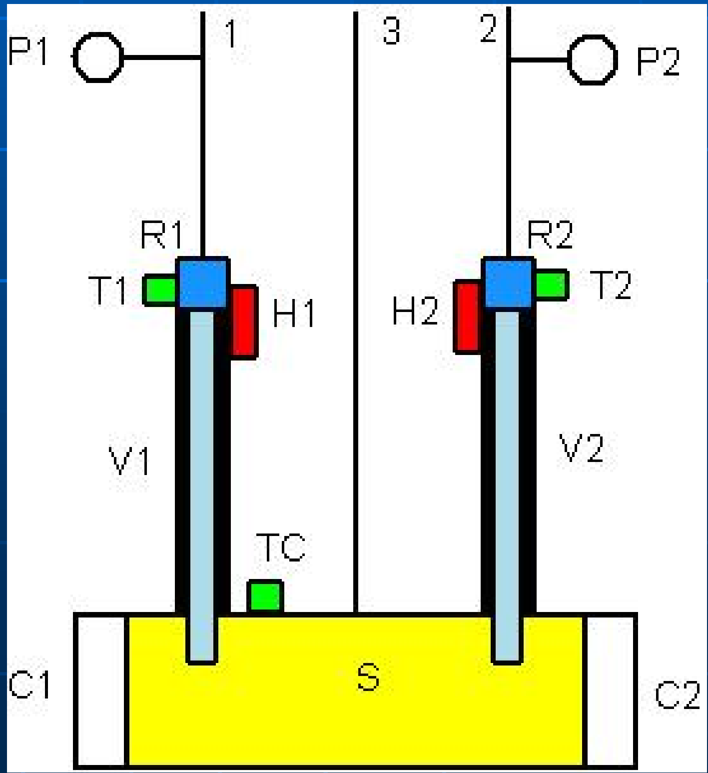
Doubtful we have annealing at 600 mK, but we do not have proof. (No evidence for pressure shifts of the sort seen very close to the MC.)

Perhaps something happens between 400 mK And 600 mK.

Another experiment:

Create sample at ~ 500 mK, push, observe flow
Remain at 500 mK, push, see flow, but smaller
Cool to ~ 360 mK, push, <u>see flow</u>, but <u>*larger*</u>
Warm to ~ 500 mK, push, see very small flow

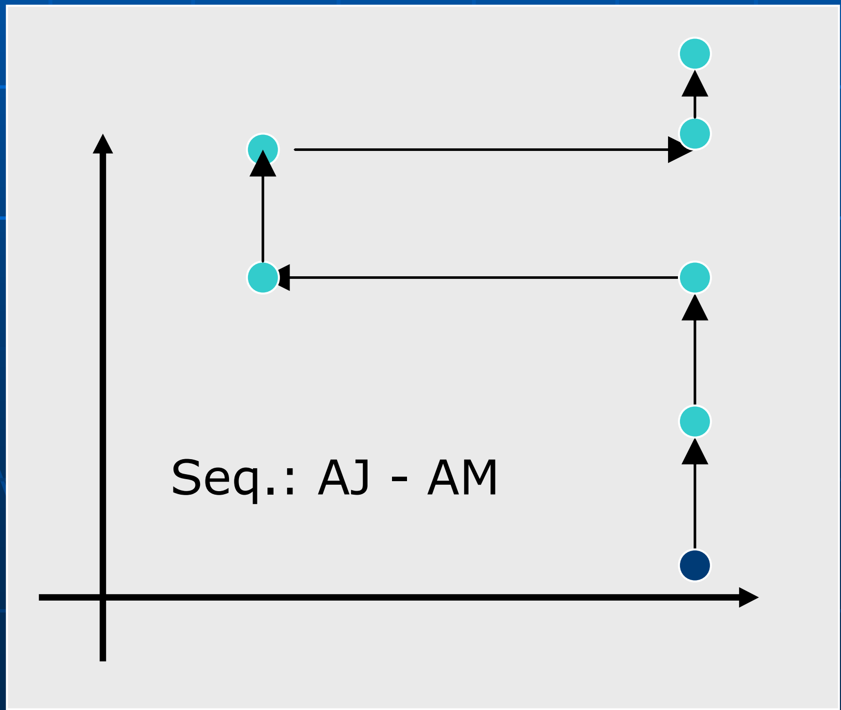


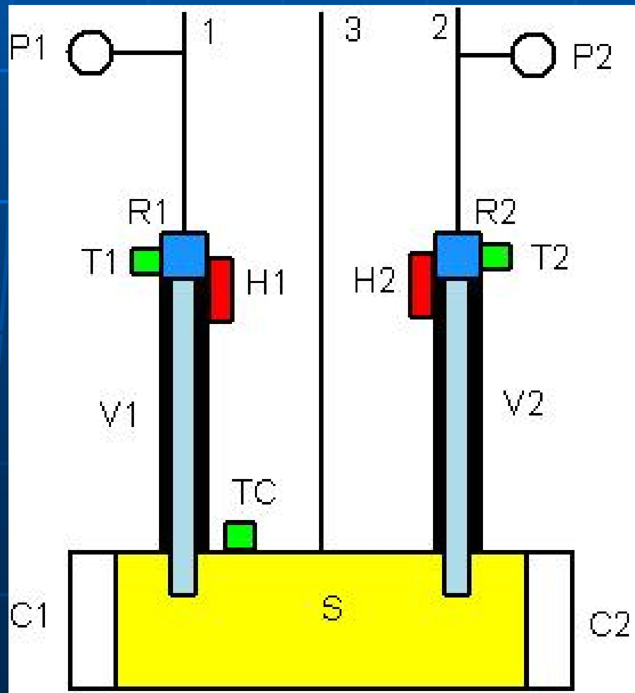


We need to repeat this sequence, but his suggests

There is indeed temperature and pressure dependence to the flow.

In this pressure regime, something may change between 500 mK and 600 mK. Passing 600 mK changes things. We doubt that this is due to annealing.



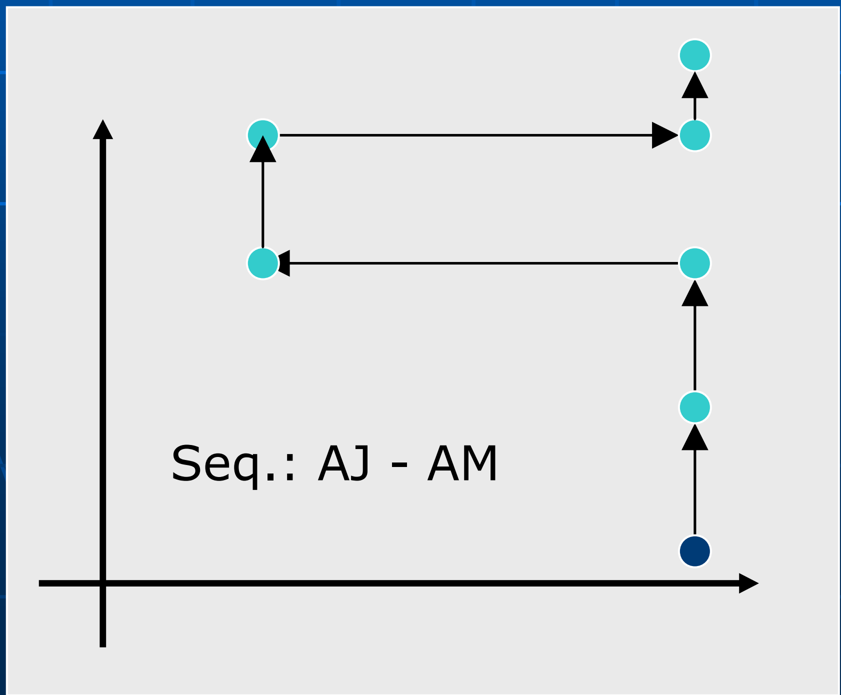


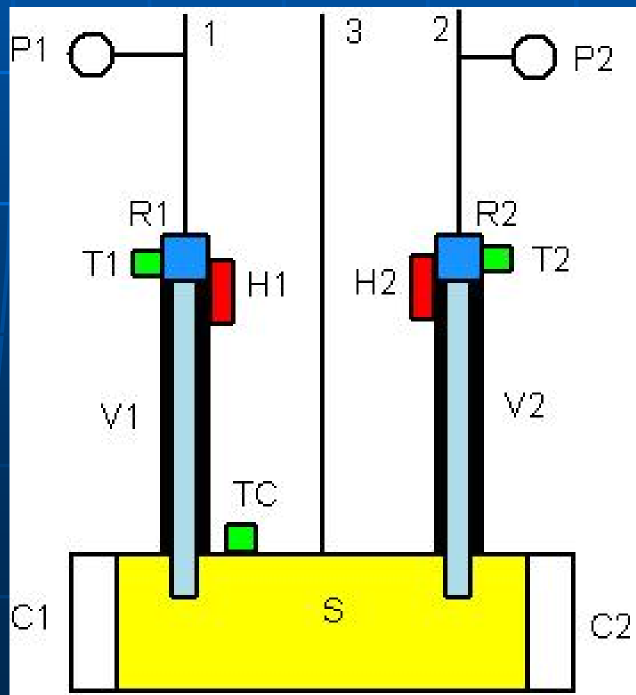
We need to repeat this sequence, but his suggests

There is indeed temperature and pressure dependence to the flow.

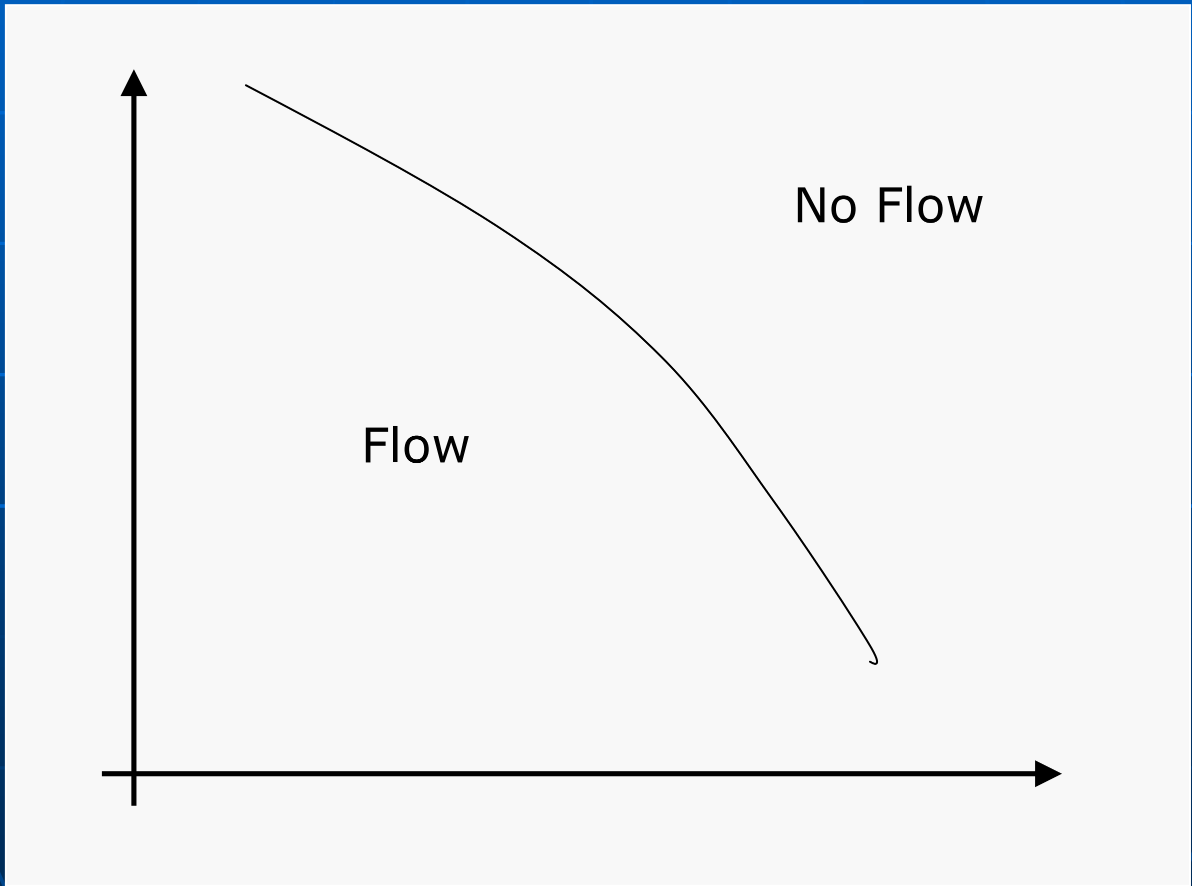
In this pressure regime, something changes between 500 mK and 600 mK. Passing 600 mK changes things. We doubt that this is due to annealing.

A possiblity is that we are seeing evidence for hysteretic behavior.

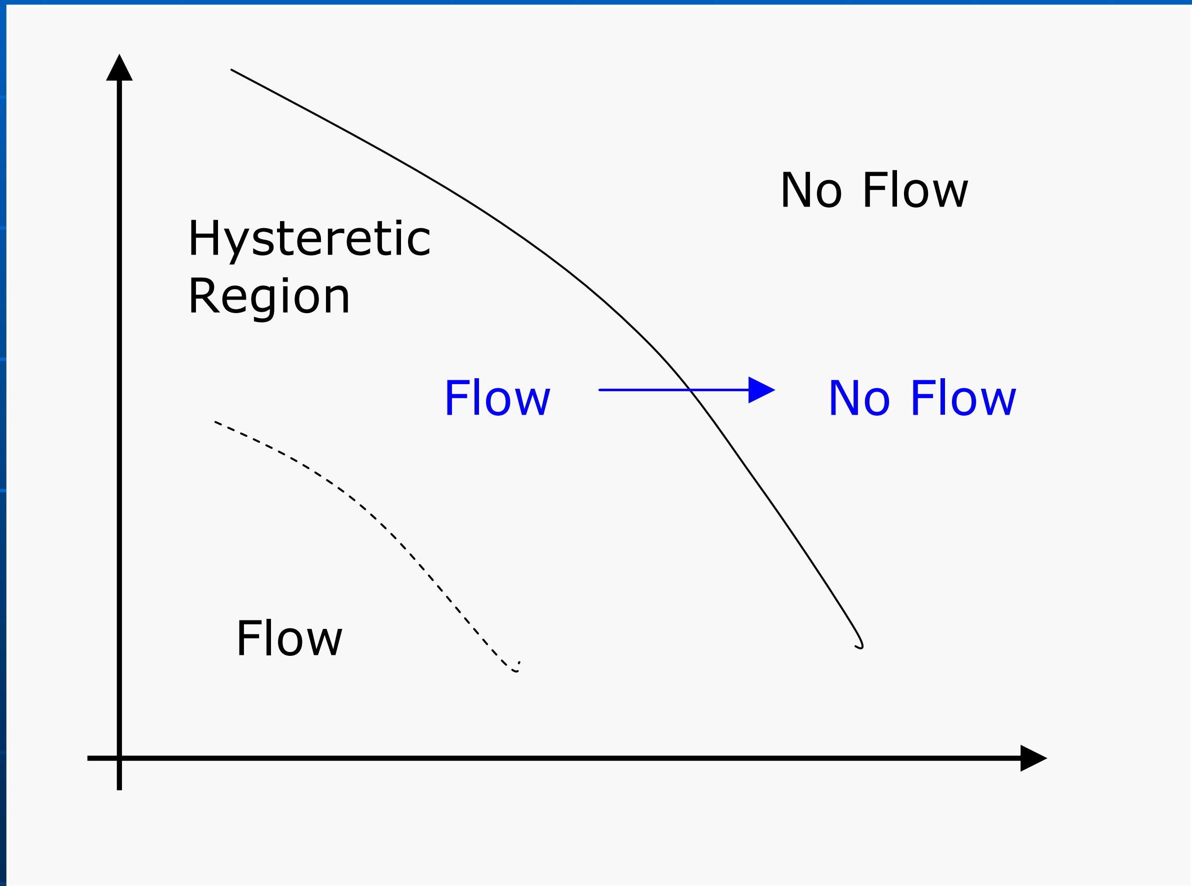




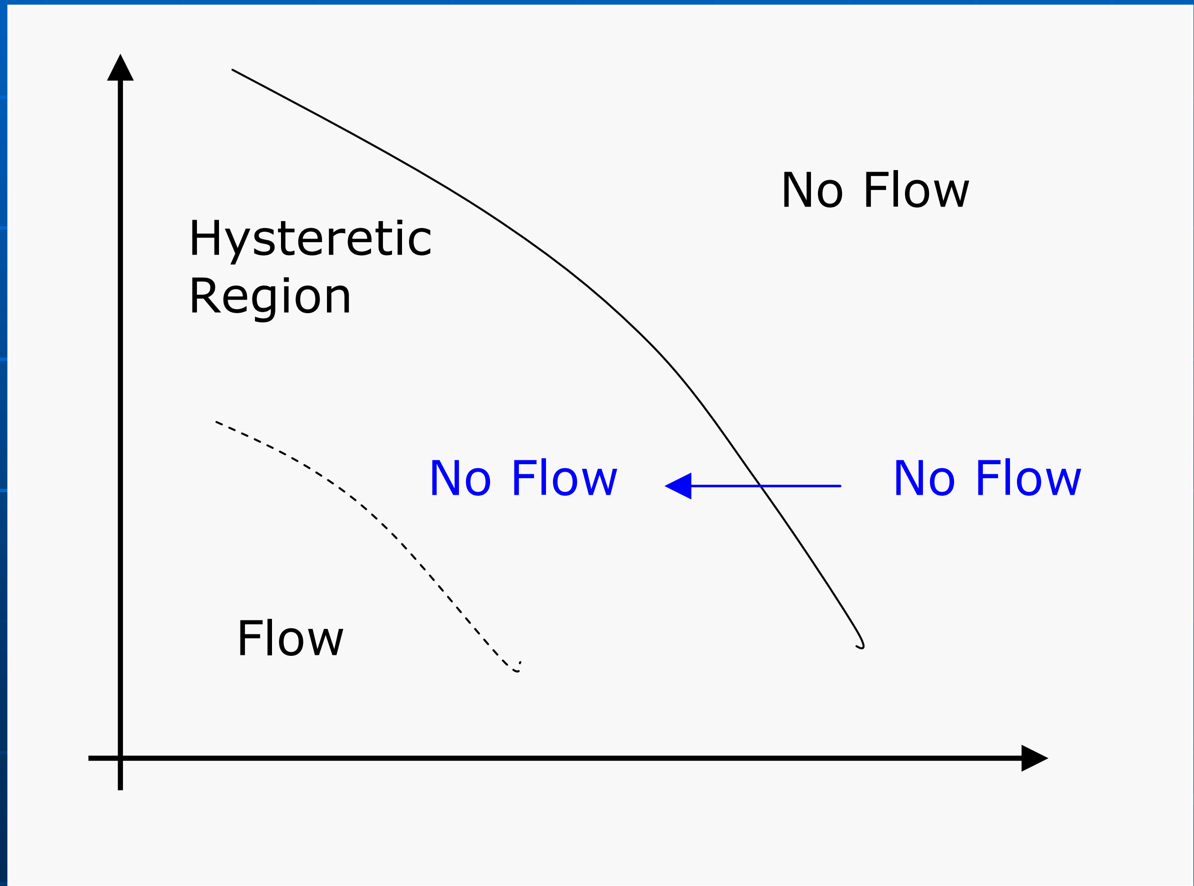
So, if we think in terms of a superfluid this may be too simple:



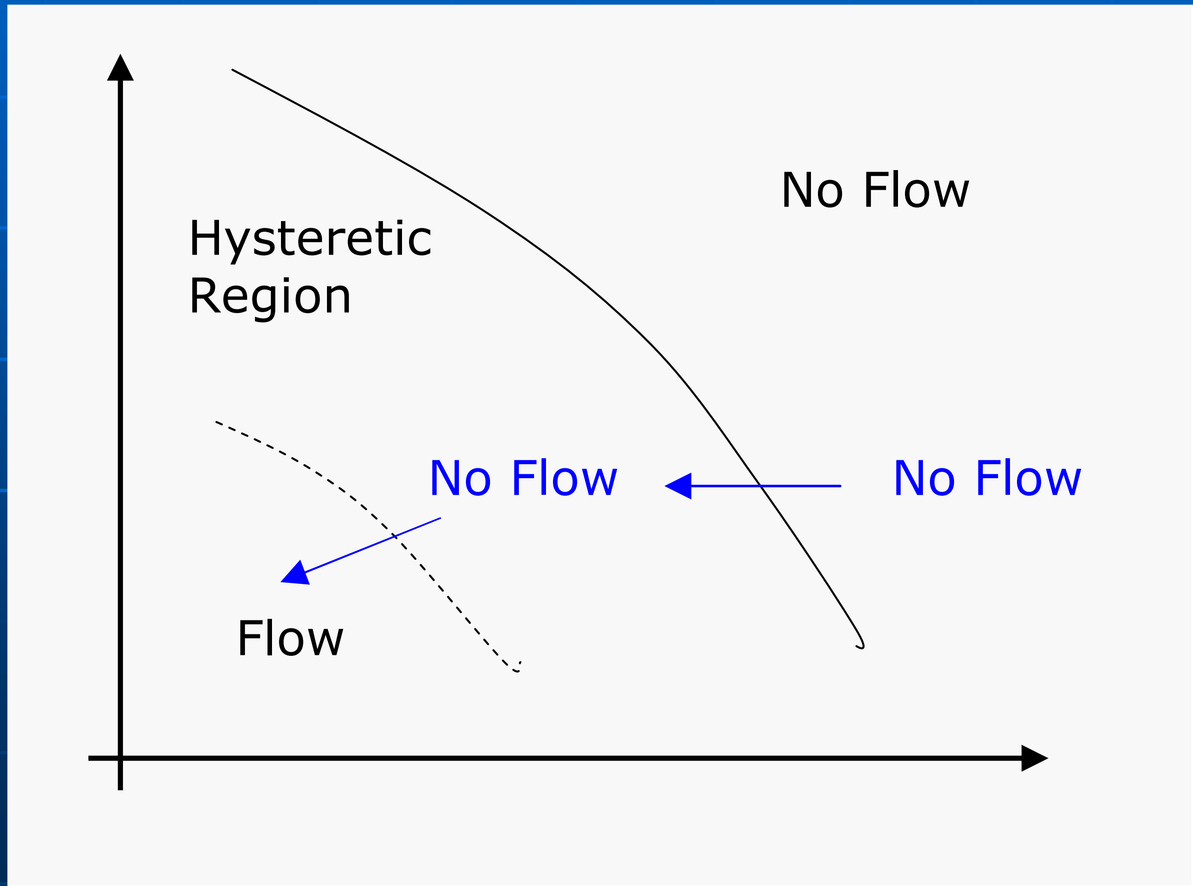
So, if we think in terms of the most recent experiments we have done we are led to think that maybe we have:



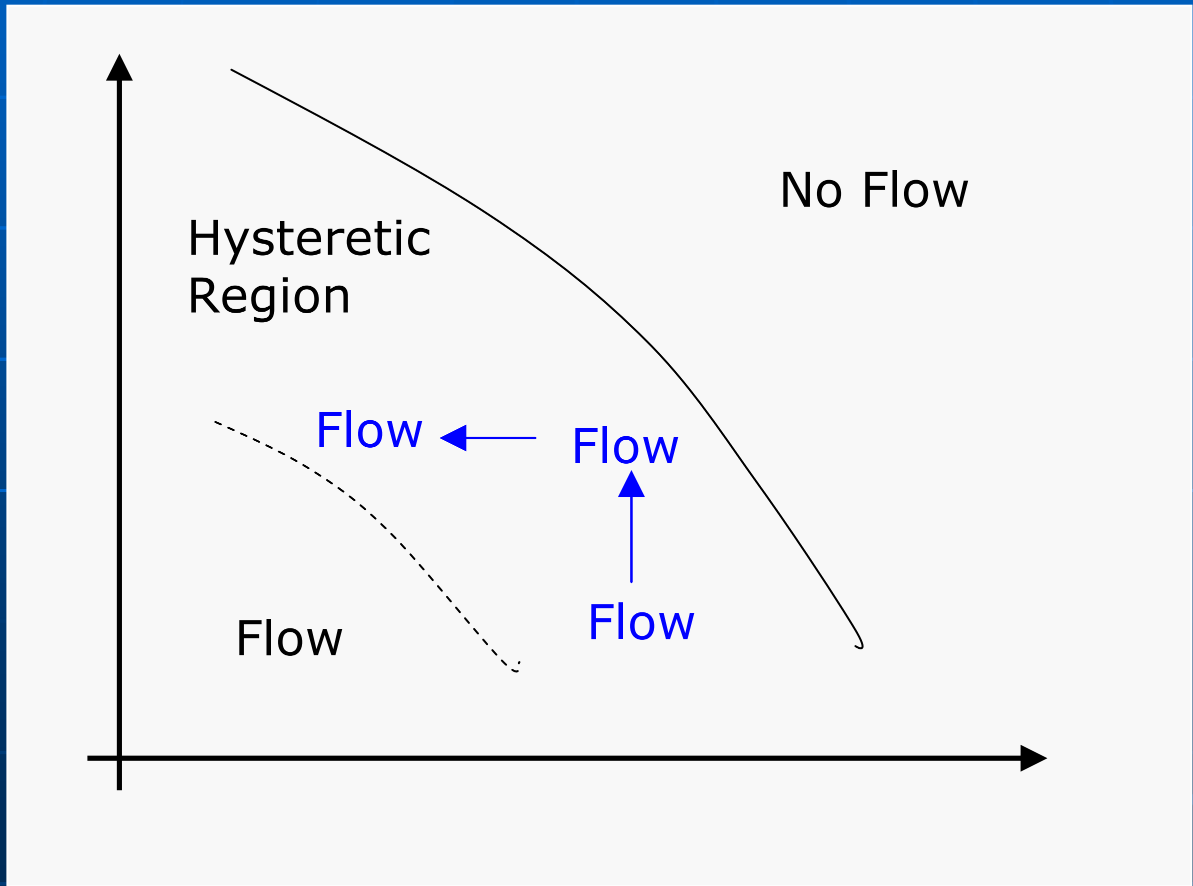
So, if we think in terms of the most recent experiments we have done we are led to think that maybe we have:



So, if we think in terms of the most recent experiments we have done we are led to think that maybe we have:



So, if we think in terms of the most recent experiments we have done we are led to think that maybe we have:



Flow in Liquid channels?

Should remain above 1.5 K (presuming the liquid channel does not anneal away). At the pressures we have studied, no long term flow is ever seen above 600 mK, under any conditions.

Should be pressure dependent. Yes, it is.

Flow along dislocations, grain boundaries?

May have a temperature at which behavior Changes that depends on pressure.
500 mK – 400 mK case is very suggestive.

Plastic flow?

Would not be a linear change in P2 as a function of time.   Not plastic flow.

Conclusions:

We have seen clear evidence for the flow of helium atoms though a cell that is filled with solid ^4He in the hcp region of the phase diagram.

Growth from superfluid or blocked capillary shows qualitatively similar behavior.

We believe that there is considerable evidence to suggest that liquid channels of the sort reported by Sasaki et al. may not be responsible for the behavior that we see.

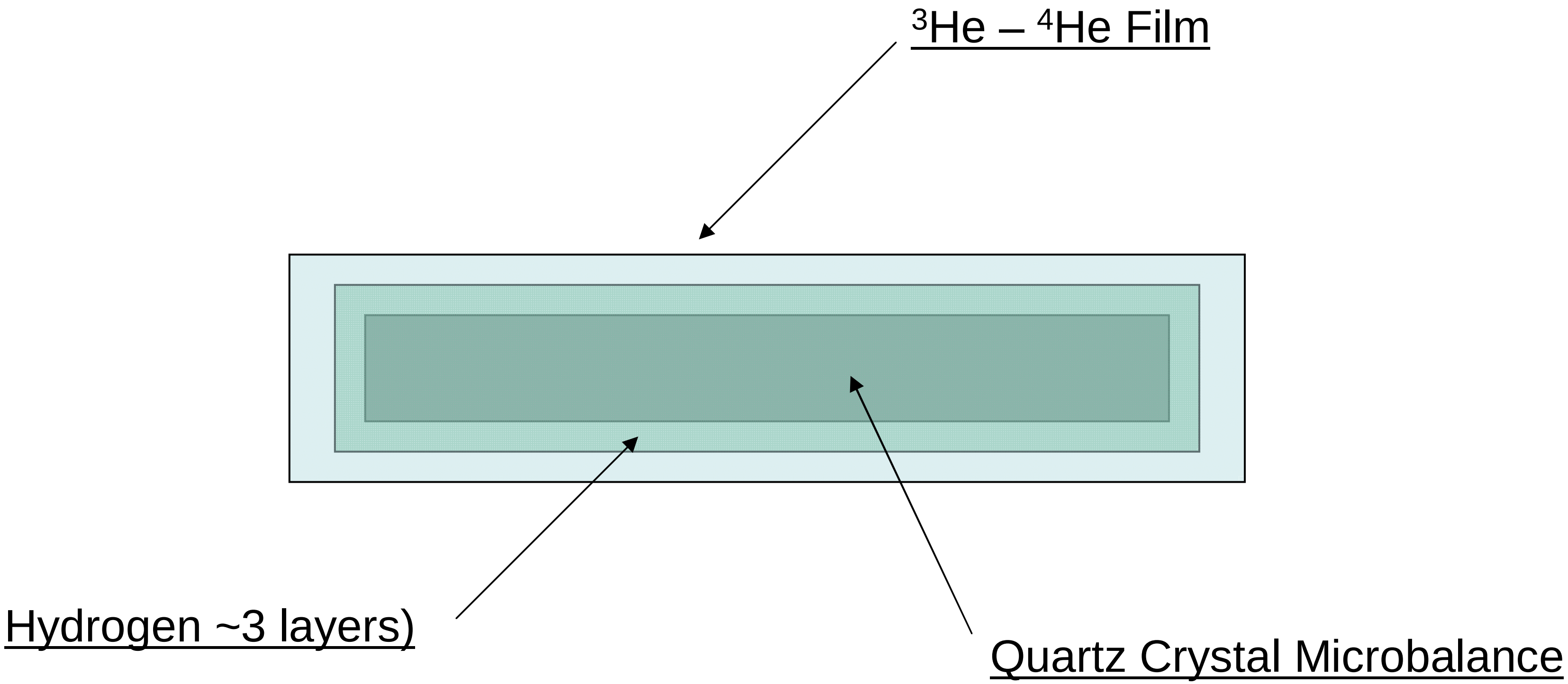
Not yet proven, hysteresis is consistent with the observations.

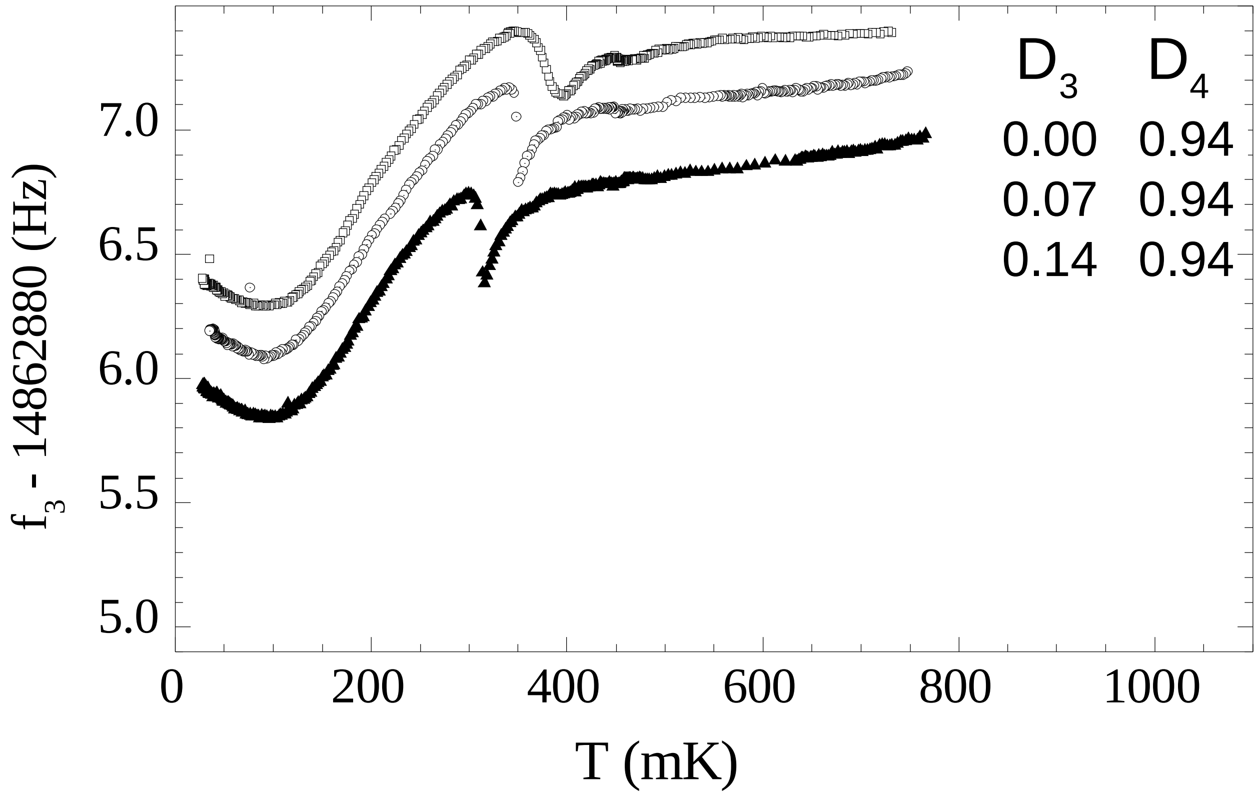
Thank you.

Experiments with 3He – 4He Mixture Films*

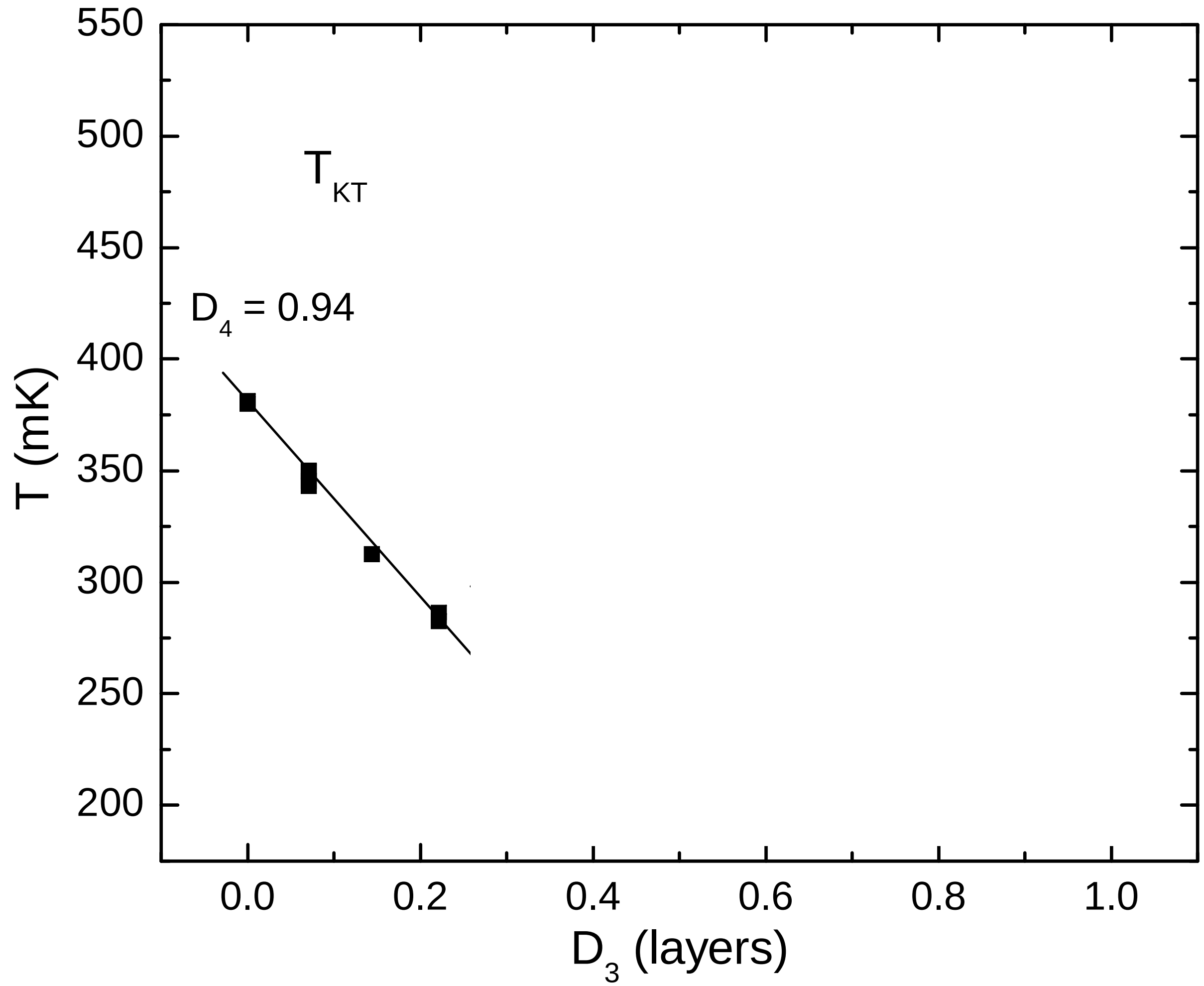
P.T. Finley, P.S. Ebey, and R.B. Hallock

*Phys. Rev. Letters, 98, 265301 (2007)

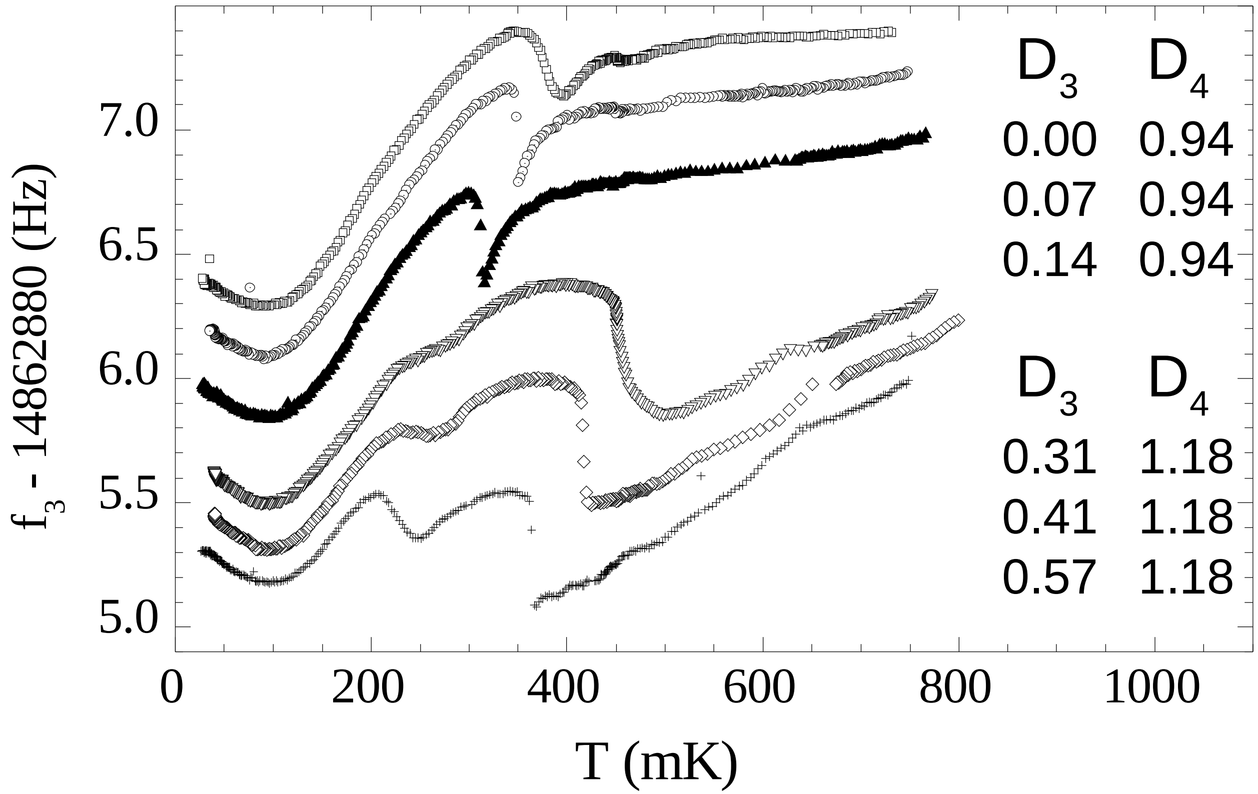

^{3}He – ^{4}He Film
Hydrogen ~3 layers)
Quartz Crystal Microbalance



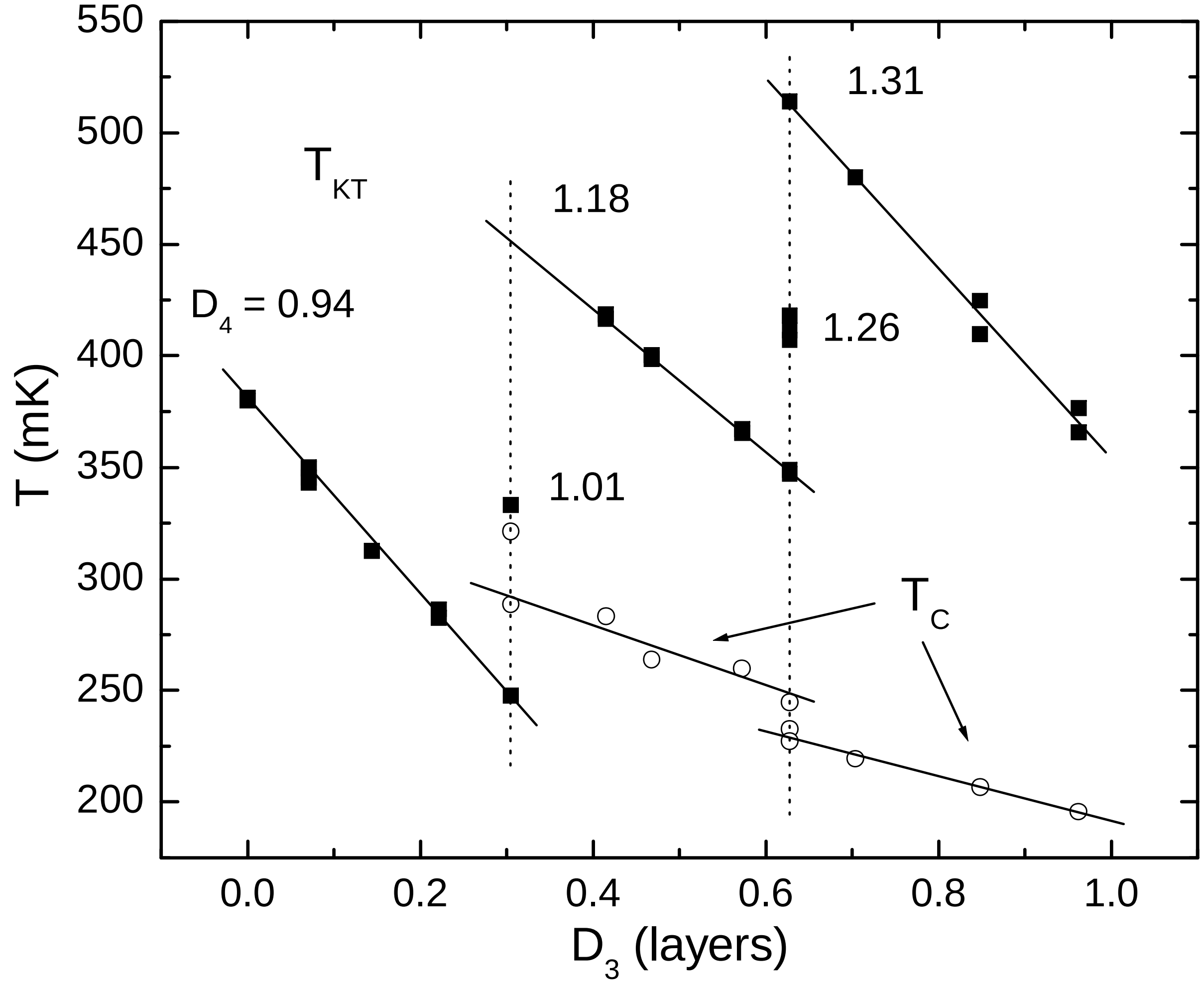
D3 D4
0.00 0.94
0.07 0.94
0.14 0.94
7.0
6.5
6.0
5.5
5.0
0
200
400
600
800
1000
f3 - 14862880 (Hz)
T (mK)



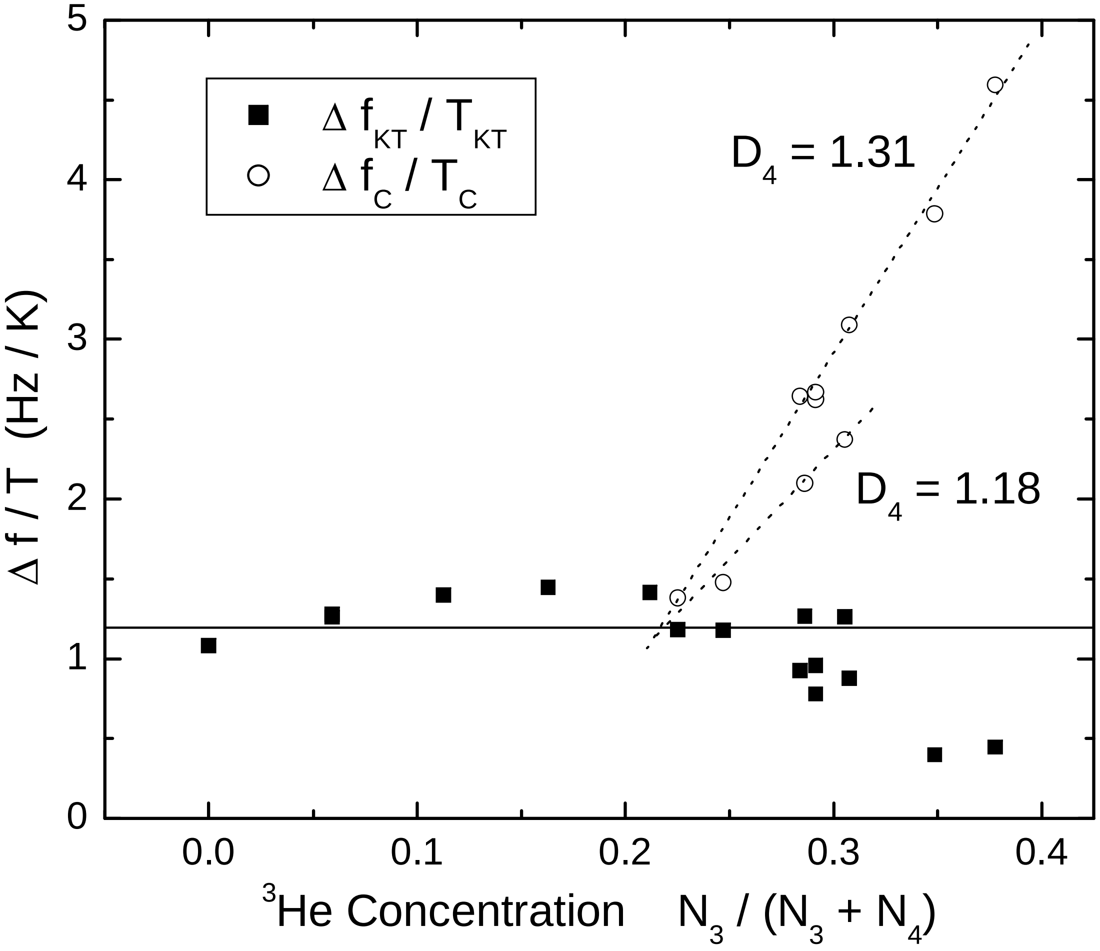
550
500
450
400
350
300
250
200
T (mK)
T$_{KT}$
D$_4$ = 0.94
0.0
0.2
0.4
0.6
0.8
1.0
D$_3$ (layers)



f_3 - 14862880 (Hz)
T (mK)
7.0
6.5
6.0
5.5
5.0
0
200
400
600
800
1000
D_3 D_4
0.00 0.94
0.07 0.94
0.14 0.94
D_3 D_4
0.31 1.18
0.41 1.18
0.57 1.18



T (mK)
D3 (layers)
TKT
TC
D4 = 0.94
1.01
1.18
1.26
1.31



Δ f / T (Hz / K)
^{3}He Concentration N$_3$ / (N$_3$ + N$_4$)
Δ f$_{KT}$ / T$_{KT}$
Δ f$_C$ / T$_C$
D$_4$ = 1.31
D$_4$ = 1.18
0
1
2
3
4
5
0.0
0.1
0.2
0.3
0.4