Workshop on Supersolid 2008

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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

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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.

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

<table>
<thead>
<tr>
<th>Sample</th>
<th>$P_{\text{bottom}}$ (bar)</th>
<th>$P_{\text{bottom}} - P_{\text{top}}$ (bar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25.77</td>
<td>-1.25</td>
</tr>
<tr>
<td>2</td>
<td>27.98</td>
<td>0.24</td>
</tr>
<tr>
<td>3</td>
<td>32.79</td>
<td>1.21</td>
</tr>
<tr>
<td>4</td>
<td>38.48</td>
<td>1.37</td>
</tr>
<tr>
<td>5</td>
<td>49.16</td>
<td>-2.12</td>
</tr>
</tbody>
</table>

Images and data set provided, thanks to John Beamish (Minnesota Workshop, 2007)
A melting curve experiment*:

No Flow

Some more melting curve experiments*:

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

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

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.
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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

We utilize this fact and create a sandwich:

- Liquid Helium in Vycor
- Solid Helium
- Bulk Liquid Helium
- Capillary to add, subtract helium
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- Liquid Helium in Vycor
- Solid Helium
- Bulk Liquid Helium
- Capillary to add, subtract helium

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:

Liquid Helium in Vycor

Solid Helium

ΔT

Bulk Liquid Helium

ΔT

Capillary to add, subtract helium

We must apply a temperature gradient across the Vycor sections for the solid to be off the melting curve.
Vycor diameter = 0.152 cm

Capacitor

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.

We will expand this region.

TC = 370 mK
Expanded view.

![Diagram showing experimental setup and data over time](image)

- **Pcell (bar)**
- **C1**
- **C2**
- **δ(TC)**

**TC = 370 mK**
Temperature spikes and pressure shifts on and very near to the melting curve.

Temperature transients: $\sim 2 \text{ mK}$

Pressure drops: $\sim 50 \text{ mbar}$

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: $\sim 2 \text{ mK}$

Pressure drops: $\sim 50 \text{ mbar}$

Liquid converting to solid?

Melting curve slope is small: $300 - 750 \text{ mK}$ yields $8 \text{ mbar drop}$.

Also work done as $PdV$. 
Temperature spikes and pressure shifts on and very near to the melting curve.

Temperature transients: $\sim 2$ mK

Pressure drops: $\sim 50$ mbar

Dislocations disappearing?

Grain boundaries disappearing?

Dislocation: diameter $\sim 5 \times 10^{-8}$ cm
Energy: $7.7 \times 10^{-16}$ J/cm
Need: $4.5 \times 10^9$ cm of dislocations

Assume $\sim 1$ K/atom along a defect.

Grain Boundary: thickness $\sim 5 \times 10^{-8}$ cm
Need: $175$ cm$^2$ of grain boundaries
Temperature spikes and pressure shifts on and very near to the melting curve.

Temperature transients: $\sim 2$ mK

Pressure drops: $\sim 50$ 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:

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

1 $\times 10^{-4}$ grams of $^4$He moved from line 1 to line 2 (in 20 hours, which is $1.4 \times 10^{-9}$ g/sec)
4.5 $\times 10^{-4}$ 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:

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

If $V = 100 \mu$m/sec, then $\xi = 2.5 \times 10^{-6}$
Quantitative detail – discrete structures conduct:

Either a line or a plane with one thickness, $x = 0.5 \text{ nm}$

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

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

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

If structures are $0.5 \text{ nm} \times 0.5 \text{ nm}$, then we need
$\sim 1.6 \times 10^4$ pipe-like conduits.

This would be a density $\sim 5.0 \times 10^4 \text{ cm}^{-2}$.
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 $V = 100$ $\mu$m/sec, then $Y = 16$ cm

If structures are 0.5 nm x 0.5 nm, then we need
$\sim 1.6 \times 10^4$ ($\sim 3.2 \times 10^8$) pipe-like conduits.

This would be a density $\sim 5.0 \times 10^4$ cm$^{-2}$ ($\sim 1.0 \times 10^9$ cm$^{-2}$).
Another Example Interpreted as Evidence for “Flow”

Pressure (bar) vs. time (minutes)

C1, C2

Sample AO

P1

P2

T_{cell} = 359 \text{ mK}
Quantitative detail (Sample AO)– full cross section conducts:

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

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

Assume full cross section is available:

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

If $V = 100 \ \mu\text{m/sec}$, 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, \( \xi VY = 0.26 \text{ cm}^2 / \text{sec} \)

If \( \xi = 1 \), then \( VY = 0.26 \text{ cm}^2/\text{sec} \)

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

If structures are 0.5 nm \( \times \) 0.5 nm, then we need
\( \sim 2.6 \times 10^4 \) pipe-like conduits.

This would be a density \( \sim 8.2 \times 10^4 \text{ cm}^{-2} \).
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 \( V = 100 \) \( \mu \)m/sec, then \( Y = 26 \) cm

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

This would be a density \( \sim 8.2 \times 10^4 \) cm\(^{-2}\) (~\( 1.6 \times 10^9 \) 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”

Sample D

P1

P2

C1

T_{cell} = 285 mK
Another: Interpreted as Long-term “No Flow”
\( \frac{(dP_2}{dt})}{(P_1 - P_2)} \) 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, see flow, but larger
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 possibility 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:
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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 $^4\text{He}$ 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

Quartz Crystal Microbalance

Hydrogen ~3 layers

$^3\text{He} - ^4\text{He}$ Film

Quartz Crystal Microbalance
$D_4 = 0.94$

$T_{KT}$
$T_{KT}$

$D_4 = 0.94$

$T_C$

$D_3$ (layers)

$T$ (mK)
\[ D_4 = 1.31 \]

\[ D_4 = 1.18 \]

\[ \Delta f / T \ (\text{Hz/K}) \]

\[ \Delta f_{KT} / T_{KT} \]

\[ \Delta f_{C} / T_{C} \]

\[ \text{\[^3\text{He} \text{ Concentration}] \ N_3 / (N_3 + N_4) \] }