Solid Helium: Defects, Deformation and Flow

John Beamish and Zhigang Cheng
University of Alberta

A Fefferman, A Haziot, X Rojas, F Souris and S Balibar
Laboratoire de Physique Statistique de l'ENS

QFS 2015 Niagara Falls August 7, 2015

Outline

defects in solid ^{4}He:

dislocations and “giant plasticity”:

low temperature flow - three experiments

open questions, challenges, ideas

Defects in classical and quantum crystals

Point defects:

- Vacancies
- Impurities (i.e. ^3He atoms in ^4He)

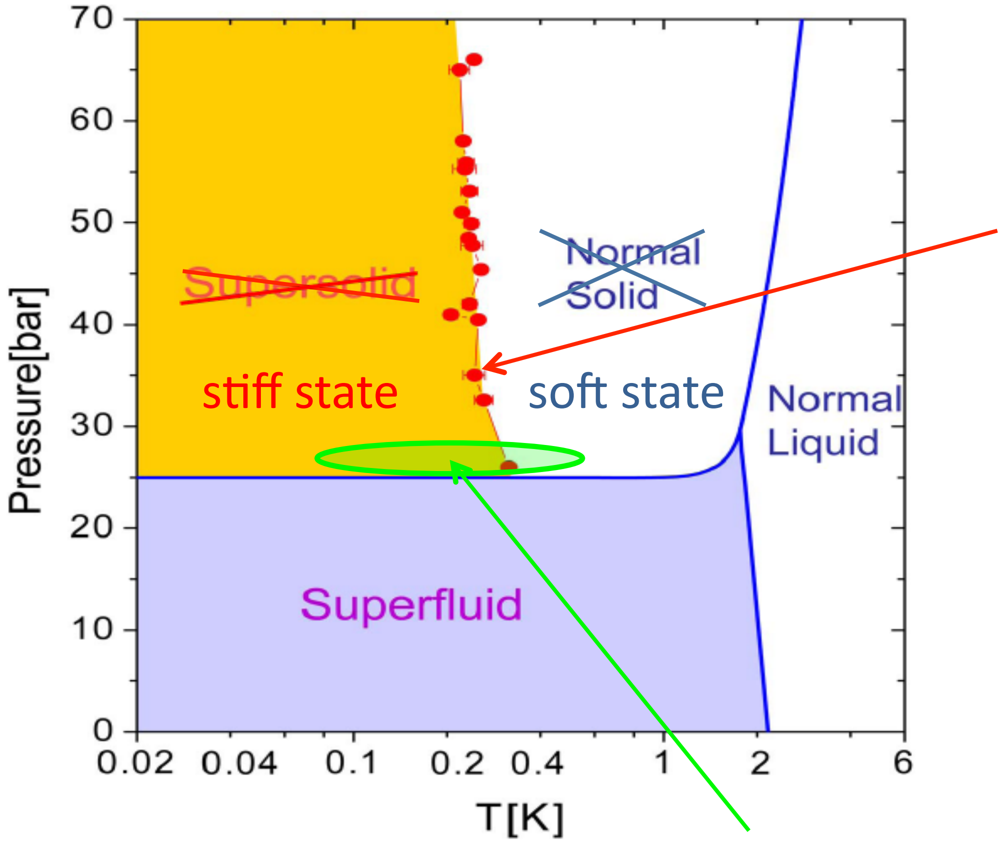
1D line defects: dislocations

- Glide, Peierls potential and kinks
- Impurity pinning by ^3He
- Jogs, climb and superclimb

2D defects:

- Stacking faults
- Grain boundaries

Solid ^{4}He (Kim and Chan 2004)



U Alberta and ENS (2007-15)

elastic stiffening, "giant plasticity"

- dislocations reduce μ at high T
- ^{3}He pins dislocations at low T

(Andrew Fefferman - QFS talk)

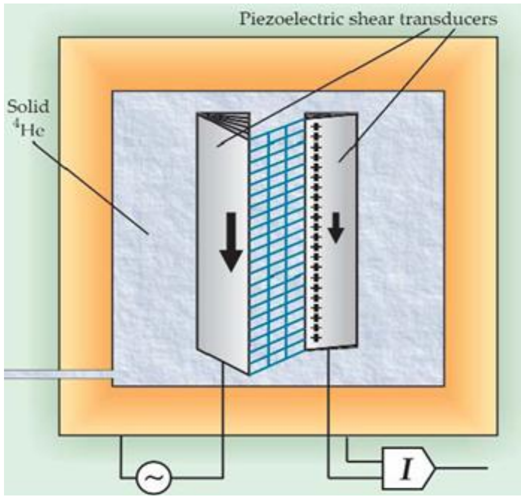
UMass (2008-15): flow!

- appears below 600 mK
- disappears above about 27 bar
- drops/disappears below about 100 mK (depends on X_3)

(Bob Hallock)

Elastic Shear Modulus

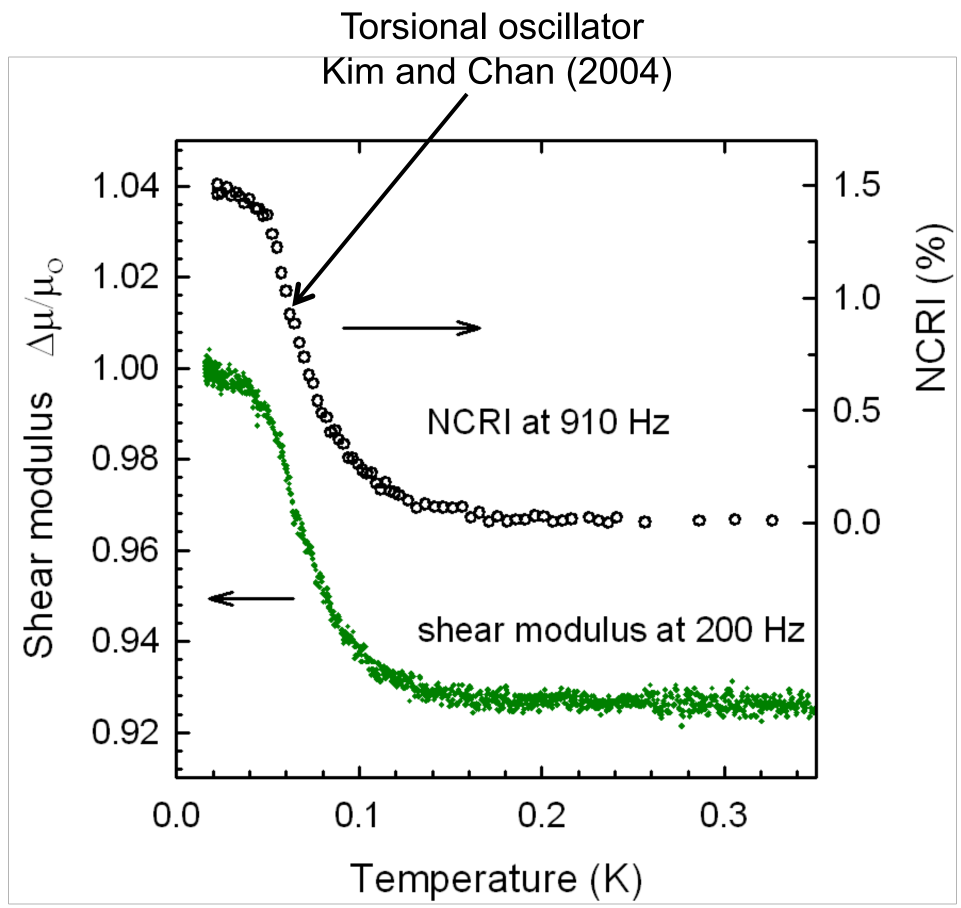
Day and Beamish (2007)



shear strain $\epsilon \propto$ voltage V

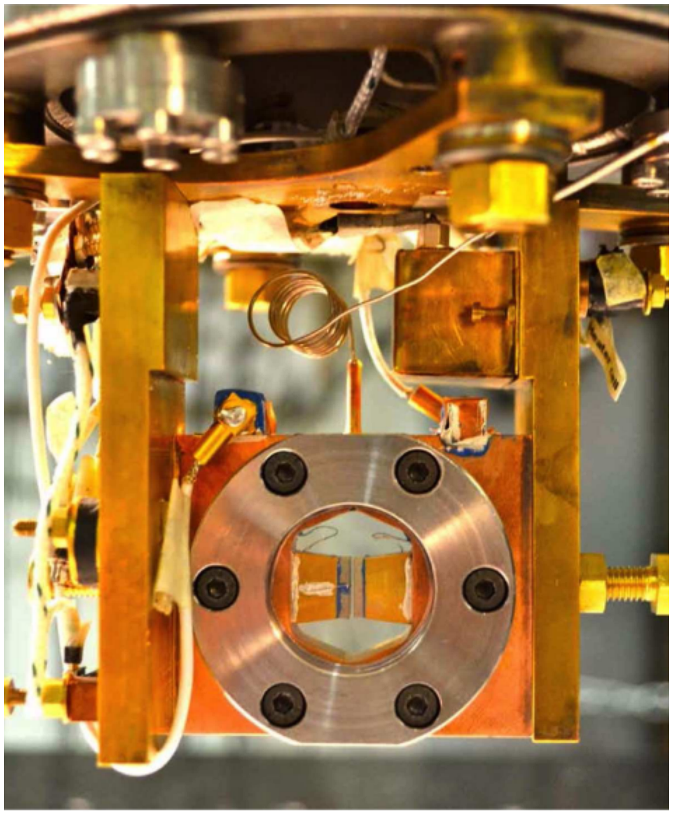
stress $\sigma \propto$ charge $q \sim i/f$

$$\mu = \sigma/\epsilon \propto i/fV$$



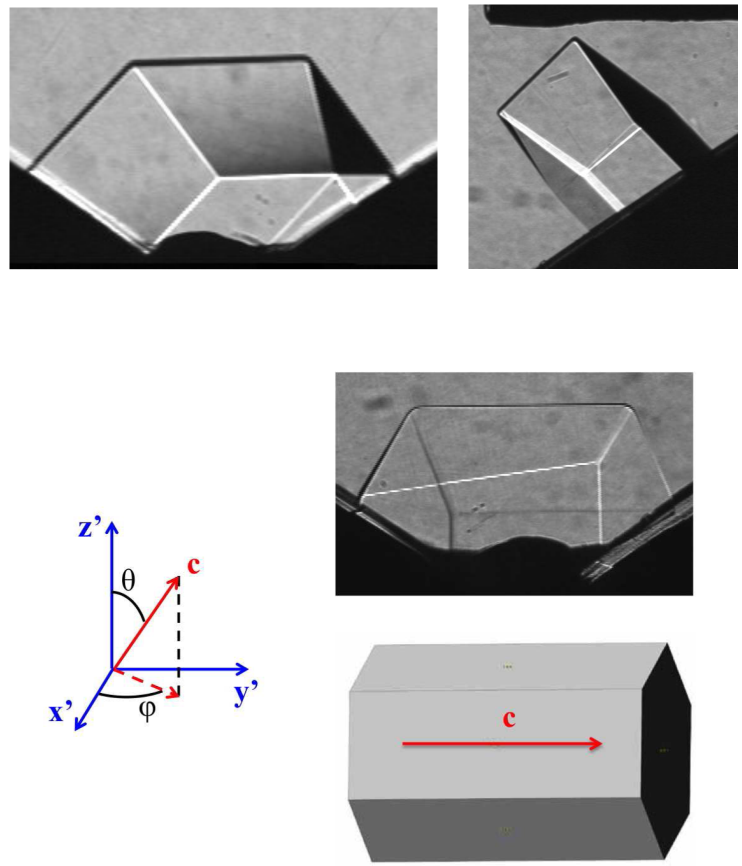
Elastic changes produce the torsional oscillator anomalies

Growth of single crystals from superfluid

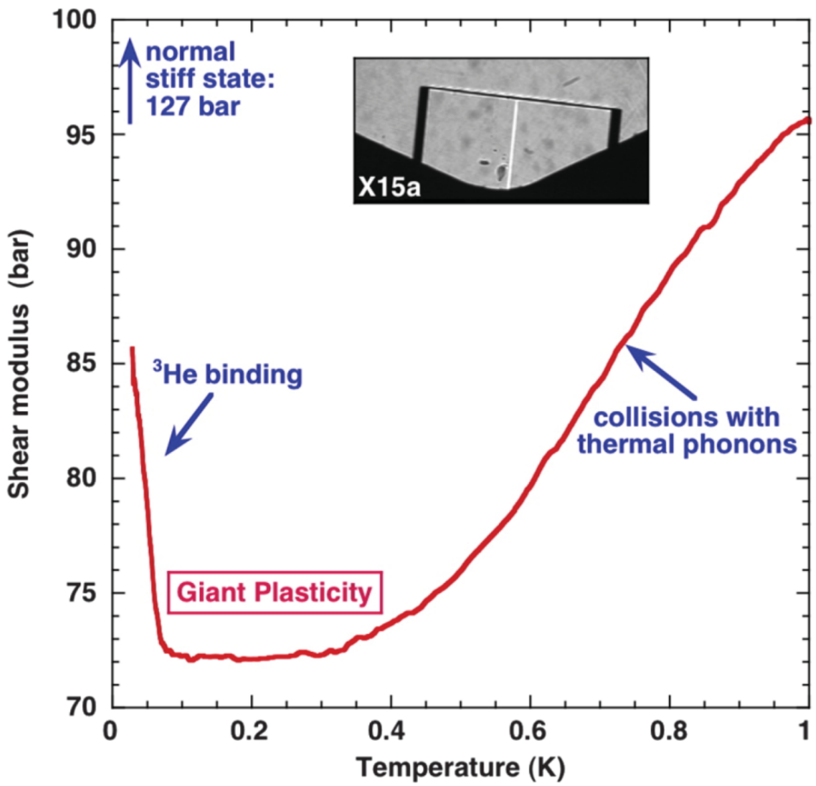


Balibar lab, ENS Paris

crystal orientations
from growth facets



Giant Plasticity in ^{4}He single crystals
(ENS Paris experiments)



dislocation densities $\Lambda \sim 10^5/cm^2$

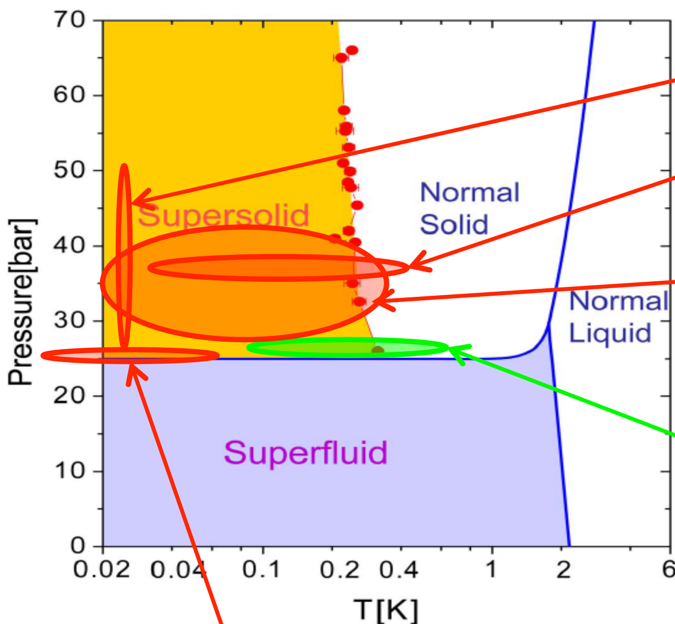
dislocation lengths $L_N \sim 200\ \mu m$

^{3}He binding energy $E_B \sim 0.7$ K

^{3}He mobile for $v < 45\ \mu m/s$

Dislocations in ^{4}He are extremely mobile and move at macroscopic speeds

Flow experiments in solid ^{4}He



Greywall (1977): no flow

Day and Beamish (2006): no flow

Rittner and Reppy (2009): no flow

Hallock, Ray and Vekhov (2008-15): flow!

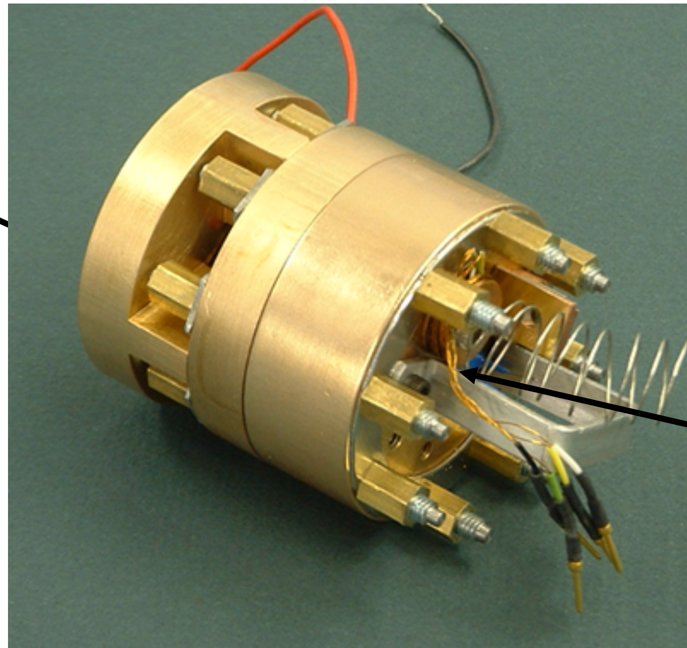
Bonfait, Godfrin and Castaing (1989): no flow to 4 mK

Sasaki et al. (2006/07): flow in some crystals with grain boundaries (liquid channels)

(No) flow experiment #1

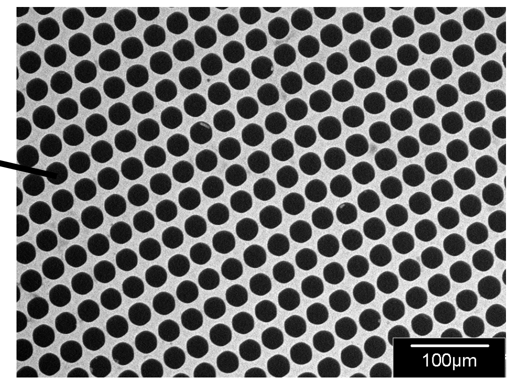
(Day and Beamish 2006)

PZT stack



pressure capacitor

$\delta P \sim 20\ \mu bar \Rightarrow \delta x \sim 0.1\ nm$



Diaphragm (squeeze):

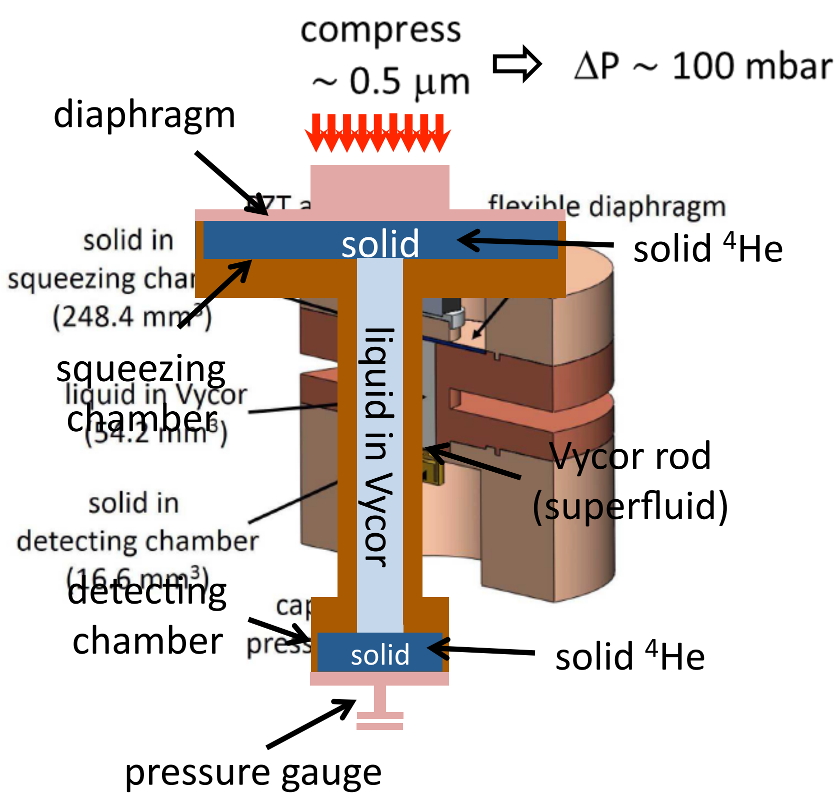
$\Delta X \sim 1\ \mu m \Rightarrow \Delta P \sim 100\ mbar$

GCA: 36,000 holes
25 μm diameter
3 mm long

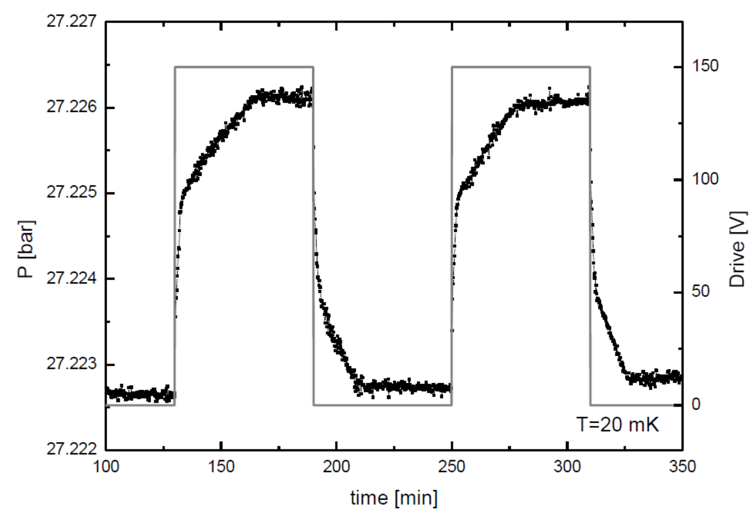
flex: **$\Delta P \sim 100\ mbar \Rightarrow \Delta x \sim 30\ nm$**

Flow experiment #2: solid-superfluid-solid junction

(Z Cheng, A Fefferman et al. UAlberta/ENS PRL 2015)



“inverse UMass sandwich”

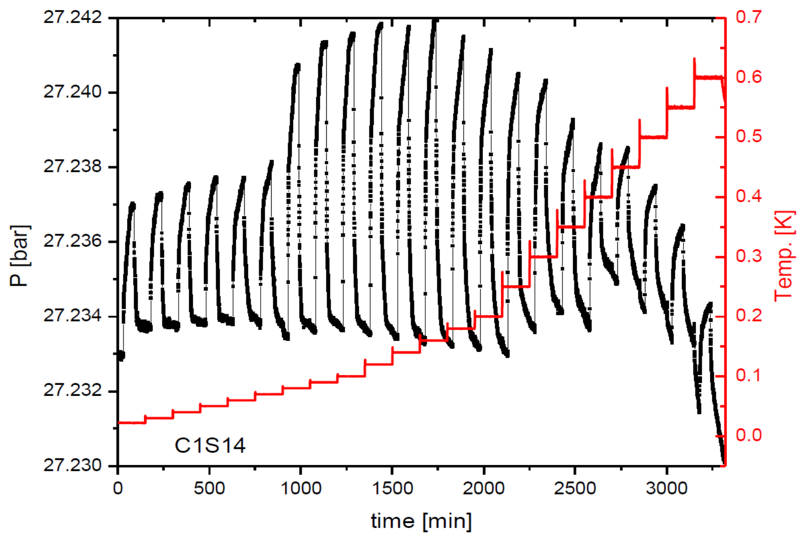


P = 27.3 bar, 120 ppb ^{3}He

“squeeze” and “unsqueeze”

constant flow (linear) regions

Temperature dependence of flow

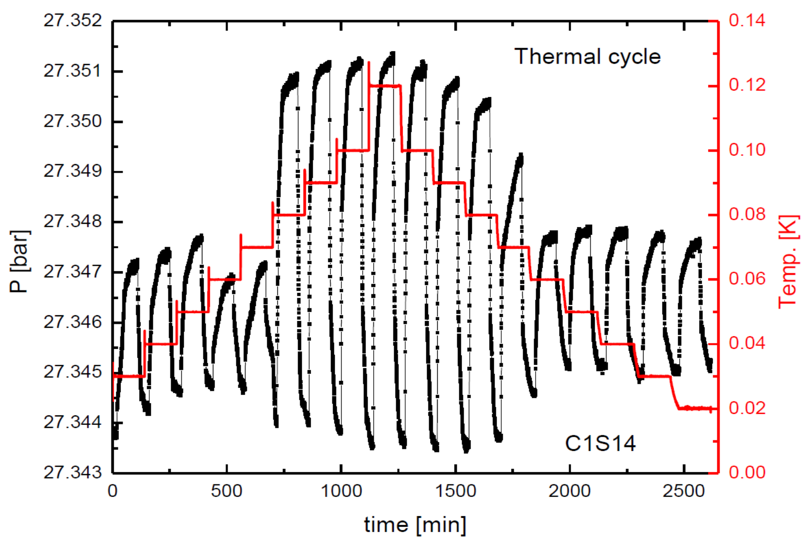


P = 27.3 bar, 120 ppm ^{3}He

flow increases suddenly at 75 mK

pressure change ~ 9 mbar
(<< than at highT)

flow disappears above ~ 600 mK

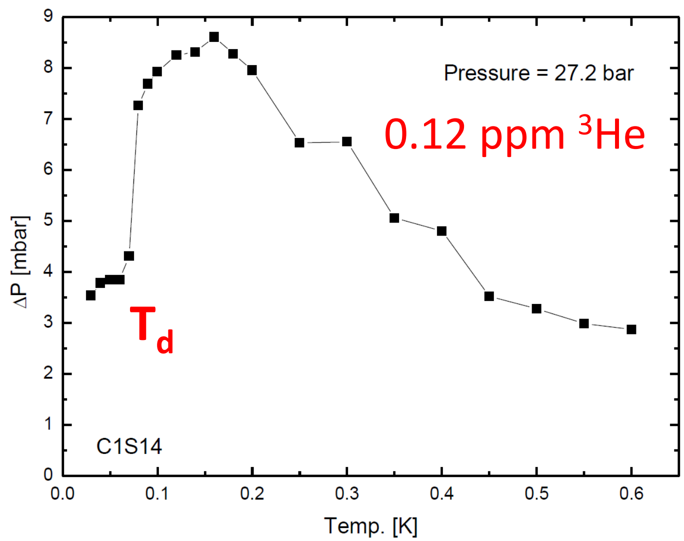


thermal cycling

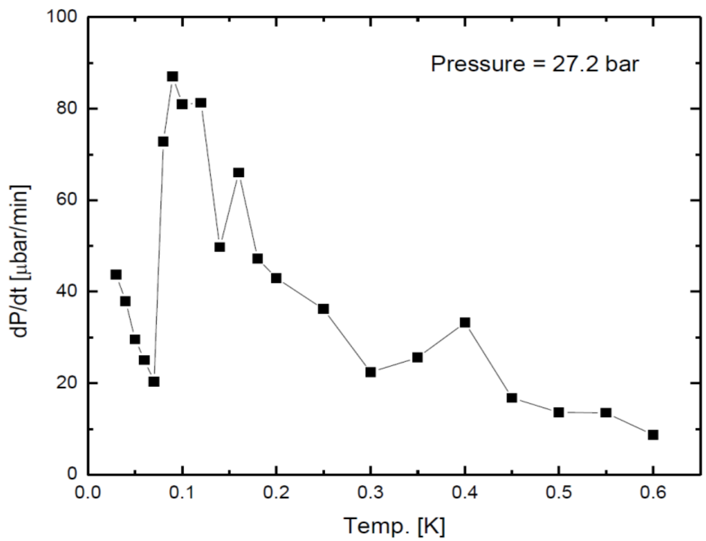
flow change at 75 mK is ~reversible

warming above 600 mK
does not destroy flow

Pressure response vs. flow



ΔP total pressure change



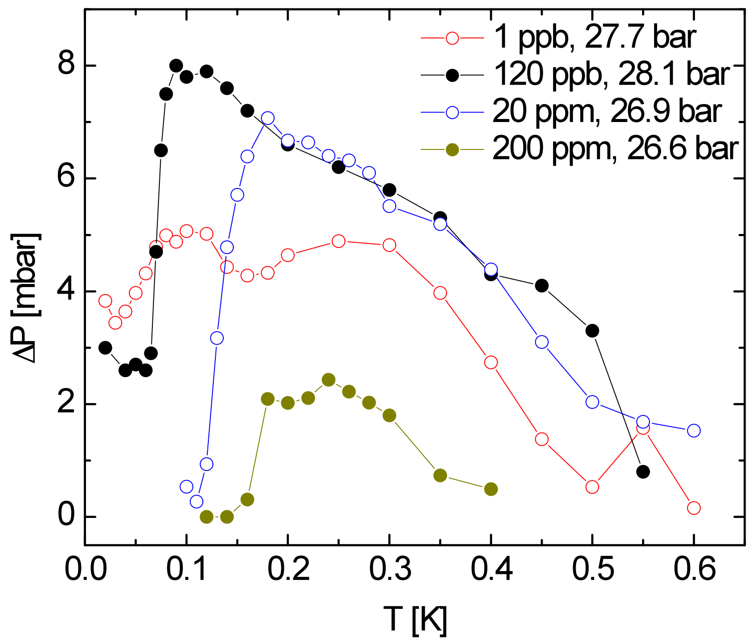
$\frac{dP}{dT}$ similar T dependence but:

- bigger drop around T_d
- increasing flow below T_d

only observed between 25.4 and 28.2 bar

ΔP varies (~2 to 11 mbar) between samples

^{3}He dependence



T_d increases with X_3

^{3}He suppresses flow below T_d

Where does the ^{3}He go at low temperature?

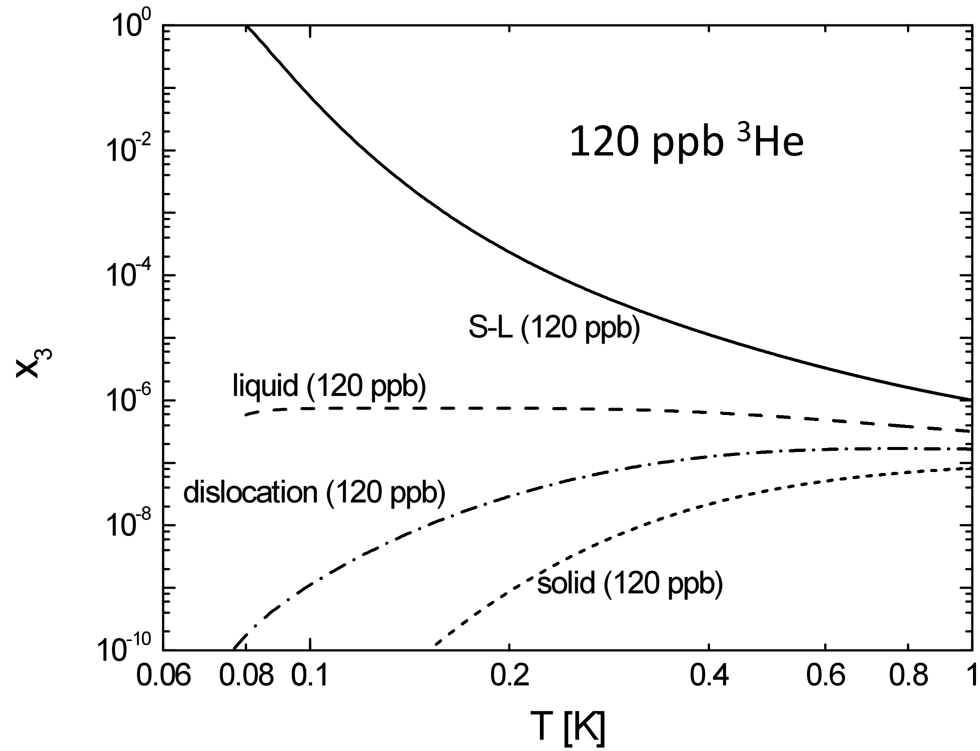
^{3}He binding energies

bulk solid — $E_s = 0$ K

dislocation — $E_{dis} = -0.7$ K

liquid — $E_l = -1.36$ K

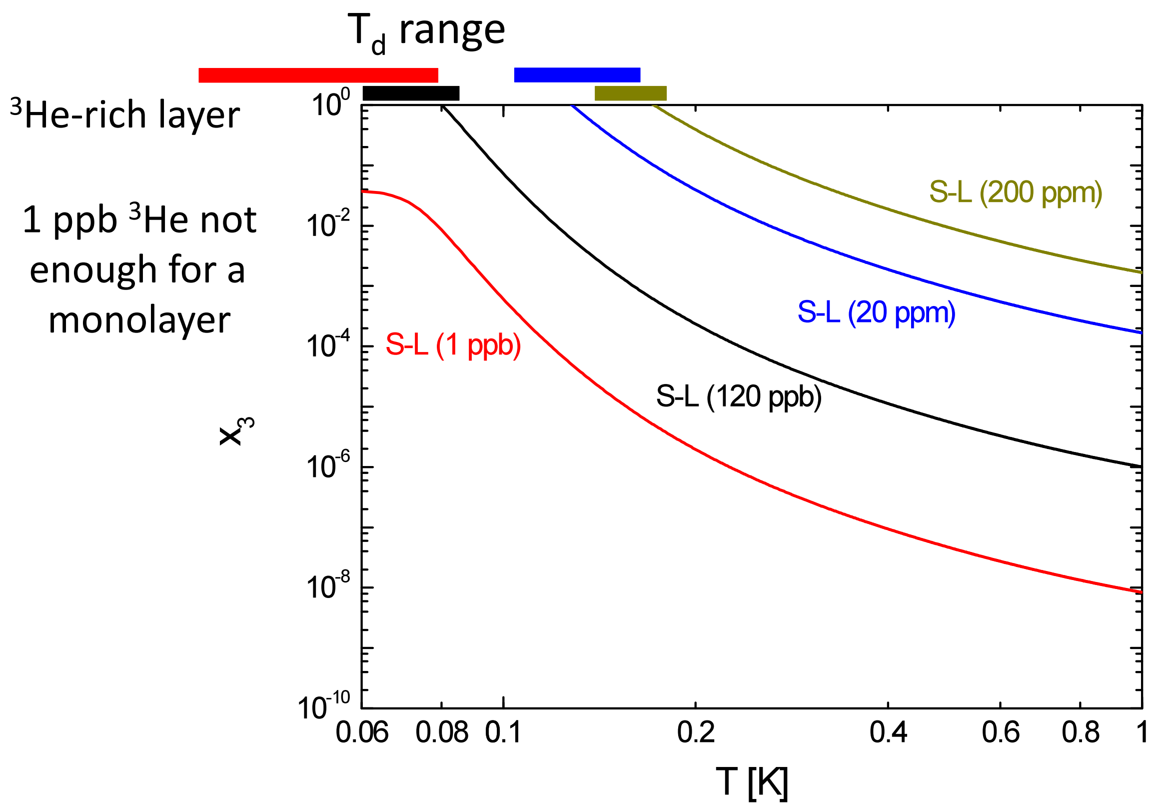
solid-liquid interface — $E_{sl} = -2.5$ K



The only place ^{3}He accumulates at low T is the solid-liquid interface (S-L)

(but the binding energy is uncertain – estimates vary from -2 to -10 K)

^{3}He concentration at solid-liquid interface

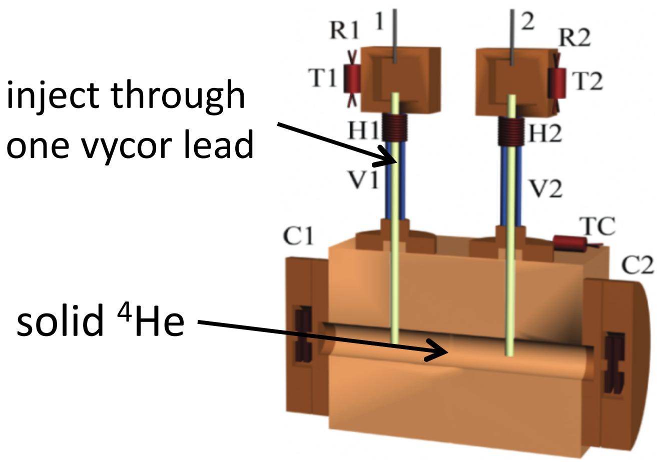


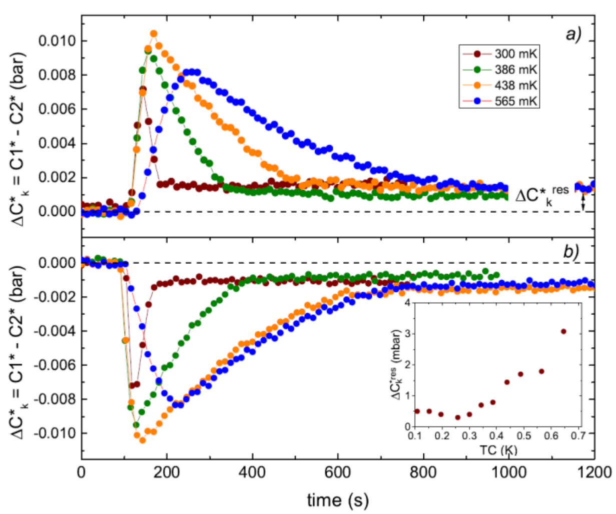
^{4}He atoms are insoluble in liquid ^{3}He

⇨ ^{3}He rich layer forms barrier to ^{4}He transport?

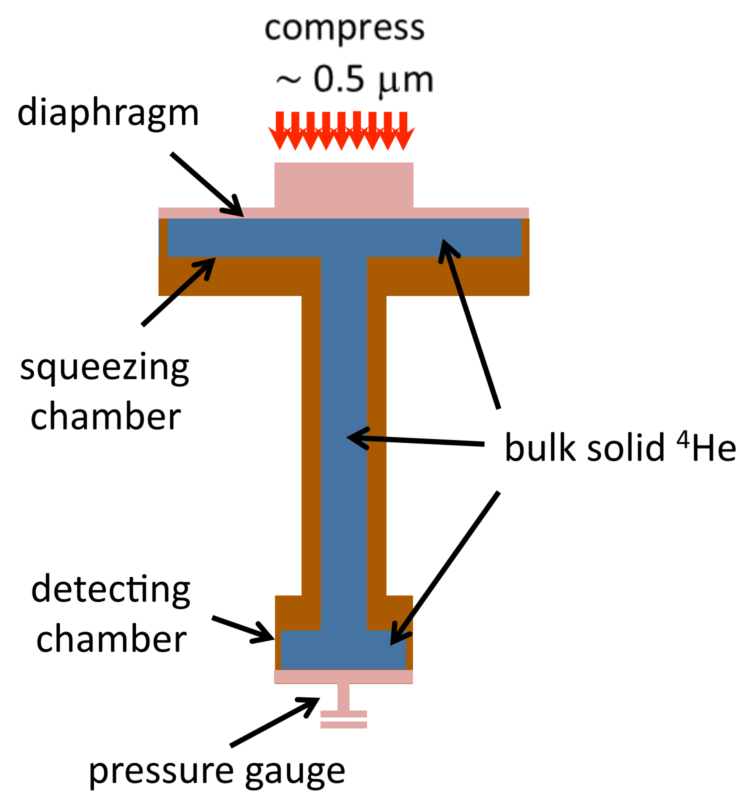
Flow experiment #3: squeezing bulk solid ^4He

Vekhov and Hallock PRB 2015

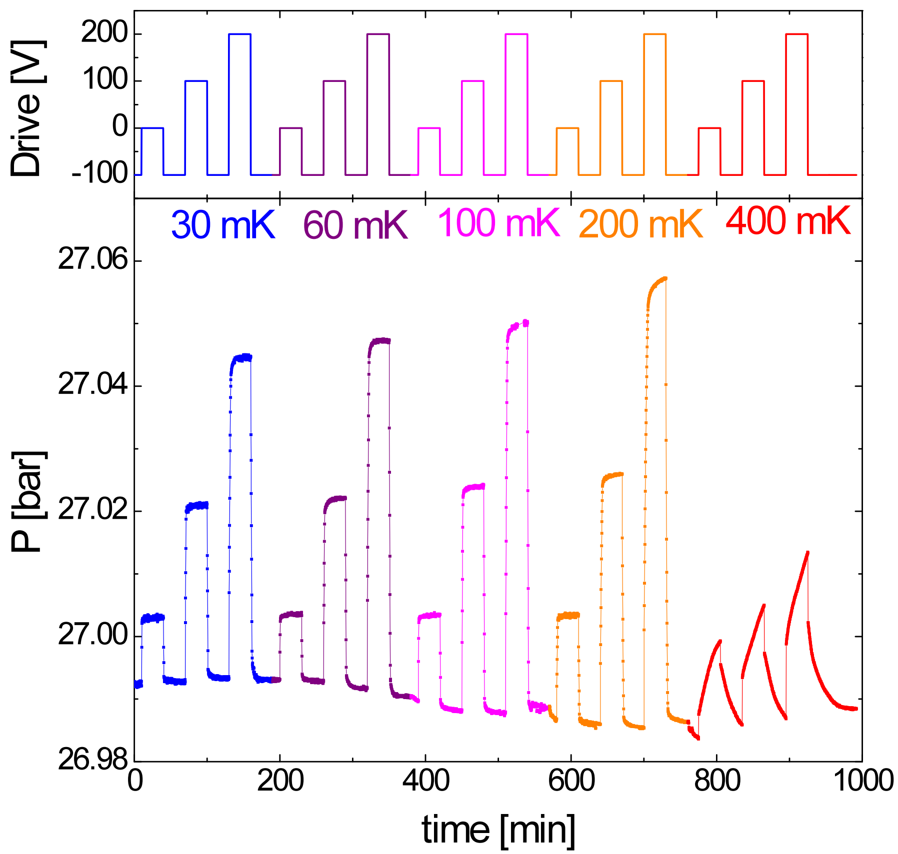




current UofA experiment
(Zhigang Cheng)



Low temperature pressure response



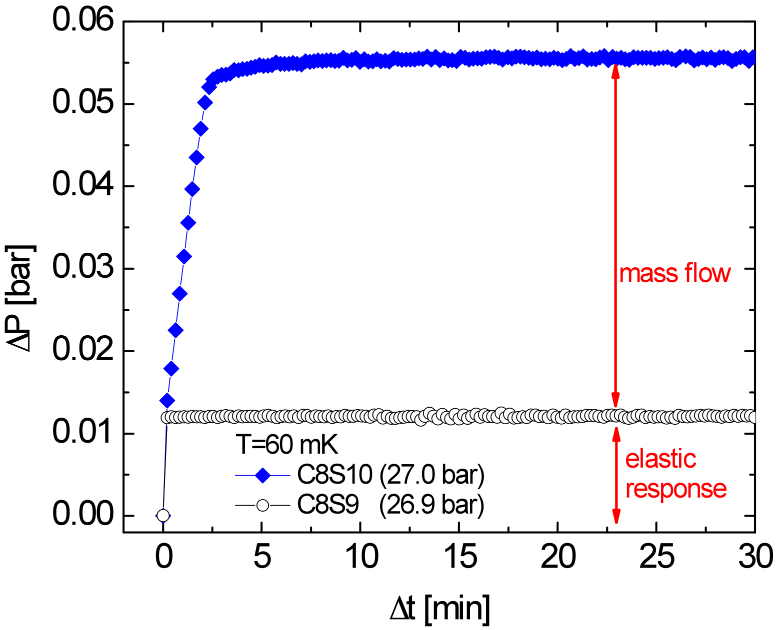
low T flow begins ~500 mK

maximum response ~ 200 mK

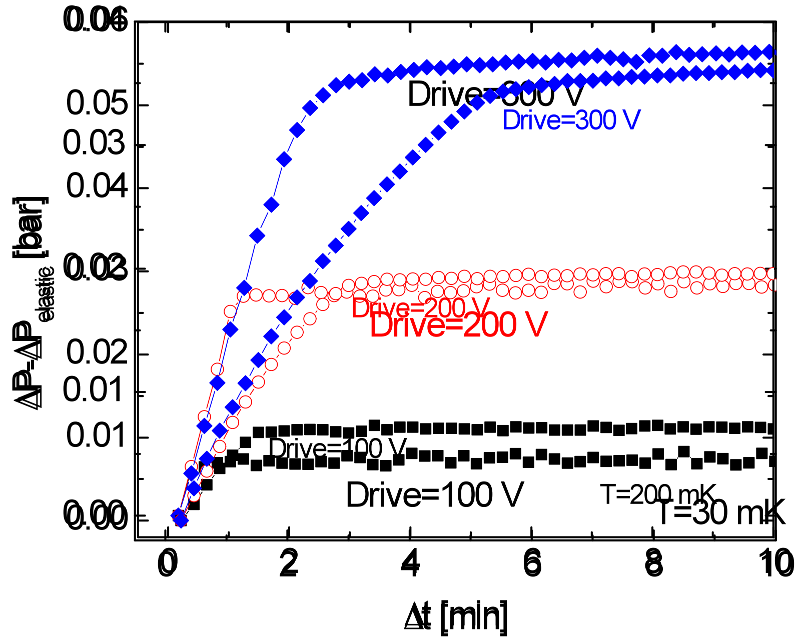
ΔP_{max} ~70 mbar at 300 V drive

(≫ $\Delta P_{elastic}$ ~12 mbar)

Flow at low temperatures



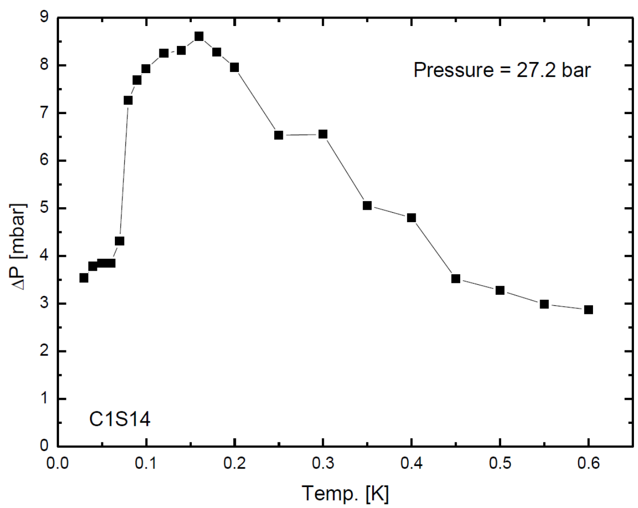
sample dependent flow



rate independent of applied pressure

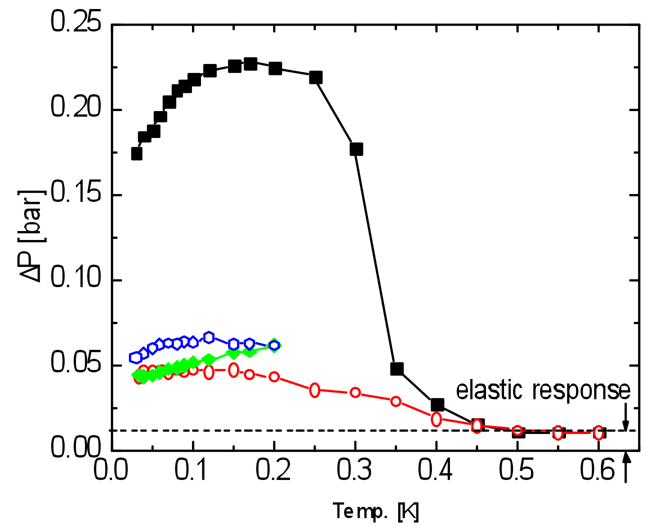
Pressure response vs. flow rate

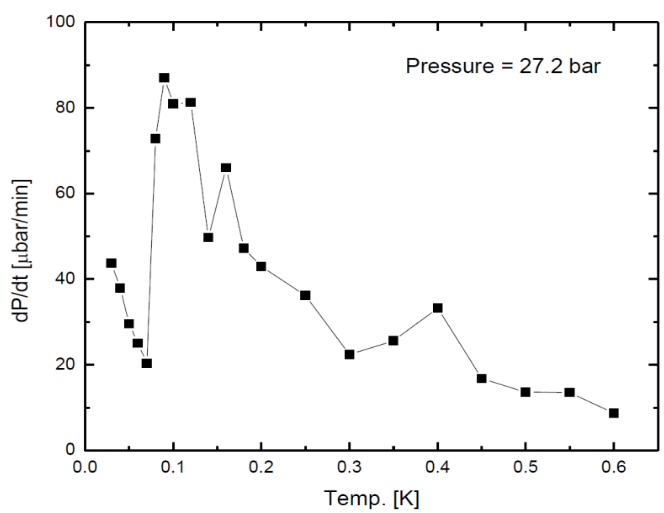
through vycor superfluid channel | **through bulk solid ^{4}He channel**



ΔP

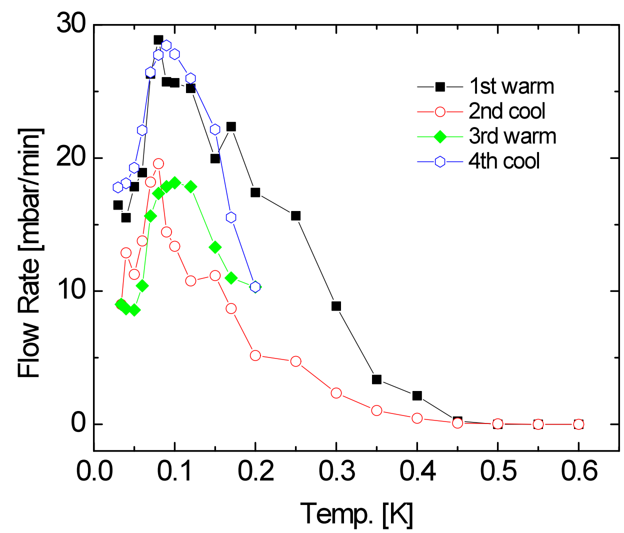
pressure change





$\frac{dP}{dT}$

flow rate



Low temperature flow: summary and questions

- mass flow can be generated by **mechanical squeezing**
- temperature, pressure, and ^{3}He dependencies of the mass flow are very similar to those seen in UMass flow experiments
- ^{3}He must **accumulate somewhere** to block flow at low temperature
- where does the ^{3}He accumulate?
  (vycor solid-liquid interface? liquid film at walls? dislocations?)
- what is the flow?
  (1D Luttinger liquid in dislocation cores? 2D superfluid at walls?)

Solid helium – challenges and opportunities

Solids are complicated – structure, defects, strains

Helium is less complicated than most solids

simple structures (hcp, bcc, fcc) and interactions (Van der Waals)

pure (10^{-11} ^{3}He) and easy to grow single crystals

⇨ can compute properties from first principles

⇨ model system for materials (e.g. plastic deformation)?

Low T, high P ⇨ no direct control or imaging of defects TEM, STM)

are there ways to decorate/image dislocations (like vortices)?

can micromechanical probes be used in solid helium?

Solid helium – challenges and opportunities

Helium is a very quantum solid

particle exchange, delocalized vacancies and ^{3}He impurities

bose (^{3}He) and fermi (^{3}He) statistics are crucial (e.g. supersolidity)

dislocations may move freely (zero point kinks and jogs?)

dislocation cores and grain boundaries may be superfluid (supersolid)

Solid helium provides new quantum systems/phenomena

2D phase transitions (superfluid films, interfaces, roughening)

1D superfluidity, Luttinger liquid, roughening (dislocations)

0D point defects (ballistic motion, zero point vacancies?)

Fully quantum computations are hard, but possible, and essential