3D superfluid made of ^{4}He monolayer under rotation and supersolid study

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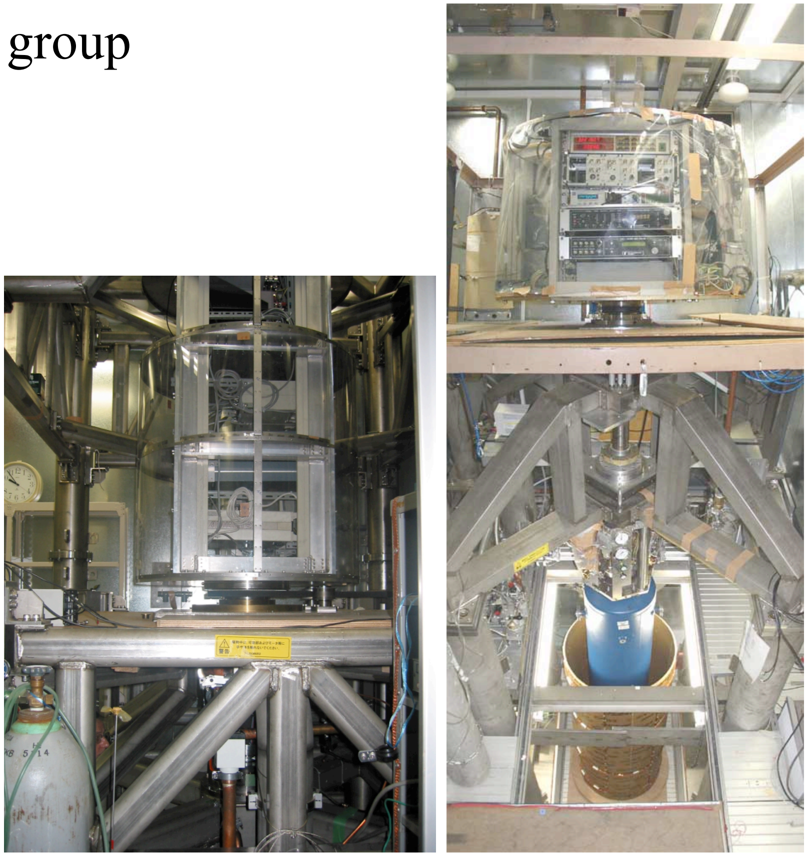
Supersolid experiments so far reported

a)	Ultrasound	Goodkind, and Kojima’s
b)	Torsional Oscillator	Chan’s, Shirahama’s, and Reppy’s groups (+ Kubota’)
c)	Flow experiment	Beamish’s group

Kubota group, ISSP, U-Tokyo:

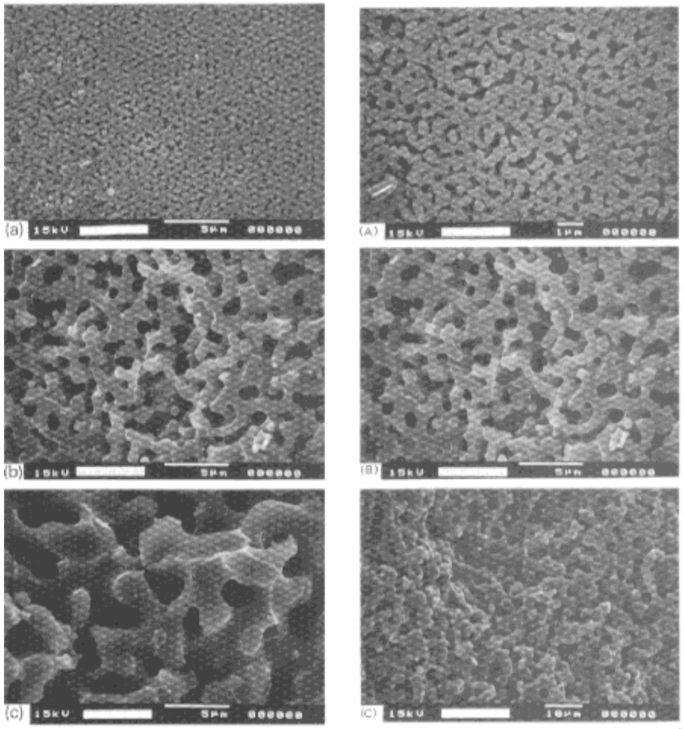
Two fast rotation cryostats
Superfluids, ^{3}He & ^{4}He studies
(under rotation)
+ new superfluids?



Back grounds:

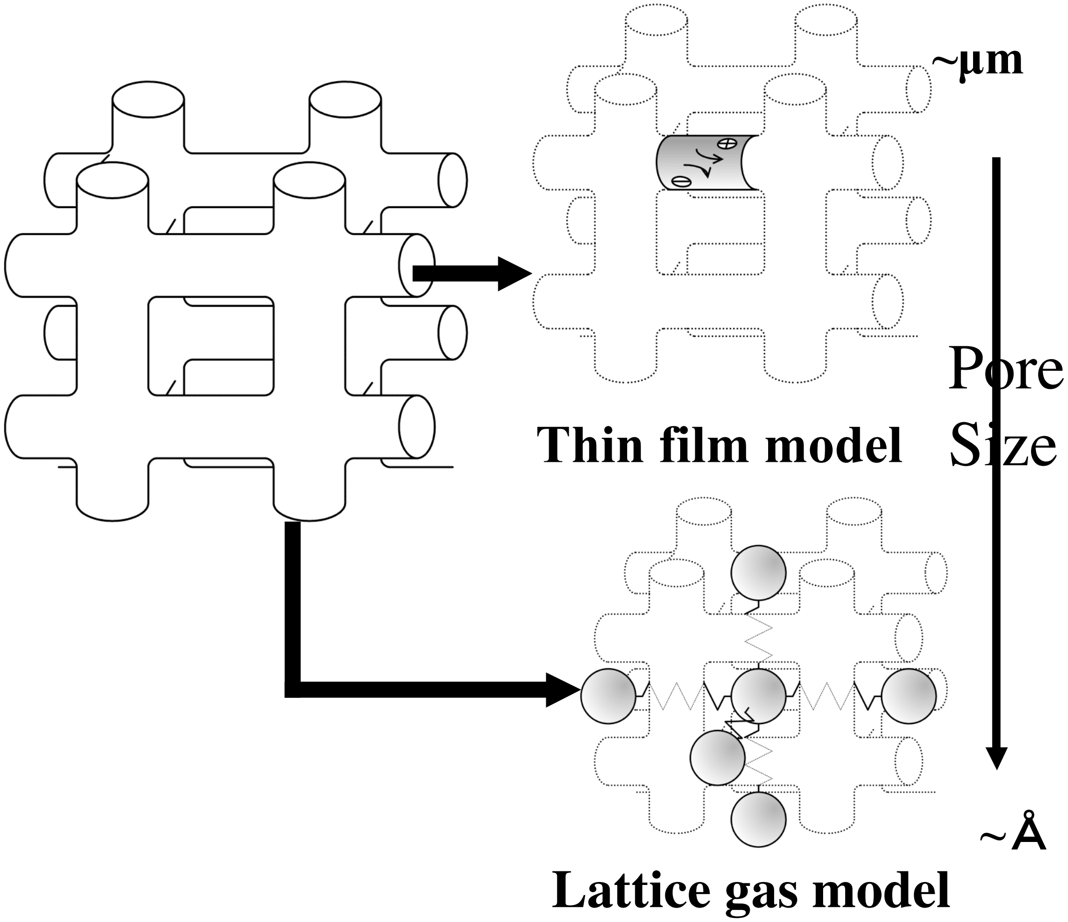
Fundamental study of quantised vortices, New superfluids search and 3D superfluid made of KT films.

He sub-monolayer Superfluid film formed on the 3D connected pore surfaces of Porous Glass substrates with well controlled pore sizes:



ig. 4. Scanning electron microscope pictures of the well-defined porous glass samples with pore diameters 2500, 5000 and 15 000 Å y Yazawa). Photos (a)-(c) are all taken with a magnification factor of 3250, whereas photos (A)-(C) are taken with a agnification factor of 6500, 3250 and 980, respectively, to make the pore sizes look almost the same. From these photos we learn at the pore shape for glasses with different pore sizes is quite the same and the ratio l/d (unit/length)/(pore diameter) is certainly larger than 1 and probably 3–5.

I. 3D superfluidity made of sub-monolayer He film condensed on 3D connected pore surface



Thermal Wave Length,

$$\lambda = \frac{2\pi\hbar}{\sqrt{3m_4 k_B T}}$$

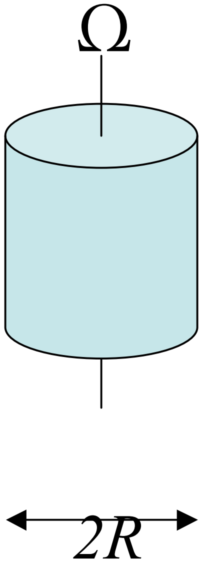
in comparison with pore Size, determines the situation.

Shirahama,Kubota,…:
Thin Film model
↕
J. Reppy: Dilute gas
BEC

Ref.: Stoof, PRA <u>45</u>, 8398 (1992), Bijlsma et.al., PRA

3D superfluid made of monolayer He films

Critical velocities:



1]. Landau critical velocity Δ/P_0 ??

2]. vortex ring nucleation critical velocity $\sim \rho_s(T)$

3]. single vortex line nucleation critical velocity ??

4]. the thermodynamic, first critical angular velocity Ωc1=

$$\Omega_{c1} = h \ln(R/a)/(2\pi m_4 R^2)$$

5]. overlapp of vortex cores, the second critical angular velocity Ωc2=

$$\Omega_{c2} = h/2\pi m_4 a^2.$$

h: Plank const., m_4: ^{4}He atomic mass, a: vortex core diameter

Important Length Scales in He film in a porous glass to determine 2D or 3D nature

Vortex Core size: a_2, a_3
Coherence length: ξ_2, ξ_3
Thermal de Broglie wave length: λ_{dB}
Phonon wave length: 1D, 2D, 3D phonon excitations
Roton wave length? ? ?

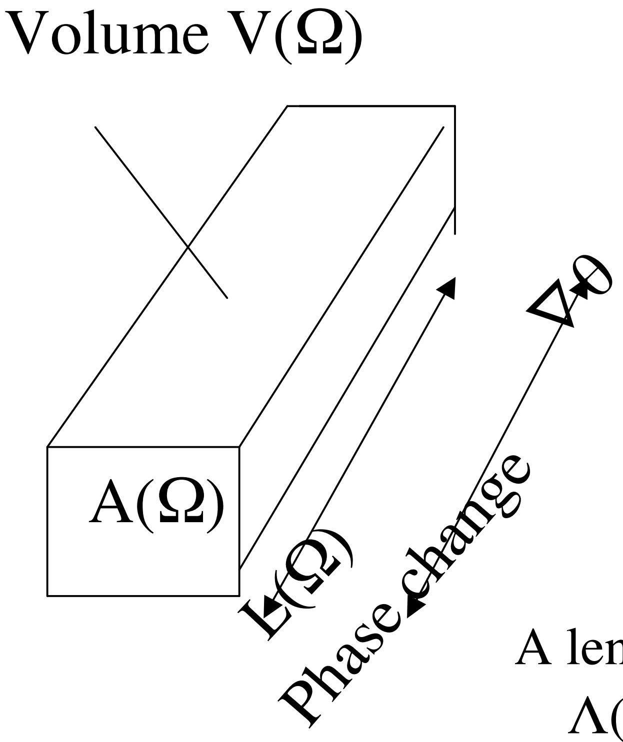
Berthold, Bishop, & Reppy, PRL(1977): Pore size < λ_{dB} 3D
Shirahama, Kubota, et. al., PRL(1990): $a_2 = 2.5$ nm: T_c is determined by 2D

Ω_{c2}(3D): where overlapping of 3D vortex cores occurs under rotation
$\Omega_{c2}(2D) >> \Omega_{c2}(3D)$ if $a_3 >> a_2$

$$\Omega_{c2} = h/2\pi m_4 a^2 .$$

Helicity Modulusγ and Josephson's Coherence Lengthξ in a 3D superfluid:

(length scale of phase fluctuation) M.E.Fisher, M.N.Barber and D. Jasnow,Phys.Rev.A8,1111



Helicity Modulus:

$\Delta F \equiv (1/2)\gamma(T) \ <\nabla\theta>^2 \ V(\Omega)$

whereas

$\Delta F=(1/2)\rho_s(T)v_s^2 \ V(\Omega)$

and

$V_s = (h/(2\pi m) \ \nabla\theta$

Therefore

$\Delta F= (1/2)\rho_s(T)\{(h/(2\pi m)\nabla\theta\}^2 V(\Omega)$

$\gamma(T) = \lim \ (\Delta F/ <\nabla\theta>^2)(L/A)$

$[\gamma(T)]=$ [energy/length]

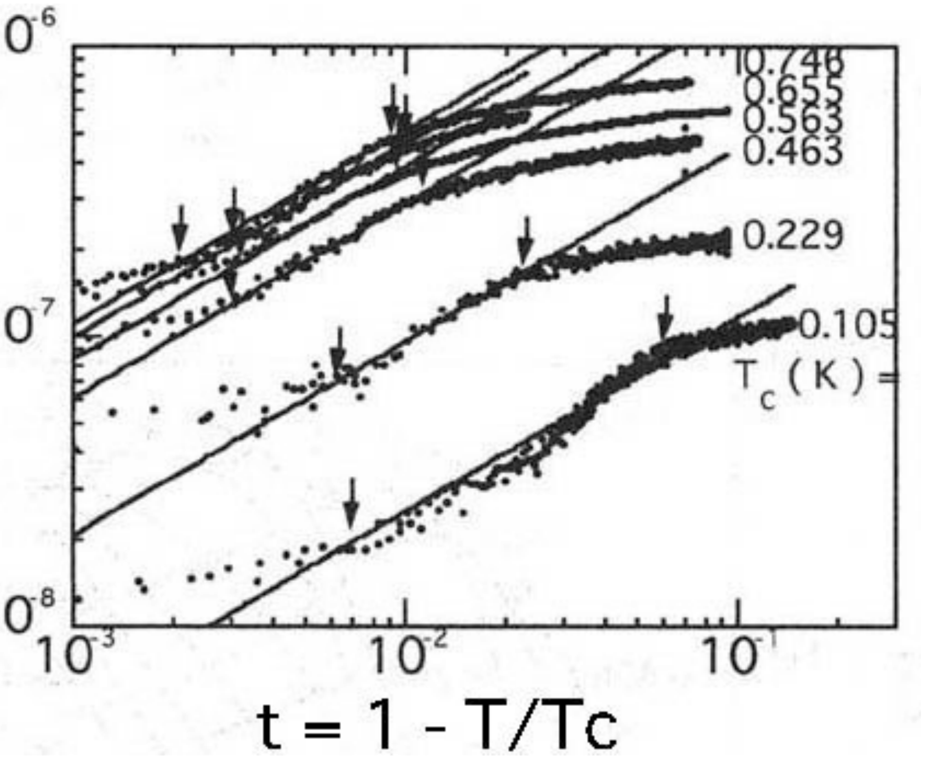
A length scale Λ represents a length scale of fluctuation:

$\Lambda(T) \cdot \gamma(T) = k_B \ T$

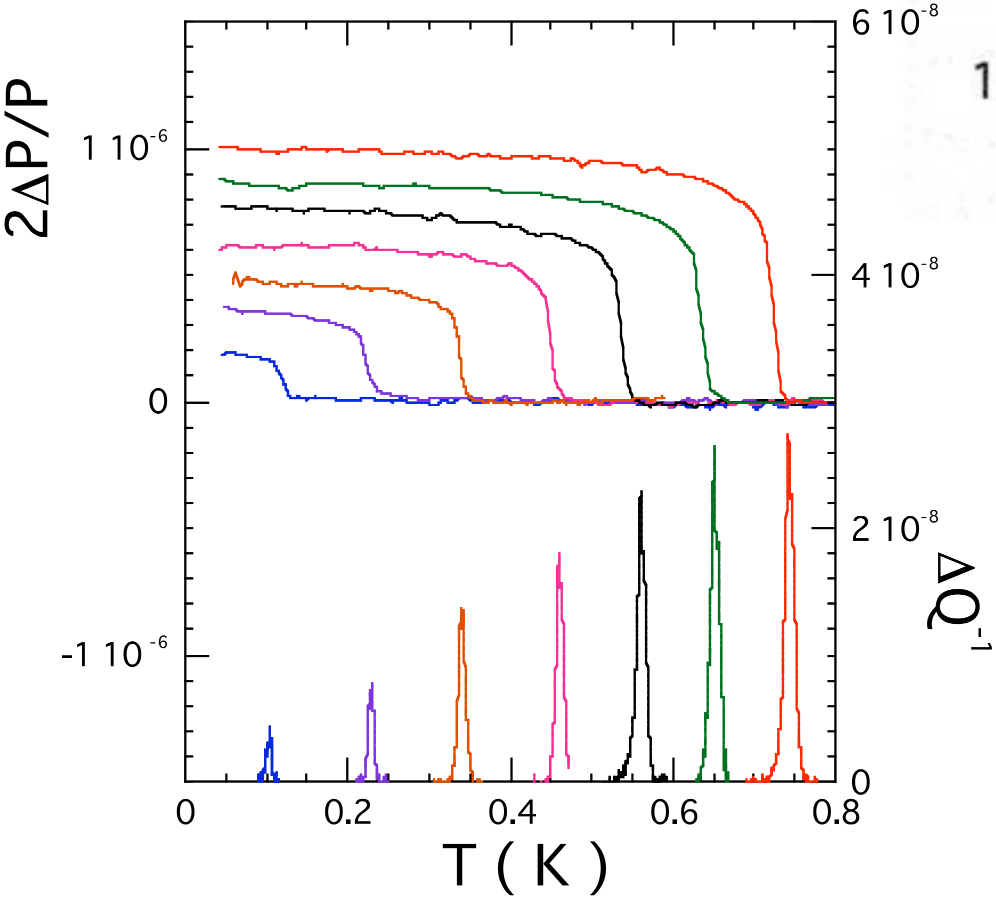
$\Rightarrow \Lambda(T) = \xi(T) = (k_B \ T)/ \ \gamma(T) = m^2 k_B \ T/\{(h/2\pi)^2 \varrho_s(T)\}$

Replacing T with Tc does not change as long as 1-T/Tc<0.2

TO Experiments : 1 μm pore system: Period shift ΔP/P --> absolute superfluid density.



Critical behavior of 3D superfluid

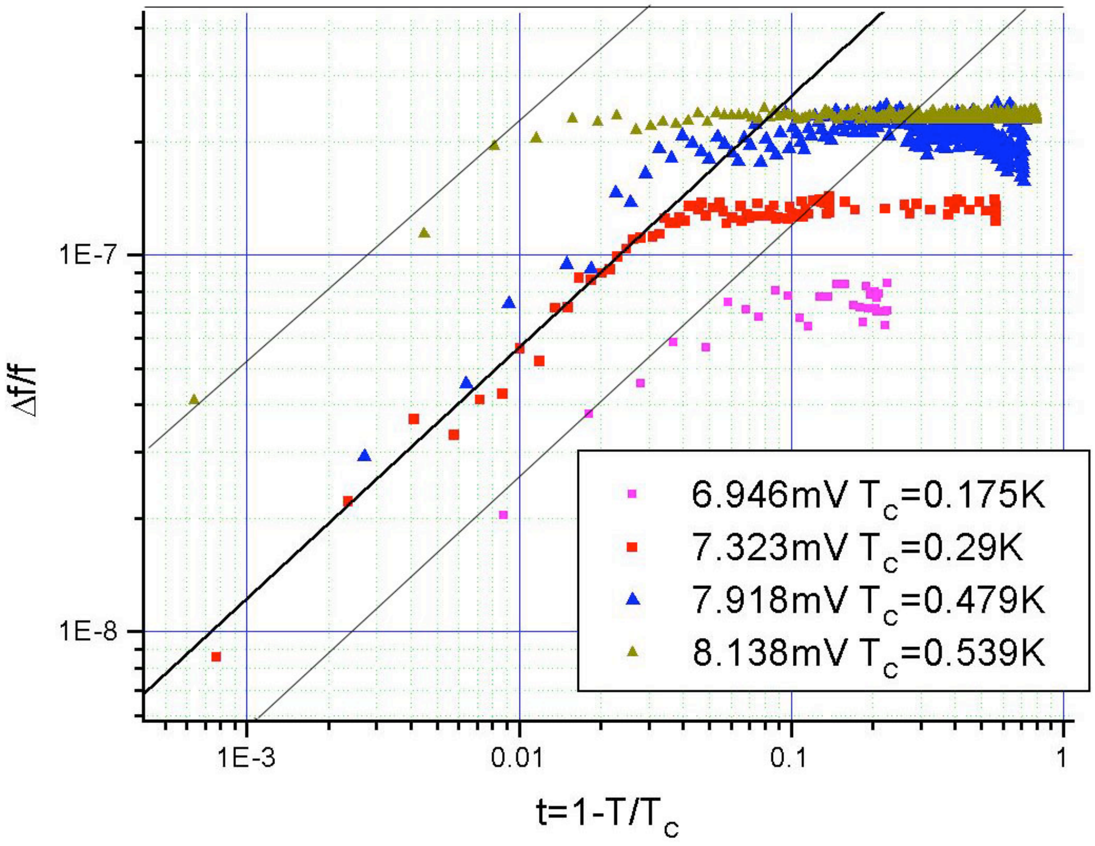


Submonolayer Sfl He Films in Porous Glass with 10 μm pores:

see: Mikhin, Syvokon, Obata, and Kubota, **Physica B** 329-333 (2003) 272-273.

We can measure the absolute superfluid density, $\rho_s(T)$ in g/cm

From which we can evaluate Josephson’s phase coherence length ξ(T): See next page.



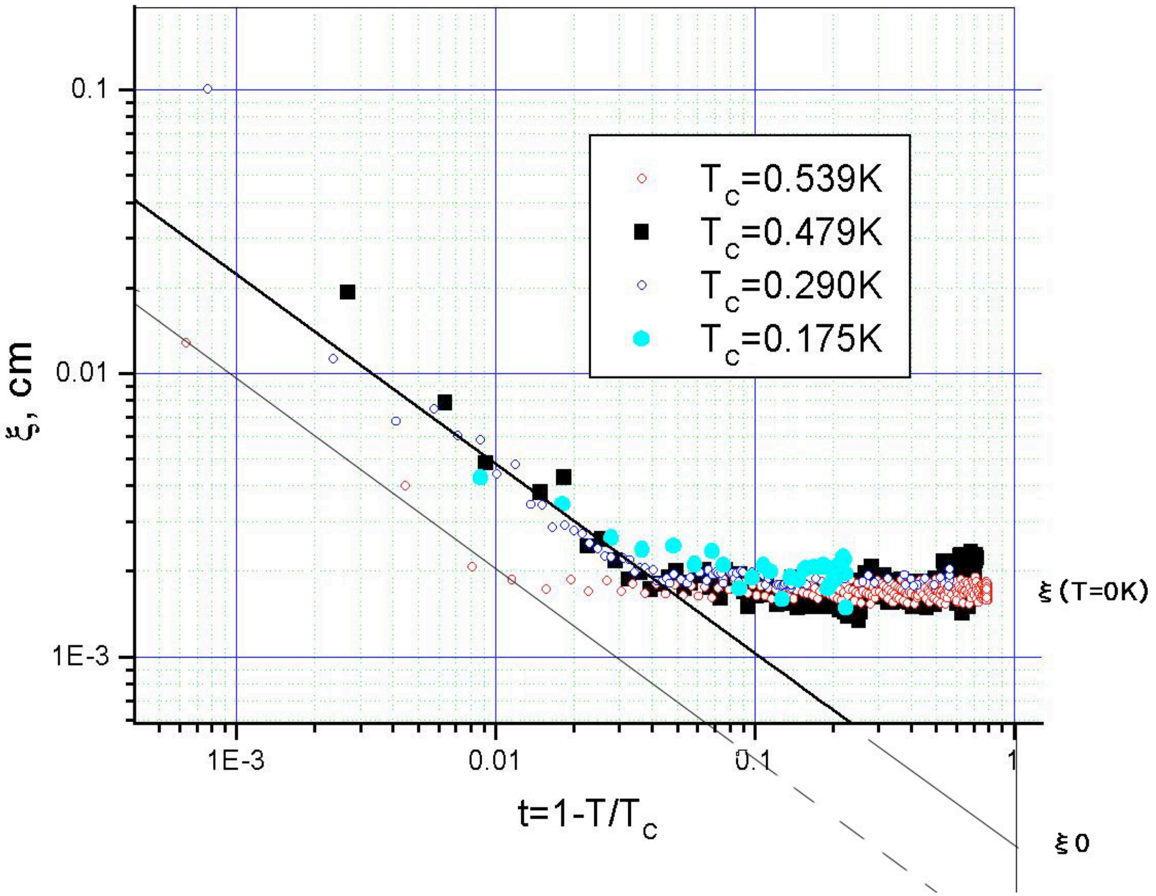
3D coherence (Josephson's) length ξ_3 of Films on 10 μm pore

Absolute superfluid density:

$\rho_s(T)$ -->$\xi(T)$,

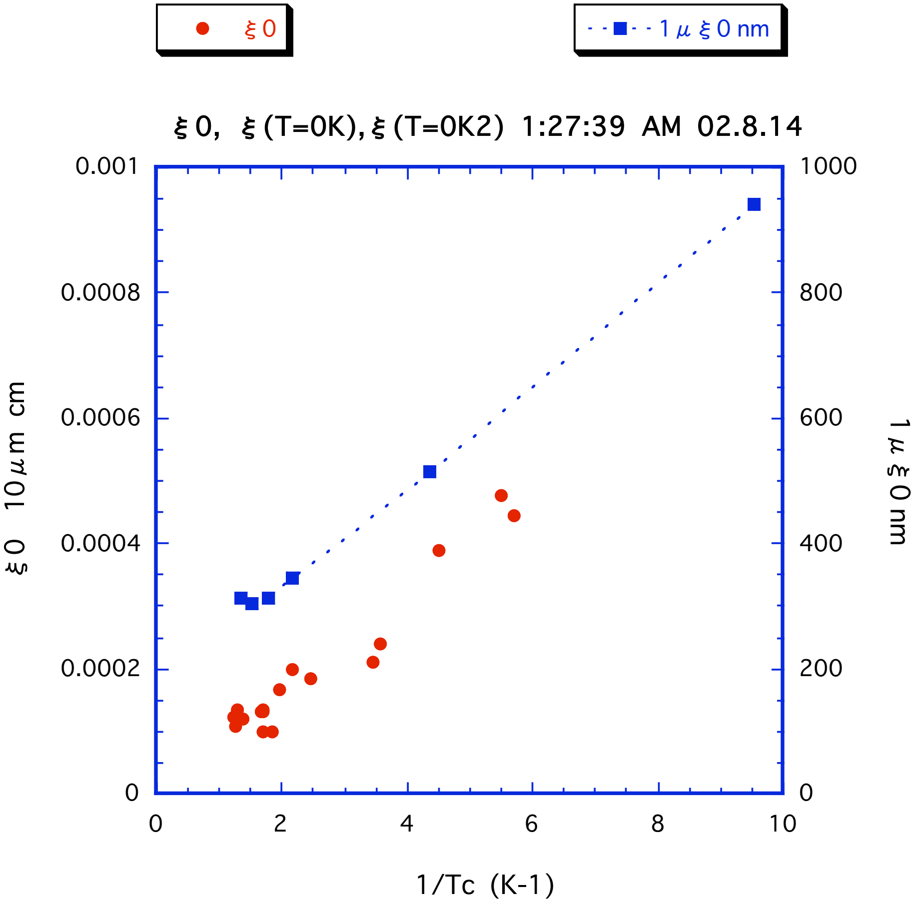
by Josephson's relation:

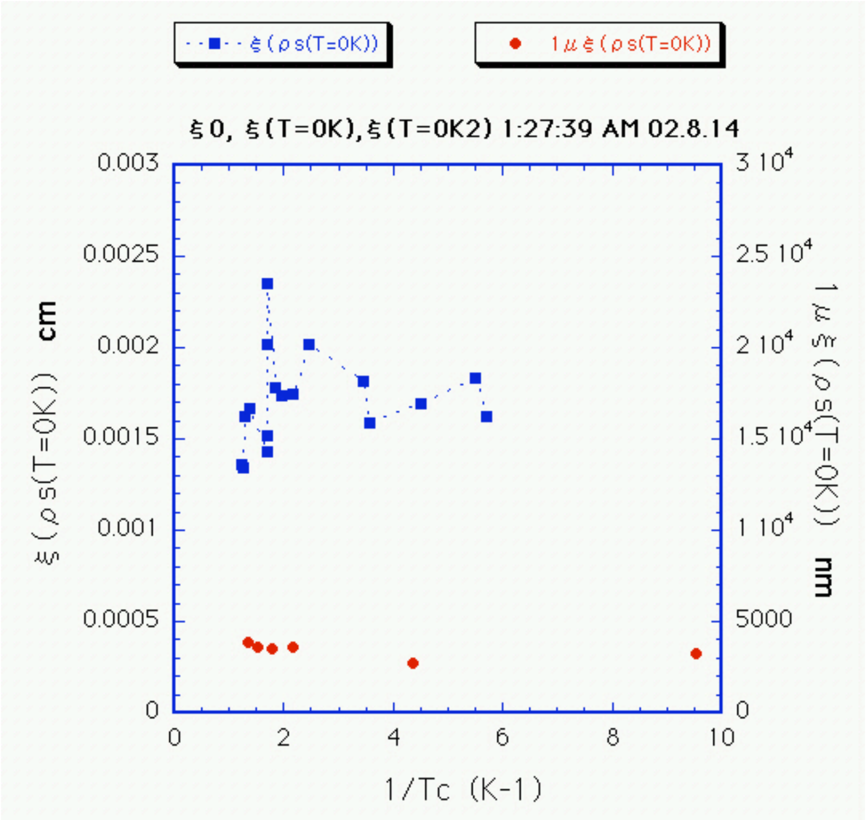
$$\xi(T) = \{k_B T\, m_{He}^2 (2\pi/h)^2\}\ 1/\rho_s(T)$$



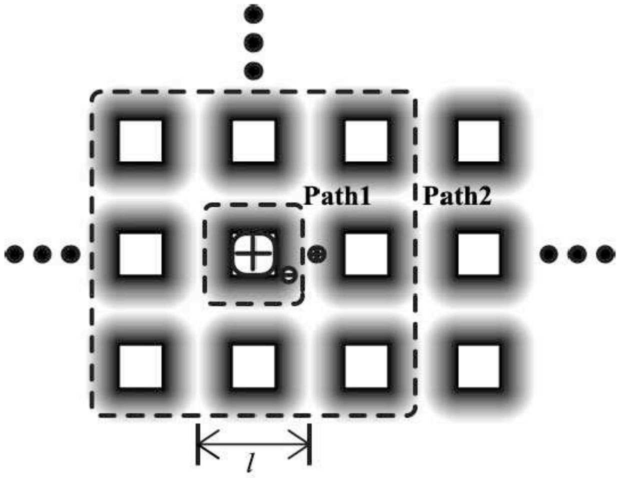
An interesting observation is $\xi(t)$ approaches a constant size as T --> 0K,(t ->1). And ξ is always larger than pore size even for 10 μm pore size porous glass!!

Comparison of ξ_0 and $\xi(T=0K)$ for 1 & 10 μm porous glasses:





With such large ξ_0 as well as $\xi(T=0K)$, experiments under Rotation have quite different meanings, yet we still need high(er) rotational speed Ω to study vortex state in such systems.



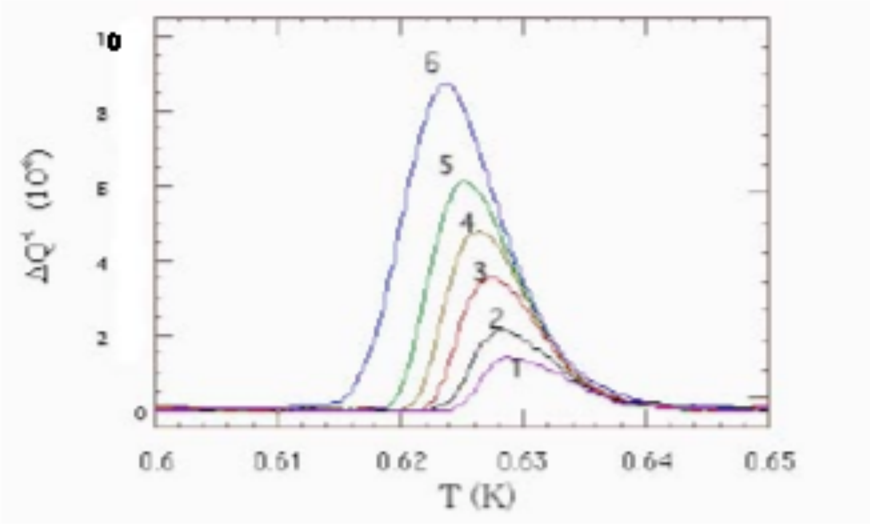
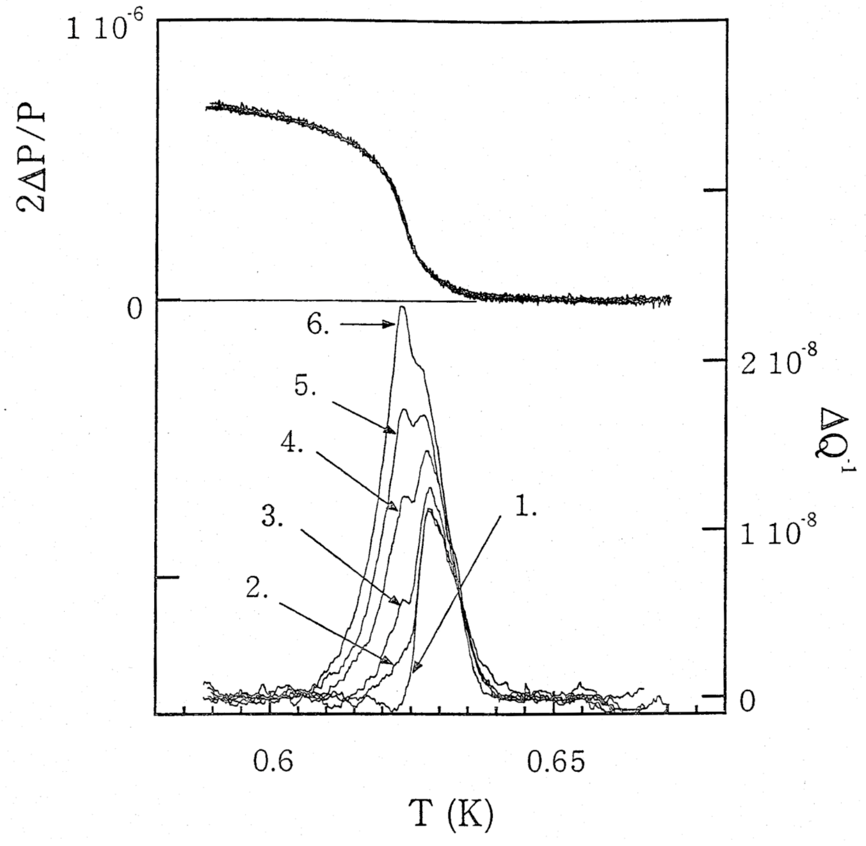


FIG. 3: Energy dissipation curves in static condition for nonlinearregime. AC drive velocity for each curve correspondsto VAC =0.095(No.1), 0.19, 0.36, 0.52, 0.66, 0.94(No.6) cm/sec respectively.

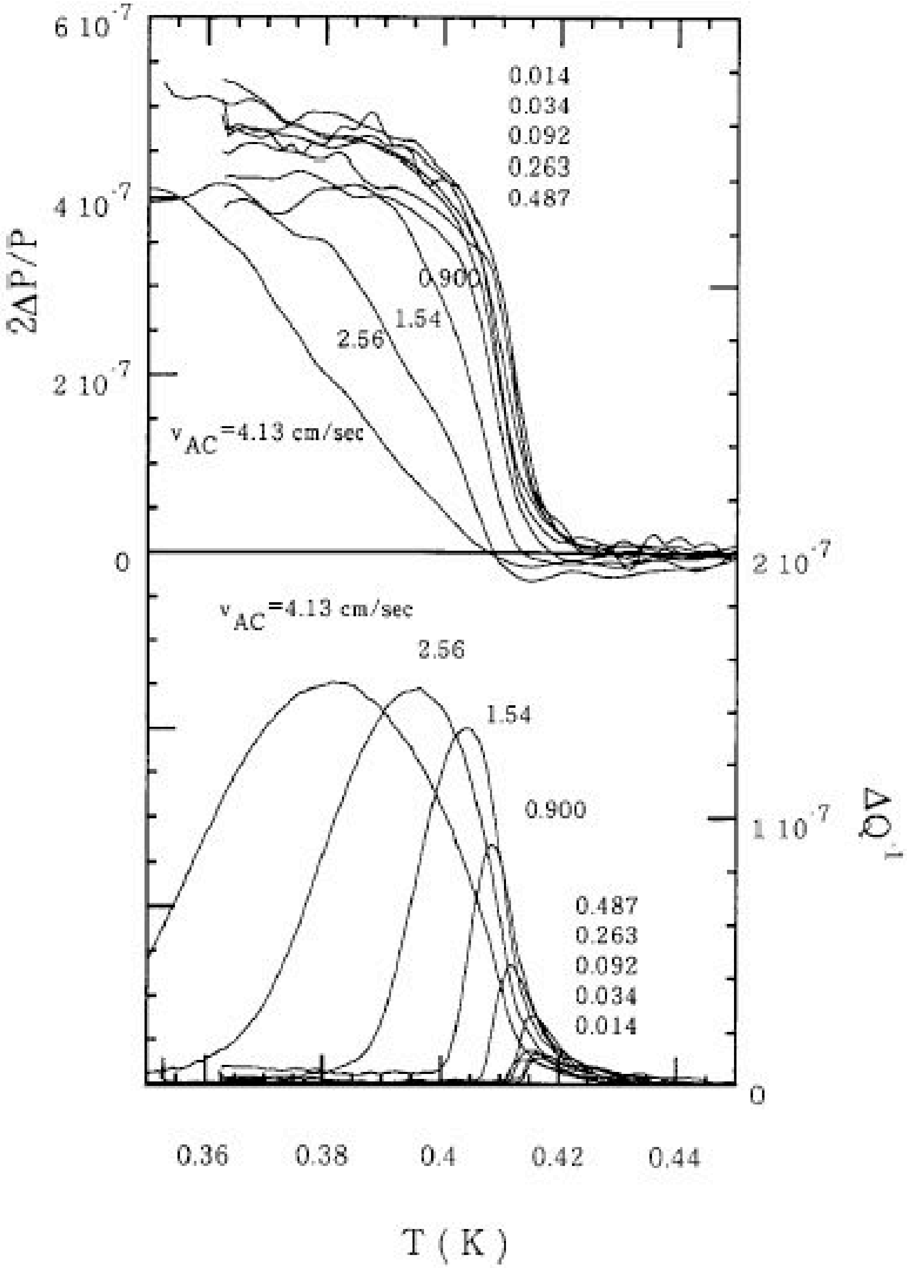
$$\begin{aligned}\Delta Q_{\Omega}^{-1} &= \frac{1}{S_{tot}}\sum_{n\geq 1} S_n(\Delta Q_{(n)}^{-1} - \Delta Q_s^{-1}) \\ &= C\sum_{n=1}^{3}(2n-1)(\Delta Q_{(n)}^{-1} - \Delta Q_s^{-1})\ , \qquad (1)\end{aligned}$$

$$[\Delta Q_{\Omega}^{-1}]_{max} = 3.5 \cdot 10^{-10}\Omega \qquad (2)$$

TO response to DC and AC rotation



TO under DC rotation:
There is no change in TO freq.
M.Fukuda, et al.PRB(2005)



AC velocity dependence of TO:
M. Fukuda, et al., in preparation

DC flow experiment with thermal drive:

430 **M. Kubota *et al.***

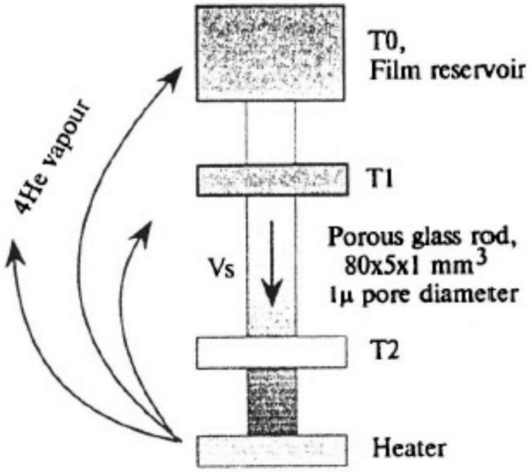


Fig. 1. Effective thermal conductance study set up for the He film system formed in the porous glass substrate. Whole system is enclosed in thick Cu body which is thermally connected to T0. Steady state mass flow is maintained by the series path, indicated by the arrows.

M. Kubota, *et al*., JLTP vol.113, (1998) 429-434.

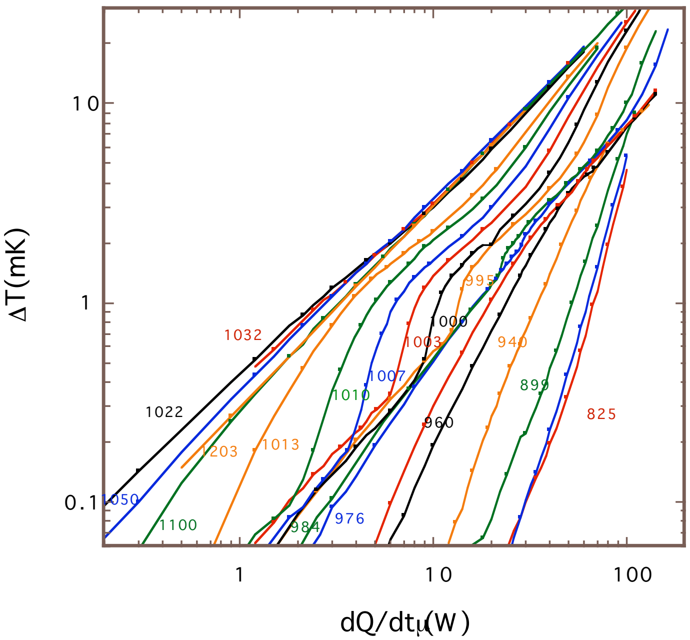


Fig. 2. The ‘crossover’ near T_c is elucidated in the log-log plot. The slope of the lines in the plot gives ideas of the dimensional crossover.

Below this flow has 3D character.

It looks as if there is a dissipative flow at all $T < T_c$; while ρ_s being measured.

Supersolid State of ^{4}He under rotation

Small superfluid density:

--->Large coherence length

Explains: similarity in the bulk and porous results.

3D vortex should be observable in the similar manner as in 3D He film systems

See: M. Kubota *et al*. Proc. LT24,

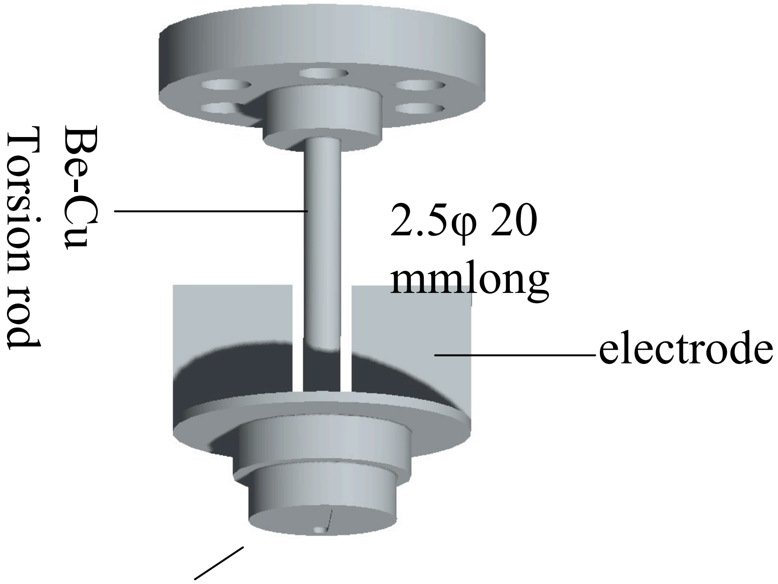
Our 1st step:
Torsional Oscillator with internal pressure gauge to observe annealing effect

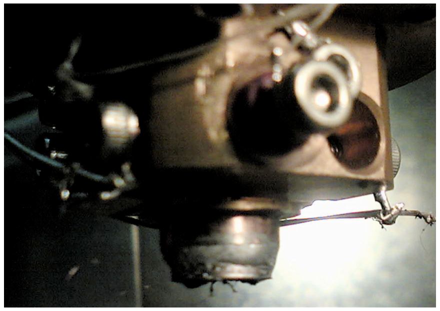
Small cell size: fast relaxation,

-->well annealed sample,

-->We did not observed supersolid signal till recent time. ???

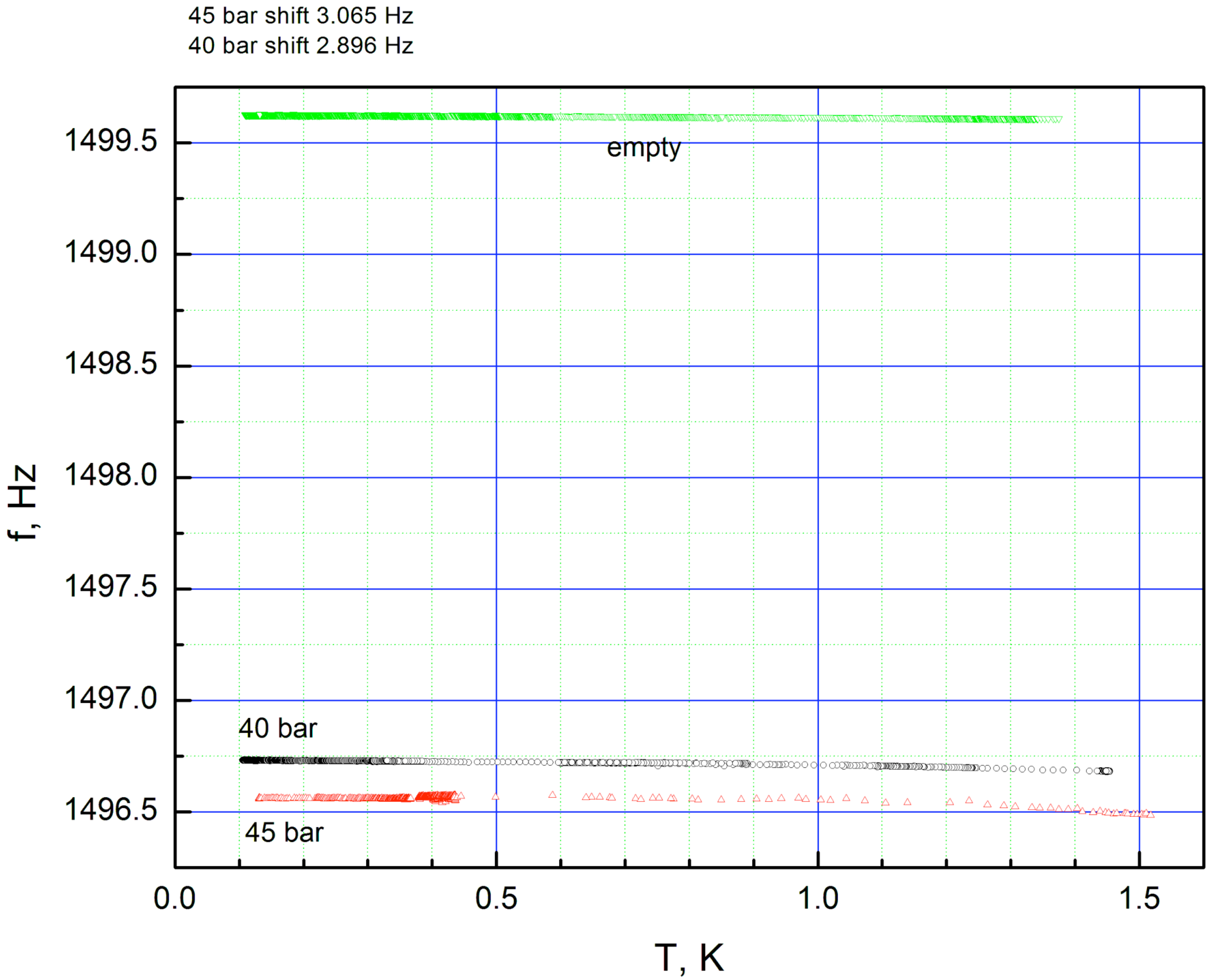
Sample volume:4t x 8φ - 0.04cc =~0.16cc





Cell inner diameter: 8 mm
Cell inner height: 4 mm
Inner Pressure Guage: 0.04 cc

TO response for empty and filled He



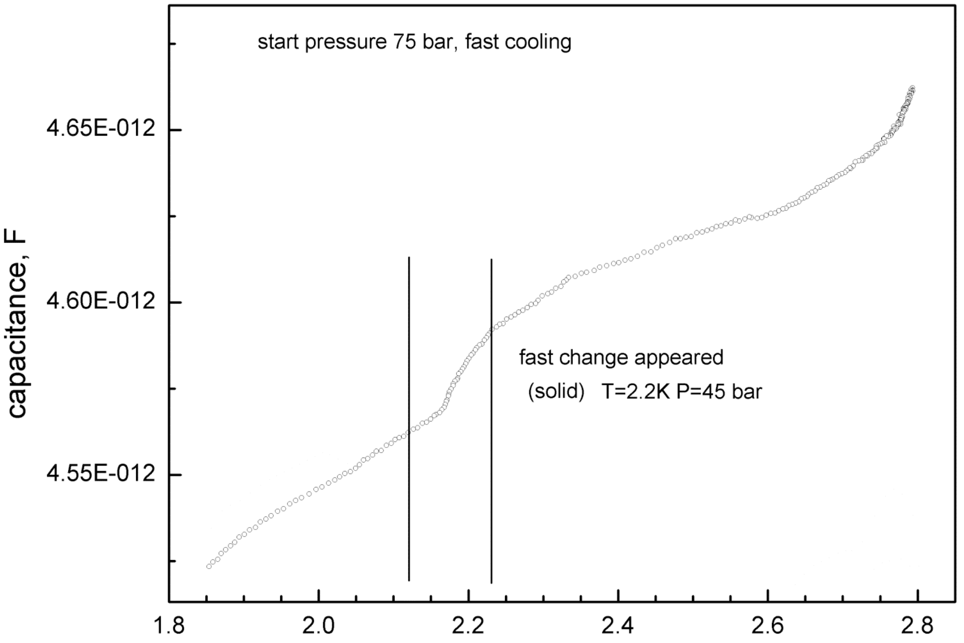
Solidification processes

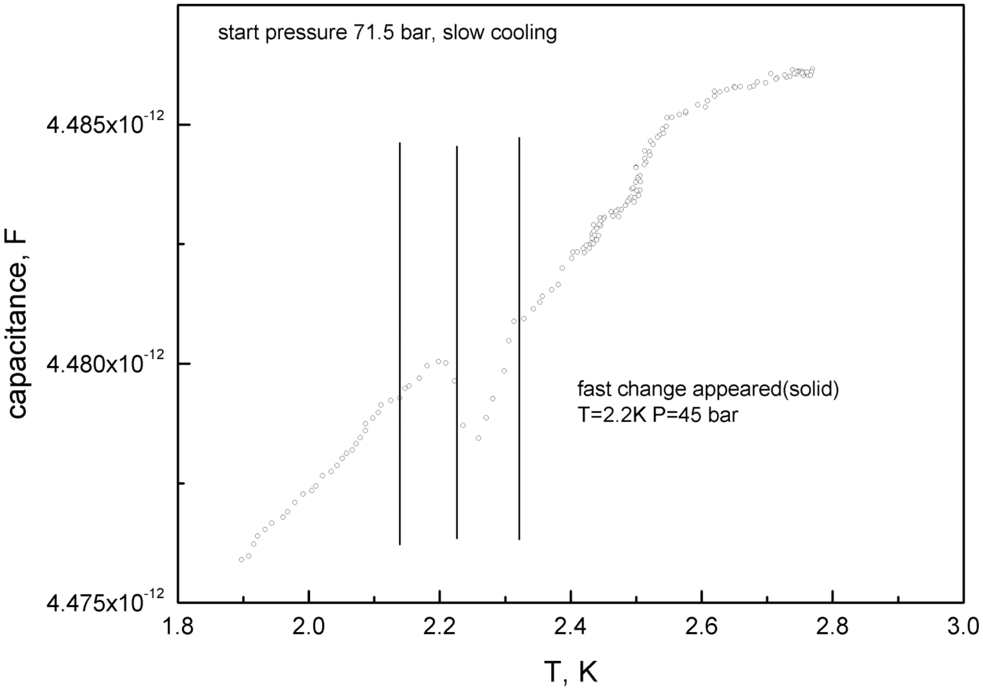
Higher P and faster cooling:

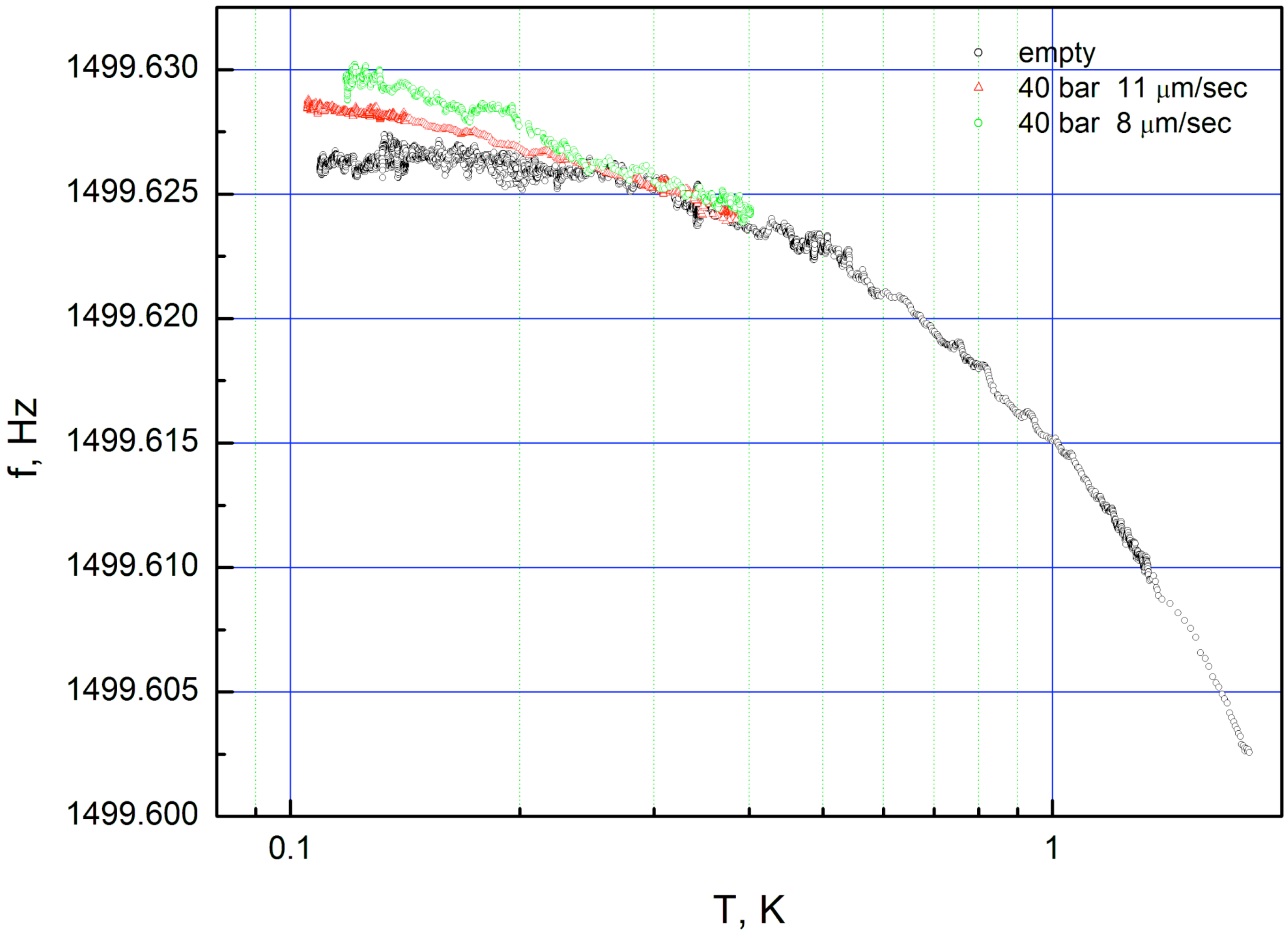
→ pressure drop across melting curve

Lower P and slow cooling:

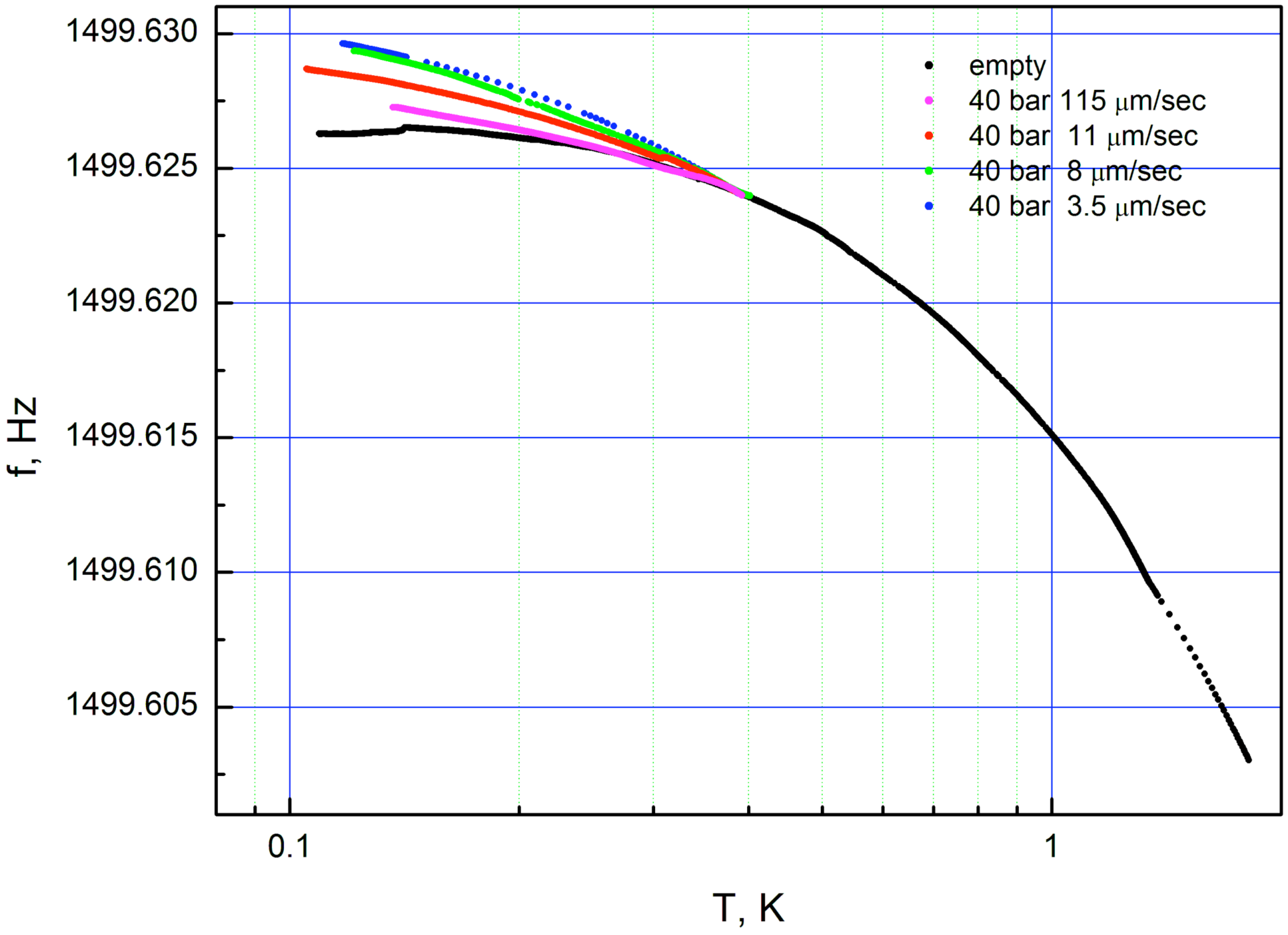
-->Pressure drop, then it recovers to almost original line.



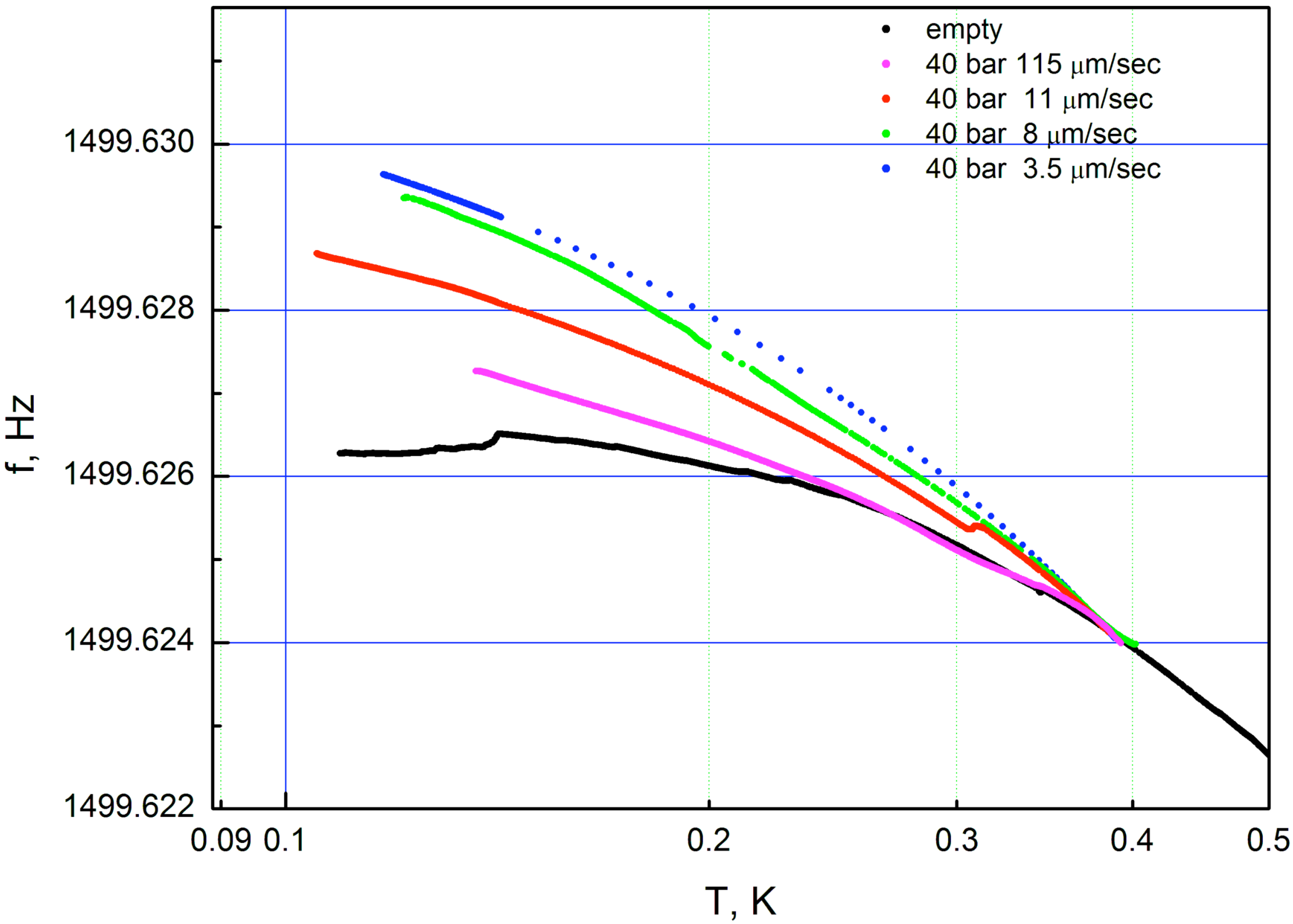


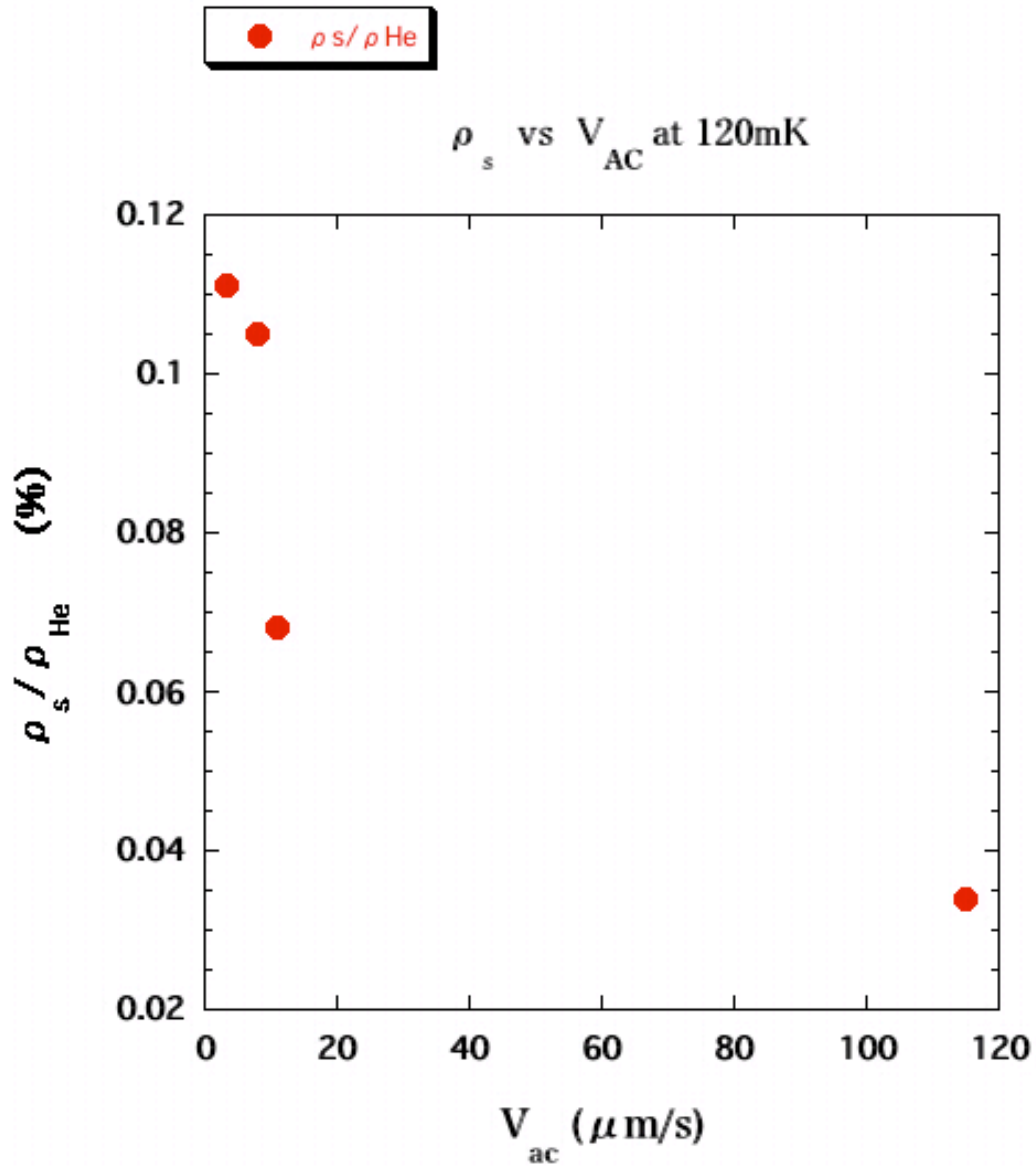

f, Hz
1499.630
1499.625
1499.620
1499.615
1499.610
1499.605
1499.600
0.1
1
T, K
empty
40 bar 11 μm/sec
40 bar 8 μm/sec

TO frequency shift for 40 bar sample, with given V_{AC} amplitude



More in detail

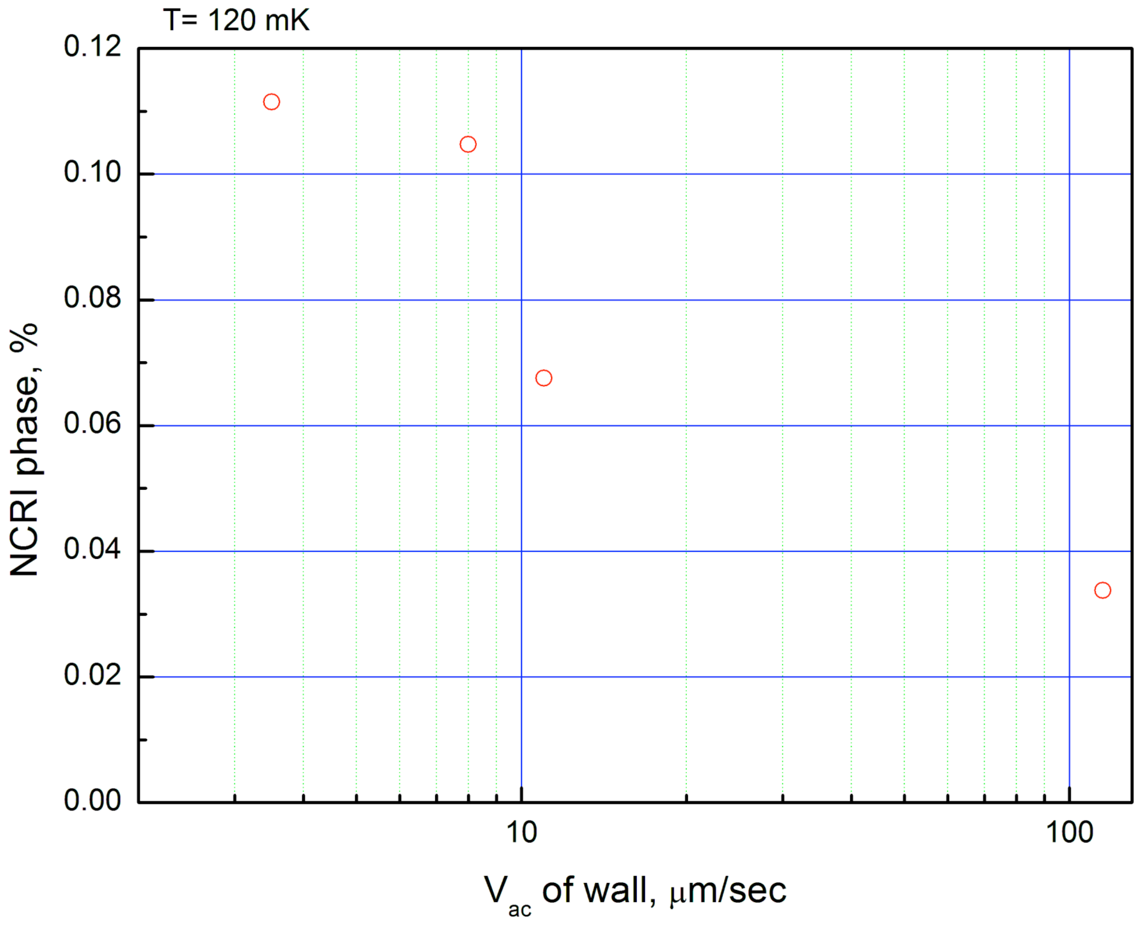


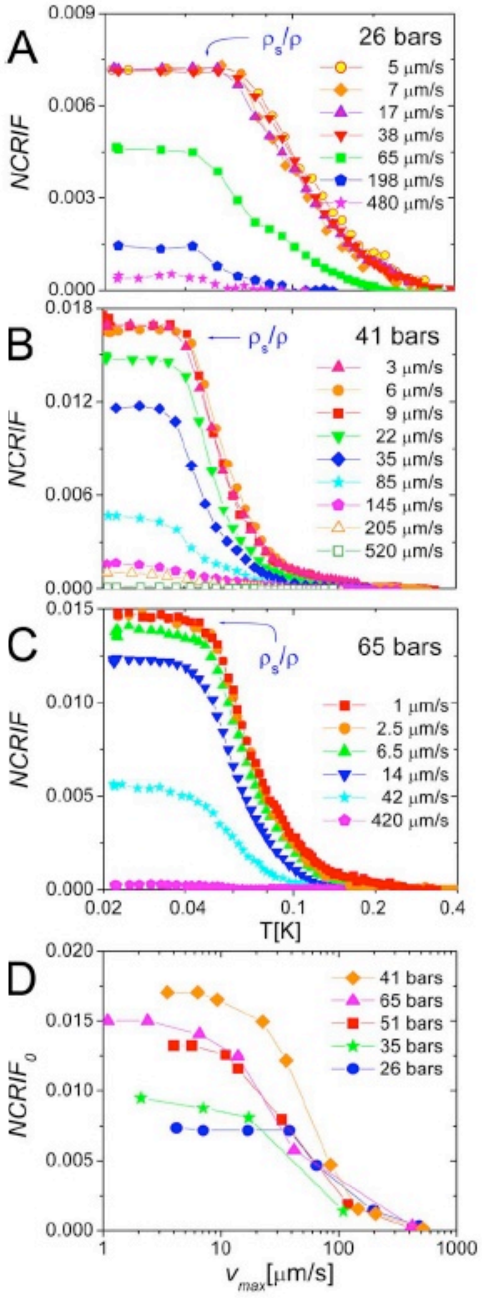

● ρ s/ ρ He
ρ s vs V AC at 120mK
ρ s / ρ He (%)
0.12
0.1
0.08
0.06
0.04
0.02
0
20
40
60
80
100
120
V ac (μ m/s)

In comparison with Kim & Chan's results

Kim & Chan, Science 2004 September

Penzyev & Kubota result (40bar) below is not inconsistent with Kim &





TO experiment under Rotation: being planned

What do we expect?:

Vortex state similar to the ones seen in 3D superfluids made of 2D films: see Kubota et al., Proc. LT24.

3D vortices would manifest themselves as an additional dissipation (peak), until Ω_{c2} is approached, where Ω_{c2} is given below.

$$\Omega_{c2} = h/2\pi m_4 a^2.$$