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Advanced Workshop on Non-Standard Superfluids and Insulators

18 - 22 July 2011

Review of experimental results on supersolidity

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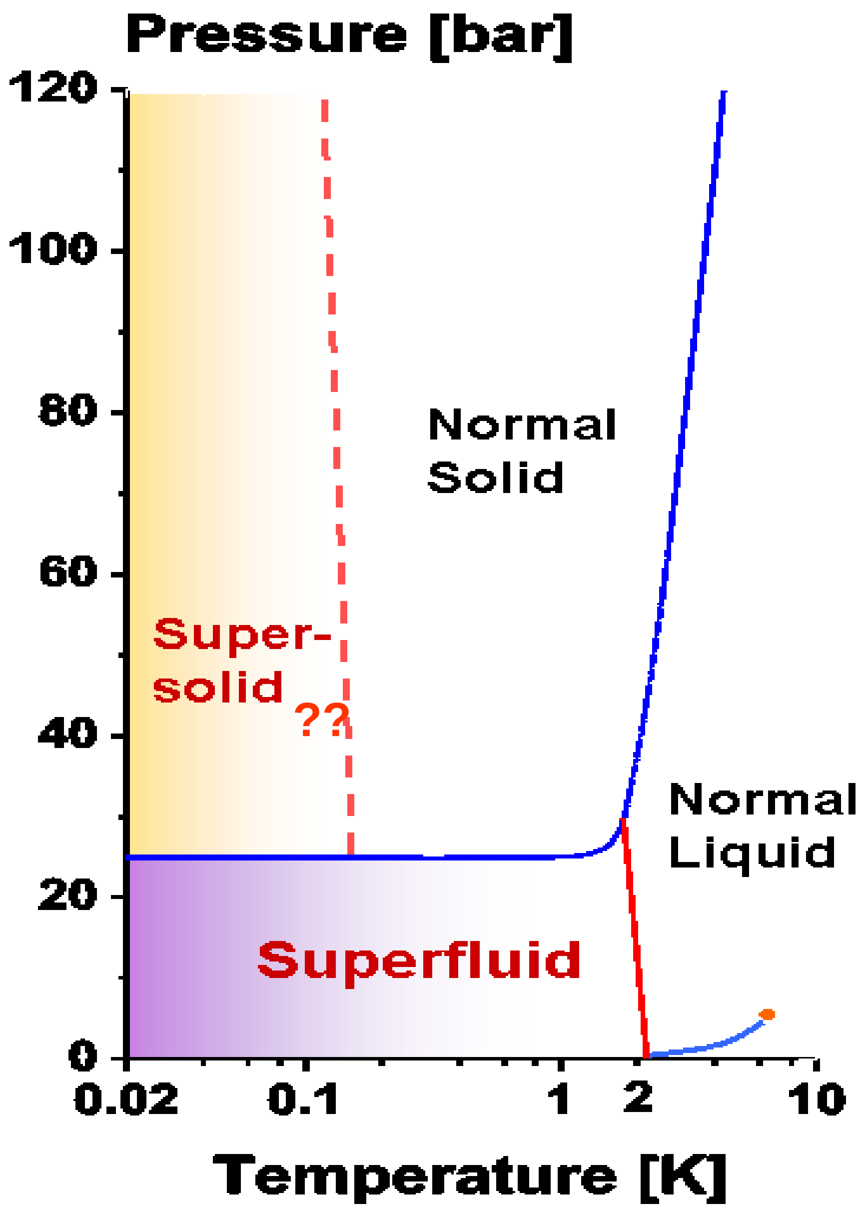
Review of experimental results on supersolidity

Is solid ^{4}He a Non Standard Superfluid ?

ICTP Workshop
July 19, 2011, Trieste

Phase diagram of liquid and solid ^4He



Outline

Key early experiments in support of interpretation of superfluidity in solid helium: Torsional oscillator (TO) results.

Shear modulus stiffening of solid helium complicates the superfluid interpretation.

Measurements on well characterized single crystals, in long path length and very rigid TOs; more puzzles

Evidence of vortices and evidence of fountain effect driven superflow; superfluid after all?

Heat capacity results, relevant or not relevant to the superfluid interpretation ?

Perspectives

'Early' history of supersolid

If solid ^{4}He can be described by a Bijl-Jastraw type wave function that is commonly used to describe liquid helium then crystalline order (with finite fraction of vacancies) and BEC can coexist.

G. V. Chester, Phys. Rev. A **2**, 256 (1970);
J. Sarfatt, Phys. Lett. **30A**, 300 (1969)
L. Reatto, Phys. Rev. **183**, 334 (1969)

Andreev and Lifshitz proposed the specific scenario of zero-point vacancies and interstitial atoms undergoing BEC and exhibit superfluidity. Andreev & Lifshitz, Zh.Eksp.Teor.Fiz. **56**, 205 (1969).

However, x-ray studies (Simmons) found the activation energy of thermal vacancies in solid He^4 to be ~10K. This suggests the density of zero point vacancies to be vanishingly small at low temperature. (Ceperley; Prokofiev, Svistunov Pollet and others (PSP))

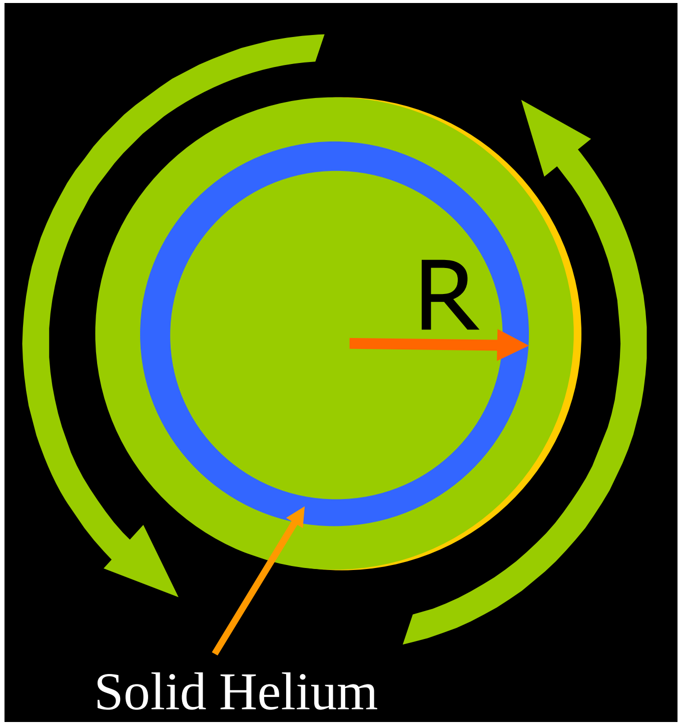
Experiments in 1980s and 1990's did not find evidence of supersolidity.

Detection of superfluidity in solid ^{4}He

Quantum exchange of particles arranged in an annulus under rotation can lead to a measured moment of inertia that is smaller than the classical value

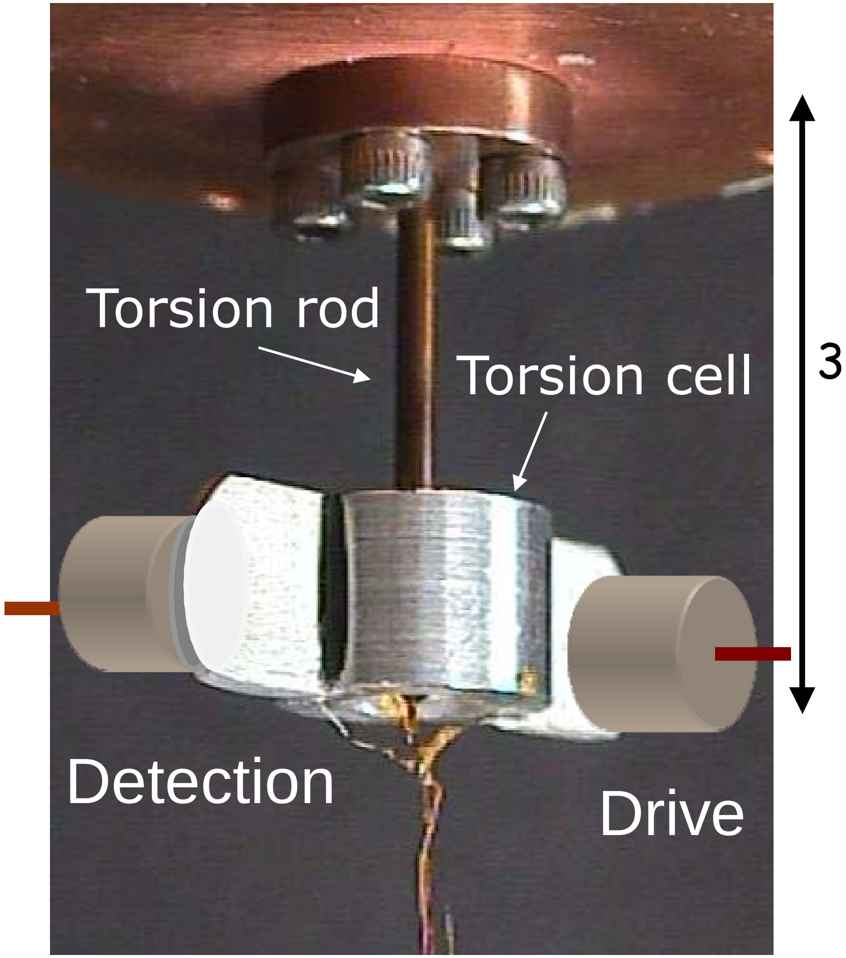
$$I(T)=I_{classical}[1-f_s(T)]$$

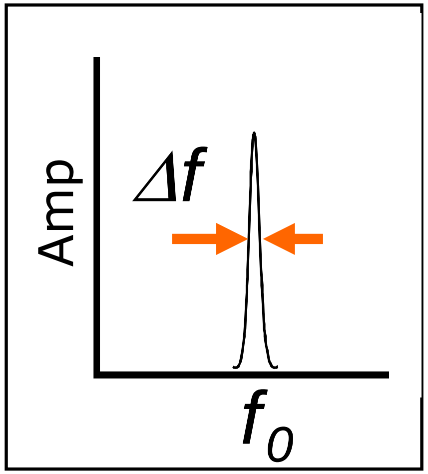
$f_s(T)$ is the supersolid or nonclassical rotational inertia (NCRI) fraction. Its upper limit was estimated by different model to range from 10^{-6} to 0.4; Leggett: $<10^{-4}$



Leggett, Can a solid be "superfluid" ? PRL 25, 1543(1970)

Torsional Oscillator technique for the detection of superfluidity





Quality Factor

Q= $f_0/\Delta f \sim 10^6$

f~ 1kHz

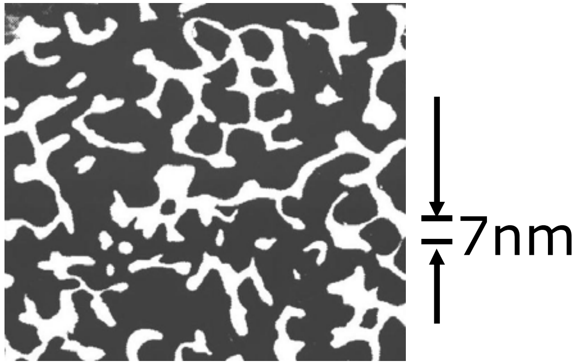
Stability in the period is ~0.1 ns

Frequency resolution of 1 part in 10^7

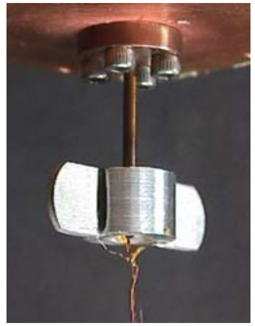
Mass sensitivity of $\sim 10^{-7}$ g

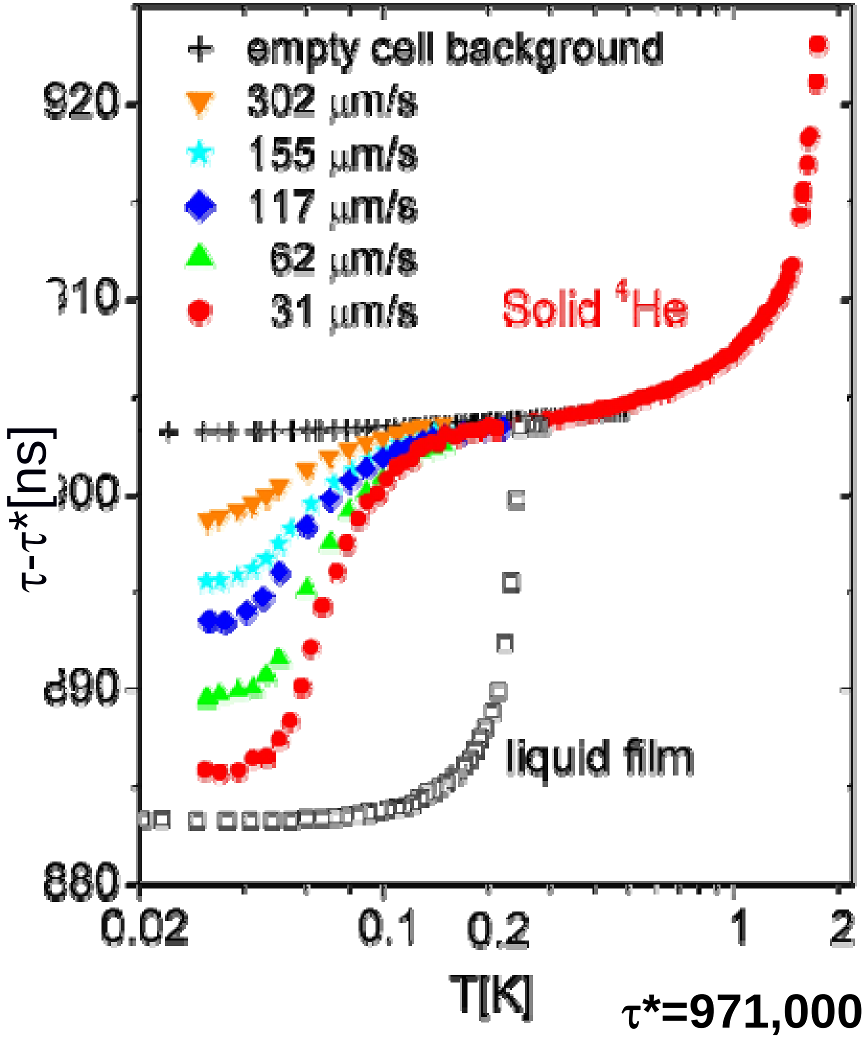
$$\tau_o = 2\pi\sqrt{\frac{I}{K}}$$

Andronikashvili, Reppy



Solid helium in Vycor glass





τ*=971,000ns

f_0=1024Hz, 62 bar

Resonant period increased by 4260ns when solid helium is added (mass loading)

Measured decoupling, $-\Delta\tau_o$=17ns

NCRI fraction, or NCRIf

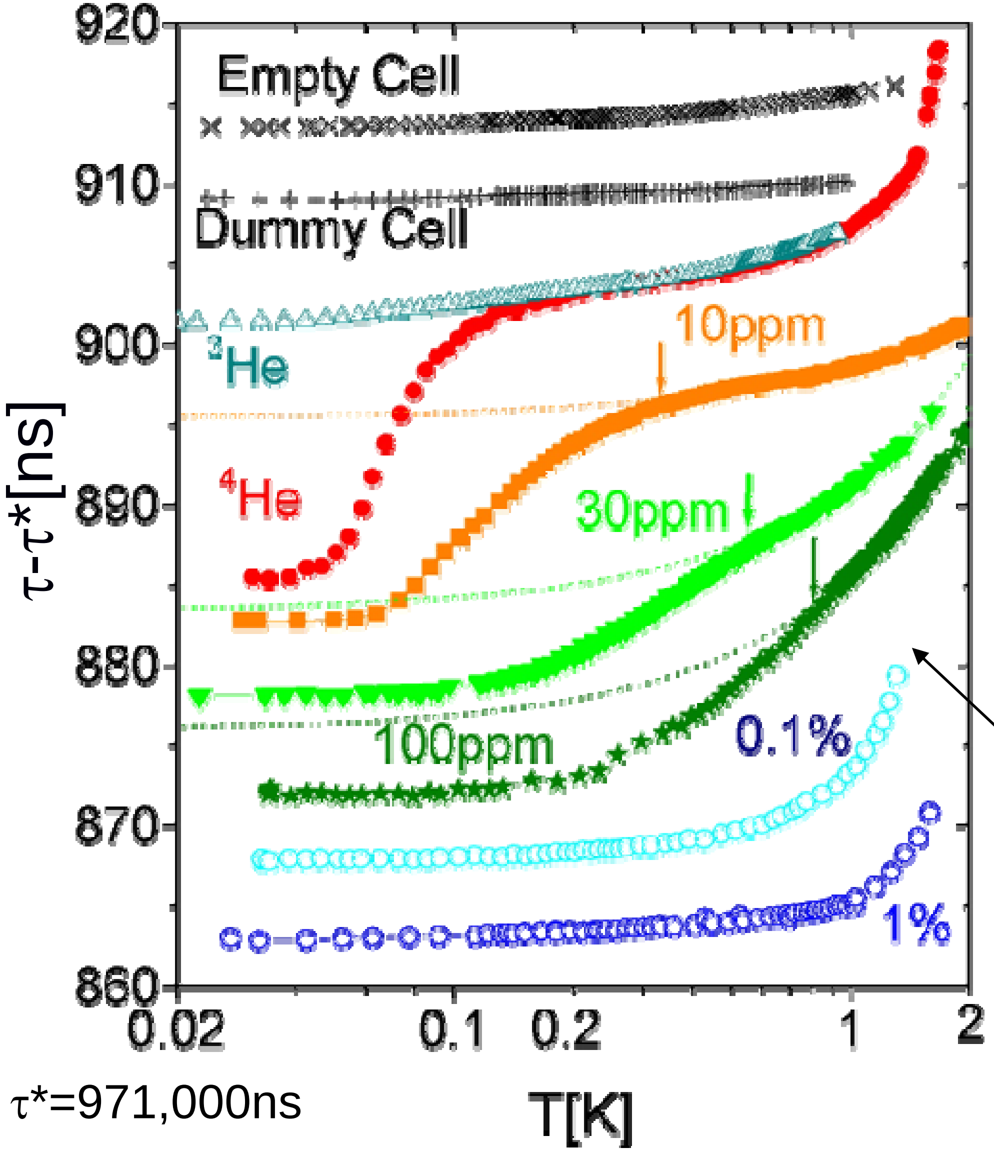
= $\Delta\tau_o$/ (mass loading) = 0.4%

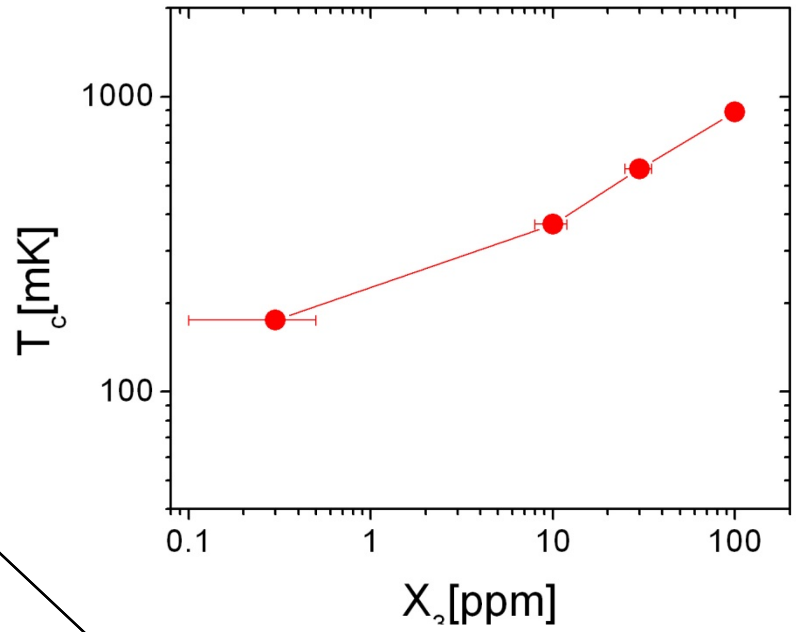
(2%, with tortuosity correction)

NCRIF ranges between 1.2 and 2% for different samples.

E. Kim & M.H.W. Chan, Nature 427, 225 (2004).

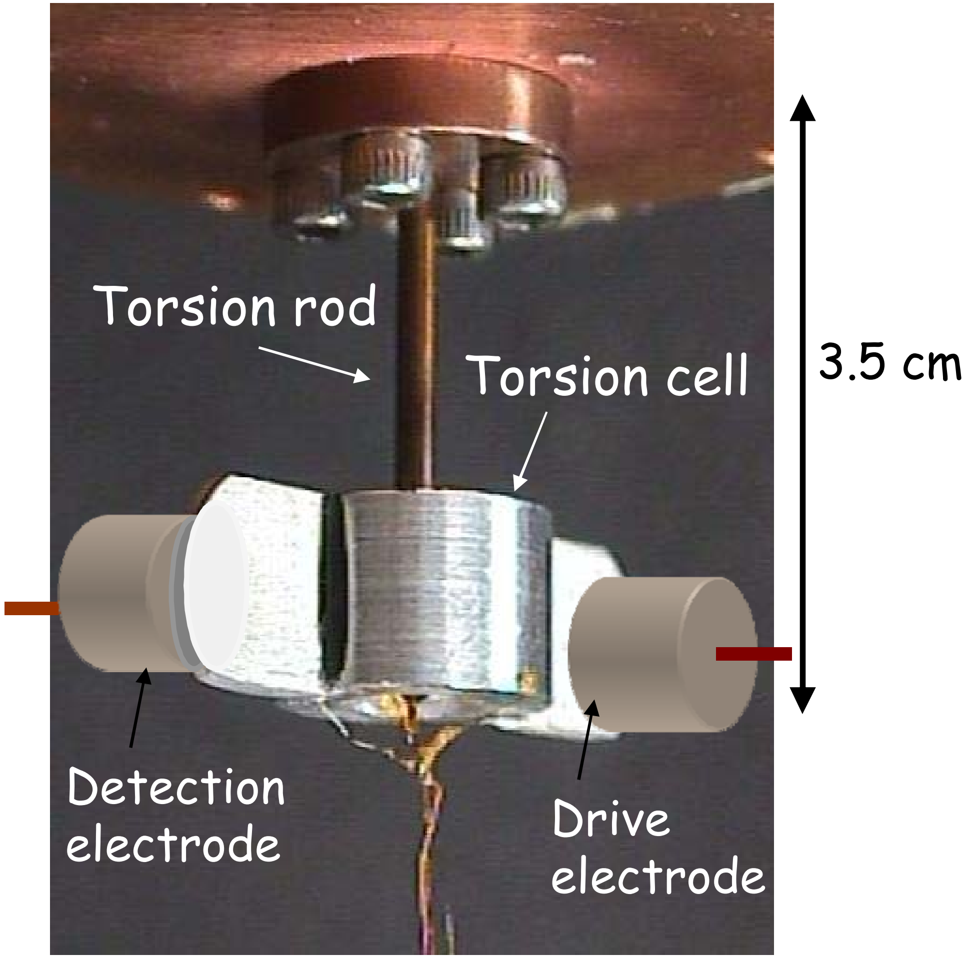
Effect of ^{3}He impurities



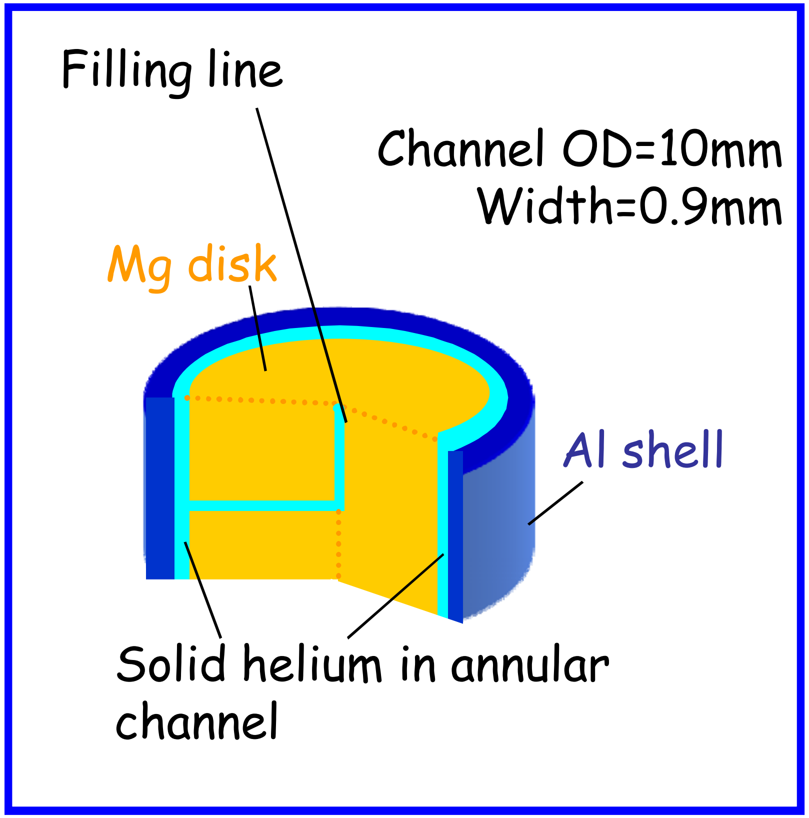


Data sets shifted vertically for
easy comparison

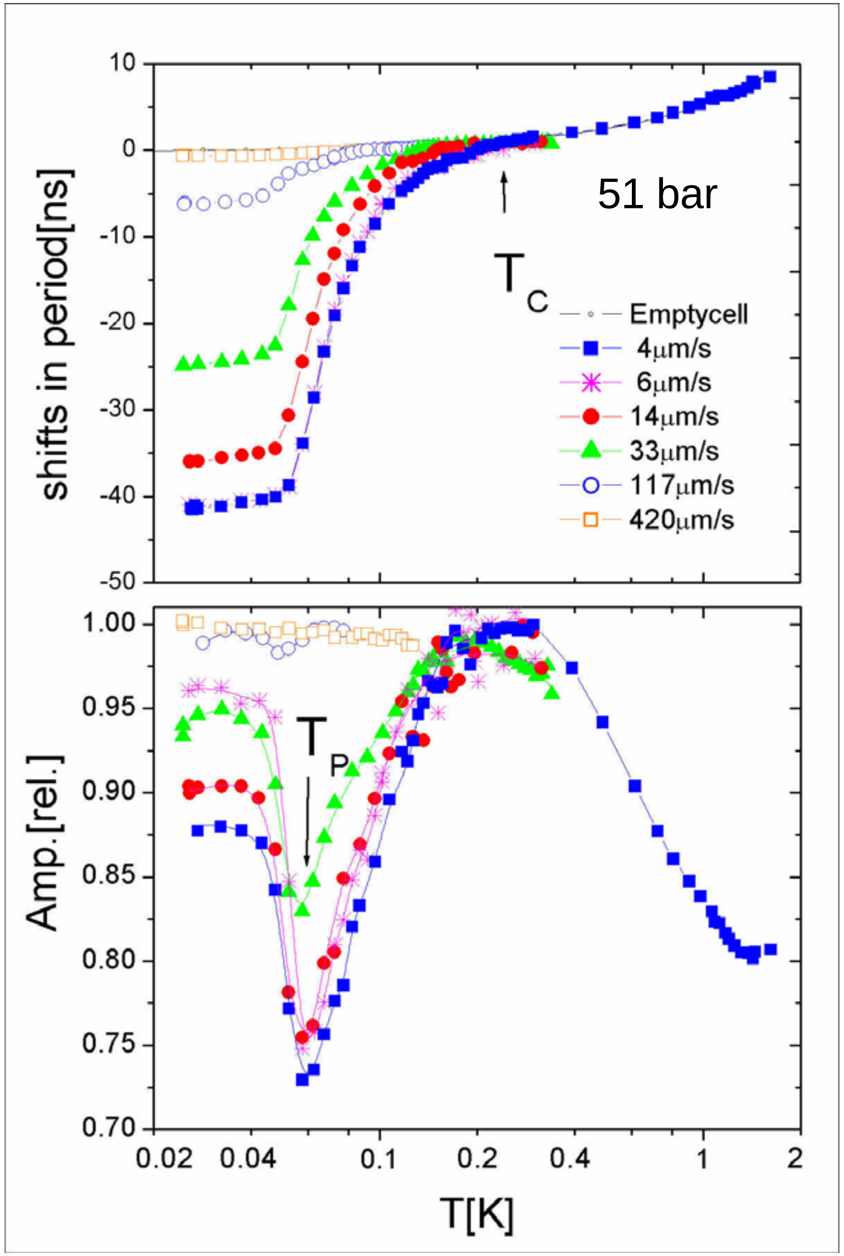
Bulk solid helium in annulus



Torsion cell
with helium in annulus



Bulk solid helium in annulus



f$_0$=912Hz

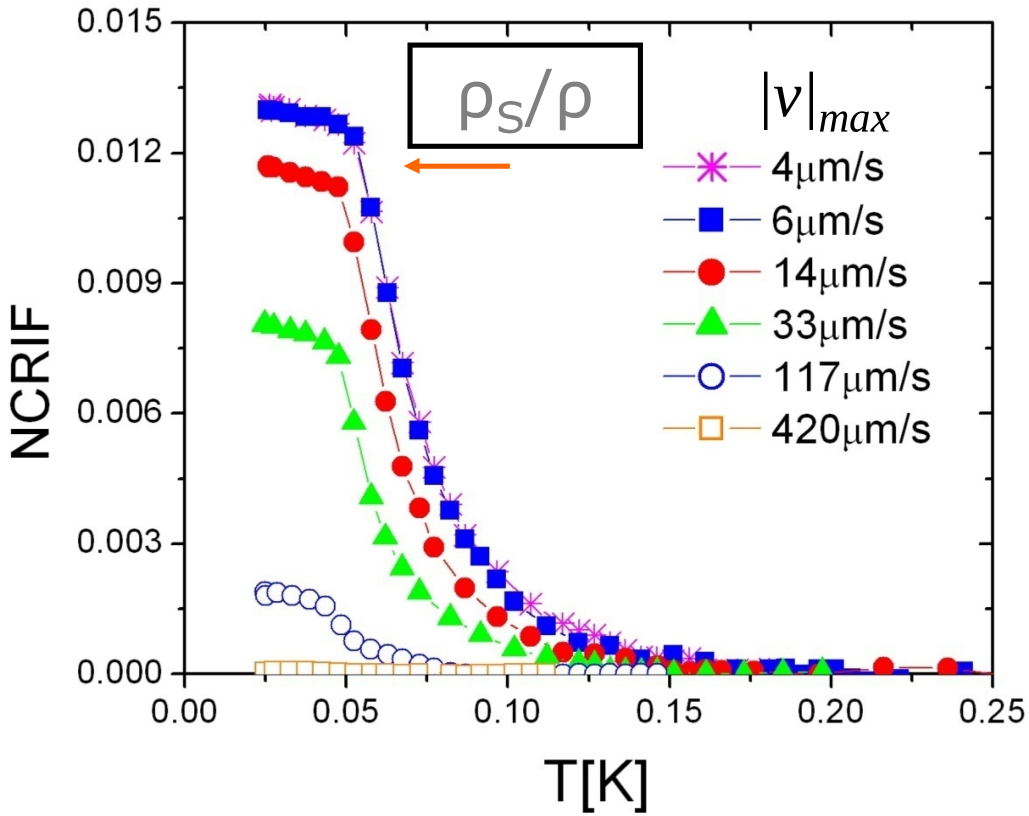
Total mass loading = 3012ns

Measured decoupling, $-\Delta\tau_o$=41ns

NCRIf = 1.4%

E. Kim & M.H.W. Chan,
Science 305, 1941 (2004)

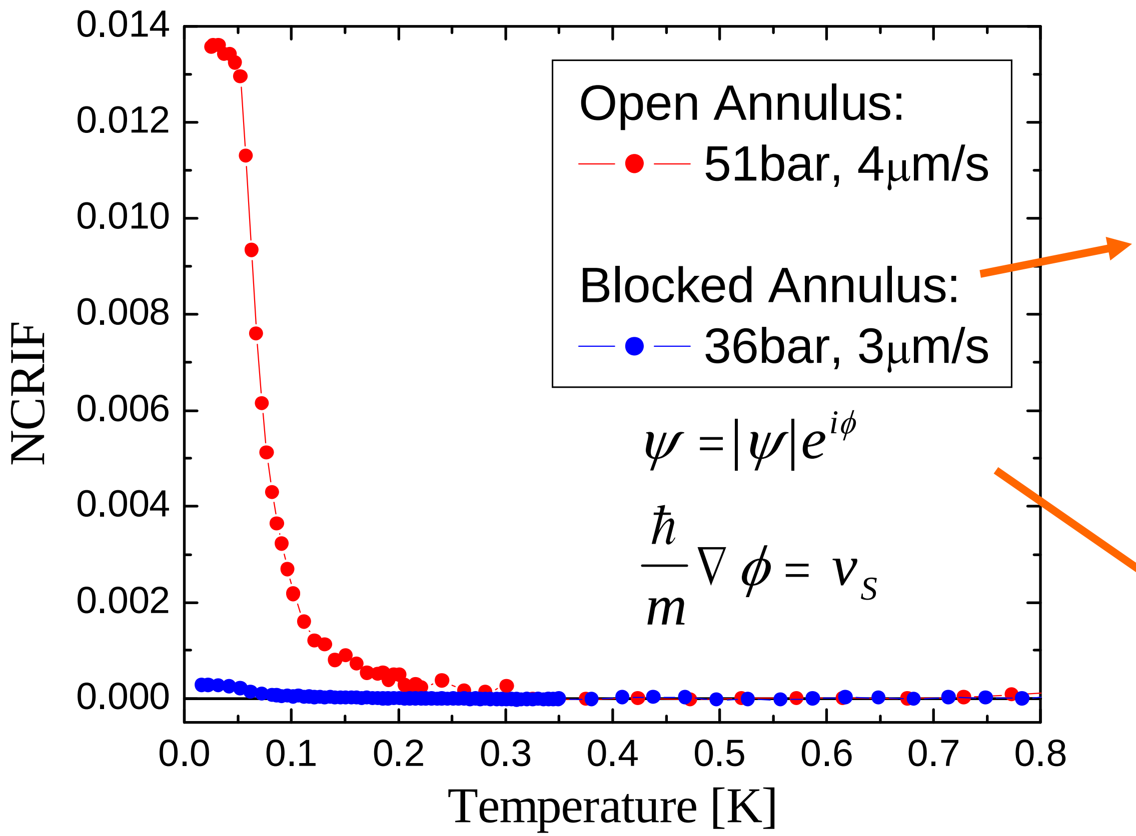
Non-Classical Rotational Inertia Fraction (NCRIF)

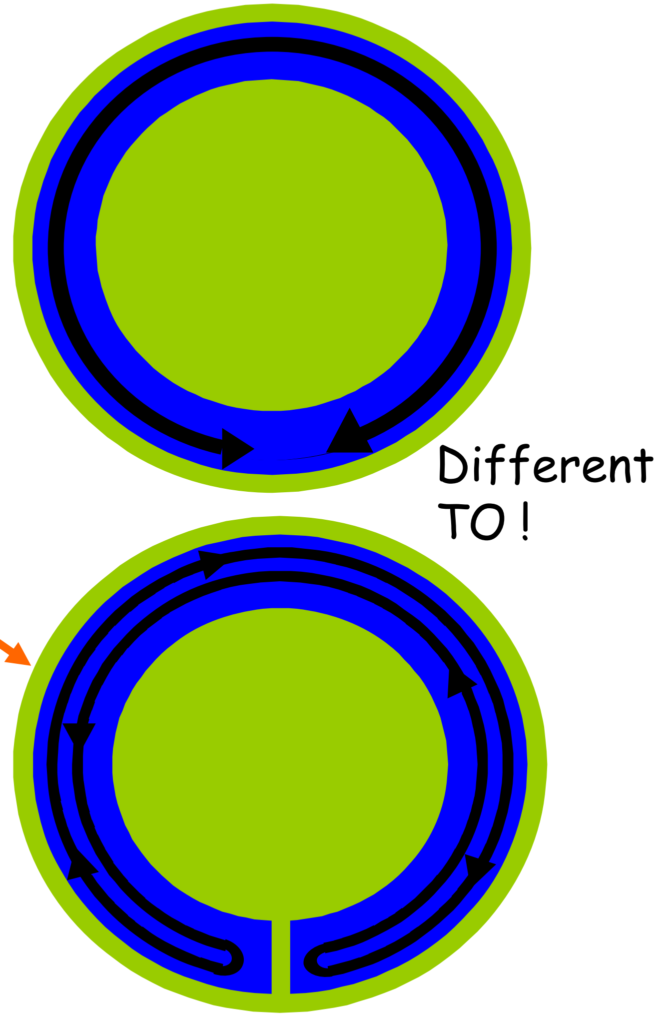


17 samples with pressure ranging from 27 to 66 bar were studied. NCRIF randomly varies between 0.7 and 1.7% with no discernible trend.

'Critical velocity' is ~10μm/s 5 orders of magnitude smaller than that found in superfluid.

The measured NCRIF is greatly reduced when the annulus is blocked. (Supporting the superflow interpretation)





E. Kim & M.H.W. Chan,
Science 305, 1941 (2004)

Summary of torsional oscillator results

NCRI seen in solid confined in porous media and in bulk by 9 groups. The temperature dependence of NCRI found is reproducible, however, NCRI fraction (NCRIF) ranges from $1.5X10^{-2}$ % to ~2%.

Anomalously large (20%) NCRIF reported(Reppy) in TO with very thin (100 μm) annular ^{4}He space. (Very likely a consequence of unusual construction of his TOs; more on this later)

'Critical velocity' ranges between 10 to 100 μm/s.

NCRIF was sometimes (not always) reduced by thermal annealing..

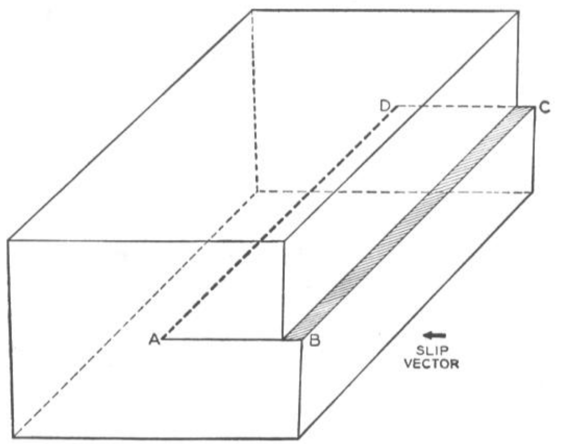
The variation in NCRI lends support to Quantum Monte Carlo simulations results (Ceperley and P &S.) that suggests superfluidity is not possible in a 'perfect' solid and NCRI is due to defects in the solid. Strong experimental support for important role of dislocation network.

Contrary view: NCRI is an intrinsic property of solid ^{4}He and disorder 'enhances' the size of NCRI. (Anderson and others).

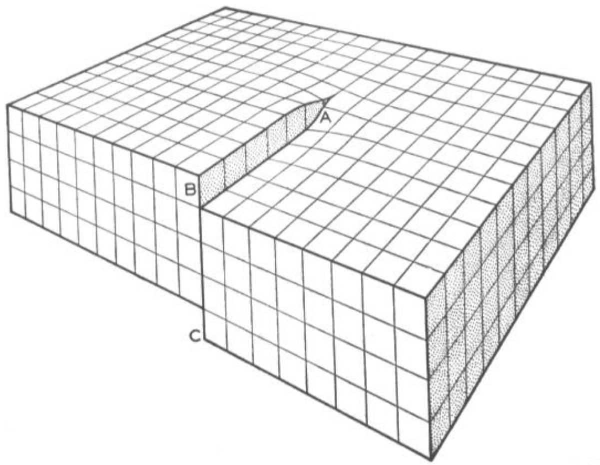
Using a TO with two resonant frequencies, Kojima found frequency dependence of NCRI consistent with Anderson's vortex liquid model. Also observe hysteretic behavior below 60 mK.

Davis et al found evidence of 'glassy dynamics' of different time scales.

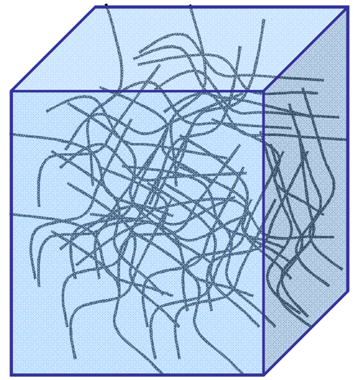
Dislocation network



edge dislocation



screw dislocation



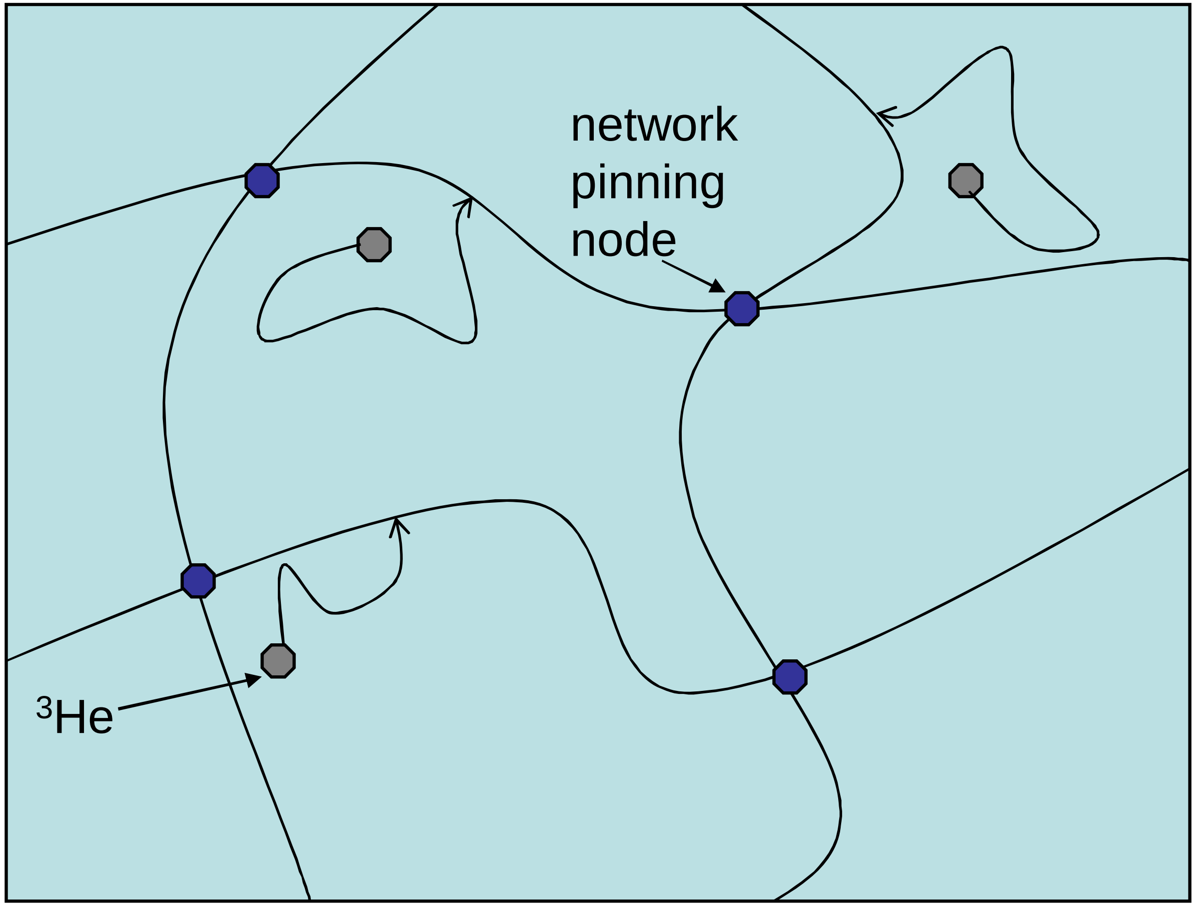
dislocation lines
join and form network

For solid samples grown near 1.5K, density was reported to be ~10^6-10^9 per cm^2.

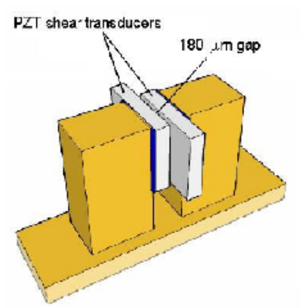
^{3}He impurities and dislocation network

- Dislocation lines intersect at nodes forming an interconnected network
- At high T ^{3}He impurities are not pinned.
- When T is reduced, ^{3}He condense onto and stiffens the dislocation network.
- Higher $n_3 \rightarrow$ higher the condensation T.

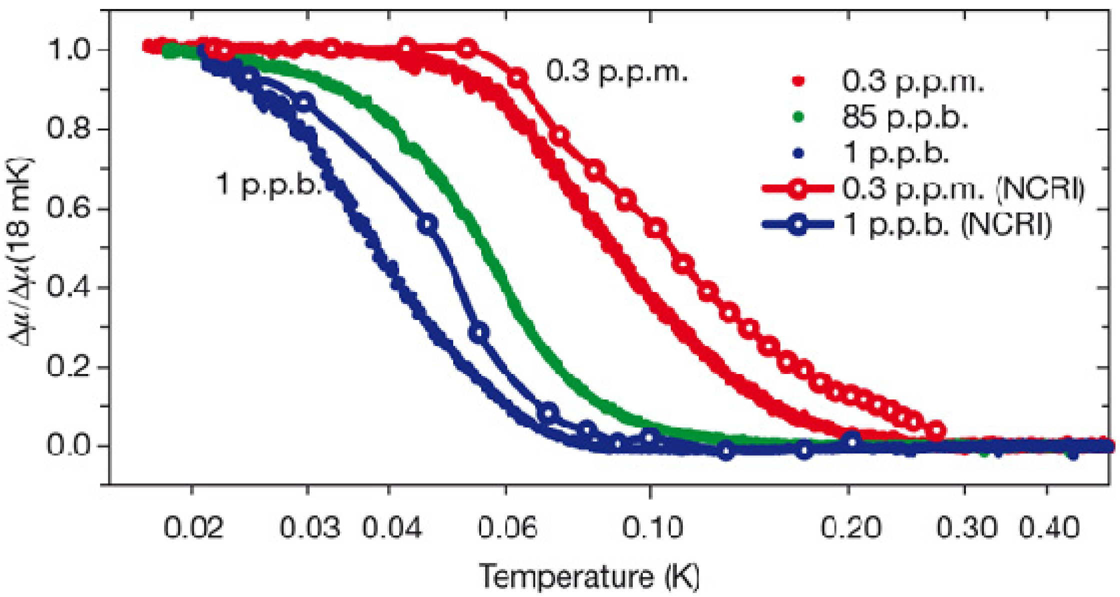
Iwasa et.al., J.Phys. Soc. Jpn. 46, 1119(1979); Paalanen, Bishop and Dail, PRL 46, 664(1981)



Shear modulus increase at low temp mirrors NCRI



Day and Beamish, Nature (London) **450**, 853 (2007).

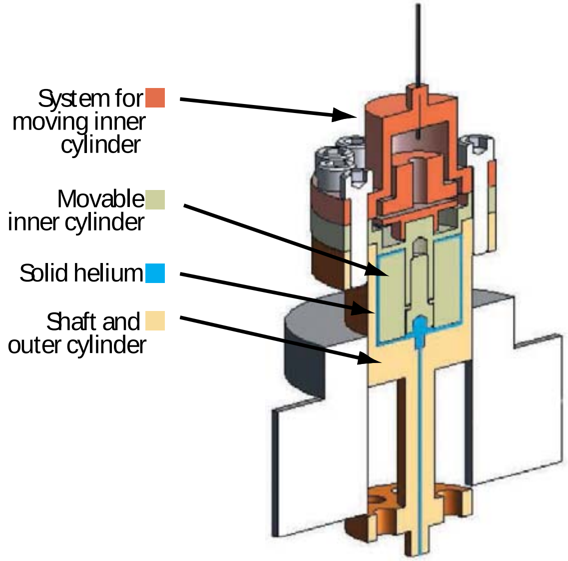


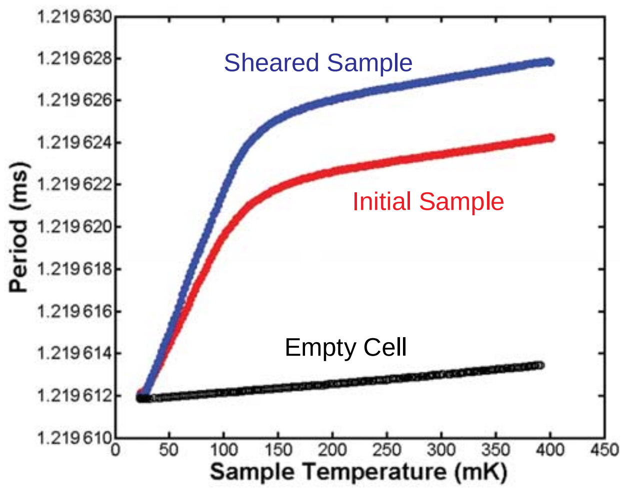
The ^{3}He concentration effect supports the interpretation that shear modulus increase is due to the condensation of ^{3}He atoms onto the dislocation network.

Balibar & Beamish showed that solid helium (dislocation network) is stiff with a reproducible shear modulus at low T. It softens at a higher, crystal quality and ^{3}He concentration dependent T. The shear modulus decreases as much as 40% (!) for high quality single crystal , 10 to 20% for polycrystalline samples.

Effect of shear modulus softening on TO results

Since solid 4He is a constituent of the TO, the stiffening of the solid at low T stiffens the TO, reducing the resonant period. The actual shear modulus effect depends on the shape and dimension of the TO cell and also the rigidity of the TO. The effect on the resonant period can be very large for some TOs.





In Reppy's thin annuli TOs, the inner cylinder is coupled to the outer shell by a thin diaphragm or a single screw. In this case solid helium in the annulus and at the top and bottom of the inner cylinder contributes significantly in mechanically coupling the inner (metal) cylinder to the outer shell. A change in the shear modulus of 20% changes the resonant period of 1 part in 10^5.

If the annulus is narrow (~100 μm), the mass loading is small (~100 ns for most of Reppy's TO) , hence the apparent (false) NCRIf can be very large, ~20 or even 80%).

Effect of shear modulus softening II

For a simple and rigid TO that operates ~1000 Hz consists of a cylindrical metal shell filled with a cylindrical solid ^{4}He sample of ~1cc, a change in shear modulus of 20% translates into a change in the resonant period of 1 part in 10^7, or a change of 0.1 ns. [Maris et.al. and also FEM simulations] Typical mass loading (due to solid helium) is 1000 ns. Hence this effect accounts for an apparent (false) NCRIf of 0.01%. This is smaller than the typical observed NCRIf of 0.1 or 1%. However, in some TOs , the low T period drop correspond to only 0.03%.

Question: Is it possible that some of the TOs assembled with epoxy and reporting 0.1 or 1% NCRIf is not as rigid as one thought and the shear modulus effect is larger than expected.

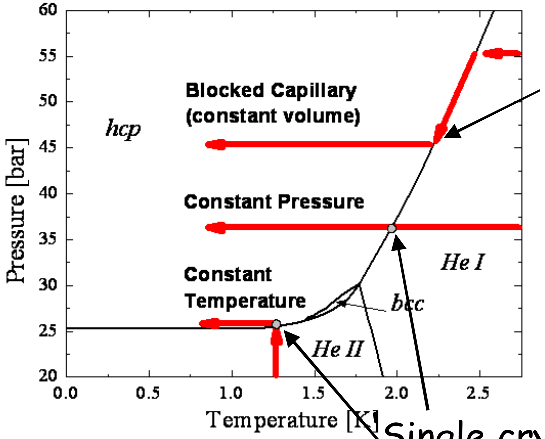
Possible Models of NCRI in solid ^4He

(I) The core of a screw dislocation is proposed to be superfluid by Shevchenko, Sov. J. of Low Temp. Phys. 13, 61(1987). This idea is confirmed in a Quantum Monte Carlo simulation study Boninsegni and PSP, PRL 99, 035301 (2007). In this model, (1) the observed NCRI in TOs is a consequence of the screw dislocation lines forming a 3-d interconnected network. (2) When the network is stiff, superfluidity is non-dissipative. (3)The variation in NCRIF is due to the variation in the density and the connectivity of the dislocation lines.

What is the major "problem" with this model? The NCRIF of such a model is too small. If we assume the density of dislocation line to be 10^9 cm^{-2} (appropriate for polycrystalline sample) with a superfluid core diameter of 0.3 nm and that the lines are all 'streamlined' to give maximum NCRIF, we will get a NCRIf of ~3x 10^{-4}%. This is three to four orders of magnitude smaller than the 'typical' NCRIf observed in most TOs.

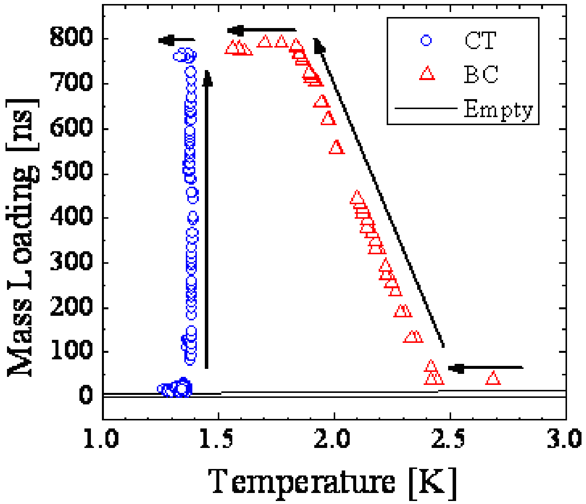
(II) The core of dislocation lines is not necessarily superfluid, however, superfluidity in solid ^4He is not dissipative only when the dislocation network is stiff.

correlation of NCRI with disorder in solid?

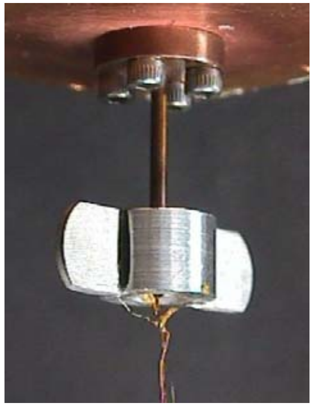


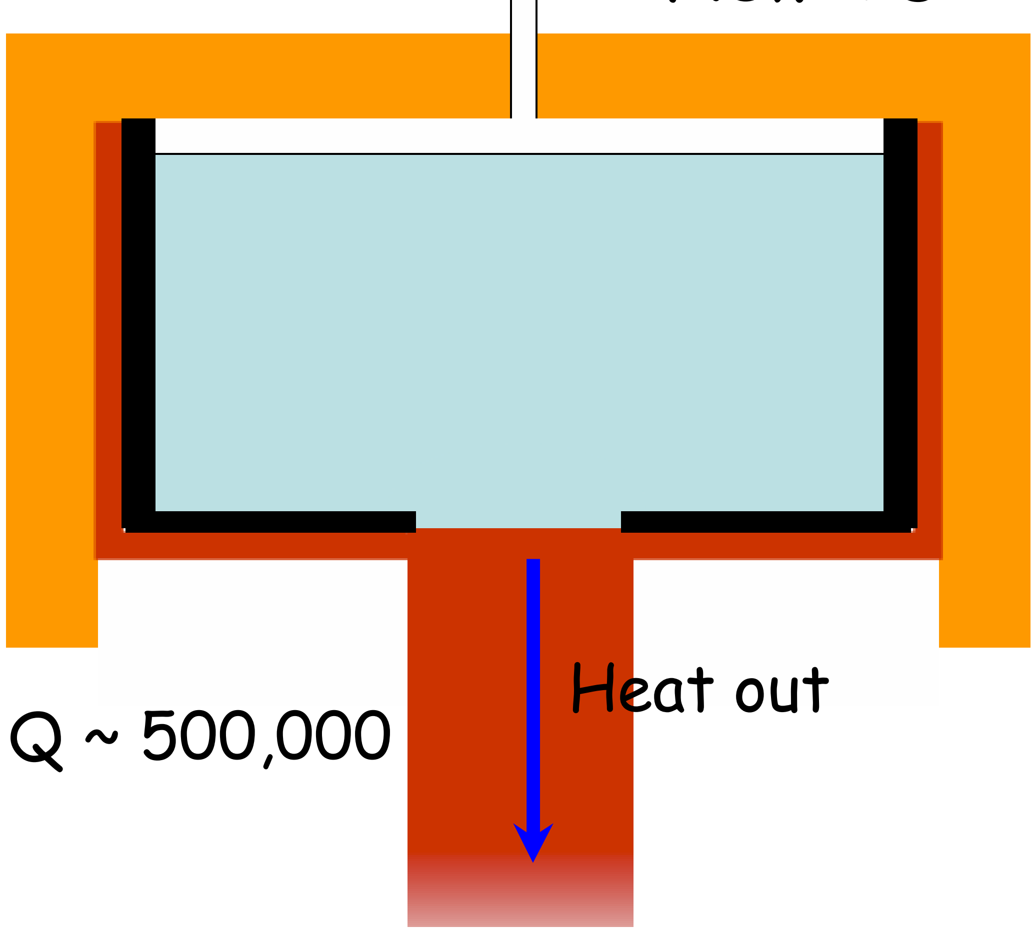
Polycrystalline samples are grown under constant vol. condition.

'Single crystal' can be grown under CP or CT condition

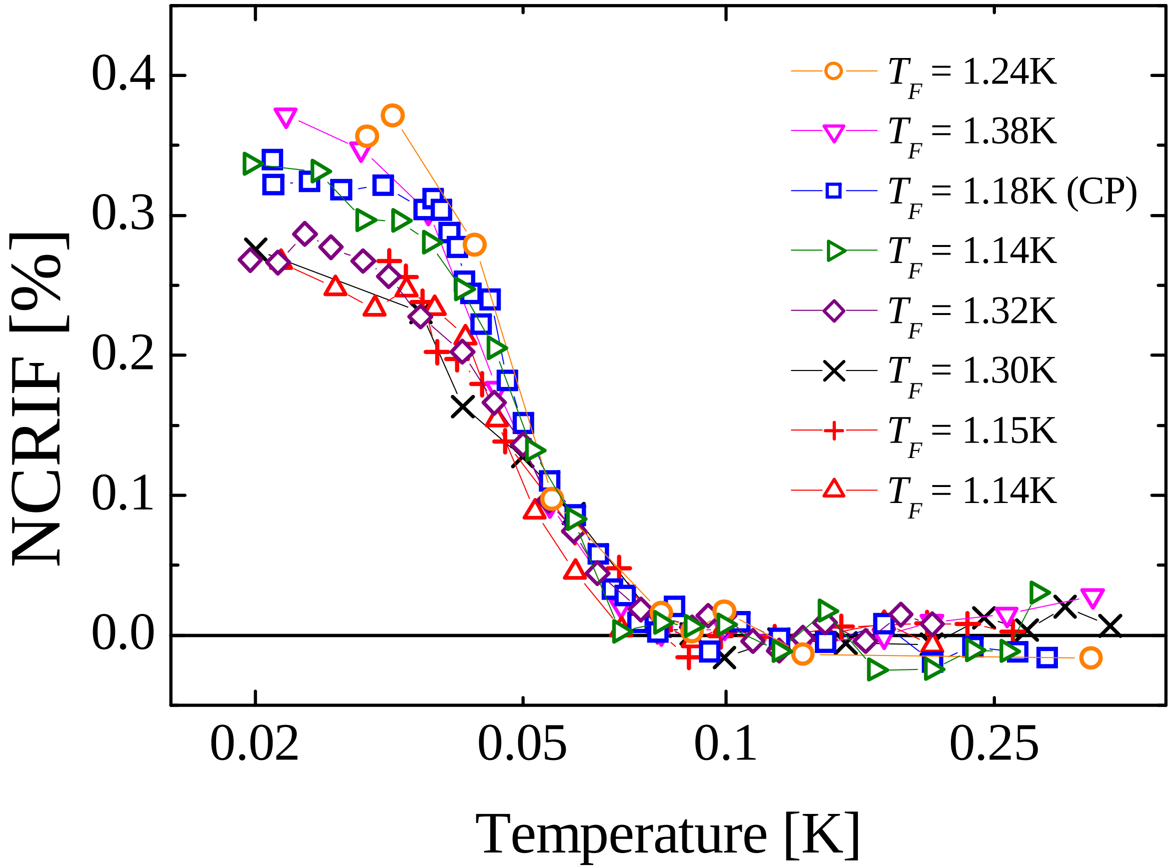


'Old' TO



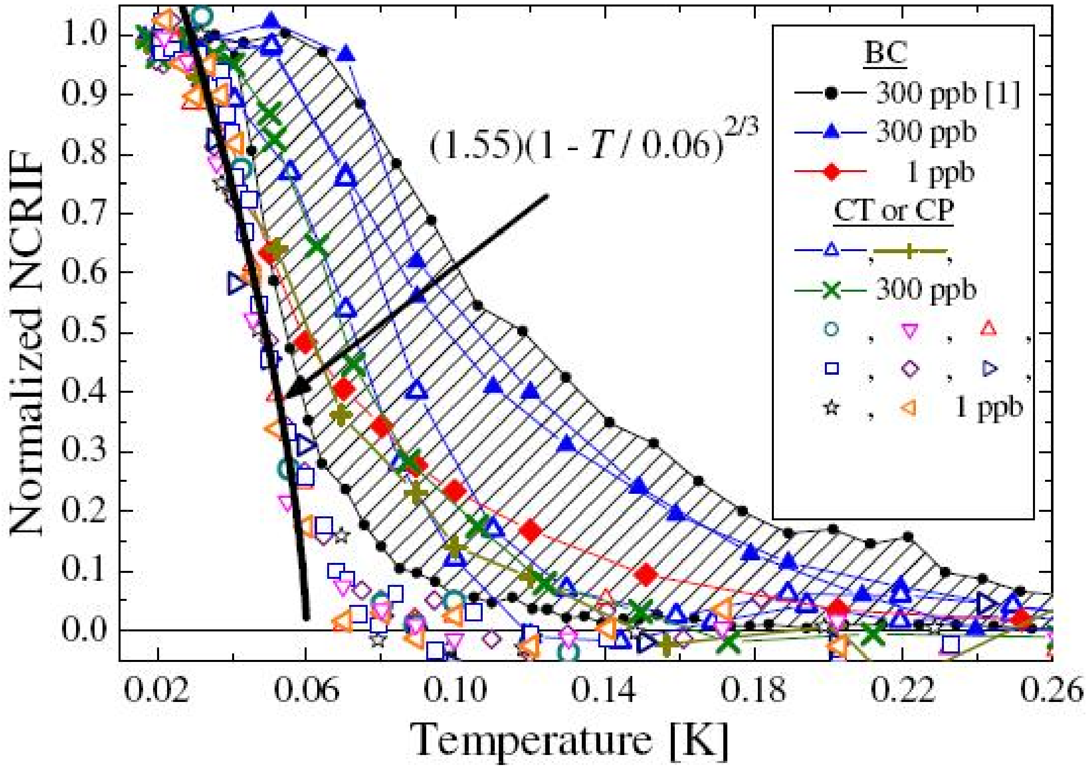


Onset temperature and magnitude of NCRI are reproducible in 8 different 'single' crystal samples grown at constant T or P from superfluid. Deviation and hysteretic behavior seen below 40 mK.



Clark, West and Chan: PRL, 99, 135302

NCRIF of solid samples grown with different procedures with different ^3He impurities.



BC:
polycrystalline

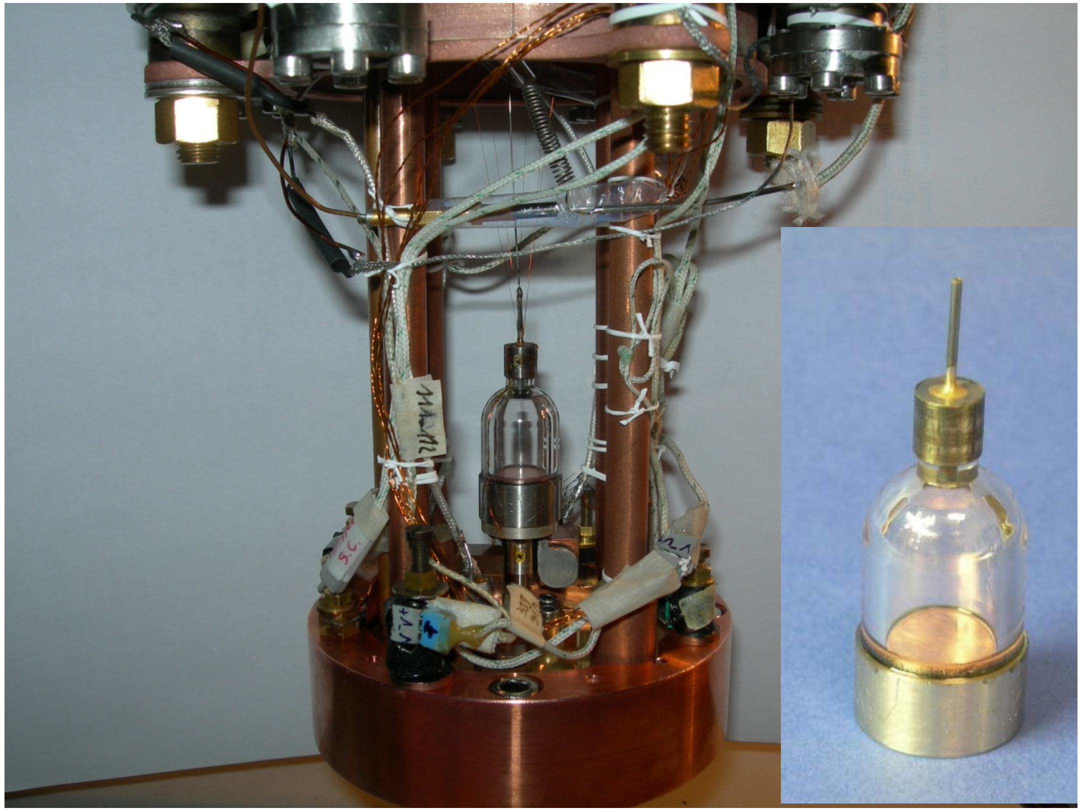
CT or CP:
'single' crystal

In polycrystalline samples onset of NCRI broadens from ~75 mK up to 300 mK. The onset also broadens with ^3He impurities.(also seen in the Vycor experiment)

However, NCRIF of 'single' crystal samples are still cell dependent!
[ranges from $1.5X10^{-2}$ % to 0.3%.

NCRI in a (sample) crystal one can see

^{4}He crystals grown from superfluid below 50 mK have very low dislocation density. To search for NCRI in such crystals and also to correlate NCRI with crystal quality, a TO experiment with a mini-bell jar sapphire torsion cell was carried out in Balibar's lab at ENS in an optical cryostat.



NCRI is present in high quality single crystal, if present, has NCRIf of less than 0.03%.

Andrew Fefferman, Xavier Rojas, Josh West, Ariel Haziot, S. Balibar & M.C.

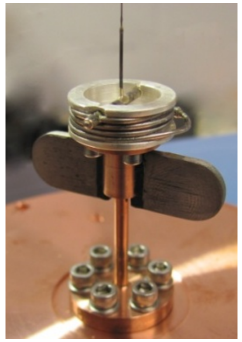
NCRI in long path length TOs

Is the NCRI phenomenon in solid ^4He macroscopic like superconductivity and superfluidity?

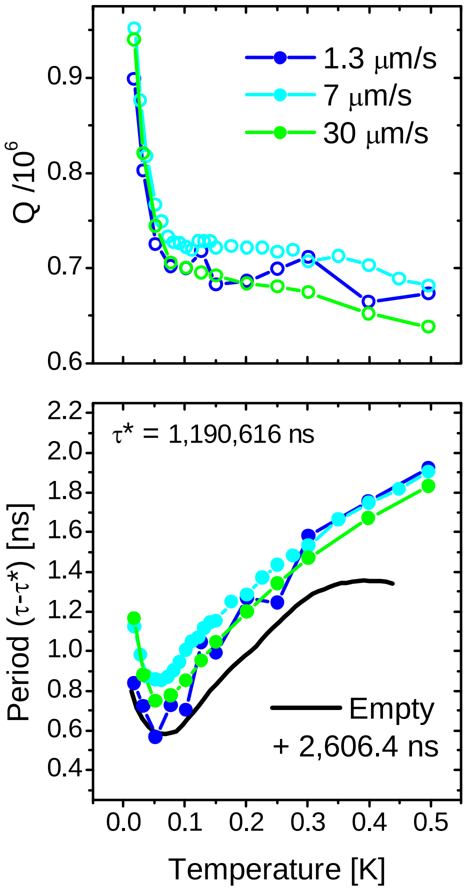
Measurements were carried out by Duk Young Kim and others in TOs where solid helium samples are confined in capillaries (wound like a persistent superconducting magnet) of 1 m and 30 cm. I.D. of the capillaries are 0.4 and 0.5 mm respectively.

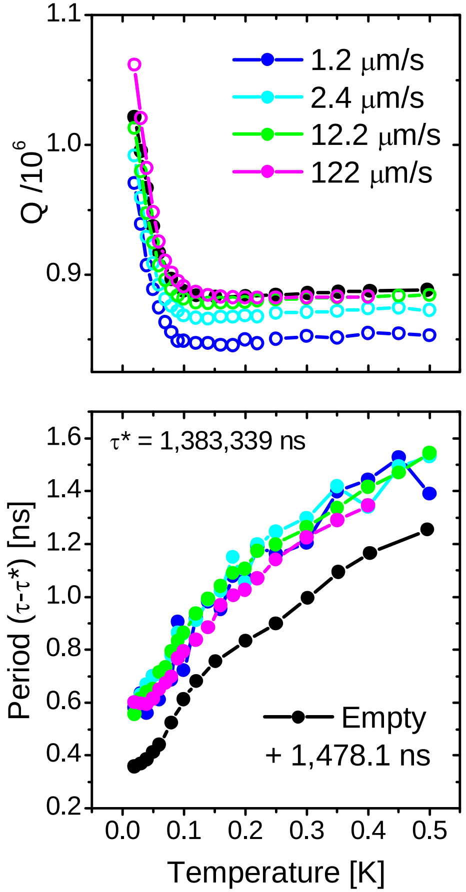
(Unfortunately?), if there is superfluidity, NCRIf was found to be less 0.007% for both the 1 m and the 30 cm cells.

1 m



30 cm





Long path length TOs, II

❖ 9 cm path length

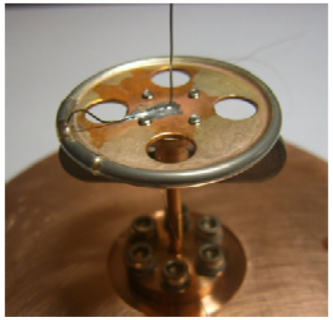
- ❑ Cross sectional area of the helium torus : 2.63 mm^2 Larger than the annulus area in conventional TOs.

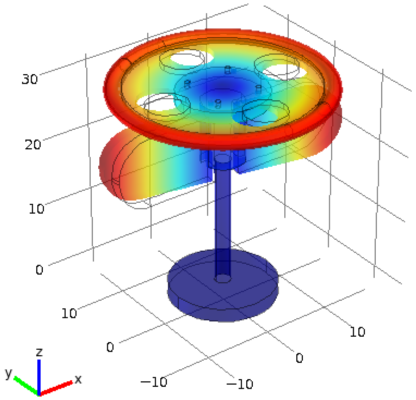
- ❑ Resonant Frequency : 570 Hz

- ❑ Mass loading: 15,000 ns

- ❑ FEM simulation
  - Expected resonant frequency change due to a 20% increase in the shear modulus of solid helium is
    $\Delta f/f = 4.6 \times 10^{-8}$
    $\Delta period = 0.08$ ns
    If translated to NCRI : 0.0005%
  - In typical TOs,
    $\Delta f/f \sim 10^{-7}$ Apparent NCRI ~0.01%

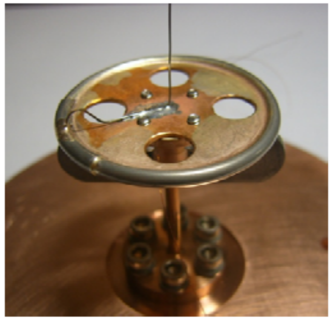
H. Maris, and S. Balibar, J. of Low Temp. Phys. **162**, 12 (2011)





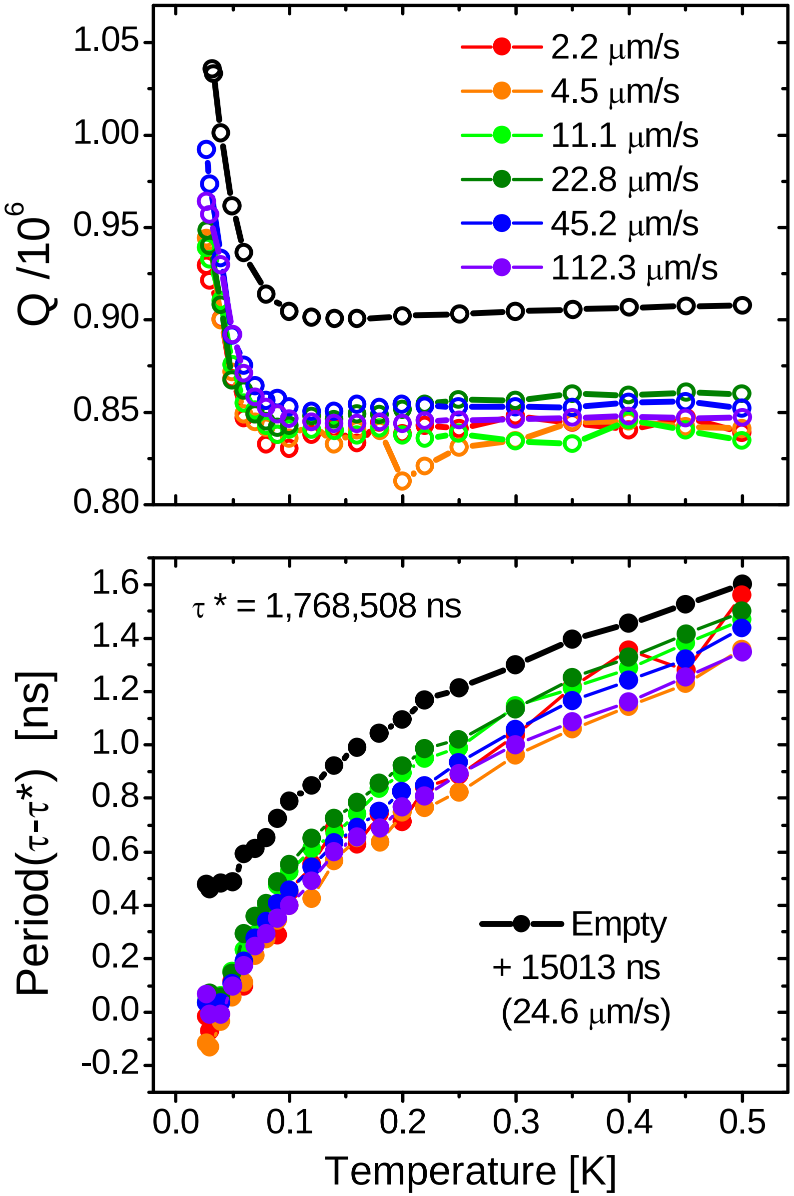
Long path length TOs, II

9 cm path length



41 bar solid

- Blocked capillary method
- Mass loading : 15,000 ns
- Period change is ~ 0.4 ns
- NCRIf ~ 0.003%
  (6 times larger than that expected due shear modulus stiffening)



Long path length (??) TOs, III

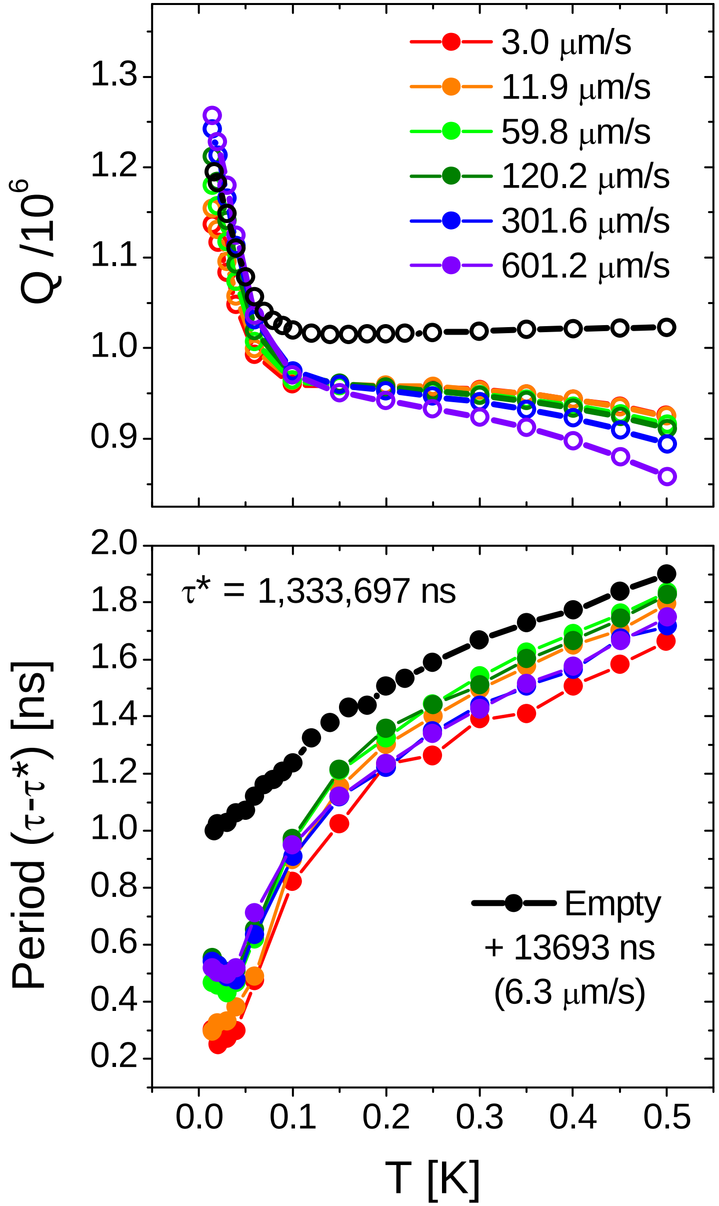
6 cm path length

- Resonant Frequency : 756 Hz
- Cross sectional area is 5.6 mm^2
- Mass loading : 13,700 ns
- 49 bar solid (Blocked capillary method)
- Period change ~ 0.6 ns
- NCRIf ~ 0.004%
- Shear modulus effect

  $\Delta f/f = 1.1 \times 10^{-7}$

  Δperiod = 0.16 ns

  If translated to NCRI : 0.001%



What can be the reason for such small NCRI in the toroidal TOs ?

1. In contrast to conventional TOs, there is no sharp corner in the helium space; hence there is no chance of any liquid inclusion or high density of grain boundaries

2. The assembly of the toroidal TOs is 'simple' (and rigid), involving no glue.. This implies in conventional (prior) TOs, the observed period drops may be results of the shear modulus effect and not NCRI. Can TOs assembled with epoxy be so floppy?

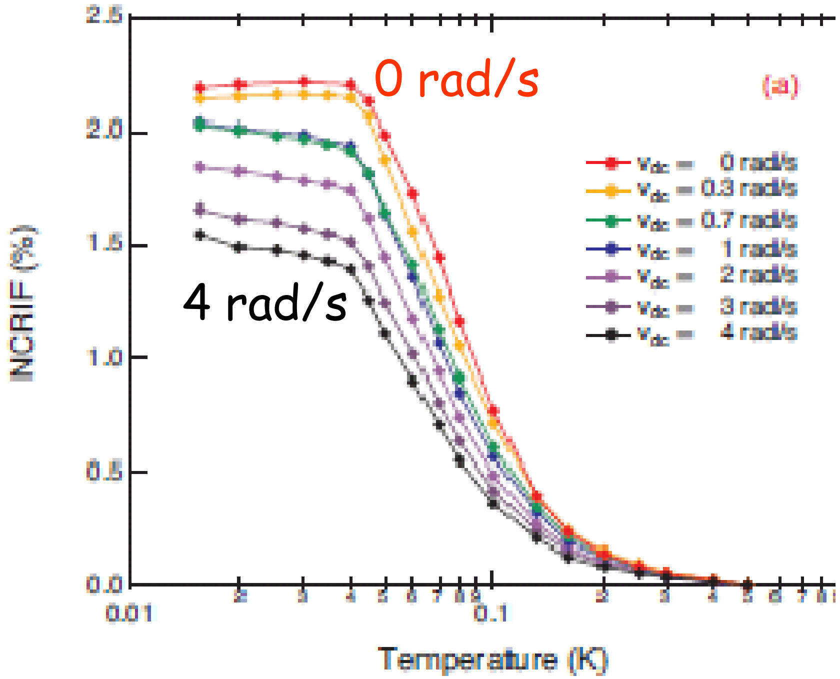
3. In a measurement with a welded (hence more rigid) TO with a standard annulus space, a signal of 0.5 ns out of a mass loading of 3500 ns (f_0 = 340 Hz) was seen, or a NCRIf of 0.015%. The period drop due to 20% shear modulus stiffening of the solid was calculated by FEM to be ~0.02 ns.

4. NCRIf found in rigid TOs are always very small, [0.004 to 0.015%]
These small NCRIf measured in these cells are reproducible in different solid samples.

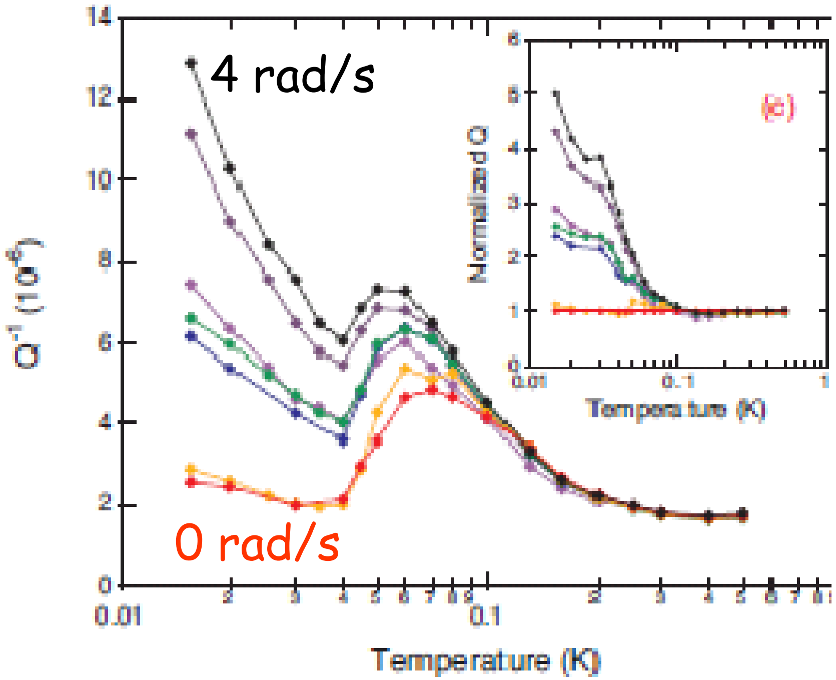
Perhaps the correct NCRIf in bulk solid is $\leq$ 0.01%; in closer agreement with that expected for the 3-D connected (superfluid) dislocation network model,

or we have under-estimated the shear modulus stiffening effect by 5 to 10 times and there is no NCRI in bulk solid ^{4}He. Then , how can we understand the blocked annulus exp. and the exp. on rotating cryostat?

TO studies under DC rotation, evidence of quantum vortices?



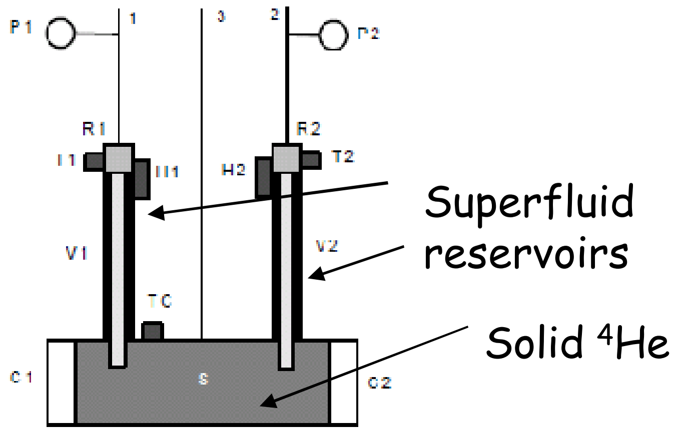
Additional dissipation and diminution of NCRI seen for solid under dc rotation.
evidence of Vortices?
DC rotation for superfluid
= magnetic field for a superconductor.



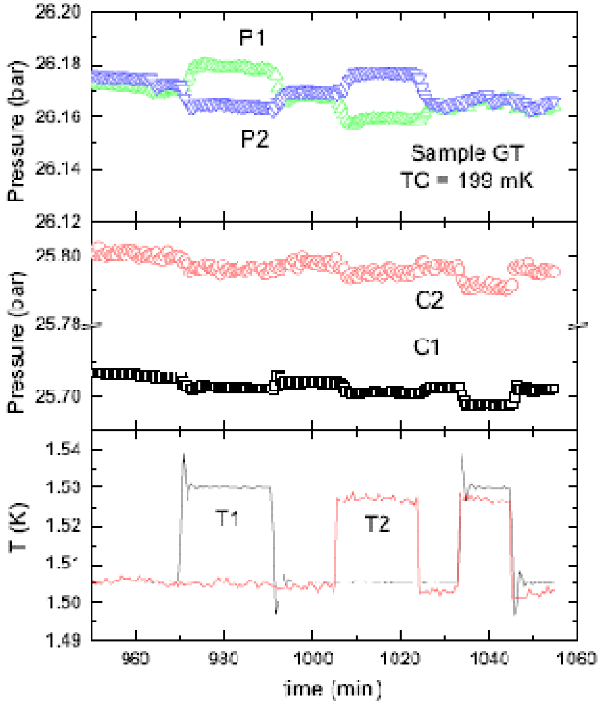
Choi, Takahashi, Kono and Kim
(KAIST and Riken)

Science 330, 1512(2010)

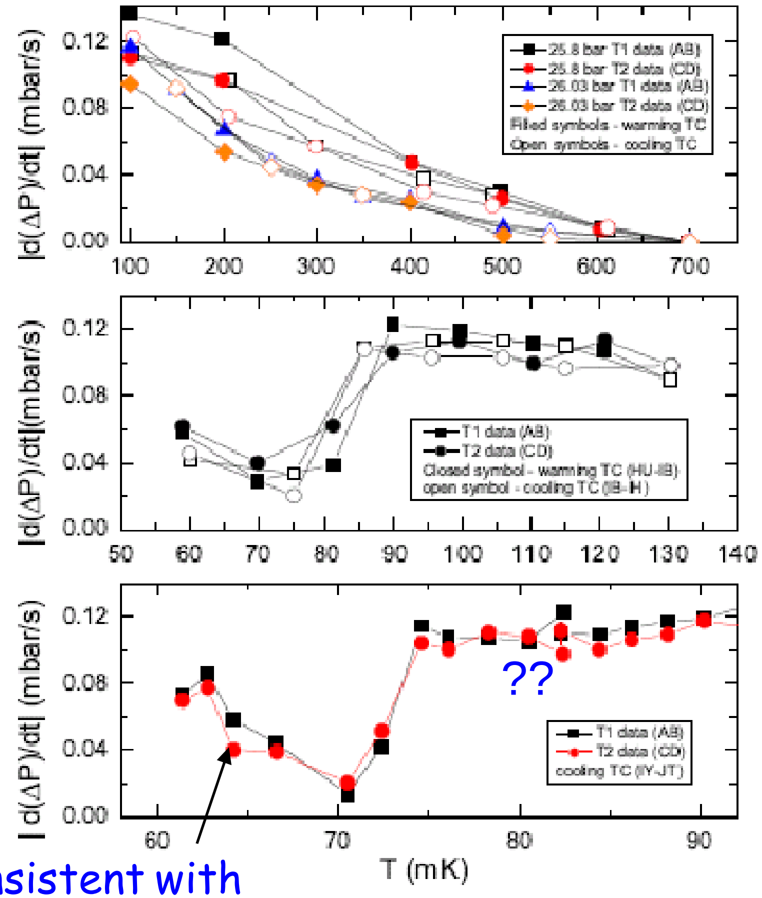
Fountain effect induced mass flow through solid ^{4}He



U. Mass sandwich



Ray and Hallock.



Consistent with NCRI?

Mass flow from one superfluid reservoir to another through solid ^{4}He.

No flow above 600 mK; drop in flow rate near 70 mK but increases at lower T.

PRL 105, 145301 (2010)

Heat capacity Measurements

Is there a peak related to NCRI onset?
Is there a linear T (glass-like) term in C_v ?

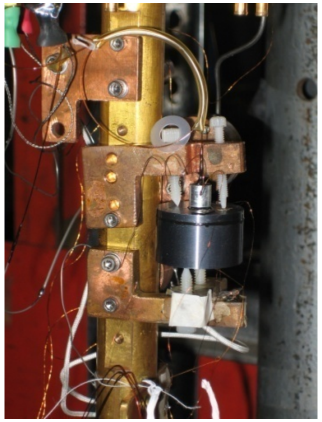
Limited resolution below ~100mK in earlier studies

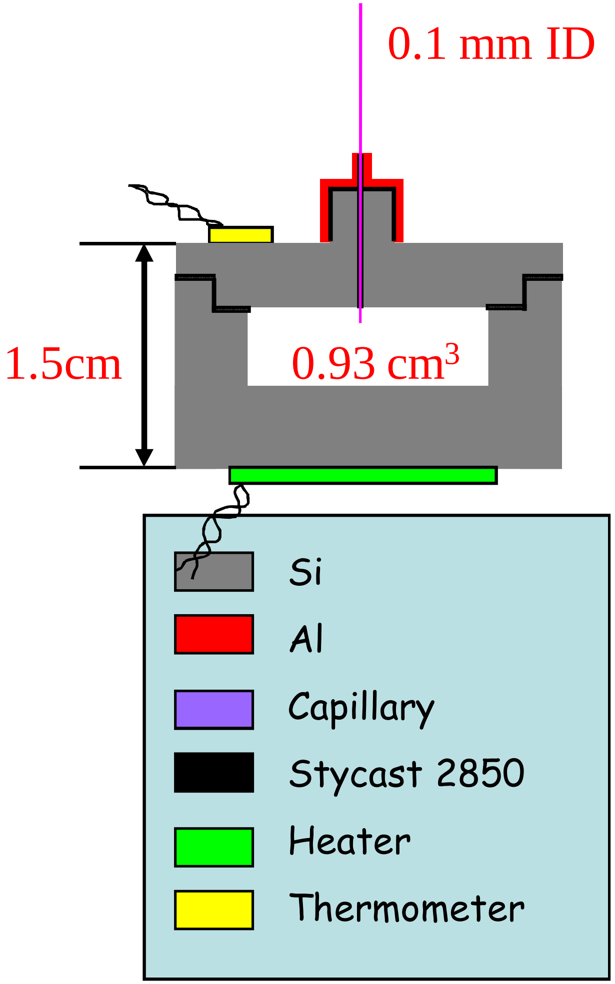
large background heat capacity due to the metallic cells.

Penn State solution? Silicon and Sapphire sample cells

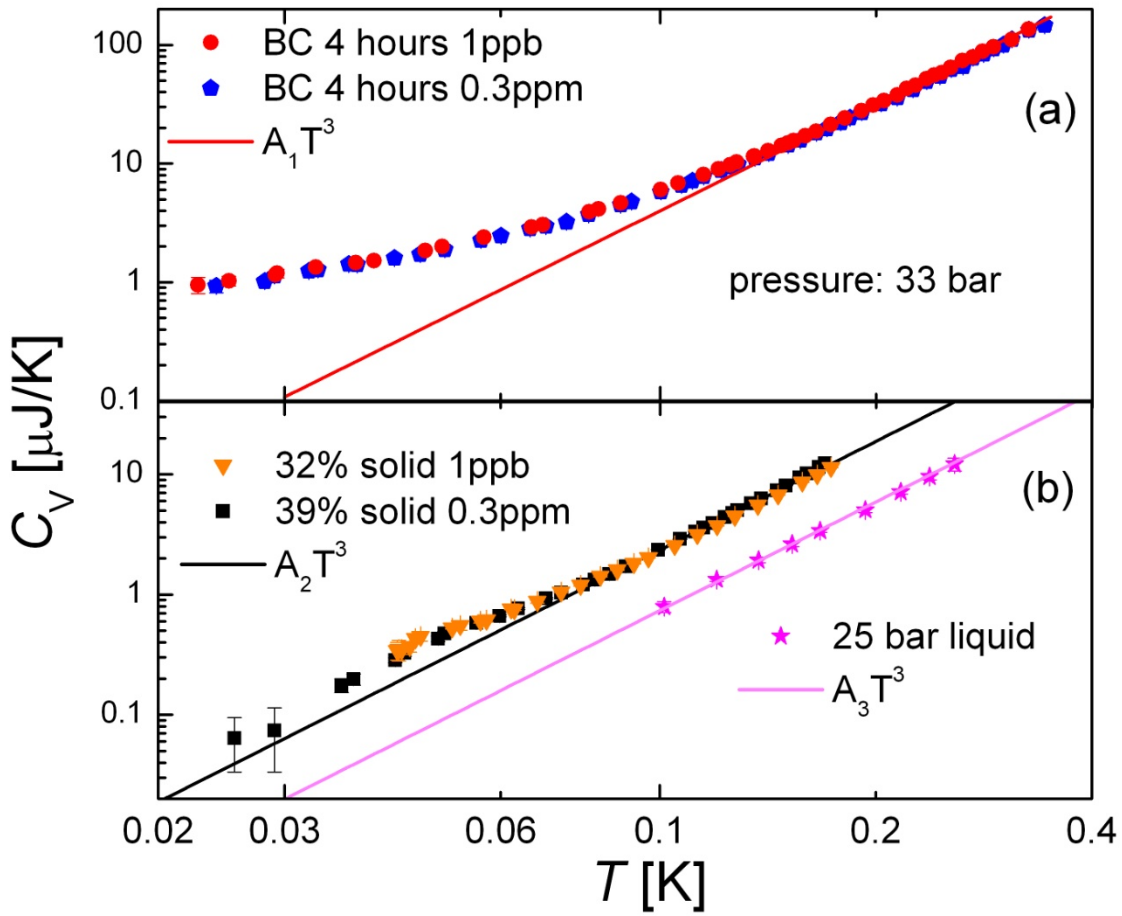
AC calorimetry

solid samples with different ^{3}He impurities were grown under blocked capillary condition, but very slowly , 4 hours and 20 hours.





Sample quality effects in heat capacity.

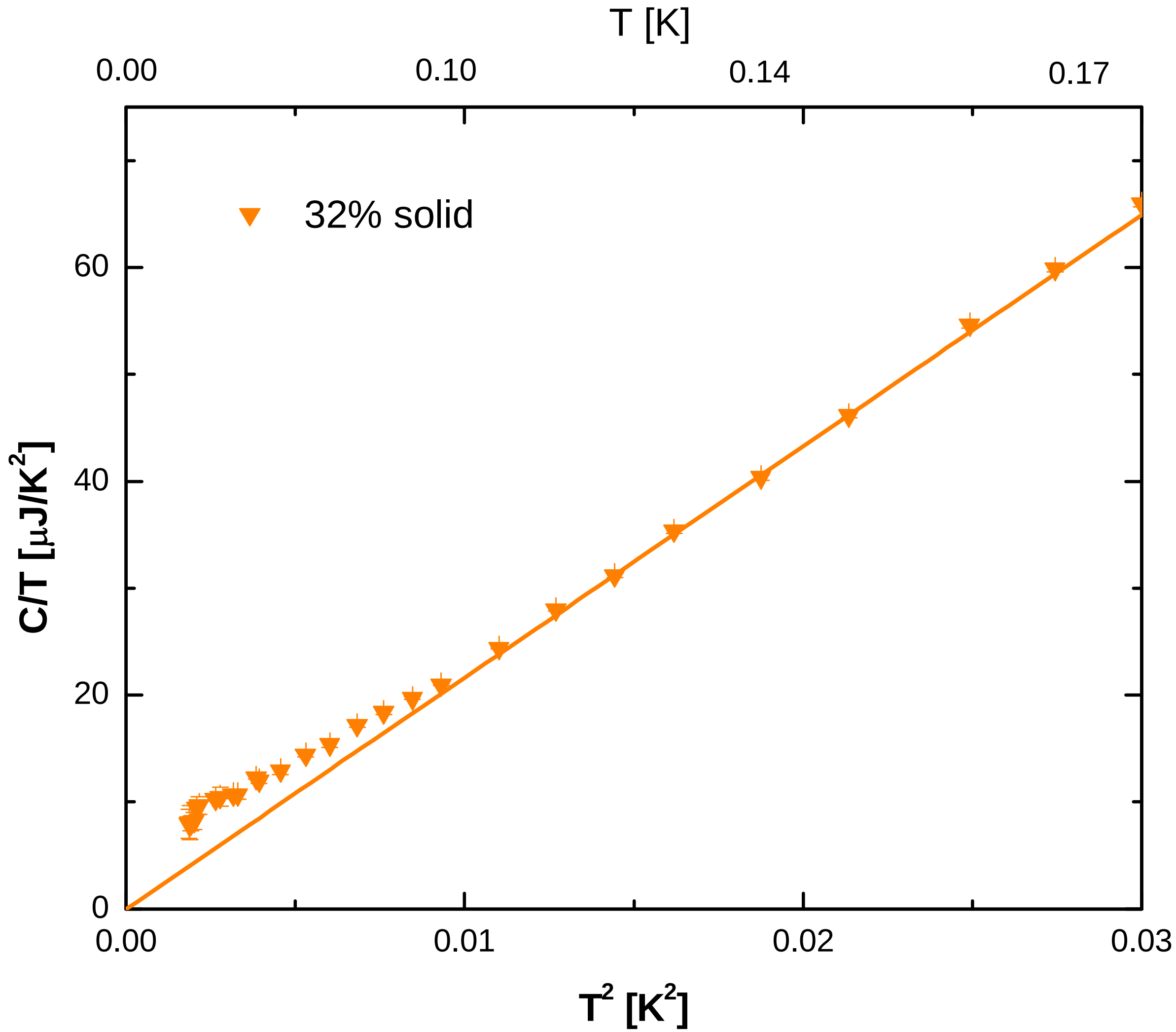


No observable difference between isotopically pure ^{4}He (1 ppb ^{3}He) and standard ultra high purity ^{4}He (0.3 ppm ^{3}He).

Deviation from T^3 is smaller for solid in coexistence with superfluid liquid.

Liquid results in excellent agreement with that of D.S.Greywall, PRB **18**, 2127(1978).

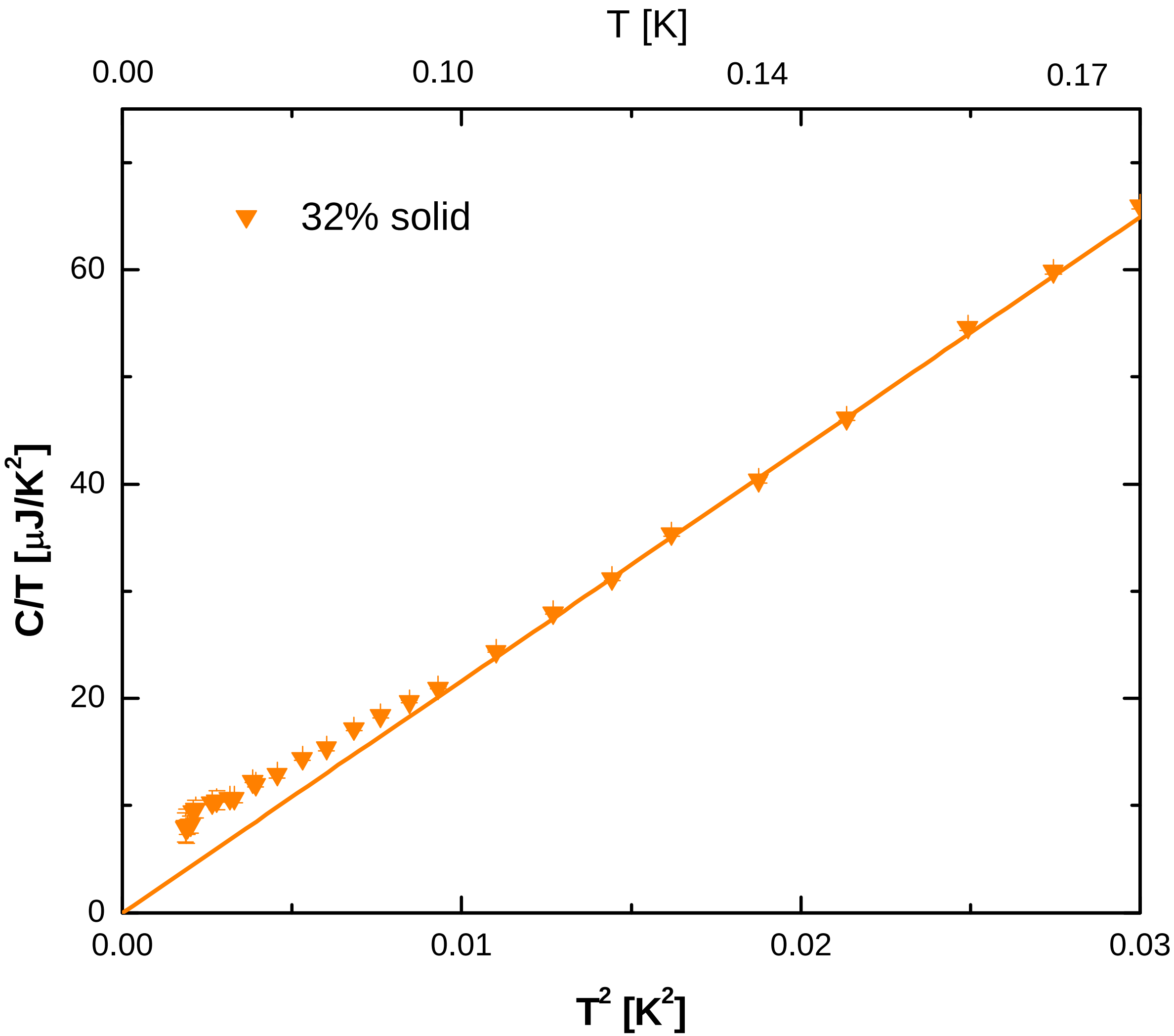
C_v/T vs. T^2



Solid (probably single crystal) in coexistence with superfluid.

Data above 100 mK extrapolate to zero. data below 40 mK also trend toward zero. i.e. no linear T term

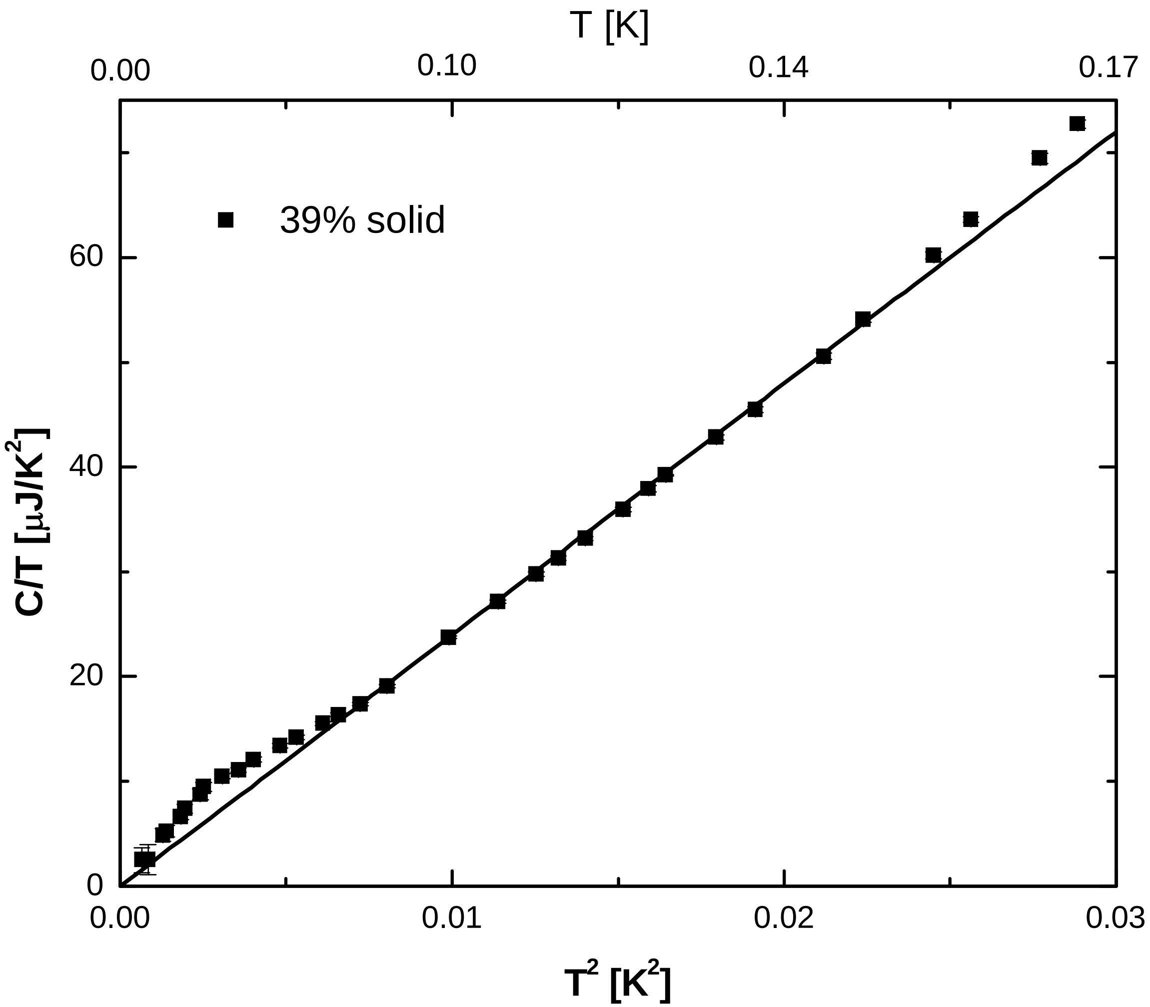
C_v/T vs. T^2



Solid (probably single crystal) in coexistence with superfluid.

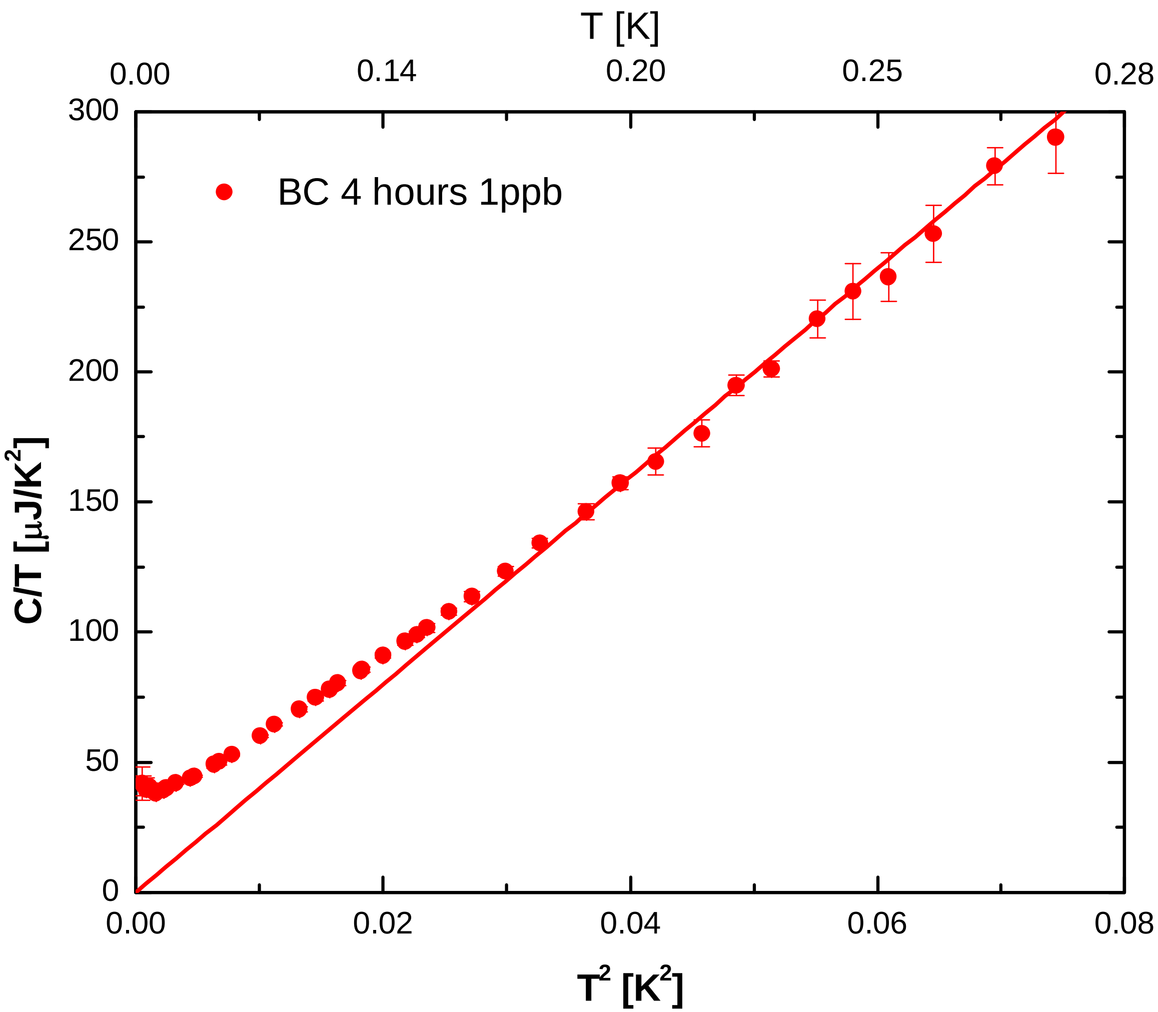
Data above 100 mK extrapolate to zero. data below 40 mK also trend toward zero. i.e. no linear T term

C/T vs. T^2



Solid (probably single crystal) in coexistence with superfluid. No linear T term.

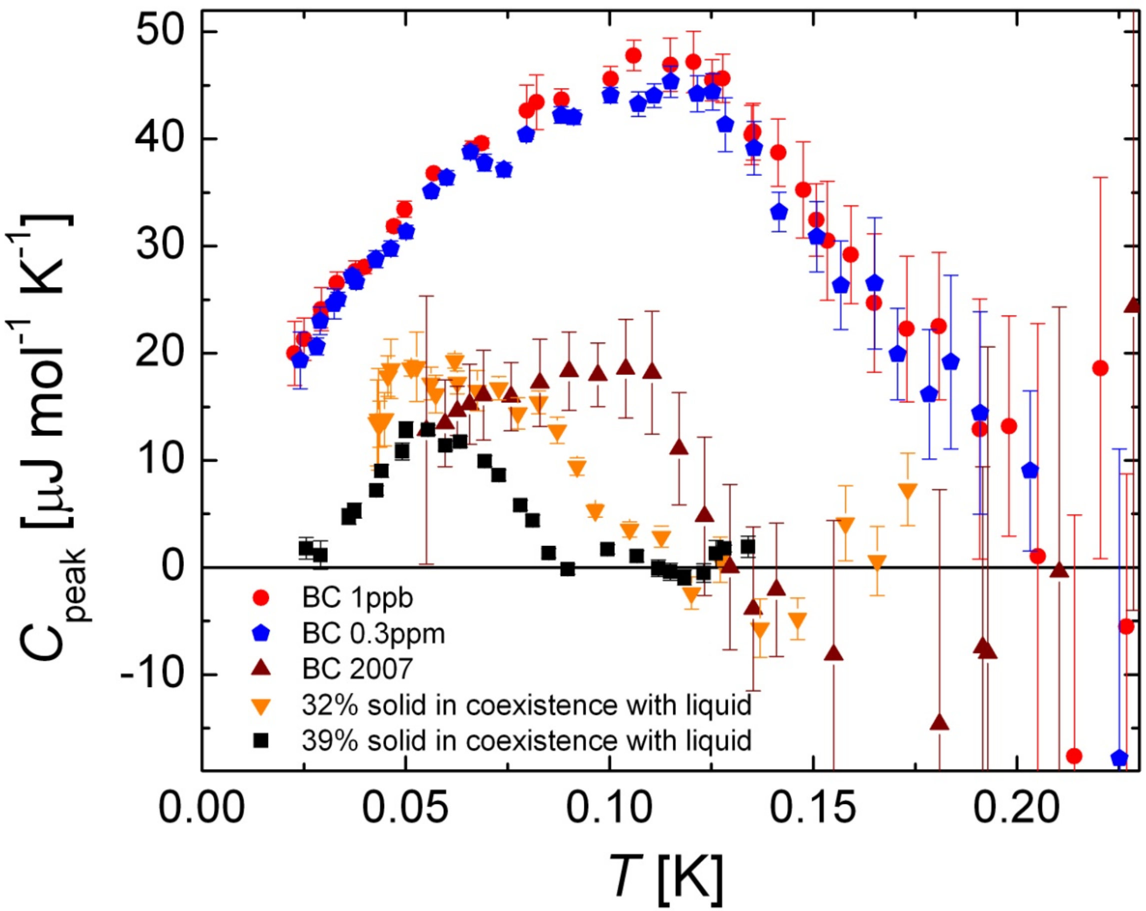
C/T vs. T^2



Polycrystalline sample grown relatively quickly (4 hours) under constant volume condition.

Data above 180 mK extrapolates to zero.

Heat capacity peak is found after subtraction of T^3 Debye term.



Peak height and position decreases with improved crystal quality but not with ^{3}He concentration.

Peak temperature for solid in coexistence with superfluid (~60 mK) is consistent with NCRI onset T of single crystal. Peak height is ~15μJ mol^{-1} K^{-1} or 2×10^{-6} k_B per atom

Lin, Clark, and Chan, *Nature* **449**,1025 (2007)
Lin, Clark, Cheng and Chan, PRL 102, 125302 (2009).

Supersolidity, real or something else?

The size of NCRIf varies from ~0.005% up to ~1%. In a well characterized single crystal sample, NCRIf was found to be ≤ 0.03%. In long path length TOs, there is no sign of NCRI within the resolution (i.e. NCRIf≤ 0.007%) and in toroidal TOs with path length of only 9 and 6 cm, NCRIf is ~ 0.005%.

Effect of shear modulus stiffening in solid ^{4}He in a TO mimics the observed NCRI behavior. The calculated shear modulus effect ranges from 3 times to 30 times smaller than the observed drop in period.

Evidence of vortices found in a TO experiment on rotating cryostat.

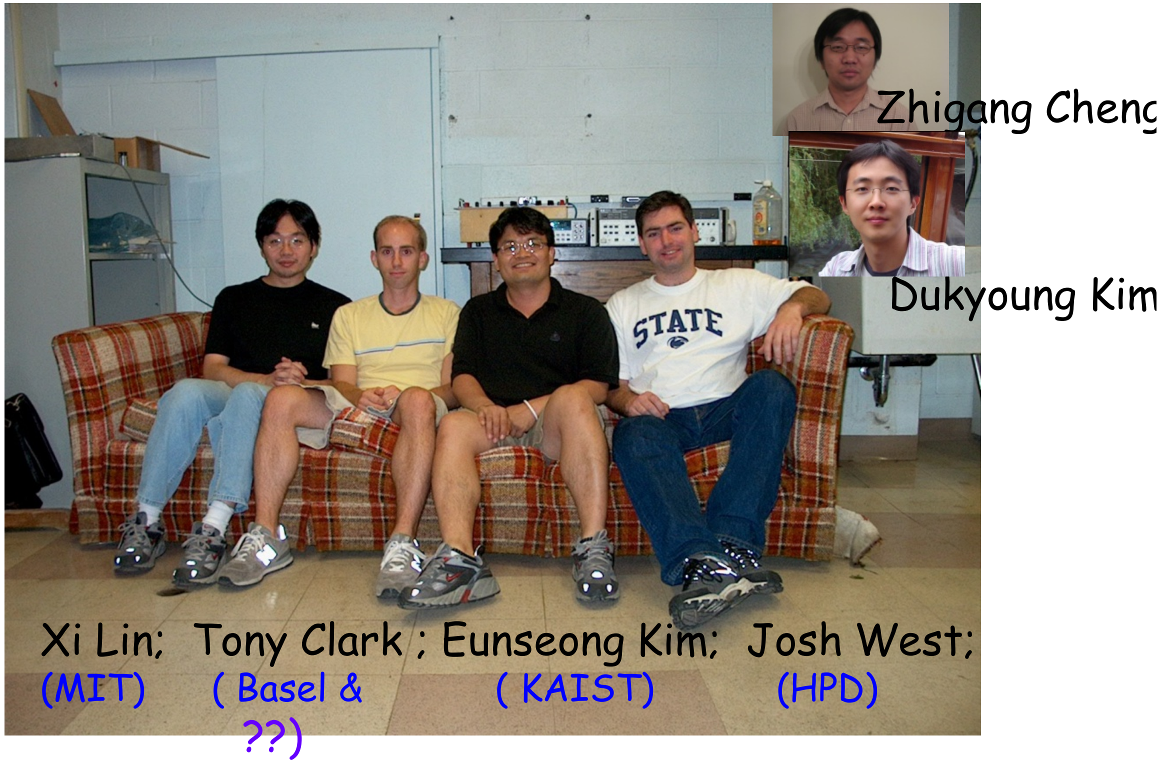
Evidence fountain effect driven superflow through solid ^{4}He.

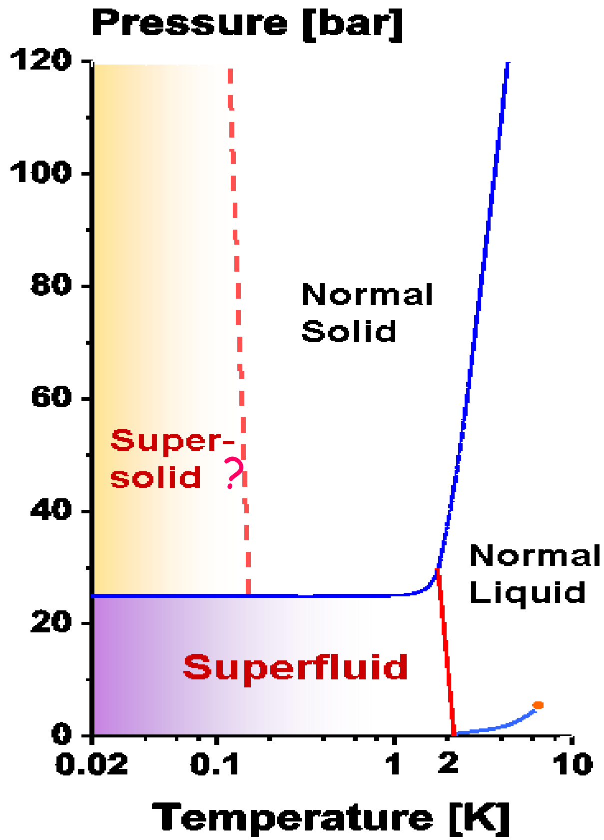
Puzzles

Heat capacity peaks found near NCRI onset, however it is not clear if the peaks are thermodynamic signatures of the supersolid-normal solid transition. (Peak position does not shift to higher T as in NCRI)

If supersolidity is a consequence of interconnected network of superfluid dislocation lines (in the stiffened state); then how can we understand the NCRI observed in Vycor glass and other porous media? Effect of DC rotation on NCRI in Vycor reported by Shirahama. Vortices in such a system?

The Penn State Team





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