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Vortex State in hcp Solid He: Vortex Fluid to Supersolid Transition, and Vortex Dynamics of the Vortex Fluid State

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Vortex state in *hcp* solid He:

Vortex fluid to Supersolid transition, and vortex dynamics of the vortex fluid state

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Supersolid state of matter: hystory and present rapid developments

History:
BEC: 1923
BEC & Superfluidity: 1938, F. London; Kapitsa,
Landau Theory of Superfluidity and BEC
BEC and Solid State: Penrose &   1956
Fermi liquid: 1957, BCS theory: 1957
Quantized flow: Vinen & Hall

Discussions about Supersolid state:
Reatto & Chester, Chester, Andreev & Lifshitz,
Long history of solid ^{4}He study, mechanical properties, dislocation dynamics, sound, …. Etc.

Acoustics measurements and anomaly near 200mK: Goodkind (~2000)
Renaissance of solid He study;
Torsional oscillation(TO) study of He in porous glass; Kim and Chan(2003~)

Superfluidity and Dimensionality

BEC occurs only in $D \geq 3$ for Ideal Gases.

→ Superfluidity in 2D: Kosterlitz-Thouless mechanism of paired quantized vortices play the role of keeping macroscopic Coherence in 2D. Confirmed both by experiments & Theory, but…

→Superfluidity in 1D systems: Not known, but Shevchenko's 3D network of 1D system Discussion; Still under Discussion

Vortex Fluid State in New Superconductors

Study of Superfluidity has been changed after the discovery of Cuprate High T_c Superconductors:

The words "Vortex State" and/or "Vortex matter" appeared: Fisher, Fisher, Huse (PRB1991)

Essence

CuO_2 plane: 2D conducting planes coupled into 3D system. These 2D subsystems supply thermally excited vortices and/or field induced vortex state.

Later modern Superconductors: Organic SC, Layered SC, MgB_2, Fe compounds SC…, They, so far studied, all have 2D Subsystems as CuO_2 plane in Cuprates.

And also vortex state, namely vortex liquid and various vortex states are common in all these systems.

Quantized vortex dynamics may not have been discussed so far for such systems.

There is no excuse !!

P.W. Anderson pointed out that so far reported “Supersolid” data are actually that of vortex fluid and real Tc for Supersolid should be found at lower T. Nature Phys. Vol.3 160 (2007).

We have found recently vortex fluid(VF) state in solid ^{4}He!

See: Phys. Rev. Lett. Vol.101, 065301 (2008).

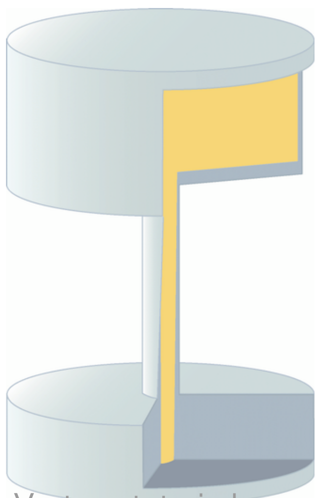
And furthermore a possible transition from VF state to real Supersolid state.

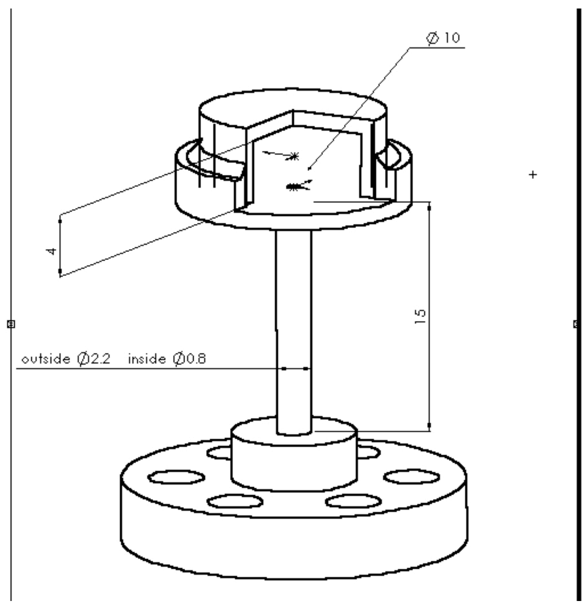
See: Penzev, Shimizu, Yasuta, and Kubota, arXiv:0902.1326.

How do we study superfluidity and vortex dynamics?

Highly Sensitive and Stable Torsional Oscillator (TO)
to Study VF as well as Supersolid Properties of Solid ^{4}He

Frequency Shift Δf → Moment of Inertia Change → Supersolid Density $\rho_{ss}(T)$, and Nonlinear Rotational Susceptibility (NLRS)
And
Amplitude→ **Q Value** of TO→detailed energy dissipation → Vortex Dynamics





Experiments under DC rotation → Vortex line penetration into bulk superfluids; so far in ^{4}He, ^{3}He, Atomic BEC's

Unique Activity of Kubota Group, ISSP U-Tokyo : Study of Essense of Superfluidity

<u>*Superfluidity in 3D Connected Monolayer He Films:*</u>

1]. Can one make a 3D Superfluid out of 2D Films, where there is no BE Condensate?

2]. What is the inter-relation between BEC and Superfluidity?

→ 3D Superfluid is Possible out of 2D Films !!!

Study of artificial 3D superfluids: (Previous activity) He "monolayer" films on 3D connected pore surface

- Obata and Kubota, PHYSICAL REVIEW B **66, 140506(R) (2002)**

TOSHIAKI OBATA AND MINORU KUBOTA

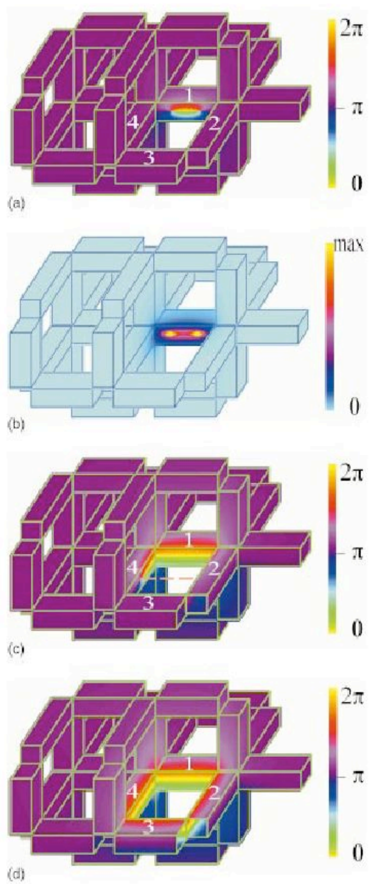
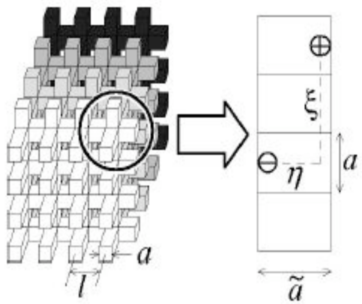
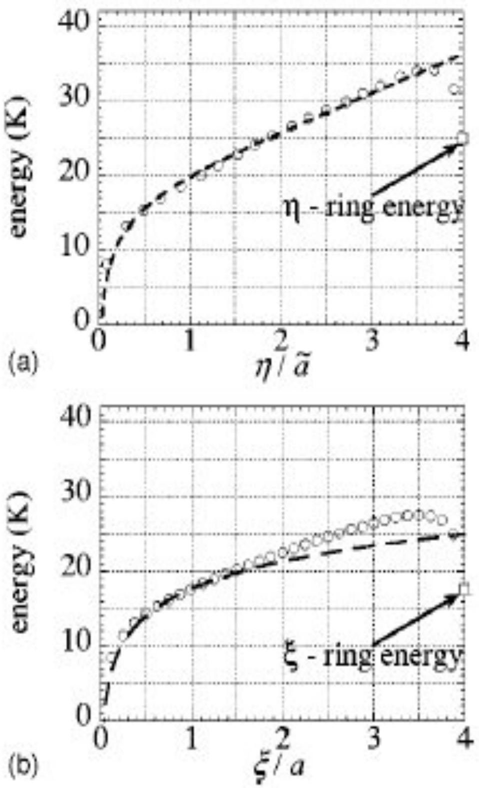


FIG. 2. (Color) A series of the calculation results. This solution is the example when vortex pair decouples along η direction. The color corresponds to the phase from 0 to 2π and it is periodical continuous in the panels (a), (c), and (d). (a) $\eta=\tilde{a}/2$. (b) The flow energy distribution of the configuration (a). (c) $\eta=2\tilde{a}$. The red broken line indicates the vortex core crossing the pore. (d) The symmetric flow pattern remaining after vortex pair annihilation.





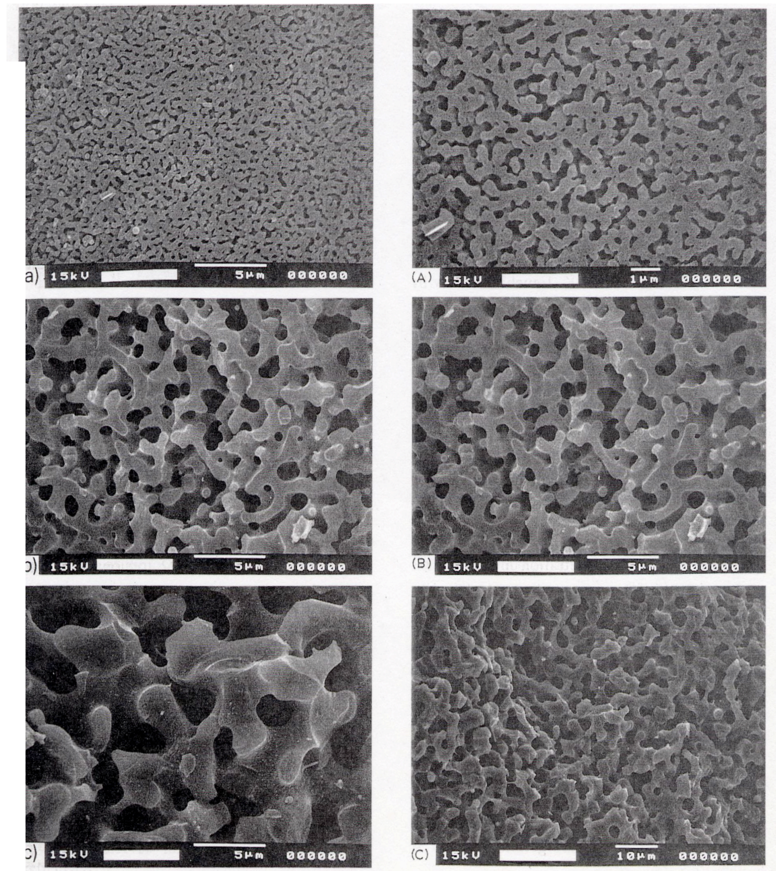


Fig. 4. Scanning electron microscope pictures of the well-defined porous glass samples with pore diameters 2500, 5000 and 15 000 Å (by Yazawa). Photos (a)–(c) are all taken with a magnification factor of 3250, whereas photos (A)–(C) are taken with a magnification factor of 6500, 3250 and 980, respectively, to make the pore sizes look almost the same. From these photos we learn that 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.

Energy dissipation goes up when excitation is increased for all known SF

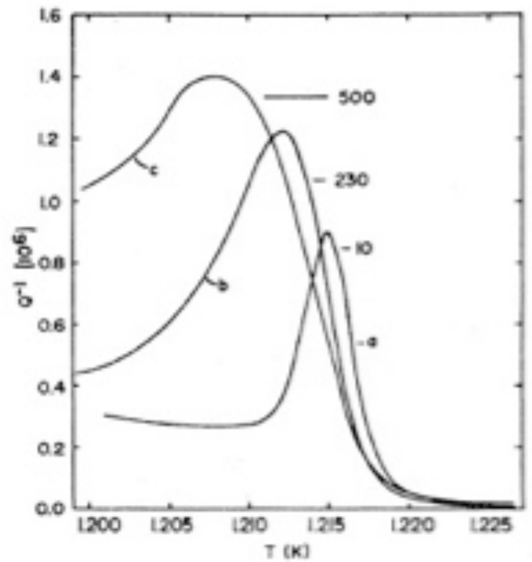


FIG. 5. Dissipation peak for a single film at three different values of cavity velocity (arbitrary units).

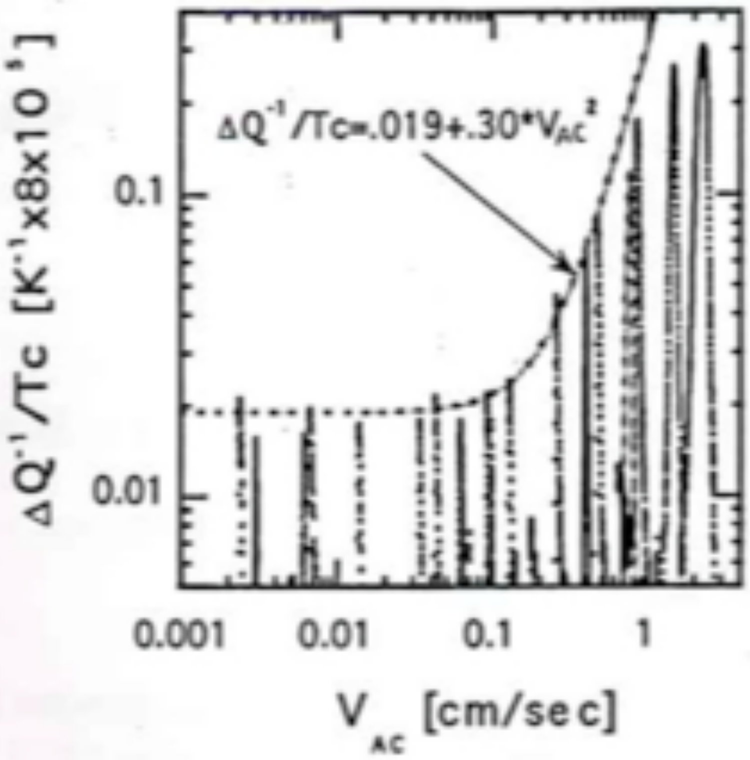
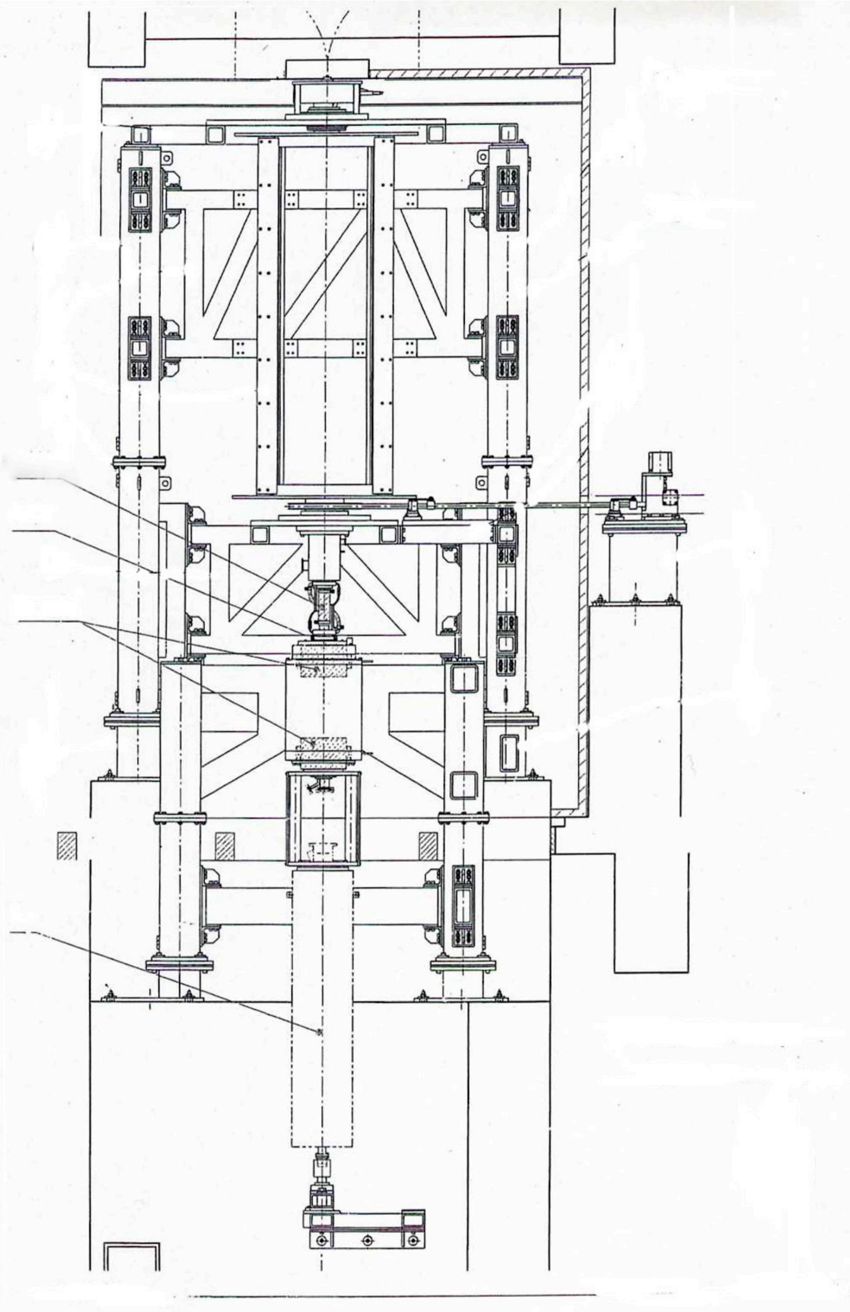


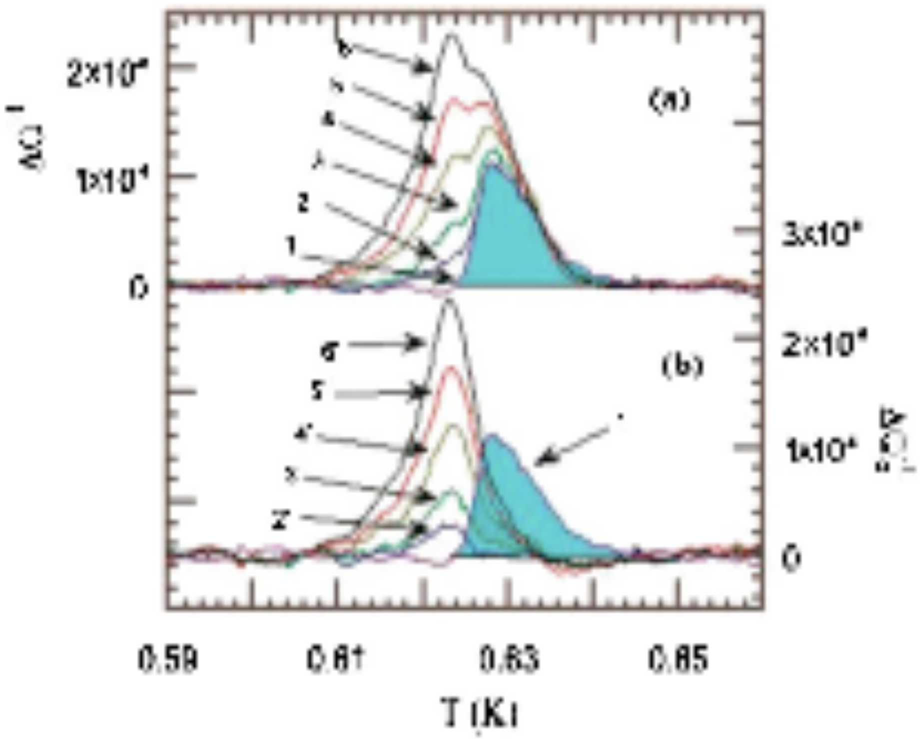
Fig. 1, Dissipation peak heights devided by each Tc, 201,414, and 1182 mK, as a function of the substrate AC velocity at the electrode position over $2x10^3$ range. The broken line is a trial fit in the given unit.

M. Fukuda, et al., Czechslovak J. Phys. Vol.46 (1996), Suppl. S1, 143.



ISSP High Speed Rotating DR

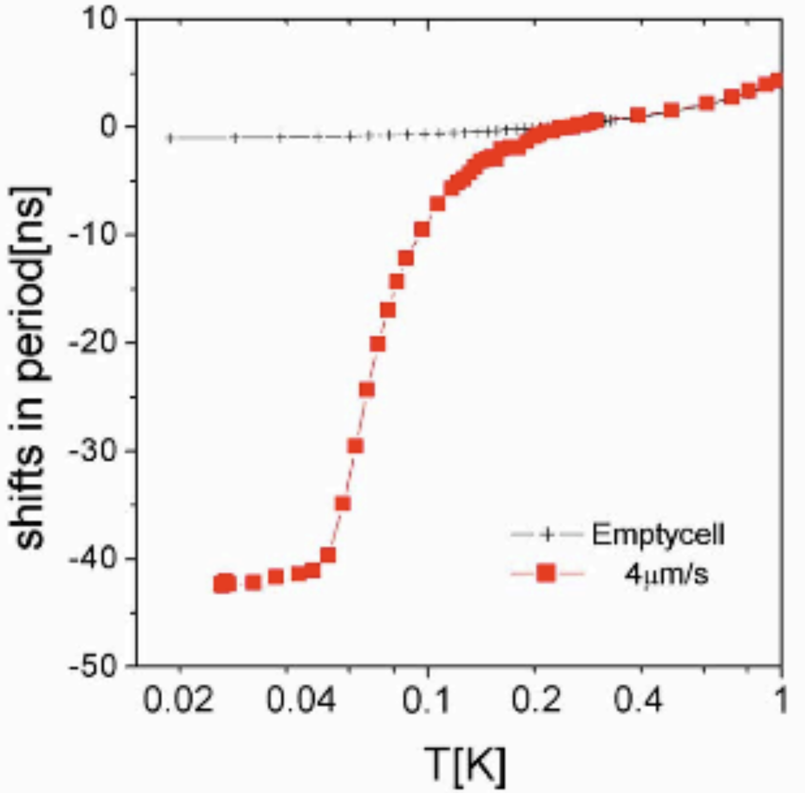
Vortex line penetration induces extra Ω-linear dissipation dQ^{-1} increase !!



Fukuda, et al., Phys. Rev. B**71, 212502 (2005)**

E. Kim and M.H.W. Chan

Solid ^4He at 51 bars



Amplitude of oscillation is 7Å

A decrease in the resonant period, similar to that found in superfluid liquid helium, appears below 0.25K

τ_0= 1,096,465ns at 0 bar
1,099,477ns at 51 bars
(total mass loading=3012ns due to filling with helium)

The nonclassical rotational (NCRI) fraction is ~1.3%

Nature, **425**, 227 (2004); Solid helium in porous glass
Science **305**, 1941 (2004); Bulk solid

Vortex Fluid State below T_o ~ 500 mK

PRL **101**, 065301 (2008) PHYSICAL REVIEW LETTERS week ending 8 AUGUST 2008

ac Vortex-Dependent Torsional Oscillation Response and Onset Temperature T_0 in Solid ^{4}He

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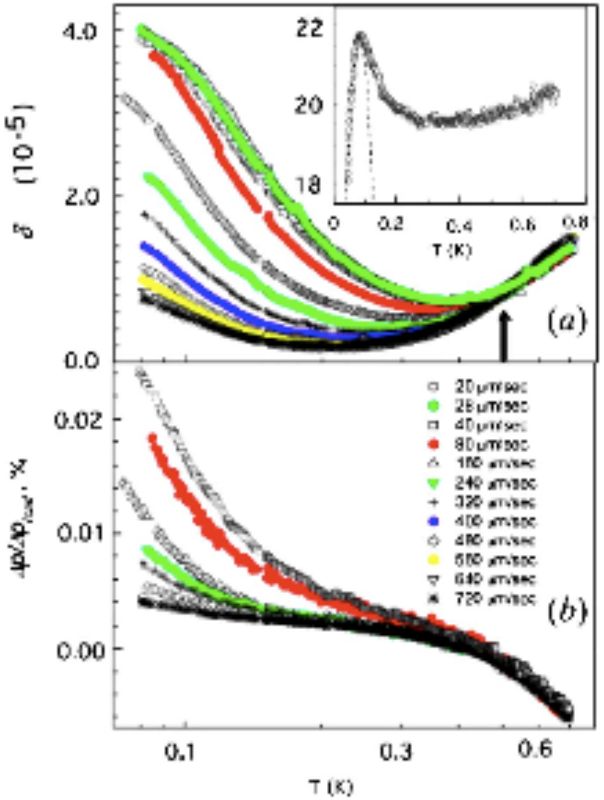
(Received 13 November 2007; published 6 August 2008)

Detailed studies of ac velocity V_{ac} and T dependence of torsional oscillator responses of solid ^{4}He are reported. A characteristic onset temperature $T_0 \sim 0.5$ K is found, below which a significant V_{ac}-dependent change occurs in the energy dissipation for the samples at ~32 bar and for one at 49 bar. A V_{ac} dependence of the so-called "nonclassical rotational inertia" fraction also appears below ~T_0. The $\log(V_{ac})$ linear dependence, which suggests involvement of quantized vorticies, was examined in the nonclassical rotational inertia fraction. We find a common $1/T^2$ dependence for this linear slope change in all of the samples for $30 < V_{ac} < 300$ μm/s. We discuss that our observation is consistent with nonlinear rotational susceptibility of the vortex fluid, proposed by Anderson above T_c below T_0.



Our study of solid ^{4}He Started with detailed TO excitation dependence.

Oposit to usual Superfluids

FIG. 1 (color online). *T* dependence of energy dissipation δ(a) and $\Delta p/\Delta p_{load}$ (b) at various Vac in μm/s for a 32 bar sample. The values of δ are presented without any artificial shift. Some data are omitted for clarity [all of the data on V_{ac} dependence are plotted in Fig. 2(a) and 2(b)]. An arrow indicates T_0 , across which Vac dependence changes. The inset in (a) indicates a typical energy dissipation peak with somewhat higher T_p . The low *T* part of the peak was fitted with a Gaussian: dashed line. The zero for $\Delta p/\Delta p_{load}$ in (b) is taken provisionally where V_{ac} dependence goes away.

Log(V_{ac}) linear dependent suppression → Suppression by formation of vortex line!!

Vortex Fluid model by
P.W. Anderson; Nature Phys. Vol.3, 161(2007).

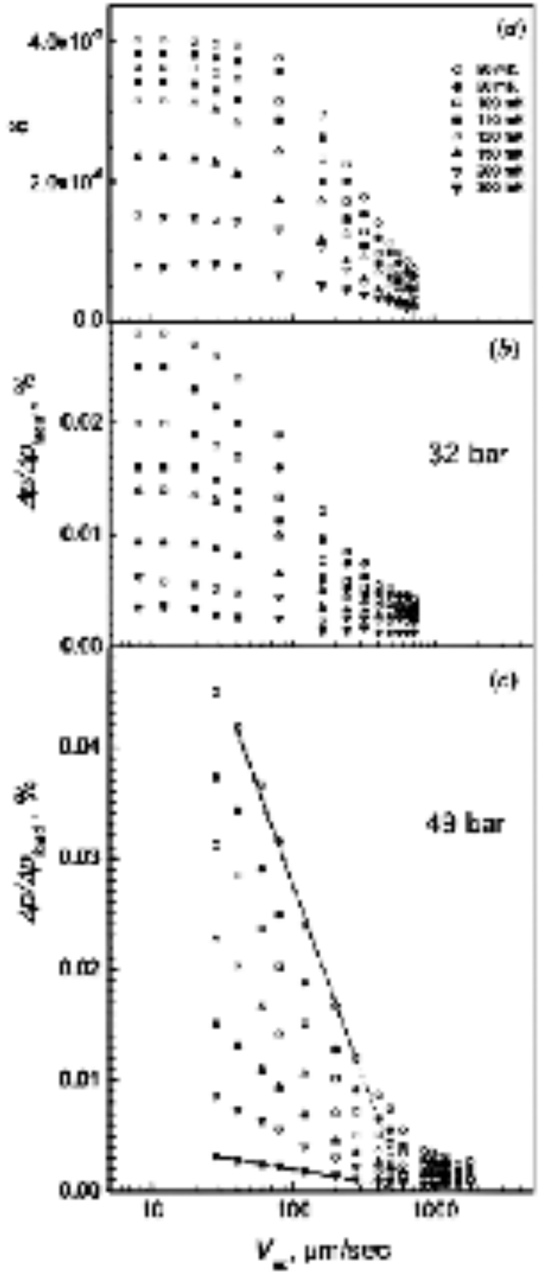
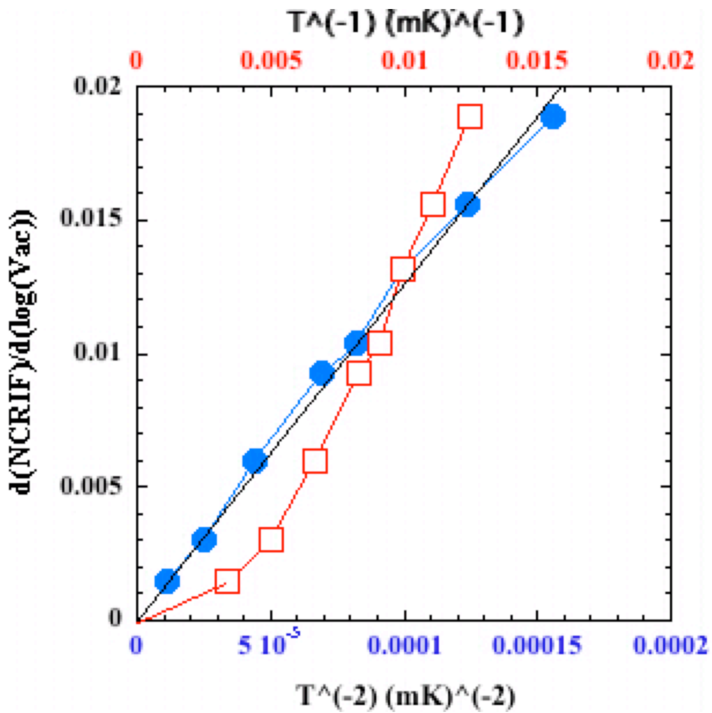


FIG. 2. δ(a) and $\Delta p/\Delta p_{load}$ (b) of 32 bar sample as a function of V_{ac} at T < 300 mK. $\Delta p/\Delta p_{load}$(c) is the data of the new sample at 49 bar. The solid lines in (c) show the linear dependence on log(V_{ac}) for the Vac range; ~30 < V_{ac} < 300 μm/s and at higher V_{ac} some other dependence appears. We observe practically the same log(V_{ac}) linear dependence as in (c) also for a 32 bar sample (b) by fitting with linear lines. Extrapolated linear lines are found to converge at a point ~600 μm/s for the V_{ac} range. This point of convergence also seems to coincide with the zero in Fig. 1(b).

High T limit behavior: the slope has $1/T^2$ Dependence !!



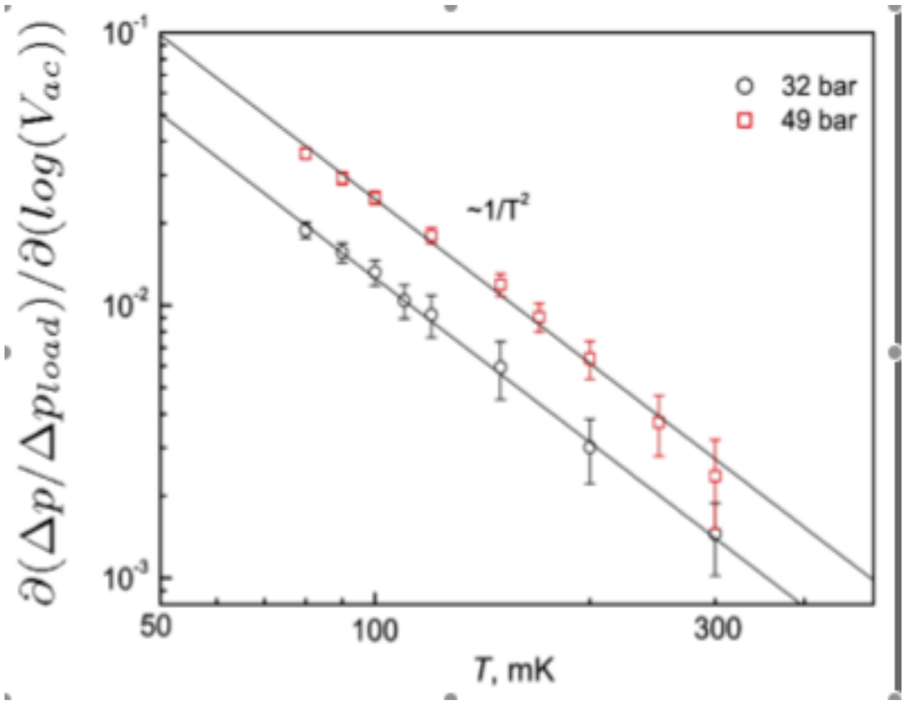


FIG. 3 (color online). T dependence of the slope $d(\Delta p/\Delta p_{load})/d[\log(V_{ac})]$. Clear $1/T^2$ dependence is seen for both of the completely independent solid ^{4}He samples at 32 and49 bar pressure.

$1/T^2$ is not the T dependence of an order parameter !!
→ Nonlinear Rotational Susceptibility (NLRS) ! Cf. Anderson

Vortex Fluid to Supersolid Transition

Possible Vortex Fluid to Supersolid Transition in Solid ^4He below~75mK

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InstituteforsolidStatePhysics, Universityof Tokyo, Kashiwanoha5-1-5, Kashiwa, 277-8581, Japan
(Dated: Feb 23, 2009)

A detailed torsional oscillator (TO) study on a stable solid ^{4}He sample at 49 bar with T_o ~ 0.5 K, is reported to T below the dissipation peak at T_p. We find hysteretic behavior starting below T_c ~75mK, in period shift, as well as in dissipation, with changes of AC excitation amplitude V_{ac}. The derived difference of non-linear rotational susceptibility $\Delta NLRS(T)_{hys}$ across the hysteresis loop under a systematic condition is analyzed as a function of V_{ac} and T. We propose that $\Delta NLRS(T)_{hys} \propto$ non-classical rortational inertia fraction, NCRIF is actually the supersolid density ρ_{ss} of the 3D supersolid state below T_c. ρ_{ss} changes linearly with T down to ~60 mK and then increases much more steeply, and approaching a finite value towardsT=0. We find an AC velocity of ~40μm/s beyond which the hysteresis starts at $T<T_c$ and a”critical ACvelocity”,~1cm/s, above which ρ_{ss} is completely destroyed. We discuss also the coherence length ξ of the supersolid.

PACSnumbers: 67.80.bd, 67.25.dk, 67.25.dt, 67.85.De.

arXiv:0903.1326

Vortex Fluid to Supersolid Transition in Solid ^{4}He below ~75mK*

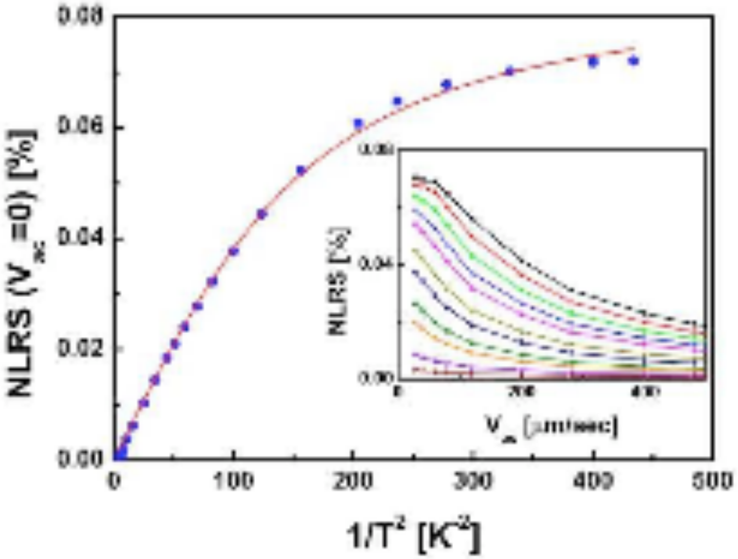


FIG. 1: NLRS(T) at $V_{ac} \to 0$, is displayed as a function of $1/T^2$. The solid line through the data points is the Langevin function f(x) =a[{exp(bx)+exp(-bx)}/{exp(bx)-exp(-bx)}-1/(bx)] with a = 0.0878 ± 0.0011, and b = 0.0148± 0.0004. Inset shows the V_{ac} dependence for data at each T <300 mK and we can safely extrapolate to $V_{ac} \to 0$.

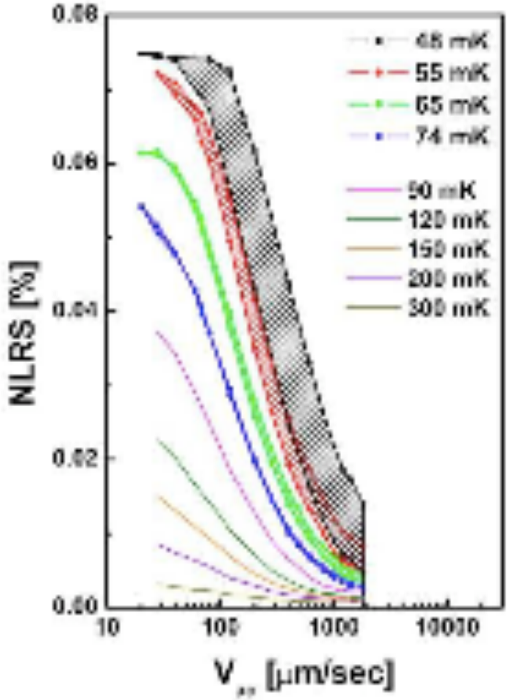


FIG. 2: The V_{ac} dependence of NLRS of solid ^{4}He sample at 49 bar pressure at constant representative T's for clarity, obtained from the measure-ment of period change of TO. Mea- surements are performed at various V_{ac} as given in the figure.

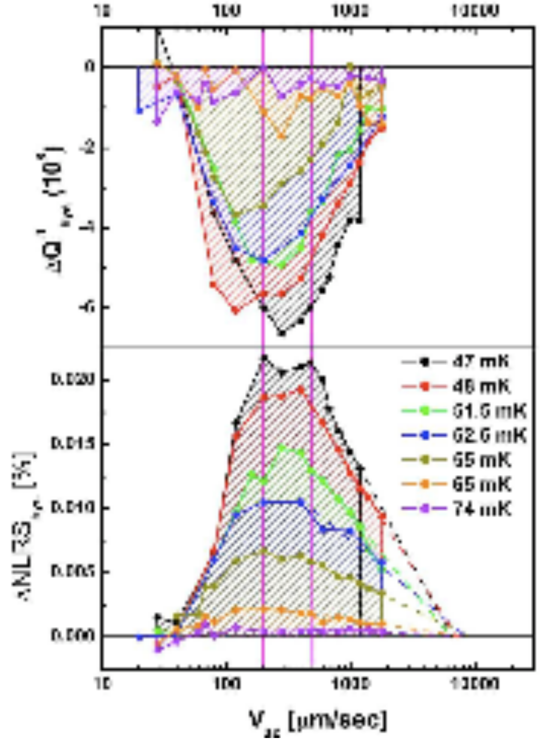


FIG. 3:"hysteretic" NCRIF as well as dissipation component vs log V_{ac}. From the linear extension of the log V_{ac} dependence we obtain a critical velocity, 6~10 mm/s to suppress the "hysteretic" $\Delta NLRS_{hys}$ = NCRIF to zero.

*Andrey Penzev, Nobutaka Shimizu, Yoshinori Yasuta, and Minoru Kubota, arXiv: 0903.1326. (2009).

Vortex Fluid to Supersolid Transition in Solid ^{4}He below ~75mK*contin.

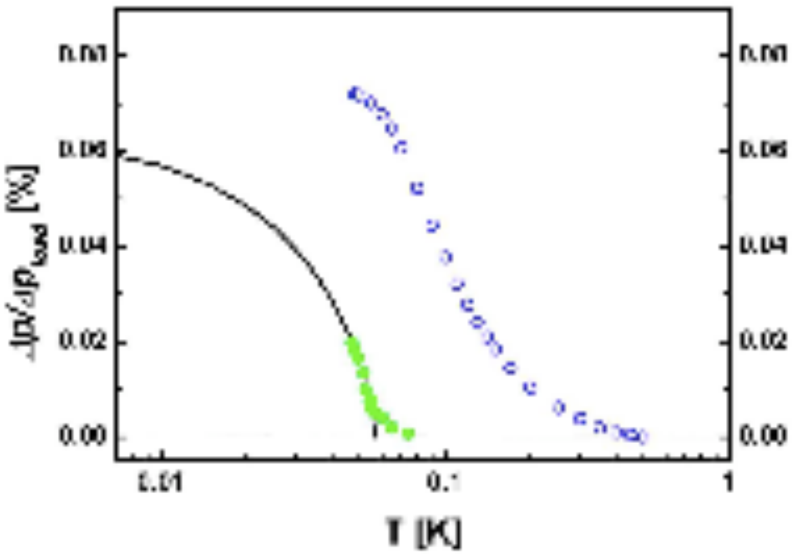


FIG. 4: The temperature dependence of the ”persistent” N C RI F =ΔN LRShys appeared as a result of the ”hysteretic Process”. It represents the persistent N C RI F produced by the process, which supports persistent circulation even after the process finished and it may represent macroscopic per- sistent current by a set of vortex rings. It would be an evi- dence of 3D macroscopic phase appearance from a certain Tc . It compares with ”paramagnetic” behavior of N LRS(open symbols), extrapolated to Vac = 0, whose 1/T 2 dependence at high T as well as Langevin function dependence suggests ”susceptibility” feature of this quantity.

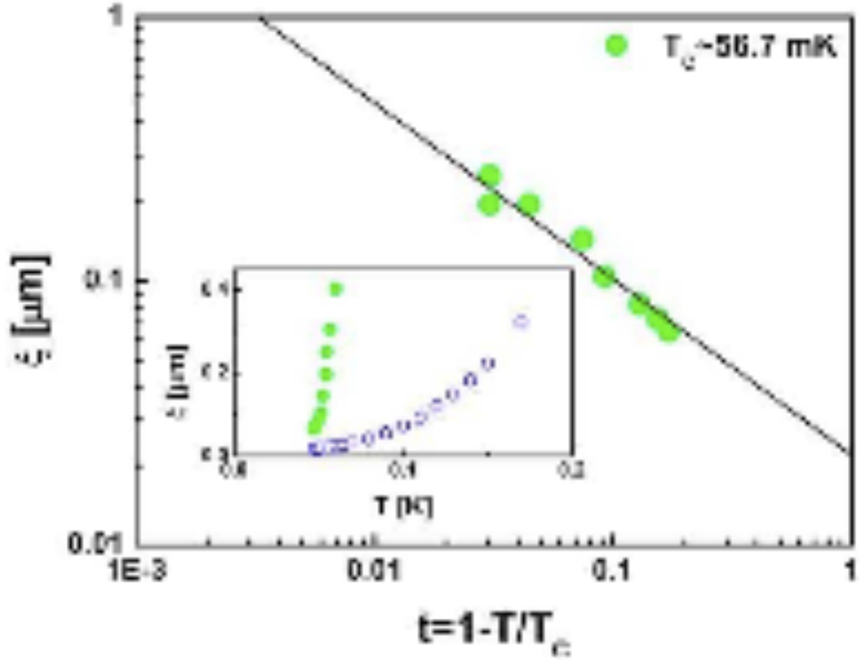


FIG. 5: Critical behavior of ξ obtained from the absoluteevaluation of supersolid fraction ρss by extrapolating to Vac =0. We took Tc = 56.7 mK and obtain ξ0 ~ 25 to 50 nm at t = 1or T = 0K by simple extrapolations, horizontal and straightextension of linear relation. Inset shows ξ for SS state andVF state(open symbols). The latter is smaller for a T .

*Andrey Penzev, Nobutaka Shimizu, Yoshinori Yasuta, and Minoru Kubota, arXiv: 0903.1326. (2009).

Is it really a supersolid below T_c?

Vortex line penetration through the sample under DC rotation?

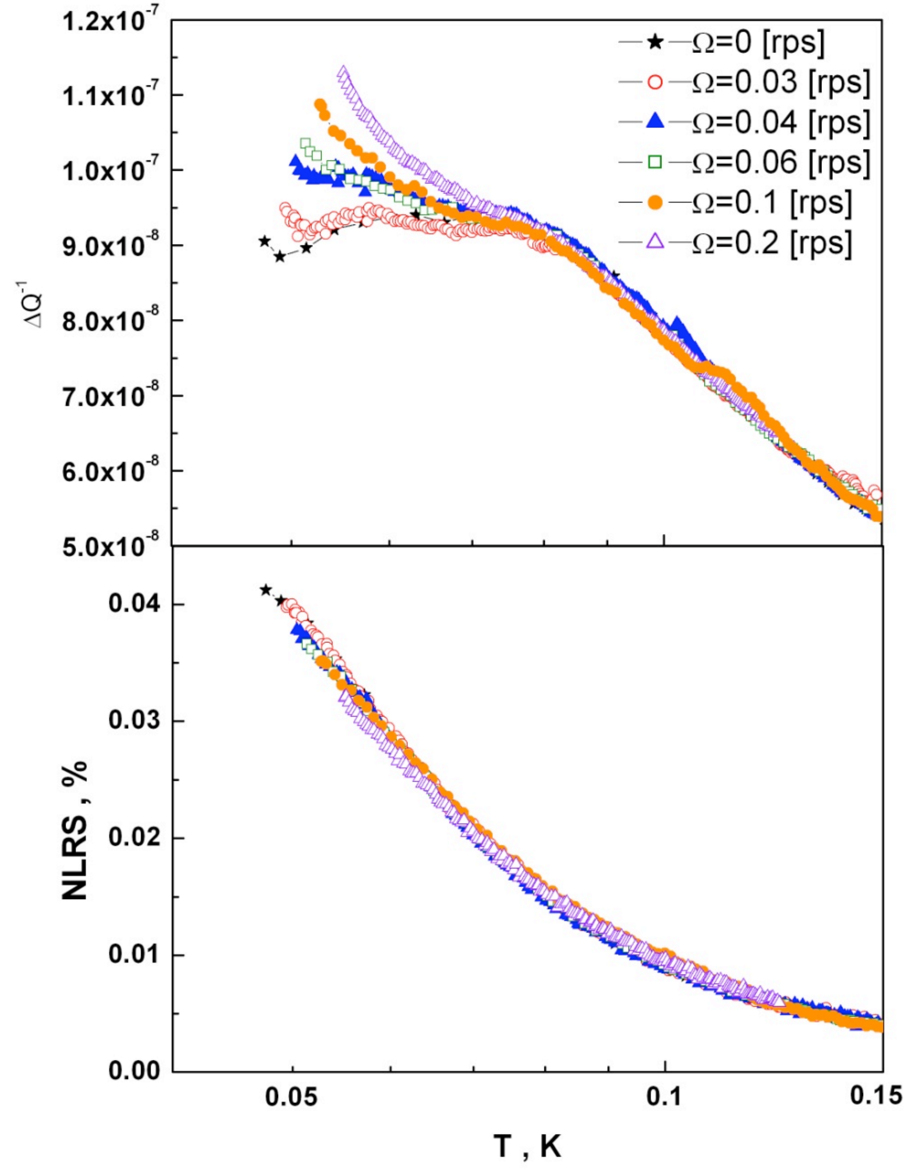
-Experimental Procedure of Measurement under DC Rotation-

1. At high Temperature（～0.5 K) Change AC excitation to Vac=200 μm/sec (Equilibrium)
2. DC Rotation Start（Ω=0→0.2 rps)
3. Cooling down
4. Measurement under T sweep（T=50mK→150mK / 3h, 9h,..)
5. Repeat with different DC Rotation Speeds

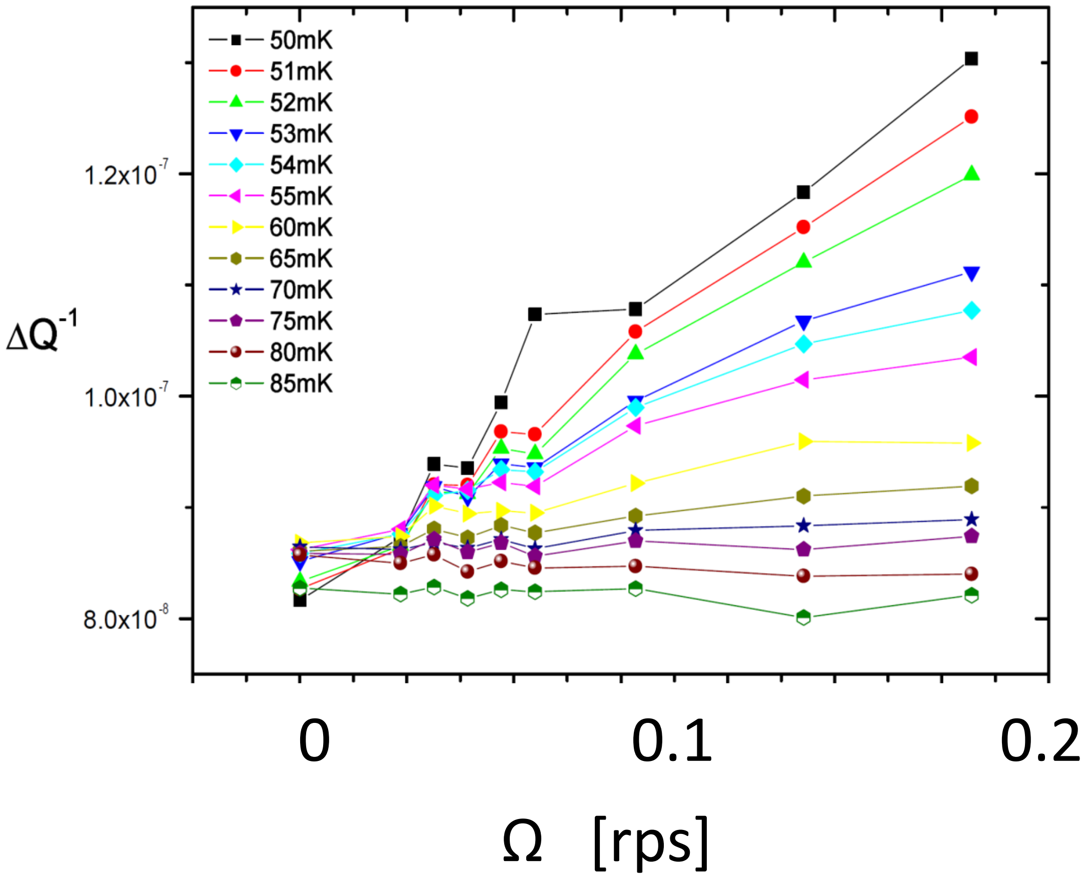
Results under DC Rotation

- Energy Dissipation below T ~80 mK Changes under DC Rotation: Faster Rotation →Larger Change !!

- No Change in NLRS (non-linear rotational susceptibility)

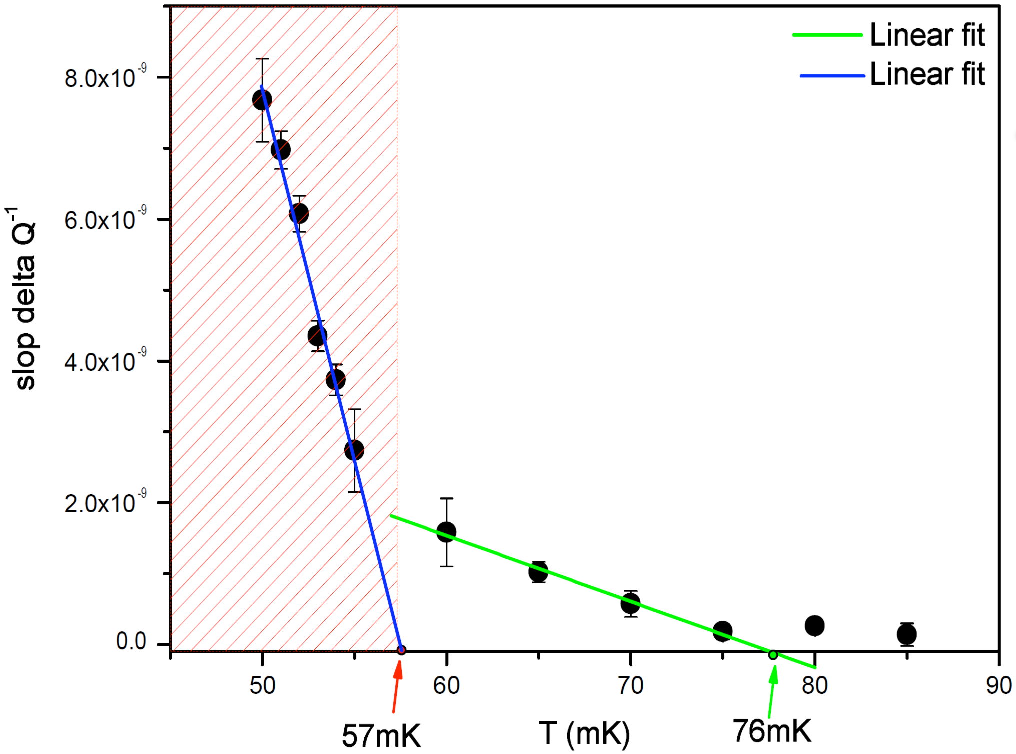


How does Energy Dissipation Change as DC Rotational Speed Ω? Linear Change!! → Vortex lines!!, Otherwise Ω^2 Dependence Should Occur!



If Dissipation ΔQ^{-1} is Caused by Supersolid Vortices, Then It Should Be Proportional to $\rho_s(T)$!

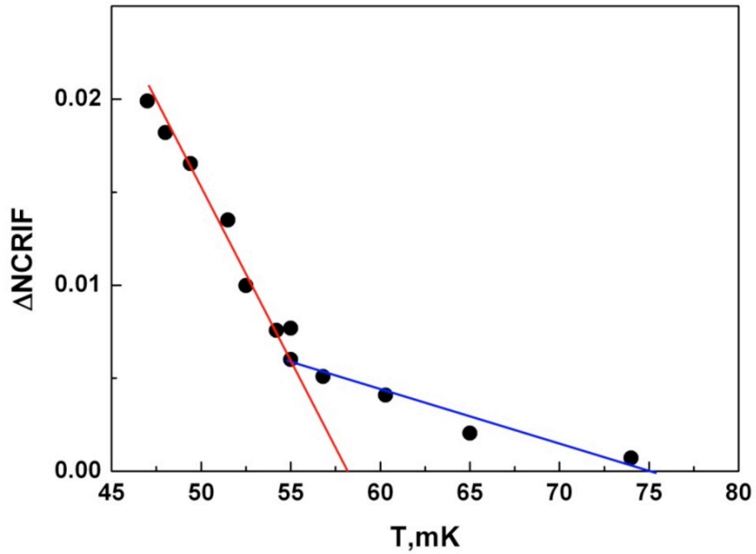
Transition Temperature(s) T_c(s) to Supersolid State and $\rho_s(T)$?

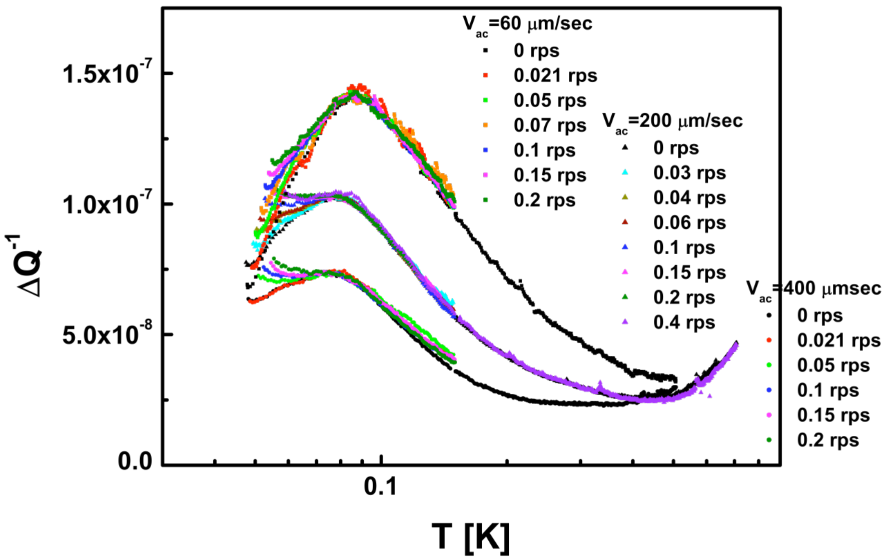


Slope $\Delta Q^{-1}/\Omega$ vs T (mK)

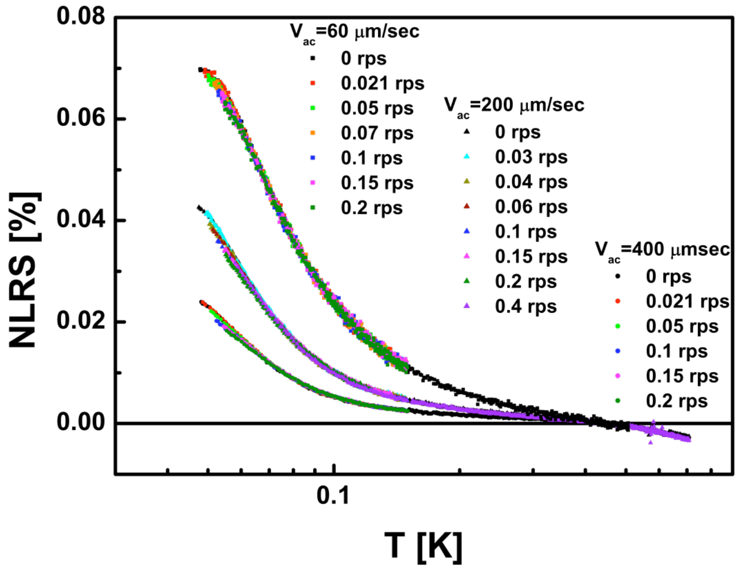
We find two characteristic temperatures, ~57mK,~76mK

Above graph looks just the same as ΔNCRIF, observation in the hysteretic behavior vs T!

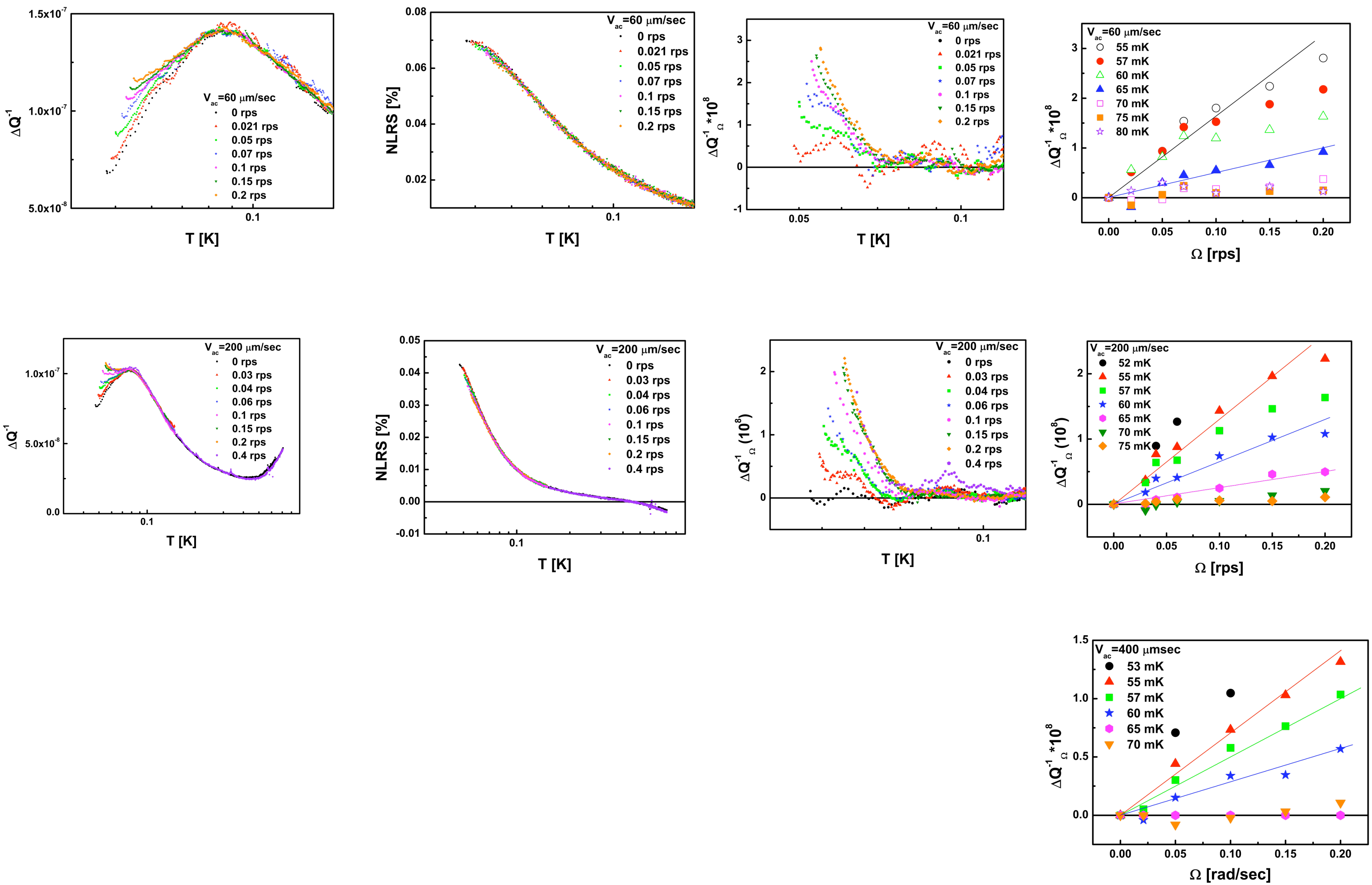




ΔQ^-1
T [K]
V_ac=60 μm/sec
0 rps
0.021 rps
0.05 rps
0.07 rps
0.1 rps
0.15 rps
0.2 rps
V_ac=200 μm/sec
0 rps
0.03 rps
0.04 rps
0.06 rps
0.1 rps
0.15 rps
0.2 rps
0.4 rps
V_ac=400 μmsec
0 rps
0.021 rps
0.05 rps
0.1 rps
0.15 rps
0.2 rps



NLRS [%]
T [K]
V_ac=60 μm/sec
0 rps
0.021 rps
0.05 rps
0.07 rps
0.1 rps
0.15 rps
0.2 rps
V_ac=200 μm/sec
0 rps
0.03 rps
0.04 rps
0.06 rps
0.1 rps
0.15 rps
0.2 rps
0.4 rps
V_ac=400 μmsec
0 rps
0.021 rps
0.05 rps
0.1 rps
0.15 rps
0.2 rps



V_ac=60 μm/sec
0 rps
0.021 rps
0.05 rps
0.07 rps
0.1 rps
0.15 rps
0.2 rps
ΔQ^-1
T [K]
NLRS [%]
ΔQ^-1_Ω *10^8
55 mK
57 mK
60 mK
65 mK
70 mK
75 mK
80 mK
Ω [rps]
V_ac=200 μm/sec
0 rps
0.03 rps
0.04 rps
0.06 rps
0.1 rps
0.15 rps
0.2 rps
0.4 rps
ΔQ^-1_Ω (10^8)
52 mK
55 mK
57 mK
60 mK
65 mK
70 mK
75 mK
V_ac=400 μmsec
53 mK
55 mK
57 mK
60 mK
65 mK
70 mK
Ω [rad/sec]

OK. Vortex line penetration is occurring at $T < T_c \sim 75$ mK!
Then what about vortex fluid (VF) state?

What should characterize VF state?

We have started study on vortex dynamics by a relaxation model, where we started similar considerations as in Quantum turbulence.

N. Shimizu, S. Nemirovskii, and M. Kubota (2009)

Quantitative Analysis of Vortex Fluid State of solid ^{4}He

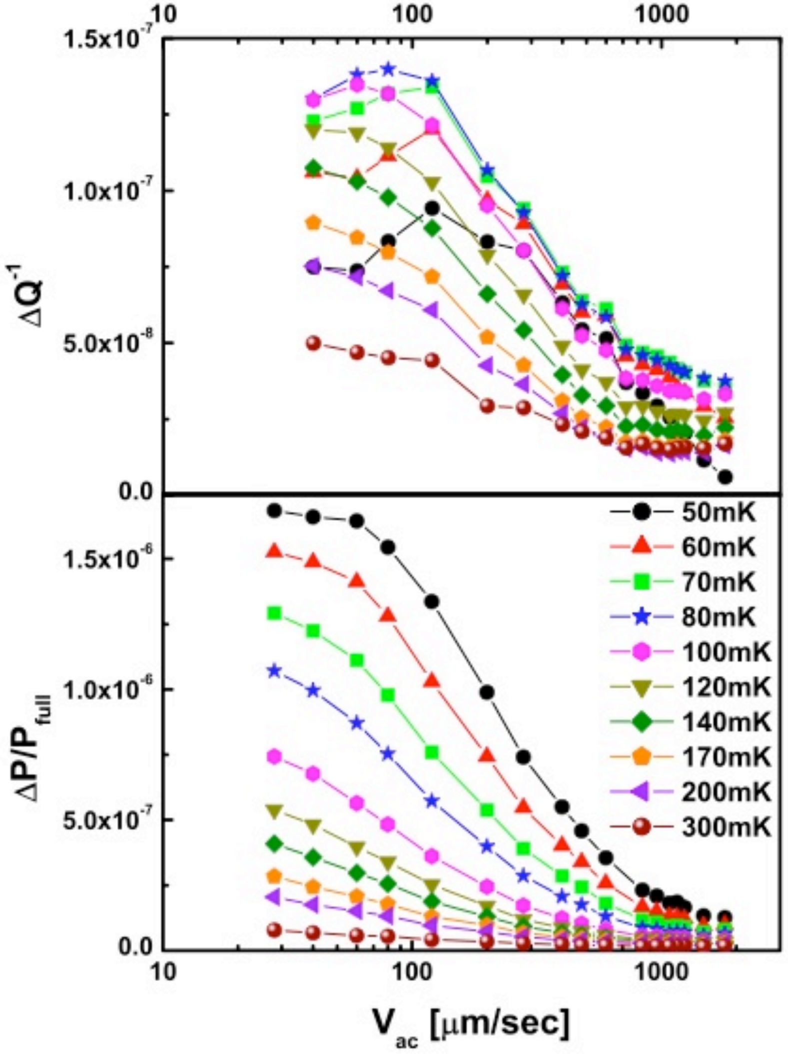


Fig. Torsional Oscillator responses of hcp ^{4}He at 49 Bar pressure. Upper column indicate energy dissipation change and Lower column shows (period shift change)/(solid He mass) = NLRS in solid He

Vortex Fluid Relaxation Model for Torsional Oscillation Responses of Solid ^{4}He

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1 Institute for Solid State Physics, University of Tokyo, Kashiwa, Chiba277-8581, Japan
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A set of detailed torsional oscillator(TO) response data of hcp 4 He to below energy dissipation peak is presented and a phenomenological model for relaxation processes in the response of Vortex fluid (vortex tangle) on rotation and torsional oscillations have been studied. Dependence of the both Nonlinear Rotational Susceptibility(NLRS) and Dissipation on T , and rim velocity Vac was studied. We could reproduce not only the unique Vac dependence, but also obtain new information of the vortex tangle system by the model calculation using parameters obtained from measured data. The results obtained may serve as a good qualitative description for the according measurements in the vortex fluid state in solid 4 He and we find an interesting peculiarity in the relaxation time at extrapolated temperature to ~30 mK from the measurement down to 50 mK. We discuss further the consequence.

Angular momentum of superfluid fraction appears only due to presence of either aligned vortices (vortex array) or due to the polarized vortex tangle having nonzero total polarization $\mathbf{P} = \mathcal{L}\langle s'_z(\xi)\rangle$ along along the applied angular velocity $\mathbf{\Omega}$ (axis z). For pure thermodynamic reasons it is clear that in the steady rotation the arrangement of the polarized vortex tangle is such that the whole set of vortices rotates with angular velocity Ω . That is quite natural supposition otherwise superfluid component would rotate either with larger angular and leave behind the whole rotating frame, or with smaller Ω and be behind. Both variants seem to be unrealistic, so in steady (direct) rotation superfluid component rotates with the applied angular velocity $\mathbf{\Omega}$ and, of course there is no deficit of moment of inertia at all. Thus, in the *steady case* there is strictly fixed relation between total polarization $\mathcal{L}\langle \mathbf{s}'(\xi)\rangle$ and applied angular velocity $\mathbf{\Omega}$ (κ is the quantum of circulation).

$$\mathbf{\Omega} = \kappa \mathbf{P} = \kappa \mathcal{L}\langle \mathbf{s}'(\xi)\rangle.$$

Angular momentum of the superfluid part can be written as

$$\mathbf{M}_{SF} = I_{SF}\mathbf{\Omega} = I_{SF}\kappa\mathbf{P}.$$

Situation is drastically changed in nonstationary (transient or oscillating) situation. The total polarization $\mathbf{P}(t)$ changes in time owing to that the both vortex line density $\mathcal{L}(t)$ and the mean local polarization $\langle \mathbf{s}'\rangle(t)$ change in time. Therefore the angular momentum of the superfluid part is

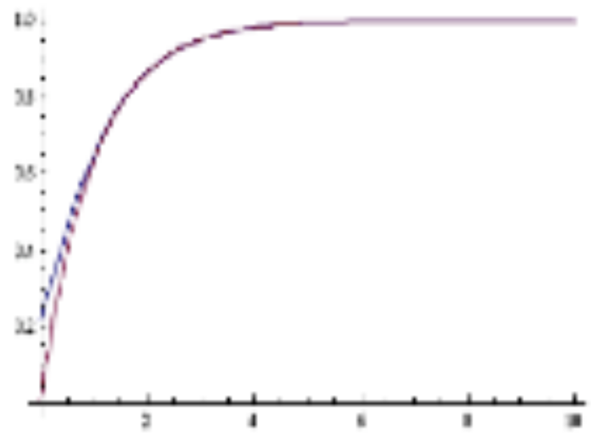
$$\mathbf{M}_{SF}(t) = I\kappa\mathbf{P}(t) = \frac{\rho_s V R^2}{2}\kappa\mathbf{P}(t) = \frac{\rho_s V R^2}{2}\frac{\kappa\mathbf{P}(t)}{\Omega}\mathbf{\Omega} = I(t)\mathbf{\Omega}.$$

Exponential adjustment

Let us suppose that equilibrium polarization is being reached in usual

exponential way ($\mathbf{P}_{eq}$ below is just the stationary value satisfying to $\mathbf{\Omega} = \kappa\mathbf{P}$)

$$\mathbf{P}(t) = \mathbf{P}_{eq}(1 - \exp(-t/\tau(\mathbf{V}_{ac}))) \quad and \quad \mathbf{M}(t) = \mathbf{M}_{eq}(1 - \exp(-t/\tau(\mathbf{V}_{ac})))$$



Torsion oscillations with relaxation processes

$$\mathbf{M} = a\Omega(t) + b\int_0^\infty \Omega(t-t')\varphi(\frac{t'}{\tau})\frac{dt'}{\tau}.$$

$$\varphi(\frac{t'}{\tau}) \sim \exp(-\frac{t'}{\tau}), \quad \tau(\mathbf{V}_{ac}) \sim \frac{1}{\alpha(T)\mathbf{V}_{ac}/R + \beta(T)}.$$

$$\mathbf{M}_{\omega->0} = (a+b)\Omega, \quad \mathbf{M}_{\omega->\infty} = a\Omega$$

$$\mathbf{M} = I_N\Omega(t) + I_{SF}\int_0^\infty \Omega(t-t')\varphi(\frac{t'}{\tau})\frac{dt'}{\tau}$$

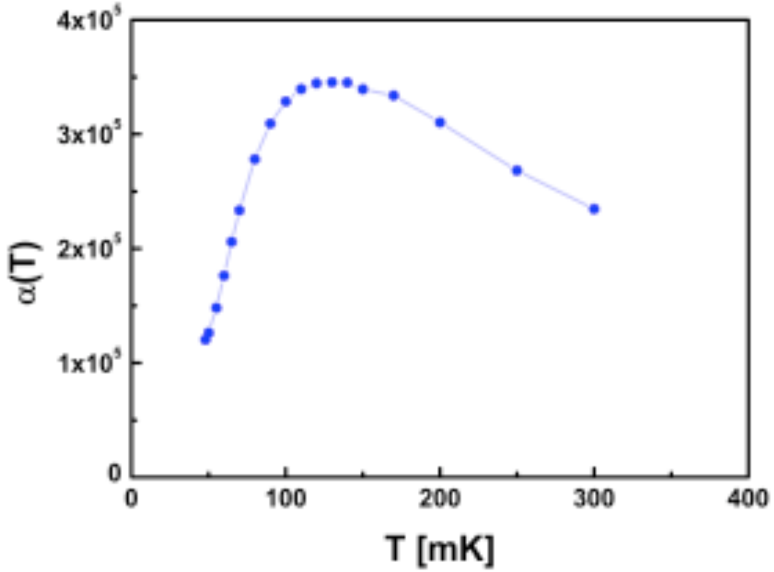
Final results

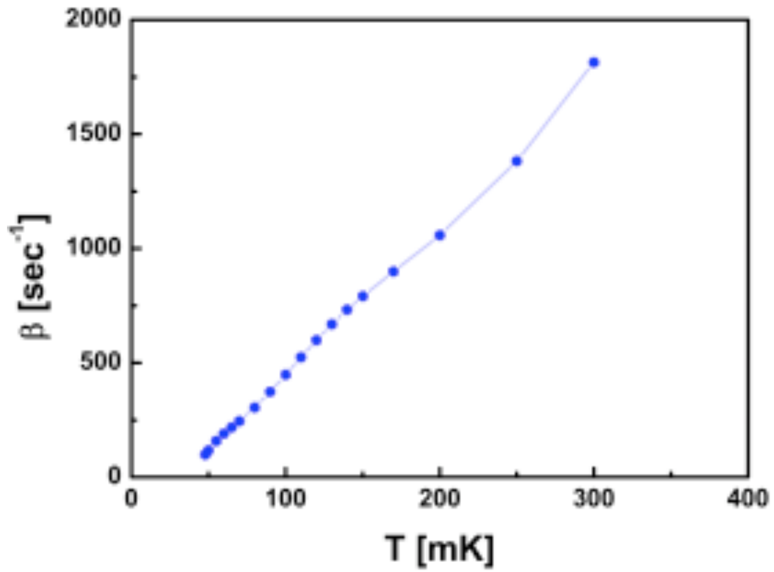
$$\frac{\Delta P}{P} = -\frac{1}{2}\frac{I_{SF}}{I_{full}}\frac{(\omega\tau)^2}{(\omega\tau)^2+1)}$$

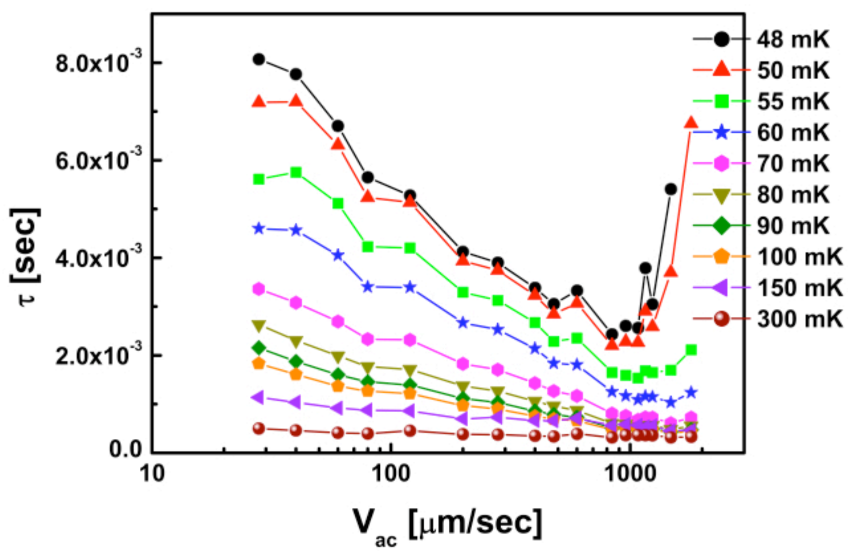
$$Q^{-1} = \frac{2\,\mathrm{Im}\,\omega}{\omega} = \frac{I_{SF}}{I_{full}}\frac{(\tau\omega)}{\tau^2\omega^2+1}$$

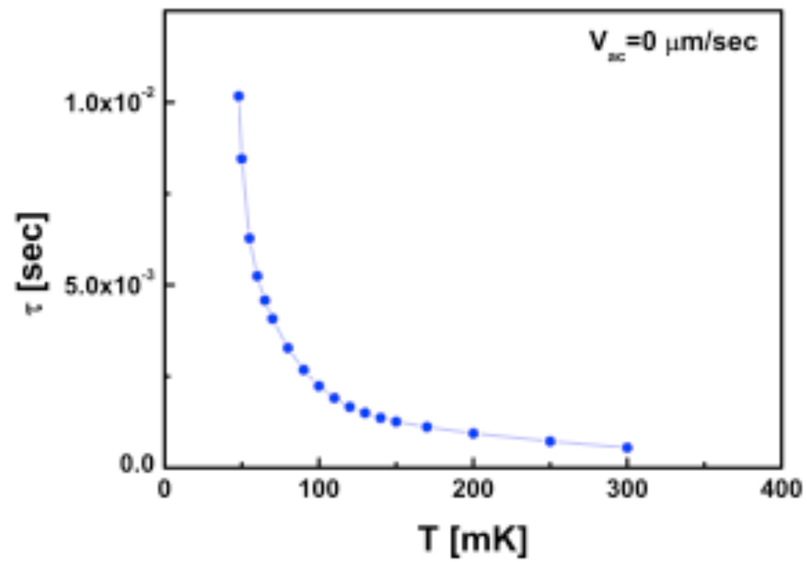
$$\tau(\mathbf{V}_{ac}) \sim \frac{1}{\alpha(T)\mathbf{V}_{ac}/R + \beta(T)}$$

Obtained parameters of vortex dynamics

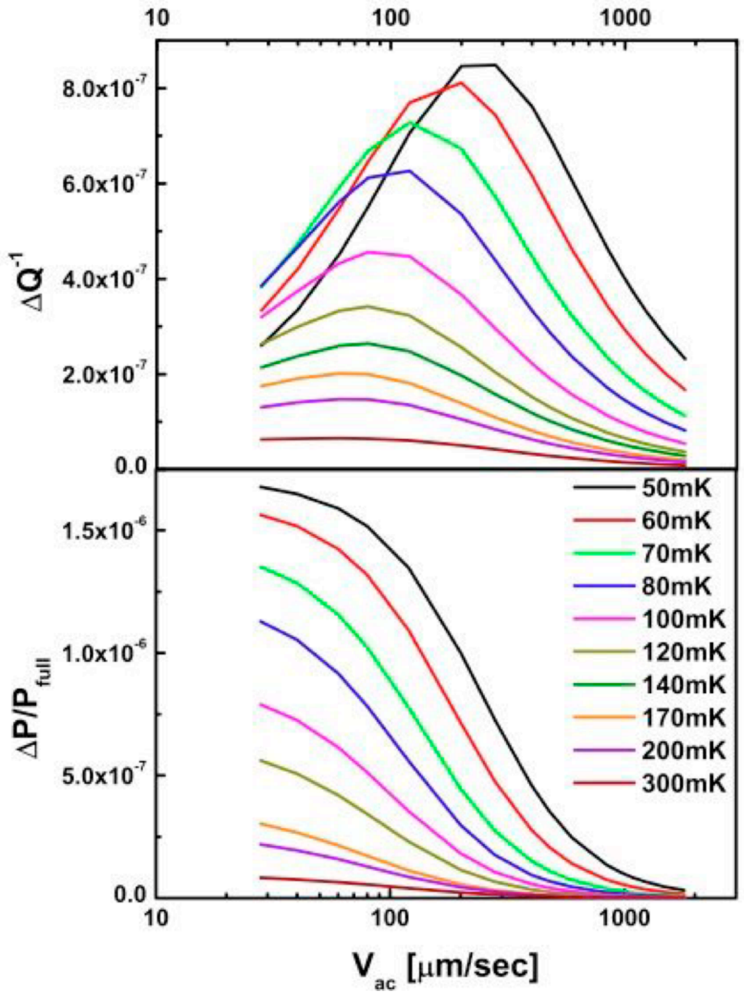








Our preliminary analysis based on vortex dynamics lead re-construction of TO responses. And we observe some extra features occurring at T< ~75 mK.



Phase Transition of the vortex system !!??
Detailed study is still in progress.

Thank you for your attention.

Kubota group at ISSP

We have been asking ourselves:
What is superfluid?

We are studying 3D connected ^{4}He monolayer superfluid systems, as well as superfluid ^{3}He in restricted geometry, especially under rotation using two rotating cryostats.