The Abdus Salam International Centre for Theoretical Physics

United Nations Educational, Scientific and Cultural Organization

IAEA International Atomic Energy Agency

1959-16

Workshop on Supersolid 2008

18 - 22 August 2008

Detailed torsional oscillator study on vortex fluid state and its transition into 3D supersolid state and observation of quantized vortices

M. Kubota
Tokyo University, Japan

Trieste, 2008. Aug.

Detailed Torsional Oscillator Study on Vortex Fluid State, Its Transition into 3D Supersolid State and Observation of Quantized Vortices

A. Penzyev, N. Shimizu, Y. Yasuta, P. Gumann, and M. Kubota
Institute for Solid State Physics, University of Tokyo (New Campus since 2000)

Summary of the present presentation

1]. Vortex fluid (VF) state was found below an Onset temperature T_o~500mK for samples at 32 and 49 bar. (Local condensate as well as quantized vortices start to appear below T_o.)

2]. VF state is characterized by its unique fluctuations, which can be controlled by AC excitation velocities, which tries to polarize the random fluctuations, where log(Vac)-linear suppression appears. We find a unique T^{-2} dependence of this suppression. Actually it follows as Langevin function: T^{-2} dependence at height T and gradual saturation towards 0K, similar as an ensemble of dipole moment systems. PRL **101, 065301 (2008)**

3a]. Transition from VF into a real 3D supersolid state was found for 49 bar sample below Tc=~75 mK and also for sample at 61 bar, by hysteretic torsional oscillator (TO) behavior's start below this T_c.

3b]. We could derive a characteristic energy gap of the order of ~400 mK.

4]. We propose **supersolid density ρ_s(T)**, which shows a unique T dependence: "T-linear" dependence for ~60 mK< T <~75 mK and steeper increase towards lower T.

5]. From the AC excitation velocity V_{ac} dependence of the hysteretic components of TO responses, we could conclude that it suggests **ρ_s(T)** is depressed totally by a **critical AC velocity** on the **order 1 cm/s**. We need to excite this state with V_{ac}> ~40 μm/s excitation.

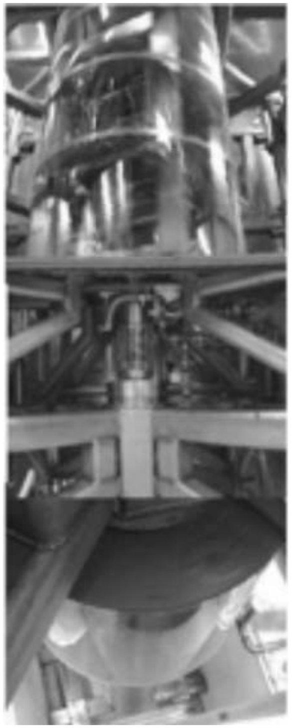
6]. Using one of our world record rotation cryostats, we studied vortex line penetration phenomena under DC rotation and TO techniques. We observed evidences of vortex line penetration below T_c, and we find the same/similar T dependence as **ρ_s(T)** from the hysteretic change.

7]. Remarkable observations: $\rho_s(T \rightarrow 0\ K) \sim$ NLRS($T \rightarrow 0$ K)

Back ground

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.

Superfluids under Rotation (SuR) series of workshops: 2003(Chuzenji-lake), 2004(Trento), Manchester(2005), Jerusalem(2007), Helsinki(expected 2009)

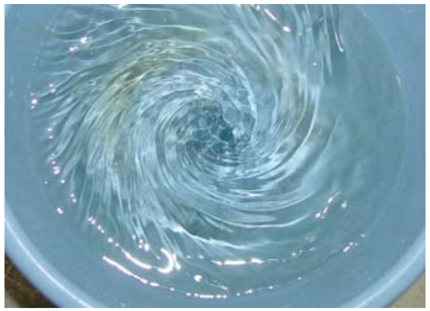
Superfluidity and Quantized vortices

What characterizes Superfluidity or Supersolidity? Which is most essential?

1. Zero viscosity : flow without Friction in a very narrow channel.

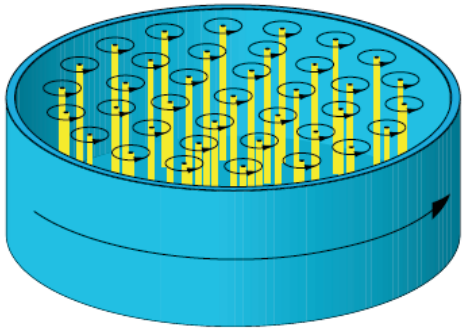
2. Quantization of flow : "quantized vortices". Under DC rotation we expect quantized vortex lines through the superfluid, but also vortex excitations might be essential for the new superfluids, including new class of superconductors.

Normal fluid vortex



One vortex enters the center part, strength of the vortex strengthens by turning fast.

Quantized vortices in superfluidity



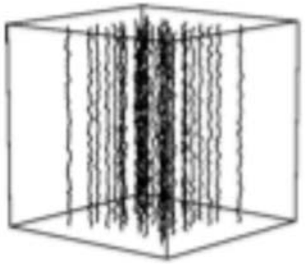
$n_V \sim \Omega$

Though strength of the vortex doesn't change even if it turns fast, the number of vortices of same strength increases. (quantization of vortex)

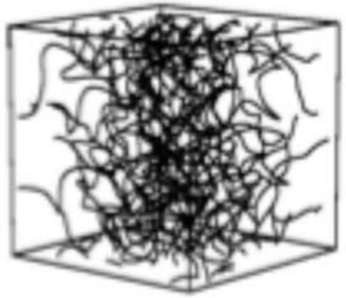
Macro 3D Vortices are known to have very high energy:

$E_v/k_B \sim 10^8$ K in cm^3 volume or so.

So It is impossible to induce vortex lines without DC rotation or flow velocity exceeding some V_c.



PHYSICAL REVIEW B **69, 134515 (2004)**



E_v is also proportional to its length L, so in a system of low D E_v gets smaller. For example, for a film of 10^{-8} cm thickness, $E_v \sim$ 1K. It becomes possible to excite vortices by thermal energy. Yet no BEC is expected in 2,1,0 D systems. However, some low D superfluidity is possible. Examples:

2D: Kosterlitz-Thouless transition occurs at $T_{KT} \sim n_2$. 2D quantized vortices are present at $T > T_{KT}$ and paired at $T < T_{KT}$, keeping macroscopic phase coherence: superflow is possible with $V_c \sim 0$, unless some pinning mechamism.

1D: ?? Lattinger Liquid ?

0D: ???

What causes superfluid transition, other than BEC?

There has been a discussion that **it is ordering in phase space! Not in the amplitude of the Condensate!** So, superfluid transition is caused by thermal excitations as vortex rings(3D) or vortices(2D) to destroy macroscopic phase coherence. G. Williams (1987):

"**Vortex ring model of the superfluid transition". *Phys. Rev. Lett. 59,1926-1929 (1987).***

Anyways**, in 3D** systems **BEC is one of the fundamental conditions** to expect superfluidity.

What about **inter-relation between BEC** (which is purely Quantum statistical property) **and interactions**, which causes phase changes from gas to liquid and then to solid?

There has been a long history!

In 1938 Fritz London discussed BEC as the essence of superfluidity in liquid ^{4}He. T_{BEC} =3.1K was calculated for ideal Bose gas with the same density as liquid ^{4}He.

Original consideration about **possible BEC in solid** was made by **Penrose and Onsager(1956)**, but with negative result.

There was a mistake!

Supersolid Theories (1960’s to 1970)

1]. Reatto and Chester, “Phonons and the properties of a Bose system”, PR Vol.155, 88-100 (1967): BEC only in 3D

2]. Andreev and Lifshitz, “Quantum Theory of defects in Crystals”, Soviet Physics, JETP vol.29, 1107- 1113 (1969).

3]. Chester, “Speculations on Bose-Einstein Condensation and Quantum Crystals”, Phys. Rev. A2, 256 – 258. (1970).

4]. A. Leggett, “Can a Solid Be “Superfluid”? ”, Phys. Rev. Lett. Vol. 25, 1543 -1546 (1970).

There had been plenty of Experimental Efforts to seek for “Supersolid State” in the World, but with Negative Results (Till 2002)

1]. Bishop, Paalanen, and Reppy, “Search for Superfluidity in hcp ^{4}He”, Phys. Rev.B24, 2844 (1981).

2]. H. Suzuki, “Plastic Flow in Solid Helium”, J. Phys.Soc. JPN Vol.35, 1472 - 1479 (1973); I. Iwasa and H. Suzuki, “Sound Velocity and Attenuation in hcp ^{4}He Crystals Containing ^{3}He Impurities”, J. Phys. Soc. Jpn.. Vol.49, 1722- 1730 (1980).

3]. Meisel, “Supersolid ^{4}He: an overview of past searches and future possibilities”, Physica B 178, 121-128 (1992).

4]. J. Goodkind, “Interaction of First and Second Sound in Solid 4He: Properties of a Possible Bose Condensate”, Phys. Rev. Lett. Vol. 89, 095301-1-4 (2002).

Rapid Developments of Supersolid Study since 2004

Original discussion (1960's and 1970) of Supersolid:

BEC of vacancies or other imperfections in solid ^{4}He $\rho_s/\rho \sim 10^{-6} \sim 10^{-4}$

Experimental Observations after 2004 :

Rather High $T_{onset}=T_o$: 0.2-0.5 K, Too high for known n_v, n_i for BEC!!

BEC cannot explain the observed $T_o \sim \alpha T_\lambda$ ($\alpha \sim$ 0.1~0.3)of liq. ^{4}He !!

Vortex Fluid State proposal by P.W. Anderson: Nature Phys. Vol.3.Mar'07

VF model can explain the following experimental facts:

1). High T_o , (supposing lower Dimensional sub system, MK)

2). Real 3D Transition is expected at lower $T_c < T_o$.

3). Dimensional crossover of excitations is often expected in known vortex fluids; Cuprate HTS, Organic SC, and Layered SC as well as Fe compounds. 2D subsystems are common in all theseSC's.

Kubota group's activities as to fundamental questions of superfluidity:

KT transition: 2D He films' superfluid transition, involving quantized vortex pairs to keep macroscopic coherence.

We have been studying 3D connected 2D films to ask the question of essence of superfluidity without condensate!?.

T. Obata and M. Kubota, "Calculation of the phase field of a vortex pair on the surface of a multiply connected substrate" Phys. Rev. B **66,** 140506R (2002).

We could observe 3D vortex lines penetration into this system by torsional oscillator technique.

M. Fukuda *et al.*," Rotation-induced three-dimensional vorticity in ^{4}He superfluid films adsorbed on a porous glass", Phys. Rev. B **71,** 212502 (2005).

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

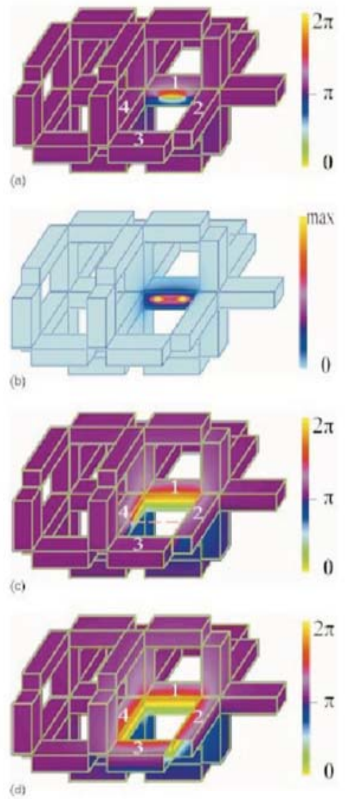
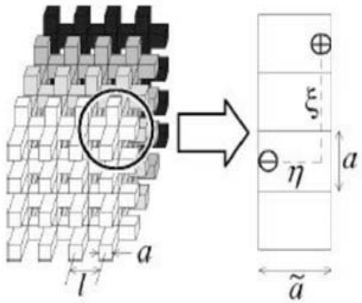
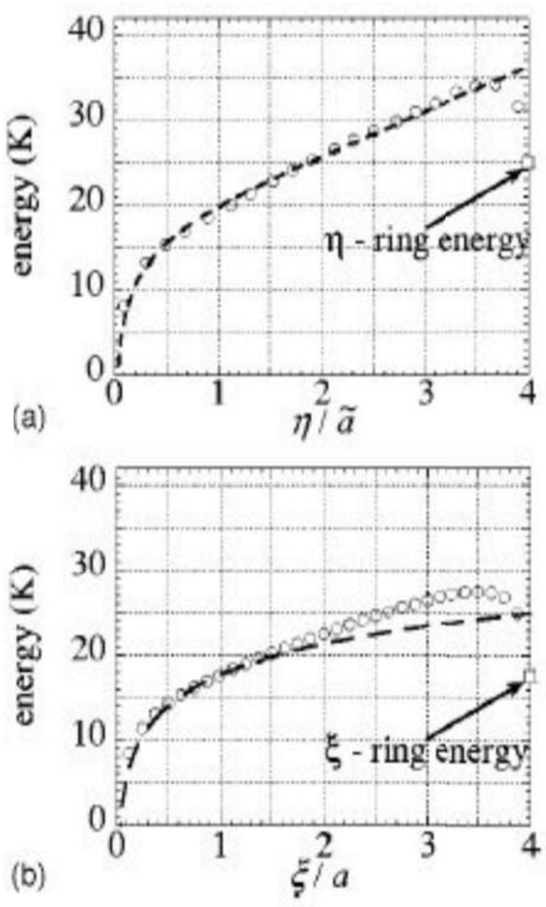
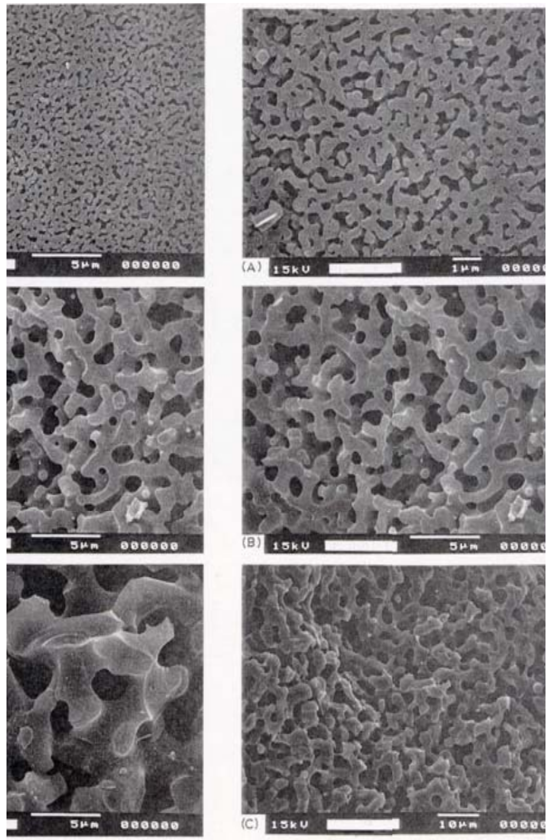


FIG. 2. (Color) A series of the calculation results. This solution is the example when vortex pair decouples along η direction. The color corresponds to the phase from 0 to 2π and it is periodical continuous in the panels (a), (c), and (d). (a) $\eta=\tilde{a}/2$. (b) The flow energy distribution of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

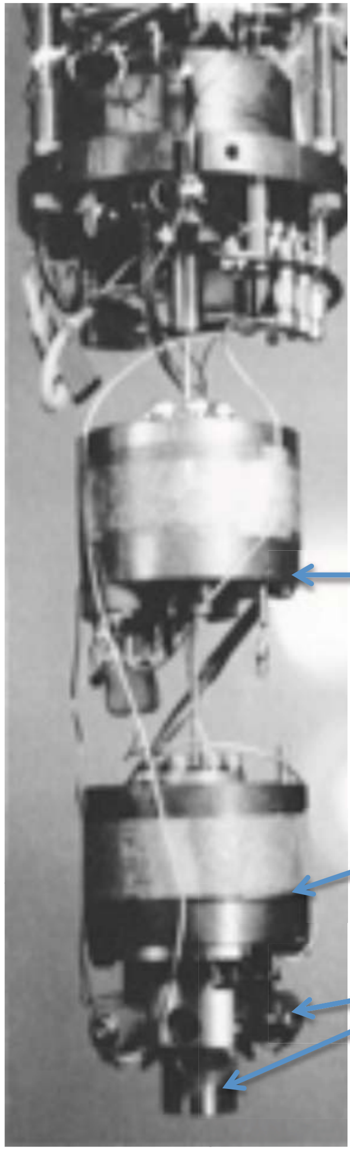




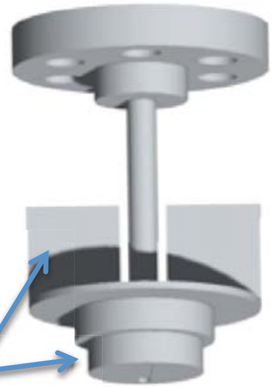


icroscope pictures of the well-defined porous glass samples with pore diameters 2500, 5000 and 1
(c) are all taken with a magnification factor of 3250, whereas photos (A)–(C) are taken
), 3250 and 980, respectively, to make the pore sizes look almost the same. From these photos w
asses with different pore sizes is quite the same and the ratio l/d (unit/length)/(pore diam
certainly larger than 1 and probably 3–5.

Torsion oscillator with High Sensitivity and high stability



- Mixing chamber of a dilution refrigerator
- 1st Vibration isolation Cu block
- 2nd Vibration isolation Cu block and the torsion oscillator with electrodes



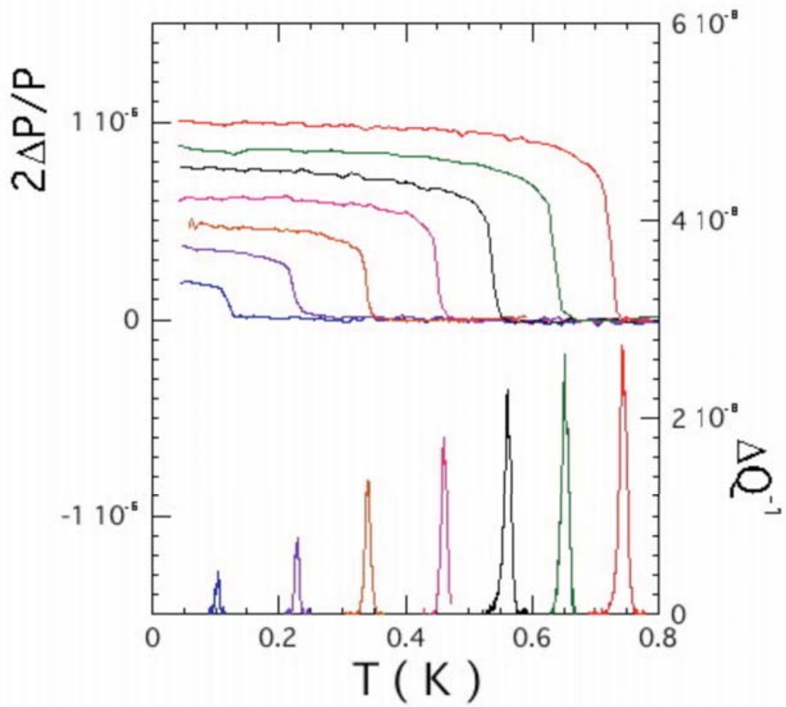
Detailed study of an artificial 3D superfluid, made of mono-layer superfluid He film

3D superfluid without condensate?

T_c is primarily determined by n_2 and modified slightly by L.

V_c is determined by h/mL, where L is unit length of the pore

3D vortex lines were detected by an extra energy dissipation peak at a constant T_R, whose height changes linearly with Ω. Its mechanism has been theoretically analyzed.



M. Fukuda, PhD Thesis 2000; Phys. Rev. B**71, 212502 (2005)**

V_{ac} Dependent Dissipation at Still condition and DC Rotation Experiments

Excitation dependent Energy dissipation
at Still condition: Larger Vac → Larger Dissipation

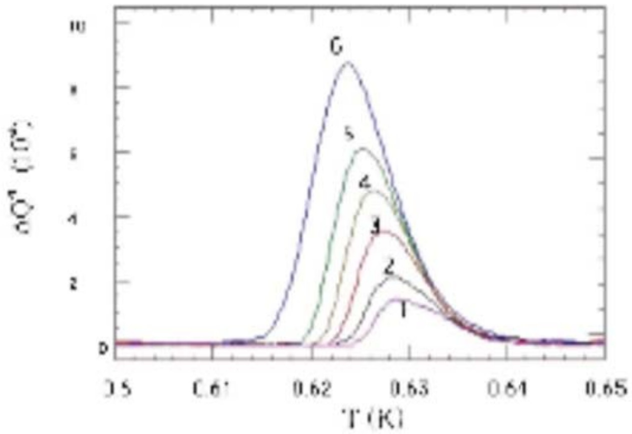
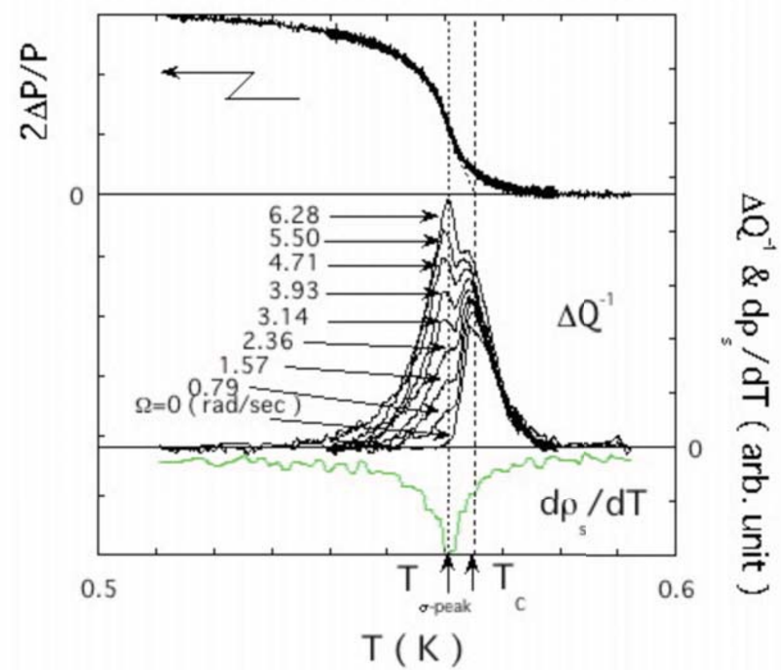


FIG. 3. (Color online) Energy dissipation curves in the static condition for the nonlinear regime. The ac drive velocity amplitude for each curve corresponds to V_{ac}=0.095(1), 0.19, 0.36, 0.52, 0.66, 0.94(6) cm/sec, respectively.

Energy dissipation under DC rotation with Increasing DC rotation speed: New "Rotational Peak" appears at lower T as Still peak. Linear Dependence of the height on Rotation Velocity



→Vortex line penetration by Rotation
→ 3D Superfluid!!

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

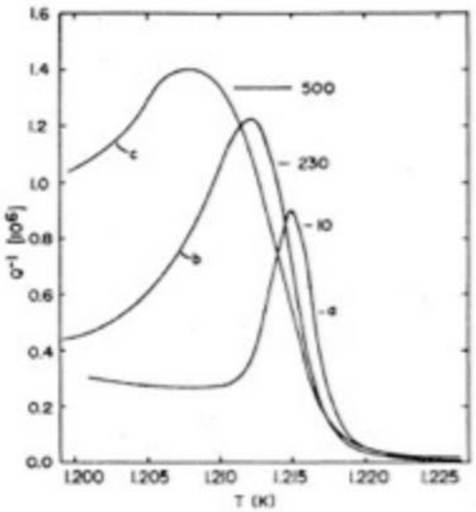


FIG. 5. Dissipation peak for a single film at three different values of cavity velocity (arbitrary units).

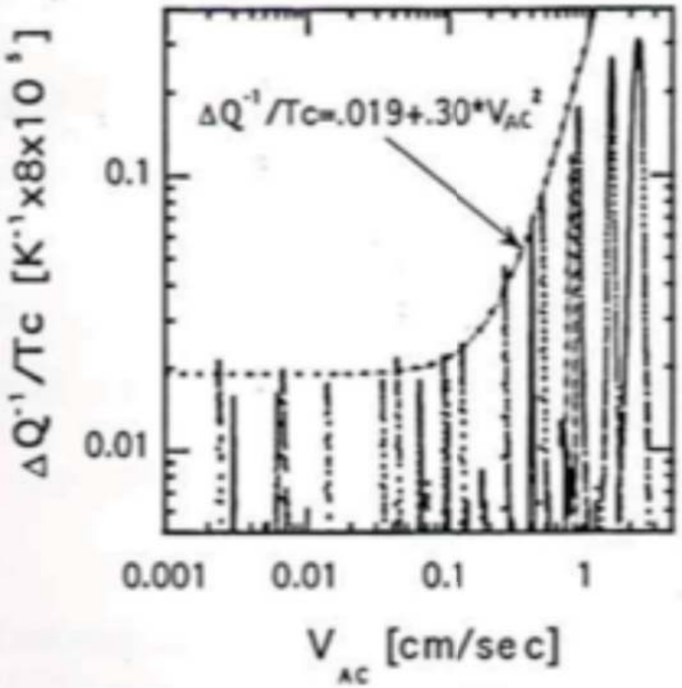
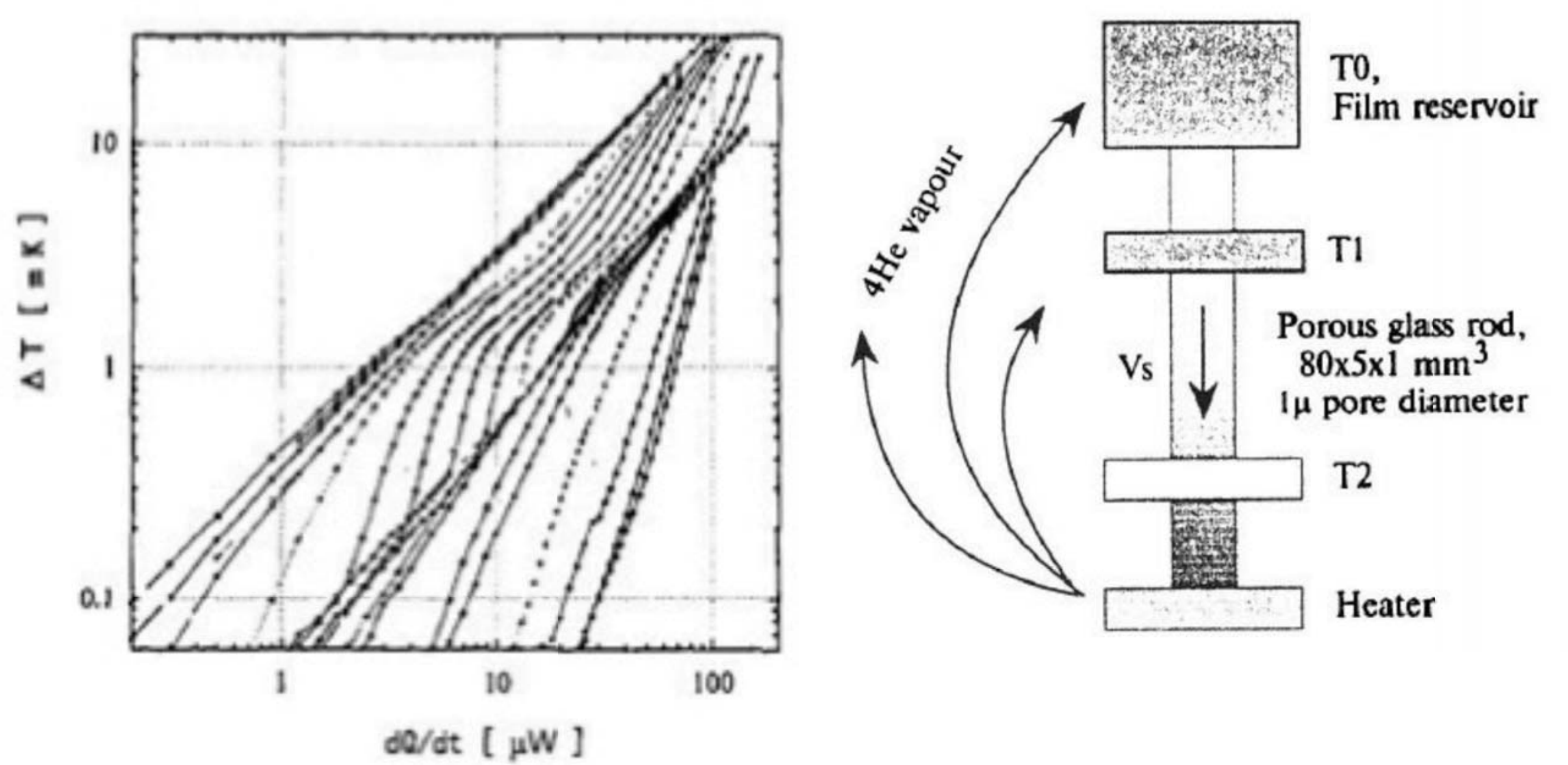
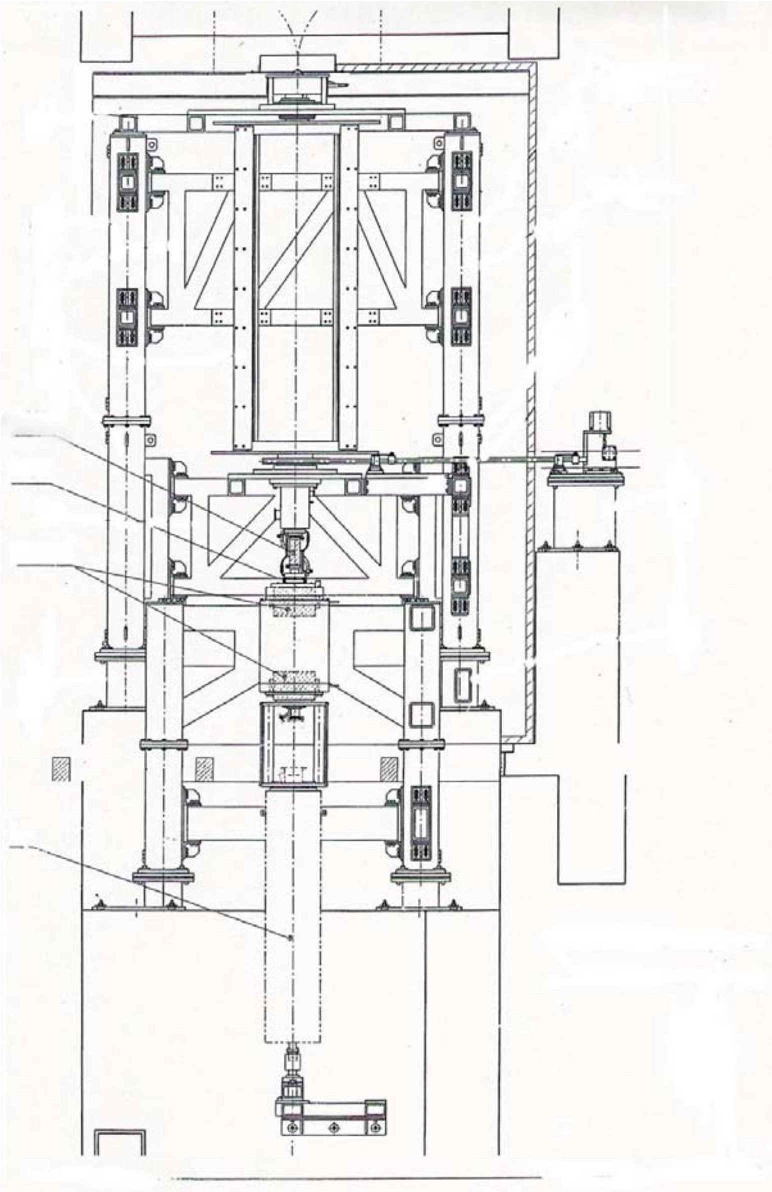


Fig. 1, Dissipation peak heights devided by each Tc, 201,414, and 1182 mK, as a function of the substrate AC velocity at the electrode position over 2×10^3 range. The broken line is a trial fit in the given unit.

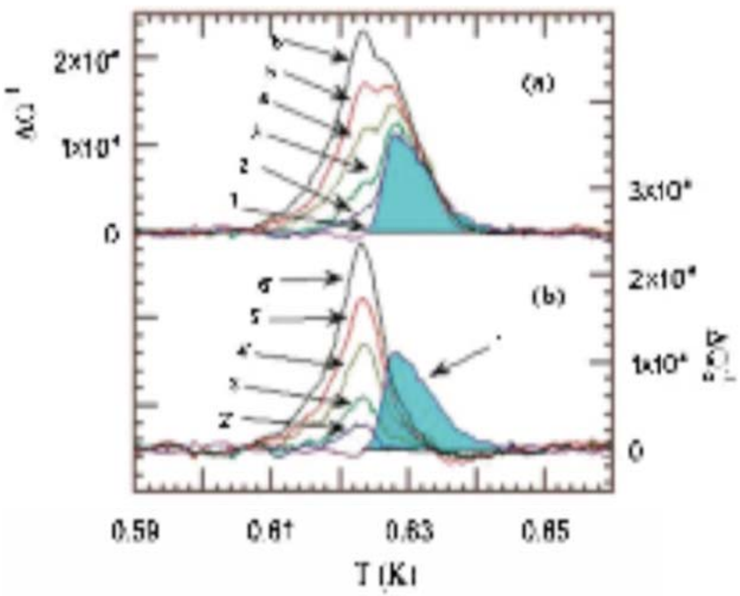
DC flow experiments for a He monolayer film in 1 μm pore porous glass: V_c(3D → 2D superflow) ~ cm/s ~ h/mL



Kubota, et al., JLTP Vol.113, (1998)



ISSP High Speed Rotating DR



Summary of the present presentation-1

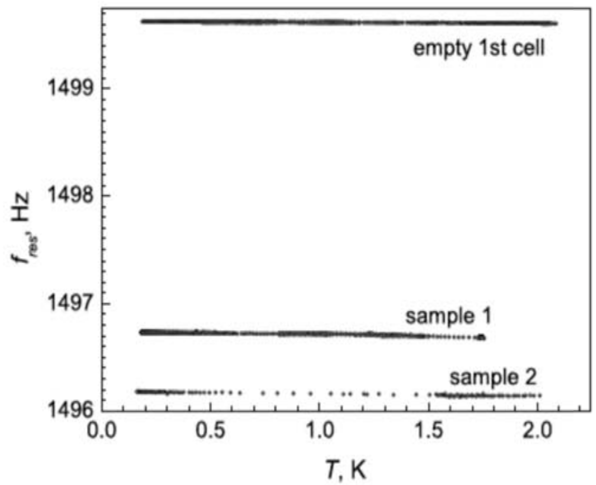
1]. Vortex fluid (VF) state was found below an Onset temperature T_o~500mK for samples at 32 and 49 bar. (Local condensate as well as quantized vortices start to appear below T_o.)

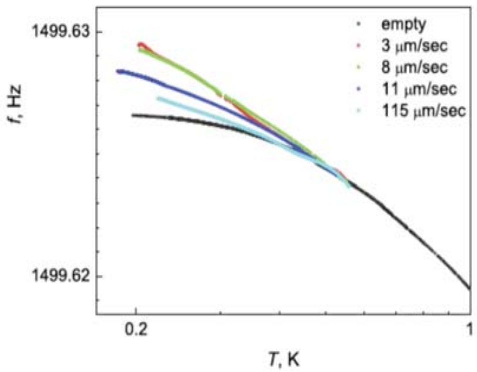
2]. VF state is characterized by its unique fluctuations, which can be controlled by AC excitation velocities, which tries to polarize the random fluctuations, where log(Vac)-linear suppression appears. We find a unique T^{-2} dependence of this suppression. Actually it follows as Langevin function: T^{-2} dependence at height T and gradual saturation towards 0K, similar as an ensemble of dipole moment systems.

PRL **101, 065301 (2008)**

Our first Solid ^{4}He Study: A. Penzyev et al.,JLTP2006

We enjoy finding our work among the earliest experiments on supersolid phenomena observations:





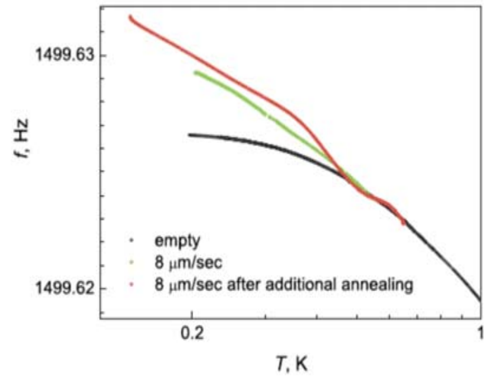


Table 1. Sample List

sample number	cell	f_{res}, Hz	initial pressure, bar	T_m, K	final pressure, bar	Δf, Hz
1	1st	1499.6	71.7	2.08	40	2.96
2	1st	1499.6	90.5	–	≈ 60	3.43
3	2nd	1534.7	74	2.15	43	3.76

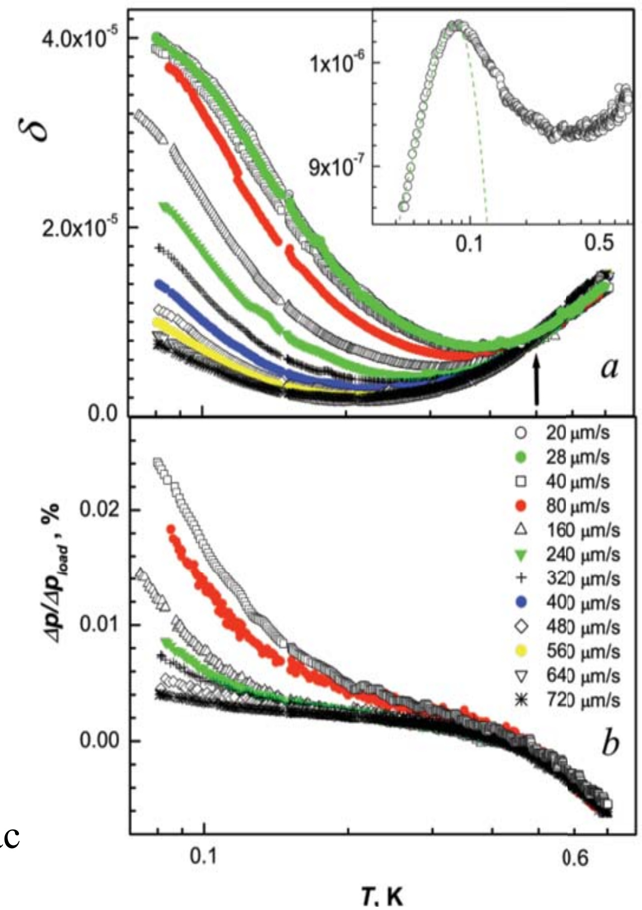
We report first VF state. And then Real 3D Supersolid Transition will be discussed later.

(We report the first evidences of 3D Supersolid phase transition by **this presentation**.)

We start with our vortex fluid state discovery: cf Penzev, Yasuta, Kubota Phys. Rev. Lett. Vol.101, 8th Aug 2008.

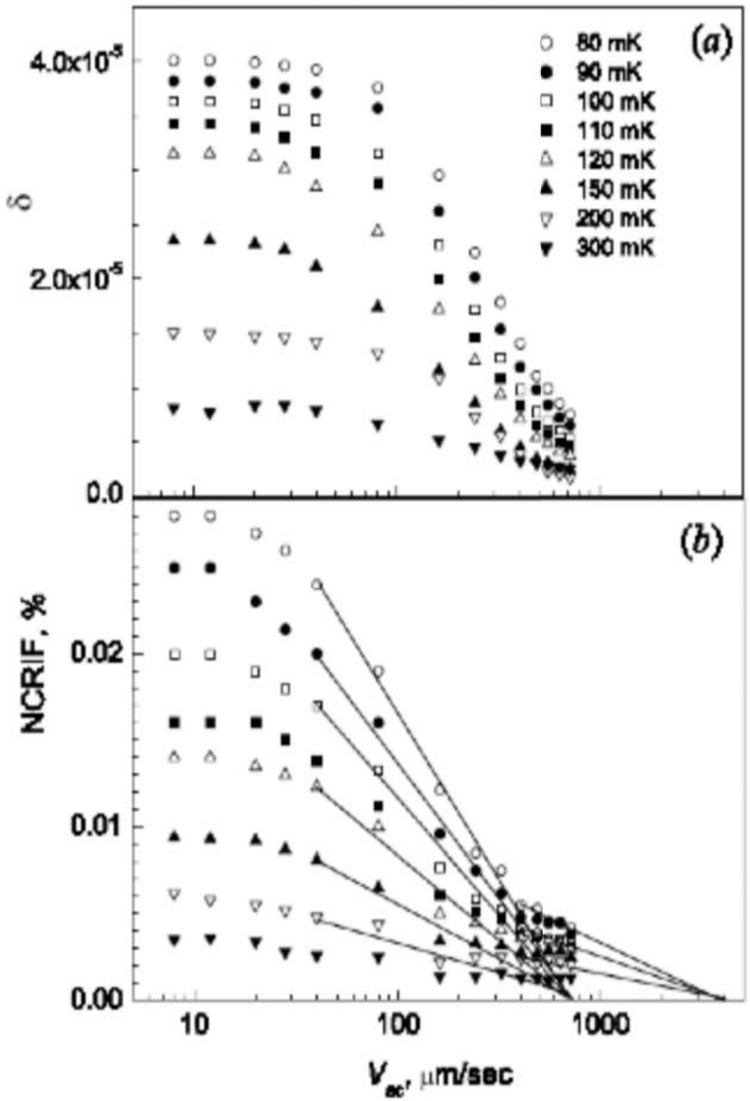
We have report first the onset Temperature, T_o observation and vortex fluid (VF) behavior at $T < T_o$.

Vortex fluid state $T_c < T < T_o$
But, without real T_c.
We realized that VF state has a unique V_{ac} Dependence.



V_{ac} dependence is completely opposite to known Superfluid Transions: KT, 3Dfilms, Bulk ^{4}He !! How one can imagine larger energy dissipation with smaller excitation? Thermal excitation itself is causing VF state fluctuations!! And what we observe is controlling process by AC excitation to polarize the VF tangle.

FIG. 2: (a) and NCRIF(b) as a function of Vac at T < 300mK. The solid lines in (b) show the nearly linear dependence on log(Vac) for two Vac ranges; 40< Vac <400µm/sand Vac > 500 µm/s. The slope for each range has a uniqueT dependence given in Fig. 4. Extrapolated lines are foundto converge at a point for each Vac range. This point of con- vergence also determines the position of the zero in Fig. 1(b).

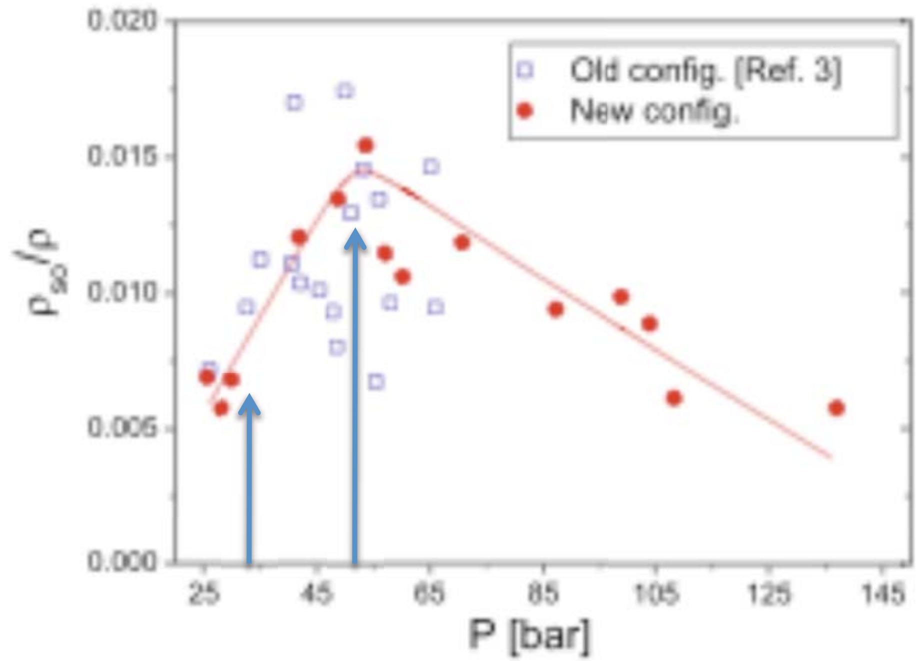


New measurements on Solid ^{4}He at 49 bar

We wanted more stable solid ^{4}He sample to study properties in a more systematic way.

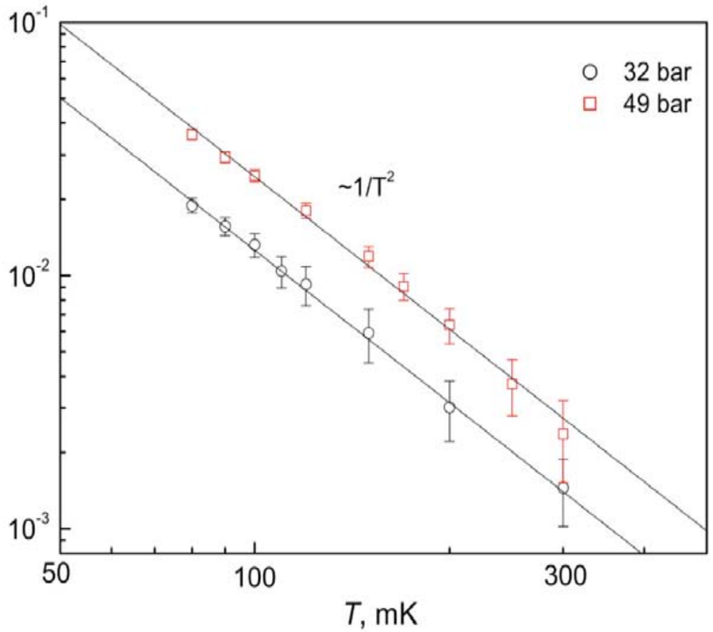
Vortex fluid state is expected above a Real 3D superfluid transition temperature, T_c.

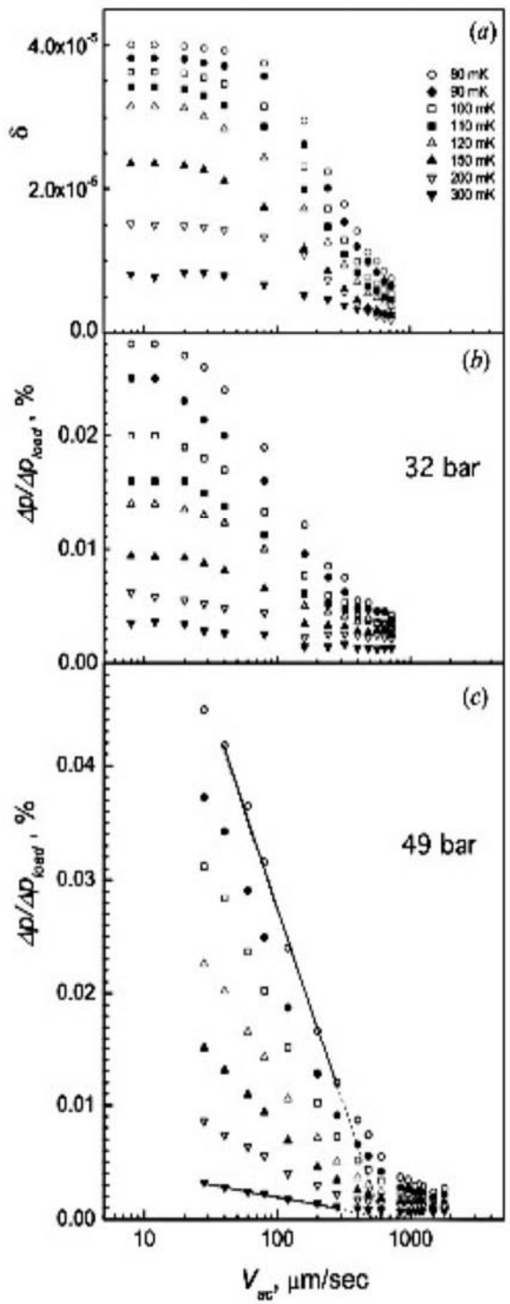
Below T_c we expect 3D coherent supersolid state, where we can expect Real phase transition and 3D vortex lines excitation under DC rotation.



Kim & Chan, PRL **97, 115302 (2006)**

Log(V_{ac}) linear depencence is more clearly observed for 49 bar solid ^{4}He sample: see box (c) right. And by plotting this slope as a function of T, one realizes a very simple relation: $1/T^2$ dependence with "right" pressure dependence.





LogV_{ac} linear dependence is clear

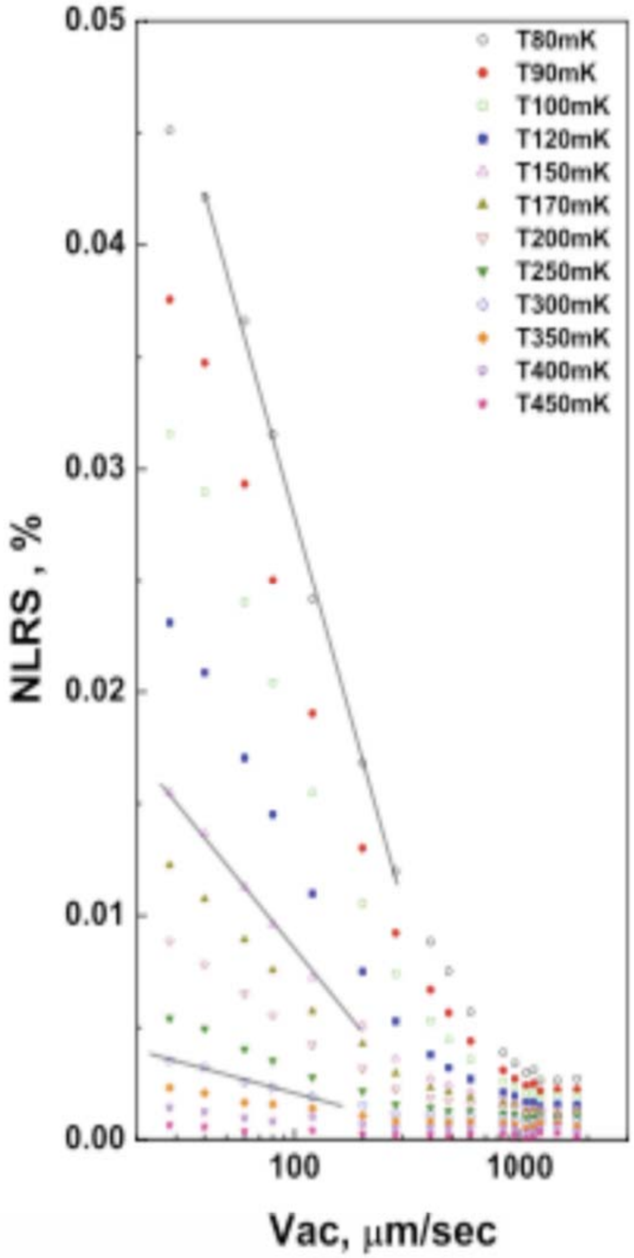
This is indicationof involvement of Quantized vortices as discussed by P.W. Anderson[2007].

Yet, it is not clear how it occurs. AC velocity field V_{ac} may forces existing randomly fluctuating vortex rings of local sizes to align. And larger the V_{ac} alinement becomes better and random fluctuation is decreased.

Is this Scenario OK?

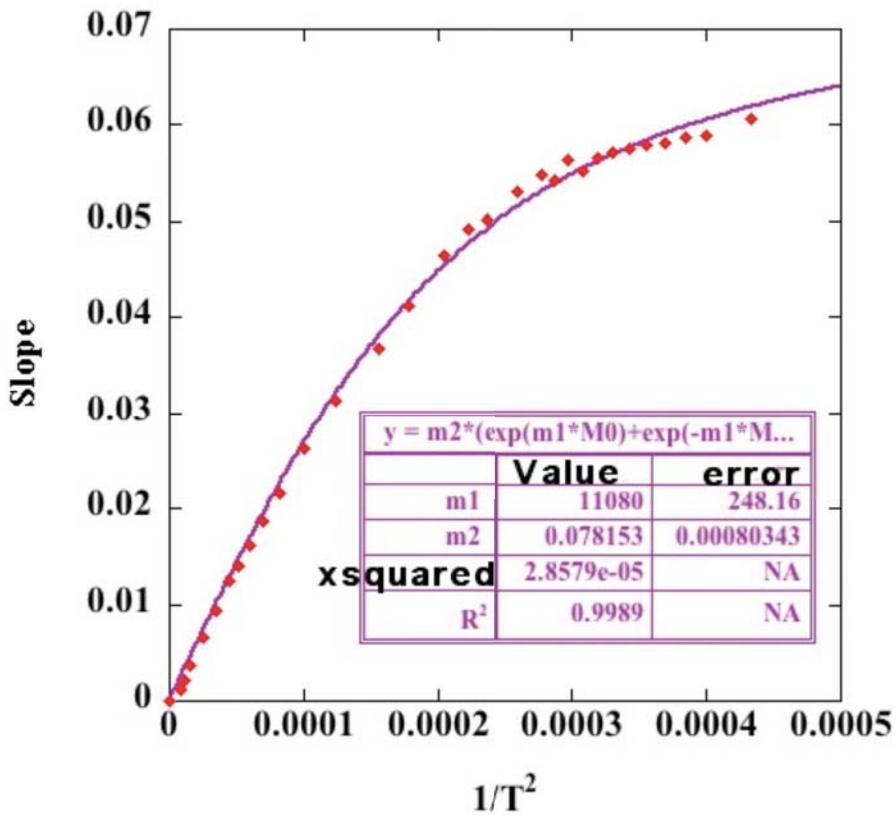
Then we do have vortex fluid state indeed.

And at further lower T, we would expect freezing of vortex fluid and we shall have real supersolid!!



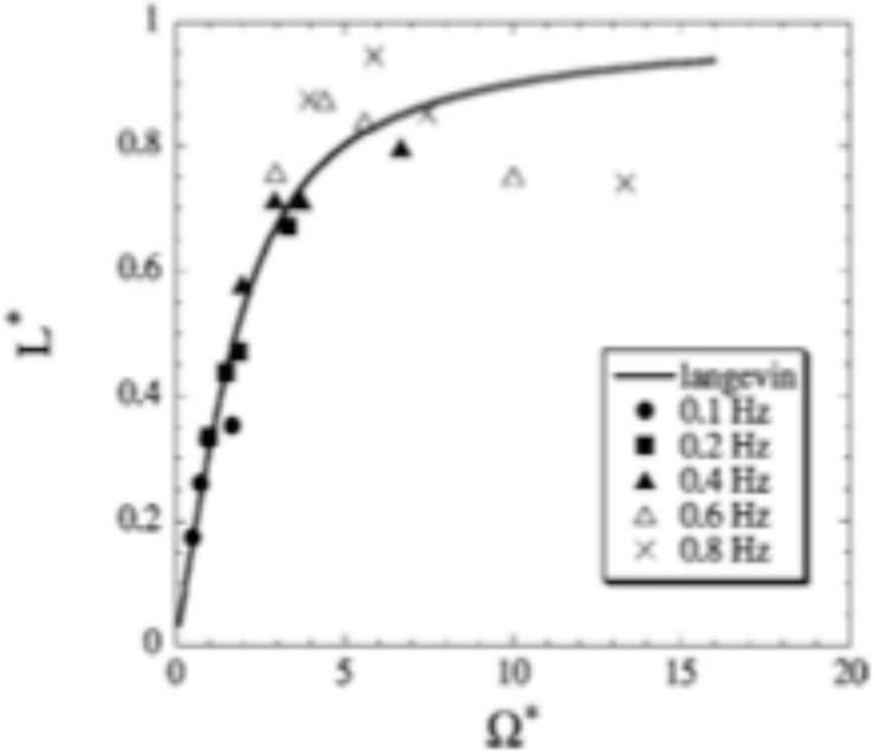
Unique Temperature Dependence of d(NLRS)/d(logVac) as pointed out by P.W. Anderson Nature Phys. Mar.(2007)

We believe that what People have been calling as NCRIF is actually Non Linear Rotational Susceptibilility (NLRS) as PW Anderson proposed.



Actually there are some more interesting observations.

1/T^2 Dependence is expected for "polarization" of superfluid turbulence at high temperature limit !! And Langevin Function over all T!!



Although we have no concrete Explanation as to the relation between d(NLRS)/d(logVac) and Polarization, it involves tangled quantized vortices in both cases of Liquid He superfluid turbulence and vortex fluid state in solid He. The latter is believed to lack 3D macroscopic coherence.

Makoto Tsubota, Carlo F. Barenghi, Tsunehiko Araki, and Akira Mitani," **Instability of vortex array and transitions to turbulence in rotating helium II ", Phys. Rev. B69,** 134515 (2004), Fig.15. L* : vortex tangle polarization,

Summary of the present presentation-2

3a]. Transition from VF into a real 3D supersolid state was found for 49 bar sample below Tc=~75 mK and also for sample at 61 bar, by hysteretic torsional oscillator (TO) behavior's start below this T_c.

3b]. We could derive a characteristic energy gap of the order of ~500 mK.

4]. We propose **supersolid density $\rho_s(T)$**, which shows a unique T dependence: "T-linear" dependence for ~60 mK< T <~75 mK and steeper increase towards lower T.

5]. From the AC excitation velocity V_{ac} dependence of the hysteretic components of TO responses, we could conclude that it suggests **$\rho_s(T)$** is depressed totally by a **critical AC velocity** on the **order 1 cm/s**. We need to excite this state with V_{ac}> ~40 μm/s excitation.

Hysteretic behavior by changing AC excitation

General observation in the vortex fluid state of solid ^4He:

1]. Smaller AC excitation produces larger amplitude signal as well as period shift. ←--> quite opposite to usual excitations. Thermally excited random vortices exists already without external excitation. It lacks macro coherence.

Hysteretic behavior starts below T_c =~76 mK in Real Supersolid state (P=~49 bar)

We have made two sets of measurements.

A set (T sweep under "equilibrium" and "non-equilibrium conditions)

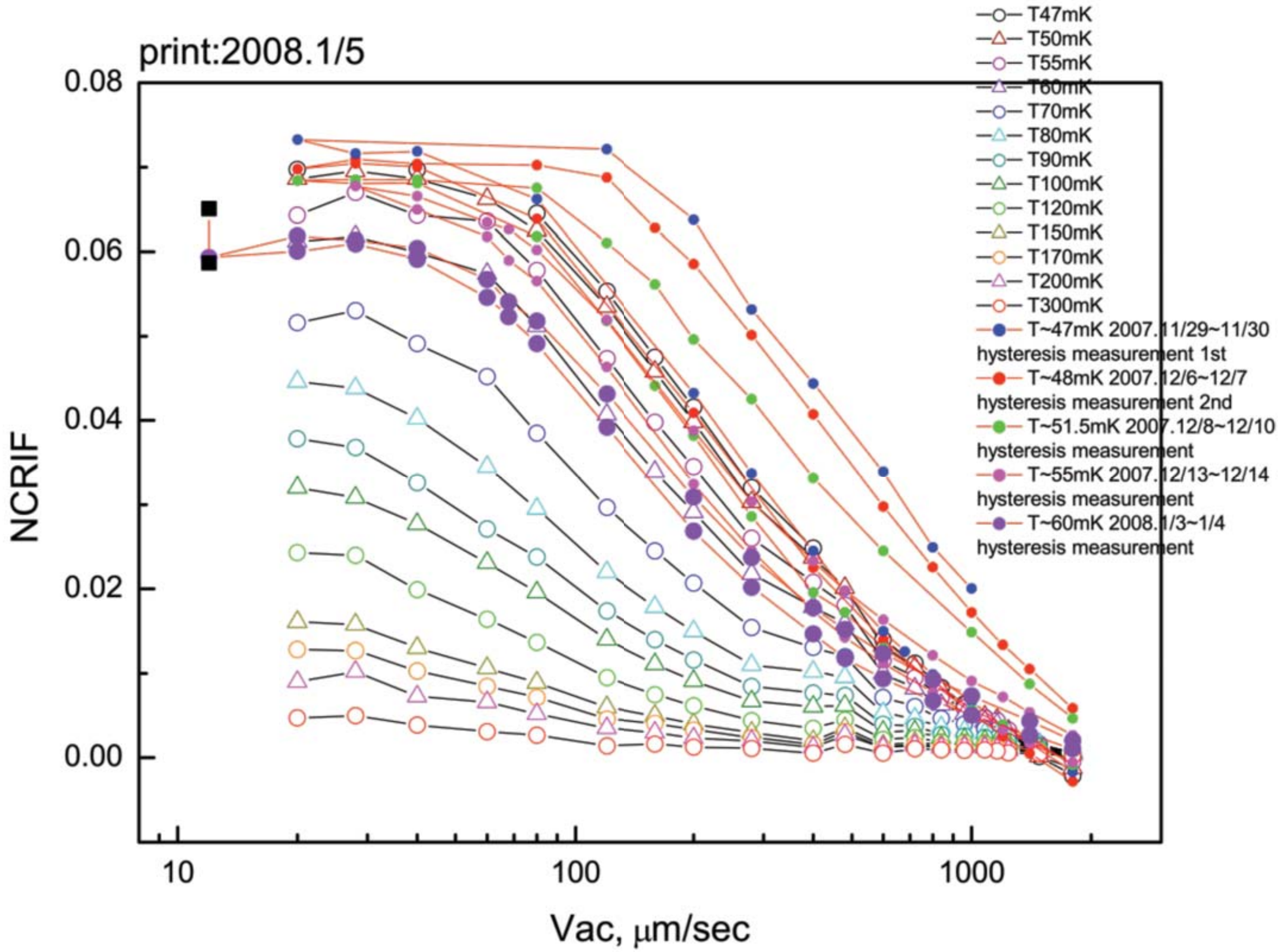
1]. Change AC excitation at T > ~500 mK, then cool down to T_{min} and sweep up T → "equilibrium" T sweep measurement.

2]. Set AC excitation at 20 μm/s (0.5mV) then cool down to T_{min} and change AC excitation at T_{min} to measuring excitation V_{ac}, then sweep up. →"non-equilibrium" T sweep measurements.

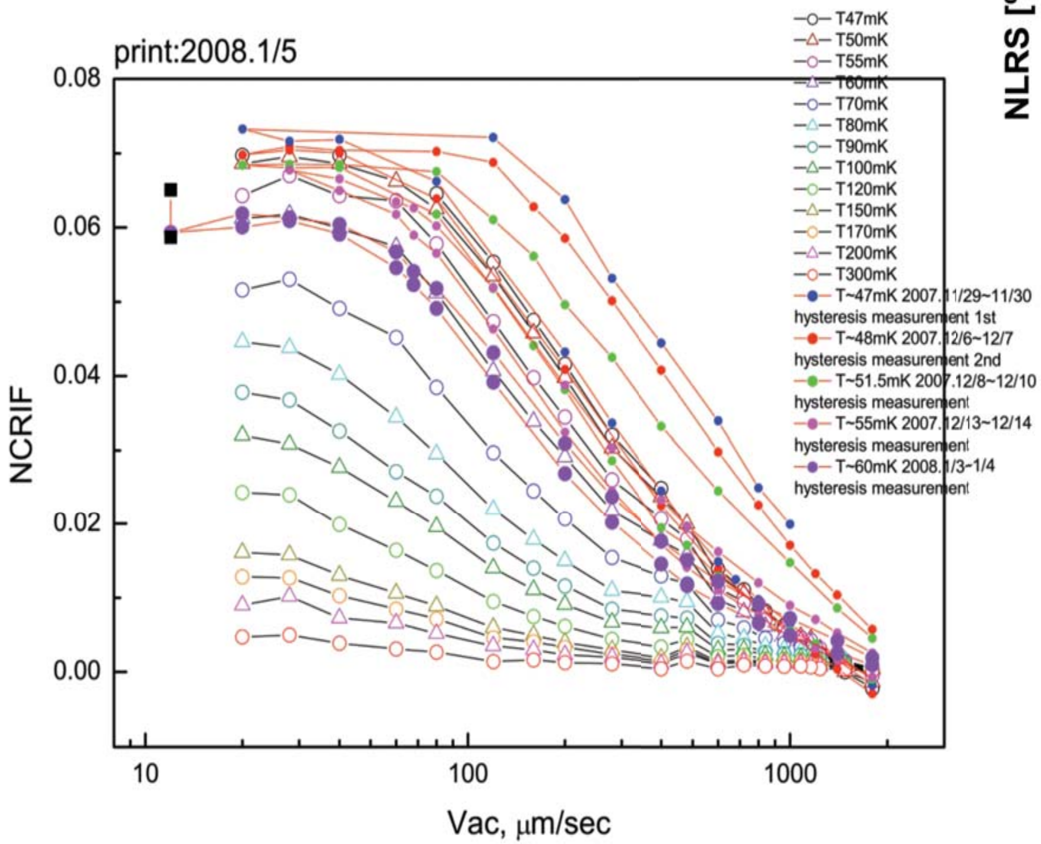
B set (V_{ac} sweep at constant T's)

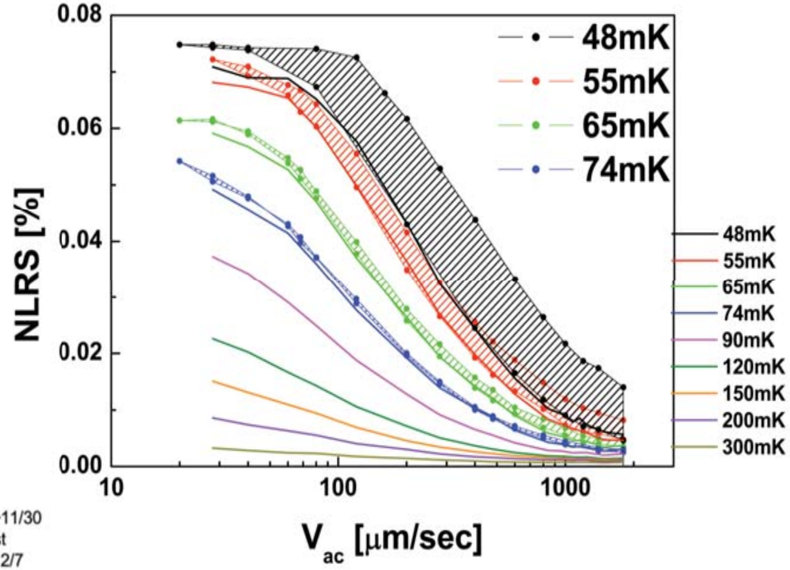
1]. Keep the sampe temperature constant and Sweep V_{ac} slowly

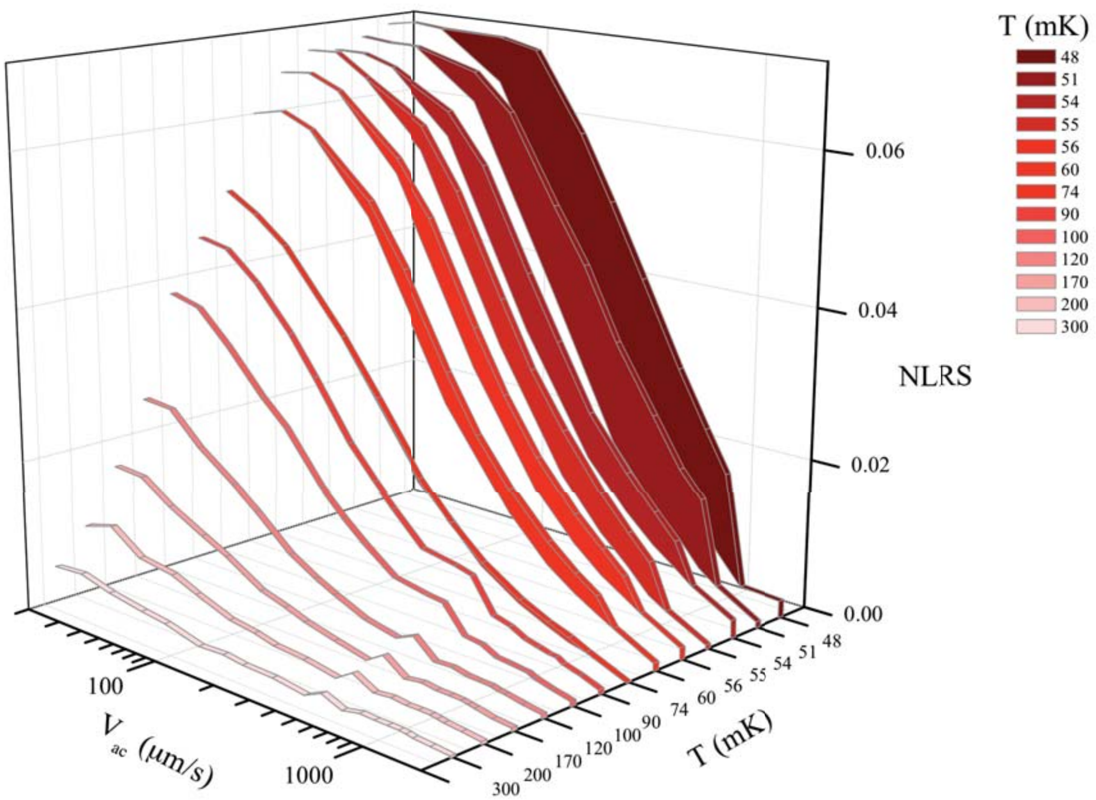
Detailed Study of V_{ac} Dependence and Appearance of Hysteretic behavior below T_c !?!



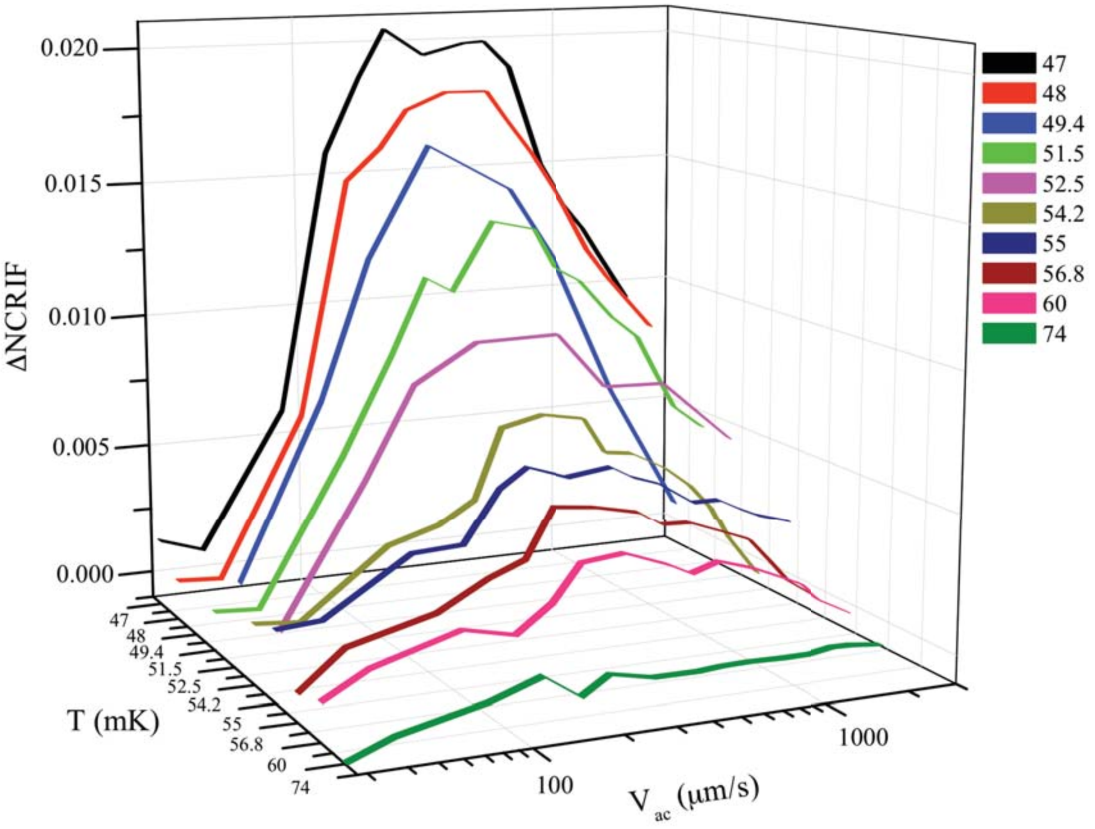
B set (V_{ac} sweep at constant T's)







T (mK)
48
51
54
55
56
60
74
90
100
120
170
200
300
0.06
0.04
0.02
0.00
NLRS
100
1000
V_{ac} (µm/s)
300
200
170
120
100
90
74
60
56
55
54
51
48
T (mK)



0.020
0.015
0.010
0.005
0.000
ΔNCRIF
47
48
49.4
51.5
52.5
54.2
55
56.8
60
74
T (mK)
100
1000
V_{ac} (μm/s)
47
48
49.4
51.5
52.5
54.2
55
56.8
60
74

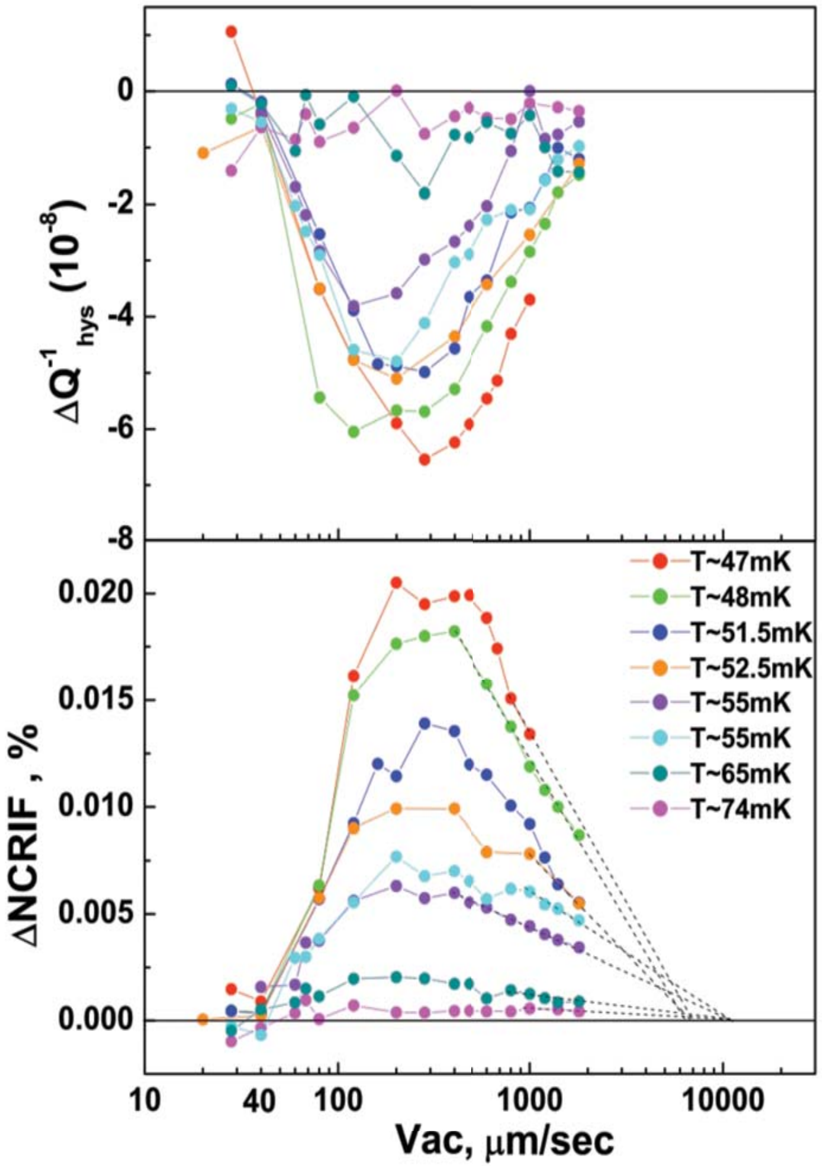
Hysteretic TO Responses T <~74mK

V_{ac} dependence of Dissipation and ΔNCRIF

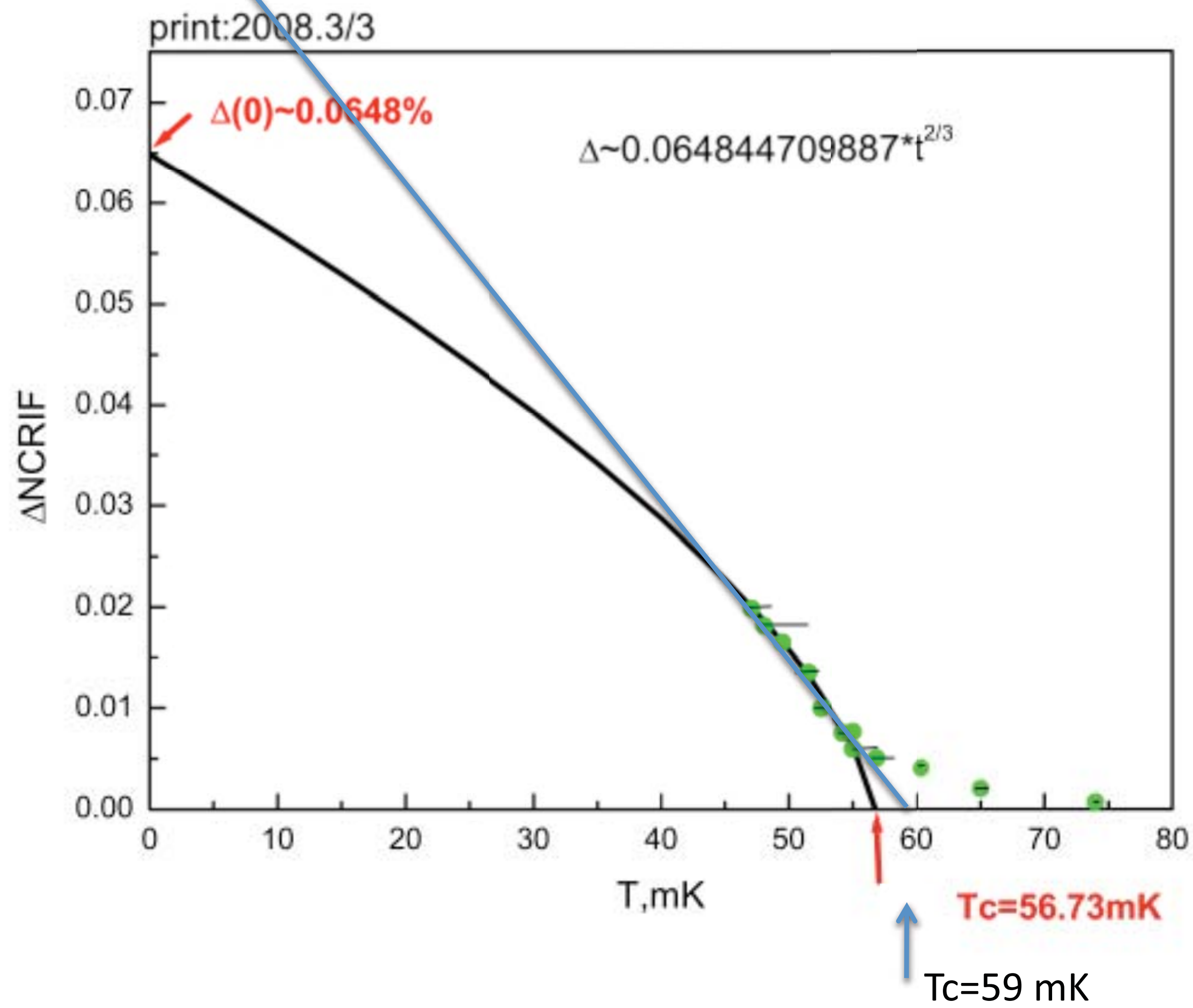
At $V_{ac} > \sim 40$ μm/s Hysteretic behavior appears.

At $V_{ac} > \sim 300$ μm/s, both quantities decreases their absolute values.

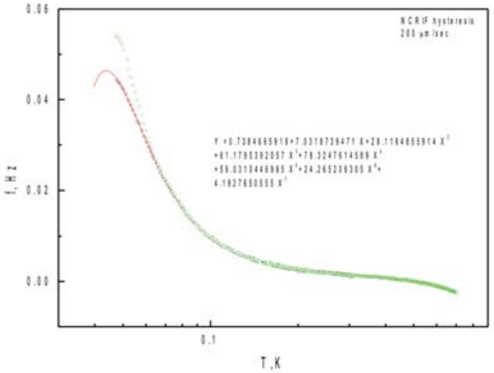
$V_{acc} \sim$ 7-10 mm/s where ΔNCRIF is depressed to 0.

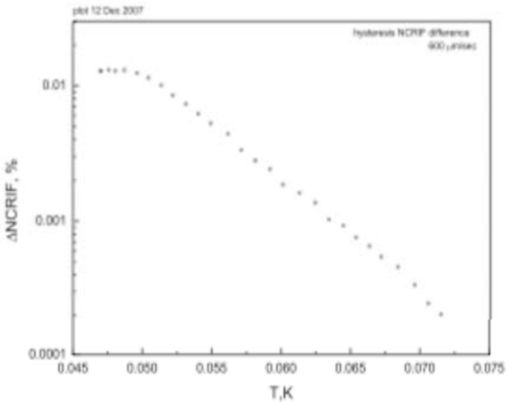


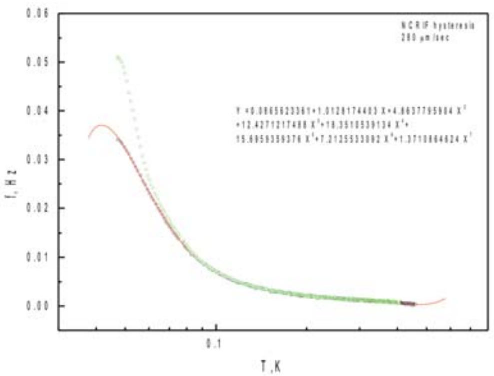
A sort of Spontaneously Induced Non-Linear Rotational Susceptibility(NLRS) = NCRI ?!!

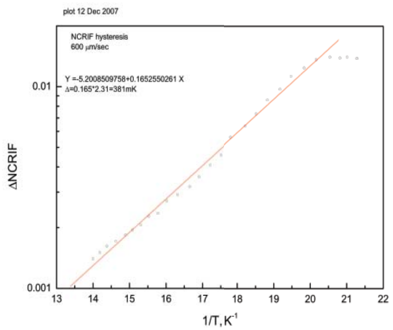


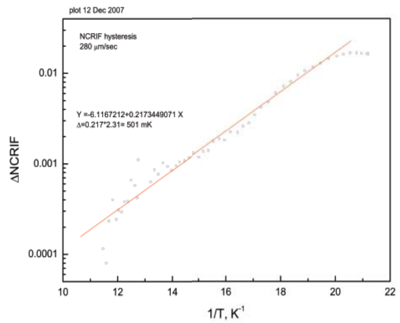
A set (T sweep under “equilibrium” and “non-equilibrium conditions)

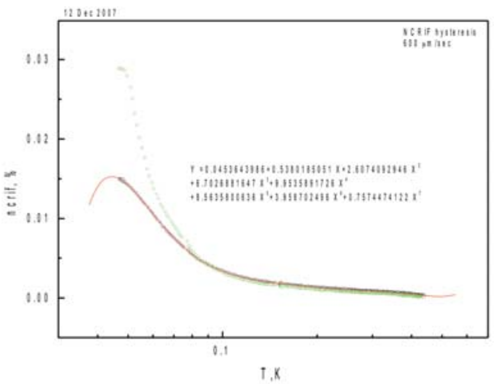


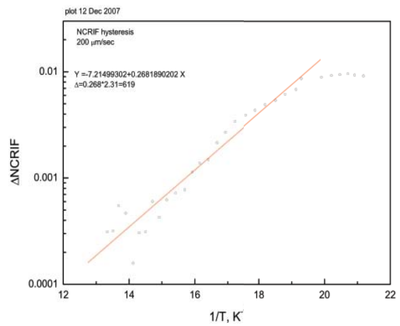


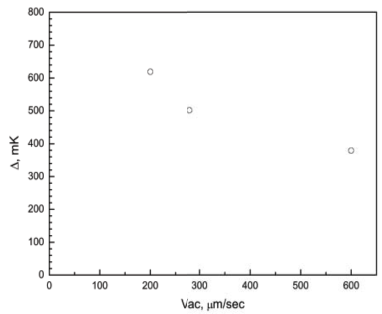




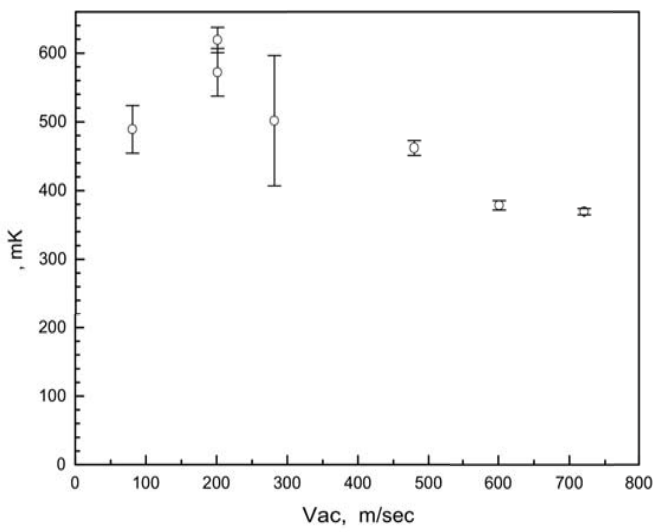


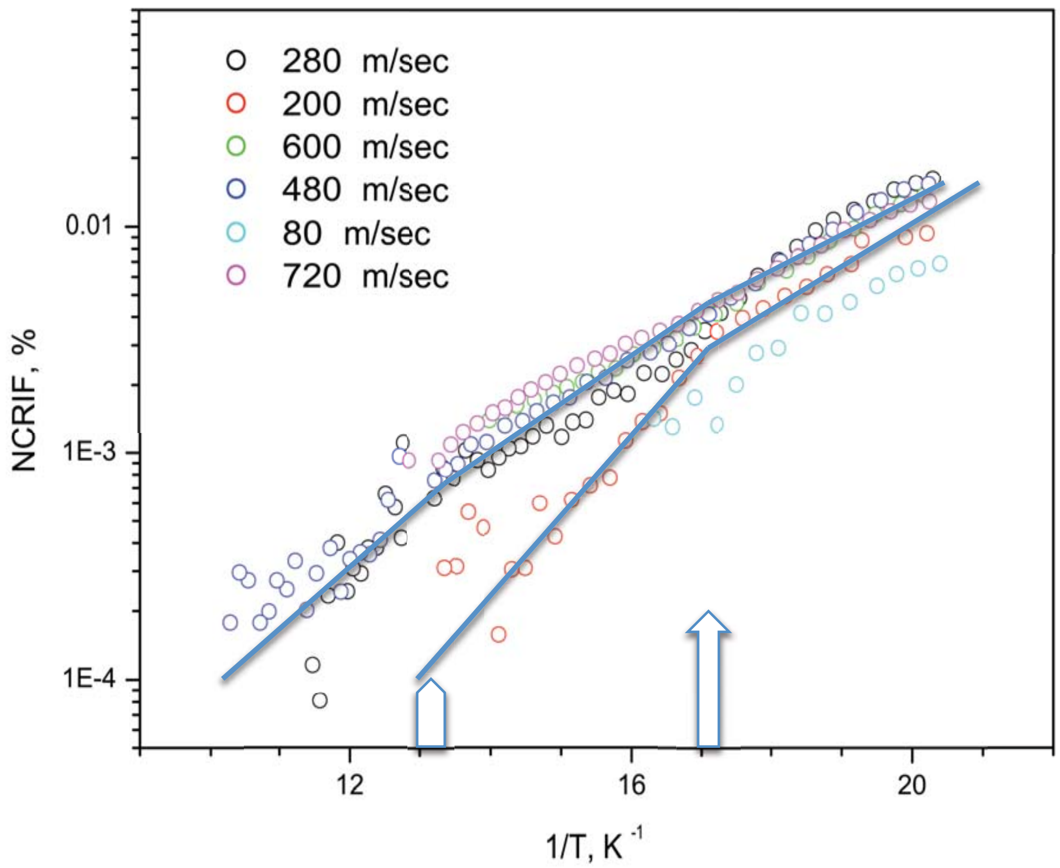






It looked as if it could be described by almost constant energy gap, but…





What does this result mean?

We may have observed the transition from vortex fluid state into Supersolid State!

But, it is strange.It looks as if it coexists with vortex fluid state!! NCRI components are additive!

Whay do we have this V_{ac} dependence?

There have been no theory which can describe experimental observations, so far.

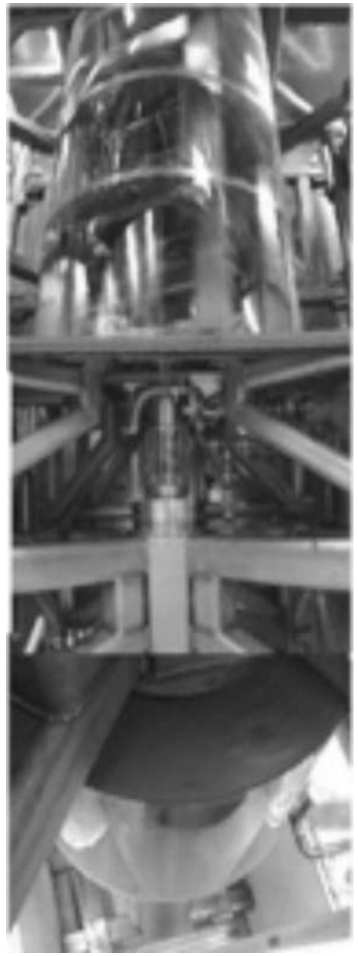
Summary of the present presentation-3

6]. Using one of our world record rotation cryostats, we studied vortex line penetration phenomena under DC rotation and TO techniques. We observed evidences of vortex line penetration below T_c, and we find the same/similar T dependence as $\boldsymbol{\rho_s(T)}$ from the hysteretic change.

7]. Remarkable observations: $\rho_s(T \rightarrow 0\ K) \sim NLRS(T \rightarrow 0\ K)$

25pWA-4: JPS 2008
Spring

Energy Dissipation Change of Solid ^{4}He under DC Rotation



東大物性研 Nobukata Shimizu

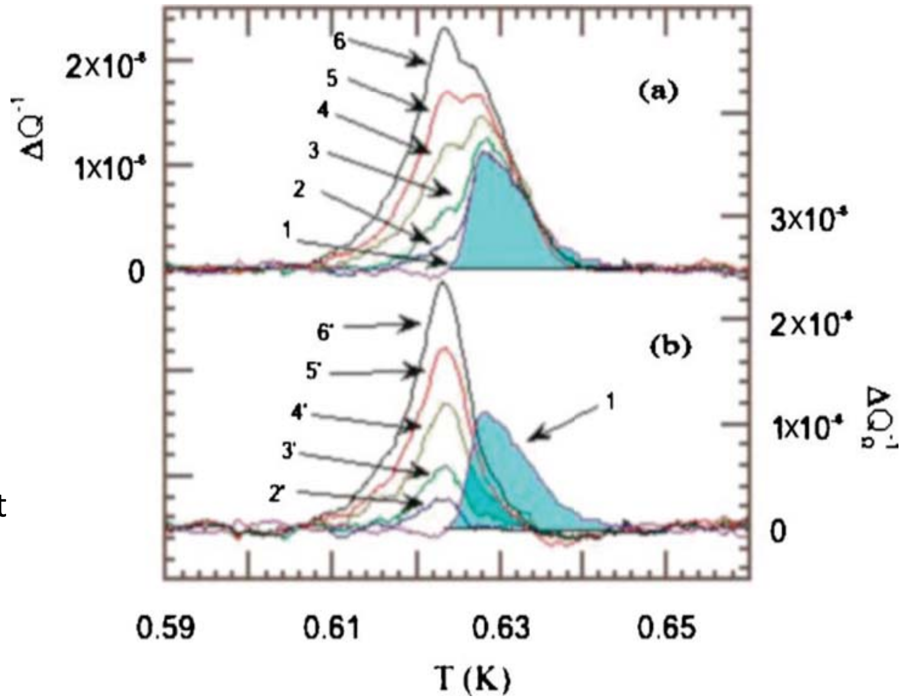
ISSP, U-Tokyo

Andrey Penzev、 Yoshinori Yasuta

Patryk Gumann、 Minoru Kubota

Introduction to DC Rotation Experiments
An example of 3D connected monolayer He film superfluid

- The figure on the right indicates torsional oscillator energy dissipation for a 3D connected monolayer ^{4}He film sample. The experiment was performed sweeping T very slowly under the given DC rotation for each number, 0 to 6.
- Energy dissipation under still condition appears because of dynamics of 2D vortex pairs and their desociation over a temperature range, where "Superfluid desnsity also changes drastically.
- Extra energy dissipation is observed at somewhat lower T than the static peak and the hight of the peak changes linearly with the DC rotation speed, or number of penetrating 3D vortex lines through the sample. It can be an evidence of the system nature of 3D superfluidity



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

1->0 rad/sec 2->0.79 rad/sec
3->1.57 rad/sec 4->3.14 rad/sec
5->4.71 rad/sec 6->6.28 rad/sec

Present experiment with solid He

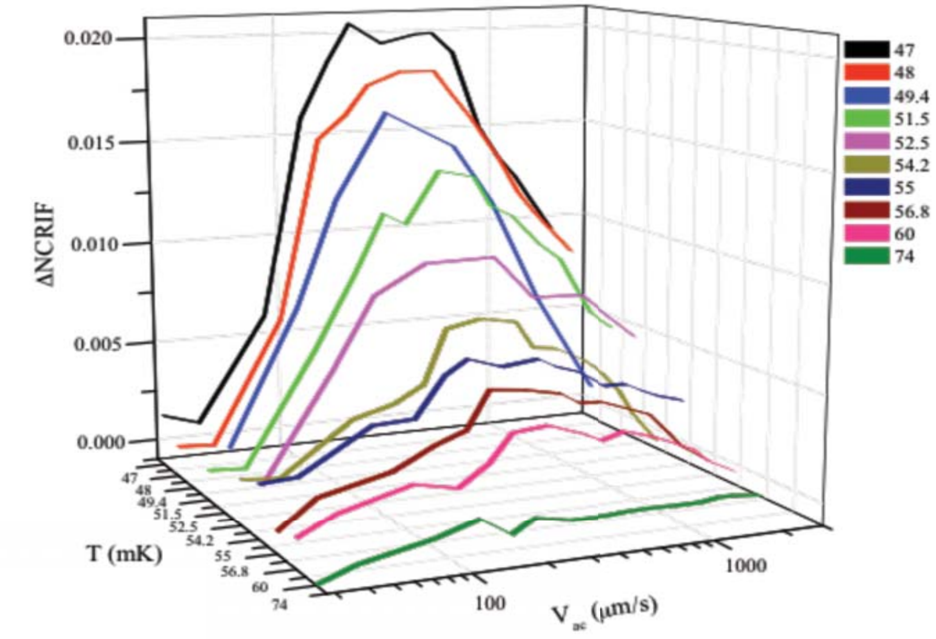
We had been studying solid He samples under DC rotation, but we could not find any significant change until December 2007, when we started to observe a "hysteretic behavior" by changing AC excitation from a small value to larger excitation at the lowest temperature.

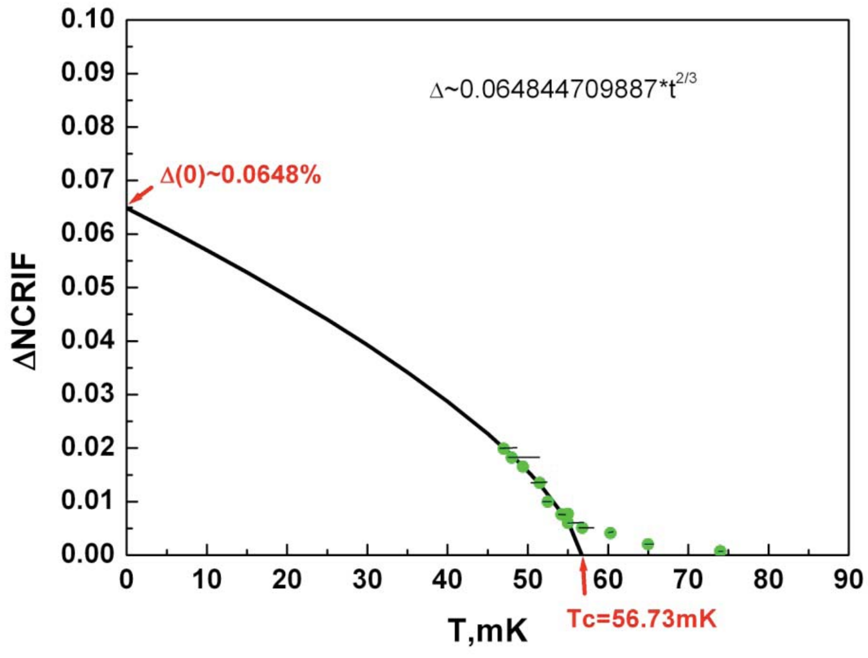
It may indicate some transition to Supersolid!!

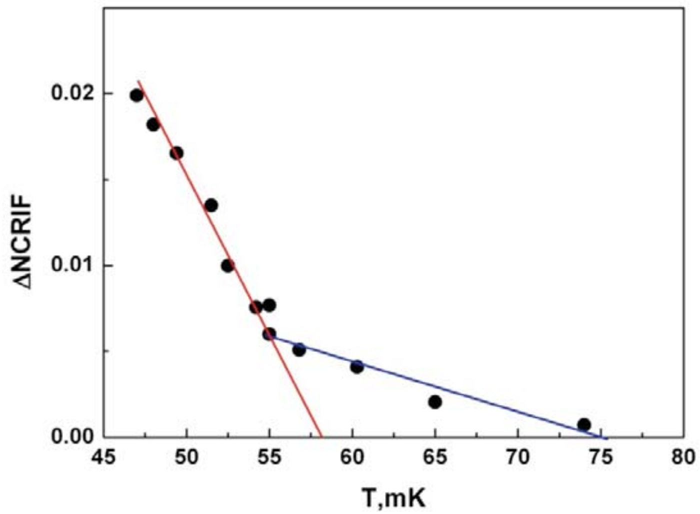
In order to confirm the 3D superfluidity we checked if 3D vortex lines are excited under rotation. The number of vorticies is expected to be proportional to rotational speed Ω and $\rho_s(T)$.

•At V_{ac}=200μm/sec the hysteretic ΔNCRIF has the maximum size.

We measure DC Rotation Effect under this AC excitation velocity first.







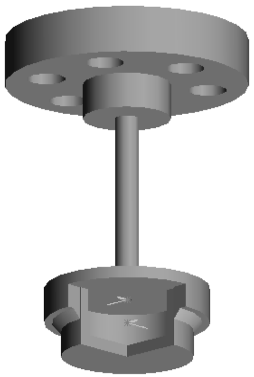
Details of Experiments

/secSolid He sample・・・blocked capillary method, same as other measurements, but seemingly quite reproducible.

P～49bar

T_{min}～48mK

DC Rotational Speed 0 to Ωmax＝0.2 rps=1.256 rad/sec



torsion rod･･･φ=2.2mm/φ=0.8 mm, L=15mm

Sample･･･ φ=10mm, h=4mm, V=314 mm^3

f = 1.00 kHz

Q ~1.5×10^6 (T <1 K)

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

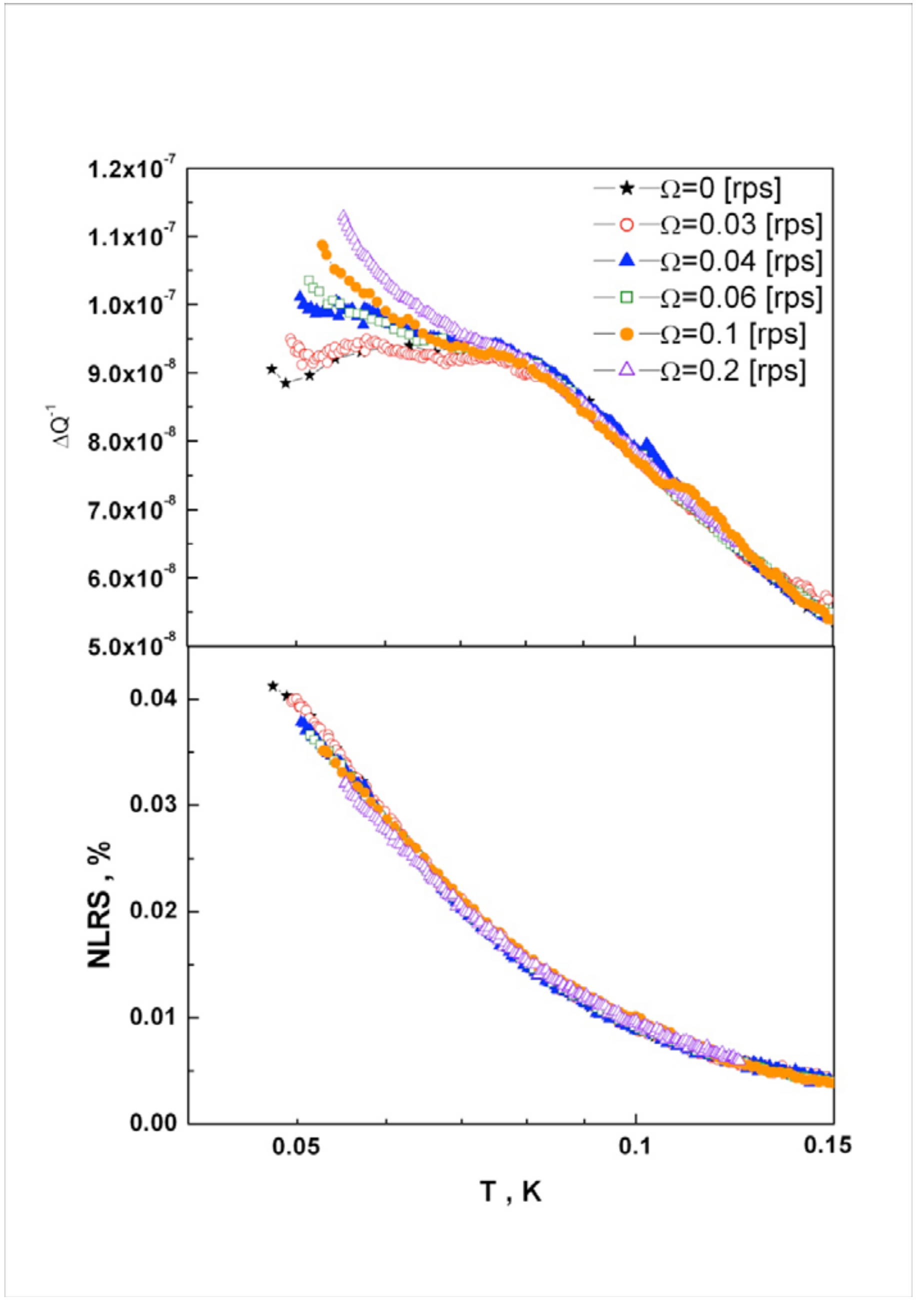
4. Measurement under T sweep（T=50mK→150mK / 3h, 9h,..)

5. Repeat with different DC Rotation Speeds

Results under DC Rotation

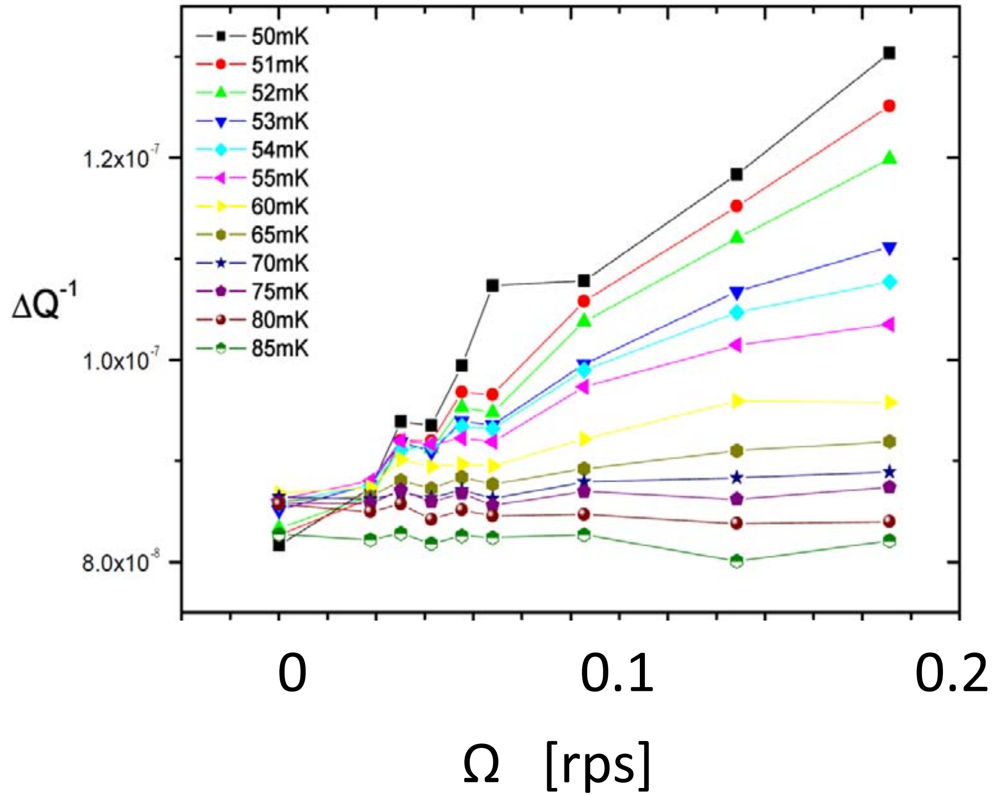
- Energy Dissipation below T ~80 mK Changes under DC Rotation: Faster Rotation →Larger Change !!

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



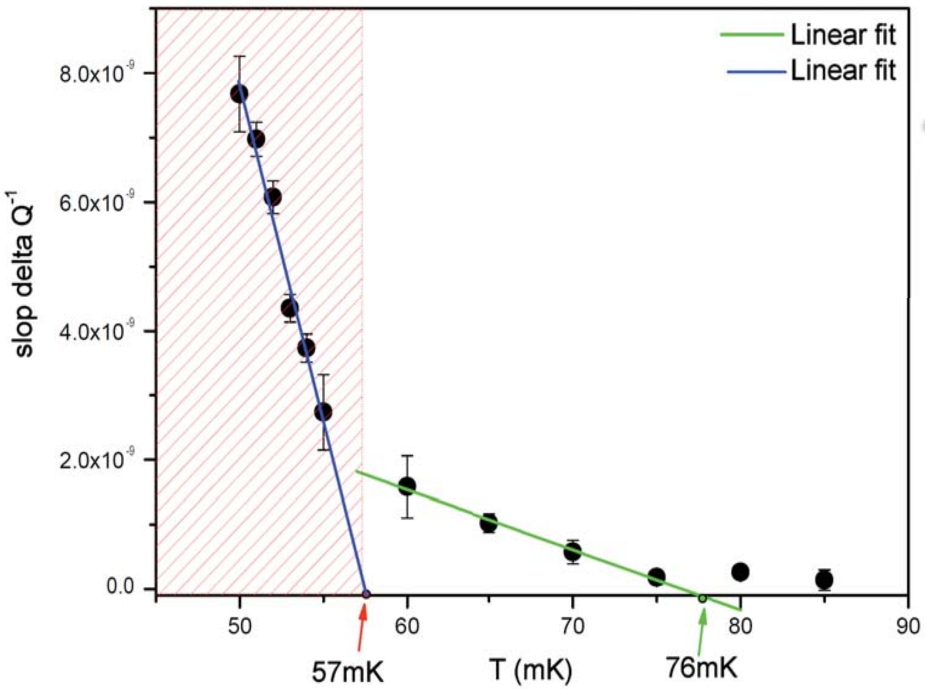
How does Energy Dissipation Change as DC Rotational Speed Ω? Linear Change!!

→ Vortex lines!!, Otherwise Ω^2 Dependence Should Occur!



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

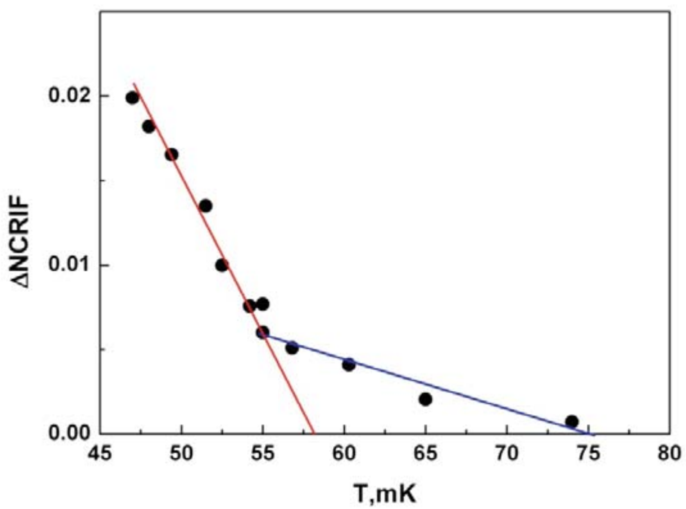
Transition Temperature(s) T_c(s) to Supersolid State and $\rho_s(T)$?



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!



What do these results mean?

1]. The quantity ΔNCRI, appeared as the change in the hysteretic behavior in the Period, really indicates "Supersolid Density, $\rho_s(T)$" of the solid He!!

2]. We have detected energy dissipation, which is proportional to DC rotational velocity Ω, and this linearity changes as a function of T, just in the same manner as the expected Supersolid ensity $\rho_s(T)$.

3]. Our observations are consistent with a scenario of Vortex Fluid at $T_c < T < T_o$, and its freezing into real Supersolid below T_c.

4]. The meaning of two characteristic temperature, ~57 mK and ~76 mK has to be clarified, probably in connection with sample crystaline orientations.

Vortex Fluid State and its Transition to Supersolid State has been found by the following people

Yoshinori Yasuta, Andriy Penzev, Nobutaka Shimizu Patryk Gumann and Minoru Kubota

Summary and Discussion

1]. What do we have now? Vortex Fluid state below T_o and 3D Supersolid below T_c for (49 bar) solid ^{4}He. The former is characterized by Non-linear rotational susceptibility: $\chi_R \sim F(1/T^2)$?? , and the latter starts below T_c with unique $\rho_s(T)$.

<u>Characteristic Temperatures:</u>

T_o=~500mK, T_c=~75mK, T_p~85mK, ($T_{p'}$~40 mK?),

<u>Characteristic Velocities:</u>

V_c=~ 1 cm/s, further study is needed to determine $V_c(T)$.

2]. Dislocation motion

Our dissipation data suggests that TO measurements does not involve activation of vortices in comparison with .

3]. Vortex physics ←→ dislocation dynamics

In any case we are discussing 1D topological defects. Some part is thermal and circulation is quantized in the former, but many features may be classical. Langevin function appears for classical dipole systems.

Discussion-continued

4]. Interesting Observations

A. $\rho_s(T \rightarrow 0K) \sim NLRS(T \rightarrow 0K)$!!??

B. Vortex fluid to 3D Supersolid a first order transition?

We observe NLRS and its hysteretic component coexist over a wide T range. David Huse points out that pinning effect may complicate the situation. But the observation A adds more for the first order transition to us.

C. Langevin function with $x=1/T^2$ is followed to our lowest T. This suggests really a thermal phenomenon of dipoles (vortex rings) is going on still to ~50 mK.

D. NCRI(T) has a unique temperature dependence: T linear change ~60 mK < T <~75 mK, then steeper increase towards lower T. T-linear change may indicate involvement of 1D.

E. Vortex fluid state has been found/discussed in the following systems:

UD Cuprate SC's, Organic SC's, Layered SC's, and newly found Fecompounds SC's, and all of them involve 2D subsystems. Solid He may also have 2D subsystem(s): basal plane, which can be there even in small pores of 20 Å or so.

5]. Remaining apparent question: What kind of thermal excitations are the **origin of the energy dissipation in TO** experiment?

Thank you for your patience
and thanks to organizers