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

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

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Summary of the present presentation

1]. Vortex fluid (VF) state was found below an Onset temperature $T_o \sim 500 \text{mK}$ 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($V_{ac}$)-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.

3a]. Transition from VF into a real 3D supersolid state was found for 49 bar sample below $T_c \sim 75 \text{mK}$ 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 $\sim 400 \text{mK}$.

4]. We propose supersolid density $\rho_s(T)$, which shows a unique T dependence: “T-linear” dependence for $\sim 60 \text{mK} < T < \sim 75 \text{mK}$ 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 $V_{ac} > \sim 40 \text{ μm/s}$ 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 $\rho_s(T)$ from the hysteretic change.

7]. Remarkable observations: $\rho_s(T \rightarrow 0 \text{ K}) \sim \text{NLRS}(T \rightarrow 0 \text{ K})$
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
- Quantized vortices in superfluidity

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

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: \( E_v/k_B \approx 10^8 \text{ K in cm}^3 \text{ volume or so.} \)

So it is impossible to induce vortex lines without DC rotation or flow velocity exceeding some \( V_c \).

\( E_v \) 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, \( E_v \approx 1\text{K} \). 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 \( T_{KT} \approx n_2 \). 2D quantized vortices are present at \( T > T_{KT} \) and paired at \( T < T_{KT} \), keeping macroscopic phase coherence: superflow is possible with \( V_c \approx 0 \), unless some pinning mechanism.

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. $T_{\text{BEC}} = 3.1K$ 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

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

Rapid Developments of Supersolid Study since 2004

Original discussion (1960’s and 1970) of Supersolid:
  BEC of vacancies or other imperfections in solid $^4\text{He}$ $\rho_\Delta/\rho \sim 10^{-6} \sim 10^{-4}$

Experimental Observations after 2004:
  Rather High $T_{\text{onset}}=T_o$: 0.2-0.5 K, Too high for known $n_v$, $n_i$ for BEC!!
  BEC cannot explain the observed $T_o \sim \alpha T_\lambda$ ($\alpha \sim 0.1\sim0.3$) of liq. $^4\text{He}$!!


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 these SC’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!?


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

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

Torsion oscillator with High Sensitivity and high stability

- Mixing chamber of a dilution refrigerator

- 1\textsuperscript{st} Vibration isolation Cu block

- 2\textsuperscript{nd} 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 $\Omega$. Its mechanism has been theoretically analyzed.

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

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.
DC flow experiments for a He monolayer film in 1 μm pore porous glass: $V_c (3D \rightarrow 2D \text{ superflow}) \sim \text{cm/s} \sim \text{h/mL}$

ISSP High Speed Rotating DR
1]. Vortex fluid (VF) state was found below an Onset temperature $T_0 \sim 500\text{mK}$ for samples at 32 and 49 bar. (Local condensate as well as quantized vortices start to appear below $T_0$.)

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 $\log(\text{Vac})$-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

<table>
<thead>
<tr>
<th>sample number</th>
<th>cell</th>
<th>$f_{res}$, Hz</th>
<th>initial pressure, bar</th>
<th>$T_m$, K</th>
<th>final pressure, bar</th>
<th>$\Delta f$, Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1st</td>
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<td>71.7</td>
<td>2.08</td>
<td>40</td>
<td>2.96</td>
</tr>
<tr>
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<td>1st</td>
<td>1499.6</td>
<td>90.5</td>
<td>–</td>
<td>$\approx$ 60</td>
<td>3.43</td>
</tr>
<tr>
<td>3</td>
<td>2nd</td>
<td>1534.7</td>
<td>74</td>
<td>2.15</td>
<td>43</td>
<td>3.76</td>
</tr>
</tbody>
</table>
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 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.
Vac 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/s and Vac > 500 μm/s. The slope for each range has a unique T dependence given in Fig. 4. Extrapolated lines are found to converge at a point for each Vac range. This point of convergence also determines the position of the zero in Fig. 1(b).
New measurements on Solid $^4\text{He}$ at 49 bar

We wanted more stable solid $^4\text{He}$ 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 dependence is more clearly observed for 49 bar solid $^4\text{He}$ 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.
Log$V_{ac}$ linear dependence is clear

This is indication of 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 $V_{ac}$ alinemenet 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!!

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

Actually there are some more interesting observations.
1/T² 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,
3a]. Transition from VF into a real 3D supersolid state was found for 49 bar sample below \( T_c = \sim 75 \text{ mK} \) 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 \( \sim 60 \text{ mK} < T < \sim 75 \text{ mK} \) 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 \( V_{ac} > \sim 40 \mu \text{m/s} \) excitation.
Hysteretic behavior by changing AC excitation

**General observation in the vortex fluid state of solid $^4$He:**
1. Smaller AC excitation produces larger amplitude signal as well as period shift. $\Leftarrow \Rightarrow$ quite opposite to usual excitations. Thermally excited random vortices exists already without external excitation. It lacks macro coherence.

**Hysteretic behavior starts below $T_c \approx 76$ mK in Real Supersolid state ($P=\approx 49$ bar)**

We have made two sets of measurements.

A set (T sweep under “equilibrium” and “non-equilibrium conditions)
1. Change AC excitation at $T > \approx 500$ mK, then cool down to $T_{\text{min}}$ and sweep up $T \Rightarrow$ “equilibrium” T sweep measurement.
2. Set AC excitation at 20 μm/s (0.5mV) then cool down to $T_{\text{min}}$ and change AC excitation at $T_{\text{min}}$ to measuring excitation $V_{\text{ac}}$, then sweep up. $\Rightarrow$ “non-equilibrium” T sweep measurements.

B set ($V_{\text{ac}}$ sweep at constant T’s)
1. Keep the sampe temperature constant and Sweep $V_{\text{ac}}$ slowly
Detailed Study of $V_{ac}$ Dependence and Appearance of Hysteretic behavior below $T_c$ !?!
B set \( (V_{ac} \text{ sweep at constant T’s}) \)
Hysteretic TO Responses T <~74mK

$V_{ac}$ dependence of Dissipation and $\Delta NCRIF$

At $V_{ac} > ~40 \ \mu m/s$
Hysteretic behavior appears.

At $V_{ac} > ~300 \ \mu m/s$, both quantities decreases their absolute values.

$V_{acc} \sim 7-10 \ mm/s$ where $\Delta NCRIF$ 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!

Why do we have this $V_{ac}$ dependence?

There have been no theory which can describe experimental observations, so far.
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 \( \rho_s(T) \) from the hysteretic change.

7]. Remarkable observations: \( \rho_s(T \to 0 \text{ K}) \sim \text{NLRS}(T \to 0 \text{ K}) \)
Energy Dissipation Change of Solid $^4$He under DC Rotation

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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 height 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


1$\rightarrow$0 rad/sec  2$\rightarrow$0.79 rad/sec
3$\rightarrow$1.57 rad/sec  4$\rightarrow$3.14 rad/sec
5$\rightarrow$4.71 rad/sec  6$\rightarrow$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 $\Omega$ and $\rho_s(T)$. 
• At $V_{ac}=200\mu m/\text{sec}$ the hysteretic $\Delta NCRIF$ has the maximum size.

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

Solid He sample · · · blocked capillary method, same as other measurements, but seemingly quite reproducible.

\[
\begin{align*}
P & \approx 49 \text{ bar} \\
T_{\text{min}} & \approx 48 \text{ mK} \\
\text{DC Rotational Speed} & \text{ 0 to } \Omega_{\text{max}} = 0.2 \text{ rps} = 1.256 \text{ rad/sec} \\
\text{torsion rod} & \cdot \cdot \cdot \varphi = 2.2 \text{ mm} / \varphi = 0.8 \text{ mm}, L = 15 \text{ mm} \\
\text{Sample} & \cdot \cdot \cdot \varphi = 10 \text{ mm}, h = 4 \text{ mm}, V = 314 \text{ mm}^3 \\

f & = 1.00 \text{ kHz} \\
Q & \approx 1.5 \times 10^6 \ (T < 1 \text{ K})
\end{align*}
\]
Experimental Procedure of Measurement under DC Rotation

1. At high Temperature (∼0.5 K) Change AC excitation to \( V_{ac}=200 \ \mu m/sec \) (Equilibrium)

2. DC Rotation Start (\( \Omega=0 \rightarrow 0.2 \ \text{rps} \))

3. Cooling down

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

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 \( \Omega \)? Linear Change!!

→ Vortex lines!!, Otherwise \( \Omega^2 \) Dependence Should Occur!

If Dissipation \( \Delta Q^{-1} \) 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, 
$\sim 57$ mK, $\sim 76$ mK

Above graph looks just the same as $\Delta$NCRIF, observation in the hysteretic behavior vs $T$!
What do these results mean?

1]. The quantity $\Delta$NCRI, 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 $\Omega$, 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, $\sim 57$ mK and $\sim 76$ mK has to be clarified, probably in connection with sample crystalline 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 $\rho_s(T)$.

Characteristic Temperatures:

$T_o \approx 500\text{mK}$, $T_c \approx 75\text{mK}$, $T_p \approx 85\text{mK}$, ($T_p', \approx 40\text{ mK}$?),

Characteristic Velocities:

$V_c \approx 1\text{ cm/s}$, 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 $\leftrightarrow$ 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. $\rho_s(T\rightarrow0K) \sim$ NLRS($T\rightarrow0K$) ??!

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