Summary and View on Anisotropic Superfluid ^{3}He

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Out line of talk

Purpose of project

Summary

1. Vortex in rotating superfluid ^3He
2. Impurity effect by aerogel on superfluid ^3He
   - 2-1 NMR experiment
   - 2-2 fourth sound experiment

View

1. Intrinsic angular momentum (IAM) problem
2. Orbital dynamics accompanied with the angular momentum vector motion
3. Odd frequency pairing issue
4. In restricted geometry,
   Half Quantized Vortex, Majorana particle, Vortex core structure and core transition, etc.

Theoretical point of view

Member of Group

K. Nagai

Inhomogeneous States in Superfluid ^{3}He Film

Superfluid state in film of liquid 3He is intrinsically inhomogeneous owing to the presence of boundaries. In particular near the A-B transition, new types of inhomogeneous states are expected.

M. Kubota

Textures and Vortices in a p-Wave Superfluid, ^{3}He-A in a Narrow Cylinder: Experimental Study Progress

In a narrow cylinder tube, two types of vortex states in superfluid A-phase have been observed, Mermin-Ho texture and disgyration texture.

Purpose of this project

We will study new quantum phenomena on anisotropic superfluid ^{3}He and understand the order parameter itself and the motion of the order parameter and also the behavior of quantum fluid clearly

by the experimental studies on

(1) (1-D defect of) quantum vortex in rotating superfluid ^{3}He

(2) superfluid ^{3}He in aerogel

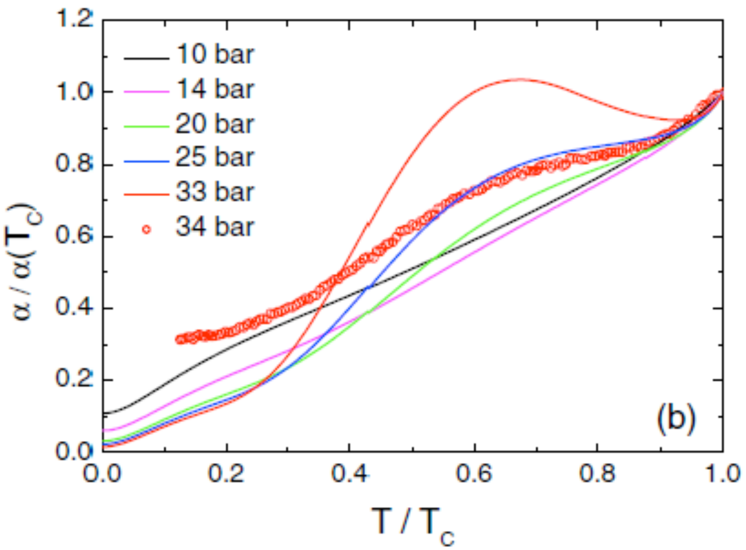
and by the theoretical study on

(3) the macroscopic quantum system of superfluid ^{3}He,
the proximity effect, boundary induced new state

Theory Group at Hiroshima University

(K. Nagai, S. Higashitani & Y. Nagato)

1. Ultrasound Absorption in Superfluid ^{3}He in Aerogel



Phys. Rev. Lett. 98, 225301(2007) , in collaboration with Frorida Group

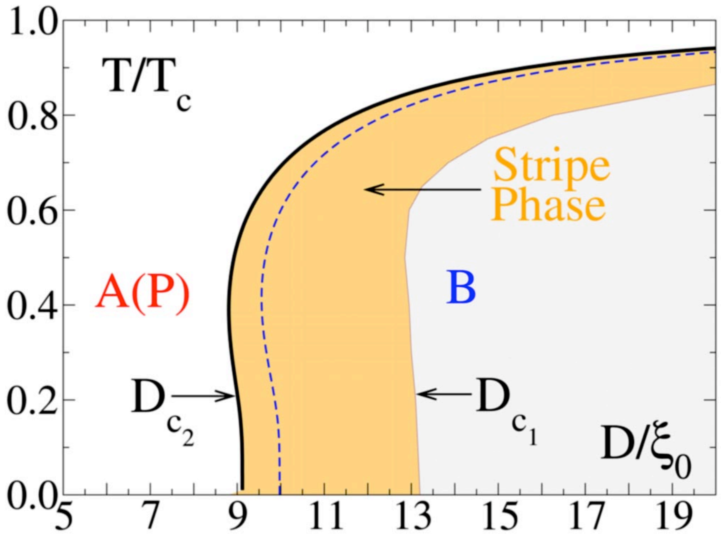
2. A New Anomaly in Transverse Acoustic Impedance of Superfluid ^{3}He-B with a Wall coated by several Layers of ^{4}He

In collaboration with TIT group

3. Properties of Superfluid ^{3}He Film (Work to be continued)

i) Strong Anisotropy in Magnetic Susceptibility
Caused by Surface Bound States

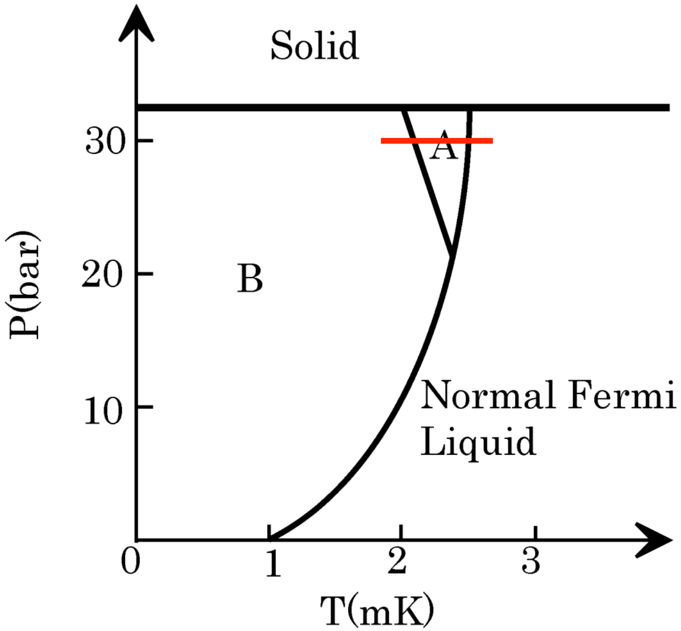
ii) Inhomogeneous States in Film
a. FFLO like State Under Magnetic Field
b. Stripe Phase proposed by Vorontsov and Sauls



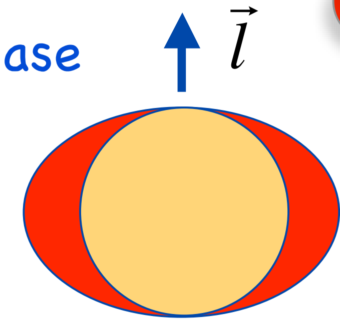
We are interested in the nature of phase transition at D_{c1}

We expect that the phase transition is of first order, or the B phase in film is always a stripe phase.
We try to solve this problem using GL equation.

1. Vortex in rotating superfluid ^{3}He



Order parameter of A phase



$$d_{\mu j} = \hat{\mathbf{d}}_{\mu} \left(\hat{\mathbf{m}} + i\hat{\mathbf{n}} \right)_j$$

$\hat{\mathbf{d}}$: *spin space*

$\hat{\mathbf{m}}, \hat{\mathbf{n}} : \hat{\mathbf{l}} = \hat{\mathbf{m}} \times \hat{\mathbf{n}}$: *real space*

Order parameter of B phase

$$d_{\mu j} = R_{\mu j}(\hat{\mathbf{n}}, \theta)$$

Relative rotation between spin and angular spaces

- broken spin-orbit symmetry
- dipole-dipole interaction

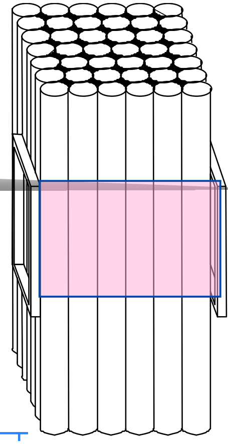
→ large internal field is induced

↓

frequency shift in NMR

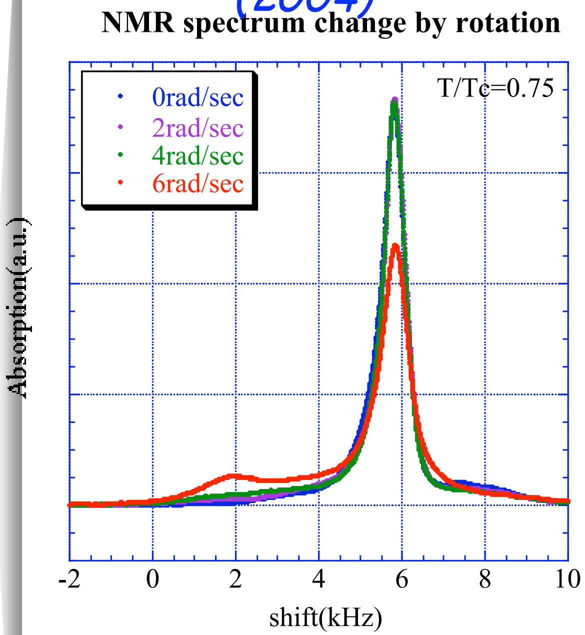
Anisotropic order parameter changes its direction spatially (texture) → Quantum vortex without singularity in A phase

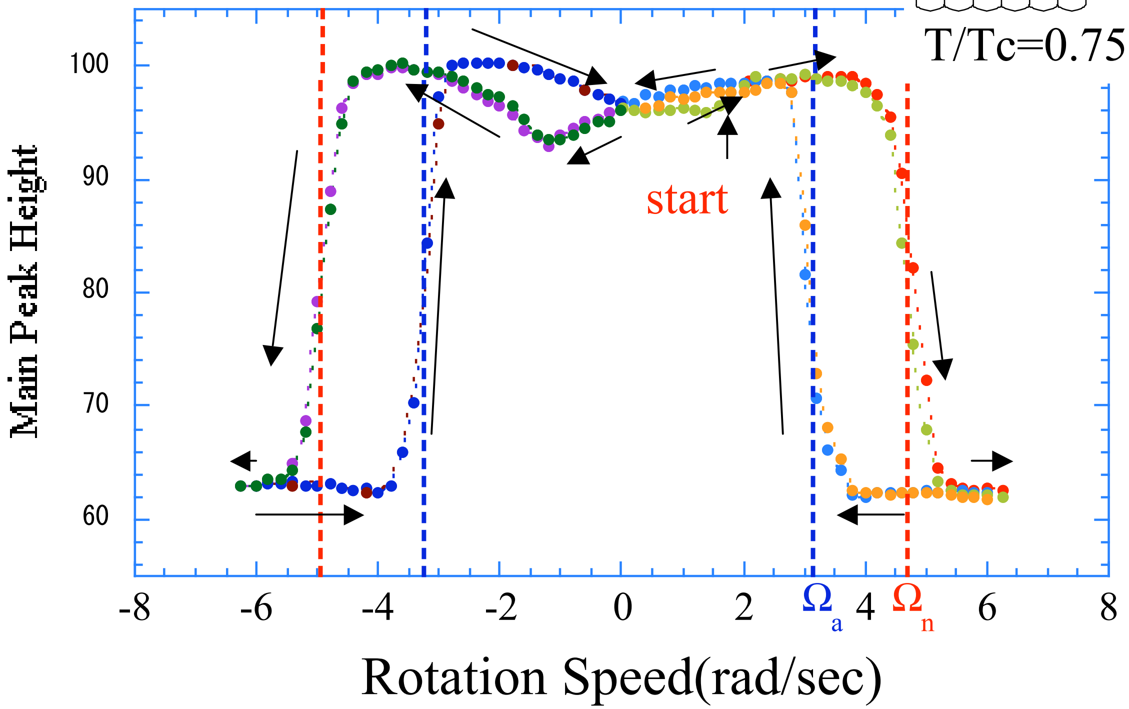
- Change of the main peak by rotation in 200μm diameter



Under rotation up to the maximum speed of 2π rad/sec

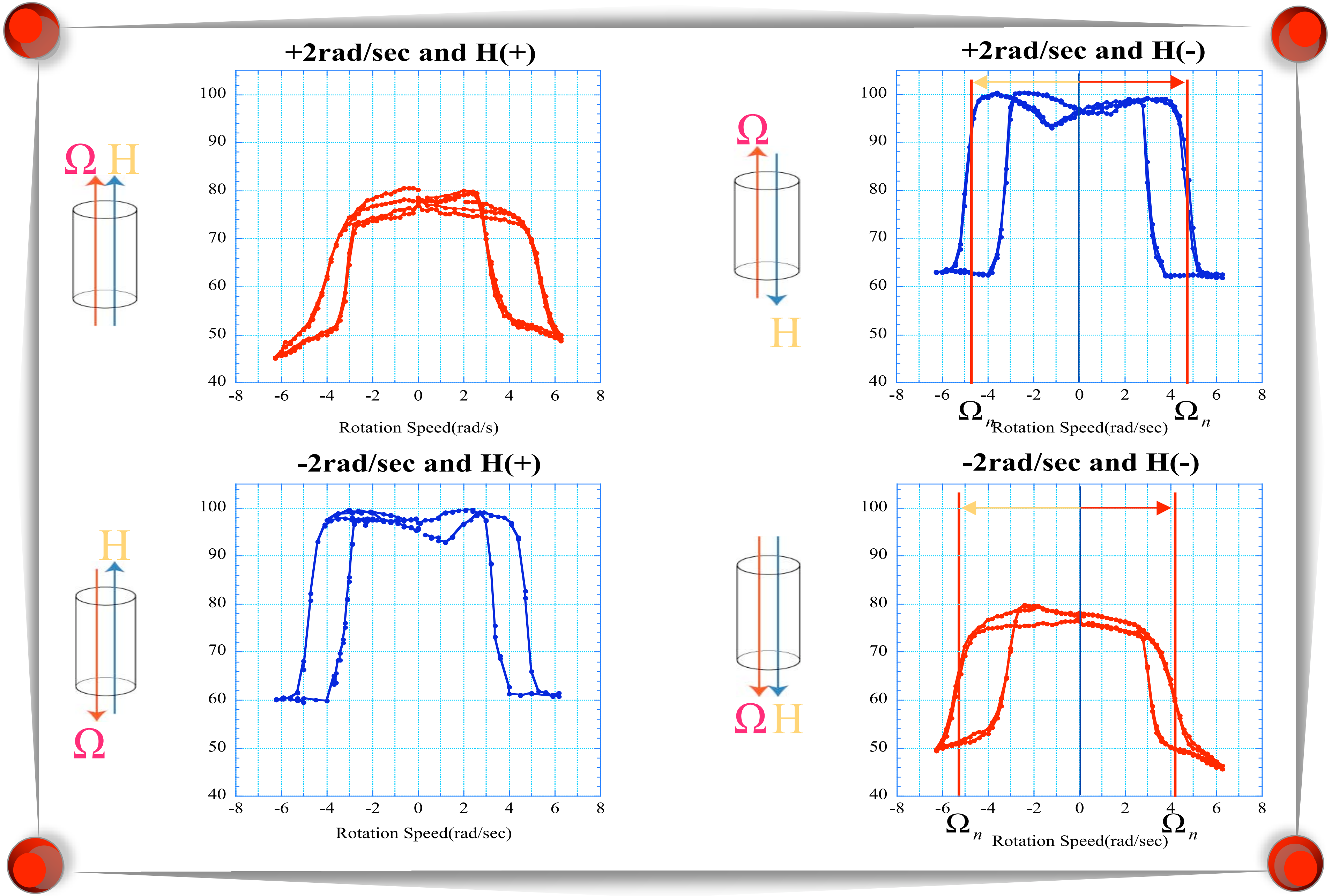
R.Ishiguro et al. Phys. Rev. Lett. 93 125301 (2004)





- Mermin-Ho texture (vortex) and one CUV
  "asymmetry behavior near 0 rad/sec"
- broad critical rotation speed for vortex moving in and out

• Memory effect & Gyro-magnetic effect



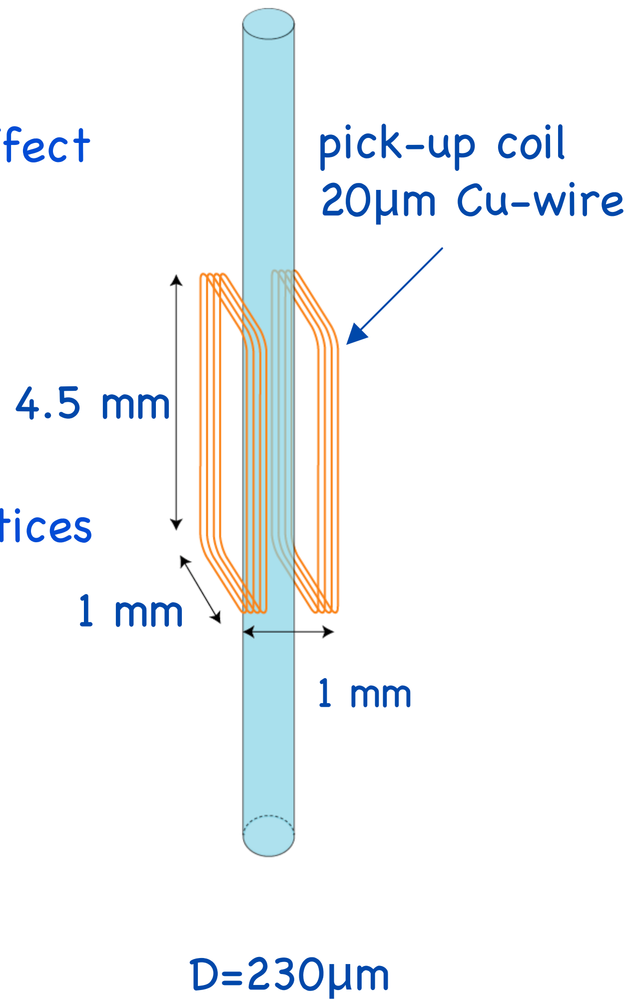
• Why one cylinder ?

1. Not averaged signal must have the intrinsic properties.

- may observe the sharp critical angular velocity
- must guarantee one kind of texture
- can check Gyro-magnetic effect and memory effect systematically

2. Dynamics of vortex can be observed.

- can directly observe a reconnection of two vortices
- can measure invading velocity into cylinder



- Change of NMR spectrum by rotation in single cylinder of 230μm diameter

- At 12 rad/s, intensity of the satellite (spin wave) signal becomes larger than that of the main signal
- Critical angular velocity of rotation, at which the CUV vortecies invade into single cylinder, is explained well by theoretical calculation by T. Takagi

Mermin-Ho (p=1)

$\Omega \approx 4 \ rad/s$

M-H + CUV (p=3)

$\Omega \approx 7 \ rad/s$

M-H + 2*CUV (p=5)

$\Omega \approx 9 \ rad/s$

M-H + 3*CUV (p=7)

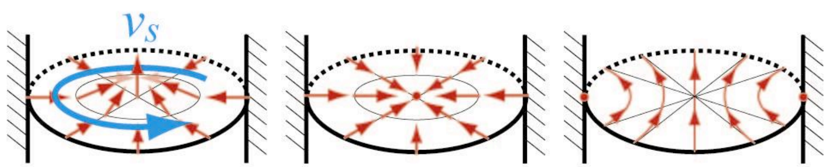
$\Omega \approx 11 \ rad/s$

M-H + 3*CUV (p=7)

- **We observed a textual transition at T/Tc>0.9 by rotation**

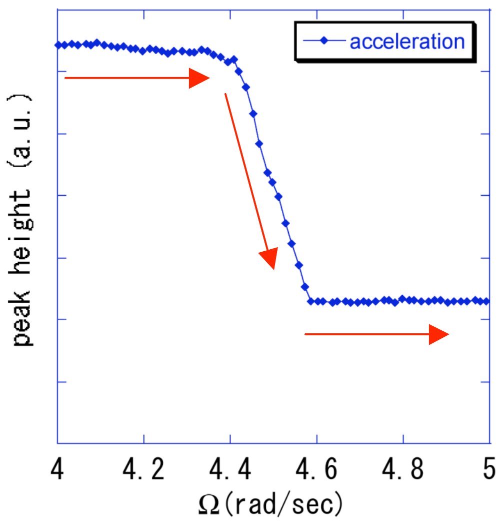
- There is a change in NMR signal before 1st CUV invades above 0.9Tc.
- With increasing angular velocity, the intensity of the main signal becomes small a bit around 1 rad/s.
- A theoretical calculation by Okayama univ. group pointed out that there happens the textural transition from the radial disgyration to Mermin-Ho texture at that angular velocity.

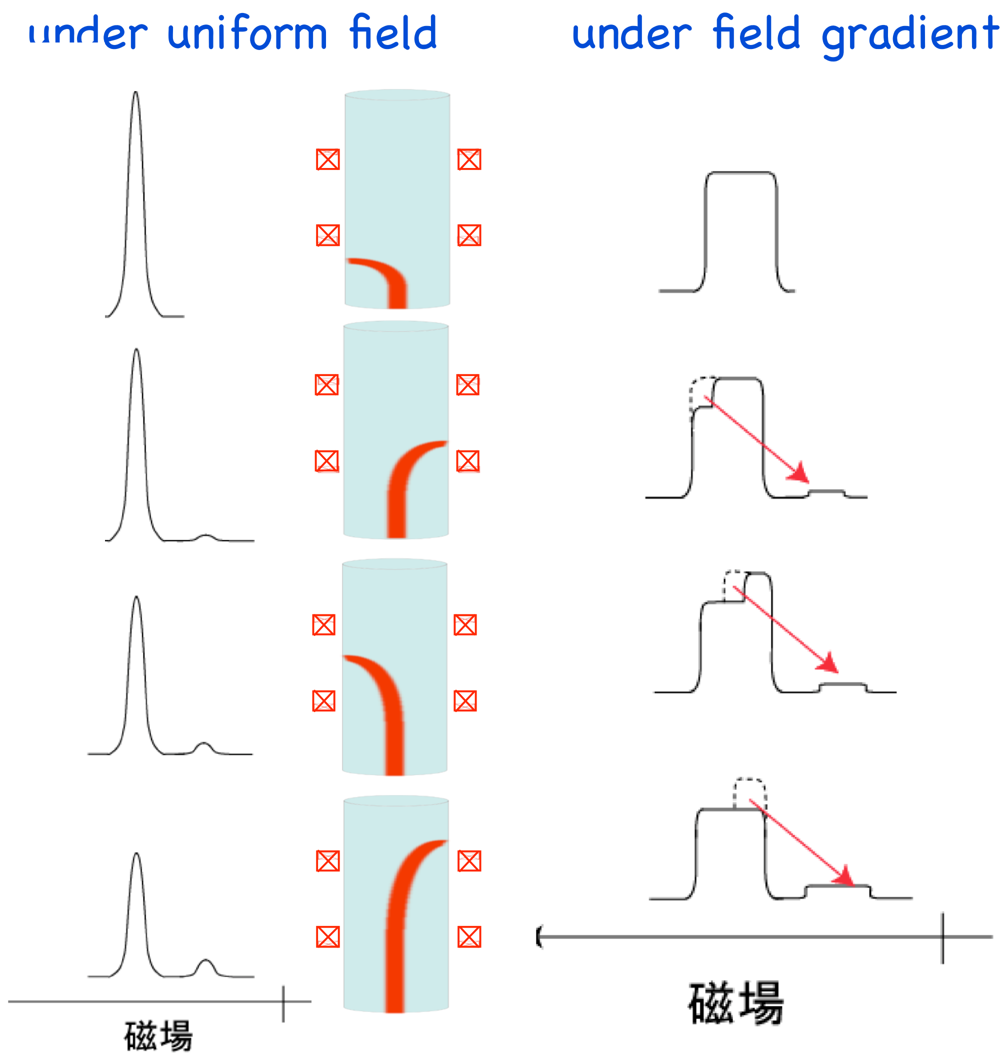
- We observed this phenomena with both 100 and 230 μm diameter cylinders.
- Such transition is easily observed by rotation but hard to observe it by changing temperature.
- At 0.82Tc, Mermin-Ho texture appears by rotation from the R-D texture but M-H texture is stable at rest. There is a metastable state.
- This M-H texture is stable even at 0.98 Tc with warming.



Mermin-Ho n=1 Radial Digyration n=0 Pan-Am n=0

• observation of the invading vortex by MRI technique



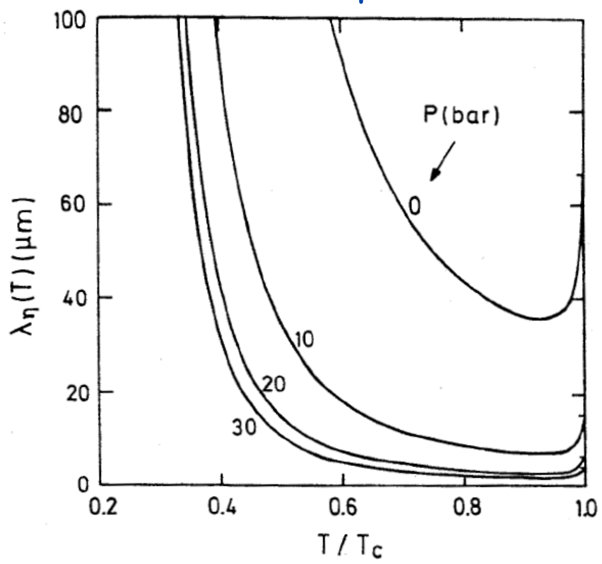


2. Impurity effect by aerogel on superfluid ^{3}He

- Suppression of superfluidity and mean free path by aerogel

superfluid density, energy gap, dipole frequency are also suppressed

bulk liquid

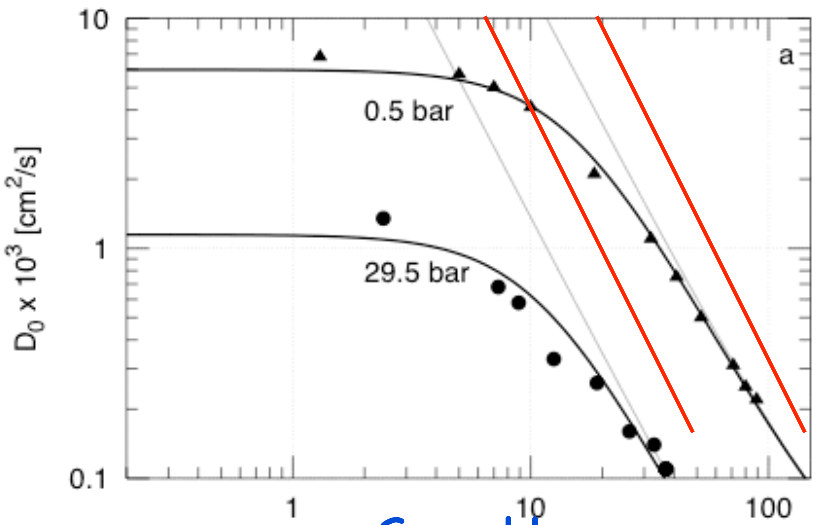


65 μm

7 μm

from D. Einzel

Transport property
spin diffusion of normal liquid ^{3}He in aerogel by NMR method



Grenoble group

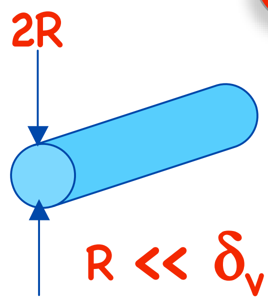
$$D = \frac{1}{3} v_F^2 (1 + F_0^a) \tau_D = \frac{1}{3} v_F (1 + F_0^a) l_{mfp} \propto T^{-2}$$

$$l_{mfp} = v_F \tau_D, \qquad \tau_D \propto T^{-2}$$ **(bulk liquid)**

• Superfluid density and Q^{-1} of the fourth sound in pores

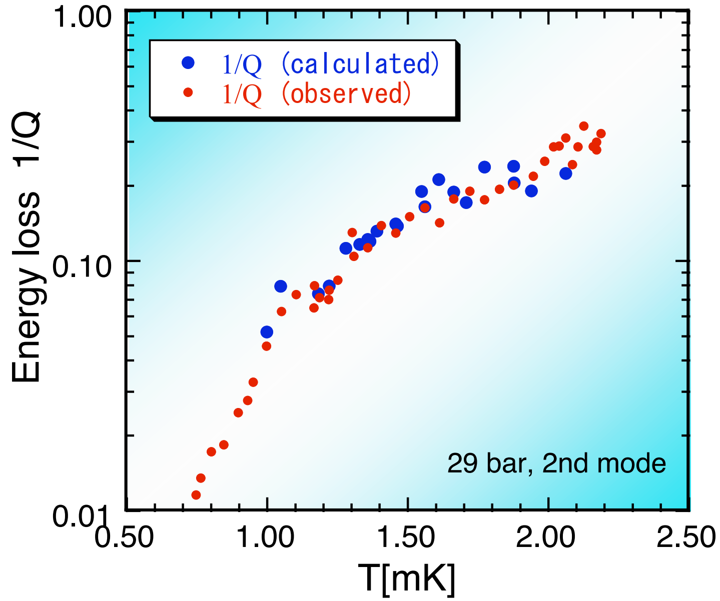
In fourth sound experiment, a small viscous motion of normal component causes energy loss.

$$\frac{\rho_s}{\rho} = \left(\frac{C_4}{C_1}\right)^2, \quad Q^{-1} = \frac{\rho_n}{4\rho_s}\left(\frac{R}{\delta_v}\right)^2\left(1+\frac{4\zeta}{R}\right) = \frac{\rho_n^2 R^2 \omega}{8\rho_s \eta}\left(1+\frac{4\zeta}{R}\right)$$



No aerogel

H.H.Jensen, , , K.Nagai et al. JLTP **51**, 81 (1981)



Y.Nago *et al.* JLTP 150 476 (2008)

What happens in the fourth sound experiments by introducing aerogel ?

⬇

Suppressions of viscosity and superfluid component may cause large energy loss ?!?!

- Superfluid density and Q^{-1} of the fourth sound in aerogel

Q^{-1} in aerogel becomes small !!
Viscous motion of the normal component seems to disappear in aerogel !!
What happens ?

Friction model

$$frictional\ force = -\frac{\rho_n}{\tau_f}(\mathbf{v}_n - \mathbf{v}_a)$$

$$Q^{-1} = \frac{\rho_n}{\rho_s}\omega\tau_f$$

S.Higashitani et al. JLTP 138,147(2005)

• basic idea of frictional model

Change of velocity profile

Hagen-Poiseuille like flow in pores

$$R << \delta_V = \sqrt{\frac{2\eta}{\rho\omega}}$$

$$\eta(T) = \frac{1}{5}\rho_0^n(T)V_{rms}^2(T)\tau_\eta(T)$$
$$= \frac{1}{5}\rho_0^n(T)V_{rms}(T)\lambda_\eta(T)$$

in Fermi liquid model

Drude like flow in aerogel

$$R >> \delta_V = \sqrt{\frac{2\eta\tau_f}{\rho}} \approx \sqrt{v_F^2\tau_a\tau_f} = \sqrt{Lv_F\tau_f}$$

Frictional force between the normal component and aerogel determines viscous penetration depth and clamps the normal component tightly

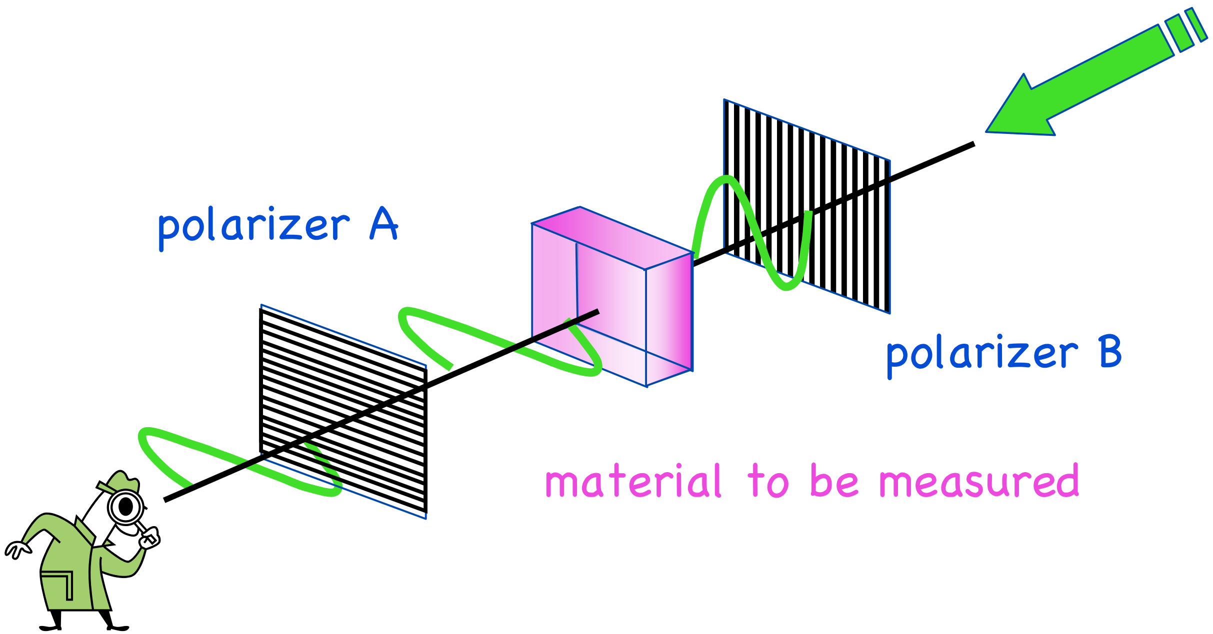
Normalized τ_f using the maximum(peak) value is very similar to each other, when we compare τ_f at several pressures.

Normalized τ_f may have the same coherence length dependence as Tc suppression.

- measurement of anisotropy in aerogel

Aerogel Birefringence Experiments

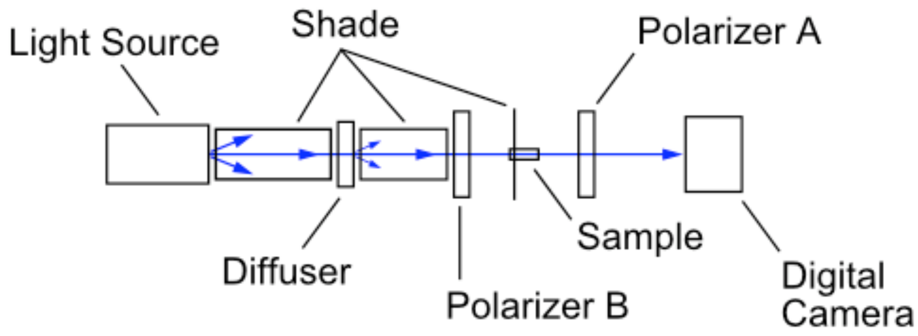
simple experiments based on anisotropic dielectric constant



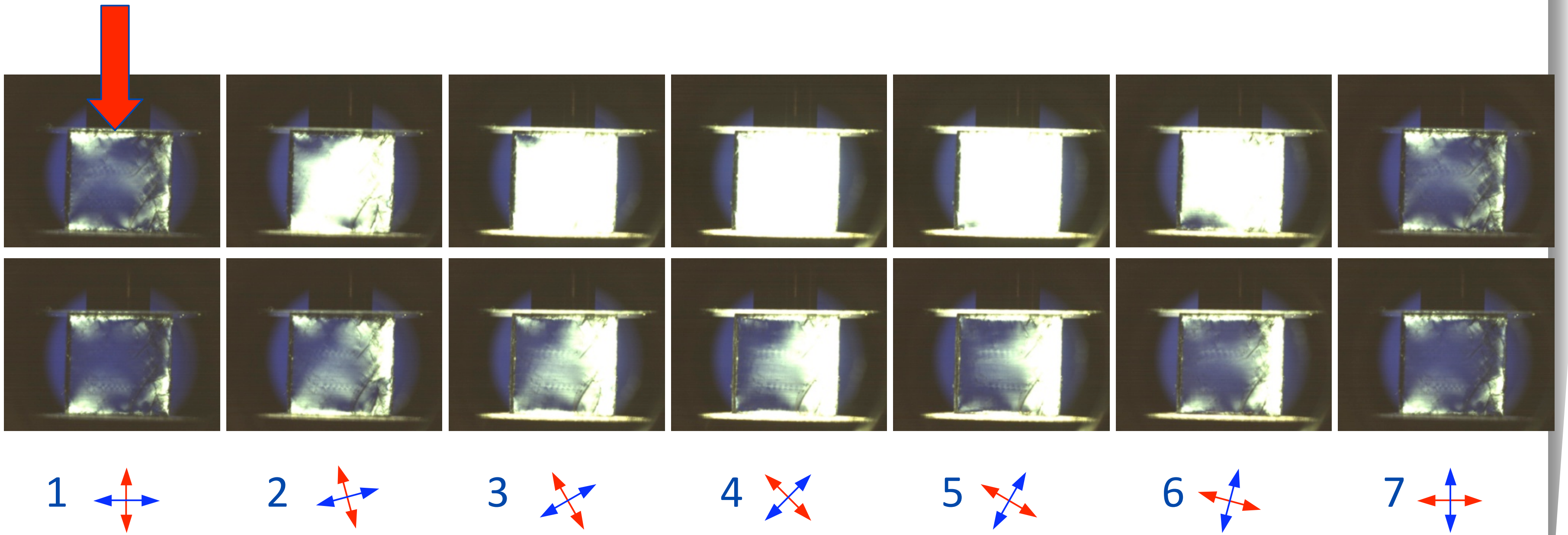
if an optical anisotropic material set between two polarizers that can change the polarization plane, we can see light through polarizer A.

- result on test piece of cubic shape

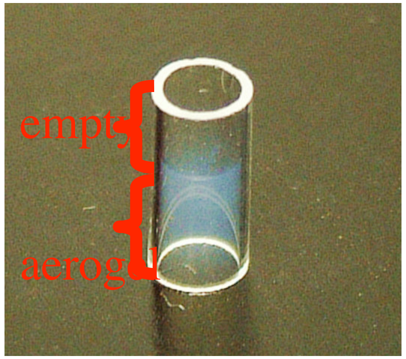
nearly Cubic of 97 % porosity
aerogel about 10 x 10 x 10 mm^3

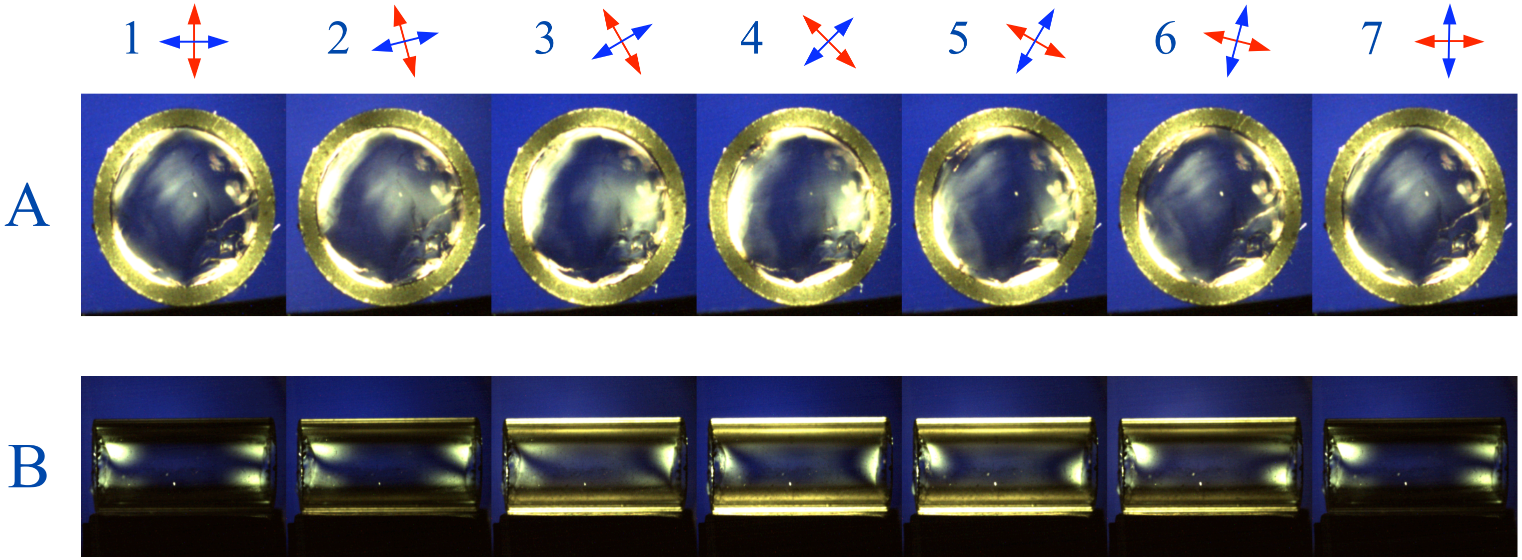


strain about 2%



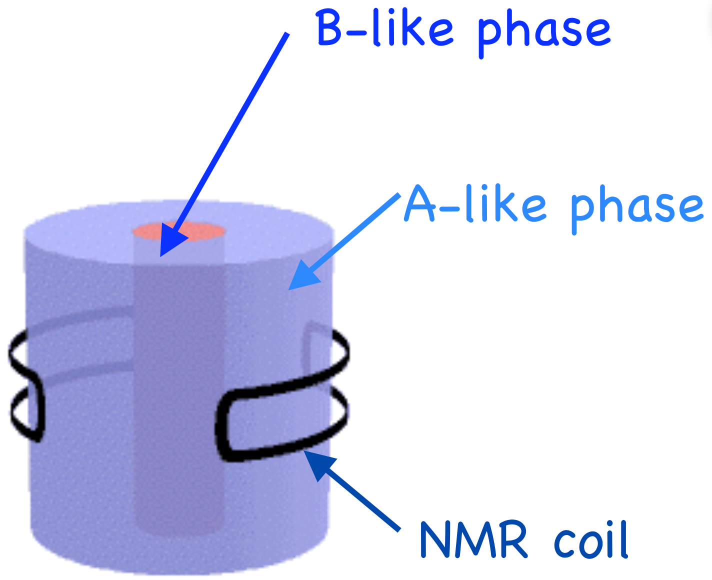
lower images without strain





This aerogel is now set in the cryostat at Kyot univ, for observing the coexisting state of A-like phase and B-like phase.

- MRI of the A-B coexisting state in collaboration with Kyoto group



We have observed the global phase separation of A-like phase and B-like phase in aerogle when both phases are coexiting.

Now we get the preliminary result of Magnetic Resonance Image showing the phase separation as we expected like the above figure.

View on superfluid ^{3}He

1. Intrinsic angular momentum (IAM) problem

2. Orbital dynamics accompanied with the angular momentum vector motion

3. Odd frequency pairing issue
   susceptibility measurement of ^{3}He may verify odd frequency paring
   in aerogel
   aerogel acts as dirty metal in S-N junction of metal

4. In restricted geometry,
   Half Quantized Vortex,
   Majorana particle,
   Vortex core structure and core transition, etc.