One-Dimensional Phonon State and Superfluidity of ^{4}He Fluid Nanotubes

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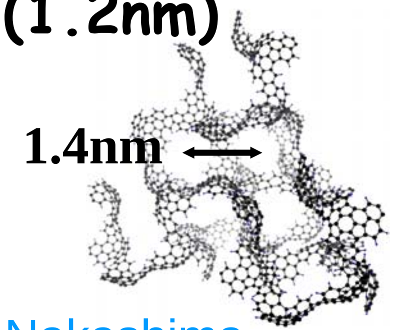
Outline

- *Nano*-Extreme Conditions of *N*-D nanopores
- Realization of 1D state of ^{4}He Bose fluids
- Torsional oscillator experiment for ^{4}He fluid nanotubes in 1D state
- Possible reason of superfluidity in 1D state

N-Dimensional Nanopores

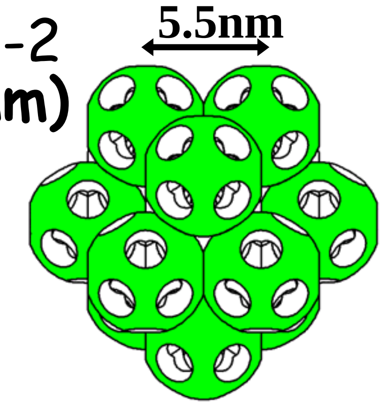
3D

ZTC
(1.2nm)



Y. Nakashima

HMM-2
(2.7nm)

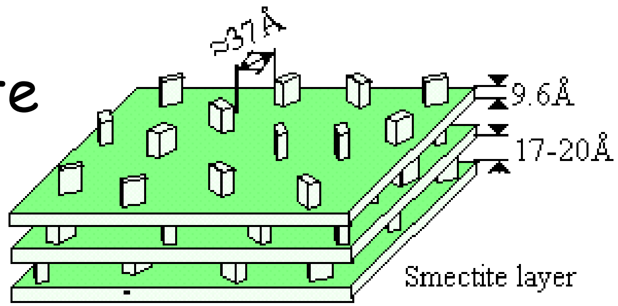


Vycor glass
(5-1000nm)
Gelsil
(2.5,3.4nm)
Porous Gold
(10^2nm)

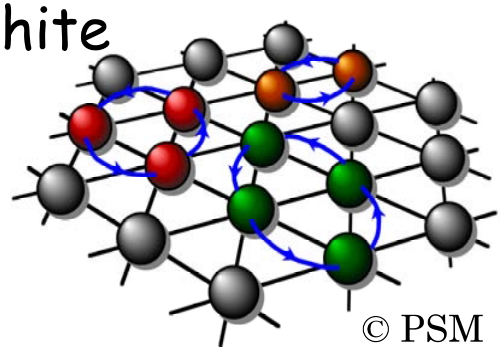
S. Kiyota

2D

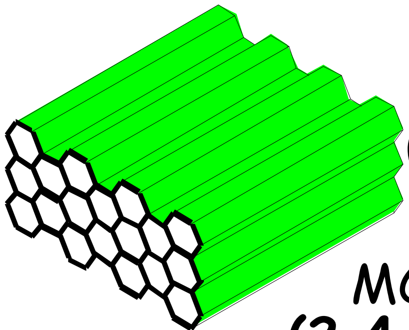
Hectorite



Graphite



1D



FSM-16
(1.5-4.8nm)
Y. Minato

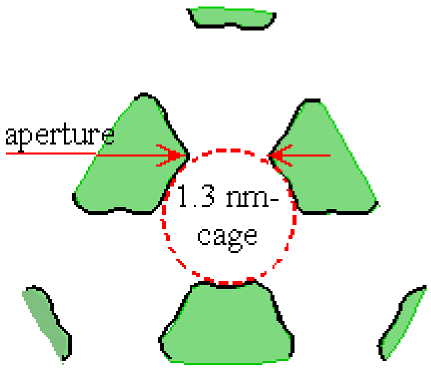
MCM-41
(2.4, 3.4nm)

Carbon
nano-tube
bundles

Extremely High-ω

M. Hieda
T. Oda

0D

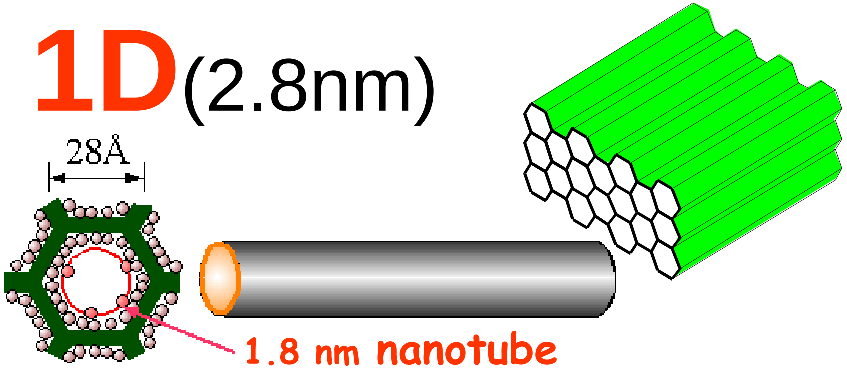


Y-Zeolite
(1.3nm-cages & 0.8nm-apertures)

T. Matsushita
K. Sahashi

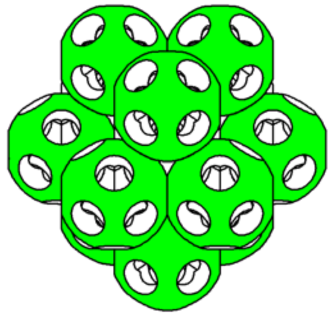
❑ Evidence of 3D Transition in 3D Nanopores

1D(2.8nm)



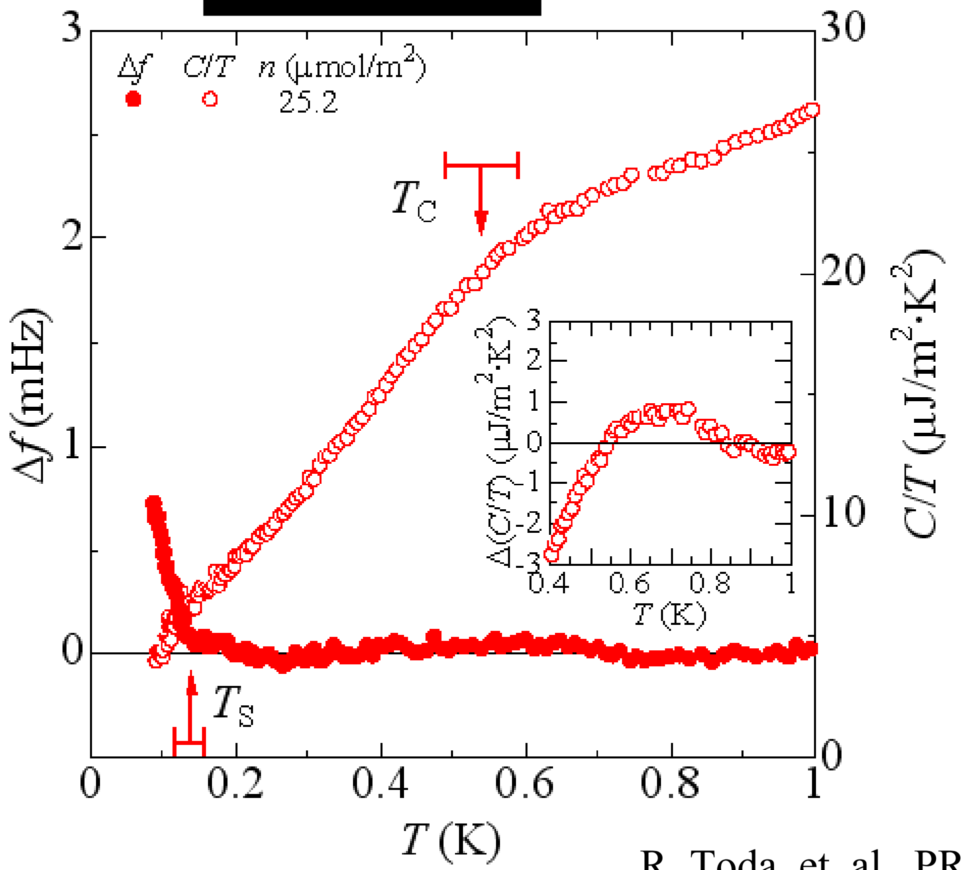
3D(2.7nm)

[3D-period]
=5.5nm

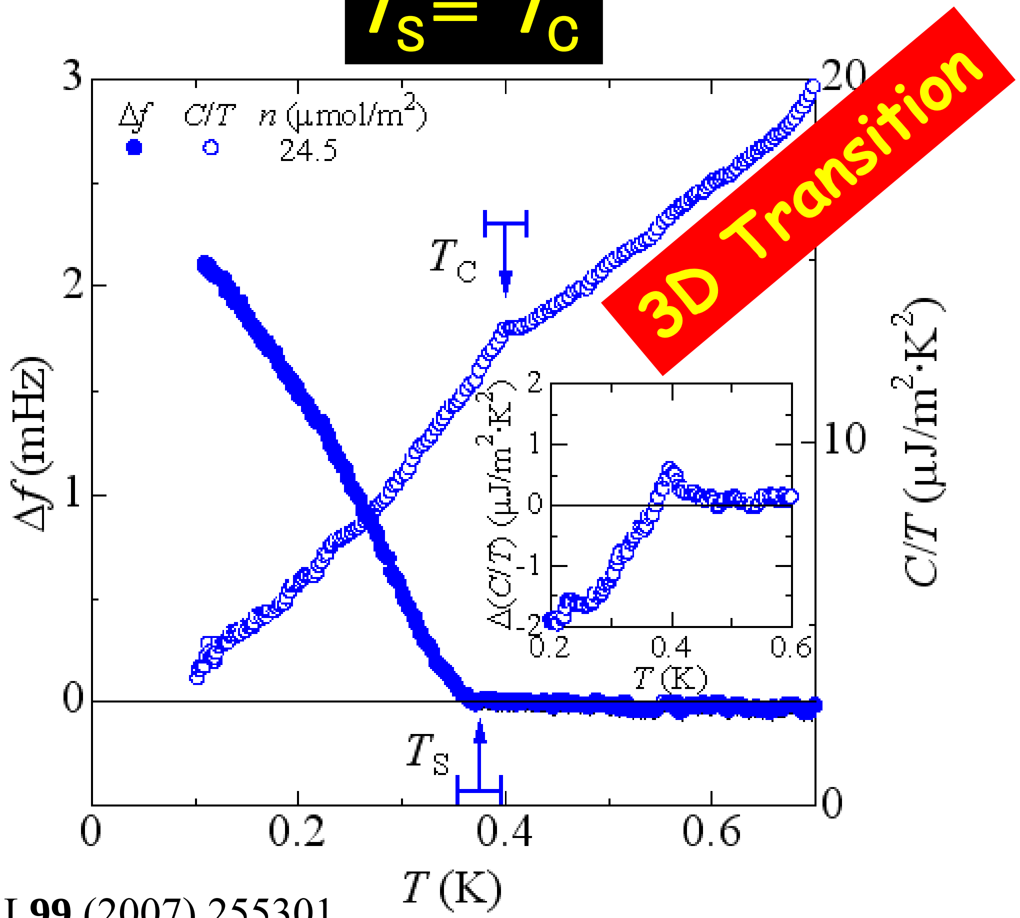


- C-Cusp at T_c on (B)-boundary
- C-Peak at T_c on (B)-boundary

$T_S << T_C$



$T_S = T_C$

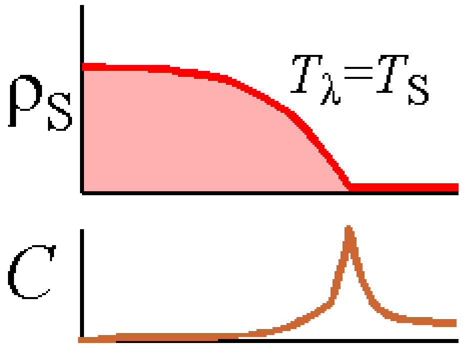


R. Toda, et. al., PRL**99** (2007) 255301

❑ Superfluidity in *N*-Dimension

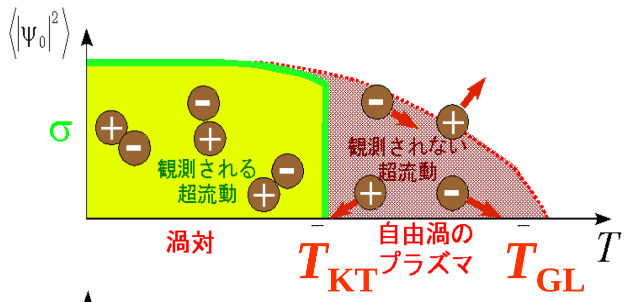
3D Long Range Ordering

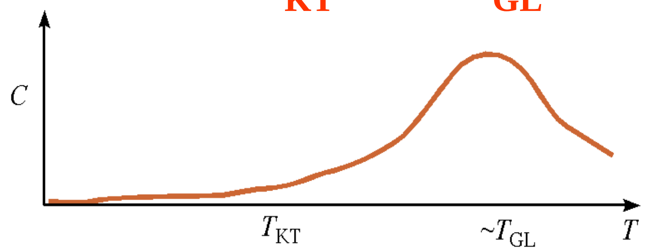
- *C* peak (T_C) = S.F. onset (T_S)



2D No Long Range Ordering
Kosterlitz-Thouless transition

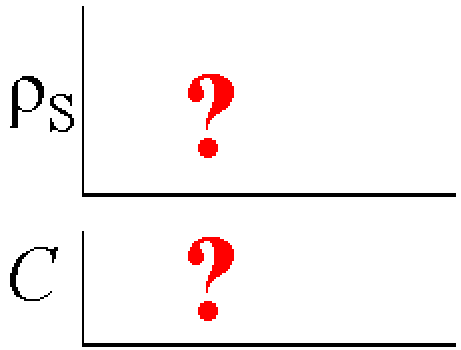
- *C* peak (anomaly) at T_{GL} >> T_{KT}





1D No Long Range Ordering

- No common understanding about superfluidity



Outline

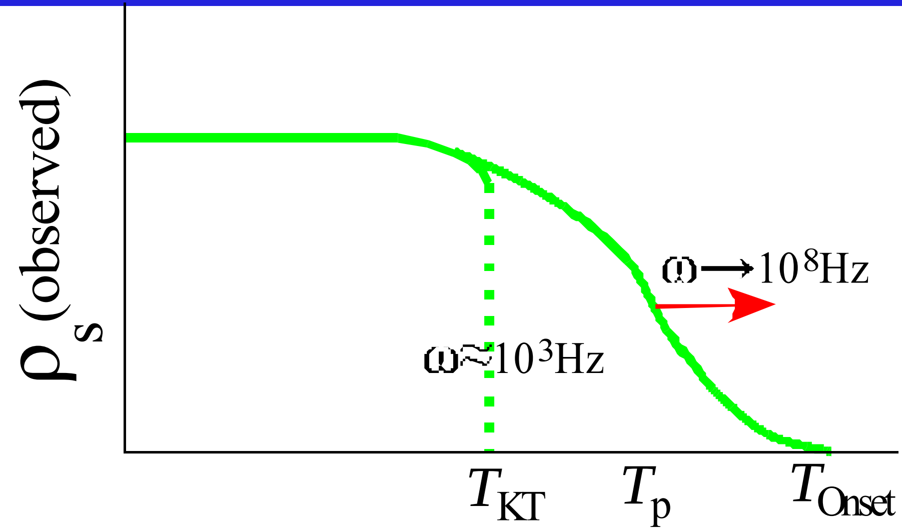
1. Realization of 1D state
   ^{4}He fluid nanotubes
   1D phonon state
2. Superfluidity in 1D state

❑ ω/2π- & *L*-Dependences of Superfluidity in Low-*D*

Superfluidity in 2D

- ω/2π Dependence

M. Hieda, et.al.,
J. Phys. Soc. Jpn. **78** (2009) 033604



- Size *L* Dependence

Dynamic KT Theory

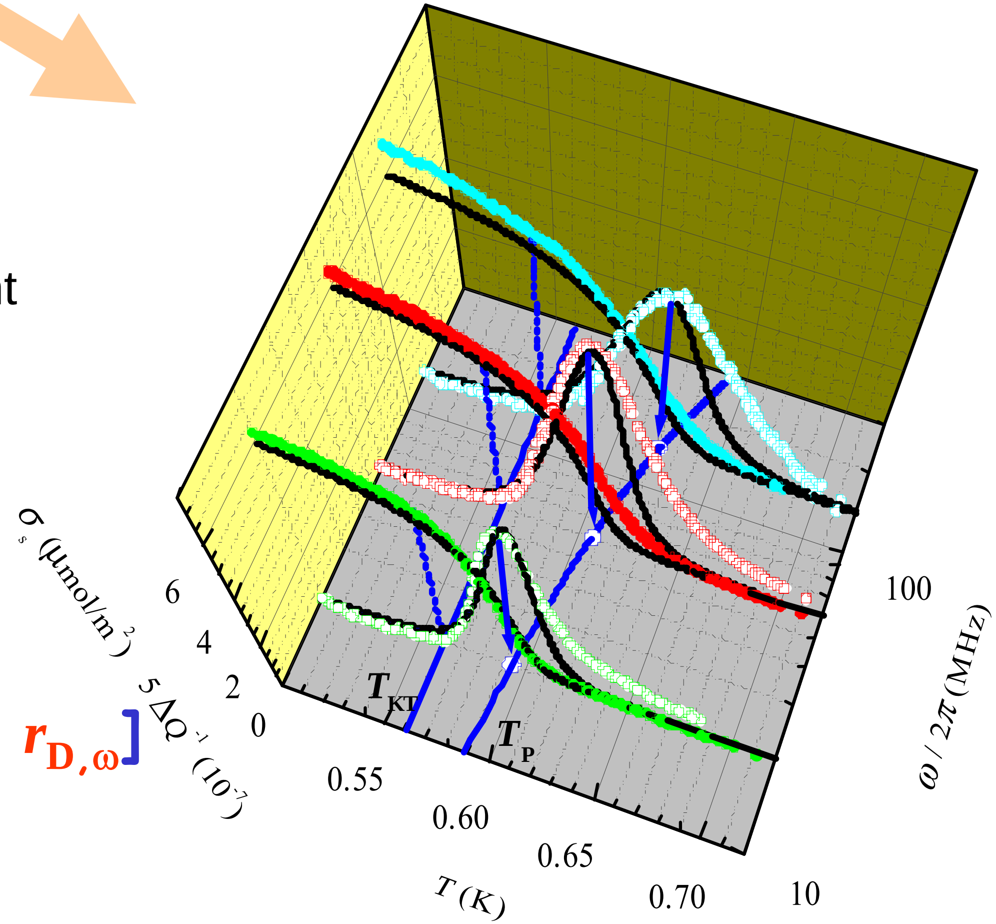
$$\rho_S(\text{observed at } \omega) = K(r_{D,\omega})$$

Stiffness Constant

$$r_{D,\omega} = \sqrt{14D/\omega}$$

Diffusion Length

D: Vortex Diffusion constant



Superfluidity depends on [2D Size *L*] against [Diffusion Length $r_{D,\omega}$]

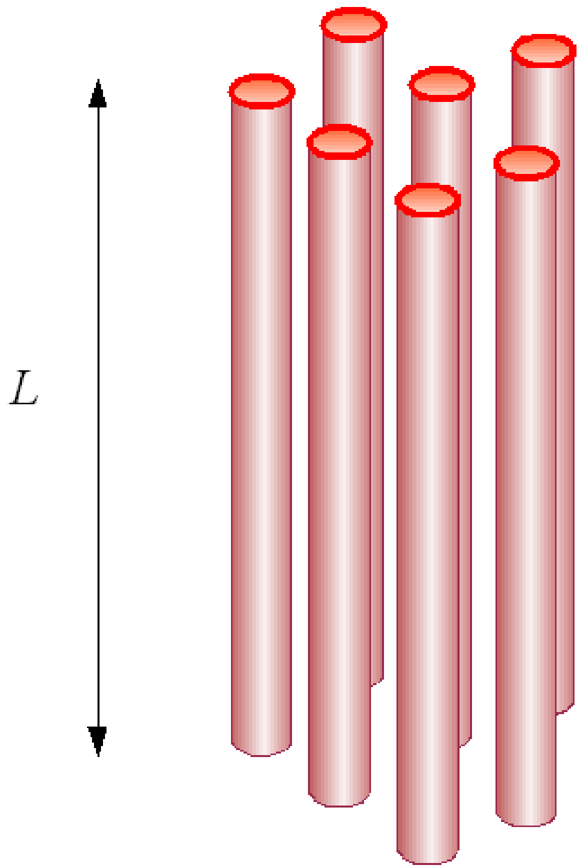
❑ "Quasi"-Conditions for 1D Nanotubes and Magnets

1D ^{4}He Nanotubes

Y. Minato: 2.4nm-1D pores

- L=finite
- $J \approx h^2/md^2$, $J' = 0$

No 3D Order

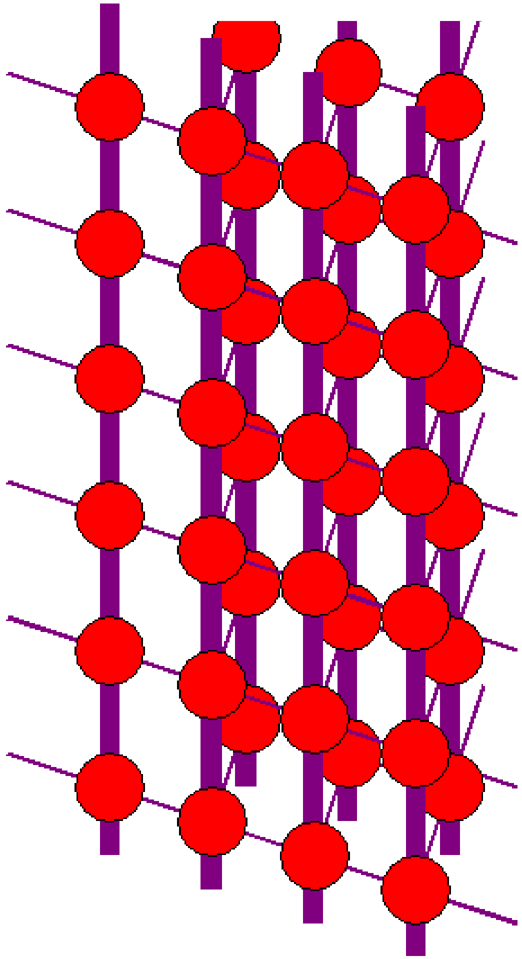


1D Magnets

T. Harada: F5PNN

- L=finite
- $J >> J' \neq 0$

3D LRO at Low T.

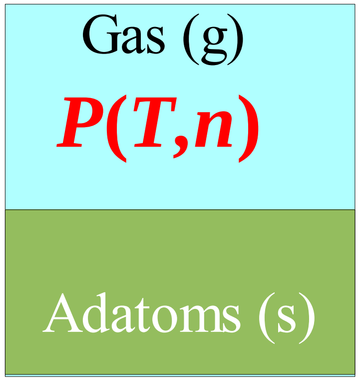


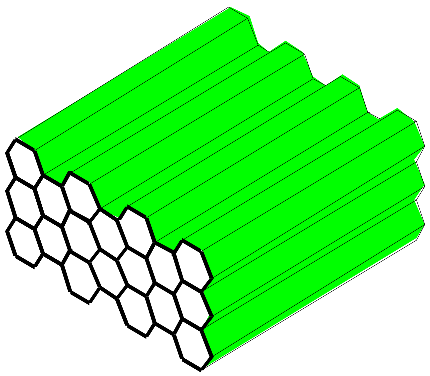
❑ First Layer at n_1 and Uniform Layer up to n_f

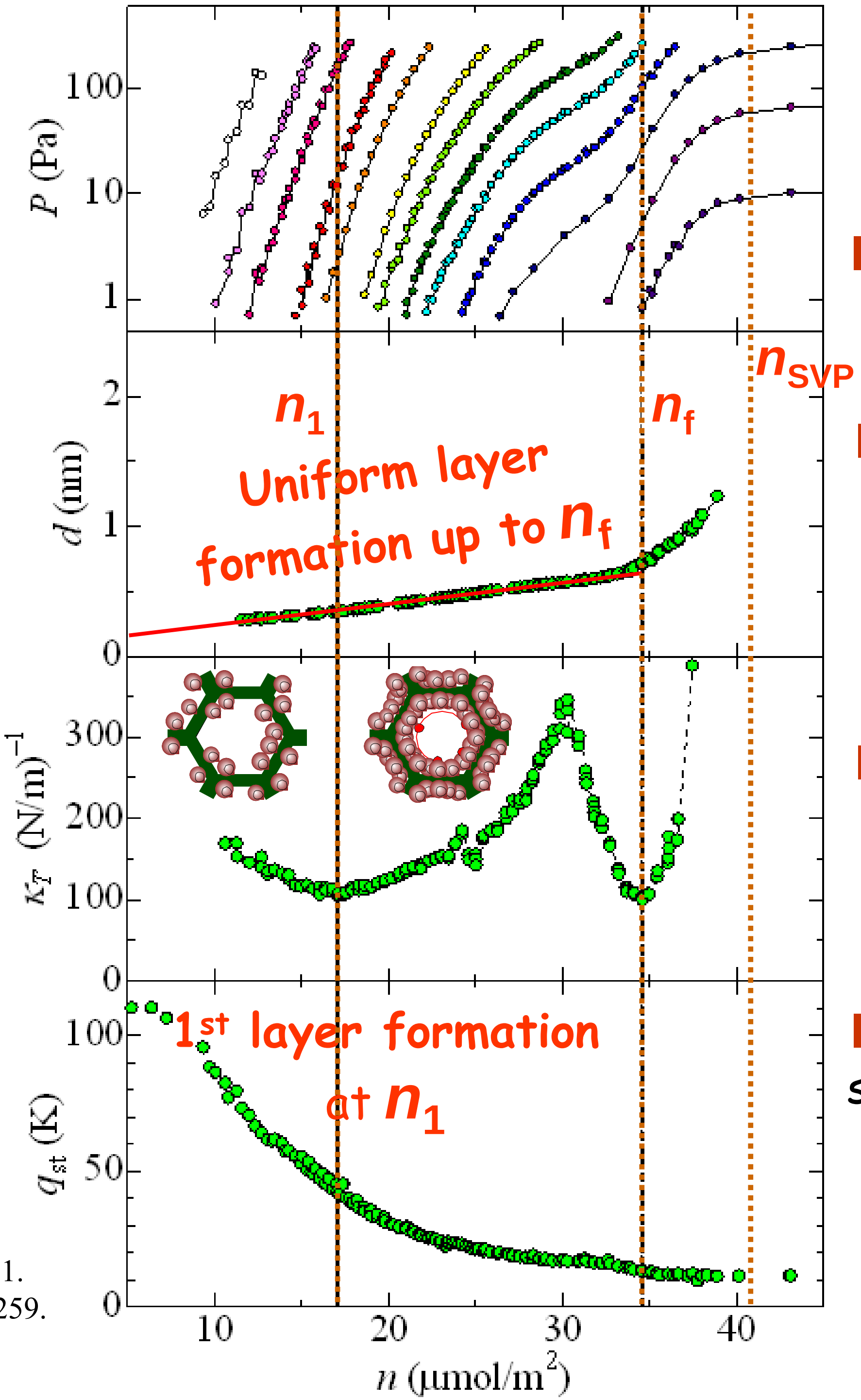
FSM (2.8nm)

Equilibrium condition

$\mu_{gas} = \mu_{adatom}$







■ Pressure isotherms of ^{4}He

■ Film thickness : δ

$$\delta = \left(\frac{T}{\Gamma}\ln\frac{P_{SVP}(T)}{P}\right)^{-1/3}$$

$$\Gamma = 1100\mathrm{K\dot{A}}^3$$

$$\mu_{\mathrm{adatoms}} = \frac{\Gamma}{\delta^3} + \mu_{\mathrm{Bulk\,Liquid}}$$

■ Compressibility : κ_T

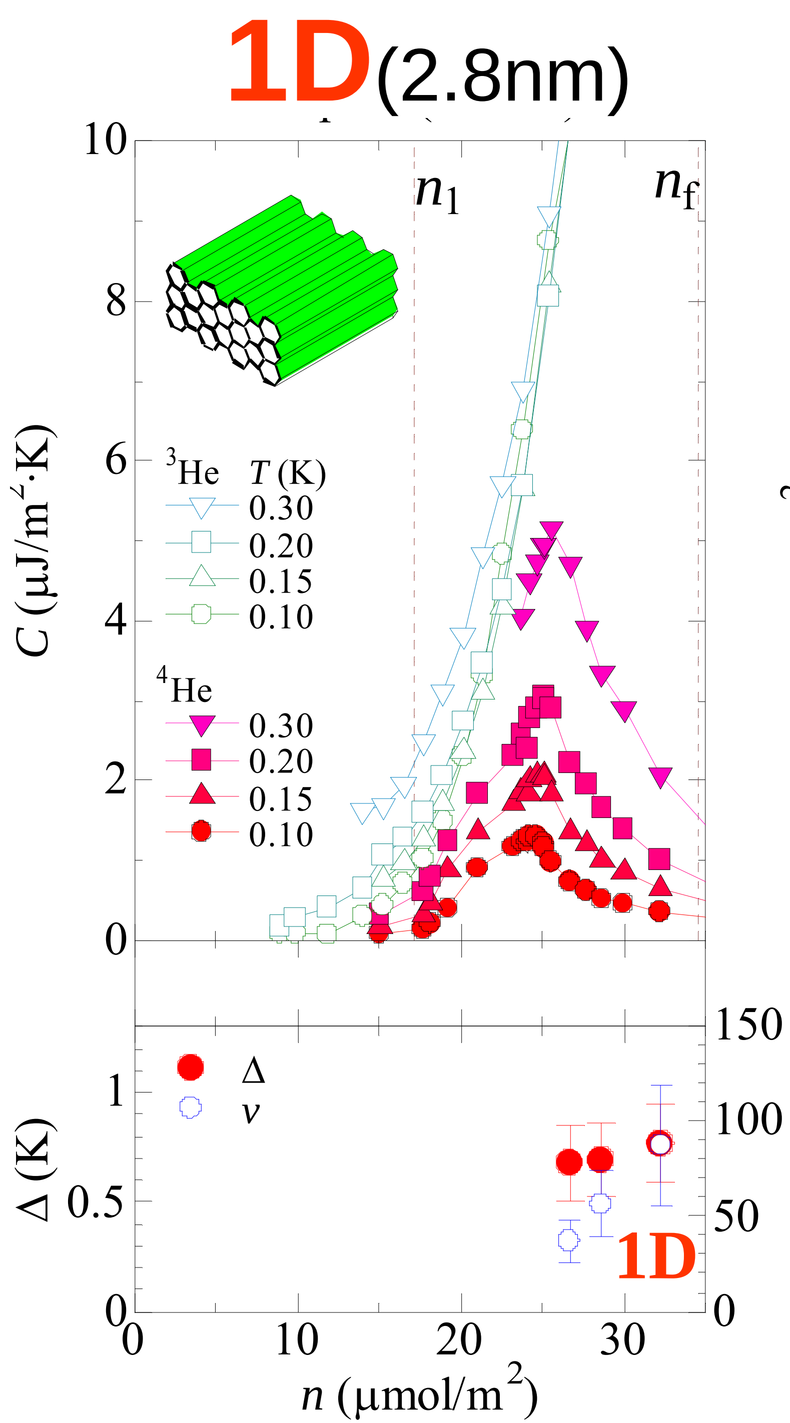
$$\kappa_T = \frac{1}{n^2 RT}\left(\frac{\partial \ln P}{\partial n}\right)^{-1}_{T=\mathrm{const.}}$$

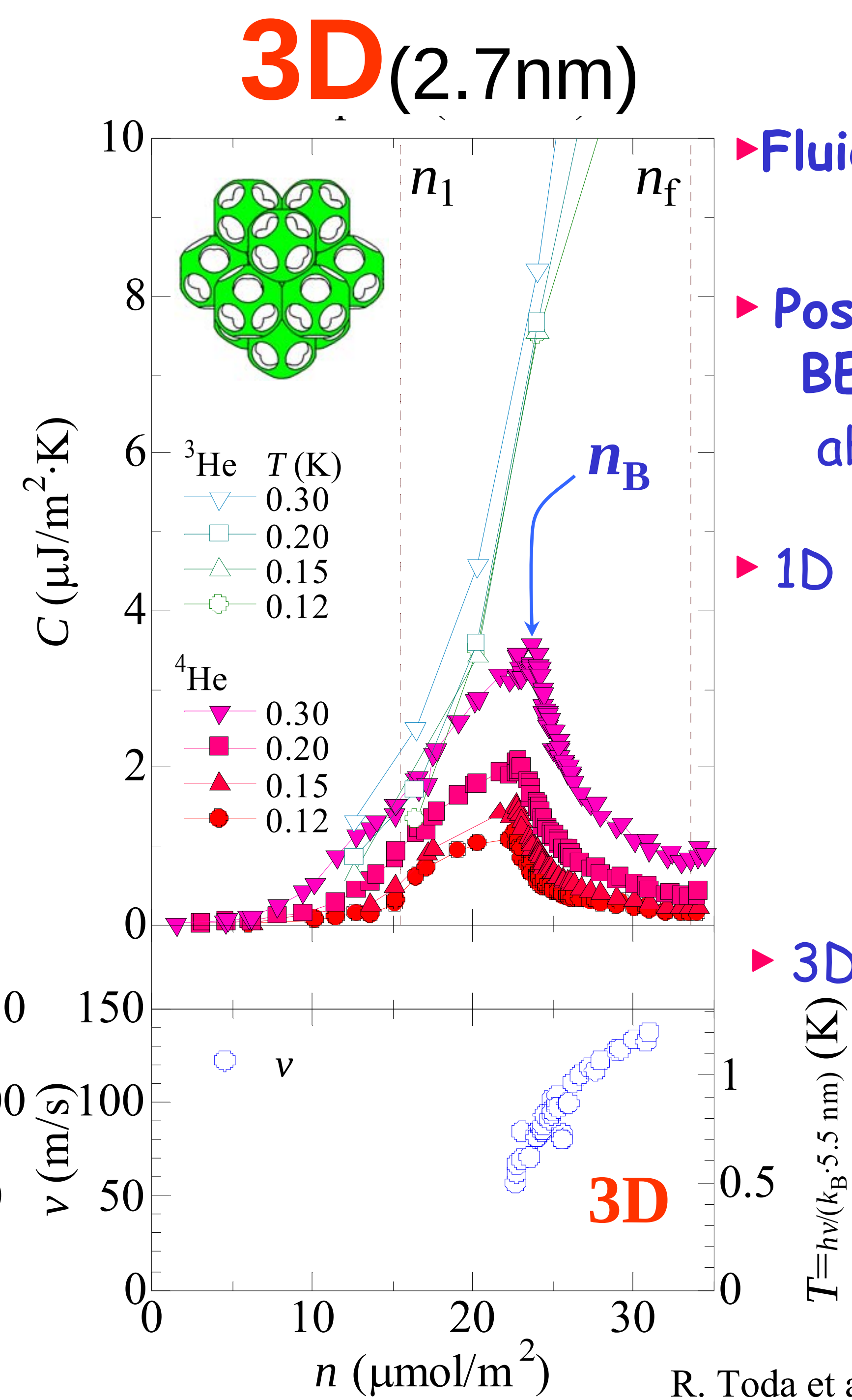
■ Isosteric heat of sorption: q_{st}

$$q_{st} = -\left(\frac{\partial P}{\partial 1/T}\right)_{n=\mathrm{const}}$$

H. Ikegami, et.al. PR **B68** (2003)092501.
J. Taniguchi, et. al, J LT P **126** (2002) 259.
N. Wada, et.al.,PRL**86** (2001) 4322

❑ Heat Capacity Isotherms of ^{4}He and ^{3}He





- **Fluid layers**

  above $1.4n_1$
- **Possibilities of BEC and SF (^{4}He)**

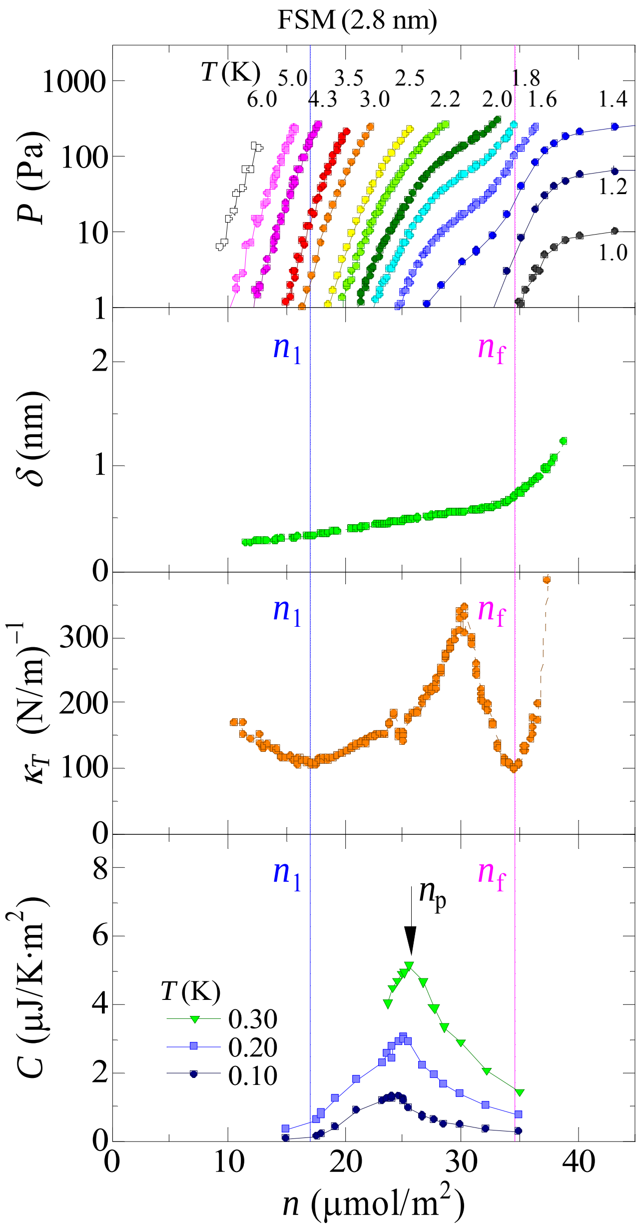
  above n_B : B-phase
- 1D phonon state

  $k_B T < \Delta$
- 3D phonon state

  $\lambda_{phonon} \geq$ [3D period]

R. Toda et al, PRL **99** (2007) 255301

❑ Phonon velocity v_C & v_P and 1D Phonon Condition

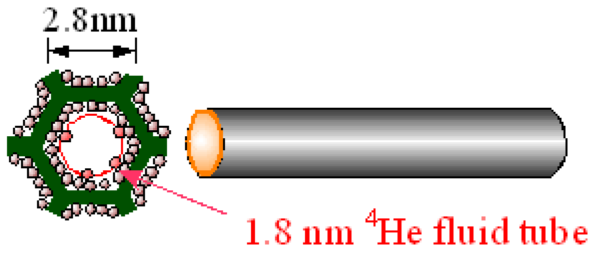


1D phonon condition

$$T < \Delta / k_B$$

or

$$\lambda_{phonon}(T) > \pi \times 1.8\text{nm}$$



Thermal phonon wave length

$$\lambda_{phonon}(T) = h v_{C \text{ or } P} / k_B T$$

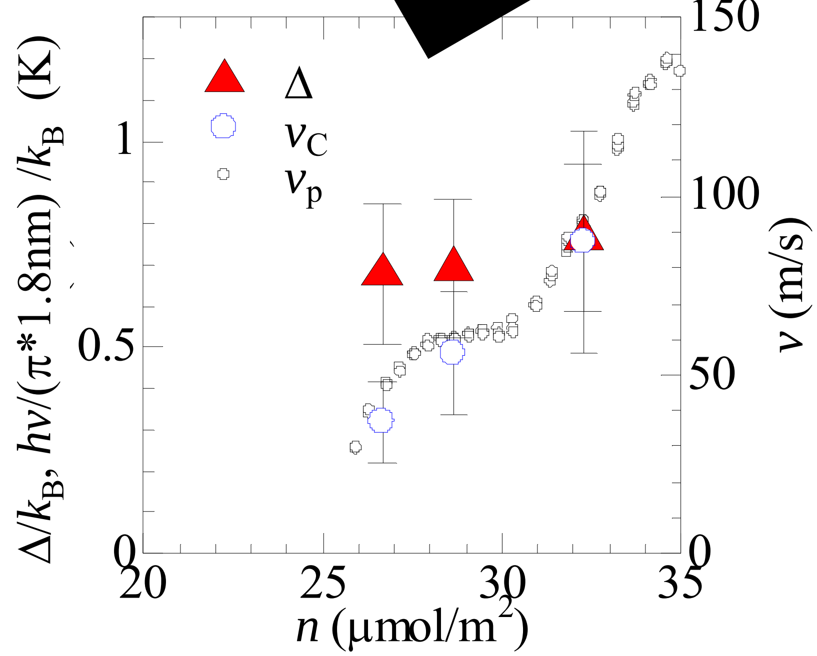
1D phonon state Below Δ/k_B

$$v_P = 1/\sqrt{\kappa_S^{*}(n-n_c)}$$

$$\kappa_S^{*} \approx \kappa_T^{*}$$

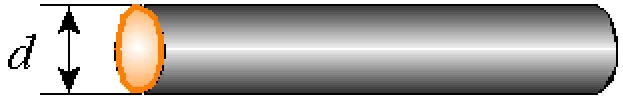
$$= \frac{1}{(n-n_c)^2 RT}\left(\frac{\partial \ln P}{\partial n}\right)^{-1}_{T=\text{const.}}$$

$$n_c = 25\mu\text{mol/m}^2$$



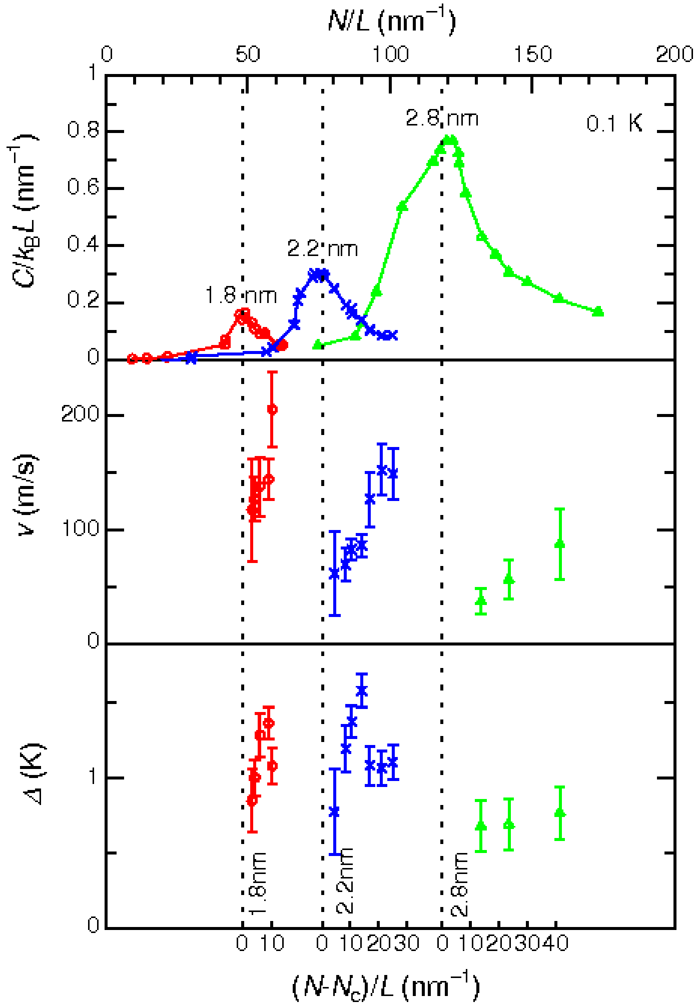
❑ Phonon Heat Capacity of Nanotube

1D phonon heat capacity of nanotube



Y.Matsushita, *et. al*,
JLTP **150**(2008)342

Phonon dispersion ($v_I \hbar k$) along tube ✚ Energy gap Δ_{01} in crosssection



1D(2.8nm)pore

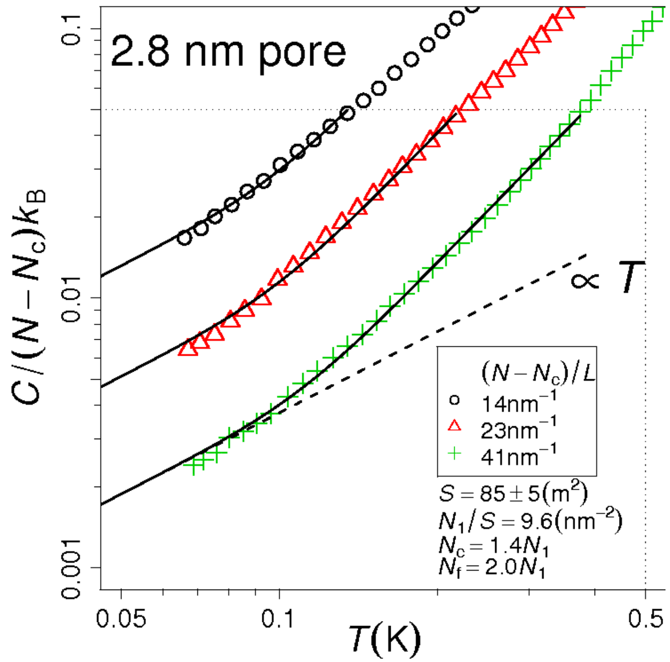
v_I

40-100 (m/sec)

λ_{phonon}~50nm@40mK

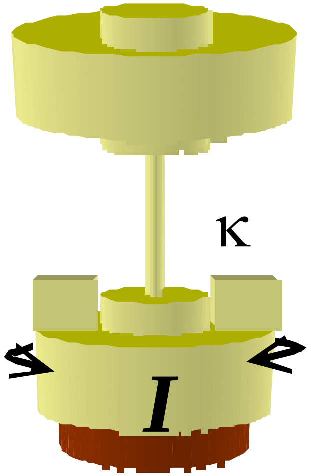
Δ_{01}/k_B

0.7-0.9 (K)



$$C = \frac{2\pi^2}{3}\frac{L_{total}}{h v_I} k_B^2 T$$

❑ Observed Superfluid of ^{4}He in 1D Nanotubes

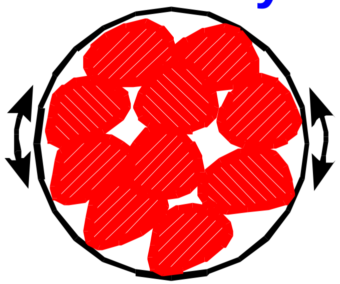


$$F = 2\pi\sqrt{\frac{\kappa}{I}}$$

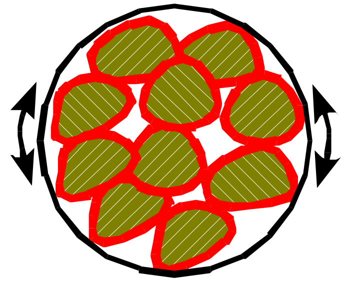
ΔF=[He in pores] + [grain surface]

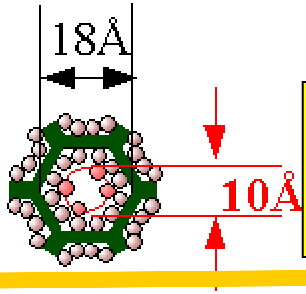
ΔF= [grain surface]

^{4}He-only

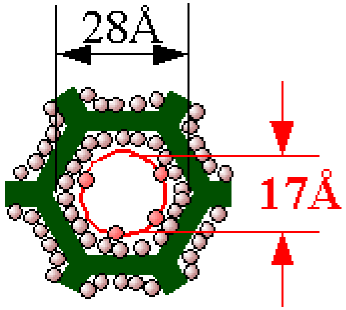


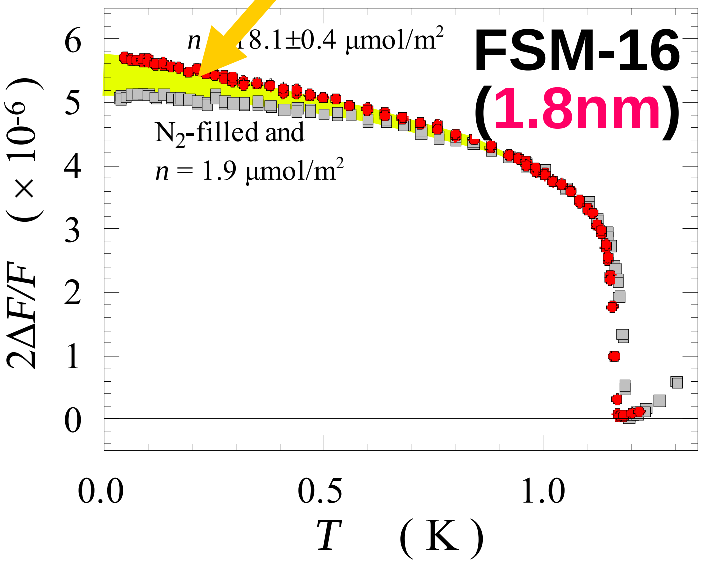
N_2-filled



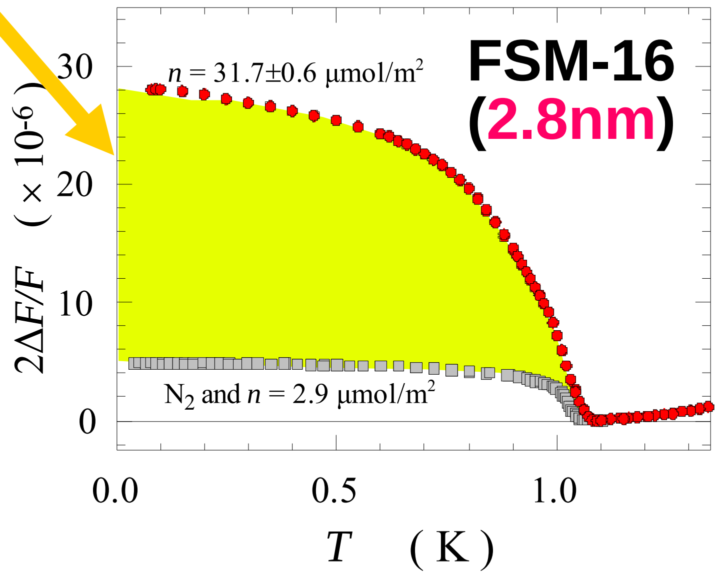


S.F. of ^{4}He in nanotubes





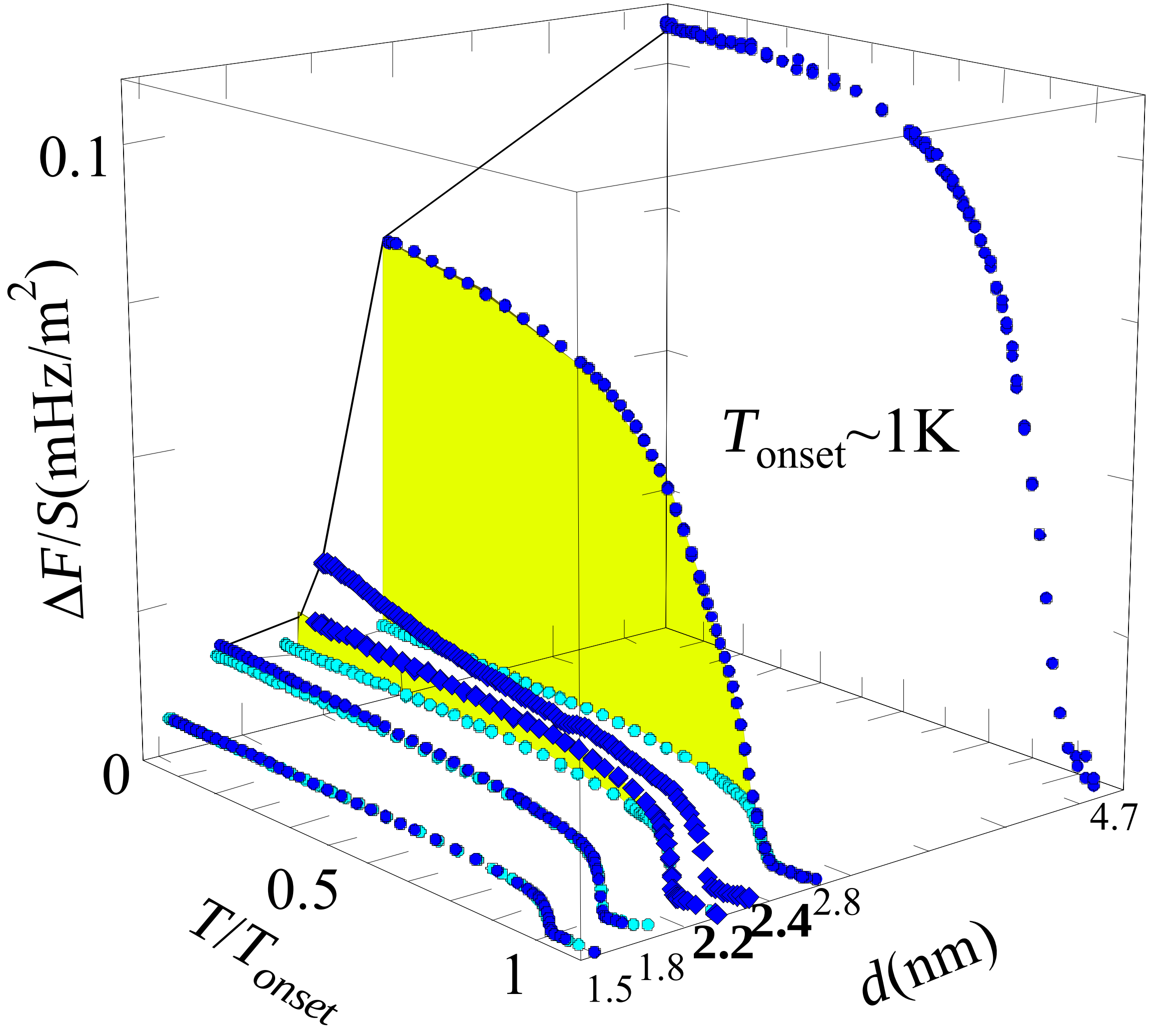
▸ Superfluid above 1.8nm diameter

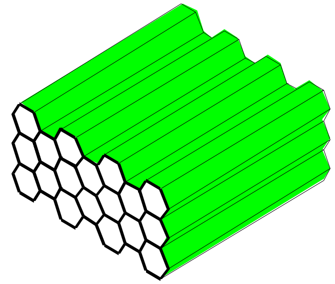


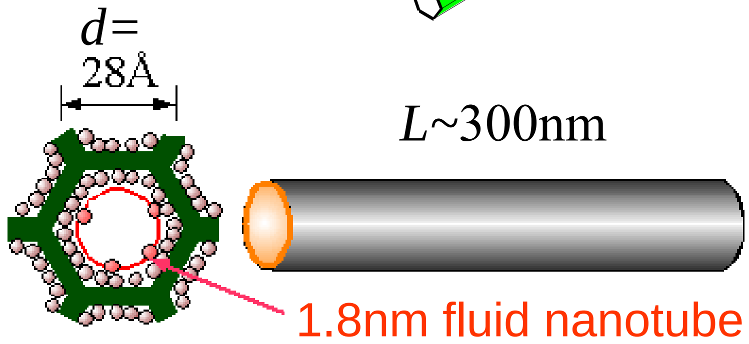
H. Ikegami, Y. Yamato, T. Okuno, J. Taniguchi, N. Wada, S. Inagaki and Y. Fukushima, Phys. Rev. **B 76**, 144503 (2007)

❑ Pore Diameter *d* Dependence of Superfluidity

Superfluid density(∝Δ*F*)







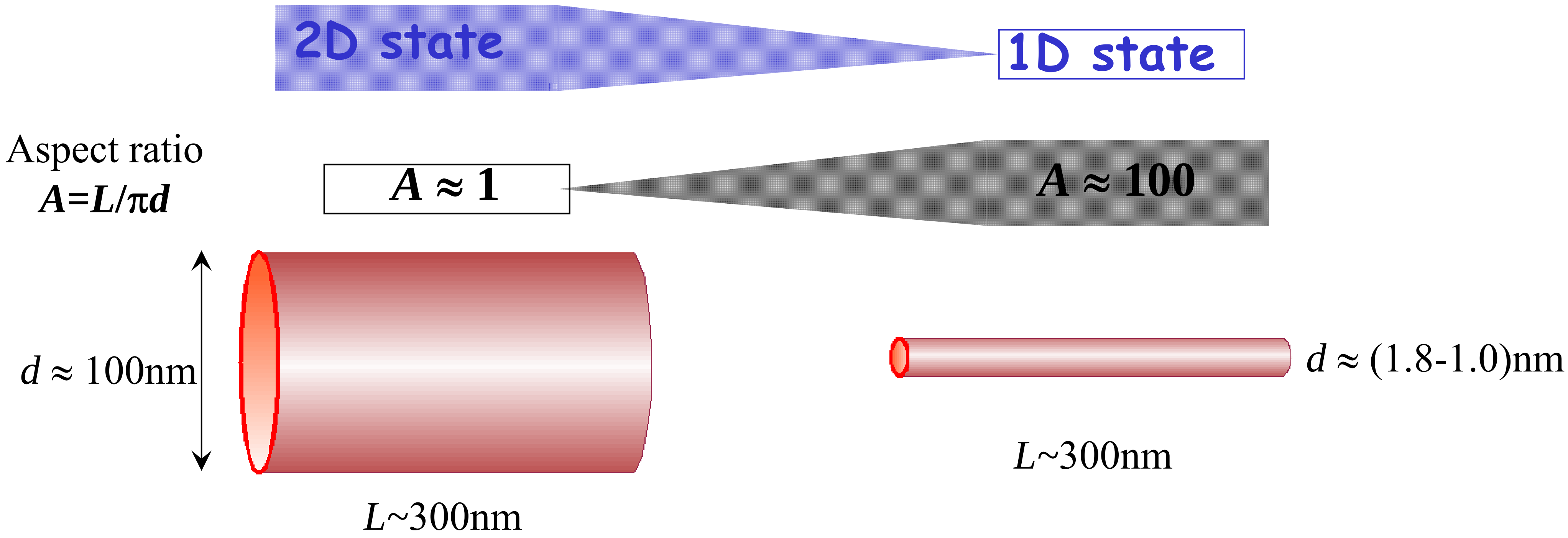
- Superfluidity above ***d*** **=1.8nm**
- Critical change of superfluidity at ***d*** **= 2.2-2.8nm**

From H. Ikegami, et al, PR**B 76** (2007) 144503
Y. Minato, to be submitted.

Superfluidity Observed for ^{4}He in 1D Nanopores

- Superfluid was observed in 1D phonon state above ***d* ≥1.8nm**
- ρ_S- *T* depends on ***d*** .

Dimensionality of ^{4}He Fluid Film Tube



❑ 2D and 1D Correlation Functions by T. Phonon

2D Correlation function

$T<T_{KT}$: Thermal phonon fluctuation

$$\langle \psi^*(r)\psi(0)\rangle \approx (1/r)^\eta$$

$$\eta = \frac{T}{2\pi K_0}$$

S. F. is observed by Torsional Oscillator

$T>T_{KT}$: S.F. vortex fluctuation

$$\langle \psi^*(r)\psi(0)\rangle \approx r^{-1/2}\exp[-r/\xi_+(T)]$$

$$\xi_+(T) \propto \exp\left[\frac{1}{b\sqrt{T-T_{KT}}}\right]$$

S. F. above T_{KT} is observed when

$$\xi_+(T) \ge r_{D,\omega} = \sqrt{14D/\omega}$$

1D Correlation function

Thermal phonon fluctuation

$$\langle \psi^*(r)\psi(0)\rangle \approx \exp[-r/\xi_+(T)]$$

$$\xi_+(T) \propto 1/T^\eta$$

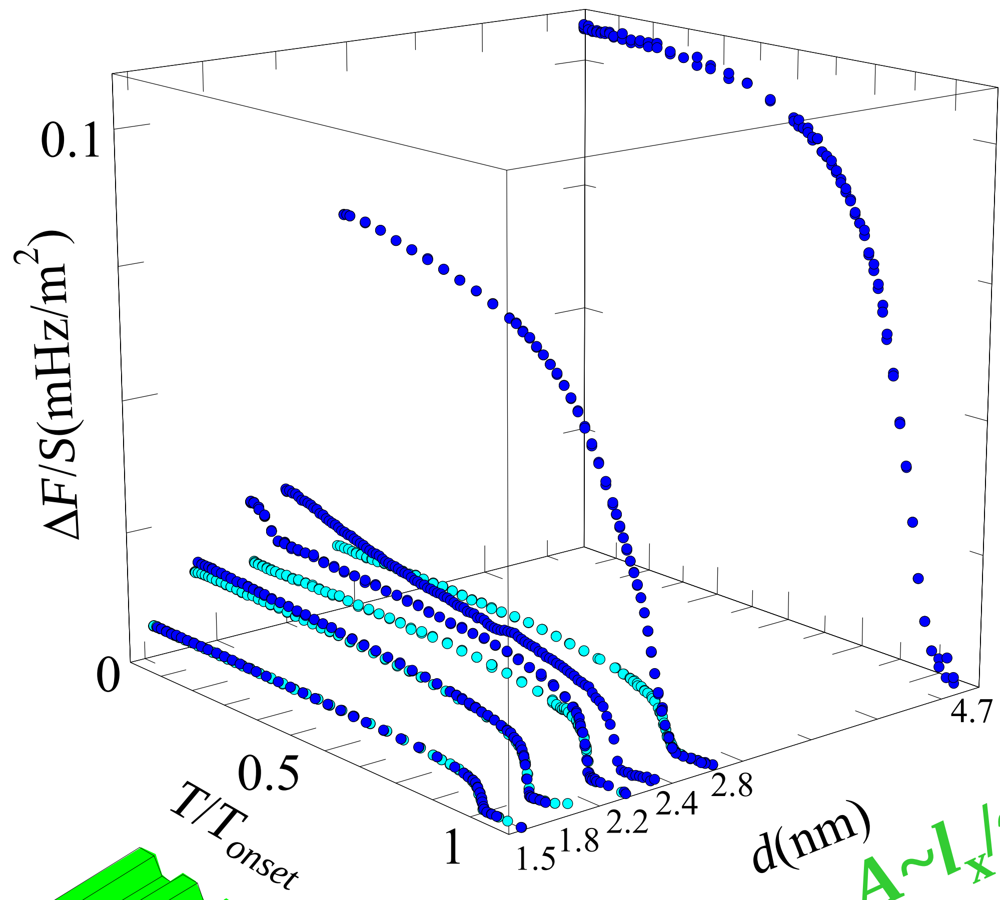
Normal fluid state at finite temperatures

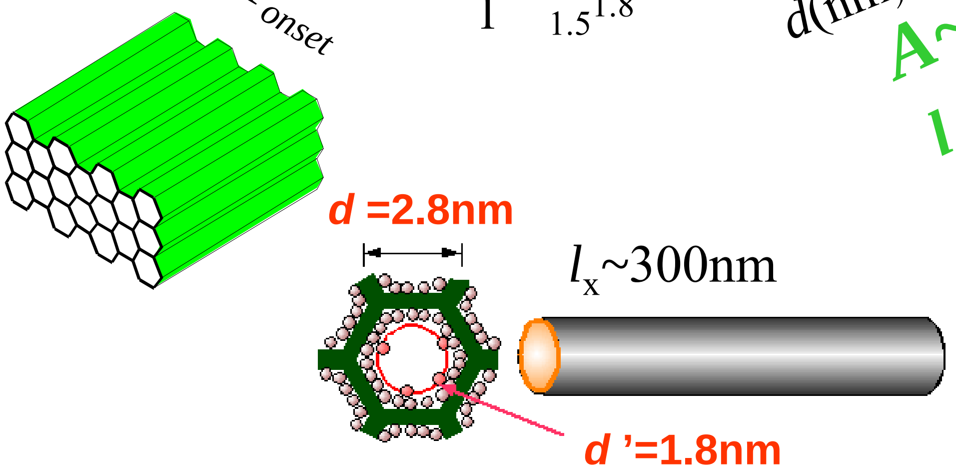
S. F. can be observed when

$$\xi_+(T) \ge [\text{1D length}]$$

❑ Pore Diameter *d* Dependence of Superfluidity

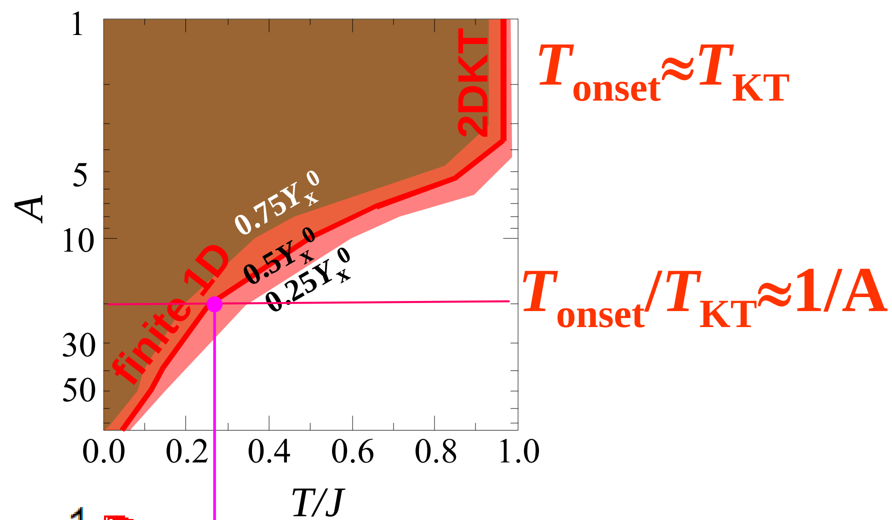
Observed superfluid density($\propto \Delta F/F$)





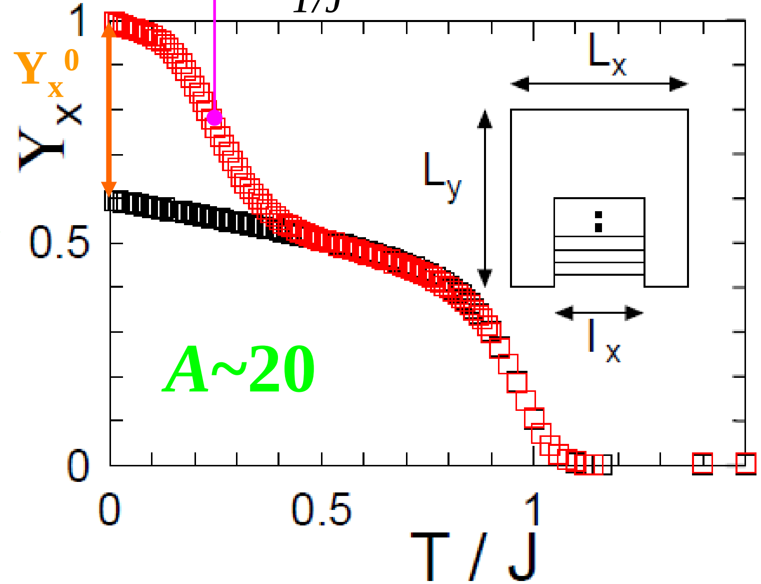
XY model with asymmetry *A*

1D thermal fluctuation of long wavelength is suppressed in the length l_x at low T.



$A \sim l_x/\pi d'$

$l_x \sim 300$nm



K. Yamashita and D. S. Hirashima, PRB 79(2009)014501

❑ Summary

- **1D phonon state** of ^{4}He fluid nanotubes was realized.
- **Superfluidity** in 1D state was observed for 1D pores above 1.8nm.
    - ρ_S- T depends on ***d*** and coverage ***n*** (d = 2.4nm).
- **Possible reason of Superfluidity** in 1D state.
    - 1D correlation length exceeds the length of ^{4}He-fluid-nanotube at low temperatures.