One-Dimensional ^{4}He and ^{3}He Quantum Fluids Formed in Nanopores

Nagoya University **Nobuo Wada** December 15, 2005

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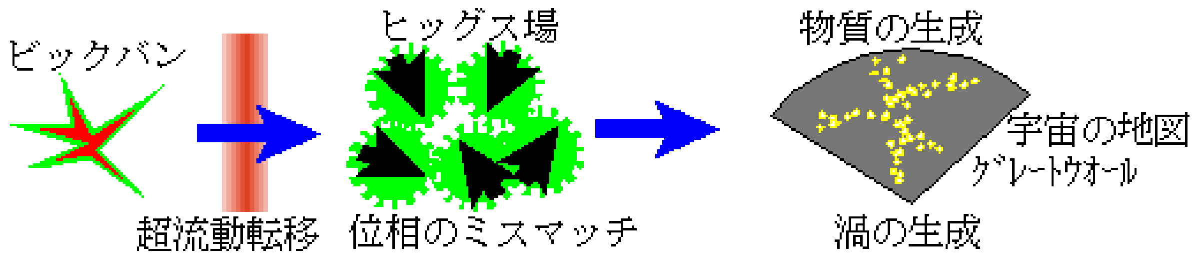
❑N-Dimensional Helium Bose Fluids

4D (bulk liquids)

- Creation of vortexes in “Big Bang”

  ^{4}He-S.F. ? ^{3}He-S.F. yes



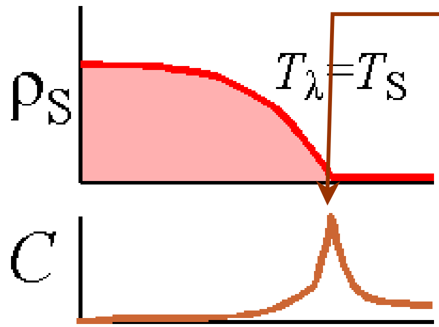
3D (bulk liquids)

^{4}He: Superfluid

2nd order transition

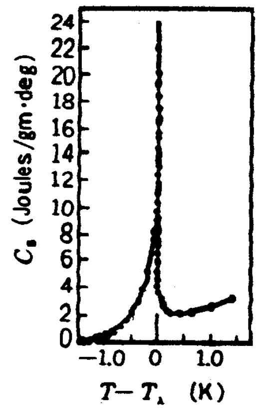
^{3}He: Fermi liquid

P-wave superfluid



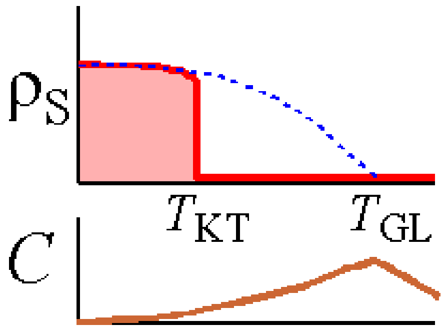
Divergence at T_λ

$C \propto \log |T - T_\lambda|$



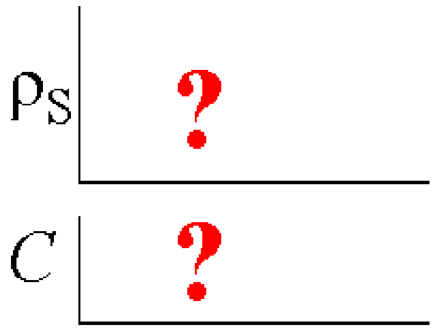
2D (liquid films)

- Kosterlitz-Thouless transition



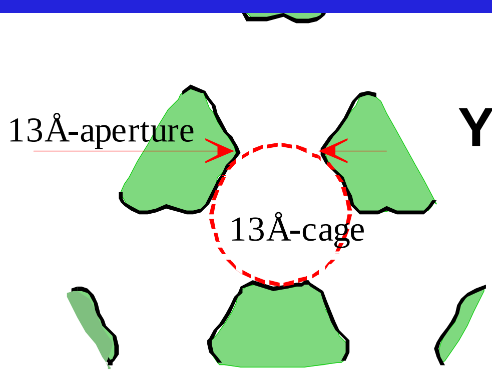
1D

- **To realize 1D ^{4}He Bose fluids in nanopores**



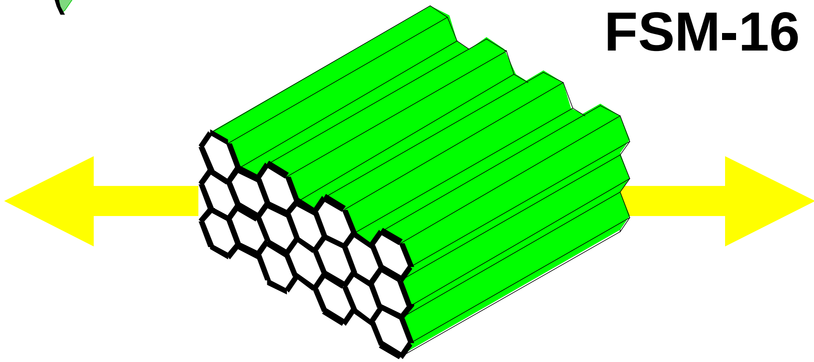
❑ N-Dimensional Nanopores

0D



Y-Zeolite

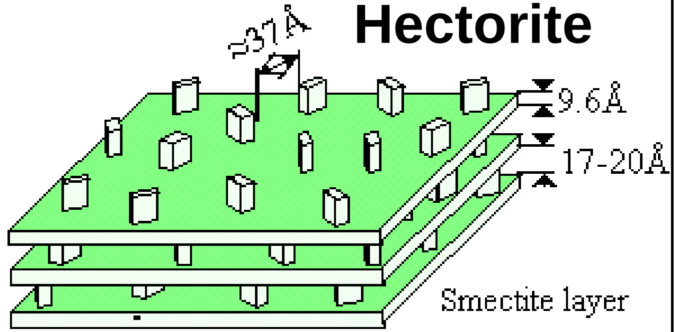
1D



FSM-16

2D

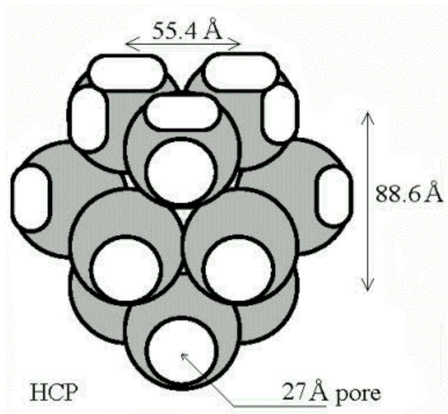
Hectorite



3D

HMM-2

27Å

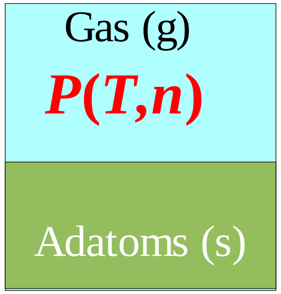


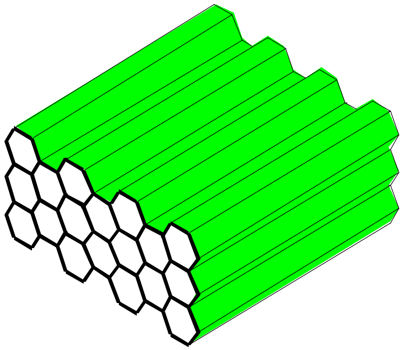
❑ Characterization of Layer Formation

Chemical potential from *P*(*T*,*n*)

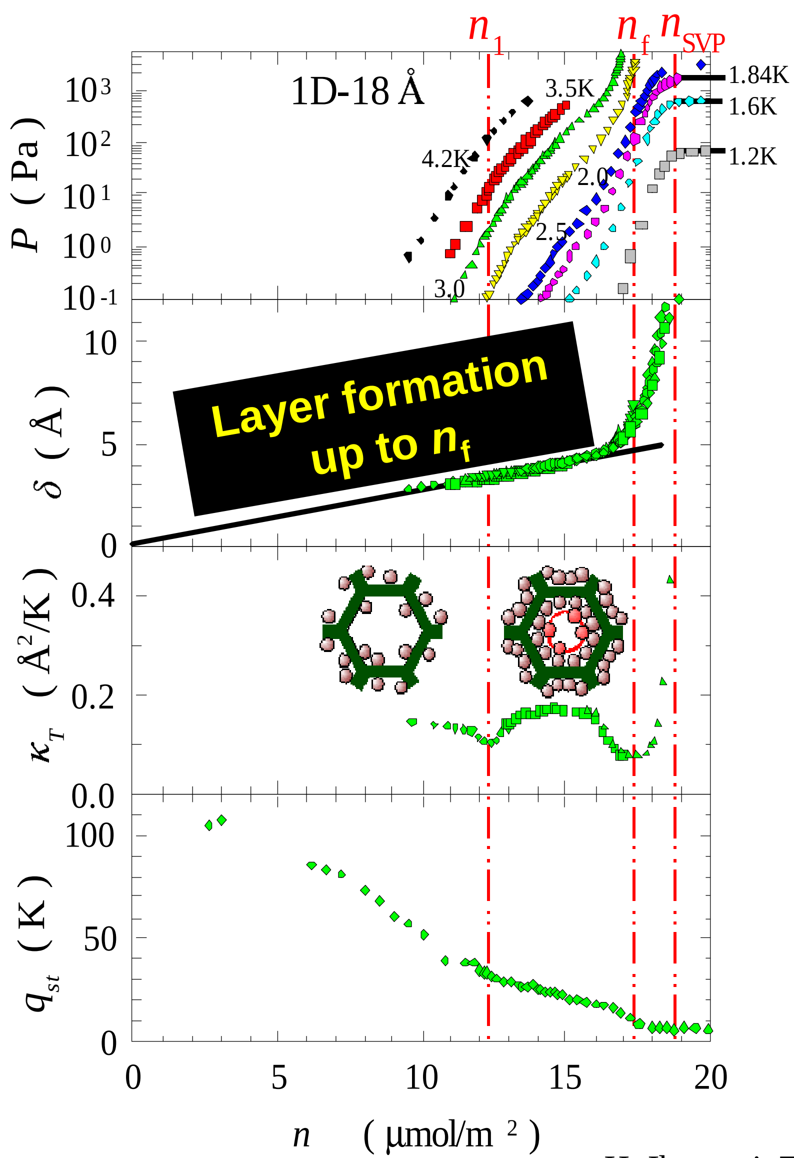
Equilibrium condition

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





FSM-16(18Å)



- Film thickness : δ

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

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

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

- Compressibility : κ_T

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

- Isosteric heat of sorption: q_{st}

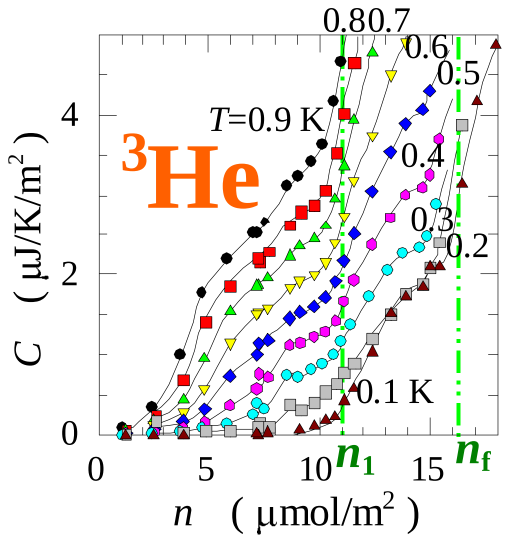
$$q_{st} = -\left(\frac{\partial\ \ P}{\partial 1/T}\right)_{n=\text{const}}$$

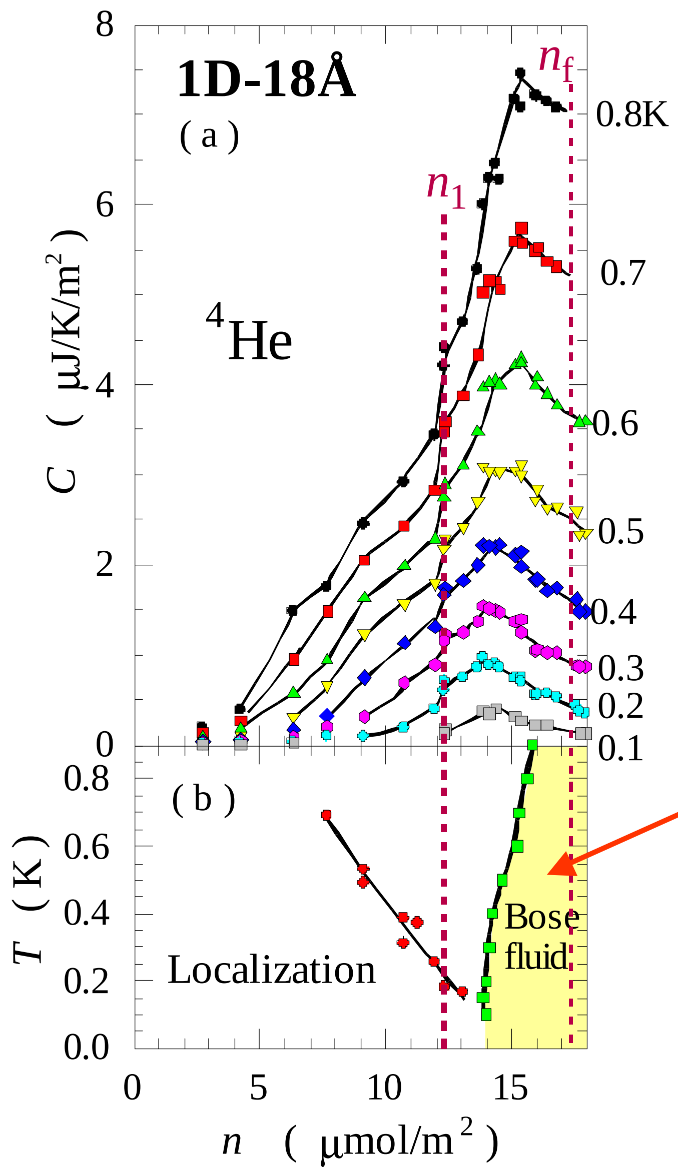
H. Ikegami, T. Okuno, Y.Yamato, J. Taniguchi, N. Wada , S. Inagaki, and Y. Fukushima , Phys. Rev. B68 (2003)092501

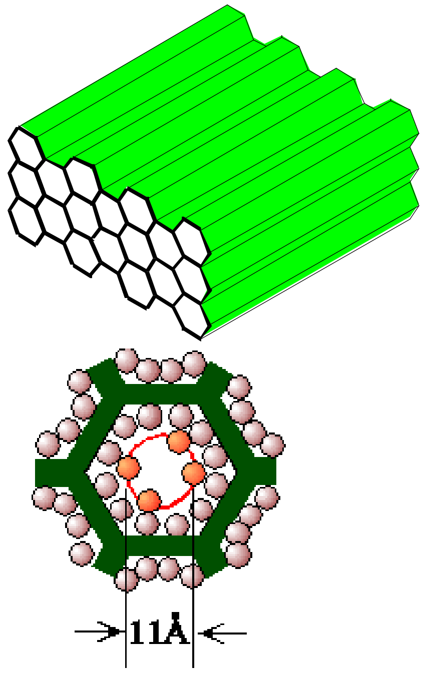
❑ ^{4}He Bose Fluids Formed in 1D-18Å Pores

FSM-16(18Å)

Quantum fluids above n_1





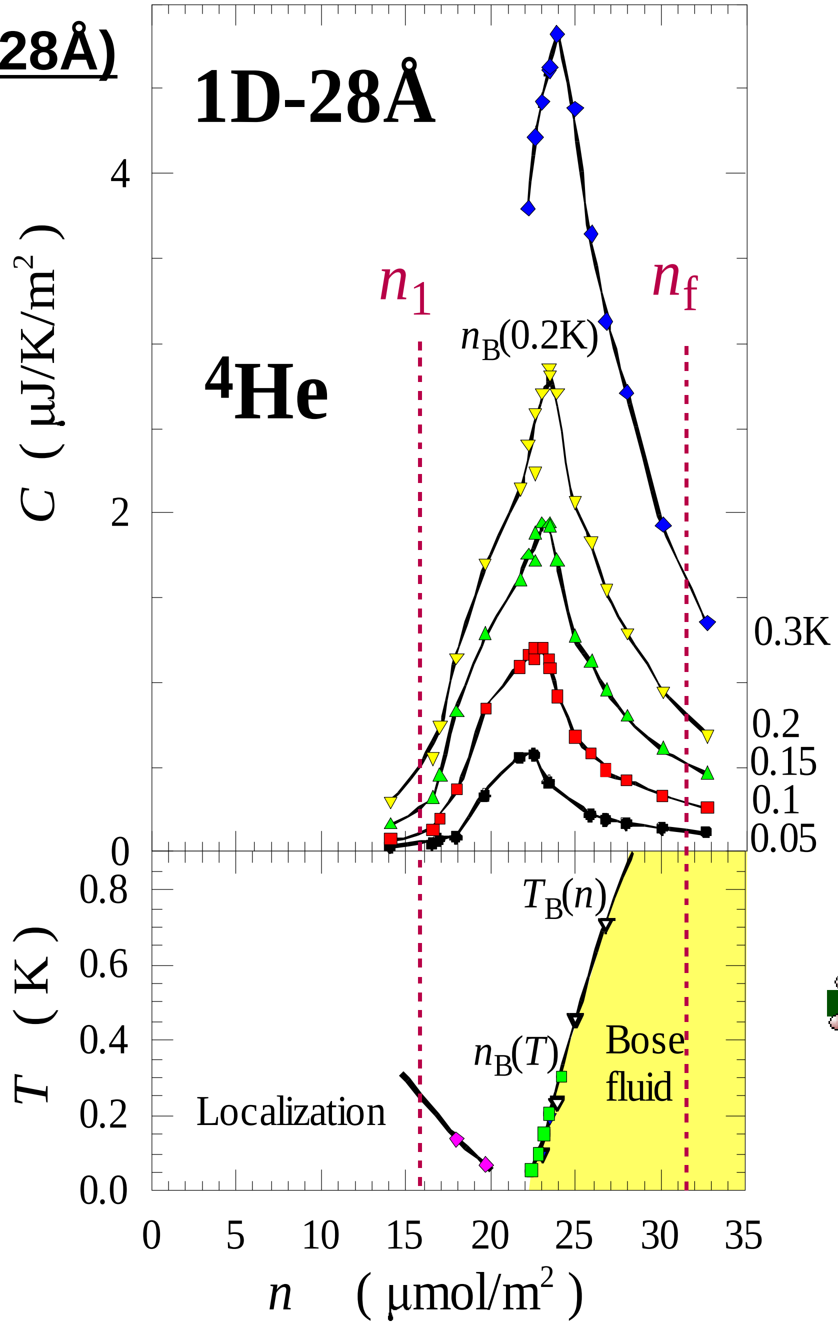


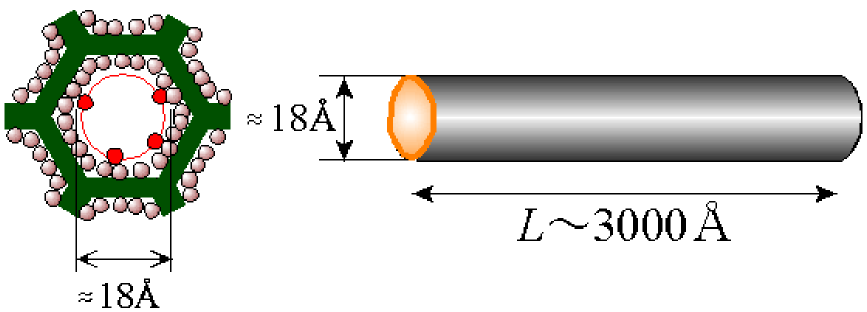
Nanotube of Bose fluid

J. Taniguchi, T. Okuno, H. Ikegami, and N. Wada, J. Low Temp. Phys. 126 (2002) 259-264.
N. Wada, J. Taniguchi, H. Ikegami, S. Inagaki, and Y. Fukushima ,Phys. Rev. Lett. 86 (2001) 4322

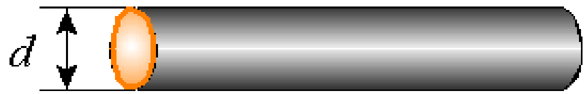
❑ ^{4}He Bose Fluids in 1D-28Å Pores

FSM-16(28Å)



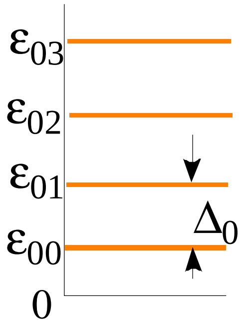


❑ 1D Condition for Phonon Heat Capacity



3D	2D
Bulk liquid ^{4}He (SVP)	^{4}He fluid films on Hectorite
$C \propto T^3$ below 0.7K	$C \propto T^2$ below 0.2-0.3K
v_I=239m/sec	v_I=100-200m/sec

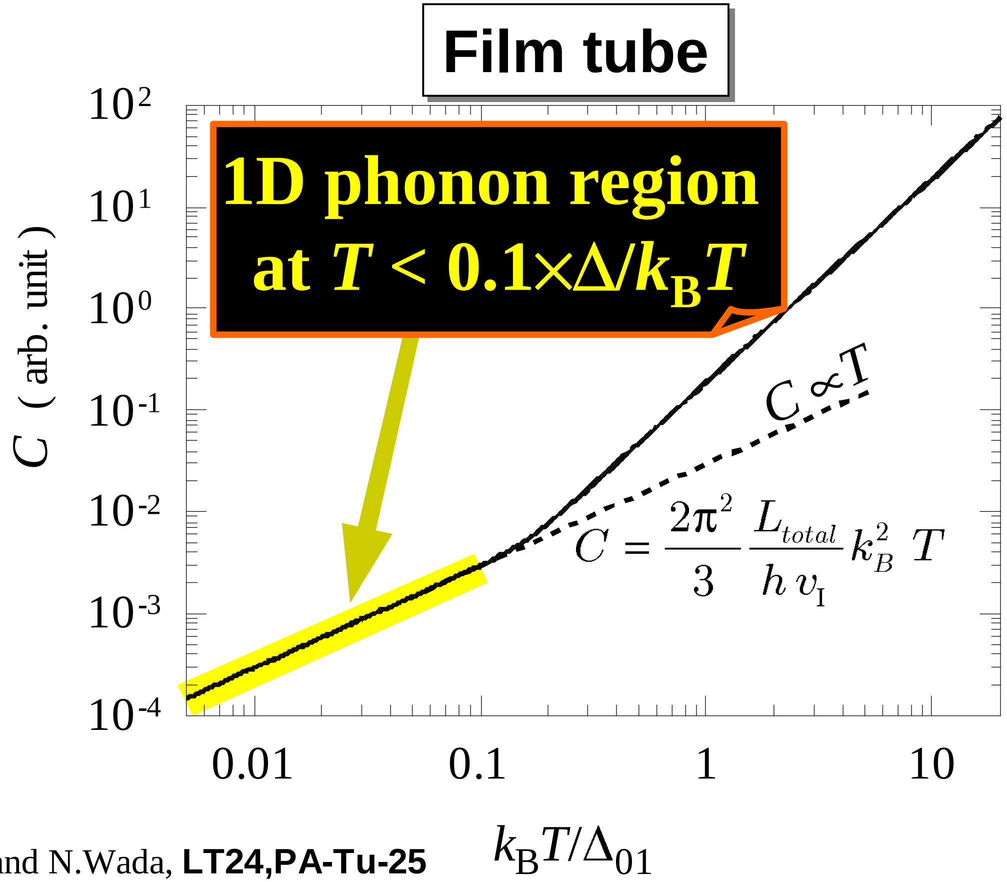
Eigen state in the crosssection



$\Delta_{01} \approx \dfrac{hv_I}{\pi d}$: Phonon

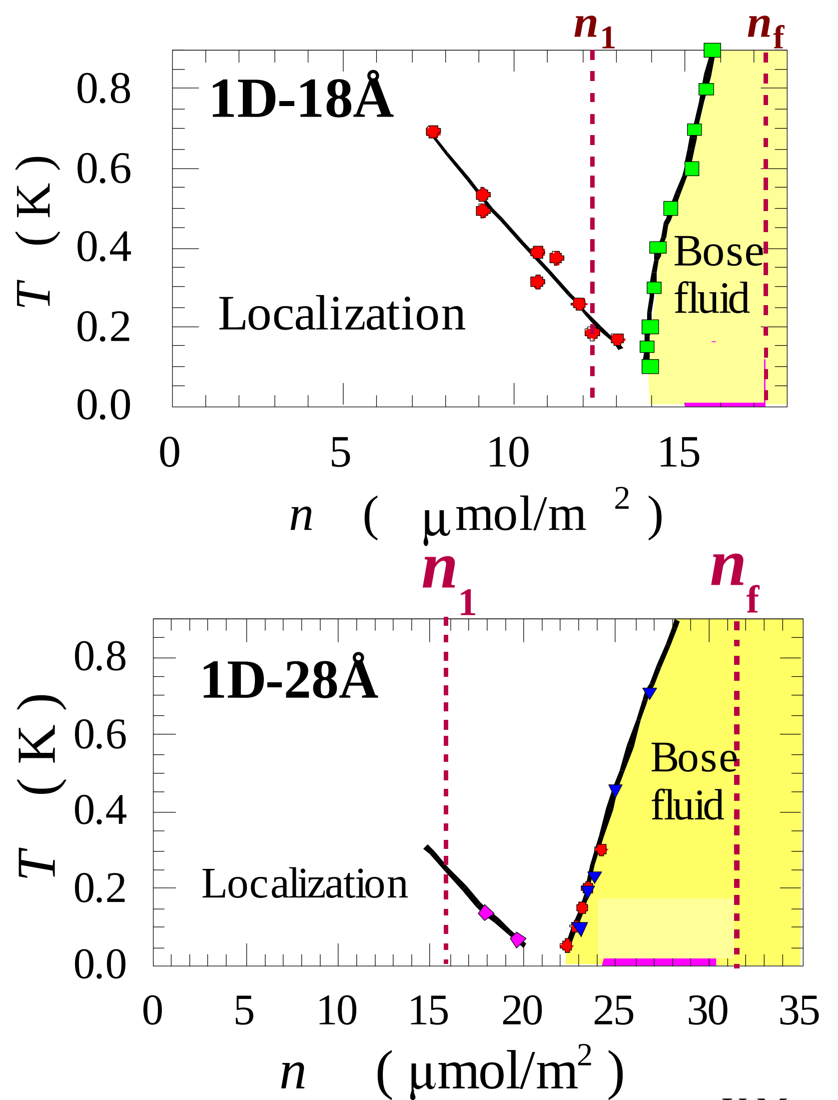
Phonon energy in 1D film tube

$$E_{k0\ell} = \sqrt{(v_I \hbar k)^2 + (k_B \Delta_{0\ell})^2}$$

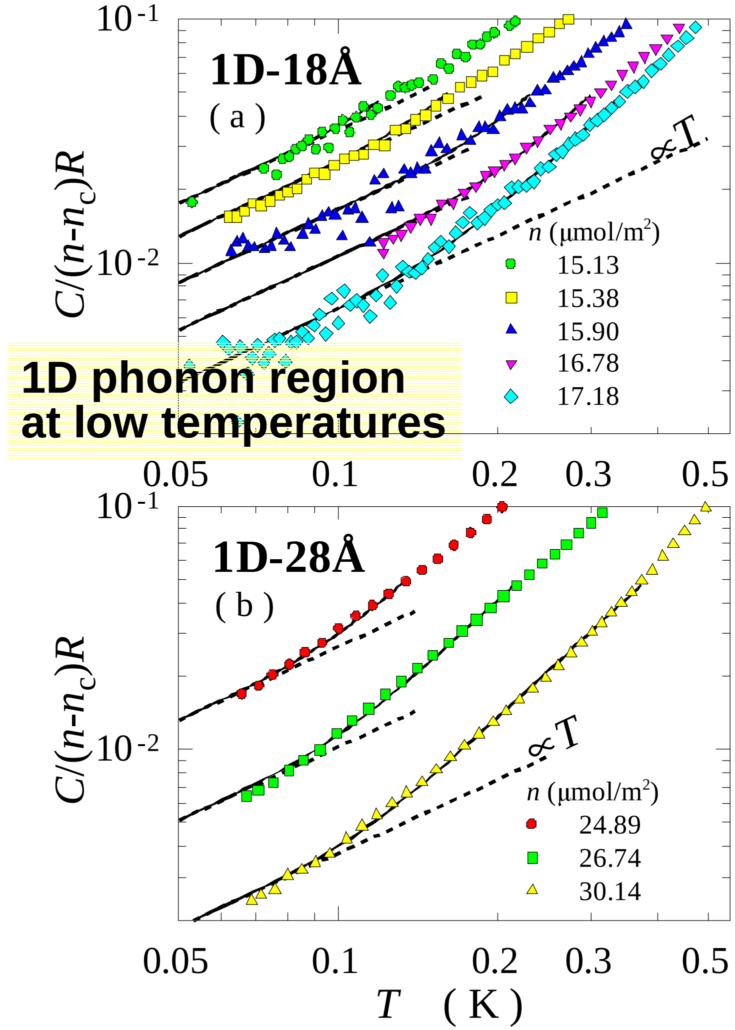


Y.Matsushita, J.Taniguchi, R.Toda, T.Matsushita, M.Hieda, and N.Wada, **LT24,PA-Tu-25**
M.W. Cole, and E.S.Hernandez, Phys. Rev. B **65,** 092501 (2002)

❑ 1D Phonon Region in 1D-18 and 28Å Nanopores

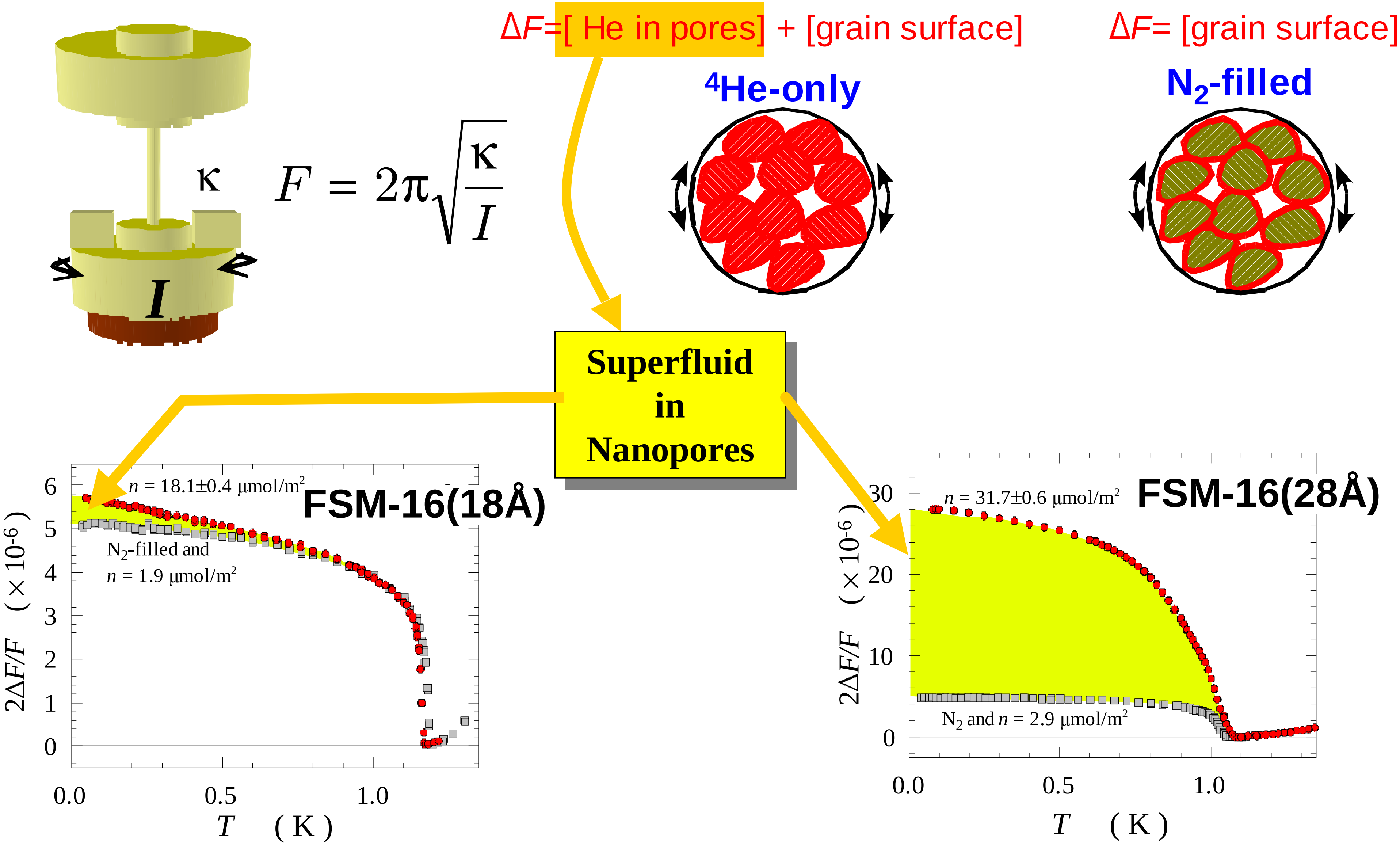


$C \propto T$ at $T < 0.1 \times \Delta_{01}/k_B$



Y.Matsushita, J.Taniguchi, R.Toda, T.Matsushita, M.Hieda, and N.Wada,
LT24, PA-Tu-25

❑ Observation of Superfluid by Oscillator

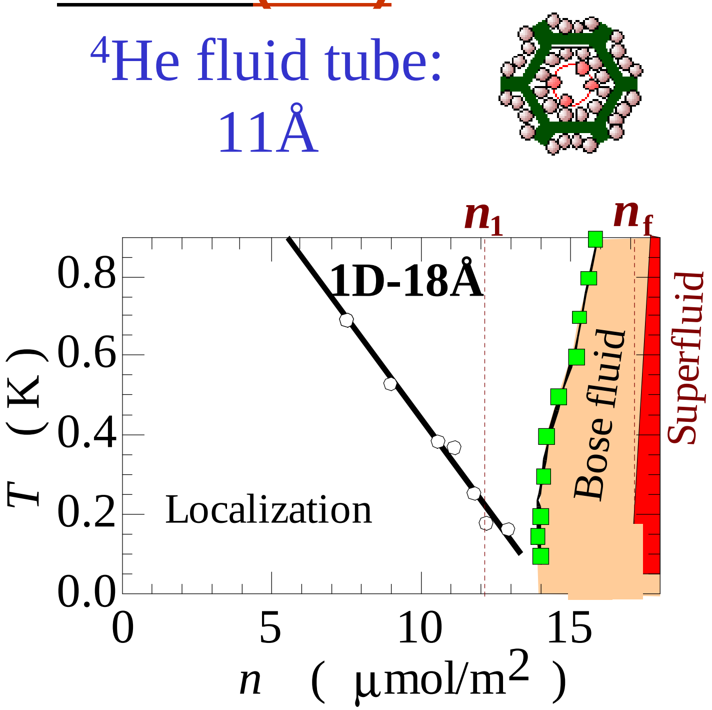


H. Ikegami, Y. Yamato, T. Okuno, J. Taniguchi, and N. Wada
J. Low Temp. Phys. **138**, 171 (2005)

❑ Phase diagrams of ^{4}He in 1D Nanopores

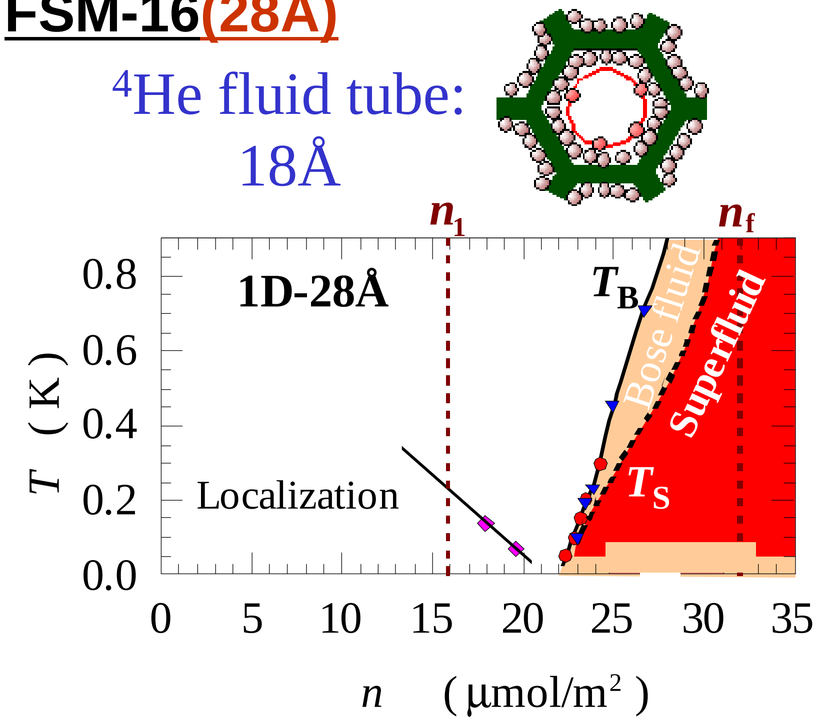
FSM-16(18Å)

^{4}He fluid tube: 11Å



FSM-16(28Å)

^{4}He fluid tube: 18Å



1D pores

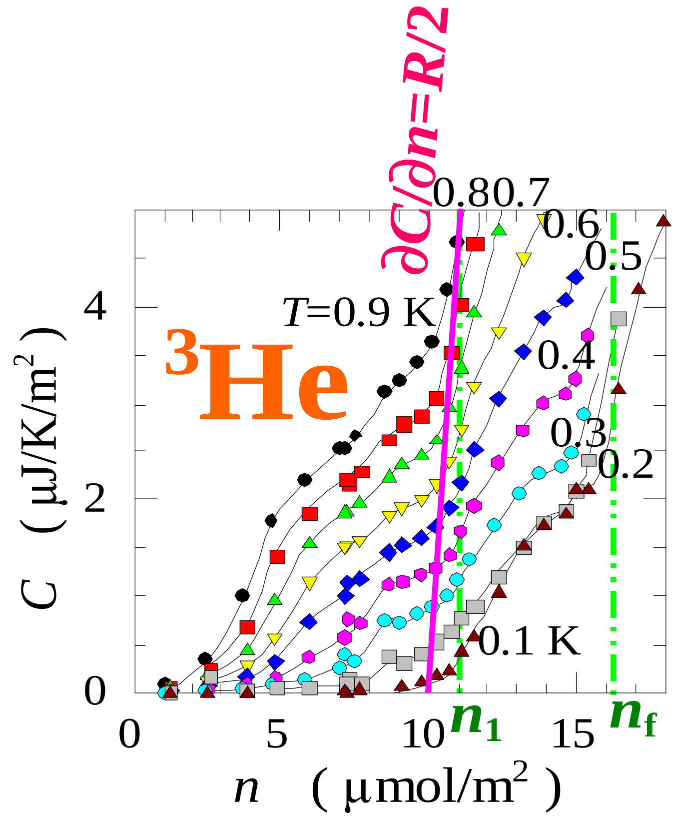
"Bose fluid" ≠ "Superfluid"

^{4}He in FSM-16

- **Nanotubes of ^{4}He Bose fluid films**
- **1D phonon state at $T < 1/10 \times \Delta_{01}/k_B$**
- **" Superfluid " ⊂ " Bose fluid "**

❑ Non-interacting ^{3}He Gas on ^{4}He layers

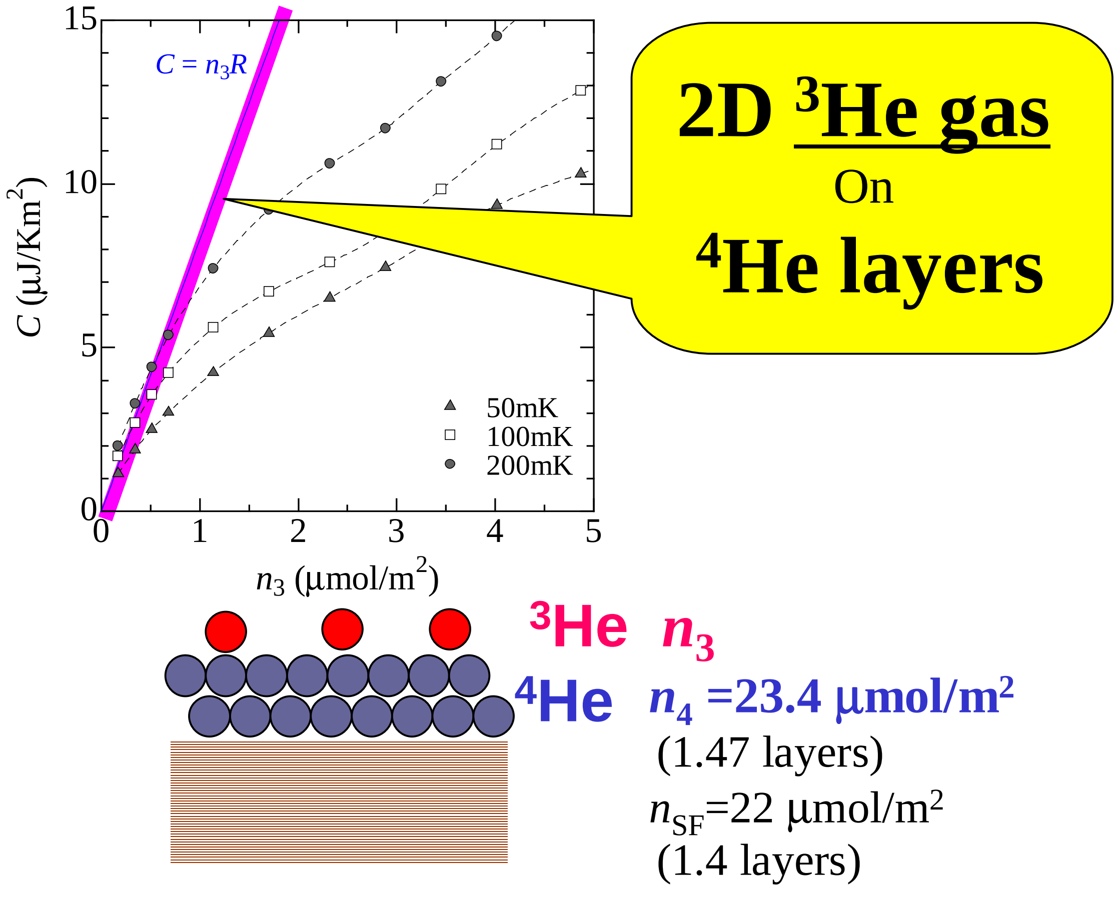
Pure ^{3}He in 1D-18Å pores



- ^{3}He fluids with some interactions

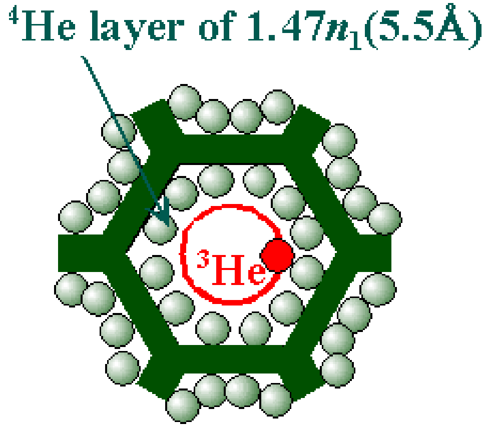
  $\partial C/\partial n < R/2$ or R

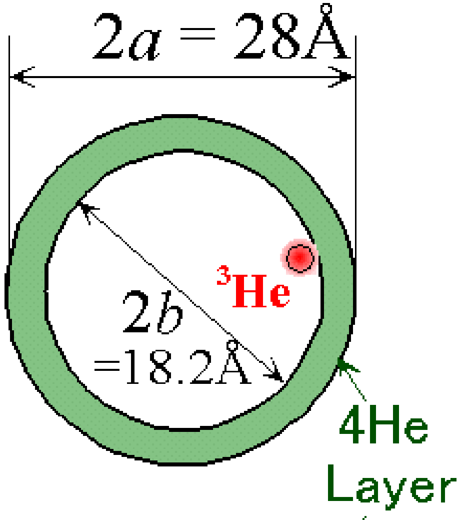
^{3}He Boltzman gas on ^{4}He-preplated 28Å pores

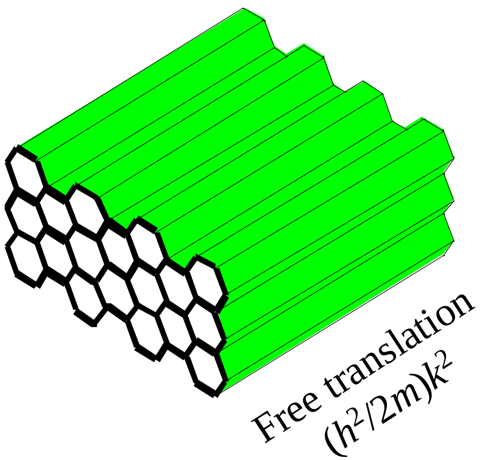


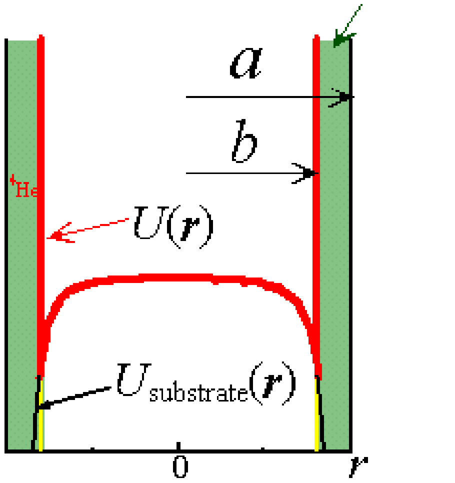
❑ Discrete Energy levels of ^{3}He in Crosssection

FSM-16(28Å)









$$E_{klm} = \frac{\hbar^2}{2m}k^2 + \Delta_{lm}$$

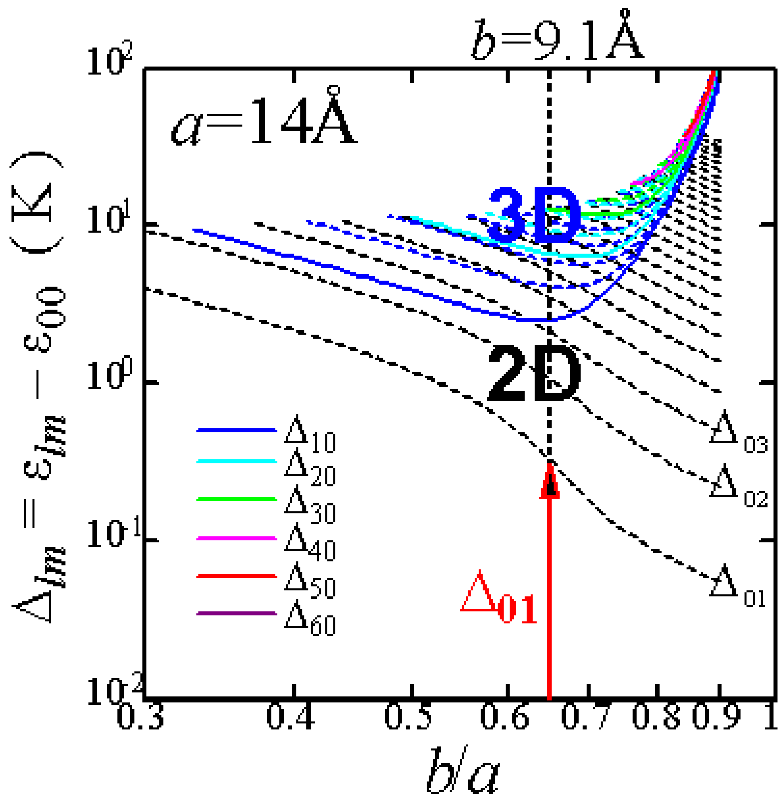
$$H = \frac{\hbar^2}{2m}\nabla^2 + U(r)$$

$$H\psi_{lm}(r,\varphi) = \varepsilon_{lm}\psi_{lm}(r,\varphi)$$

$$\Delta_{lm} = \varepsilon_{lm} - \varepsilon_{00}$$

l : number of nodes in r

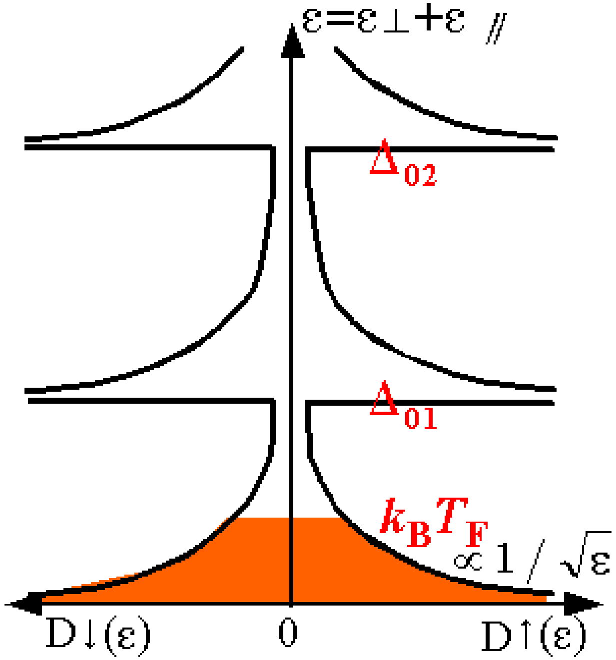
m : number of nodes in φ

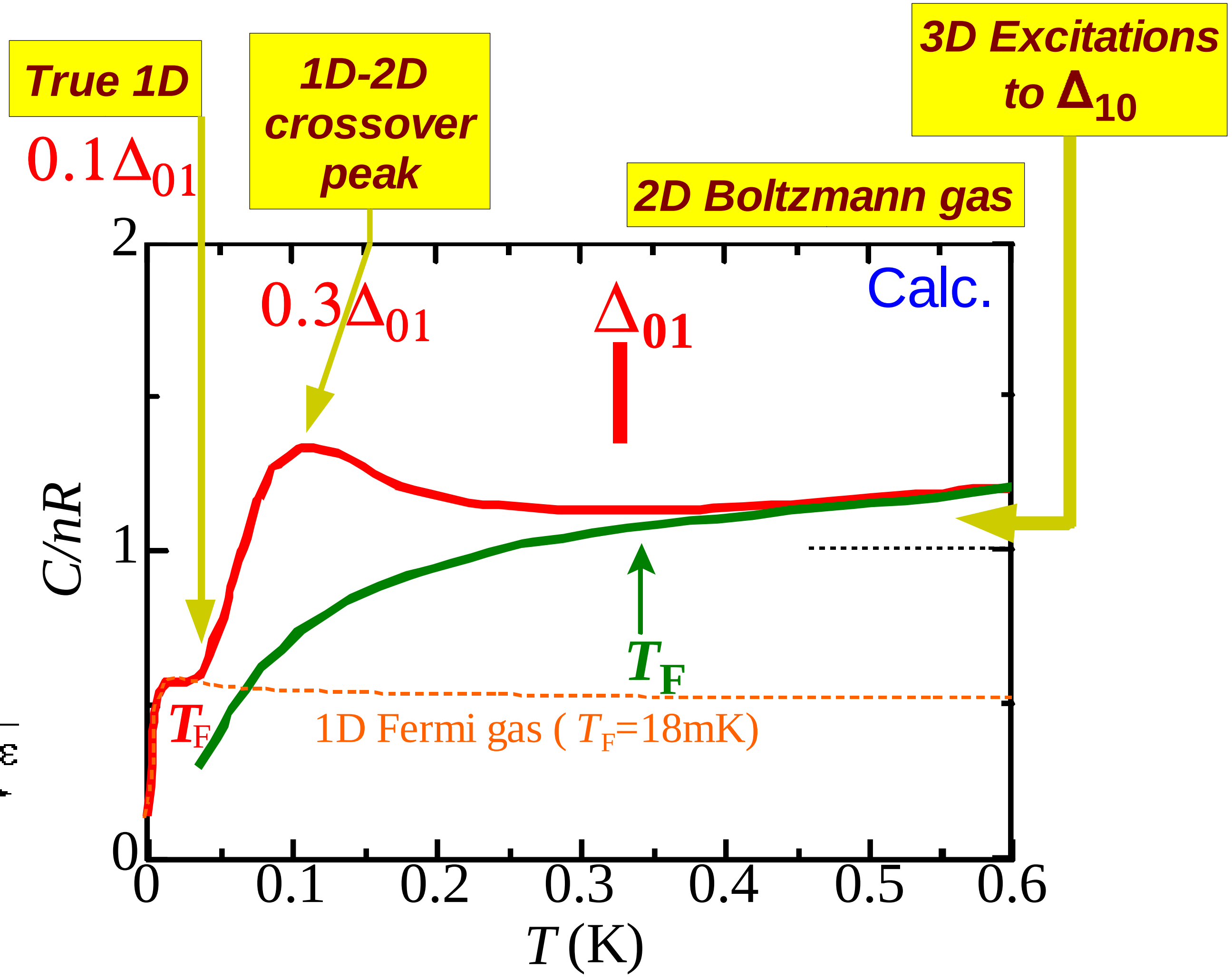


T. Matsushita, R. Toda, J. Taniguchi, H. Ikegami, and N. Wada : J. Low Temp. Phys. **138** (2005) 289-294.

Y. Matsushita, J. Taniguchi, A. Yamaguchi, H. Ishimoto, H. Ikegami, T. Matsushita, N. Wada, S.M. Gatica, M.W. Cole, and F. Ancilotto : J. Low Temp. Phys. **138** (2005) 211-216.

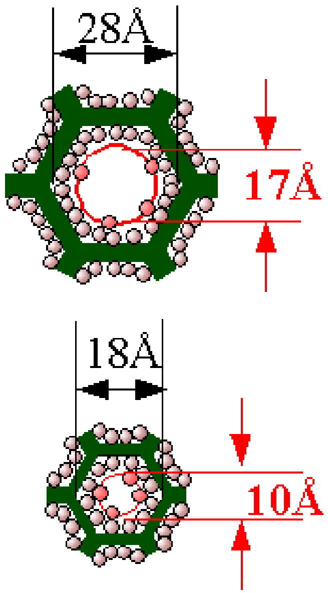
❑ ^{3}He Heat Capacity of 1D-2D Crossover

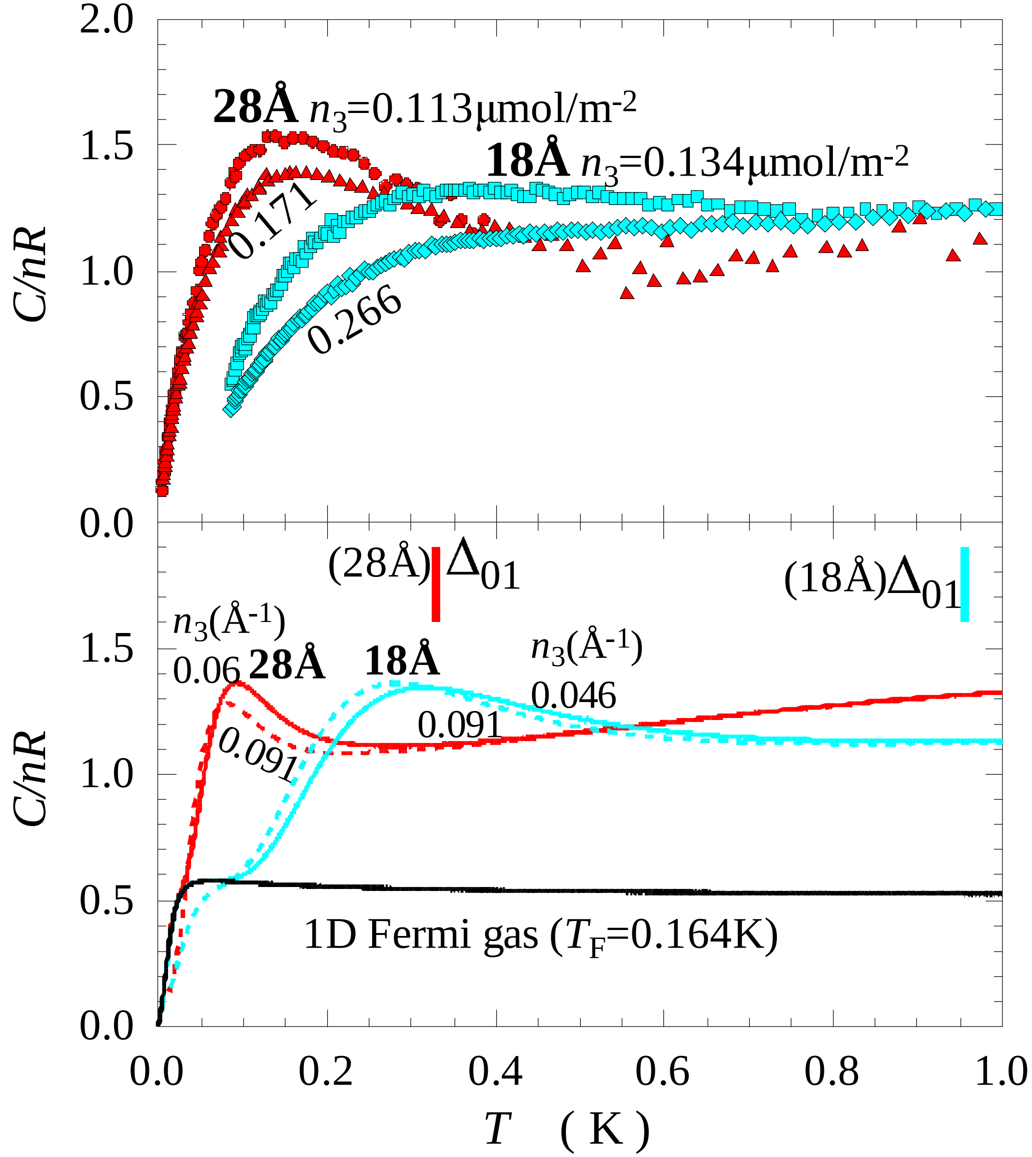




❑ 1D-2D Crossover Heat Capacities of ^{3}He

FSM-16
Preplated with
^{4}He layers





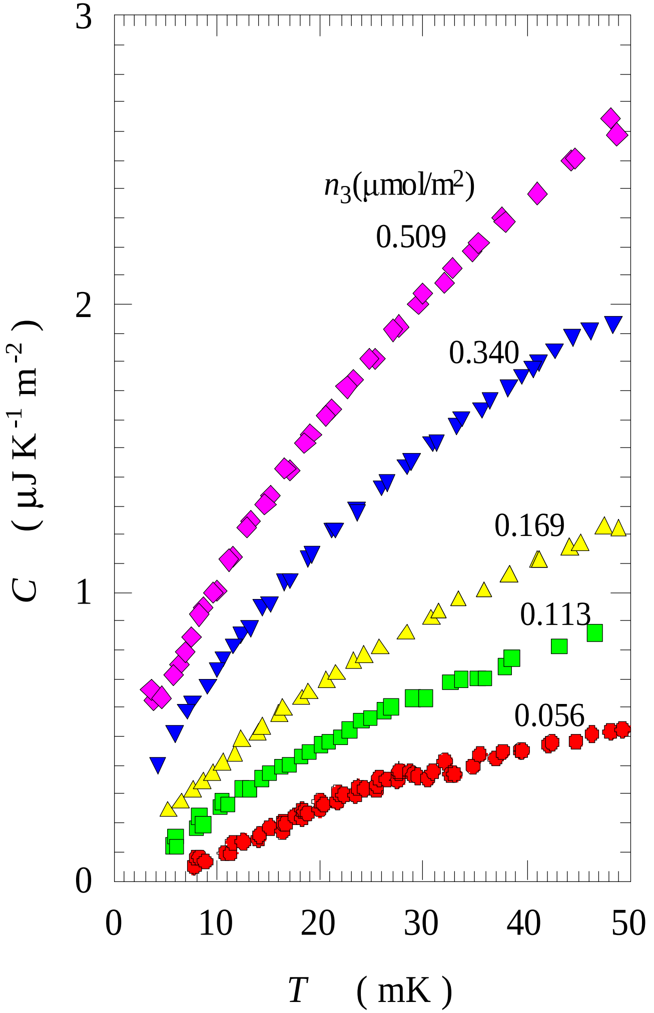
1D-2D
crossover peak
(28Å):≈0.15K
(18Å):≈0.35K

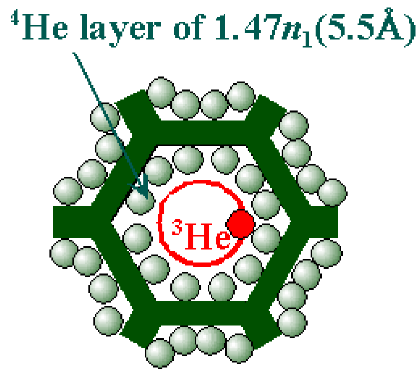
Y. Matsushita, J. Taniguchi, A. Yamaguchi, H. Ishimoto, H. Ikegami, T. Matsushita, N. Wada, S.M. Gatica, M.W. Cole, and F. Ancilotto
J. Low Temp. Phys. **138** (2005) 211-216.

Y. Matsushita, T. Matsushita, R. Toda, M.Hieda, N. Wada,
LT24, PA-Tu-29

❑ Degenerate ^{3}He of 1D Nanotubes

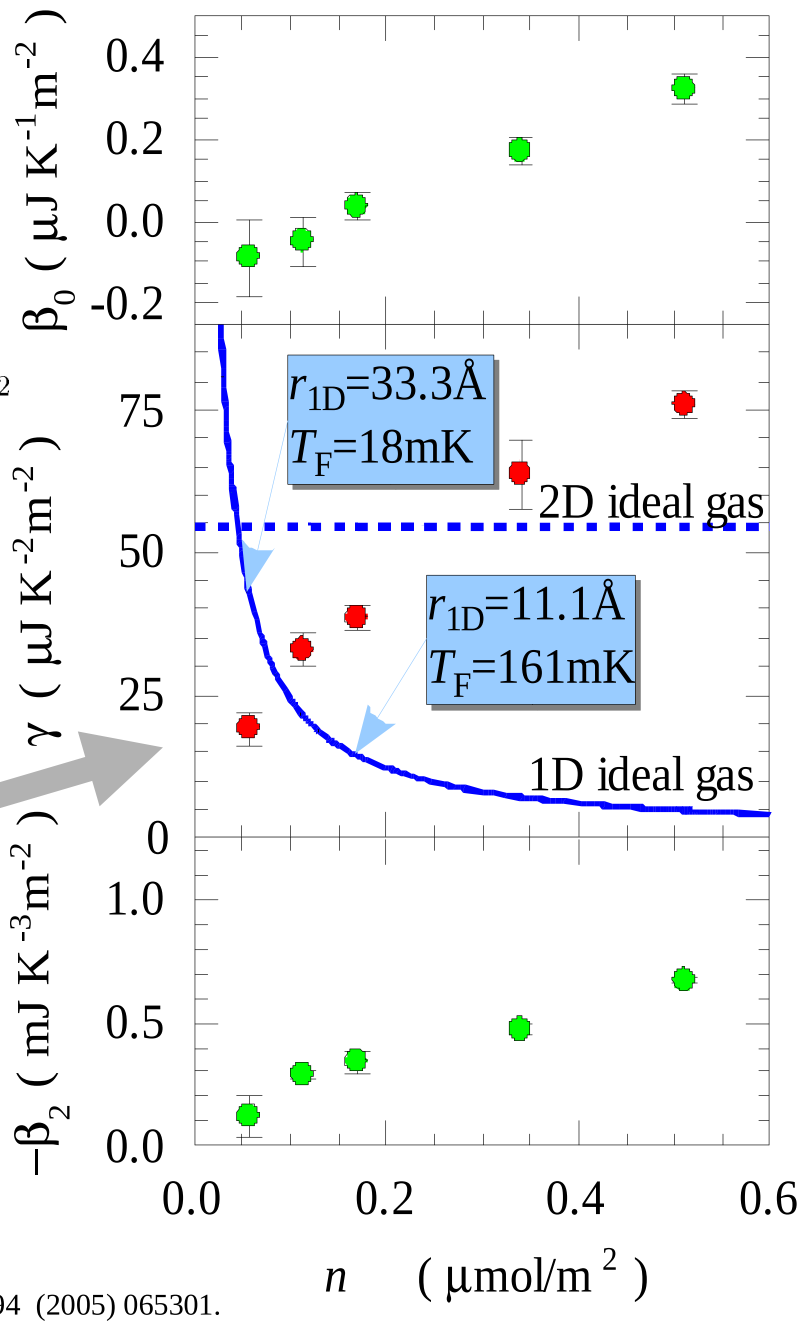
^{3}He nanotube(18Å)
in
1D-28Å pores





$$C / n = \beta_0 + \gamma T + \beta_2 T^2$$

γ vs *n*
Not $\gamma \propto 1/n$ of
1D ideal gas

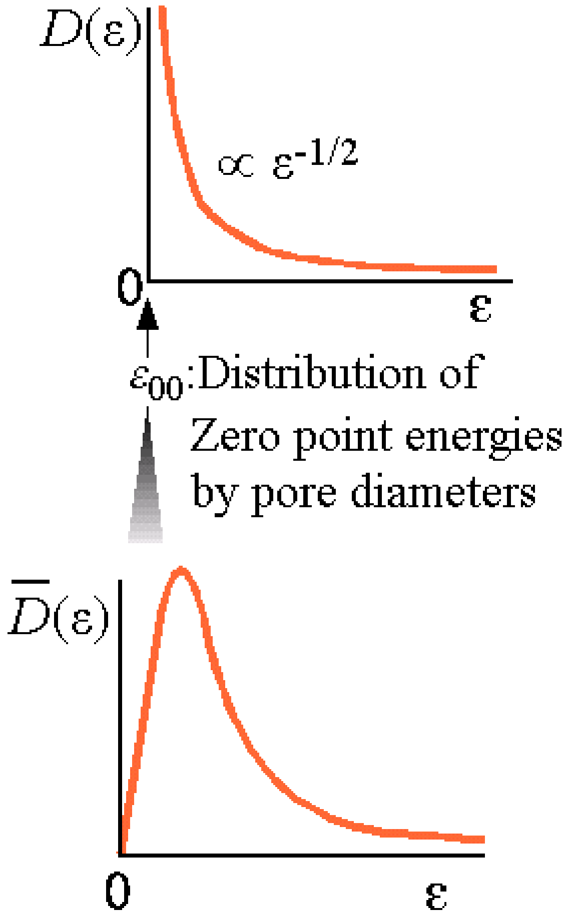


J. Taniguchi, A. Yamaguchi, H. Ishimoto, H. Ikegami, T. Matsushita, N. Wada,
S. M. Gatica, M. W. Cole, F. Ancilotto, S. Inagaki, and Y. Fukushima: Phys. Rev. Lett. 94 (2005) 065301.

❑ Possible Degenerate States of ^{3}He in 1D Pores

Heterogeneity of pores

M.W. Cole, F. Ancilotto, and S.M. Gatica,
J. Low Temp. Phys. **138** 195-200 (2005).

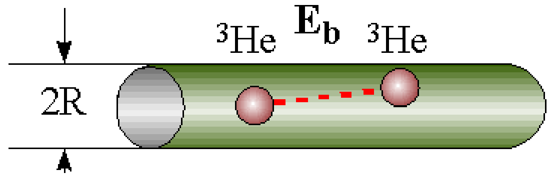


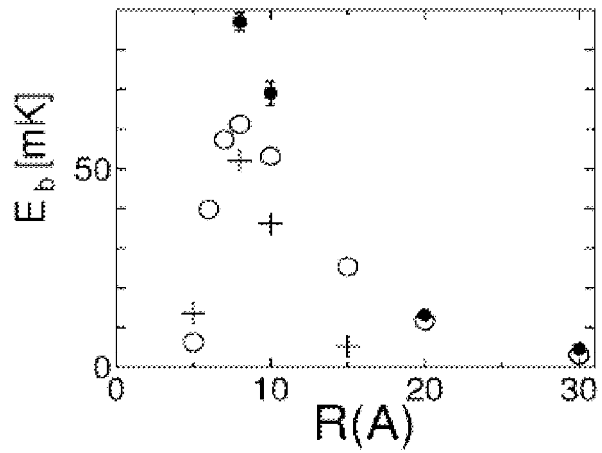
^{3}He-^{3}He interactions

Y. Okaue, and D.S. Hirashima,
J. Phys. Chem. Solids (2005) in press.

Y. Okaue, Y. Saiga, and D.S. Hirashima
LT24 PA-Tu-34

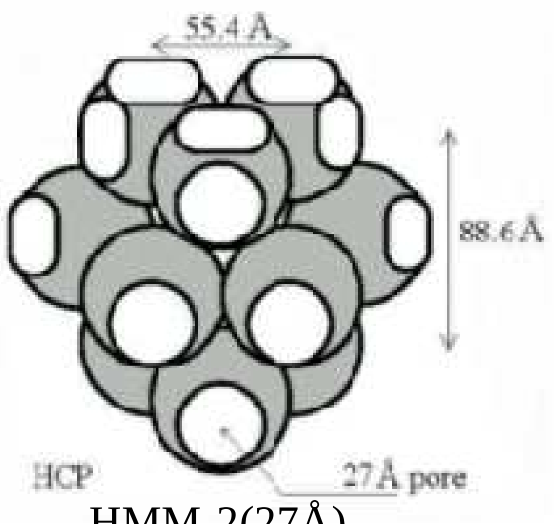
Possible binding energy $E_b \approx 50$mK





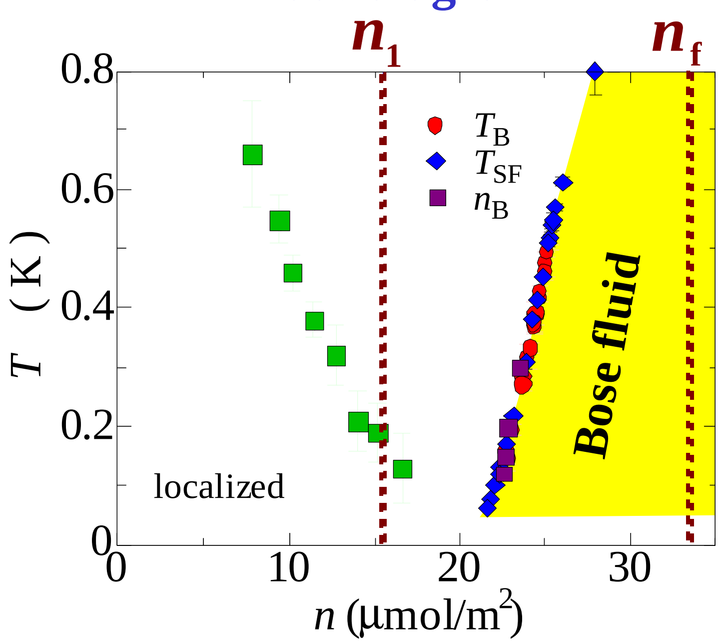
Bose Fluid of ^{4}He in 3D-27Å Nanopores

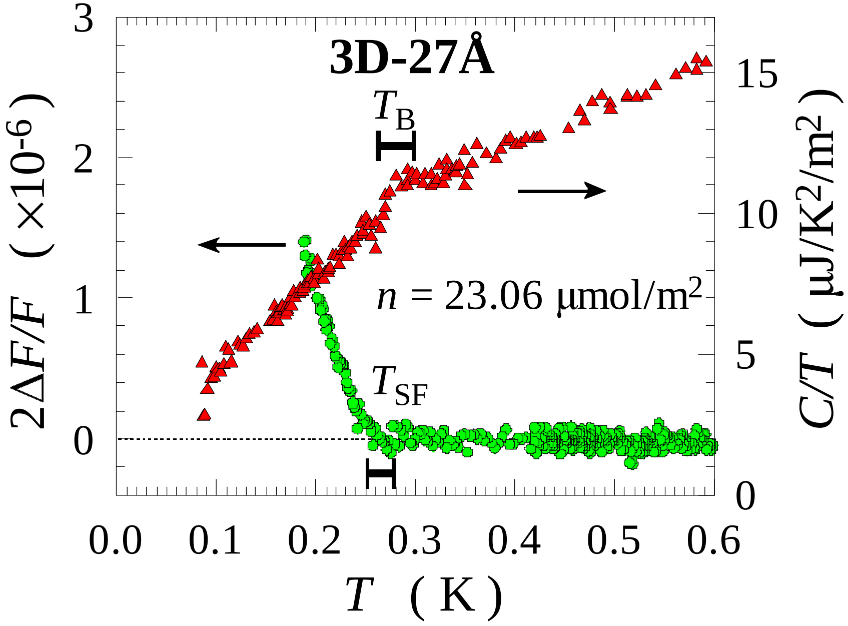
3D-nanopores



HMM-2(27Å)

Phase diagram





^{4}He in 3D Nanopores

- **" Superfluid " = " Bose fluid "**

R.Toda, T.Yamada, J.Taniguchi, T.Matsushita, and N.Wada, Physica B, **329-333**, 282 (2003).

T.Yamada, R.Toda, Y.Matsushita, T.Matsushita, and N.Wada, J. Low Temp. Phys., **134**, 601 (2004).

❑ Our studies in " Superclean Materials"

^{4}He Bose fluids in nanopores

- To realize 0D, 1D, 2D and 3D Bose fluids
- BEC and superfluid in *N*-dimensional ^{4}He Bose fluids

^{3}He Fermi fluids in nanopores

- To study 1D-^{3}He fluids
- Interactions in *N*-dimensional degenerate ^{3}He fluids