Tokyo, Dec. 15, 2005

Ground State of ^{3}He Atoms Confined in a Narrow Tube

D. Hirashima, Nagoya University

1 . Ground state of ^{3}He atoms confined in a narrow tube

Experiment by Ishimoto-Wada's group
(J. Taniguchi et al. PRL 94('05) 065301.)

2. Zero point of motion of quantum particles

3. How to polarize a few electrons (without a magnetic field)

Multiple spin exchanges

1. ^{3}He “liquid” confined in nanopores (diameter ∽28A)

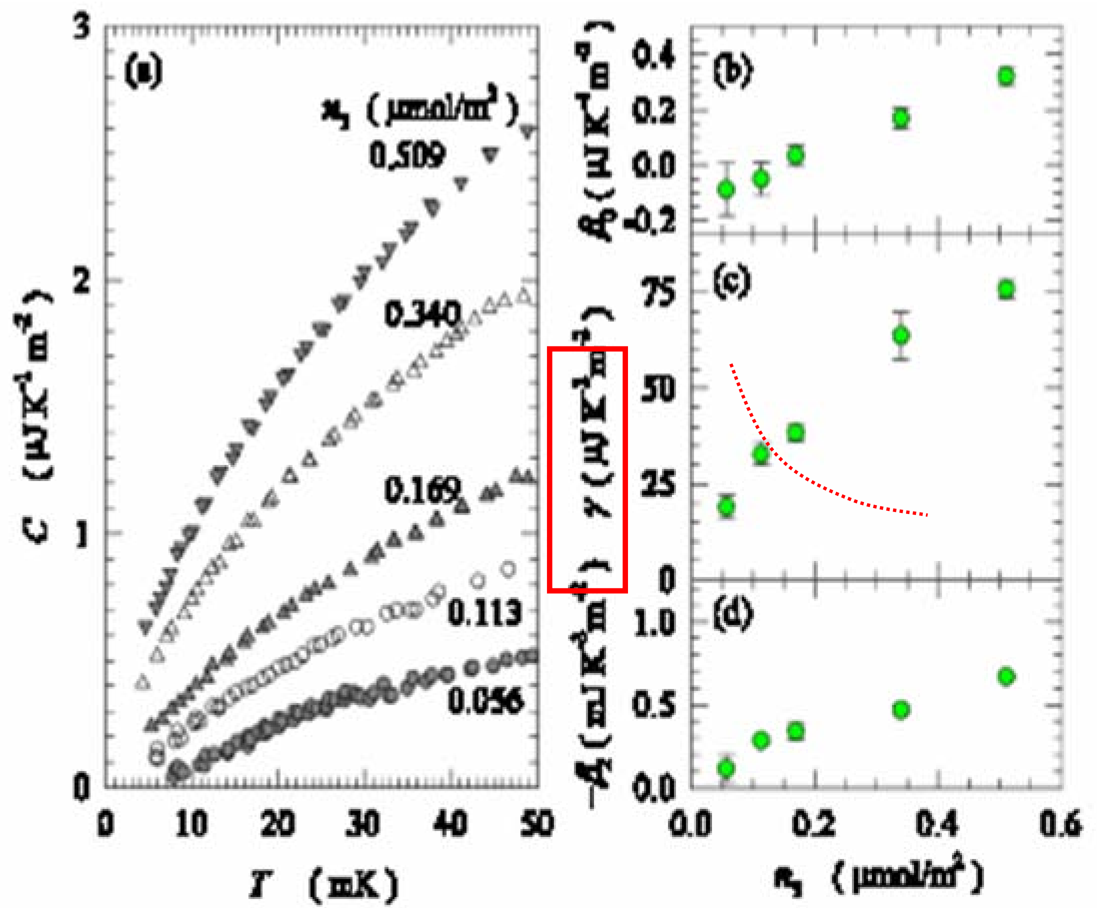
(J. Taniguchi et al, PRL. **94** (‘05) 065301.)

(1) Specific heat linear in T, C∽ γ T, at low temperatures.
(2) Dimensional crossover from 1D-like state at low T to 2D-like state at higher T.

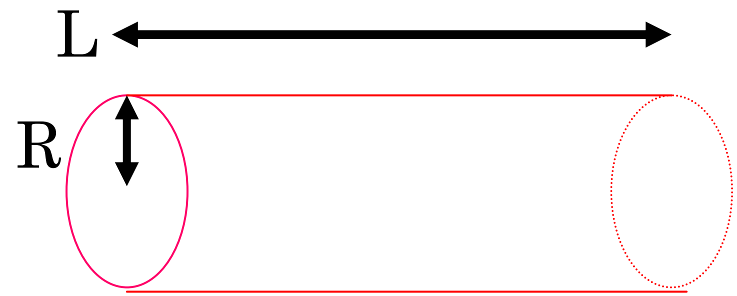
(3) Density dependence of γ is a puzzle, disagreeing with what is expected for 1D “Fermi liquid”.

1. Inhomogeneity of pore diameter ???
   + free fermions
   M. W. Cole et al (’05)

2. Condensation into a liquid state ???
   Y. Okaue, Y. Saiga & D. Hirashima



1-2. Model and Method



$$H = -\frac{\hbar^2}{2m}\sum_{i=1}^{N}\nabla_i^2 + \frac{1}{2}\sum_{i\neq j}^{N} V_{\text{int}}(r_{ij}) + \sum_{i=1}^{N} V_{\text{adsorp}}(r_i)$$

$V_{\text{int}}(r) = \text{Lennard} - \text{Jones},\ \text{Aziz},\ \textit{or}\ \text{Korona potential.}$

For ^{3}He, the **quantum parameter** $\eta = \dfrac{\hbar^2}{m\sigma^2\varepsilon} = 0.24$

σ : hardcore diameter , ε : potential depth

The critical value of the quantum parameter for the formation of a two-body bound state is

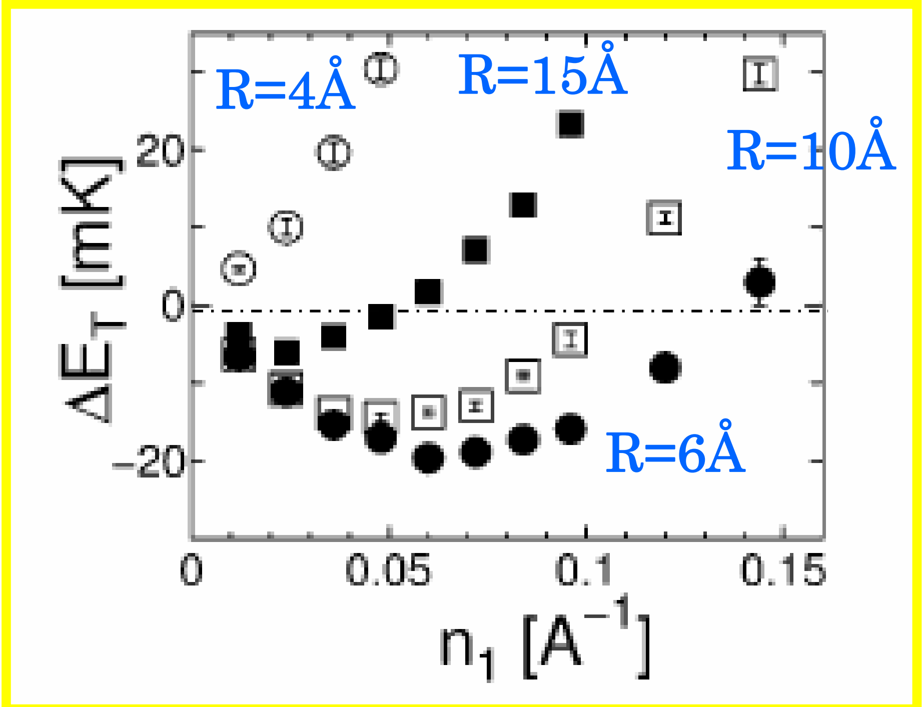
$$\eta_c = 0.179$$

in 3D and 1D. → No ^{3}He dimer in 3D and 1D.

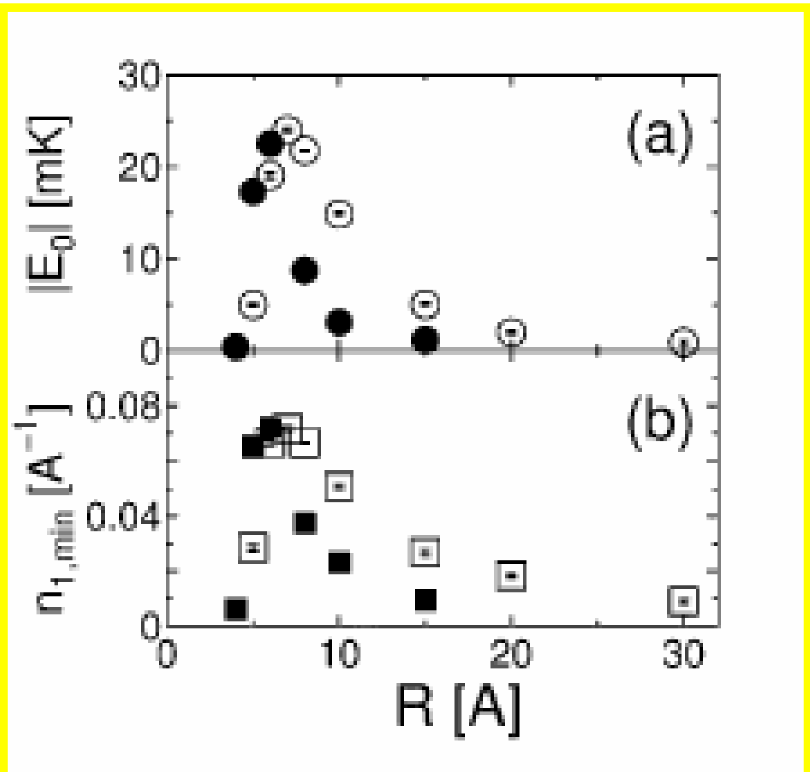
Ground state of 3He atoms in a narrow tube: N=60-108

Variational Monte Carlo method

Depend. of the ground state energy on linear density



Binding energy and condensation density



Condensation into a liquid state at R>4Å.

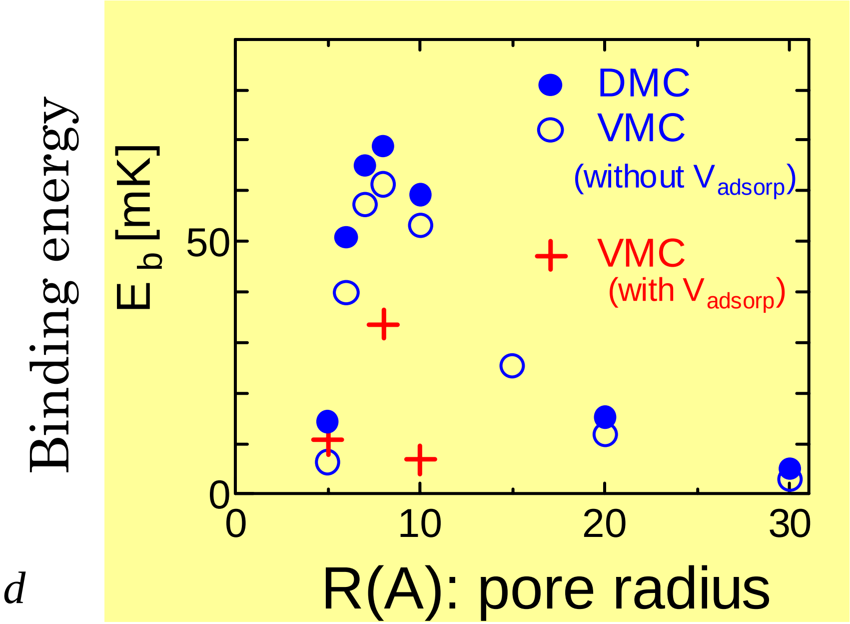
Binding energy (per particle) ~ 20 mK

Interparticle distance ~ 15 Å

open symbols: no adsorption potential
closed symbols: adsorption potential

Two ^{3}He atoms in quasi-one dimension

No bound state in 1D & 3D, but
Confinement-induced bound state



Y. Okaue and D. Hirashima, 2005.

In d-Dimensional fermion systems,

Kinetic energy $\langle K \rangle / N \propto n_d^{\,2/d}$

Potential energy $\langle V \rangle / N \propto n_d$

In (quasi-)1D, **<K>/N << <V>/N** in the low density limit, $\mathbf{n_1 \rightarrow 0}$.

Cf. Confinement-induced resonance in **ultracold atoms** trapped in a quasi-1D potenatial. [M. Olshanii, ('98), T. Bergeman et al. ('03)]

At finite temperatures !!!!!

No phase transition at a finite temperature.

Uniform gas phase (with large density fluctuations) at finite T.

Decrease in γ is seen in a rather dense region.

Inhomogeneity ?????

Distribution of pore diameter, adsorption potential ....

Distribution of the binding energy E_0
Adsorption centers

2. Zero-point motion of quantum particles:

Solidification of quantum gas (liquid)

Hydrogen molecules adsorbed on graphite [H. Wiechert ('91)]

Commensurate phase $\sqrt{3}\times\sqrt{3}$

H_2 $T_{\mathrm{melt}} = 20.44\mathrm{K}$

D_2 $T_{\mathrm{melt}} = 18.1\ \mathrm{K}$

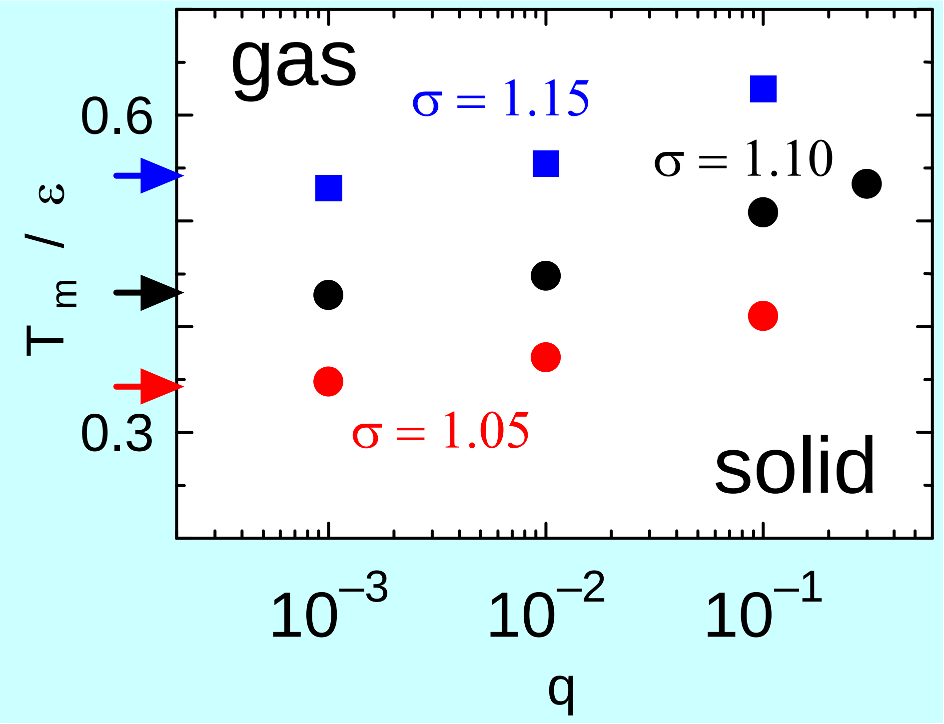
Lighter molecules solidify at a higher temperatures.

cf. ^{3}He, ^{4}He $T_{\mathrm{melt}} \approx 3\ \mathrm{K}$

Quantumness (zero point motion) promotes localization ??

cf. Quantum localization (Tsuneyuki, Imada)
Quantum melting of domain walls (Momoi)

Solidification of quantum particles adsorbed on a periodic substrate



Hirashima, Momoi & Takagi, JPSJ 72 ('03) 1446.

Path integral MC (distinguishable particles)

$$q = \frac{\hbar^2}{2ma^2\varepsilon}$$

a : lattice constant

σ : hardcore diameter

Lighter mass promotes solidification.

3. How to polarize a few electrons (without a magnetic field) in quantum structures (dots)

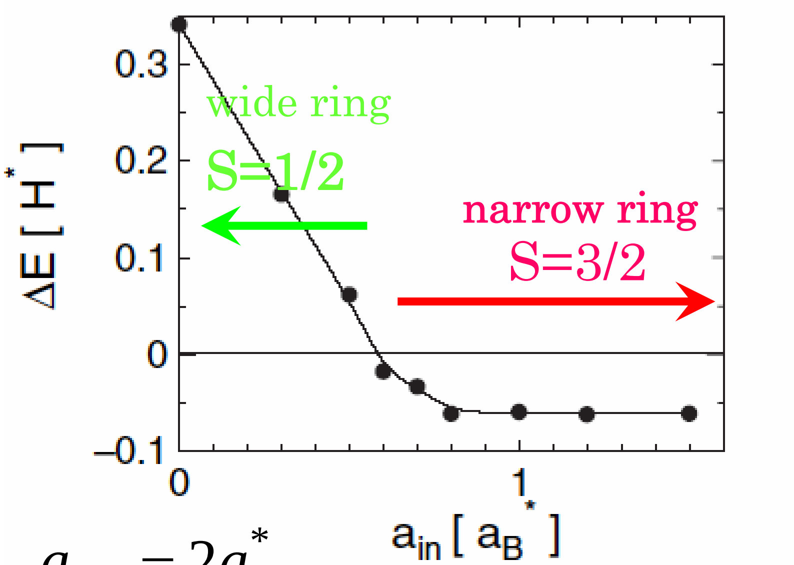
Control of shape of a dot → Control of exchange paths

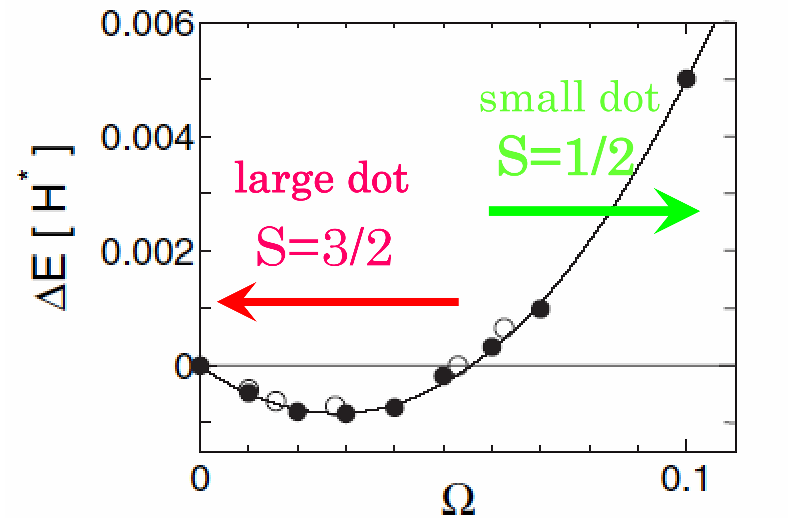
Three electrons in quantum structures (J. Usukura, Y. Saiga & D. Hirashima, JPSJ 74 ('05) 1231)

Quantum ring

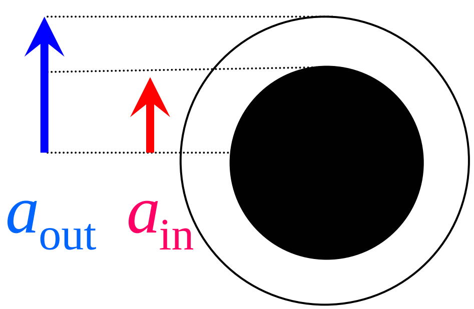
$\Delta E = E_{3/2} - E_{1/2}$

Harmonic confinement





$a_{\mathrm{out}} = 2a_{\mathrm{B}}^{*}$



Three electrons on a ring (no two-electron exchanges)

→ Fully polarized state S=3/2

(C. Herring, PR B 11 ('75) 2056.)

1 . Ground state of ^{3}He atoms confined in a narrow tube

2. Zero point of motion of quantum particles

3. How to polarize a few electrons (without a magnetic field)