Non-Classical Rotational Inertia in Two-Dimensional ^{4}He Solid on Graphite

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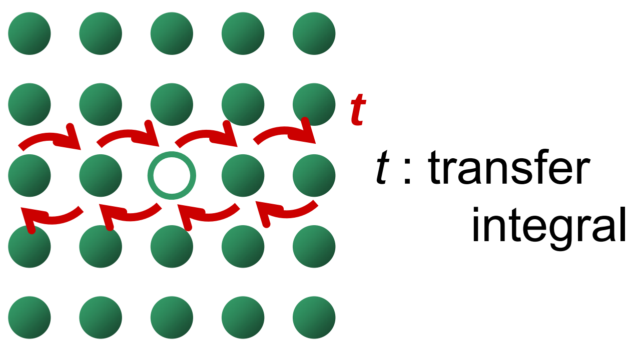
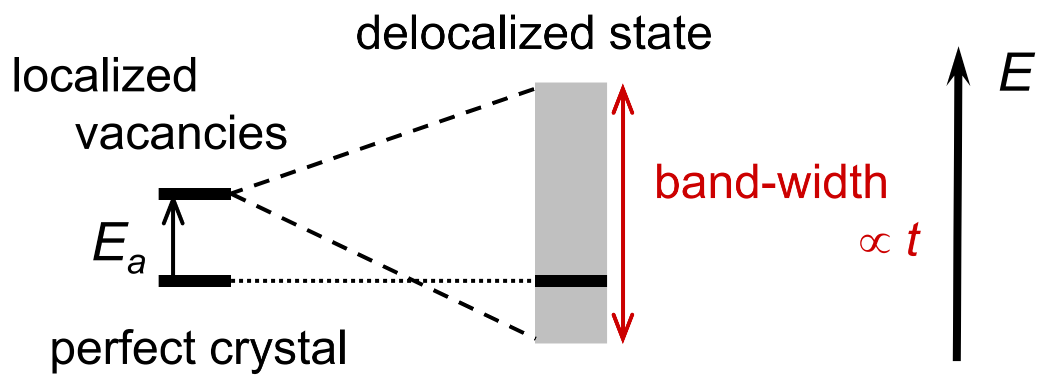
● Zero-point vacancies (ZPVs) in a quantum solid and superfluidity of ZPVs

(A. F. Andreev and I. M. Lifshitz, *Sov. Pys. JETP*, **29**, 1107 ('69))

- Vacancies in a **quantum solid** are delocalized in the solid due to the zero-point fluctuation → **Bloch state of the vacancies**





- At 0 K, a finite density of vacancies exists in a quantum solid when the band-width is large enough.

  → **Zero-point vacancies (ZPVs)**

- The ZPVs in solid ^{4}He are Bose particles.

  → Bose-Einstein condensation of ZPVs at low temperatures, leading to **superfluidity of ZPVs** in a bosonic quantum solid.

This scenario is one of the theoretical predictions of ZPVs and supersolidity due to the ZPVs in a quantum solid.

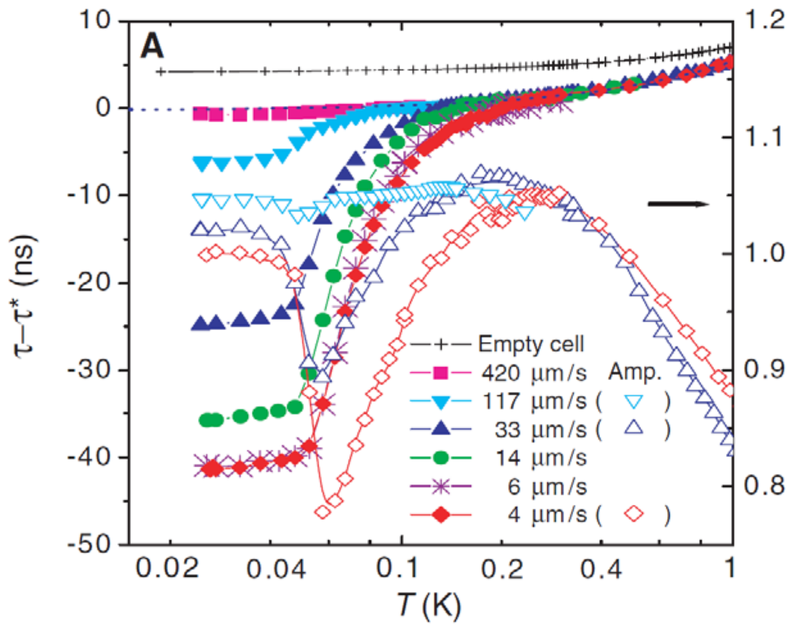
● Experimental discovery of NCRI in solid ^{4}He

(E. Kim and M. H. W. Chan, *Nature*, **427**, 225 ('04); *Science*, **305**, 1941 ('04).)

•By torsional oscillator (TO) studies, Kim and Chan discovered **non-classical rotational inertia (NCRI)** in solid ^{4}He.

•The supersolid behaviors depend on **sample preparation**:

✓**Cooling rate** in sample preparation
✓**Geometry** of the sample cell (*S* / *V*)
✓**Annealing effects**



• These strongly suggest that **crystal imperfections** in the solid samples, such as **dislocation lines** or **grain boundaries**, are strongly associated with the observed supersolid behaviors.

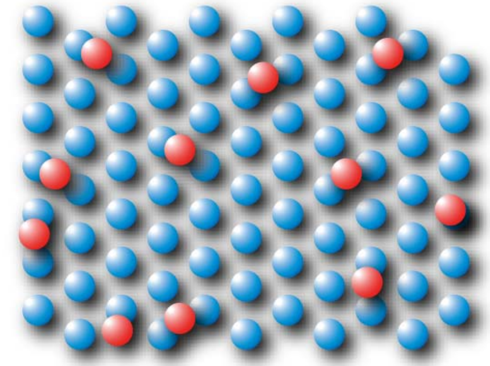
•If it is true, the supersolid behavior cannot be expected in a perfect ^{4}He crystal at 0 K.
The simple ZPVs scenario does not describe the observed behaviors.

● Two-dimensional (2D) ^{3}He system on graphite

Y. Matsumoto, D. Tsuji, S. Murakawa, H. Akisato, H. Kambara, and H. Fukuyama, *JLTP*, **138**, 271 ('05).

The existence of ZPVs has been proposed in 2D ^{3}He on graphite

- The 1st layer : ^{4}He monolayer of 12.03 nm^{-2}
- The 2nd layer : **^{3}He** submonolayer
  → 2D Fermi system



•At the low density region → **2D Fermi fluid**

•At the four sevenths density $\rho_{4/7}$ (6.85 nm^{-2})
→ **registered 4/7 phase** (**2D solid ^{3}He**)

•At just below $\rho_{4/7}$ → a **novel quantum phase**
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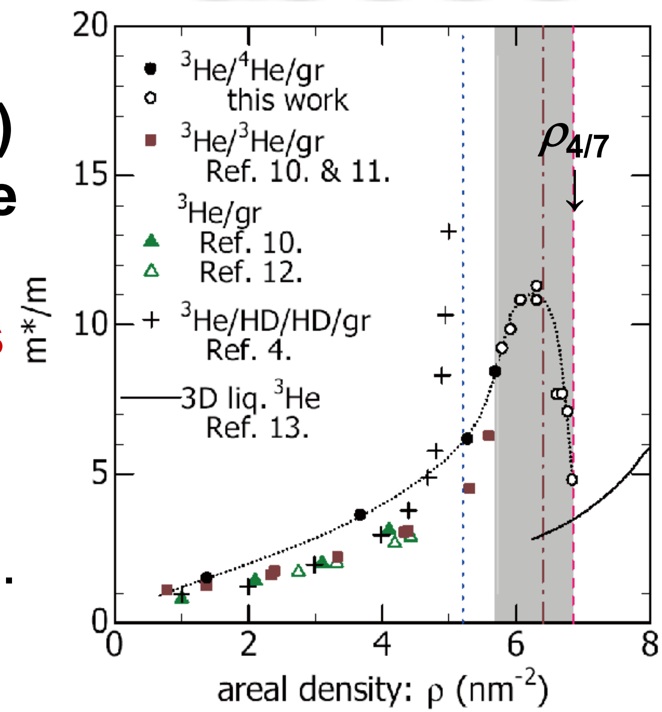
a **Mott localized phase** **doped with ZPVs**

•The thermodynamic properties of the phase demonstrate **delocalization of ZPVs** **in the 2D ^{3}He solid**.

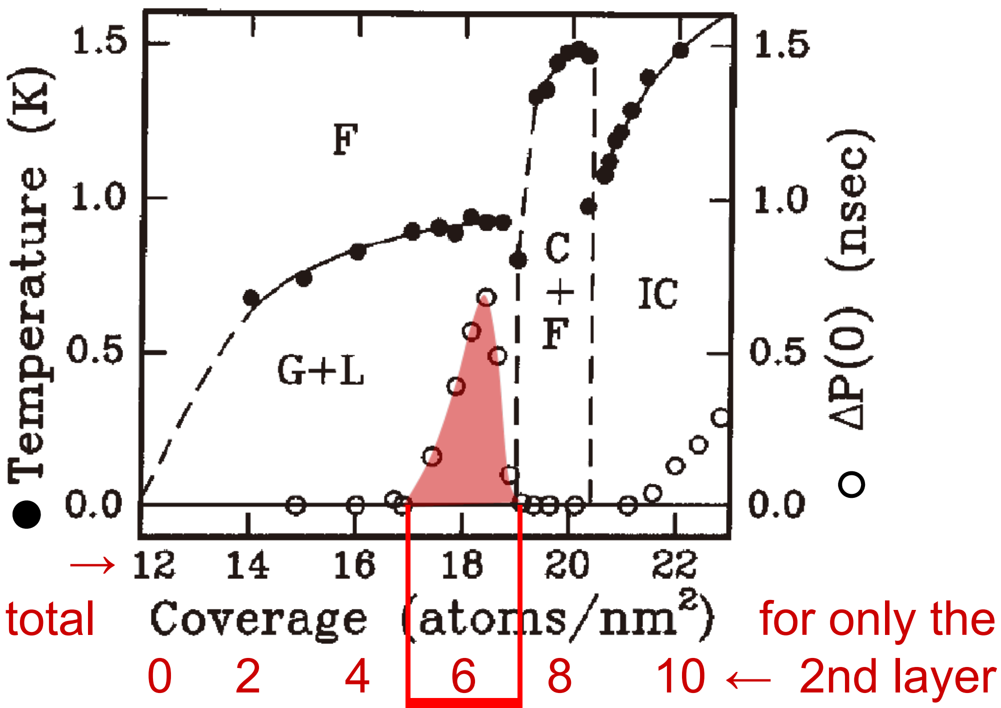


•The proposal of the mobile ZPVs in 2D ^{3}He solid suggests that **mobile ZPVs also exist in 2D ^{4}He solid**.

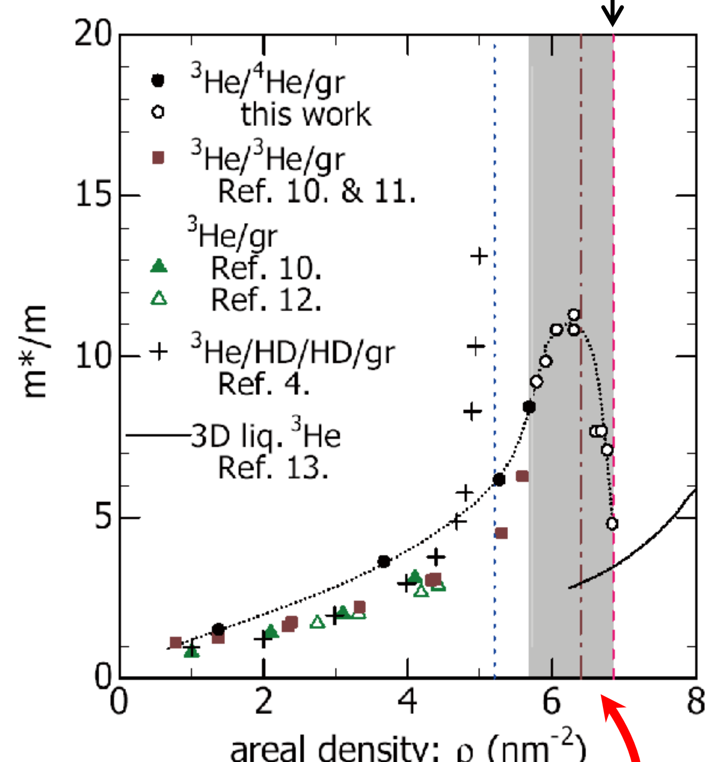
•**Superfluidity of the ZPVs**, namely **supersolidity**, is expected because the ZPVs in solid ^{4}He are Bose particles.

•Crowell and Reppy (CR) have found a peculiar superfluid behavior for the ^{4}He films on graphite at the coverage between 17 and 19 nm^{-2}

(Crowell and Reppy, *PRL* **70**, 3291 ('93); *PRB* **53**, 2701 ('96))



4/7 phase (6.85 nm $^{-2}$)



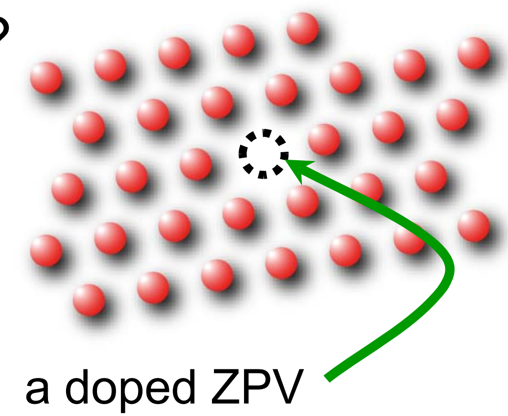
corresponding coverage

● The aim of the present investigation

Motivation:

•The origin of the peculiar superfluid behavior observed by Crowell and Reppy.

•As in the 2D ^{3}He system on graphite, do **ZPVs exist** in a 2D ^{4}He system?



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Experimental:

•By **TO studies, possible ZPVs** and **2D supersolid state** in **adsorbed ^{4}He films on graphite** are investigated.

•Frequency shift Δf of the TO is investigated at various ^{4}He coverage in order to confirm the **reentrant Δf** observed by CR,

•**Oscillation velocity v_{osc} dependence of NCRI** is examined.

● Setup of the torsional oscillator (TO)

- Graphite substrate: Grafoil (surface area: 21.68 m^3)
- Commercial ^4He gas
- The TO made of BeCu

  resonance frequency : $f \sim 1043.9$ Hz

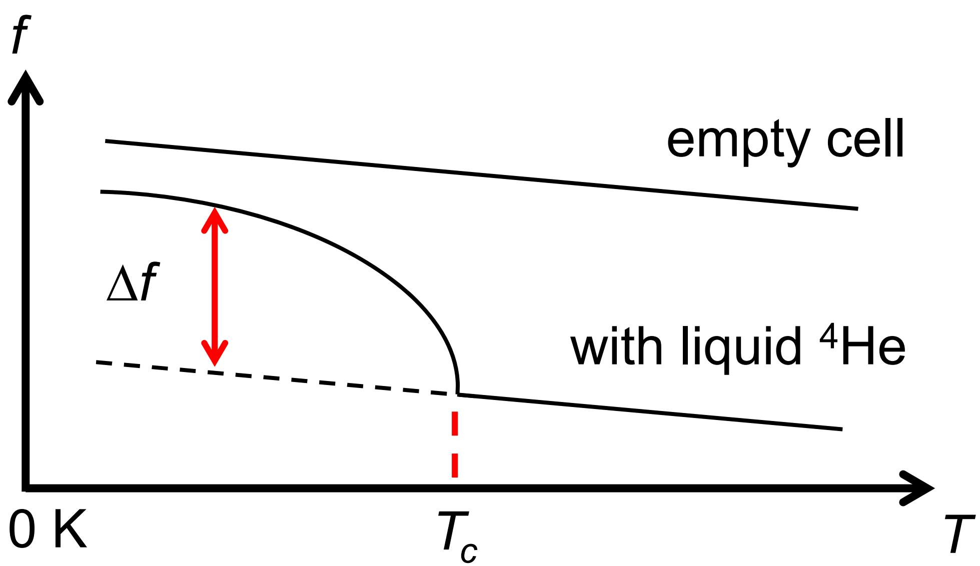
  Q-value : $Q = 3.0\times10^6$ at 10 mK

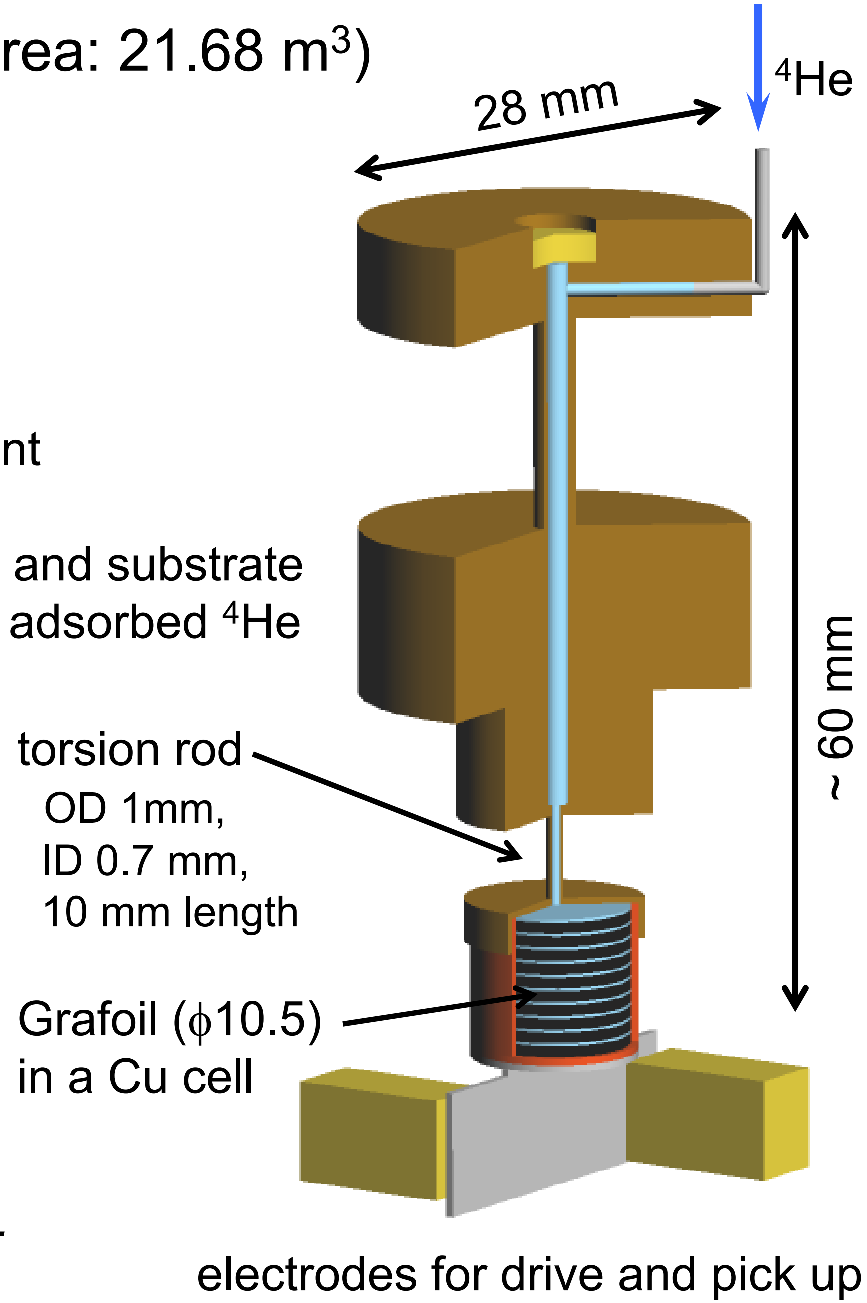
$$f = \frac{1}{2\pi}\sqrt{\frac{\kappa}{I_{\mathrm{cell}} + I_{\mathrm{He}}}}$$

κ : torsion spring constant

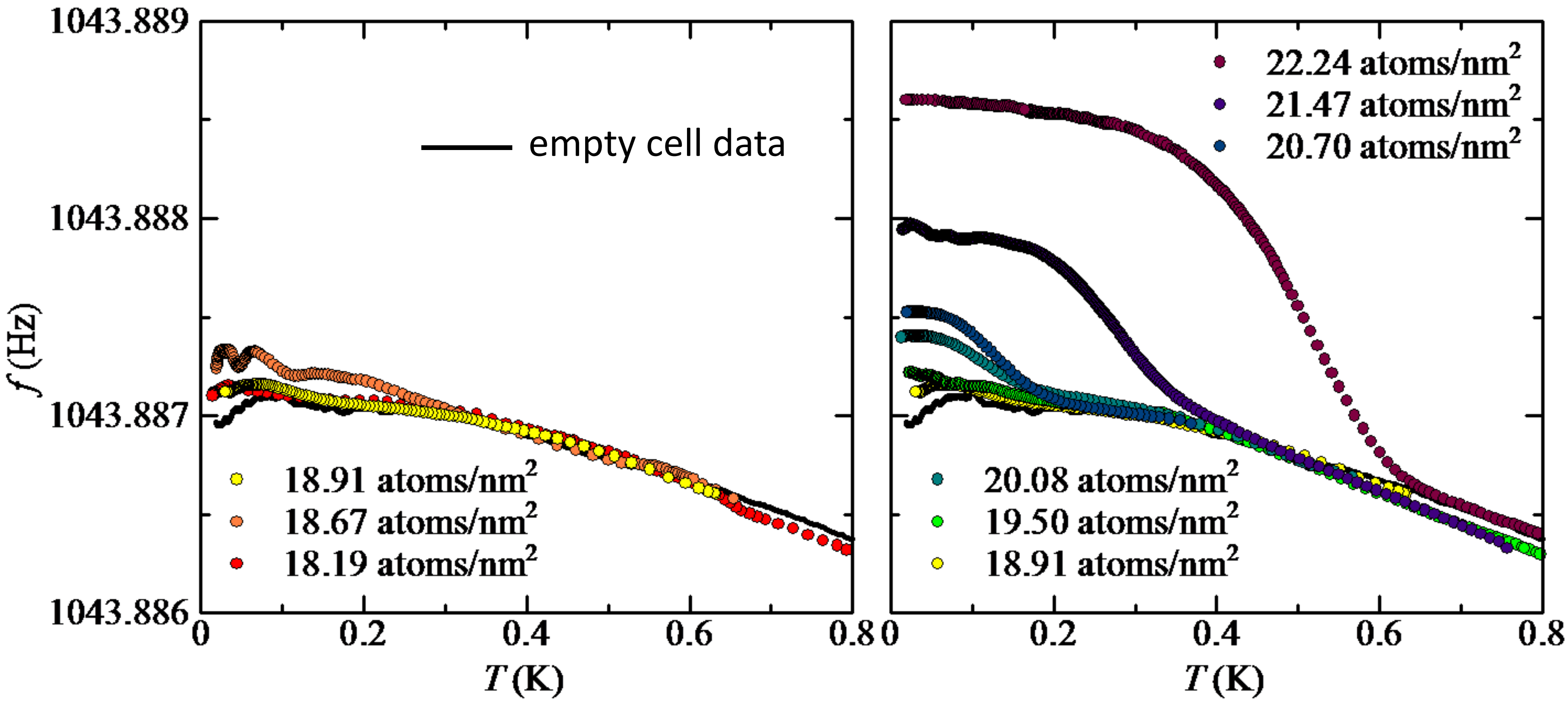
I_{cell} : inertia momentum of the sample cell and substrate

I_{He} : inertia momentum of adsorbed ^4He





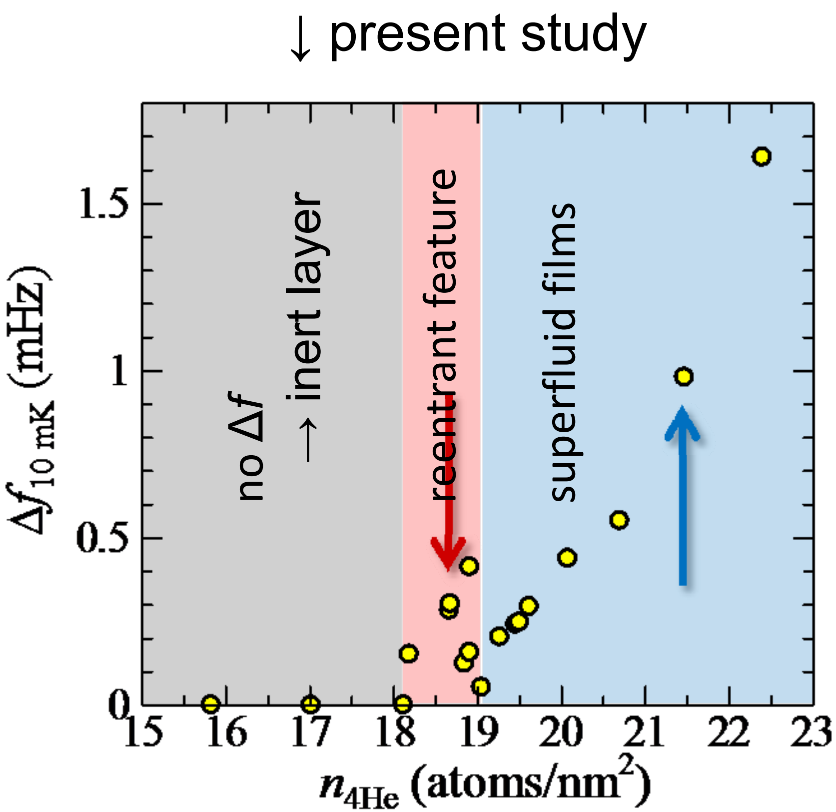
● Frequency shift Δf at v_{osc} ~ 100 μm/s



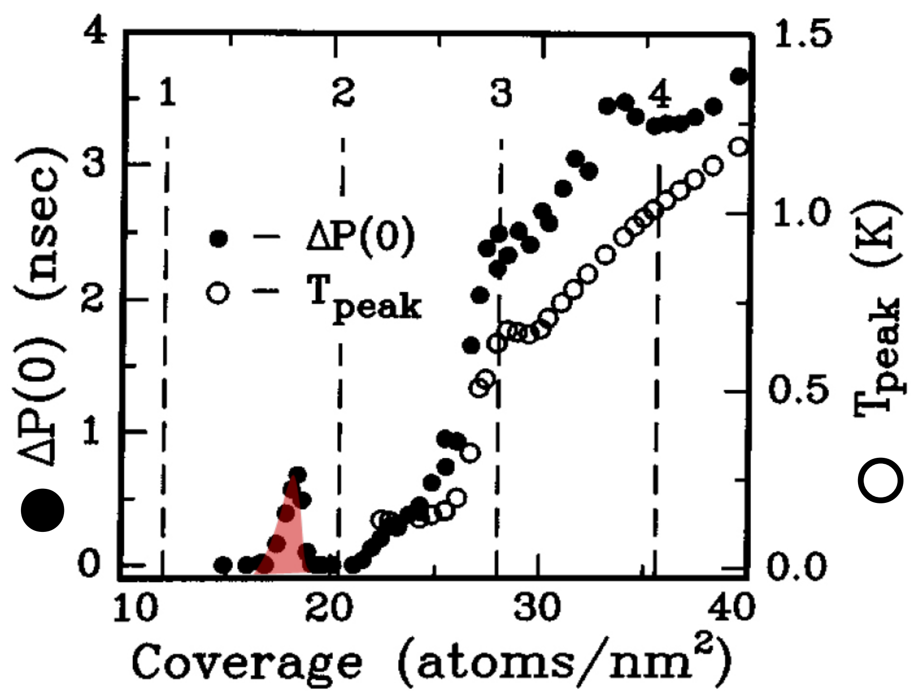
- Up to 18 atoms/nm^2 — no Δf → inert layer
- At 18.19 atoms/nm^2 — a finite Δf is observed
- 18 -19 atoms/nm^2 — **reentrant behavior in Δf**
- Over ~19 atoms/nm^2 — increase in Δf with the coverage; superfluidity of liquid films

● Δ*f* at 10 mK as a function of ^4He coverage

(v_{osc} ~ 100 μm/s)



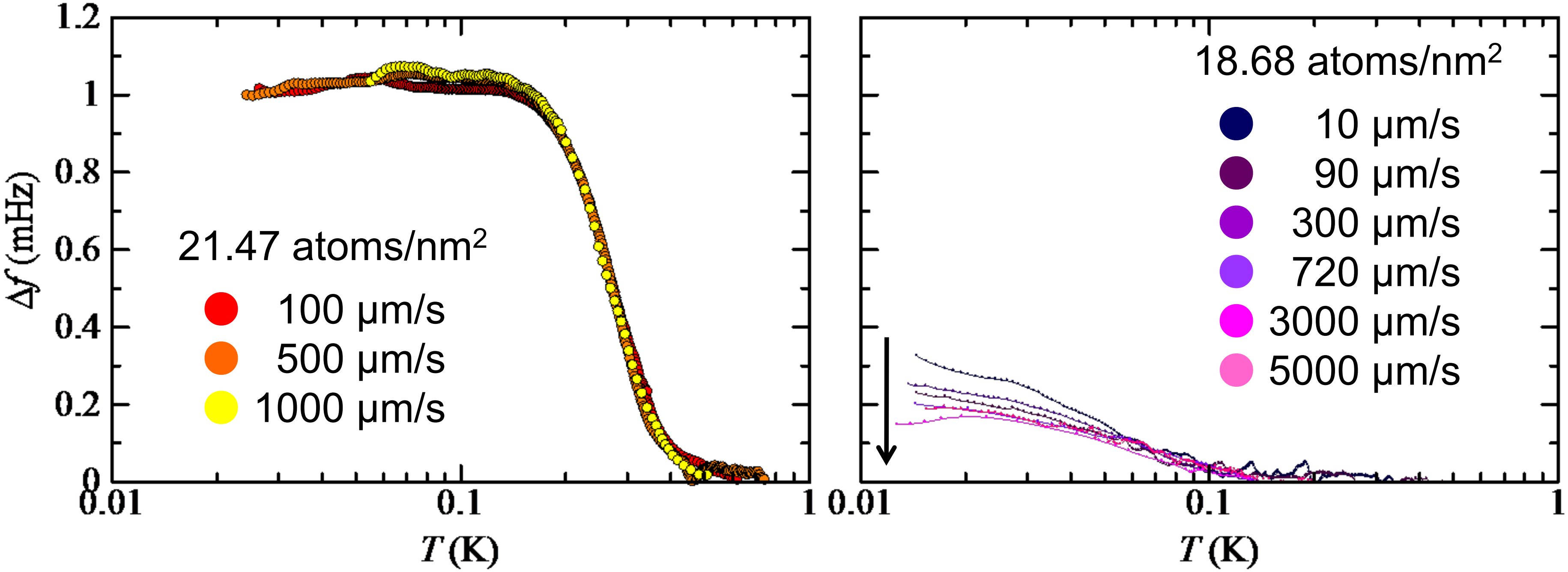
Crowell and Reppy, *PRB* **53**, 2701 ('96)



- **Reentrant frequency shift** is observed at 18 - 19 atoms/nm².
  → Our observation is in agreement with the results by Crowell and Reppy (CR).

- In the present studies a finite Δ*f* is observed at 19 - 20 atoms/nm², while no Δ*f* was observed at the coverage by CR.

● Oscillation velocity v_{osc} dependence of Δf for 21.47 and 18.68 atoms/nm^2 samples

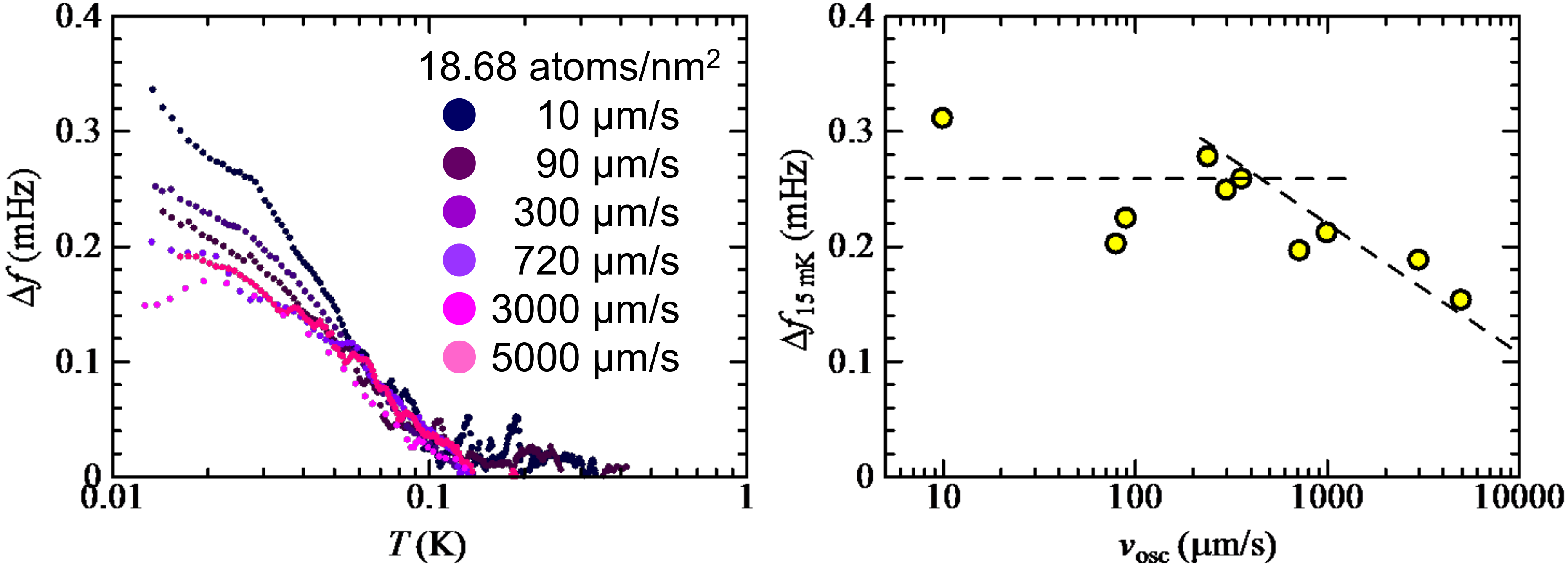


- 21.47 atoms/nm^2 sample
  → The size of Δf is independent of the v_{osc} up to 1000 μm/s.
- 18.68 atoms/nm^2 sample (reentrant Δf)
  → The Δf seems to decrease with the v_{osc}.

The *v*-dependent Δf is a common feature to NCRI of bulk solid ^{4}He.

The Δf in the reentrant region is associated with **a 2D supersolid state**.

○v_{osc} dependence of Δf for 18.68 atoms/nm^2 sample



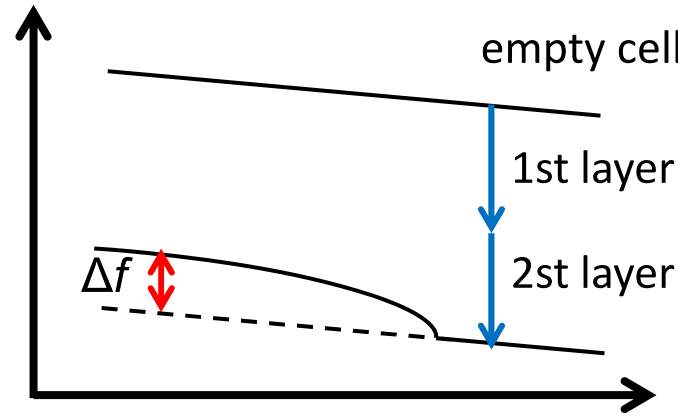
- In the low v_{osc} region, the Δf seems to be independent of v_{osc}.
- In the high v_{osc} region (over ～500 μm/s), the Δf is suppressed.
  But a finite Δf is observed at even 5000 μm/s,
  which differs from the behavior of NCRI in 3D solid ^{4}He.

Nyéki, *et al*. have reported that Δf is independent of v_{osc} up to 500 μm/s
(2009 APS, J. Saunders' Group, Royal Holloway Univ. of London)

→ This might be characteristic behavior in 2D supersolid state.

● NCRI fraction for 18.68 atoms/nm² sample

	coverage	reduction in f by ^{4}He adsorption
Total	18.68 atoms/nm²	162.5 mHz
1st layer	12.0 atoms/nm²	104.4 mHz
2nd layer	6.68 atoms/nm²	58.11 mHz



- The 2nd layer reduces the f by 58.11 mHz
- Δf at low T and at low v_{osc} is ~0.3 mHz
  → The NCRI fraction in the 2nd layer: 0.3 mHz / 58.11 mHz ~ 0.52%
- Surface **tortuosity factor**, χ, of Grafoil is ~0.98 for ^{4}He superfluid films
  (Crowell and Reppy, *PRB* **53**, 2701 ('96))
  → Only 2% of total NCRI value is observable by TO study
- If the χ factor for the present system is same value,
  the total NCRI fraction is 0.52%/0.02 = 26%.

→ 26% of the 2nd layer is decoupled from the substrate.

● Estimate of the density of the ZPVs

- On the assumption that the ZPVs exist in the present 2D ^{4}He, how high is the **areal density of the ZPVs** in the present system?

- Density of the 4/7 phase

  the 1st ^{4}He layer → 12 atoms/nm^2
  4/7 density of the 1st layer → 6.85 atoms/nm^2

- Density of the 2nd layer for the present 18.68 atoms/nm^2 sample

  → (18.68 – 12) atoms/nm^2 = 6.68 atoms/nm^2

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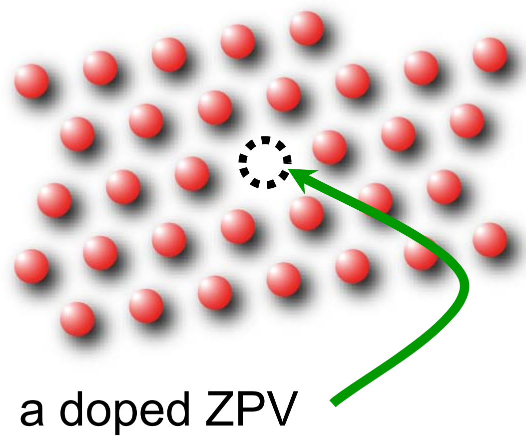
The density of the ZPVs
=(6.85 – 6.68) / 6.85 ~ 2.5%



According to path integral quantum Monte Carlo simulation by Takagi (Fukui University, Japan), the 4/7 phase is unstable over ~ 2% of the vacancy doping.

● Summary

•In order to investigate the possible **ZPVs** and **2D supersolid state,** TO studies were carried out for adsorbed ^{4}He films on graphite.

•**Peculiar Δf (reentrant feature)** was observed in the coverage between 18 and 19 atoms/nm^2.
This is in agreement with the results by CR.

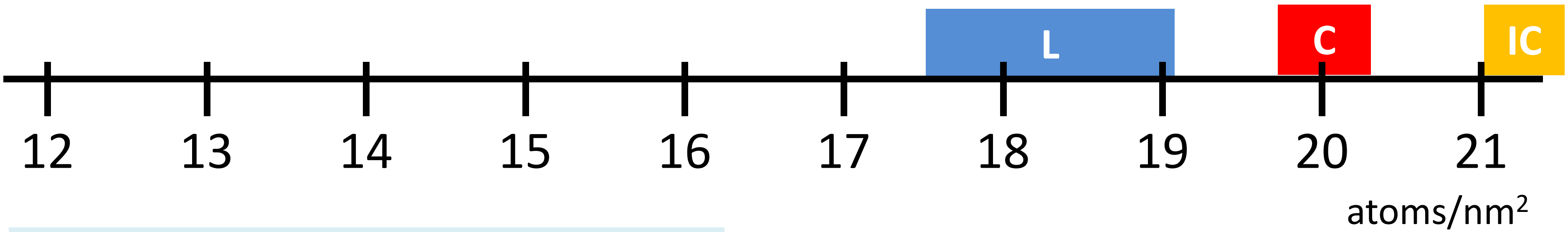
•The size of Δf at 18 and 19 atoms/nm^2 decreases with the v_{osc}, while the Δf over 19 atoms/nm^2 is independent of the velocity.
The ***v*-dependent Δf** is a common feature to the case of bulk solid ^{4}He.
→ **The reentrant Δf is associated with 2D supersolid state**.

•At even 5000 μm/s, a finite frequency shift is observed.
→ Characteristic behavior in 2D supersolid state?

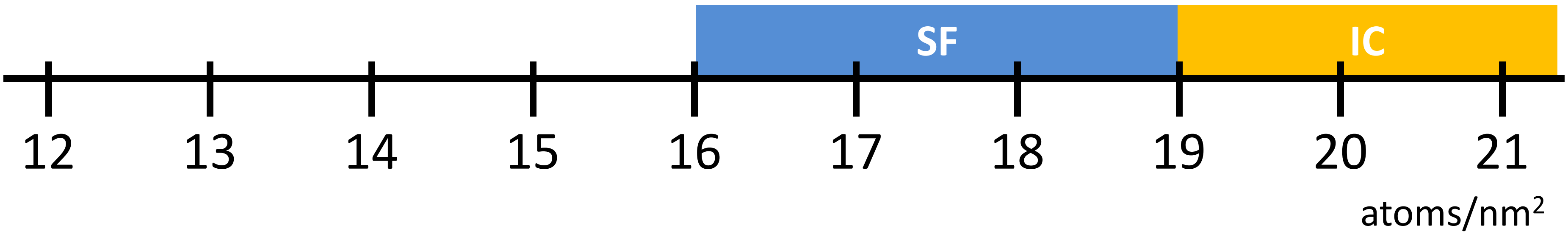
•The NCRI fraction of the 18.68 atoms/nm^2 sample is about 0.52%.
This suggests that **26% of the 2nd layer is decoupled**.

•In the present sample, the density of ZPVs is 2.5%.

Pierce and Manousakis, PRL81,156 ('98); *PRB* **59**, 3802 ('99)
path-integral Monte Carlo simulation



Corboz *et al.*, *PRB* **78**, 245414 ('08)
path-integral Monte Carlo simulation



Greywall and Busch, *PRL* **67**, 3535 (91), Greywall, *PRB* **47**, 309 ('93): heat capacity
Crowell and Reppy, *PRB* **53**, 2701 ('96): TO