Torsional Oscillator Experiments on Helium Films on Graphite; The Search for a Two Dimensional Supersolid

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Why Graphite as Substrate?

- Flat - minimalised disorder
- Helium film grows in layers.
- We can control the growth.
- Two solid He layers solidify
- Triangular lattice symmetry
- Cooling to submillikelvin range

Adsorption potential

+ Periodic potential arising from atomic structure of surface

**2D Helium on Graphite**

- Strongly correlated fermions or bosons
- Subject to an external triangular lattice potential
- Tuning parameters: interatomic distance, binding potential
- No impurities

**Experimental techniques**

3He: NMR, heat capacity, neutron diffraction, vapour pressure
4He: heat capacity, torsional oscillator, neutron diffraction, third sound, vapour pressure

**Temperature range** ~ 15 µK to 15 K

**Quests**

Superfluidity of a $^3$He monolayer
2D superfluid-insulator transition
2D supersolid
Exfoliated Graphite

Fukuyama, JPSJ 77 (2008) 111013

Grafoil – atomically flat platelets 10-20 nm long, rolled, angle spread ±15°
- surface area ~ 20 m²/g
- density ~ 50% of bulk
- “deep sides”, edges 3-5%
- possible to cool below 1mK
Layered Helium Films

Registered solid
(commensurate phase superlattice)
\( \sqrt{3} \times \sqrt{3} \) 6.4 nm\(^{-2}\)

\[ \text{\(\sqrt{3} \times \sqrt{3}\)} \]

Fukuyama, JPSJ 77 (2008) 111013
Sibling system: 4/7 Phase in 3He films

\[
\frac{\text{2nd layer density}}{\text{1st layer density}} = \frac{\rho_2}{\rho_1} = \frac{4}{7}
\]

Existence of 4/7 solid is clearly identified both experimentally and theoretically

- Frustrated spin ½ magnet
- Mott insulator
- Gapless spin-liquid ground state

Elser, PRL62 (1989) 2405

Takagi, J Phys Conf Ser 150 (2009) 032102
Motivation I

Quantum phase transition from a superfluid to a Mott insulator in a gas of ultracold atoms

Heidarian & Damle, PRL 95, 127206 (2005), Melko et al, PRL 95, 127207 (2005), Bonisegni & Prokof’ev, PRL 95, 237204 (2005) + ...

Revived theoretical interest

Triangular lattice symmetry supports formation of supersolid

Can we study this phenomenon in 2D helium-4? (alternative system of bosons in externally imposed lattice potential)

Greiner et al, Nature 415, Jan 2002

Wessel and Troyer, PRL 95, 127205 (2005)
Searching for Supersolid

Superfluid response + Broken translational symmetry
$^4$He/Gr 2$^\text{nd}$ Layer - Phase Diagram

Pierce & Manusakis, PRL 81, 156 (1997) and PRB 59, 3802 (1999)

1$^\text{st}$ layer solid

Puddling

Commensurate 4/7 phase

Vacancies?

Total coverage on PM scale [ nm$^{-2}$ ]
4/7 Phase in 4He films

Greywall, Busch: PRL 67 (1991) 3535


Corboz et al., PRB78 (2008) 245414

FIG. 1: Phase diagram of the first layer (a) and the second layer (b). There is no commensurate solid phase in the second layer.
Motivation II

Crowell & Reppy, PRB 53, 2701 (1993)

- Superfluid response in 2nd layer
- $20 \text{ mK} - 600 \text{ mK}$
- $-\ln T$ like dependence
- No dissipation peaks reported

Chan, Science 319, 1207 (2008)

3D “Supersolidity”
- Sample annealing (disorder) and impurities play important role
Andronikashvili's experiment
Bulk liquid $^4$He

$p_s / \rho$

$p_n / \rho$

$T \text{[K]}$

E.L. Andronikashvili, Zh.Eksp.Teor.Fiz. 16 (1946) 780

Bishop & Reppy, PRB 22, 2701 (1980)
Liquid $^4$He films

Resonant frequency

$$\omega = \sqrt{\frac{k}{I}}$$

Amplitude$_{\text{Drive}=\text{const}} \sim Q$

$$\Delta \left( \frac{1}{Q} \right) \approx \text{Dissipated Energy}$$

Kosterlitz-Thouless theory

$$\frac{\rho_s(T_c^-)}{T_c} = \frac{2}{\pi} k_B \frac{m^2}{\hbar^2}$$

Bishop & Reppy, PRB 22, 2701 (1980)

FIG. 2. The reduced period shift, $2\Delta P/P$, and dissipation $Q^{-1}$ are shown for a superfluid transition temperature of 1.215 K. The solid lines are fits using the dynamic theory of AHNS (Ref. 6) and the dashed curve is the result of the static theory.
Experimental Cell: Torsional Oscillator

2 mK - 4000 mK (weak thermal link to the copper demagnetisation stage)

torsion element 1: contains exfoliated graphite sample $\sim 35 \, \text{m}^2$

torsion element 2: coin silver cylinder, with two Mg electrodes biased at 100V

isolation mass + torsion rod (copper) mounted to cold-plate

Measure frequency shift and dissipation

quality factor $Q \sim 250000 - 550000$

working frequency $\sim 1423 \, \text{Hz}$;
detecting changes $< 10 \, \mu\text{Hz} \sim 2 \times 10^{-7} \, \text{g}$
L+G Region

Dissipation maximum at constant temperature in L + G region; moves to lower T in L region.
Transition L+G $\rightarrow$ L

Extra decoupling = superfluid
For $n \geq 18.14$ nm$^{-2}$

18.14 nm$^{-2}$ chosen as a reference to evaluate additional decoupling on top of the slip process
Homogeneous Fluid Region

New peak appears & sharp increase of $\Delta f$ for $n_x > 18.85$ nm$^{-2}$
Super-response around C phase

\[ \Delta f(T^*) = \frac{\rho_s(T^*)}{\rho_s(0)} = \frac{1}{2} \]

Temperature [K]

after full composite background subtraction

Total coverage on PM scale [nm²]
Super-Response Overview

Not a simple structureless superfluid
Superlattice density is a “pivotal” point in coverage dependence of superresponse.

\[
\frac{\Delta f(T^*)}{\Delta f(0)} = \frac{\rho_s(T^*)}{\rho_s(0)} = \frac{1}{2}
\]
Scaling

\[ \rho_s(T) = \frac{\rho_s(0)}{1 + (T/T_0)^\alpha} \]

Jason Ho, private communication, 2010
What is the value of super-fraction?

Compare with measurements of a KT superfluid monolayer in the same cell (3rd layer, \( n_3 \sim 5.5 \text{ nm}^{-2} \))

**Super-fraction at** \( T \to 0: \)

~ 39% of 2nd layer for 19.18 nm\(^2\) sample
~ 27% of 2nd layer for 19.78 nm\(^2\) sample

*\( x \)-factor for this cell = 0.942*

Measurements at perimeter velocity

\( 25 \div 55 \, \mu \text{m/s} \)

checked up to ~ 500 \( \mu \text{m/s} \)
Super-response from superlattice?

Key: since $\Delta N \Delta \phi \geq 1$, number fluctuations required to define phase. [For this reason a commensurate solid cannot be a supersolid]


In 2D, $\Delta$ for 3He impuriton is much larger than in the bulk [Ziouzia, PhD Thesis, London]

These number fluctuations are intrinsic to the 4/7 superlattice structure [Watanabe, Imada, JPSJ 76 2007]. Fluctuations into the 3rd layer.

The 2nd layer superlattice phase is unstable. [Corboz et al., PRB 78 2008]
Monte Carlo simulations

Two Monte Carlo simulations of the 2\textsuperscript{nd} layer disagree about stability of the 4/7 superlattice solid phase.

- Stable 4/7 phase
- Superfluid phase only

Corboz et al., PRB78 (2008) 245414

Pierce & Manousakis, PRL 81, 156 (1997) and PRB 59, 3802 (1999)
Momentum deficit in Quantum Glass

Reduced rotational inertia due to presence of tunelling two-level systems.

If “bulk” velocity $v(t) \neq 0$ the TLS has nonzero mean values of momenta $<p>_1$ in both stationary states. In the ground state the projection of $<p>_1$ onto $v$ is negative.

**No superflow**

[Andreev, JETP Lett 85 2007, ZhETF 136 2009, Korshunov Pis’ma v ZhETF 90 2009 ]

$$\rho_d = \frac{N}{3h^2} \left< m^2 J^2 a^2 \right> \ln \frac{U}{\max(\Delta, T)}$$

$$v_c \sim \frac{\hbar}{ma} \quad \text{In the 4/7 phase}$$

$$a \sim 4.1 \text{ Å} \Rightarrow v_c \sim 3.9 \text{ m/s}$$

$U$ - characteristic height of energy barrier
$J$ - tunneling amplitude

$$\Delta \approx 1 \text{ mK} ?$$
**Motivation:** Does vacancy doped commensurate phase $\sqrt{7} \times \sqrt{7}$ (4/7 phase) have a supersolid response?

- High precision TO measurements from 2mK to 4K. Second layer density is the tuning parameter.
- $1^{st}$ layer interaction with the substrate present all time $\rightarrow$ careful measurements can distinguish that from ‘super-’ response; sensitive to 2nd layer structure
- Unusual temperature dependence of momentum deficit; no sharp onset: $\Delta f(T) \sim -\ln T$ near onset while $\Delta f(T) \sim T$ as $T \rightarrow 0$.
- $\Delta f(0)$ is tuned by $n_2$. Plateau-feature when $n \approx n_0$ (4/7) and vanishes near at incommensurate 2nd layer density $n_i$. Possible QCP at $n_i$.
- More than 25% of the 2nd layer contributes to super- signal when approaching $n_0$. 

Motivation: Does vacancy doped commensurate phase $\sqrt{7} \times \sqrt{7}$ (4/7 phase) have a supersolid response?

- After “pre-cursor” feature plot of $\Delta f(0)$ vs $T^*$ shows two clear regimes. Boundary correlates with qualitative change in dependence of $\Delta f$ on $\ln T$.

- For a significant coverage range there is data collapse in $\Delta f(T)/\Delta f(0)$ vs $T/T^*$ coordinates.

- Quantum glass model qualitatively agrees with observed $\Delta f(T) \sim -\ln T$ dependence. Energy scales involved need to be addressed.

- We need experimental evidence on the structure of putative 4/7 phase in the $T \to 0$ limit.