Electrons on Liquid Helium – a unique system to study correlated electron ensembles

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Outline

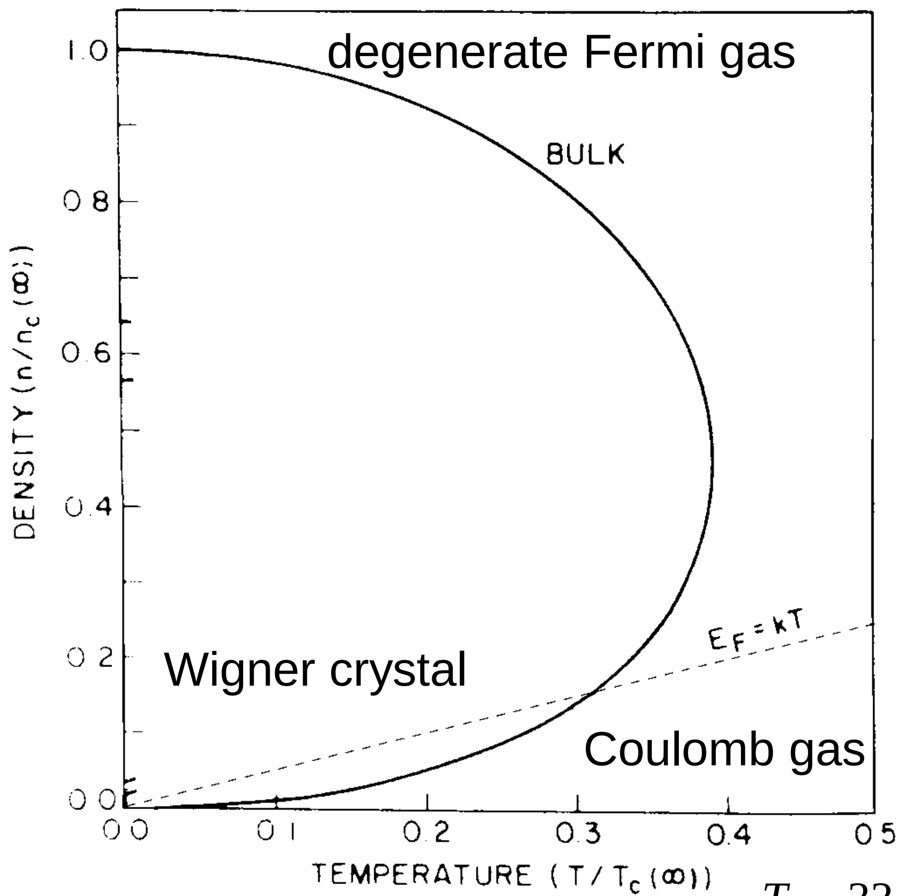
⇨ - **Phase diagram** of correlated electron systems in 2D

- Surface state electrons in **confined geometry** in the classical regime

- Towards **confined electrons** in the **quantum regime**

Phase Diagram

$n_c = 2.4 \times 10^{12} \text{cm}^{-2}$



$T_c = 33\,\text{K}$

Peeters and Platzman,
PRL **50,** 2021 (1983)

$E_{\text{Kin}} \sim T$ (thermal)

$E_{\text{Pot}} \sim \sqrt{n}$ (Coulomb)

$E_F \sim n$ (Fermi)

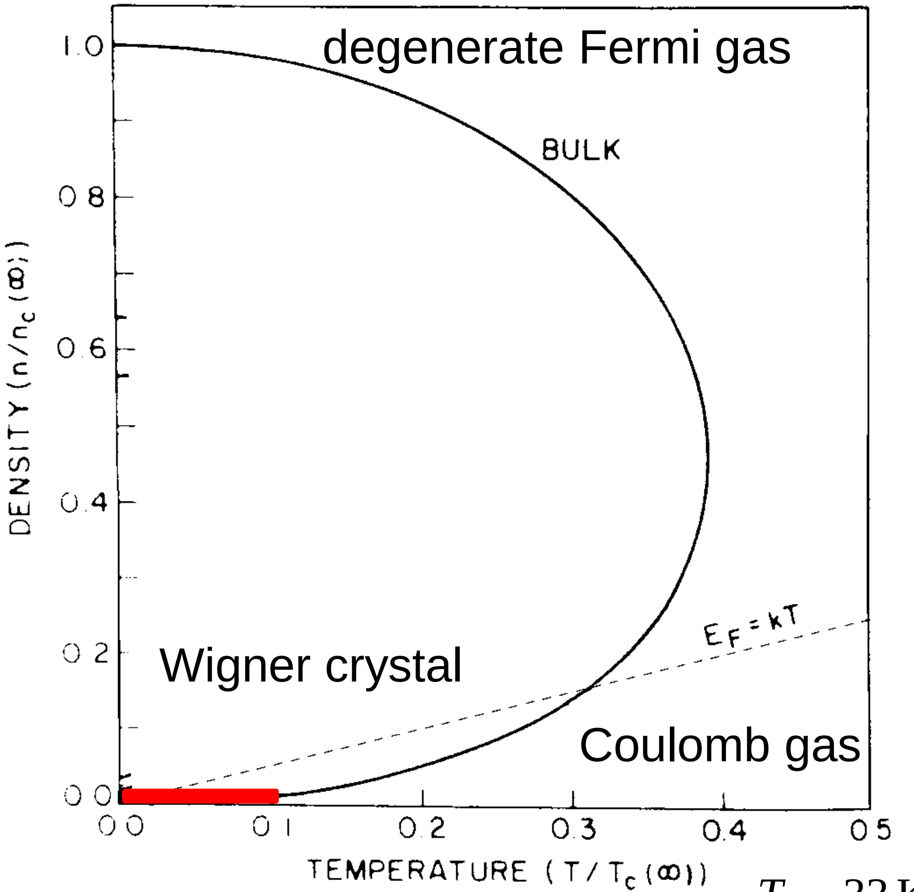
$$\Gamma = \frac{\langle E_{Pot} \rangle}{\langle E_{Kin} \rangle}$$

Covers intriguing classical and quantum-mechanical phenomena, e.g.

Wigner crystallization and melting: KTHNY scenario (dislocations, disclinations)

Phase Diagram

$n_c = 2.4 \times 10^{12} cm^2$



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$E_{Kin} \sim T$ (thermal)

$E_{Pot} \sim \sqrt{n}$ (Coulomb)

$E_F \sim n$ (Fermi)

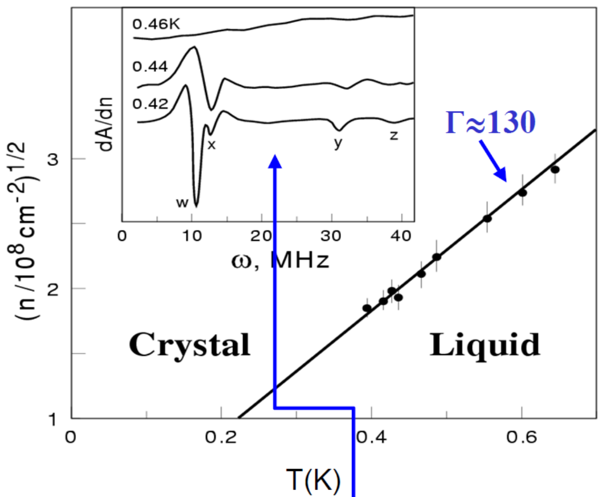
$$\Gamma = \frac{\langle E_{Pot} \rangle}{\langle E_{Kin} \rangle}$$

But: on bulk liquid ^4He,
an electro-hydrodynamic instability occurs
at $n > 2 \times 10^9$ cm^{-2}

Peeters and Platzman,
PRL **50,** 2021 (1983)

Wigner Crystal Melting

on bulk liquid helium

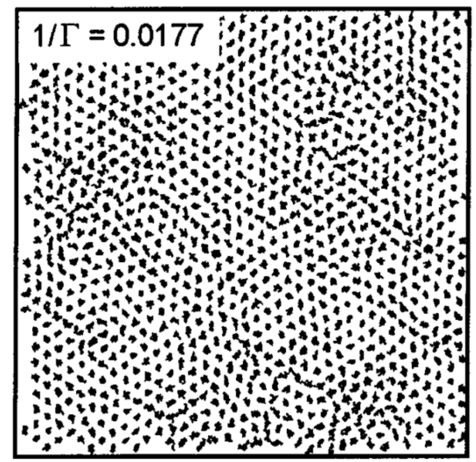


Grimes & Adams (1979); Fisher, Halperin, & Platzman (1979).

Resonances at the frequencies of capillary waves with **q=G,** reciprocal lattice vectors

Details of the melting of a classical SSE crystal?

2-stage melting of a classical 2D crystal



Hexatic phase of a **colloidal crystal**

Zahn et al., PRL 82, 2721 (1999)

Particle trajectories ⇒ dislocation, disclinations, correlation functions etc.

Can one image a crystal of surface state electrons?

SSE on solid neon and hydrogen

Wigner Crystallization on solid Ne

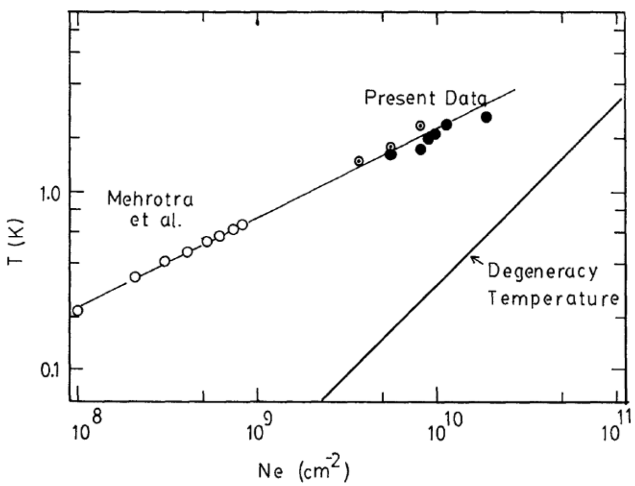


Fig. 3. Phase diagtram of the Wigner crystal. ● from Fig. 1 and ◉ from Fig. 2. The data in the low N_e region are taken from ref. 5. The solid line in the lower part of the figure gives the degeneracy temperature for two dimensional electrons.

K. Kajita

Journal of the Physical Society of Japan
Vol. 54, No. 11, November, 1985, pp. 4092–4095

- max. density achieved: 2×10^{10} cm^{-2}
- no quantum corrections yet
- problem: surface roughness

SSE mobility on solid H_2/thin He film

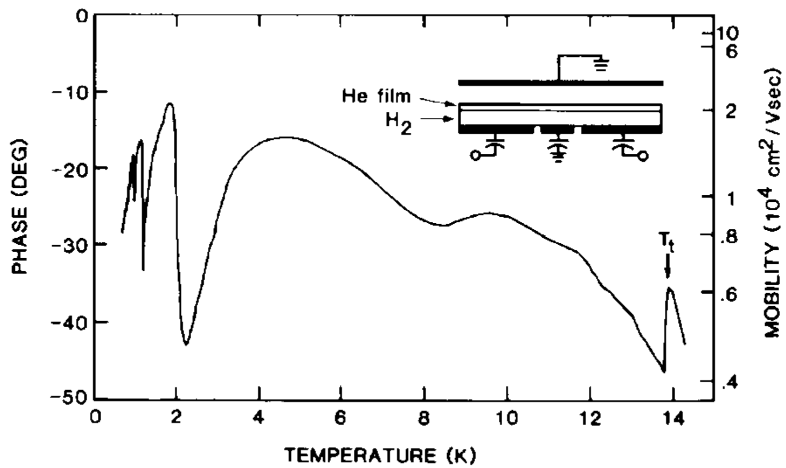
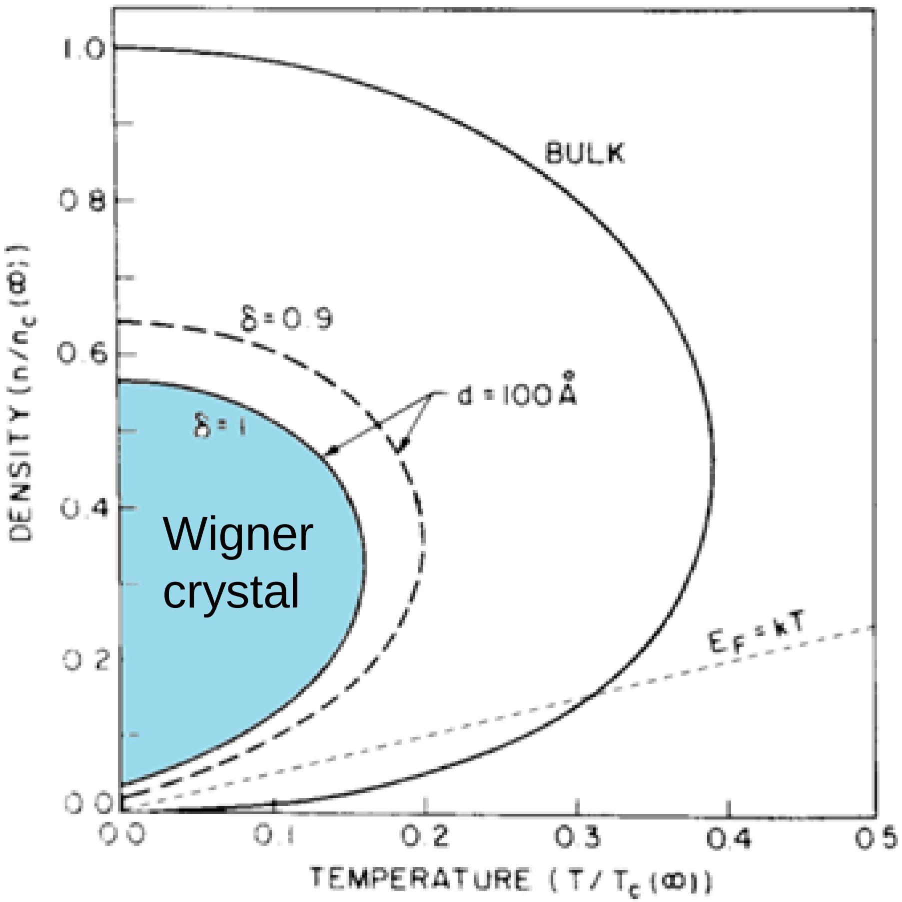


FIG. 1. Phase shift for electrons on solid H_2 covered by a He film with a temperature-dependent thickness. The He gas pressure was 0.35 mbar at 5 K. The electron mobility is given on the right-hand scale. Inset: Sketch of the sample cell.

M.A. Paalanen, Y. Iye, Surf. Sci. 170, 80 (1986)
D. Cieslikowsk, A.J. Dahm, PL, PRL 58, 1751 (1987)
Theory: E. Krotscheck, M.D. Miller, PR B 75, 205440 (2007)

Covering the solid with a thin layer of He does not improve the mobility – on the contrary!

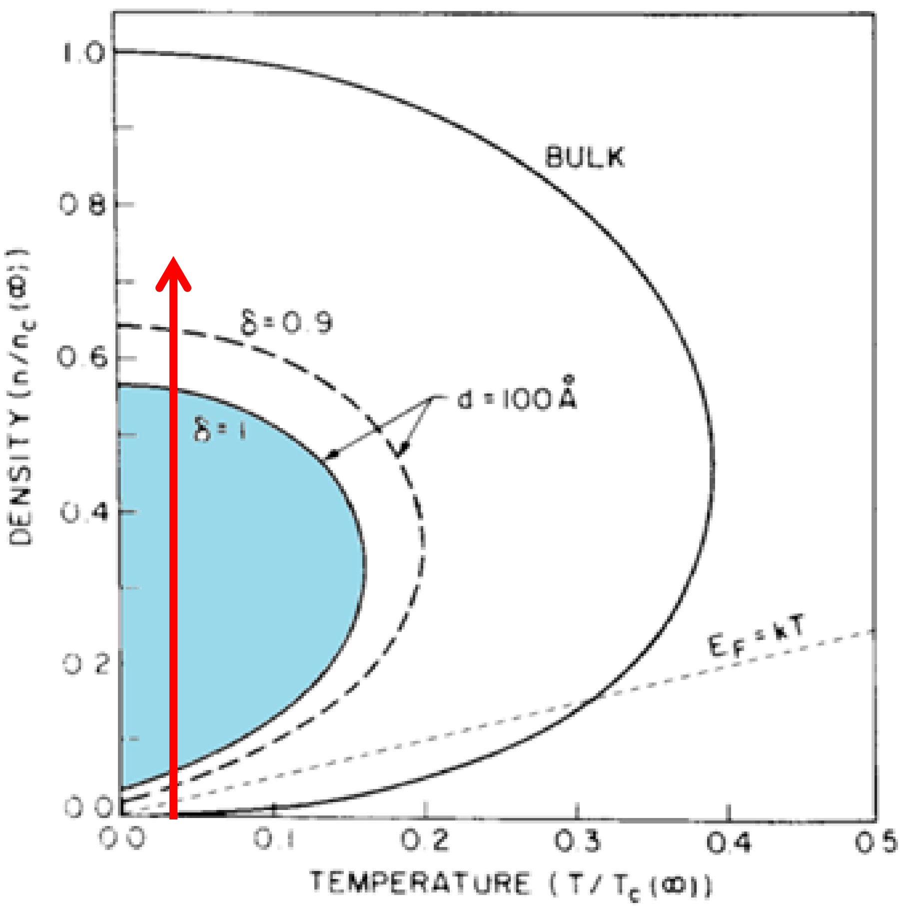
SSE on Helium Films

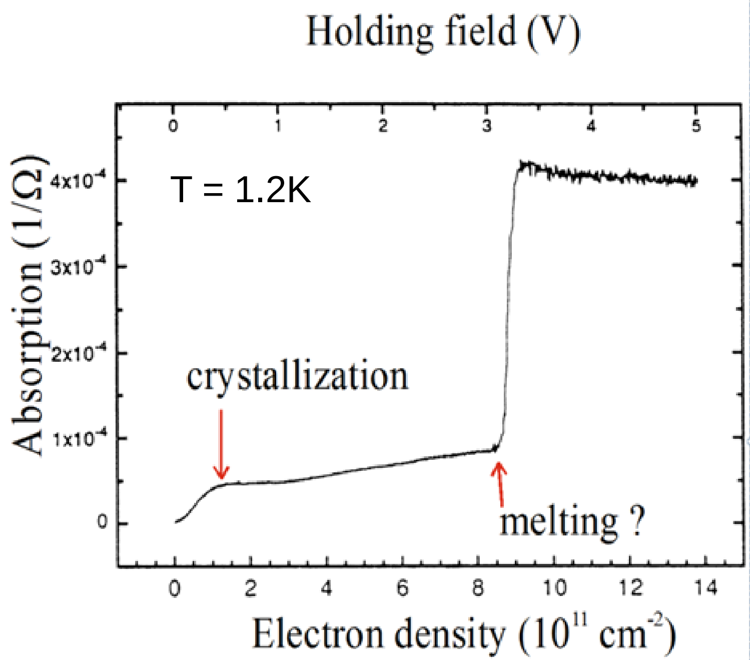


- Stability of the liquid surface improved due to vdWaals forces
- Additional “advantage“ of He films: because of shielding effects by the substrate quantum corrections to Wigner crystallization should take place at lower temperature, quantum melting at smaller density

⇨ more easily accessible?

SSE on Helium Films





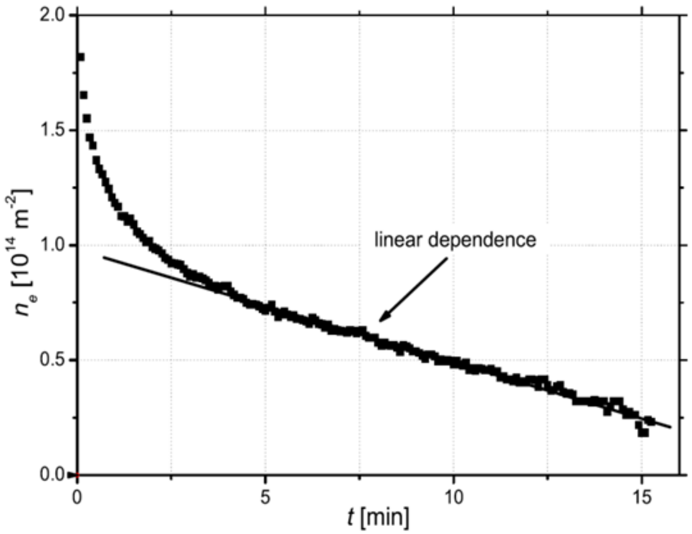
Wigner crystallization and quantum melting (?) of SSE on a He film (supported by SiO_2/Si substrate) measured by microwave absorption (T.Günzler et al., Surf.Sci.361/62,831 (1996))

- a density of 10^{12} cm^{-2} has been reached, but insufficient reproducibility so far (charging up of substrate)
- systematic measurements are still missing

Stability of Electrons on <u>He Film/Metal Substrate</u>

Loss of SSE through the He film

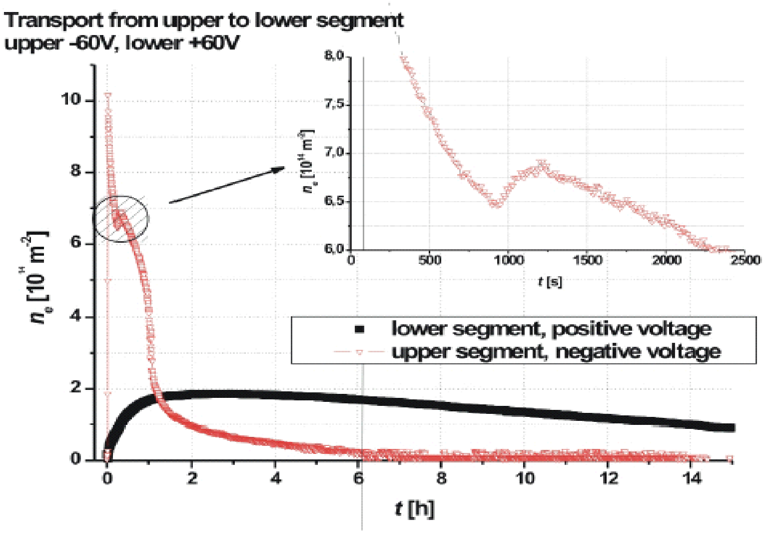
J. Angrik et al., J. Low Temp. Phys. 137, 335 (2004)



Electron density on a He film, supported by a gold substrate, as a function of time after charging

Following a fast initial exponential-like decay a linear drop of the density is observed.

Transport between 2 Au segments



Electron densities on two neighboring gold segments, separated by 100µm gap
- red: upper segment,
charged to 10^{11}e/cm^2 at time t=0
- black: lower segment, charged from upper segment by applying a potential difference of 120V

Loss mechanism??? – Loss depends on history of charging!

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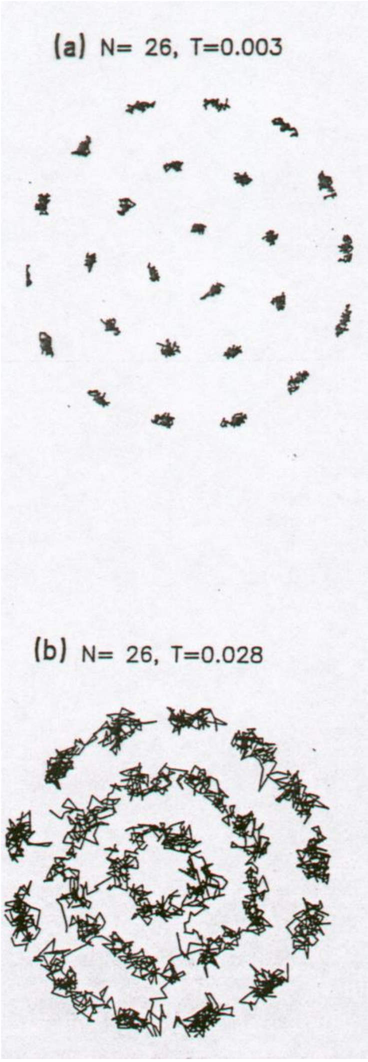
“Classical“ 2D Electron Dot

F. Peeters et al.
Phys. Rev. **B49**, 2667 (1994)

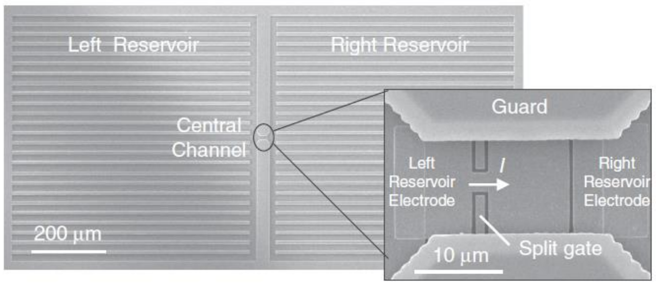
melting of a laterally confined **classical 2D systems** is **different from KTHNY** szenario

- So far no experimental verification of this prediction with SSE in confined geometry
- Could “spectroscopy“ of such dots by transport measurements (see Kono&Rees) be possible?



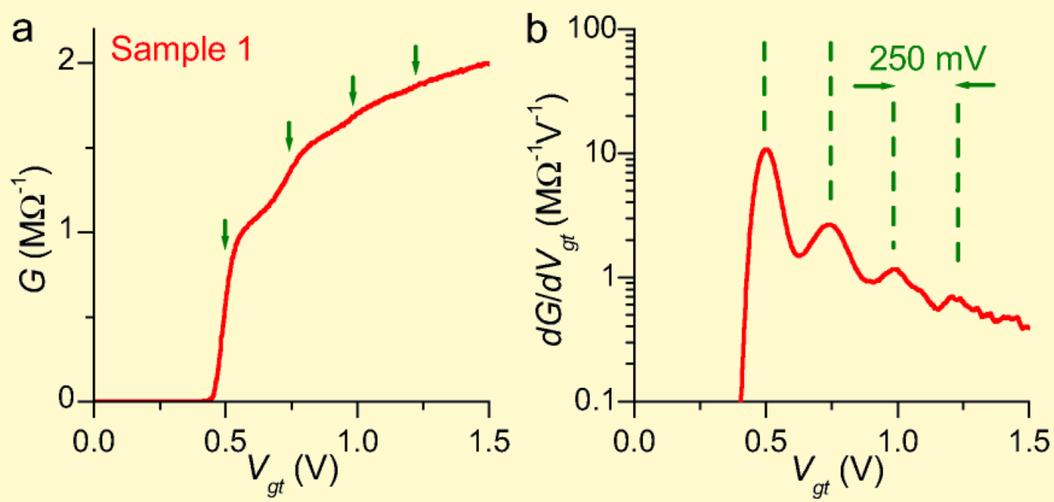
particle trajectories

Conductance steps in a classical “point contact“



Conductance steps

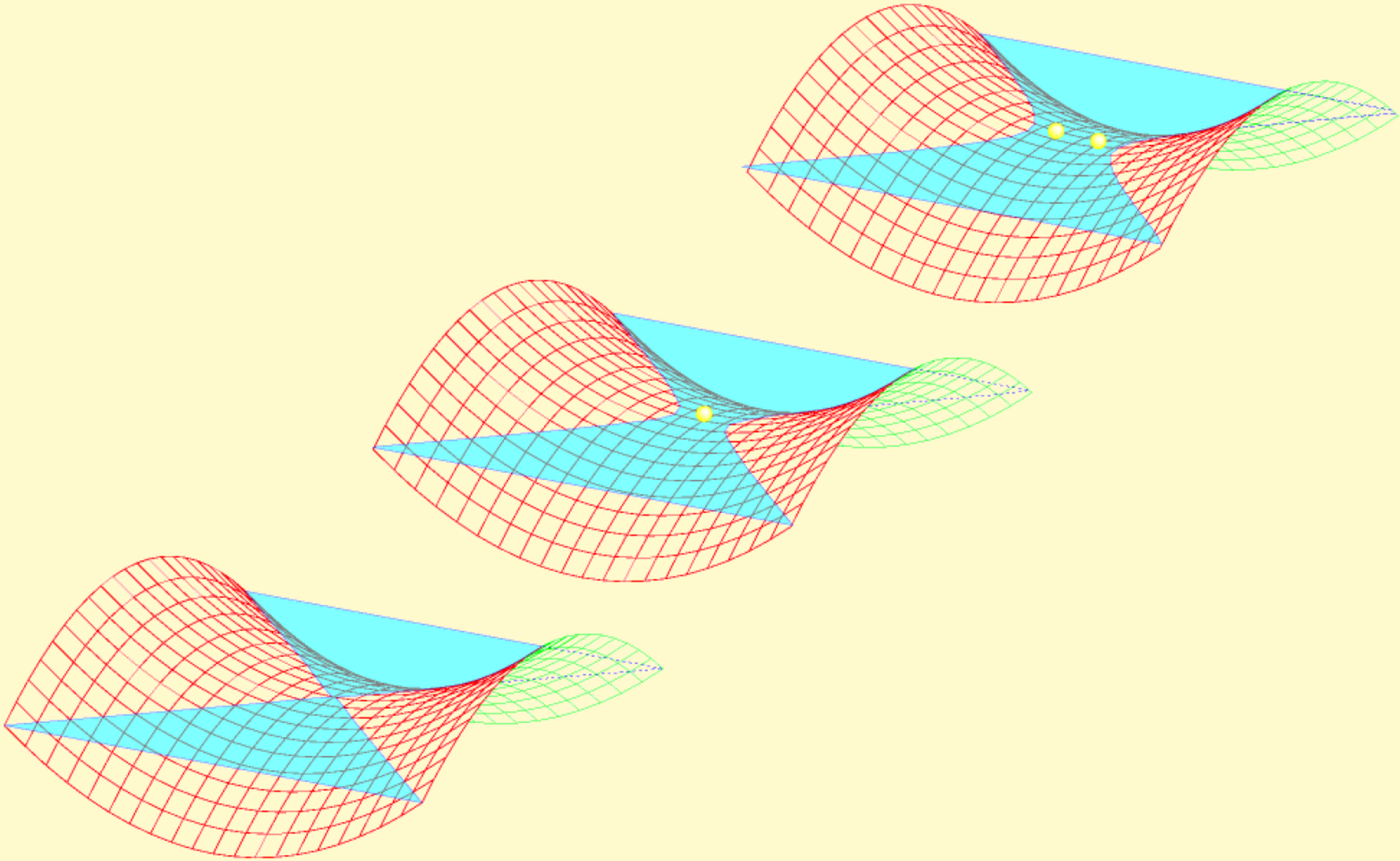
After the threshold a current shows step-like structure.



D.G. Rees et al., PRL 106, 026803 (2011)

Electron rows

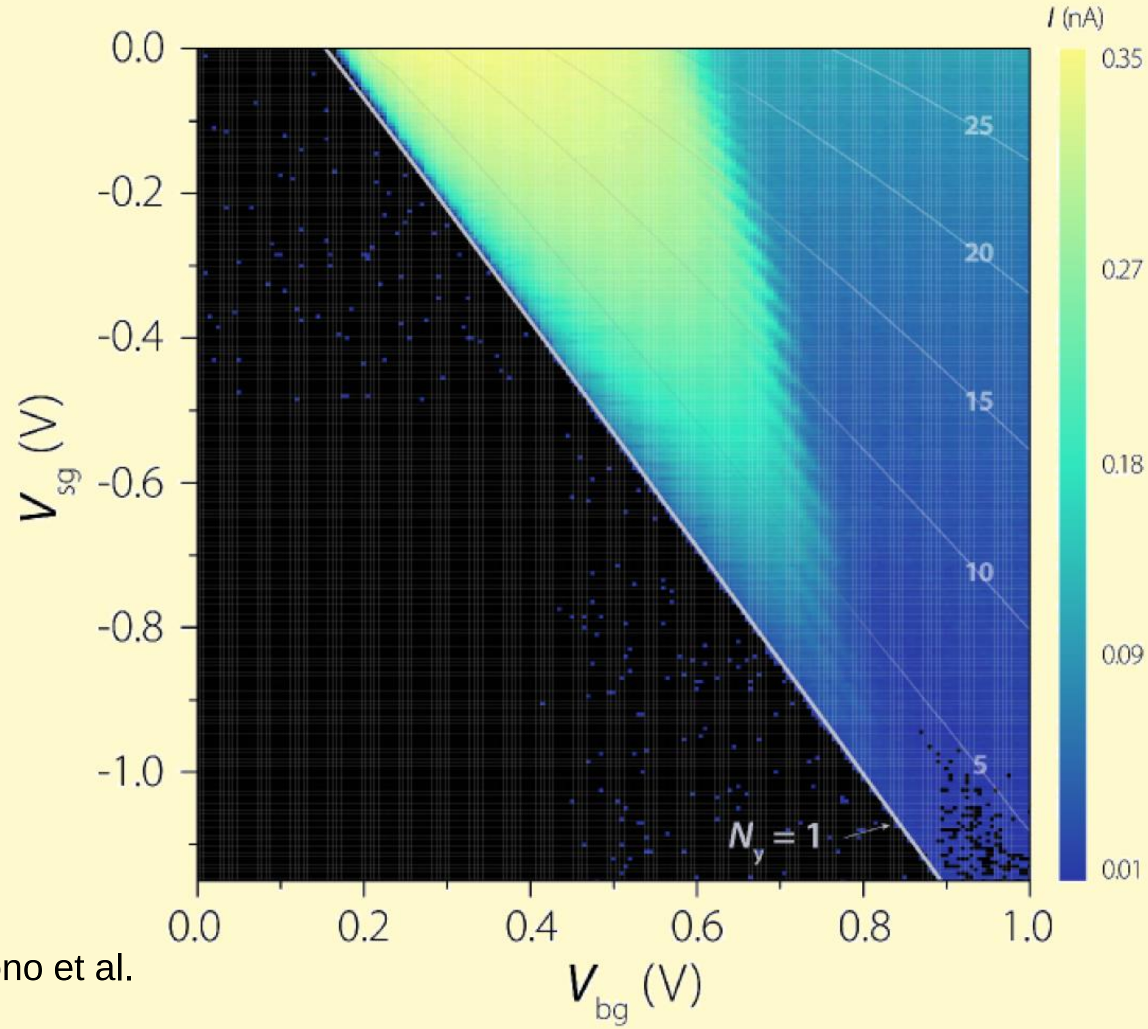
The step-like structure is attributed to a successive row formation at the point contact.



D. Rees, K. Kono et al.

Fringing of the phase boundary

Fringing of the phase boundary is due to a structural stability of electron-row formation in a channel.



D. Rees, K. Kono et al.

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Quantized Conductance (degenerate systems)

B.J. van Wees et al., PRL**60**, 848 (1988)

N. Agrait et al., Physics Reports **377**, 81 (2003)

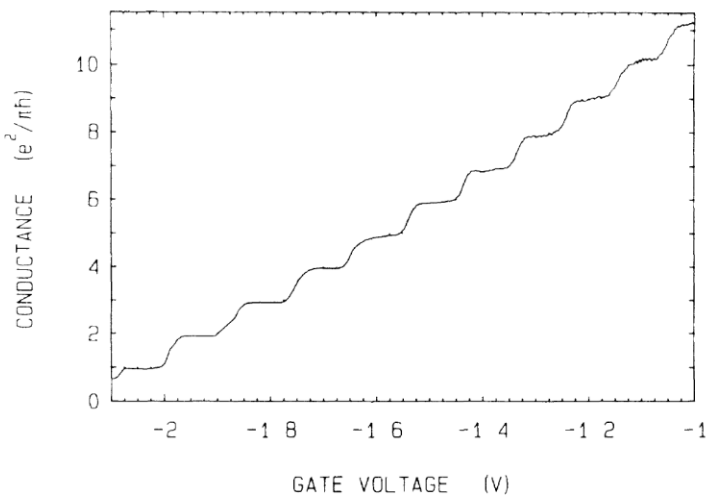
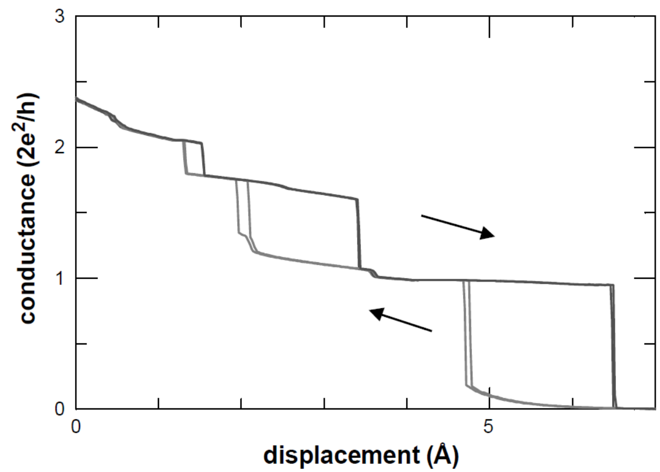


FIG. 2. Point-contact conductance as a function of gate voltage, obtained from the data of Fig. 1 after subtraction of the lead resistance. The conductance shows plateaus at multiples of $e^2/\pi\hbar$.

Degenerate 2D electron gas
in a semiconductor

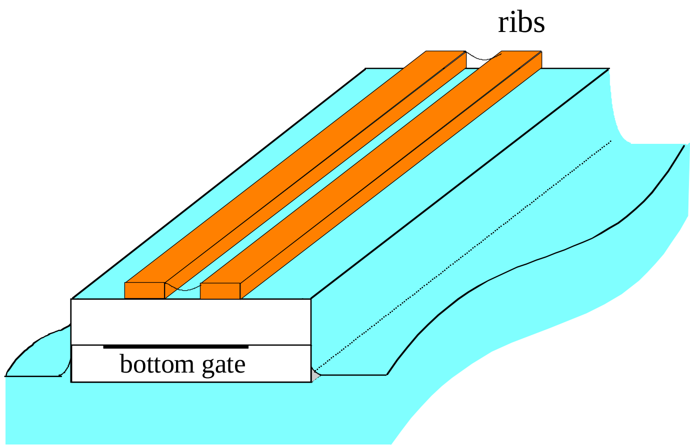


Atomic point contact (gold)

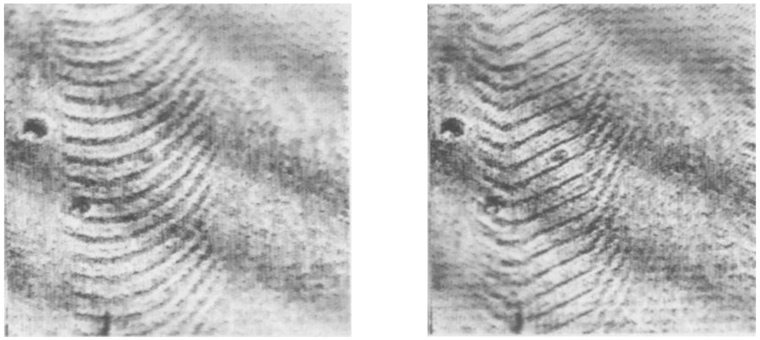
Width of constriction comparable to Fermi wavelength: Landauer-Büttiker theory

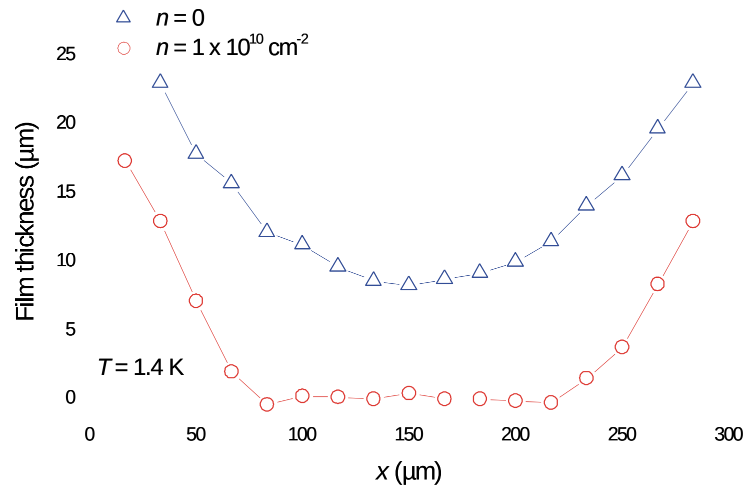
Electrons at High Density in a Helium Channel

Complication: the meniscus deforms due to electrostatic pressure



n=0 n=10^{10}cm^{-2}

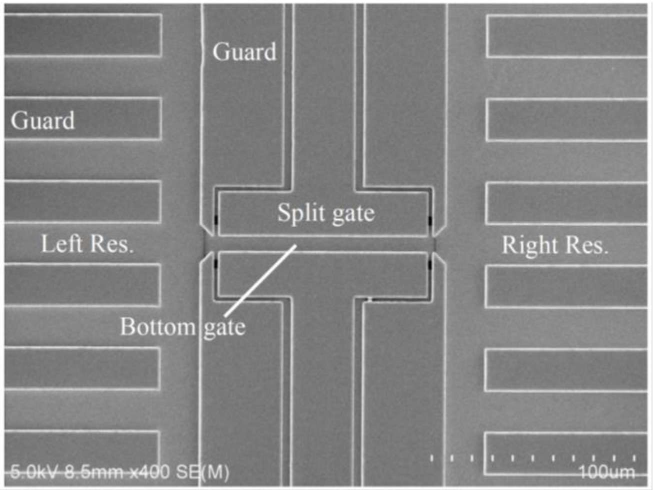


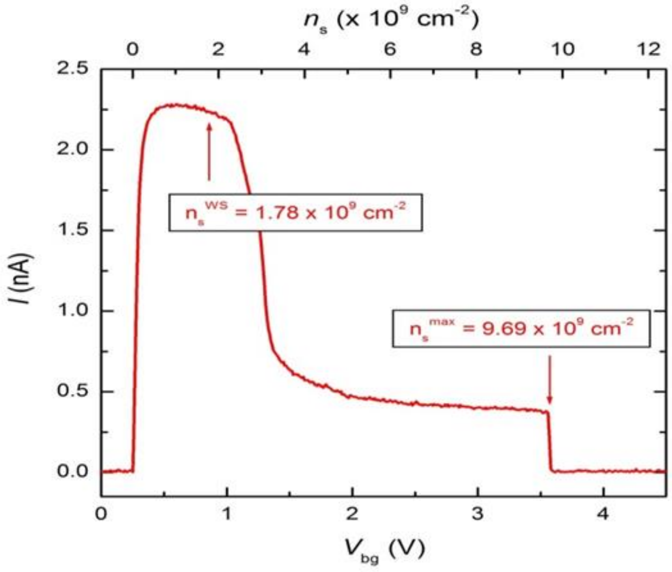


Measurement of the helium surface profile by interferometry

A. Valkering et al.,
Physica B284-288, 172 (2000)

Stability in a Split-gate Device





SSE transport in a micron-sized channel between two reservoirs

(D. Rees)

- Mobility measurements reveal a sudden irreversible **electron loss at $n_s \approx 10^{10}$ cm^{-2}** (higher than on bulk He, due to surface tension)

- **Can one reach even higher densities by tailoring the channel geometry?**

Tunneling of SSE?

perpendicular to surface

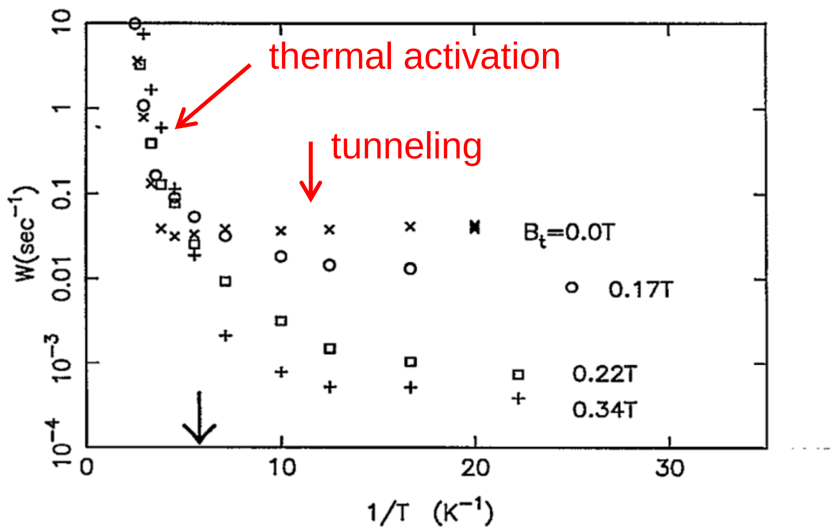
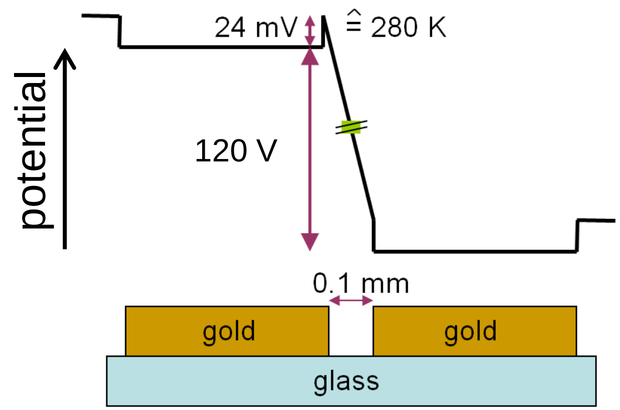


FIG. 2. Escape rates vs inverse temperature for several values of B_t. Here $n = (0.55 \pm 0.05) \times 10^8$ cm^{-2} and $V_t = 6.5$ V. The arrow marks the liquid-solid transition.

L. Menna et al., PRL 70, 2154 (1993)

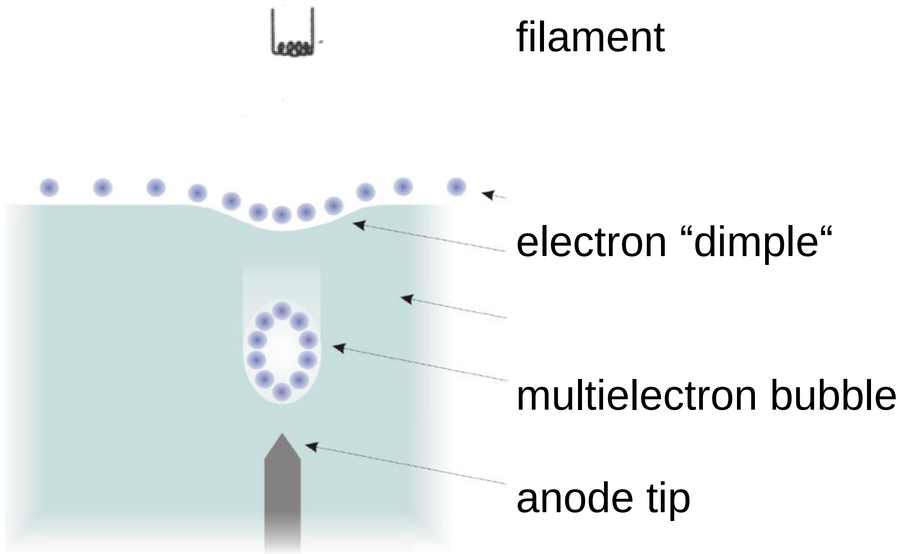
parallel to surface



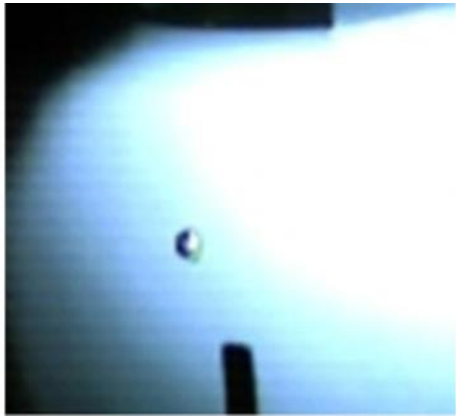
Electron transport between 2 gold segments (covered with a helium film)

Tunneling through potential barrier parallel to surface?

Multielectron Bubbles



schematic set-up



E.M. Joseph, V. Vadakkumbat, A. Pal, A. Ghosh,
J. Low Temp. Phys. 175, 78 (2014)
see also U. Albrecht et al., Europhys. Lett.3, 705 (1987)
J. Tempere et al., Phys. Rev. B70, 224303(2004)
W. Guo et al., Phys. Rev. B78, 014511(2008)

- Are MEBs stable or just metastable?
- How to trap them?
- Can one reach the qm regime for the SSE?
- How to investigate their properties?

Conclusions and open questions

Surface State Electrons on liquid helium are a unique platform for studying highly correlated electron systems

- in 2D, e.g. classical melting of a Wigner crystal
- in confined geometry, e.g. classical lane formation in channels, friction, …

To be demonstrated: challenges

- in 2D: entire phase diagram of Wigner crystals (in particular quantum melting)
- in confined geometry: cross-over from classical to quantum-mechanical behavior, e.g. transport through dots, tunneling problems (“tunneling time“)

- and more, e.g. Wigner crystals on patterned substrates

  i) nanostructured

  ii) magnetically patterned (flux lines in type II supercond. substrate)

  …