Surface electrons on helium under microwave excitation

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2D electron systems

GaAs/AlGaAs heterostructures
- impurity scattering limits mobility
\[ \mu \approx 37 \cdot 10^6 \text{ cm}^2 \text{ V}^{-1} \text{ s} \]
- highest mobility

I/F Quantum Hall Effects
- vanishing dissipative conductivity
\[ \sigma_{xx} = \frac{\rho_{xx}}{\rho_{xx}^2 + \rho_{xy}^2} \rightarrow 0, \quad \rho_{xx} \rightarrow 0 \]

Radiation-induced zero-resistance states

R. Mani et al., Nature 2002
M. Zudov et al., PRL 2003
Electrons on He

- no impurities, smoothest surface

$\mu \gtrsim 100 \cdot 10^6 \ \text{cm}^2 / \text{V} \cdot \text{s}$ - the highest mobility!

barrier of 1eV

Electrons on surface of liquid He

$\sqrt{\langle \xi^2 \rangle} \approx 0.2 \ \text{Å}$

T-dependent scattering

Vapor-atoms: $N_{vapor} \propto T^{3/2} \exp(-Q / kT)$

Ripplons: $n_q = \frac{1}{\exp(\hbar \omega_q / kT)-1} \propto T$

Elastic scattering

$\frac{M_{He}}{m_e} \approx 10^4$

$\omega_q \approx \sqrt{\frac{\sigma}{\rho} q^{3/2}} \quad \hbar \omega_q << \frac{\hbar^2 q^2}{2m}$
Quantum Computing with Electrons Floating on Liquid Helium

P. M. Platzman* and M. I. Dykman

A quasi-two-dimensional set of electrons ($1 < N < 10^9$) in vacuum, trapped in one-dimensional hydrogenic levels above a micrometer-thick film of liquid helium, is proposed as an easily manipulated strongly interacting set of quantum bits. Individual electrons are laterally confined by micrometer-sized metal pads below the helium. Information is stored in the lowest hydrogenic levels. With electric fields, at temperatures of $10^{-2}$ kelvin, changes in the wave function can be made in nanoseconds. Wave function coherence times are 0.1 millisecond. The wave function is read out with an inverted dc voltage, which releases excited electrons from the surface.

- Long decoherence time
- Microwave absorption
  
  $\text{Mike Lea, Royal Holloway}$

- Inelastic 2-ripplon decay
  
  $2\hbar \omega_q = \frac{\hbar^2 q^2}{2m}$

- Single electron manipulation
  
  $\text{Yury Mukharsky, Saclay}$
  
  $\text{Mike Lea, Royal Holloway}$

- Scalability
  
  $\text{Steve Lyon, Princeton University}$
  
  $\text{David Schuster, University of Chicago}$
  
  + many others
Rydberg levels

Parity symmetry-breaking of states $\psi_n$:

$$\langle n | z | n \rangle \neq 0$$

Lian-Fu Wei (talk on Monday)

Linear Stark effect

MW resonance: $\hbar \omega = E_2 - E_1$

2-level system

$\hbar \omega$
Microwave absorption

Transition rate equations:

\[
\frac{\partial \bar{n}_2}{\partial t} = B_{12} \bar{n}_1 - B_{21} \bar{n}_2 - A_{21} \bar{n}_2 = 0
\]

\[
\bar{n}_1 + \bar{n}_2 = 1
\]

\[
B_{12} = B_{21} \propto W
\]

2-level system
Electron heating

2D energy subbands

\[ E = E_n + \frac{\hbar^2 k_{||}^2}{2m} \]

Very fast thermalization with \( T_e \gg T \)

\[ \tau_{ee} \sim \omega_p \approx 10^{-11} \text{s} \]

Energy balance

\[ \hbar \omega \frac{\bar{n}_2}{\tau_{\text{decay}}} = \frac{T_e - T}{\tau_{\text{in}}} \]

Poster by Olesya Sarajlic yesterday
Landau quantization

2D energy subbands

$$E = E_n + \frac{\hbar^2 k_{||}^2}{2m}$$

What is we apply magnetic field?

$$E = E_n + \hbar \omega_c (l + 1/2)$$

Qubits with electrons on liquid helium

M. I. Dykman,$^{1,*}$ P. M. Platzman,$^2$ and P. Sedighrad$^1$

Magneto-transport

- scattering rate in \( B=0 \)
- scattering rate in \( B \neq 0 \)

\[
\Gamma = \hbar \nu_B \quad \text{and} \quad \frac{\nu_B}{\nu_0} \approx \frac{\hbar \omega_c}{\Gamma} \Rightarrow \\
\Gamma = \hbar \sqrt{\frac{2}{\pi}} \omega_c \nu_0(T)
\]

Ando and Uemura, 1974

- Drude model
  
  \[
  \omega_c \ll \nu_0
  \]

- deviation from Drude model
  
  \[
  \frac{\sigma_{xx}}{\sigma_0} = \frac{\nu_0^2}{\omega_c^2 + \nu_0^2}
  \]

\( \omega_c \gg \nu_0 \)
Many-electron effects

Average force on electron: \( e\overline{E}_f = k\delta \)

Typical frequency: \( \frac{m}{k} = \omega_p = \sqrt{\frac{2\pi e^2 n_s^{3/2}}{m}} \)

\[
\frac{k\delta^2}{2} \approx k_B T_e \implies \overline{E}_f \approx n_s^{3/4} \sqrt{4\pi k_B T_e}
\]

\( X - X' \)

\( eE_f (X - X') \)

Fang-Yen, Dykman, Lea PRB 1997
Inter-subband dynamics

Decay rate (short-range scattering)

\[ \nu_{2 \to 1} = \frac{\nu_{2 \to 1}^{(0)}}{\sqrt{\pi}} \sum_m \exp \left[ -\frac{(E_2 - E_1 - \hbar \omega_c m)^2}{\Gamma_{1,2}^2} \right] \]

\[ 2\Gamma_{1,2}^2 = \Gamma_1^2 + \Gamma_2^2 \quad \text{- overlapping of LLs} \]

Add \( eE_f L \) to energy change

and average over distribution \( \rho(E_f) \sim e^{-E_f^2/\bar{E}_f^2} \)

replace \( \Gamma_{1,2} \rightarrow \Gamma_{1,2}^2 + 2(eE_f L)^2 \)

**Graphical Elements:**
- DOS(E)
- Ground subband
- Excited subband
- \( E_1, E_2 \)
- \( \hbar \omega_c \)
- Typical scattering length
- \( n_s = 2 \times 10^6 \text{ cm}^{-2} \)
- \( T = T_e = 0.9 \text{ K} \)
- \( B \) vs. \( T \) in Tesla (Teslas)
Experimental method

Sommer-Tanner method (1971)

\[
\frac{I_{\text{out}}}{V_{\text{in}}} = G(\sigma_{xx})
\]

complex admittance

Effective scattering rate

\[
\vec{F}_{\text{friction}} = -N_e m \nu_{\text{eff}} \langle \vec{v}_e \rangle
\]

\[
\sigma_{xx} = \frac{e^2 n_s \nu_{\text{eff}}}{m_e (\omega_c^2 + \nu_{\text{eff}}^2)}
\]

\[
\sigma_{xy} = \frac{\omega_c}{\nu_{\text{eff}}} \sigma_{xx}
\]
Magneto-oscillations

$\sigma_{xx} (10^{-9} \Omega^{-1})$

Magnetic field $B$ (T)

$T=0.6$ K
79 GHz

$\sigma_{xx} (10^{-9} \Omega^{-1})$

$B$ (T)

$\nu_s = 3 \times 10^6$ cm$^{-2}$
$T=0.6$ K
Drude

$\sigma_{xx} \approx \frac{e^2 n_s \nu_{eff}}{m_e \omega_c^2}$

Enhancement of scattering

$\frac{\omega}{\omega_c} = i$
Short-range scattering

Effective collision rate \( \nu_{\text{eff}} = \nu_{\text{intra}} + \nu_{\text{inter}} \)

\[
\nu_{\text{inter}} = \frac{(\hbar \omega_c)^2}{2\sqrt{\pi}k_B T_e} \sum_l \rho_l \left[ \frac{n_1}{\Gamma_1} + \frac{n_2}{\Gamma_2} \right]
\]

\[
\nu_{\text{inter}} = \left( \bar{n}_2 + \bar{n}_1 e^{\frac{E_2 - E_1}{k_B T_e}} \right) \frac{(\hbar \omega_c)^2}{2\sqrt{\pi}k_B T_e} \sum_l \rho_l \frac{\lambda_{21}}{\Gamma_{1,2}} \exp \left[ -\frac{(E_2 - E_1 - \hbar \omega_c m^*)^2}{\Gamma_{1,2}^2} \right]
\]

\[
\Gamma_{1,2}^2 \rightarrow \Gamma_{1,2}^2 + 2(eE_f L)^2
\]

Very dynamical and nonlinear process!

\[
\nu_{2 \rightarrow 1} \Rightarrow \bar{n}_1, \bar{n}_2 \Rightarrow B_{12} (\bar{n}_1 - \bar{n}_2) \Rightarrow k_B T_e \Rightarrow E_f \sim \sqrt{T_e}
\]

\( \rho_l \) - Boltzmann occupancy of LLs

\( m^* = \text{round} \left( \frac{E_2 - E_1}{\hbar \omega_c} \right) \)

Yuriy Monarkha
Population dynamics

$n_s=2\times10^6$ cm$^{-2}$
$T=T_e=0.6$ K

$\Delta\sigma_{xx} (10^{-9} \Omega^{-1})$

Absorption (s$^{-1}$)

Ocupancies

$V_{21}$ (s$^{-1}$)
Density-of-states

\( n_s = 2 \times 10^6 \text{ cm}^{-2} \)
\( T = T_e = 0.3 \text{ K} \)

\( \Delta \sigma_{xx} (10^{-11} \Omega^{-1}) \)

Sign-changing contribution?!
Effective collision rate \( v_{\text{eff}} = v_{\text{intra}} + v_{\text{inter}} \)

Anomalous contribution \( v_{\text{inter}} = v_N + v_A \)

\[
v_A = -\left( \bar{n}_2 - \bar{n}_1 e^{-\frac{E_2 - E_1}{k_B T_e}} \right) \frac{(\hbar \omega_c)^2}{\sqrt{\pi}} \sum_l \rho_l \frac{\lambda_{21}}{\Gamma_{1,2}^2} \exp \left[ -\frac{(E_2 - E_1 - \hbar \omega \, m^*)^2}{\Gamma_{1,2}^2} \right] \frac{(E_2 - E_1 - \hbar \omega \, m^*)}{\Gamma_{2,1}}
\]

Simple picture

Yu. Monarkha, 2011
Electron temperature

Onset of oscillations

\[ eE_f R_c \geq \hbar \omega_c \]

onset magnetic field

\[ B_0 \approx 1.7 \times 10^{-5} n_3^{3/8} T_e^{1/2} \]

Lea, Dykman 1994

Electron temperature

\[ T_e \approx 1.7 \text{ K} \]
Zero conductivity

\[ \sigma_{xx} (10^{-11} \text{ S}) \]

\[ \frac{\omega}{\omega_c} \]

\[ T = 0.2 \text{ K} \]

Tensor relation

\[ \sigma_{xx} = \frac{\rho_{xx}}{\rho_{xx}^2 + \rho_{xy}^2} \rightarrow 0, \quad \rho_{xx} \rightarrow 0 \]
Radiation-induce zero-resistance states (ZRS) in high-mobility 2DEG

R. Mani et al., Nature 2002

M. Zudov et al., PRL 2003

More on theory today: Ivan Dmitriev
Maxim Khodas
Alexei Chepelianskii
Negative linear conductivity

Yu. Monarkha, 2011

Instability and spontaneous formation of current domains at $\sigma_{xx} < 0$

Andreev, Aleiner, Millis PRL 2003

In 2D at zero magnetic field:

\[
\begin{align*}
\frac{\partial \rho_s}{\partial t} &= -\nabla j = \sigma \nabla^2 V \\
\nabla^2 V &= -\rho_s \delta(z) \\
\rho_k &\sim \exp\left(-\frac{\sigma k}{2} t\right) \rightarrow \infty
\end{align*}
\]
MW absorption

What about absorption saturation?

E. Collin et al., PRL 2002
Onset magnetic field

\[ B_0 \approx 1.7 \times 10^{-5} n_3^{3/8} T_e^{1/2} \]

Overheating of electrons \( T_e \approx 2 \text{ K} \)

Absorption saturation

\[ \bar{n}_1, \bar{n}_2 \rightarrow 1/2 \]

But what about inhomogenous broadening?!
Trapping and ballistic transport at edges

Chepelianskii and Shepelyansky, PRB 2009

\[ B \]

\[ I_{\text{inner}} = eE \cos(\omega t) \]

\[ I_{\text{outer}} \]

\[ \text{Photocurrent (pA)} \]

\[ 0 \quad 1 \quad 2 \quad 3 \]

\[ -0.3 \quad 0.0 \quad 0.3 \]

\[ \text{Time (s)} \]

\[ \text{ON and OFF} \]

\[ \cos(t \epsilon E \omega) \]

\[ \cos(t \epsilon E \omega^2) \]
Redistribution of charge

Charge trapping leading to zero $\sigma_{xx}$?

OR

Negative $\sigma_{xx}$ leading to redistribution?

Current domains (Corbino)
Self-organized oscillations

Charge redistribution

MW on

Photocurrent (pA)

Time (s)
Sound of electrons

Recoded by Masamitsu Watanabe
Thank you!
Phase relation

Time (s)

Photocurrent (pA)

-40
0
40

0.042 0.044 0.046 0.048

B
W
E
N
C

0.090 0.092 0.094 0.096 0.098

Photocurrent (pA)

-40
0
40

0.042 0.044 0.046 0.048
Hall gyrator (?)

M. Lea et al. LT18, Kyoto 1987

\[ I_x Z - I_y R_H = 0 \]
\[ I_x R_H + I_y Z = 0 \]

Resonance at \( \omega \approx (R_H C)^{-1} \sim 100 \text{ Hz} \)

due to inductance \( L = R_H^2 C \)

Time-dependent frequency: \( R_H = \frac{B}{n_s e} \)