Photoconductivity response at cyclotron-resonance harmonics in electrons-on-helium system

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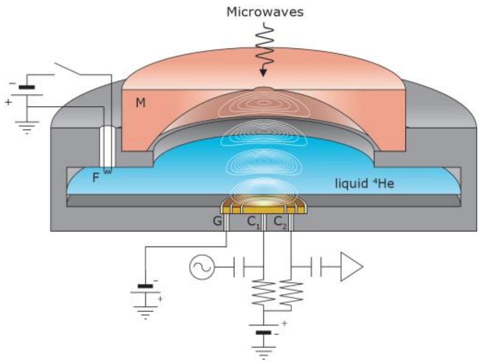
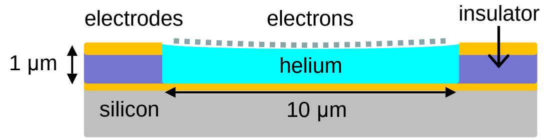
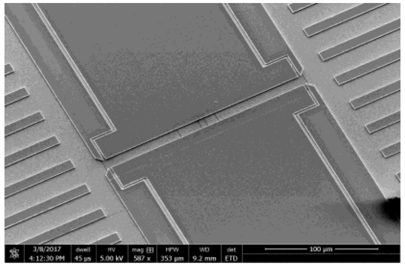
2D electrons on helium





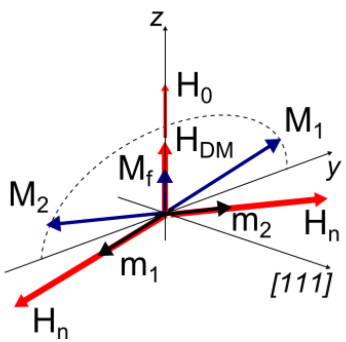


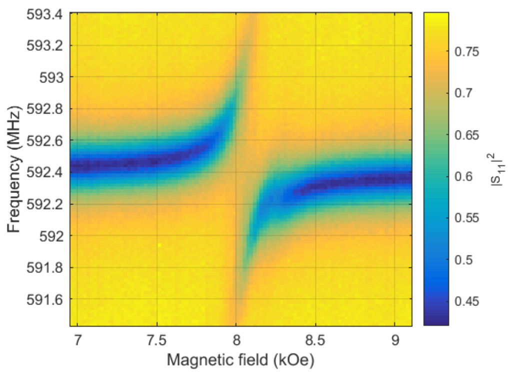
PRL115, 256802 (2015)
PRL117, 056803 (2016)

PRB 94, 195311 (2016)

Nuclear spins ensembles in $MnCO_3$

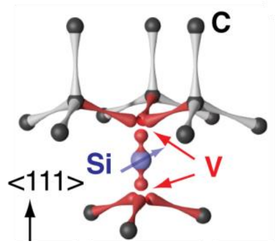
PRL114, 226402 (2015)



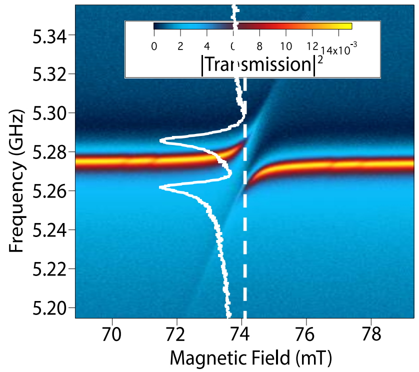


Impurity spins in diamond

Current experiments



NV and SiV centers



Outline of the talk

- Photo-excited magnetotransport in 2DEG in semiconductors

- Photoconductivity response in electrons-on-helium system

- First observation of polarization dependence

Theoretical support from
Yuriy Monarkha, IELTP, Kharkov

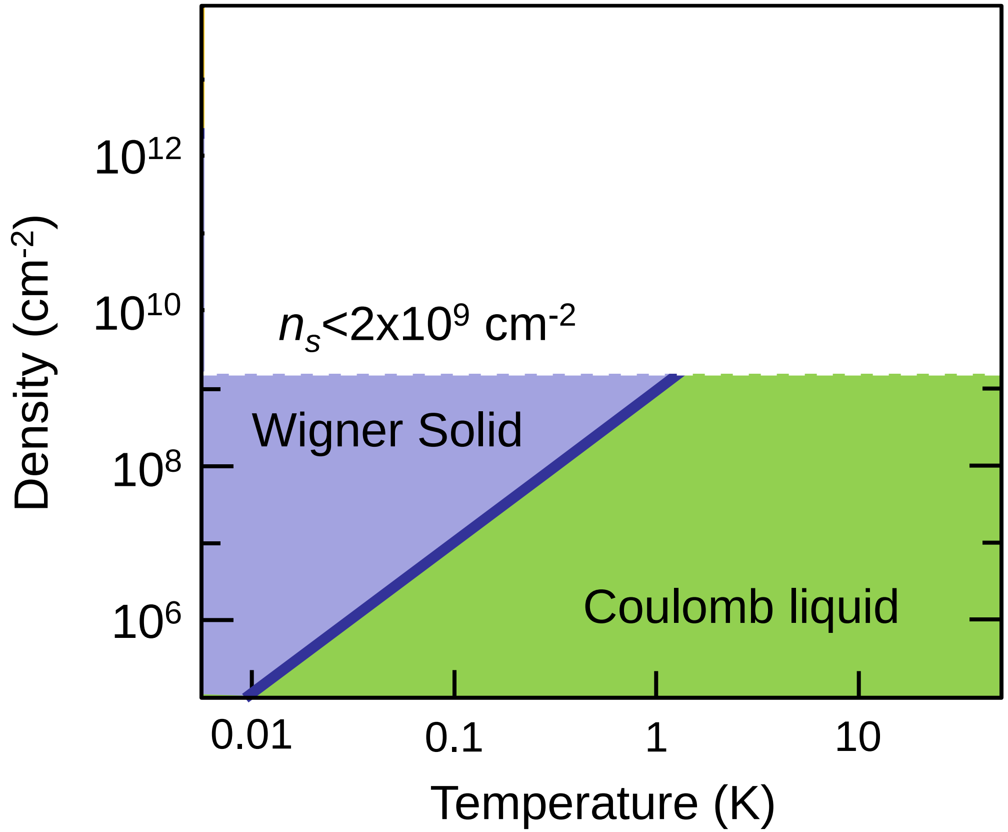
2DES: in semiconductors and on helium

$$r_p = \frac{V_C}{E_f} = \frac{e^2\sqrt{\pi n_s}}{4\pi\varepsilon\varepsilon_0}\frac{m^*}{\hbar^2\pi n_s}$$

Quantum fluctuations

$$\Gamma_p = \frac{V_C}{E_{th}} = \frac{e^2\sqrt{\pi n_s}}{4\pi\varepsilon\varepsilon_0 k_B T}$$

Thermal fluctuations

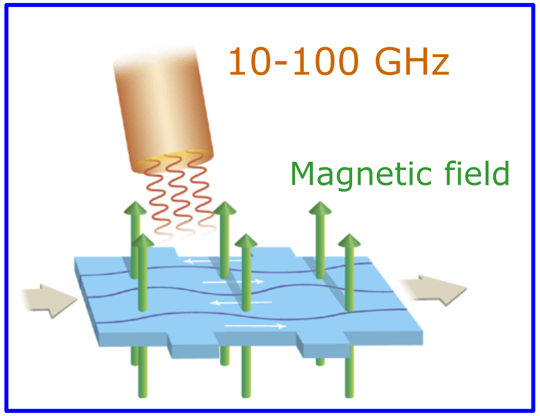


No Quantum Hall Effects, but beautiful many-body physics of strongly correlated 2DES with well understood disorder!

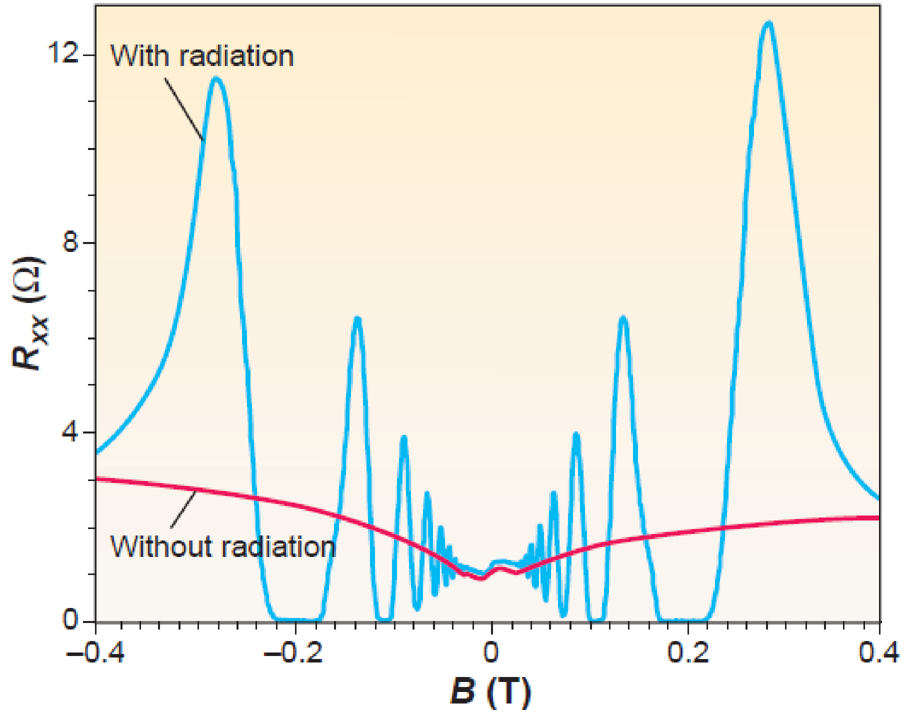
Microwave-Induced Resistance Oscillations (MIRO)

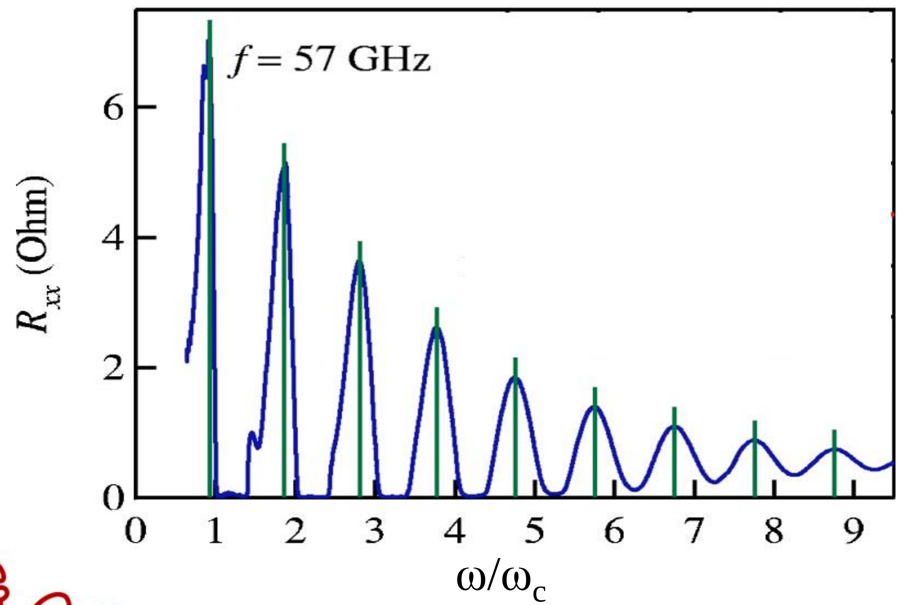
R. Mani et al, Nature 420, 646 (2002)

2DEG in GaAs heterostructures:



$$R_{xx} = \frac{V_x}{I_x}$$

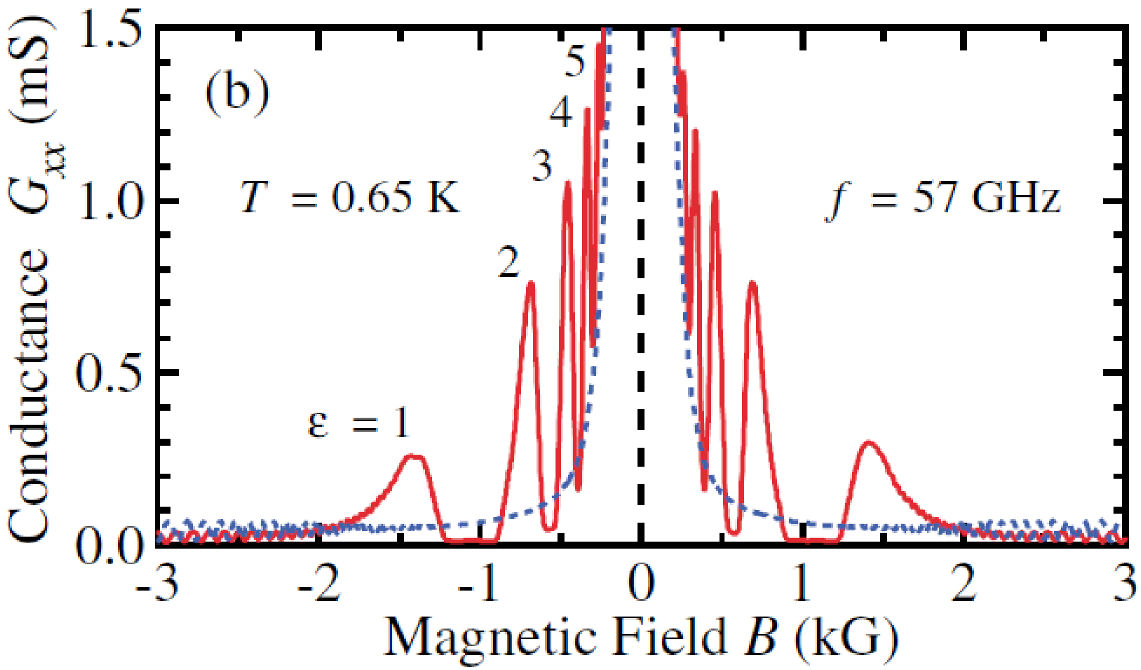




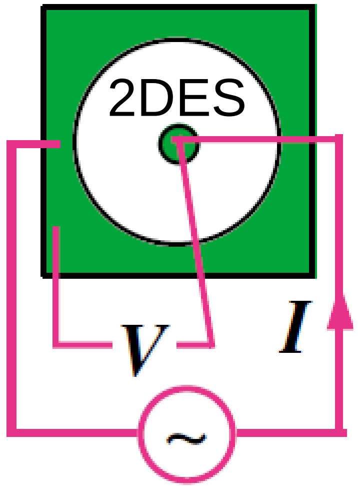
$$R_{xx} \rightarrow 0$$

Zero-Resistance States (ZRS)

MIRO and ZRS in semiconductors



Corbino electrodes



$$G_{xx} = \frac{I_x}{V_x}$$

$$\sigma_{xx} = \frac{\rho_{xx}}{\rho_{xx}^2 + \rho_{xy}^2}$$

Yang et al, PRL 91, 096803 (2003)

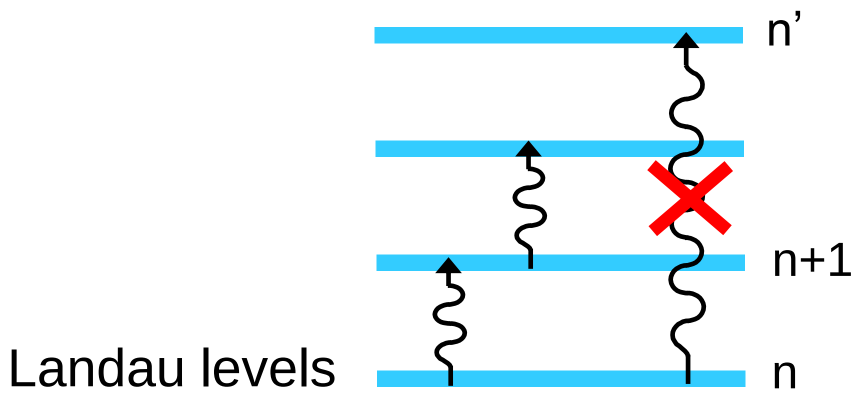
$$\frac{\partial \rho_s}{\partial t} = -\nabla \vec{j} = \sigma \nabla_r^2 V$$
$$\nabla^2 V = -\rho_s \delta(z)$$

$$\delta\rho_k \sim \exp\left(-\frac{\sigma k}{2} t\right) \to \infty$$

Instability and formation of current domains

Andreev, Aleiner, Millis, PRL 2003

Mechanism of MIRO in semiconductors

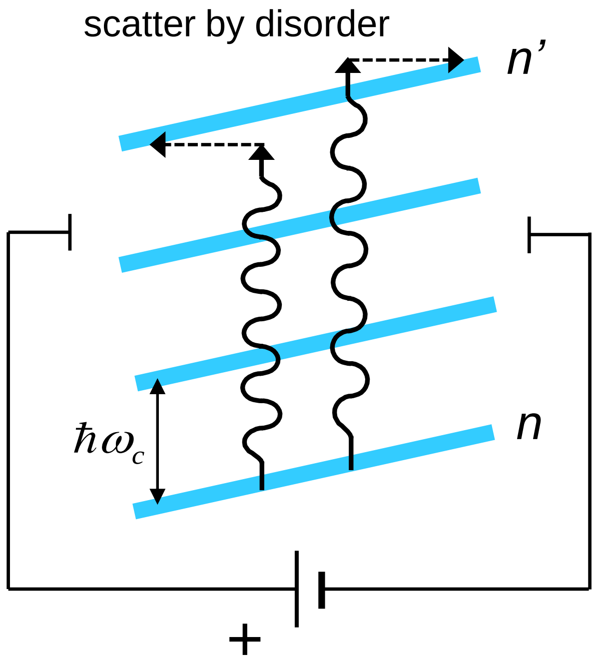


Displacement model

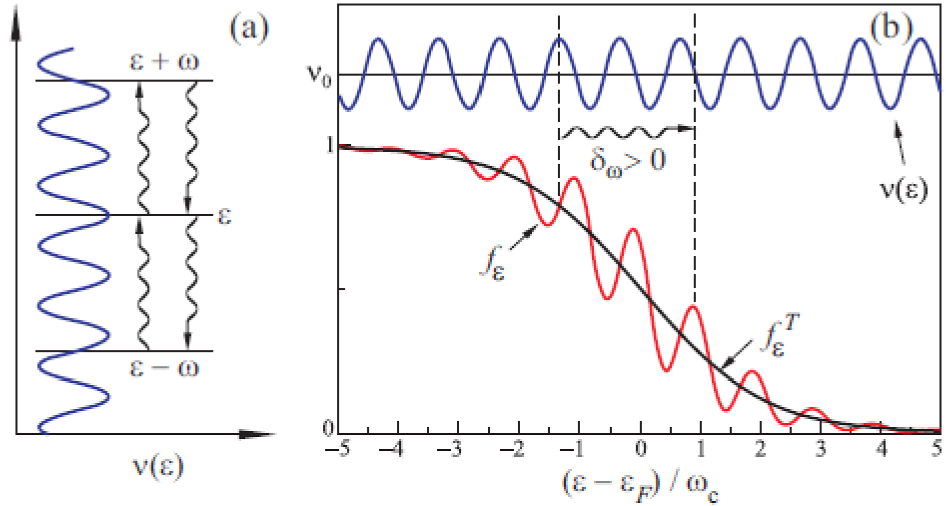
P. W Anderson, W. F. Brinkman: arXiv:0202129

Durst et al. PRL 91, 086802 (2003)

V. I. Ryzii, Sov. Phys. Solid State, 11, 2078 (1970)



Inelastic model



For review see Dmitriev et al. RMP 84, 1709 (2012)

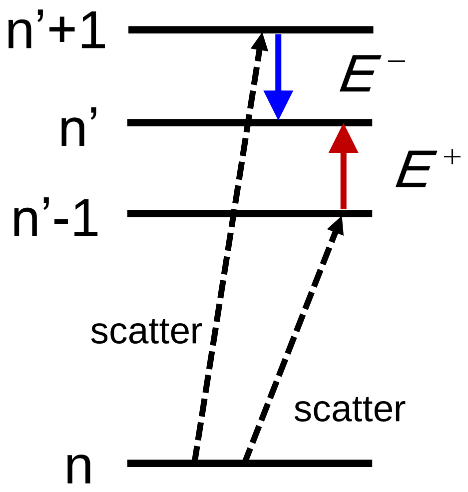
Displacement model for electrons on helium

Matrix element of interaction with MW:

$$\langle n', X' | H_{e-MW} | n, X \rangle = \frac{e l_B \delta_{X,X'}}{\sqrt{2}} \left[\sqrt{n}\, \delta_{n',n-1} \left(E^+ e^{i\omega t} + E^- e^{-i\omega t} \right) + \sqrt{n+1}\, \delta_{n',n+1} \left(E^+ e^{-i\omega t} + E^- e^{i\omega t} \right) \right]$$

In the second order:

$$w_{i\to f} = \frac{2\pi}{\hbar} \left| \sum_m \frac{\langle f | H_{int} | m \rangle \langle m | H_{int} | i \rangle}{E_i - E_f} \right|^2 \delta(E_f - E_i - \hbar\omega),$$



where $H_{int} = H_{e-MW} + H_{e-ripplon}$

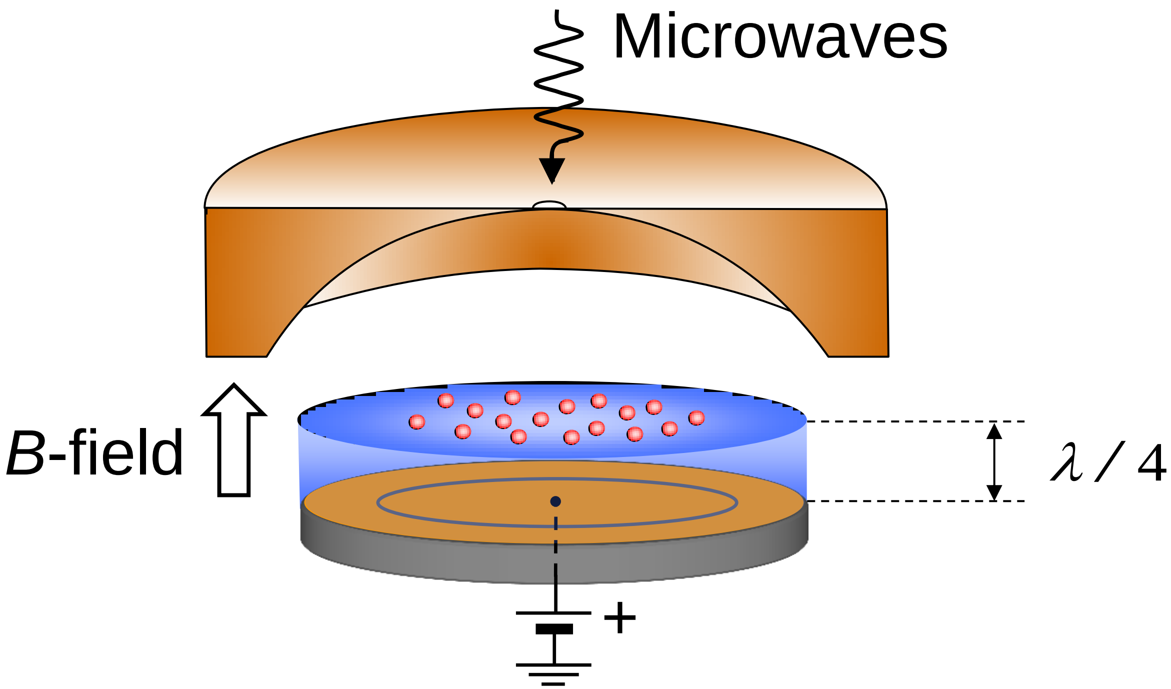
Contributes to dc conductivity of electrons!

$$\sim \frac{e^2 E_{MW}^2}{4 m_e^2 \omega^2 l_B^2}$$

$$\sigma_{xx} = \frac{e n_s l_B}{E_{dc}} \sum_q q_y \left(w_{r,q} + w_{MW,q} \right)$$

Yu. Monarkha, Low Temp. Phys. 40, 482 (2014)

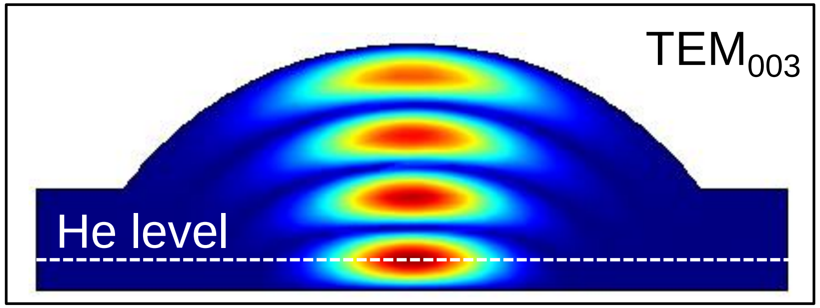
Electrons-on-helium system in cavity



Resonant mode: TEM_{00q}

Frequency : 35-90 GHz

Quality factor: 1,000-10,000



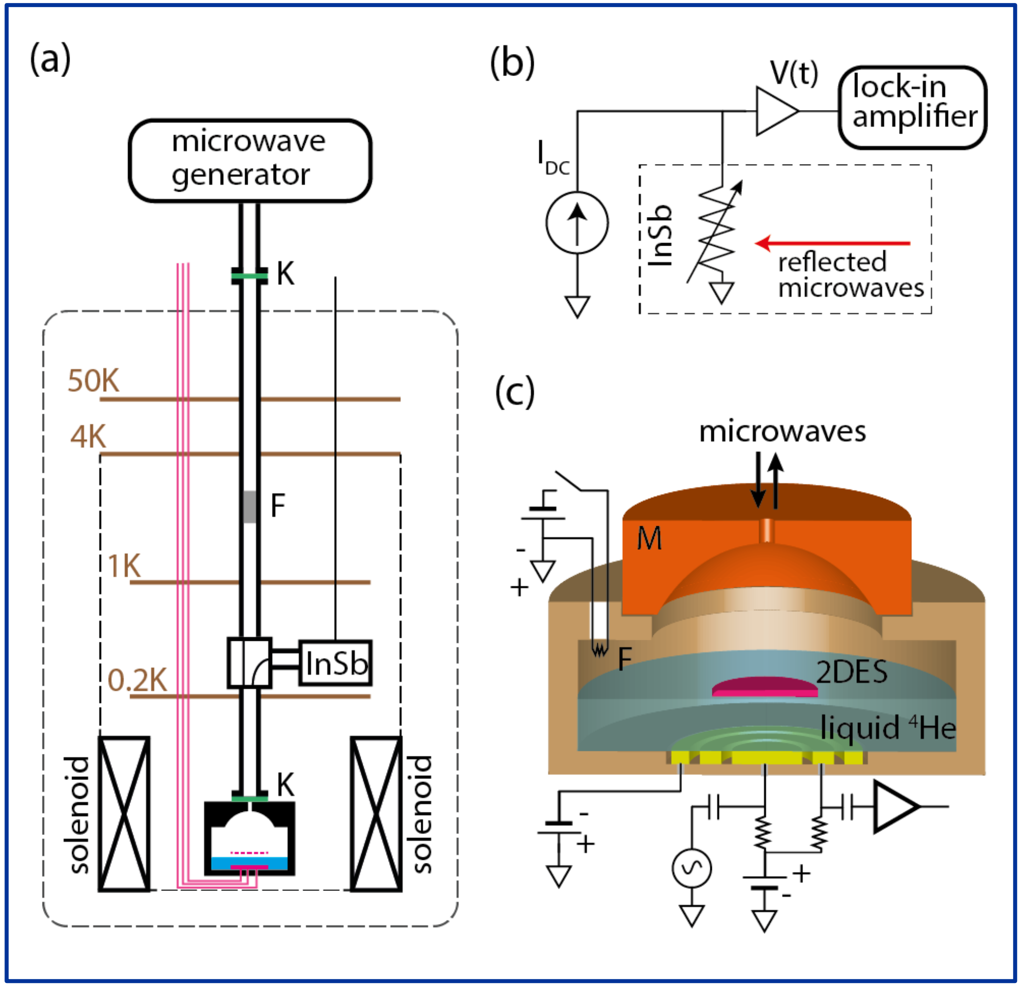
For input MW power $P_{in} \approx 100\ \mu W$

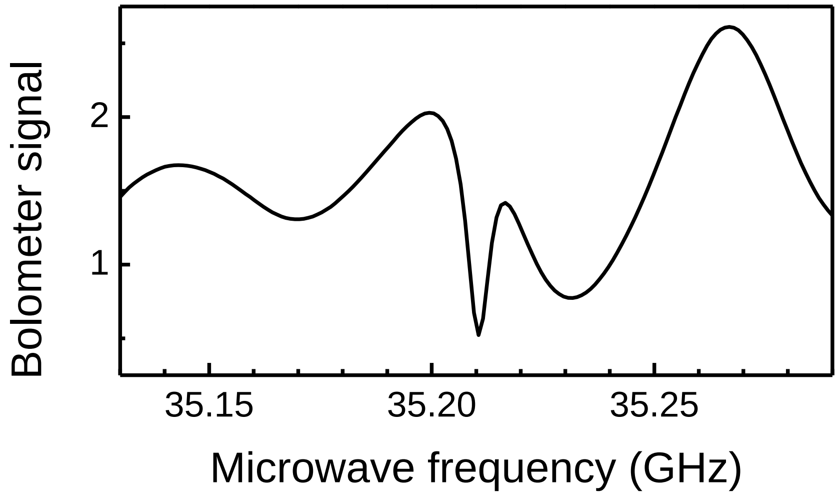
$$E_{MW} = \sqrt{\frac{\eta_0 P_{in}}{S_w}} \approx 0.3\ \mathrm{V/cm}$$

In a high-Q cavity

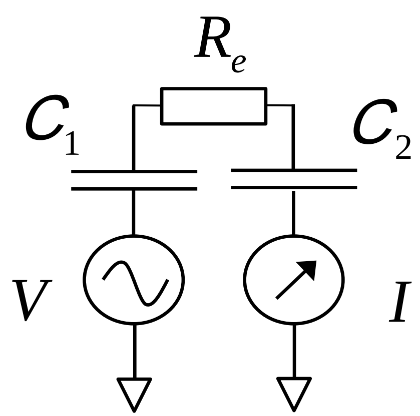
$$E_C = \sqrt{\frac{Q P_{in}}{S_w \varepsilon_0 \lambda \omega}} \approx \sqrt{\frac{Q}{2\pi}} E_{MW}$$

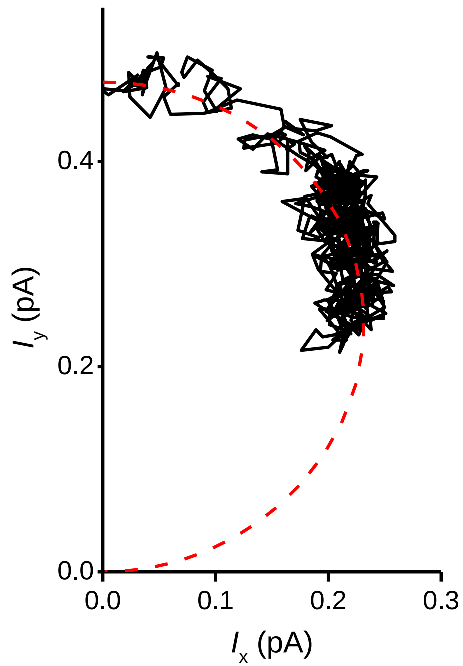
Experimental setup





Sommer-Tanner

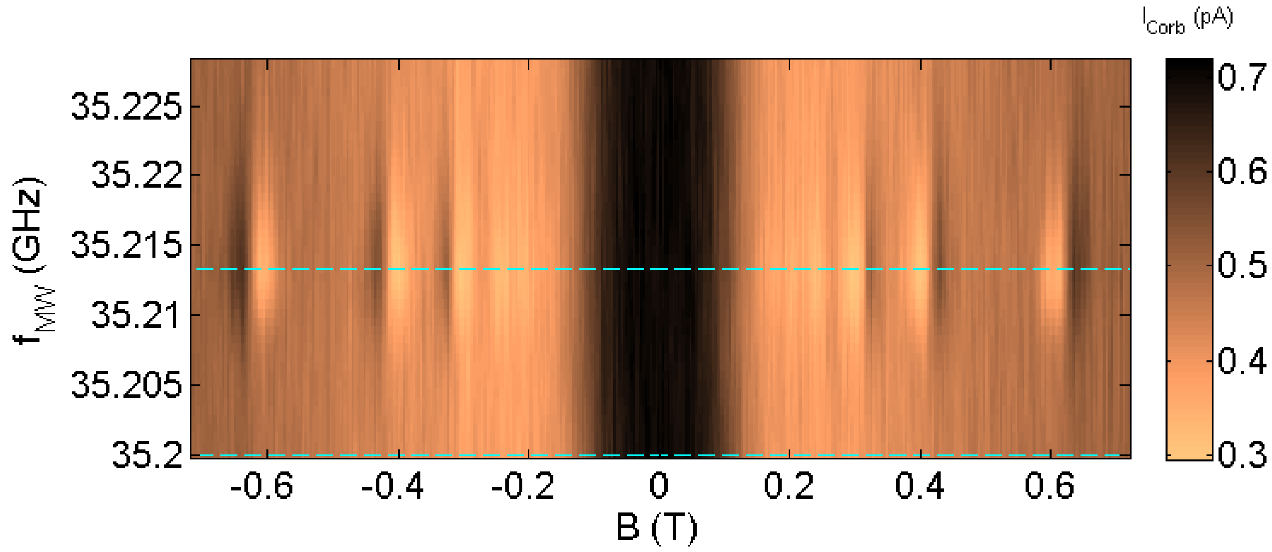


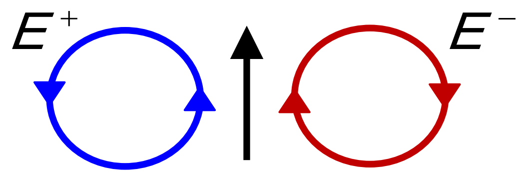


Abdurakhimov et al., PRL117, 056803 (2016)

MIRO in electrons on helium

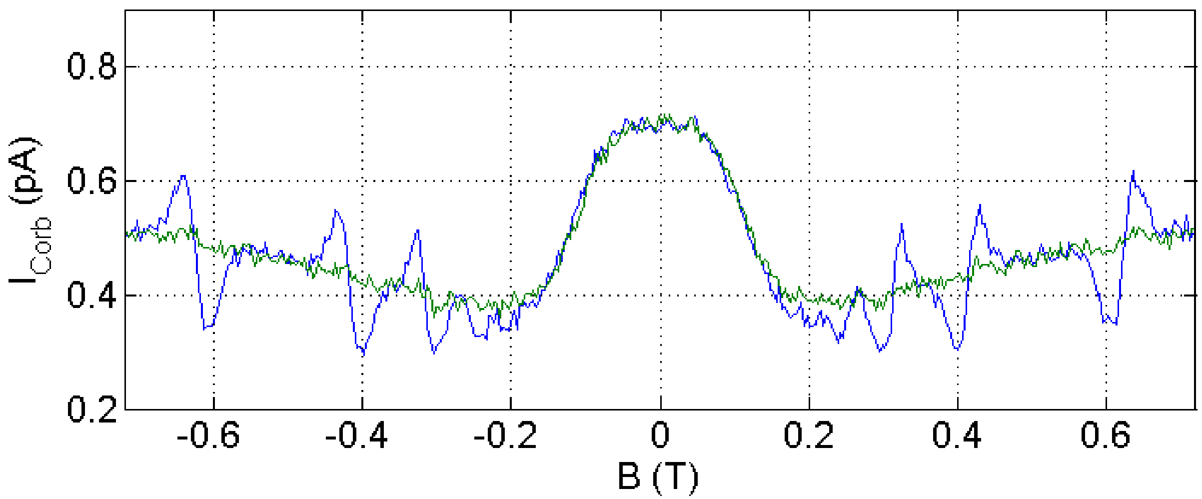
MIRO response to linearly-polarized microwave field





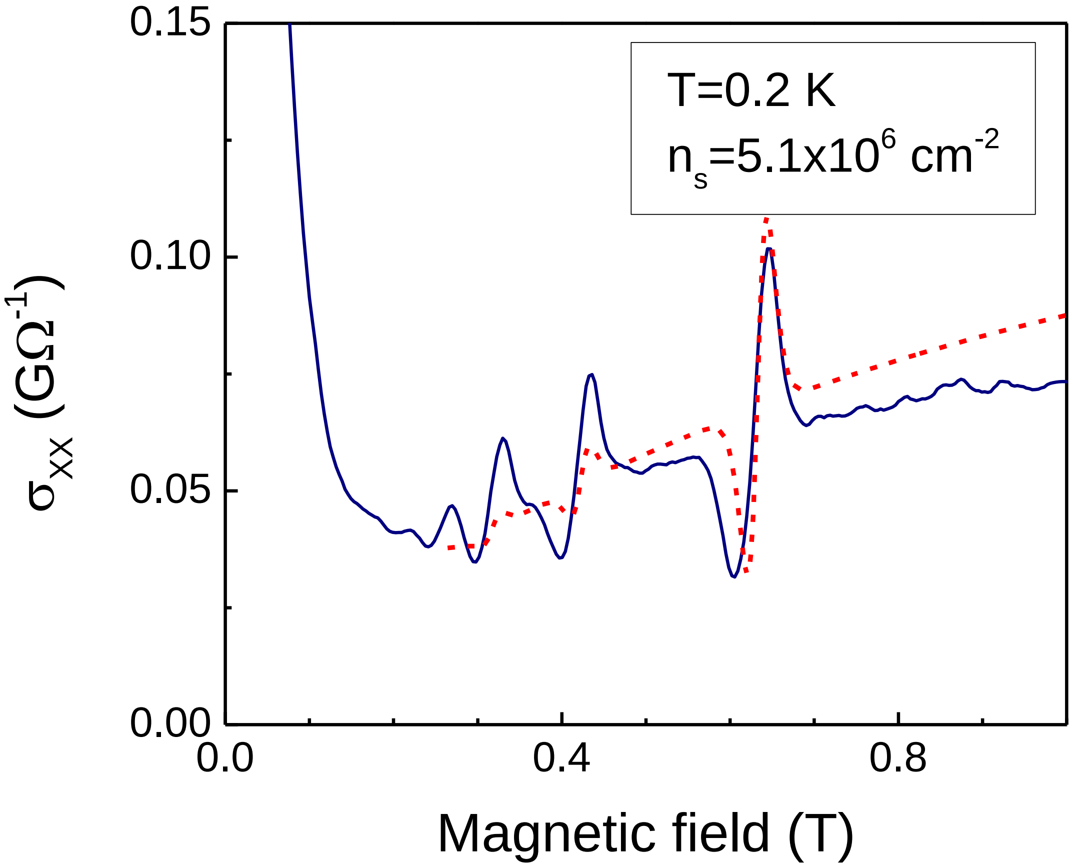
Linearly-polarized

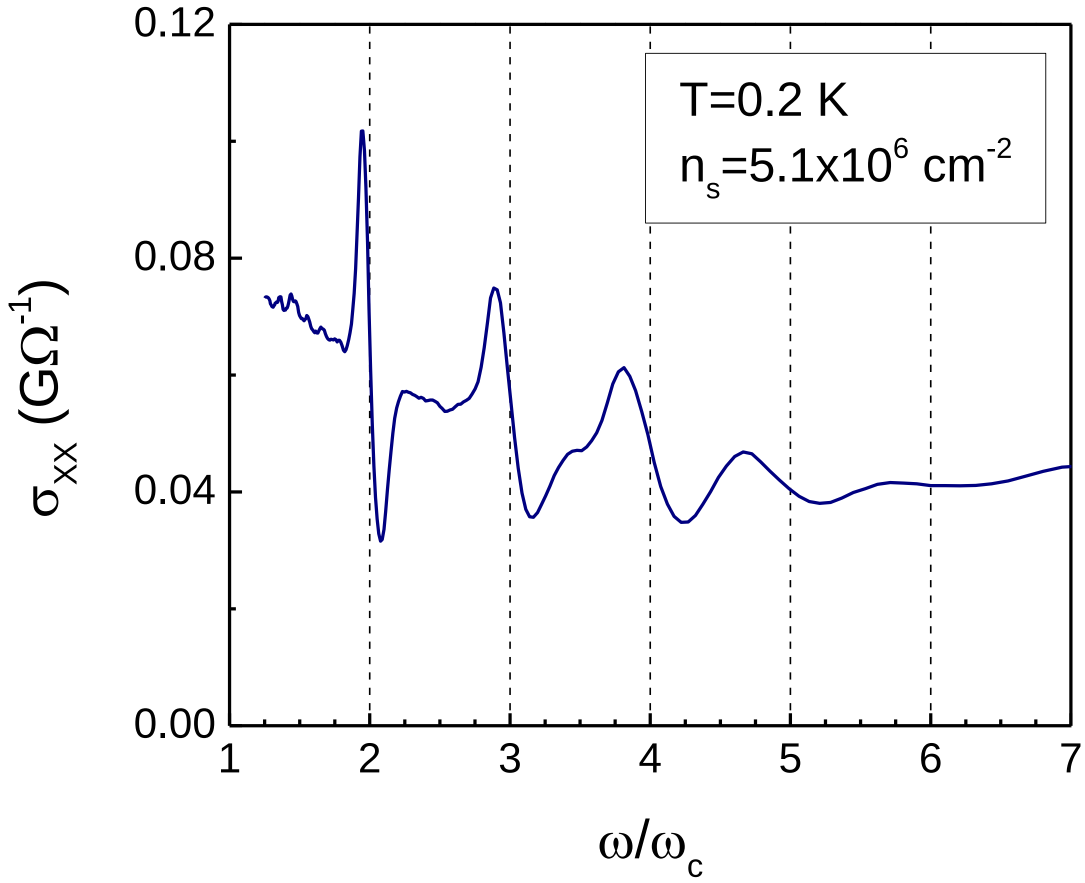
35 GHz microwaves



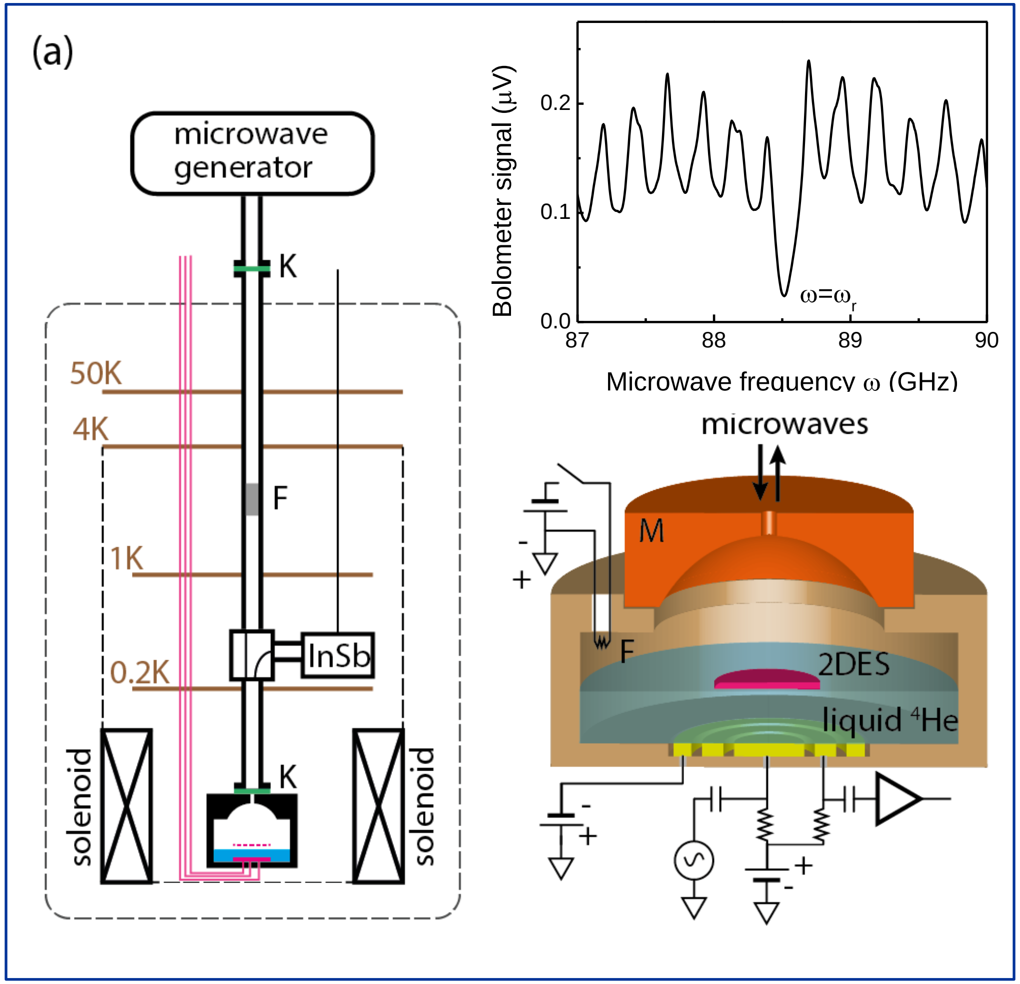
MIRO in electrons on helium

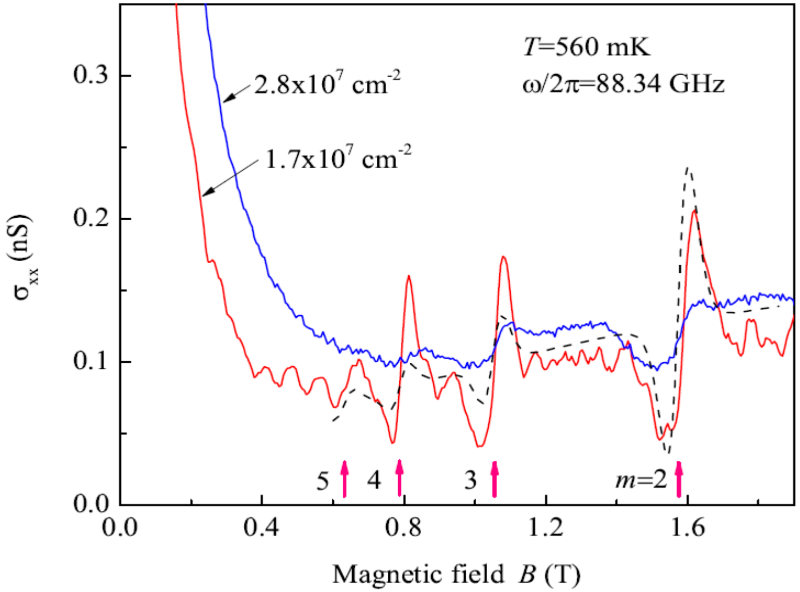
Theoretical calculations by Yuriy Monarkha

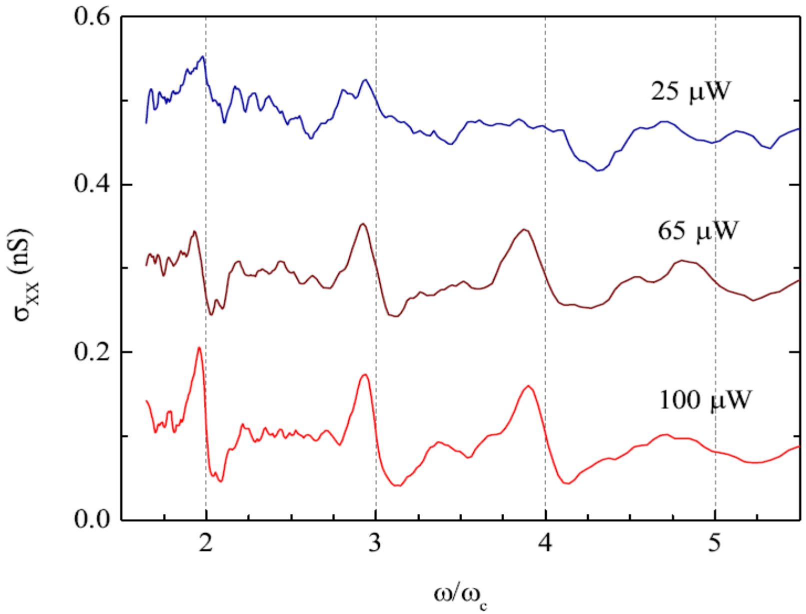




MIRO in electrons on helium: experiment at 90 GHz

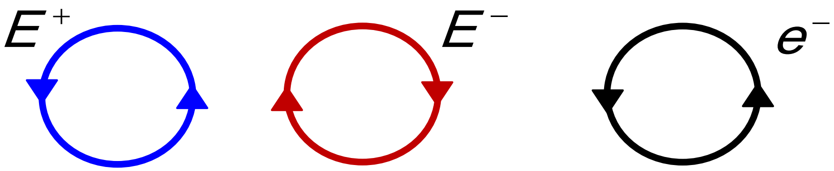






Yamashiro et al., PRL 115, 256802 (2015)

Effect of MW polarization: displacement mechanism



$$\sigma_{xx} = \frac{e n_s l_B}{E_{dc}} \sum_q q_y \left(w_{r,q} + w_{MW,q} \right),$$

where $$w_{MW,q} \propto \frac{e^2 E_{MW}^2}{4 m_e^2 \omega^2 l_B^2} \times \left| \frac{E^- e^{i\varphi}}{\omega_c + \omega} - \frac{E^+ e^{-i\varphi}}{\omega_c - \omega} \right|^2$$

Yu. Monarkha, Low Temp. Phys. 43, 819 (2017)

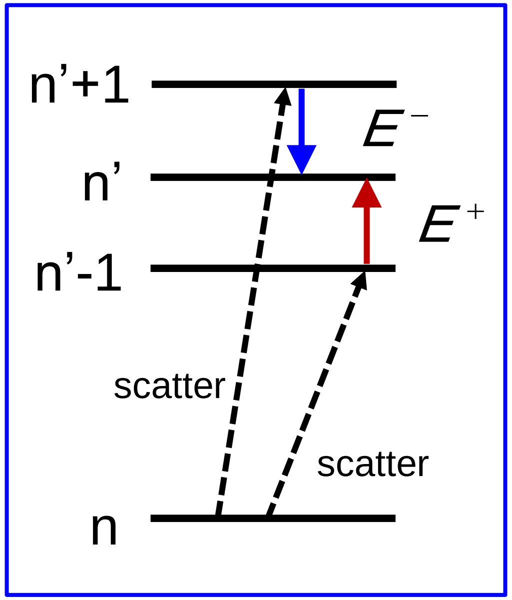
After summing over ripplon wavevectors **q**

$$\Delta\sigma_{xx} \propto \underbrace{\frac{\left|E^-\right|^2}{(m+1)^2}}_{\text{left-circular}} + \frac{\left|E^-\right| \times \left|E^+\right|}{m^2 - 1} + \underbrace{\frac{\left|E^+\right|^2}{(m-1)^2}}_{\text{right-circular}},$$

where $m = \frac{\omega}{\omega_c}$.

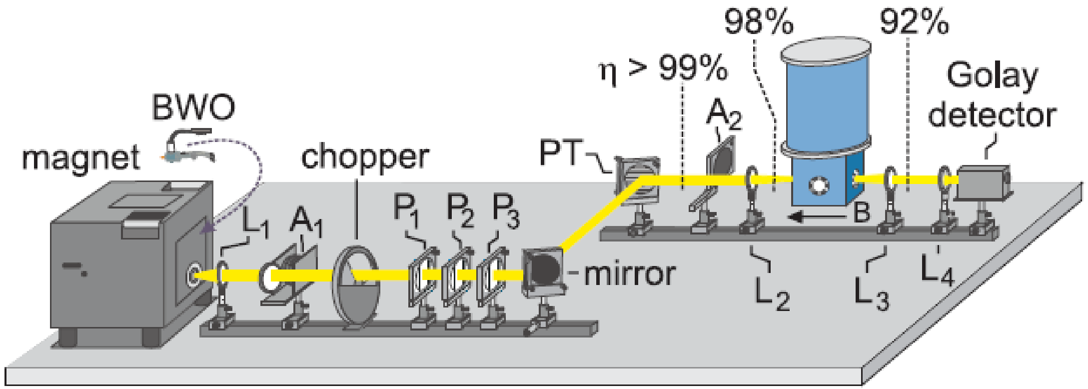
$$\text{ratio} = \frac{(m+1)^2}{(m-1)^2}$$

Effect of MW polarization

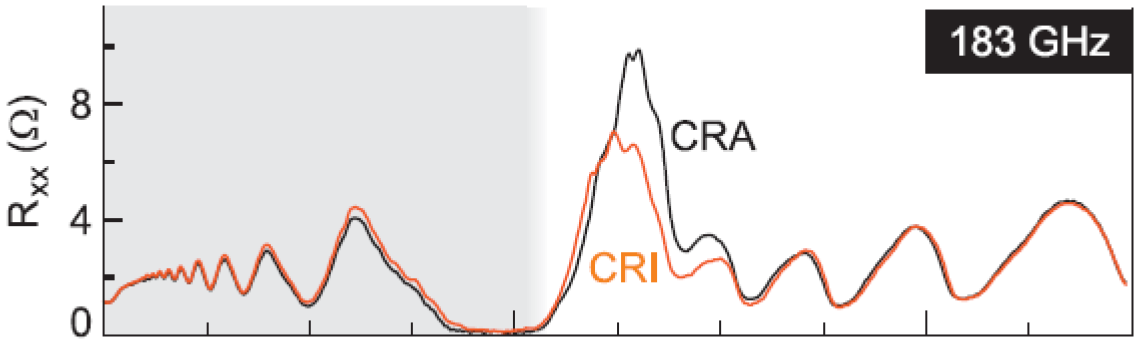


MIRO should <u>depend on </u>polarization of microwaves!

But .. in semiconductors they <u>don't</u>!!



Smet et al. PRL 95, 116804 (2005)



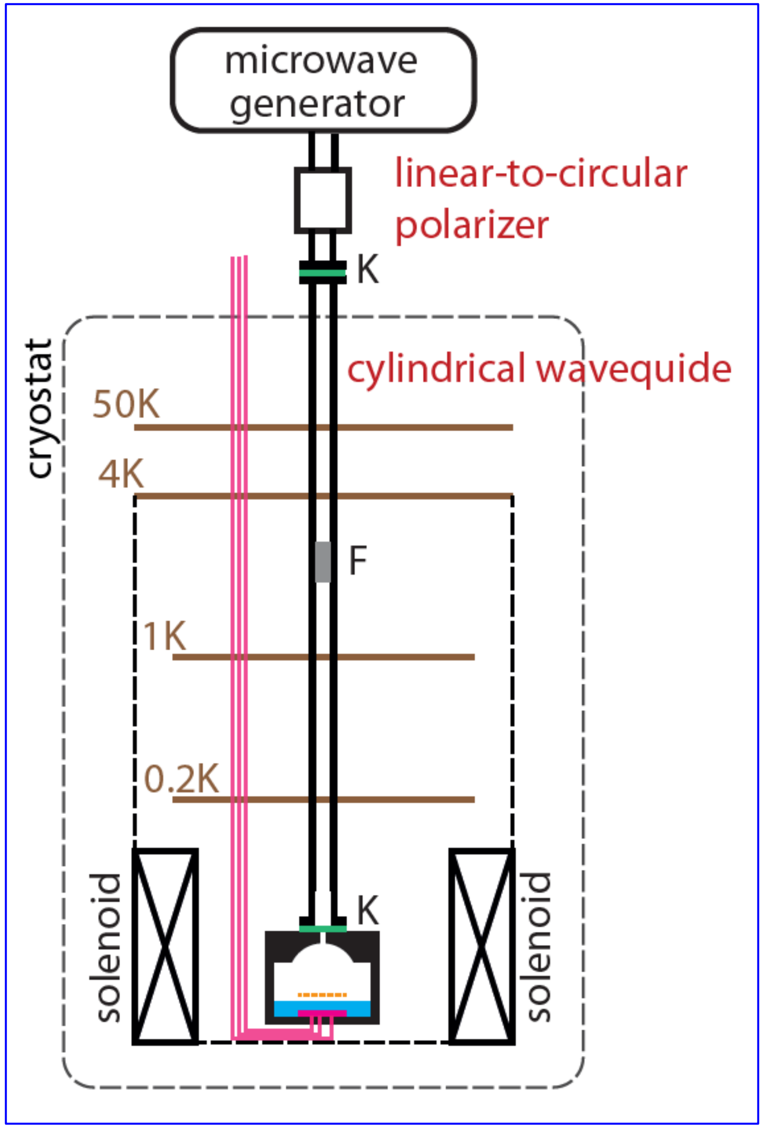
MIRO are completely <u>immune to</u>

the sense of circular polarization!!

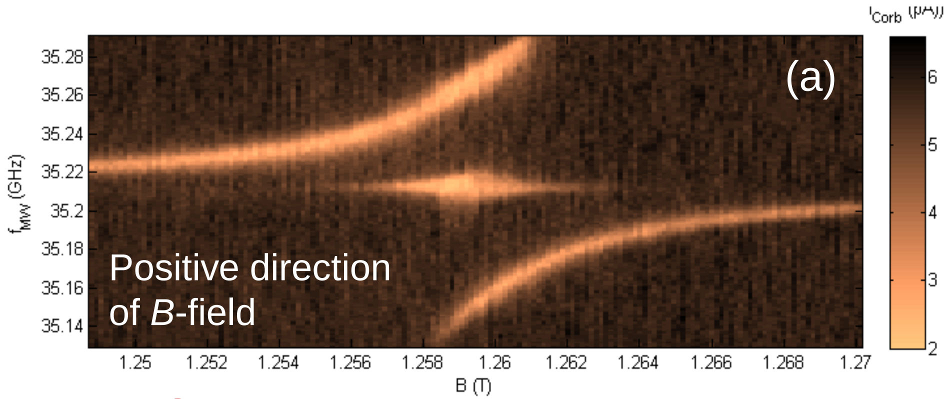
..also, later experiments by

Ganichev *et al*.

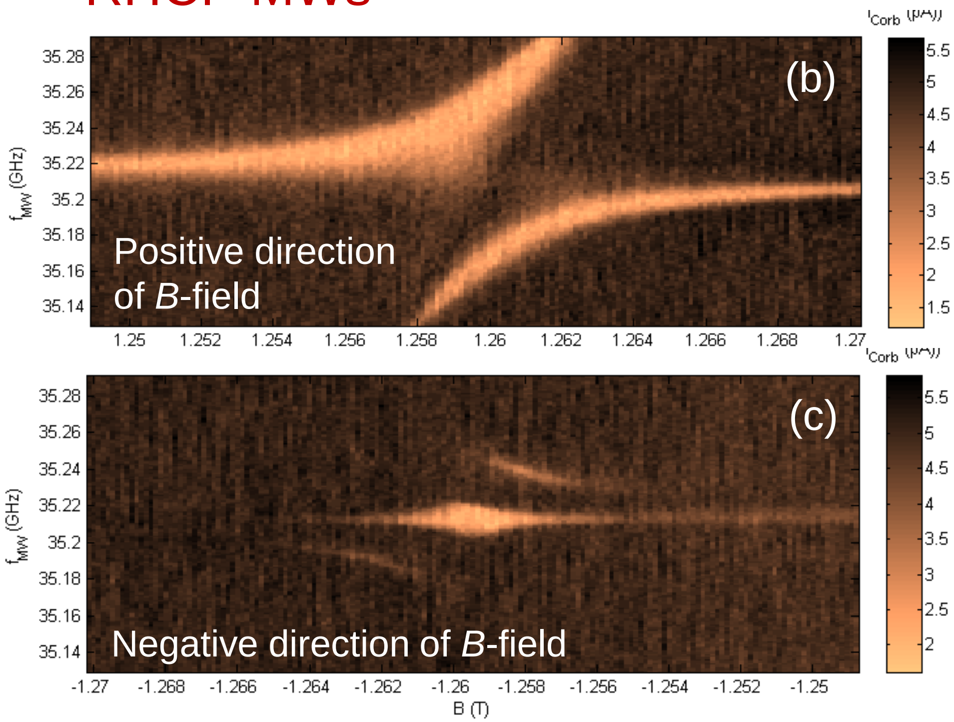
Effect of MW polarization: Cyclotron Resonace



Linearly-polarized MWs

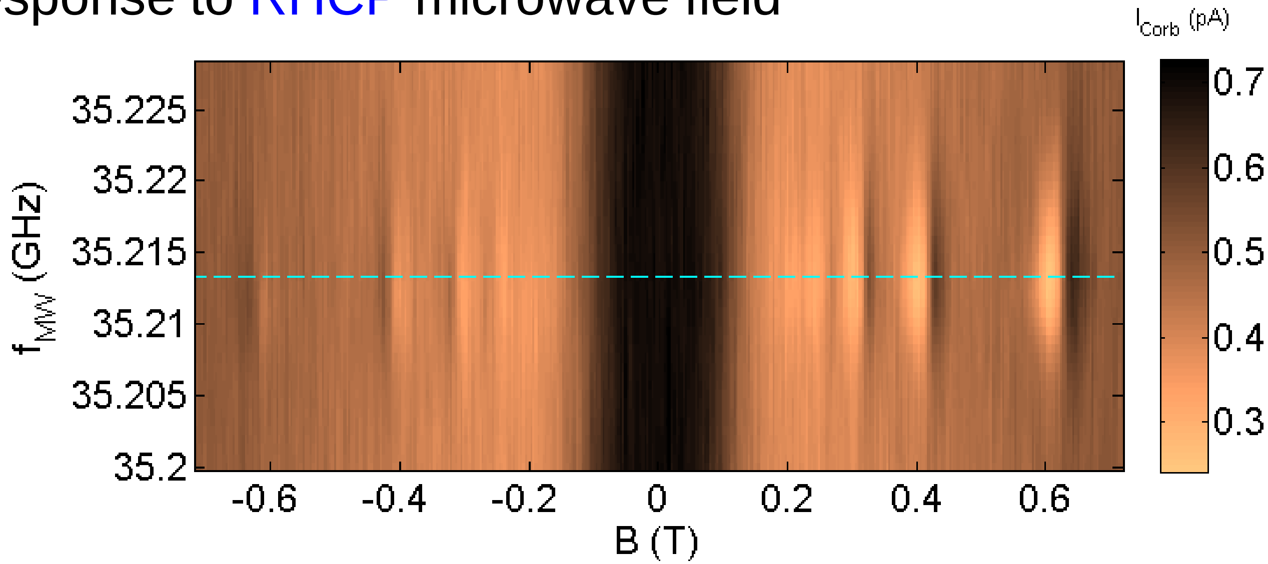


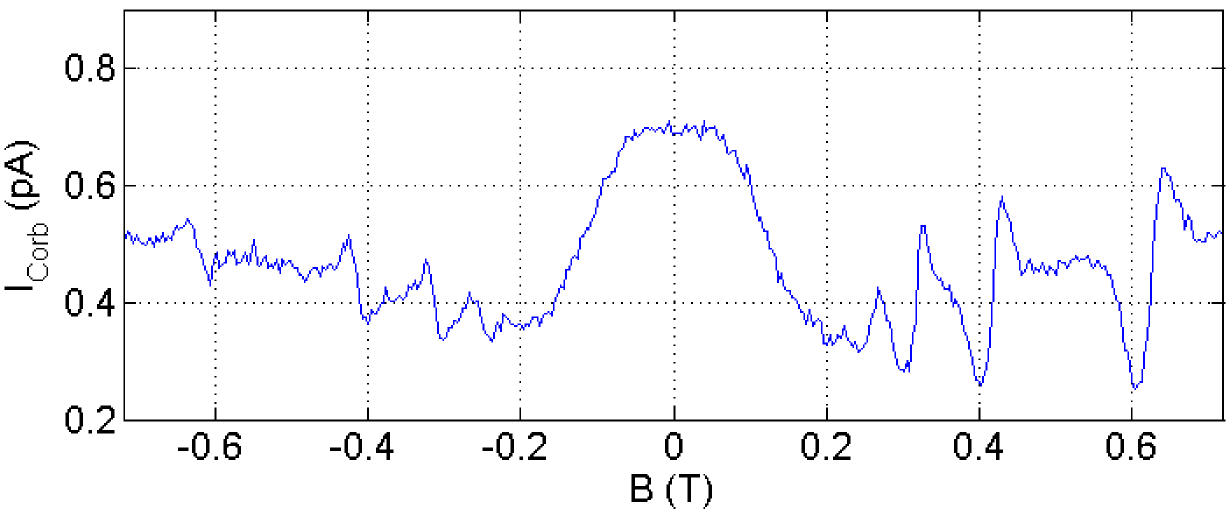
RHCP MWs



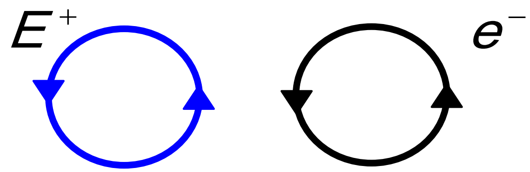
Effect of MW polarization: MIRO

MIRO response to RHCP microwave field

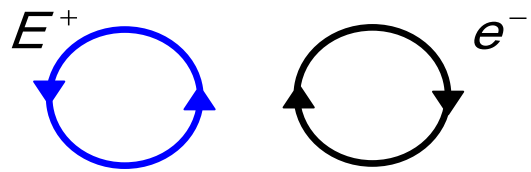




Positive direction of *B*-field

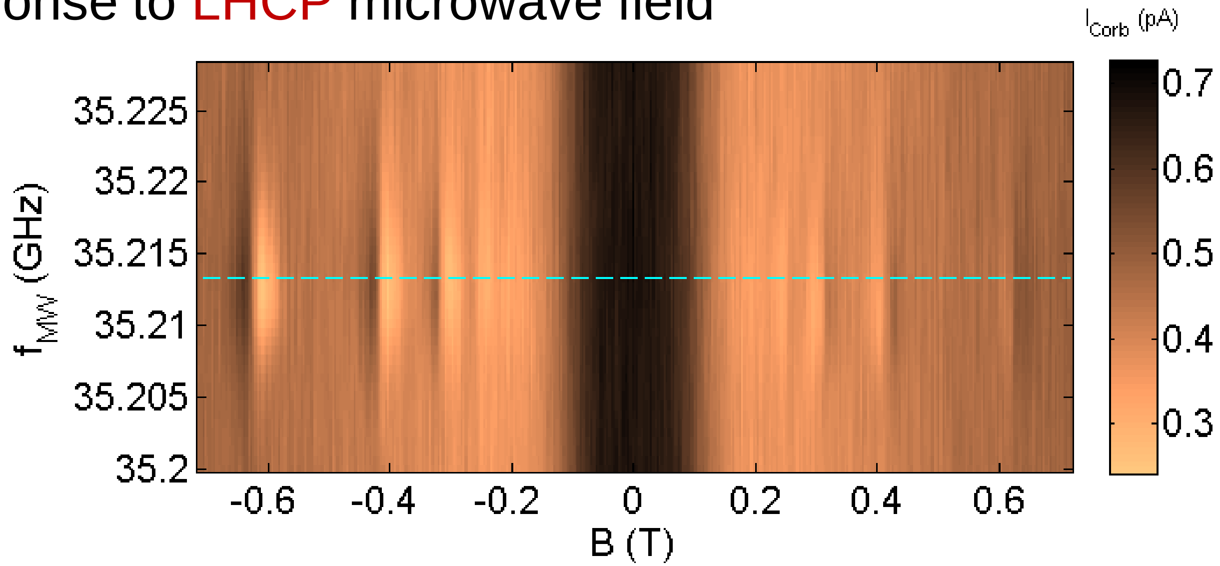


Negative direction of *B*-field

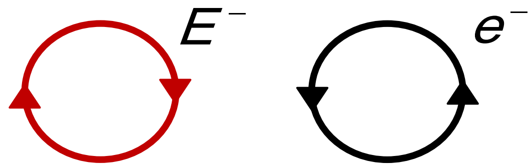


Effect of MW polarization: MIRO

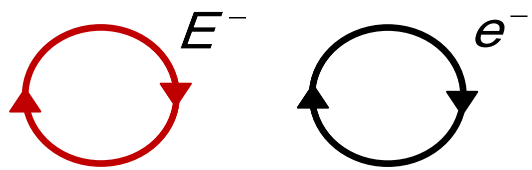
MIRO response to LHCP microwave field

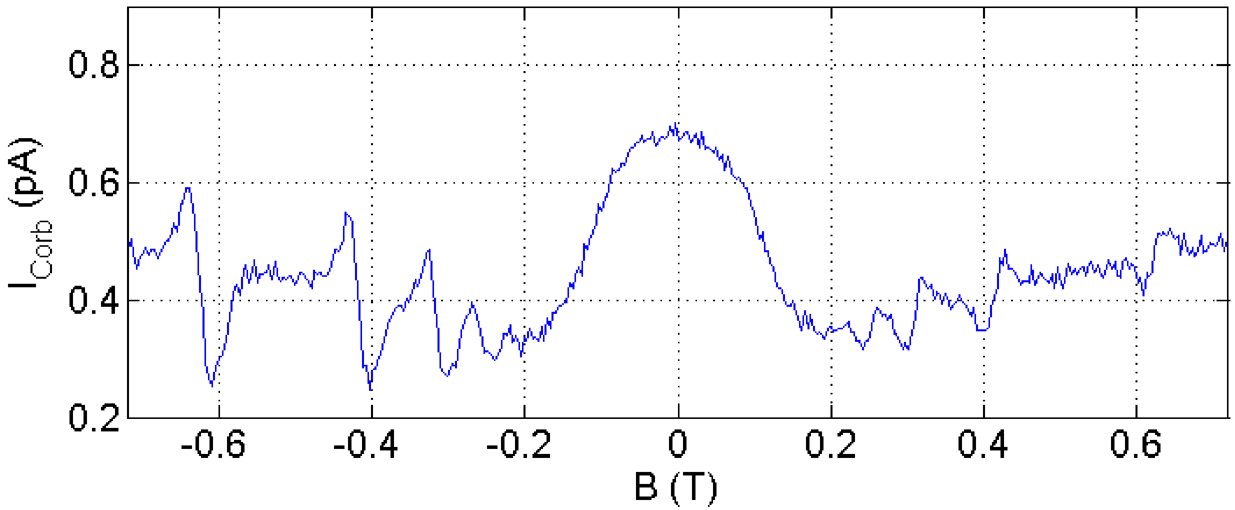


Positive direction of *B*-field

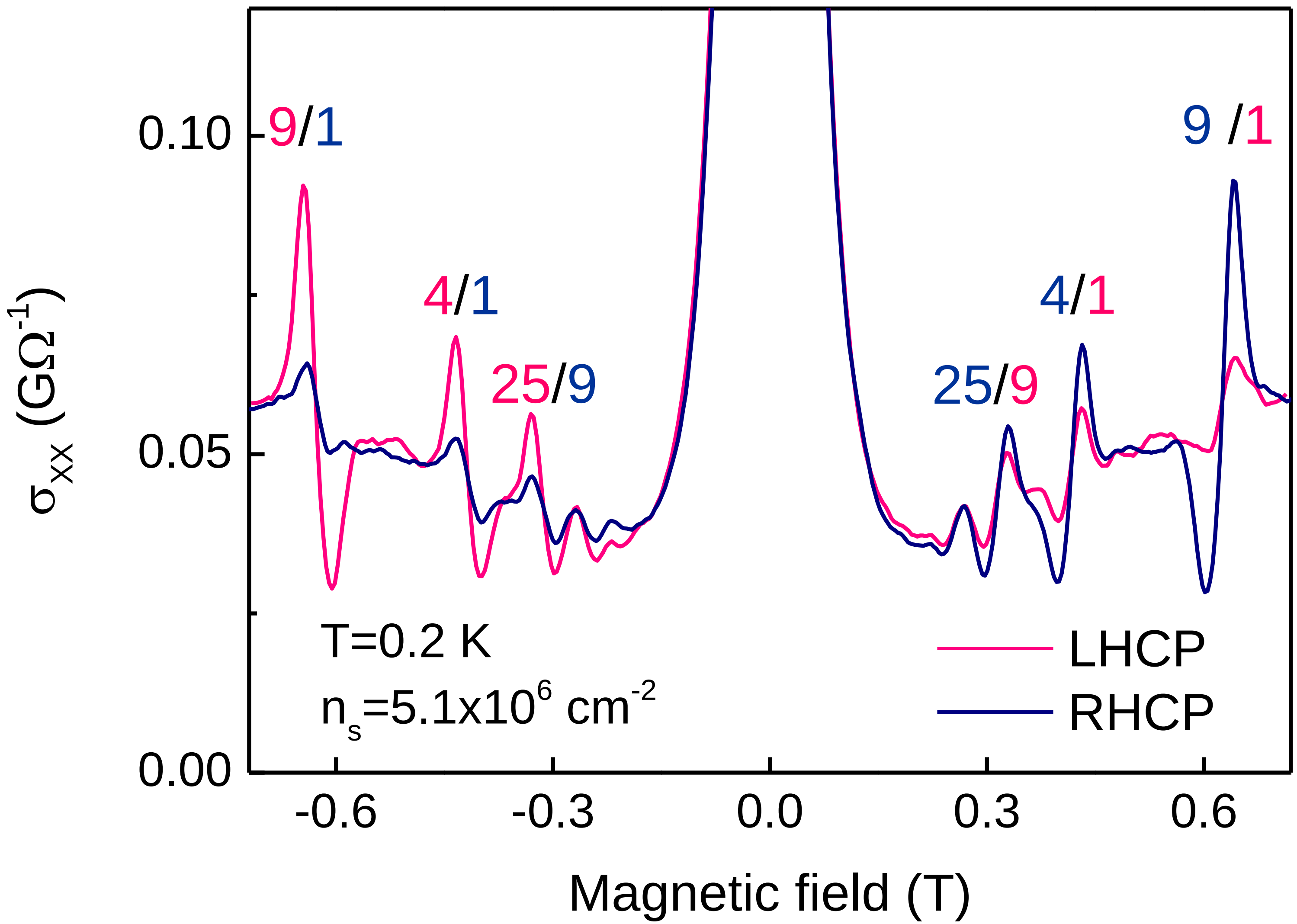


Negative direction of *B*-field

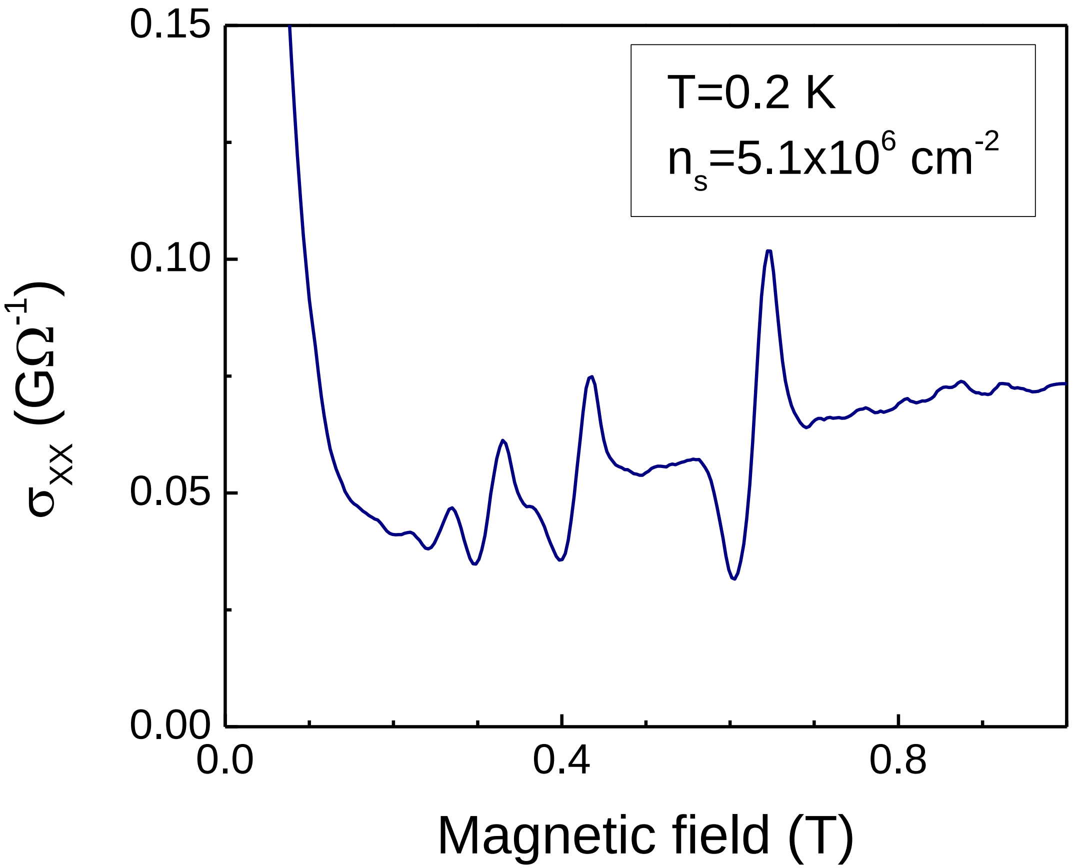




Effect of MW polarization: MIRO



Summary



First observation of MIRO in the electron-on-helium system

Both displacement and inelastic are applicable for electrons on helium and account reasonably for experiment

Polarization dependence is confirmed experimentally for the first time and consistent with both models