Warming in systems with discrete spectrum

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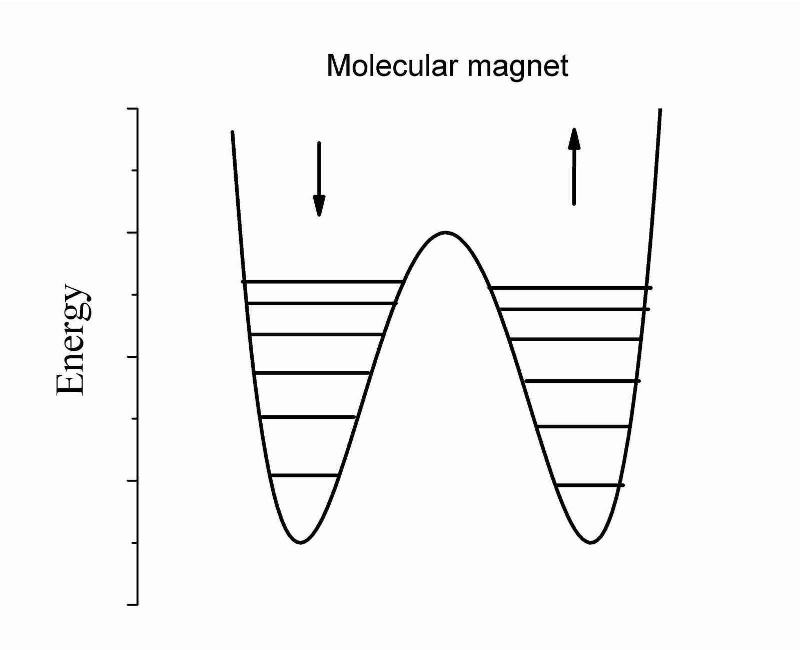
OUTLINE

- Introduction
- Experimental setup
- Results
- Conclusion

A similarity between molecular magnets and 2D electrons in magnetic field. Both systems have discrete energy spectrum, demonstrate Landau-Zener transitions between levels and can be heated.



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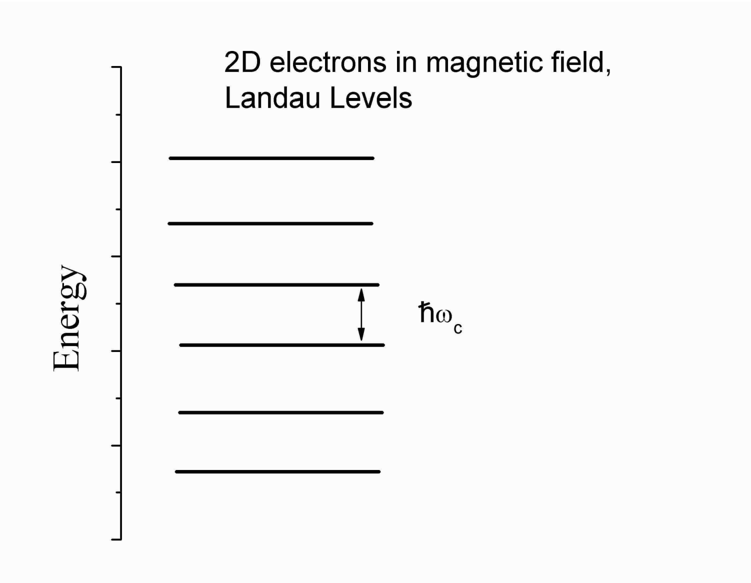


- **“ 'Magnetic flames' in molecular magnets exhibit properties akin to fire. In a groundbreaking experiment, researchers from The City College of New York (CCNY) and Lehman College have measured the speed of magnetic avalanches and discovered that the process is analogous to the flame front of a flammable substance. The discovery of a "magnetic flame" could make it easier for engineers to study the dynamics of fire. “**

  (http://www.physorg.com/news5967.html)

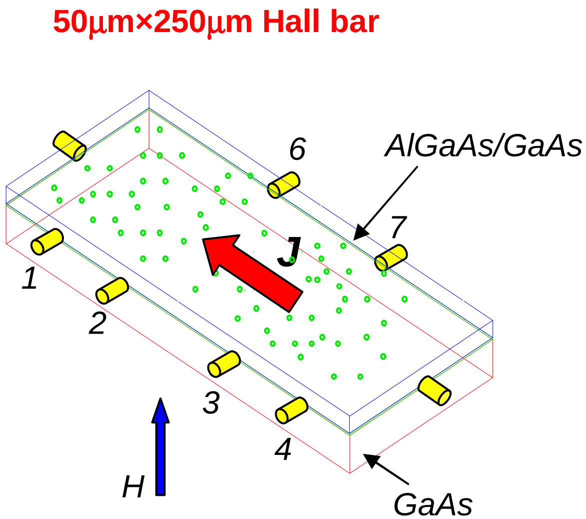
a) Why does the warming of 2D electrons in crossed electric and quantized magnetic fields change the 2D conductivity

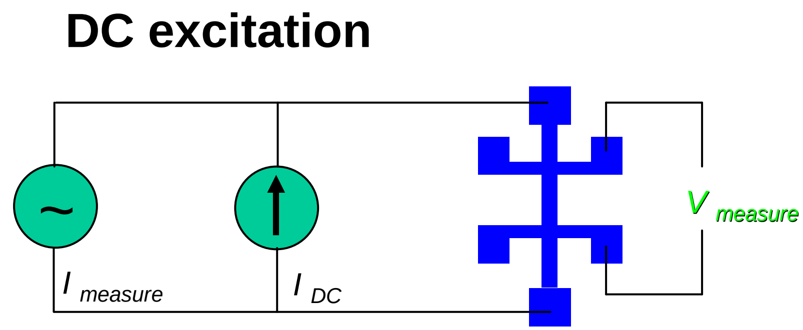
b) What is distribution function of the overheated electrons?

c) Can one use a temperature to describe the warming?

d) Can the warming help engineers?

Experimental setup



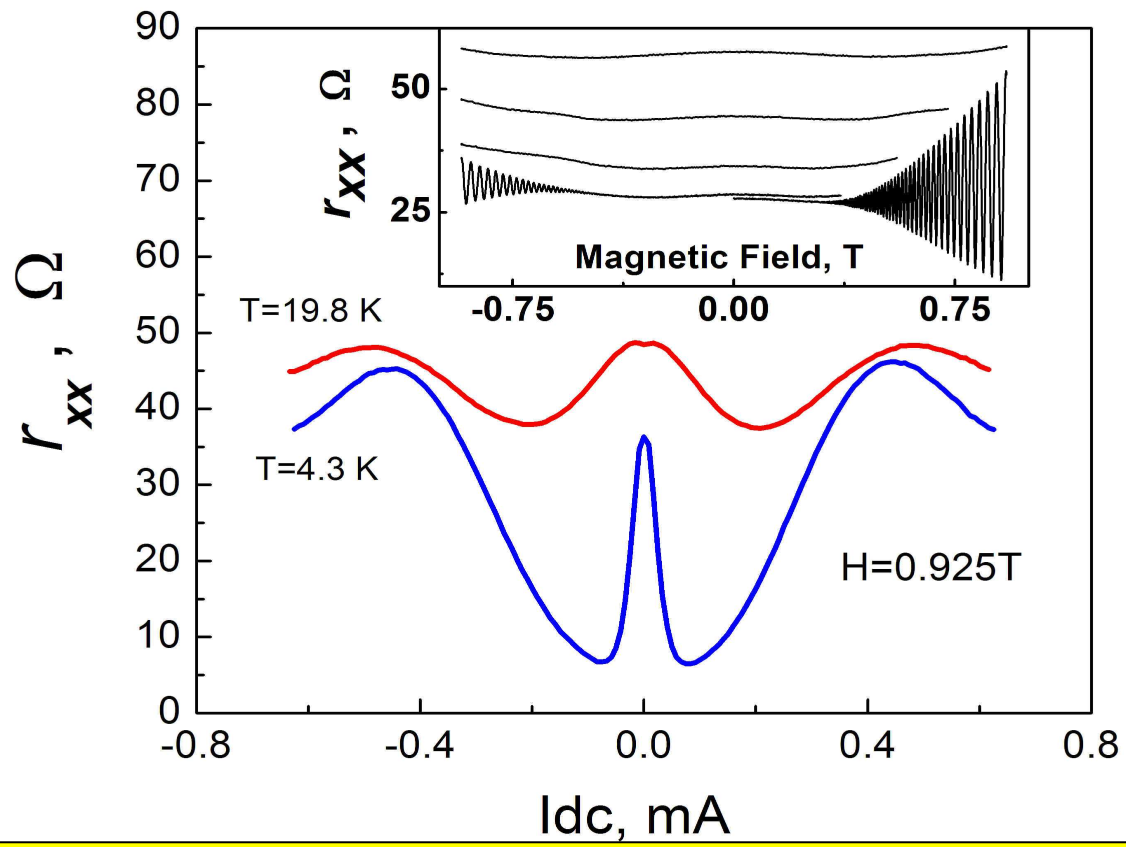


Sample N1: $\mu 1 = 0.93 \times 10^{6}$ cm^2/Vs; $n1_e \sim 1.2 \times 10^{16}$ m^{-2}

Sample N2: $\mu 2 = 0.82 \times 10^{6}$ cm^2/Vs; $n2_e \sim 0.85 \times 10^{16}$ m^{-2}

Nonlinear transport in DC electric field

Strongly nonlinear behavior of 2D electrons is found in response to crossed *dc* electric field E and magnetic field B



Dependence of differential resistance r_{xx} on DC bias in magnetic field as labeled.

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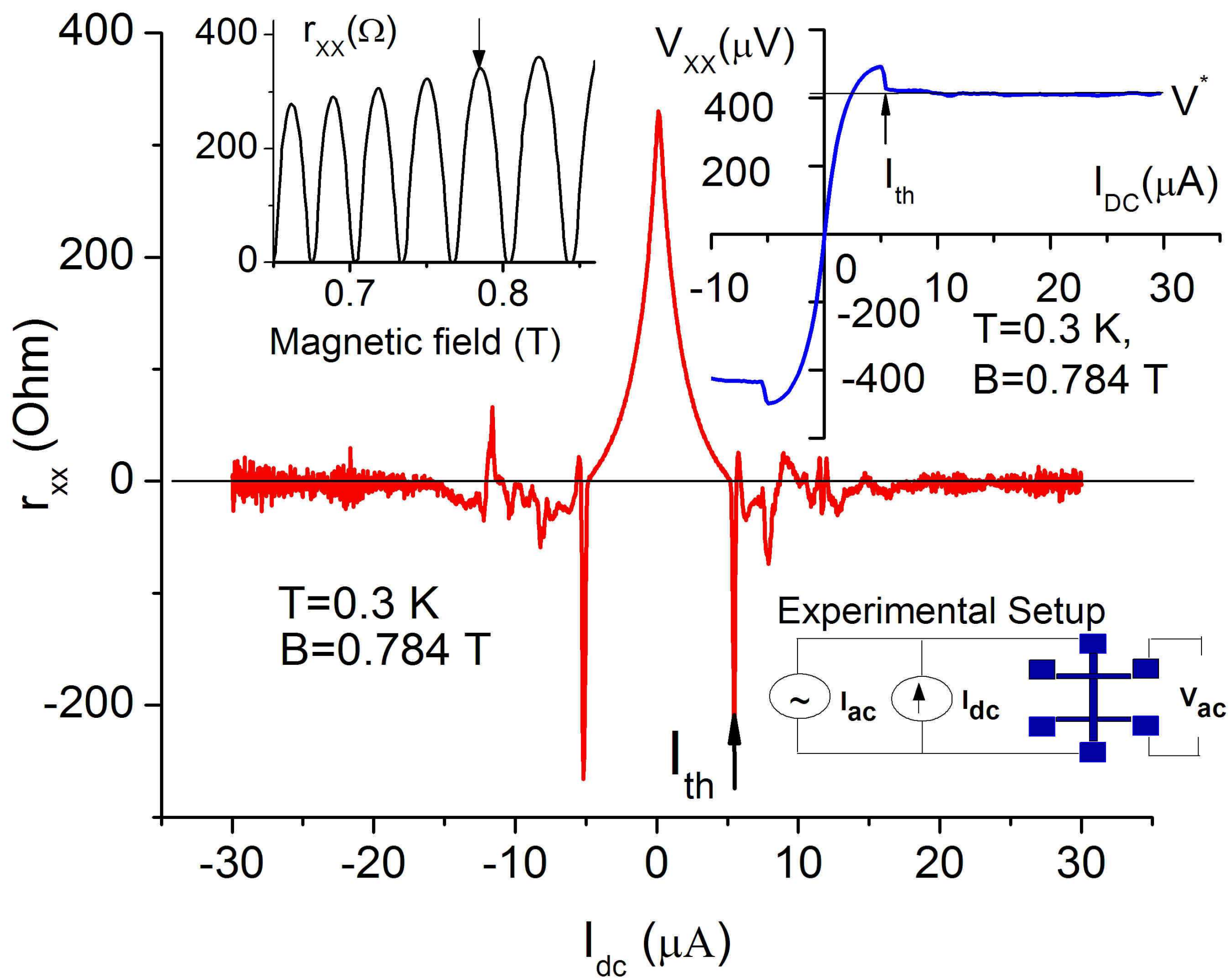
• J. Zhang, S. Vitkalov, A. A. Bykov, A. K. Kalagin, and A. K. Bakarov, Phys. Rev. **B75**, 081305(R) (2007).
• C. L. Yang, J. Zhang, R. R. Du, J. A. Simmons, and J. L. Reno, Phys. Rev. Lett. **89**, 076801 (2002).
•W. Zhang, H.-S. Chiang, M. A. Zudov, L. N. Pfeiffer, and K.W. West, Phys. Rev. **B75**, 041304(R) (2007).

The nonlinearity is so strong that the 2D electron system forms a state with zero differential resistance (ZDR)



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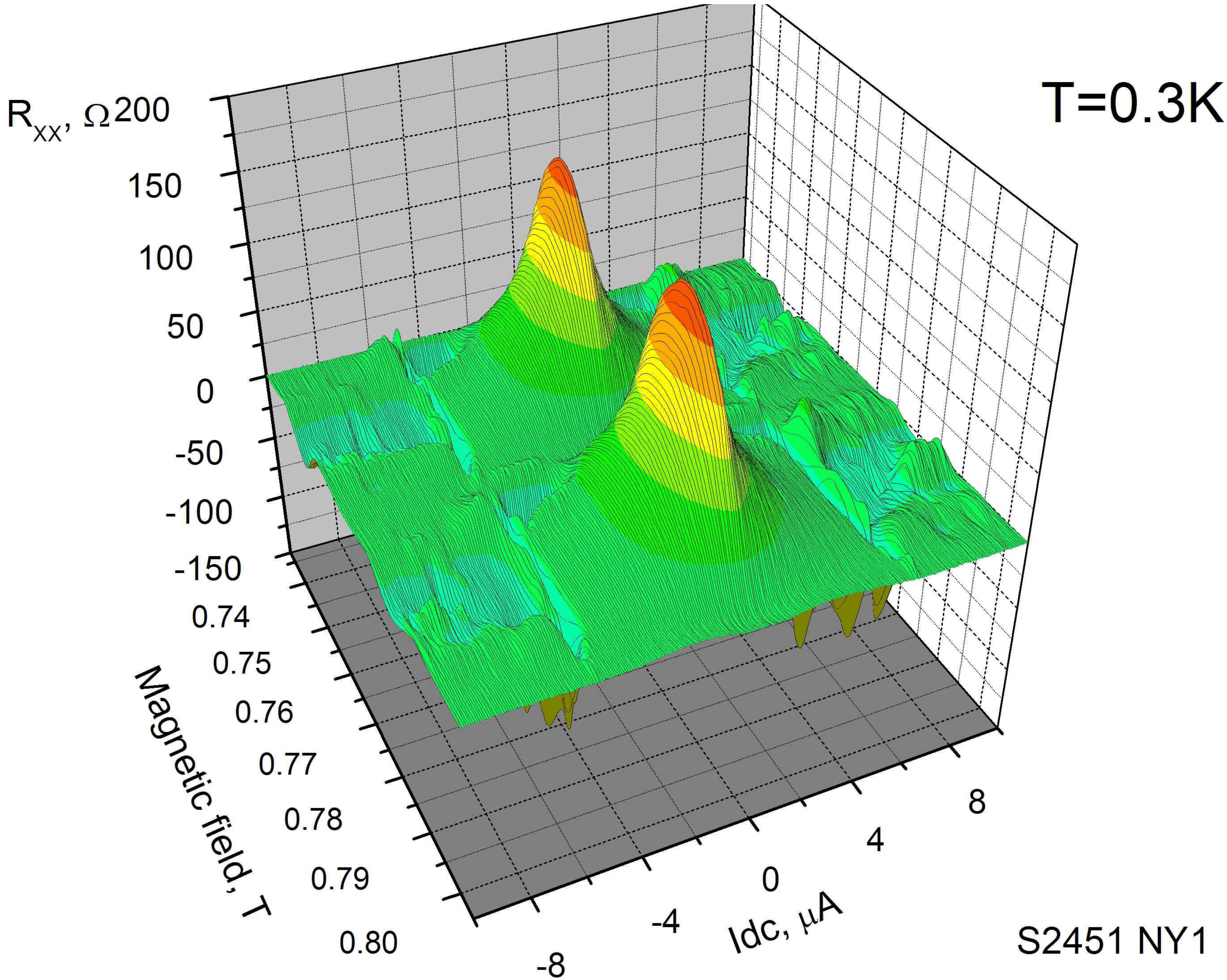
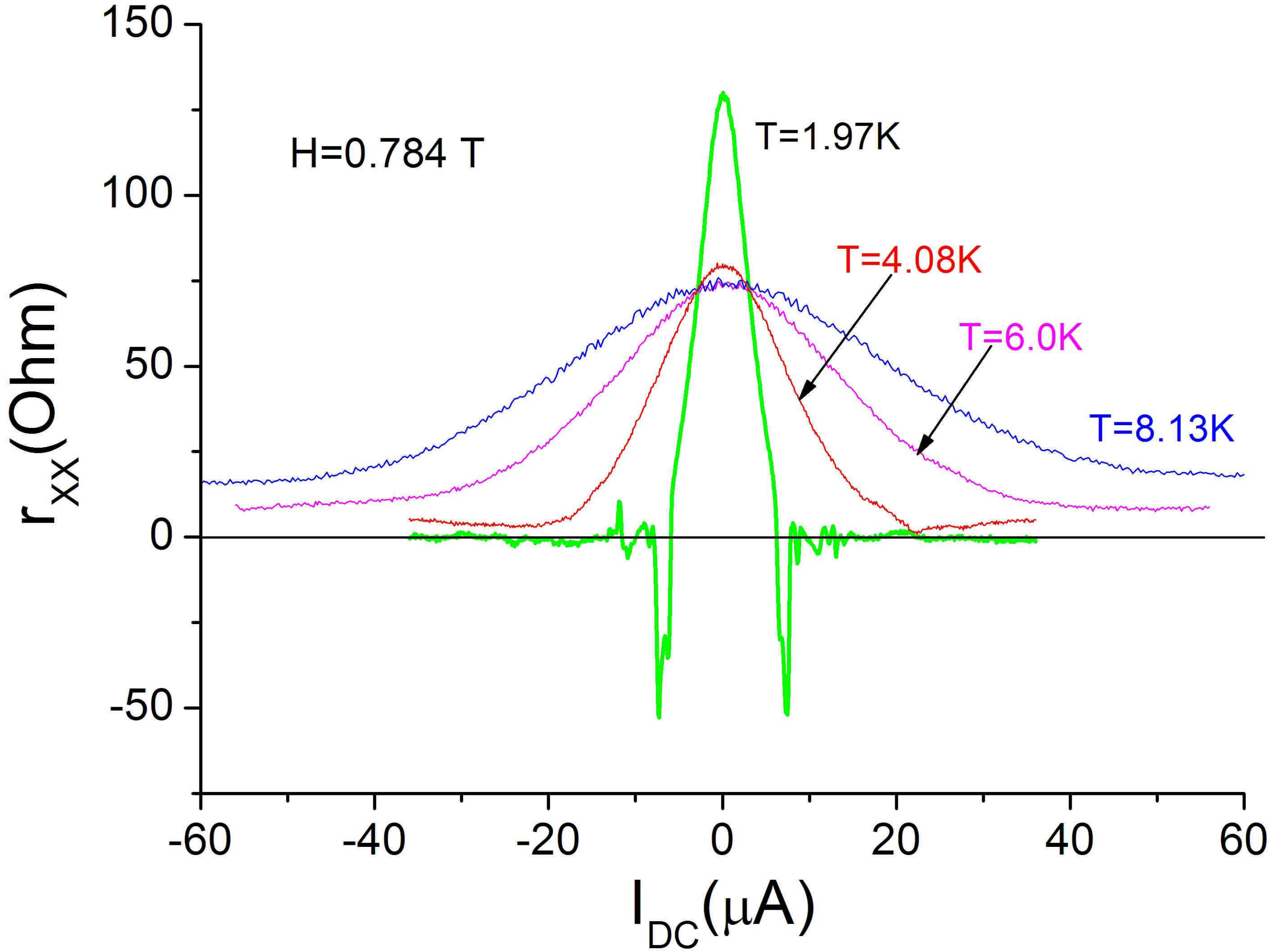
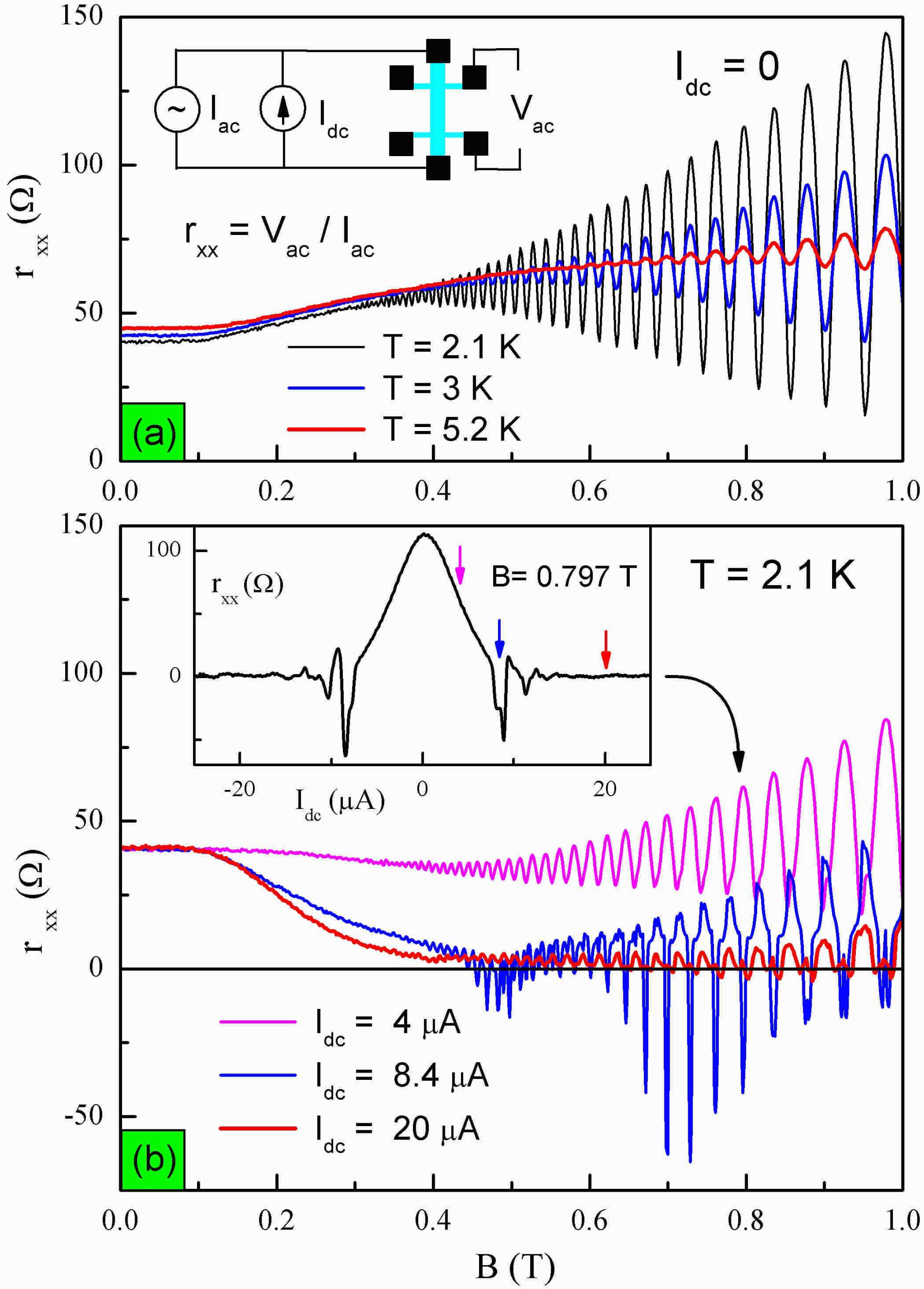


T=0.3K
R_{xx}, Ω
200
150
100
50
0
-50
-100
-150
0.74
0.75
0.76
0.77
0.78
0.79
0.80
Magnetic field, T
-8
-4
0
4
8
Idc, μA
S2451 NY1

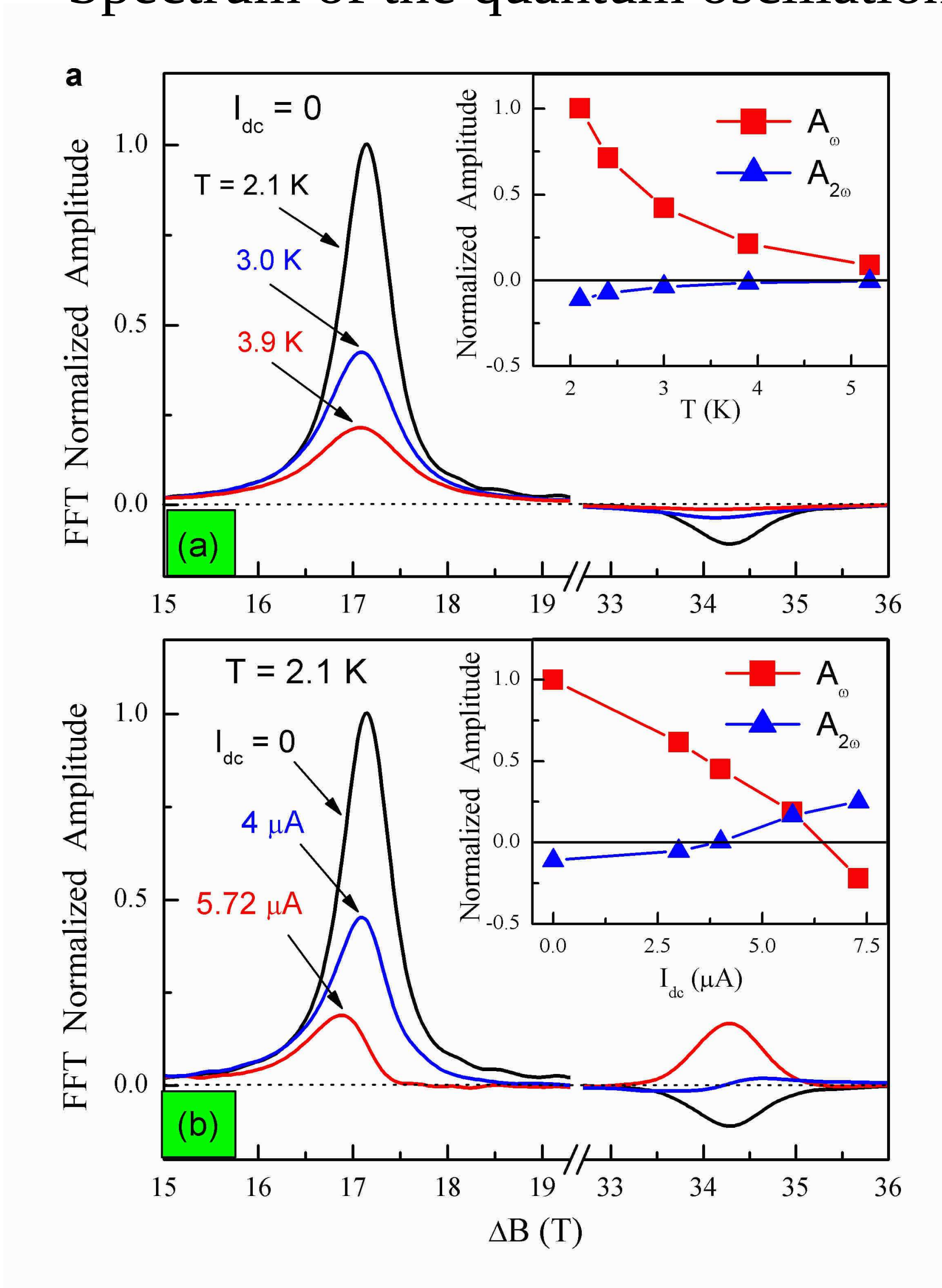
The nonlinearity of the 2D electrons depends considerably on temperature





I_{ac}
I_{dc}
V_{ac}
$I_{dc} = 0$
$r_{xx} = V_{ac} / I_{ac}$
T = 2.1 K
T = 3 K
T = 5.2 K
(a)
r_{xx} (Ω)
B= 0.797 T
T = 2.1 K
I_{dc} (μA)
I_{dc} = 4 μA
I_{dc} = 8.4 μA
I_{dc} = 20 μA
(b)
B (T)

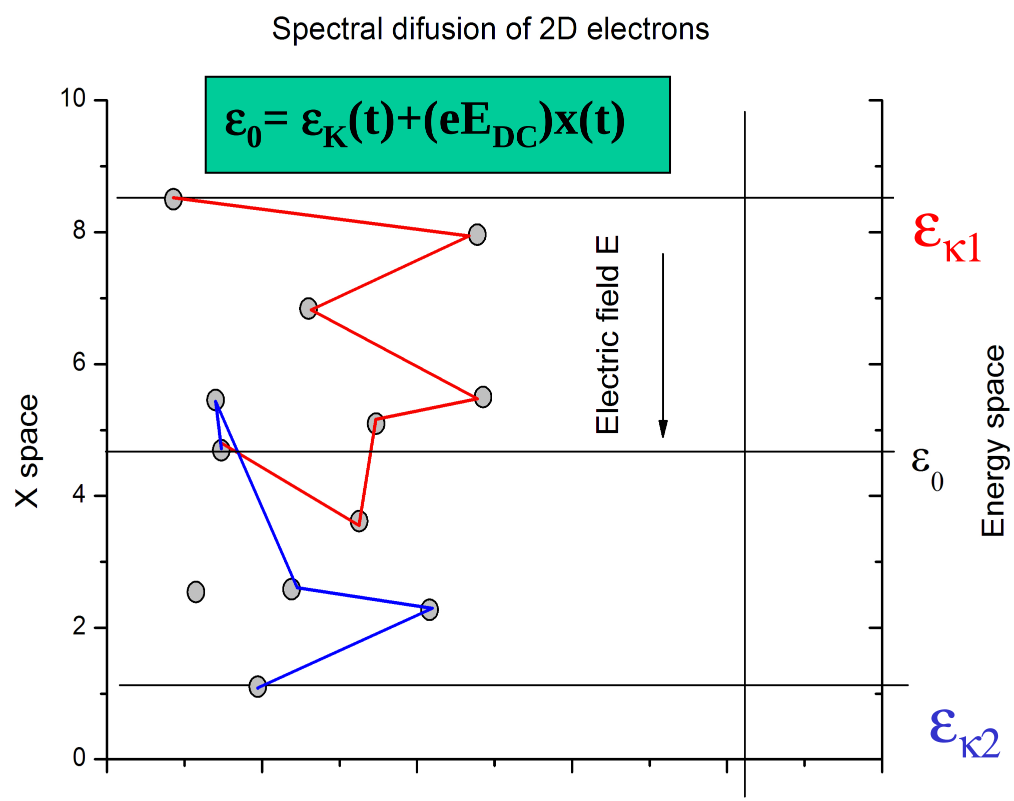
Spectrum of the quantum oscillations



Due to impurity scattering electron moves randomly in magnetic field with diffusion coefficient:

$\mathbf{D=v_F^2/(2\ \omega_c^2\ \tau_p\ ).}$

In view of conservation of the total energy $\boldsymbol{\varepsilon_0= \varepsilon_K(t)+(eE_{DC})x(t)}$ in DC electric field E_{DC} the spatial diffusion is translated into diffusion in ε-space, with a diffusion coefficient $(eE_{DC})^2D$:



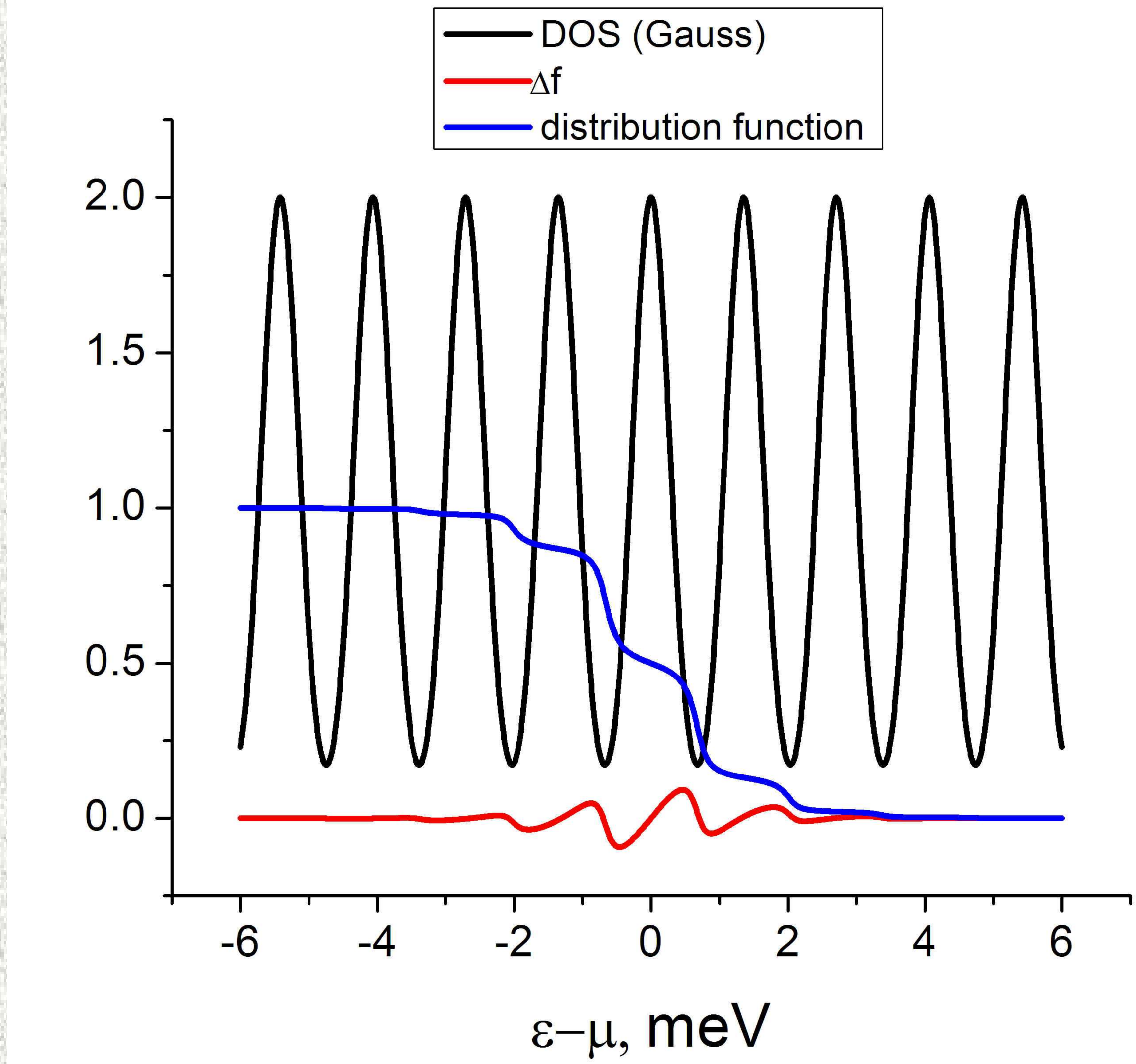
$$\frac{\partial f}{\partial t}-\frac{E_{dc}^2\sigma_{dc}^D}{\nu_0\nu}\frac{\partial}{\partial\varepsilon}\left[\nu^2(\varepsilon)\frac{\partial f}{\partial\varepsilon}\right]=-\frac{f-f_0}{\tau_{in}}$$

where υ_0 is density of states DOS at B=0T and υ is relative variations of the DOS due to Landau quantization; τ_{in} is inelastic relaxation time.

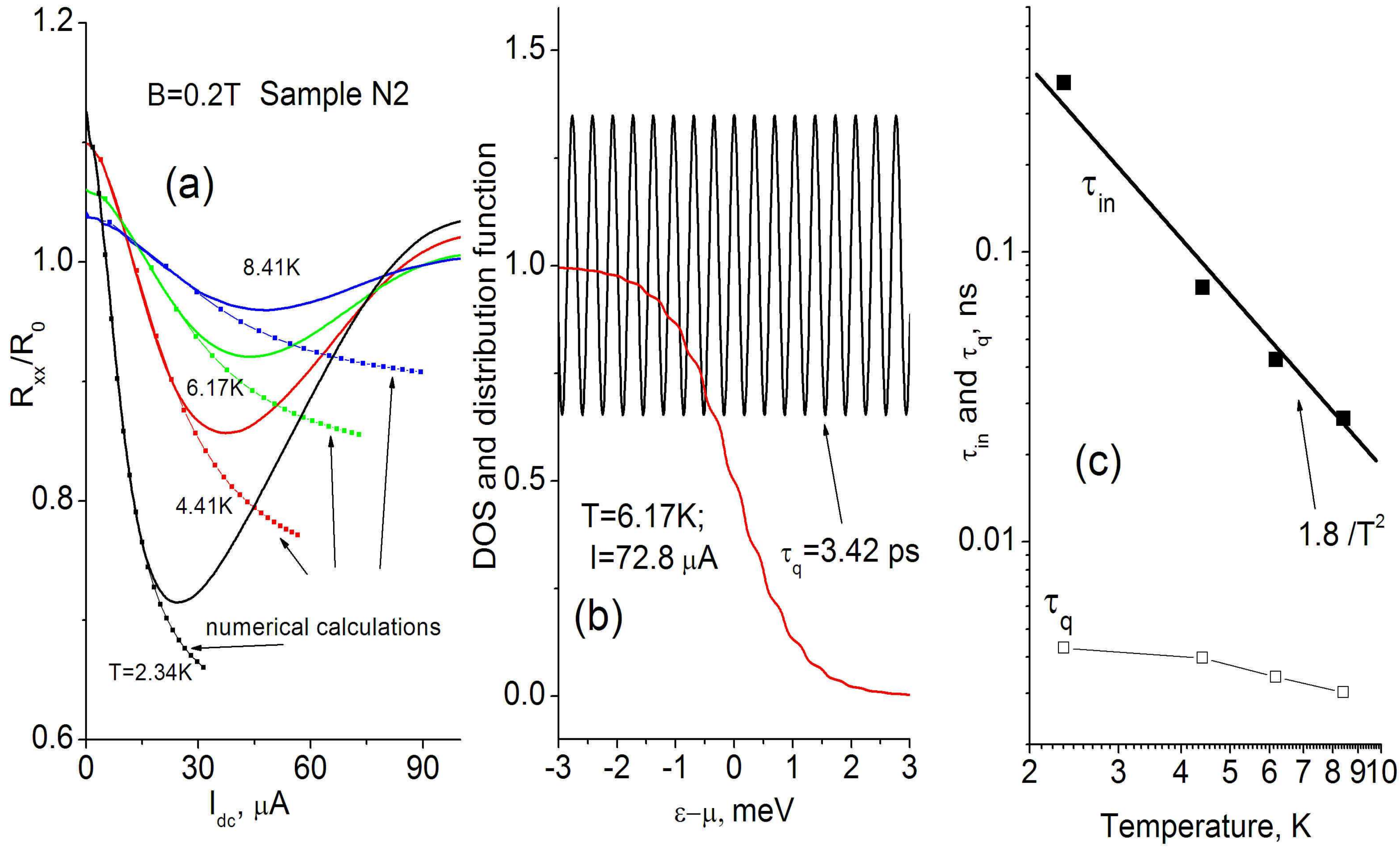
$$\sigma_{nl}=\int\sigma(\epsilon)(-\partial f/\partial\epsilon)d\epsilon$$

Dmitriev *etal*, PRB 2005

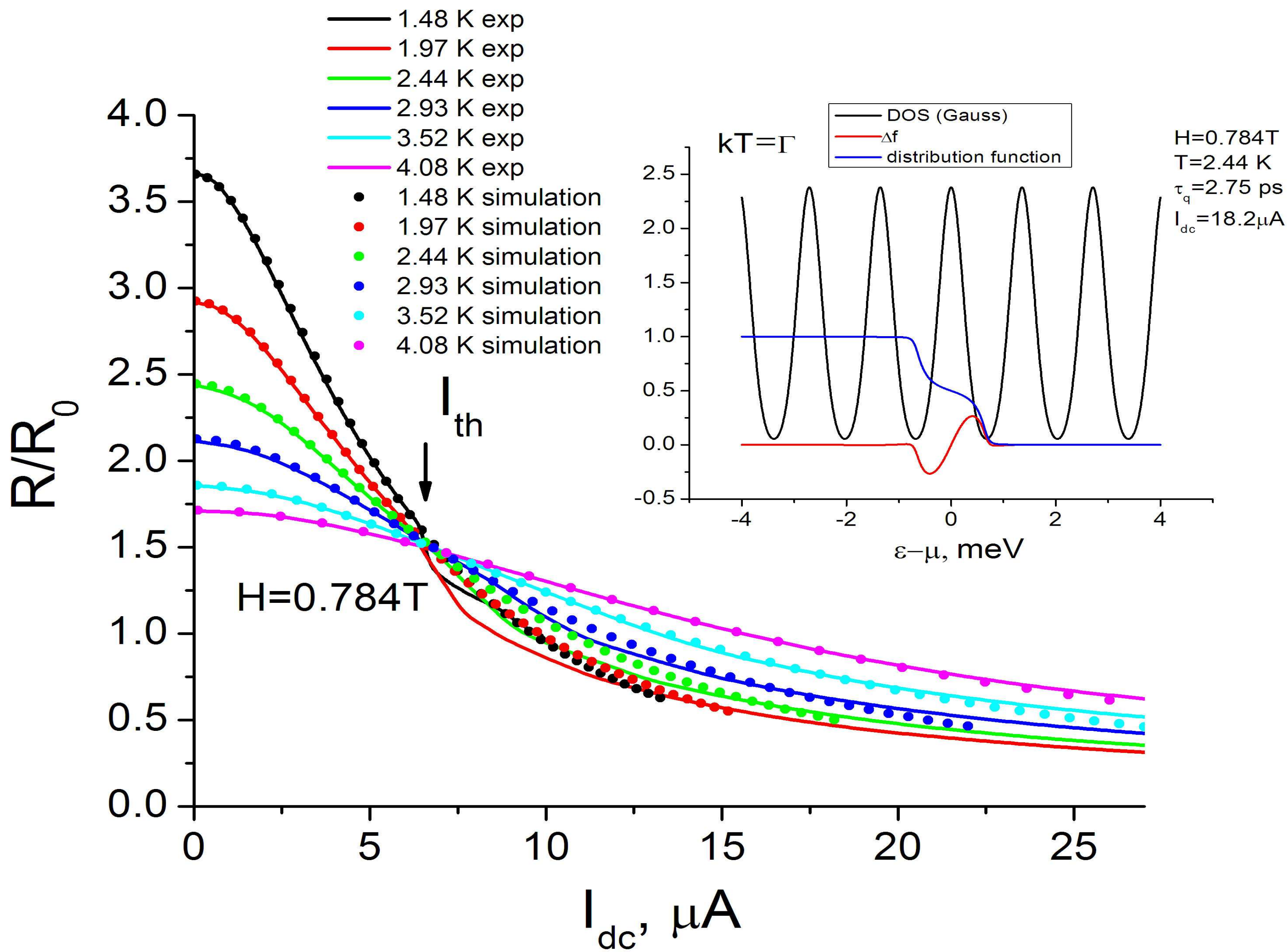
- The spectral diffusion is strong inside Landau levels and weak between them.
- At a quasi stationary state the spectral flow is constant at any energy, making the gradient of the distribution function to be small inside the Landau levels.
- A weak inelastic scattering does not change considerably the picture, because the rate of the spectral diffusion is determined by much faster elastic impurity scattering.



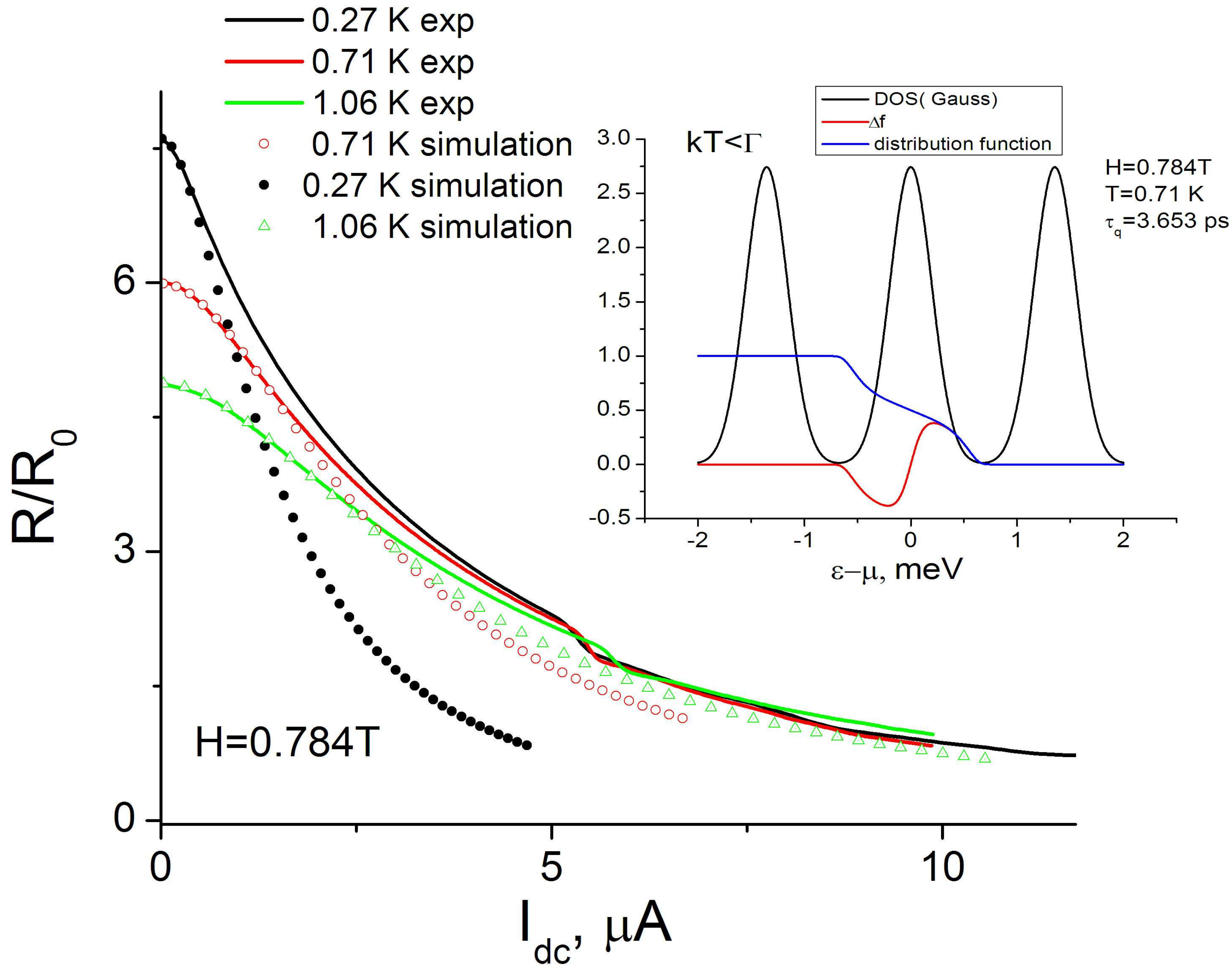
Small magnetic fields: overlapping levels



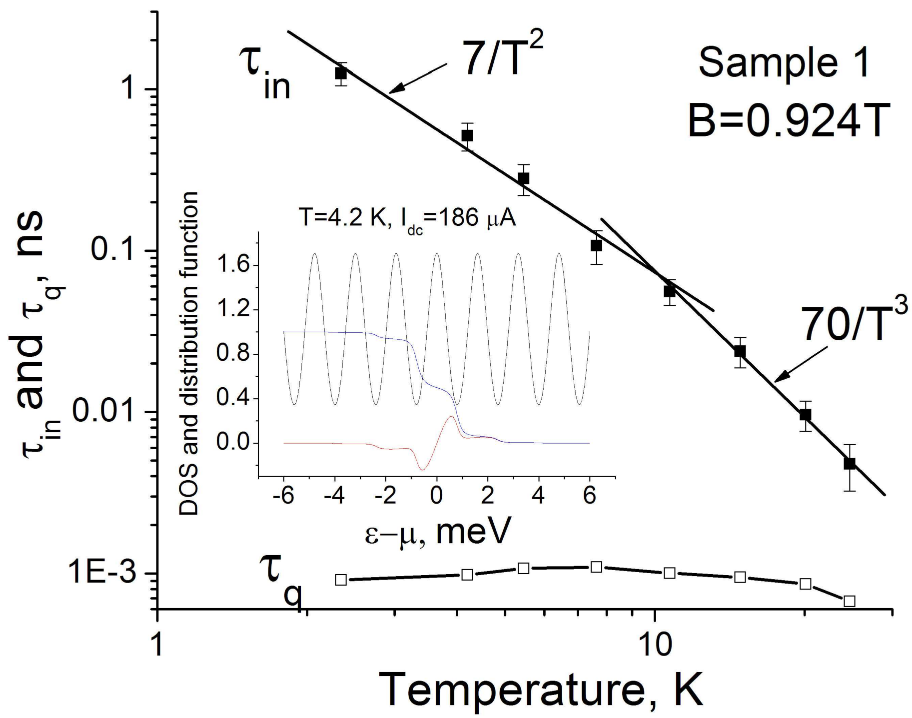
Strong magnetic fields: separated levels. Moderate T

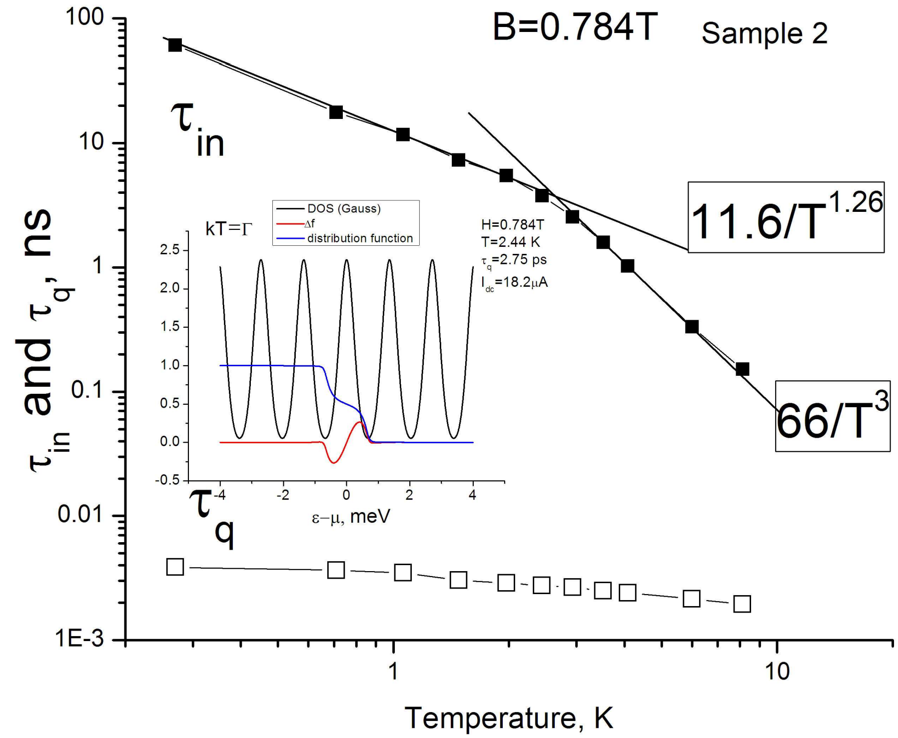


Strong magnetic fields: separated levels. Low T

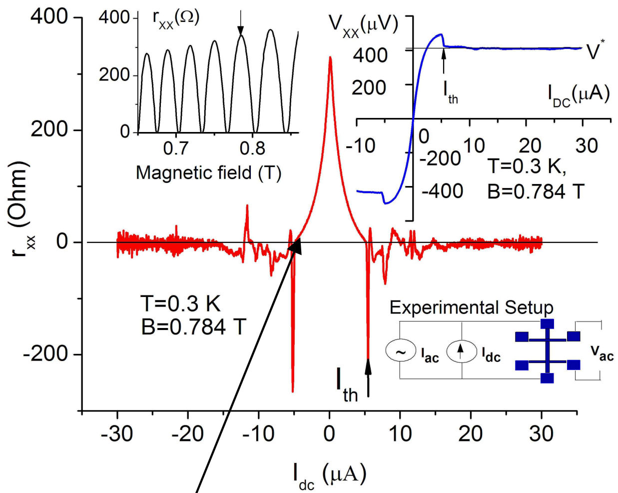


Temperature dependence of the inelastic rate. High B.

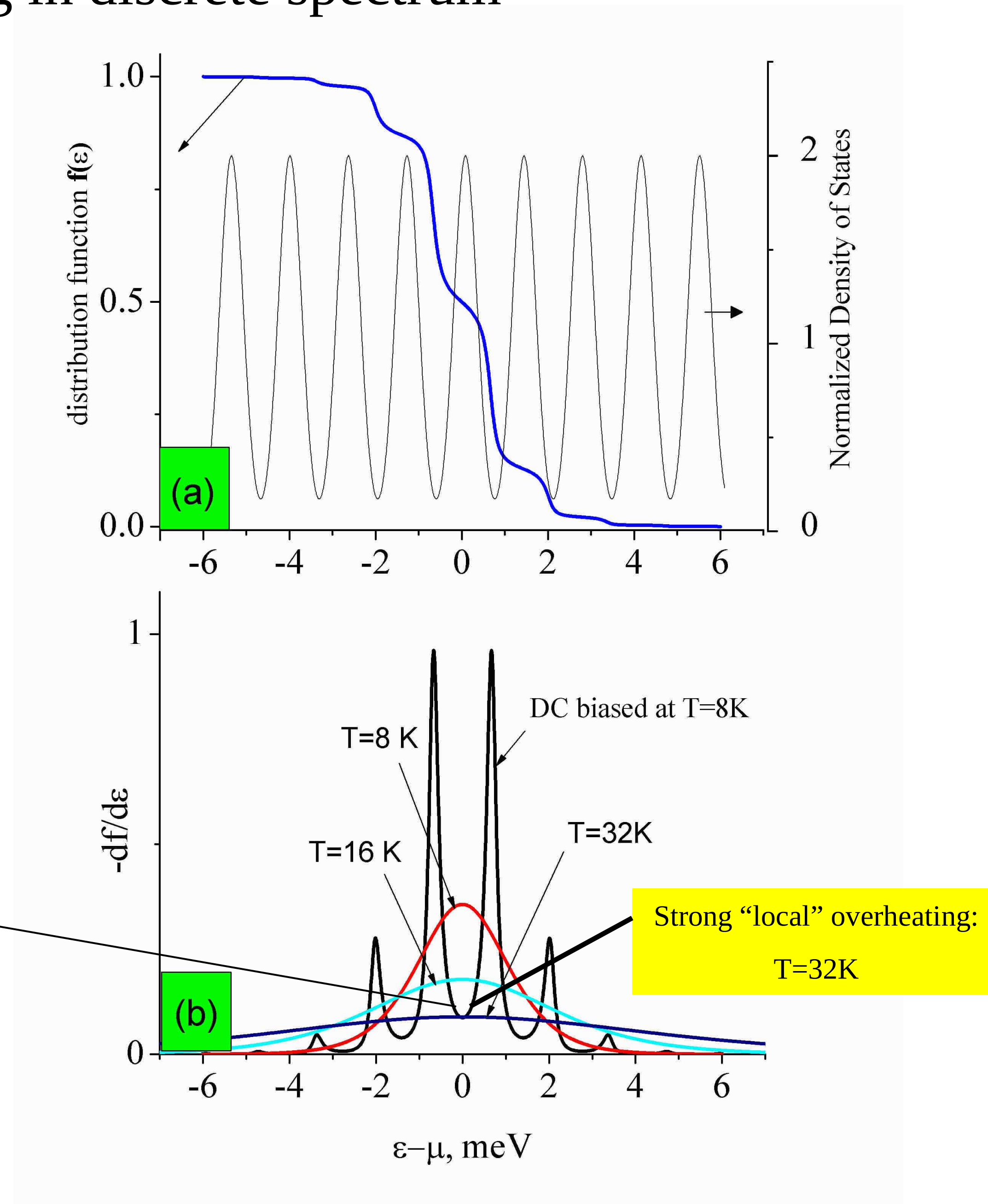




Warming in discrete spectrum



$$\sigma_{nl} = \int \sigma(\epsilon)(-\partial f/\partial\epsilon)d\epsilon$$



Summary

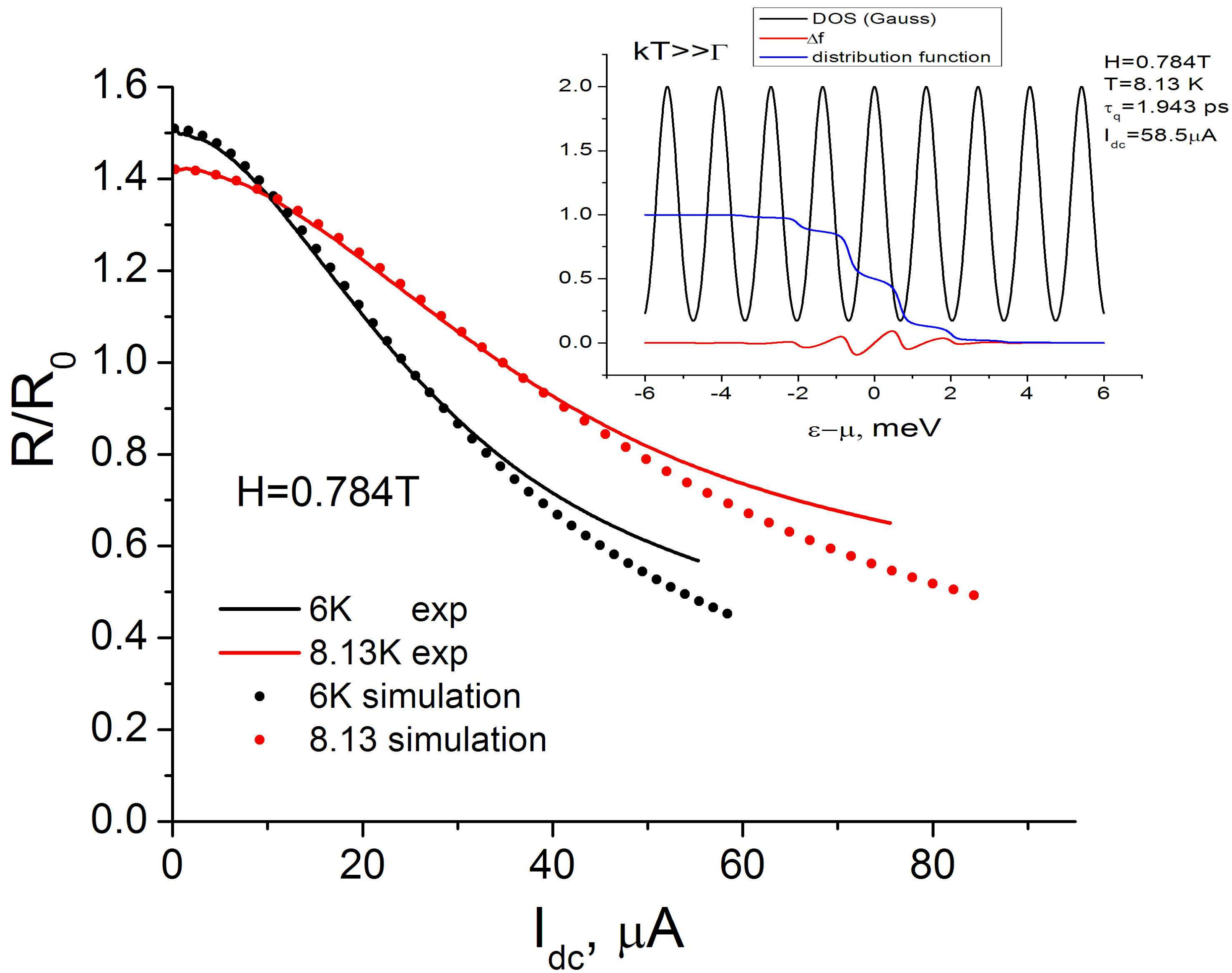
- Strong nonlinearity of longitudinal resistance of 2D electrons is observed in quantized magnetic fields. The nonlinear response cannot be explained by an increase of electron temperature due to the heating.

- In broad range of temperatures and the magnetic fields good agreement is found between the experiment and theory considering the nonlinearity as result of non-uniform spectral diffusion of the electrons.

- DC warming of the 2D electrons in quantized magnetic fields creates significant deviations of the electron distribution function from the Fermi-Dirac form resulting in the strong decrease of the resistance.

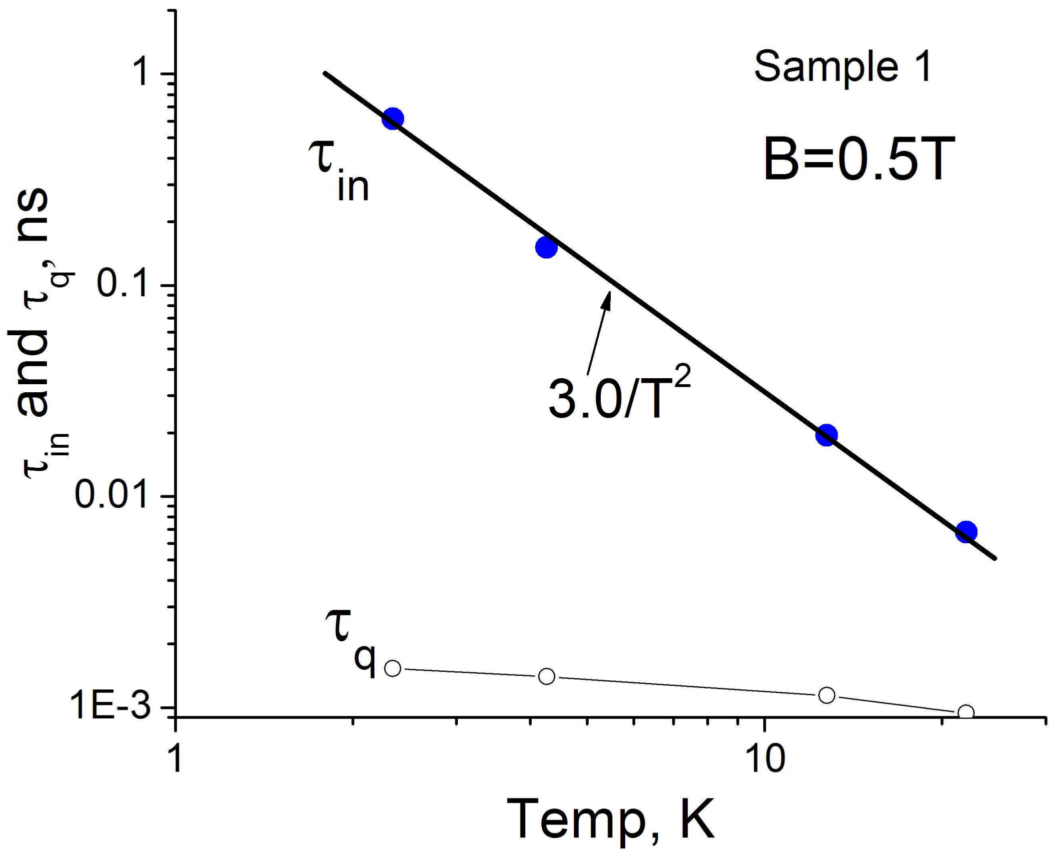
Happy Birthday, Eugene!

Strong magnetic fields: separated levels. High T



Small magnetic fields: overlapping levels

- At small magnetic fields the DOS and the spectral diffusion oscillate weakly with the energy.
- The inelastic scattering time is proportional to $1/T^2$
- The distribution function is relaxed by the electron - electron scattering in agreement with the theory



Numerical evaluations of spectral diffusion and the nonlinearity

(1) $$\sigma_{xx} = \int d\varepsilon \sigma_D \nu^2(\varepsilon)\left(-\frac{\partial f}{\partial \varepsilon}\right)$$

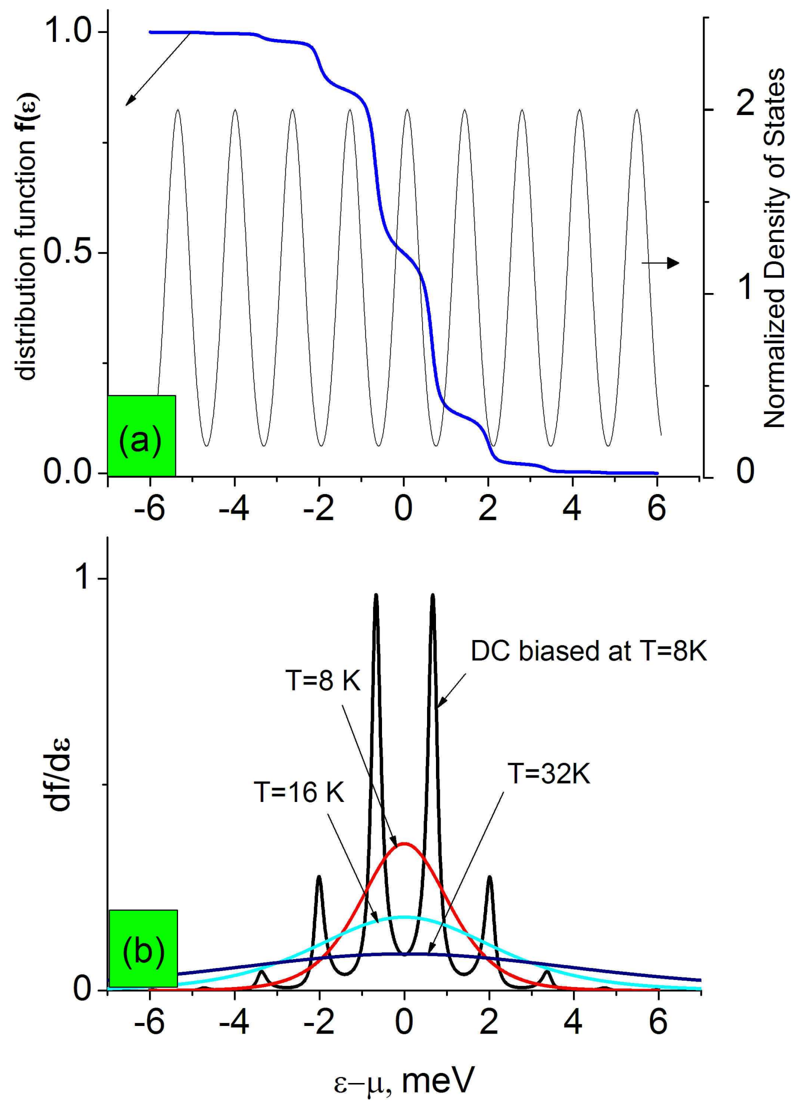
(2) $$\nu(\epsilon) = \sqrt{\omega_c \tau_q} \sum_n exp\left(-\frac{(\epsilon - n\omega_c)^2}{\omega_c/\pi\tau_q}\right)$$

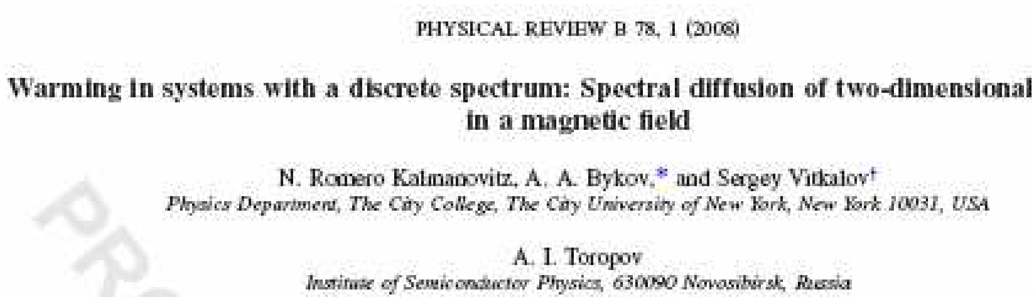
(3) $$\frac{\partial f}{\partial t} - \frac{E_{dc}^2 \sigma_{dc}^D}{\nu_0 \nu}\frac{\partial}{\partial \varepsilon}\left[\nu^2(\varepsilon)\frac{\partial f}{\partial \varepsilon}\right] = -\frac{f - f_0}{\tau_{in}}$$

- Step#1. Using (1) and (2), we have obtained quantum scattering time τ_q by comparison with experiment at zero *dc* bias
- Step#2. Using (2) and (3) we have calculated numerically the distribution function at different *dc* biases.
- Step#3. Substituting the solution for the distribution function in the limit of $t \gg \tau_{in}$ in eq.(1) we have calculated numerically the conductivity at different *dc* biases.
- Step#4. From comparison with experiment we have obtained the inelastic scattering time τ_{in} .

Q:Can we measure the number π?
A: Unlikely

- Is the spectral non-uniform diffusion and the strong overheating relevant to other complex physical systems with a discrete spectrum, for example, the air?





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Warming in systems with a discrete spectrum: Spectral diffusion of two-dimensional in a magnetic field

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