Todays program

(1) Tasks & Course overview

(2) Exam structure

(3) Quantum oscillations (continued)

(4) Magneto-resistance

#	Dates	Title	Exercise	(1=easy, 10=hard)	**Tasks**
1	22.2	Introduction	VESTA	**2-3**	**Read Chap. 1**
2	01.3	Crystal structures	Daniel - info	**4**	**Read Chap. 2, Ex. 1**
3	08.03	Reciprocal space	Discuss Ex. 1	**6**	**Read Chap. 2, Ex. 2**
4	15.03	Scattering Theory	Discuss Ex. 2	**8-9**	**Read Chap. 3, Ex. 3**
5	22.03	Crystal bindings	Discuss Ex. 3	**5**	**Read Chap. 4, Ex. 4**
6	29.03	Phonons	Discuss Ex. 4	**5-6**	**Read Chap. 5, Ex. 5**
7	05.04	Thermal properties	Discuss Ex. 5	**5-6**	**Read Chap. 6, Ex. 6**
8	12.04	Electron gasses, C_{el}	Discuss Ex. 6	**5-6**	**Read Chap. 7, Ex. 7**
--	19.04	EASTER HOLIDAY	-------------------	**0**	**RECAP**
9	26.04	Electronic band struc.	Discuss Ex. 7	**5-6**	**Read Chap. 8, Ex. 8**
10	03.05	Semi-conductors	Discuss Ex. 8	**6**	**Read Chap. 9, Ex. 9**
11	10.05	Fermi surfaces & Metals - I	Discuss Ex. 9	**8**	**Read Chap. 9, Ex. 10**
12	17.05	Fermi surfaces & Metals - II	Discuss Ex. 10	**8**	**Read Chap. 9, Ex. 11**
13	24.05	Guest lecture	Discuss Ex. 11	**--**	
14	31.05	Repetition		**4**	

#	Dates	Title	Tasks
10	03.05	Semi-conductors	**Read Chap. 6: Motion in magnetic fields p. 163-167** **Read Chap. 9: Introduction to Fermi surfaces p. 235-244** **Read Chap. 9: Experimental methods in FS studies p. 255-265**
11	10.05	Fermi surfaces & Metals - I	**Read Chap. 9: Experimental methods in FS studies p. 255-265**
12	17.05	Fermi surfaces & Metals - II	**Read Chap. 9 : Calculation of energy bands 244 -255**
13	24.05	Guest lecture	**Electronic band structure: Tight-binding model**
14	31.05	Repetition	

Course overview

Crystal lattice phenomena’s

-- Crystal structures (Real and reciprocal space)
-- Scattering theory (Bragg’s law, Form Factor, Structure factor)
-- Crystal bindings (Equilibrium lattice constants, binding energies)
-- Lattice vibrations (Phonon dispersions, density of state, heat capacity)

Electronic phenomena’s

-- Free electron gas (Fermi Dirac distribution, density of states)
-- Band structure (electronic masses, Fermi surfaces)
-- Electronic measurements (Heat capacity, resistivity, Hall effect, quantum oscillations)
-- Electronic phases (metals, semi-metals, semi-conductors, band insulators)

Todays program

(1) Tasks & Course overview

(2) Exam structure

(3) Quantum oscillations (continued)

(4) Magneto-resistance

Exam – time line

31th of May (13h00-17h00) – Last lecture: Repetition of course content

6th of June (14.00-17.00) in Y36-J-33 – Questions and Answers session with Stefan

8-9th of June (9h00 – 17h30) in Y-36-H-48 – Oral exam

9th of June (17h30): Beer in StudiBar

MY AVAILABILITY BEFORE EXAM:
1st of June in office.
After 1st of June no around but can be reached on:

johan.chang@physik.uzh.ch
skypename: johan.chang7

Exam Structure

~7 min – Presentation:

Topics: (1) Crystal structures,
(2) Crystal Bindings,
(3) Reciprocal lattice+ scattering theory,
(4) Crystal vibrations (Phonons),
(5) Heat capacity
(6) Band structure
(7) Semiconductors
(8) Resistivity & Hall effect

~7 min – Discussion 1:

Questions to the lecture material (Example next slide)

~7 min – Discussion 2:

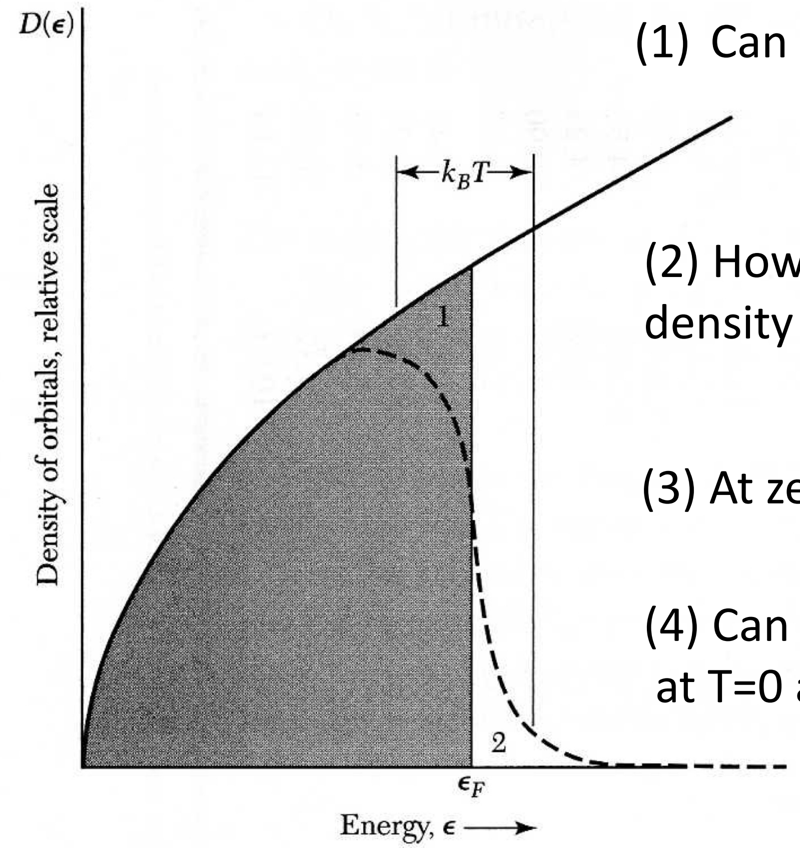
Questions to the exercises (Example next slide)

End Exam

5 min - evaluation

2 min – Results: Passed / failed, grade will be known at a later point.

Question example:
Electronic density of state & Fermi Dirac



(1) Can you draw or state the dispersion of a free electron?

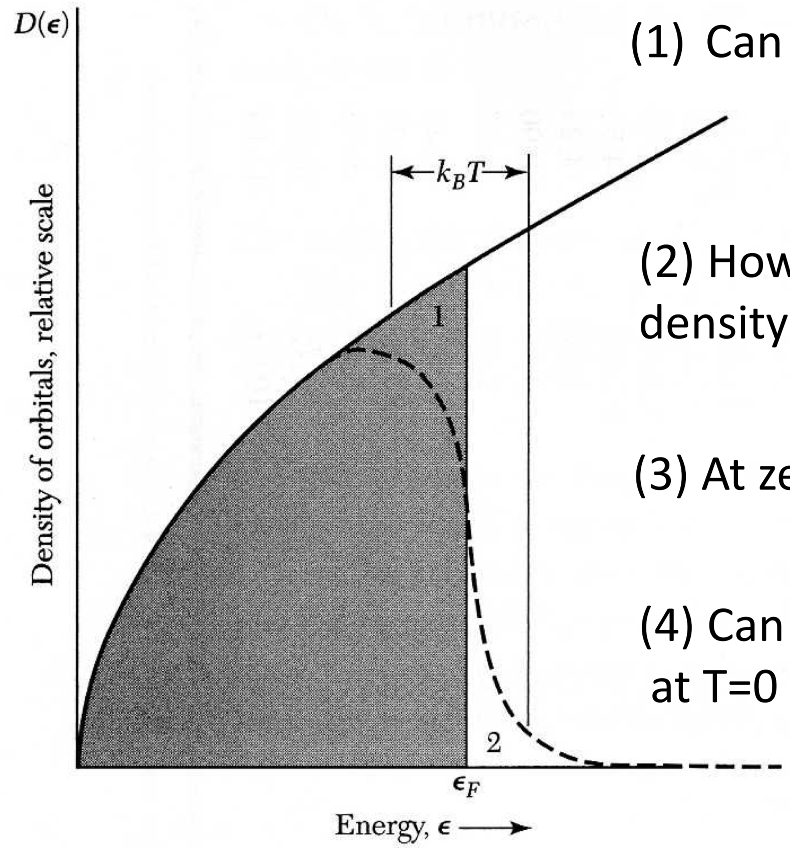
(2) How would you derive (rough arguments) the density of states for a free electron gas?

(3) At zero – temperature how is the Fermi energy defined?

(4) Can you draw schematically the Fermi Dirac distribution at T=0 and T=300 K?

Discussion 1:

Electronic density of state & Fermi Dirac



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(2) How would you derive (rough arguments) the density of states for a free electron gas?

(3) At zero – temperature how is the Fermi energy defined?

(4) Can you draw schematically the Fermi Dirac distribution at T=0 and T=300 K?

Discussion 2:

Exercise 5 *Sphere packings*

Calculate the ratio c/a of an ideal hexagonal dense sphere packing (hcp) and its packing density. Compare the packing density to that of an fcc lattice and explain your findings.

Questionnaire

The university is asking us / you to evaluate this course:
Some of you have already given feedback using the link below:

Festkörperphysik (PHY210.1, VVZ-Nr. 1872)
– Link: https://www.sae.uzh.ch/lvb/UU6MC

It would be great to have the opinions of as many of you as possible before 21th of May where the evaluation is closing.

Todays program

(1) Tasks & Course overview

(2) Exam structure

(3) Quantum oscillations (continued)

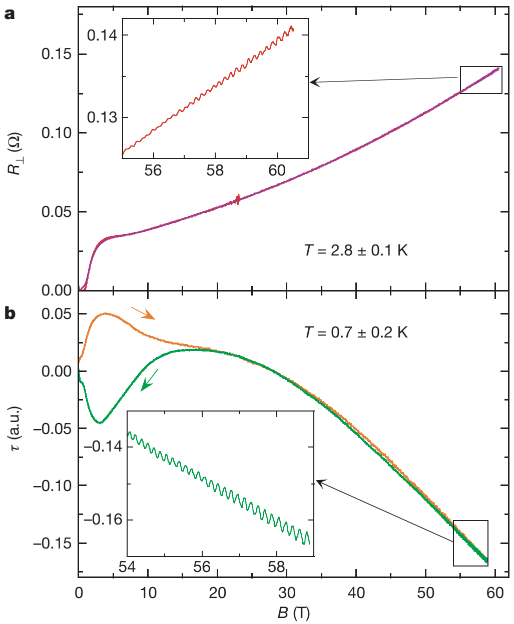
(4) Magneto-resistance

Summary of previous lecture

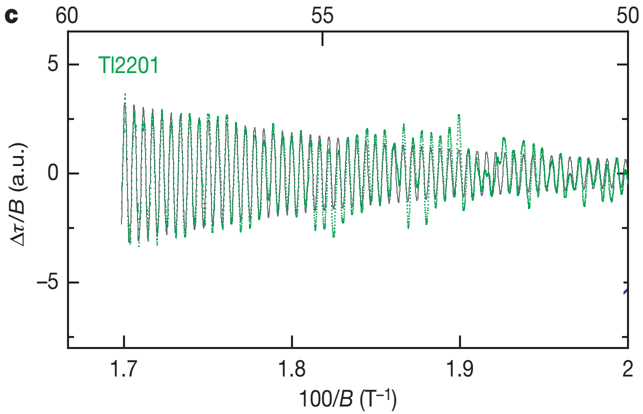
(1) Quantum Oscillation experiments:

Exercise 2 *Quantum oscillations on quasi two-dimensional systems*
In $Tl_2Ba_2CuO_{6+\delta}$, quantum oscillations with a frequency of $F = 18.1\,\mathrm{kT}$ are observed (B. Vignolle et al., Nature **455**, 952-955 (2008)).
(a) Use the Onsager relation ($S = 2\pi\frac{eF}{\hbar}$) to calculate the Fermi surface area.
(b) If we assume a circular Fermi surface shape what is the Fermi momentum?

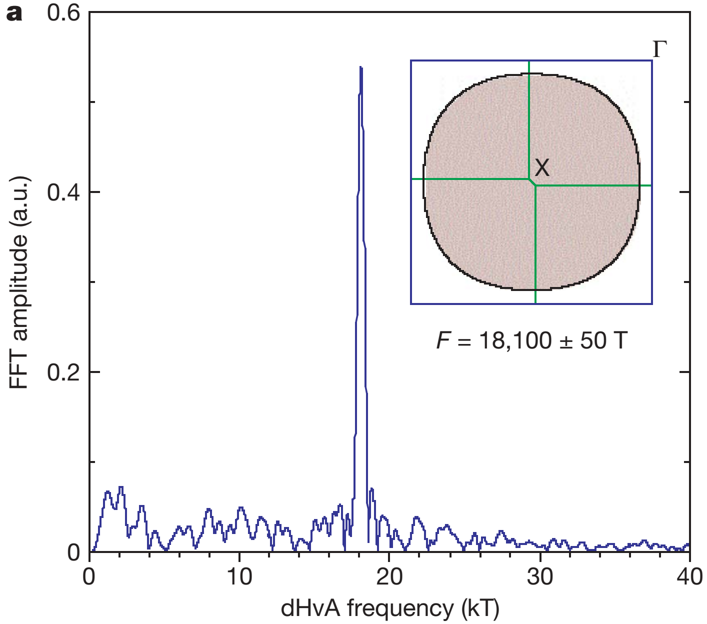
(a) RAW DATA



(b) OSCILATIONS VERSUS 1/B



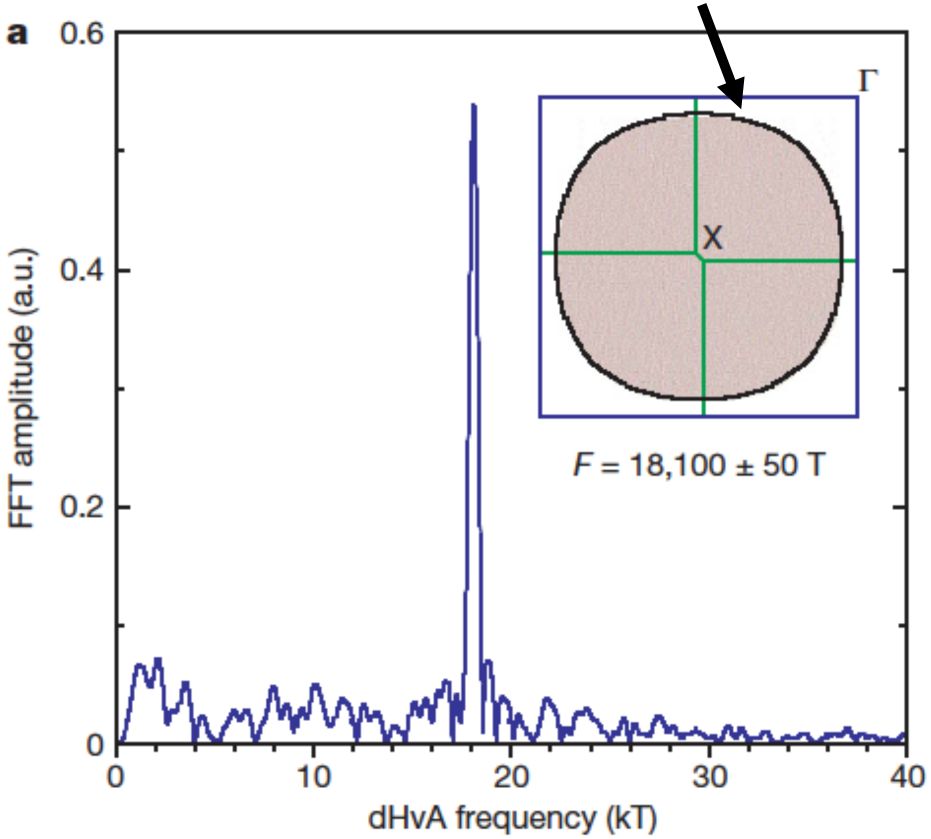
(c) Fourier Transform

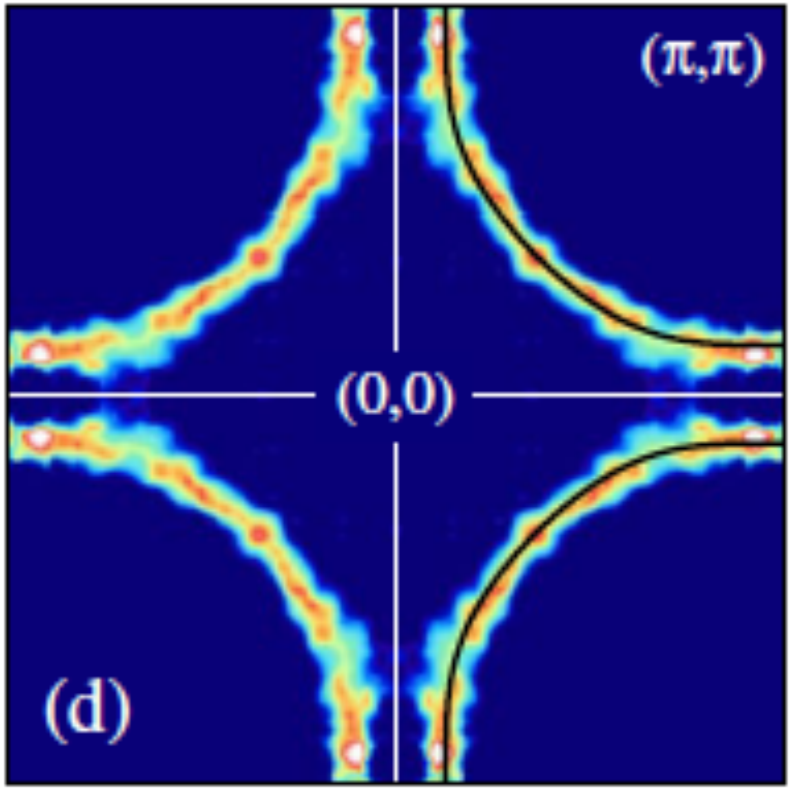


Fermi surface: $Tl_2Ba_2CuO_{6+y}$ (Tl2201)

ARPES vs Quantum Oscillations

Band Structure Calculations





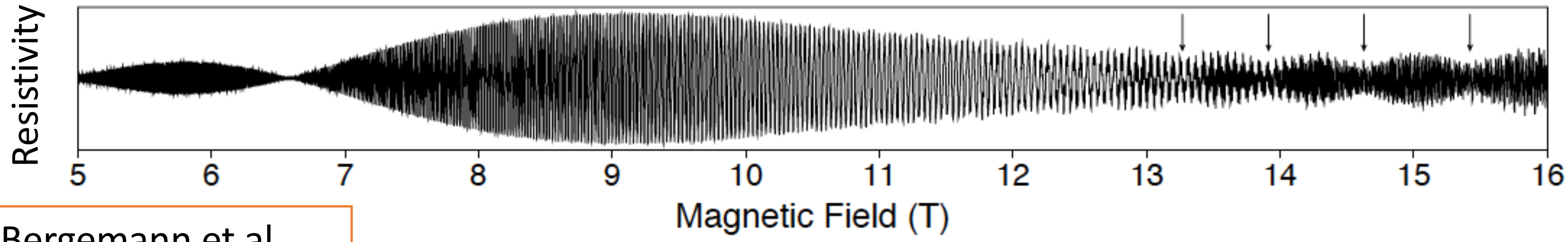
Nature 455, 952 (2008)

PRL **95**, 077001 (2005)
Data taken @ Swiss Light Source

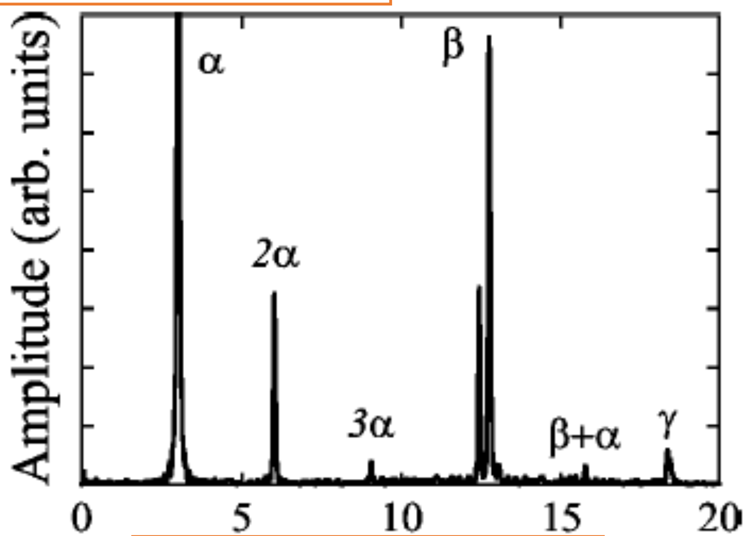
Quantum Oscillation (QO) experiments

Angle-resolved Photo-Emission Spectroscopy (ARPES)

Multi – band metals: Sr_2RuO_4

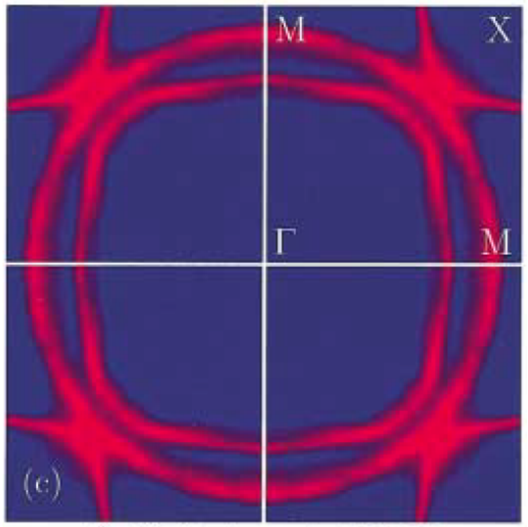


Bergemann et al,
PRL 84, 2662 (2000)



A.P. Mackenzie et al,
JPSJ 67, 385 (2003)

Quantum Oscillation (QO) experiments



A. Damascelli et al,
PRL 85, 5194 (2000)

Angle-resolved Photo-Emission Spectroscopy (ARPES)

QUANTUM OSCILLATIONS:

Temperature dependence

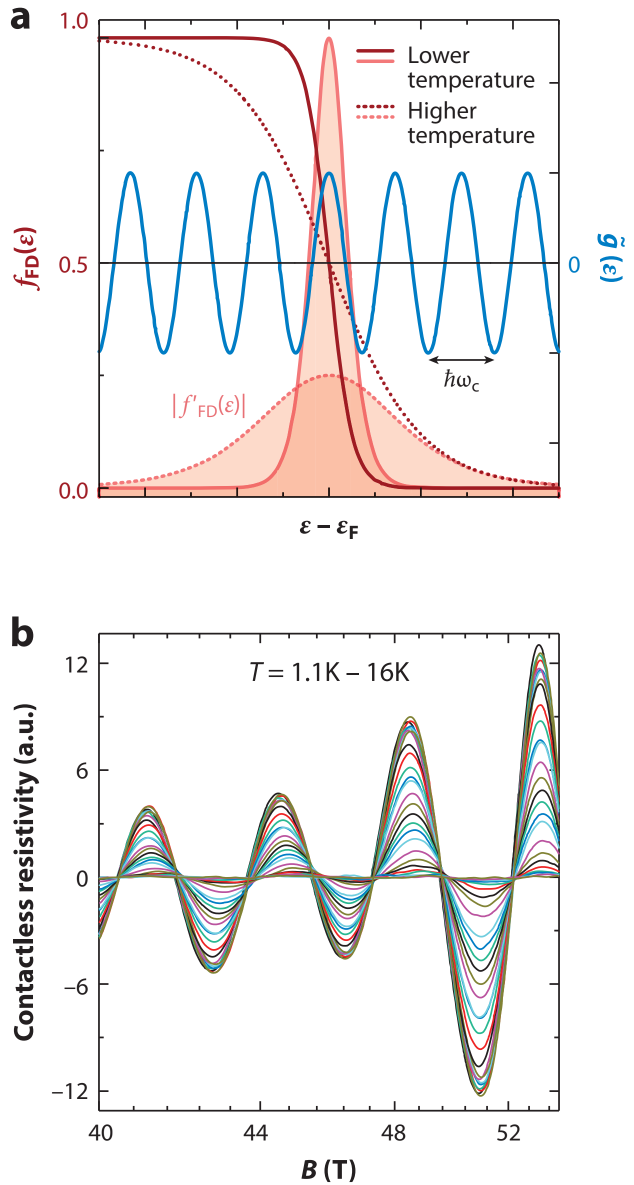
Thermal Condition:

$$\hbar\omega_c > k_B T$$

Landau level splitting > thermal energy

$$\omega_c = \frac{eB}{m^*}$$

Temperature dependence of the oscillatory amplitude yield information about the electronic mass.



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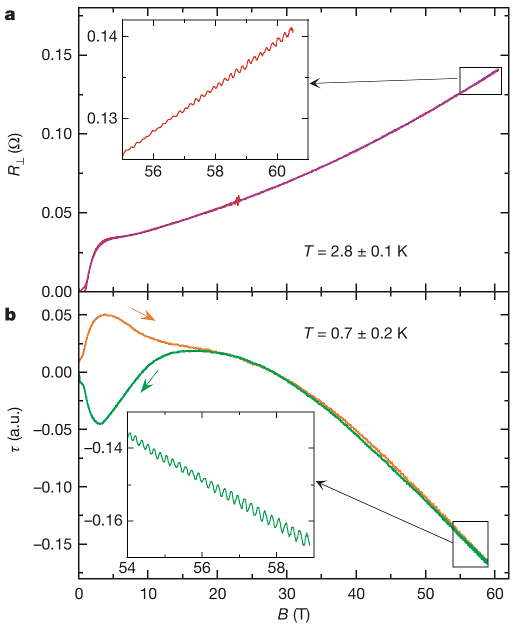
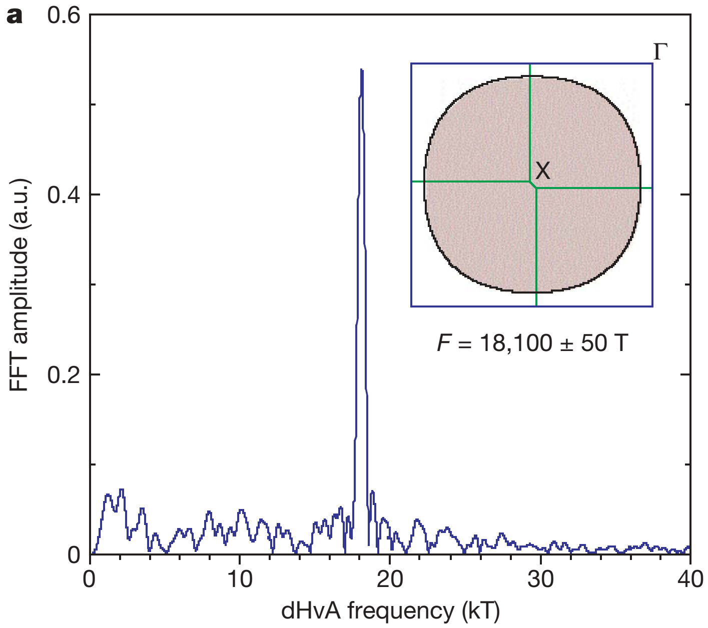
Electronic Mass

(1) Quantum Oscillation experiments:

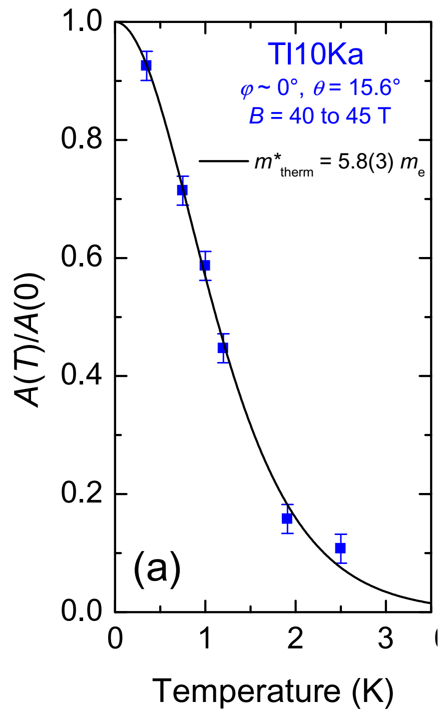
(a) RAW DATA



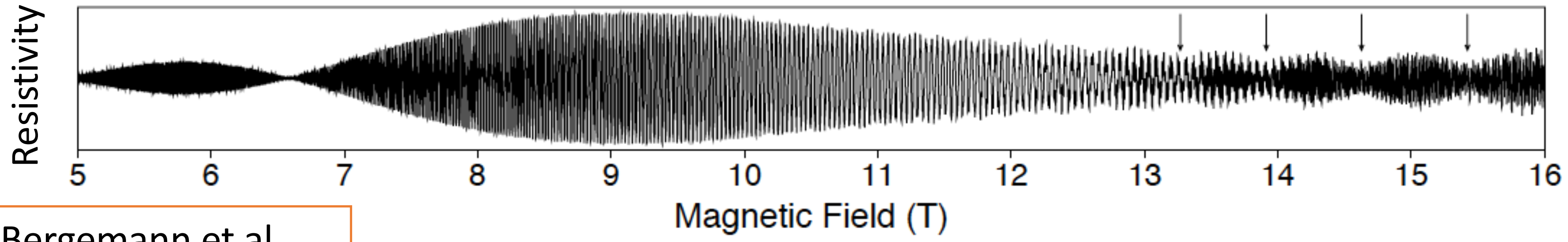
(b) Fourier Transform



(c) T-dependence



Multi – band metals: Sr_2RuO_4



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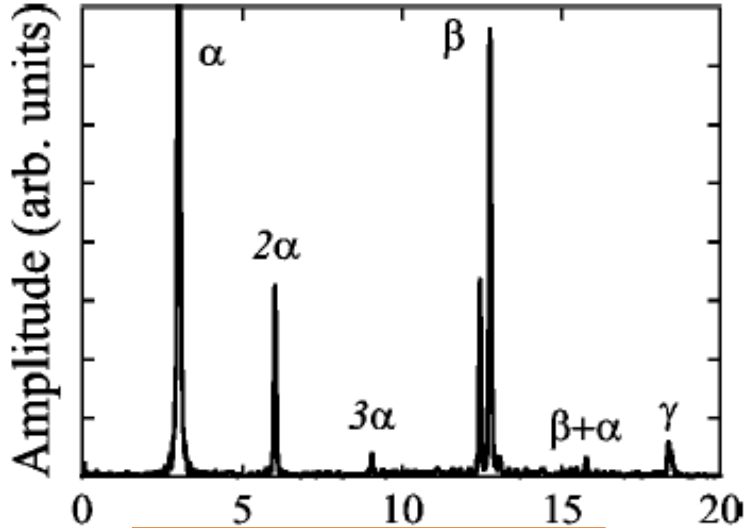

A.P. Mackenzie et al,
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TABLE II. Summary of quasiparticle parameters of Sr_2RuO_4.

Fermi-surface sheet	α	β	γ
Character	Holelike	Electronlike	Electronlike
k_F ($Å^{-1}$)[a]	0.304	0.622	0.753
m^* (m_e)[b]	3.3	7.0	16.0

A.P. Mackenzie et al,
RMP 75, 657 (2003)

Quantum Oscillation (QO) experiments

Fermi surface – Gold and Copper

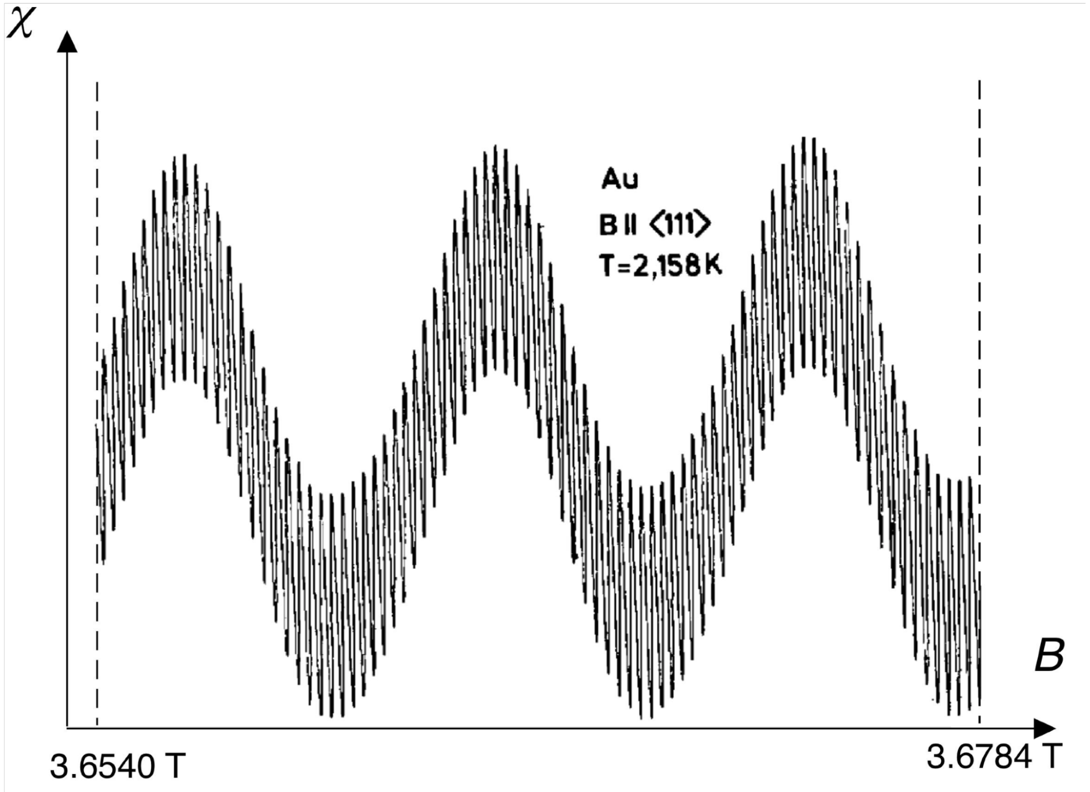
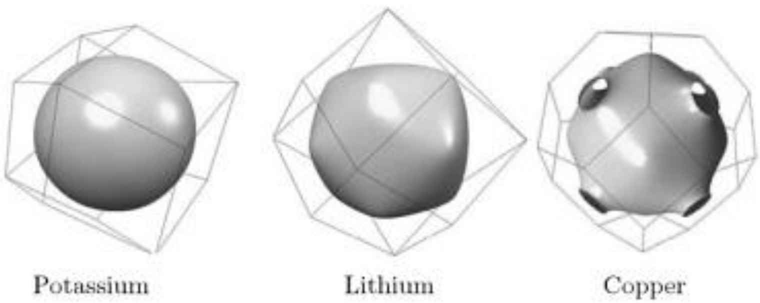
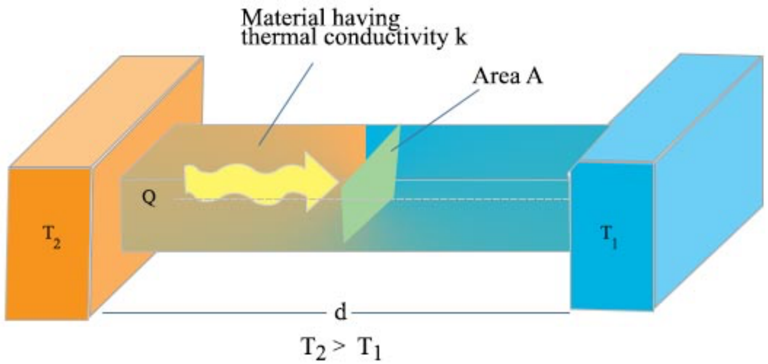
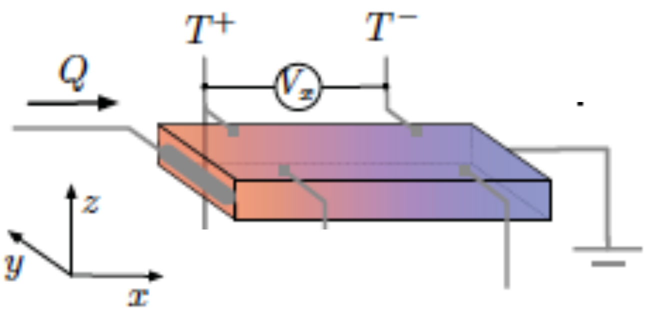


Figure 1: The spin susceptibility of gold in a magnetic field.



Material Property	Coefficient	In classed
Resistivity		
Hall coefficient		
Heat capacity		
Thermal conductivity		
Thermopower / Seebeck effect		





Material Property	Coefficient	In classed
Resistivity	$\rho = \frac{m^*}{ne^2\tau}$ or $\sigma = \frac{ne^2\tau}{m^*}$	Discussed / Proven
Hall coefficient	$R_H = \frac{-1}{en}$	Discussed / Proven
Heat capacity	$\frac{C}{T} = \gamma = \frac{1}{3}\pi^2 k_B^2 DOS(\varepsilon_F) \propto m^*$	Discussed / Proven
Thermal conductivity	$\frac{\kappa}{T} = \frac{nk_B^2\pi^2\tau}{3m^*}$	Not proven
Thermopower / Seebeck effect	$\frac{S}{T} = \frac{\pm\pi^2}{2}\frac{k_B}{e}\frac{1}{T_F} \propto \frac{m^*}{n}$	Not proven

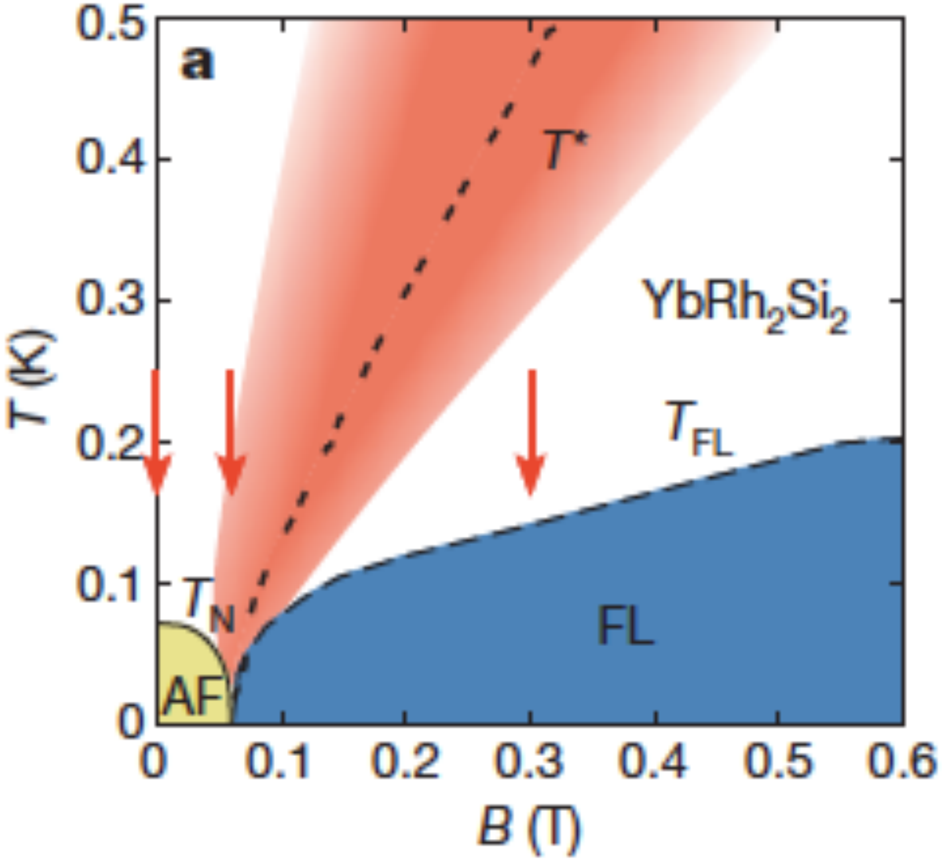
Wiedemann Franz Law

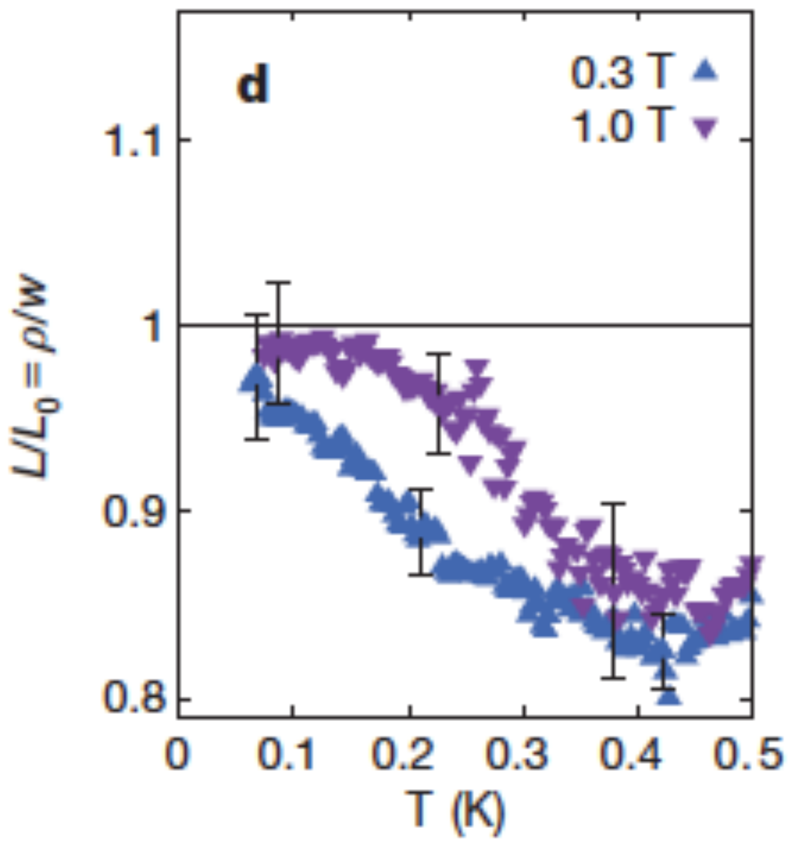
$$\frac{\kappa}{\sigma T} = \square$$

Lorenz Number

$$L_0 = \frac{\pi^2}{3}\frac{k_B{}^2}{e^2}$$

Wiedemann Franz Law





Nature 484, 494 (2010)

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Resistivity	$\rho = \frac{m^*}{ne^2\tau}$ or $\sigma = \frac{ne^2\tau}{m^*}$	Discussed / Proven
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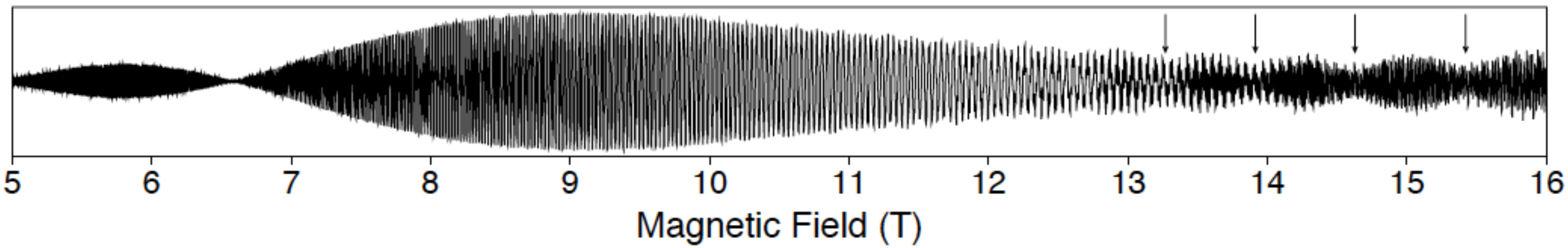
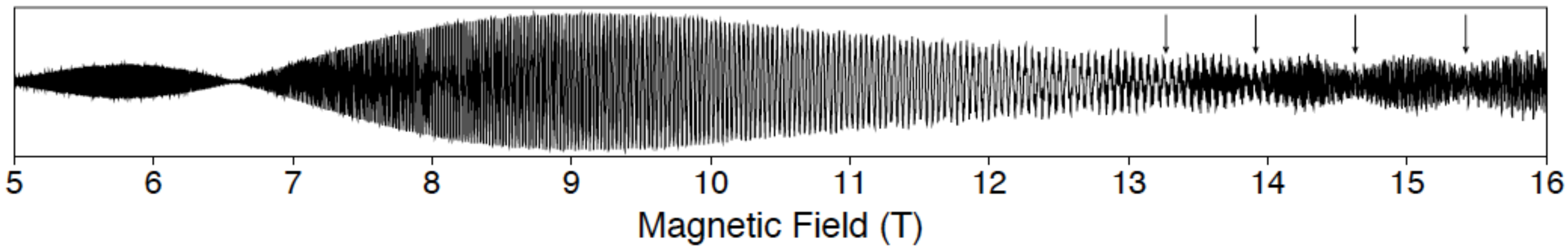
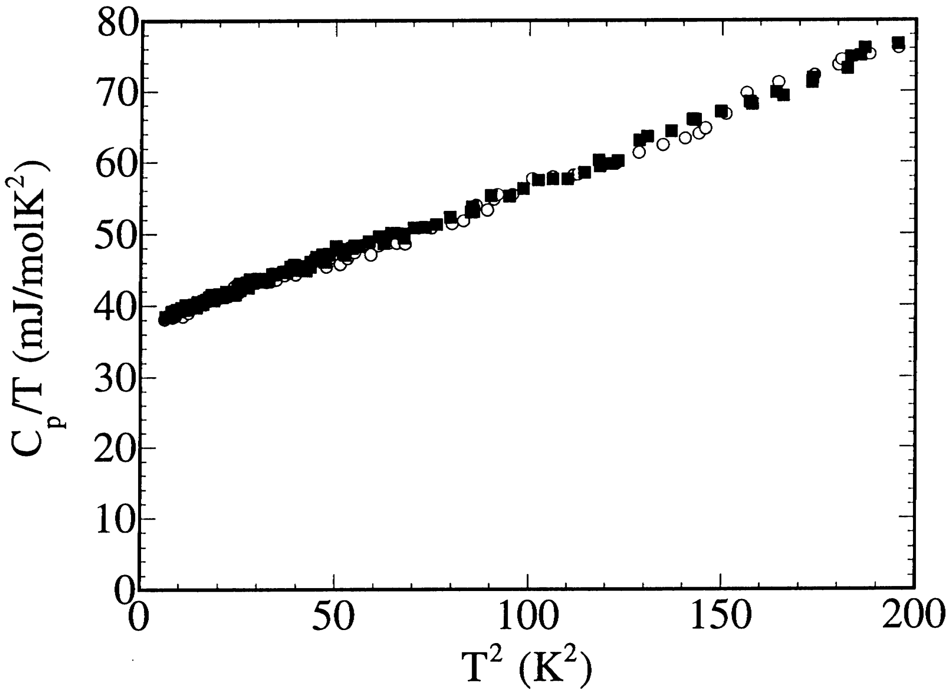


Multi – band metals: Sr_2RuO_4



Heat Capacity



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(1) Tasks & Course overview

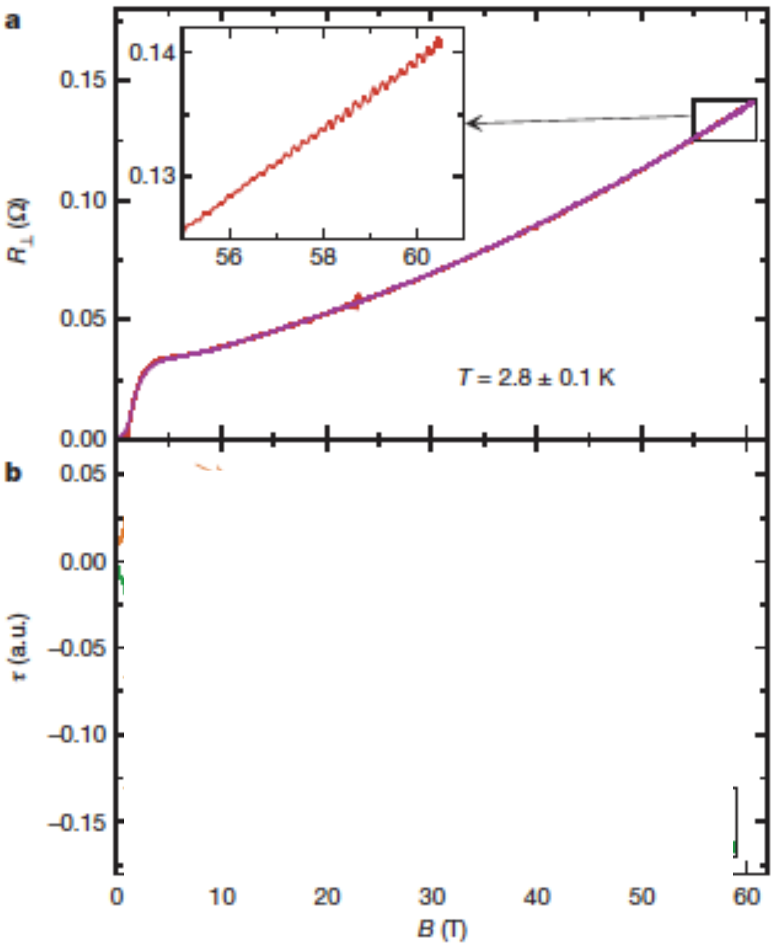
(2) Exam structure

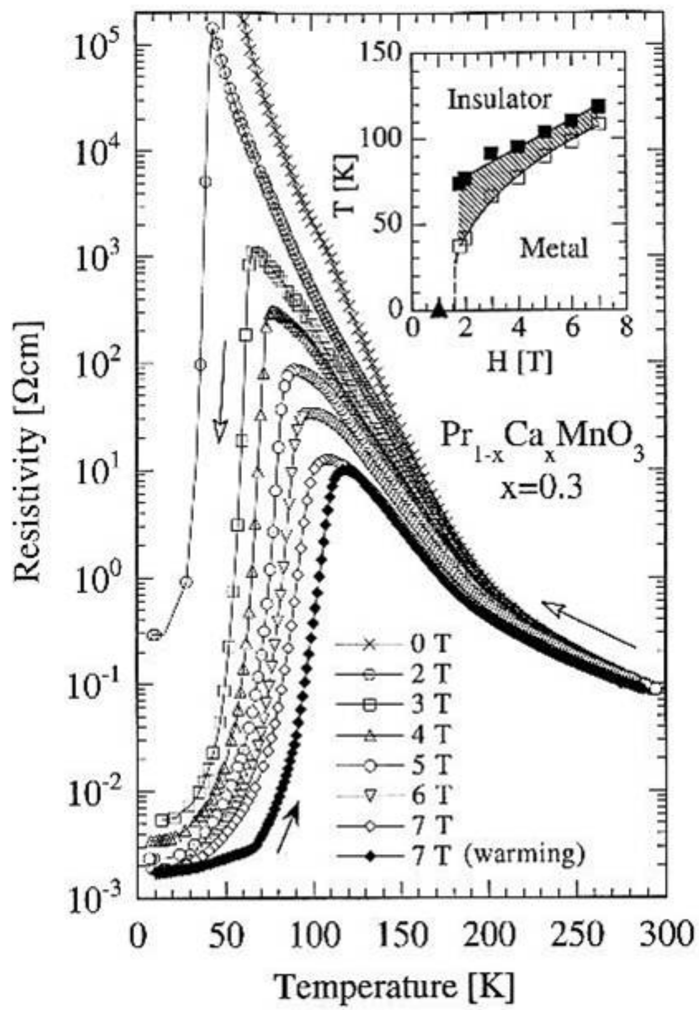
(3) Quantum oscillations (continued)

(4) Magneto-resistance

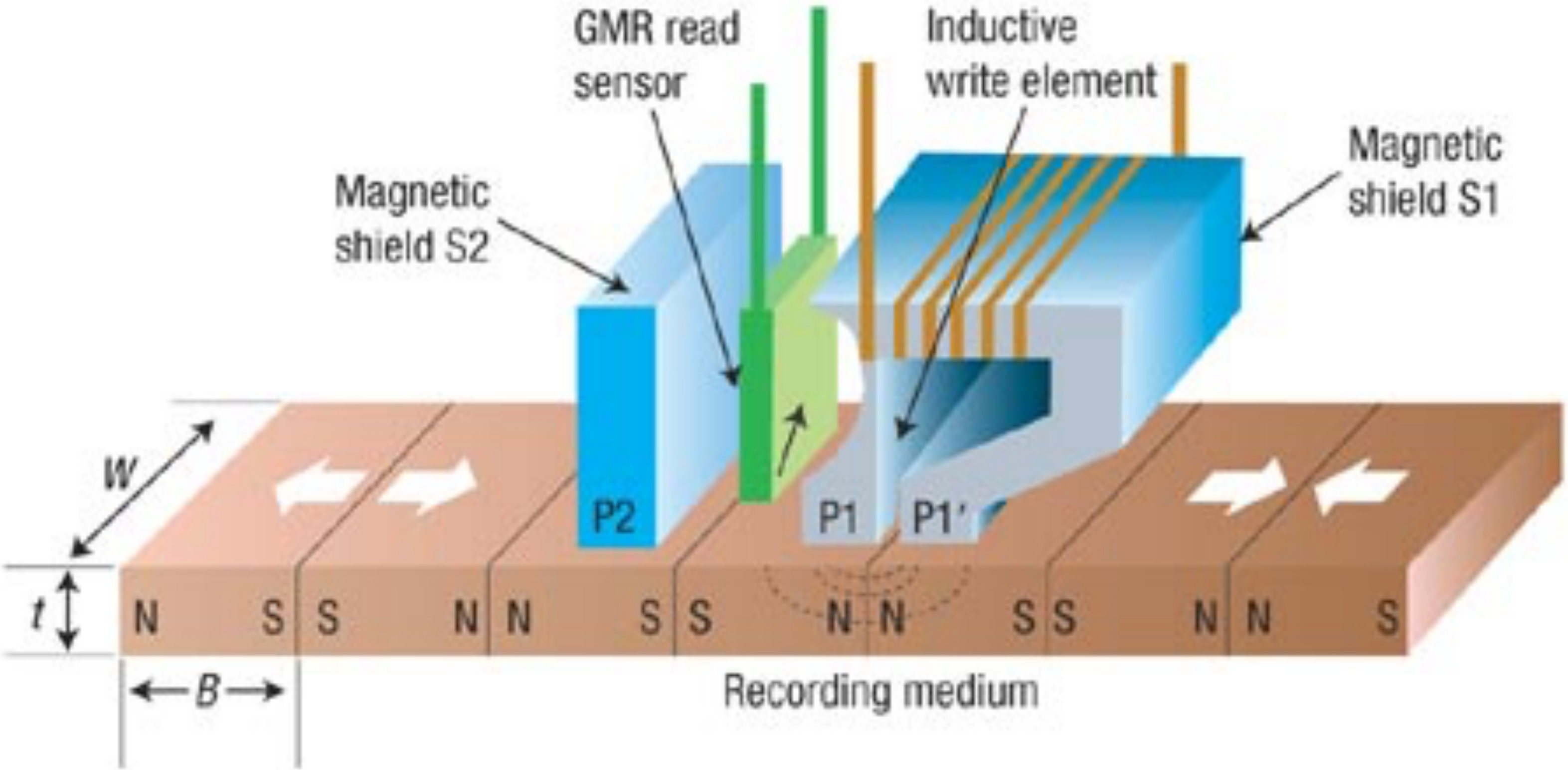
Magneto-resistance

Magnetoresistance is the tendency of a material to change the value of its electrical resistance in an externally-applied magnetic field.





Application of Magneto-resistance

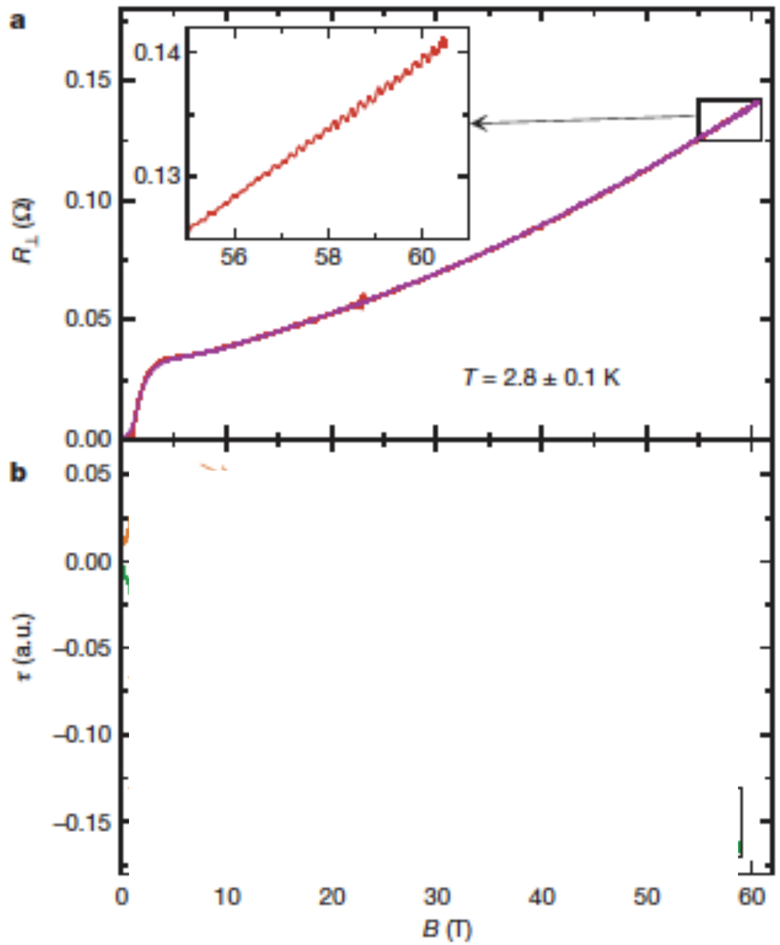


Nobel Prize 2007: Magneto-resistance

The Nobel Prize in Physics 2007 was awarded jointly to Albert Fert and Peter Grünberg *"for the discovery of Giant Magnetoresistance"*

Magneto-resistance

Magnetoresistance is the tendency of a material to change the value of its electrical resistance in an externally-applied magnetic field.



One route to Magneto-resistance

Exercise 2 *Hall effect: Multiband scenario*

In the lecture we derived single-band expressions for the resistivity $\rho = m/ne^2\tau$ and the Hall coefficient $R_\mathrm{H} = -1/ne$. It is convenient to write the relation between the current density $\mathbf{j}$ and the electric field $\mathbf{E}$ as $\mathbf{E} = \boldsymbol{\rho}\mathbf{j}$ where:

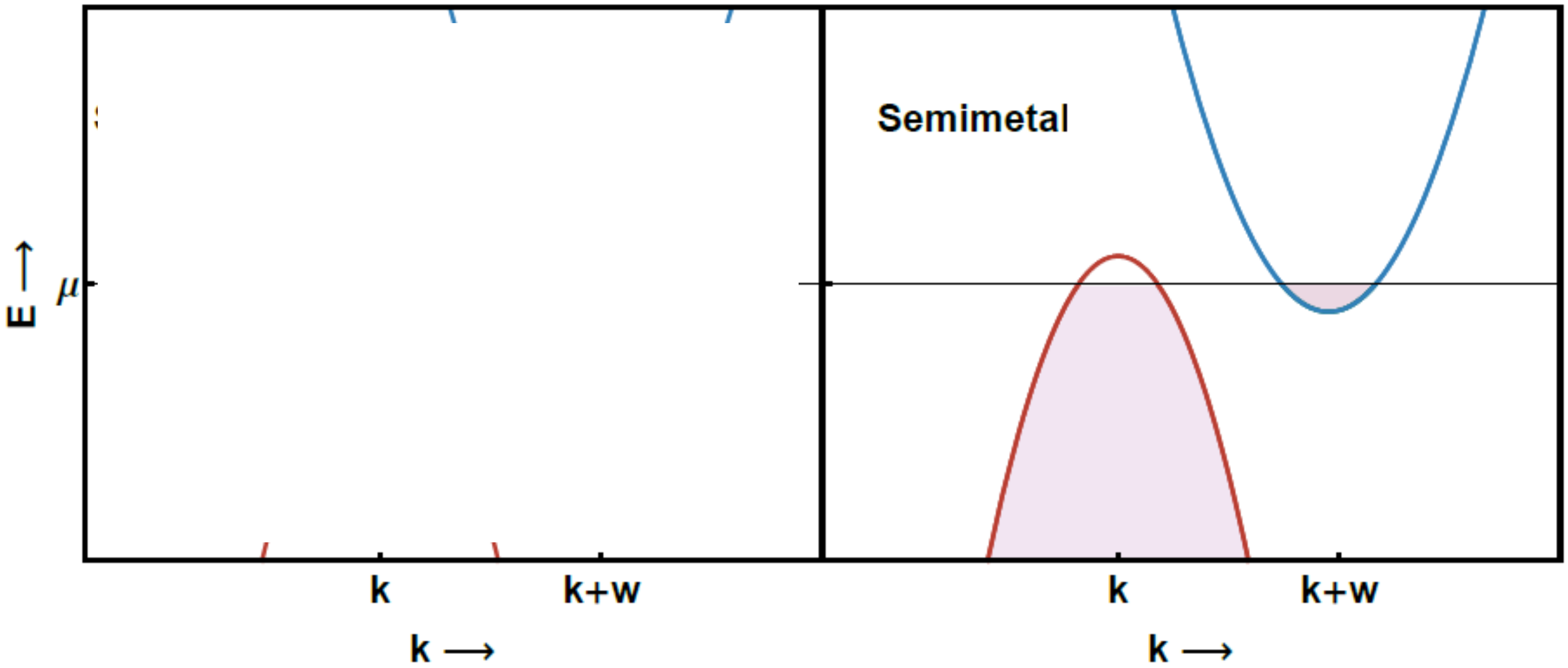
$$\boldsymbol{\rho} = \begin{pmatrix} \rho & -R_\mathrm{H}B \\ R_\mathrm{H}B & \rho \end{pmatrix} \tag{1}$$

(a) Let us consider a metal where more than one band crosses the Fermi level. When applying an electric field $\mathbf{E}$, the current $\mathbf{j}_n$ on the n^th band is: $\mathbf{j}_n = \boldsymbol{\rho}_n^{-1}\mathbf{E}$ where

$$\boldsymbol{\rho}_n = \begin{pmatrix} \rho_n & -R_{\mathrm{H},n}B \\ R_{\mathrm{H},n}B & \rho_n \end{pmatrix}. \tag{2}$$

Show that the total induced current $\mathbf{j}$ is given by $\mathbf{E} = \boldsymbol{\rho}\mathbf{j}$ where $\boldsymbol{\rho} = (\sum \boldsymbol{\rho}_n^{-1})^{-1}$.

Consider two bands crossing the Fermi level



One route to Magneto-resistance

(b) If only two bands are crossing the Fermi level, show that:

$$R_{\mathrm{H}} = \frac{R_{\mathrm{H},1}\rho_2^2 + R_{\mathrm{H},2}\rho_1^2 + R_{\mathrm{H},1}R_{\mathrm{H},2}(R_{\mathrm{H},1} + R_{\mathrm{H},2})B^2}{(\rho_1 + \rho_2)^2 + (R_{\mathrm{H},1} + R_{\mathrm{H},2})^2 B^2} \tag{3}$$

$$\rho = \frac{\rho_1\rho_2(\rho_1 + \rho_2) + (\rho_1 R_{\mathrm{H},2}^2 + \rho_2 R_{\mathrm{H},1}^2)B^2}{(\rho_1 + \rho_2)^2 + (R_{\mathrm{H},1} + R_{\mathrm{H},2})^2 B^2} \tag{4}$$

Hint: It is allowed to use Mathematica. If you do so, print out the code and the output.

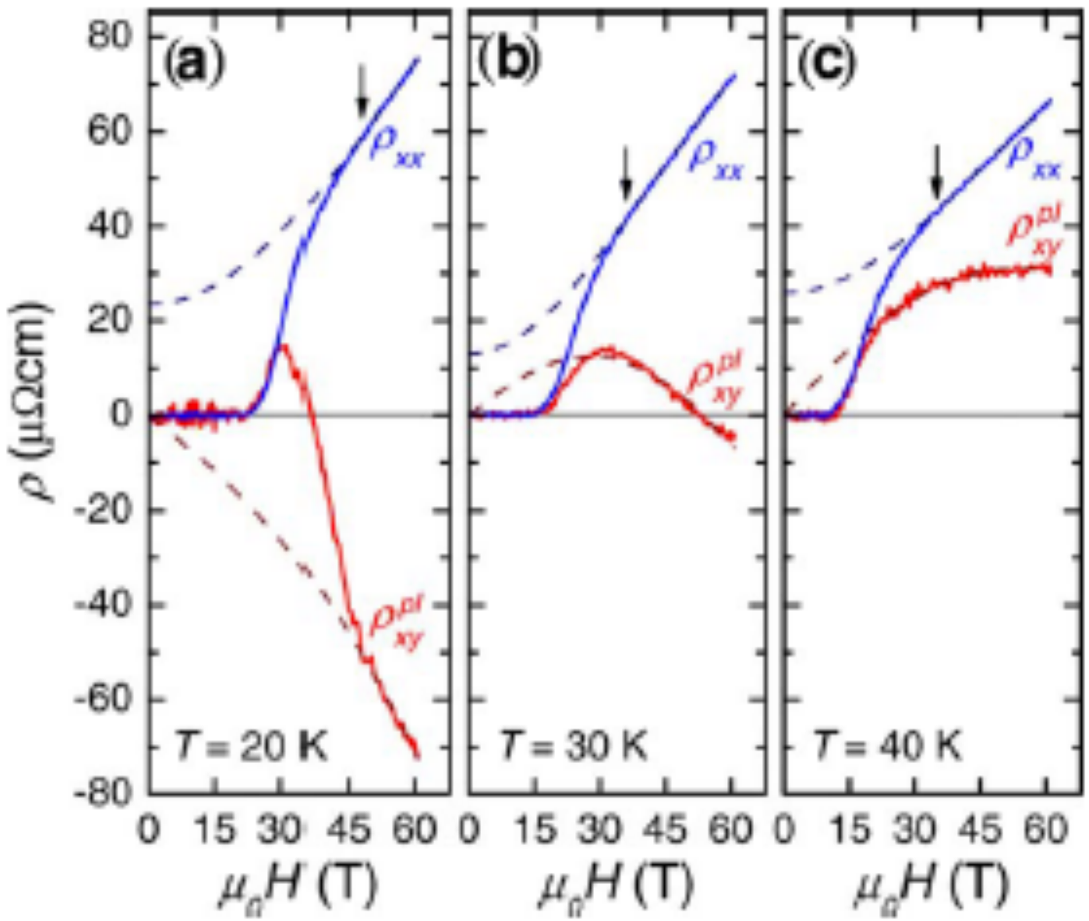
(c) Magnetic field dependence of resistivity is called magneto-resistance. If the two-band system has both electron-like and hole-like carries so that $|R_{\mathrm{H},1}| \approx |R_{\mathrm{H},2}|$, what is the field dependence of ρ.

(d) The mobility can be expressed as $\mu = e\tau/m$. Use the low-field limits of equations 3 and 4 to derive the following two expressions:

$$\sigma = ne\mu_{\mathrm{e}} + pe\mu_{\mathrm{h}} \tag{5}$$

$$R_{\mathrm{H}} = \frac{p\mu_{\mathrm{h}}^2 - n\mu_{\mathrm{e}}^2}{e(p\mu_{\mathrm{h}} + n\mu_{\mathrm{e}})^2}. \tag{6}$$

Magneto-resistance



PHYSICAL REVIEW B **82**, 020514(R) (2010)