Metallic Criticality in the Charge Transport of $BaFe_2(As_{1-x}P_x)_2$

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Arkady Sheckter, Ross D. McDonald, Mun K. Chan, Brad Ramshaw
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GORDON AND BETTY MOORE FOUNDATION

NATIONAL HIGH MAGNETIC FIELD LABORATORY

Outline

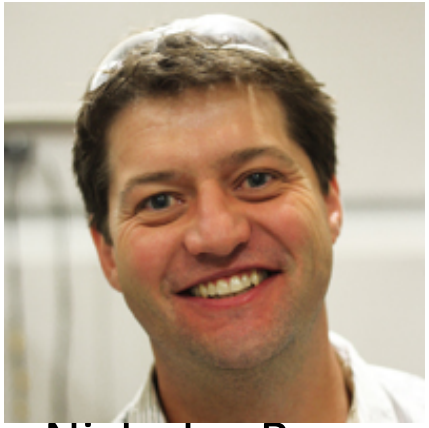
- Phenomenology of Quantum Critical metals
  - T-linear resistivity, 1/T Hall effect
  - Fan-like critical region

- High Field Magnetoresistance in Ba-122
  - T-linear/B-linear MR
  - Scaling between T and B, with the same exponent

- Phenomenology of R_H
  - 1/T enhancement at low temperatures
  - Reduction of R_H at high fields and cut-off at high dopings

Brought to you by:

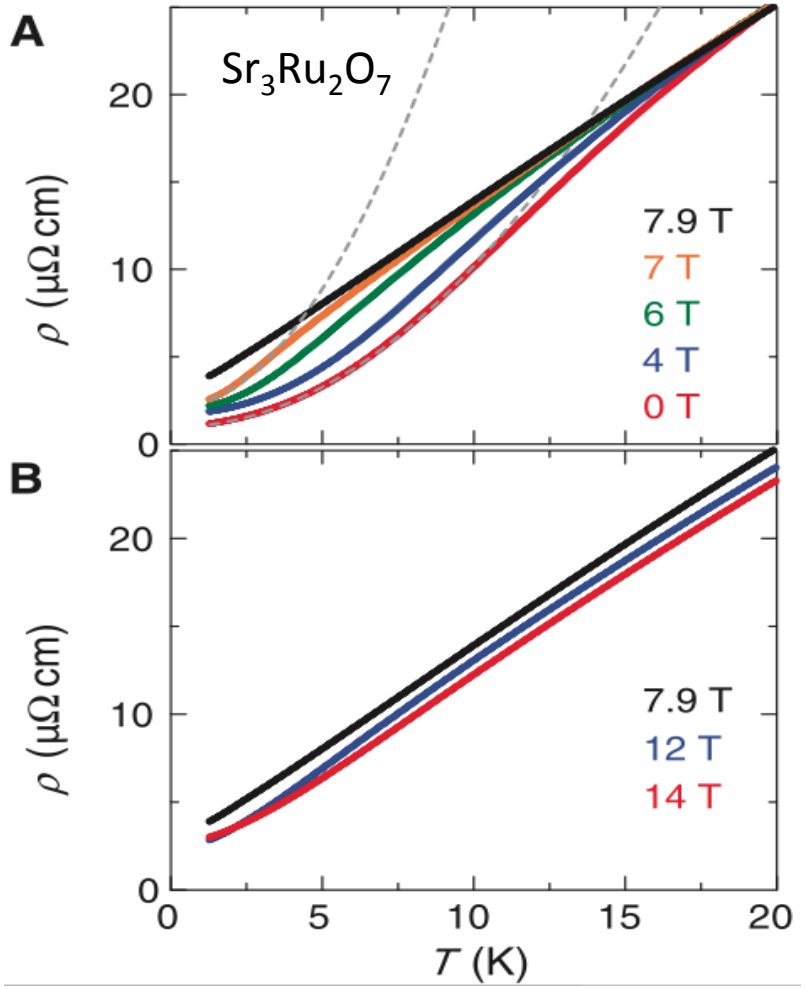
- NHMFL collaborators Arkady Shechter, Ross McDonald, Mun Chan & Brad Ramshaw

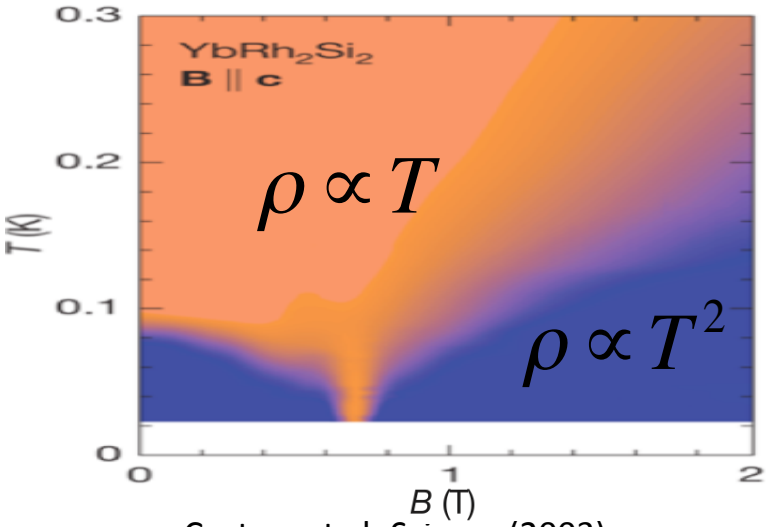
- Colleagues at Berkeley Nicholas Breznay, Toni Helm, Nikola Maksimovic & James Analytis



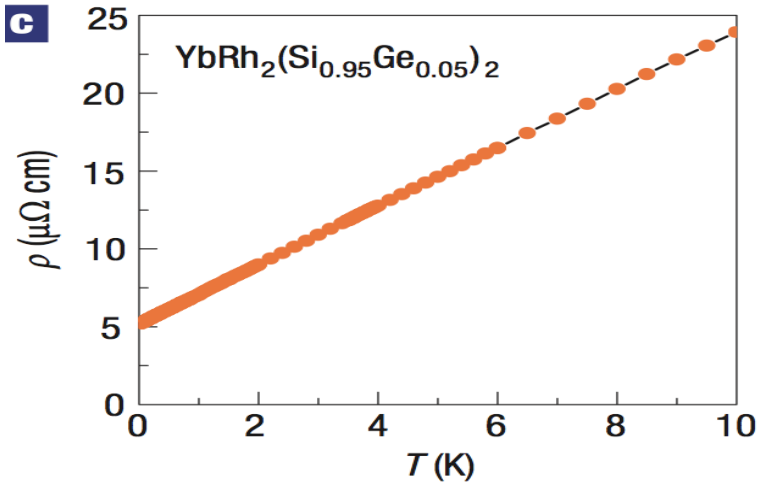

T-linear Resistivity in Quantum Critical Metals



Bruin et al, *Science* (2013)

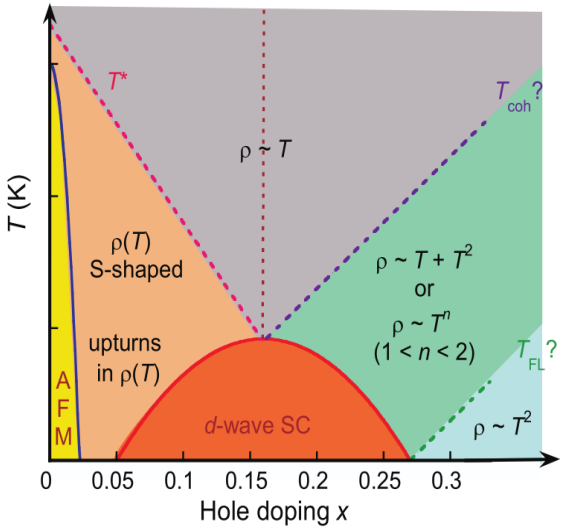


Custers et al, *Science* (2003)

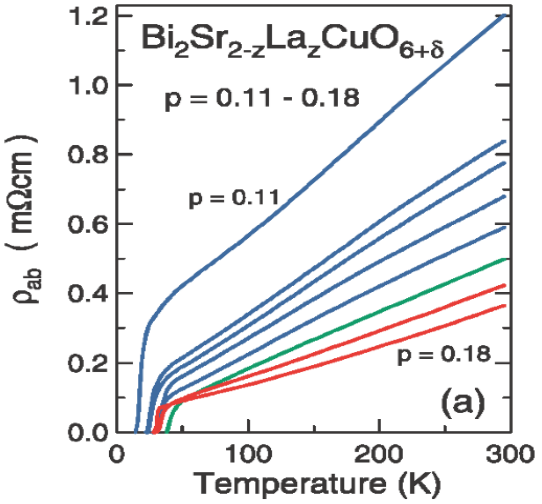


P. Gegenwart, et al, Nat. Phys. (2008)

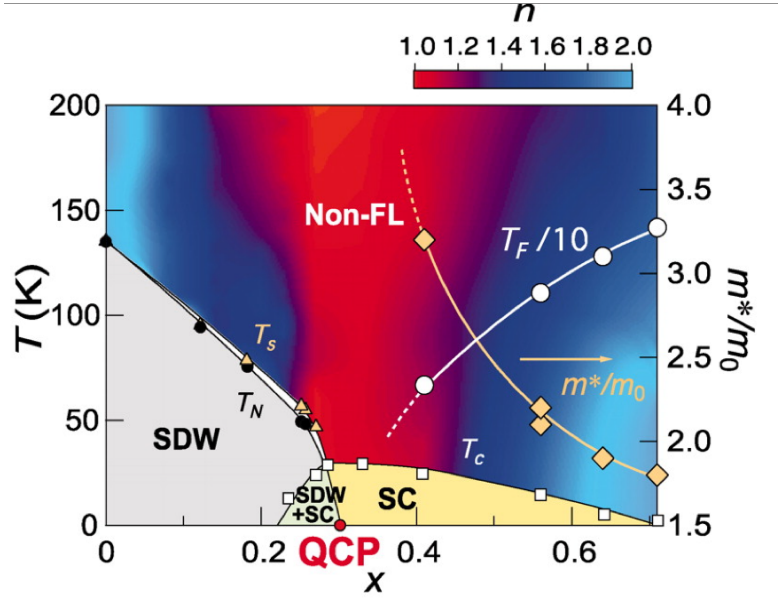
(Nonmagneto-)Transport in High-T_cs



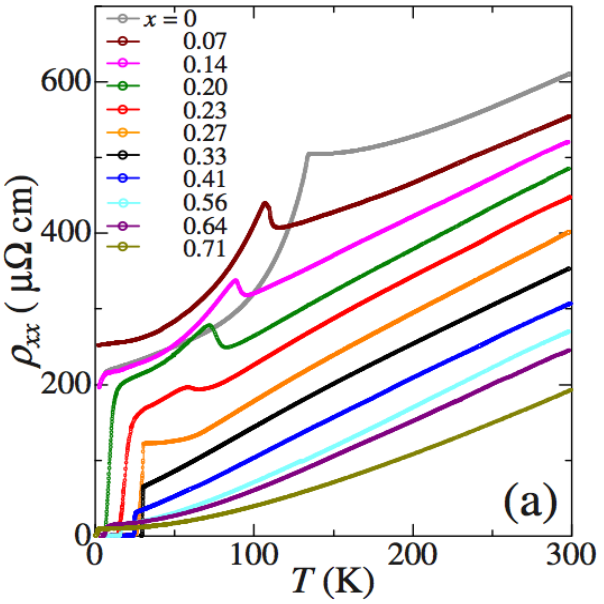
N.E. Hussey, Journal of Physics: Condensed Matter (2008)



Y. Ando, PRL (2004)



K. Hashimoto et al., *Science* (2012)



Kasahara et al., Phys. Rev. (2010)

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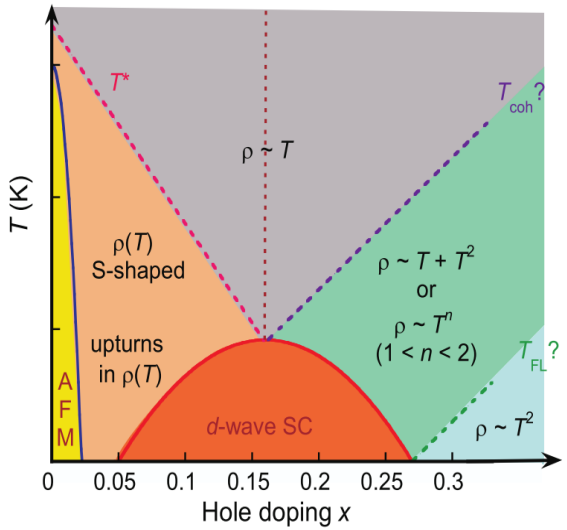
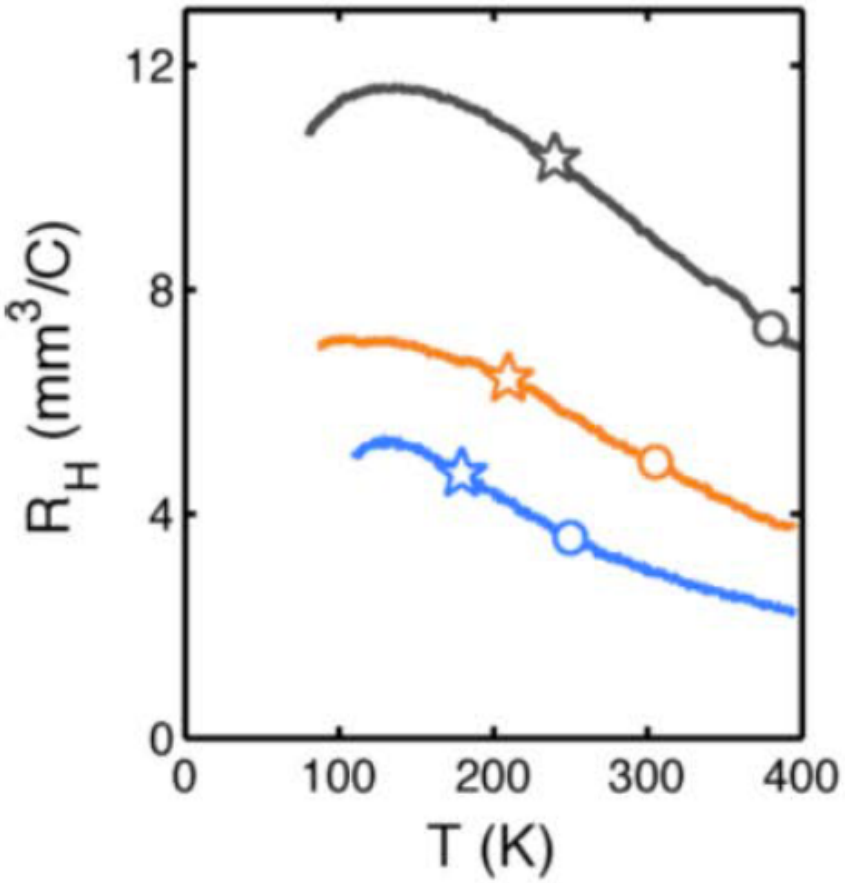
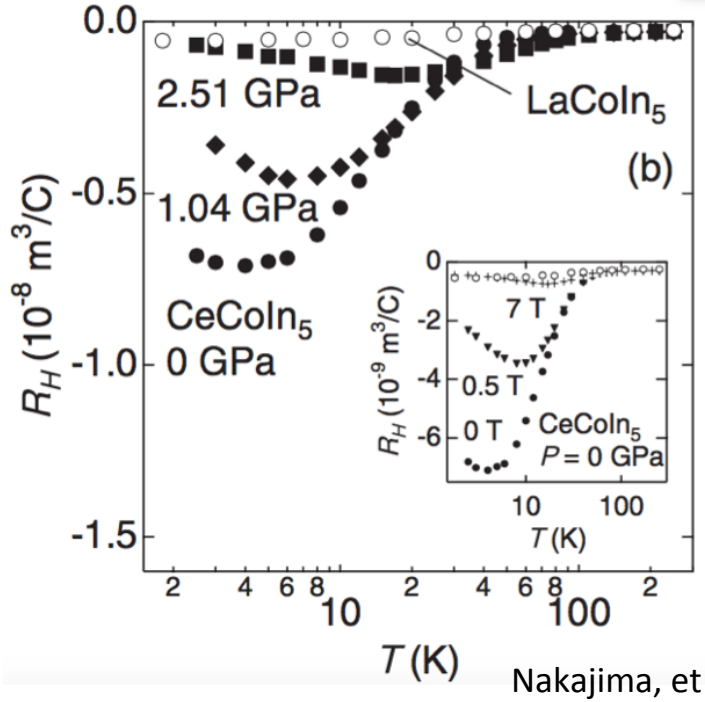


N.E. Hussey, Journal of Physics: Condensed Matter (2008)

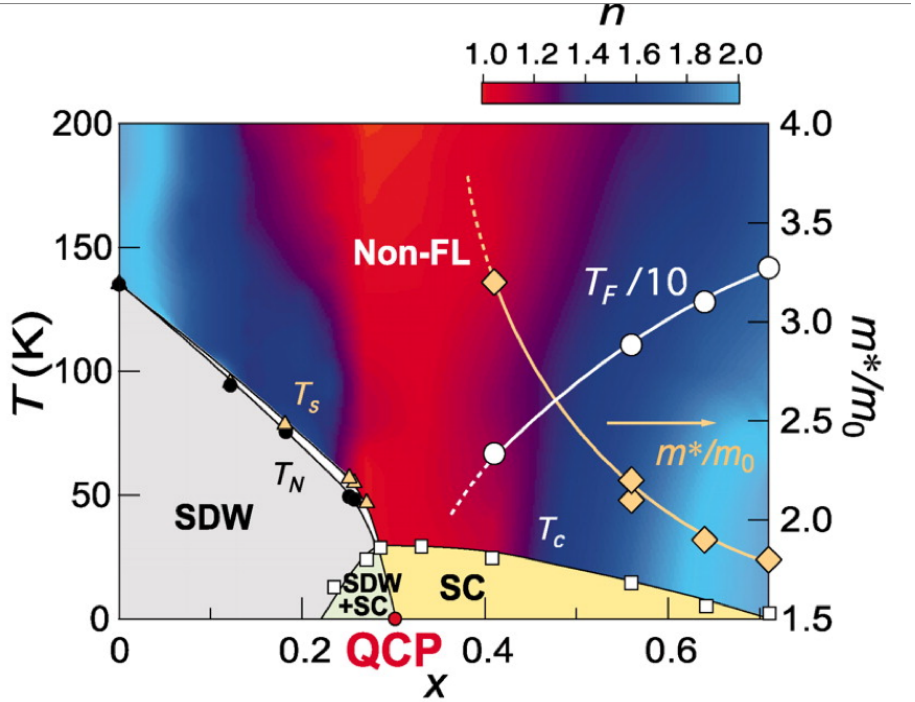
Hg-1201, from Barisic, et al, PRL (2016)



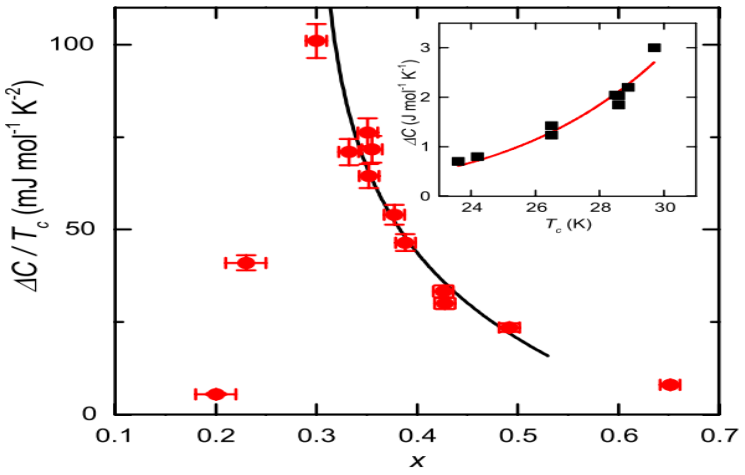


Nakajima, et al, JPSJ (2006)

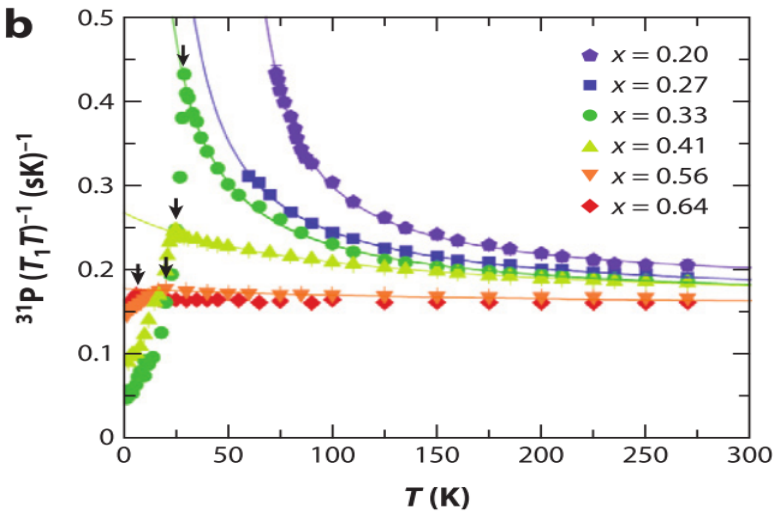
$BaFe_2(As_{1-x}P_x)_2$



K. Hashimoto et al., *Science* (2012)



P. Walmsley, et al, *Phys. Rev. Lett.* (2013)

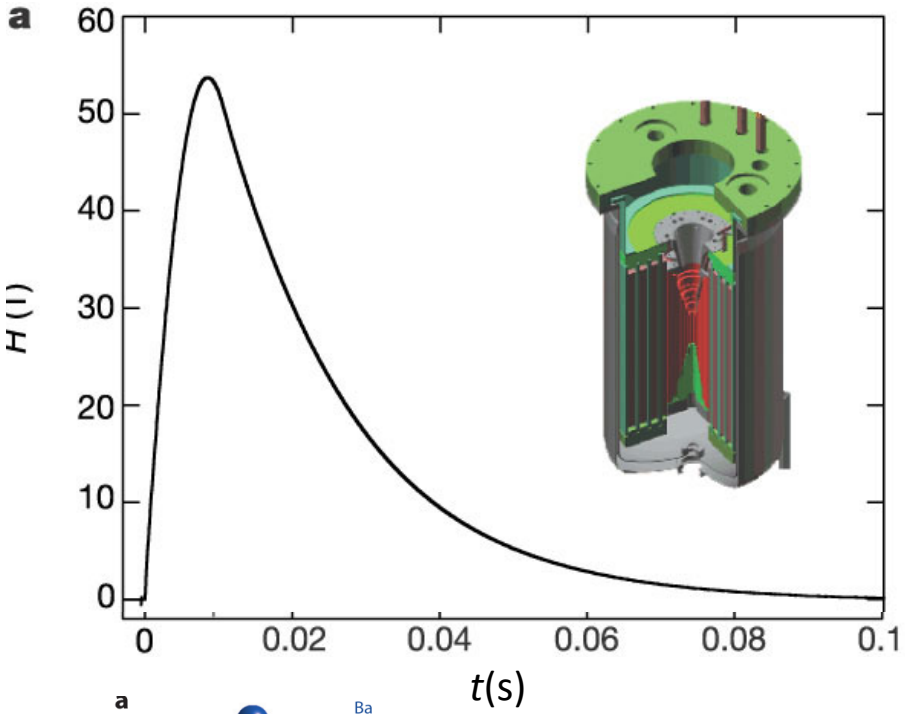


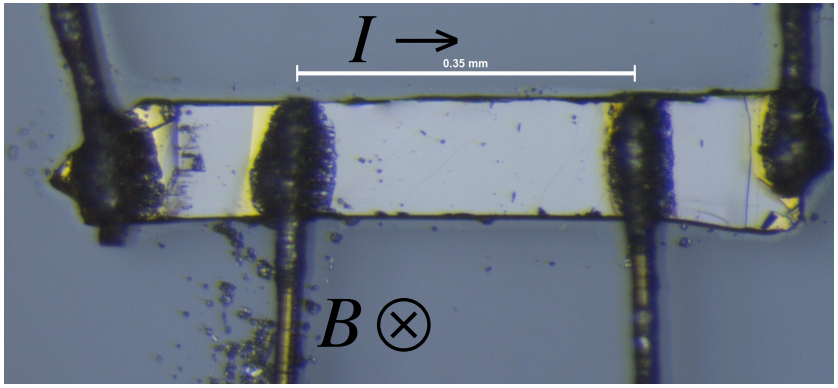
Y. Nakai, et al., *Phys. Rev. Lett.* (2010)

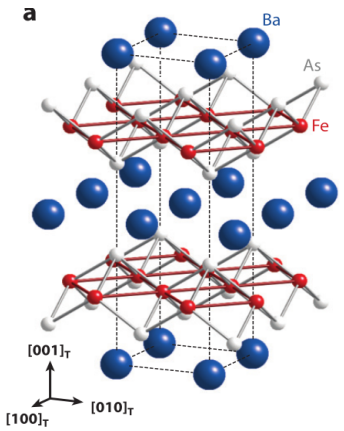
- Signs of strong correlations/criticality are seen in a number of probes: Quantum oscillations, heat capacity, penetration depth, NMR, charge transport.
- Normal state at optimal doping is (barely) accessible at low temperatures: H_{c2} ~ 45 Tesla

Ultra-High Magnetic fields: NHMFL Pulsed Field Facility at Los Alamos National Lab

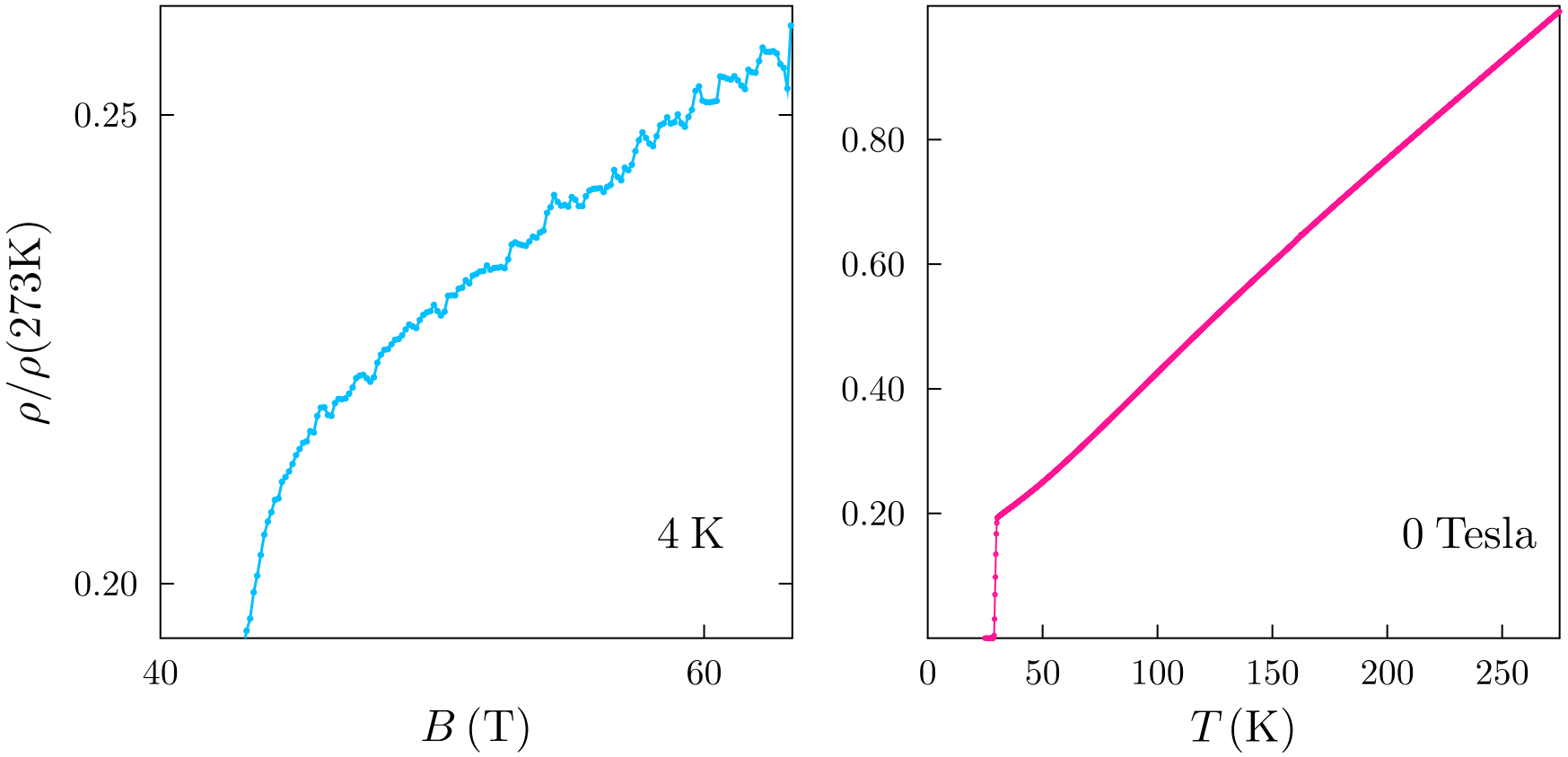
http://www.lanl.gov







Low-T magnetotransport



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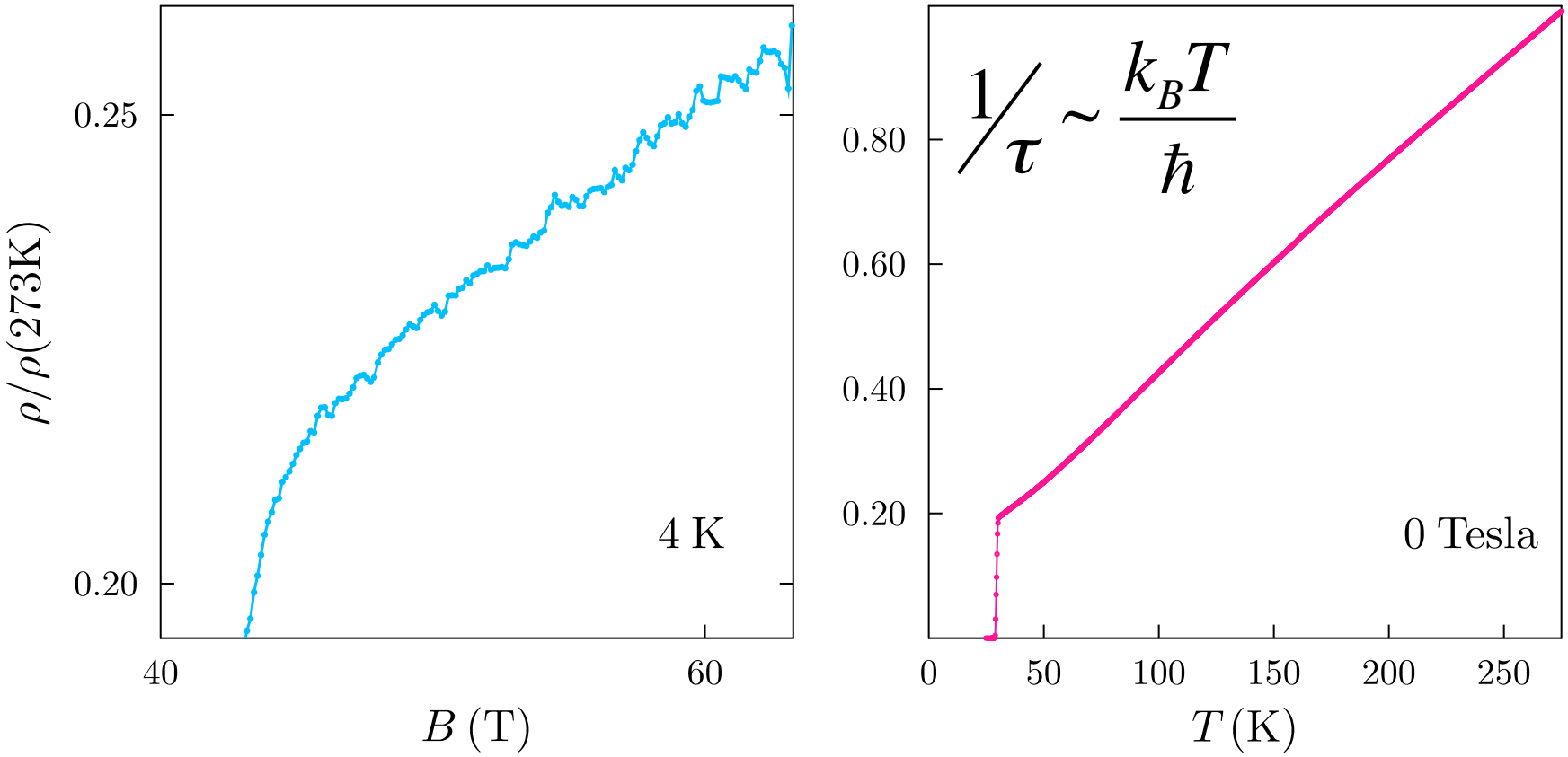

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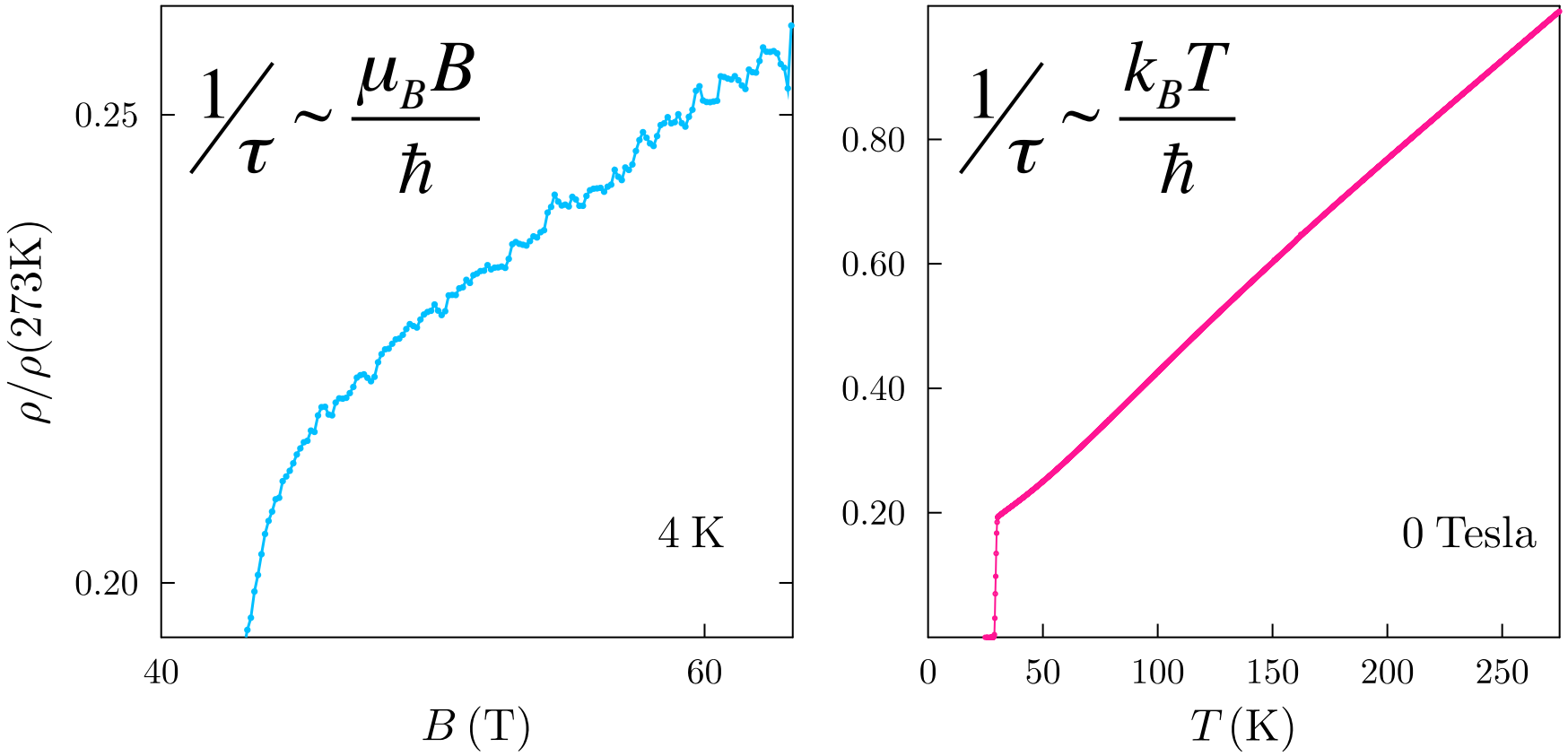

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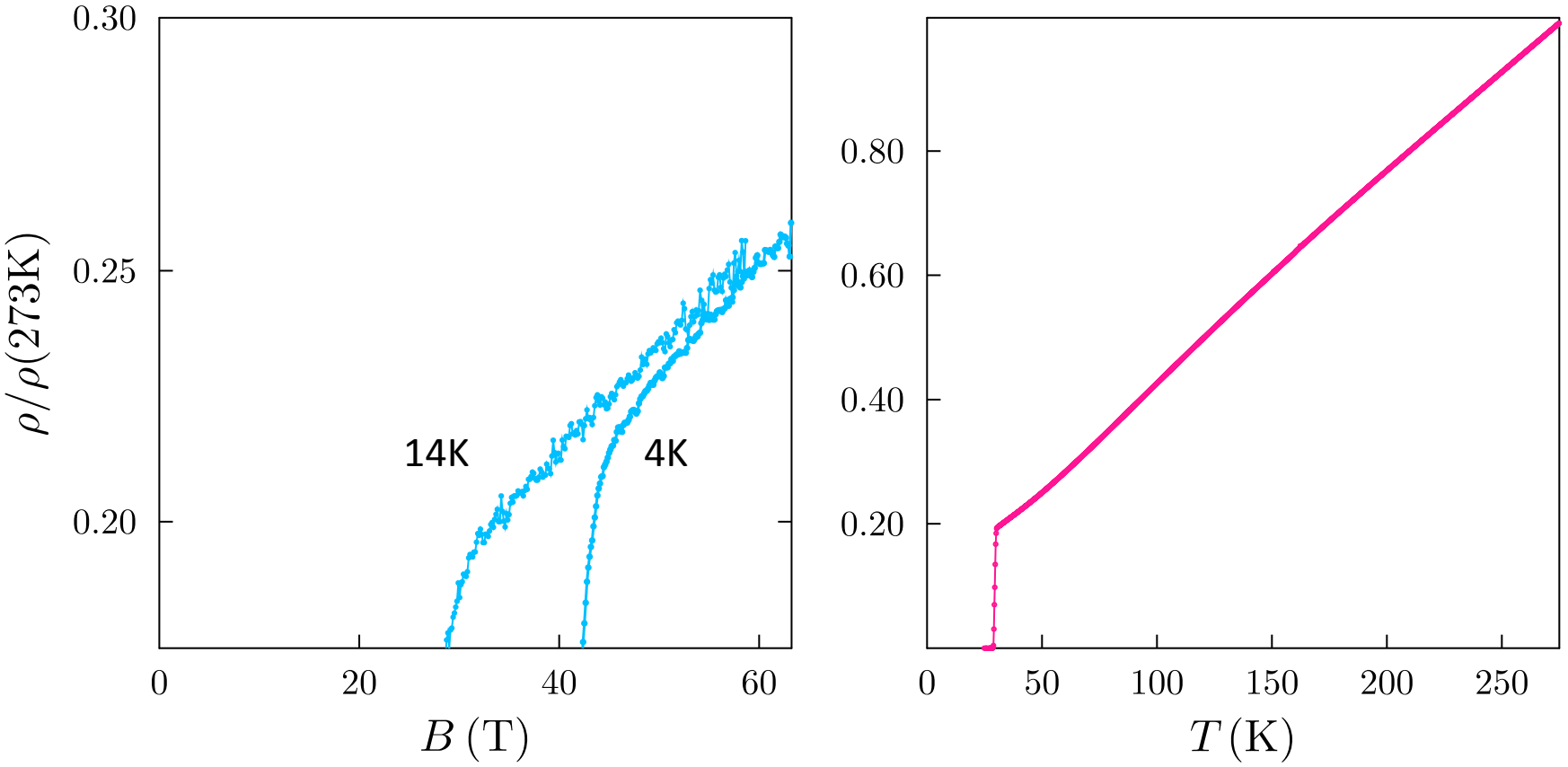

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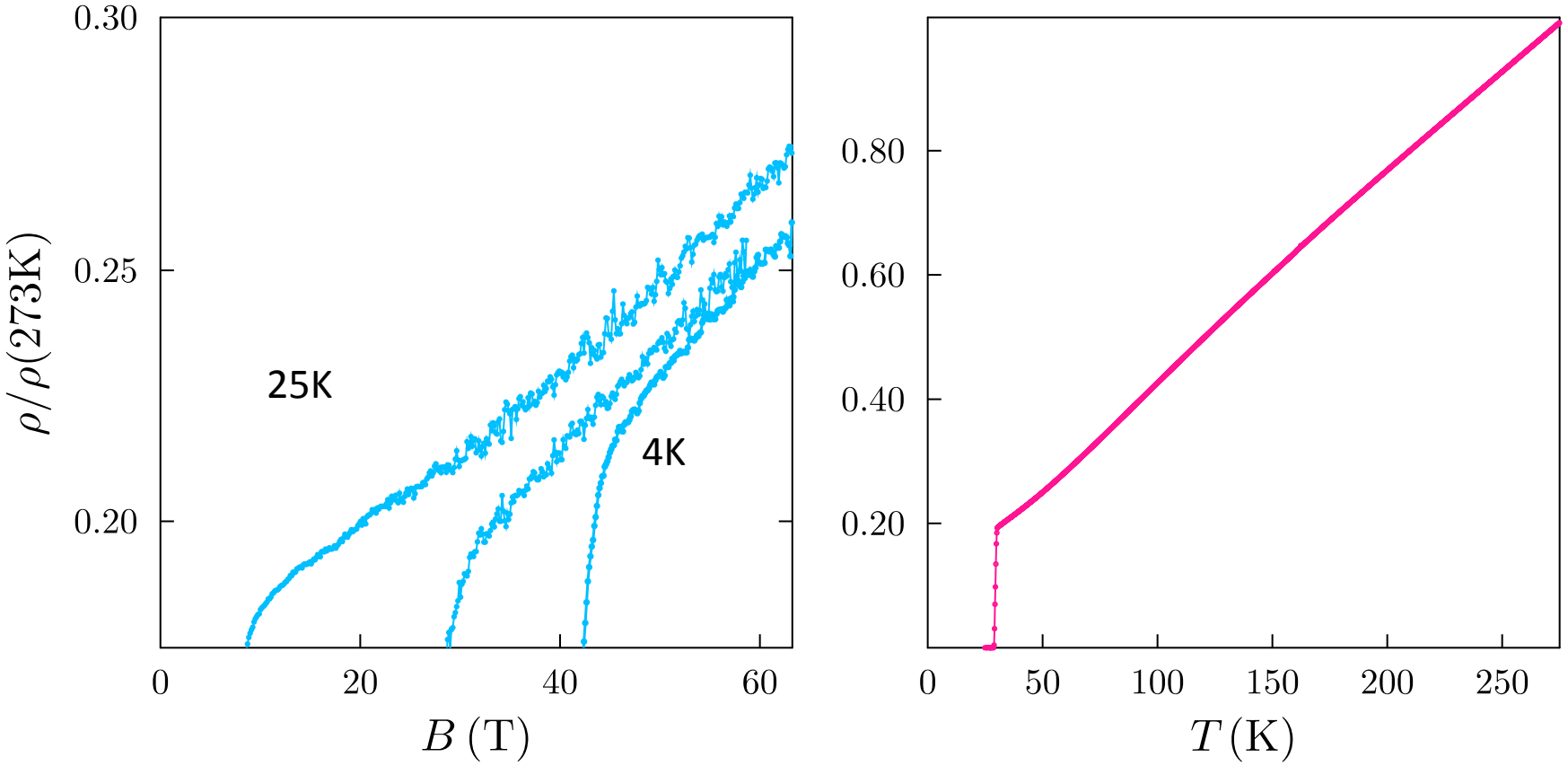

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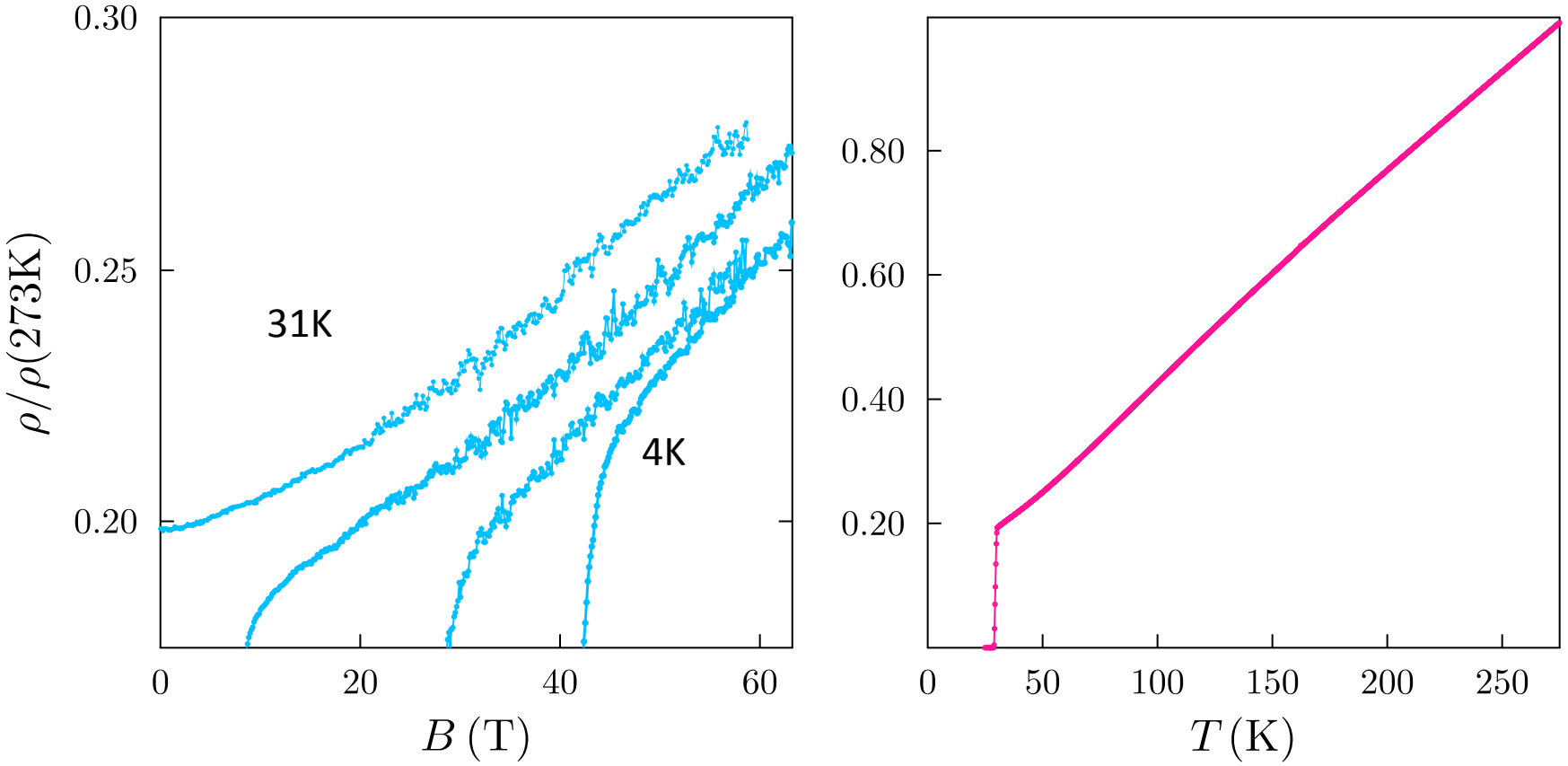

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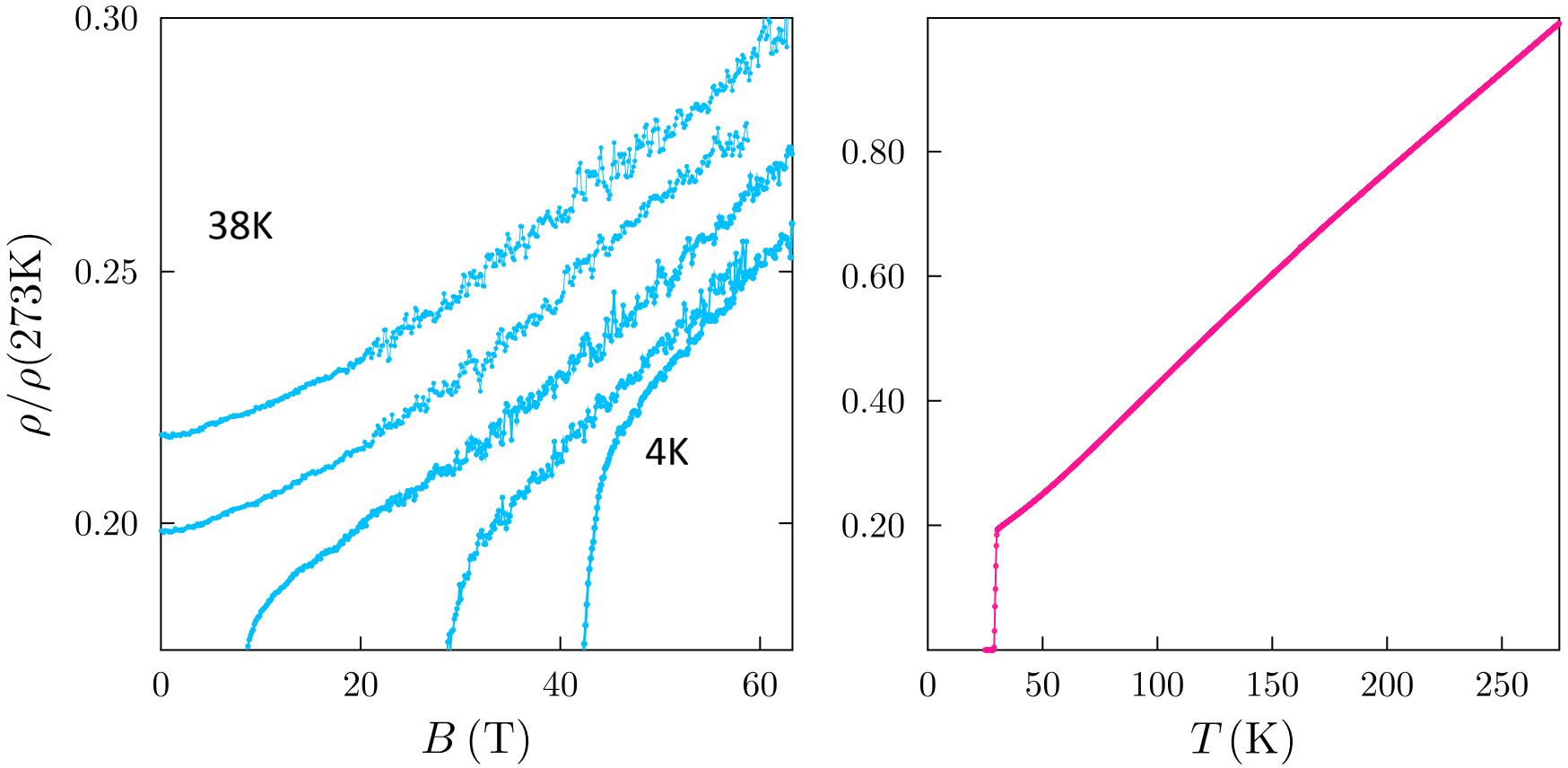
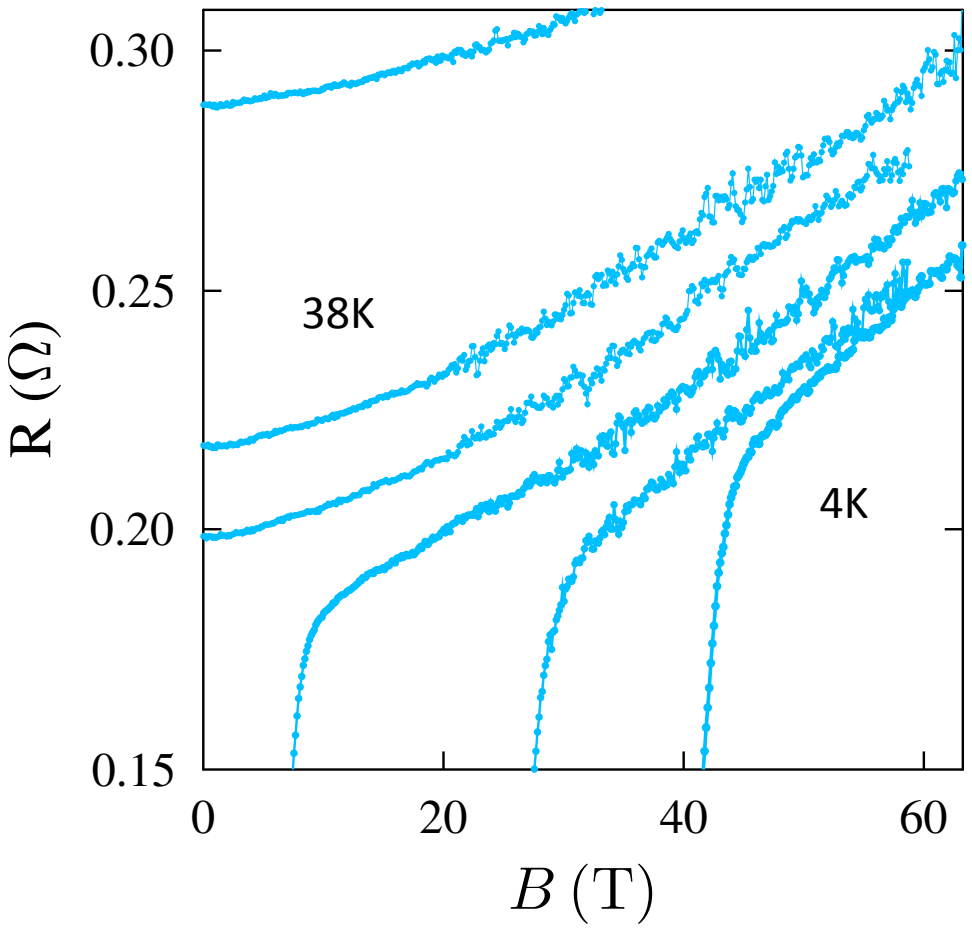


Low-T magnetotransport

$$R \propto T \times f\left(B/T\right)$$



B/T Scaling in the magnetotransport

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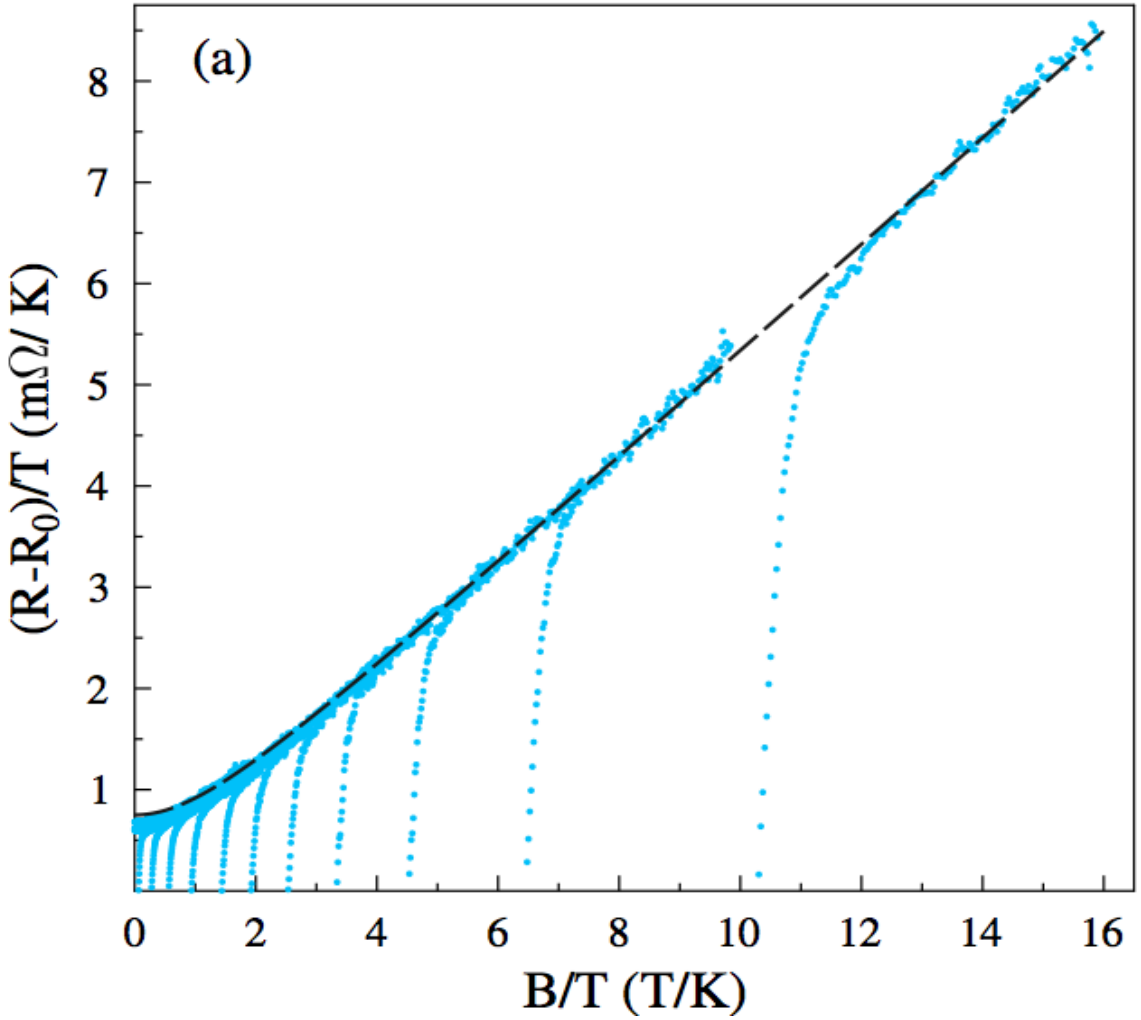

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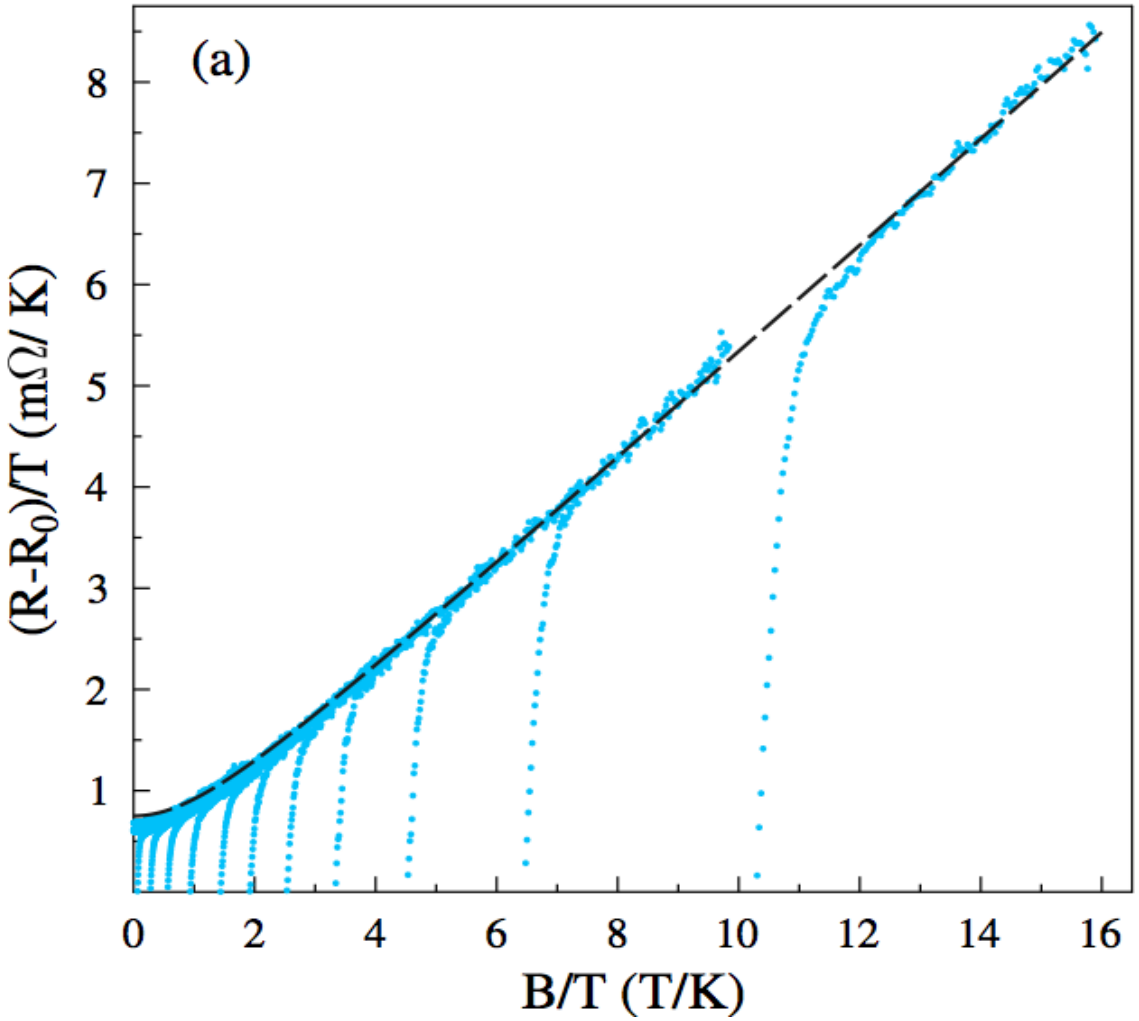
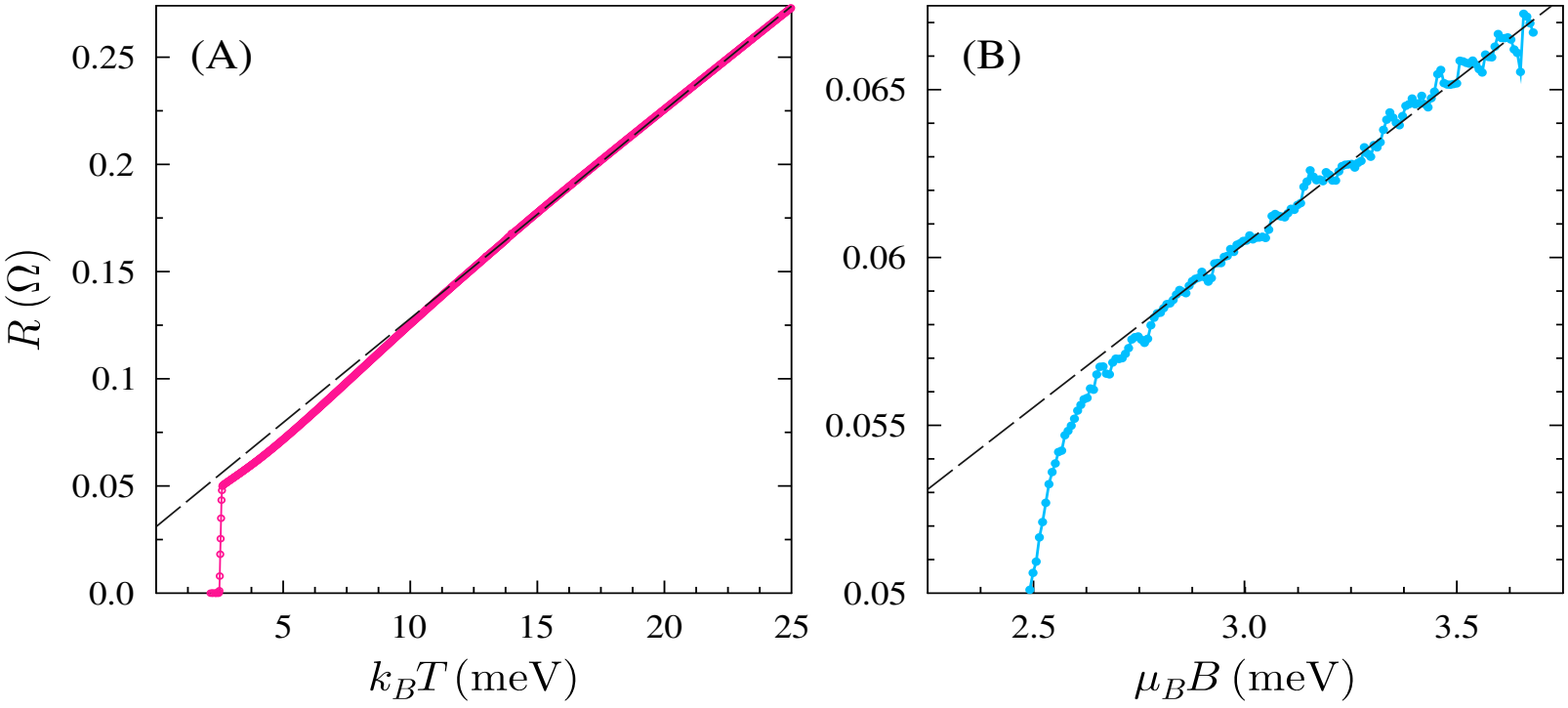


$$\rho \propto \sqrt{(\alpha k_B T)^2 + (\beta \mu_B B)^2} \equiv \Gamma$$

Intercepts and slopes



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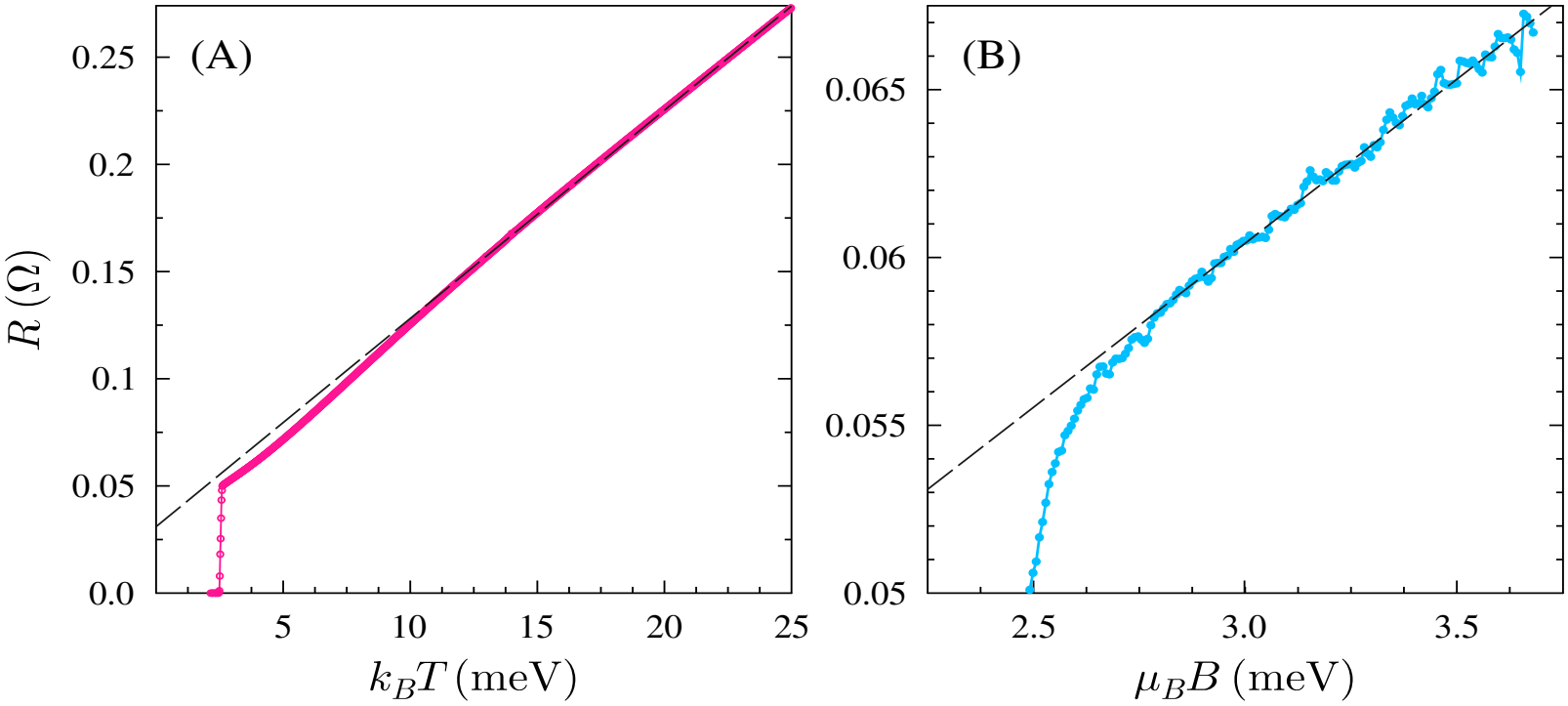

Within a few percent Alpha = Beta in:

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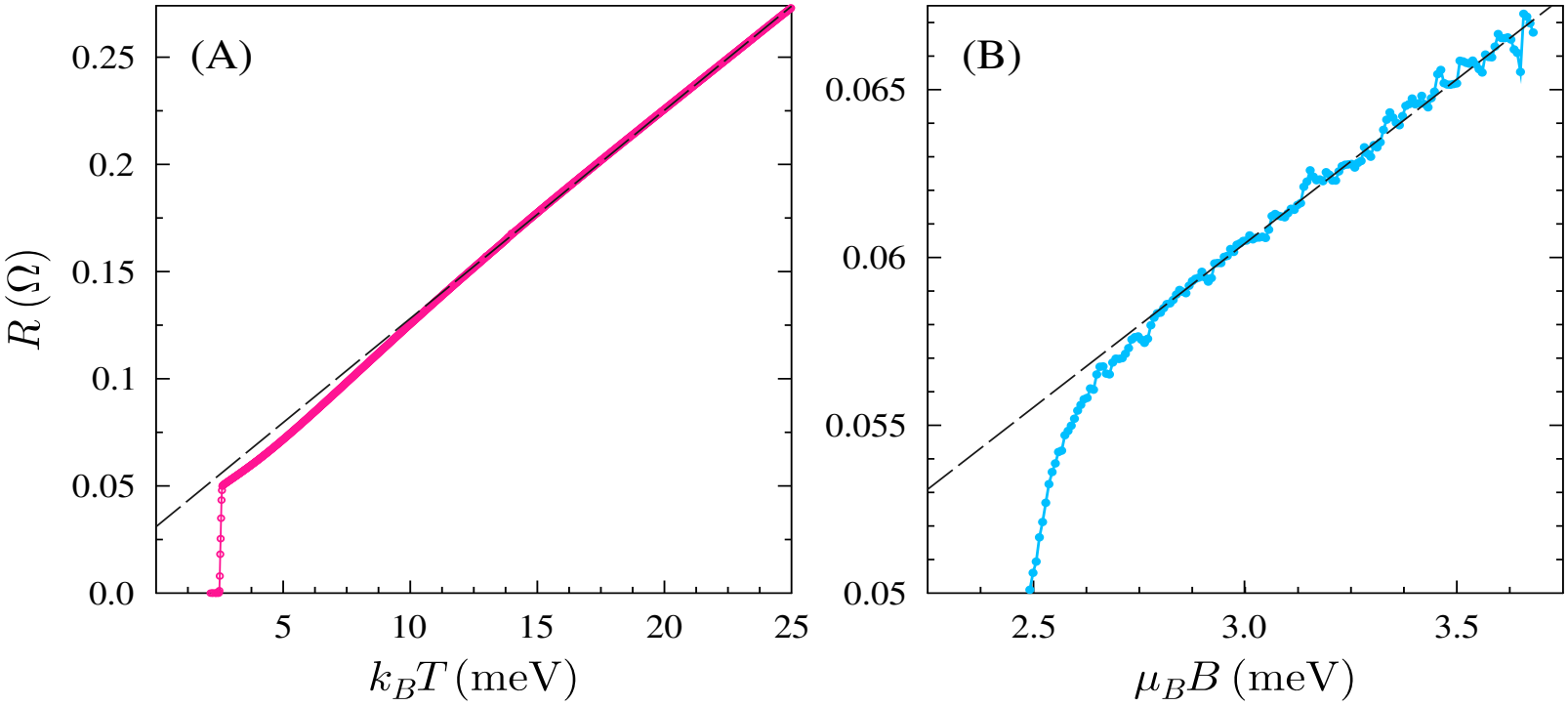
Intercepts and slopes



Within a few percent Alpha = Beta in:

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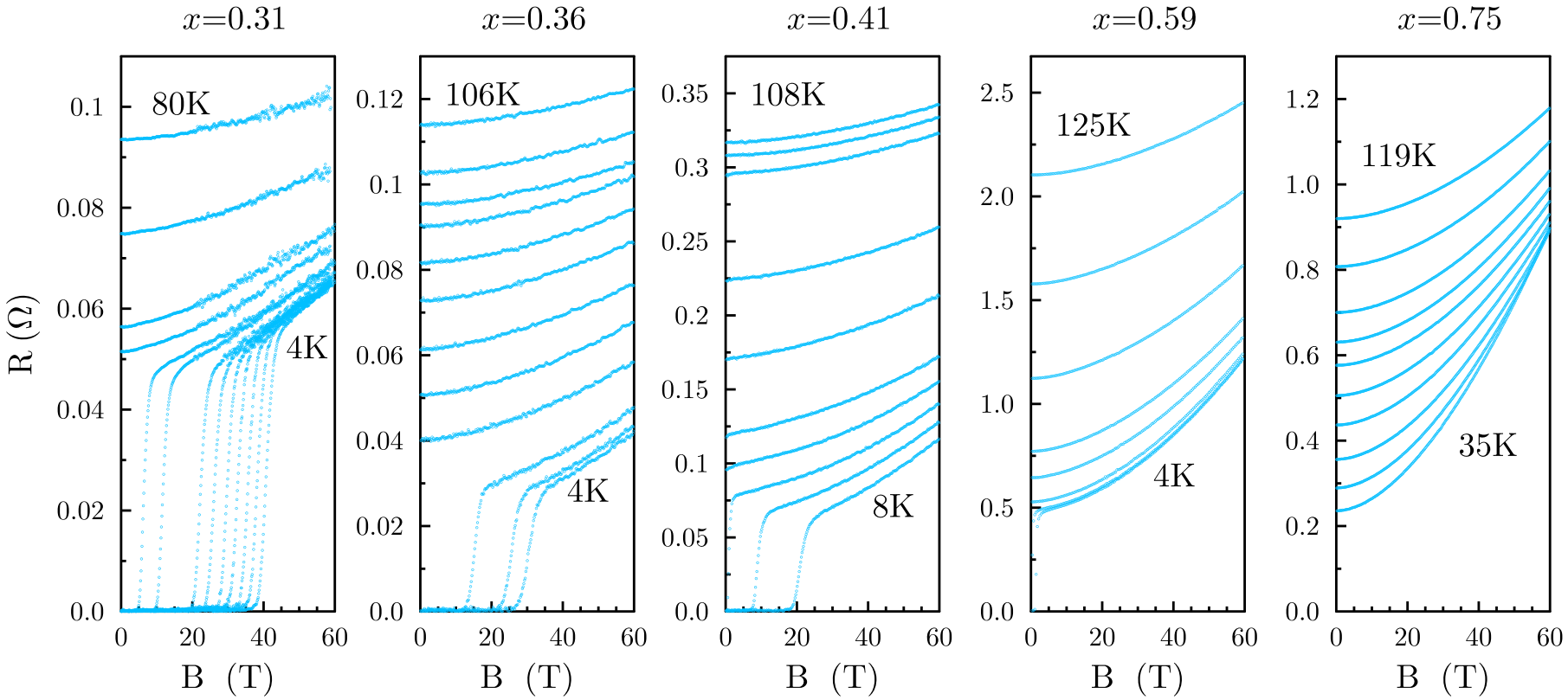
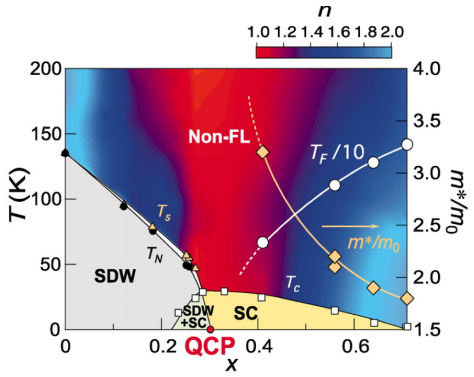
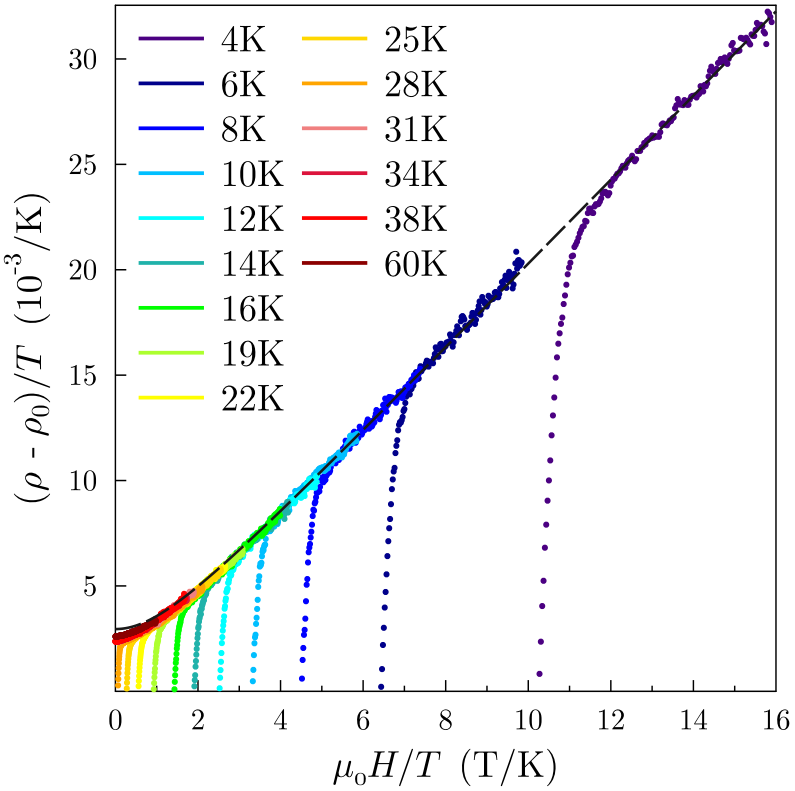
Intercepts at T = 0 or B = 0 are equal.

Magnetotransport across the phase diagram





Quantum Critical Magnetoresistance?



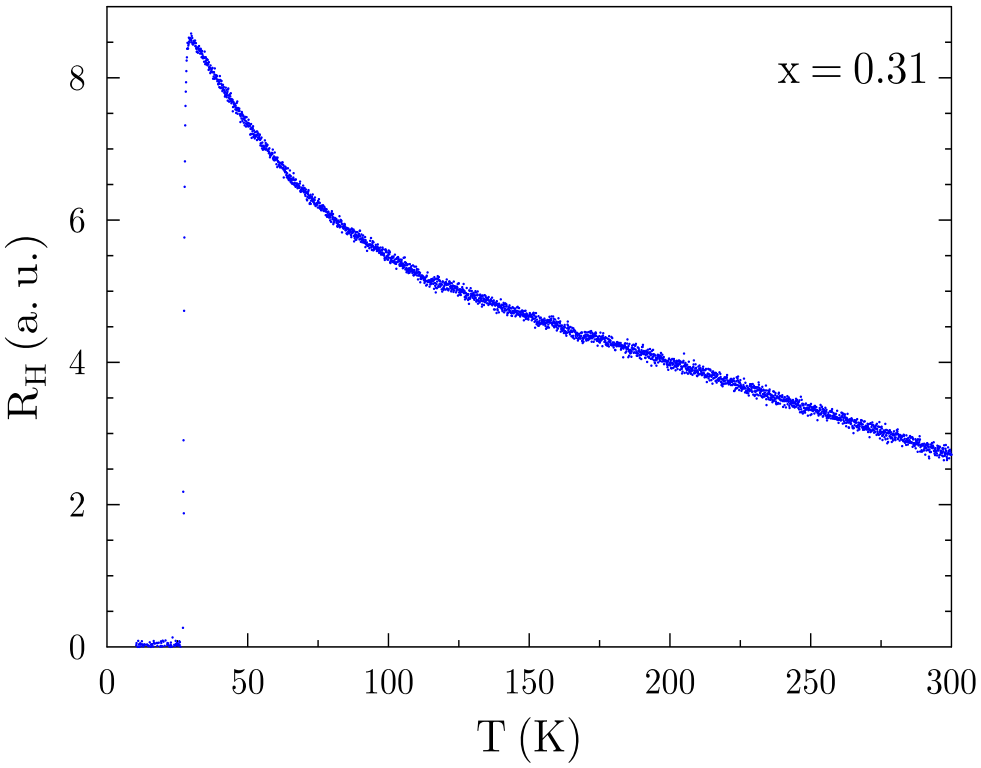
I. M. Hayes, et al, *Nature Physics* (2016)

$$\rho \propto \sqrt{(\alpha k_B T)^2 + (\beta \mu_B B)^2}$$

There is a magnetic analogue to the T-linear resistivity at optimal doping and low temperatures.

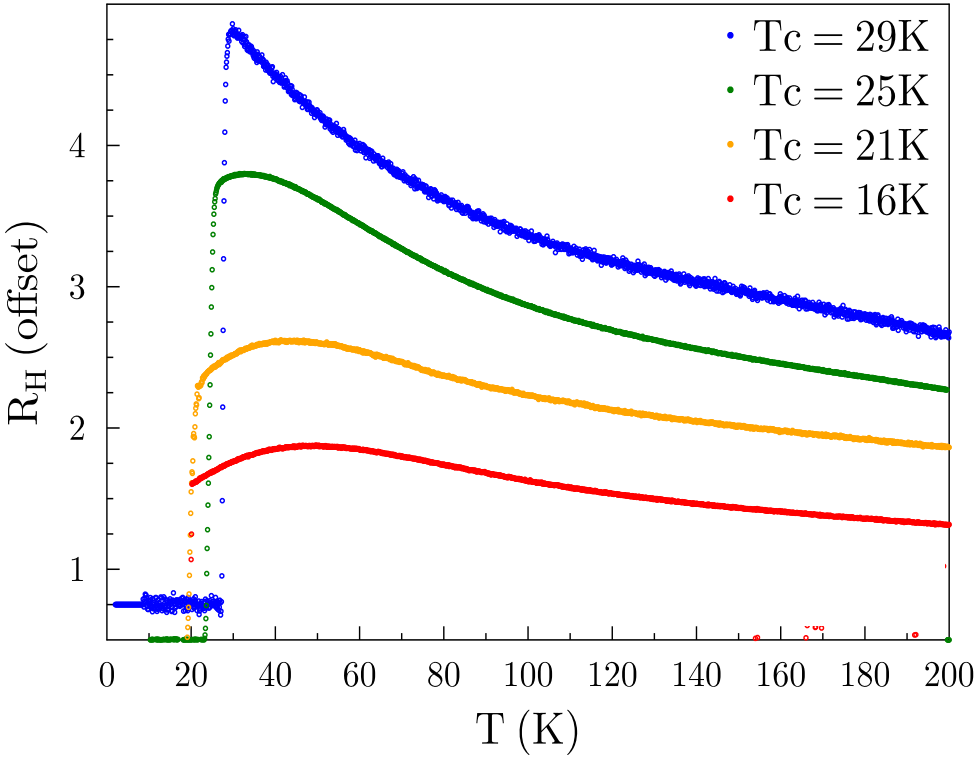
T and B have the same exponent and therefore the same scaling dimension.

Hall Effect in Ba-122



Low Field (3 Tesla)

R_H across the phase diagram



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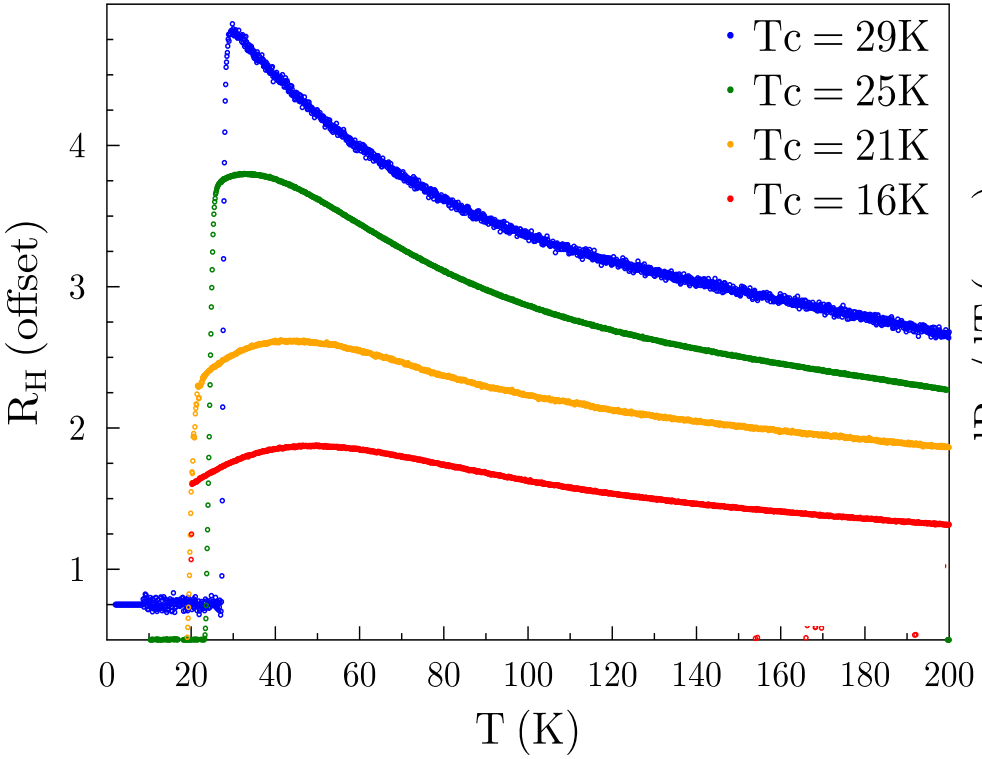

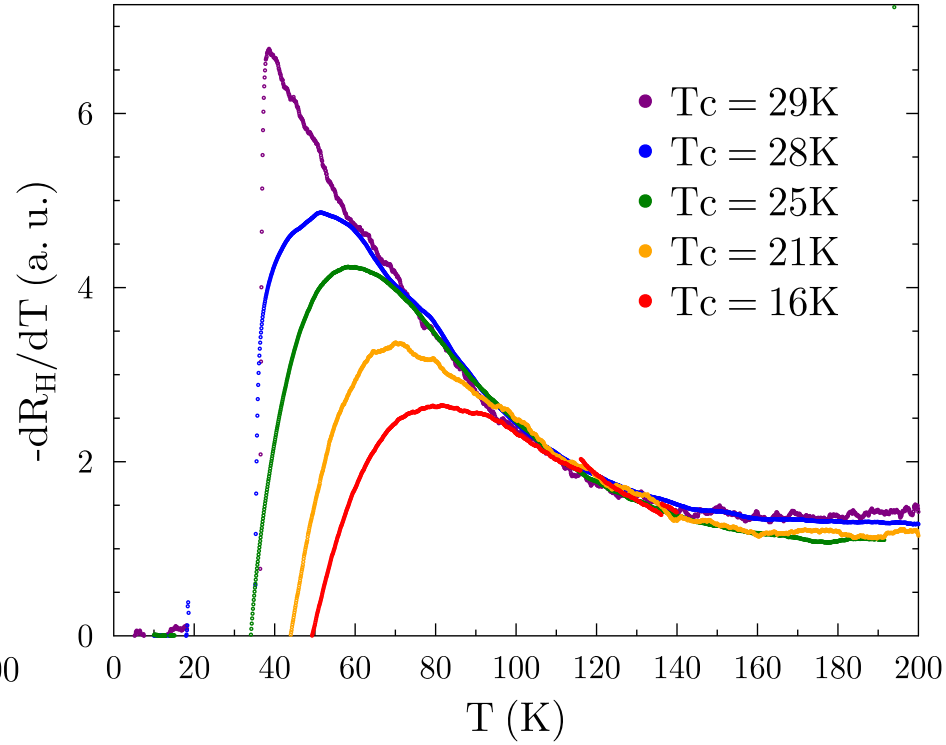

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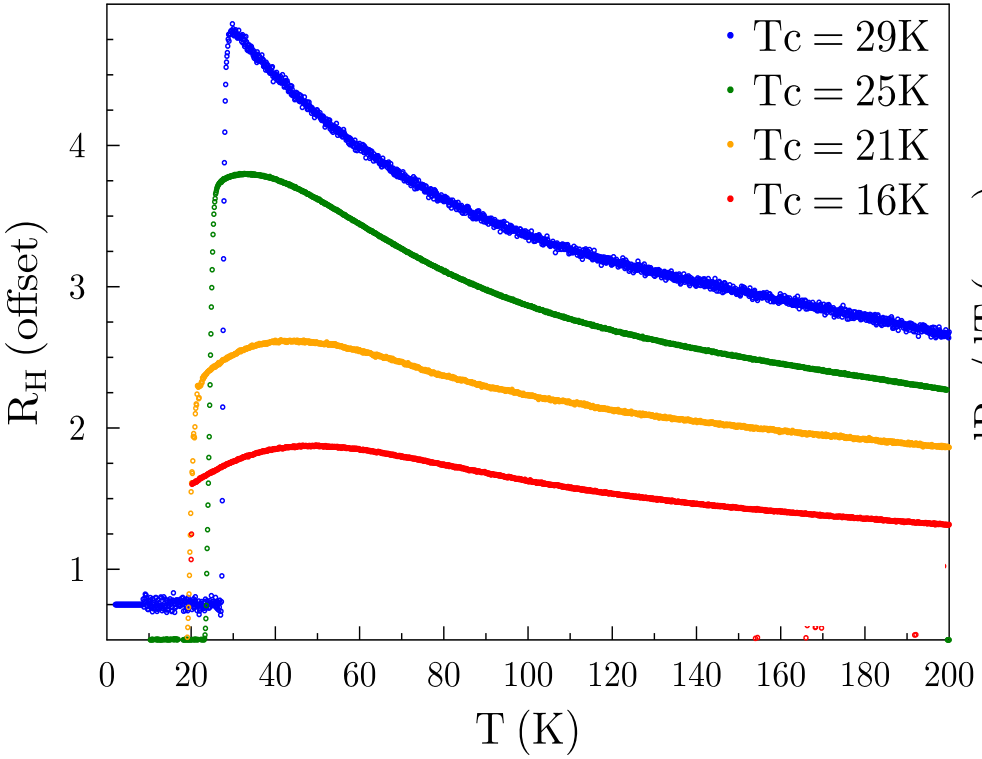
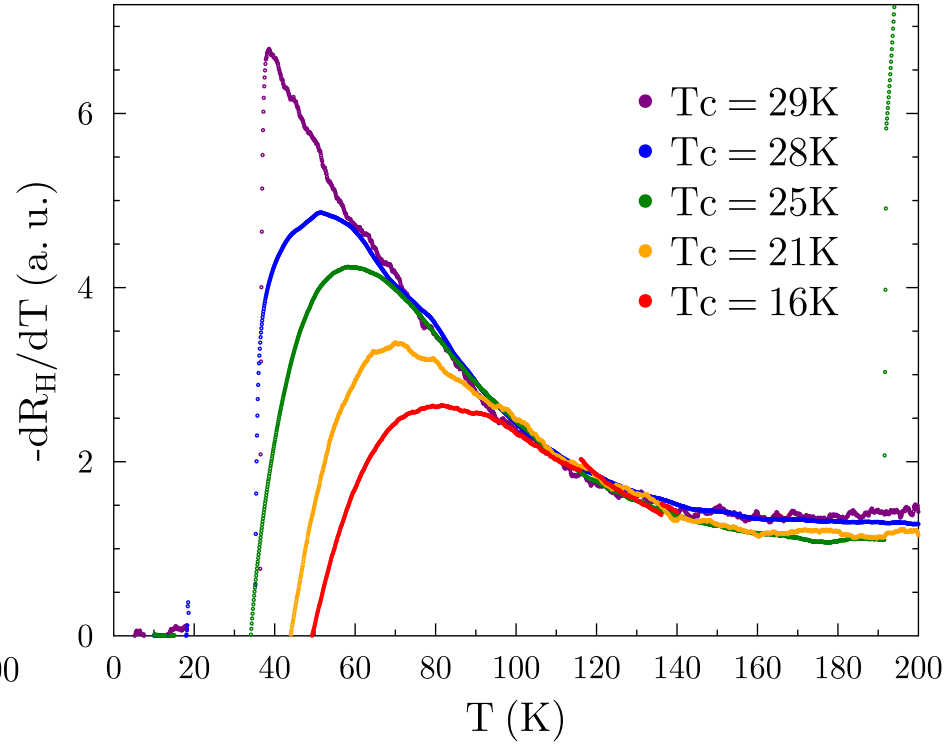
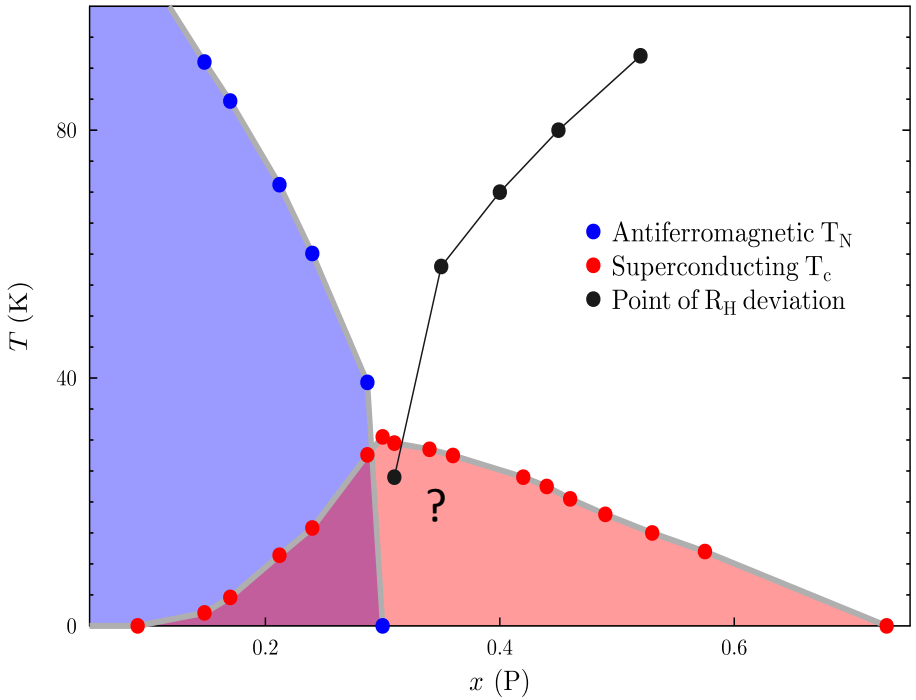
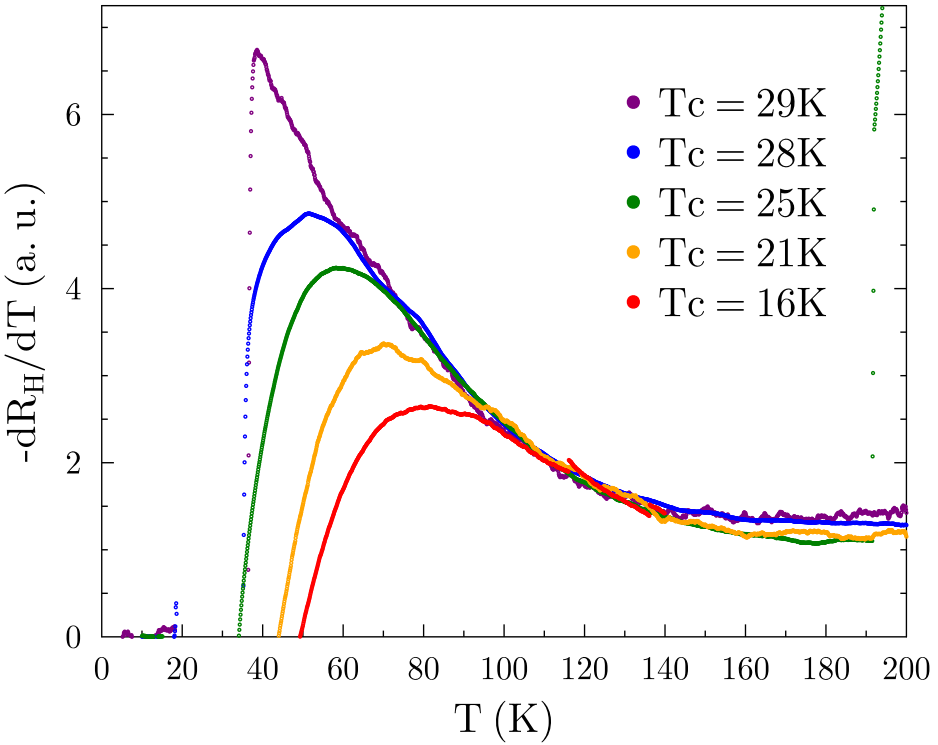




$$R_H \sim A(x) f(T)$$

R_H across the phase diagram





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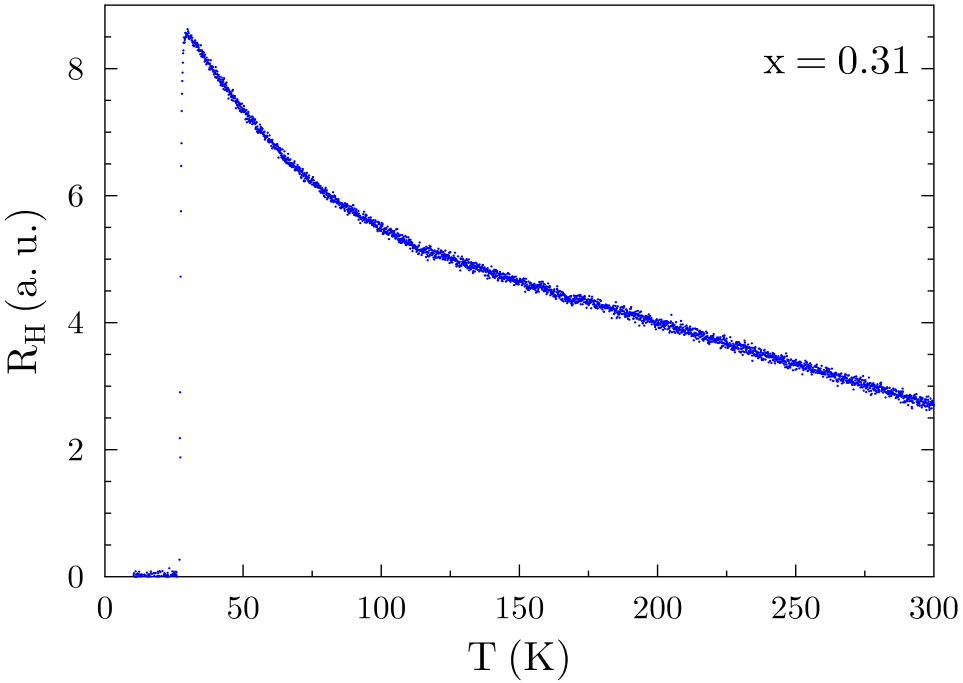
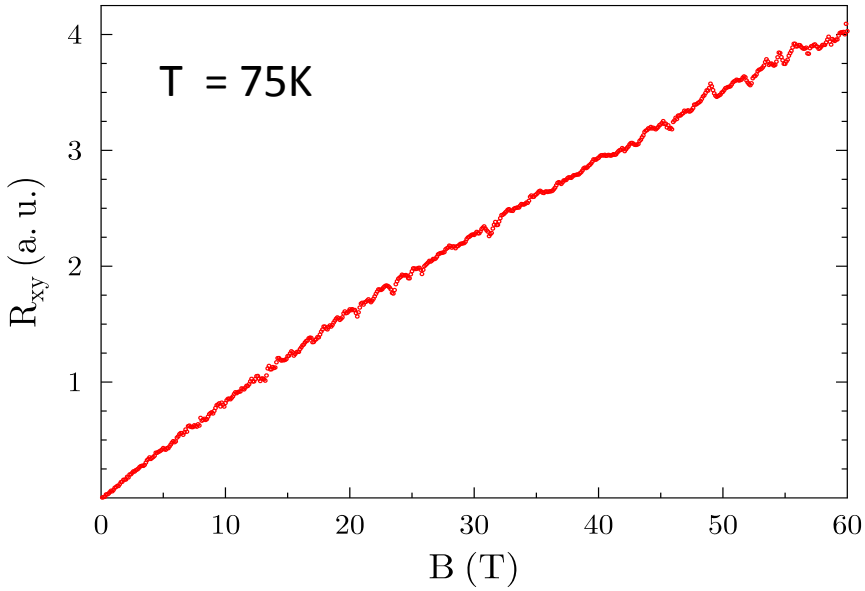
High Field Hall Effect in Ba-122





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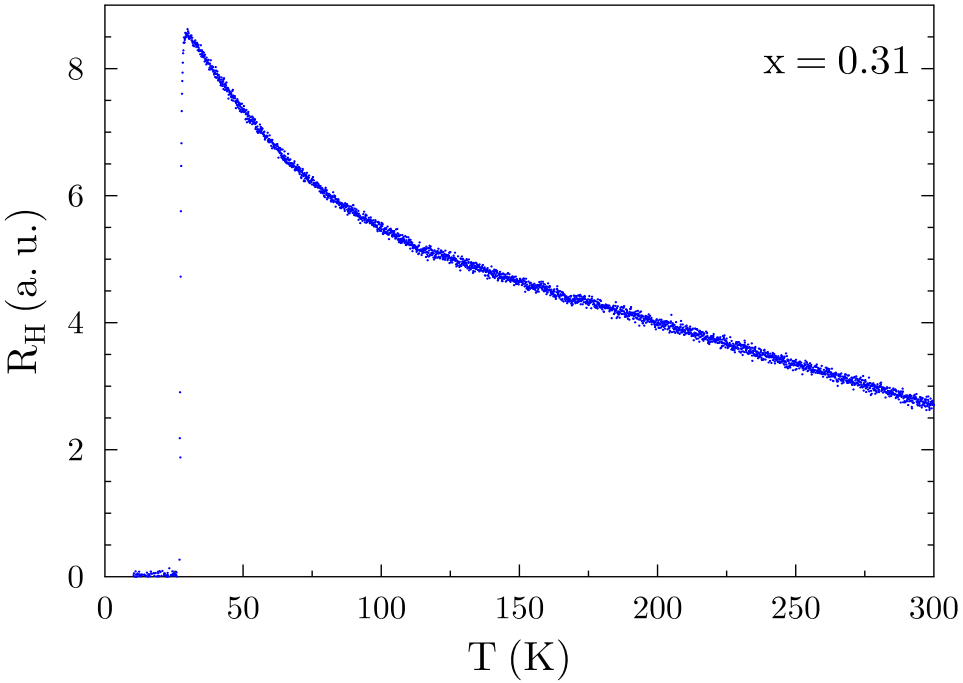

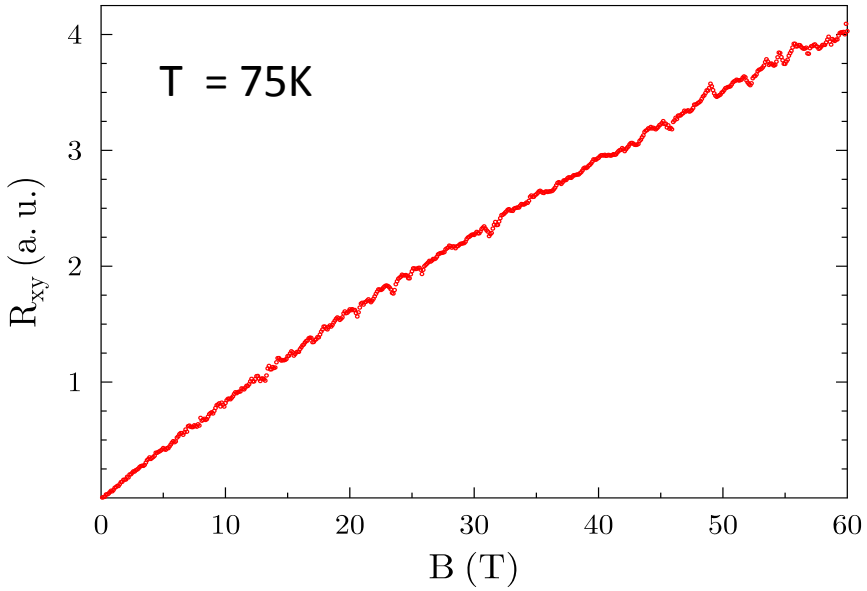

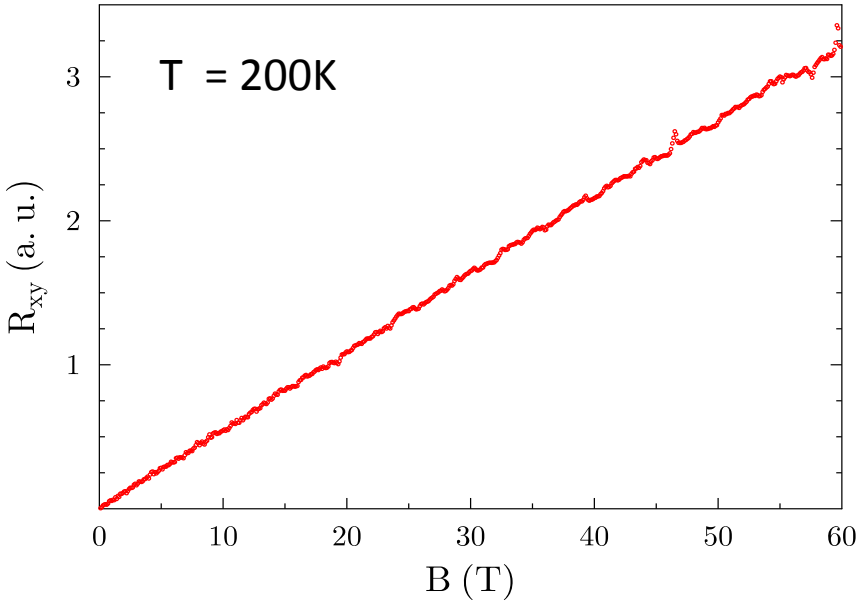

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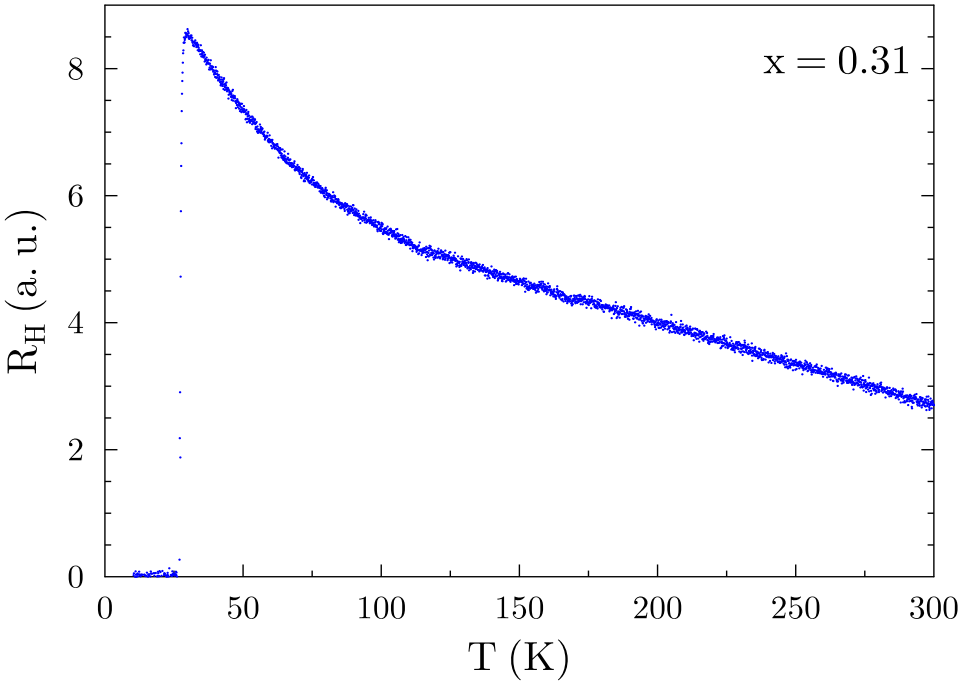

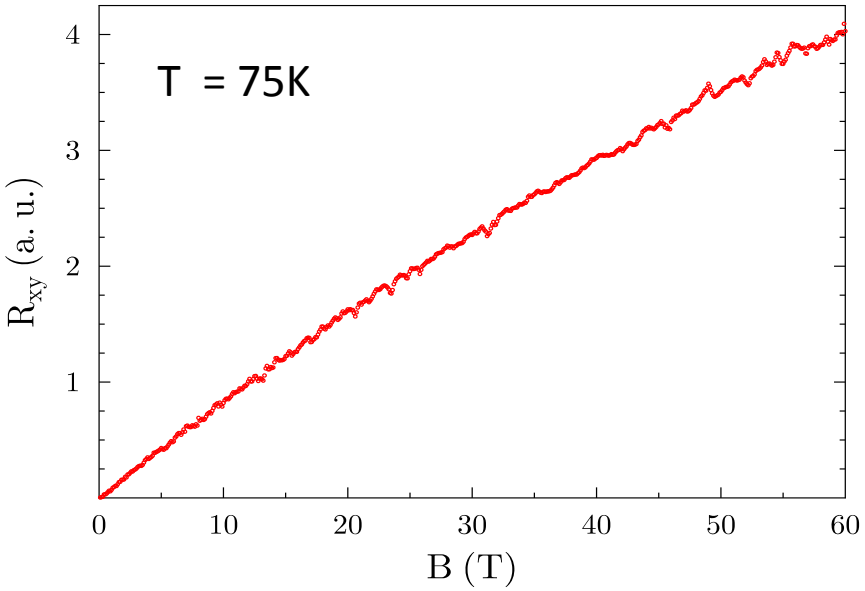

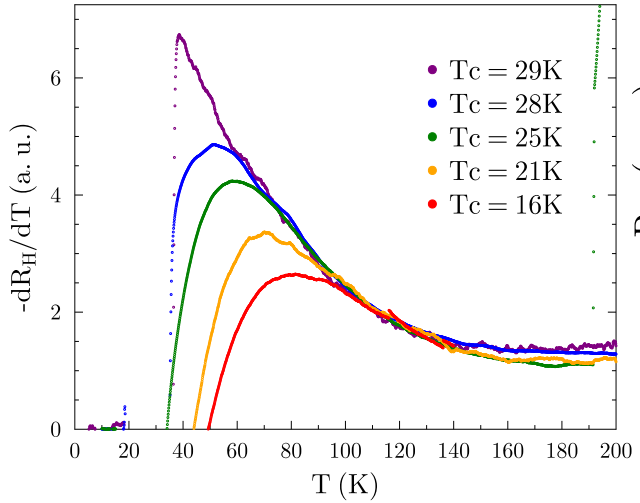

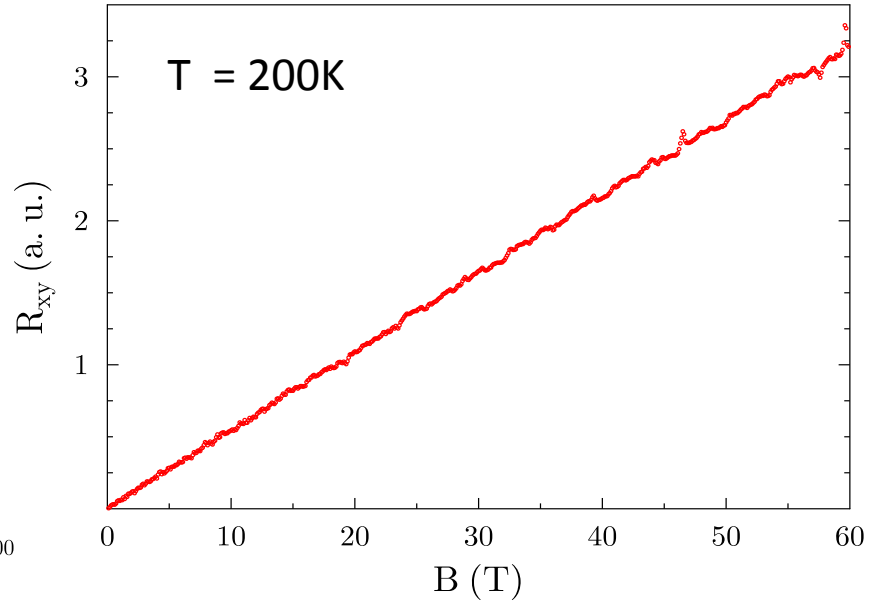

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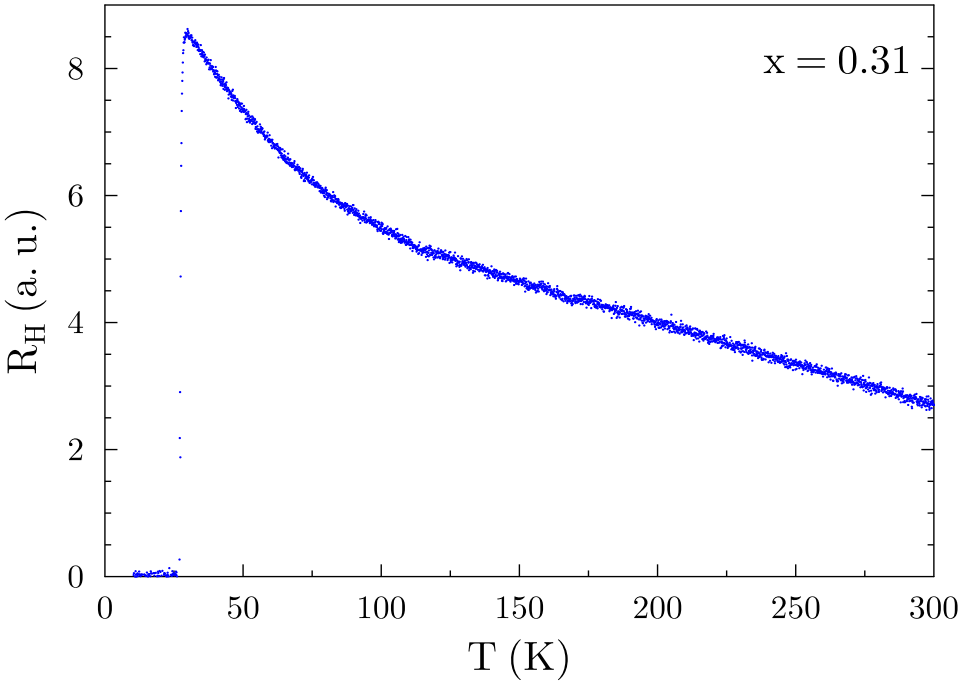

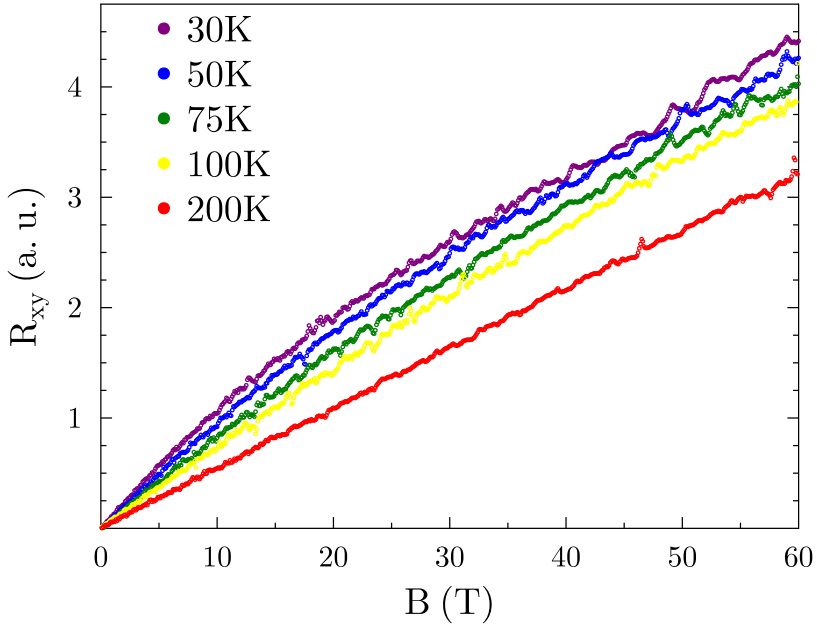

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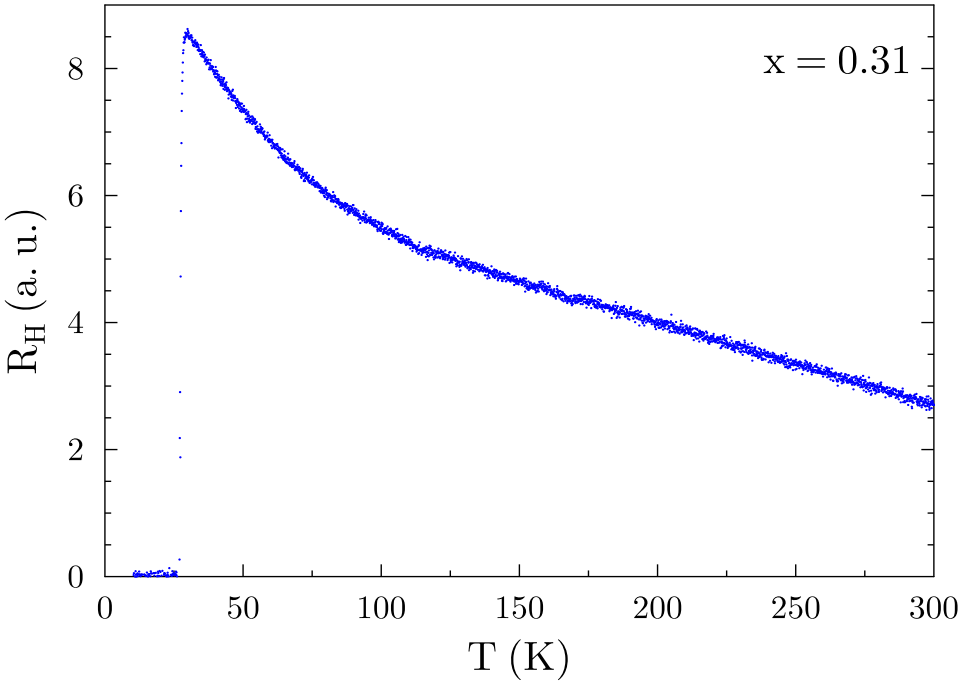
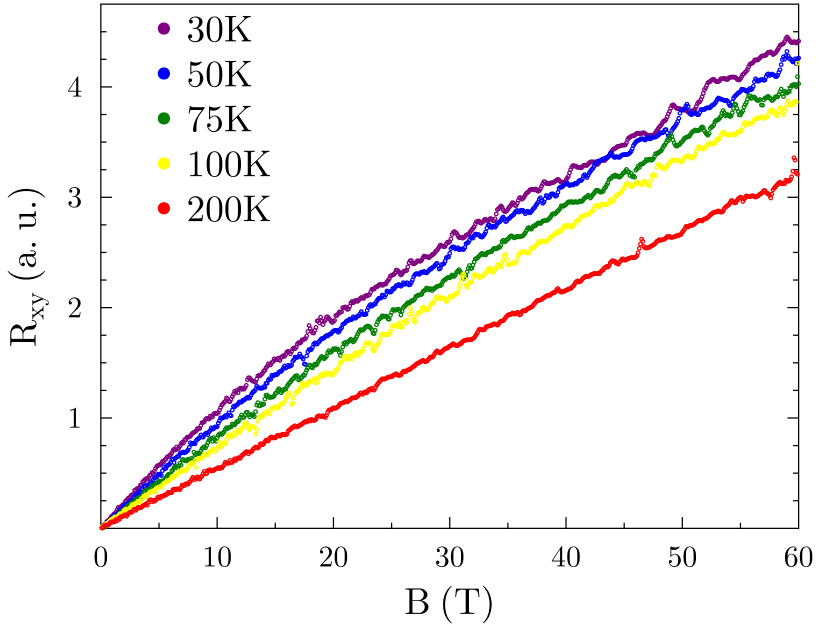
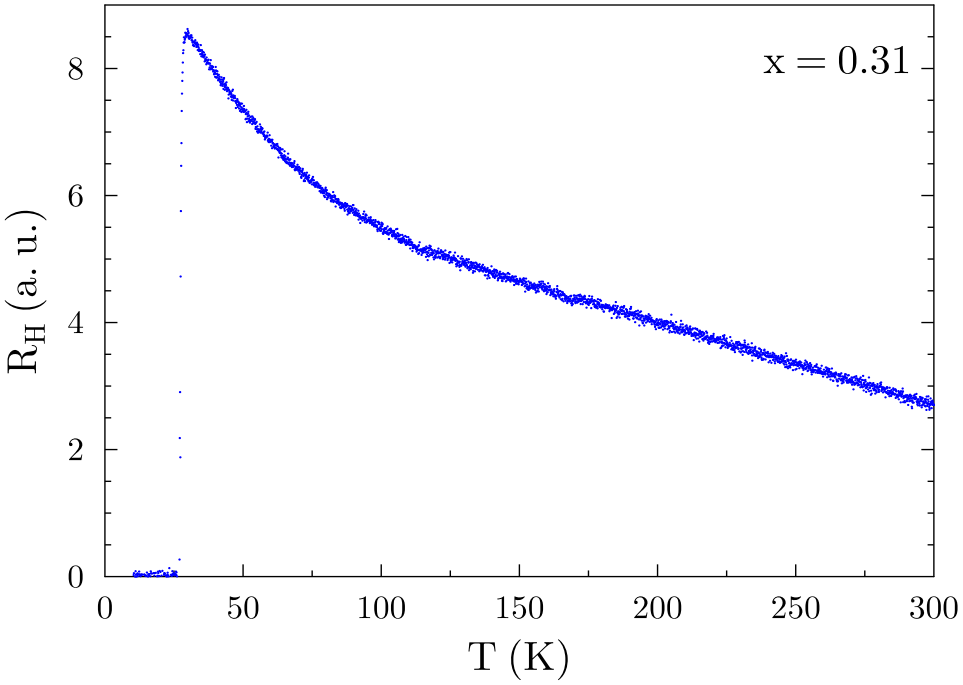
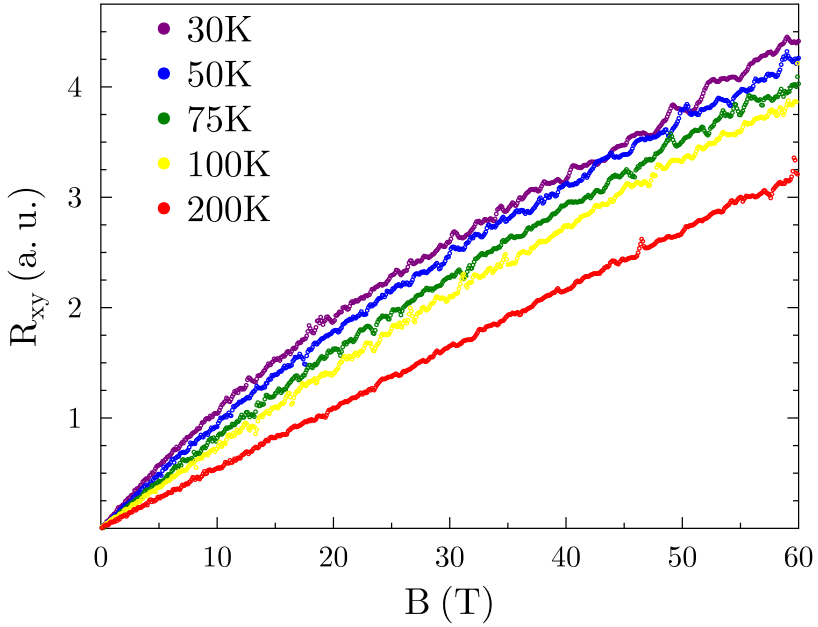




$$R_H = R_{HBackground}(T) + \frac{1}{T} f(B/T)$$

High Field Hall Effect in Ba-122

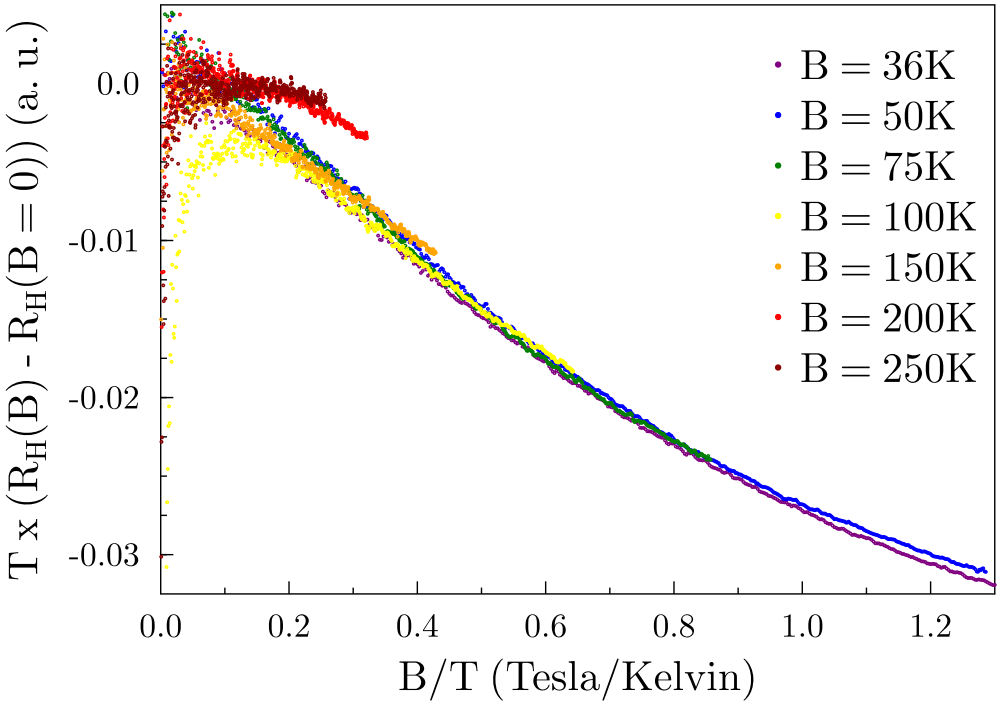


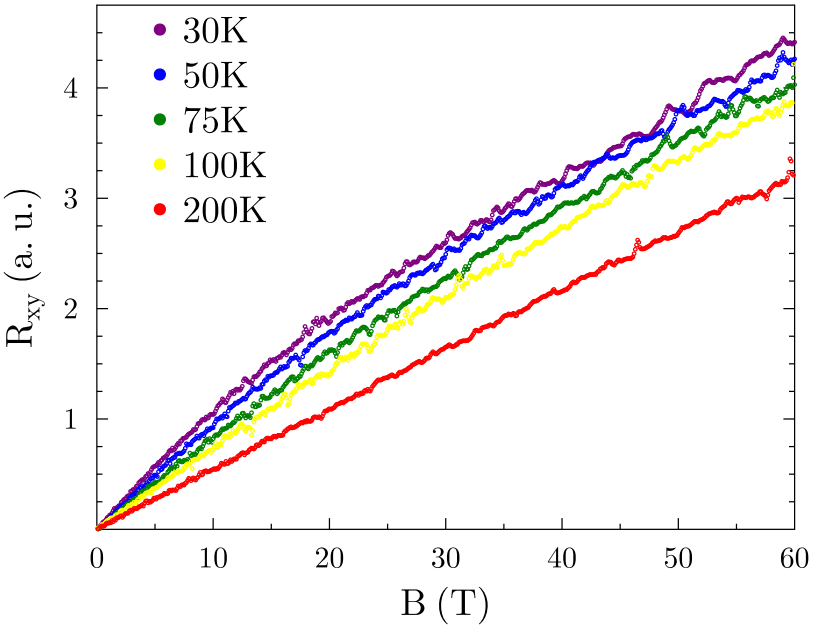


$$R_H = R_{HBackground}(T) + \frac{1}{T} f(B/T)$$

$$T(R_H - R_{HBackground}(T)) = f(B/T)$$

High Field Hall Effect in Ba-122



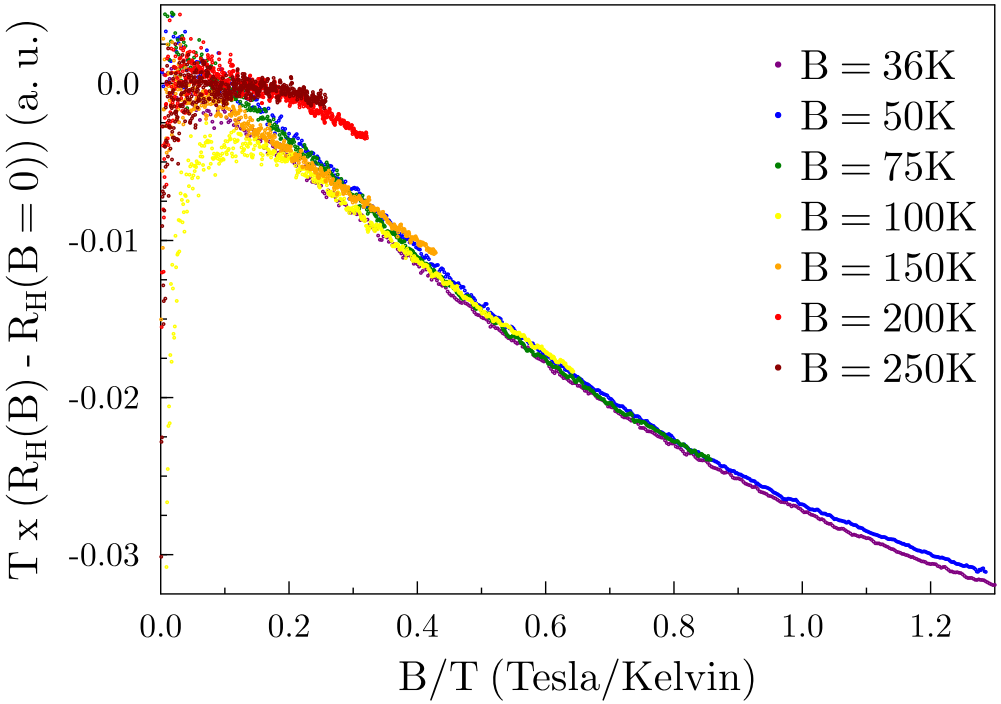


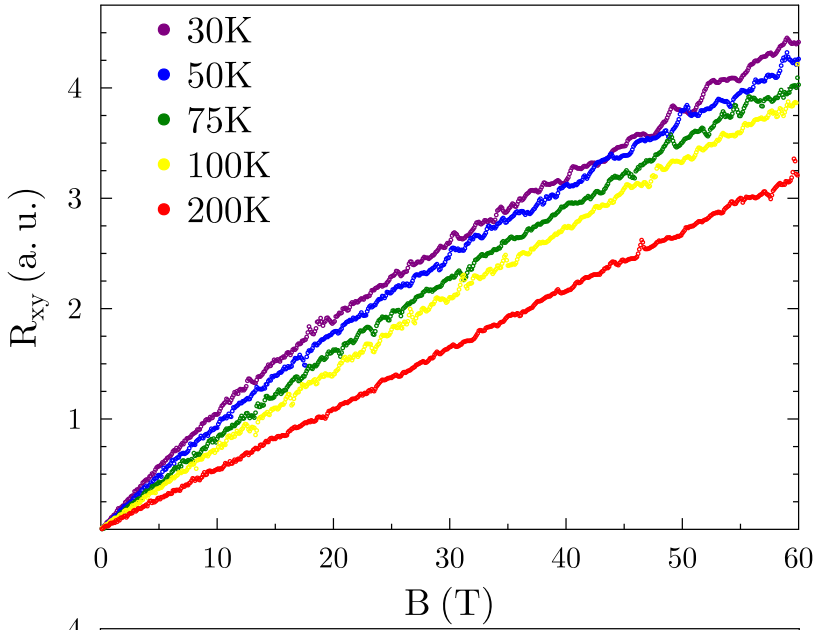
MR curves collapse for T < 150K, where the R_H upturn is pronounced.

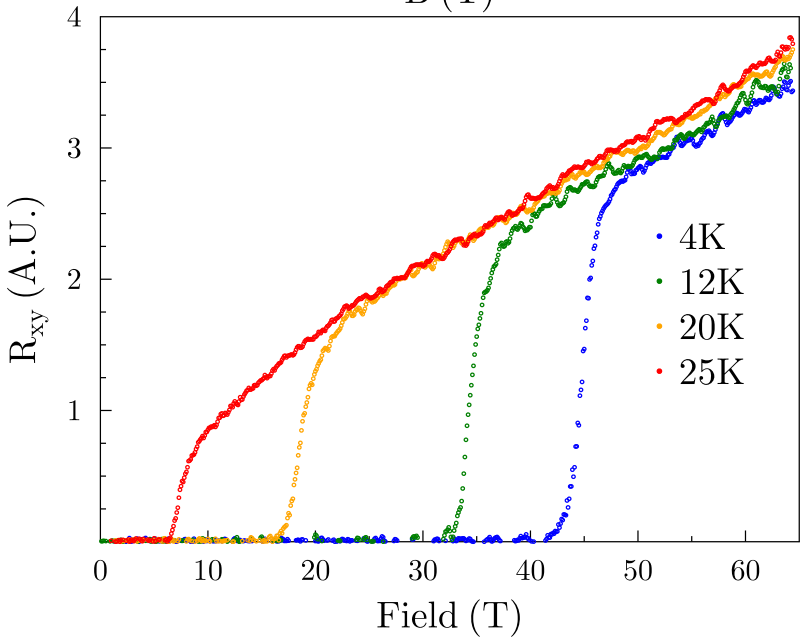
$$R_H = R_{HBackground}(T) + \frac{1}{T} f(B/T)$$

$$T(R_H - R_{HBackground}(T)) = f(B/T)$$

High Field Hall Effect in Ba-122



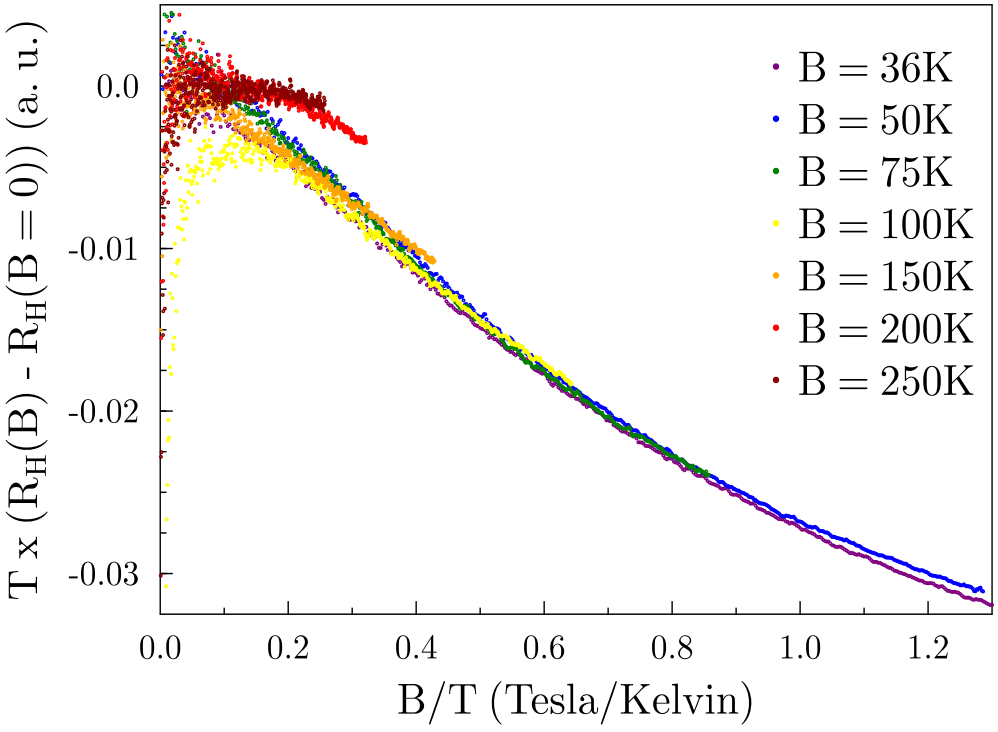


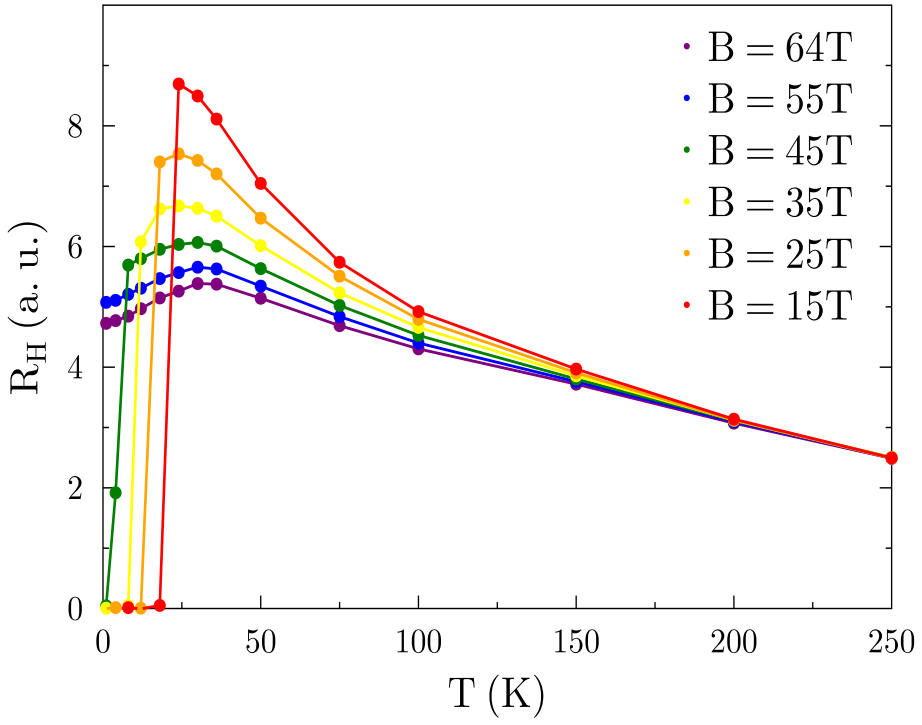


MR curves collapse for T < 150K, where the R_H upturn is pronounced.

Downturn in R_H below 30K means the data collapse only for 30K < T < 150K.

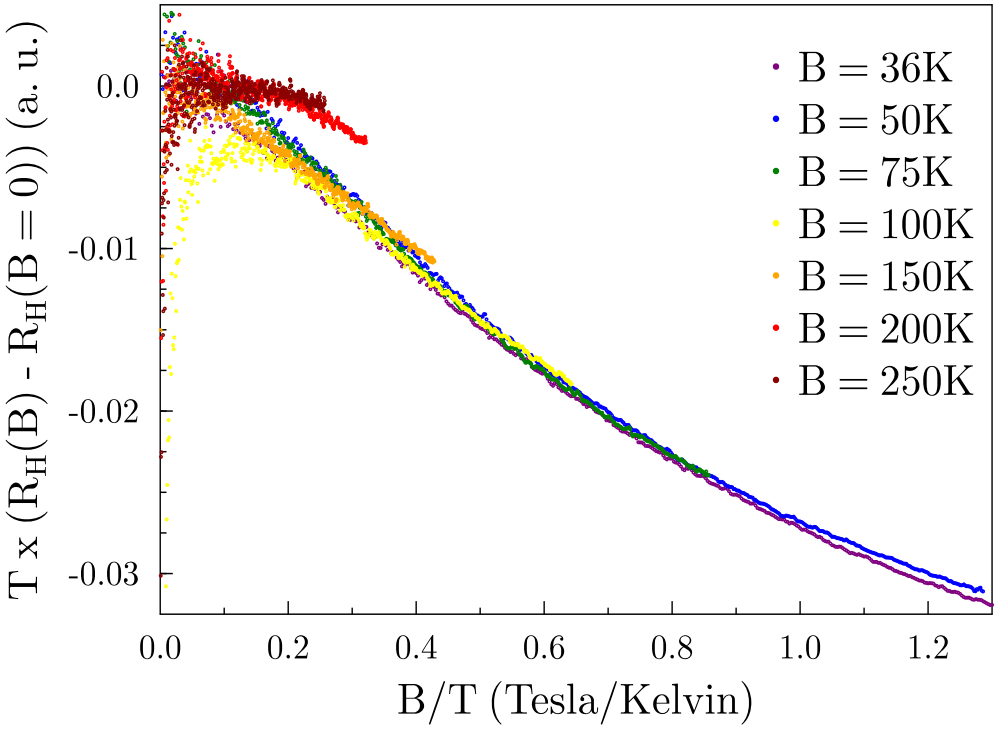
High Field Hall Effect in Ba-122

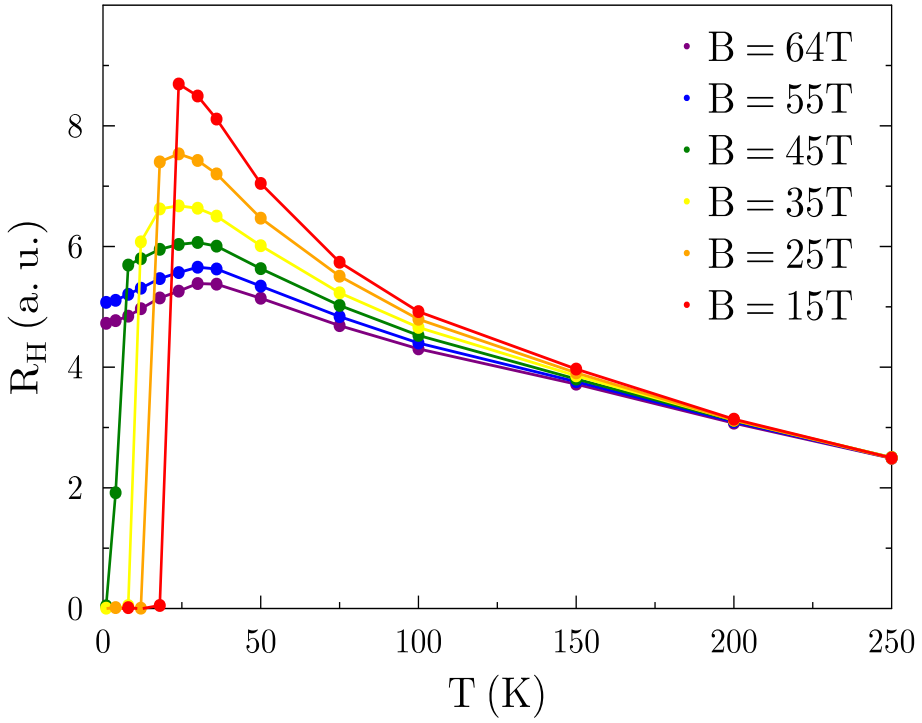




R_H versus T at high fields closely resembles R_H versus T at low fields and higher doping.

High Field Hall Effect in Ba-122





R_H versus T at high fields closely resembles R_H versus T at low fields and higher doping.

64 Tesla ~ 40K cut-off using the scale factor from the B-linear scaling

Summary and Outlook

- Rho_{xx} in Ba-122 shows scaling between B and T with both T- and B-linear resistivity, consistent with the interpretation that both tune a cut-off energy scale for charge relaxation.

- R_H shows a steep upturn at low temperatures similar to what is seen in cuprates and HF superconductors. The upturn is cut-off at successively higher temperatures as one moves away from optimal doping. R_H is reduced at high-fields as well as high temperatures

- It is a open question why field behaves as both a tuning parameter and a scaling parameter in the Hall Channel