Inverse spin Hall effect as a means to study non-linear spin fluctuation

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[5]RIKEN-CEMS, Japan

KITP conference "Concept in spintronics" Oct 4th

Applications of spin Hall effect (SHE)

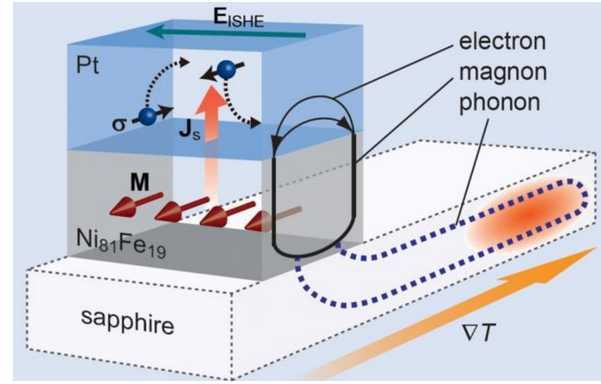
- Detection of spin Seebeck effect via ISHE

  Pt/Py/sapphire

  K. Uchida *et al.* Nature (2008); Nat. Mat

  Pt/YIG

  K. Uchid

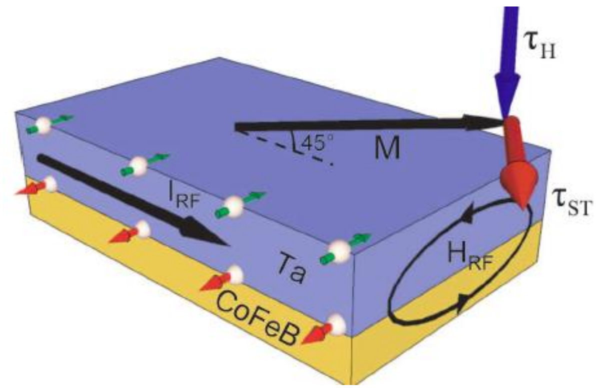


Spin currents ⇔ Charge currents

- S netization via SHE

  a/CoFeB (α_H = –15%),
  Pt/Co (α_H = 7%)

  L. Liu *et al.* Science (2012); Phys. Rev. Lett. (2012).



The other application of SHE has not been demonstrated yet.

- Detection of non-linear spin fluctuation via ISHE

Outline

- Introduction
  - *spin Hall effect (SHE) and anomalous Hall effect (AHE)*
  - *AHE of pure Ni and Fe*
  - *Kondo's model for AHE*
- SHE in NiPd alloys
  - *experimental setup (spin absorption technique)*
  - *anomaly near Curie temperature T_C*
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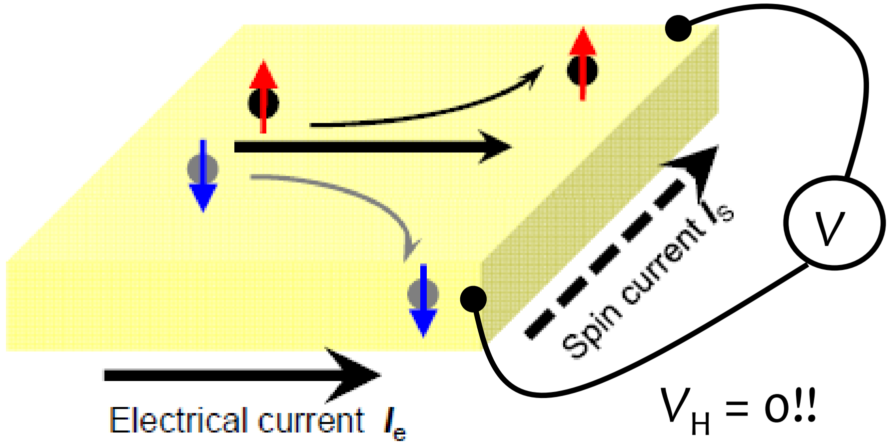
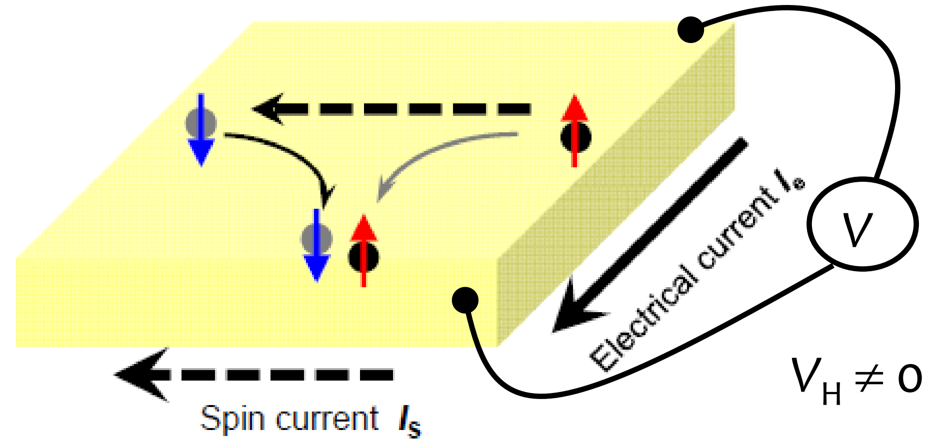
  - *extended Kondo's model*
- Summary

Direct & Inverse Spin Hall effect

Spin-orbit interaction



Direct spin Hall effect (DSHE)

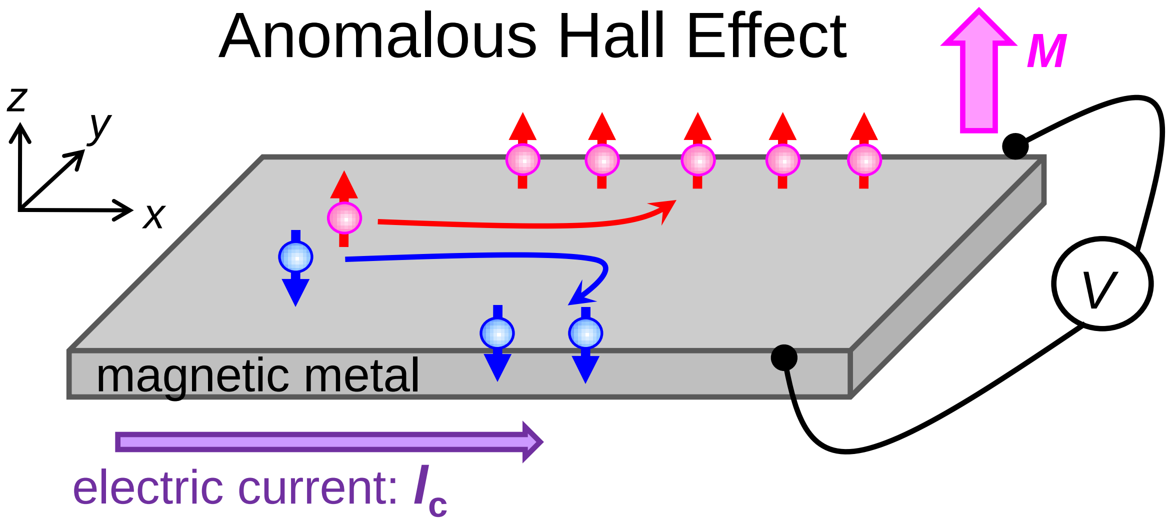


Inverse spin Hall effect (ISHE)

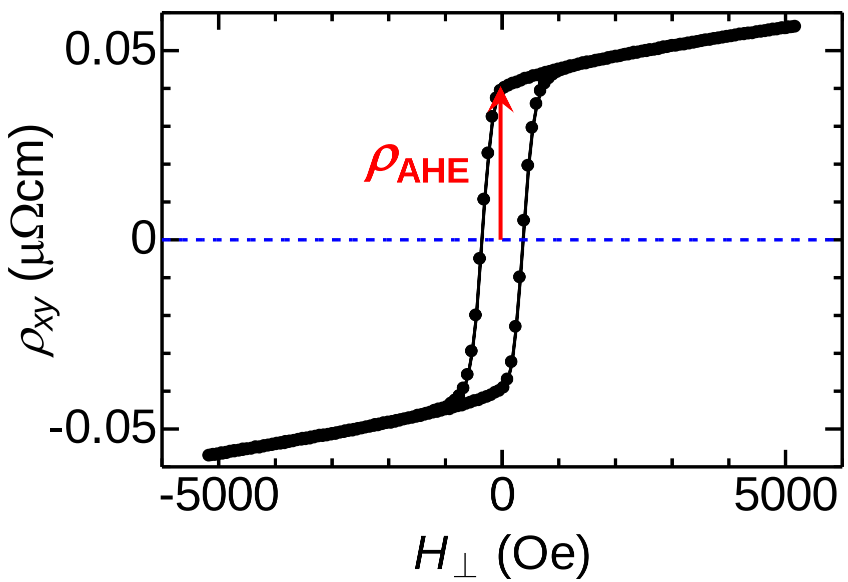
Un-polarized charge current ⇔ Transverse spin current

Y. K. Kato *et al.* Science **306**, 1910 (2004).
J. Wunderlich *et al.* Phys. Rev. Lett**. 94**, 047204 (2005)

Anomalous Hall effect (AHE)



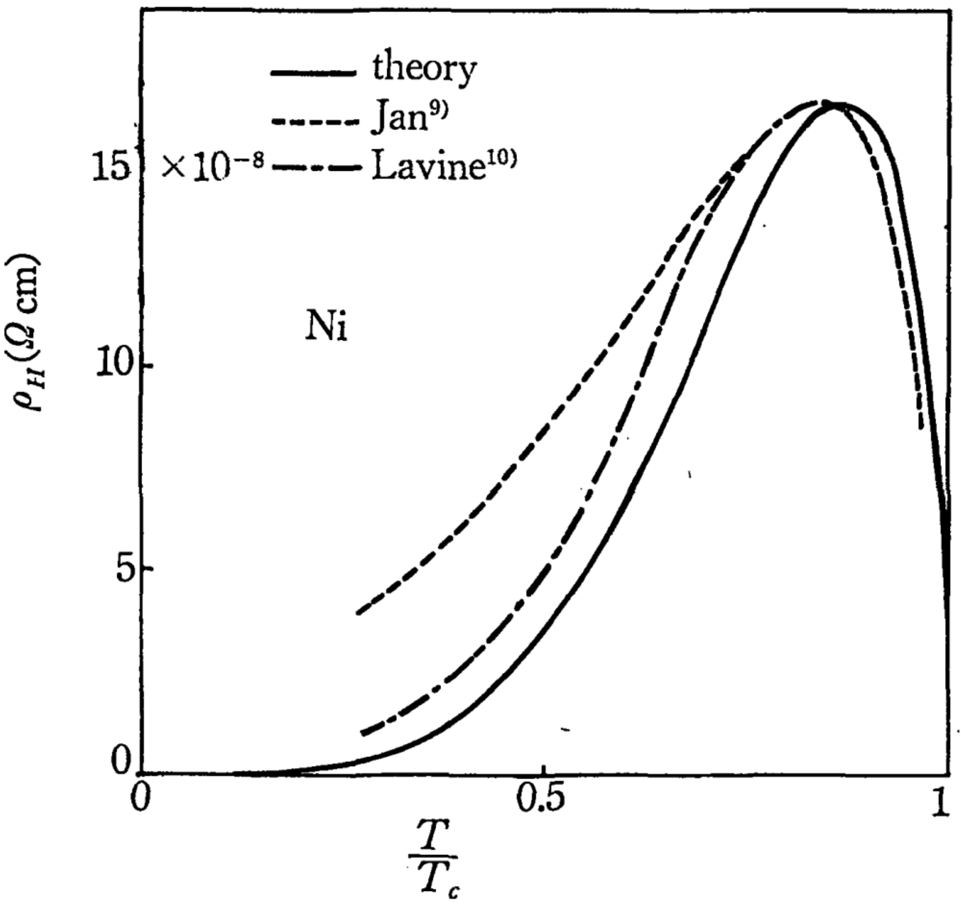
$V_H \neq 0$

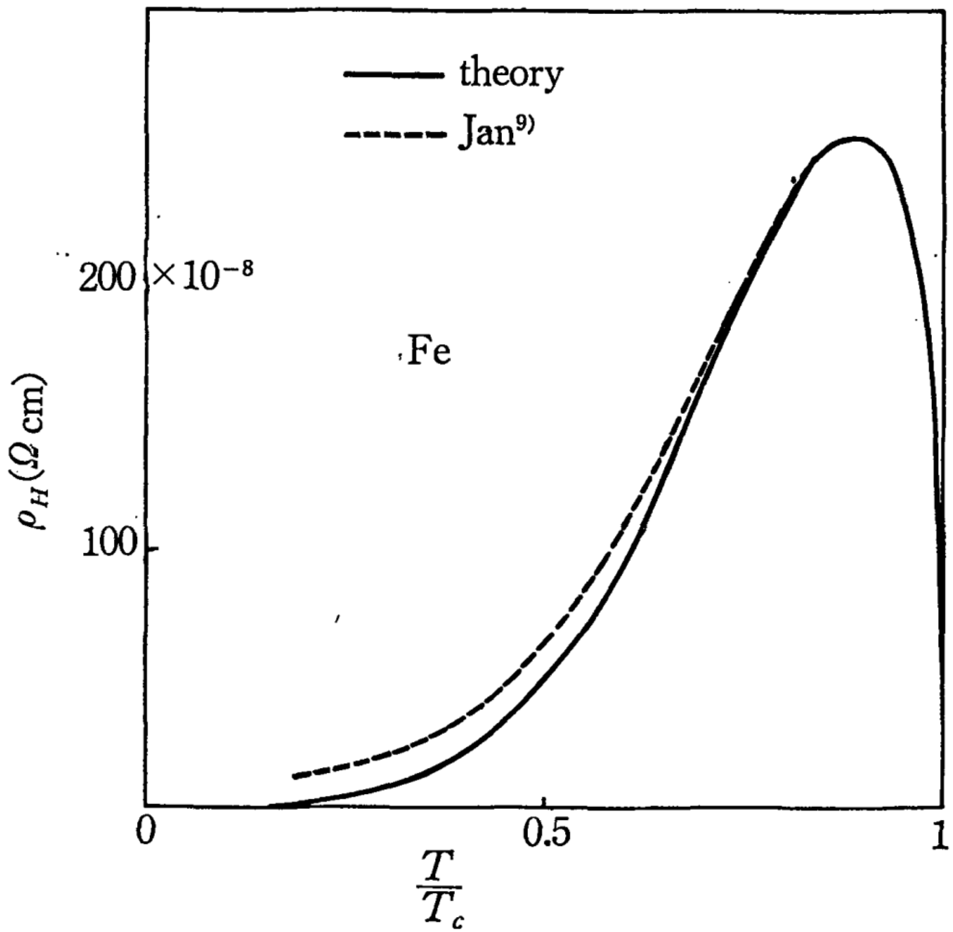


- What is an essential difference between SHE and AHE?

AHE of pure Ni & Fe

intrinsic AHE for pure ferromagnetic metals





J. P. Jan, Helv. Phys. Acta **25**, 677 (1952).
J. M. Lavine, Phys. Rev. **123**, 1273 (1961).

J. P. Jan, Helv. Phys. Acta **25**, 677 (1952).

To explain the peak in ρ_{xy} below T_C...

- Karplus & Luttinger's theory

$$\rho_{xy} \propto \rho_{xx}^2 \langle \boldsymbol{m} \rangle$$

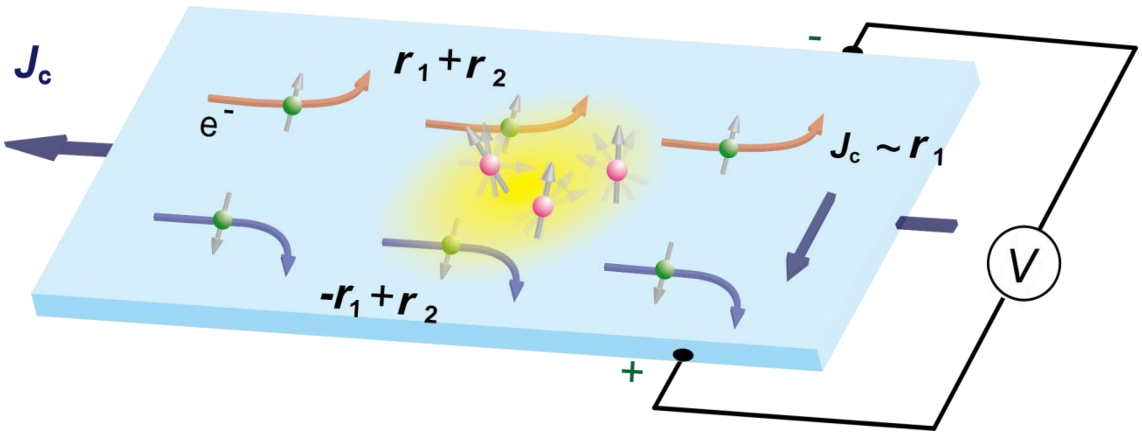
R. Karplus & J. M. Luttinger, Phys. Rev. **95**, 1154 (1954).

- Kondo's theory

$$\rho_{xy} \propto \left\langle \left(\boldsymbol{m} - \langle \boldsymbol{m} \rangle \right)^3 \right\rangle$$

J. Kondo, Prog. Theor. Phys. **27**, 772 (1962).

Interaction between conduction electron and localized moment

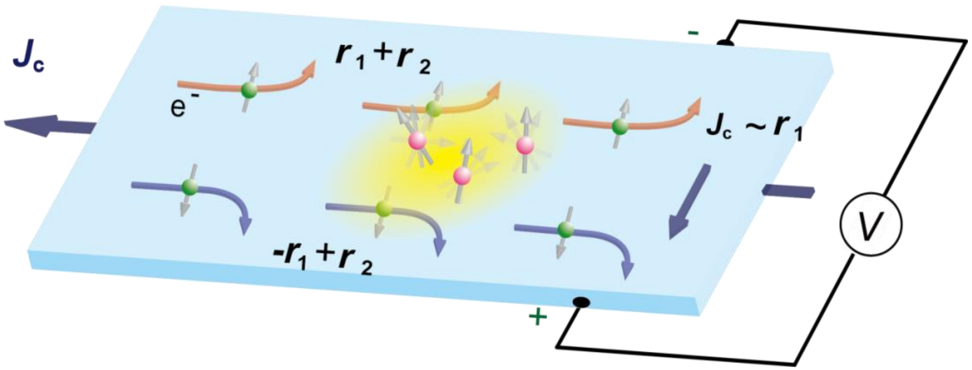


r_1 : $\langle (\boldsymbol{m} - \langle \boldsymbol{m} \rangle)^3 \rangle$

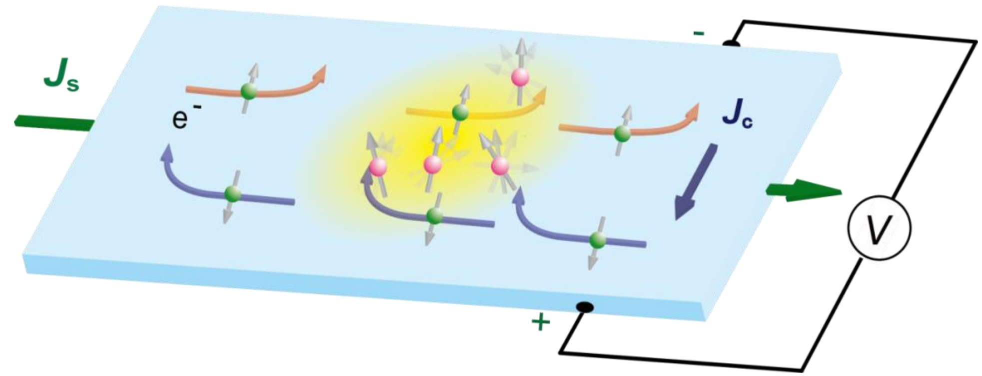
r_2 : $2C_2 \langle (\boldsymbol{m} - \langle \boldsymbol{m} \rangle)^2 (\boldsymbol{m}^2 - \langle \boldsymbol{m}^2 \rangle) \rangle$

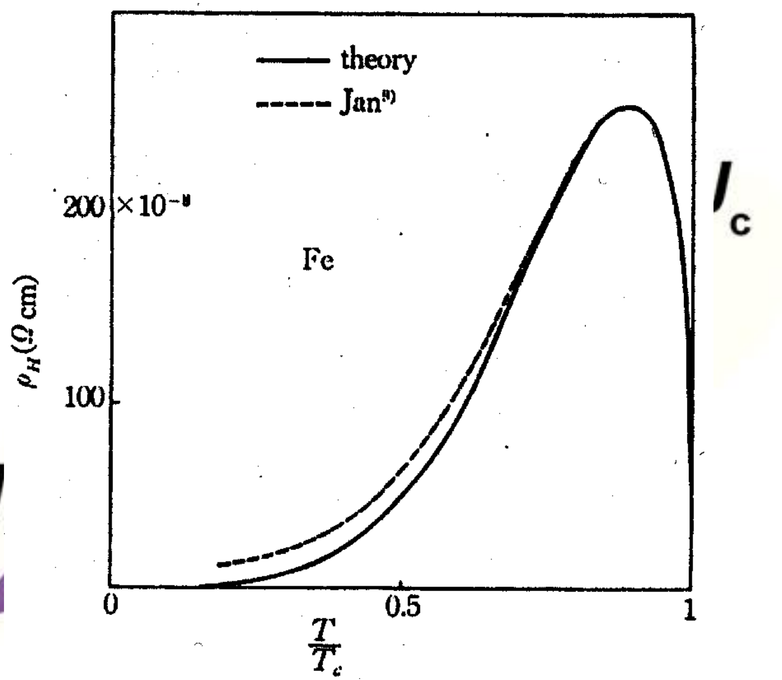
Kondo's work for ISHE?

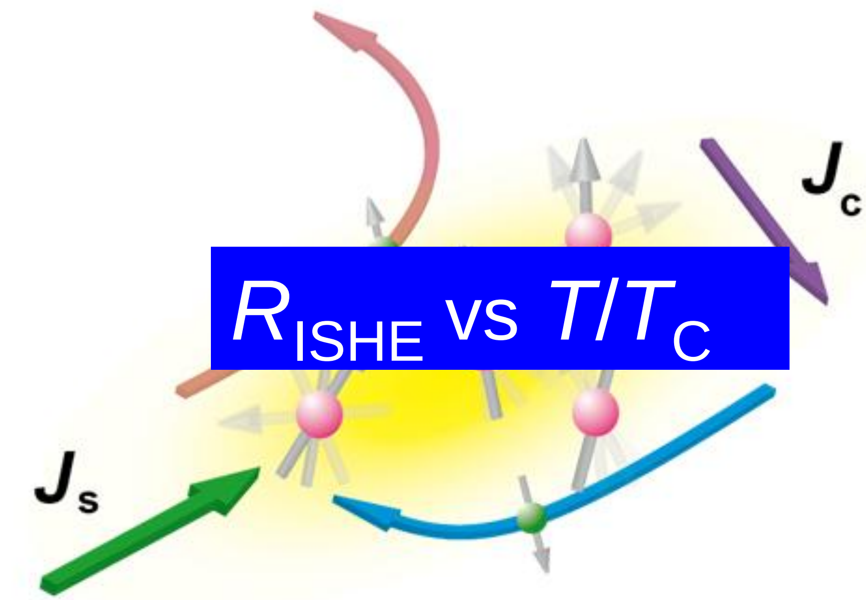
AHE



ISHE







R_{ISHE} vs T/T_C

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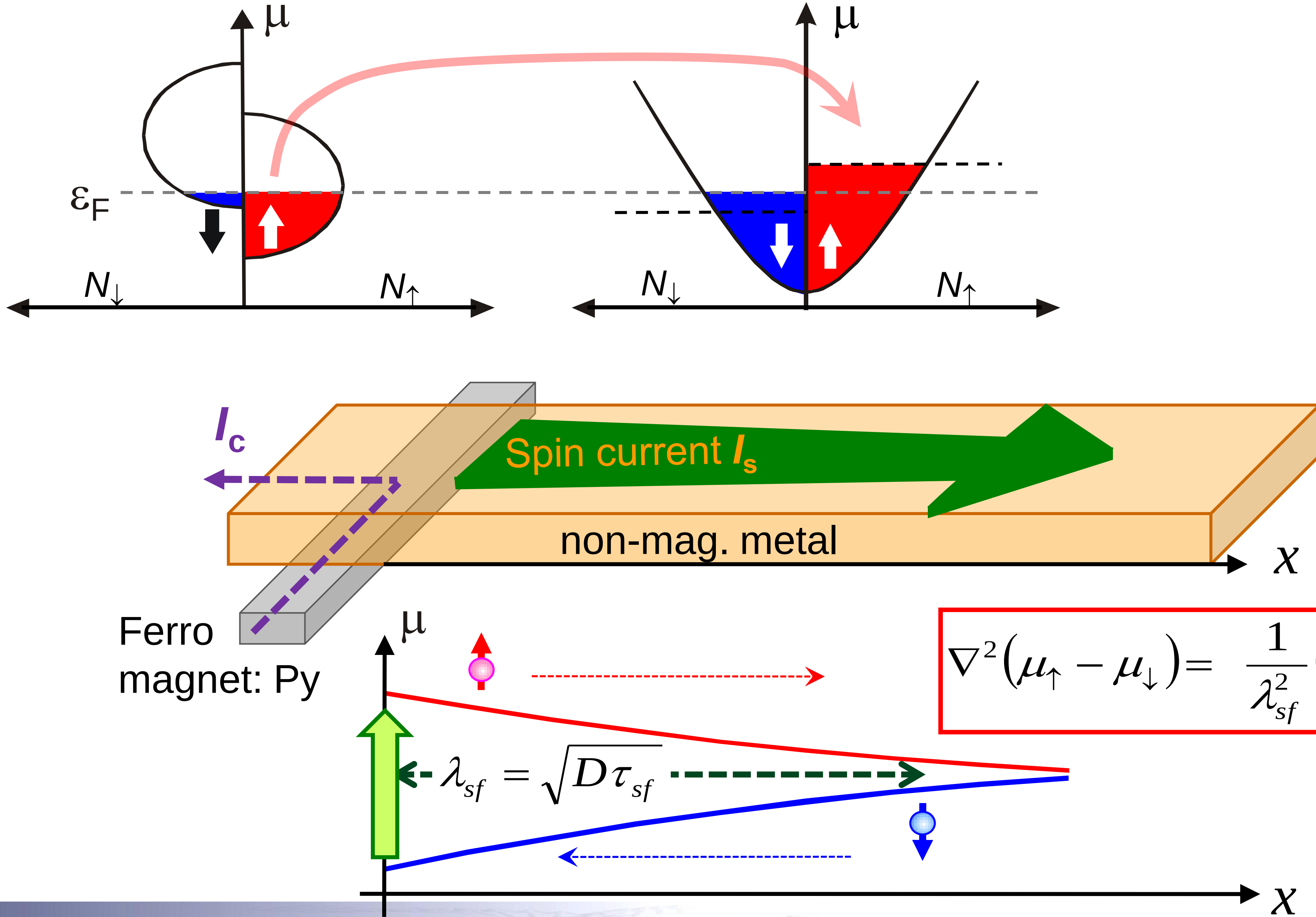
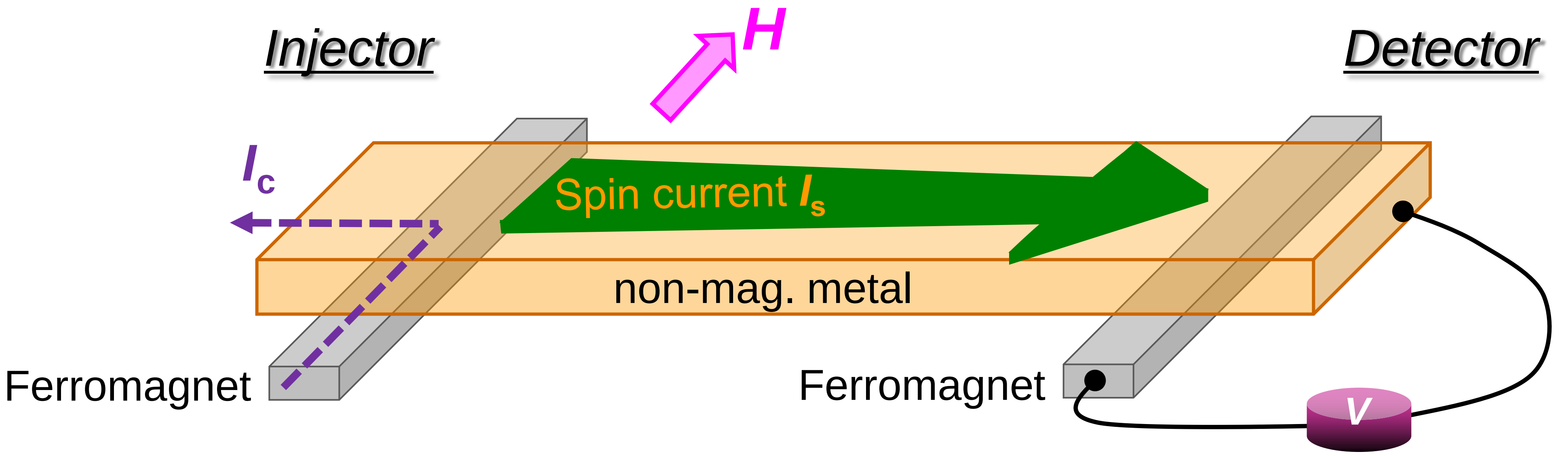
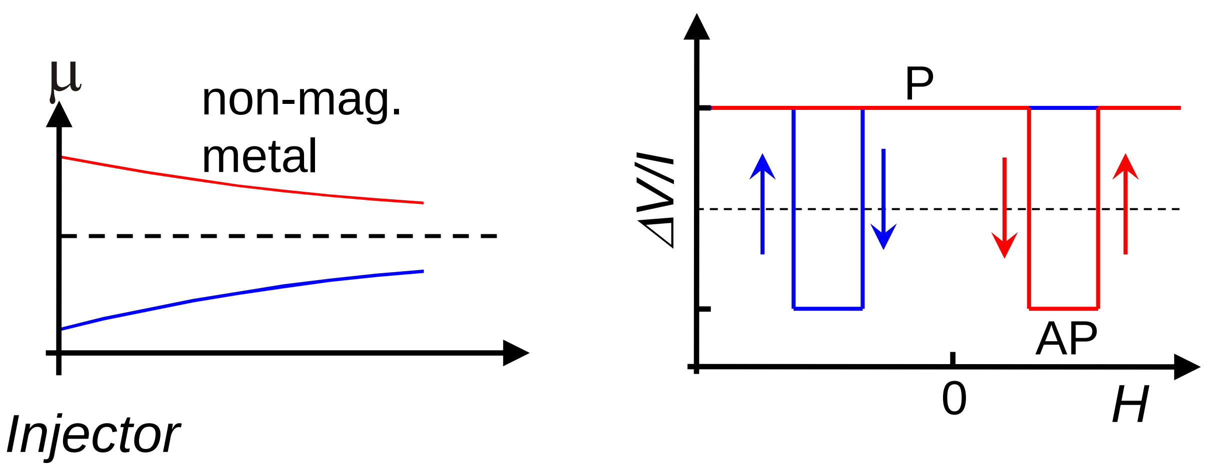
Non-local spin injection

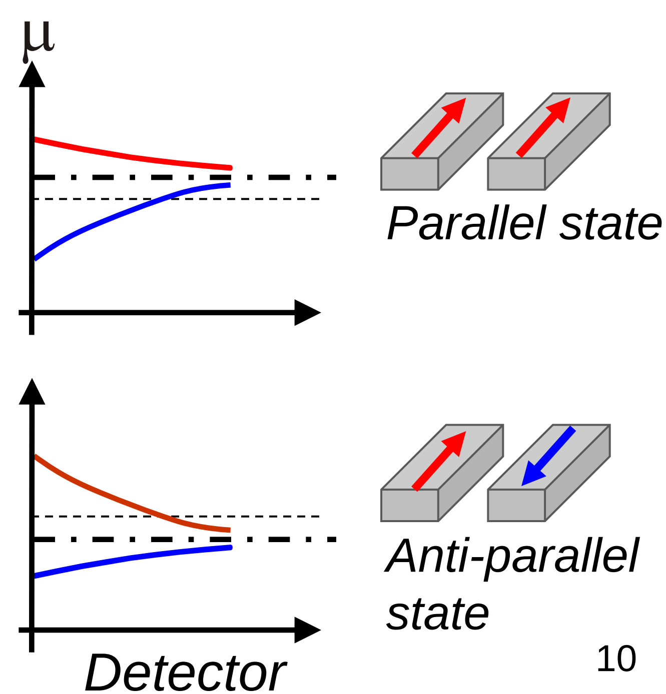


$$\nabla^2(\mu_\uparrow - \mu_\downarrow) = \frac{1}{\lambda_{sf}^2}(\mu_\uparrow - \mu_\downarrow)$$

Electrical detection of non-local spin signal



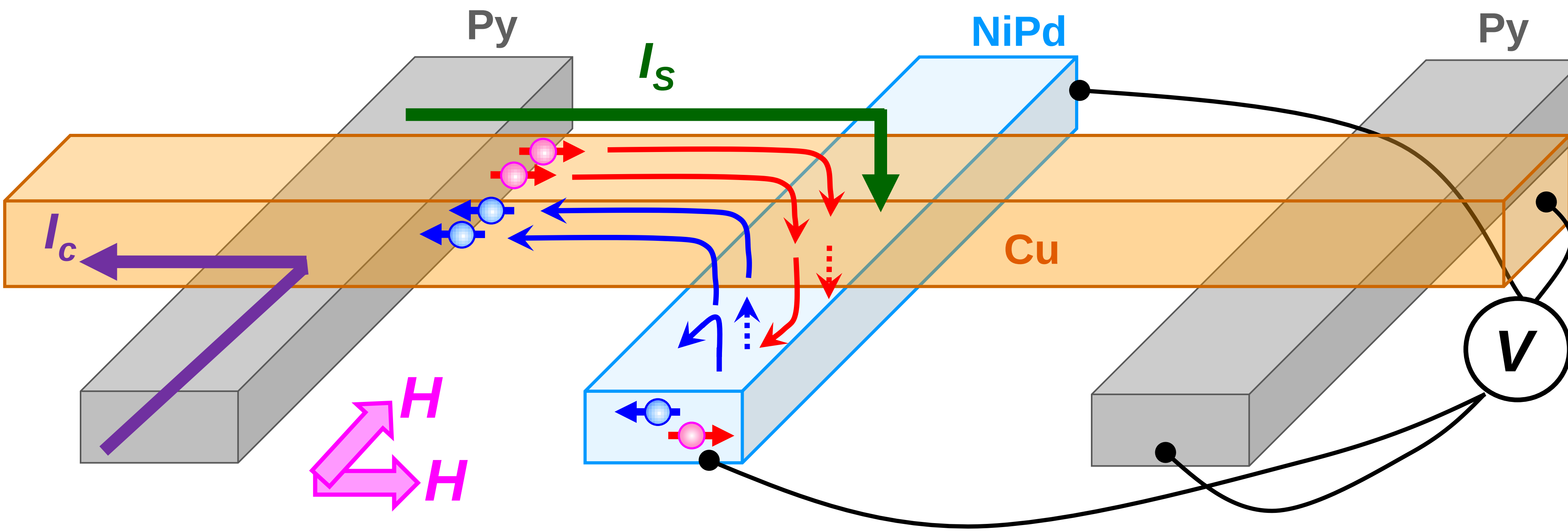




Spin absorption method

Spin absorption technique & ISHE

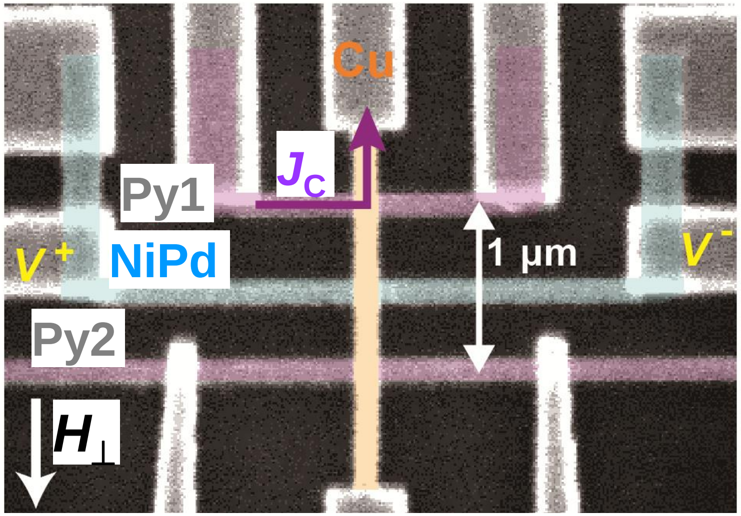
Y. Niimi *et al.*, Phys. Rev. Lett. **106**, 126601 (2011).



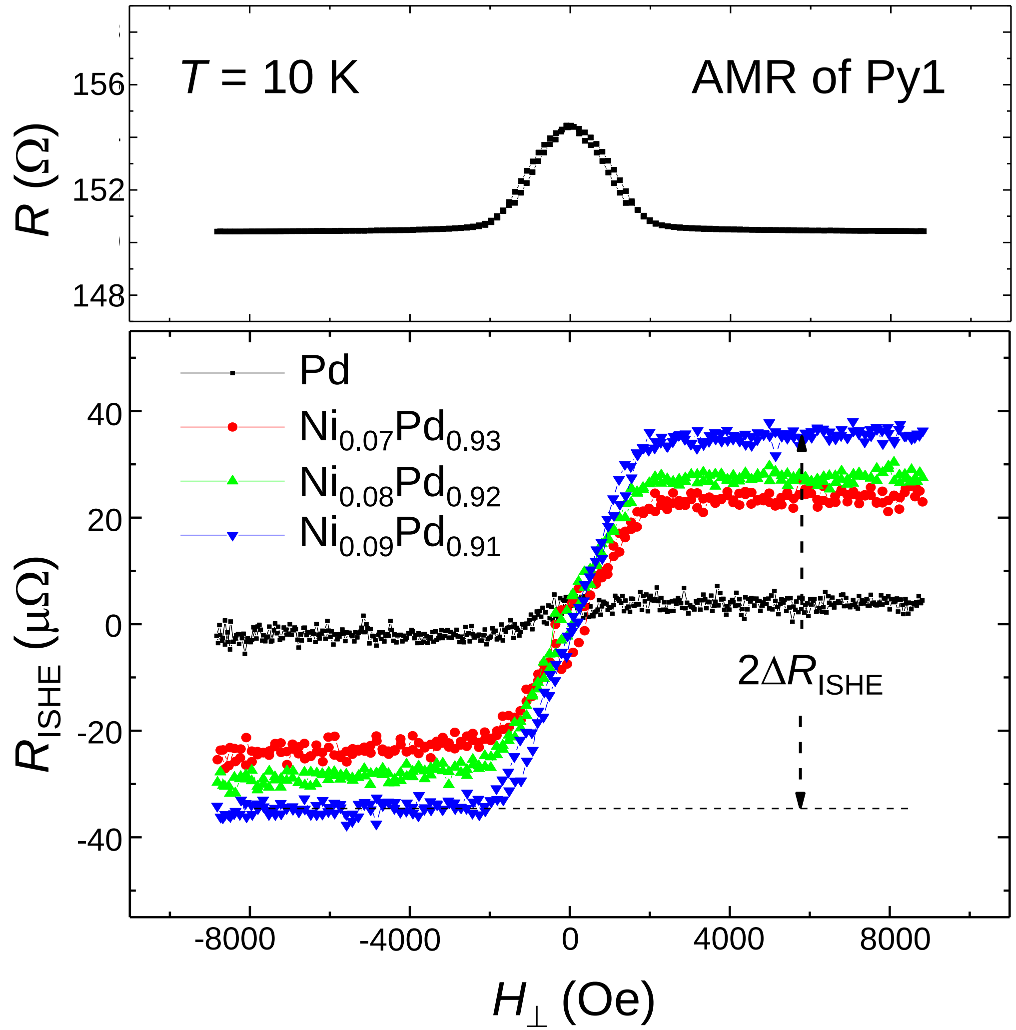
Spin current I_S into NiPd can be experimentally determined by measuring NLSV.

ISHE for Ni_xPd_{1-x} alloys

Ni_xPd_{1-x}: weakly ferromagnetic alloy

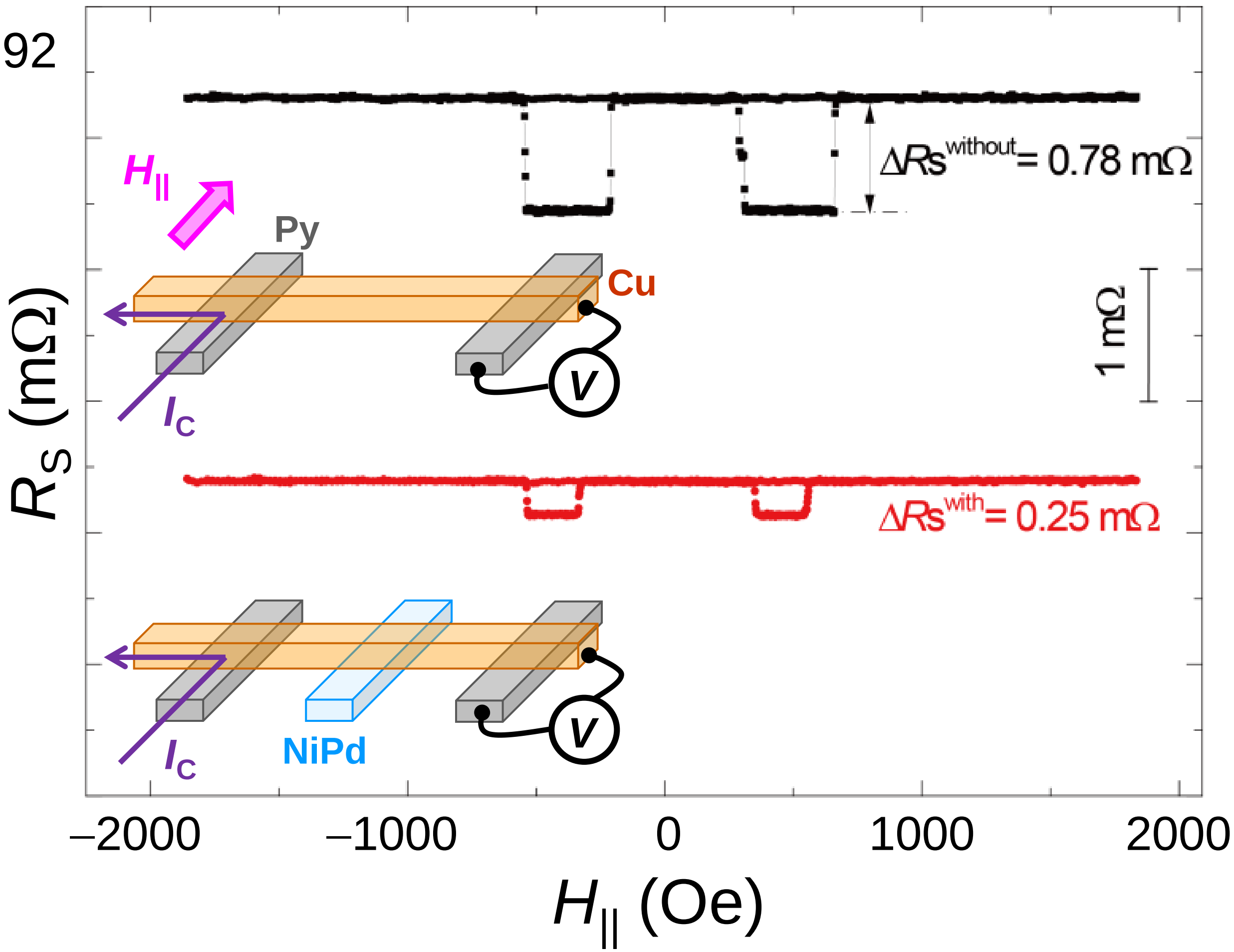


size: w = 100 nm, t = 20 nm



Spin absorption into NiPd alloy

$Ni_{0.08}Pd_{0.92}$



$$\eta \equiv \frac{\Delta R_S^{with}}{\Delta R_S^{without}} = 0.32$$

$$\lambda_{Ni_{0.08}Pd_{0.92}} = 10 \text{ nm}$$

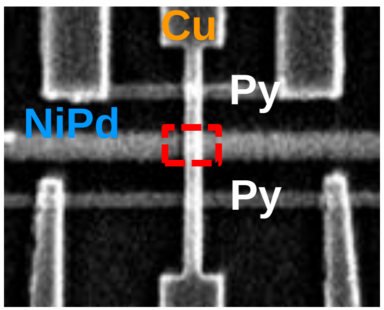
$$\eta \equiv \frac{\Delta R_S^{with}}{\Delta R_S^{without}} \approx \frac{2\frac{R_{NiPd}}{R_{Cu}}\sinh(L/\lambda_{Cu})}{\tanh(t_{NiPd}/\lambda_{NiPd})\{\cosh(L/\lambda_{Cu})-1\}+2\frac{R_{NiPd}}{R_{Cu}}\sinh(L/\lambda_{Cu})}$$

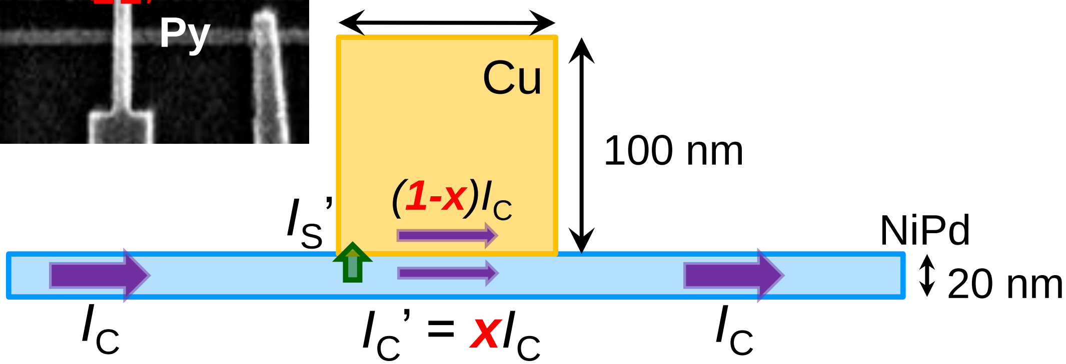
S. Takahashi and S. Maekawa, PRB **67**, 052409 (2003).

Spin Hall resistivity as a function of ρ_{imp}

$$\rho_{SHE} = \frac{w_{NiPd}}{x} \frac{I_C}{\bar{I}_S} \Delta R_{SHE}$$

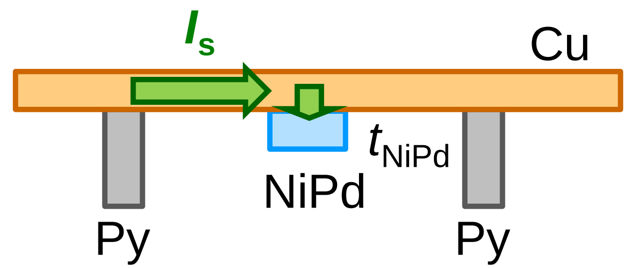
Correction factor for shunting by Cu bridge





x **= 0.36**$\pm$0.08 which is not so sensitive to ρ_{NiPd}

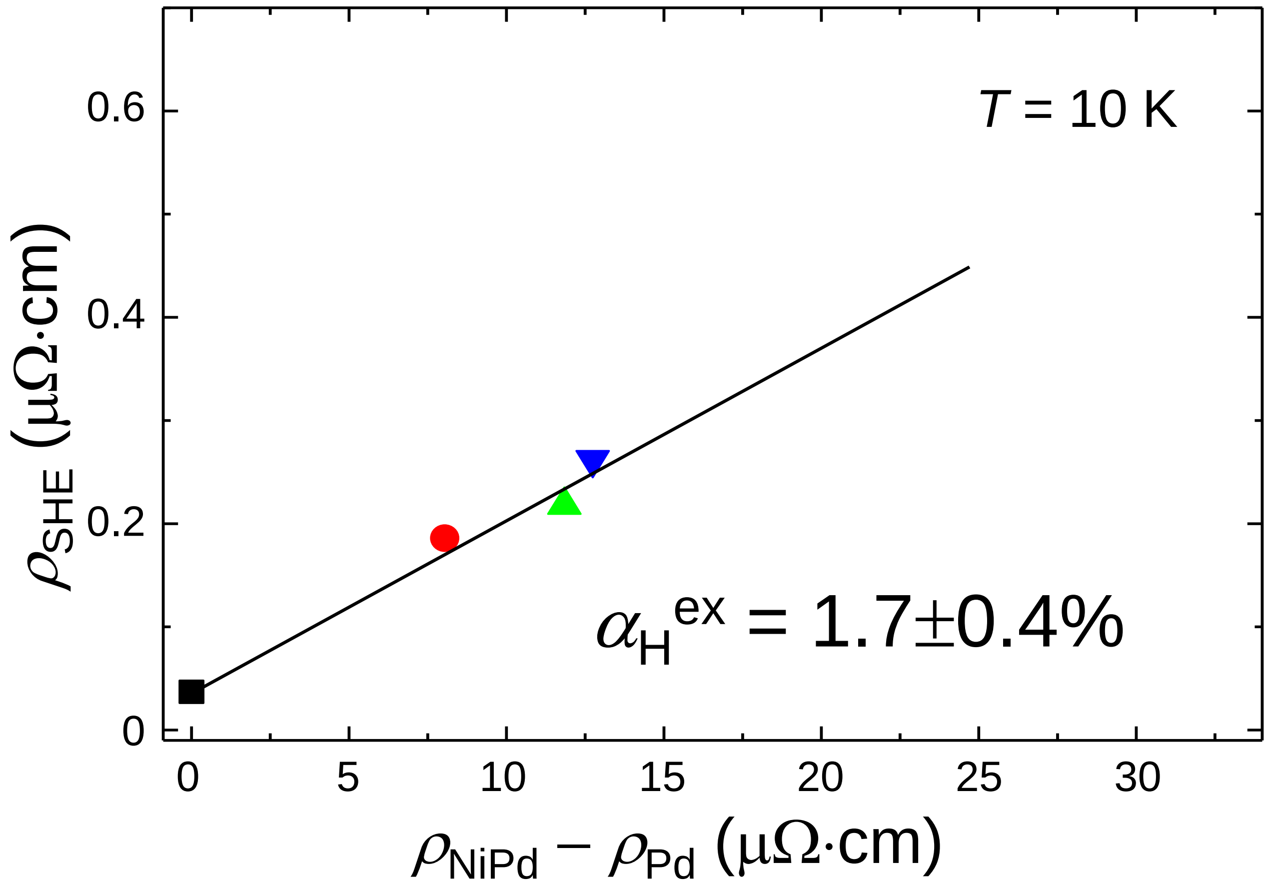
Effective pure spin current ($\bar{I}_S$)



$$\frac{\bar{I}_S}{I_C} = \frac{\int_0^{t_{NiPd}} I_S(z)dz}{t_{NiPd} I_C}$$

$$= \frac{\lambda_{NiPd}}{t_{NiPd}} \frac{\left(1-e^{-t_{NiPd}/\lambda_{NiPd}}\right)^2}{1-e^{-2t_{NiPd}/\lambda_{NiPd}}} \frac{I_S(z=0)}{I_C}$$

Spin Hall resistivity of NiPd as a function of ρ_{imp}

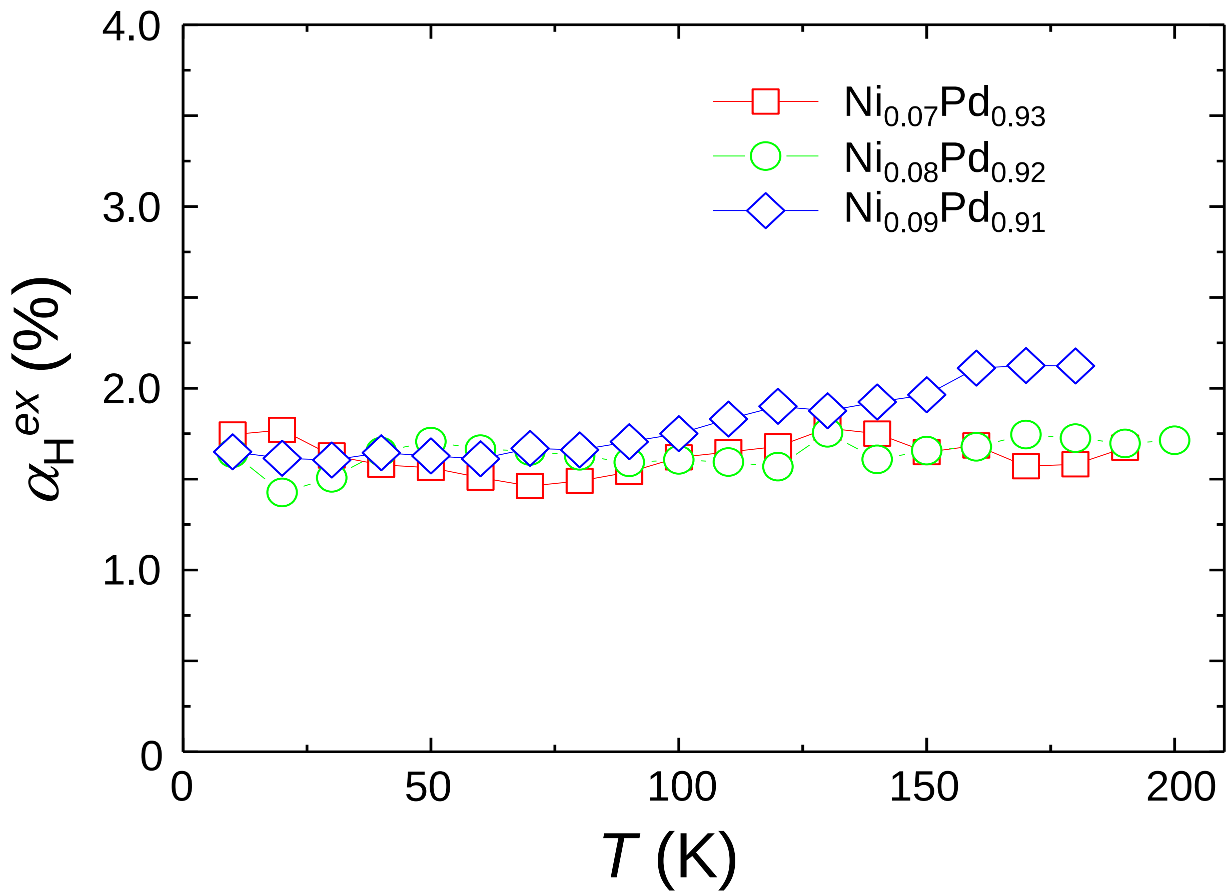


$$\rho_{SHE} = \rho_{SHE}^{in} + \alpha_H^{ex} \cdot (\rho_{NiPd} - \rho_{Pd})$$

$\alpha_H^{in} \equiv \rho_{SHE}^{in} / \rho_{Pd} \sim 0.6\%$

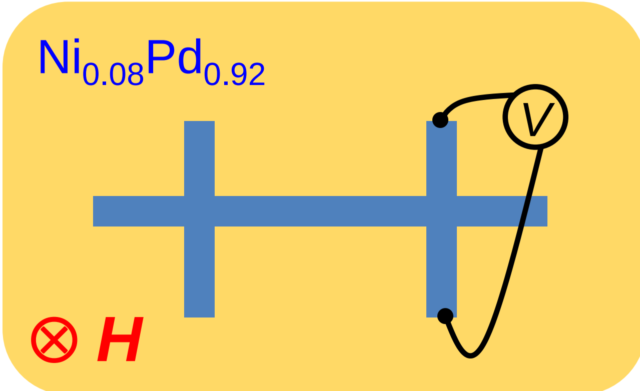
M. Morota, Y. N. *et al.*, PRB **83**, 174405 (2011).

Temperature dependence of SH angle

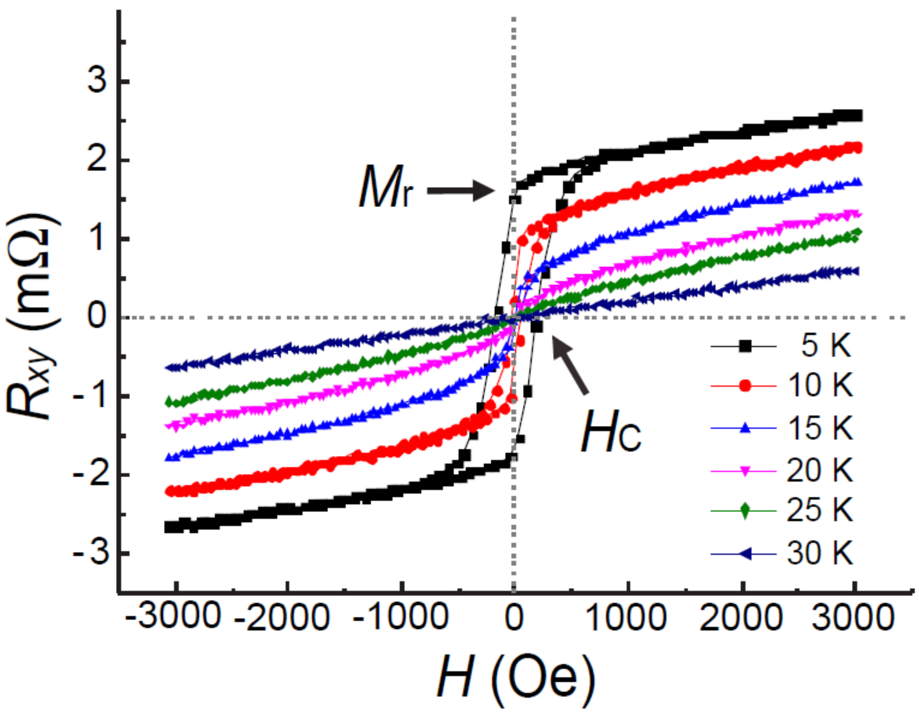


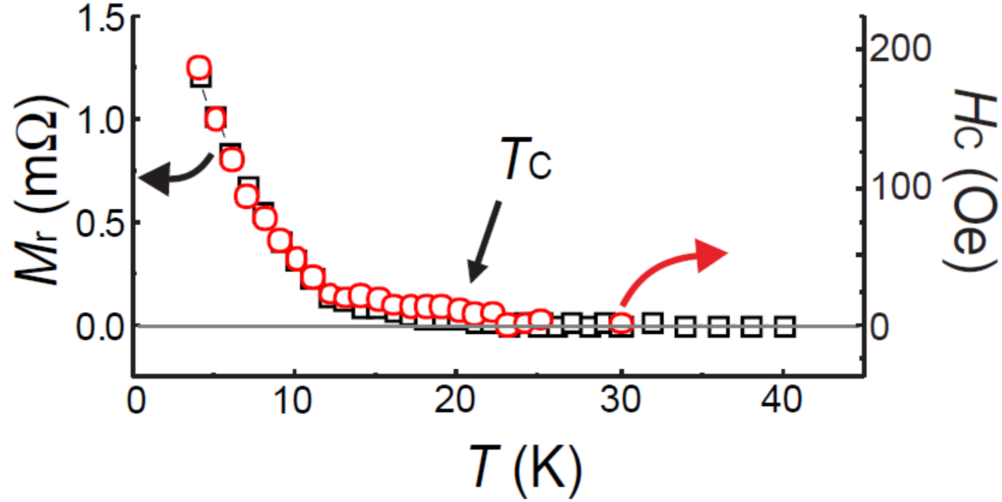
almost independent of T ➡ skew scattering mechanism

AHE for Ni_xPd_{1-x} alloys



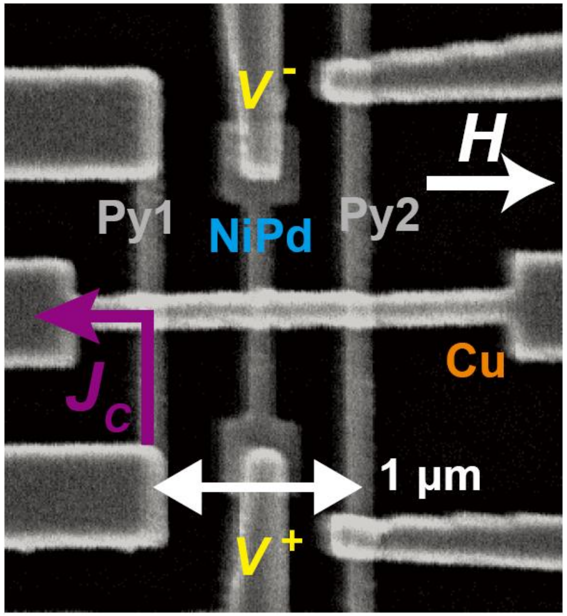
Ni_xPd_{1-x}	T_C
$Ni_{0.07}Pd_{0.93}$	16 K
$Ni_{0.08}Pd_{0.92}$	21 K
$Ni_{0.09}Pd_{0.91}$	32 K

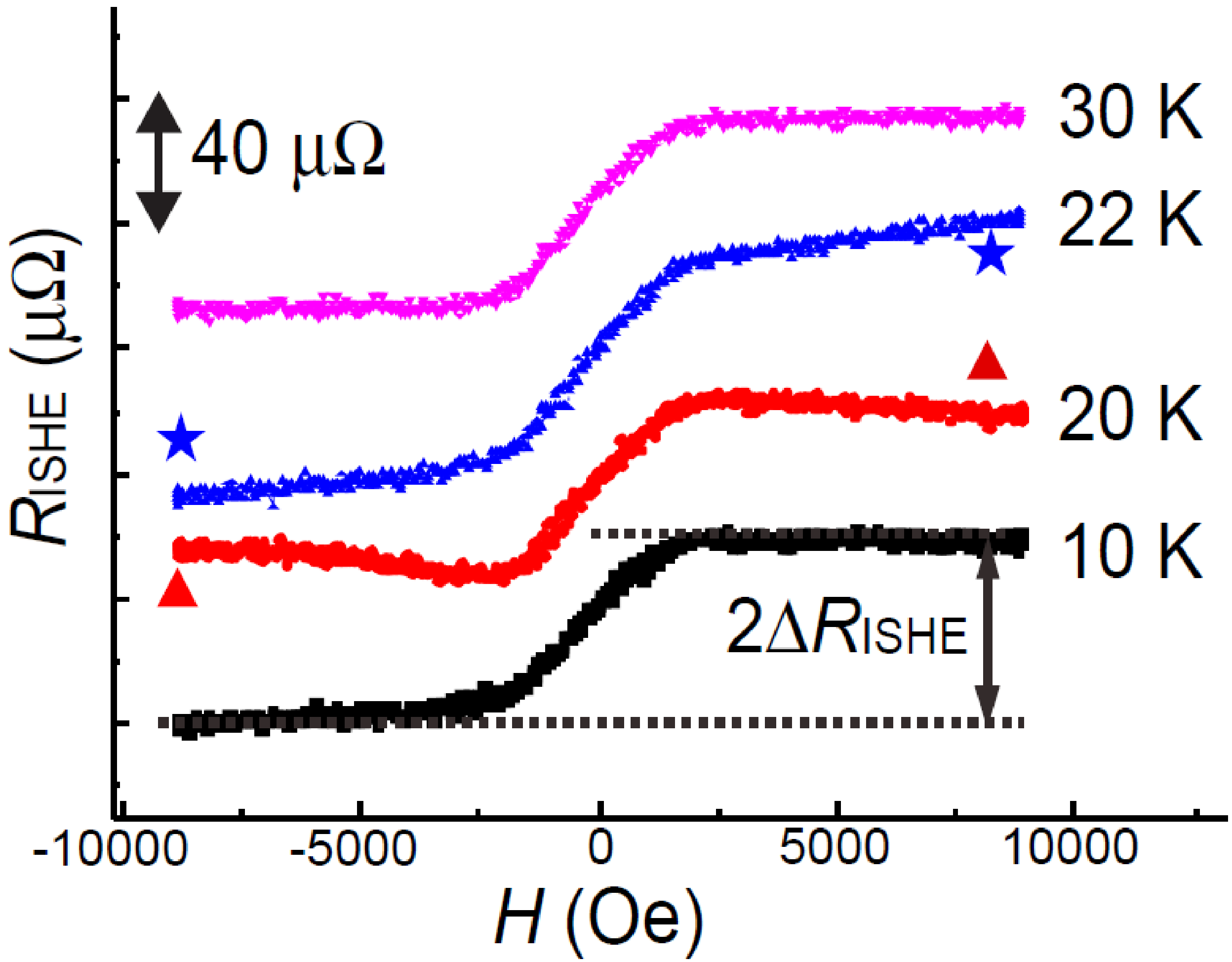




ISHE of NiPd near T_C

$Ni_{0.08}Pd_{0.92}$

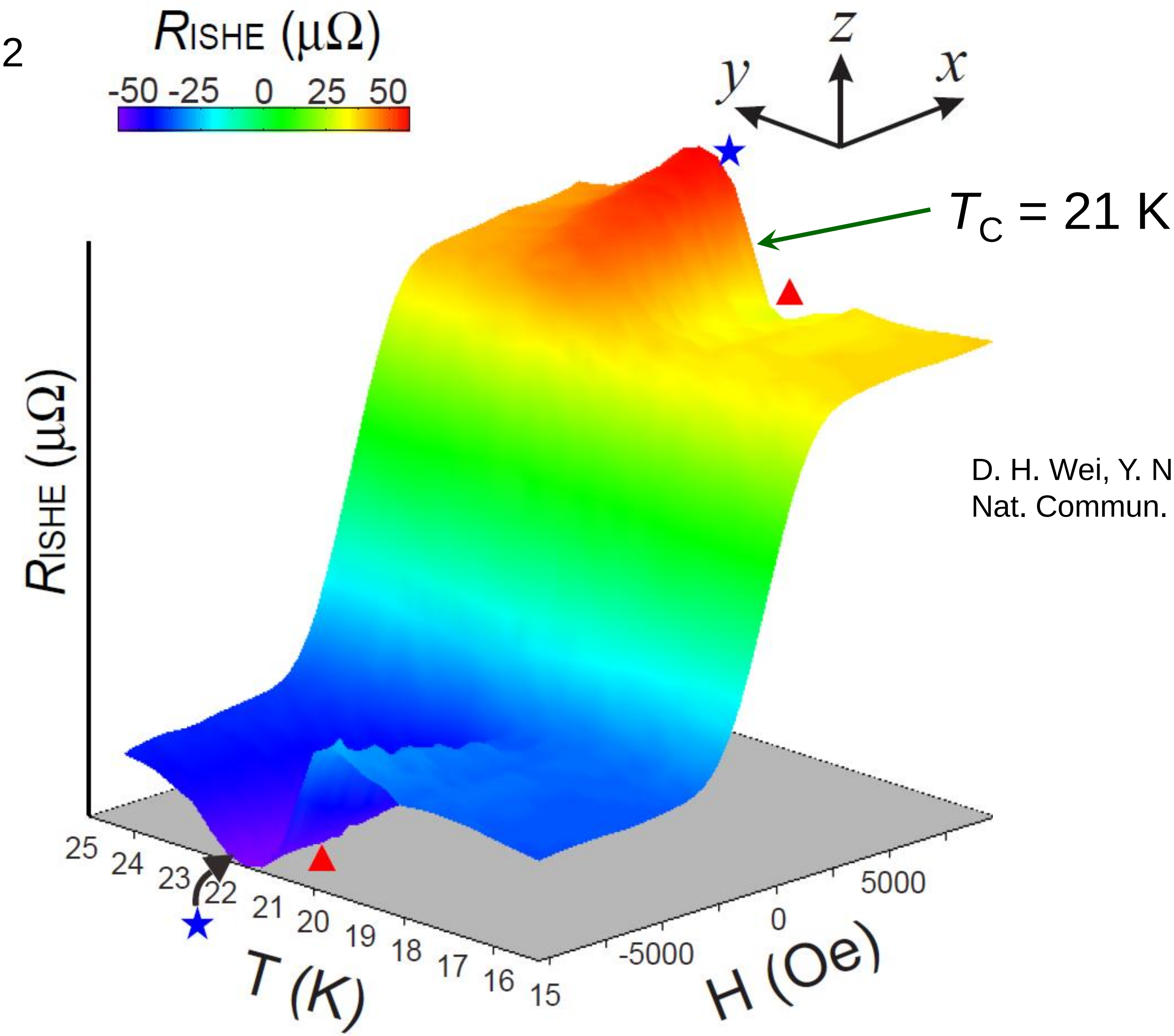




D. H. Wei, Y. N. *et al.*,
Nat. Commun. **3**, 1038 (2012).

3D plot of R_{ISHE} near T_C

$Ni_{0.08}Pd_{0.92}$



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3D plot of R_{ISHE} near T_C

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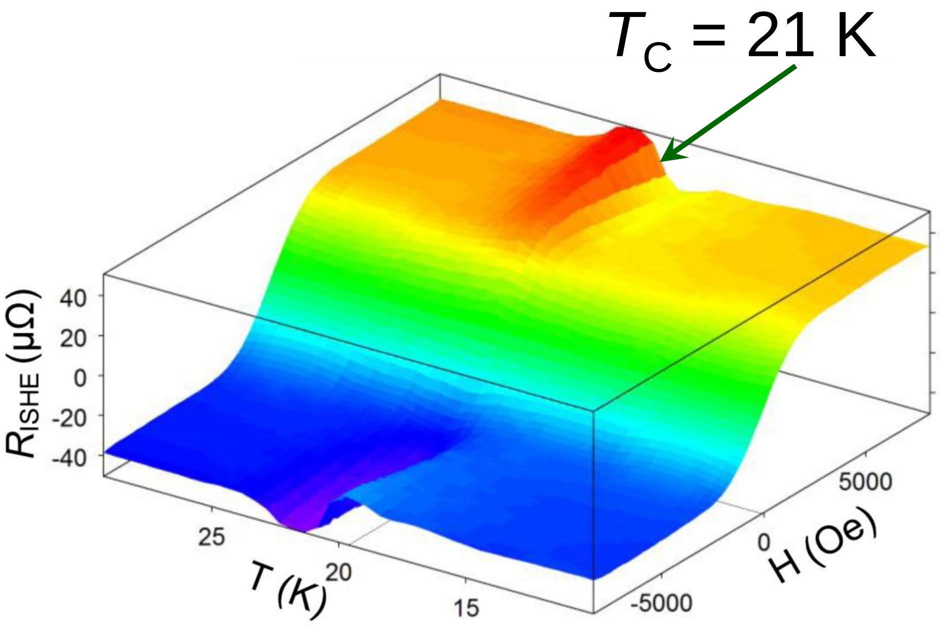
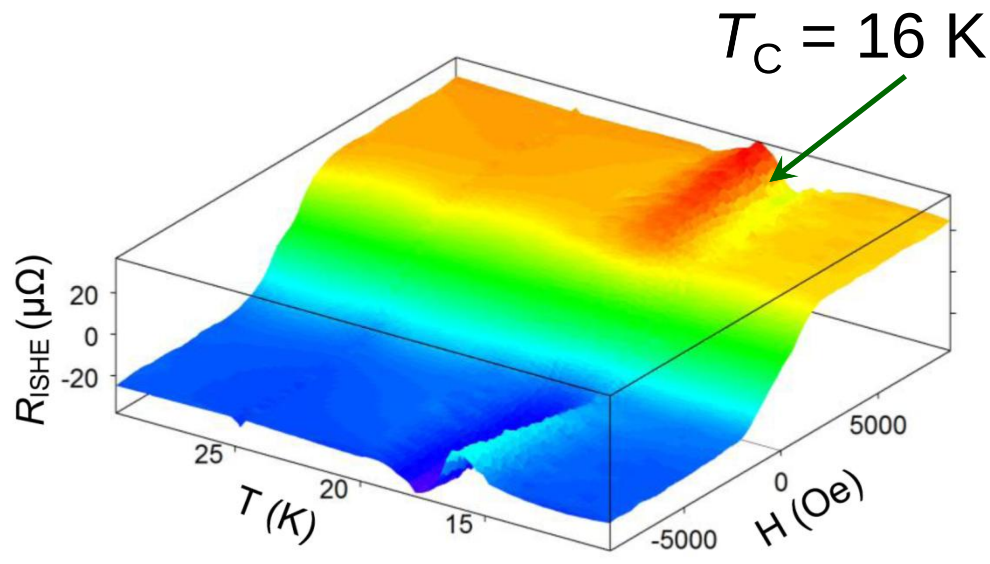


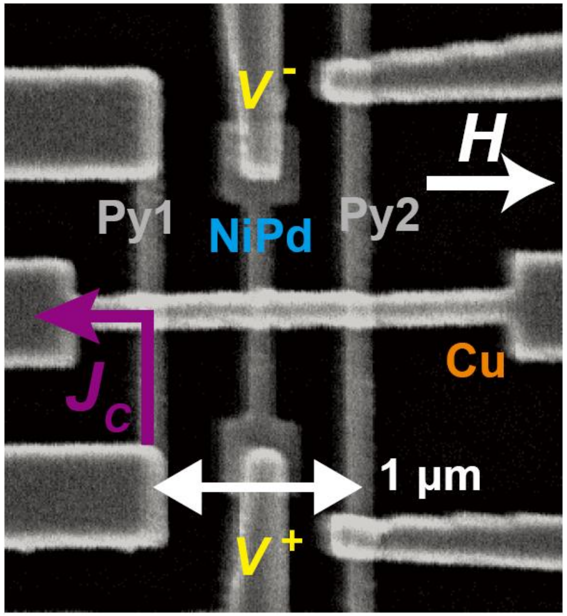
$Ni_{0.07}Pd_{0.93}$

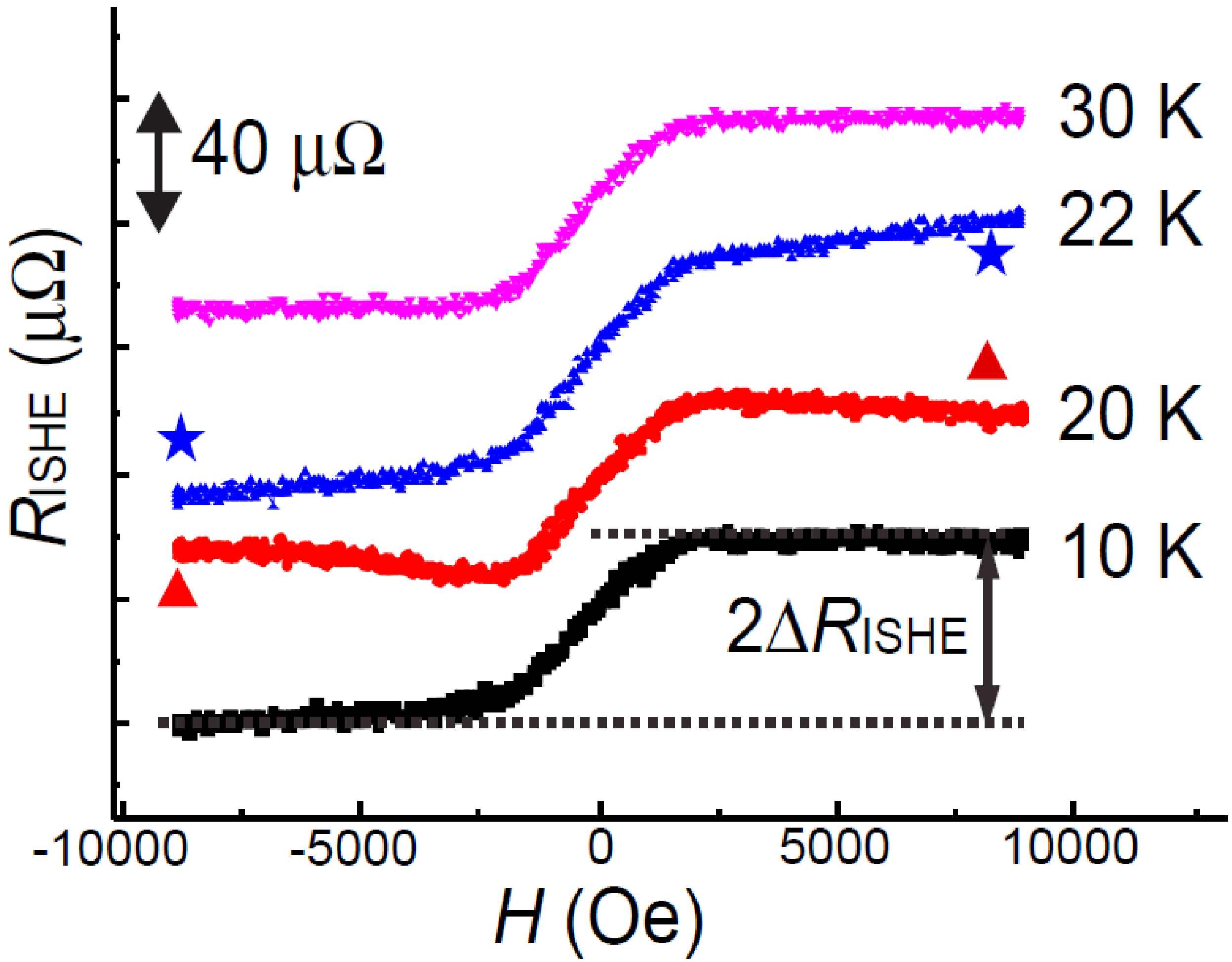


- The anomalous behavior near T_C is quite reproducible!

ISHE of NiPd near T_C

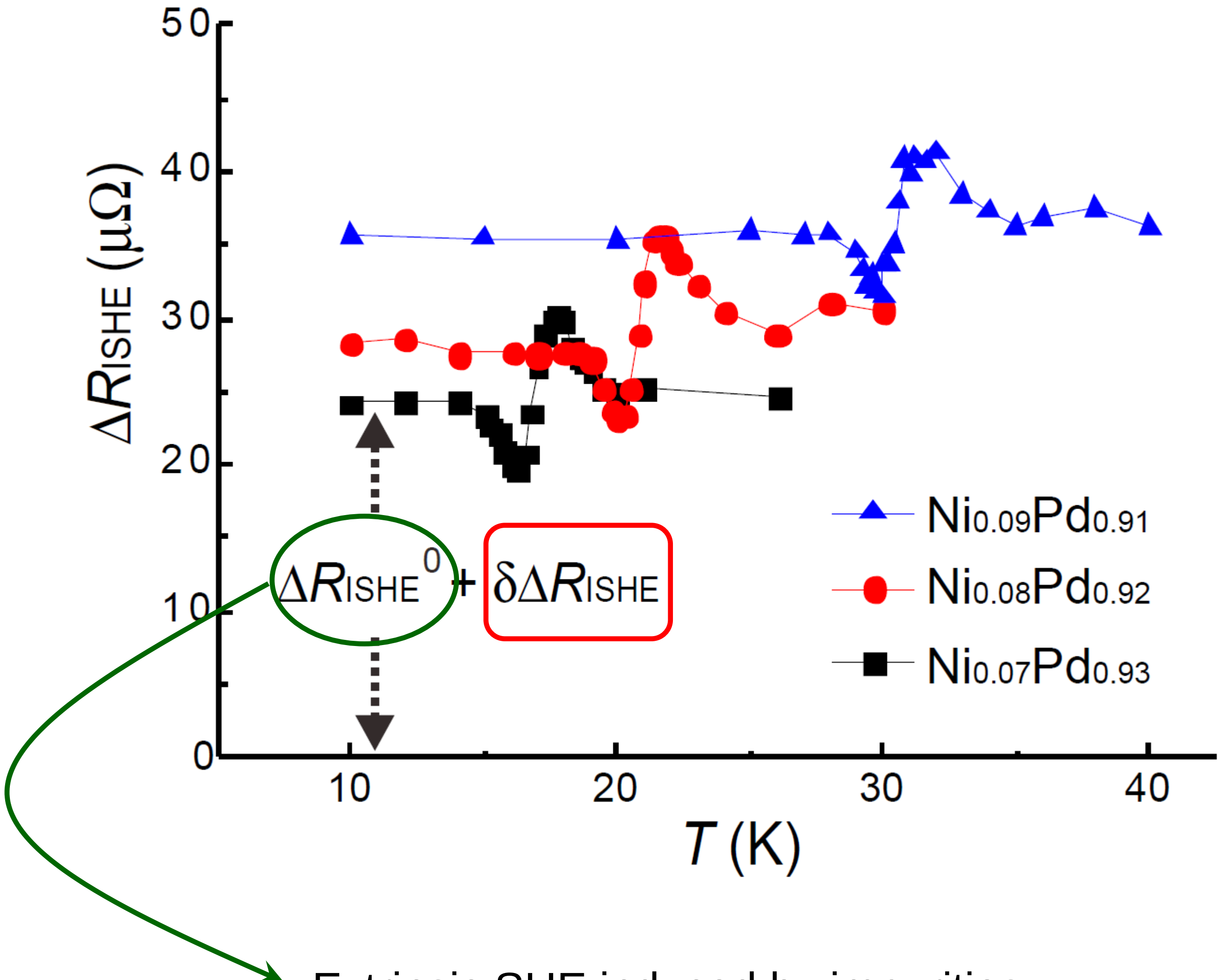
$Ni_{0.08}Pd_{0.92}$





D. H. Wei, Y. N. *et al*.,
Nat. Commun. **3**, 1038 (2012).

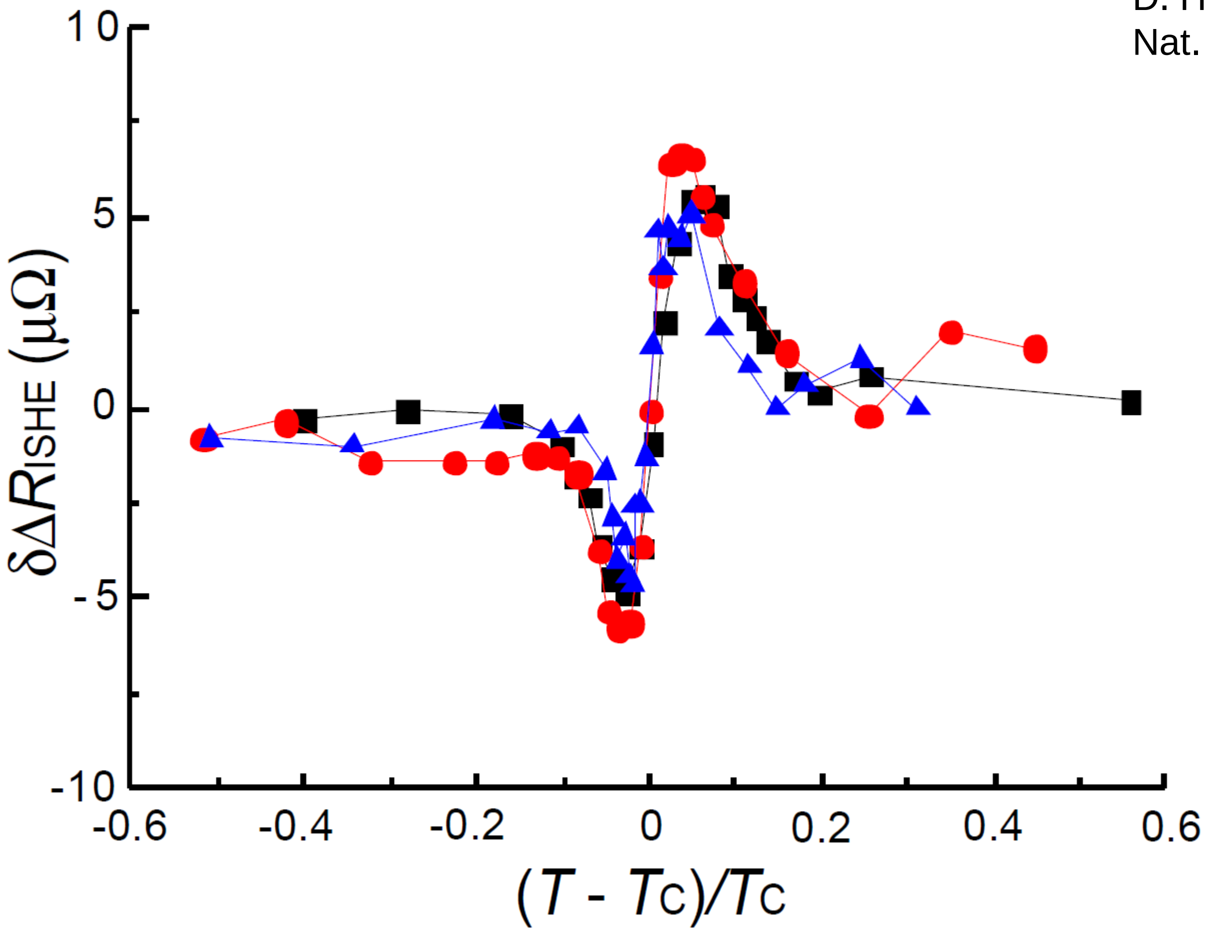
Anomalous part of R_{ISHE} near T_C



Extrinsic SHE induced by impurities

$\delta\Delta R_{ISHE}$ as a function of reduced temperature

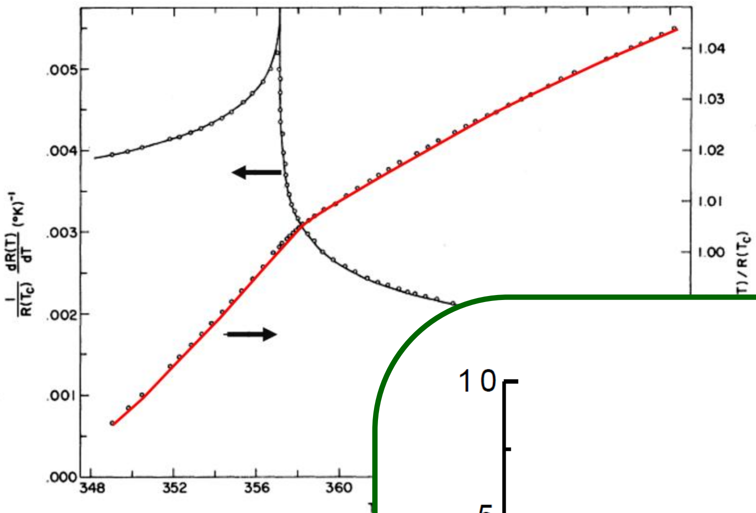
D. H. Wei, Y. N. *et al.*,
Nat. Commun. **3**, 1038 (2012).



- The anomalous part is almost independent of the Ni concentration.

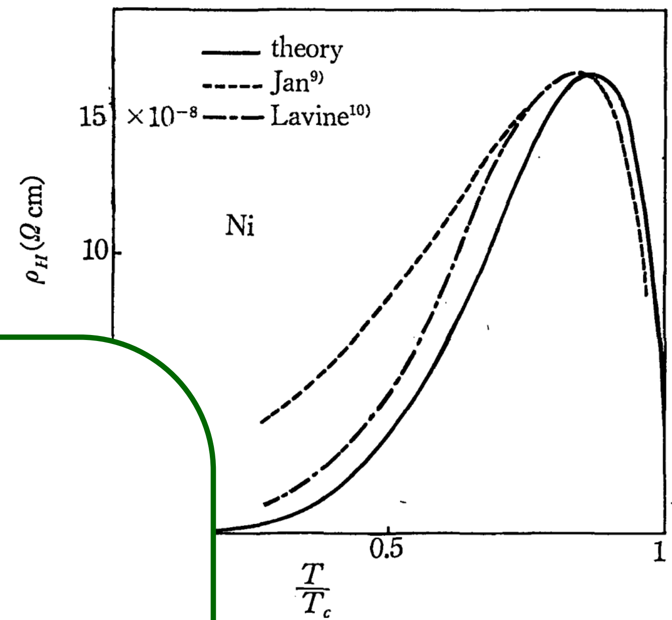
Anomalies near T_C

Anomaly in ρ_{xx} of pure Ni



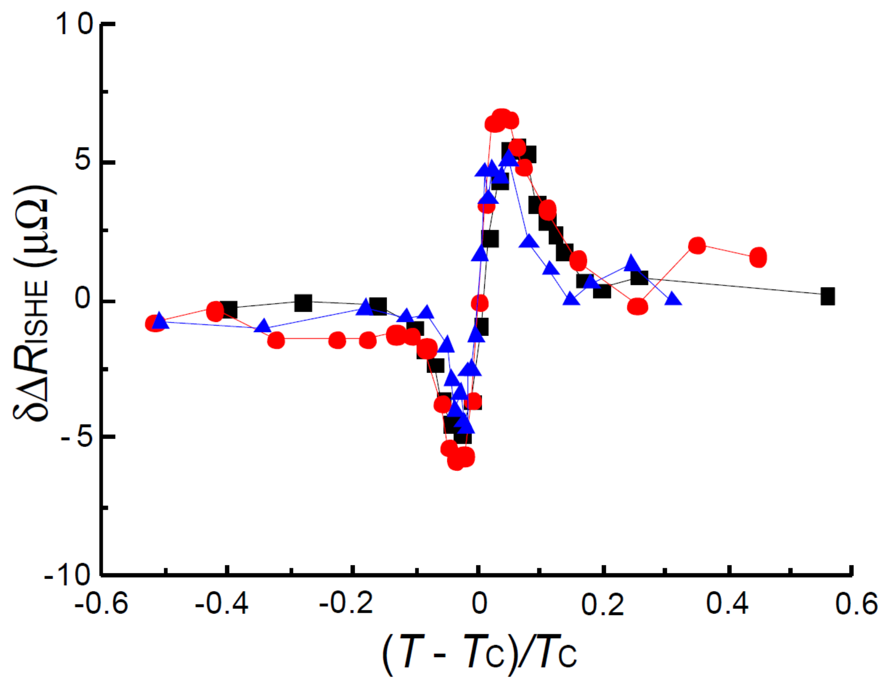
F. C. Zumsteg *et al.*,

Anomaly in ρ_{xy} of pure Ni



lv. Phys. Acta **25**, 677 (1952).

Phys. Rev. **123**, 1273 (1961).



Anomaly in R_{ISHE} of NiPd alloys

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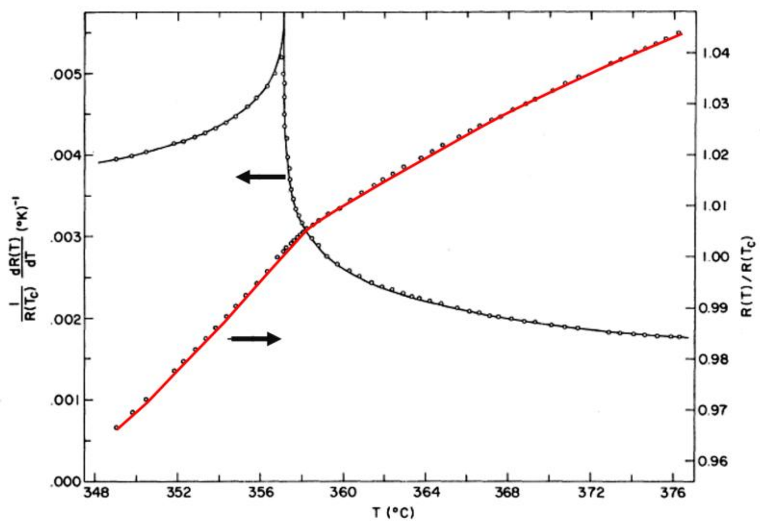
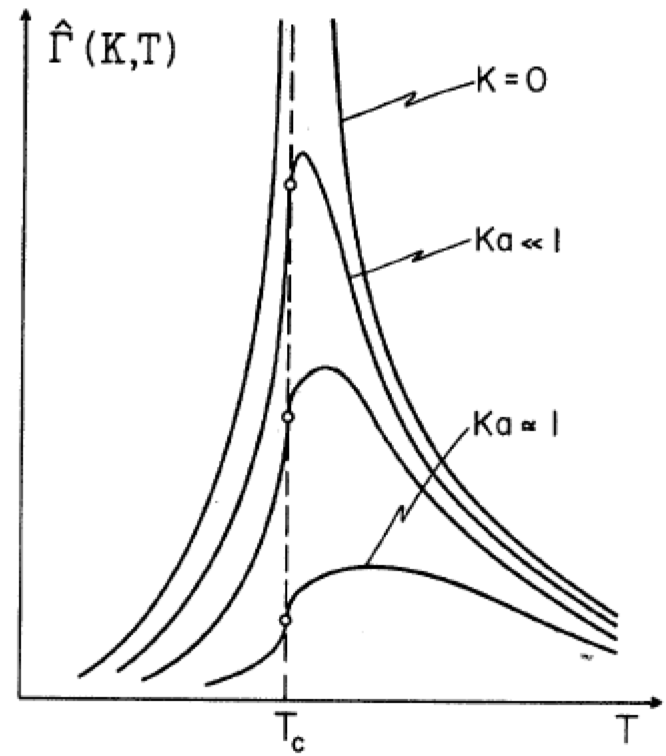
To explain the anomaly in ρ_{xx} near T_C...

Anomaly in ρ_{xx} of pure Ni



F. C. Zumsteg *et al*., PRL **24**, 520 (1967).

M. E. Fisher and J. S. Langer, PRL **20**, 1344 (1967).



$$\rho_{xx} \propto \langle (m - \langle m \rangle)^2 \rangle \propto \chi_0$$

first Born approximation!!

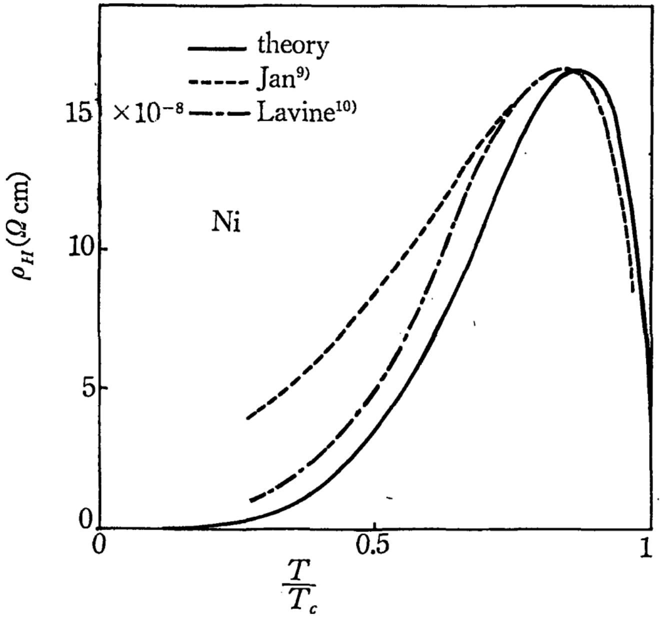
Smearing of ρ_{xx} just on T_C

$$\rho_{xx} \propto \langle (m_i - \langle m_i \rangle)(m_j - \langle m_j \rangle) \rangle \propto \chi_0^{loc}$$

contributions come only when *i* and *j* are within a certain cutoff distance.

To explain the anomaly in ρ_{xy} below T_C...

Anomaly in ρ_{xy} of pure Ni



J. P. Jan, Helv. Phys. Acta **25**, 677 (1952).
J. M. Lavine, Phys. Rev. **123**, 1273 (1961).

- Karplus & Luttinger's theory

R. Karplus & J. M. Luttinger, Phys. Rev. **95**, 1154 (1954).

$$\rho_{xy} \propto \rho_{xx}^2 \langle m \rangle$$

- Kondo's theory

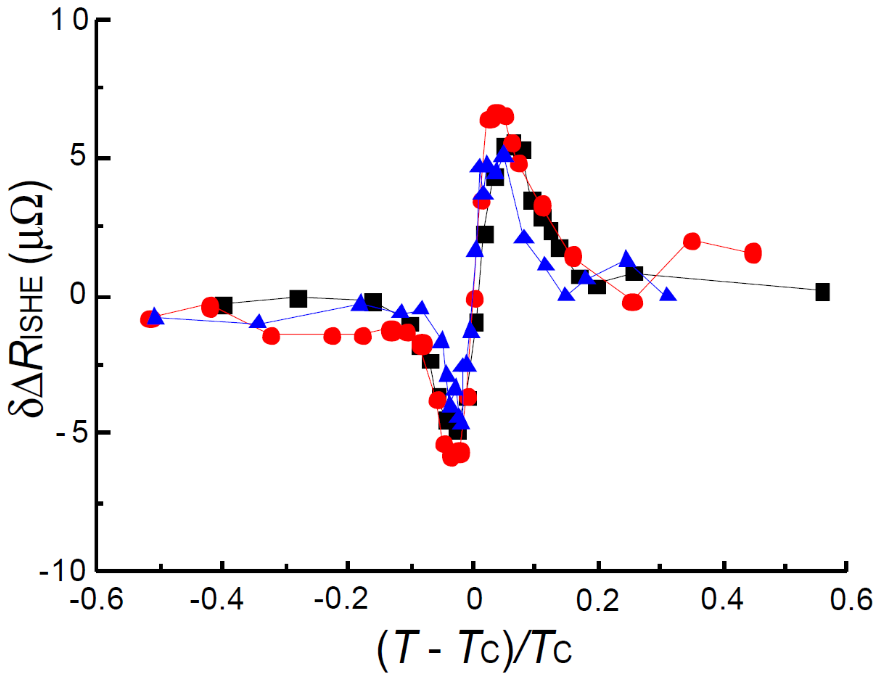
J. Kondo, Prog. Theor. Phys. **27**, 772 (1962).

$$\rho_{xy} \propto \langle (m - \langle m \rangle)^3 \rangle$$

second Born approximation!!

To explain the anomaly in R_{ISHE} near T_C...

Anomaly in $\boldsymbol{R}_{\mathbf{ISHE}}$ of NiPd alloys



D. H. Wei, Y. N. et al., Nat. Commun. **3**, 1038 (2012).

- Karplus & Luttinger's theory

  R. Karplus & J. M. Luttinger, Phys. Rev. **95**, 1154 (1954).

  $$\rho_{xy} \propto \rho_{xx}{}^2 \langle m \rangle$$

  For ISHE, <m> varnishes above T_C.

- Kondo's theory

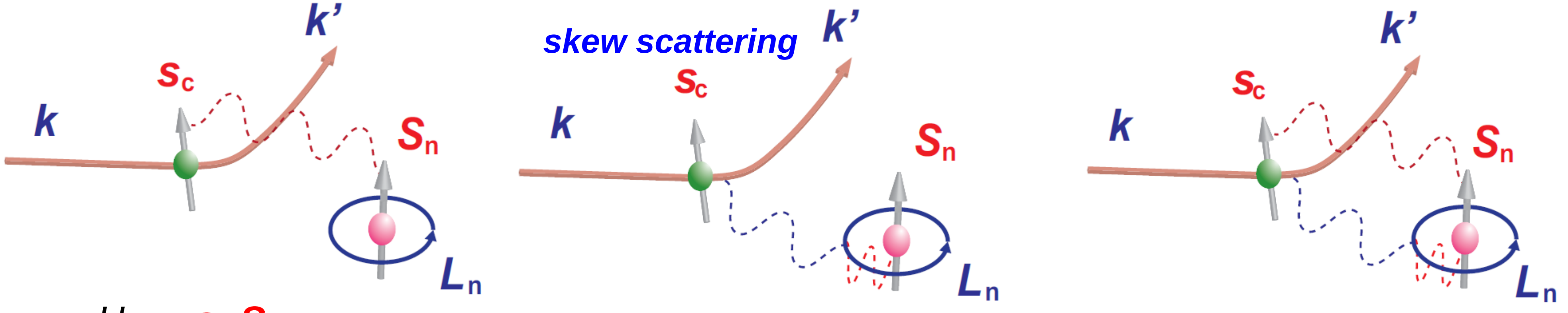
  J. Kondo, Prog. Theor. Phys. **27**, 772 (1962).

  $$\rho_{xy} \propto \langle (m - \langle m \rangle)^3 \rangle$$

The Kondo's theory has to be extended for the ISHE configuration.

Kondo's theory

s-d exchange interaction | spin-orbit interaction (1) | spin-orbit interaction (2)



$H_{ex} \sim \mathbf{s}_c \cdot \mathbf{S}_n$

$$H_{SO}^{(1)} \sim (\mathbf{L}_n \cdot (\mathbf{k} \times \mathbf{k}'))(\mathbf{S}_n \cdot \mathbf{L}_n) \sim (\mathbf{k} \times \mathbf{k}') \cdot \mathbf{S}_n$$

$$H_{SO}^{(2)} \sim H_{SO}^{(1)} \cdot H_{ex} \sim (\mathbf{L}_n \cdot (\mathbf{k} \times \mathbf{k}'))(\mathbf{S}_n \cdot \mathbf{L}_n)(\mathbf{S}_n \cdot \mathbf{s}_c) \sim (\mathbf{k} \times \mathbf{k}')\, \mathbf{s}_c \cdot \mathbf{S}_n \mathbf{S}_n$$

To obtain the transition probability from ***k*** to ***k'***

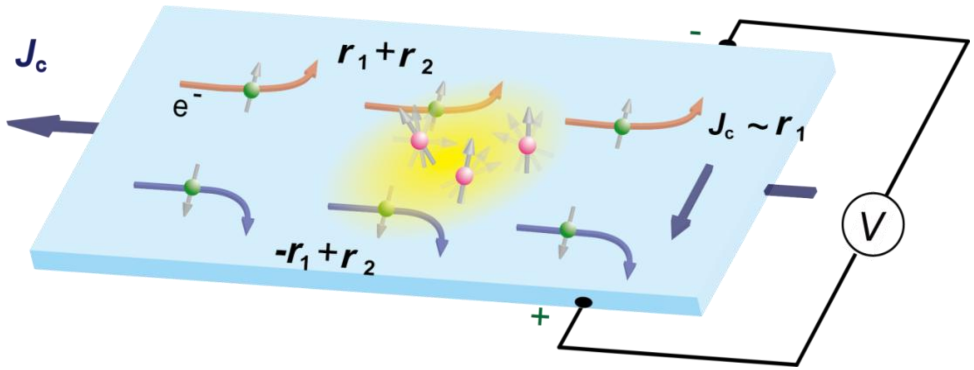
SO(1): $\langle H_{ex} H_{SO}^{(1)} H_{ex} \rangle \sim \langle \mathbf{S}_n^3 \rangle \langle \mathbf{s}_c^2 \rangle \equiv r_1 \langle \mathbf{s}_c^2 \rangle$ ⟶ r_1 : third-order spin correlation

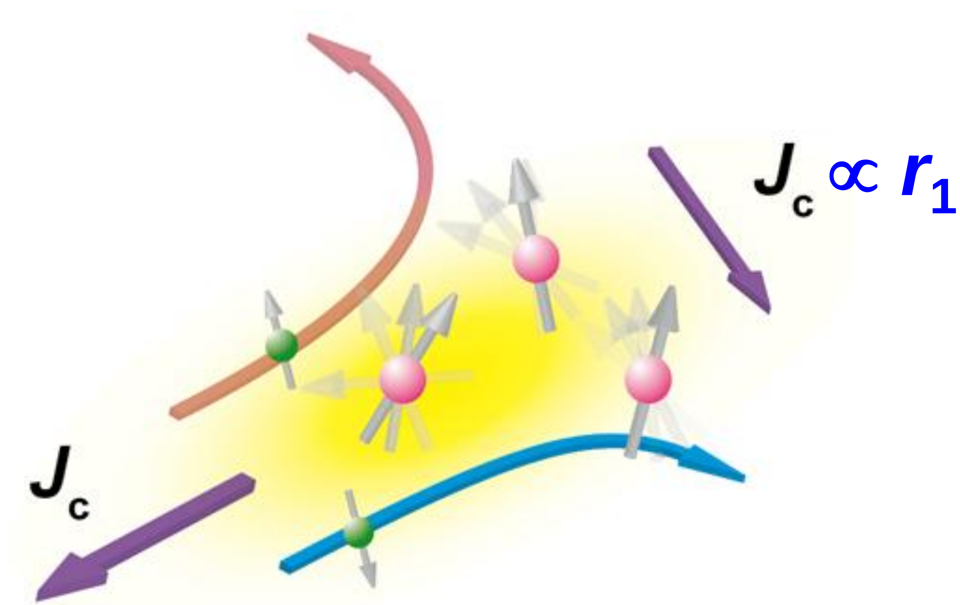
SO(2): $\langle H_{ex} H_{SO}^{(2)} H_{ex} \rangle \sim \langle \mathbf{S}_n^4 \rangle \langle \mathbf{s}_c^3 \rangle \equiv r_2 \langle \mathbf{s}_c^3 \rangle$ ⟶ r_2 : fourth-order spin correlation

**$H_{SO}^{(1)}$ and $H_{SO}^{(2)}$ appear in the s-d Hamiltonian to the same order with respect to the SO coupling constant λ of the localized moment.

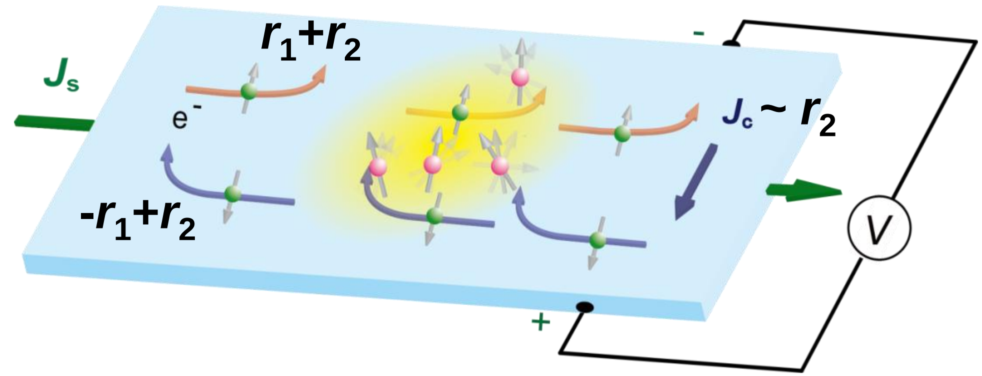
AHE vs ISHE

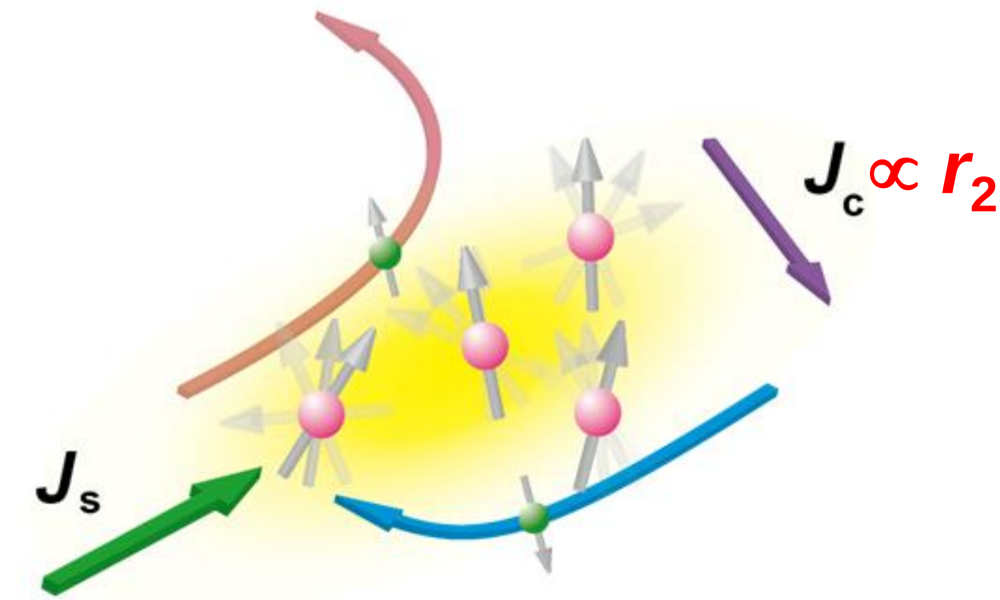
AHE



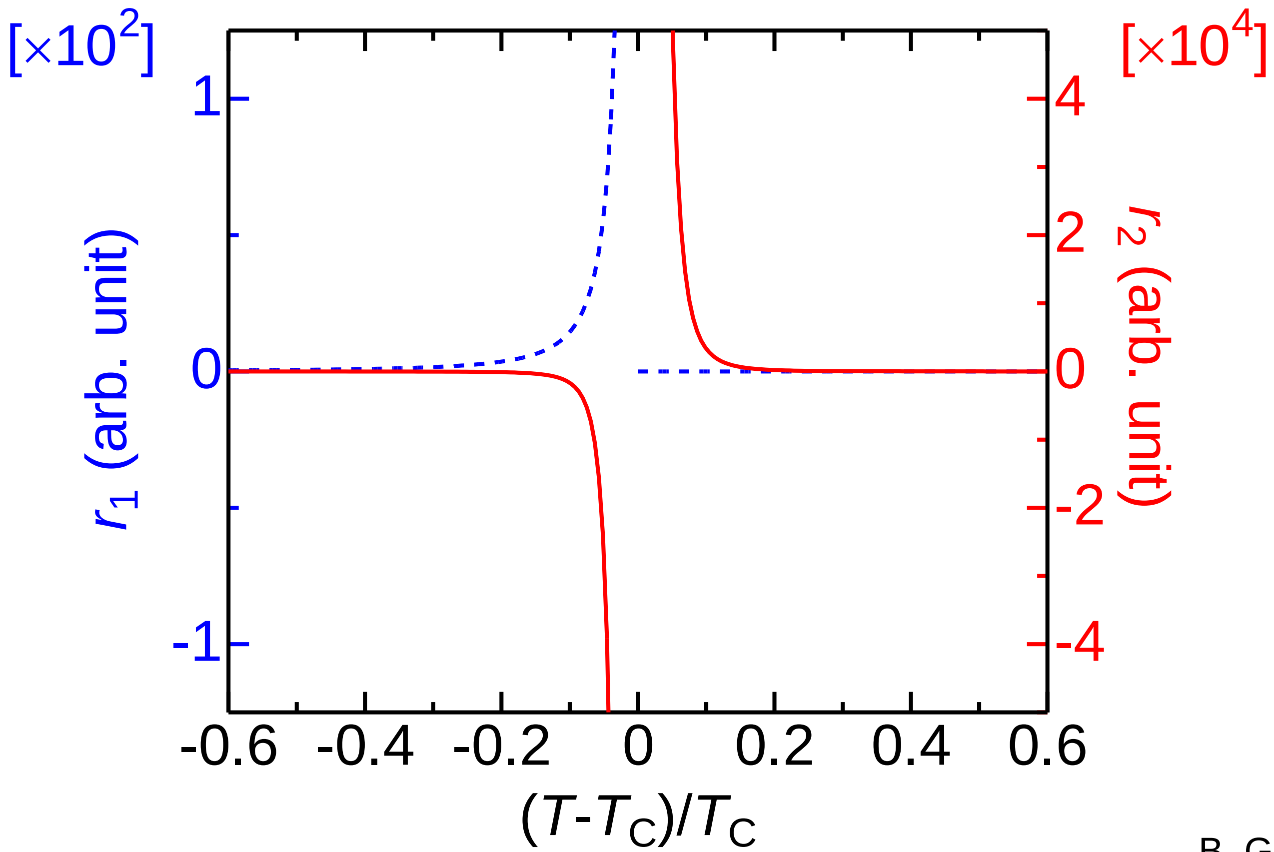


ISHE





Temperature dependence of r_1 and r_2



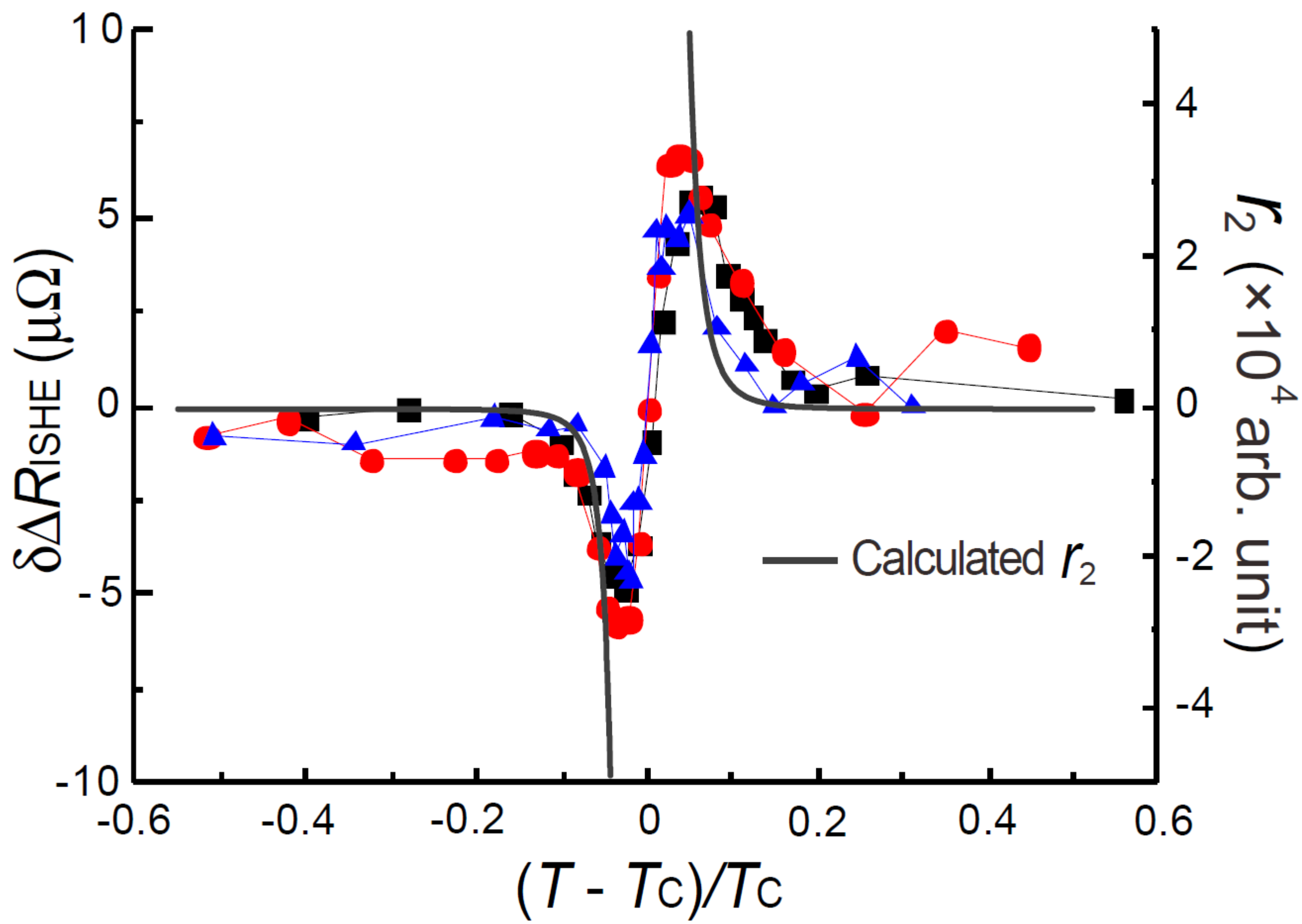
B. Gu, T. Ziman, and S. Maekawa, PRB **86**, 241303(R) (2012).

$$r_1 = \langle (m - \langle m \rangle)^3 \rangle \propto \chi_1$$

$$r_2 = 2c_2 \langle (m - \langle m \rangle)^2 \, (m^2 - \langle m^2 \rangle) \, \rangle \propto 2c_2 \, \chi_2$$

c_2 = -1/2 for Ni

Anomalous part of R_{ISHE} near T_C



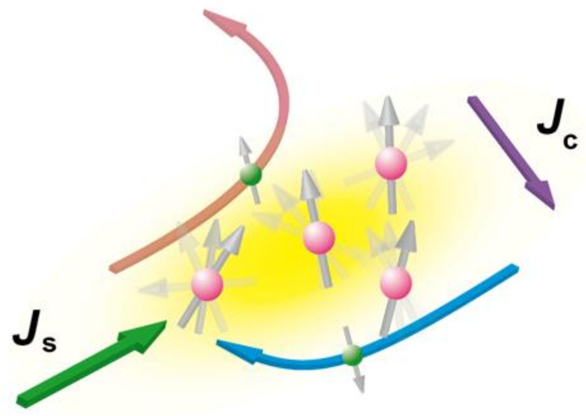
- The anomaly in ρ_{xx} near T_C can be explained by r_2 except for just on T_C.

Comparison to uniform non-linear susceptibilities

$$M_{tot} = M_{tot,0}(T) + \chi_0^{uni} H + \chi_1^{uni} H^2 + \chi_2^{uni} H^3 + \cdots,$$

$$\chi_1^{uni} = \beta^2 \left\langle \left(M_{tot} - \langle M_{tot} \rangle \right)^3 \right\rangle$$ 1st order nonlinear susceptibility

$$\delta \Delta R_{ISHE} \propto r_2 \propto \chi_2^{uni} \approx \beta^3 \left\langle \left(M_{tot} - \langle M_{tot} \rangle \right)^4 \right\rangle$$ 2nd order nonlinear susceptibility



$\propto r_2$

Summary

- We have studied inverse spin Hall effects (ISHE) of weakly ferromagnetic Ni_xPd_{1-x} alloys (x = 0.07~0.09). **Anomalies in R_{ISHE} near T_C were clearly observed for each Ni concentration**. The shape of the anomaly is asymmetric with respect to T_C and does not depend on x.

- The experimentally observed anomaly can be well-explained with the generalized version of **the Kondo's theory**, which was **originally developed to explain the anomaly in anomalous Hall effect (AHE)** in pure Ni and Fe.

- **The higher-order spin fluctuations (i.e., r_1 and r_2 terms)** introduced in the generalized Kondo's theory give an **essential difference between SHE and AHE**.