The spin Hall and spin Nernst effect

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Collaborations

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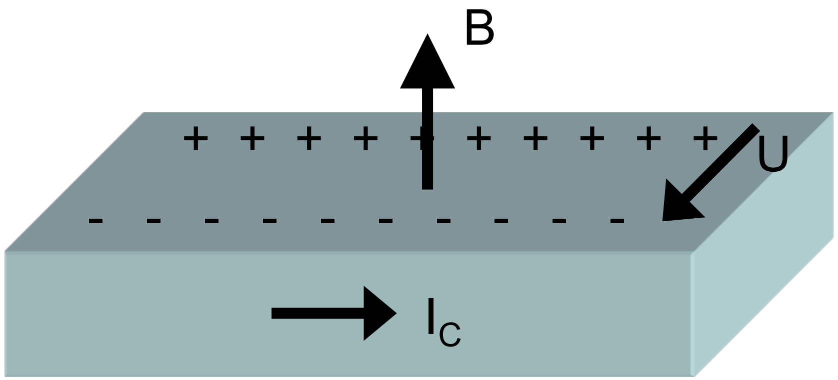
Spin Hall effect

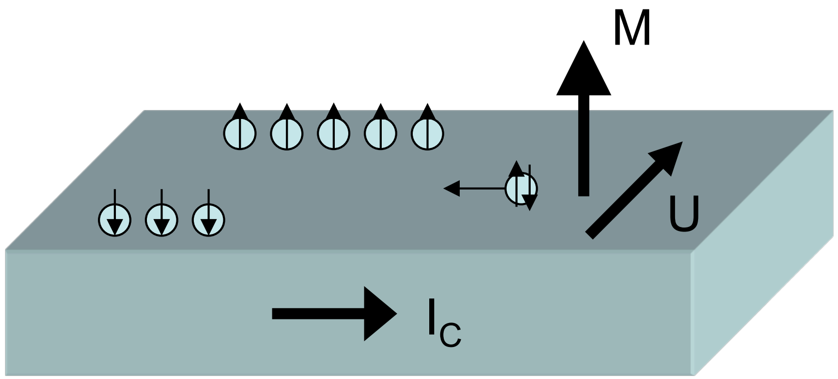
Basics

Hall effect



Lorentz force

anomalous Hall effect

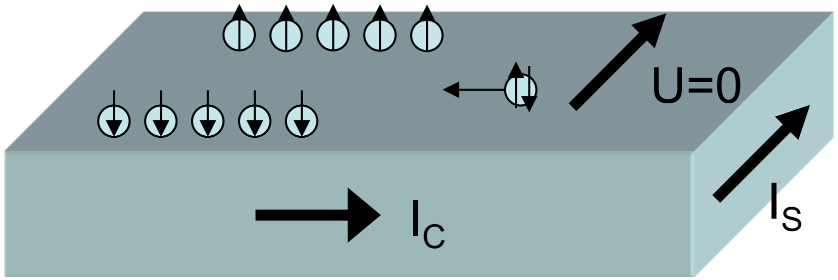


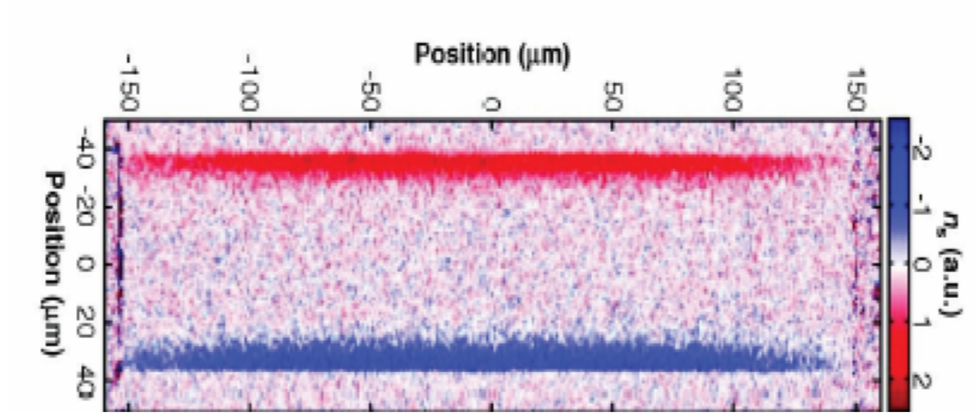
spin-orbit scattering

$$\vec{s} * \vec{L}$$

Spin Hall effect

anomalous Hall effect M=0 (Hirsch 1999)





No charge current perpendicular to I_C

Spin current (spin accumulation)

Y.K. Kato, R.C. Myers,
A.C. Gossard, and D.D. Awschalom,
Science 306, 1910 (2004);
Kimura (2007)

Origin of the spin Hall effect

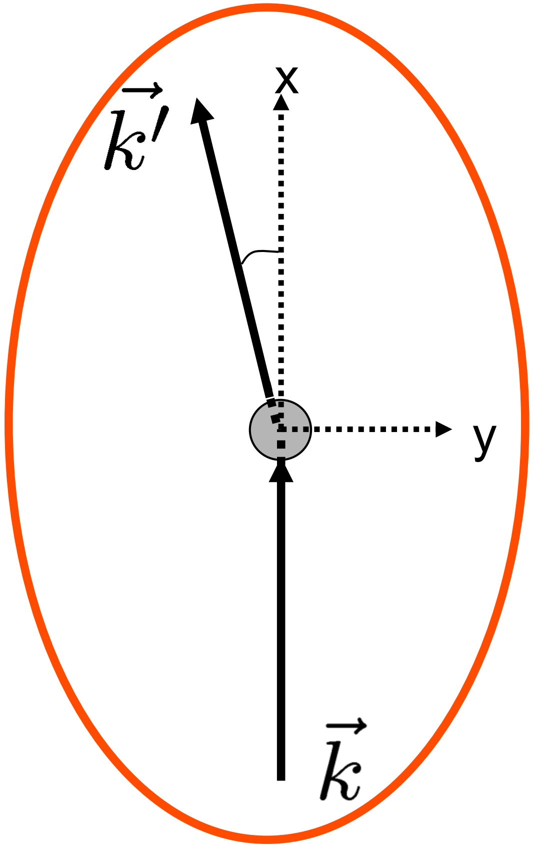
intrinsic spin Hall effect

$$\vec{v}_{\vec{k}} = \frac{\partial \mathcal{E}_{\vec{k}}}{\partial \vec{k}} + \underbrace{e\vec{E} \times \vec{\Omega}_{\vec{k}}}_{\vec{v}_a}$$

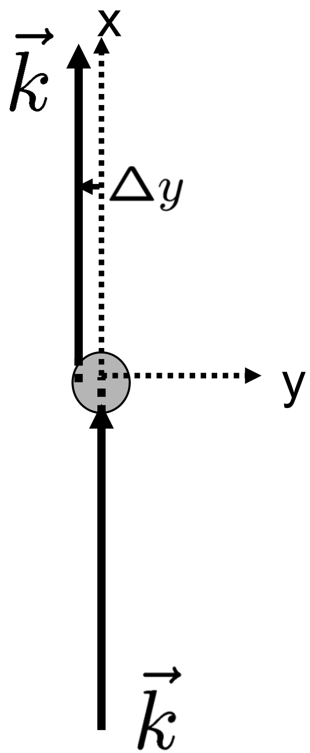
Berry curvature $\vec{\Omega}_{\vec{k}}$ causes

anomalous velocity $\vec{v}_a$

skew scattering



side jump



Sinova 2005;
Guo 2005; Guo 2008;...

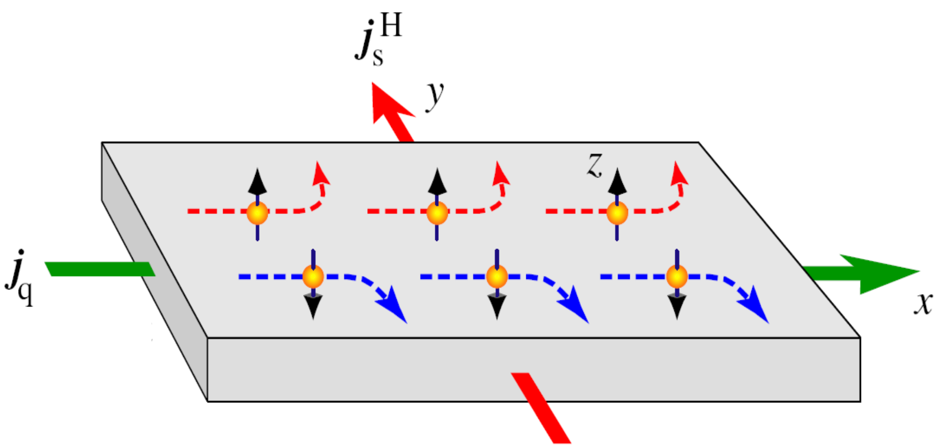
Smit 1955/58; Berger 1970/72; Crepieux 2001

Nagaosa, Sinova et al., Rev. Mod. Phys. **82**, 1539 (2010)

Measurement

SHE

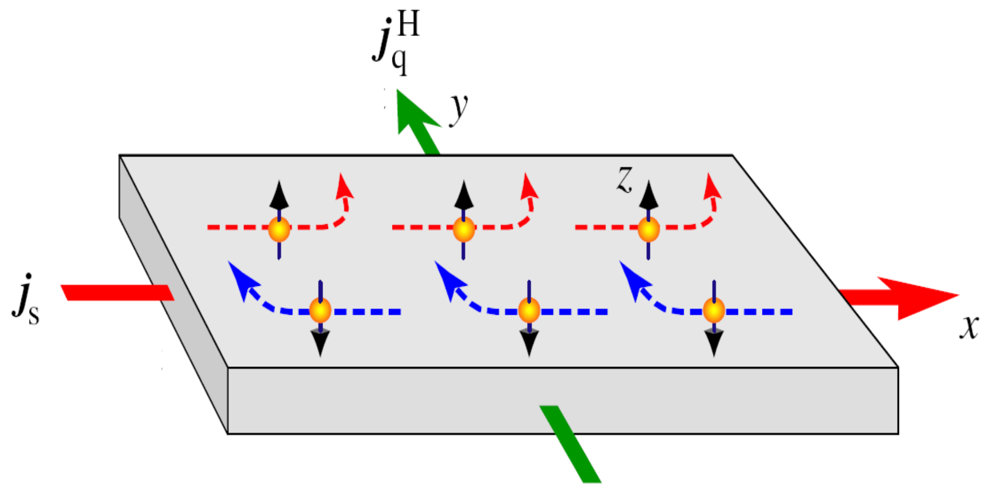
spin current



charge current

ISHE

charge current



spin current

S. Takahashi and S. Maekawa, Sci. Technol. Adv. Mater. 9, 014105 (2008)

Experimental results: Spin Hall angle

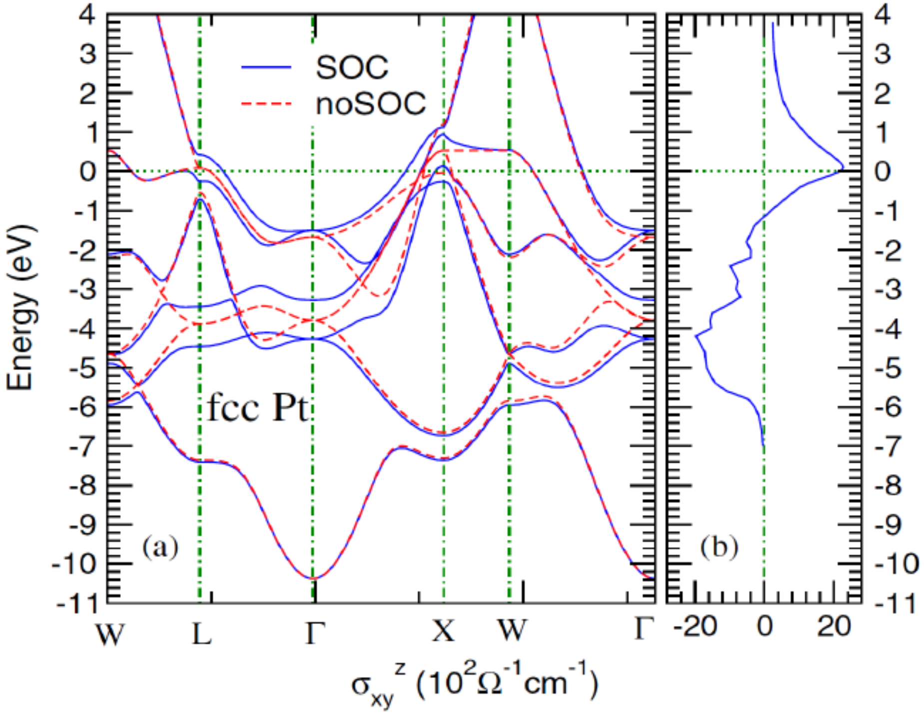
$$\alpha = \sigma_{s_z}^{xy} \;/\; \sigma^{xx}$$

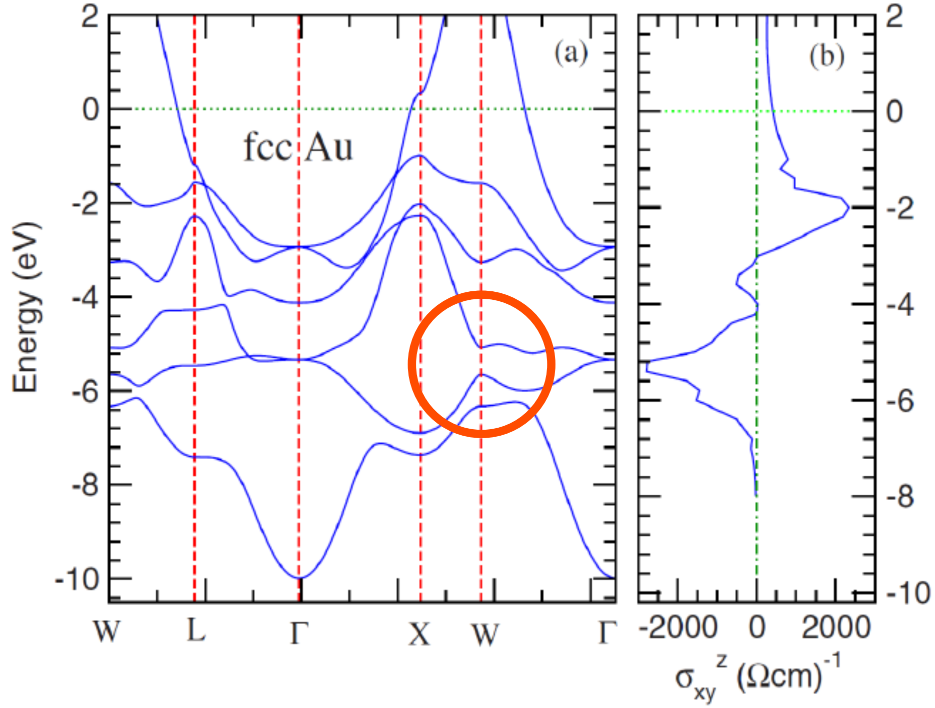
Al:	S.O. Valenzuela and M. Tinkham, Nature Letters 2006	0.0002
Cu:	T. Kimura et al., PRL 2007	0.0002
Cu(Ir):	Y. Niimi, PRL 2011	-0.026
Cu(Bi):	Y. Niimi, PRL 2012	0.24
Pt:	M. Morota et al., PRB 20011	0.02
Au:	T. Seki et al., Nature Materials 2008	0.1
	L. Vila et al., PRL 2007	0.002

Intrinsic spin Hall effect

Intrinsic spin Hall conductivities

$$\sigma_{s_z}{}^{xy} = \frac{e^2}{\hbar\,(2\pi)^3} \int^{E_F} dE\; \Omega^z(E)$$





Pt: **2000** $\frac{\hbar}{e}(\Omega\ cm)^{-1}$

Au: **400** $\frac{\hbar}{e}(\Omega\ cm)^{-1}$

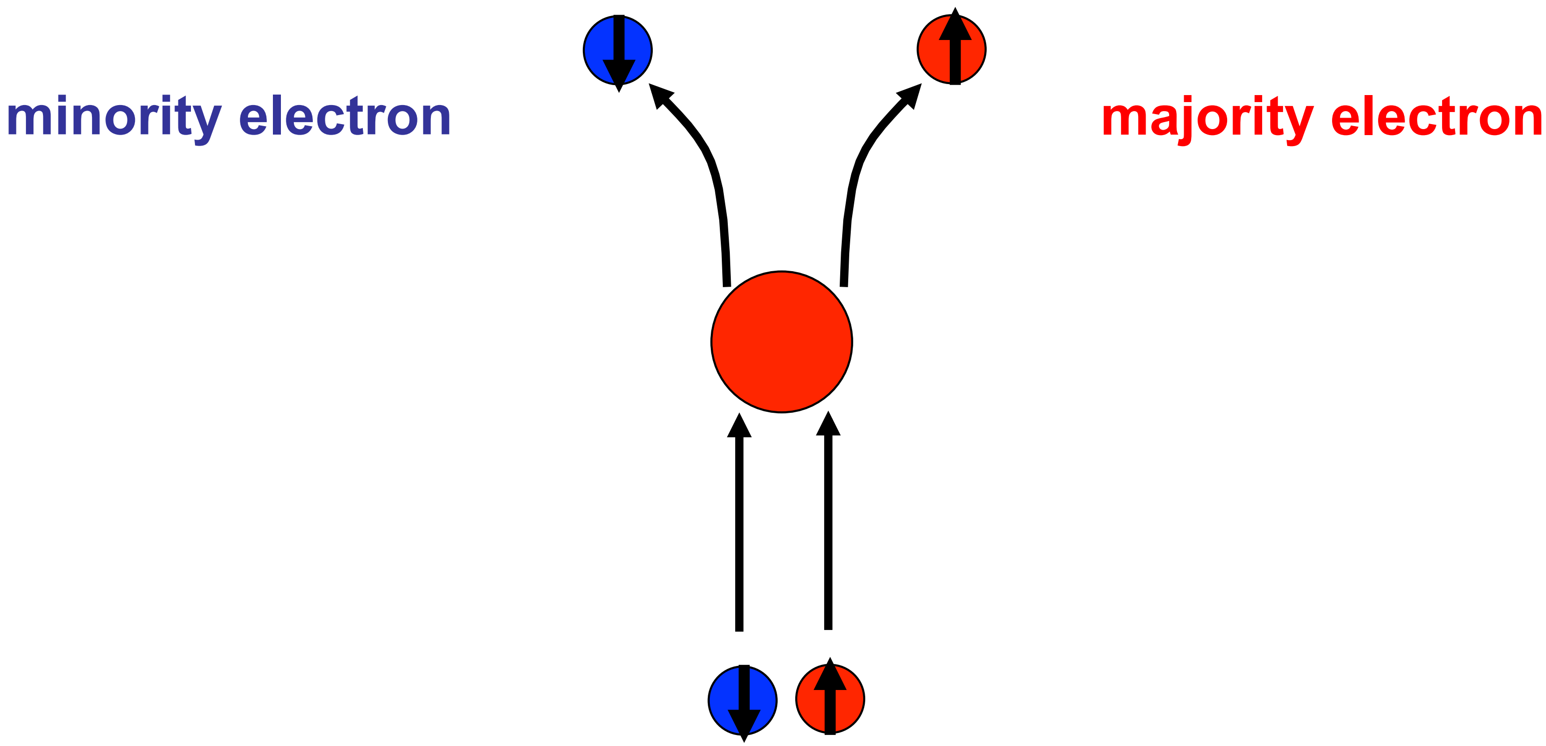
Guo et al., PRL **100**, 096401 (2008); J. Appl. Phys. **105**, 07C701 (2009)

Skew scattering contribution

M. Gradhand, D.V. Fedorov, P. Zahn, and I. M., Phys. Rev. B **81**, 020403 (R) (2010)
M. Gradhand, D.V. Fedorov, P. Zahn, and I. M., Phys. Rev. Lett.**104,** 186403 (2010)
M. Gradhand, D.V. Fedorov, P. Zahn, and I. M., Phys. Rev. B **81**, 245109 (2010)
S. Lowitzer, M. Gradhand et al., Phys. Rev. Lett. **106**, 056601 (2011)
M. Gradhand et al., J. Phys.: Condens. Matter **24**, 213202 (2012)
M. Gradhand et al., SPIN **2**, 1250010 (2012)
D. Fedorov et al., Phys. Rev. B **88**, 085116 (2013)

Skew scattering

left-right asymmetry of the scattering process with respect to the spin state of the electron

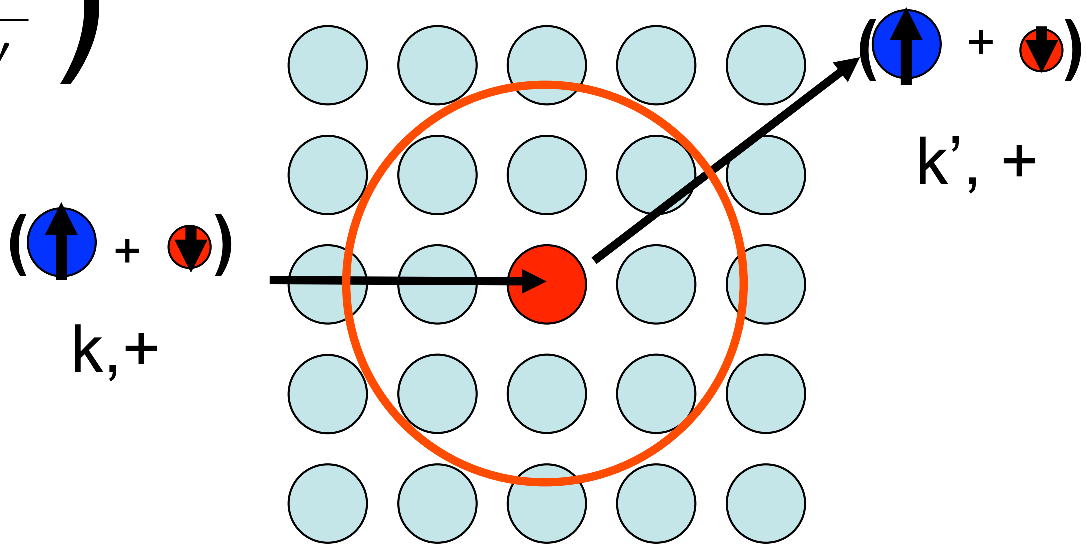


But: Spin-orbit coupling in the host – spin-mixed wavefunctions

Microscopic scattering probability

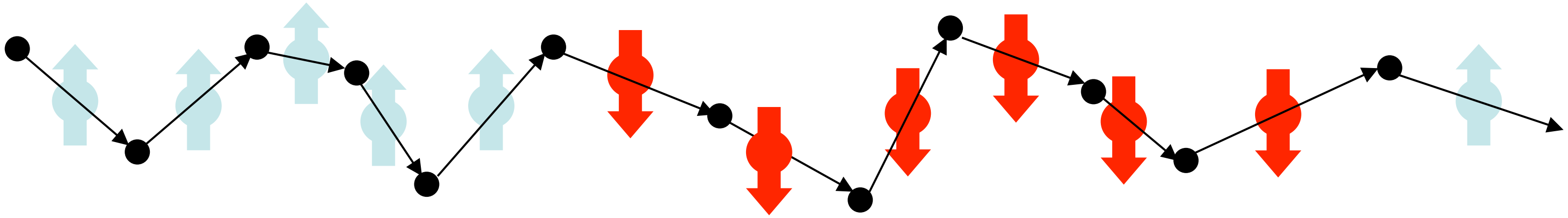
$$P_{kk'}^{nn'} = 2\pi c_0 N |T_{kk'}^{nn'}|^2 \delta(E_k - E_{k'})$$

$$\begin{pmatrix} P_{kk'}^{++} & P_{kk'}^{-+} \\ P_{kk'}^{+-} & P_{kk'}^{--} \end{pmatrix}$$



M. Gradhand et al., PRB **81**, 020403(R) (2010)

Relaxation time



$$\left(\tau_k^{nn'}\right)^{-1} = \sum_{k'} P_{kk'}^{nn'}$$

Spin-conserving scattering

$$\left(\tau_k^{nn}\right)^{-1} = \sum_{k'} P_{kk'}^{nn}$$

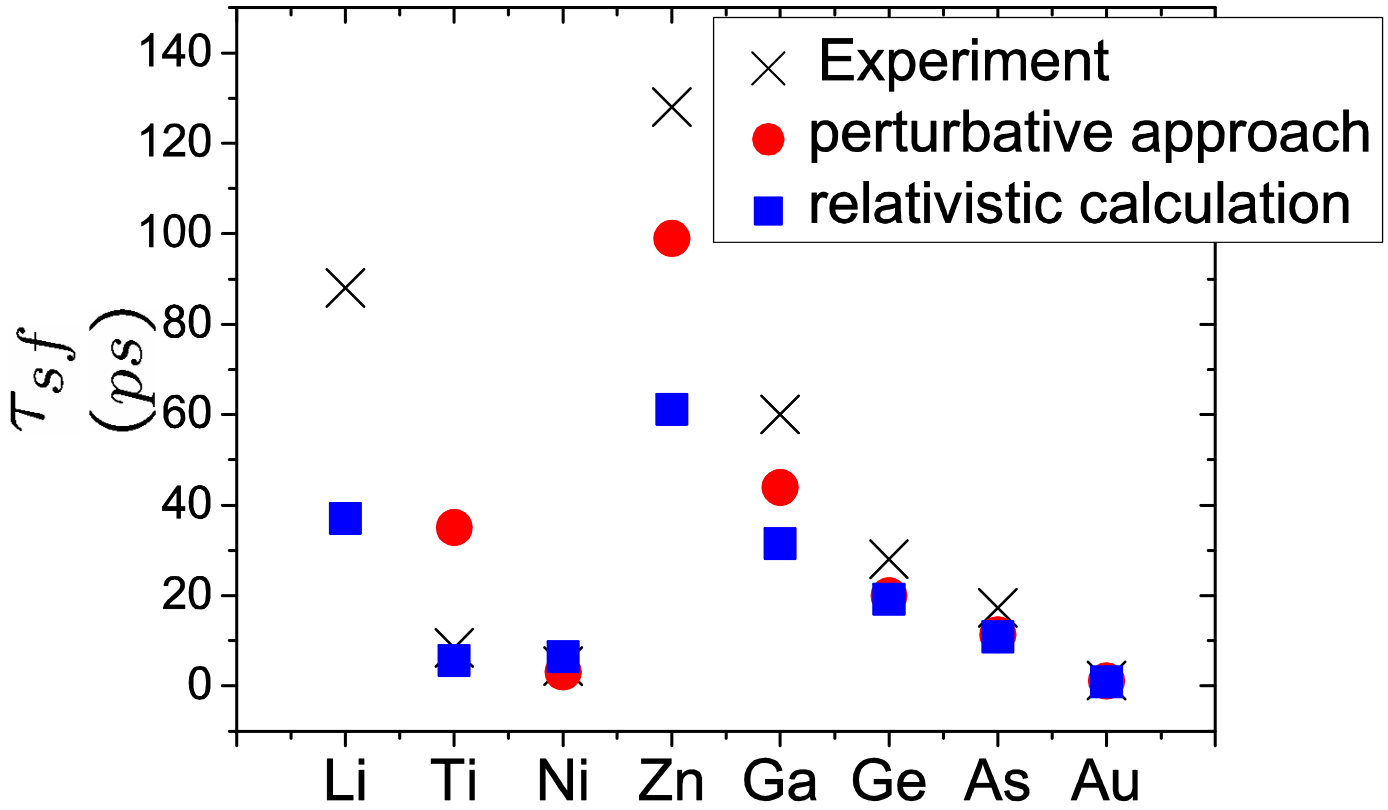
Femto-seconds

Spin-flip scattering

$$\left(\tau_k^{sf}\right)^{-1} = \sum_{k'} P_{kk'}^{+-}$$

Pico-seconds

Spin-relaxation time of dilute Cu alloys



c_0 = 1 at. %

P. Monod and S. Schultz, J. Phys. **43**, 393 (1982)

Linearized Boltzmann equation

$$\mathbf{\Lambda}^n(\mathbf{k}) = \tau_k^n \left[\mathbf{v}_k^n + \sum_{k'n'} P_{k'k}^{n'n} \mathbf{\Lambda}^{n'}(\mathbf{k}') \right]$$

$$\mathbf{\Lambda}^+(\mathbf{k}) = \left((\tau_k^{++})^{-1} + (\tau_k^{+-})^{-1} \right)^{-1} \left[\mathbf{v}_k^+ + \sum_{k'} \left[P_{k'k}^{++} \mathbf{\Lambda}^+(\mathbf{k}) + P_{k'k}^{-+} \mathbf{\Lambda}^-(\mathbf{k}) \right] \right]$$

$$\mathbf{\Lambda}^-(\mathbf{k}) = \left((\tau_k^{--})^{-1} + (\tau_k^{-+})^{-1} \right)^{-1} \left[\mathbf{v}_k^- + \sum_{k'} \left[P_{k'k}^{--} \mathbf{\Lambda}^-(\mathbf{k}) + P_{k'k}^{+-} \mathbf{\Lambda}^+(\mathbf{k}) \right] \right]$$

Scattering-in term (vertex corrections)

Linearized Boltzmann equation

$$\mathbf{\Lambda}^n(\mathbf{k}) = \tau_k^n \left[\mathbf{v}_k^n + \sum_{k'n'} P_{k'k}^{n'n} \mathbf{\Lambda}^{n'}(\mathbf{k}') \right]$$

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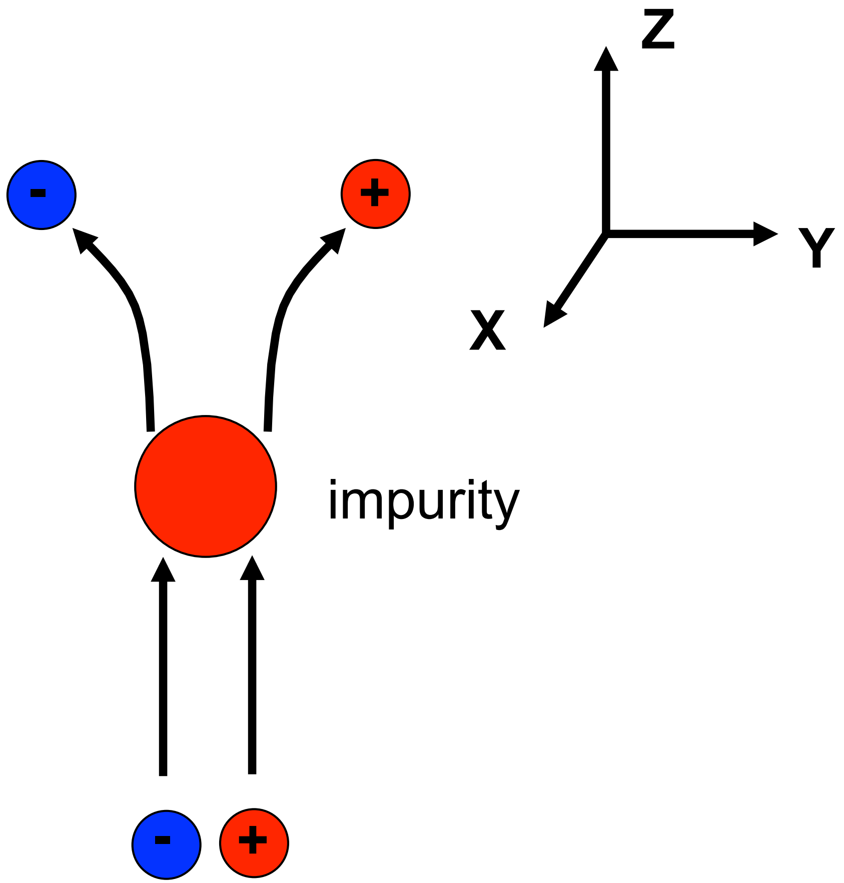
$$\mathbf{\Lambda}^-(\mathbf{k}) = \left((\tau_k^{--})^{-1} + (\tau_k^{-+})^{-1} \right)^{-1} \left[\mathbf{v}_k^- + \sum_{k'} \left[P_{k'k}^{--} \mathbf{\Lambda}^-(\mathbf{k}) + P_{k'k}^{+-} \mathbf{\Lambda}^+(\mathbf{k}) \right] \right]$$

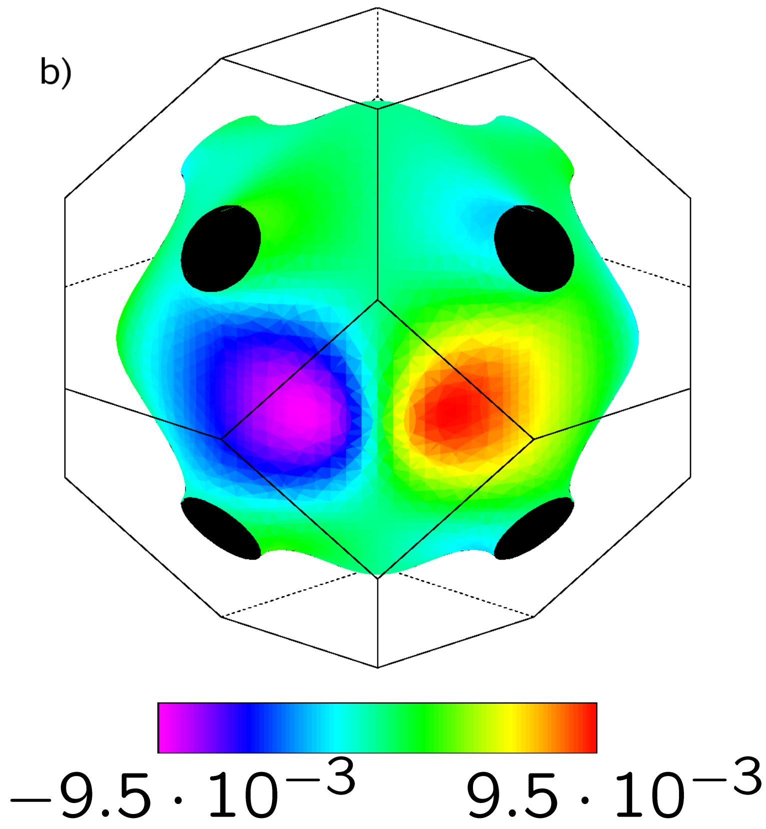
Scattering-in term (vertex corrections)

Asymmetry of the microscopic transition probability

$$k_0 = (1,0,0)$$

$$P^{++}_{k_0k'} - P^{--}_{k_0k'}$$





M. Gradhand et al., PRL **104**, 186403 (2010)

Linearized Boltzmann equation

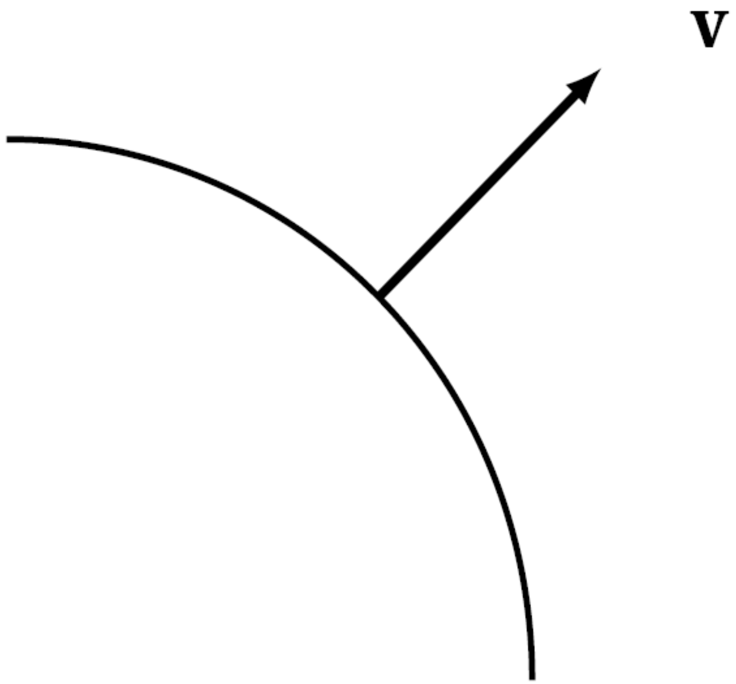
$$\mathbf{\Lambda}^n(\mathbf{k}) = \tau_k^n \left[\mathbf{v}_k^n + \sum_{k'n'} P_{k'k}^{n'n} \mathbf{\Lambda}^{n'}(\mathbf{k}') \right]$$

$$\mathbf{\Lambda}^+(\mathbf{k}) = \left((\tau_k^{++})^{-1} + (\tau_k^{+-})^{-1} \right)^{-1} \left[\mathbf{v}_k^+ + \sum_{k'} \left[P_{k'k}^{++} \mathbf{\Lambda}^+(\mathbf{k}) + P_{k'k}^{-+} \mathbf{\Lambda}^-(\mathbf{k}) \right] \right]$$

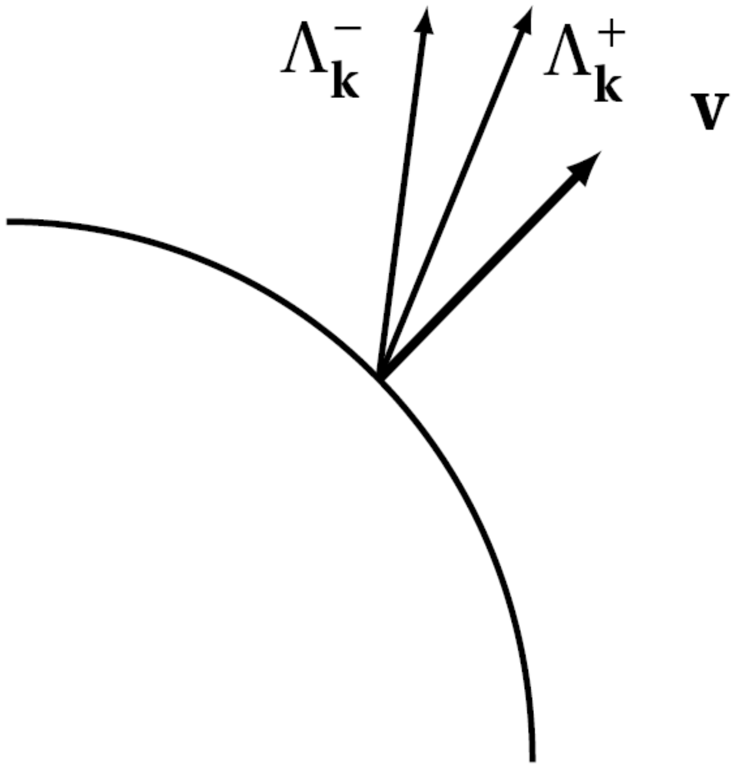
$$\mathbf{\Lambda}^-(\mathbf{k}) = \left((\tau_k^{--})^{-1} + (\tau_k^{-+})^{-1} \right)^{-1} \left[\mathbf{v}_k^- + \sum_{k'} \left[P_{k'k}^{--} \mathbf{\Lambda}^-(\mathbf{k}) + P_{k'k}^{+-} \mathbf{\Lambda}^+(\mathbf{k}) \right] \right]$$

Scattering-in term (vertex corrections)

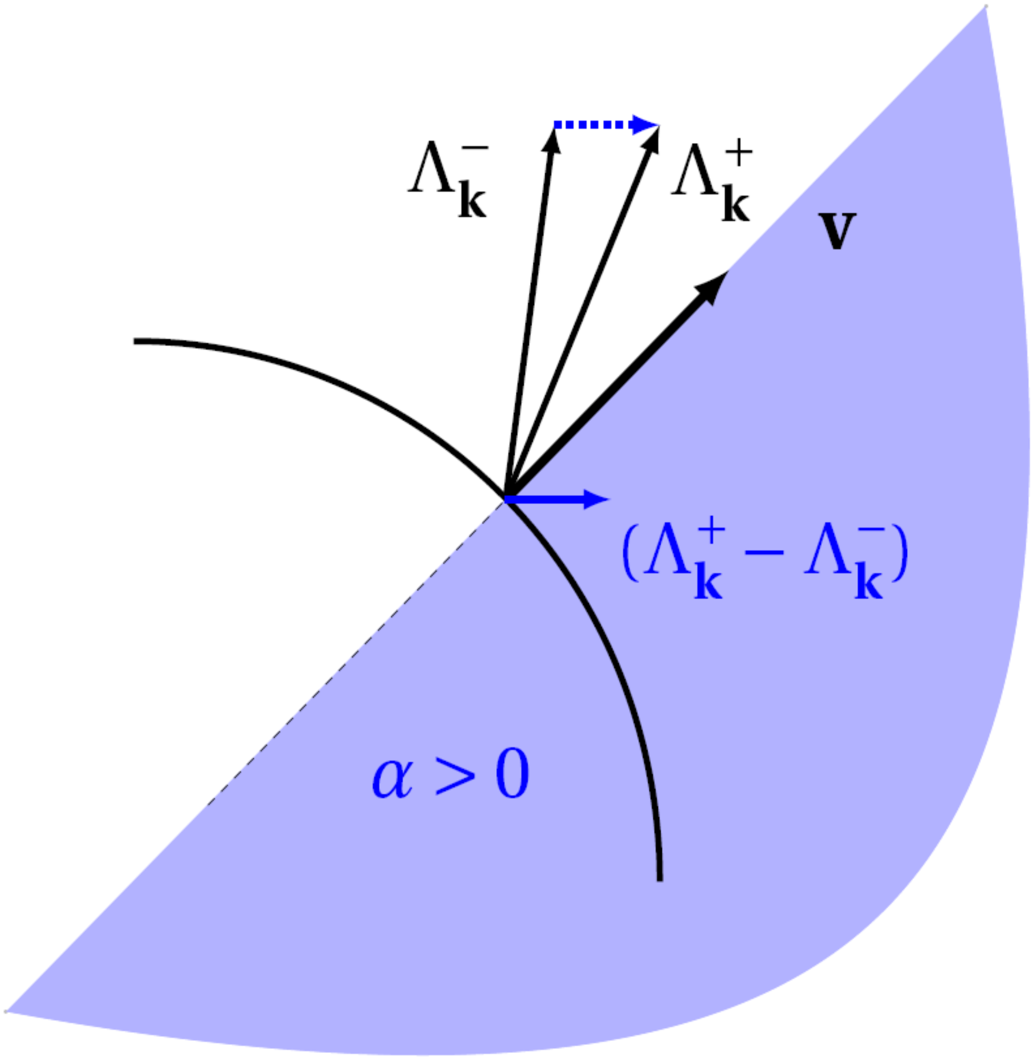
Spin anisotropy of the vector mean free path



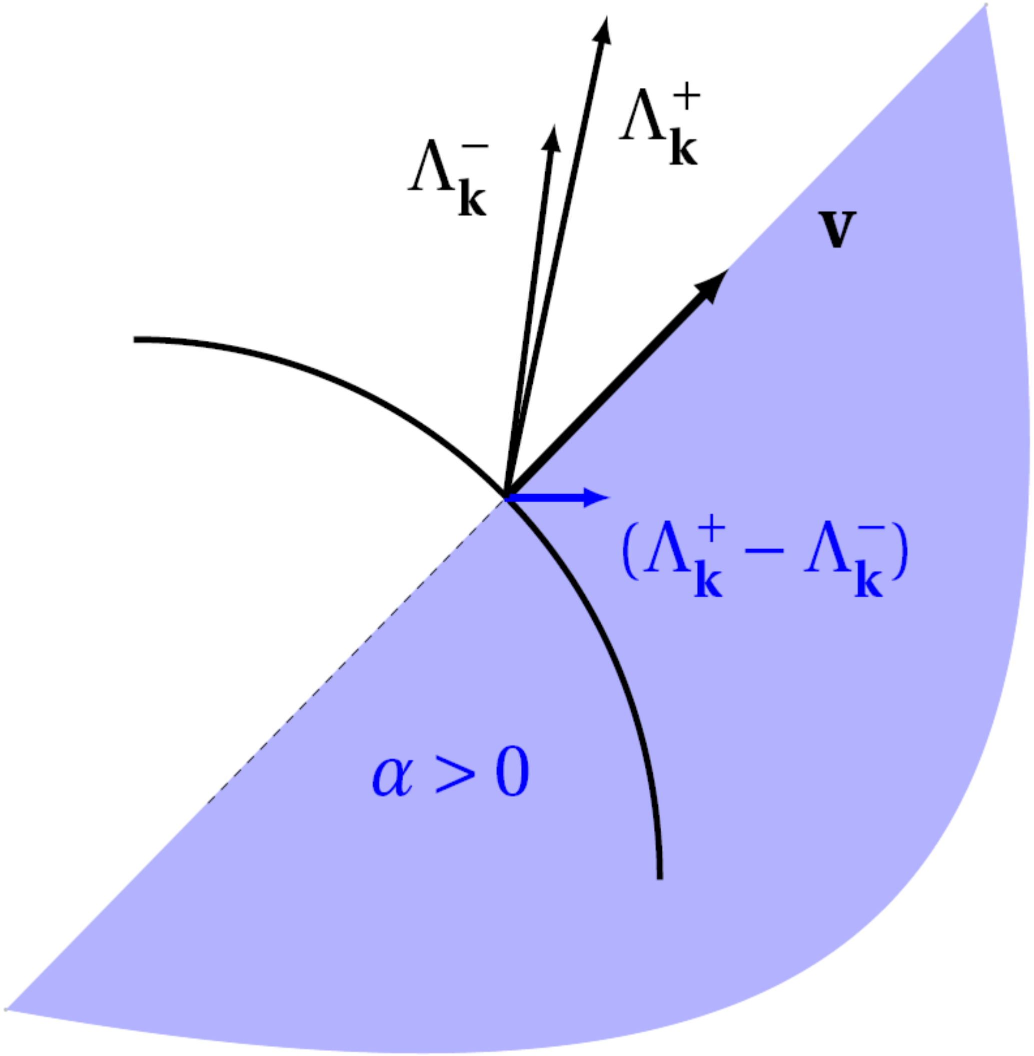
Spin anisotropy of the vector mean free path



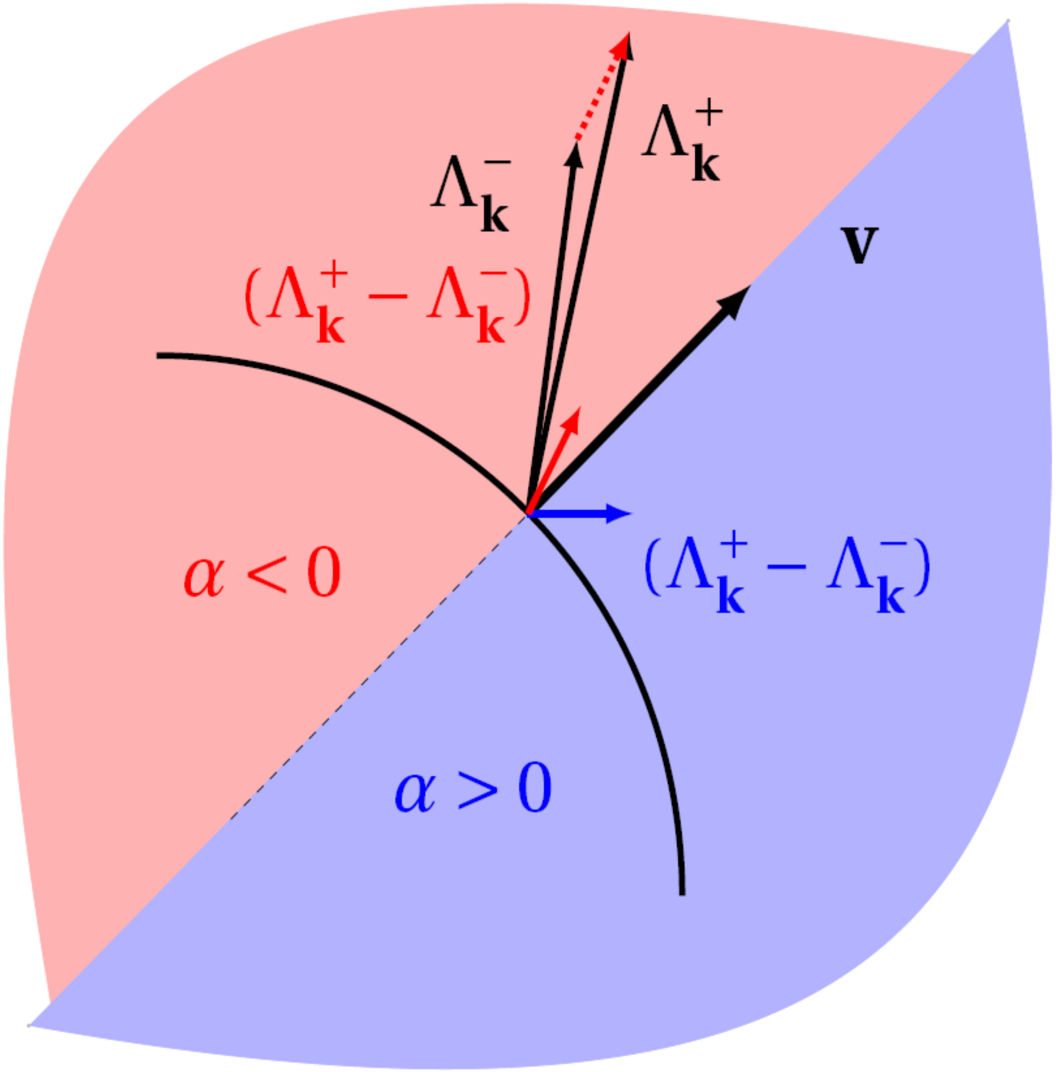
Spin anisotropy of the vector mean free path



Spin anisotropy of the vector mean free path



Spin anisotropy of the vector mean free path



Conductivities

Charge conductivity:

$$\underline{\boldsymbol{\sigma}} = \underline{\boldsymbol{\sigma}}^{+} + \underline{\boldsymbol{\sigma}}^{-} = \frac{e^2}{(2\pi)^3} \sum_n \iint dS \frac{1}{|\mathbf{v}_k^n|} \mathbf{v}_k^n \circ \boldsymbol{\Lambda}^n(\mathbf{k})$$

Spin conductivity:

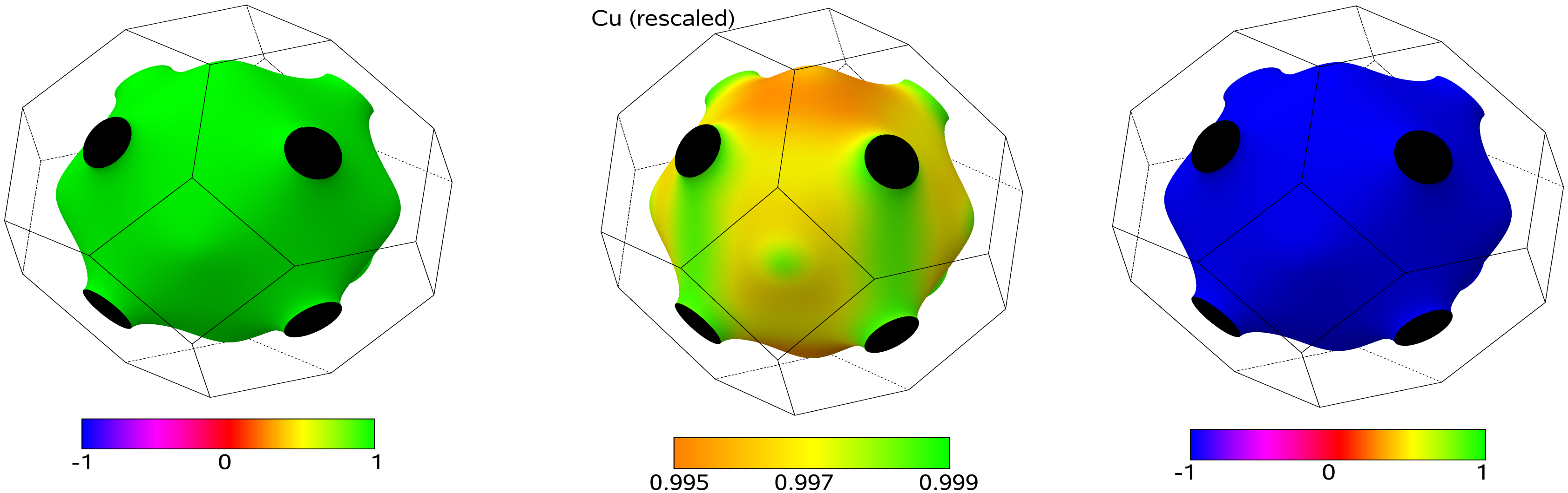
$$\underline{\boldsymbol{\sigma}}_{s_z} = \underline{\boldsymbol{\sigma}}^{+} - \underline{\boldsymbol{\sigma}}^{-} = \frac{e^2}{(2\pi)^3} \sum_n \iint dS \frac{s_z^n(k)}{|\mathbf{v}_k^n|} \mathbf{v}_k^n \circ \boldsymbol{\Lambda}^n(\mathbf{k})$$

Spin polarization: $s_z^n(k) = \left\langle \Phi_k^n \left| \beta \hat{\sigma}_z \right| \Phi_k^n \right\rangle$

F. Pientka et al., PRB **86**, 054413 (2012)

Spin character of Cu states

$$\left\langle \Phi_k^{+}(\mathbf{r}) \left| \beta \hat{\sigma}_z \right| \Phi_k^{+}(\mathbf{r}) \right\rangle \qquad \left\langle \Phi_k^{-}(\mathbf{r}) \left| \beta \hat{\sigma}_z \right| \Phi_k^{-}(\mathbf{r}) \right\rangle$$

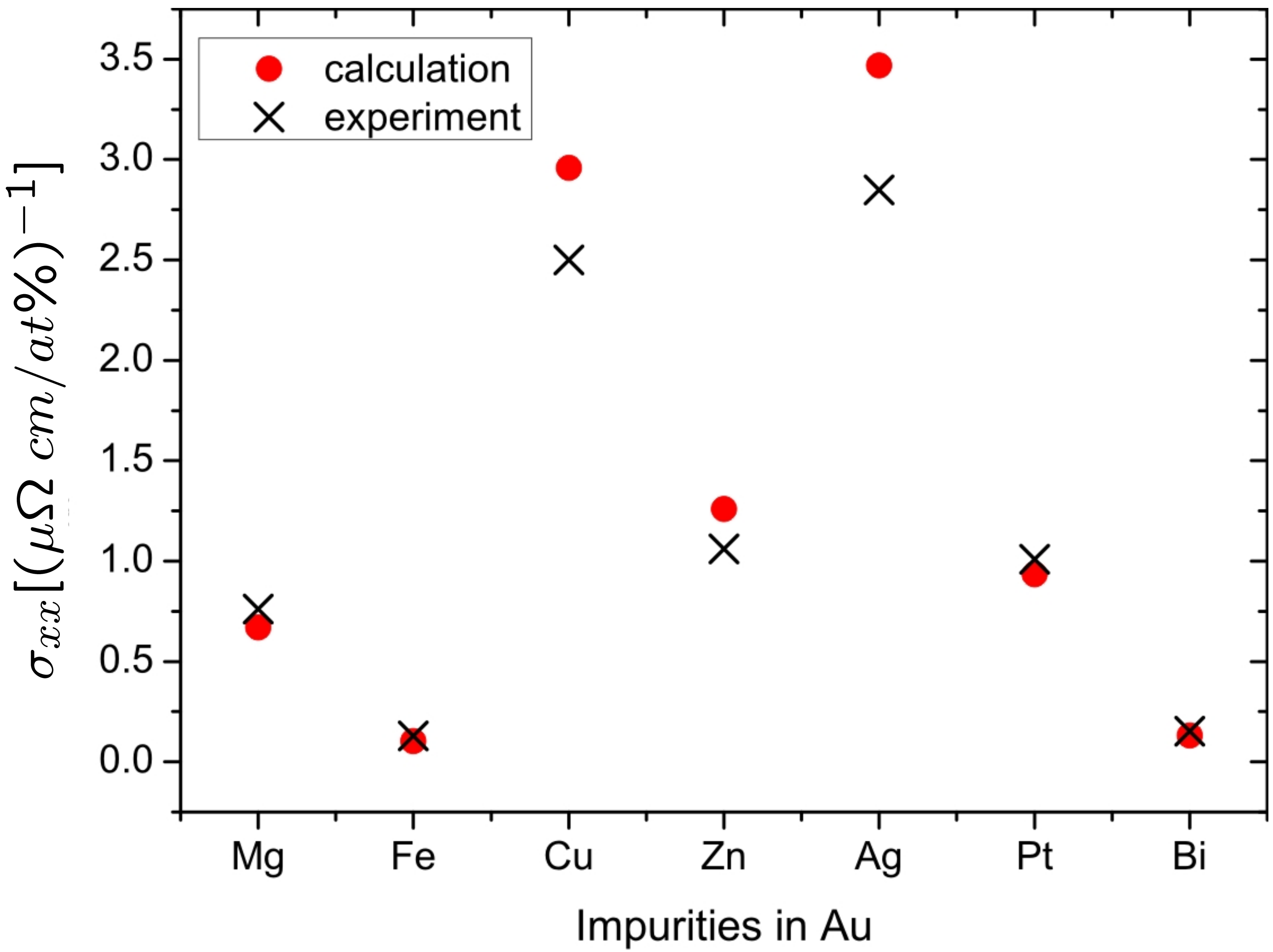


-1 0 1 0.995 0.999 -1 0 1

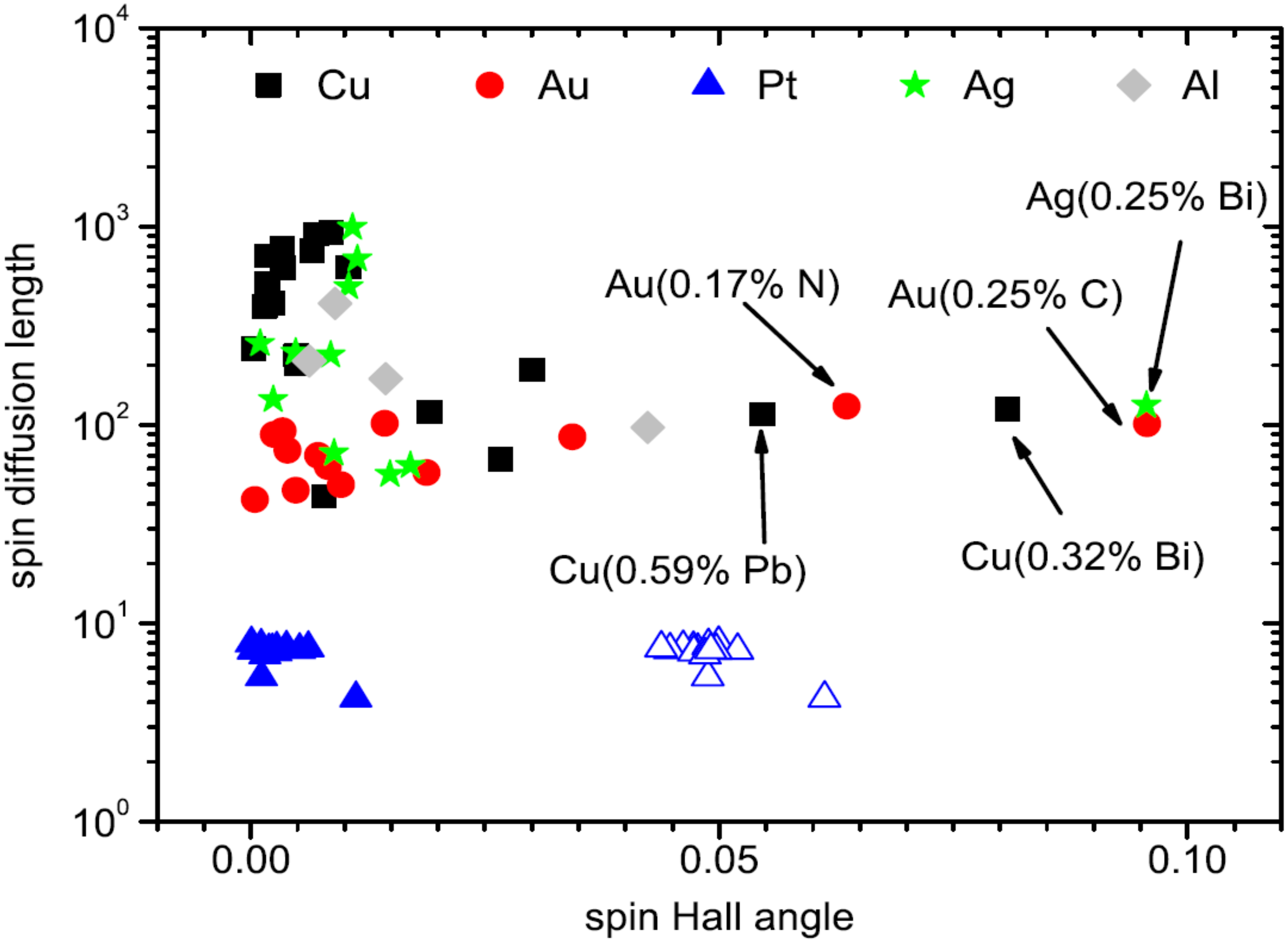
well defined spin character in Cu

M. Gradhand et al., PRB **80**, 224413 (2009)

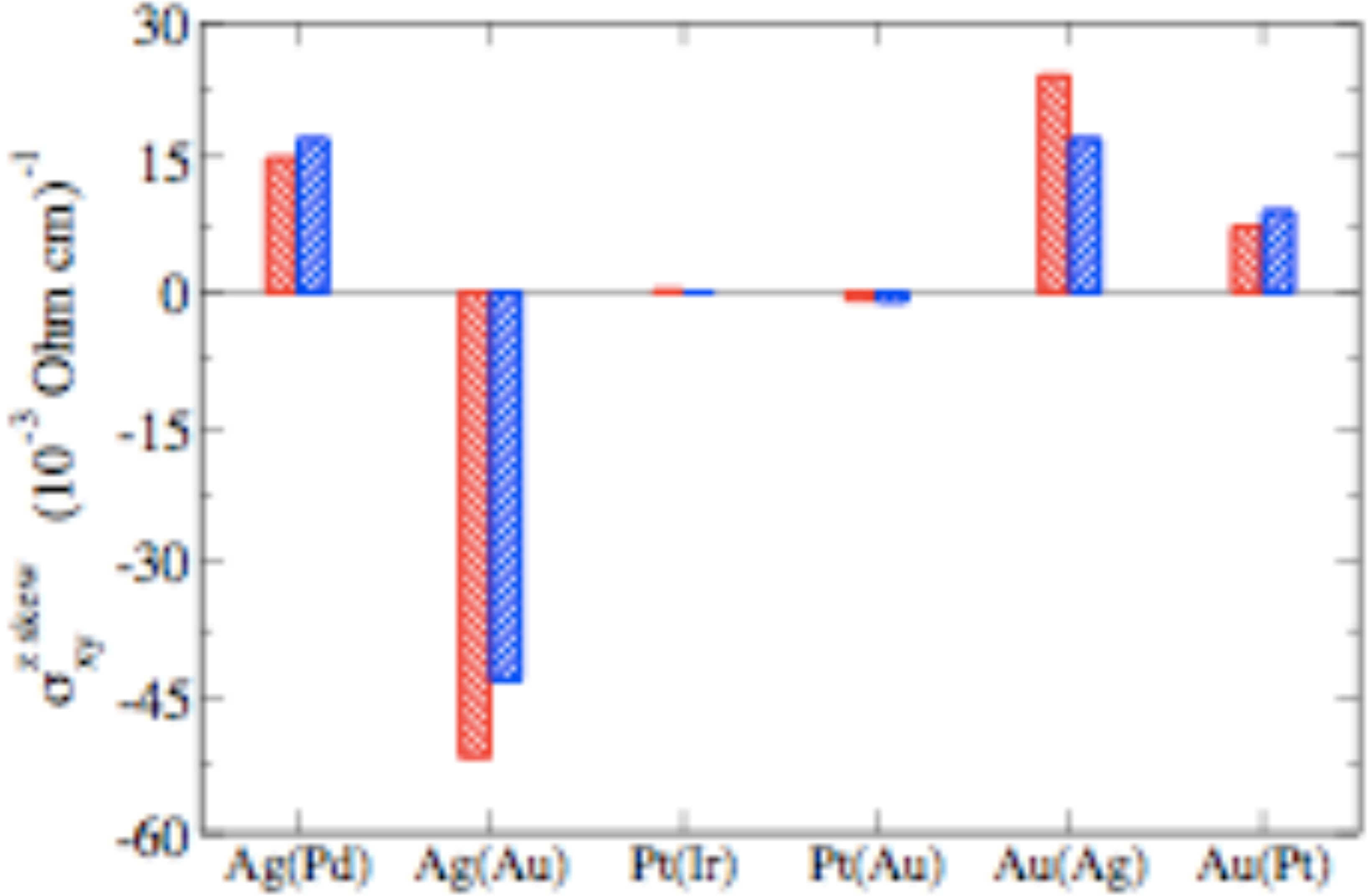
Conductivity of dilute Au alloys



Searching for optimal material



Boltzmann versus Kubo



A. Lowitzer et al., PRL **106**, 056601 (2011)

Signatures of the optimal material

Skew-scattering contribution:

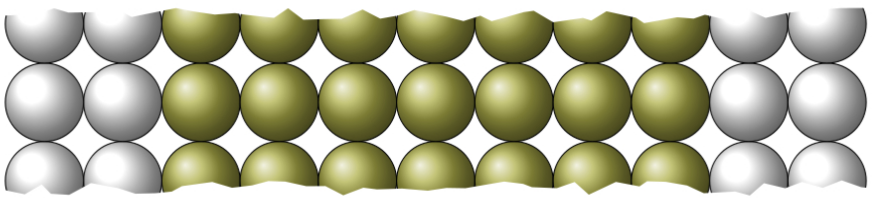
- Low impurity concentration
- Large difference of spin-orbit interaction between host and impurity
- Reduction by interband transitions
- Single-sheeted Fermi surfaces

Intrinsic contribution:

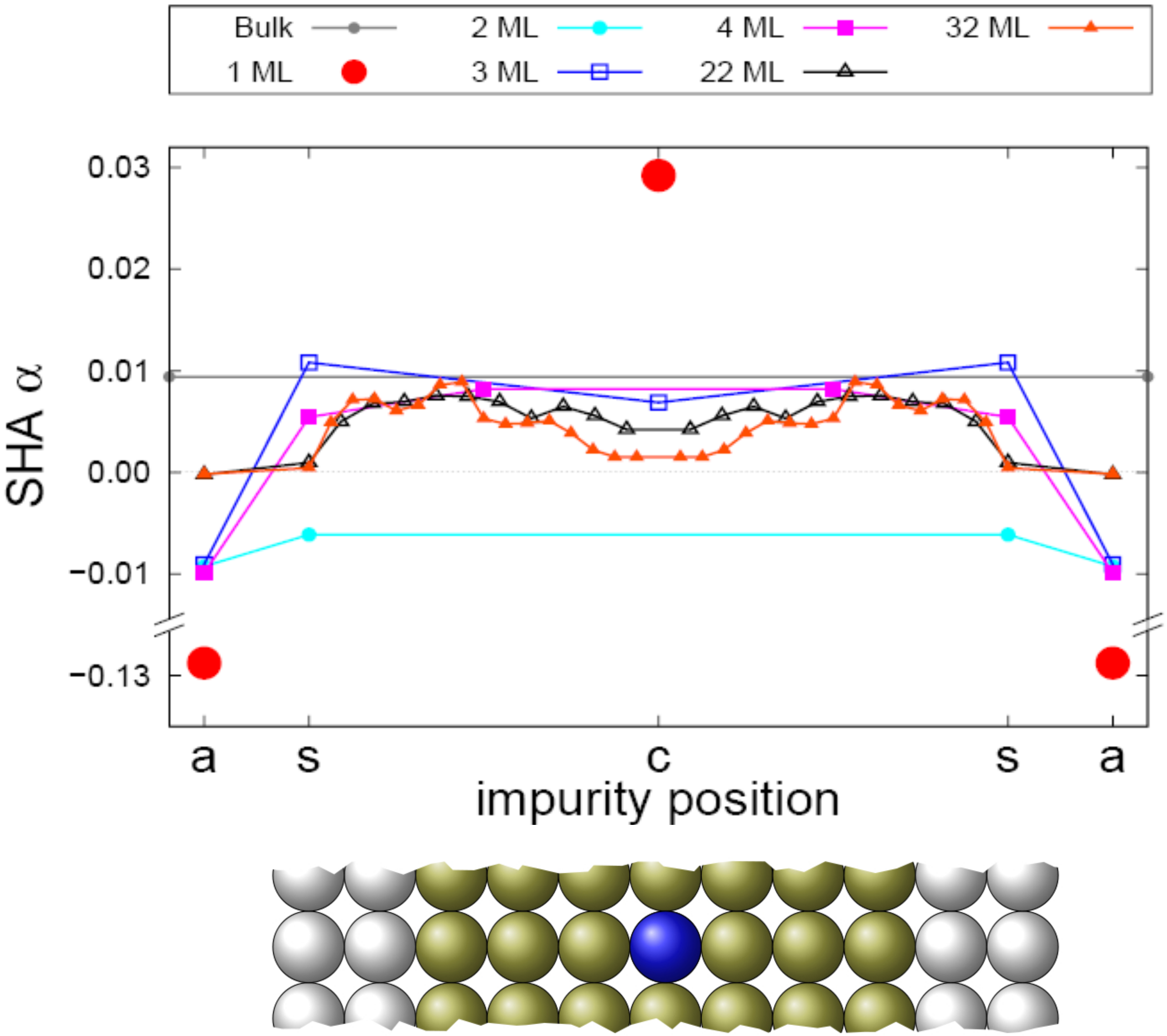
- Enhancement by interband transitions
- Multi-sheeted Fermi surface

Spin Hall effect in ultrathin films

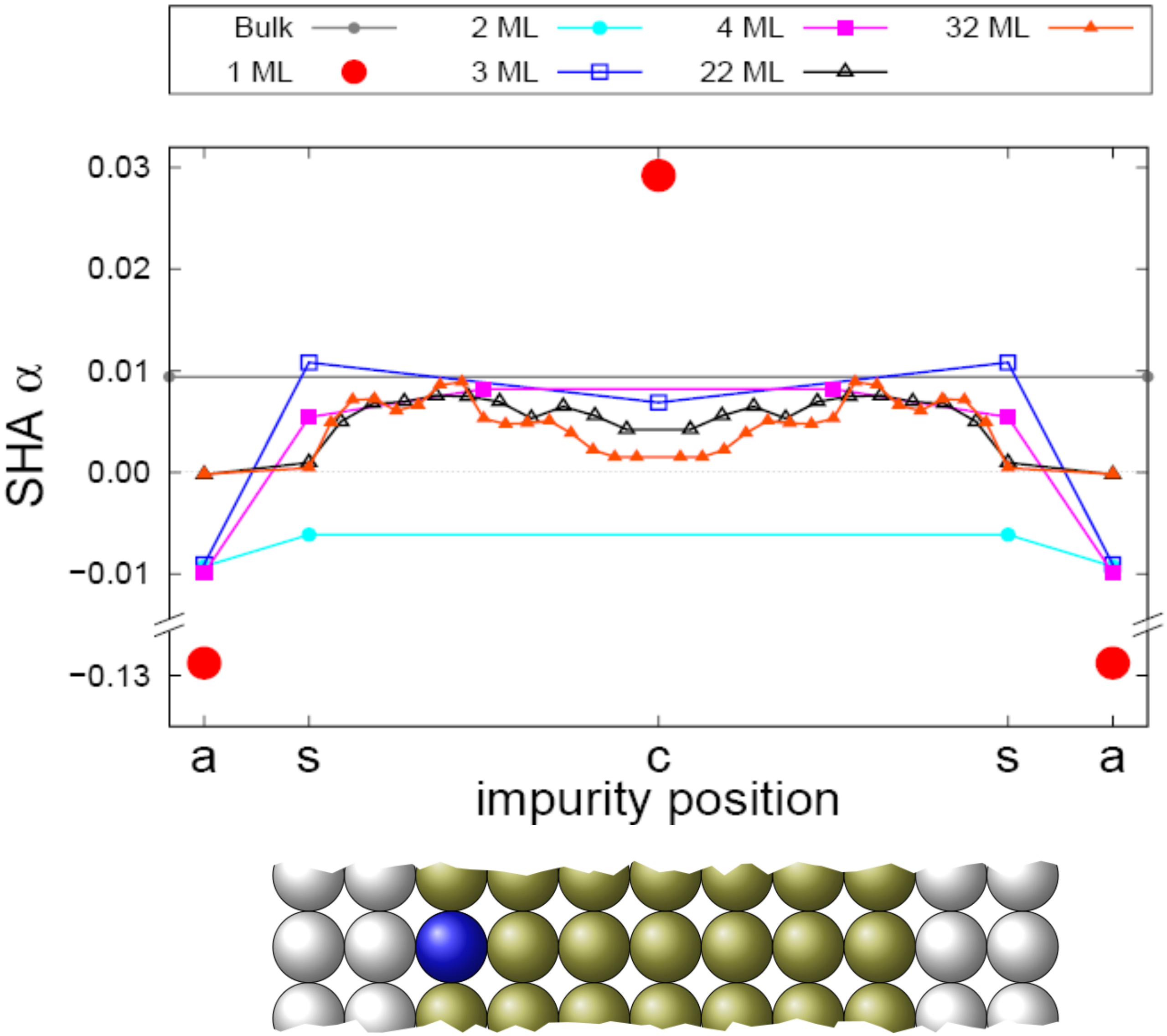
C. Herschbach, M. Gradhand, D.V. Fedorov, and I. M., Phys. Rev. B **85**, 195133 (2012)



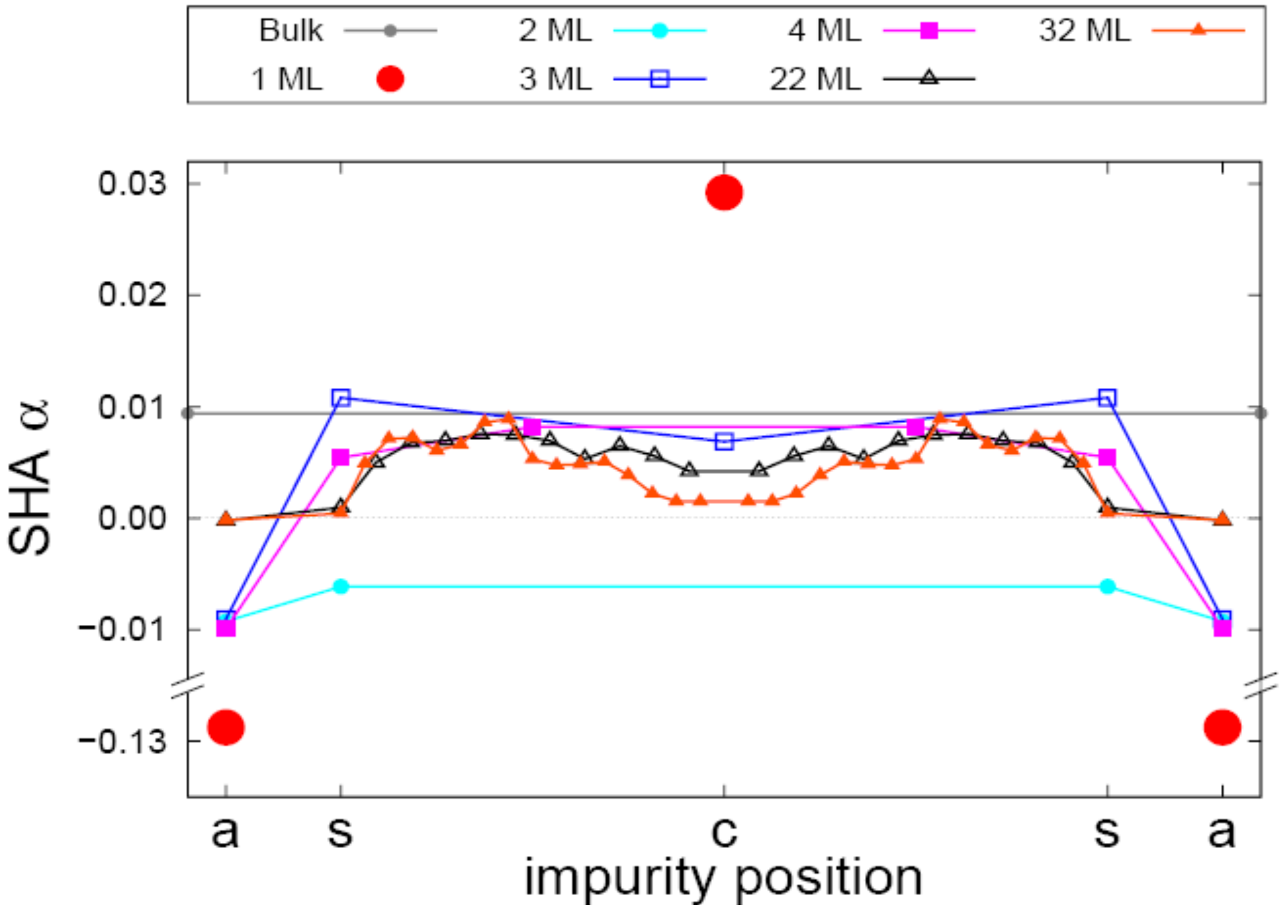
Spin Hall angle of Au(111) films with Pt impurities

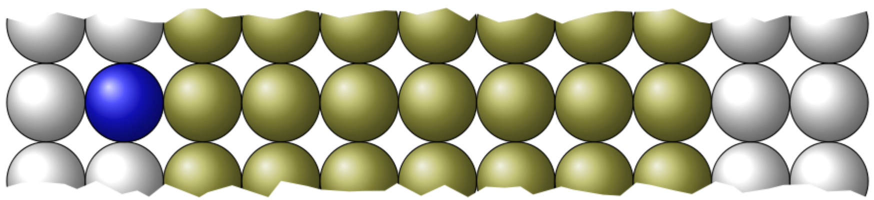


Spin Hall angle of Au(111) films with Pt impurities

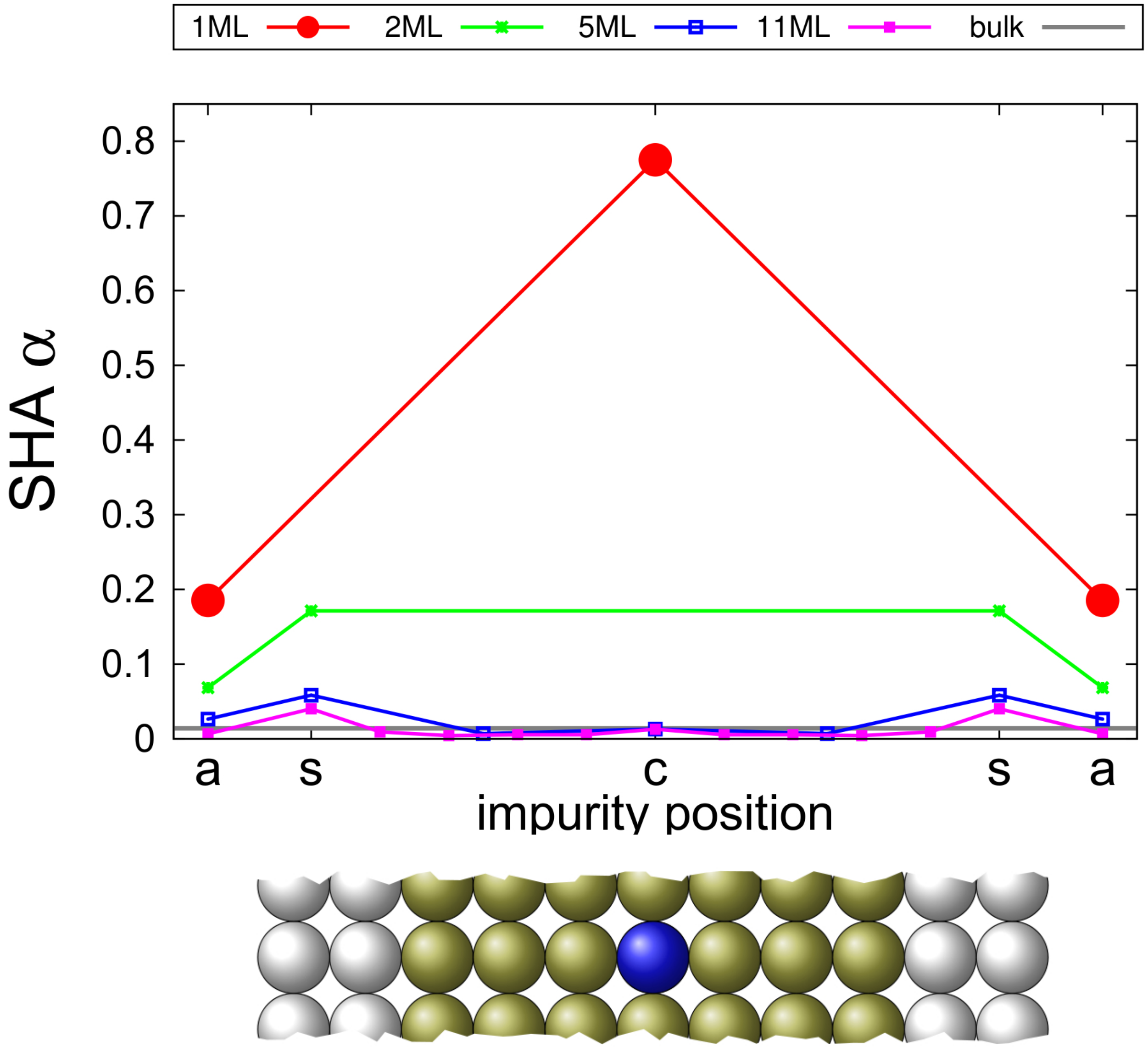


Spin Hall angle of Au(111) films with Pt impurities

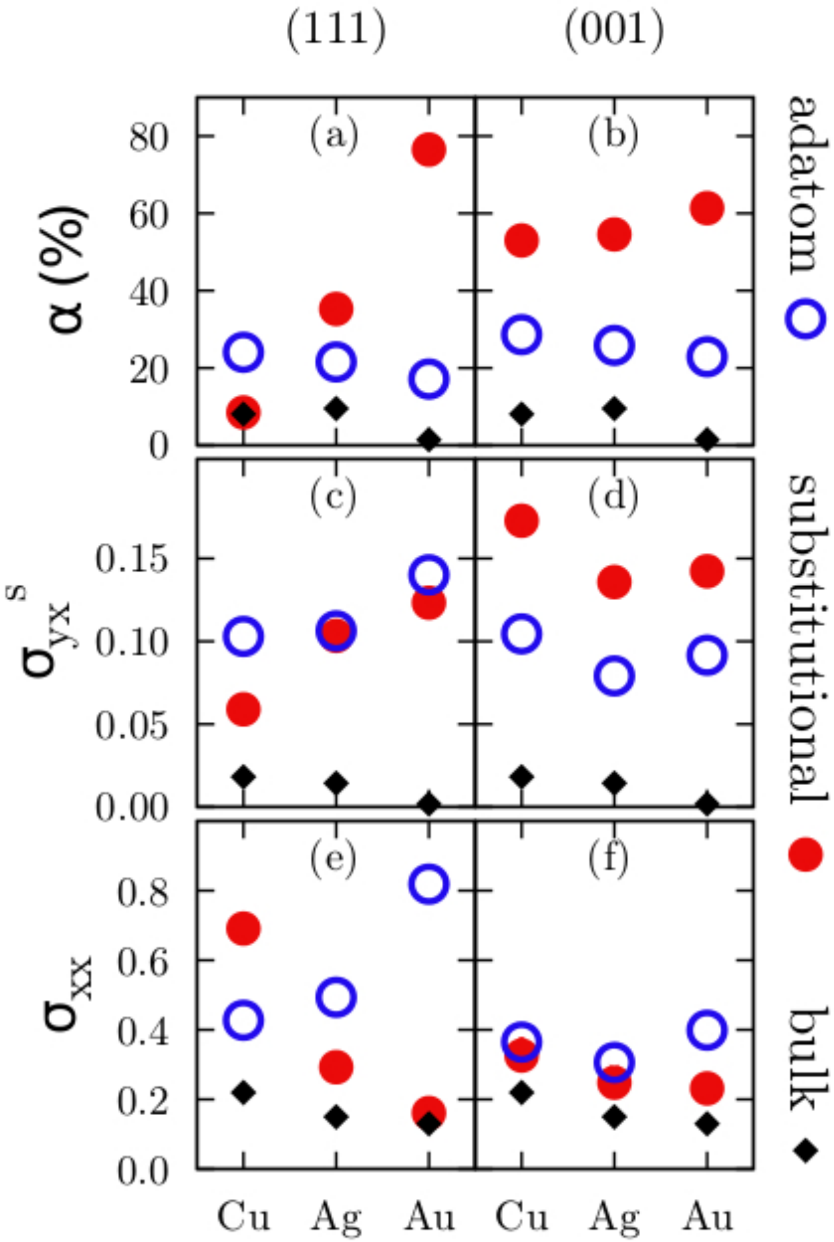




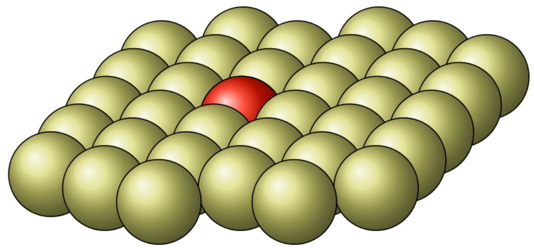
Spin Hall angle of Au(111) films with Bi impurities



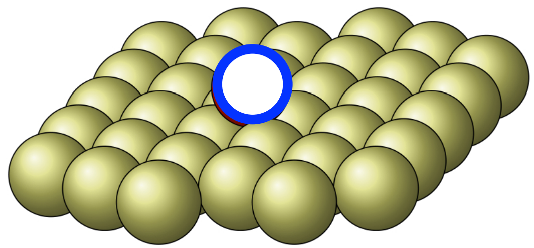
Ultrathin noble metal films with Bi impurities



substitutional Bi



Bi adatom

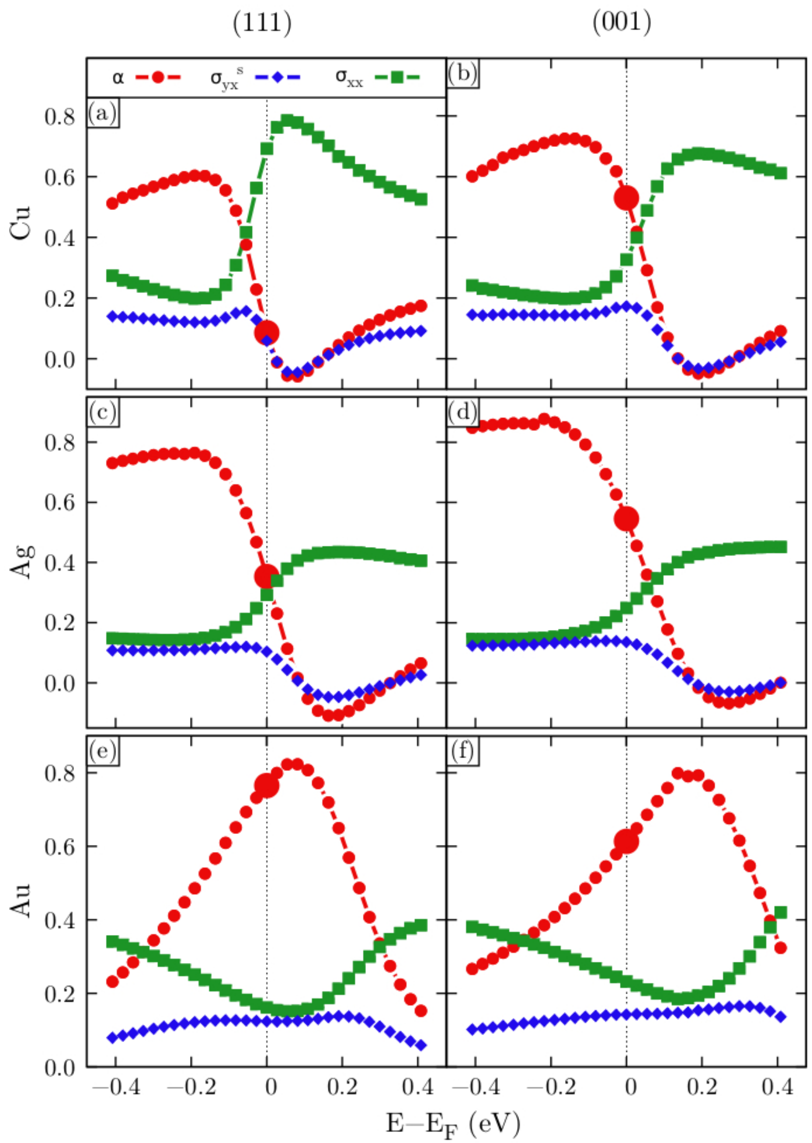


Energy dependence

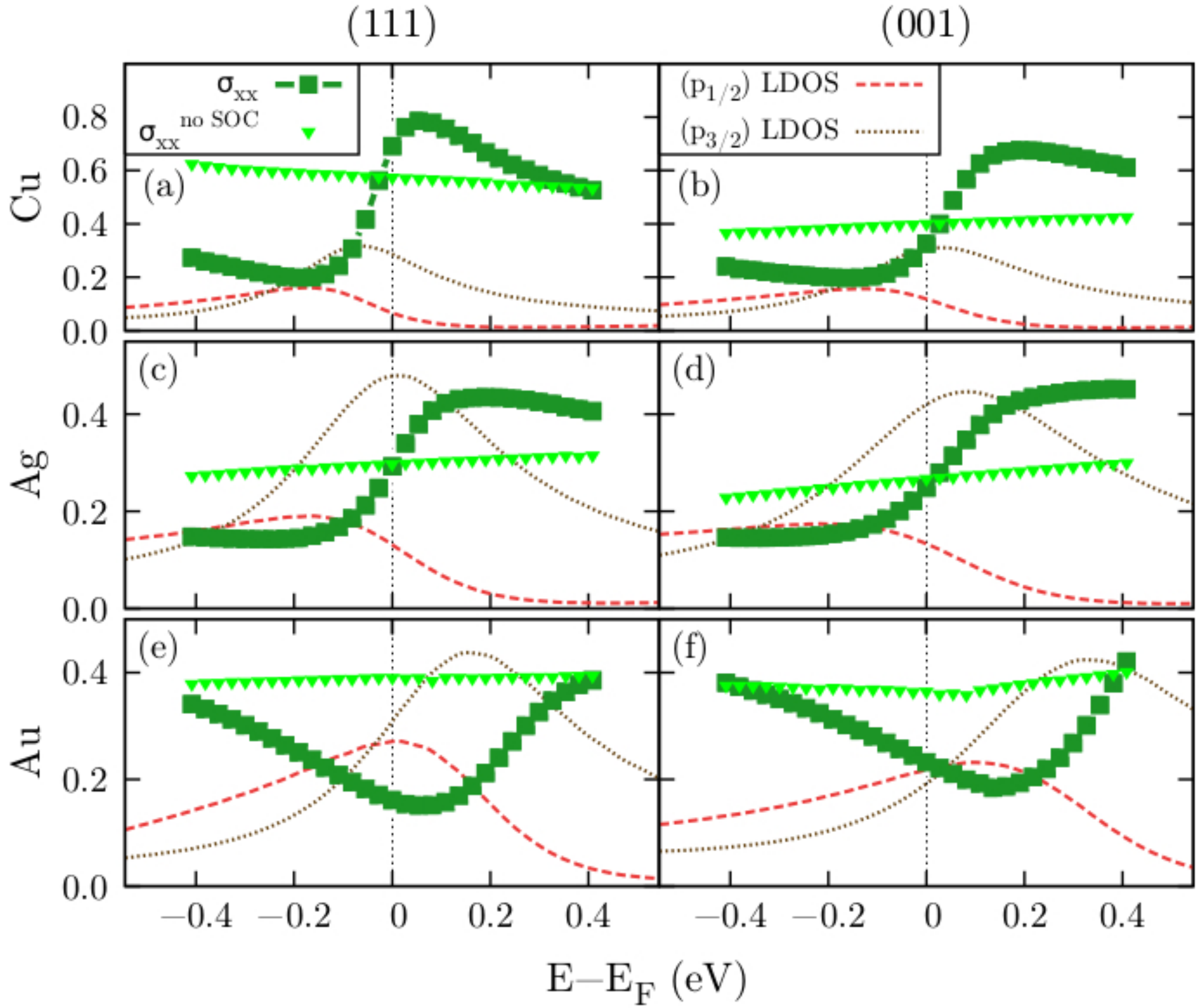
α

$\sigma^{xy}_{s_z}$

σ^{xx}

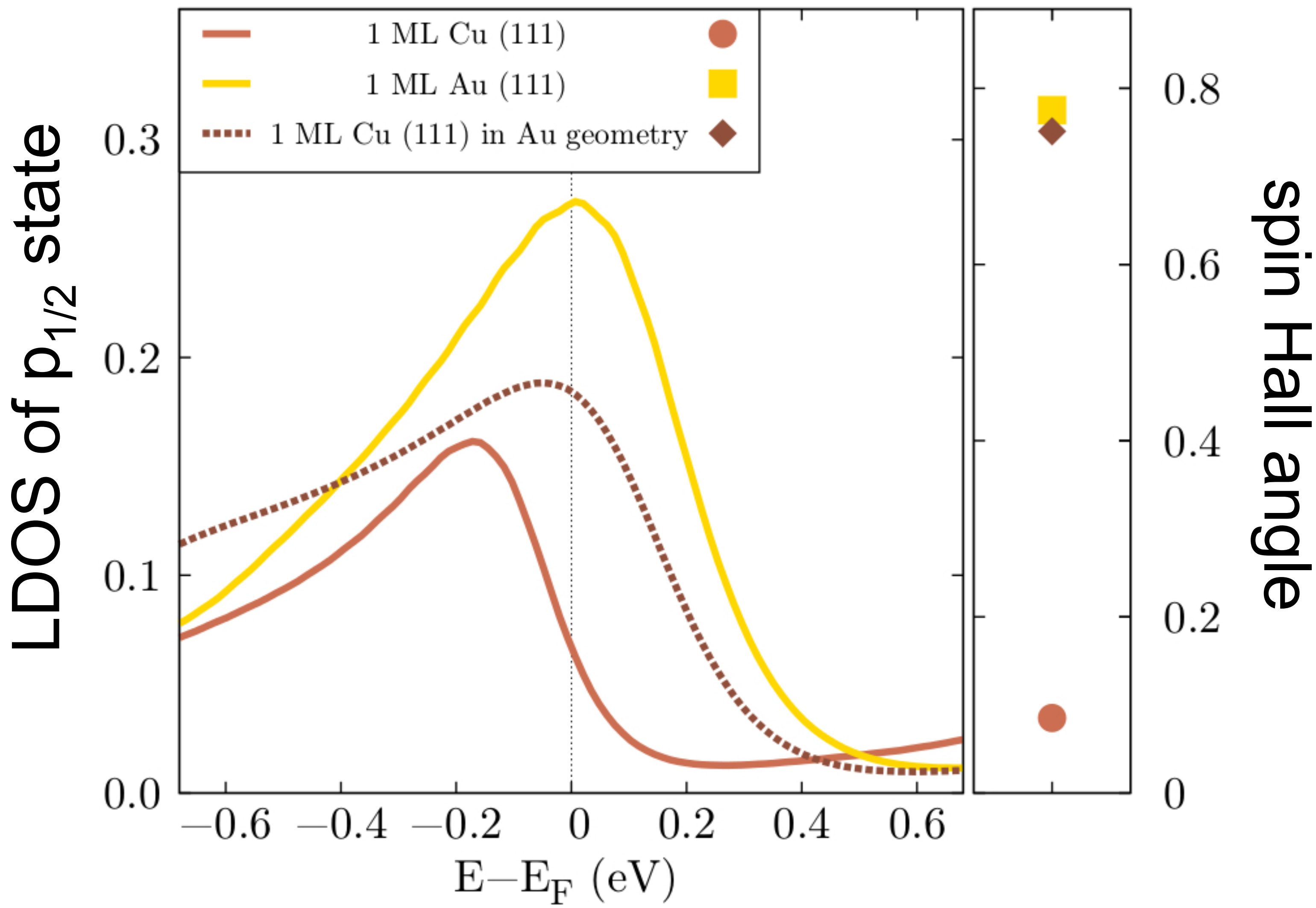


Energy dependence of σ^{xx} without soc



σ^{xx}

Strain-enhanced spin Hall angle



Influence of quantum confinement

Quantum confinement:

- Modulation of the absolute values
- Possible reversal of sign by adatoms
- Gigantic effect in one-monolayer films
- Role of the longitudinal conductivity
- Strain-enhanced spin Hall angle