Spin- polarized currents in non-collinear antiferromagnets

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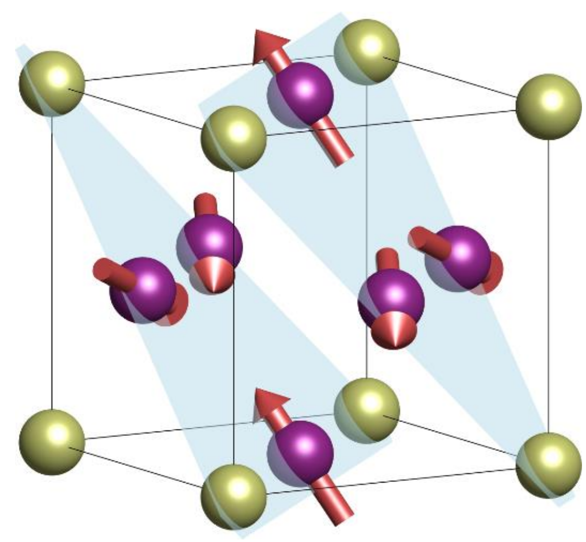


Antiferromagnetic spintronics

Rising interest in antiferromagnets for spintronics applications

Some advantages over ferromagnets:

- ✓ Fast dynamics
- ✓ No stray fields, insensitive to magnetic fields
- ✓ Wide range of antiferromagnetic materials including metals, semiconductors, insulators, multiferroics, superconductors…

but

The antiferromagnetic order is difficult to manipulate and detect

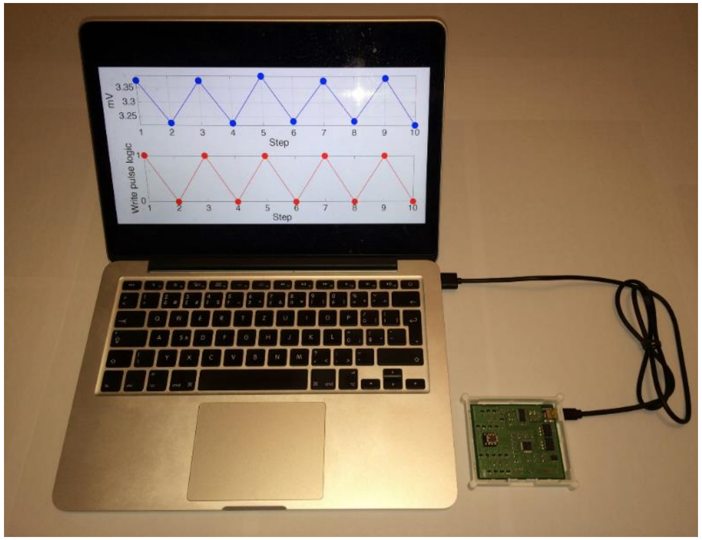
Many spintronics effects, which exist in ferromagnets are prohibited by symmetry in most antiferromagnets

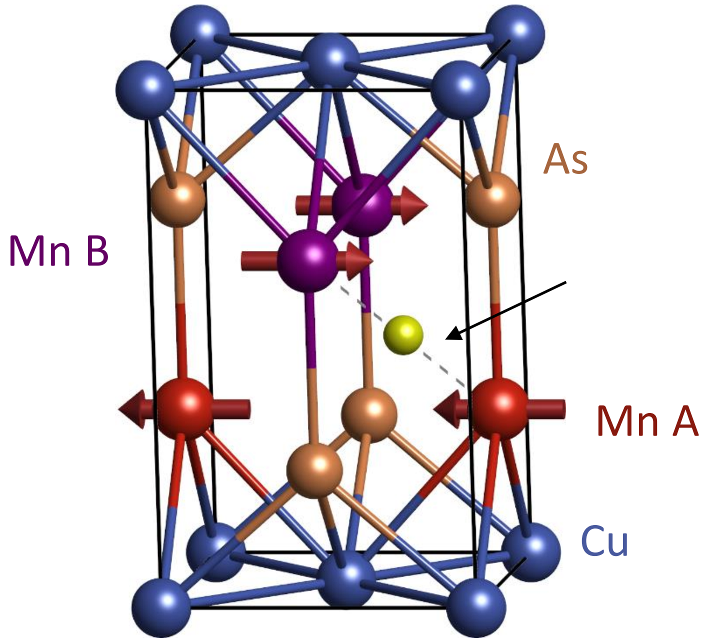
Spin-orbit torques in antiferromagnets

Electrical control and detection of the antiferromagnetic order has been demonstrated

A key to efficient manipulation of the antiferromagnetic order is using a **staggered magnetic field**

Can be generated by spin-orbit torque

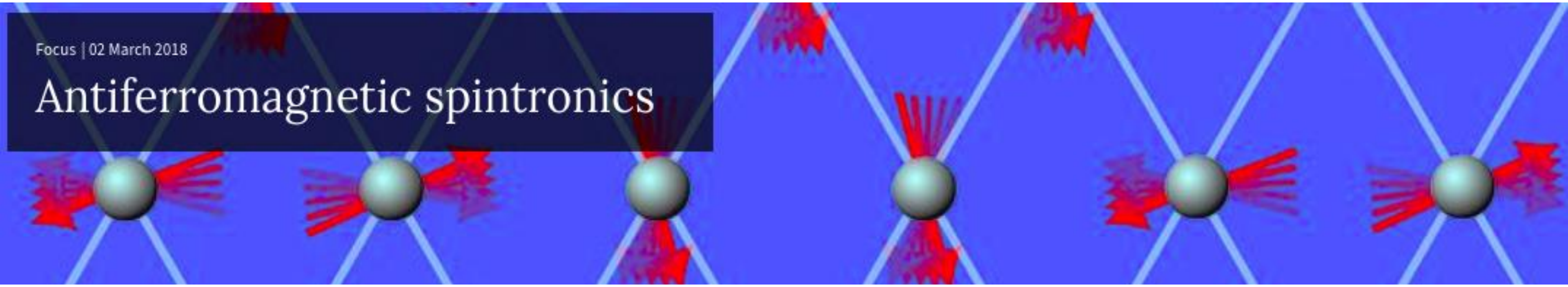




CuMnAs

Zelezny et al., PRL 113, 157201 (2014)
Wadley et al., Science 351, 587–590 (2016)
Bodnar et al., arXiv:1706.02482
Meinert et al., arXiv:1706.06983

Nature physics focused issue on antiferromagnetic spintronics



Overview - *T. Jungwirth et al., Nature Physics* ***14****, 200–203 (2018)*

Transport - *J. Železný et al., Nature Physics* ***14****, 220-228 (2018)*

Opto-spintronics - *P. Němec et al., Nature Physics* ***14****, 229-241 (2018)*

Spin textures and dynamics - *O. Gomonay et al., Nature Physics* ***14****, 213-216 (2018)*

Topology - *L. Šmejkal et al., Nature Physics* ***14****, 242-251 (2018)*

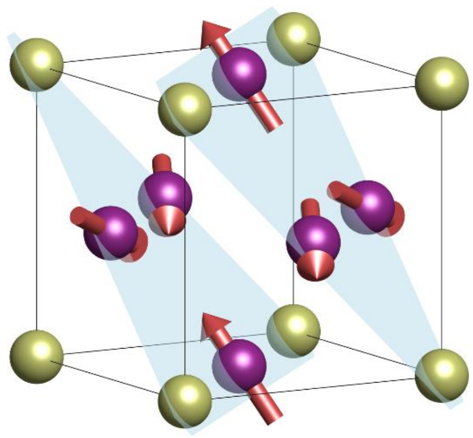
Synthetic antiferromagnets - *R. A. Duine et al., Nature Physics* ***14****, 217-219 (2018)*

Non-collinear antiferromagnets

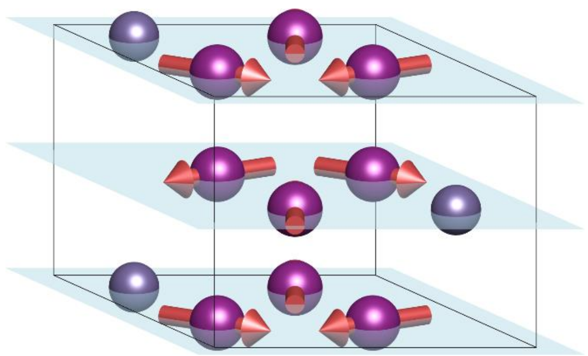
Non-collinear order is common in antiferromagnets

The most commonly used antiferromagnets are non-collinear alloys of Mn-Ir

Triangular antiferromagnets Mn3X



Mn_3Rh, Mn_3Pt, Mn_3Ir



Mn_3Ga, Mn_3Ge, Mn_3Sn

- Experimentally studied and relevant for technology
- Simplest example of a non-collinear magnetic order

Triangular antiferromagnets

- Néel temperatures above room temperature

- Large anomalous Hall effect -> also XMCD, Kerr effect, Anomalous Nernst effect

Chen et al., PRL 112, 017205 (2014) *Kubler et al., EPL 108, 67001 (2014)* *Feng et al., PRB 92, 144426 (2015)*

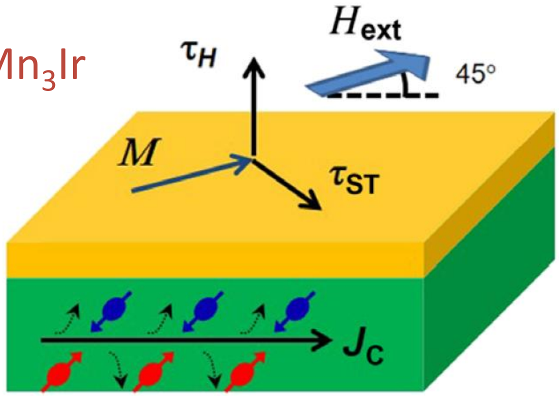
Nayak et al. Sci. Adv. 2016;2:e1501870 *Naktsuji et al. Nature 527, 212 (2015)* *Ikhlas et al., Nature Physics 13, 1085–1090 (2017)*

- Large spin-orbit torque generated by spin-Hall effect in Mn_3Ir

Zhang et al. Sci. Adv. 2016;2:e1600759

Thsitoyan et al., Phys. Rev. B 92, 214406 (2015)

Young-Wang Oh et al., Nature Nanotech. 11, (2016)



- Cancellation of anisotropy in the hexagonal antiferromagnets

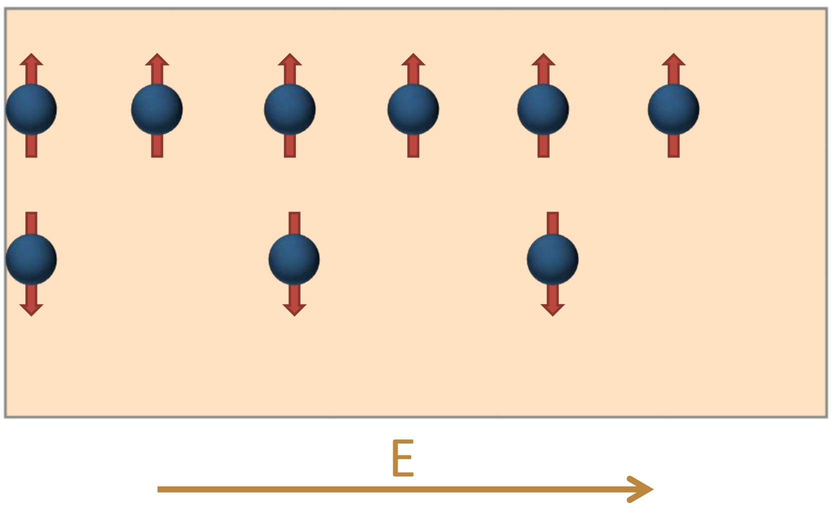
Field which can orient the domains: Mn_3Ir: > 60 T

Mn_3Sn: 0.03 T

Tomiyoshi et al., J. Phys. Soc. Japan 51, 2478 (1981)

Spin currents

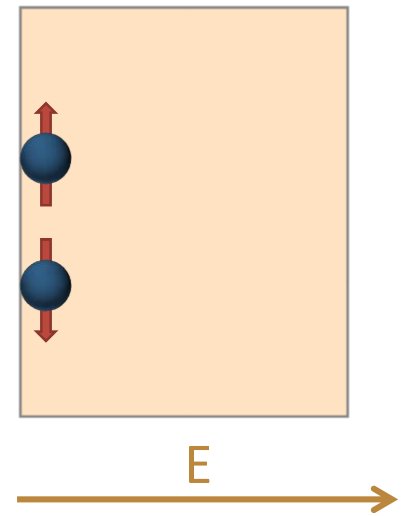
Spin-polarized current in ferromagnets



Odd under time-reversal

Non-relativistic origin

Spin-Hall effect



Even under time-reversal

Relativistic origin

Spin currents are responsible for giant and tunneling magnetoresistance, spin-transfer torque, spin-orbit torque,…

Definition of spin current

Spin current operator is normally defined as: $\hat{j}^s_{ij} = \frac{1}{2}\{\hat{s}_i, \hat{v}_j\}$

Issues with this definition:

1. Spin is not conserved so the spin current does not satisfy the continuity equation

$$\frac{\partial S_z}{\partial t} + \nabla \cdot \mathbf{J}_s = \mathcal{T}_z$$

Shi et al., PRL 96, 076604 (2006)

2. Spin current can occur in equilibrium

Rashba, Phys. Rev. B 68, 241315(R) 2003

3. Spin currents also can exist in insulators
4. Spin current cannot be directly measured

But it's a well defined (and useful) physical quantity!

For accurate estimates and comparison with experiment it's best to calculate directly spin accumulation, torque…

Linear response

$$\delta A = \chi^I \mathbf{E} + \chi^{II} \mathbf{E}$$

$$\chi^I = -\frac{e\hbar}{\pi} \sum_{\mathbf{k},n,m} \frac{\Gamma^2 \mathrm{Re}\left(\langle n\mathbf{k}| \hat{A} |m\mathbf{k}\rangle \langle m\mathbf{k}| \hat{\mathbf{v}} \cdot \hat{\mathbf{E}} |n\mathbf{k}\rangle \right)}{[(E_F - \varepsilon_{n\mathbf{k}})^2 + \Gamma^2][E_F - \varepsilon_{m\mathbf{k}})^2 + \Gamma^2]},$$

$$\chi^{II} = -2\hbar e \sum_{\mathbf{k},n\neq m}^{\substack{n \text{ occ.} \\ m \text{ unocc.}}} \frac{\mathrm{Im}\left(\langle n\mathbf{k}| \hat{A} |m\mathbf{k}\rangle \langle m\mathbf{k}| \hat{\mathbf{v}} \cdot \hat{\mathbf{E}} |n\mathbf{k}\rangle \right)}{(\varepsilon_{n\mathbf{k}} - \varepsilon_{m\mathbf{k}})^2},$$

These two parts have precisely opposite transformation under time-reversal

Under time-reversal: $\langle n\mathbf{k}| \hat{A} |m\mathbf{k}\rangle \rightarrow \langle n\mathbf{k}| T^{-1} \hat{A} T |m\mathbf{k}\rangle^*$

We use a constant band broadening to simulate disorder

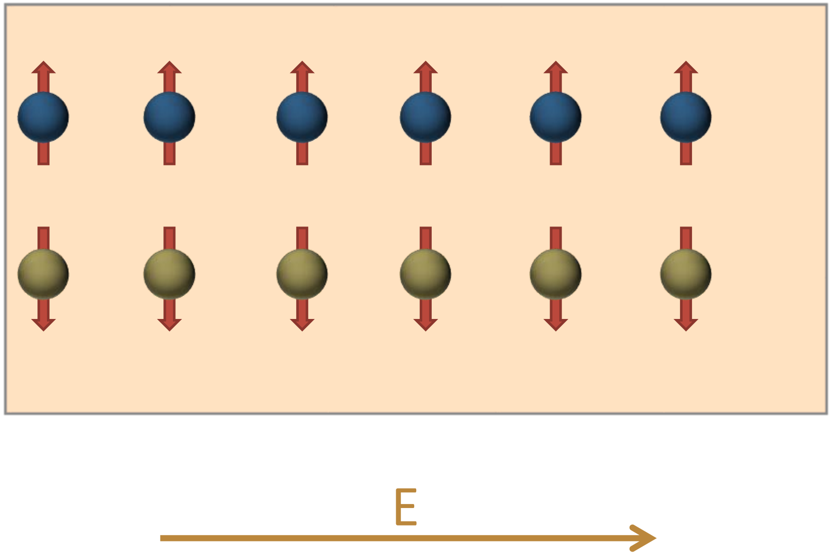
Linear response

		"Real" part	"Imaginary" part
Conductivity:	$\hat{A} = -e\hat{\mathbf{v}}$	even - ordinary conductivity	odd - Anomalous Hall effect
Spin-orbit torque:	$\hat{A} = \hat{\mathbf{T}}$	Odd - field-like torque	even – antidamping-like torque
Spin current:	$\hat{A} = \frac{1}{2}\{\hat{\mathbf{s}}, \hat{\mathbf{v}}\}$	odd – spin-polarized current in ferromagnets	even - spin Hall effect

Odd components can only exist in magnetic materials

Spin-polarized current

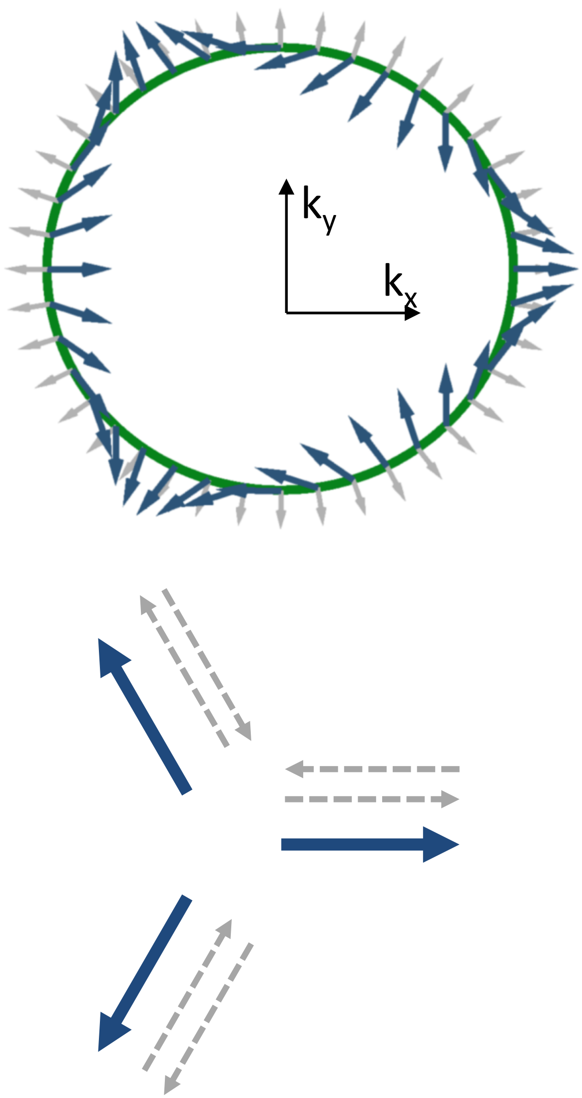
In collinear antiferromagnets spin-polarized current is typically not allowed by symmetry

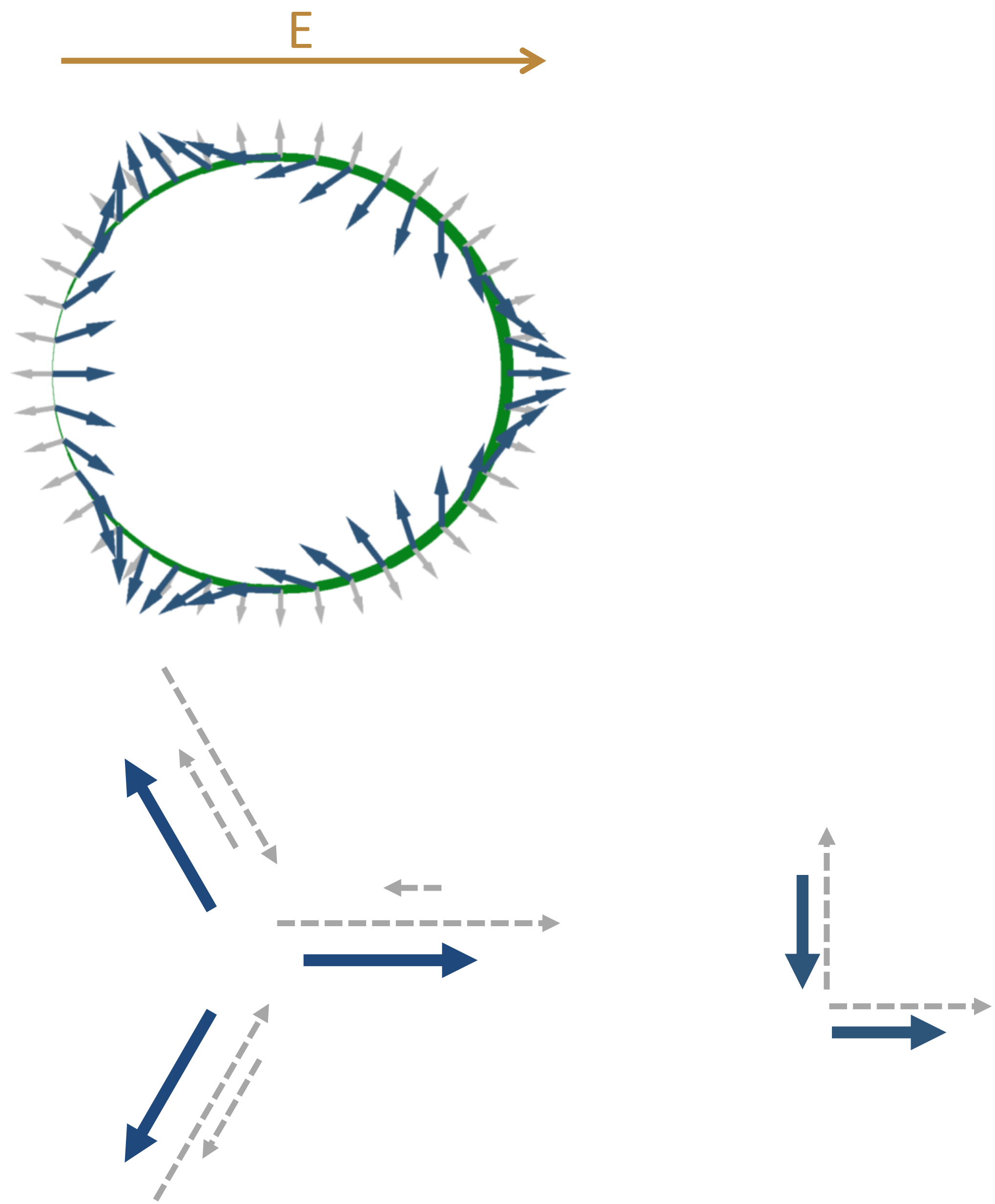


In the **non-collinear antiferromagnets** spin-polarized current is **present**

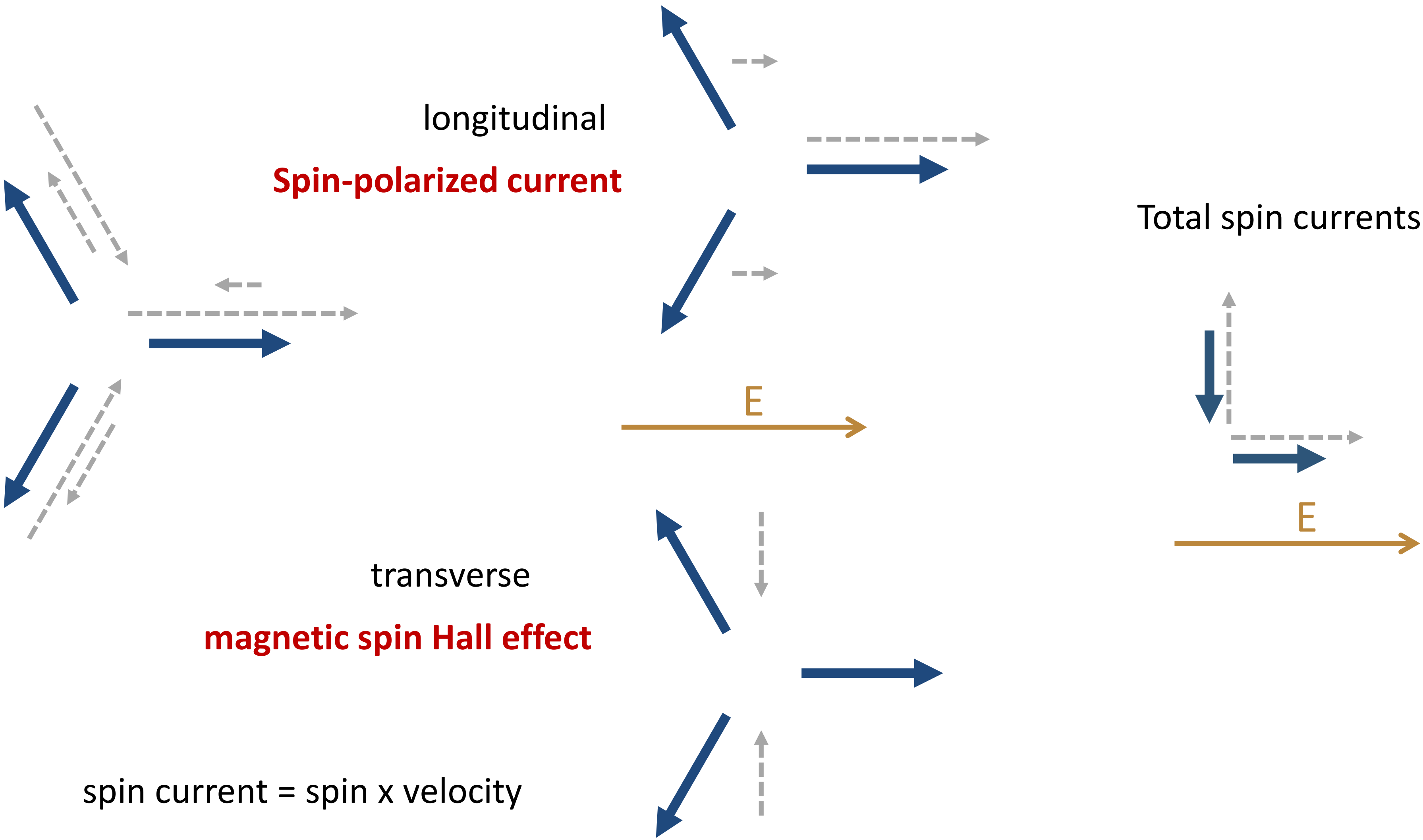
Origin of the odd spin currents

Spin current = spin × velocity





Origin of the odd spin currents



Zelezny et al., PRL 119, 187204 (2017)

Odd spin currents in ferromagnets

Spin current longitudinal with the charge current -> spin-polarized current

Symmetry of the spin currents in Bcc Fe with M || x:

$$\sigma^x = \begin{pmatrix} \sigma_{xxx} & 0 & 0 \\ 0 & \sigma_{xxx} & 0 \\ 0 & 0 & \sigma_{xxx} \end{pmatrix}$$
$$\sigma^y = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$
$$\sigma^z = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Without spin-orbit coupling

$$\sigma^x = \begin{pmatrix} \sigma_{xxx} & 0 & 0 \\ 0 & \sigma_{xyy} & 0 \\ 0 & 0 & \sigma_{xyy} \end{pmatrix}$$
$$\sigma^y = \begin{pmatrix} 0 & \sigma_{yxy} & 0 \\ \sigma_{yyx} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$
$$\sigma^z = \begin{pmatrix} 0 & 0 & \sigma_{yxy} \\ 0 & 0 & 0 \\ \sigma_{yyx} & 0 & 0 \end{pmatrix}$$

With spin-orbit coupling

Transverse spin currents with magnetic origin: **Magnetic spin Hall effect**

Magnetic spin Hall effect

Odd – magnetic spin Hall effect

$$\sigma^x = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\sigma^y = \begin{pmatrix} 0 & \sigma_{yxy} & 0 \\ \sigma_{yyx} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

$$\sigma^z = \begin{pmatrix} 0 & 0 & \sigma_{yxy} \\ 0 & 0 & 0 \\ \sigma_{yyx} & 0 & 0 \end{pmatrix}$$

Even - spin Hall effect

$$\sigma^x = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -\sigma_{xzy} \\ 0 & \sigma_{xzy} & 0 \end{pmatrix}$$

$$\sigma^y = \begin{pmatrix} 0 & 0 & -\sigma_{zxy} \\ 0 & 0 & 0 \\ \sigma_{zyx} & 0 & 0 \end{pmatrix}$$

$$\sigma^z = \begin{pmatrix} 0 & \sigma_{zxy} & 0 \\ \sigma_{zyx} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Symmetry and origin distinct from the conventional spin Hall effect

Odd: $\sigma(\mathbf{M}) = -\sigma(-\mathbf{M})$

Even: $\sigma(\mathbf{M}) = \sigma(-\mathbf{M})$

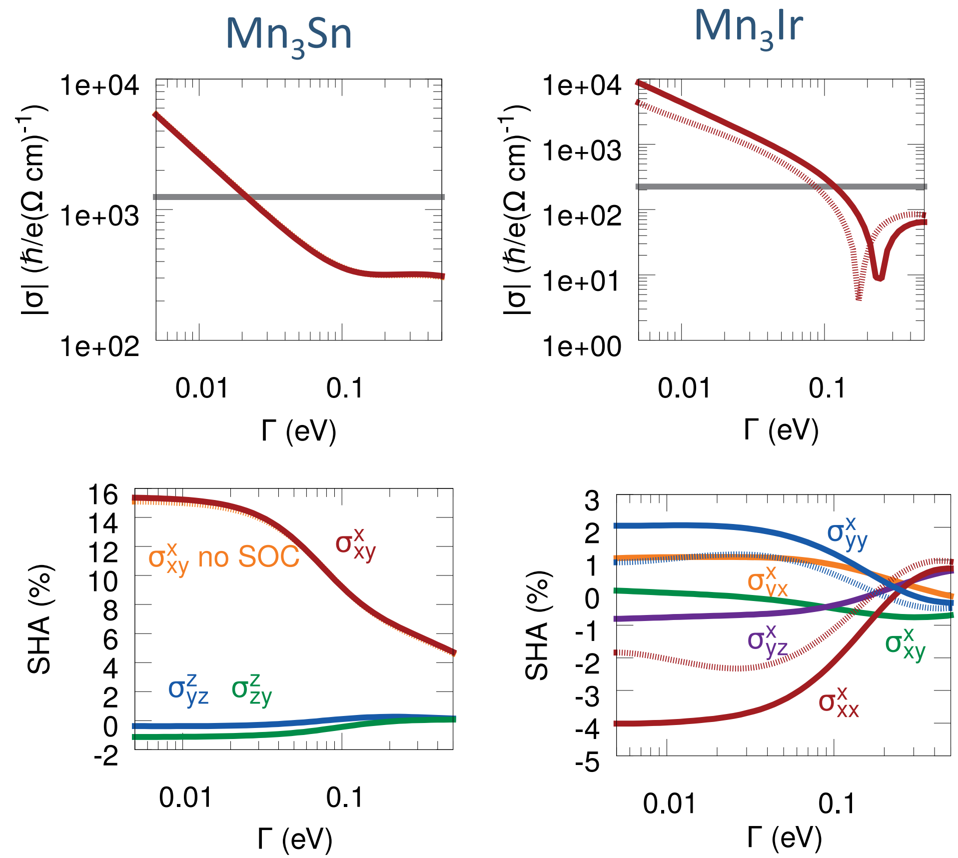
No experimental evidence so far

Calculations

The odd spin currents **depend strongly on disorder** unlike the intrinsic spin Hall effect

Spin current angle: $\alpha = \frac{e}{\hbar}\frac{\sigma^{i}_{jk}}{\sigma_{kk}}$

Experimental evidence of the magnetic spin Hall effect reported by Prof. Otani and Prof. Nakatsuji



	$\alpha_{\parallel}$ (%)	$\alpha_{\perp}$ (%)
Mn3Ga	13.7	13.5
Mn3Ge	5.1	5.0
Mn3Sn	12.4	12.4
Mn3Rh	1.1	0.7
Mn3Ir	3.5	1.9
Mn3Pt	4.2	1.9

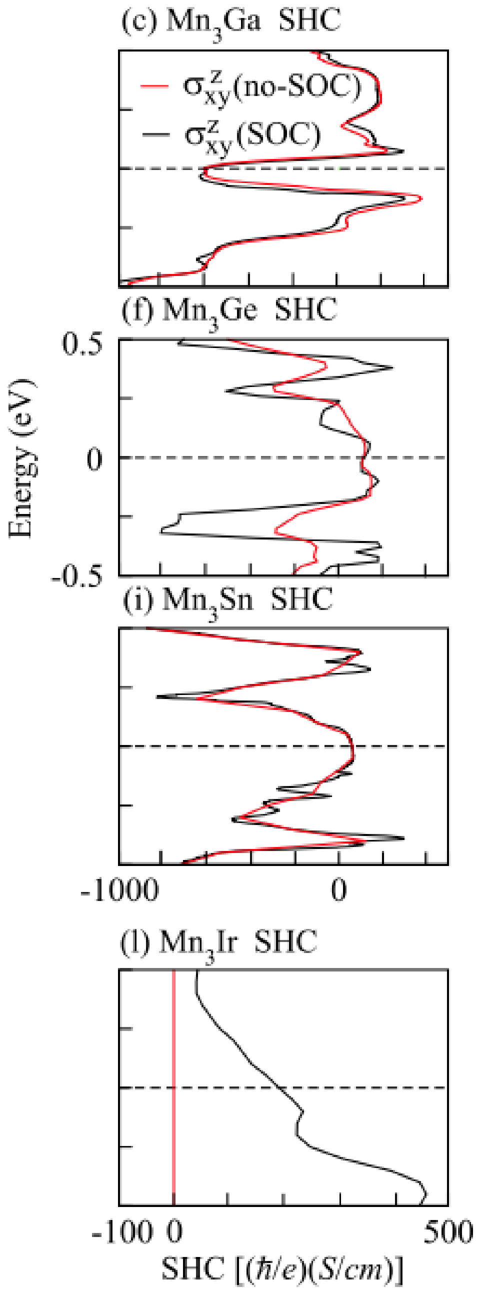
Spin currents are smaller than typically in ferromagnets, but still relatively large

In BCC Fe $\alpha_{\parallel} \sim 18\%$

$\alpha_{\perp} \sim 1\%$

Zelezny et al., PRL 119, 187204 (2017)

SHE calculations



Spin Hall effect exist in these materials even without spin-orbit coupling!

Yang Zhang et al., Phys. Rev. B 95, 075128 (2017)

Yang Zhang et al., New J. Phys. 20, 073028 (2018)

Origin of the spin-Hall effect

Non-collinear magnetic order plays a similar role as the spin-orbit coupling

$$H = H_0 + H_{\text{so}} + H_{\text{ex}}$$

Spin-independent

$$\sim \boldsymbol{\sigma} \cdot (\nabla V \times \mathbf{p})$$

$$\sim \boldsymbol{\sigma} \cdot \hat{\mathbf{M}}(\mathbf{r})\Omega_{xc}(\mathbf{r})$$

$[H_{\text{so}}, \sigma] \neq 0$ for σ_x, σ_y and σ_z

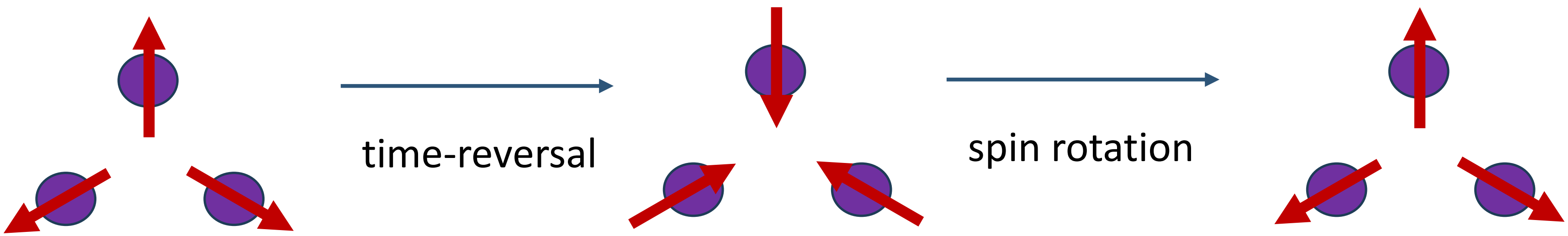
If $\widehat{\mathbf{M}}(r)$ is collinear, e.g. along $\hat{z}$, then $[H_{\text{ex}}, \sigma_z] = 0$

Symmetry without spin-orbit coupling

When spin-orbit coupling and magnetism are not present then **arbitrary spin rotation is a symmetry of the system**

Spin-orbit coupling and magnetism break the spin rotation symmetries

In a coplanar system time-reversal + 180° spin rotation is a symmetry without SOC



No AHE in a coplanar magnetic system

"Spin groups" or "spin-space" groups

Litvin et al., Physica 76, 538-554 (1974)

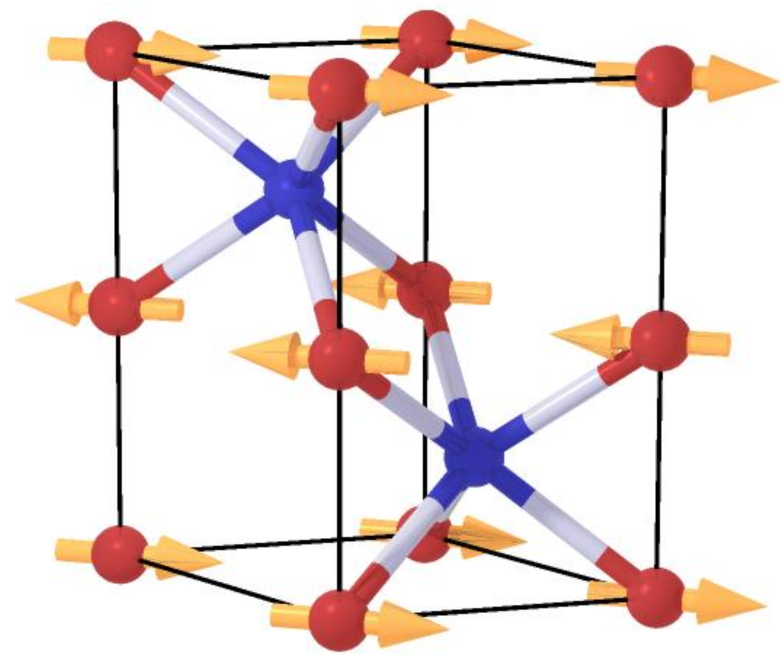
Brinkman et al., Proc. Royal Soc. London A, 294, 343-358 (1966)

What is the role of non-collinearity

The spin Hall effect can only exist without spin-orbit coupling in a non-collinear magnetic system

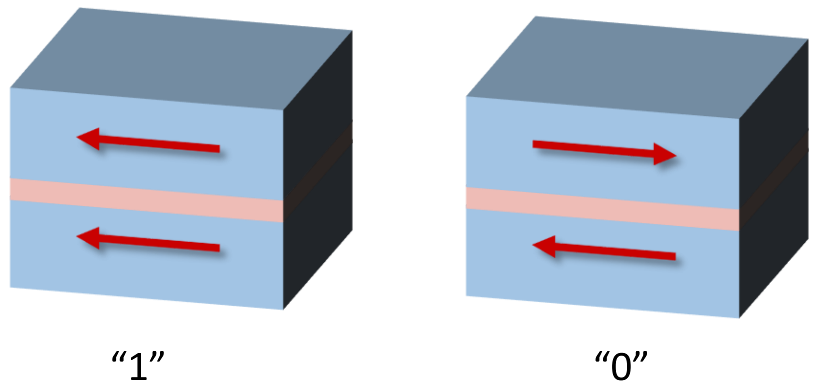
The spin-polarized current and magnetic spin-Hall effect can also exist in a collinear ferromagnetic and antiferromagnetic systems

Example of collinear antiferromagnet with the spin-polarized current and magnetic spin-Hall effect

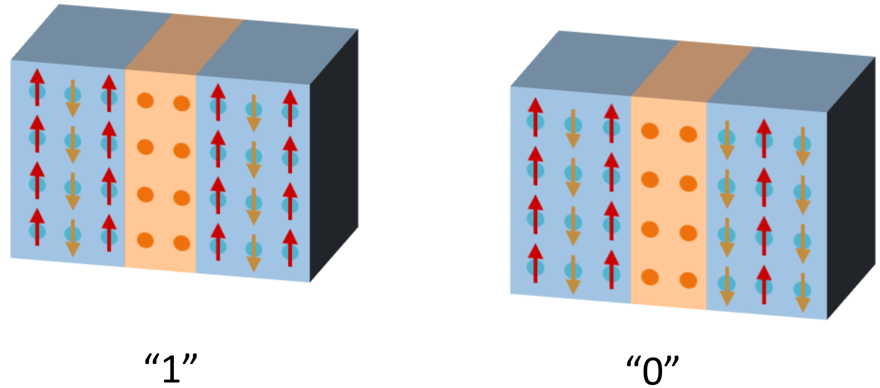


MnTe

Antiferromagnetic junctions

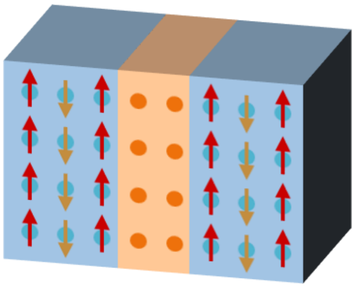


FM junction

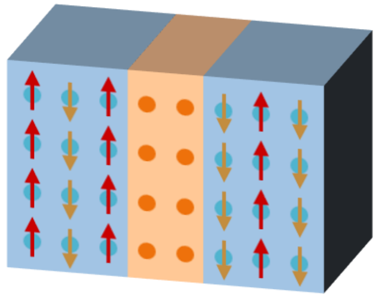


AFM junction

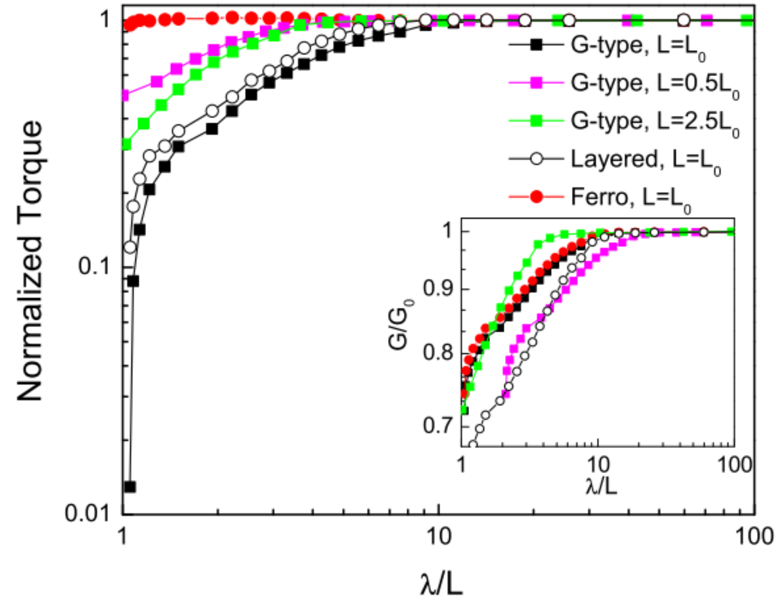
Antiferromagnetic junctions



"1"



"0"



Theoretically proposed but strongly sensitive to disorder and never observed experimentally

Saidaoui et al., PRB 89, 174430 (2014)

"It is simply not possible to achieve spin transfer torque in a spin-valve composed of two antiferromagnets in the semiclassical limit."

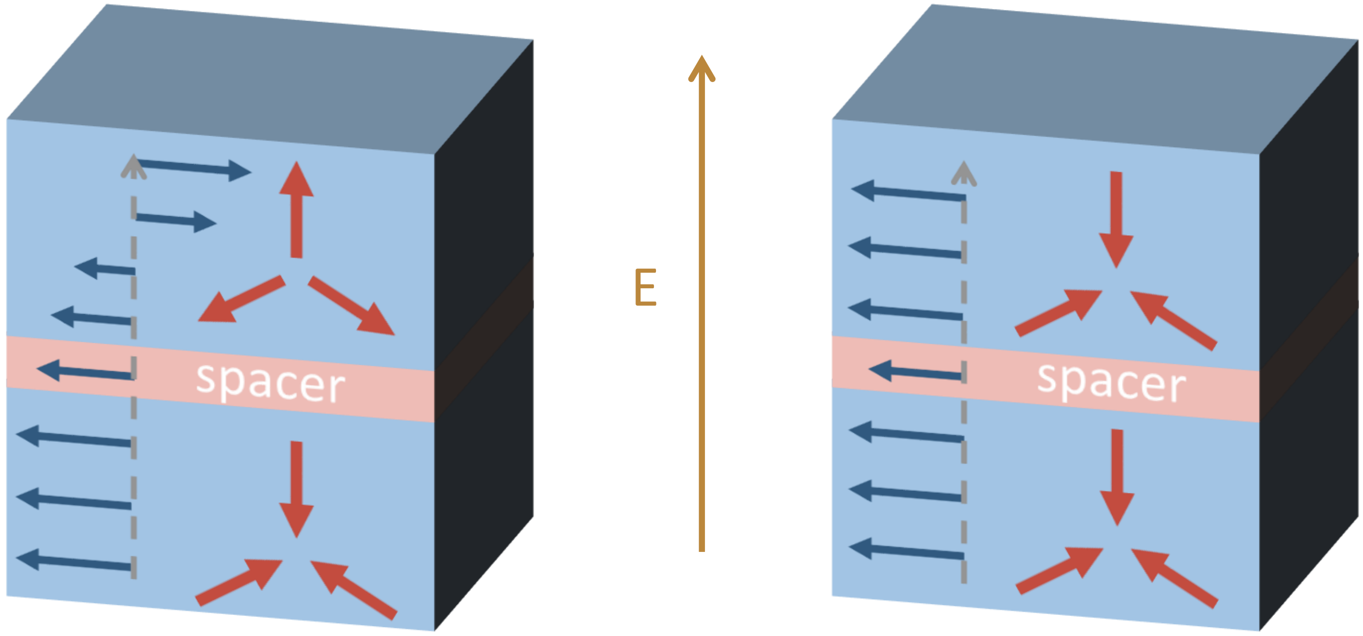
A. Manchon, Journal of Physics: Condensed Matter 29 (2017)

*J. Železný et al., Nature Physics **14**, 220-228 (2018)*

Spin-polarized current

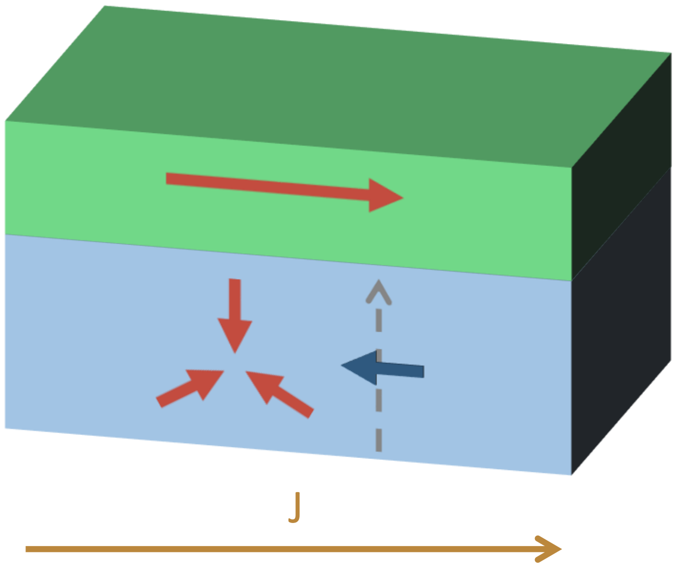
In non-collinear antiferromagnets, current is spin-polarized and thus same approach can be used as in ferromagnets

Giant or tunneling magnetoresistance and spin-transfer torque should be present



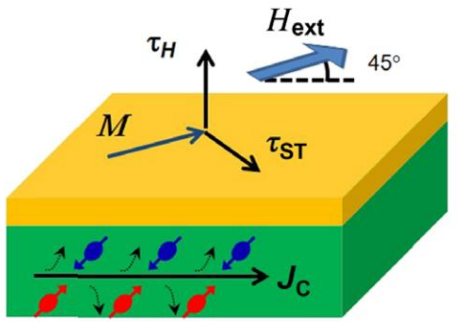
Transverse spin currents

- Both magnetic and conventional spin Hall effect is present
- Both could be used for spin-orbit torques, but they have different symmetry



Symmetry matters for the spin-orbit torque

Symmetry of the spin Hall effect



For SOT out-of-plane spin-polarization is preferential

SHE normally has in-plane spin-polarization

$$\sigma^x \quad \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -\sigma \\ 0 & \sigma & 0 \end{pmatrix}$$

$$\sigma^y \quad \begin{pmatrix} 0 & 0 & \sigma \\ 0 & 0 & 0 \\ -\sigma & 0 & 0 \end{pmatrix}$$

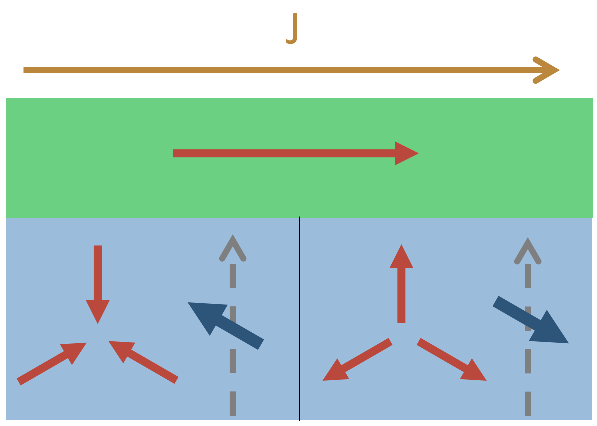
$$\sigma^z \quad \begin{pmatrix} 0 & -\sigma & 0 \\ \sigma & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Both magnetic and conventional spin Hall effect can have the out-of-plane spin-polarization in the triangular antiferromagnets

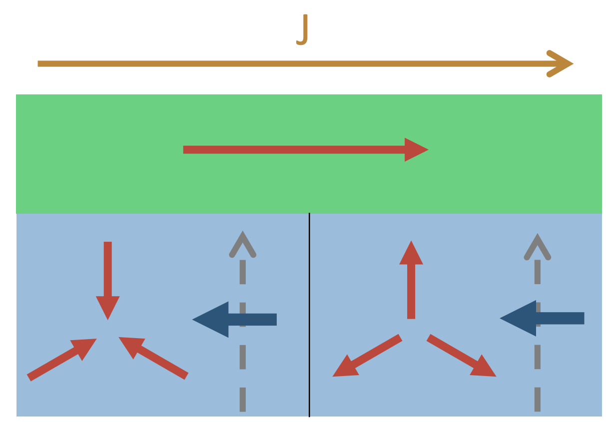
The spin Hall effect and the magnetic spin Hall effect can be controlled by manipulating the magnetic order

Transverse spin currents

Magnetic and conventional spin Hall effect will depend differently on presence of magnetic domains



odd



even

Sensitive to the antiferromagnetic order and presence of domains

Thsitoyan et al., PRB 92, 214406 (2016)

Zhang et al., Science Advances 2, (2016)

Young-Wan oh et al., Nature Nanotech., (2016)

Detection of 180° reversal

In antiferromagnets AMR is usually used for electrical detection of switching

Only possible to detect 90° switching

$$\sigma = \sigma^{\mathrm{even}} + \sigma^{\mathrm{odd}}$$

AMR: $\sigma^{\mathrm{even}}(\mathbf{M}_1, \mathbf{M}_2, \ldots) = \sigma^{\mathrm{even}}(-\mathbf{M}_1, -\mathbf{M}_2, \ldots)$

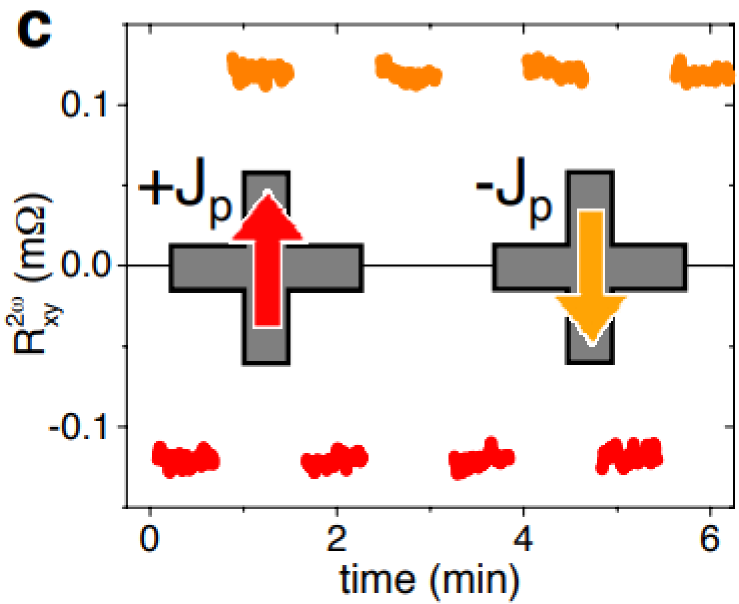
AHE: $\sigma^{\mathrm{odd}}(\mathbf{M}_1, \mathbf{M}_2, \ldots) = -\sigma^{\mathrm{odd}}(-\mathbf{M}_1, -\mathbf{M}_2, \ldots)$

AHE not present in most antiferromagnets

Detection of 180° reversal

Higher order effects: $j_i = \chi_{ijk} E_j E_k$

χ^{odd} present in magnetic materials with broken inversion symmetry



J. Godinho et al., arXiv:1806.02795

Codes

Symmetry

https://bitbucket.org/zeleznyj/linear-response-symmetry

- Symmetry of linear and higher order response
- SHE is also implemented
- Symmetry of magnetic interactions

$$H = H_{ij} M_i M_j + H_{ijkl} M_i M_j M_k M_l + \ldots$$

- Expansion in magnetic moment direction

$$\chi(\mathbf{M}) = \chi^0 + \chi_i M_i + \chi_i j M_i M_j + \ldots$$

Linear response

https://bitbucket.org/zeleznyj/wannier-linear-response

- Calculation of various linear response properties (AHE, SHE, AMR) based on Wannier90 Hamiltonians or tight-binding Hamiltonians

Summary

- Noncollinear antiferromagnets are very attractive for spintronics since they **combine advantages of ferromagnets and antiferromagnets**

  - ✓ Spin-polarized current
  - ✓ AHE, Kerr effect
  - ✓ spin Hall effect (without SOC)
  - ✓ Detecting 180° switching possible

  - ✓ Fast magnetic dynamics
  - ✓ Insensitive to external magnetic fields
  - ✓ No stray fields

- Consequences beyond non-collinear AFMs
  - Spin-polarized current not limited to ferromagnets
  - In magnetic materials a transverse current distinct from the spin Hall effect can exist
  - Spin-Hall effect can exist without SOC

J. Železný et al., PRL 119, 187204 (2017)

Yang Zhang et al., New J. Phys. 20, 073028 (2018)