Ultrafast manipulation of Heisenberg exchange and Dzyaloshinskii Moriya interactions in antiferromagnetic insulators

Juan Manuel Losada Sosnovsky

Supervisors: Arne Brataas and Alireza Qaiumzadeh

QuSpin (NTNU)

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Spintronics

Study and use the intrinsic spin of the electrons, in addition to their charge, to build devices. Example: Magnetoresistive random access memory.

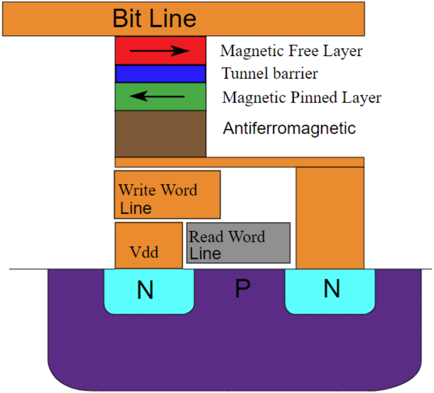

Figure: Source: Wikipedia

Antiferromagnetic Spintronics

The development of information technology demands devices with high storage density, high energy efficiency and high write-read speeds. Antiferromagnets have appear as a natural alternative to ferromagnets due to some advantages:

- Robustness against magnetic disturbances.
- No hysteresis loss.
- Produce no stray fields.
- Ultrafast dynamics (femtosecond).

Antiferromagnetic Spintronics

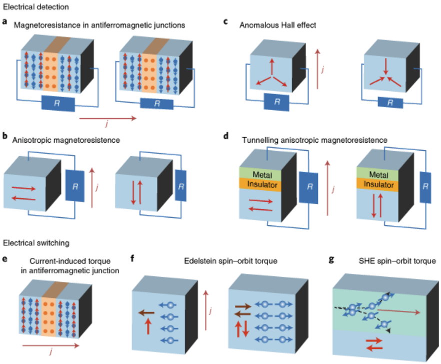

Figure: Source: Nature, Spin transport and spin torque in antiferromagnetic devices

Spin models

Heisenberg model

$$\hat{H} = \sum_{\langle i,j \rangle} J \boldsymbol{S}_i \boldsymbol{S}_j$$

In antiferromagnets $J > 0$ ($J < 0$ for ferromagnets). Mentink, J. H. et al. showed that it is possible to manipulate the exchange constant by applying a laser field. $J = J_0 + \Delta J$.

Spin models

The Dzyaloshinskii-Moriya interaction (DMI):

$$\boldsymbol{D}_{ij}\boldsymbol{S}_i \times \boldsymbol{S}_j$$

- Arises from the spin orbit coupling.
- It favours canted order, i.e. weak ferromagnetism in AFM.
- Enables topological objects such as chiral skyrmions and chiral domain walls.

Spin models

Heisenberg model with DMI

$$\hat{H} = \sum_{\langle i,j \rangle} J \boldsymbol{S}_i \boldsymbol{S}_j + \sum_{\langle i,j \rangle} \vec{D}_{ij} \boldsymbol{S}_i \times \boldsymbol{S}_j$$

The ratio between the exchange interaction and the DMI controls the tilt angle of the canted spins.

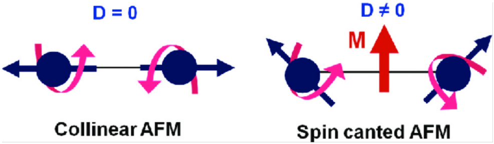

Figure:
Source: Nanoscale

Spin models

If we can manipulate J and D we can control the canting angle.

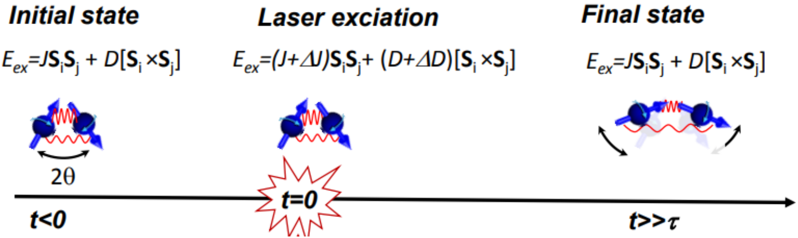

Figure: Source: Kimmel presentation

Model

Strongly correlated electrons in a planar honeycomb lattice can be described by:

Kane-Mele-Hubbard model

$$\hat{H} = -t_1 \sum_{\langle i,j \rangle, \sigma} \hat{c}^{\dagger}_{i\sigma} \hat{c}_{j\sigma} - \sum_{\langle\langle i,j \rangle\rangle, \sigma, \sigma'} (\delta_{\sigma,\sigma'} t_2 - i\Delta \nu_{ij} \sigma^z_{\sigma,\sigma'}) \hat{c}^{\dagger}_{i\sigma} \hat{c}_{j\sigma'} + \mathrm{U}\hat{D}$$

Where $\hat{D} = \sum_{i=1}^{M} \hat{n}_{i\uparrow} \hat{n}_{i\downarrow}$ is the doublon number operator.

Model

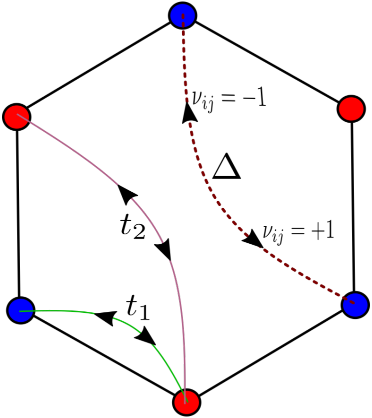

Figure: A honeycomb cell with NN hopping t_1, NNN hopping t_2, intrinsic SOI Δ, and $\nu_{ij} = \pm 1$ for clockwise and counterclockwise hopping.

Model

The effective spin Hamiltonian in the strongly correlated regime takes the form:

$$\hat{H}_{\text{eff}} = \sum_{\langle i,j \rangle} J_1 \boldsymbol{S}_i \boldsymbol{S}_j + \sum_{\langle\langle i,j \rangle\rangle} \{ J_2 \boldsymbol{S}_i \boldsymbol{S}_j + \boldsymbol{D}_{2,ij} \boldsymbol{S}_i \times \boldsymbol{S}_j + \boldsymbol{S}_i \boldsymbol{\Gamma} \boldsymbol{S}_j \}$$

With:

$$J_{1(2)} = \frac{2t_{1(2)}^2}{U},$$
$$\boldsymbol{\Gamma} = \frac{2\Delta^2}{U} \text{diag}(-1,-1,1),$$
$$\boldsymbol{D}_{ij} = \frac{4t_2\Delta}{U} \nu_{ij} \hat{\mathrm{e}}_z.$$

Method

$$\hat{H} = -\hat{T} + \mathrm{U}\hat{D}$$

$\hat{T}$ is a hopping operator, and $\hat{D}$ is the doublon number operator.

$$\hat{D} = \sum_{i=1}^{M} \hat{n}_{i\uparrow}\hat{n}_{i\downarrow}$$

$$\hat{T} = \sum_{i,j,\sigma,\sigma'} t_{ij}^{\sigma\sigma'} \hat{c}_{i\sigma}^{\dagger}\hat{c}_{j\sigma'}$$

$\mathrm{U} \gg t_{ij}^{\sigma\sigma'}$, strongly correlated regime.

Method

To account for the laser illumination we use several techniques:

- Peierls substitution.
- Apply time dependent unitary transformation.
- Expand unitary transformation and transformed Hamiltonian.
- Determine unitary transformation.

Peierls substitution

In the presence of a vector potential $\boldsymbol{A}(t)$ the hopping amplitudes acquire a time dependent phase:

$$t_{ij}^{\sigma\sigma'}(t) = t_{ij}^{\sigma\sigma'} e^{ie\boldsymbol{R}_{ij}\boldsymbol{A}(t)}$$

The Hamiltonian is time dependent.

Unitary transformation

Apply $\hat{U}(t) = e^{-i\hat{S}(t)}$,

$$\hat{H}'(t) = e^{i\hat{S}(t)}\hat{H}(t)e^{-i\hat{S}(t)} - e^{i\hat{S}(t)} i d_t e^{-i\hat{S}(t)}$$

The goal is $\hat{H}'(t)$ to be block diagonal in $\hat{D}$ up to certain order in the hopping amplitudes.

Expand transformed Hamiltonian

Formally $\hat{T}(t) = \eta \hat{T}(t)$, where η plays the role of a bookkeeping parameter in the perturbative expansion.

$$\hat{S}(t) = \sum_{\nu} \eta^{\nu} \hat{S}^{(\nu)}(t)$$
$$\hat{H}'(t) = \sum_{\nu} \eta^{\nu} \hat{H}'^{(\nu)}(t)$$

The transformed Hamiltonian can be written:

$$\hat{H}'(t) = \sum_{m} \frac{1}{m!} \mathrm{ad}^{m}_{i\hat{S}(t)} \left(\hat{H}(t) - \sum_{n} \frac{1}{(n+1)!} \mathrm{ad}^{n}_{-i\hat{S}(t)} (d_t \hat{S}(t)) \right)$$

Determine unitary transformation

We decompose the hopping operator as $\hat{T}(t) = \sum_{d,m} \hat{T}_{d,m} e^{im\omega t}$, where $\hat{T}_{d,m}$ changes the doublon number by d.

$$\hat{H}'^{(0)}(t) = \mathrm{U}\hat{D}$$

$$\hat{H}'^{(1)}(t) = -\sum_{m} \hat{T}_{0,m}(t) e^{im\omega t}$$

$$\hat{H}'^{(2)}(t) = \frac{1}{2}\sum_{mn}\left(\frac{\left[\hat{T}_{1n}, \hat{T}_{-1(m-n)}\right]}{\mathrm{U}+n\omega} - \frac{\left[\hat{T}_{-1n}, \hat{T}_{1(m-n)}\right]}{\mathrm{U}-n\omega}\right) e^{im\omega t}$$

Projecting onto the low energy subspace

In the strongly correlated limit we can assume that the Hamiltonian acts only within the $d = 0$ subspace, i.e. $\hat{H}_{\text{eff}} = \langle \hat{P}_0 \hat{H}'(t) \hat{P}_0 \rangle$. Obtaining:

$$\hat{H}_{\text{eff}} = - \sum_{i,j,\sigma_1,\sigma_2,\sigma_3,\sigma_4} \hat{c}^{\dagger}_{i\sigma_1} \hat{c}_{j\sigma_2} \hat{c}^{\dagger}_{j\sigma_3} \hat{c}_{i\sigma_4} t_{ij}^{\sigma_1\sigma_2} t_{ji}^{\sigma_3\sigma_4} \left\{ \sum_n \frac{\mathcal{J}_n^2(\alpha_{ij})}{\text{U} + n\omega} \right\}$$

Where $\alpha_{ij} = e\boldsymbol{R}_{ij}\boldsymbol{A}$.

Results

If we apply this procedure to the Kane Mele Hubbard model, we get:

$$\tilde{H}_S(\omega) = \sum_{\langle i,j \rangle} \tilde{J}_{1,ij} \boldsymbol{S}_i \boldsymbol{S}_j + \sum_{\langle\langle i,j \rangle\rangle} \left\{ \tilde{J}_{2,ij} \boldsymbol{S}_i \boldsymbol{S}_j + \boldsymbol{S}_i \tilde{\boldsymbol{\Gamma}}_{ij} \boldsymbol{S}_j + \tilde{\boldsymbol{D}}_{ij} \boldsymbol{S}_i \times \boldsymbol{S}_j \right\}$$

with the following renormalized spin interactions:

$$\tilde{J}_{1(2),ij} = 2t_{1(2)}^2 \sum_n \frac{\mathcal{J}_n^2(\alpha_{ij})}{U + n\omega},$$

$$\tilde{\boldsymbol{\Gamma}}_{ij} = 2\Delta^2 \mathrm{diag}(-1,-1,1) \sum_n \frac{\mathcal{J}_n^2(\alpha_{ij})}{U + n\omega},$$

$$\tilde{\boldsymbol{D}}_{ij} = 4t_2\Delta \sum_n \frac{\mathcal{J}_n^2(\alpha_{ij})}{U + n\omega} \nu_{ij} \hat{\mathrm{e}}_z.$$

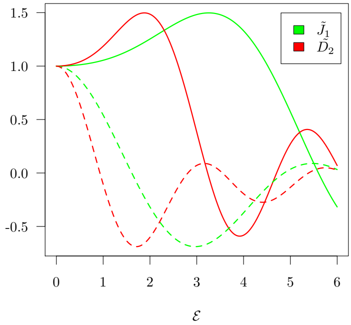

Figure: $\frac{J_1}{J_1^0}$ and $\frac{D_{2,ij}}{D_{2,ij}^0}$ are plotted as function of $\mathcal{E}$. Similar results are obtained in [1] for J_1. Solid lines are for $\omega = 4$ and dashed lines are for $\omega = 14$.

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[1] Mentink, J. H. *et al.* Ultrafast and reversible control of the exchange interaction in Mott insulators. *Nature Communications.* arXiv: arXiv:1407.4761v1 (2015).

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