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Dynamics & Magnetoresistance of 1D Domain Walls & Skyrmions

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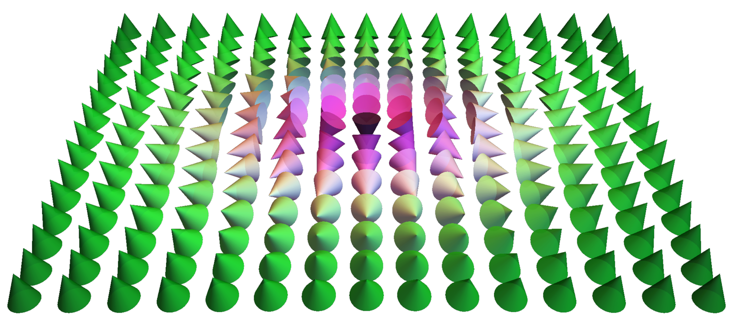
In one dimensional ferromagnetic wires domains of collinear ferromagnetic order can be separated by different types of topological, and non-topological, domain walls. Domains of opposite orientation are typically separated by either Bloch or Neel domain walls, whereas domains of the same orientation can be separated by magnetic impurities, or by a one dimensional equivalent of a skyrmion which may be found in quasi-one dimensional wires. We make a thorough investigation of the different magnetoresistance which can be caused by these various forms of domain walls, paying particular attention to the one dimensional skyrmion. We go on to consider the different current induced dynamics and stability of these various magnetic deformations.

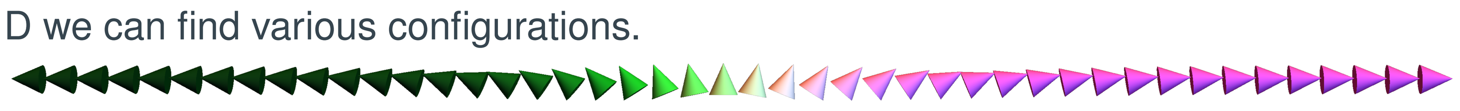
Motivation

Skyrmions are well known topological objects in 2D magnetic condensed matter systems of a special type. In 1D materials it is also possible to find a variety of twists and separating regions of collinear magnetization. These can also be protected "topologically" between bulk orientations. Indeed one can even define a winding number to catagorize them.



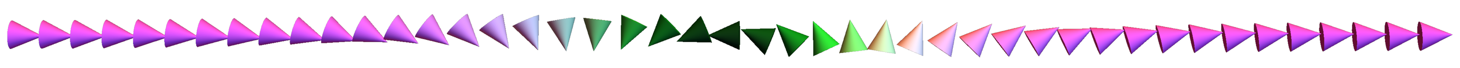
A 2D Skyrmion.

In 1D we can find various configurations.



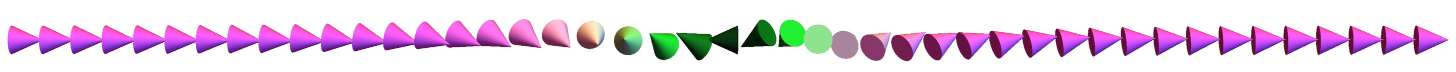
$\nu = \frac{1}{2}$

Here is a domain wall (DW).



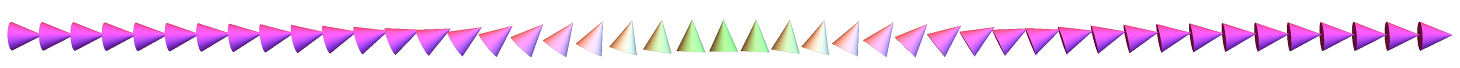
$\nu = 1$

Here is a 1D Skyrmion. This is protected by anisotropy, which can also be thought of as a symmetry protection.



$\nu = 1$

Here is an out-of-plane 1D Skyrmion. Typically we can expect that this will not be stable.



$\nu = 0$

Here is a simple impurity. Typically we can expect that this will not be stable.

In terms of the classical bulk magnetization $\vec{M}$ we can define a winding number

$$\nu = \frac{1}{2\pi}\int \mathrm{d}z\phi_z \quad \text{where} \quad \vec{M}(z) = M(\sin[\phi_z]\cos[\theta_z], \sin[\phi_z]\sin[\theta_z], \cos[\phi_z])$$

We want to know what the magnetoressitance is for these various textures, how they interact, how they move, and how stable they are.

We consider the 1D magnetic wire with a certain profile of magnetization $\mathbf{M}(\mathbf{x})$ which changes direction in the $x-y$ plane. The Hamiltonian for the conduction electrons is, neglecting the Coulomb interaction,

$$H = -\frac{\hbar^2}{2m}\frac{d^2}{dz^2} - g\,\vec{\sigma}\cdot\vec{M}(z)$$

where g is the coupling constant.

Dynamics and Stability

Landau-Lifschitz-Gilbert Equations with relaxation[1] and non-adiabatic torque[2]:

$$\begin{aligned}\partial_t\vec{M} = -\tfrac{1}{1+\alpha^2}\Big[&\gamma\vec{M}\times\mathcal{H} + \tfrac{\alpha\gamma}{M}\vec{M}\times(\vec{M}\times\mathcal{H}) \\ &+\tfrac{b_j(1+\alpha\xi)}{M^2}\vec{M}\times(\vec{M}\times(\vec{j}_e.\nabla)\vec{M}) + \tfrac{b_j(\xi-\alpha)}{M}\vec{M}\times(\vec{j}_e.\nabla)\vec{M}\Big]\end{aligned}$$

$\mathcal{H}$ is the effective field:

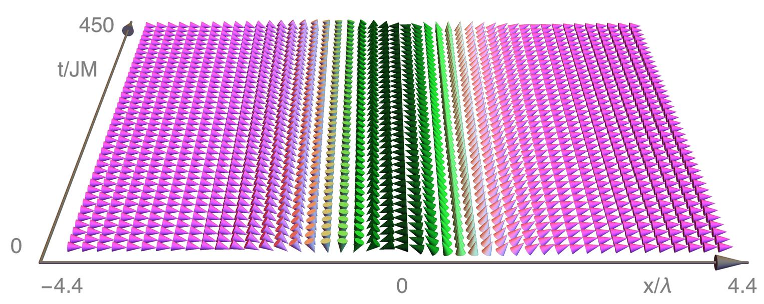
$$\mathcal{H} = J\vec{S} + \alpha_{ik}\frac{\partial^2\vec{M}}{\partial x_i \partial x_k} + KM_x\vec{x}$$

$f_0(M)$ homogeneous exchange

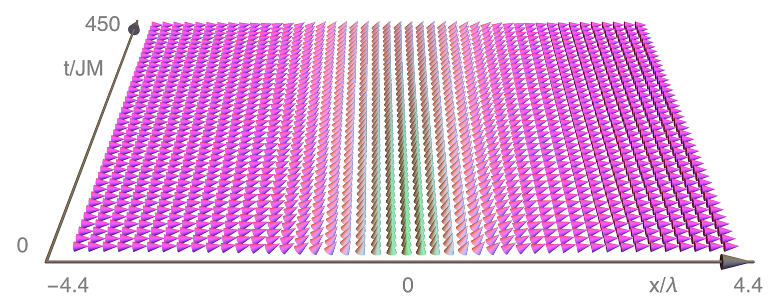
α_{ik} inhomogeneous exchange

$\vec{H}_{\mathrm{ext}}$ external magnetic field

K anisotropy



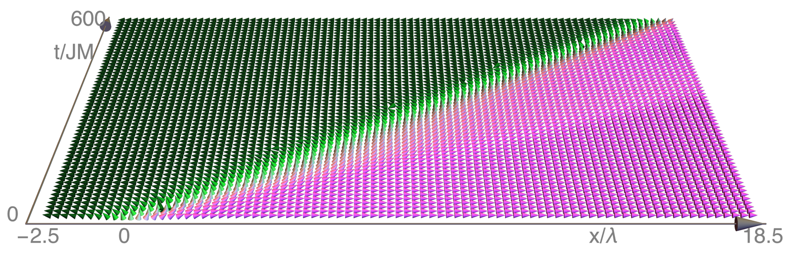
A stable Skyrmion.



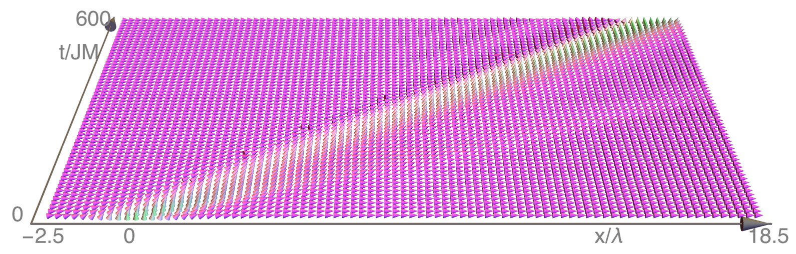
An impurity texture, which slowly relaxes.

Current Induced Dynamics

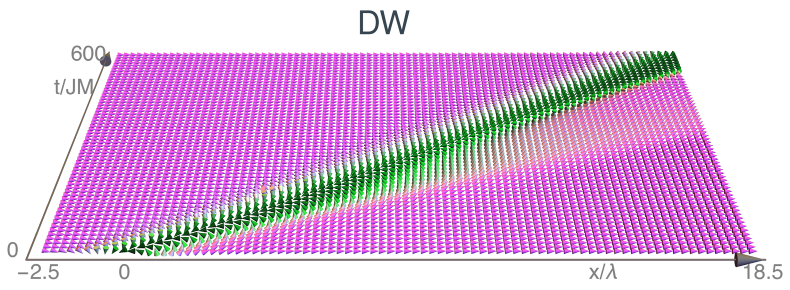
Apply constant currents:



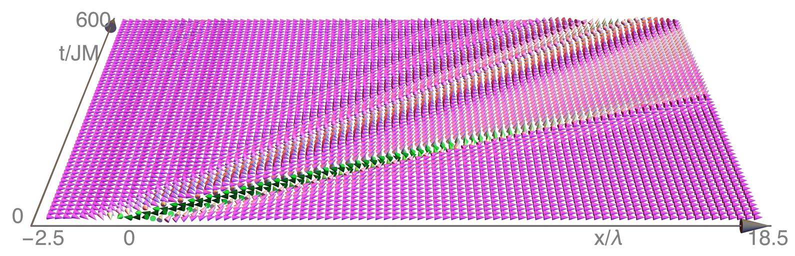
DW



Impurity texture



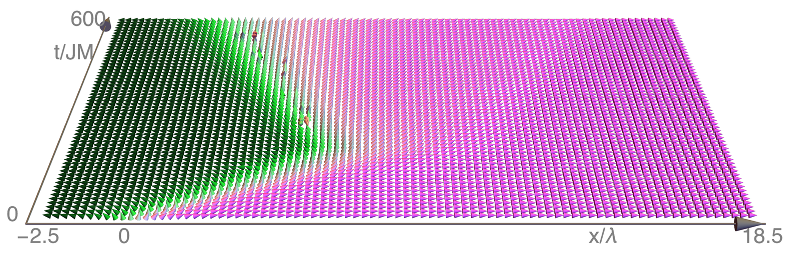
Skyrmion



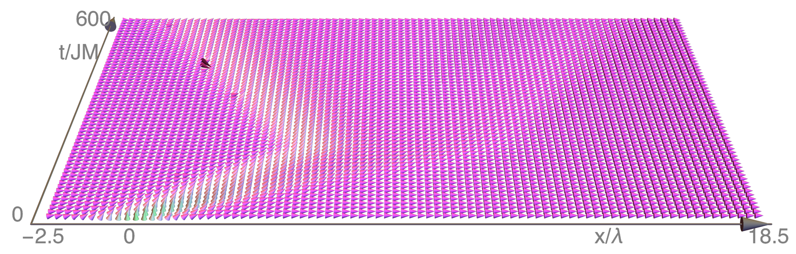
An out-of-plane Skyrmion

Pulsed Current Induced Dynamics

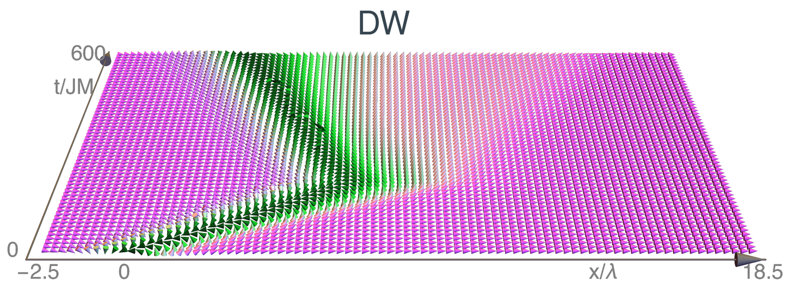
Apply top hat shaped pulsed currents:



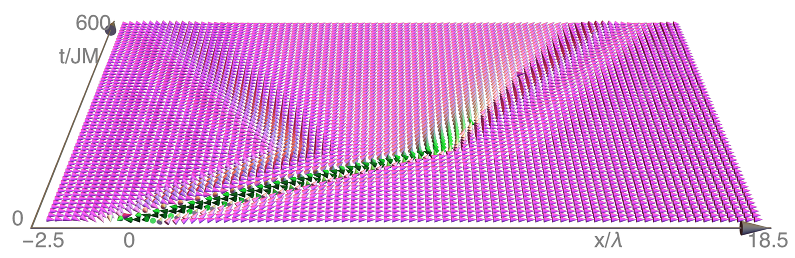
DW



Impurity texture



Skyrmion



An out-of-plane Skyrmion

The 1D "Skyrmions" can be stabilised using a magnetic field applied along the length of the wire.

Open Questions

- Full catalogue of dynamics for different spin textures
- Electron mediated interactions between the different magnetic structures[3, 4, 5]
- Contribution of bound states at the magnetic texture to the magnetoresistance
- Magnetoresistance from different textures, electron interaction effects?[6, 7]
- Effects on domain wall motion of applied magnetic fields

We have the Schrödinger equation, in a convenient representation,

$$\begin{pmatrix} -\frac{\hbar^2}{2m}\frac{\mathrm{d}^2}{\mathrm{d}z^2} - \varepsilon & -gM_-(z) \\ -gM_(z)+ & -\frac{\hbar^2}{2m}\frac{d^2}{dz^2} - \varepsilon \end{pmatrix}\begin{pmatrix}\varphi(z) \\ \chi(z)\end{pmatrix} = 0$$

where $\varphi(z)$ and $\chi(z)$ are the spinor components of the wavefunction $\Psi(z)$ and $M_\pm(z) = M_x(z) \pm iM_y(z)$.

Either by an "exact" numerical solution or by using the semiclassical solution we can find the differential conductance, where r_j is the backscattering in each spin channel $j = 1, 2$.

$$G = \frac{e^2}{2\pi}\sum_j\left[1 - |r_j|^2\right]$$

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