ANTIFERROMAGNETIC SOLITONS
(DROPLETS AND SKYRMIONS):
A WAY TO TERAHERTZ SPINTRONICS

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**MOTIVATION:** DROPLET SOLITON in FM driven by Spin Torque
\[ \theta = \theta(r), \quad \varphi = \omega t + \ldots \quad \omega \text{ is precession frequency} \]

Non-topological droplet was simulated (M. A. Hoefer et al, PRB 2010) and observed (Mohseni et al, Science 2013) \( \omega \) till 30 GHz

2D topological soliton (skyrmion) simulated (Y. Zhou et al, Nat. Comm., 2015)
1D solitons (NT or 360-degree DW) in nanowires: Iacocca et al, PRL 2014

**Bound states of a large number of magnons in a three-dimensional ferromagnet (magnons drops)**

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(Submitted September 12, 1976)

[Ivanov and A.M. Kosevich, JETP Letters 1976; JETP 1977]
SOLITONS:

mathematics – exactly integrable PDE \((x+t)\) LLE

including DWs of LLE

physics

1. Long-living (or infinite lifetime) localized in space 
2. Topologically-non-trivial

magnetic solitons in FM and AFM – static, topological; or dynamic; topological or non-topological (droplets)
Ferromagnet (FM) magnetization $\vec{M} = M_s \vec{m}$, $\vec{m}^2 = 1$ Unit vector $\vec{m}$.

Antiferromagnet (AFM) Neel vector; $\vec{L} = \vec{M}_1 - \vec{M}_2 = M_s \vec{l}$, $\vec{l}^2 = 1$ is the principal variable (order parameter),

$$\vec{l}^2 = 1 \text{ OR } \vec{m}^2 = 1, \text{ sphere}
\text{ statics is equivalent for FM and AFM}
\text{ angular variables } \theta, \phi
\vec{l} = \vec{e}_z \cos \theta + \sin \theta(\vec{e}_x \cos \phi + \vec{e}_y \sin \phi)$$

$$W[\theta, \phi] = \int \frac{d\mathbf{x}}{\nu_0} \left\{ \frac{A}{2} \left[ (\nabla \theta)^2 + \sin^2 \theta (\nabla \phi)^2 \right] + w_{\text{anis}}(\theta, \phi) \right\} \quad (1D, 2D)$$

$$w_{\text{anis}}(\theta, \phi) = \frac{K}{2} \sin^2 \theta + \frac{K'}{4} \sin^4 \theta$$
1D topological solitons DOMAIN WALLS

$180^0$ DW static, topological $\pi_0$

Minimum of the energy for given topology

$$W = \frac{A}{R} + KR, \quad R \sim \sqrt{A/K} = r_0$$

EP FM $360^0$ DW static, topological $\pi_1$

One candidate for AFM soliton spin-torque oscillator is ready! 1D
2D: mapping of $x, y$ plane (stereographic) on the sphere $\bar{I}^2 = 1$ 

$\pi_2$ topological charge $S^{(2)} \{r\} \rightarrow S^{(2)} \{\text{spin}\}$

Fig. 36. The structure of a two-dimensional topological soliton with $\nu = 1$.

Isotropic case: Belavin-Polyakov soliton (JETP Lett. 1975)

$$\tan \frac{\theta}{2} = \frac{R}{r}, \phi = \nu \chi + \phi_0, \nu = \pm 1, \pm 2, \ldots \quad E = 4\pi A$$

“Skyrmion”

Anisotropy $E = 4\pi A + \eta KR^2$ no minimum, collapse!

How to stabilize it?

two ways: (i) extra-terms; (ii) dynamics [magnon droplets]

Never 2D, 1D or 3D; 3D: different field, SU(2): \( l_\mu^2 = 1, \mu = 1 - 4 \).

\( \pi_3 \) topological charge

for FM or AFM \( \vec{l} \) Hopf solitons ("Hopfions") \( S^{(3)}_{\{r\}} \rightarrow S^{(2)}_{\{spin\}} \)

Localized topological solitons in a ferromagnet

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FIG. 2. Soliton shape for \( R >> \lambda_0 \). Arrows indicate direction of magnetization at certain points outside and inside a torus and at the center of domain boundary.

Hopf index (topological charge): linking coefficient for preimages
How to stabilize 2D soliton? (Skyrmion)
two ways: (i) extra-terms; (ii) dynamics [magnon droplets]

minimum of the static energy

\[ A'[\left(\nabla \tilde{l}\right)^2]^2 \text{ (NN+NNN, RKKY, …)} \]

\[ D\tilde{l} \cdot (\nabla \times \tilde{l}) \text{ (DMI)} \]

\[ E = 4\pi A + \eta KR^2 + \frac{A'}{R^2} \]

standard: \( r_0 = \sqrt{\frac{A}{K}} \sim a\sqrt{\frac{J}{K}} \)

but here

\[ r'_0 = \frac{4\sqrt{A'}}{K} \sim a\frac{4\sqrt{J'}}{K} \ll r_0 ! \]


Both mechanisms are working for AFMs as well! (statics)

YBaCuO cuprate plane – no inversion center – stable 2D solitons

[Ivanov, Baryakhtar, JETP Letters 1993]
How to stabilize 2D soliton? (Skyrmion)

two ways: (i) extra-terms; (ii) dynamics [magnon droplets]

<no extra-terms needed, but –relaxation + compensated by spin torque>

FM: 2D topological soliton (skyrmion) was simulated (Y. Zhou et al, Nat. Comm., 2015)

genral idea: minimum of energy for a fixed value of some integral of motion

δ[W − λI] ∼ ∆L = 0

Both for FM and AFM: uniaxial magnet = \( S_z^{tot} \) is conserved (+ some other Is)

\[ \delta[W − \hbar \omega S_z^{tot}] = 0 \]

\( \varphi = \omega t \), for FM and AFM

Dynamics is different: LLE for FM, or σ-model equation for \( \bar{l} \) only

\[ M = \frac{M_s}{\gamma H_{ex}} \left( \bar{l} \times \frac{\partial \bar{l}}{\partial t} \right) \]

\[ S_z^{tot} = \frac{s}{\gamma H_{ex}} \int dx \frac{\partial \varphi}{\partial t} \sin^2 \theta = \frac{s \omega}{\gamma H_{ex}} \int dx \sin^2 \theta \]

\[ A \nabla^2 \theta - \sin \theta \cos \theta [K + A(\nabla \varphi)^2 - \omega^2 / \gamma H_{ex}] + K' \sin^3 \theta \cos \theta = 0 \]

\{−ω sin θ, for FM\}

Precessional 180° Domain Wall (forbidden for FMs !)


[Recently: the motion of such DW by magnons -Se Kwon Kim, Tserkovnyak, Tchernyshyov, PRB 2014]
AFMs \( \vec{I} = \vec{e}_z \cos \theta + \sin \theta (\vec{e}_x \cos \varphi + \vec{e}_y \sin \varphi) \), \( \varphi = \omega t + \ldots \)
\( \theta(r), [\text{or } \theta(\vec{r} - \vec{v}t)] \) \( \omega \) is precession frequency
Two-parameter solitons: velocity and frequency vs. linear momentum and number of magnons

Spin-Transfer Droplet: \( V=0 \)

Larmor theorem \( \omega \sim H / \gamma \)

FM vs. AFM:: Different effects

180 vs 90 degrees in the soliton center \( \gamma H_{SF} < \omega < \gamma H_1 \)

1D: “magnetic field is less than for spin-flop” precessional 180 – degree domain wall
2D, 3D non-topological or 2D topological - Skyrmions

\[ Q = 0 \]

\[ Q = \pm 1, \pm 2, ... \]

\[ \varphi = \omega t + Q \chi, \quad r, \chi \text{ – polar coordinates in the AFMs plane} \]

2D, 3D: precessional 90 – degree soliton \( \omega \sim \gamma H_{SF} \sim \text{THz} \)

The polar angle \( \theta(r) \) and schematics of the dynamics (precession) of the vector \( \vec{l} \) for large-radii AFM solition; dashed line – the same for ferromagnetic soliton.

AFM with DMI: precession of the magnetic moment perp. to EA

Much better for spin-torque oscillator, because precession is present for ALL soliton area (not DW only, as for FM).

Low current, THz frequency

< in preparation>
Thank you for your attention!