Vortices and solitons in condensed matter

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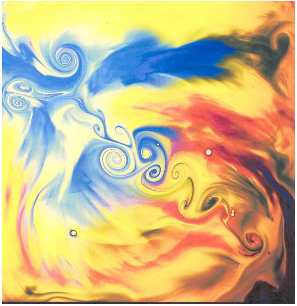
KTH, 25 January 2019

Vortices in fluids

Vortex is a part of the fluid rotating clockwise or anticlockwise in closed loops.

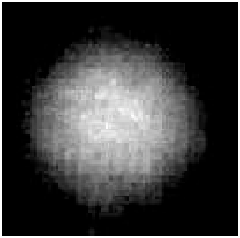


A particle crosses across the surface of a fluid at a high speed. Vortices and antivortices (oppositely circulating fluid) are created.

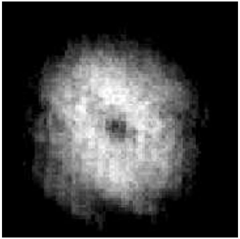
Atomic Bose-Einstein condensates (BEC)

Vapours of Rb, Li, etc in temparatures $T \sim 10\, nK$

Ground state

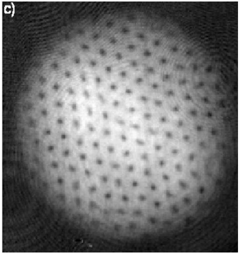


Quantized vortex



[Dalibard group]

Vortex lattice



[Ketterle group]

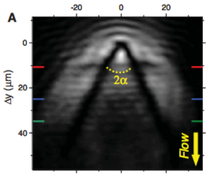
Superfluid flow

The fluid is flowing rotating around a region with zero fluid density, without deceleration.

[Komineas, Review on "Solitary waves in BECs", Eur. Phys. J. Special Topics 147, 133-152 (2007)]

Bose-Einstein condensates of exciton-polaritons in semiconductors

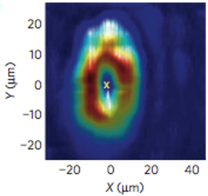
Polaritons are quasiparticles with small effective mass. Therefore they Bose-condense at higher temperatures.



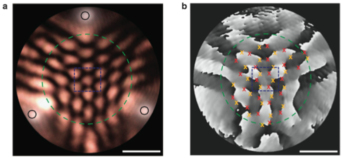
Solitons are localised density depletions of the fluid.

Picture (experiment): [Amo et al, Science 2011]

Theory on polariton solitons: [Komineas, Shipman, Venakides, PRB, Physica D, 2015]



[Sanvitto etal, 2010]

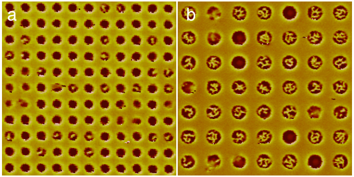


vortex-antivortex lattice

[Tosi et al, Nat. Comm. 2012]

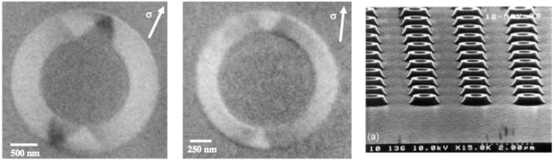
Vortices in polariton condensates.

Ferromagnetic materials (ferromagnetic elements)



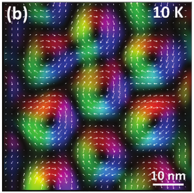
FePt dots, diameter 0.5-1μm.

[Moutafis, Komineas et al, PRB 76, 104426 (2007)]



Co ring particles

[Kläui et al, J. Phys.: Condens. Matter, 2003]



MnSi films

[Tonomura et al, NanoLett 2012]

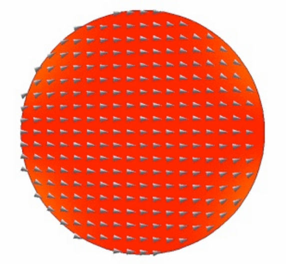
A ferromagnetic film

The magnetisation vector $\mathbf{M} = \mathbf{M}(x, y, t)$

has constant length at every point (x, y) in the film: $\mathbf{M}^2(x, y, t) = M_s^2$, where M_s is called the *saturation magnetisation*.

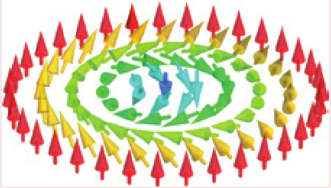
Magnetic states

Uniform



Ferromagnetic state

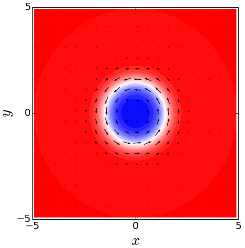
Non-uniform (magnetic solitons)



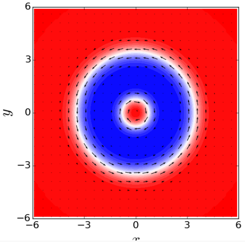
Skyrmion

Skyrmions in ferromagnets in Dzyaloshinksii-Moriya materials

Skyrmion

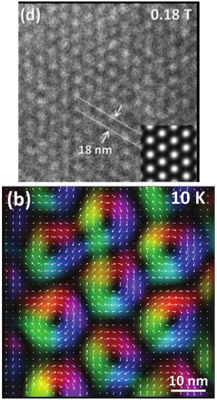


Skyrmionium



Experimental observations

Skyrmion lattice



[Tonomura et al, Nanoletters 2012]

Dynamics of topological and non-topological solitons

Fundamental relation for evolution of topological density [Papanicolaou, Tomaras (1991), Komineas, Papanicolaou (1996 & 2015)]:

$$\dot{q} = -\epsilon_{\mu\nu}\partial_\mu(\mathbf{f}\cdot\partial_\nu\mathbf{m}) = \epsilon_{\mu\nu}\,\partial_\mu\partial_\lambda\sigma_{\nu\lambda}, \quad \mu,\nu,\lambda = 1,2$$

where $\mathbf{f}\cdot\partial_\mu\mathbf{m} = -\partial_\nu\sigma_{\mu\nu}$.

The tensor $\sigma_{\mu\nu}$ has components

$$\sigma_{11} = \frac{1}{2}\,(\partial_2\mathbf{m}\cdot\partial_2\mathbf{m} - \partial_1\mathbf{m}\cdot\partial_1\mathbf{m}) + \frac{\kappa}{2}(m_1^2 + m_2^2) + \lambda(m_1\partial_2 m_3 - m_3\partial_2 m_1$$

$$\sigma_{12} = -\,\partial_1\mathbf{m}\cdot\partial_2\mathbf{m} + \lambda(m_3\partial_1 m_1 - m_1\partial_1 m_3)$$

$$\sigma_{21} = -\,\partial_1\mathbf{m}\cdot\partial_2\mathbf{m} + \lambda(m_2\partial_2 m_3 - m_3\partial_2 m_2)$$

$$\sigma_{22} = \frac{1}{2}\,(\partial_1\mathbf{m}\cdot\partial_1\mathbf{m} - \partial_2\mathbf{m}\cdot\partial_2\mathbf{m}) + \frac{\kappa}{2}(m_1^2 + m_2^2) + \lambda(m_3\partial_1 m_2 - m_2\partial_1 m_3$$

But, this talk is not about the technical part of this subject.

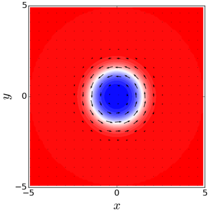
Let us move on and look at some exciting phenomena.

Force on a topological skyrmion and Hall motion

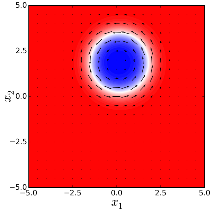
Apply a force, e.g., an external non-homogeneous magnetic field.

Force direction $\longrightarrow$

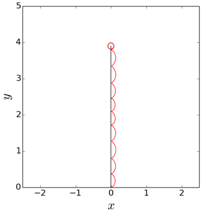
$t = 0$



$t \approx 20$



Trajectory



Topological Skyrmion dynamics (Hall motion)

It is spontaneously pinned in the absence of force.

When forced, propagates with constant velocity, perpendicular to force.

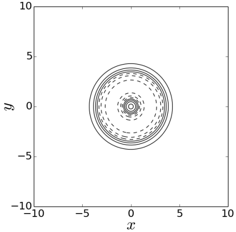
[Komineas, Papanicolaou, Phys. Rev. B 92, 064412 (2015)]

Force on a skyrmionium and Newtonian dynamics

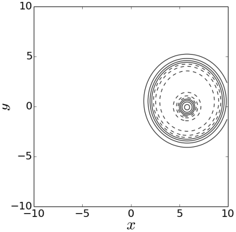
Apply the same force, e.g., an external non-homogeneous magnetic field.

Force direction $\longrightarrow$

$t = 0$



$t = 160$



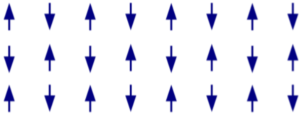
Non-topological Skyrmion dynamics (Newtonian)

Propagates freely in the absence of force. When forced, it accelerates.

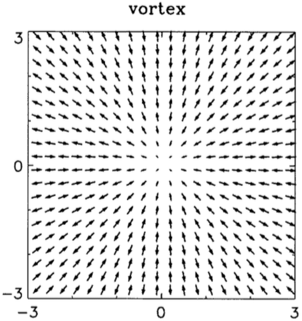
[Komineas, Papanicolaou, Phys. Rev. B 92, 064412 (2015)]

Antiferromagnets

Antiferromagnetic ground state

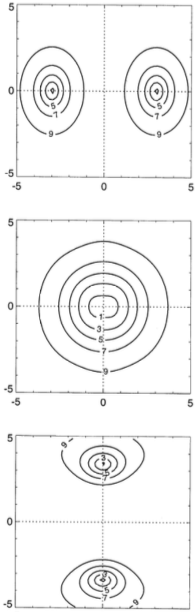


Vortices in Antiferromagnets



The in-plane projection of spin (s_1, s_2).

Right-angle scattering of vortices in antiferromagnets



AFM Vortices can propagate.

Figure shows contour plots for out-of-plane field component.
Figure entries

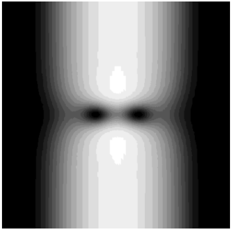
- Two vortices are set in a head-on collision course.
- They overlap.
- They reemerge after scattering, at a perpendicular direction.

[SK, Physica D 155, 223-234 (2001)]

Vortex rings in fluids, superfluids, ...

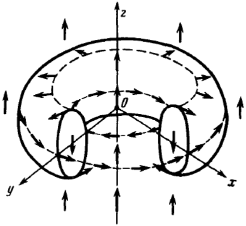
Rings of air in a fluid:
they propagate along their axis.
Fuid flow goes around the ring.

Vortex rings in trapped BEC



[Komineas, Papanicolaou, PRL 2002]

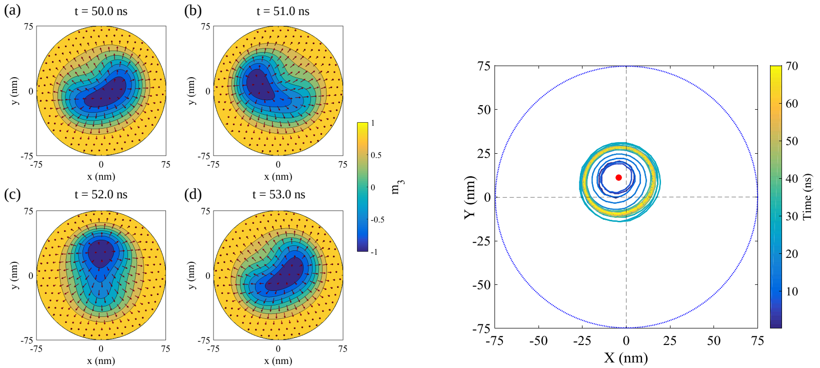
Vortex rings in Ferromagnets



[Dzyaloshinskii, Ivanov, JETP Lett., 1979]

Recent work: Chiral skyrmion auto-oscillations

We inject spin-polarized current uniform in space, constant in time.



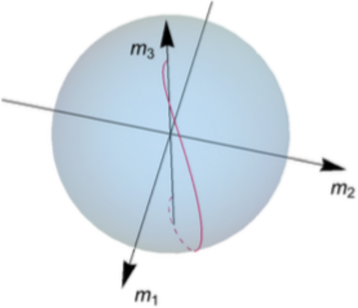
[Left] Snapshots of skyrmion for a full cycle. [Right] Skyrmion trajectory.

We obtain sustained skyrmion rotation around a point off the disc center.

[Sisodia, Komineas, Muduli, https://arxiv.org/abs/1808.01436 (2018)]

Recent work: Chiral domain wall propagation

Propagating domain wall profile on the Bloch sphere



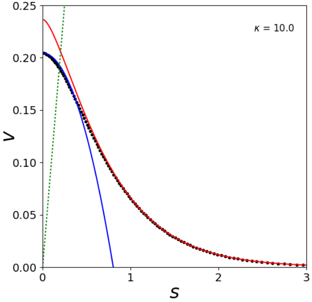
[Komineas, Melcher, Venakides, https://arxiv.org/abs/1806.02082 (2018)]

Consider a model with exchange, easy-axis anisotropy and DMI.

- We prove existence of traveling domain wall (DW) solutions.
- We find detailed features of traveling DW numerically.
- The velocity of the DW scales proportionally to anisotropy and DMI. Thus, thinner walls travel faster.
- No theoretical limit to velocity, in contrast to Walker walls.

Recent work: Skyrmion profile (*)

Numerical solution (black dots)
Analytical solution
(red and blue lines)



[Komineas, Melcher, Venakides, (2019)]

The skyrmion profile contains multiple length scales.
For large anisotropy it shows

- polynomial behaviour (Belavin-Polyakov soliton) up to ~ 3 skyrmion radii,
- exponential behaviour for large distances.
- We obtain the skyrmion radius.

Concluding remarks

- Vortices are ubiquitous in condensed matter.
- Terminology includes: vortices, bubbles, skyrmions, vortex rings, etc.
- Fundamental phenomena remain unexplored: Newtonian skyrmion dynamics, right-angle scattering of solitons, vortex rings.

12th International Symposium on Hysteresis Modeling and Micromagnetics
Heraklion, Crete, May 19-22, 2019
Paper submission deadline: 5th February.

HMM CRETE 2019