Topology in magnetic systems

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Introduction

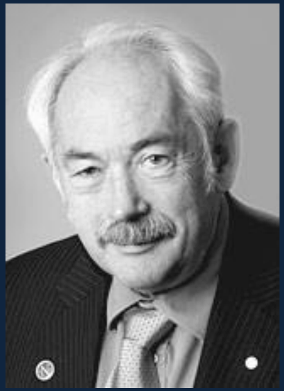
Electron = Charge + Spin

- **There has been great achievements on the "charge" properties in semiconductor research since <u>artificial structures</u> were introduced in late 1960s to early 1970s.**

- **Similar pathway has been followed on the "spin" properties in magnetism research since artificial structures were introduced in 1980s.**

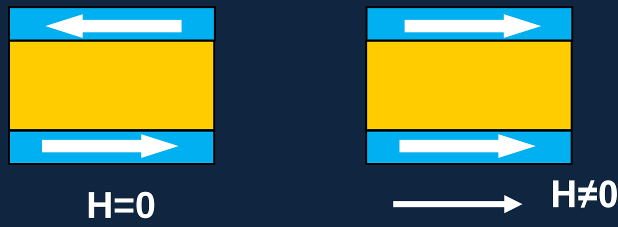
- **There is increasing interest on the combination of "charge" and "spin" to develop spintronics technology, especially since the discovery of Giant Magnetoresistance (2007 Nobel Prize in physics).**

Albert Fert



Peter Grünberg

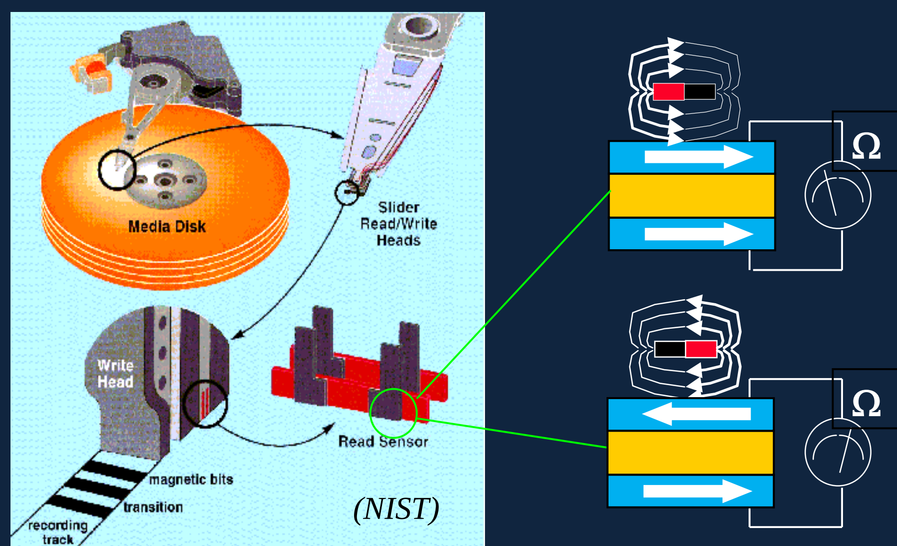
Antiferromagnetic Coupling and Giant Magnetoresistance (GMR)



P. Grünberg, et. al., PRL **57**, 2442 (1986).

GMR = [R(0)-R(H)]/R(H) = 10-100%

M. N. Baibich, et al., PRL **61**, 2472 (1988).
G. Binasch, et al. PRB **39**, 4828 (1989).



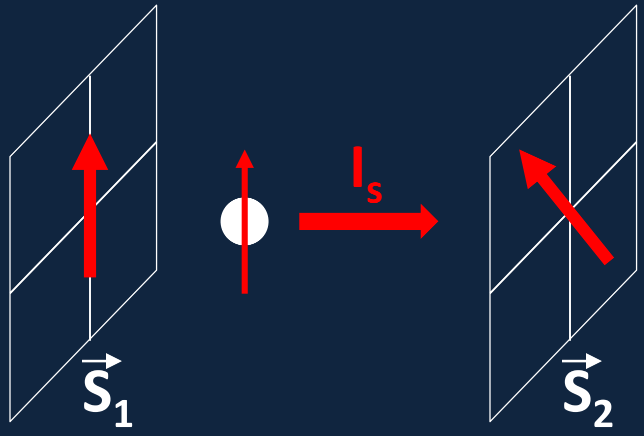
What will be the next breakthrough?

No one knows for sure, but two have emerged recently.

- Spin torque effect (spin current)

2013 Buckley Prize: Spin-Transfer Torque

J.C. Slonczewski, J. of Magn. Magn. Mat. 159, L1-L7 (1996).
L. Berger, Phys. Rev. B 54, 9353 (1996).



$$\dot{\vec{S}}_2 \sim \frac{I_e g}{e} \vec{S}_2 \times (\vec{S}_1 \times \vec{S}_2)$$

The flow of spins (I_s) delivers a torque to S_2.

- Topological effect (vortices, skyrmions)

Topology and Skyrmion

Topology

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Topology and Skyrmion

Topology

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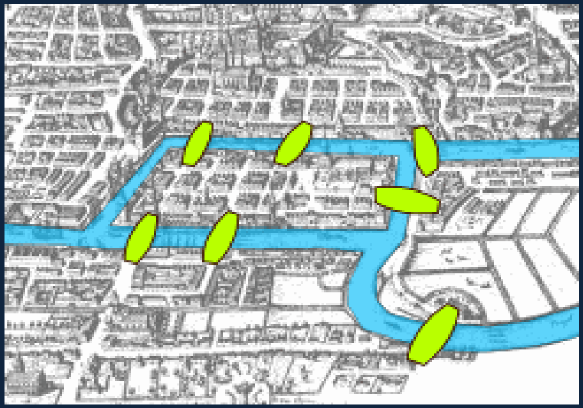
Königsberg Bridge Problem



Is it possible to find a route through the city that will cross each bridge once and only once?

Topology and Skyrmion

Topology

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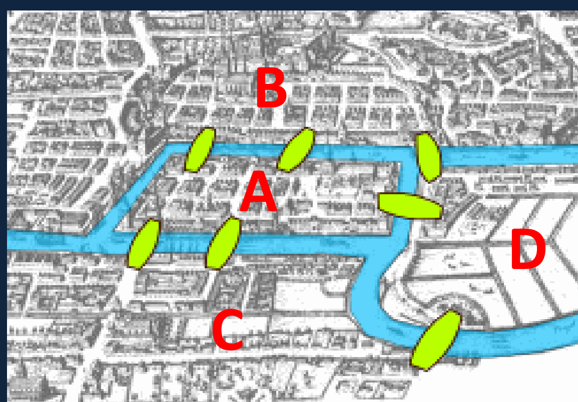
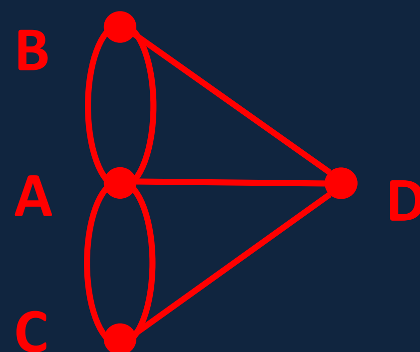
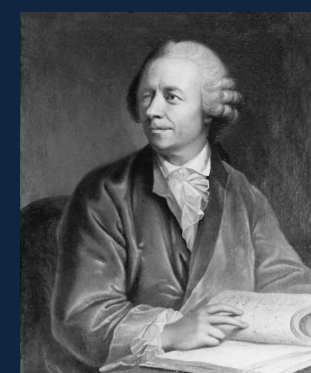
Königsberg Bridge Problem







Leonhard Euler
4/15/1707-9/18/1783

Topology and Skyrmion

Topology

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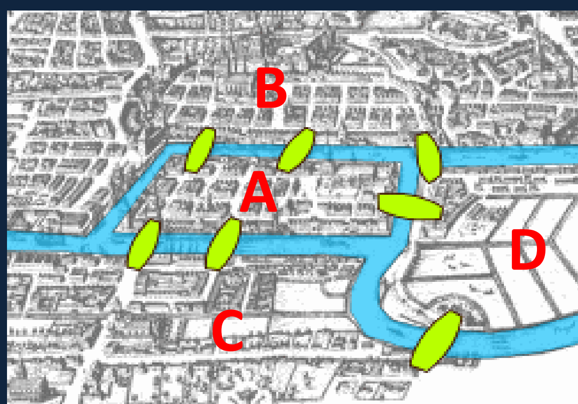
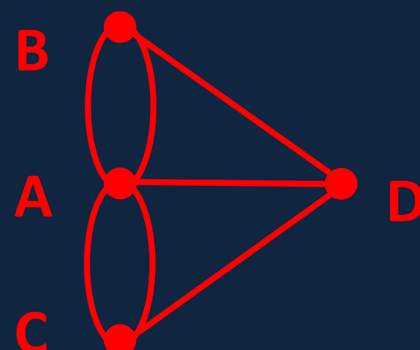
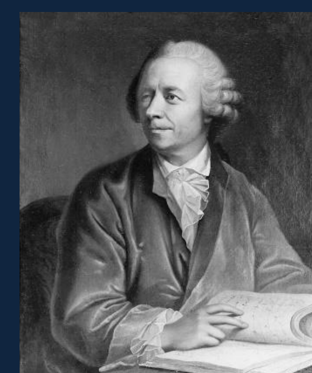
 = 

Königsberg Bridge Problem





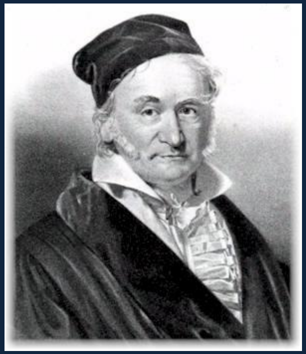
"This question is so banal, but seemed to me worthy of attention in that [neither] geometry, nor algebra, nor even the art of counting was sufficient to solve it."



Leonhard Euler
4/15/1707-9/18/1783

Linking Number

What’s the number of times that one closed loop winds around the other closed loop?



Johann Carl Friedrich Gauss
4/30/1777-2/23/1855

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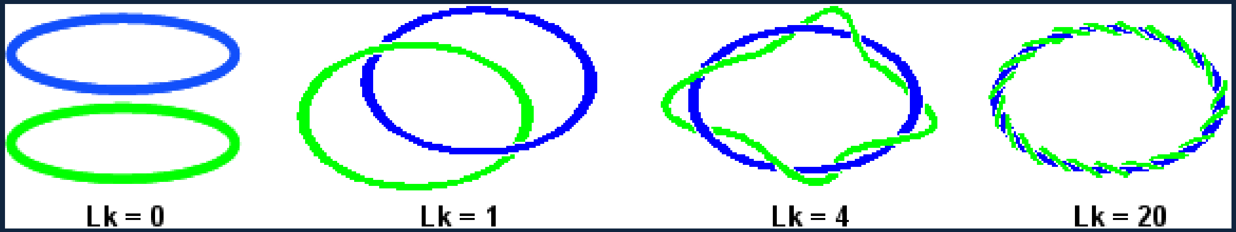
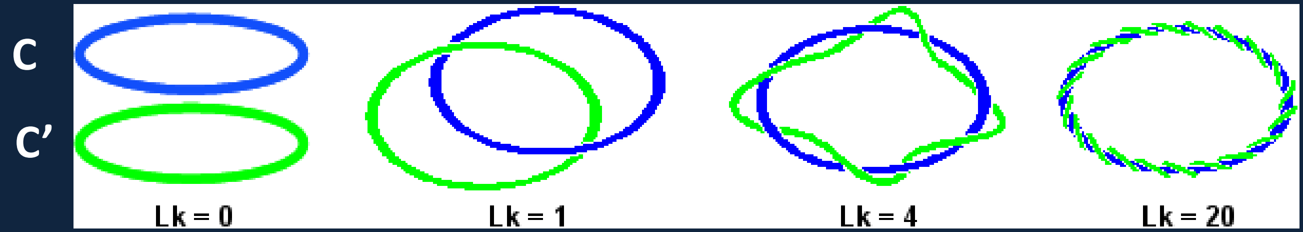


linking number $$n = \frac{1}{4\pi} \oint_C \oint_{C'} \frac{(d\vec{r} \times d\vec{r}\,') \cdot (\vec{r} - \vec{r}\,')}{|\vec{r} - \vec{r}\,'|^3}$$

Linking Number

What's the number of times that one closed loop winds around the other closed loop?

Johann Carl Friedrich Gauss
4/30/1777-2/23/1855



linking number $$n = \frac{1}{4\pi} \oint_C \oint_{C'} \frac{(d\vec{r} \times d\vec{r}\,') \cdot (\vec{r} - \vec{r}\,')}{|\vec{r} - \vec{r}\,'|^3}$$

Electromagnetism

Biot–Savart law

$$\vec{B}(\vec{r}) = \frac{\mu_0 I_0}{4\pi} \oint_{C'} \frac{d\vec{r}\,' \times (\vec{r} - \vec{r}\,')}{|\vec{r} - \vec{r}\,'|^3}$$

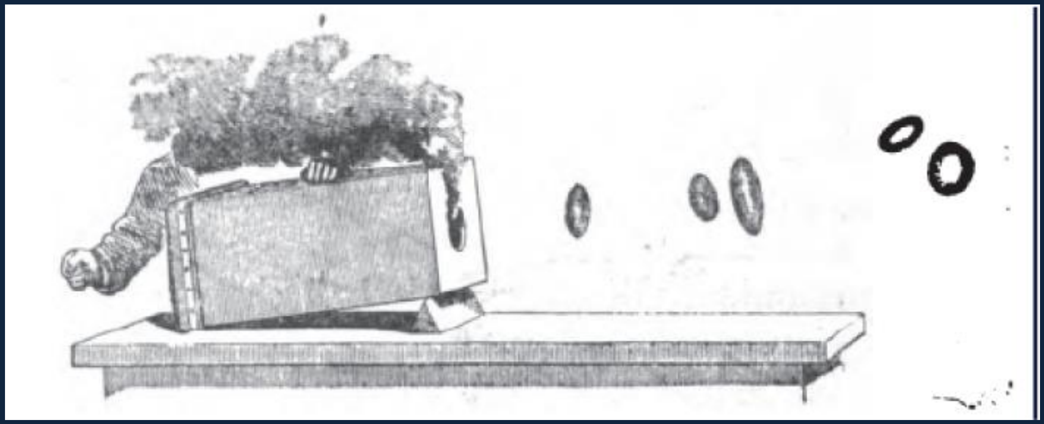
Ampère's law

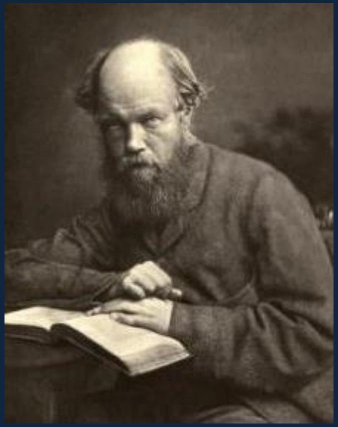
$$\oint_C \vec{B}(\vec{r}) \cdot d\vec{r} = \mu_0 I_{enc} = \mu_0 n I_0$$

$\Rightarrow$

$$\frac{1}{4\pi} \oint_C \oint_{C'} \frac{[d\vec{r}\,' \times (\vec{r} - \vec{r}\,')] \cdot d\vec{r}}{|\vec{r} - \vec{r}\,'|^3} = n$$

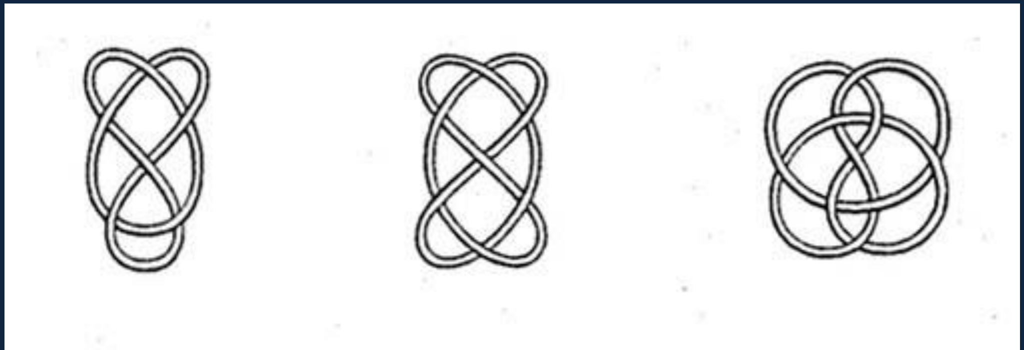
Experiment: Smoke Rings





Peter Guthrie Tait
4/28/1831-7/4/1901

Elements = knots of swirling vortices in the ether



Knots from the second part (1884) of Tait's trailblazing paper.

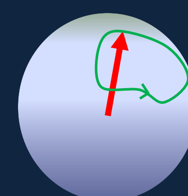
Tony Skyrme
12/5/1922-6/25/1987

Skyrme, T. H. R. A Non-Linear Theory of Strong Interactions. *Proc. R. Soc. London Ser. A* **247**, 260-278 (1958).

Skyrme, T. H. R. A unified field theory of mesons and baryons. *Nuclear Physics* **31**, 556-569 (1962).

Skyrmions in 2D Heisenberg system

$$H = -J \sum_{<i,j>} \vec{S}_i \cdot \vec{S}_j = J \int d^2\vec{r} \left[\nabla \vec{n}(\vec{r})\right]^2 \qquad \vec{n} \equiv \frac{\vec{S}}{S}$$



Berry Phase = S x Solid Angle

Question: How many static solutions?

Answer: Many solutions which are “quantized” by an integer index N.

Metastable states of two-dimensional isotropic ferromagnets

A. A. Belavin and A. M. Polyakov

Gor'kii State University
(Submitted October 4, 1975)
Pis'ma Zh. Eksp. Teor. Fiz. **22**, No. 10, 503–506 (20 November 1975)

$$q = \frac{1}{8\pi} \int \epsilon_{\alpha\beta\gamma} \epsilon_{\mu\nu} n^{\alpha} \frac{\partial n^{\beta}}{\partial x_{\mu}} \frac{\partial n^{\gamma}}{\partial x_{\nu}} d^2x \qquad (5)$$

Skyrmion Number

$$N = \int \frac{dxdy}{4\pi} \vec{n} \cdot \left(\partial_x \vec{n} \times \partial_y \vec{n}\right) = \text{integer}$$

Mapping of 2D spins from the xy plane to a sphere

Skyrmion solution

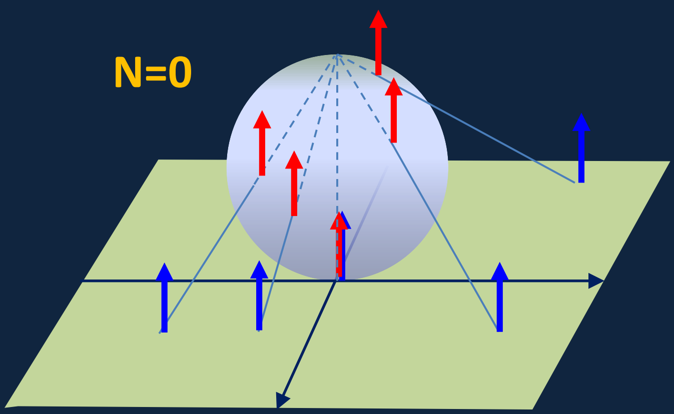
$$\vec{S} = (\sin\theta\cos\phi, \sin\theta\sin\phi, \cos\theta) \quad \Leftrightarrow \quad w = (x, y)$$

$$w = x + iy = \frac{S_x + iS_y}{1 - S_z} = ctg(\theta/2)e^{i\phi}$$

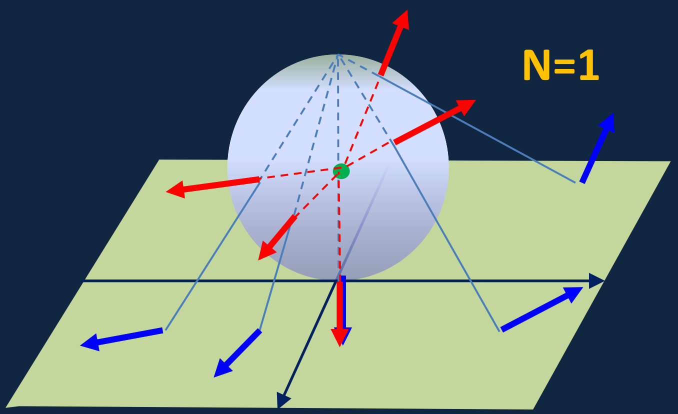
Skyrmion Number

$$N = \int \frac{dxdy}{4\pi}\vec{n}\cdot\left(\partial_x\vec{n}\times\partial_y\vec{n}\right)$$

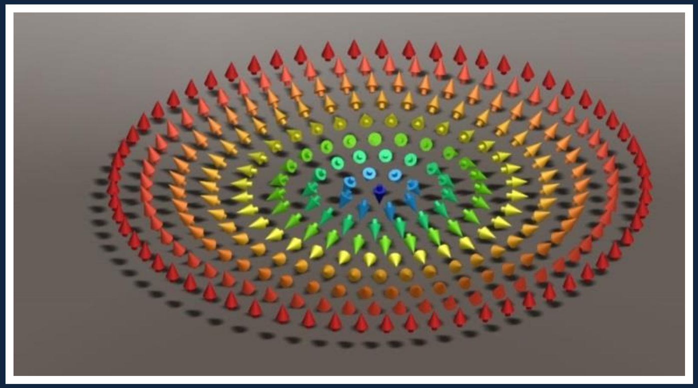
N=0



N=1



$$\begin{cases} S_x = \dfrac{2Rr}{R^2 + r^2}\cos(\theta + \phi) \\ S_y = \dfrac{2Rr}{R^2 + r^2}\sin(\theta + \phi) \\ S_z = \dfrac{R^2 - r^2}{R^2 + r^2} \end{cases}$$



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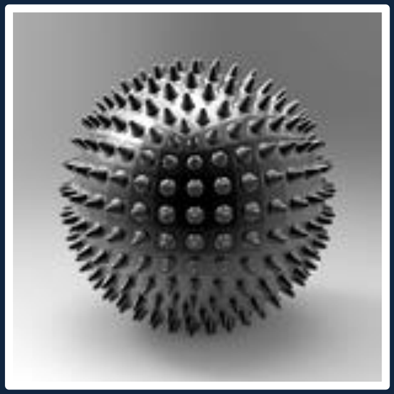

Skyrmion of N=1

Spiky Ball

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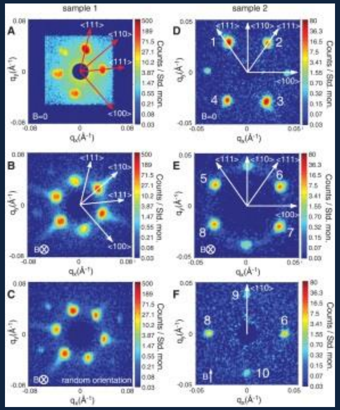
Creation of magnetic Skyrmions in experiment

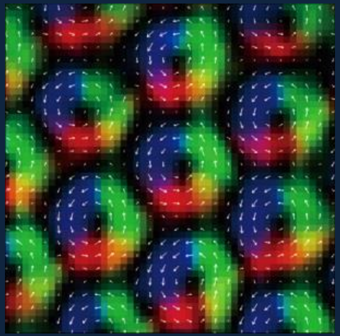
- **Dzyaloshinskii-Moriya (DM) interaction** $H_{DM} = -\vec{D}_{DM} \cdot \left(\vec{S}_i \times \vec{S}_j\right)$

U. K. Rößler, A. N. Bogdanov, & C. Pfleiderer, "Spontaneous skyrmion ground states in magnetic metals". Nature **442**, 797-801 (2006).

S. Mühlbauer et al. "Skyrmion Lattice in a Chiral Magnet". Science **323**, 915-919 (2009).

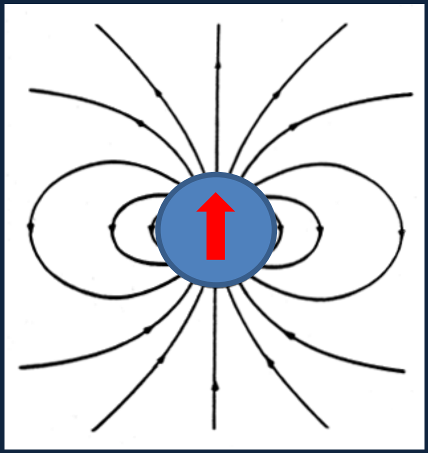
X. Z. Yu et al. "Real-space observation of a two-dimensional skyrmion crystal" Nature 465, 901–904 (17 June 2010).





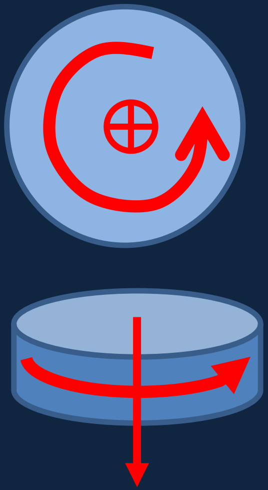
Naoto Nagaosa & Yoshinori Tokura, "Topological properties and dynamics of magnetic skyrmions". Nature Nanotechnology **8**, 899-911 (2013).

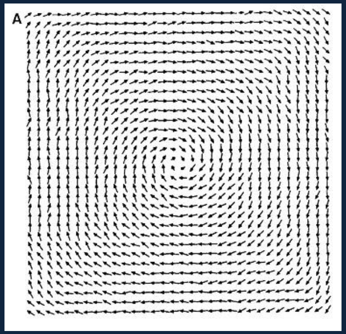
Magnetic Vortex vs skyrmion

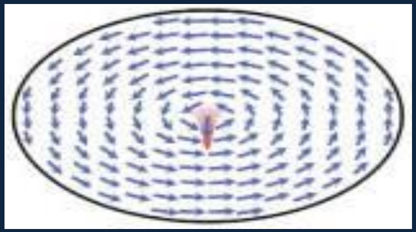


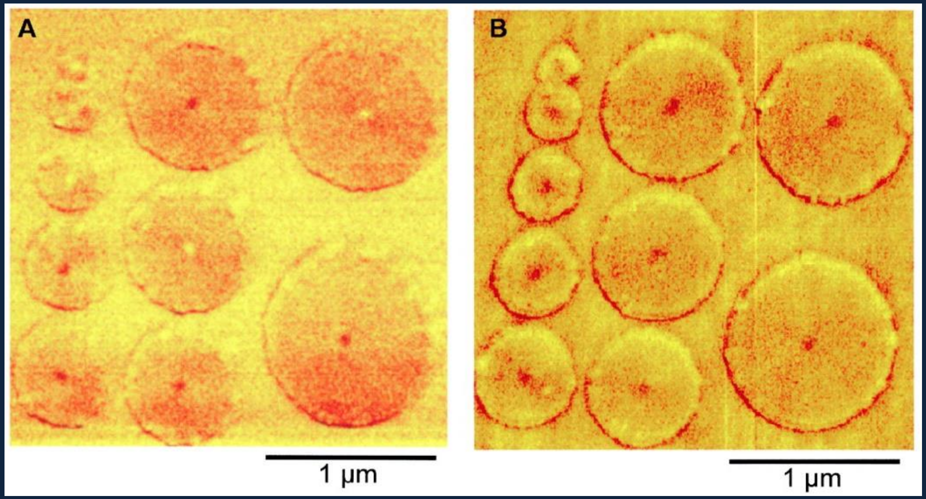
$$\sigma_M = \vec{M} \cdot \hat{n}$$

$$H = -J \sum_{<i,j>} \vec{S}_i \cdot \vec{S}_j$$

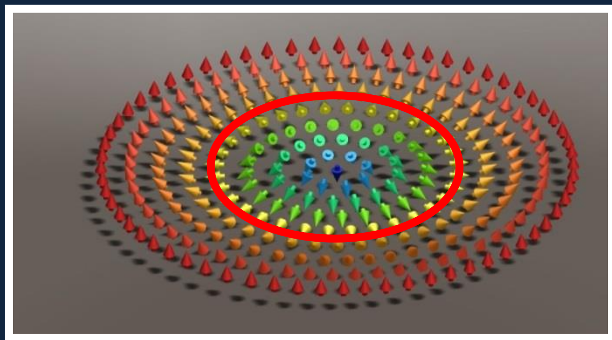


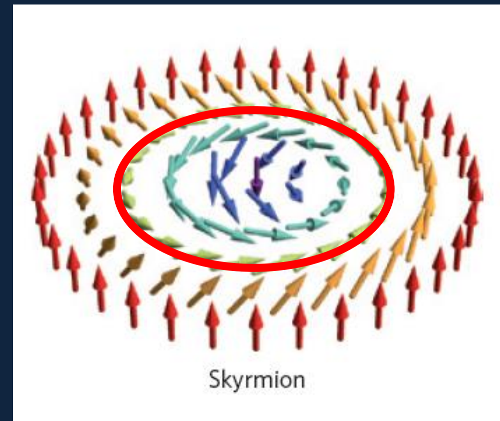






T. Shinjo et. al. *Science* **289**, 930-932 (2000).





One magnetic vortex is ½ skyrmion

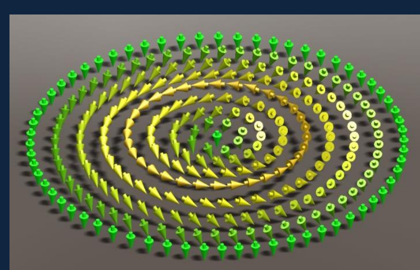
O. A. Tretiakov and O. Tchernyshyov, *Phys. Rev. B* **75**, 012408 (2007).

One skyrmion = vortex + surrounding out-of-plane spins

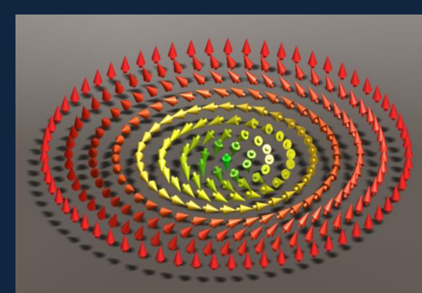
$$N = \int \frac{dxdy}{4\pi} \vec{n} \cdot \left(\partial_x \vec{n} \times \partial_y \vec{n} \right)$$

N=0 vortex core // $S_{surronding}$

N=1 vortex core // $-S_{surronding}$



N=0

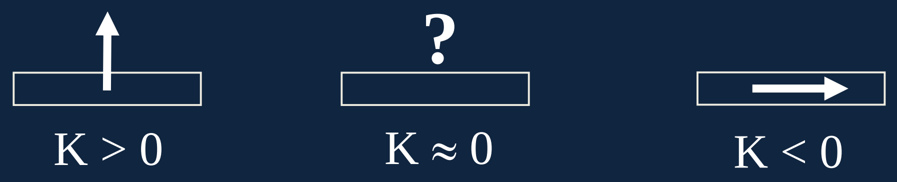


N=1

Stripe, bubble, and artificial skyrmions in magnetic thin films

Spin Reorientation Transition (SRT)

$H = -J \Sigma S_i \bullet S_j - K \Sigma S_{iz}^2$ What will happen at $K \approx 0$?



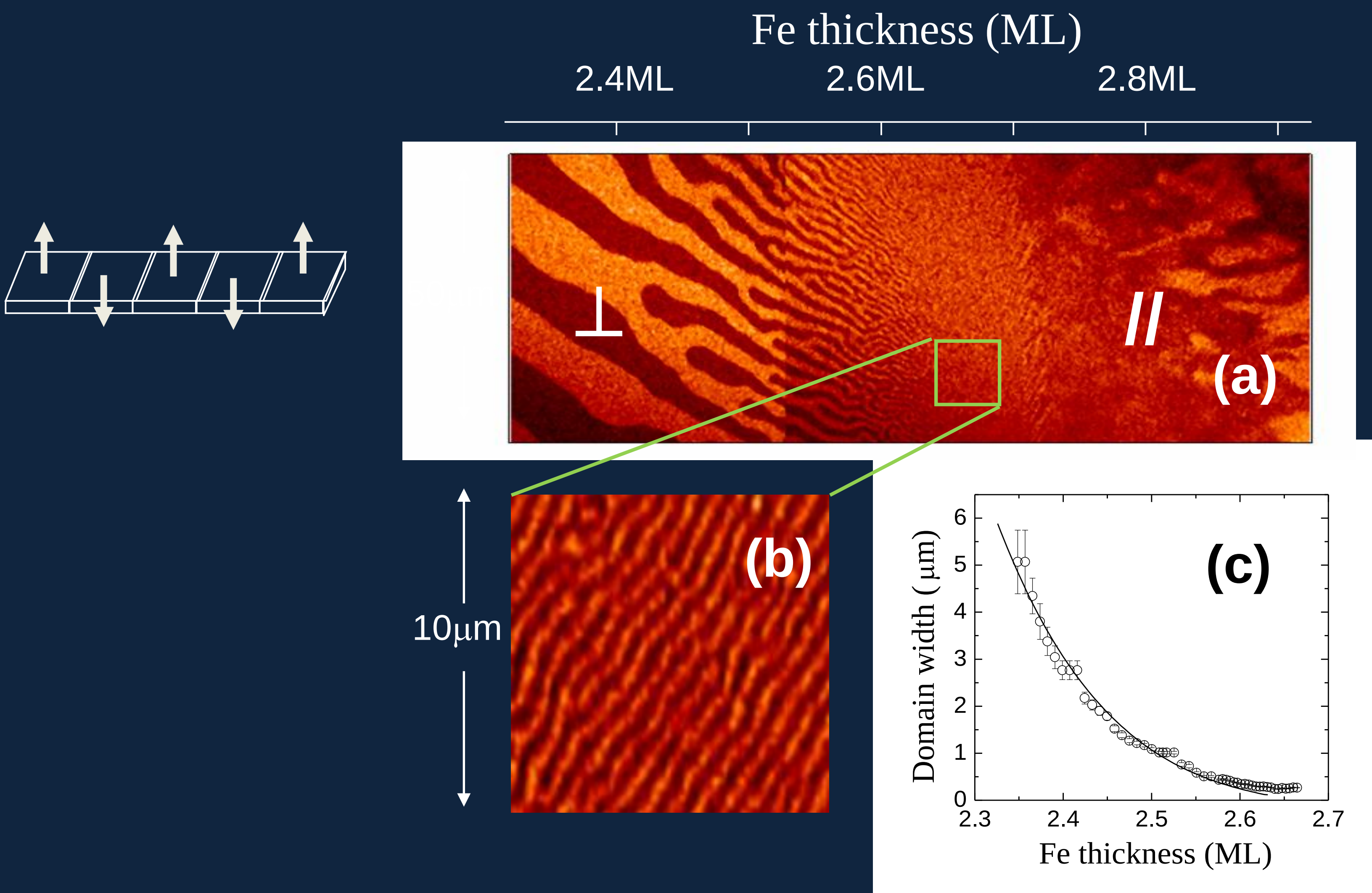
- **Spin-orbit interaction gives $-KS_z^2$ if z symmetry is broken.**
- **Dipolar interaction gives $2\pi M^2 S_z^2$.**

For example, $E = -Ku_z^2 = -(K_S/d - 2\pi M^2)S_z^2$

Changing d to tune K around zero.

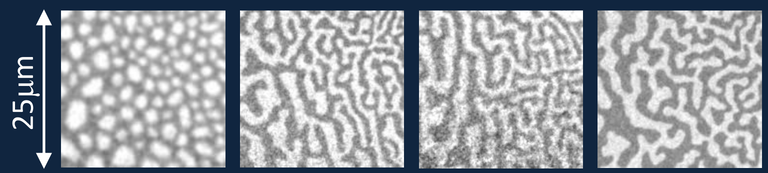
Stripe Phase

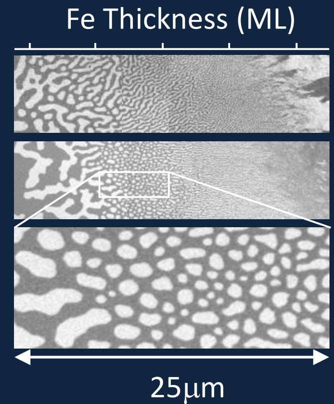
- Y. Z. Wu, C. Won, A. Scholl, A. Doran, H. W. Zhao, X. F. Jin, and Z. Q. Qiu, *Phys. Rev. Lett.* **93**, 117205 (2004).



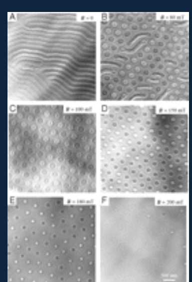
Bubbles and Skyrmions

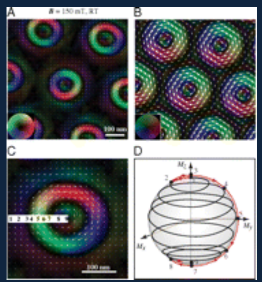
- J. Choi, J. Wu, C. Won, Y. Z. Wu, A. Scholl, A. Doran, T. Owens, and Z. Q. Qiu, "Magnetic bubble domain phase at the spin reorientation transition of ultrathin Fe/Ni/Cu(001) film", *Phys. Rev. Lett.* **98**, 207205 (2007).



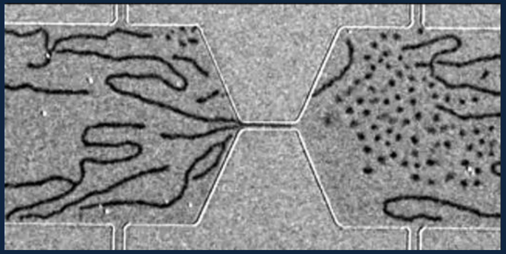


- Xiuzhen Yu *et al.* "Magnetic stripes and skyrmions with helicity reversals." *Proceedings of the National Academy of Sciences* **109**, 8856-8860 (2012).

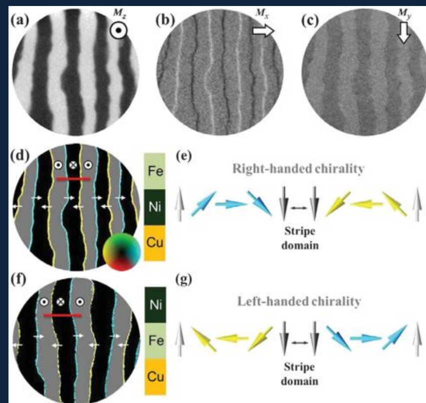


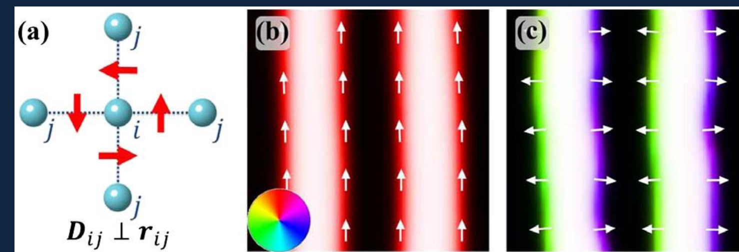


- Wanjun Jiang *et al.* "Blowing magnetic skyrmion bubbles." *Sciences* **349**, 283-286 (2015).

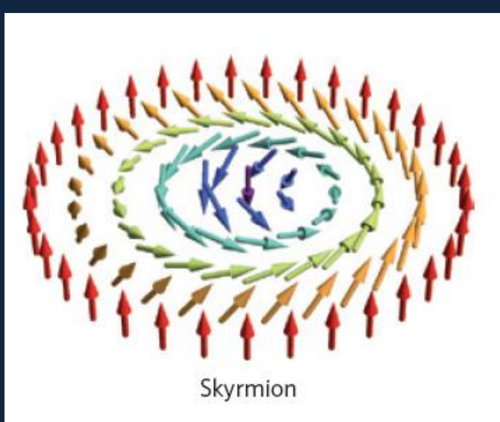


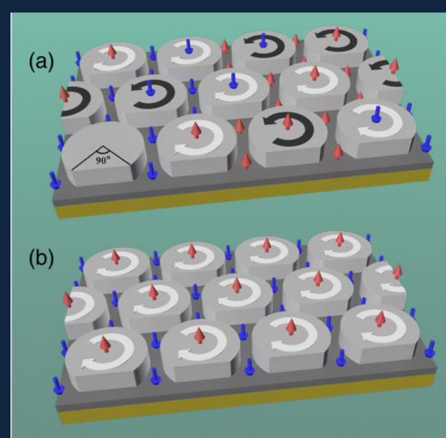
- G. Chen *et al.* “Novel chiral magnetic domain wall structure in Fe/Ni/Cu(001) films”, *Phys. Rev. Lett.* **110**, 177204 (2013).

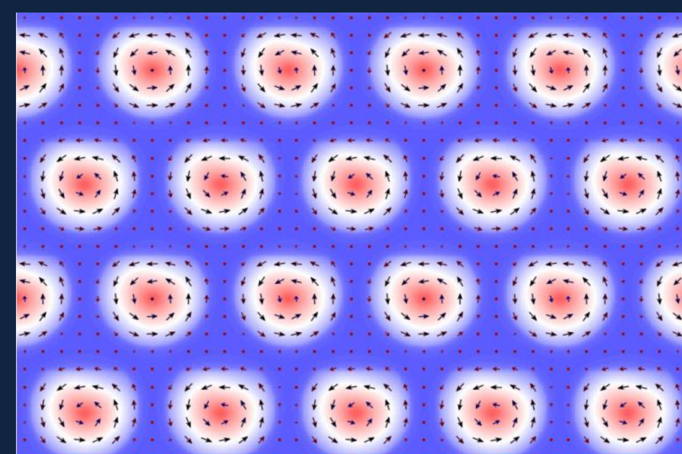




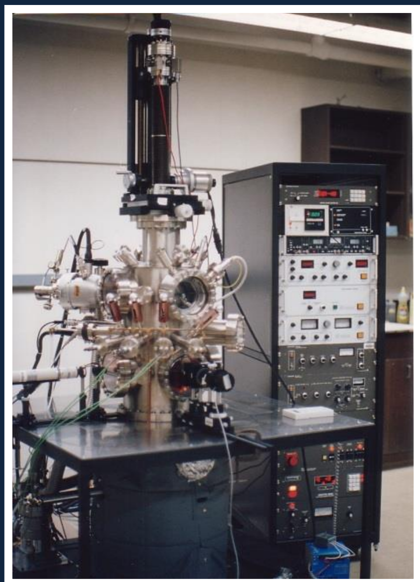
- L. Sun, *et al.* “Creating an Artificial Two-Dimensional Skyrmion Crystal by Nanopatterning.” *Phys. Rev. Lett.* **110**, 167201 (2013).

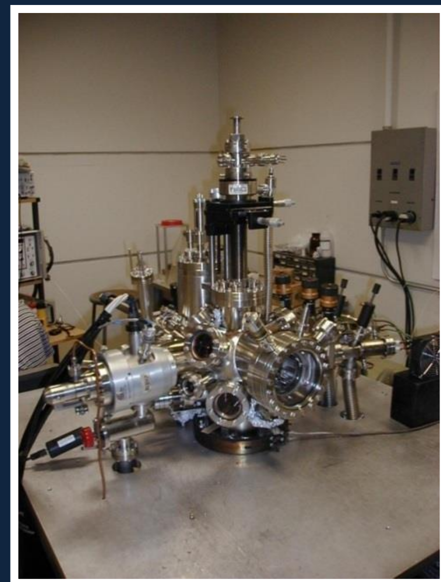


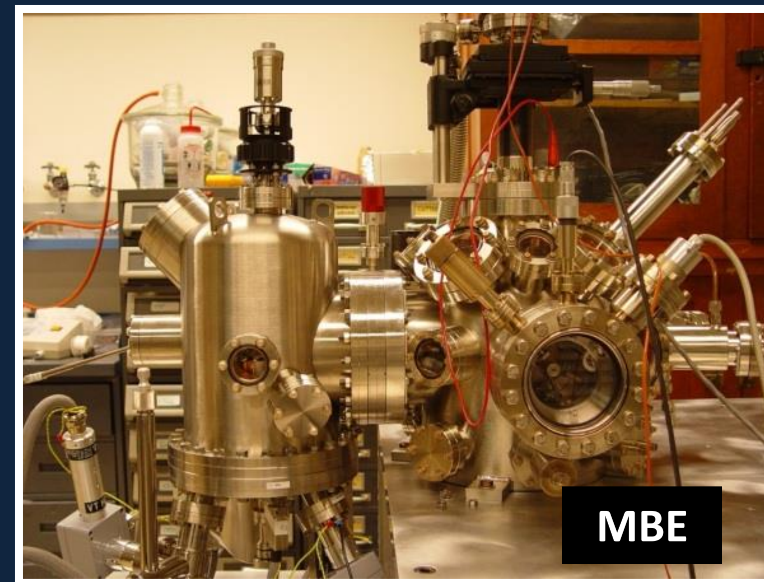


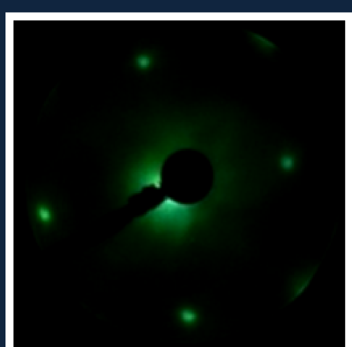


MBE grown magnetic thin films









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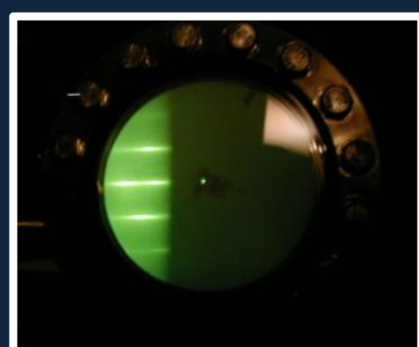
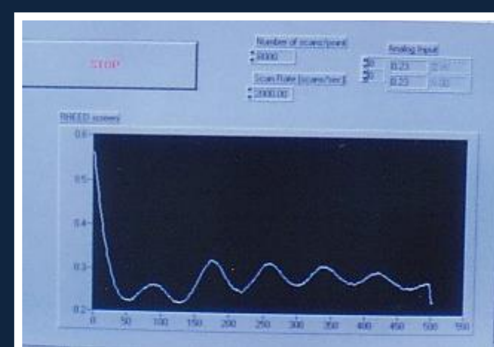
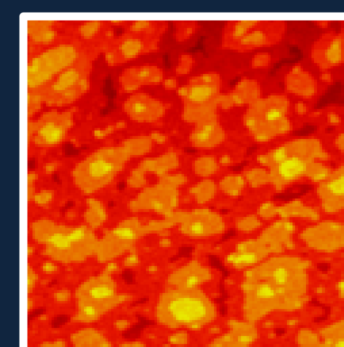


RHEED



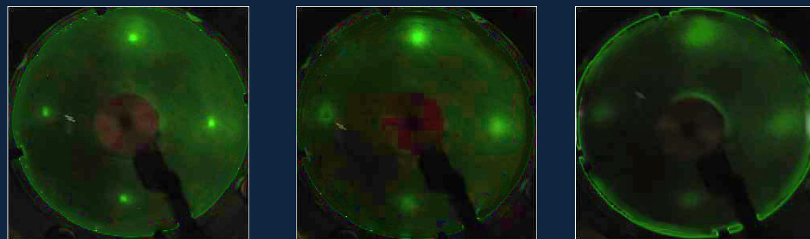
RHEED Oscillations

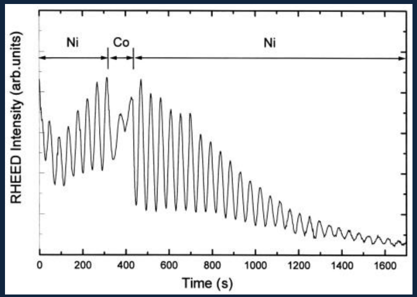


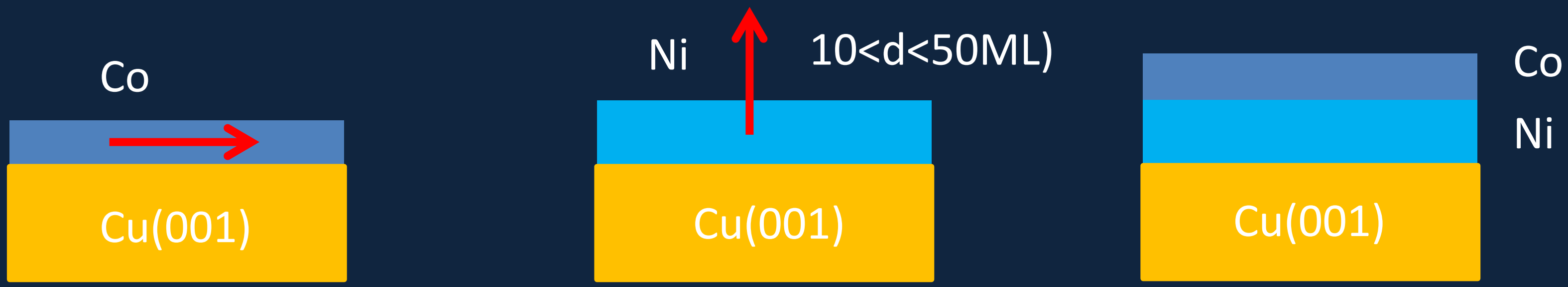
STM

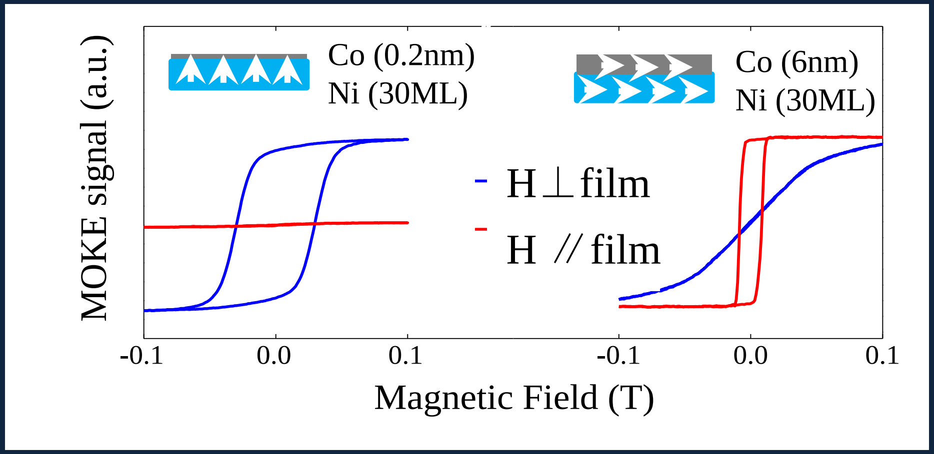
Co/Ni/Cu(001)

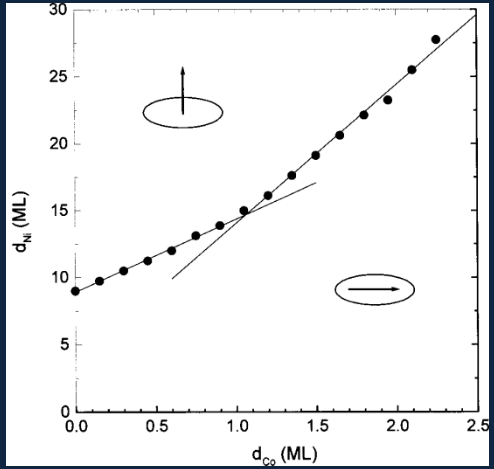
Cu(001) 30ML Ni/Cu(001) 6nm Co/Ni/Cu(001)



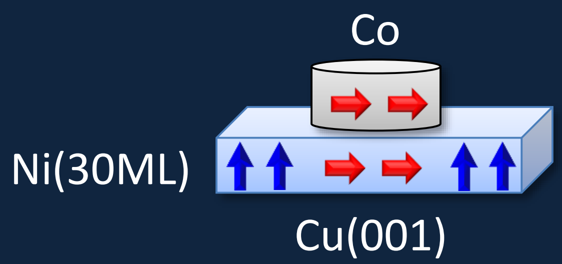


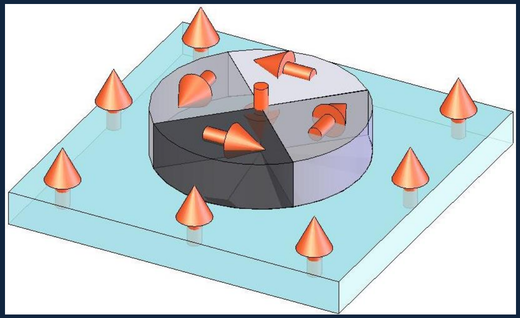


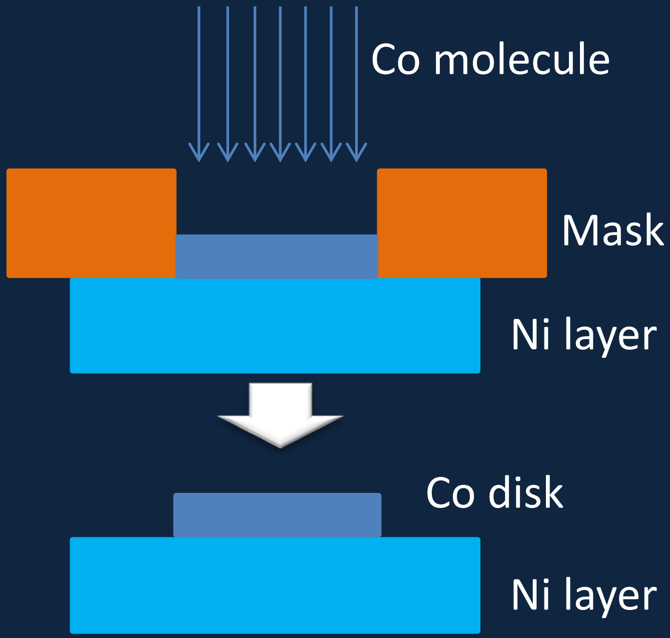


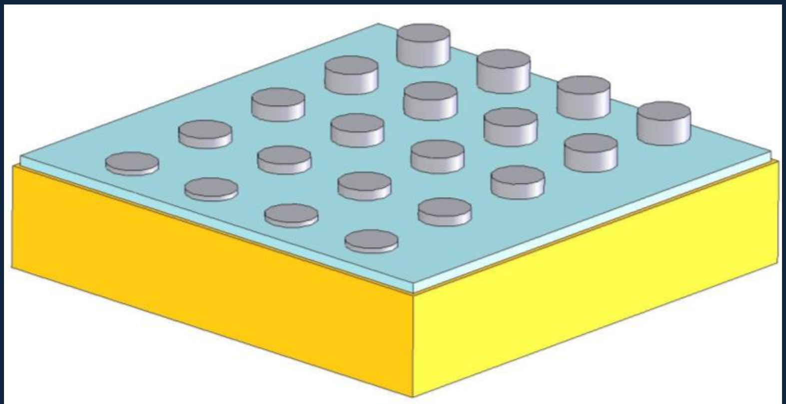


Co(disk)/Ni(30ML)/Cu(001)



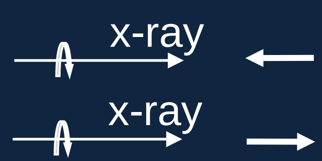


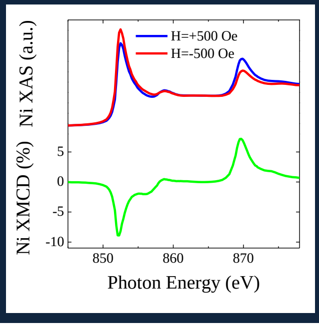




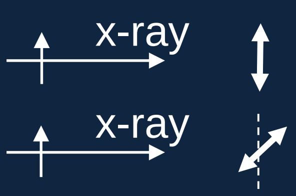
X-ray Magnetic Dichroism — Element-resolved measurement

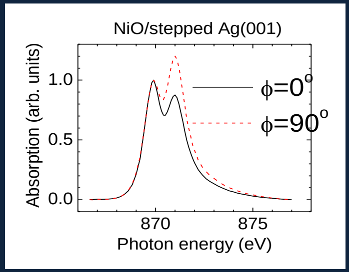
XMCD



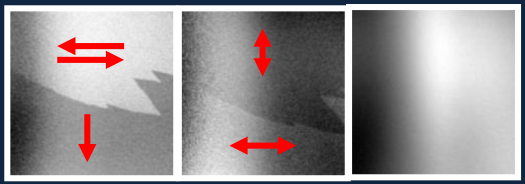


XMLD



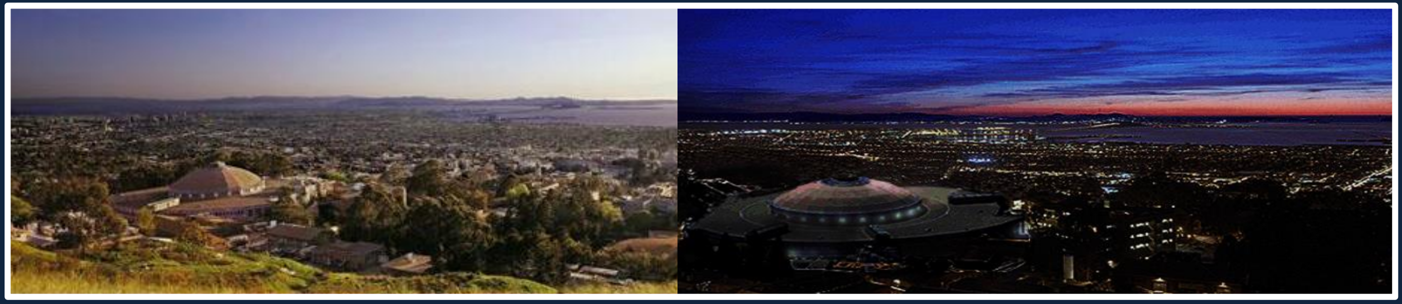


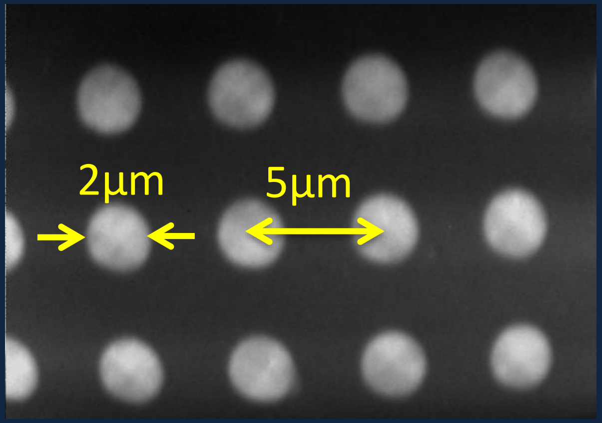
PEEM

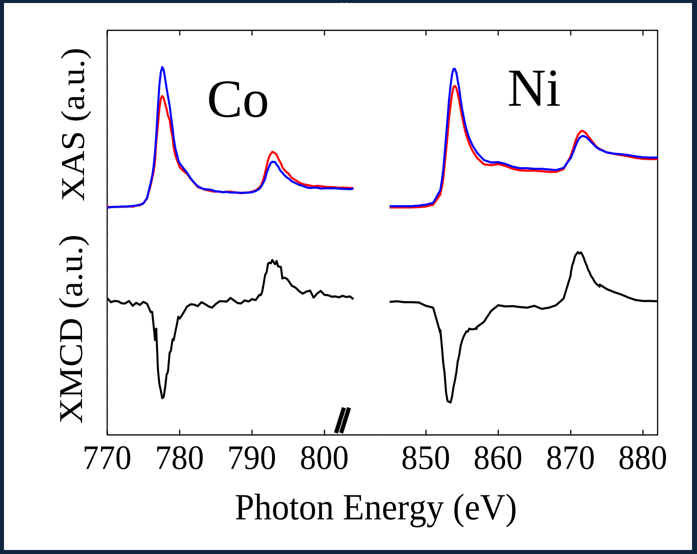


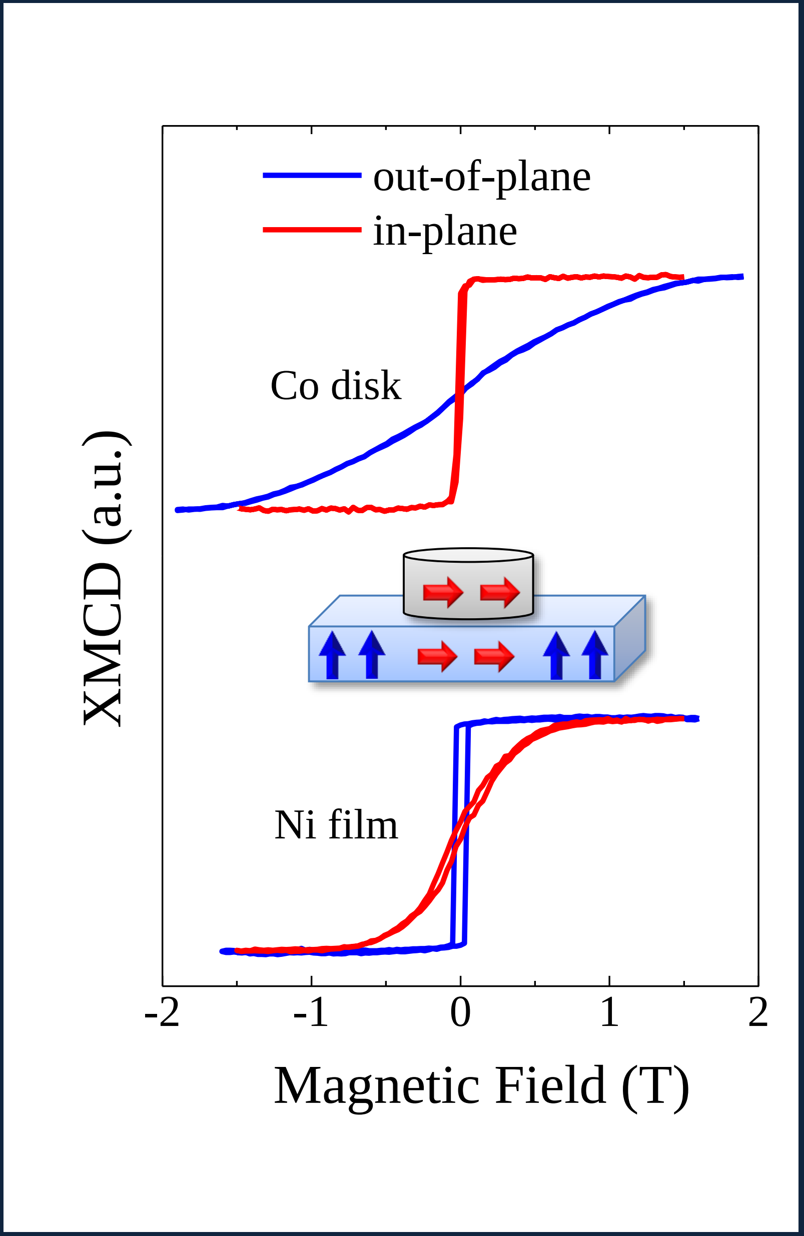
Fe XMCD Ni XMLD Ni XMCD

NiO(14ML)/Fe(15ML)/Ag(001)

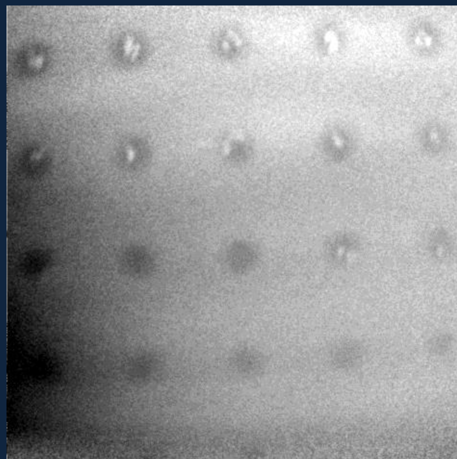



2µm
5µm

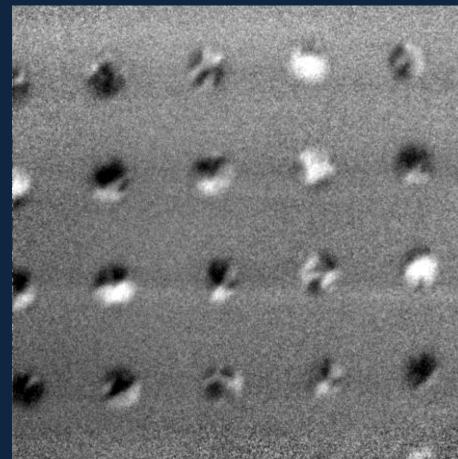

Co
Ni
XAS (a.u.)
XMCD (a.u.)
770 780 790 800 850 860 870 880
Photon Energy (eV)


out-of-plane
in-plane
Co disk
Ni film
XMCD (a.u.)
-2 -1 0 1 2
Magnetic Field (T)

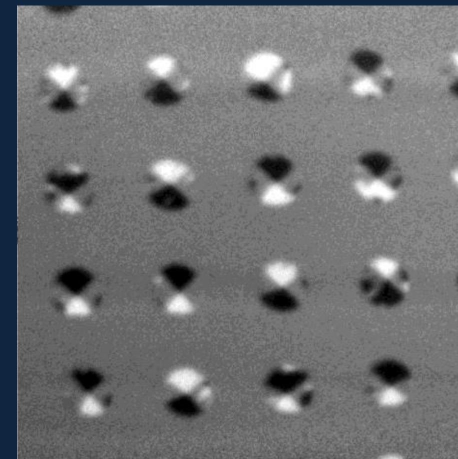
d_{Co}=1nm

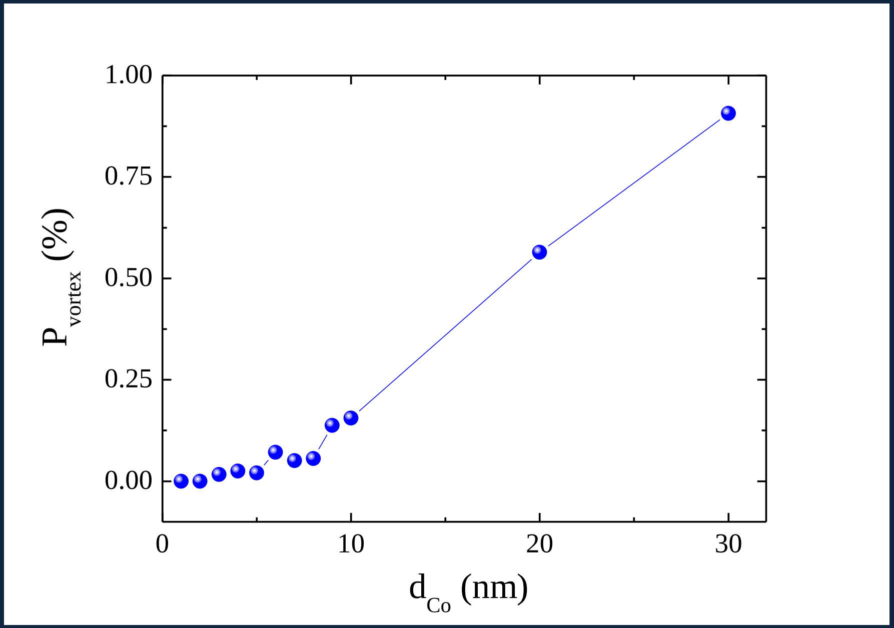


d_{Co}=3nm

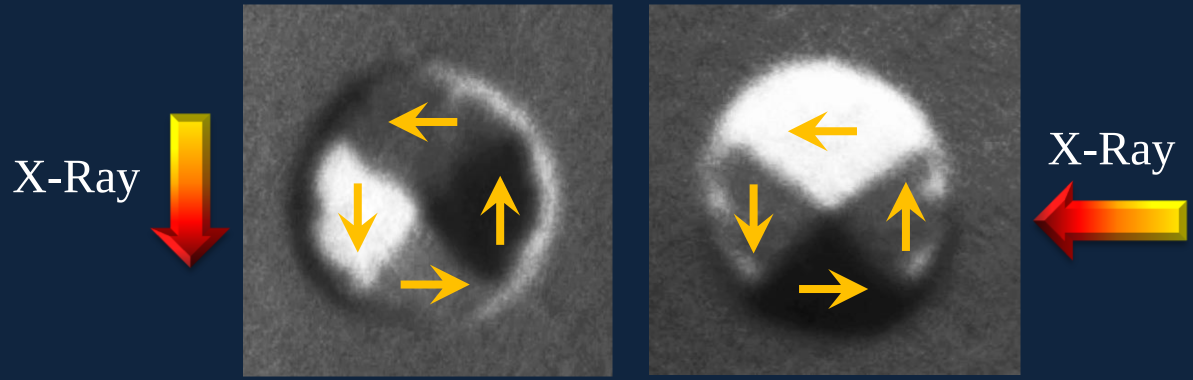


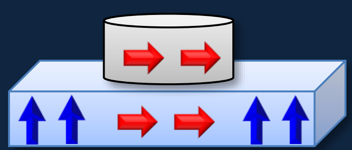
d_{Co}=30nm

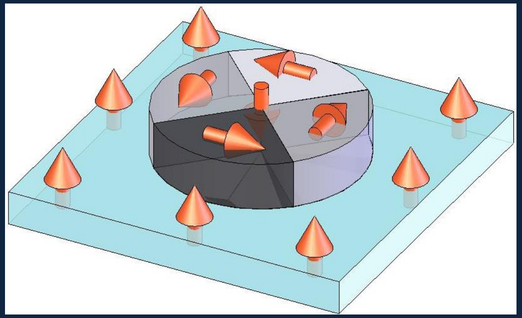




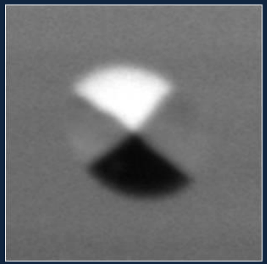
Co(disk)/Ni(30ML)/Cu(001)







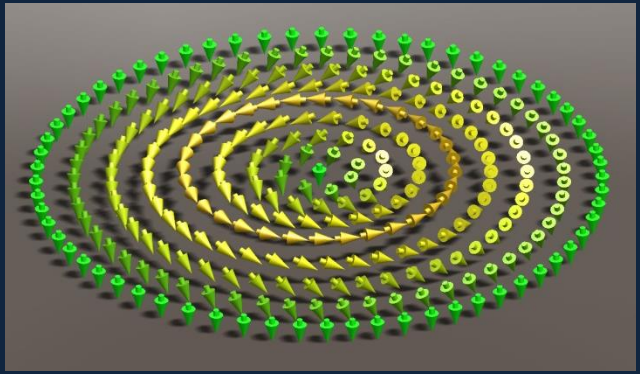
Ni(5ML)/Co(disk)/Cu(001)



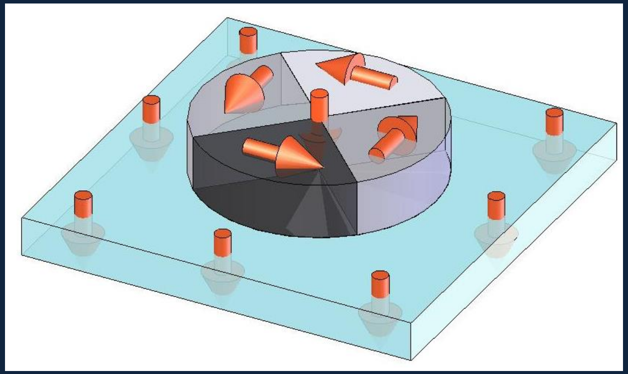
Co domain

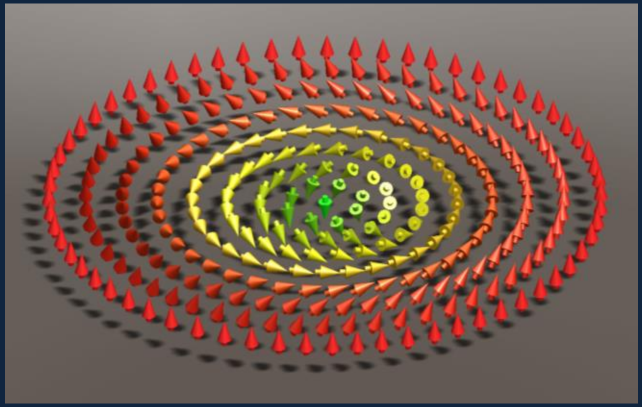
Ni domain

Preparing N=0 and N=1 Skyrmions

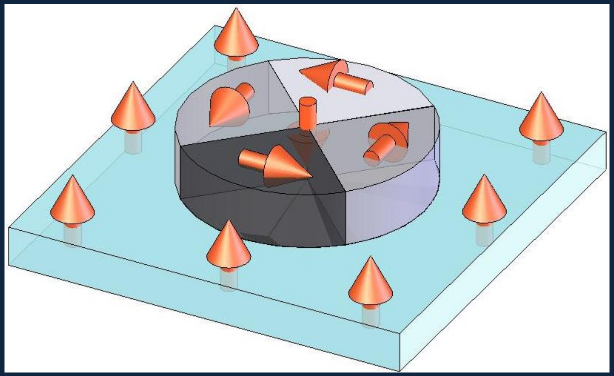


N=0



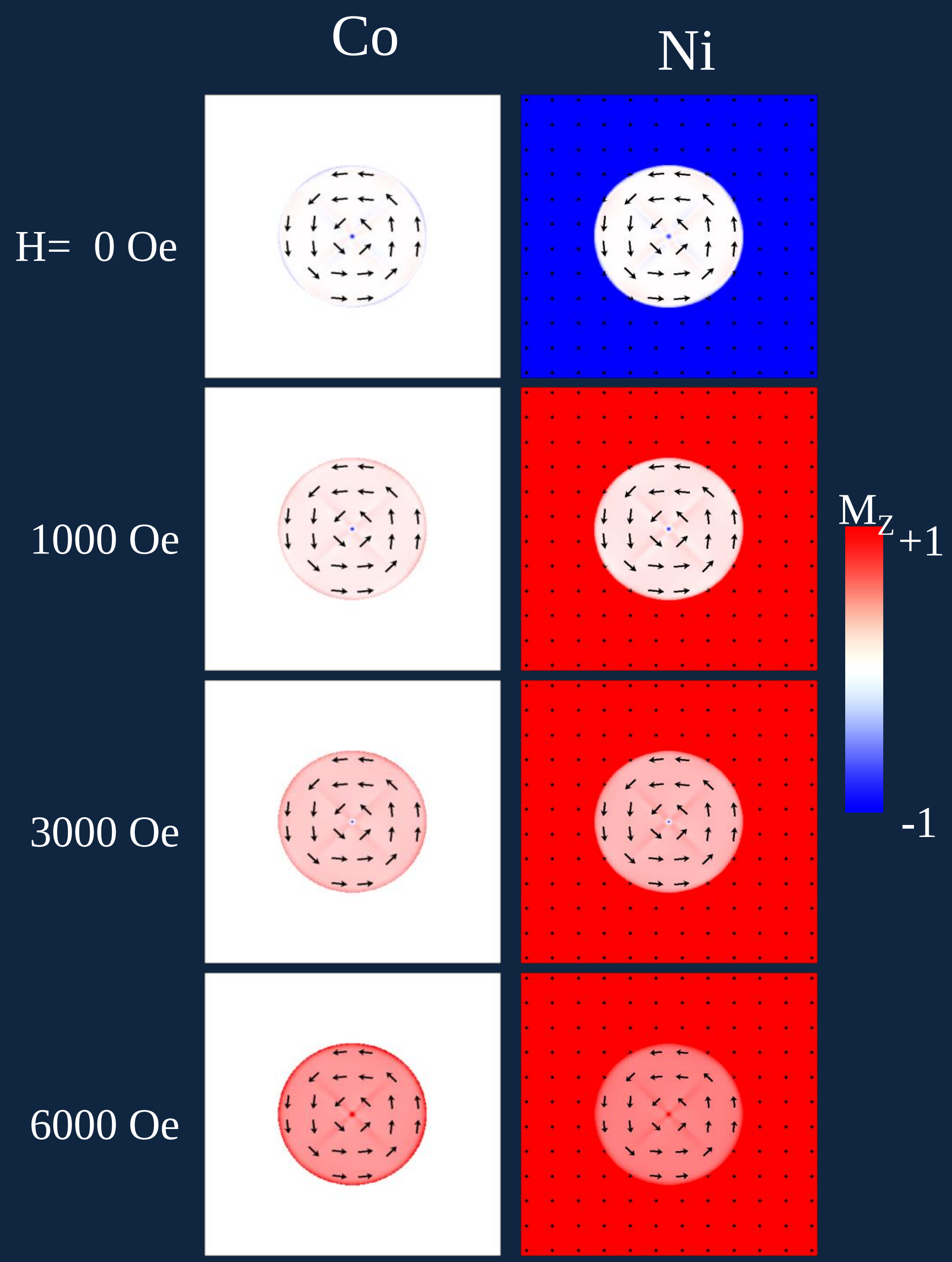


N=1

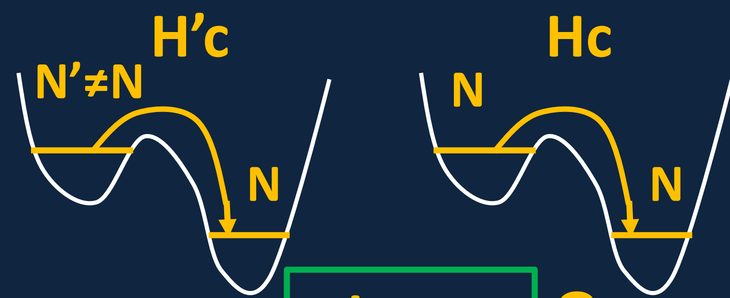


N=0 State: H=20,000Oe and then H=0

N=1 State: H=-800 Oe to N=0 state and then H=0

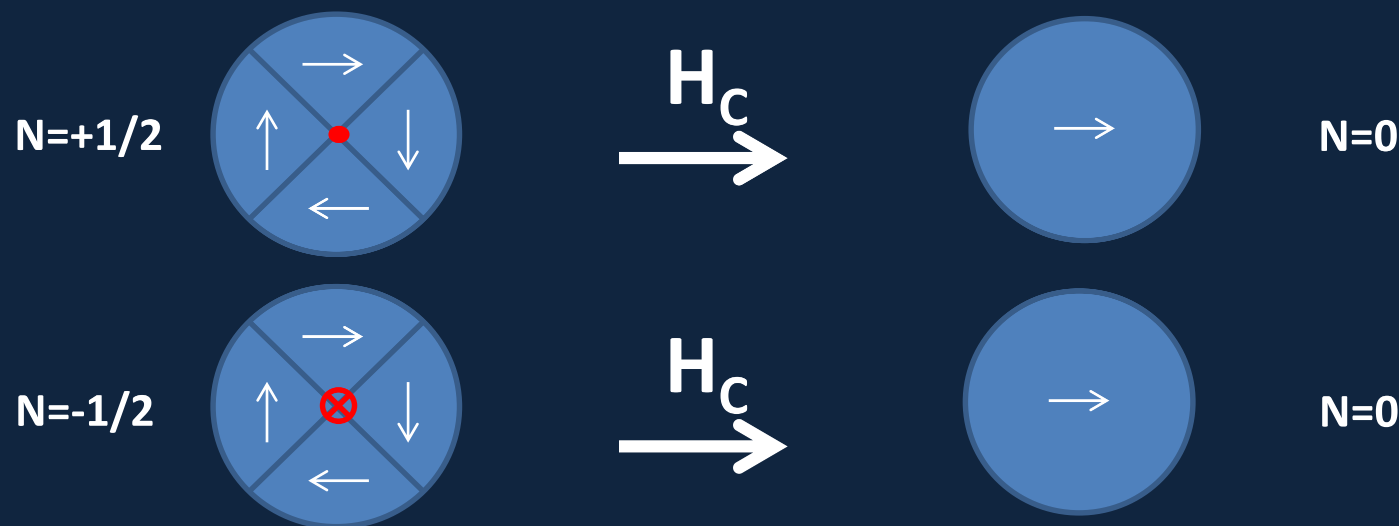

Co
Ni
H= 0 Oe
1000 Oe
3000 Oe
6000 Oe
M_Z
+1
-1

Searching for the topological effect of Skyrmions



H'c > Hc ?

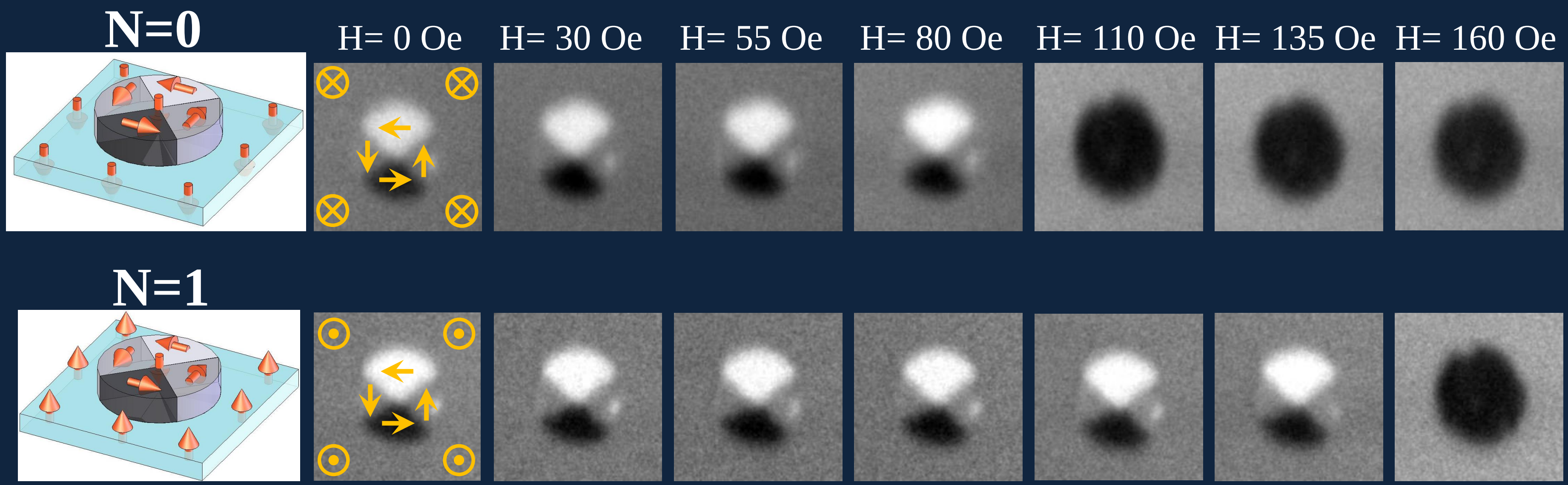
Vortex core annihilation



Apply an in-plane field to saturate the vortex state into a single domain state.

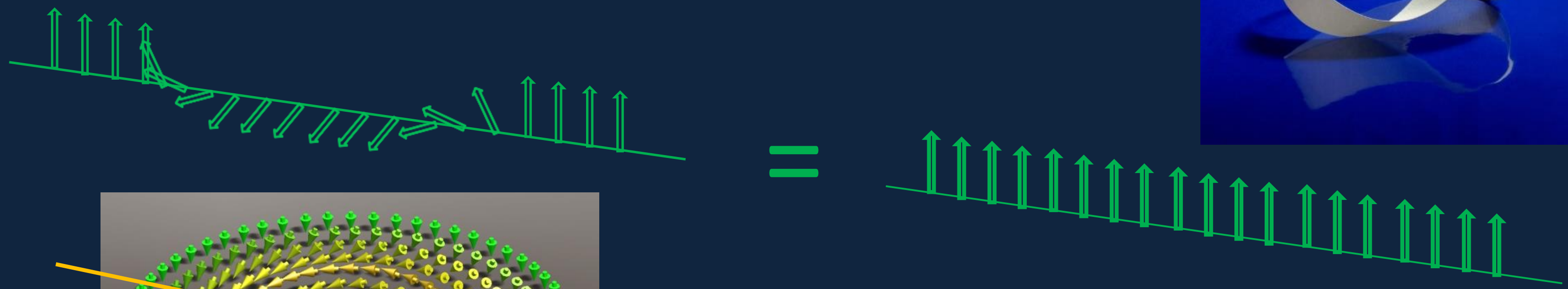
Skyrmion core annihilation

Apply an in-plane filed to saturate the middle vortex into a single domain state.

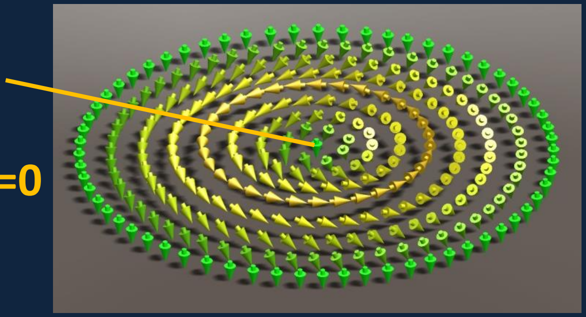


The critical field for N=1 is greater than N=0 state, suggesting a topological effect in the Skyrmion core annihilation process.

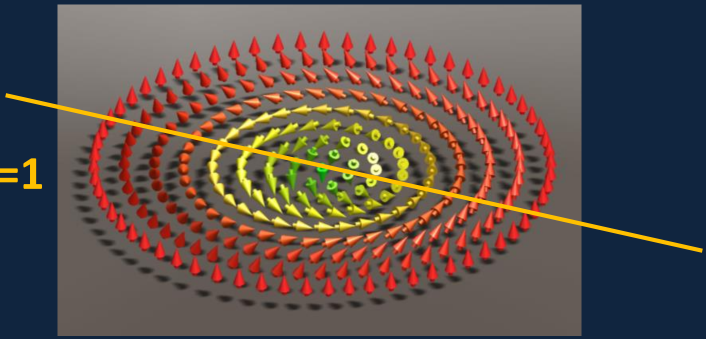
Topology of a domain wall



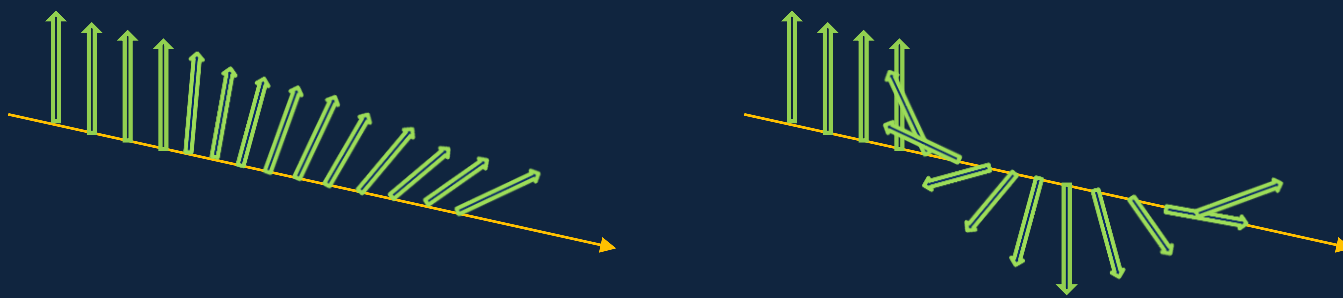
N=0



N=1

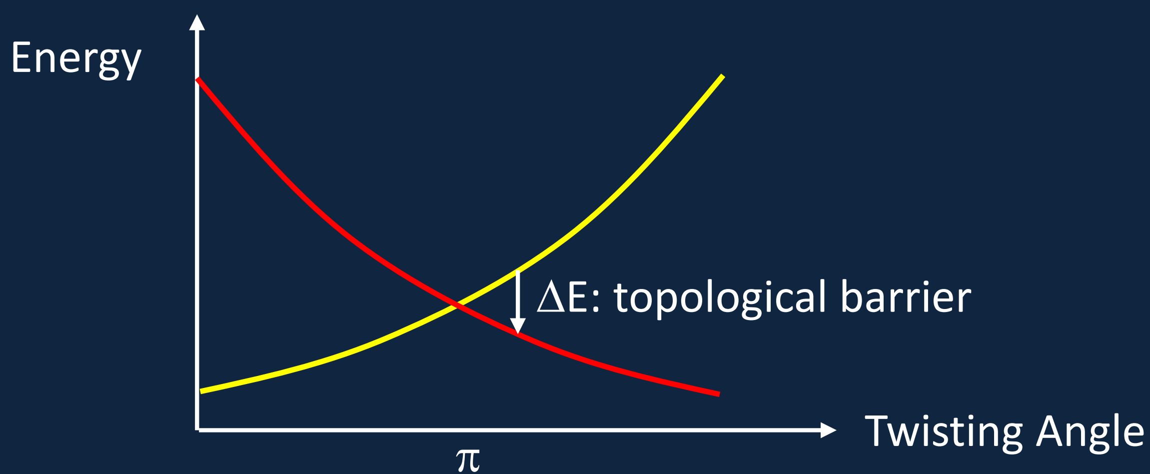


Breaking the topology of the domain wall



Left-handed

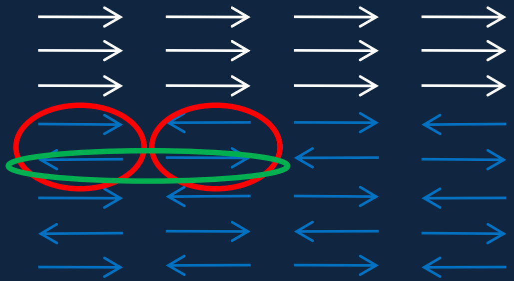
Right-handed

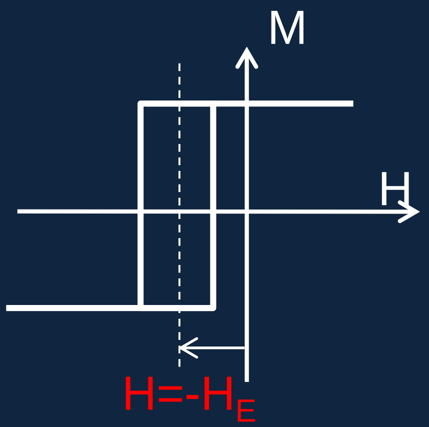


Exchange bias

$$\sum_i \vec{S}_{F,i} \neq 0$$ FM

$$\sum_i \vec{S}_{AF,i} = 0$$ AFM

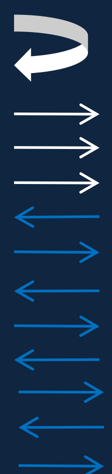




W. H. Meiklejohn and C. P. Bean, Phys. Rev. **102**, 1413 (1956).

Mauri's Model

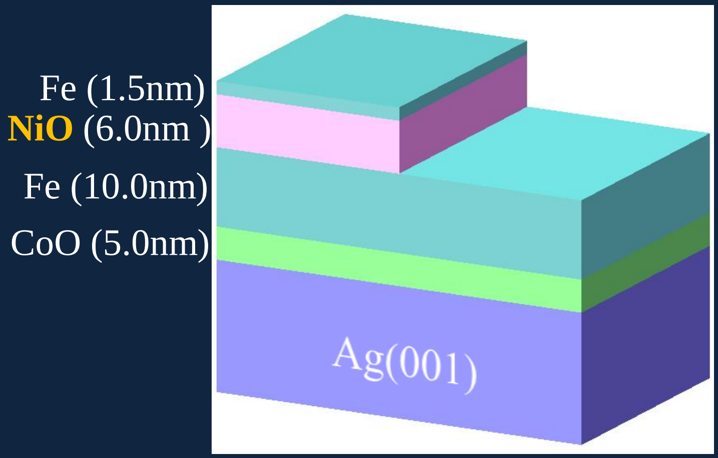
The FM rotation winds up an AFM domain wall, leading to the exchange bias.

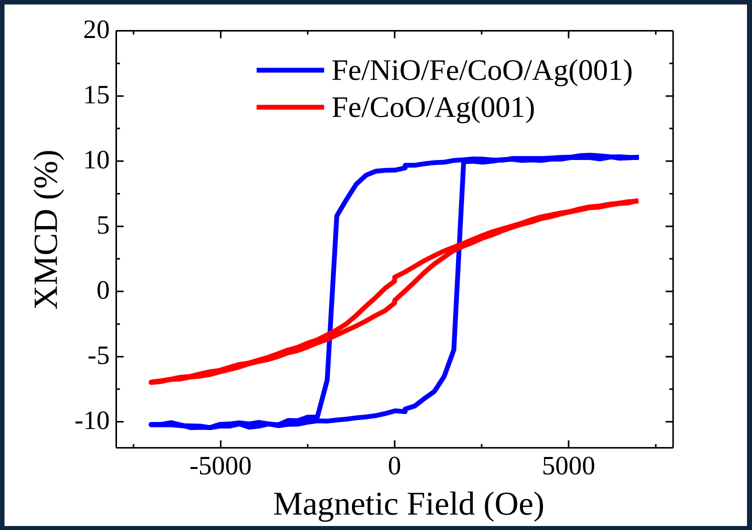


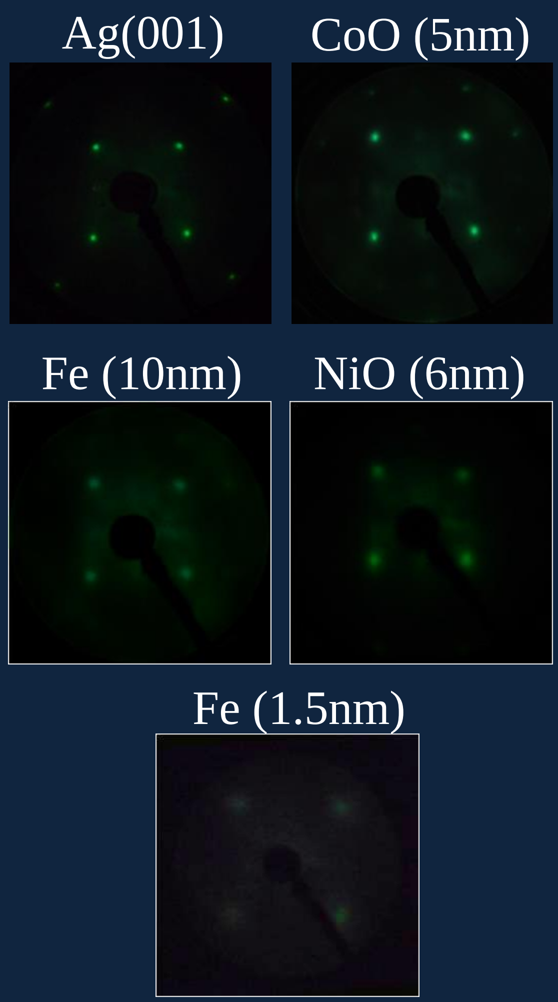
Winding up

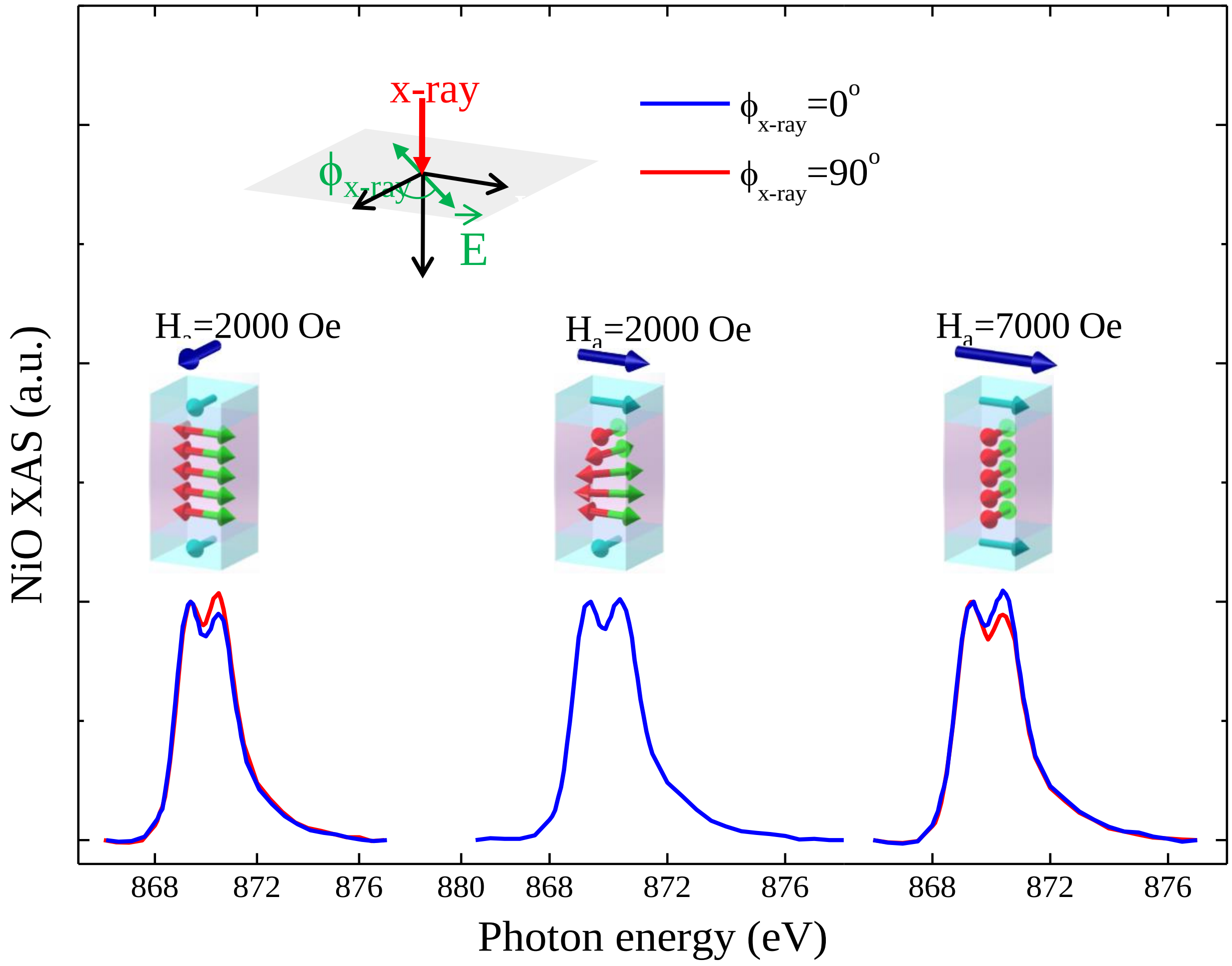
Fixed

Chirality switching of AFM NiO domains

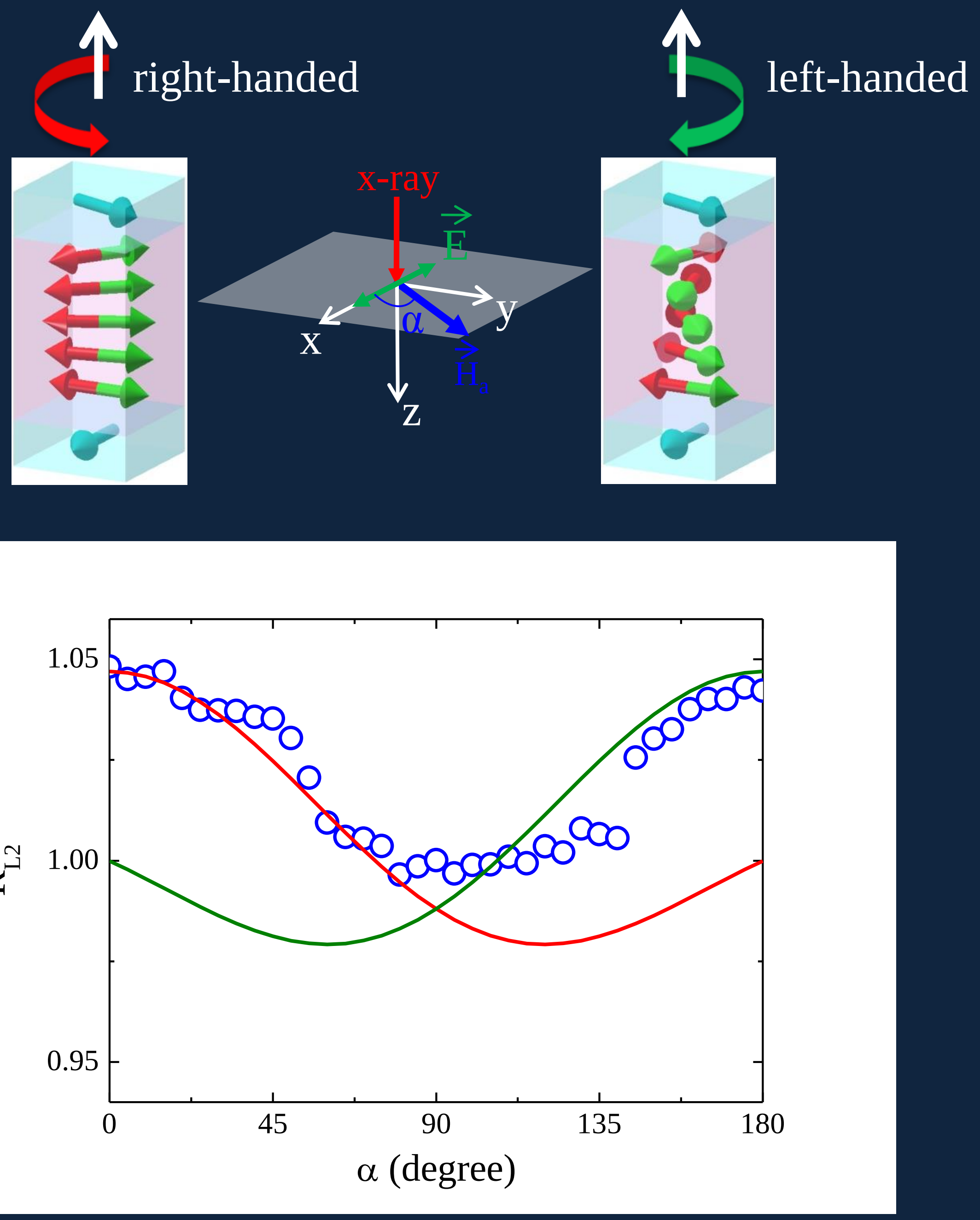








x-ray
$\phi_{x\text{-}ray}$
E
$\phi_{x\text{-}ray}=0^o$
$\phi_{x\text{-}ray}=90^o$
H_a=2000 Oe
H_a=2000 Oe
H_a=7000 Oe
NiO XAS (a.u.)
868
872
876
880
868
872
876
868
872
876
Photon energy (eV)


right-handed
left-handed
x-ray
E
y
x
α
H
z
R_L2
1.05
1.00
0.95
0
45
90
135
180
α (degree)

Summary

- Artificial Skyrmions can be created by embedding a magnetic vortex into a perpendicular magnetized background.

- The Skyrmion number can be controlled by the relative orientation of the vortex core to the perpendicularly magnetized background.

- Artificial Skyrmion exhibits a topological effect in the core annihilation process.

- NiO domain wall exhibits a topological effect by switching its chirality.

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