# Current Trends in Magnetoelectrics

(Based on the talks delivered at Gordon Conference 2016)

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# Theory of Magnetoelectric Multipoles
(N.A. Spaldin)

Hamiltonian for a magnetic material in the field **H(r)**

$$H_{\text{int}} = -\int \boldsymbol{\mu}(\boldsymbol{r}) \cdot \boldsymbol{H}(\boldsymbol{r}) d^3\boldsymbol{r}$$

$$H_{\text{int}} = -\int \boldsymbol{\mu}(\boldsymbol{r}) \cdot \boldsymbol{H}(0) d^3\boldsymbol{r} - \int r_i \mu_j(\boldsymbol{r}) \partial_i H_j(0) d^3\boldsymbol{r} - \dots,$$

If ***H(r)*** is non-uniform

$$H_{\text{int}} = -\boldsymbol{m} \cdot \boldsymbol{H}(0) - a(\nabla \cdot \boldsymbol{H})_{\boldsymbol{r}=0} - \boldsymbol{t} \cdot [\nabla \times \boldsymbol{H}]_{\boldsymbol{r}=0} - q_{ij}(\partial_i H_j + \partial_j H_i)_{\boldsymbol{r}=0} - \dots .$$

where $\boldsymbol{m} = \int \boldsymbol{\mu}(\boldsymbol{r}) d^3\boldsymbol{r}$.

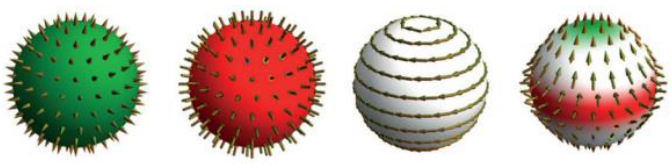
This expansion eventually leads to "***magnetoelectric monopoles***"

$$a = \frac{1}{3} \int \boldsymbol{r} \cdot \boldsymbol{\mu}(\boldsymbol{r}) d^3\boldsymbol{r}$$

$$= \frac{1}{3} \sum_\alpha \int_{\text{as}} [(\boldsymbol{r} - \boldsymbol{r}_\alpha) + \boldsymbol{r}_\alpha] \cdot \boldsymbol{\mu}(\boldsymbol{r}) d^3\boldsymbol{r}$$

$$= \frac{1}{3} \sum_\alpha \left[ \int_{\text{as}} (\boldsymbol{r} - \boldsymbol{r}_\alpha) \cdot \boldsymbol{\mu}(\boldsymbol{r}) d^3\boldsymbol{r} + \boldsymbol{r}_\alpha \cdot \int_{\text{as}} \boldsymbol{\mu}(\boldsymbol{r}) d^3\boldsymbol{r} \right]$$

$$= \frac{1}{3} \sum_\alpha \left[ \int_{\text{as}} (\boldsymbol{r} - \boldsymbol{r}_\alpha) \cdot \boldsymbol{\mu}(\boldsymbol{r}) d^3\boldsymbol{r} + \boldsymbol{r}_\alpha \cdot \boldsymbol{m}_\alpha \right],$$



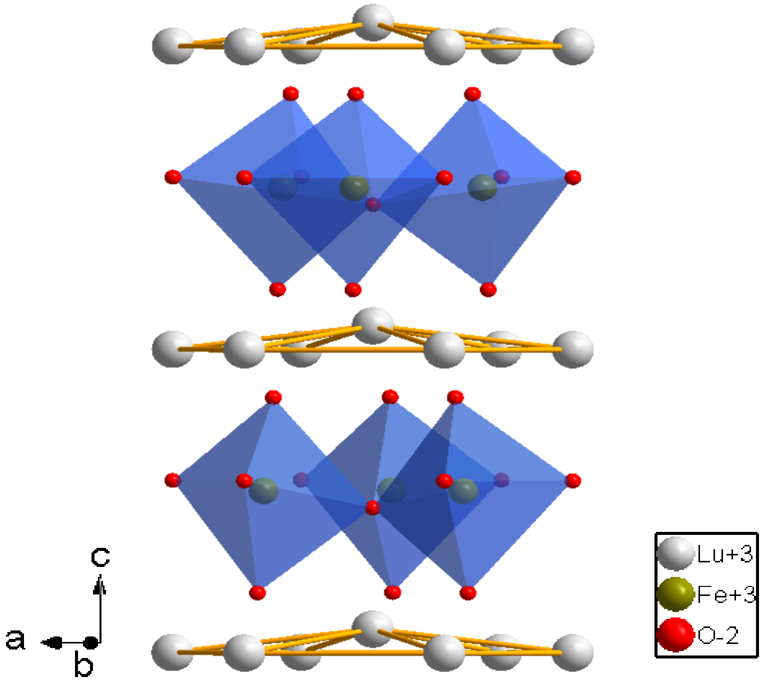
*Pictorial depiction of magnetoelectric poles*

N. A. Spaldin et al. PRB **88**, 094429 (2013)
F. Thole et al. PRB **93**, 195167 (2016)
N. A. Spaldin et al. TPCM **20**, 434203 (2008)

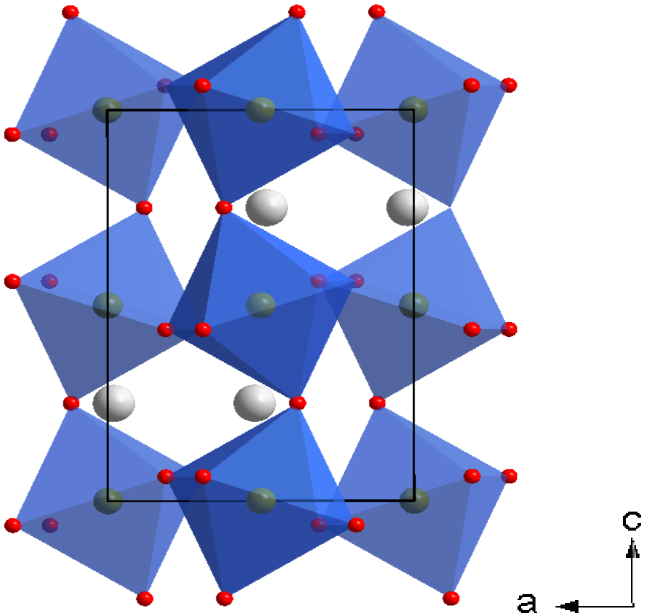
# Using Raman Spectra for structural analysis of multilayer films

Different phonon modes have different signature profiles in Raman Spectra. Phonon modes corresponding to tilting and rotation of bipyramids, and other distortions can be analyzed using Raman spectra.

*Advanced Functional Materials 229 5044 (2012)*




Hexagonal $LuFeO_3$

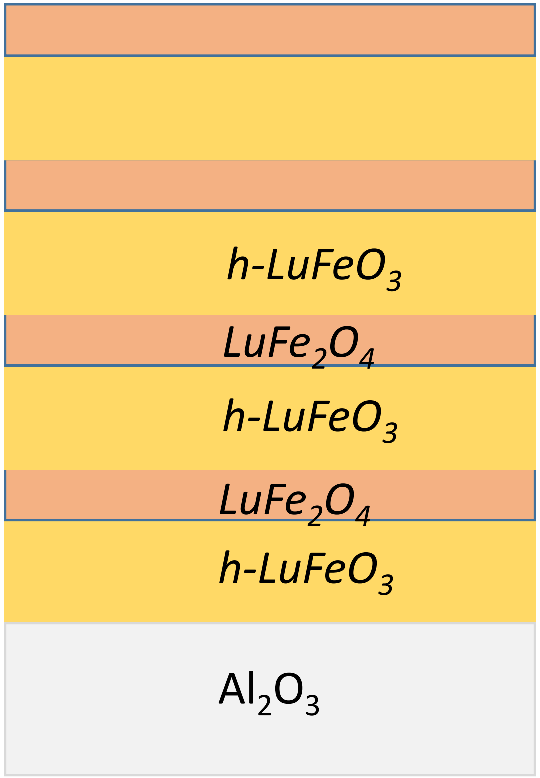



Orthorhombic $LuFeO_3$

# *h*-LuFeO3/LuFe2O4 multiferroic superlattice structure

Julia Mundy, Schlom, Ramesh – *in press*

The ferromagnetic transition temperature of this superlattice structure is reported to be 280 K, significantly larger than *h*-LuFeO3.




They also showed the gradation of polarization within a h-LuFeO3 layer as a function of distance from the consecutive LuFe2Or layer. This is likely due to gradation in oxygen vacancies within h-LuFeO3.

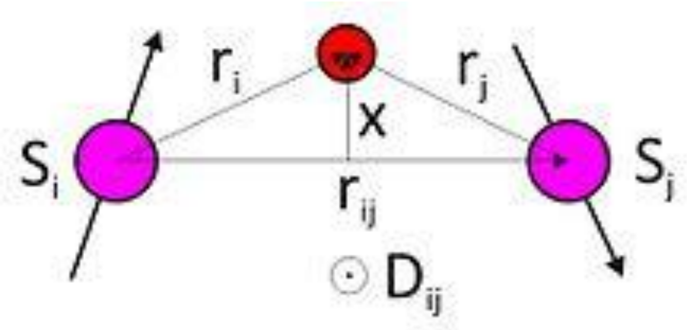
# Skyrmions

- ❑ Vortexes of spins with a material.
- ❑ Could be static or dynamic.
- ❑ Stem from DM interaction

## DM interaction

Induced by:

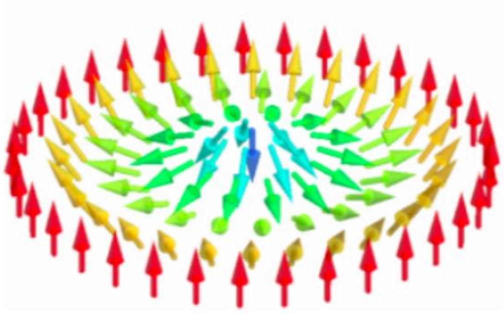
- ❑ Lack of inversion symmetry
- ❑ Strong spin-orbit coupling



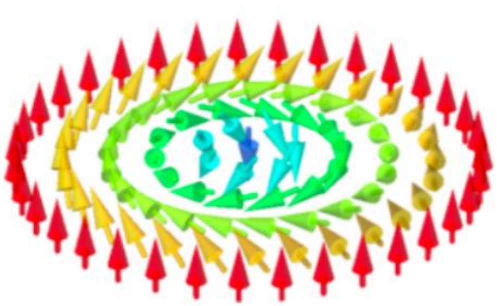

$$\mathcal{H}_{DM} = -\boldsymbol{D}_{12} \cdot (\boldsymbol{S}_1 \times \boldsymbol{S}_2).$$

Energy is minimized when

$$\boldsymbol{R}_{12} \perp \boldsymbol{D}_{12} \text{ or } \boldsymbol{R}_{12} || \boldsymbol{D}_{12}.$$



$\boldsymbol{R}_{12} || \boldsymbol{D}_{12}.$

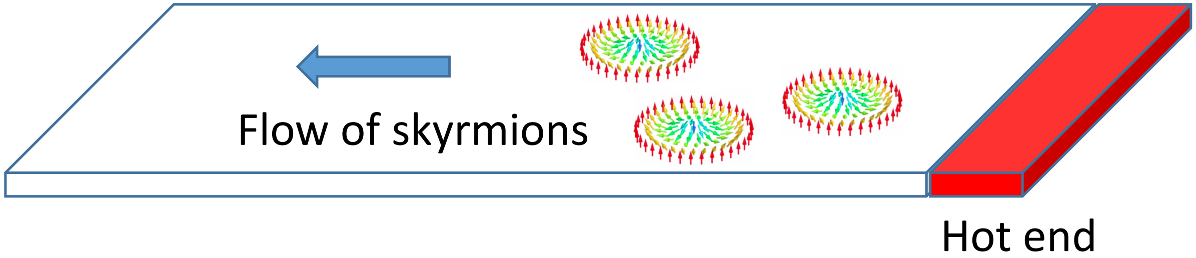


$\boldsymbol{R}_{12} \perp \boldsymbol{D}_{12}$

# Skyrmions

Current work on skyrmions include

- ❑ Finding ways to stabilize skyrmions at normal temperatures
- ❑ Incorporating skyrmions in memory devices
- ❑ Controlling the dynamics of skyrmions and exploring their potential for application in devices.

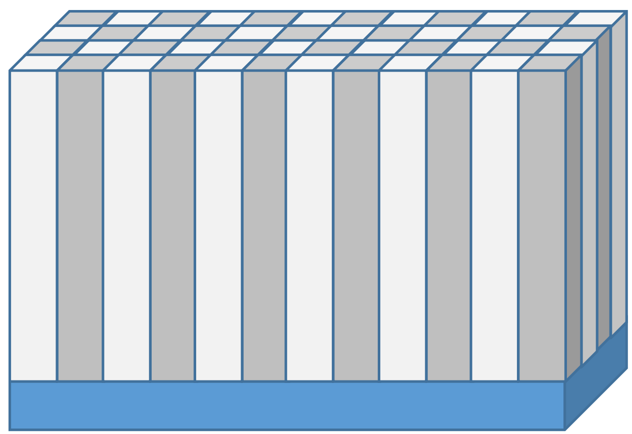



*A proposed design for a Seebeck device implementing Skyrmions*

# Magnetoelectric Coupling and Heterostructures

- Heterostructures are more promising cadidates as magnetoelectric materials than homogeneous materials.
- Heterostructures makes it possible to incorporate more surfaces, thus, enhancing interfacial effects.
- Coupling between layers at interfaces are tunable and useful in device application.

Pillars of multiferroic materials



Substrate

*A recently reported experimental study on magnetoelectric heterostructure*

***Thank you!***