

Synthesis, magnetism, and magnetoelectricity of hexaferrite systems

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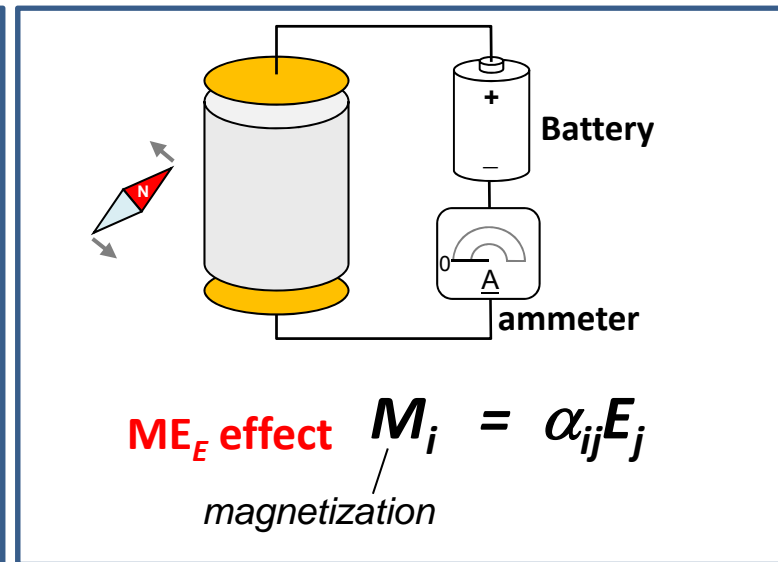
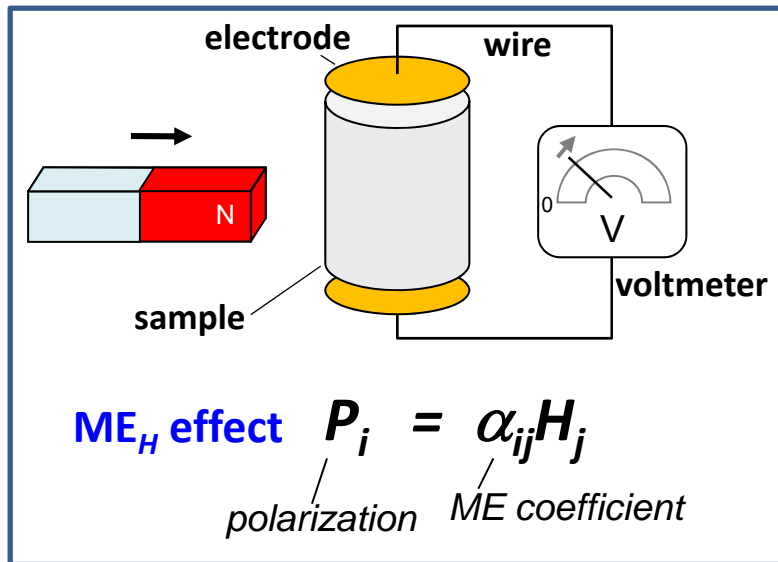
Magnetoelectric multiferroics working at room temperature

Modern Trends in Magnetism

Program of the workshop in honor of Igor Dzyaloshinskii on the occasion of his 80th birthday

Magnetolectric (ME) effect

Magnetolectric effect \Rightarrow Induction of **Polarization** by **Magnetic fields** (ME_H)
Magnetization by **Electric fields** (ME_E)



Early history of the ME effect [from "The electrodynamics of magneto-electric media" by T. H. O'Dell]

Researcher [year]	work
P. Curie [1894]	First proposal of the ME effect on symmetry grounds.
Piccard [1924]	Suggests the impossibility of the effect on symmetry grounds.
Debye [1926]	Suggests the effect is impossible.
Van Vleck [1932]	Devotes a section of his book to the reason why no ME effect can exist.
Landau & Lifshitz [1957]	Shows that the ME effect should exist in magnetic crystals.

Zh. Eksp. Teor. Fiz. 37, 881 (1959) [Sov. Phys. JETP 10, 628 (1960)]

*ON THE MAGNETO-ELECTRICAL EFFECT
IN ANTIFERROMAGNETS*

I. E. DZYALOSHINSKIĬ

Institute for Physical Problems, Academy of
Sciences, U.S.S.R.

Submitted to JETP editor June 17, 1959

J. Exptl. Theoret. Phys. (U.S.S.R.) **37**, 881-882
(September, 1959)

LANDAU and Lifshitz¹ have shown that there may occur in some antiferromagnetic crystals a peculiar phenomenon, namely that if a crystal is placed in a constant magnetic (or electric) field, an electric (or magnetic) moment proportional to the field is produced in the crystal.

This phenomenon, which can naturally be called the magnetoelectric effect, is intimately connected with the magnetic symmetry of the substance. Indeed, the thermodynamic potential of such a solid must contain terms proportional to the product of the first powers of the electrical and magnetic field components ($\Phi \sim EH$). It is at once clear that this is impossible in a paramagnetic crystal, since its thermodynamic potential is invariant with respect to a change in the time direction ($t \rightarrow -t$, R-transformation) in which, as is well known, the magnetic field changes sign while the electrical

SOVIET PHYSICS JETP

VOLUME

Letters to the Editor

*THE MAGNETOELECTRIC EFFECT IN
ANTIFERROMAGNETICS*

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Institute for Physico-Technical and Radio-
Technical Measurements

Submitted to JETP editor December 28, 1959

J. Exptl. Theoret. Phys. (U.S.S.R.) **38**, 984-985
(March, 1960)

LANDAU and Lifshitz¹ showed the possibility of the existence of a linear relationship between the electric and magnetic field in a substance for cer-

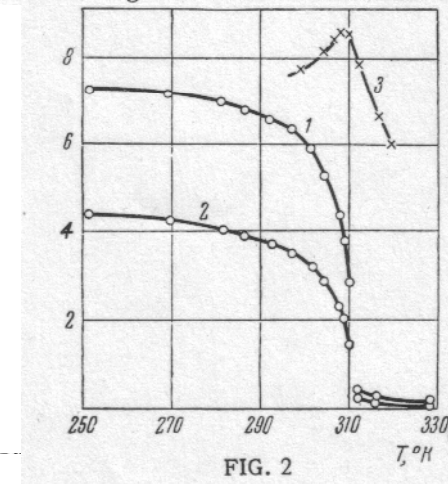


FIG. 2

J. Exptl. Theoret. Phys. **38**, 984 (1960)

$$M_i = \alpha_{ij} E_j \quad M_i \text{ is linearly proportional to the applied electric field } E_j \text{ through the ME coefficients } \alpha_{ij}.$$

Since E is a polar 1st rank tensor & M is an axial 1st rank tensor, the ME effect is an axial 2nd rank tensor which transforms as follows.

$$\begin{aligned} M'_i &= \pm |a| a_{ij} M_j = \pm |a| a_{ij} \alpha_{jk} E_k \\ &= \pm |a| a_{ij} \alpha_{jk} a_{lk} E'_l = \alpha'_{il} E'_l \quad \Rightarrow \quad \alpha'_{il} = \pm |a| a_{ij} a_{lk} \alpha_{jk} \end{aligned}$$

In matrix form, the linear ME effect transforms in a similar way in going from the original to the transformed system.

$$\begin{aligned} (M') &= \pm |a| (a) (M) = \pm |a| (a) (\alpha) (E) \quad \Rightarrow \quad (\alpha') = \pm |a| (a) (\alpha) (a)_t \\ &= \pm |a| (a) (\alpha) (a)_t (E') = (\alpha') (E') \end{aligned}$$

$(a)_t$: the transpose of (a)

The ME effect vanishes for all symmetry groups containing time reversal symmetry ($1'$).

$$(\alpha') = (-1)(+1)(+1)(\alpha)(+1) = (-\alpha) = (\alpha) = 0$$

The ME effect also disappears for ordinary inversion symmetry ($\bar{1}$) operations.

$$(\alpha') = (+1)(-1)(-1)(\alpha)(-1) = (-\alpha) = (\alpha) = 0$$

For space inversion accompanied by time inversion ($\bar{1}'$), the ME effect is permitted.

$$(\alpha') = (-1)(-1)(-1)(\alpha)(-1) = (\alpha) = (\alpha)$$

The first magnetoelectric material: Cr_2O_3

Crystal structure: corundum ($=\text{Al}_2\text{O}_3$)

Antiferromagnet with $T_N = 307$ K

Magnetic point group: $\bar{3}'m'$

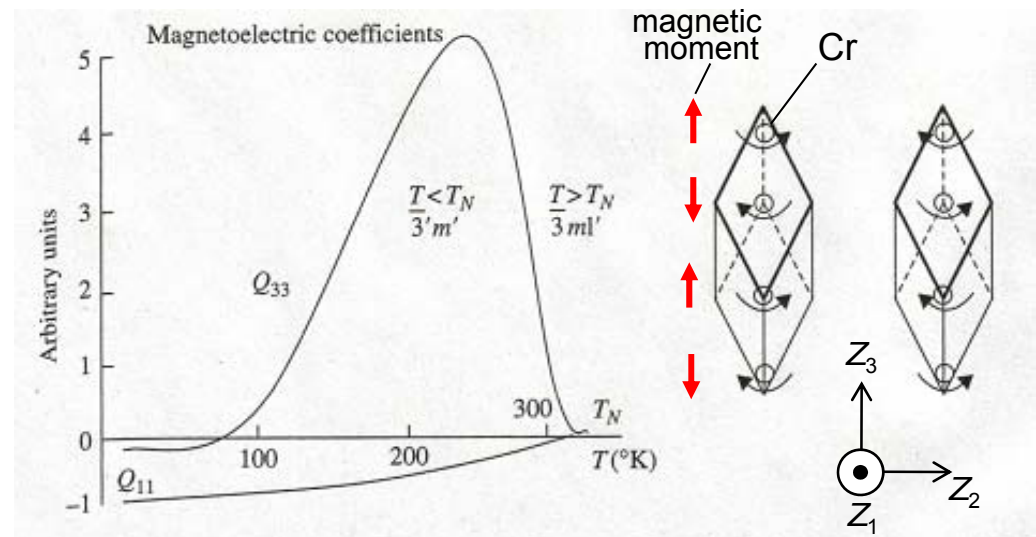
Generating elements

$$m' \perp Z_1, \bar{3}' \parallel Z_3$$

Applying Neumann's Principle,

The symmetry of any physical property

of a crystal must include the symmetry elements of the point group of the crystal.



$$m' \perp Z_1$$

Time reversal

Handedness change by mirror

$$\begin{pmatrix} \alpha'_{11} & \alpha'_{12} & \alpha'_{13} \\ \alpha'_{21} & \alpha'_{22} & \alpha'_{23} \\ \alpha'_{31} & \alpha'_{32} & \alpha'_{33} \end{pmatrix} = (-1)(-1) \begin{pmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} \alpha_{11} & \alpha_{12} & \alpha_{13} \\ \alpha_{21} & \alpha_{22} & \alpha_{23} \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} \begin{pmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} = \begin{pmatrix} \alpha_{11} & -\alpha_{12} & -\alpha_{13} \\ -\alpha_{21} & \alpha_{22} & \alpha_{23} \\ -\alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix} = \begin{pmatrix} \alpha_{11} & \alpha_{12} & \alpha_{13} \\ \alpha_{21} & \alpha_{22} & \alpha_{23} \\ \alpha_{31} & \alpha_{32} & \alpha_{33} \end{pmatrix}$$

This equality can be satisfied if $\alpha_{12} = \alpha_{13} = \alpha_{21} = \alpha_{31} = 0$



$$\begin{pmatrix} \alpha_{11} & 0 & 0 \\ 0 & \alpha_{22} & \alpha_{23} \\ 0 & \alpha_{32} & \alpha_{33} \end{pmatrix}$$

$\bar{3}' // Z_3$

Time reversal

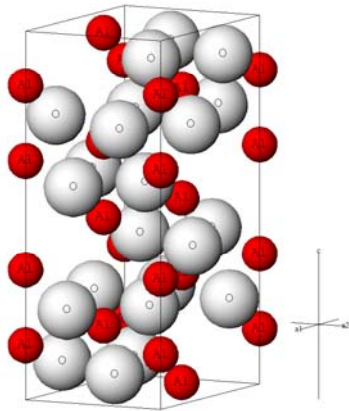
Handedness change by inversion

$$\begin{pmatrix} \alpha'_{11} & \alpha'_{12} & \alpha'_{13} \\ \alpha'_{21} & \alpha'_{22} & \alpha'_{23} \\ \alpha'_{31} & \alpha'_{32} & \alpha'_{33} \end{pmatrix} = (-1)(-1) \begin{pmatrix} 1/2 & -\sqrt{3}/2 & 0 \\ \sqrt{3}/2 & 1/2 & 0 \\ 0 & 0 & -1 \end{pmatrix} \begin{pmatrix} \alpha_{11} & 0 & 0 \\ 0 & \alpha_{22} & \alpha_{23} \\ 0 & \alpha_{32} & \alpha_{33} \end{pmatrix} \begin{pmatrix} 1/2 & \sqrt{3}/2 & 0 \\ -\sqrt{3}/2 & 1/2 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

$$= \begin{pmatrix} (1/4\alpha_{11}+3/4\alpha_{22}) & (-\sqrt{3}/4\alpha_{11}+\sqrt{3}/4\alpha_{22}) & (\sqrt{3}/2\alpha_{23}) \\ (\sqrt{3}/4\alpha_{11}-\sqrt{3}/4\alpha_{22}) & (3/4\alpha_{11}+1/4\alpha_{22}) & (-1/2\alpha_{23}) \\ (\sqrt{3}/2\alpha_{32}) & (-1/2\alpha_{32}) & (\alpha_{33}) \end{pmatrix}$$

$$= \begin{pmatrix} \alpha_{11} & 0 & 0 \\ 0 & \alpha_{22} & \alpha_{23} \\ 0 & \alpha_{32} & \alpha_{33} \end{pmatrix}$$

This equality can be satisfied if $\alpha_{11} = \alpha_{22}$ & $\alpha_{23} = \alpha_{32} = 0$



Therefore the magnetoelectric matrix for point group $\bar{3}'m'$ is

$$\begin{pmatrix} \alpha_{11} & 0 & 0 \\ 0 & \alpha_{11} & 0 \\ 0 & 0 & \alpha_{33} \end{pmatrix}$$

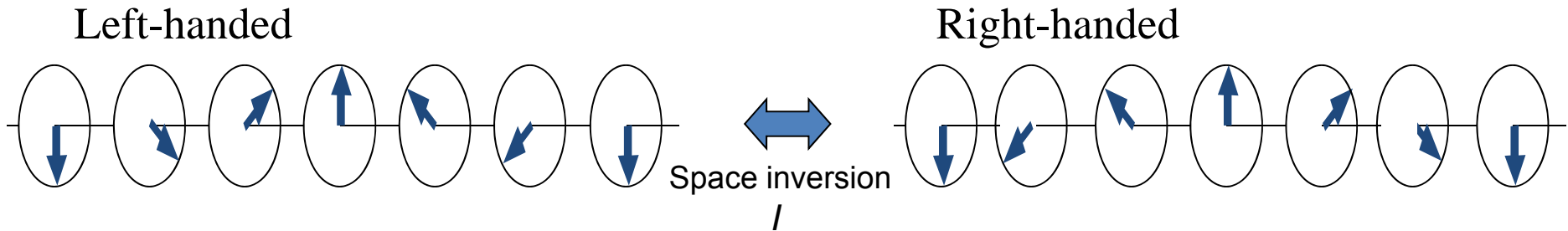
Magnetoelectric matrices for the 90 magnetic point groups

1, $\bar{1}'$	$\begin{pmatrix} Q_{11} & Q_{12} & Q_{13} \\ Q_{21} & Q_{22} & Q_{23} \\ Q_{31} & Q_{32} & Q_{33} \end{pmatrix}$	$4', \bar{4}, 4'/m'$	$\begin{pmatrix} Q_{11} & Q_{12} & 0 \\ Q_{12} & -Q_{11} & 0 \\ 0 & 0 & 0 \end{pmatrix}$
2, $m', 2/m'$	$\begin{pmatrix} Q_{11} & 0 & Q_{13} \\ 0 & Q_{22} & 0 \\ Q_{31} & 0 & Q_{33} \end{pmatrix}$	32, $3m', \bar{3}'m', 422, 4m'm', \bar{4}'2m', 4/m'm'm', 622, 6m'm', \bar{6}'m'2, 6/m'm'm',$	$\begin{pmatrix} Q_{11} & 0 & 0 \\ 0 & Q_{11} & 0 \\ 0 & 0 & Q_{33} \end{pmatrix}$
2', $m, 2'/m$	$\begin{pmatrix} 0 & Q_{12} & 0 \\ Q_{21} & 0 & Q_{23} \\ 0 & Q_{32} & 0 \end{pmatrix}$	$4'22, 4'mm', \bar{4}2m, \bar{4}2'm', 4'/m'mm'$	$\begin{pmatrix} Q_{11} & 0 & 0 \\ 0 & -Q_{11} & 0 \\ 0 & 0 & 0 \end{pmatrix}$
222, $m'm'2, m'm'm'$	$\begin{pmatrix} Q_{11} & 0 & 0 \\ 0 & Q_{22} & 0 \\ 0 & 0 & Q_{33} \end{pmatrix}$	$32', 3m, \bar{3}'m, 42'2', 4mm, \bar{4}'2'm, 4/m'mm, 62'2', 6mm, \bar{6}'m2', 6/m'mm,$	$\begin{pmatrix} 0 & Q_{12} & 0 \\ -Q_{12} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$
22'2', $2mm, m'm2', m'mm$	$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & Q_{23} \\ 0 & Q_{32} & 0 \end{pmatrix}$	23, $m'3, 432, \bar{4}'3m', m'3m',$	$\begin{pmatrix} Q_{11} & 0 & 0 \\ 0 & Q_{11} & 0 \\ 0 & 0 & Q_{11} \end{pmatrix}$
3, $\bar{3}', 4, \bar{4}', 4/m', 6, \bar{6}', 6/m',$	$\begin{pmatrix} Q_{11} & Q_{12} & 0 \\ -Q_{12} & Q_{11} & 0 \\ 0 & 0 & Q_{33} \end{pmatrix}$	Other magnetic groups	$\begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}$

Only 58 of the 90 magnetic point groups are magnetoelectric.

Broken of space inversion symmetry in **spiral** spin systems

K. Shiratori & E. Kita, JPSJ 48, 1443 (1980)

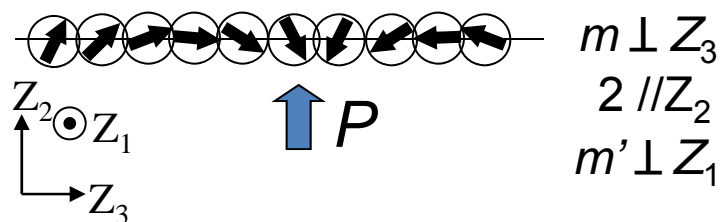


The Left- & Right-handed spiral structures are inverted by I to each other. However, these two spiral structures are not identical.

Thus, the inversion symmetry is broken by a spiral spin order.

To make system ferroelectric,

1. **Cycloidal** spiral structure

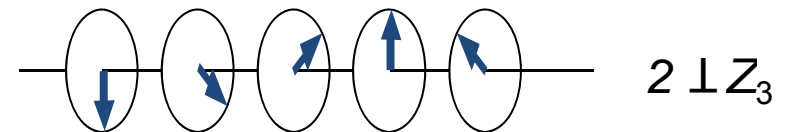


***Spin-current (inverse DM) mechanism**

Katsura et al, PRL 2005, Harris et al. PRL 2005
Sergienko et al. PRB 2006, Mostovoy, PRL 2006

2. **Screw** spiral structure

+ **low** crystal symmetry



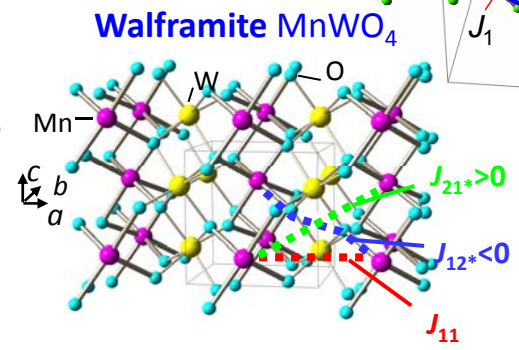
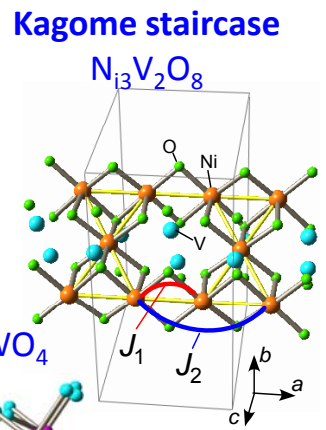
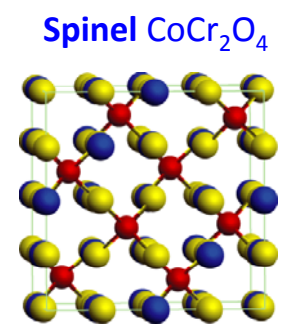
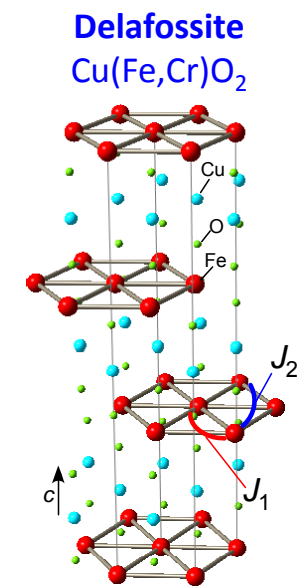
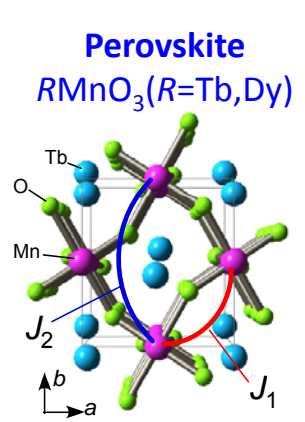
e.g., monoclinic $2/m$ (non-polar) $\xrightarrow{\text{Removal of } I}$ monoclinic 2 (polar)

***p-d hybridization mechanism**

Jia et al. PRB 2006, Arima, JPSJ 2007

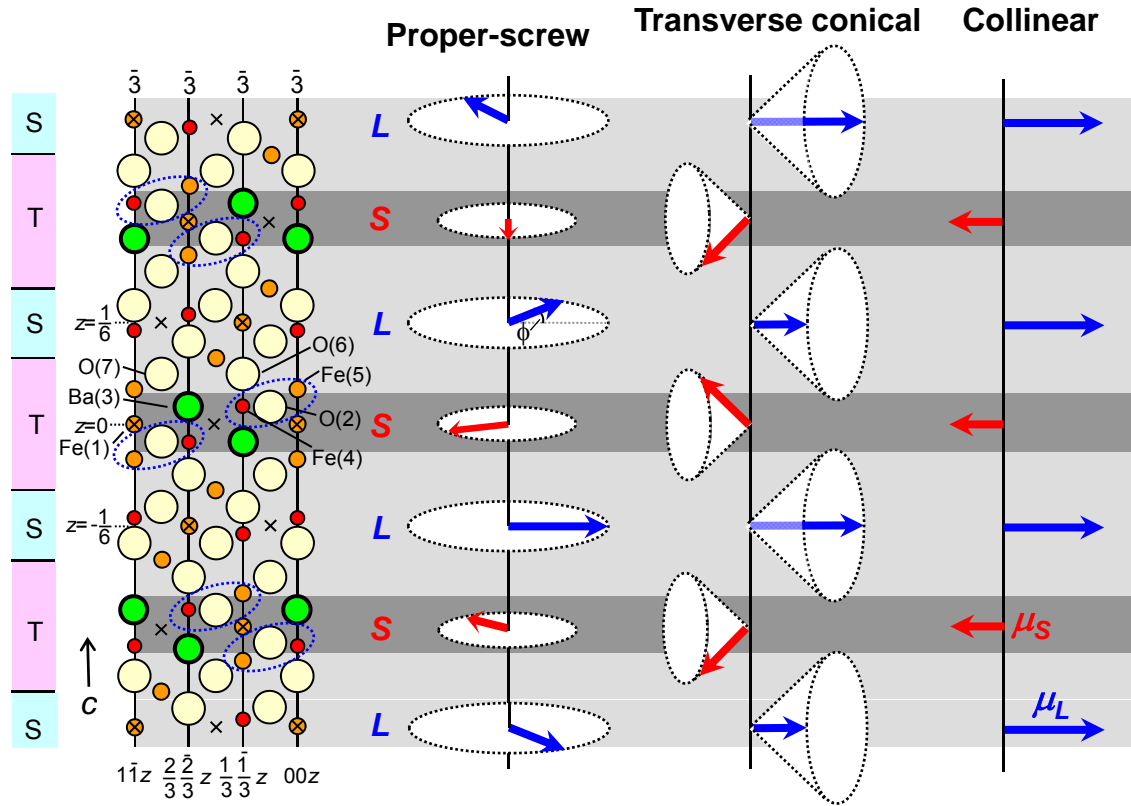
List of spin-spiral-driven ferroelectrics

Compound	Crystal structure	Magnetic ion	Proposed spin structure	Temperature range (K)	Ref.
$RMnO_3$ ($R=Tb$, etc.)	O (mmm) [perovskite]	Mn^{3+} $S=2$	cycloidal	≤ 28	Kimura <i>et al.</i> (2003)
$Ni_3V_2O_8$	O (mmm)	Ni^{2+} $S=1$	cycloidal	3.9~6.3	Lawes <i>et al.</i> (2005)
$(Ba,Sr)_2M_2Fe_{12}O_{22}$	R ($-3m$) [haxaferrite]	Fe^{3+} $S=5/2$	screw, L-conical ($B=0$) T-conical ($B>0$)	$\leq \sim 110$	Kimura <i>et al.</i> (2005)
$CuFeO_2$	R $-3m$ [delafossite]	Fe^{3+} $S=5/2$	collinear ($B=0$) screw ($B>0$)	≤ 11	Kimura <i>et al.</i> (2005)
$CoCr_2O_4$	C ($m3m$) [spinel]	Co^{2+} $S=3/2$ Cr^{3+} $S=3/2$	T-conical	≤ 26	Yamasaki <i>et al.</i> (2006)
$MnWO_4$	M ($2/m$) [wolframite]	Mn^{2+} $S=5/2$	cycloidal	7~12.5	Taniguchi <i>et al.</i> (2006)
$RbFe(MoO_4)_2$	R ($-3m$)	Fe^{3+} $S=5/2$	screw	≤ 3.8	Kenzelmann <i>et al.</i> (2006)
$LiCu_2O_2$	O (mmm)	Cu^{2+} $S=1/2$	cycloidal	≤ 23	Park <i>et al.</i> (2007)
$LiCuVO_4$	O (mmm)	Cu^{2+} $S=1/2$	cycloidal	≤ 2.4	Naito <i>et al.</i> (2007)
CuO	M ($2/m$) [tenorite]	Cu^{2+} $S=1/2$	cycloidal + screw	212~230	Kimura <i>et al.</i> (2008)
$ACrO_2$ ($A=Ag, Cu$)	R ($-3m$) [delafossite]	Cr^{3+} $S=3/2$	screw	≤ 24	Seki <i>et al.</i> (2008)
$FeVO_4$	Tri (-1)	Fe^{3+} $S=5/2$	cycloidal	≤ 16	Daoud-Aladine <i>et al.</i> (2009)
$CuCl_2$	M ($2/m$) [distorted CdI_2]	Mn^{2+} $S=5/2$	cycloidal	≤ 24	Seki <i>et al.</i> (2010)



Magnetoelectric Y-type hexaferrite $(\text{Ba,Sr})_2\text{Me}_2\text{Fe}_{12}\text{O}_{22}$ ($\text{Me}=\text{Zn, Mg, etc.}$)

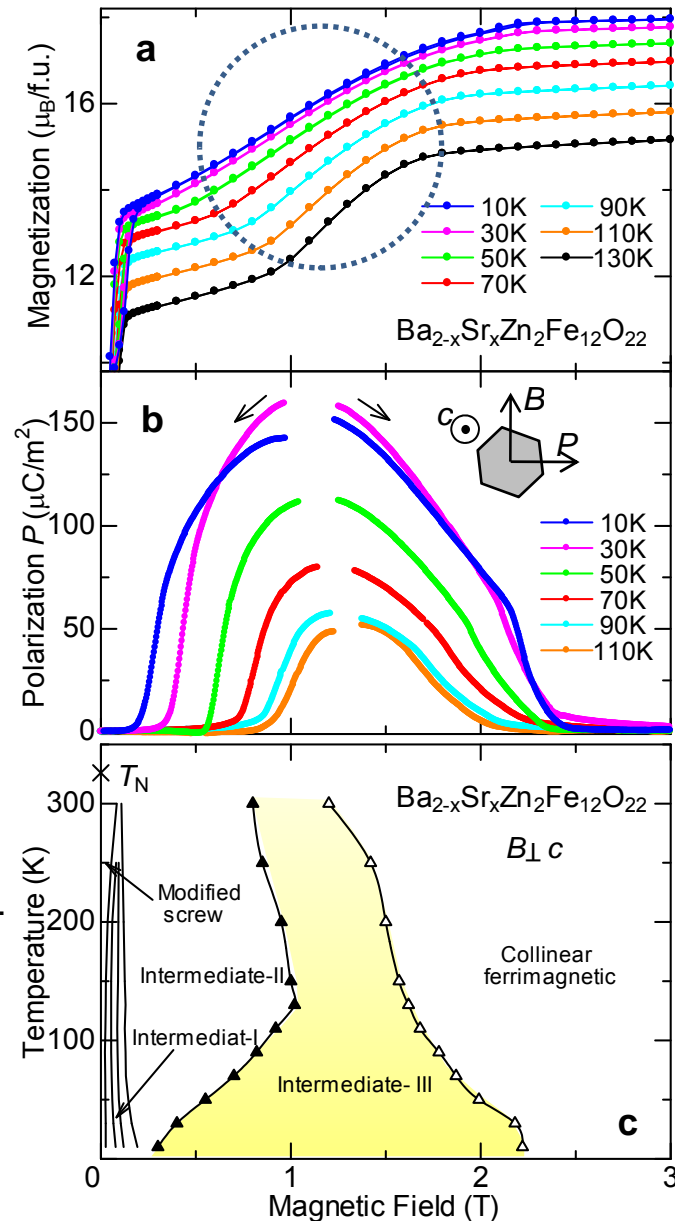
Kimura et al., PRL. 94, 137201 (2005)



Ishiwata et al., PRB 81, 174418 (2010).

Ferroelectric intermediate-III phase survives up to near room temperature.

Transverse conical spiral spin order can induce P via the spin-current mechanism.



However, suppression of resistivity does not allow experimental observation of polarization above $\sim 110\text{K}$.

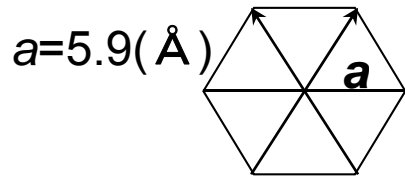
Purpose of our study

We pursue **room-temperature magnetoelectrics** in other types of hexaferrites.

Hexaferrite showing

1. a spiral magnetic order above room temperature
2. highly insulating electric property at room temperature

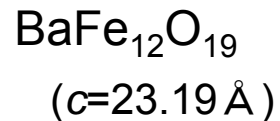
Classification of hexagonal ferrites (hexaferrites) - chemical formula -



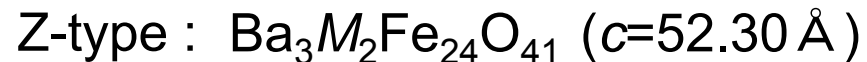
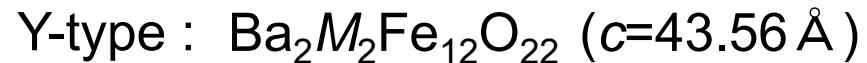
J. Smit & H.P.J. Wijn, Ferrite (Philips' Technical Library, 1959)

M-type

(magnetoplumbite)



Refrigerator magnet

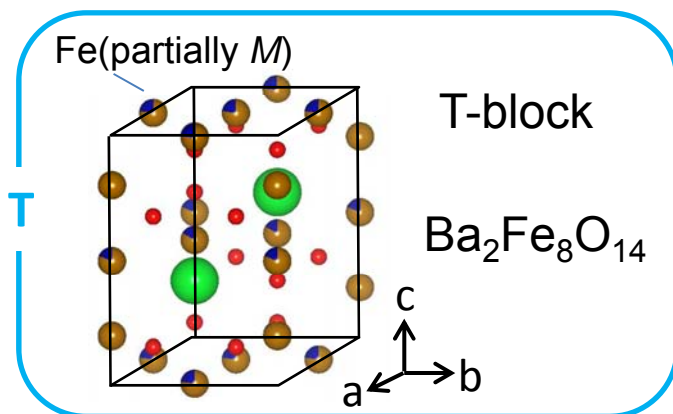
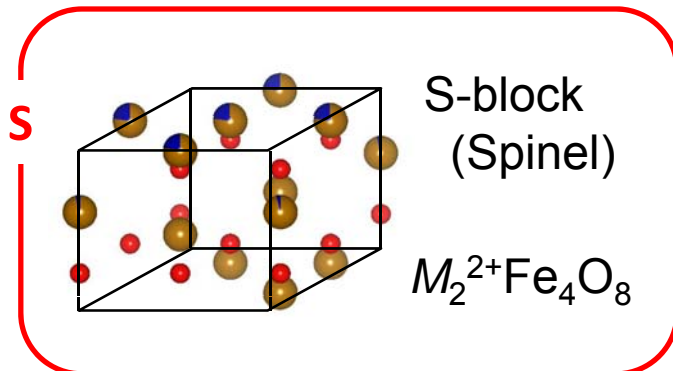
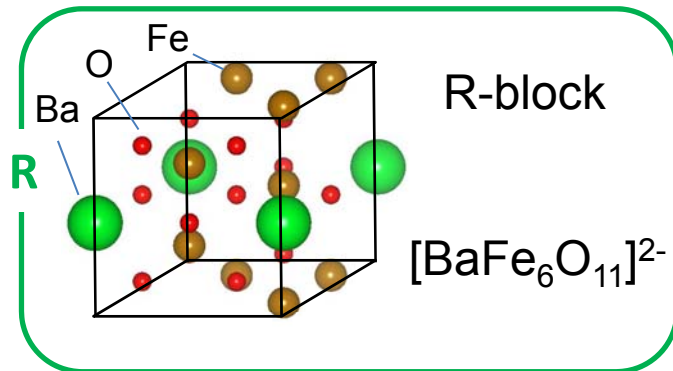


(M = divalent metal)

Classification of hexagonal ferrites

- Stacking sequence composed of 3 types of blocks-

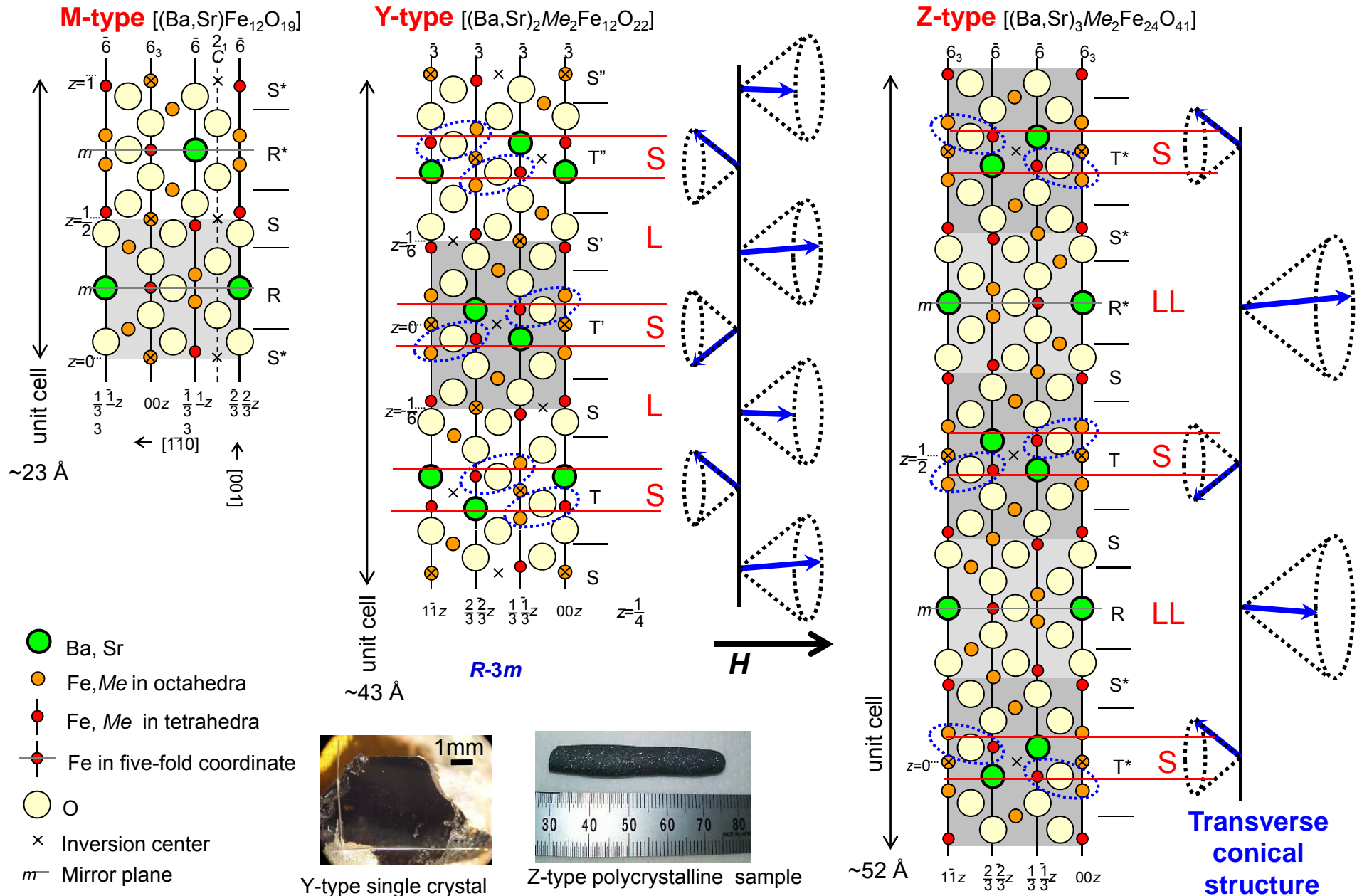
J. Smit & H.P.J. Wijn, Ferrite (Philips' Technical Library, 1959)



	Chem. form.	stacking	c(Å)	S.G.
M	$\text{BaFe}_{12}\text{O}_{19}$	RSR^*S^*	23.19	$P6_3/mmc$
W	$\text{BaM}_2\text{Fe}_{16}\text{O}_{27}$	$\text{RS}_2\text{R}^*\text{S}_2^*$	32.84	$P6_3/mmc$
Y	$\text{Ba}_2\text{M}_2\text{Fe}_{12}\text{O}_{22}$	$(\text{TS})_3$	43.56	$R-3/m$
Z	$\text{Ba}_3\text{M}_2\text{Fe}_{24}\text{O}_{41}$	$\text{RSTSR}^*\text{S}^*\text{T}^*\text{S}^*$	52.3	$P6_3/mmc$
X	$\text{Ba}_2\text{M}_2\text{Fe}_{28}\text{O}_{46}$	$(\text{RSR}^*\text{S}^*)_3$	84.11	$R-3/m$
U	$\text{Ba}_4\text{M}_2\text{Fe}_{36}\text{O}_{60}$	$(\text{RSR}^*\text{S}^*\text{TS}^*)_3$	113	$R-3/m$

The prime (') and asterisk (*) symbols indicates that the corresponding block is rotated 120° or 180° about the c axis, respectively.

Crystal structures of M-, Y-, & Z-type hexaferrites

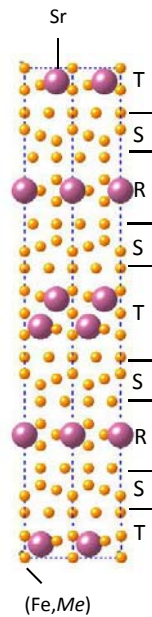
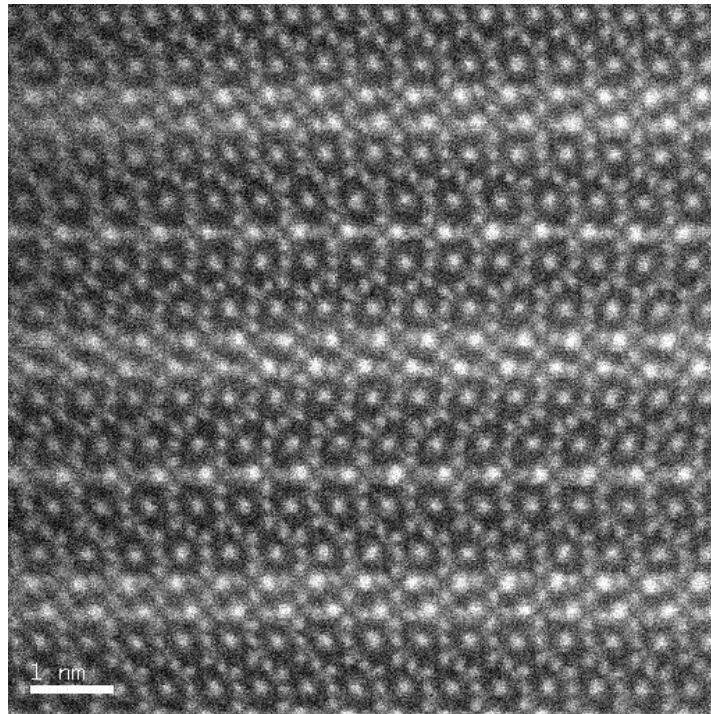


*Sample synthesis

Z-type $(Ba,Sr)_3Co_2Fe_{24}O_{41}$ & U-type $(Ba,Sr)_4Co_2Fe_{36}O_{60}$ studied here are *polycrystalline* samples prepared by the conventional solid-state reaction technique.

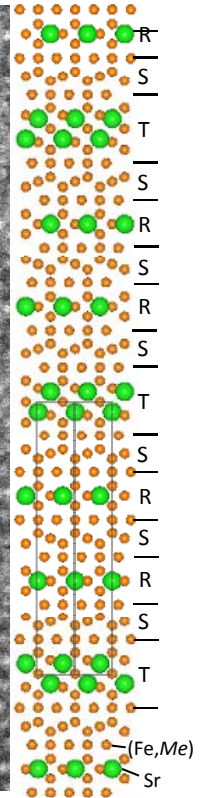
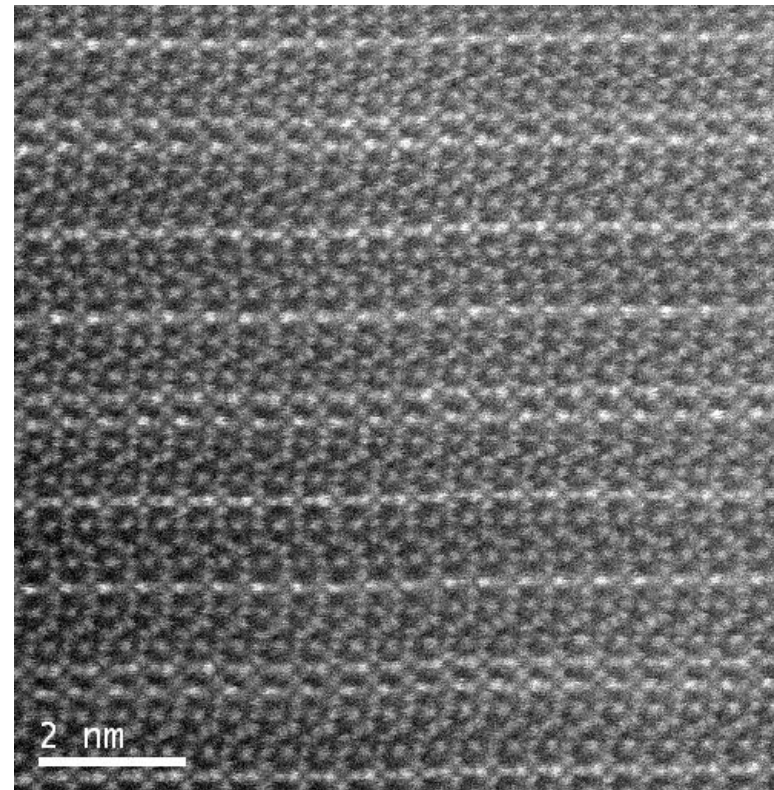
Z-type $(Ba,Sr)_3Me_2Fe_{24}O_{41}$

RSTSR**S**T**S**



U-type $(Ba,Sr)_4Me_2Fe_{36}O_{60}$

(RSR**S**TS*)₃

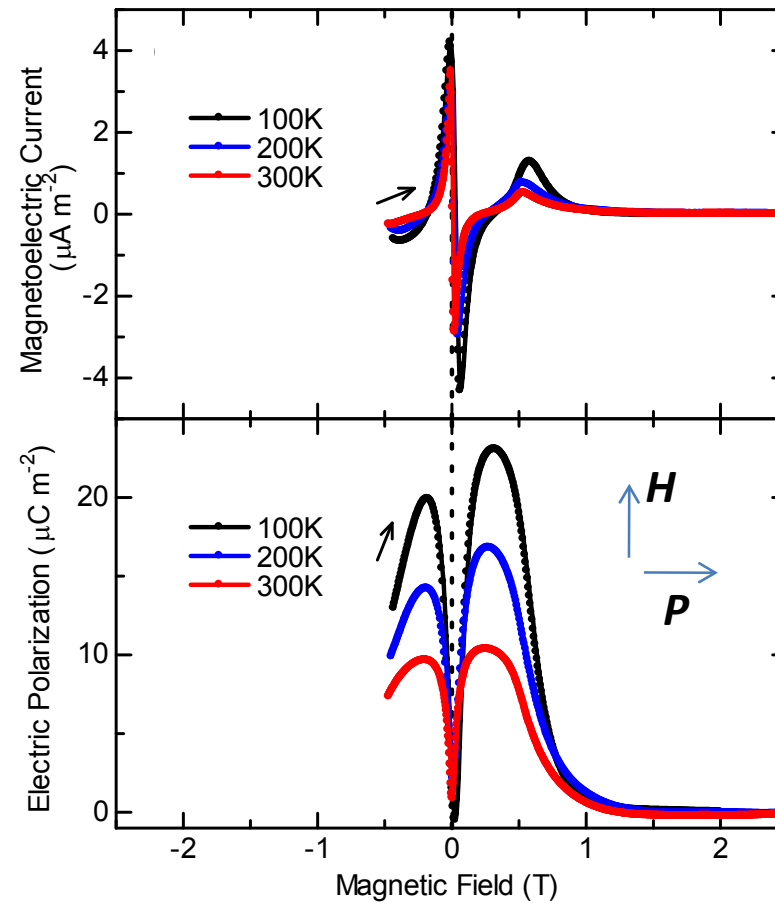
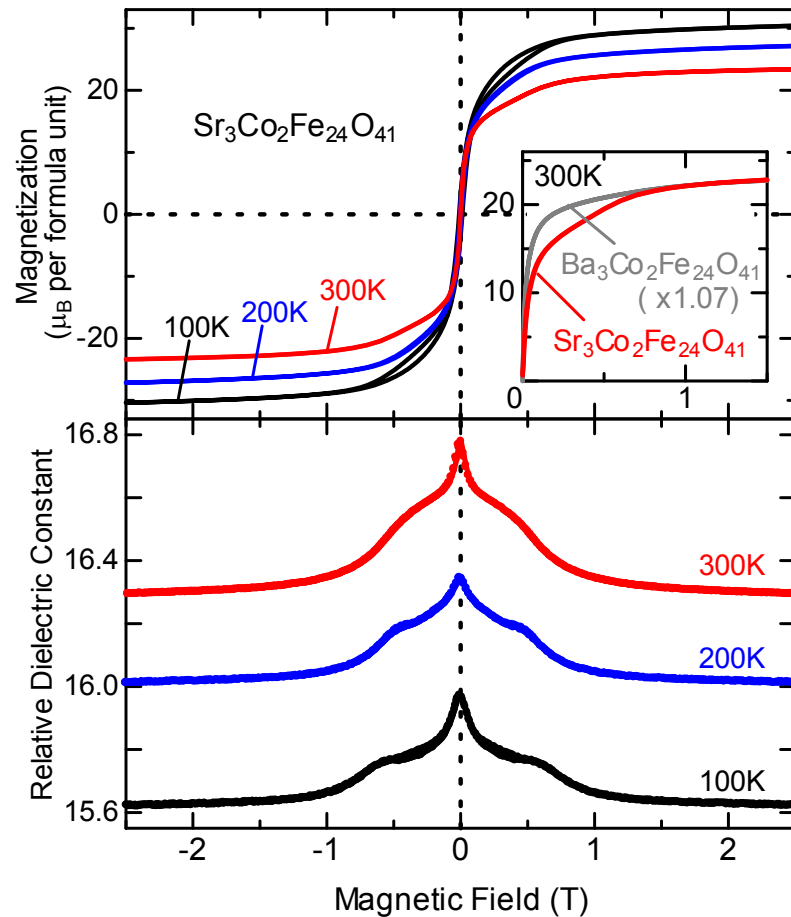


[100]-zone high-angle annular dark-field scanning TEM (HAADF-STEM) images for two hexaferrite samples

Magnetic & magnetoelectric properties of Z-type $\text{Sr}_3\text{Co}_2\text{Fe}_{24}\text{O}_{41}$

polycrystalline ceramics sintered in oxygen.

Kitagawa et al., Nature Mater. 9, 797 (2010).



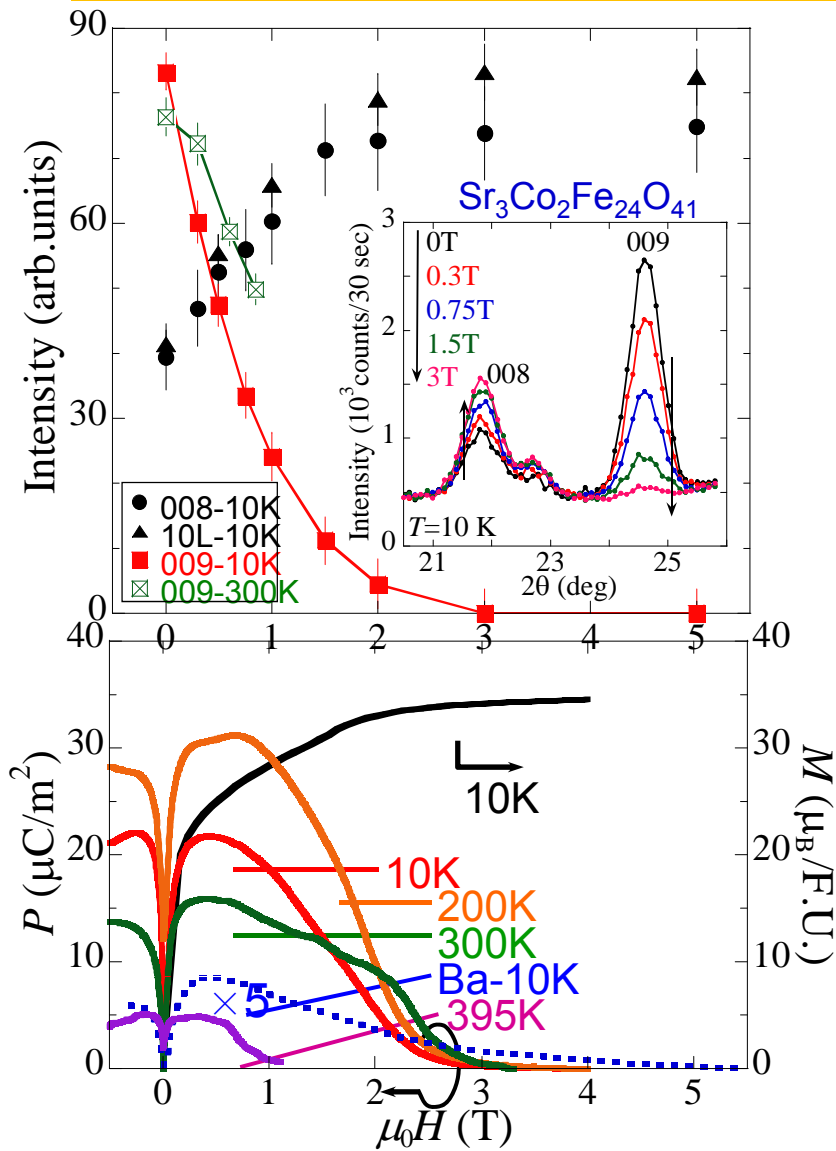
ME effects are observed at a wide T range including room temperature.

*ME coefficient defined as $\alpha = \mu_0 dP/dB$

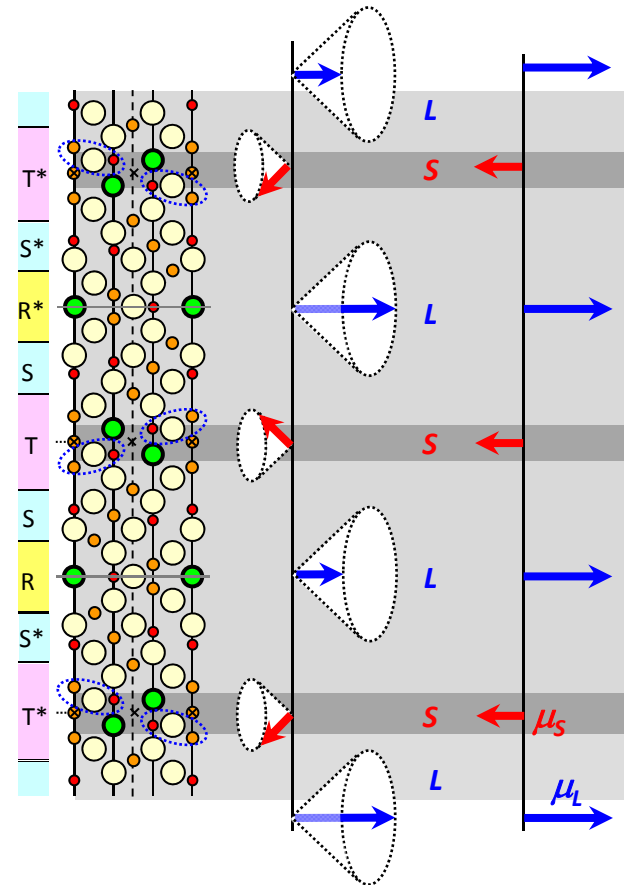
The α exceeds 1×10^{-10} s/m below 0.04 T and reached a maximum $\sim 2.5 \times 10^{-10}$ s/m at 0.003 T.
(c.f. α in Cr_2O_3 : 4×10^{12} s/m)

Origin of magnetoelectric effect –Neutron diffraction, H -dependence-

Soda et al., PRL 106, 087201 (2011).

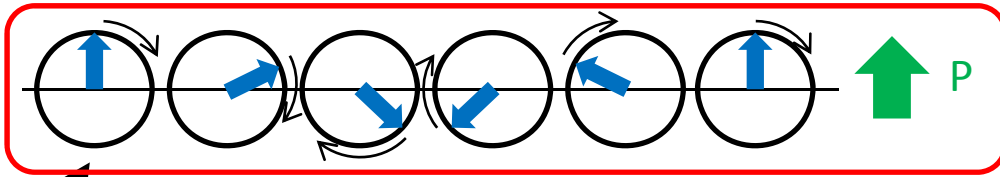
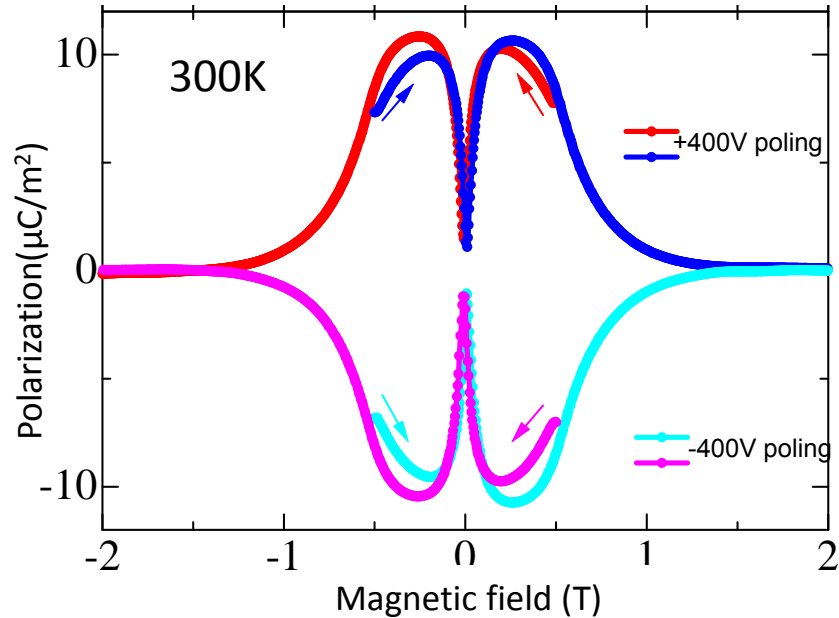


Proposed spin structure related to ME effect in Z-type $\text{Sr}_3\text{Co}_2\text{Fe}_{24}\text{O}_{41}$

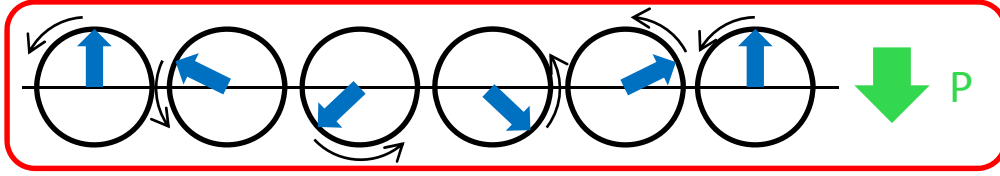


In analogy with Y-type hexaferrites, the r.t. ME effect can be understood in terms of P induced by a transverse conical spin structure through the spin-current mechanism.

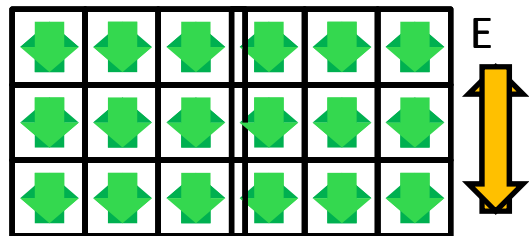
Non-volatility of reversible polarization



By changing the direction of electric field, polarization can be reversed, which means the rotation of spiral is also reversed.



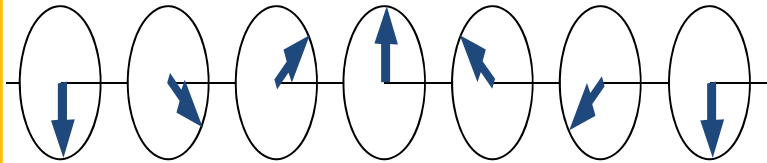
Ferroelectric domains are aligned by a poling electric field.



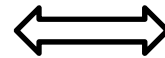
Once sample becomes ferroelectric, polarization is memoried unless samp becoms paraelectric.

This result has the promise of ME device applications including non-volatile memory where information is stored as **electrically-detectable & -controllable spin-helicity**.

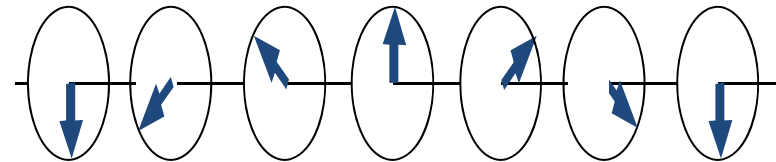
Left-handed spin-helicity (0)



E and/or H

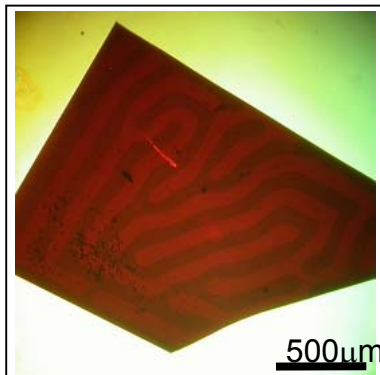


Right-handed spin-helicity (1)



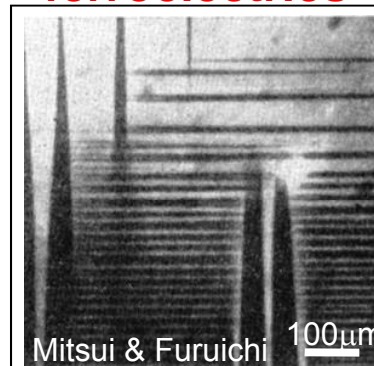
Formation of domain structures by phase transitions in solids

ferromagnet



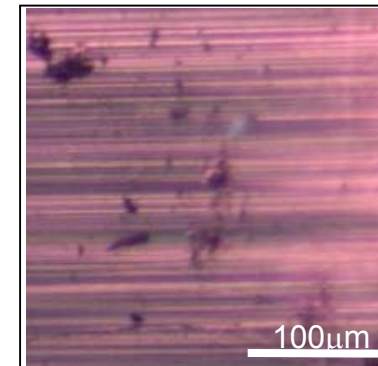
Magnetic domains

ferroelectrics



Ferroelectric domains

ferroelastics



Twins

****Observation of spin-chiral domains in spiral magnets
by scanning resonant x-ray microdiffraction***

Imaging spiral magnetic domains in Ho by circularly polarized Bragg diffraction

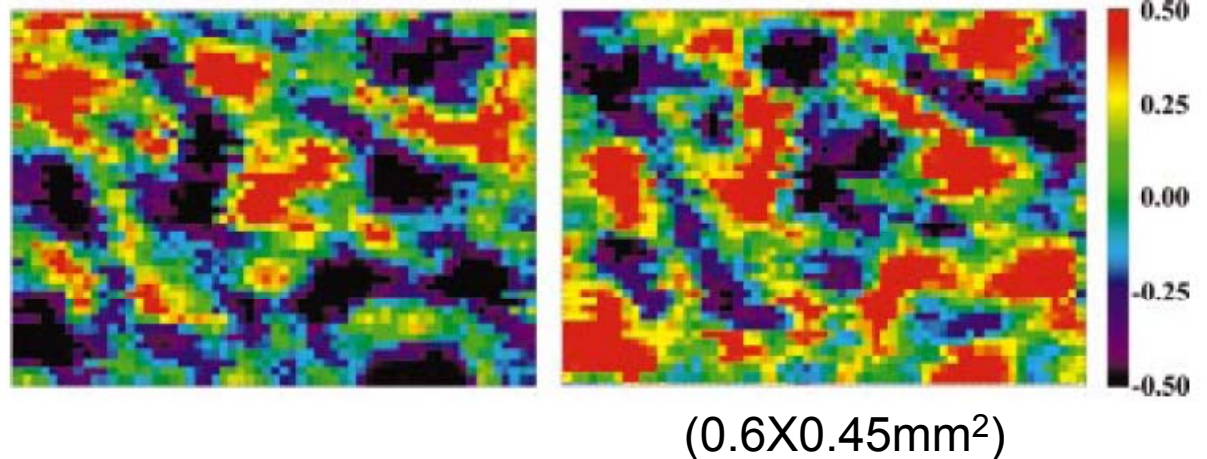
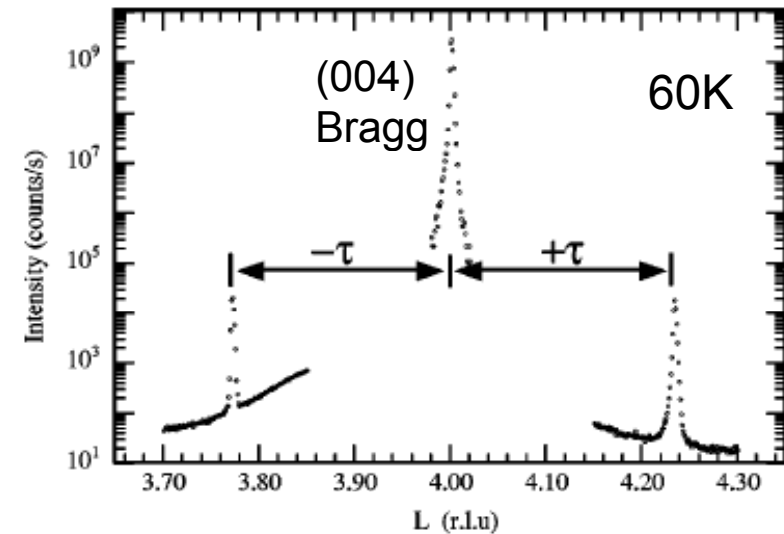
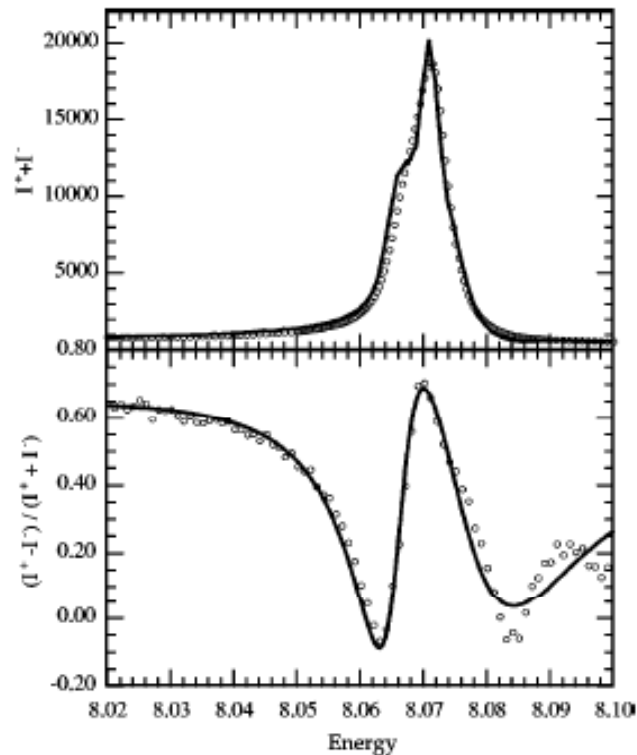
J.C. Lang et al., J. Appl. Phys. 95, 6537 (2004).

Ho metal

[spiral magnetic order with $(0,0, L \pm \tau)$ below $T_N=133\text{K}$]

X-ray energy $E \sim 8.071\text{ eV}$ (\sim Ho L_3 -edge $2p \rightarrow 5d$)

Size of circularly polarized x-ray beam
 $25\ \mu\text{m} \times 25\ \mu\text{m}$



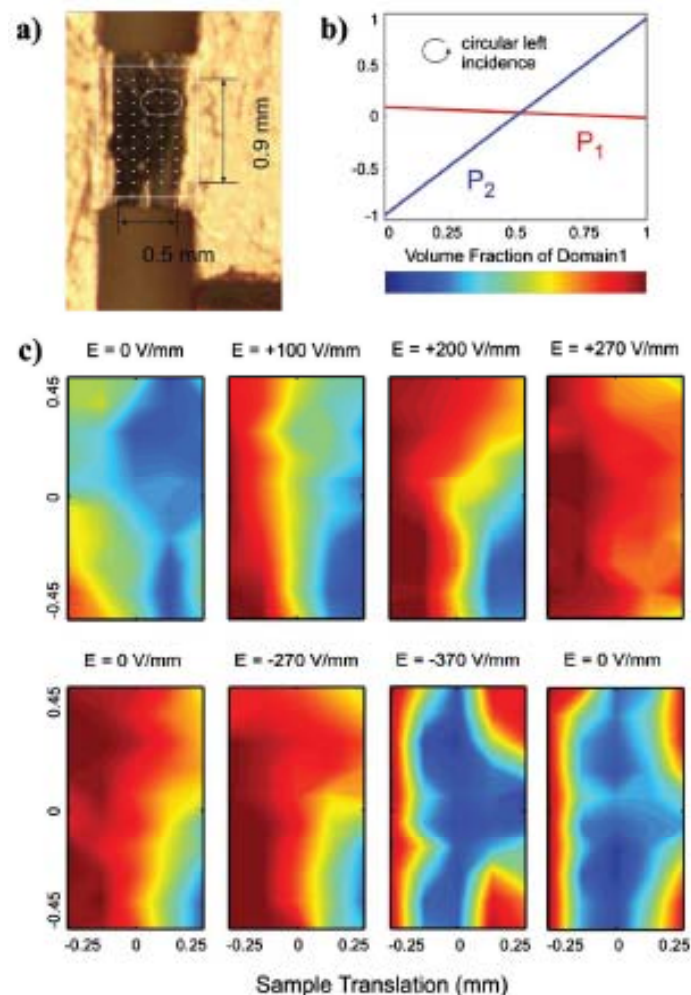
Imaging spiral magnetic domains in multiferroics by circularly polarized X-ray



Fabrizi, Phys. Rev. B **82**, 024434 (2010).

Nonresonant X-ray

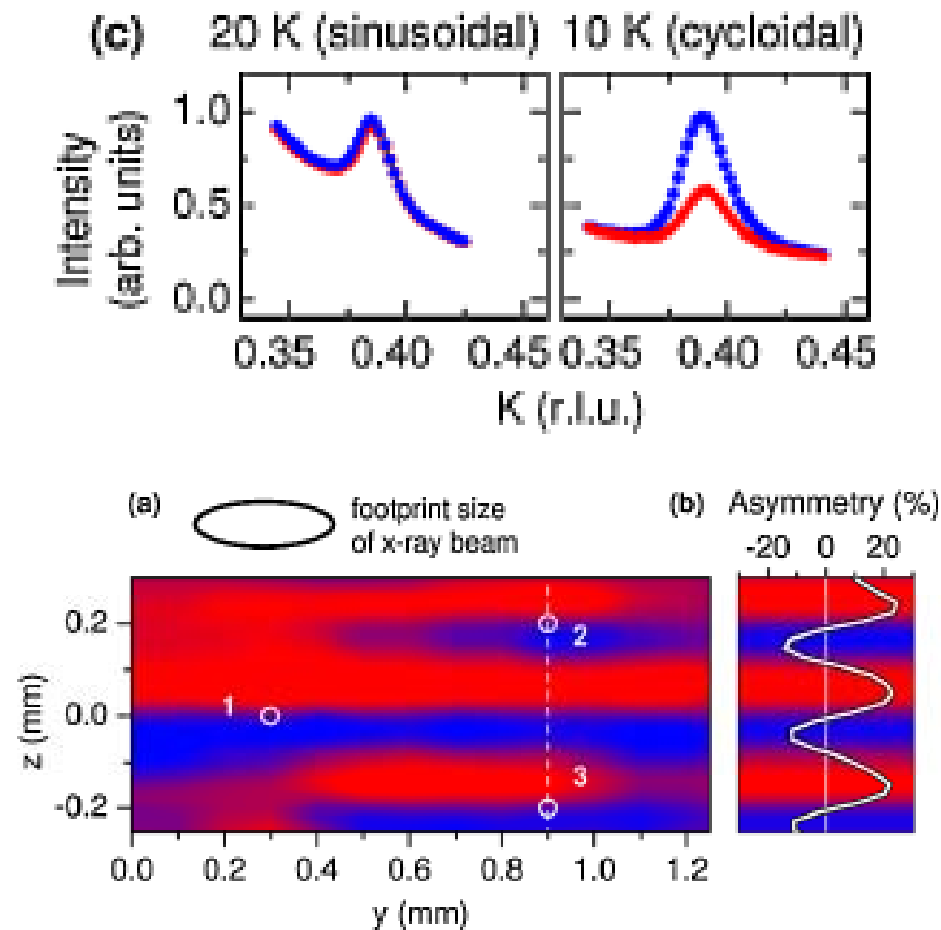
Beam size $\approx 380 \times 250 \mu\text{m}^2$



Schierle, Phys. Rev. Lett. **105**, 167207 (2010).

X-ray energy : Dy M₅-edge

Beam size $\approx 300 \times 100 \mu\text{m}^2$



Imaging spin-chiral domains in Y-type $\text{Ba}_{0.5}\text{Sr}_{1.5}\text{Zn}_2\text{Fe}_{12}\text{O}_{22}$ by circularly polarized X-ray

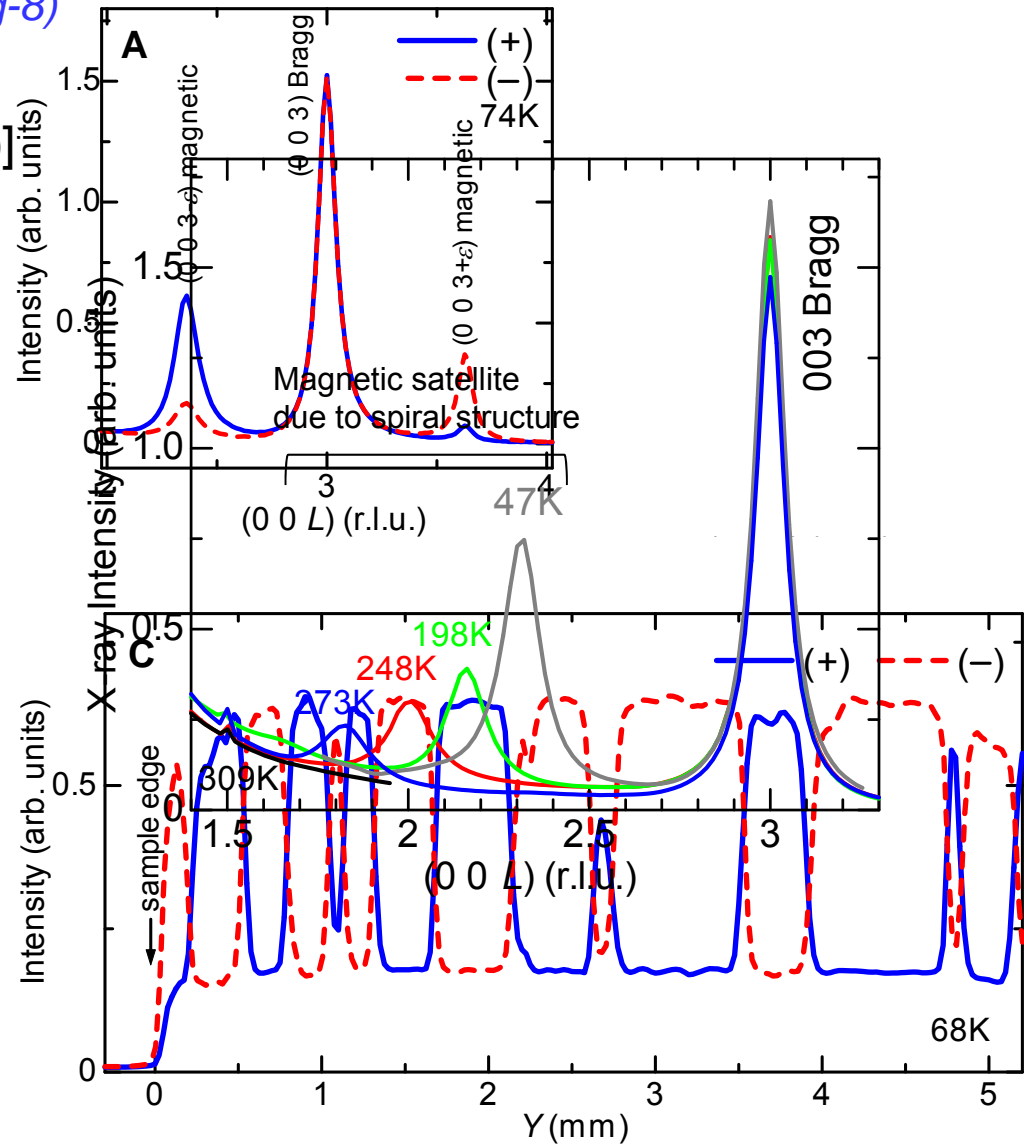
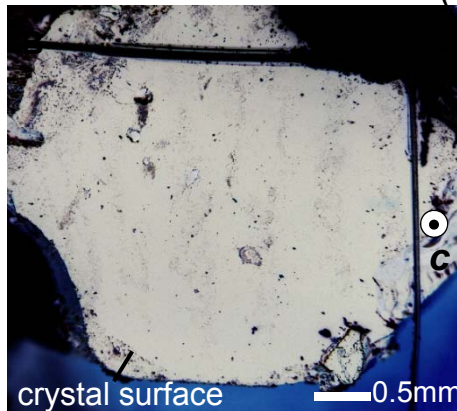
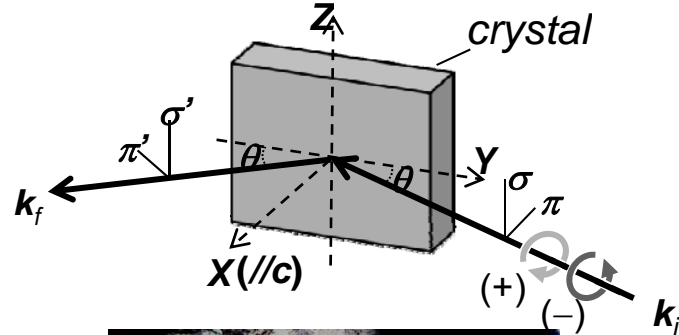
Sample $\text{Ba}_{0.5}\text{Sr}_{1.5}\text{Zn}_2\text{Fe}_{12}\text{O}_{22}$ $T_N \sim 310$ K magnetic satellite $(0,0,3n \pm \epsilon)$

Experimental conditions (@BL17SU, Spring-8)

Incident x-ray energy 710 eV
[at Fe L_3 edge ($2p \rightarrow 3d$)]

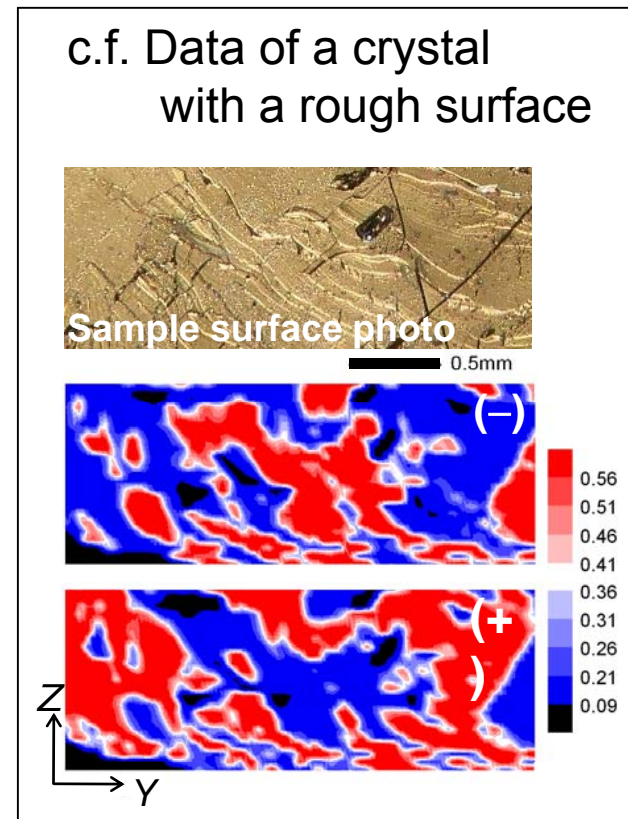
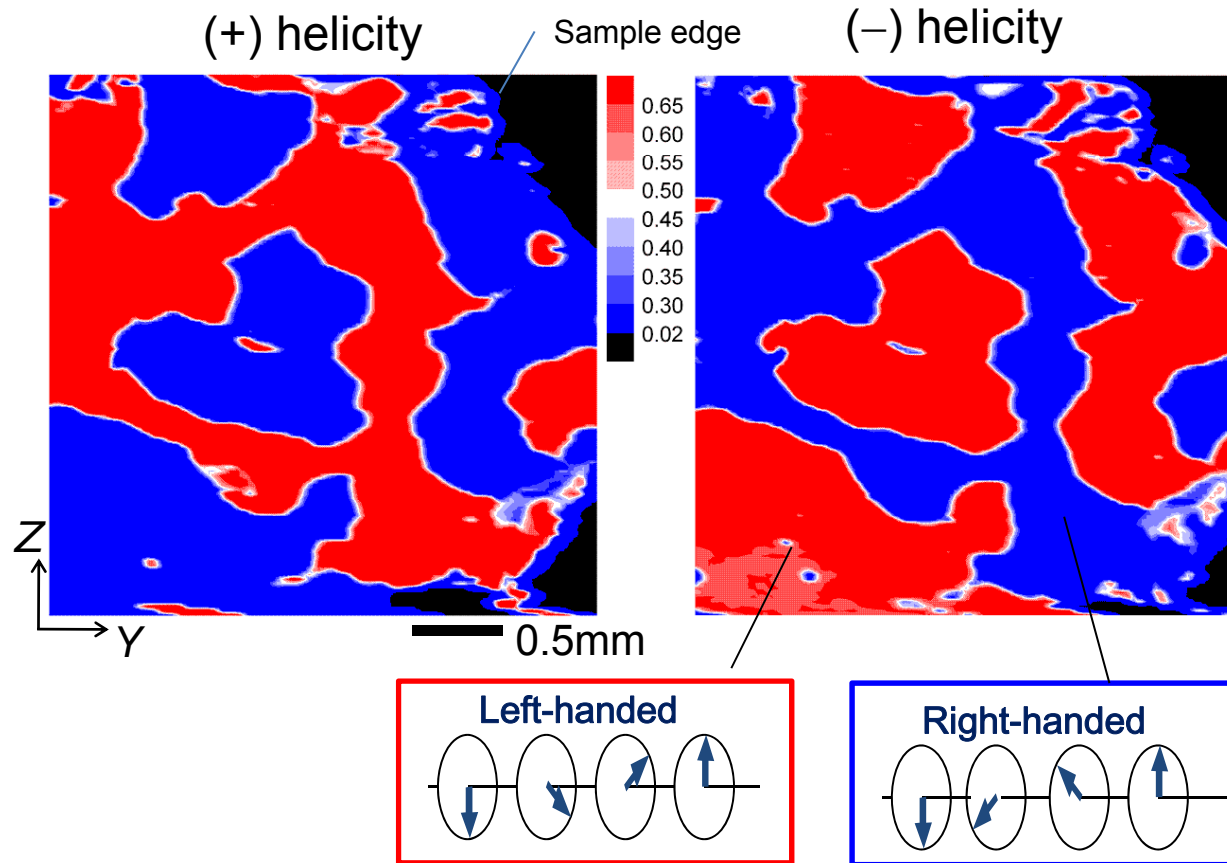
Illuminated sample area $60 \times 15 \mu\text{m}^2$
with a $25 \mu\text{m}$ step

Penetration depth ~ 40 nm



Spatial images of spin-chiral domain structure in $\text{Ba}_{0.5}\text{Sr}_{1.5}\text{Zn}_2\text{Fe}_{12}\text{O}_{22}$ at 68 K

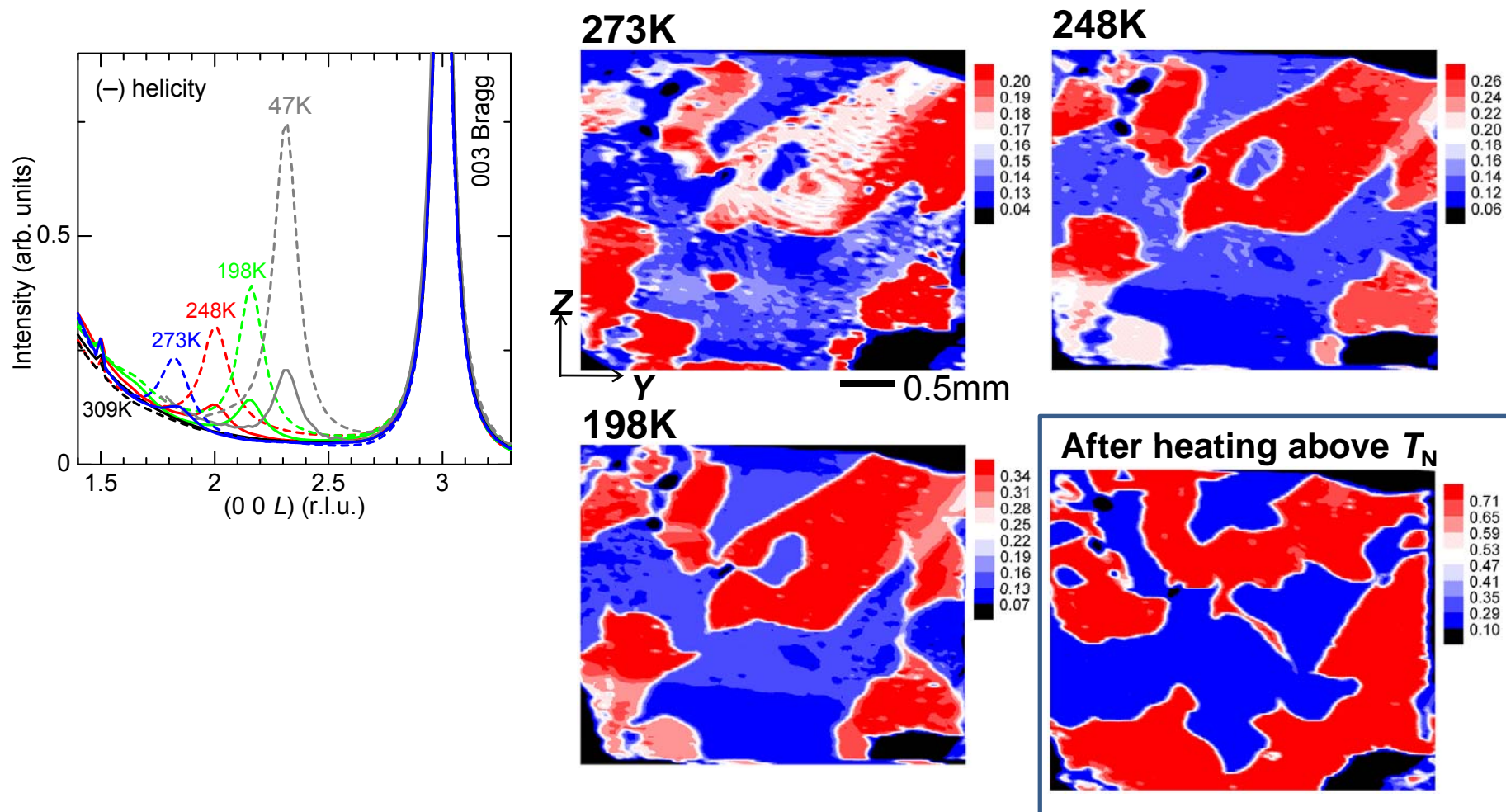
Y. Hiraoka, Y. Tanaka et al., PRB 84, 064418 (2011).



- *Red and blue regions correspond to either a left- or right-handed spin-chiral monodomain.
- *The observed domains are irregular in shape with a size on a **submillimeter** scale.
- *There is a tendency that the domain boundaries are clamped at surface defects.
- *The observed domains were apparently smaller in size than those on a smooth surface.

Thermal effect on the spin-chiral domain structure in $\text{Ba}_{0.5}\text{Sr}_{1.5}\text{Zn}_2\text{Fe}_{12}\text{O}_{22}$

Y. Hiraoka, Y. Tanaka et al., PRB 84, 064418 (2011).



The domain structure is robust with respect to the variation of T and time once they are formed, but is not reproducible once the crystal is heated above T_N .

Summary

Recent progress on study of magnetoelectric hexaferrites has been presented.

***Room temperature (< 400K) magnetoelectrics working in low H (~100 Oe)**

Hexaferrites $\text{Sr}_3\text{Co}_2\text{Fe}_{24}\text{O}_{41}$ with the Z-type structure

$\text{Sr}_4\text{Co}_2\text{Fe}_{36}\text{O}_{60}$ with the U-type structure

***Observation of spin-chiral domains by scanning resonant x-ray microdiffraction**

Hexaferrites $\text{Ba}_{0.5}\text{Sr}_{1.5}\text{Zn}_2\text{Fe}_{12}\text{O}_{22}$ with the Y-type structure

