Coupled electric and magnetic effects in frustrated Mott insulators: currents, dipoles and monopoles

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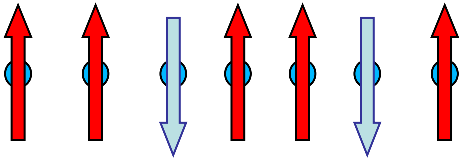
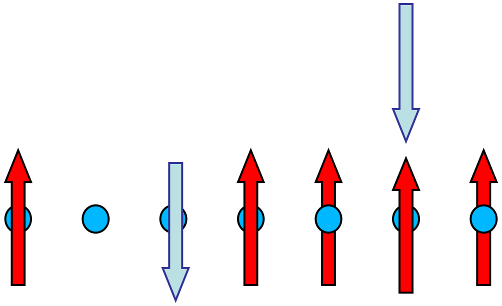
- Introduction
- Spontaneous currents and dipoles in Mott insulators
- Dipoles on monopoles in spin ice
- Conclusions

$$\mathcal{H} = -t \sum_{\langle ij \rangle, \sigma} c^{\dagger}_{i\sigma} c_{j\sigma} + U \sum_i n_{i\uparrow} n_{i\downarrow}$$

The Hubbard model

$$E_{\mathrm{g}} \sim U - 2zt$$

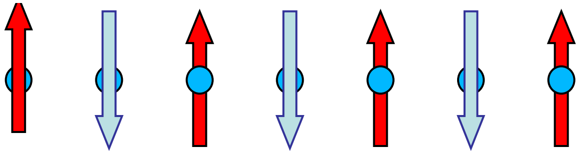




n=1, U>t: **Mott insulator**

Localized electrons/localized magnetic moments

$$H_{eff} = \frac{2t^2}{U} \sum_{(ij)} \mathbf{S}_i \mathbf{S}_j .$$



$\Delta E = 0$ $\qquad\qquad$ $\Delta E = -\frac{2t^2}{U}$

Fig. 1. Two possible configurations and corresponding energy gain for non-degenerate orbitals.

Electronic Orbital Currents and Polarization in Mott Insulators

L.N. Bulaevskii, C.D. Batista, M. Mostovoy and D. Khomskii

PRB **78**, 024402 (2008)

D. Khomskii J.Phys.-Cond. Mat. **22**, 164209 (2010)

Mott insulators

$$H = -\sum_{ij\sigma} t_{ij} (c^{+}_{i\sigma} c_{j\sigma} + c^{+}_{j\sigma} c_{i\sigma}) + \frac{U}{2} \sum_{i} (n_i - 1)^2,$$

Standard paradigm: for U>>t and one electron per site electrons are localized on sites. All charge degrees of freedom are frozen out; only spin degrees of freedom remain in the ground and lowest excited states

$$H_S = \frac{4t^2}{U} (\vec{S}_1 \cdot \vec{S}_2 - 1/4).$$

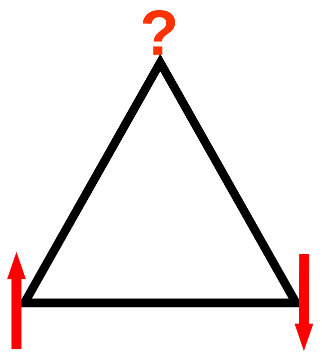
Not the full truth!

For certain spin configurations there exist in the ground state of strong Mott insulators **spontaneous electric currents** (and corresponding orbital moments)!

For some other spin textures there may exist a **spontaneous charge redistribution**, so that $\langle n_i \rangle$ is not 1! This, in particular, can lead to the appearance of a spontaneous **electric polarization** (a purely ***electronic mechanism of multiferroic behaviour***)

These phenomena, in particular, appear in frustrated systems, with **scalar chirality** playing important role

Spin systems: often complicated spin structures, especially in frustrated systems – e.g. those containing triangles as building blocks

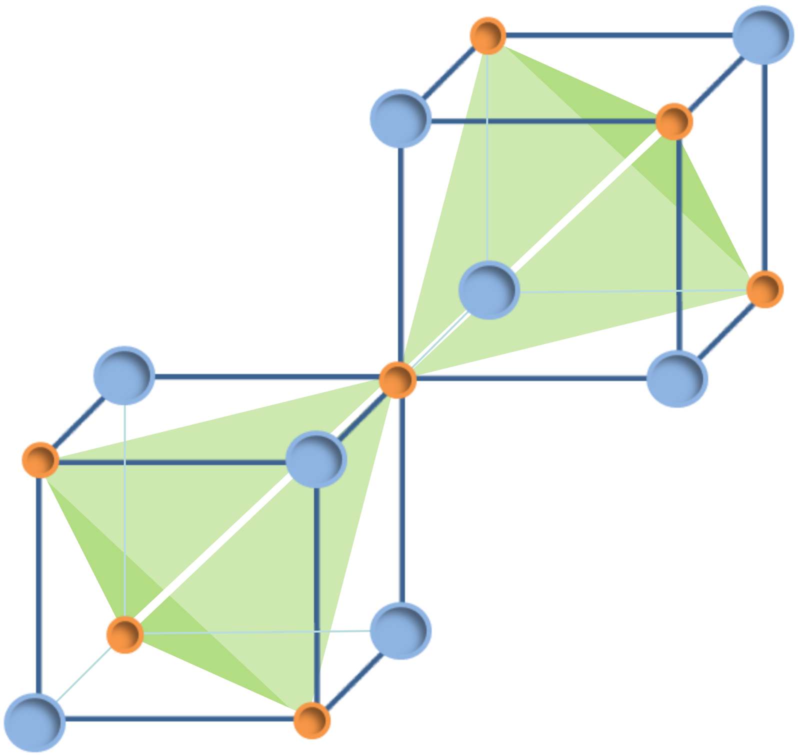


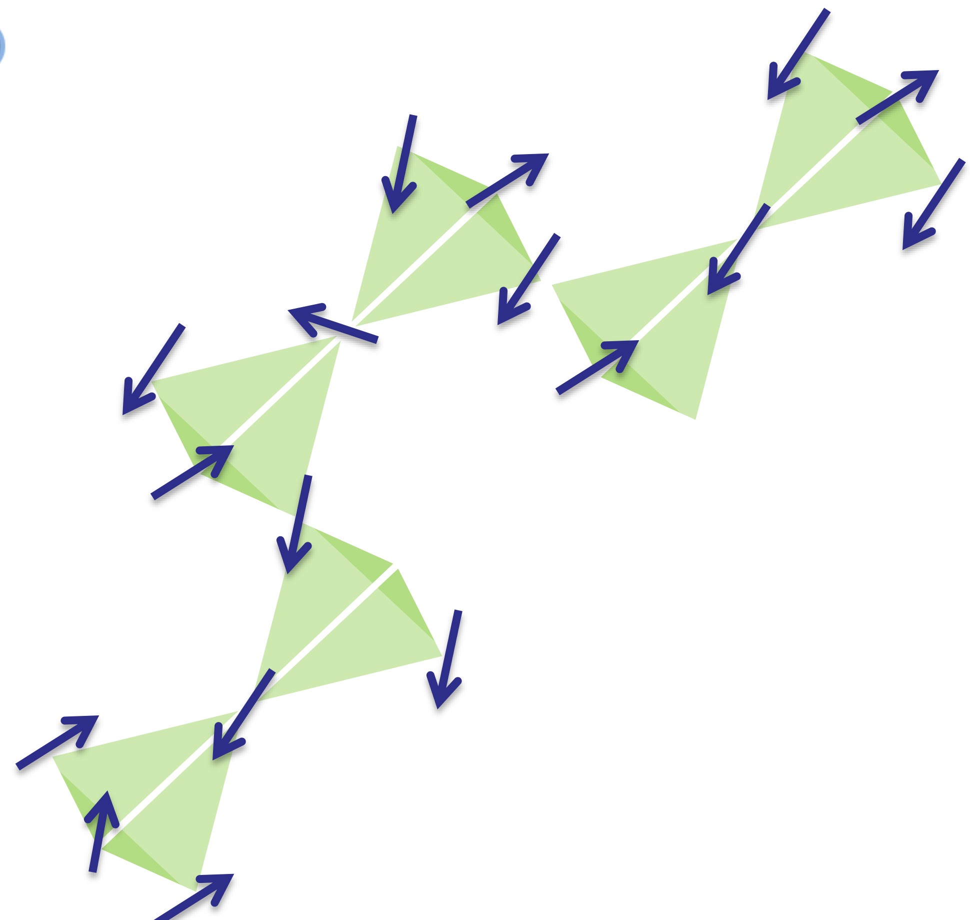
- Isolated triangles (trinuclear clusters) - e.g. in some magnetic molecules (V15, …)
- Solids with isolated triangles ($La_4Cu_3MoO_{12}$)
- Triangular lattices
- Kagome
- Pyrochlore

The Cathedral San Giusto, Trieste, 6-14 century

Spinels:

The B-site pyrochlore lattice: geometrically frustrated for AF





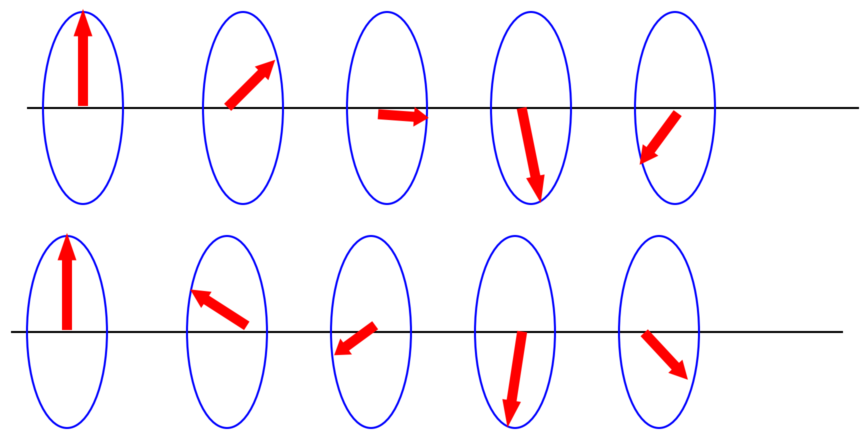
Often complicated ground states; sometimes $\langle \vec{S}_i \rangle = 0$ →

→ spin liquids

Some structures, besides $\langle \vec{S}_i \rangle$, are characterized by:

Vector chirality

$$\left[\vec{S}_i \times \vec{S}_j\right]$$

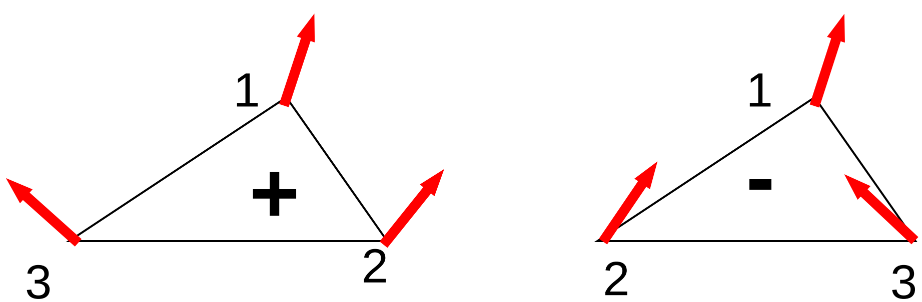


Scalar chirality

$$\chi_{123} = \vec{S}_1\left[\vec{S}_2 \times \vec{S}_3\right]$$

- solid angle

χ may be + or - :

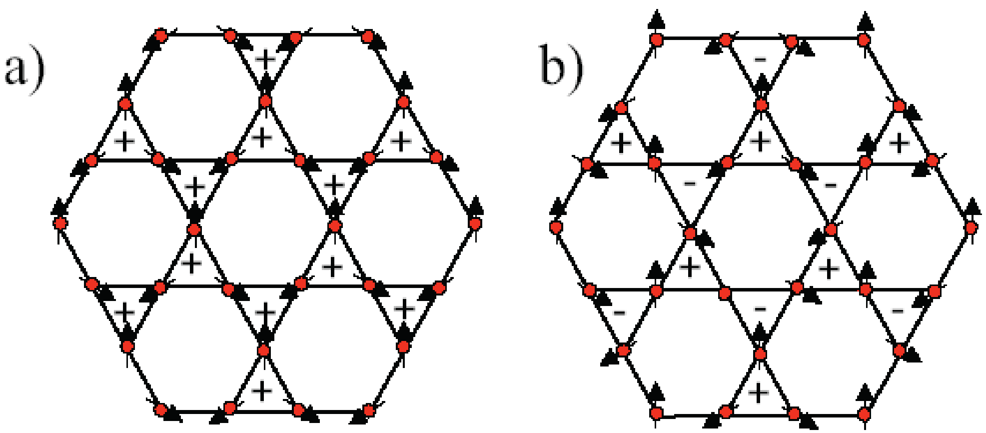


Scalar chirality χ is often invoked in different situations:

- Anyon superconductivity
- Berry-phase mechanism of anomalous Hall effect
- New universality classes of spin-liquids
- Chiral spin glasses

Chirality in frustrated systems: Kagome

a) Uniform chirality (q=0) b) Staggered chirality (√3x√3)



But what is the scalar chirality physically?

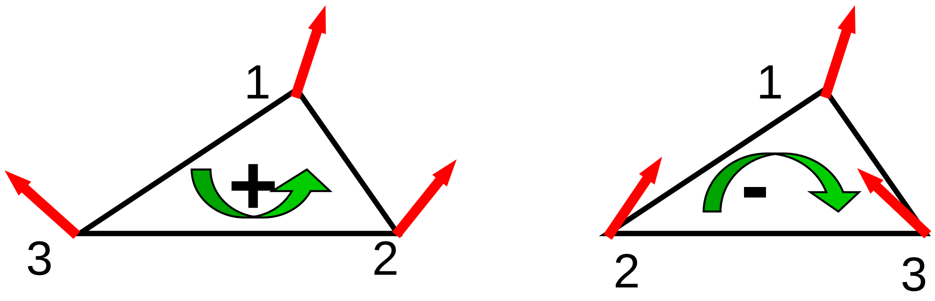
What does it couple to?

How to measure it?

Breaks time-reversal-invariance T and inversion P - like currents!

$\chi_{123} \neq 0$ means spontaneous circular electric current $j_{123} \neq 0$ and orbital moment $L_{123} \neq 0$

$$L_{123} \propto j_{123} \propto \chi_{123}$$



Couples to magnetic field:

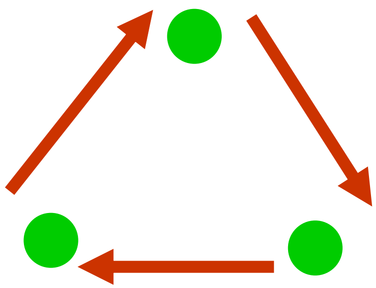
$$-\vec{L}\vec{H} \sim -\chi H$$

Difference between Mott and band insulators

$$H = -\sum_{ij\sigma} t_{ij}(c^+_{i\sigma}c_{j\sigma} + c^+_{j\sigma}c_{i\sigma}) + \frac{U}{2}\sum_i (n_i - 1)^2, \qquad \langle n_i \rangle = 1.$$

- Only in the limit $U \to \infty$ electrons are localized on sites.
- At $t/U \neq 0$ electrons can hop between sites.

$$H_S = \frac{4t^2}{U}(\vec{S}_1 \cdot \vec{S}_2 - 1/4).$$



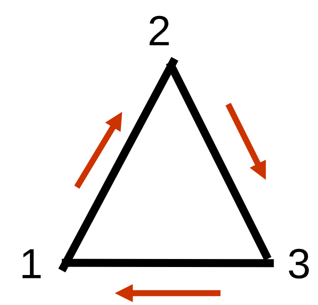
Orbital current

Spin current operator and scalar spin chirality

- Current operator for Hubbard Hamiltonian on bond ij:

$$\vec{I}_{ij} = \frac{iet_{ij}\vec{r}_{ij}}{\hbar r_{ij}} \sum_{\sigma} (c^{+}_{i\sigma} c_{j\sigma} - c^{+}_{j\sigma} c_{i\sigma}).$$

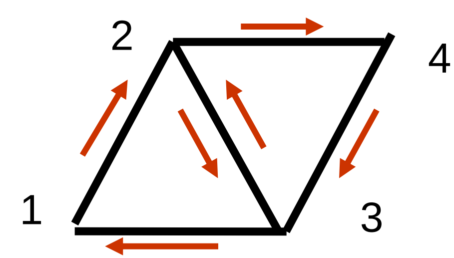
- Projected current operator: odd # of spin operators, scalar in spin space. For smallest loop, triangle,



$$\vec{I}_{S,12}(3) = \frac{\vec{r}_{ij}}{r_{ij}} \frac{24et_{12}t_{23}t_{31}}{\hbar U^2} [\vec{S}_1 \times \vec{S}_2] \cdot \vec{S}_3.$$

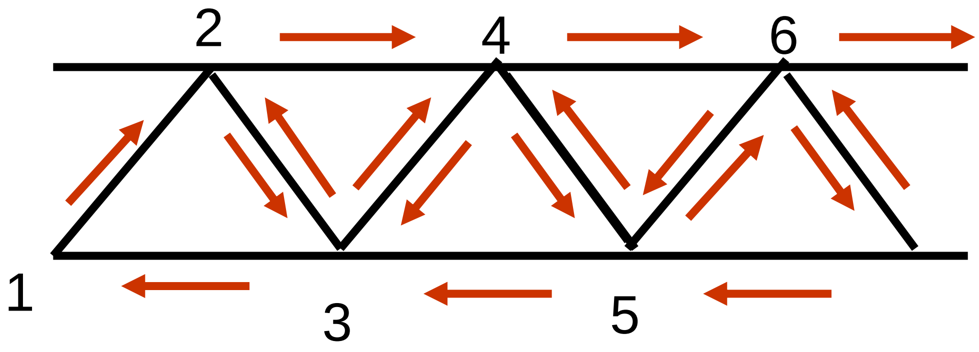
- Current via bond 23

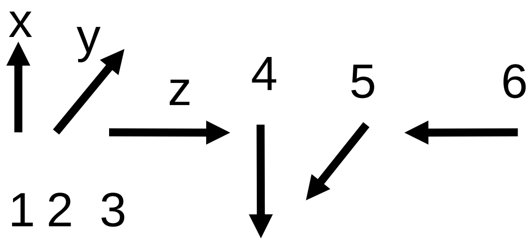
$$I_{S,23} = I_{S,23}(1) + I_{S,23}(4).$$



- On bipartite nn lattice I_S is absent.

Boundary and persistent current





$$\chi = const$$

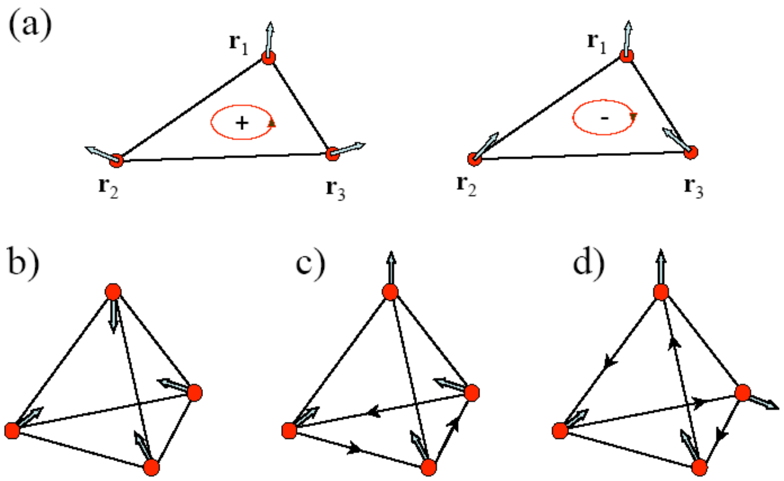
Boundary current in
gaped 2d insulator

Orbital currents in the spin ordered ground state $\langle \vec{S}_i \rangle \neq 0$

- Necessary condition for orbital currents is nonzero average chirality

$$\chi_{12,3} = [\vec{S}_1 \times \vec{S}_2] \cdot \vec{S}_3, \qquad \langle \chi_{ij,k} \rangle \neq 0.$$

- It may be inherent to spin ordering or induced by magnetic field

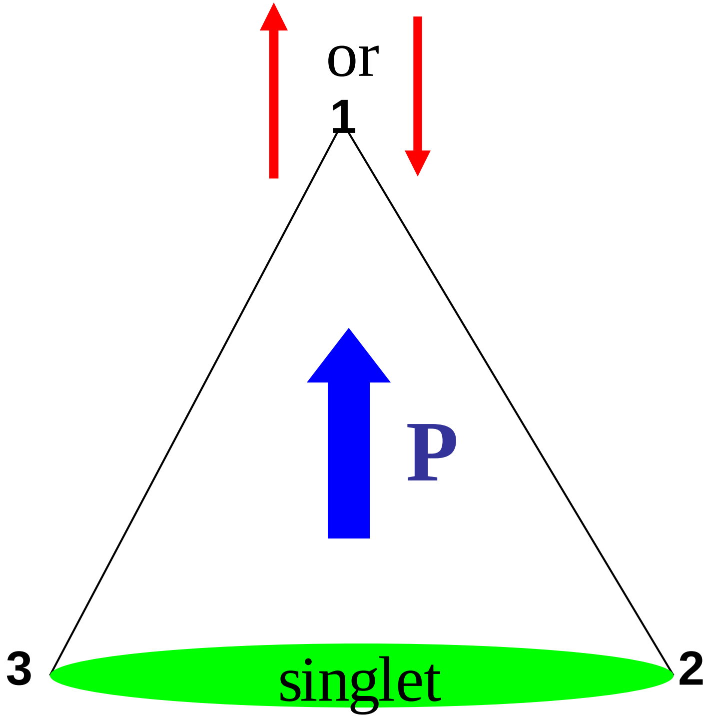


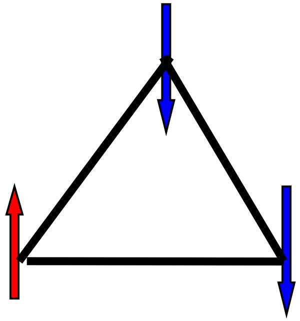
Triangles with $\pm$ chirality

Tetrahedra with [111] anisotropy

Electronic polarization on triangle

$$\langle n_1 \rangle = 1 + \delta n_1 = 1 - 8\left(\frac{t}{U}\right)^3 \left[\mathbf{S}_1(\mathbf{S}_2 + \mathbf{S}_3) - 2\mathbf{S}_2\mathbf{S}_3\right]$$

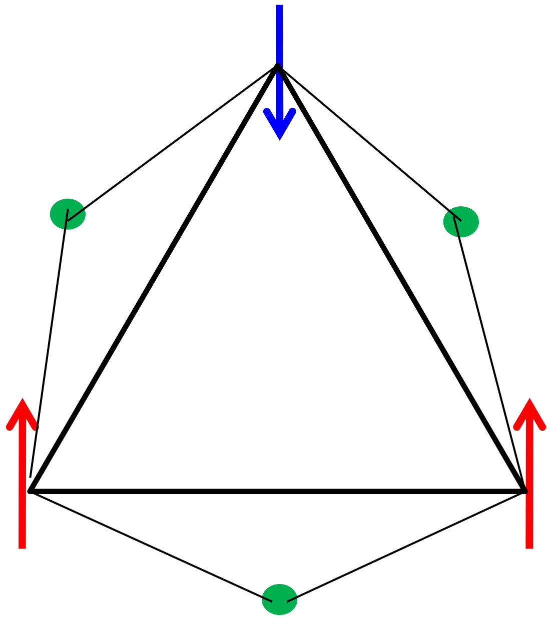




Purely electronic mechanism of multiferroic behavior!

Dipoles are also created by lattice distortions (striction); the expression for

polarization/dipole is the same, $\mathbf{D} \sim \mathbf{P} \sim \mathbf{S}_1(\mathbf{S}_2 - \mathbf{S}_3) - 2\mathbf{S}_2\mathbf{S}_3$ (M.Mostovoy)



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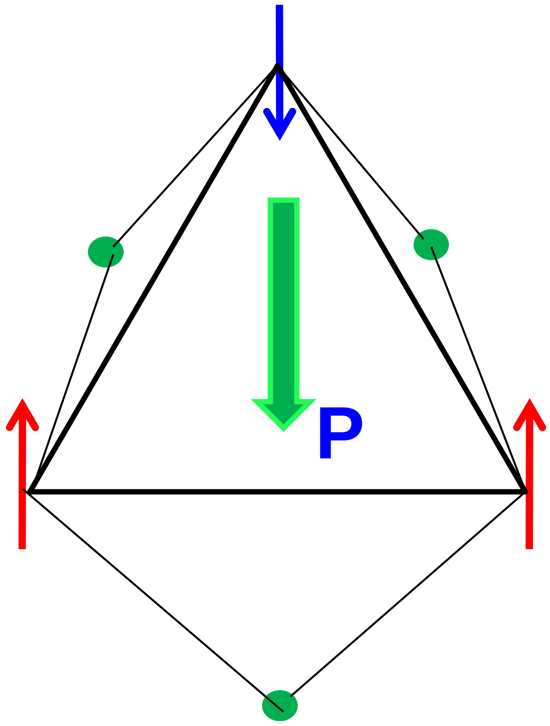
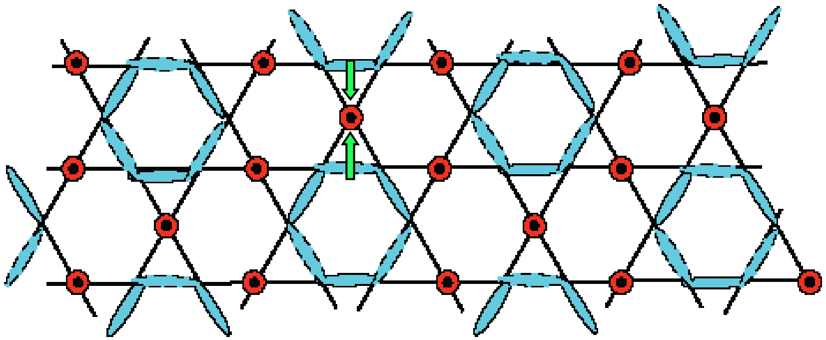


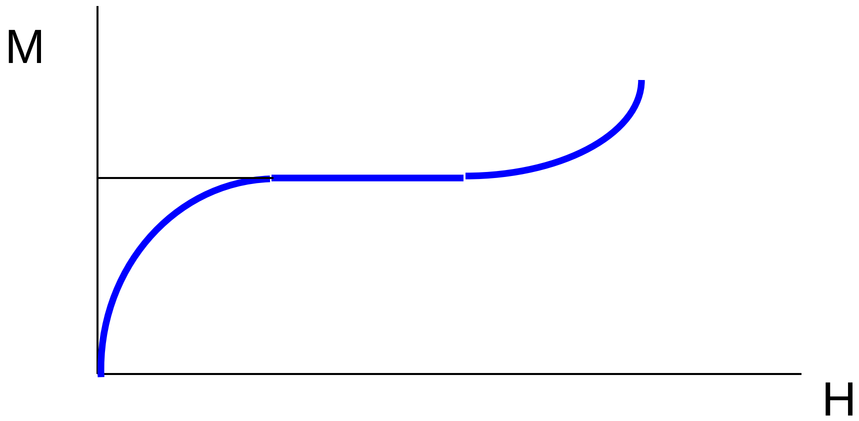
Charges on kagome lattice



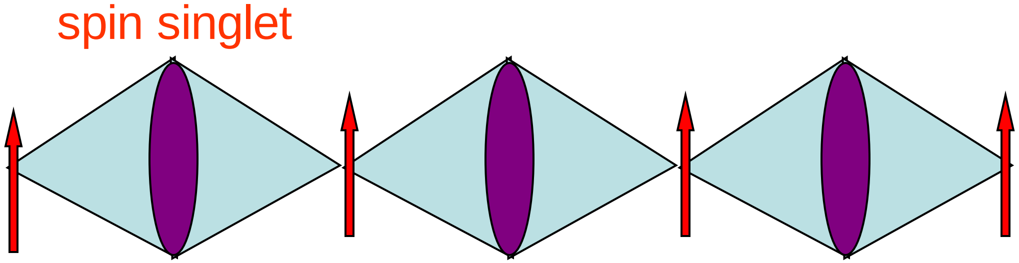
1/3 magnetization plateau:

Charge ordering for spins 1/3 in magnetic field: spin-driven CDW

•Typical situation at the magnetization plateaux!

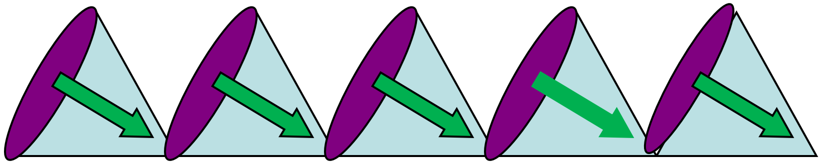


- Diamond chain (azurite $Cu_3(CO_3)_2(OH)_2$)

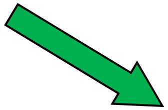


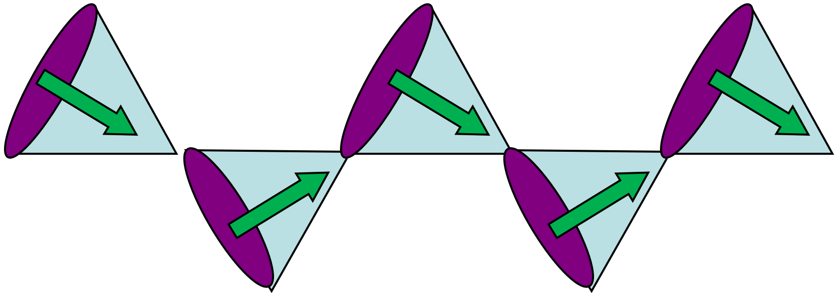
-will develop S-CDW

- Saw-tooth (or delta-) chain



Net polarization





Net polarization

$Cu_2(AsO_4)(OH)\cdot 3H_2O$ (euchroite)

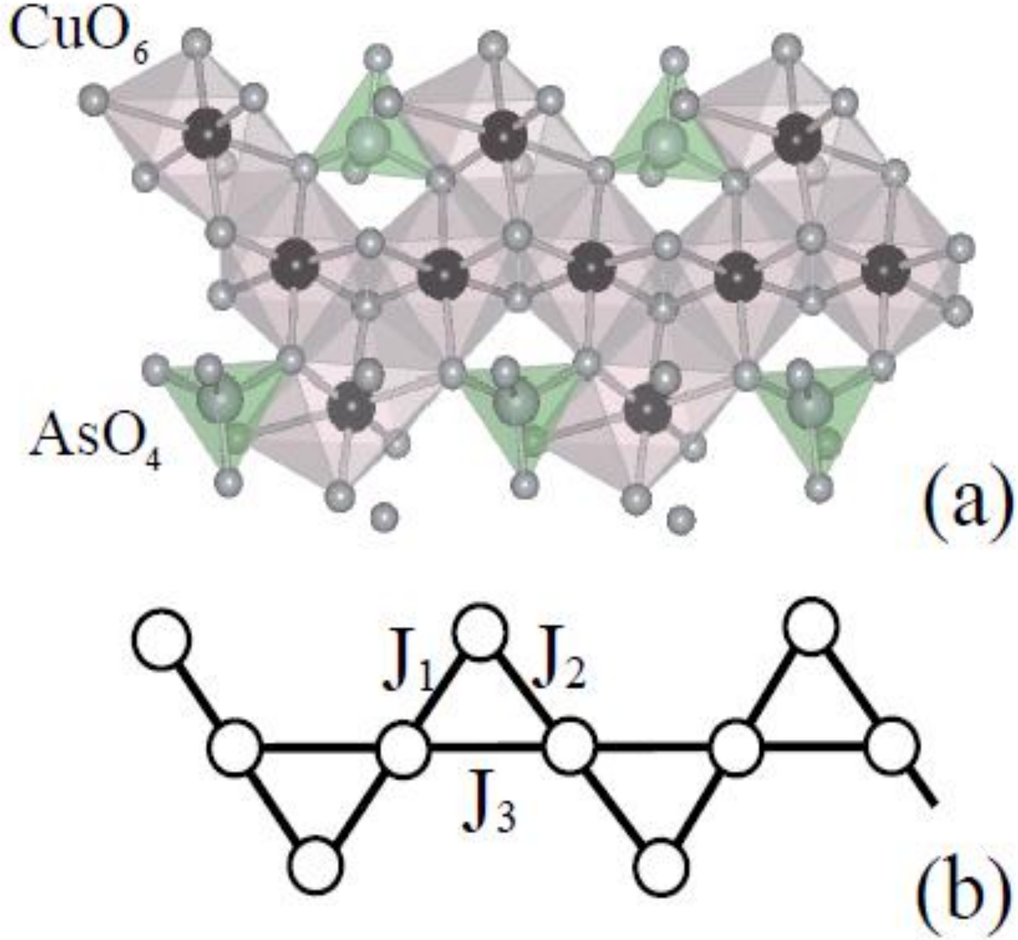


Figure 1. (a) Structure of euchroite, (b) schematic view of the delta chain.

Isolated triangle: accounting for DM interaction

- DM coupling: $H_{DM} = \sum_{ij} D_{ij} \vec{S}_i \times \vec{S}_j .$
- For V15 $H_{DM} \approx D_z L_z S_z .$
- Splits lowest quartet into 2 doublets $|+\uparrow\rangle, |-\downarrow\rangle$ and $|+\downarrow\rangle, |-\uparrow\rangle$ separated by energy $\Delta = D_z .$
- Ac electric field induces transitions between $\chi = \pm 1.$
- Ac magnetic field induces transitions between $S_z = \pm 1/2.$

ESR : magnetic field (**-HM**) causes transitions

$$|1/2,\chi\rangle \to |-1/2,\chi\rangle,\ or\ |-1/2,\chi\rangle \to |1/2,\chi\rangle$$

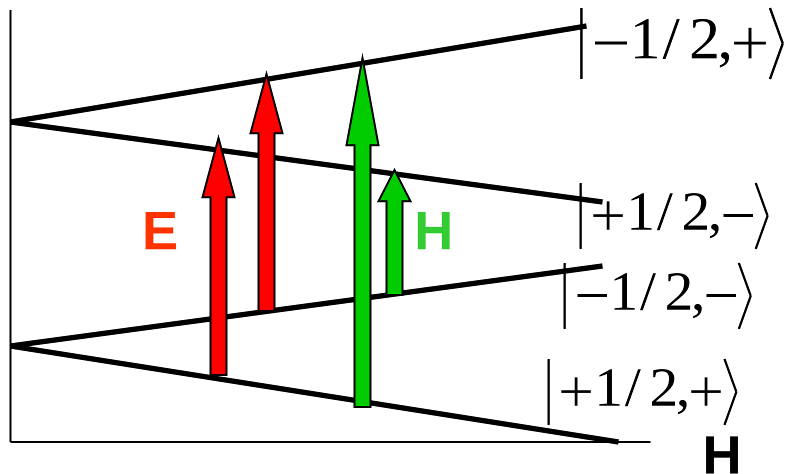
Here: electric field (**-Ed**) has nondiagonal matrix elements in χ:

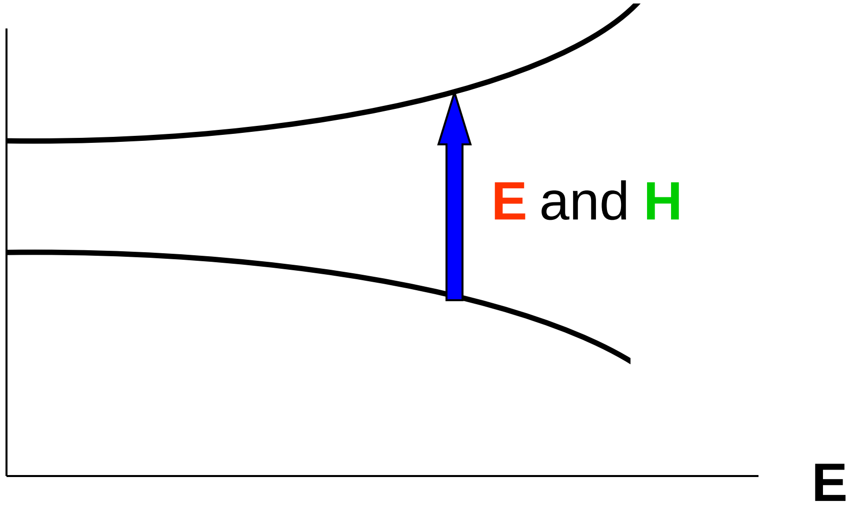
$$\langle \chi = + |\mathbf{d}| \chi = - \rangle \neq 0$$

electric field will cause

dipole-active transitions $|S^z, +\rangle \Leftrightarrow |S^z, -\rangle$

-- ESR caused by electric field E !





Triangle: S=1/2, chirality (or pseudosin T) = ½

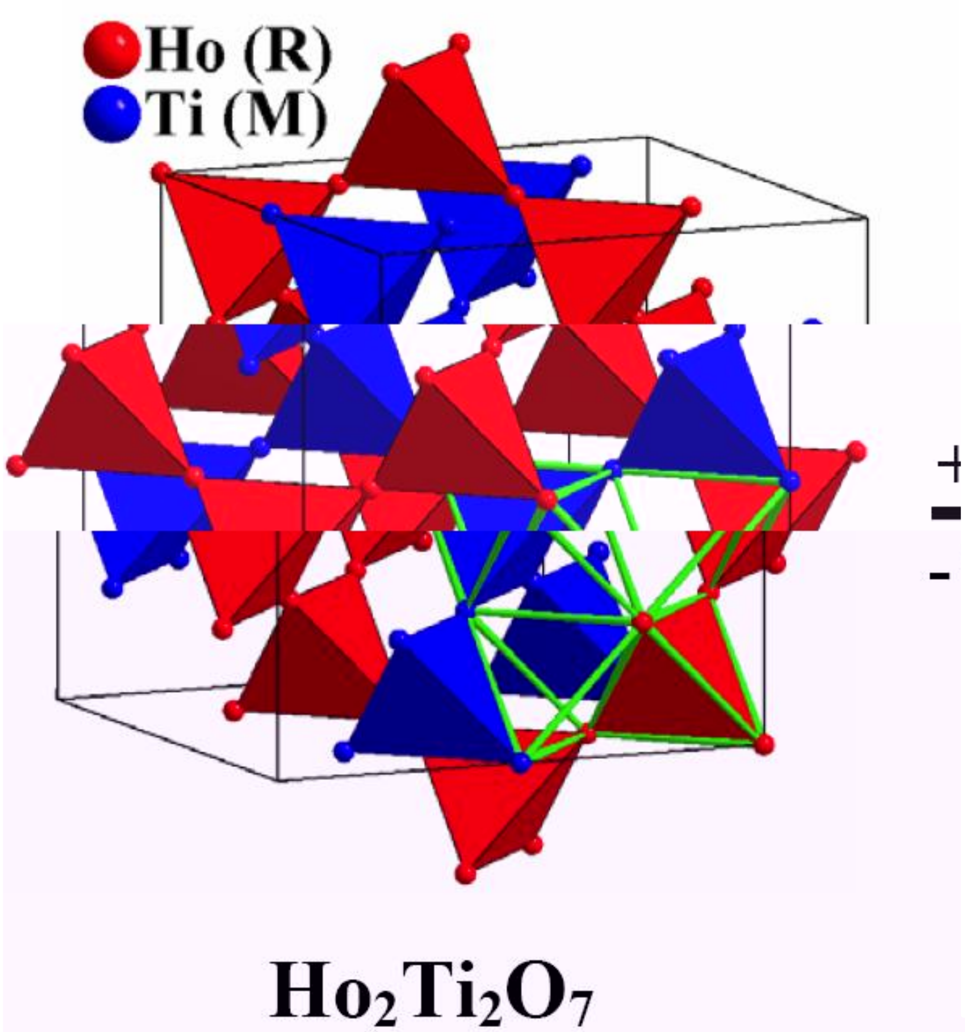
Can one use chirality instead of spin for quantum computation etc, as a qubit instead of spin?

We can control it by magnetic field (chirality = current = orbital moment) and by electric field

Georgeot, Mila, PRL (2010)

Monopoles and dipoles in spin ice

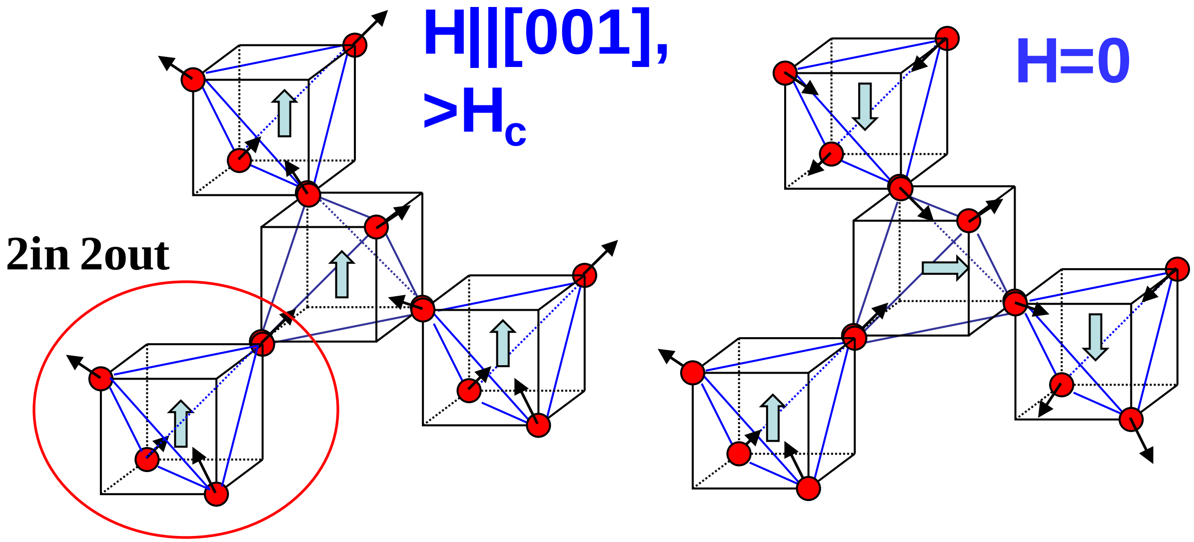
Pyrochlore: Two interpenetrating metal sublattices



pyrochlore $R_2Ti_2O_7$・・ geometrical spin frustration

R=Ho

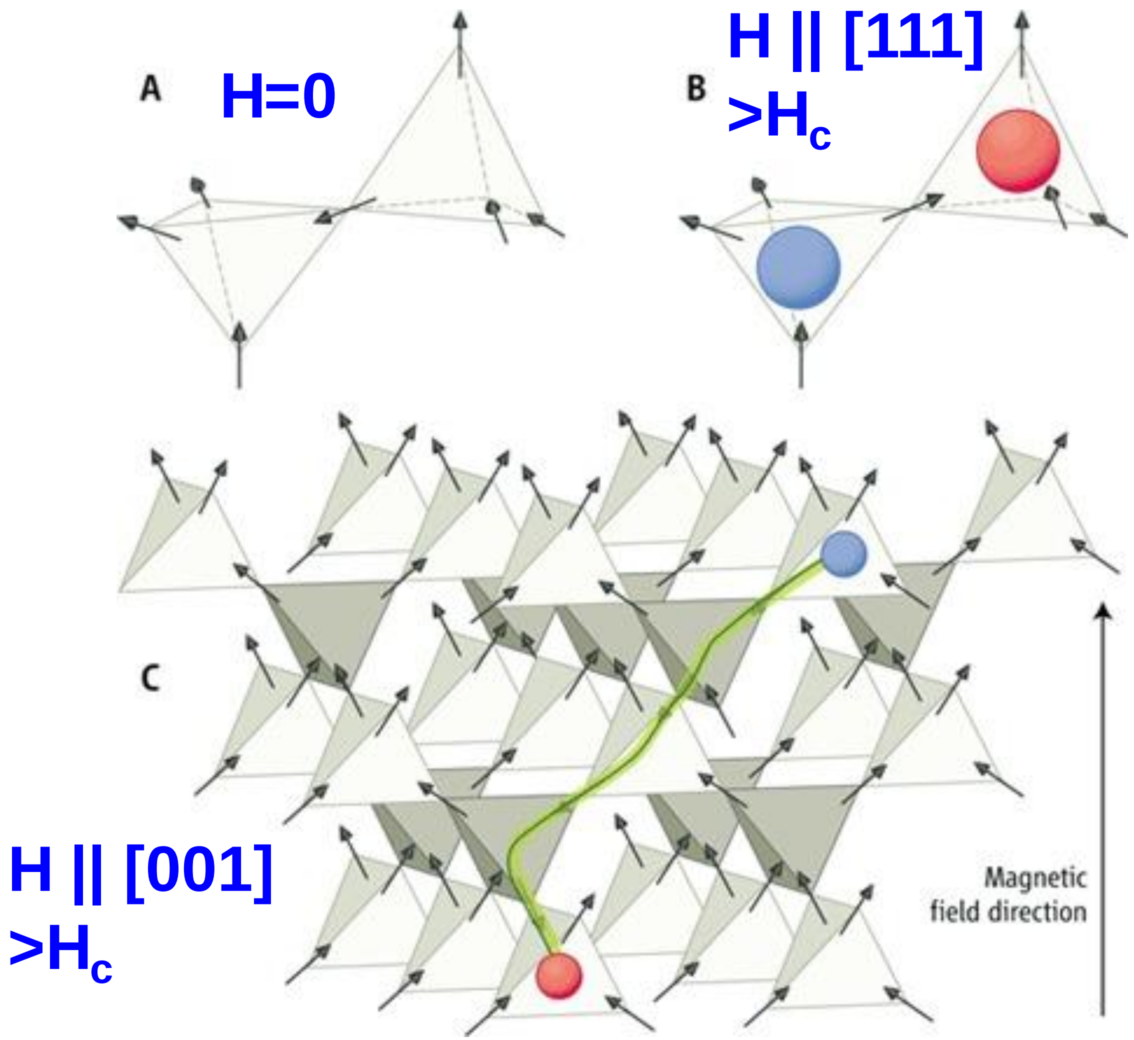
Ferromagnetic interaction, Ising spin (spin ice)



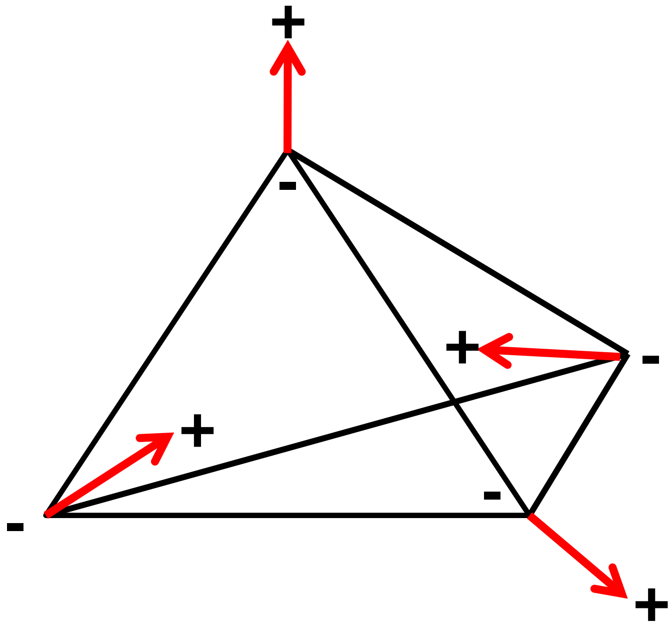
R=Gd

Antiferromagnetic interaction, Heisenberg spin

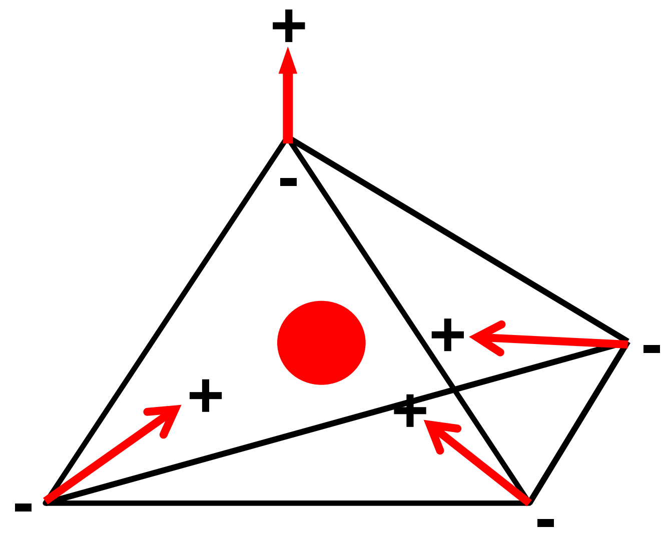
Excitations creating magnetic monopole (Castelnovo, Moessner and Sondhi)



M J P Gingras Science 2009;326:375-376



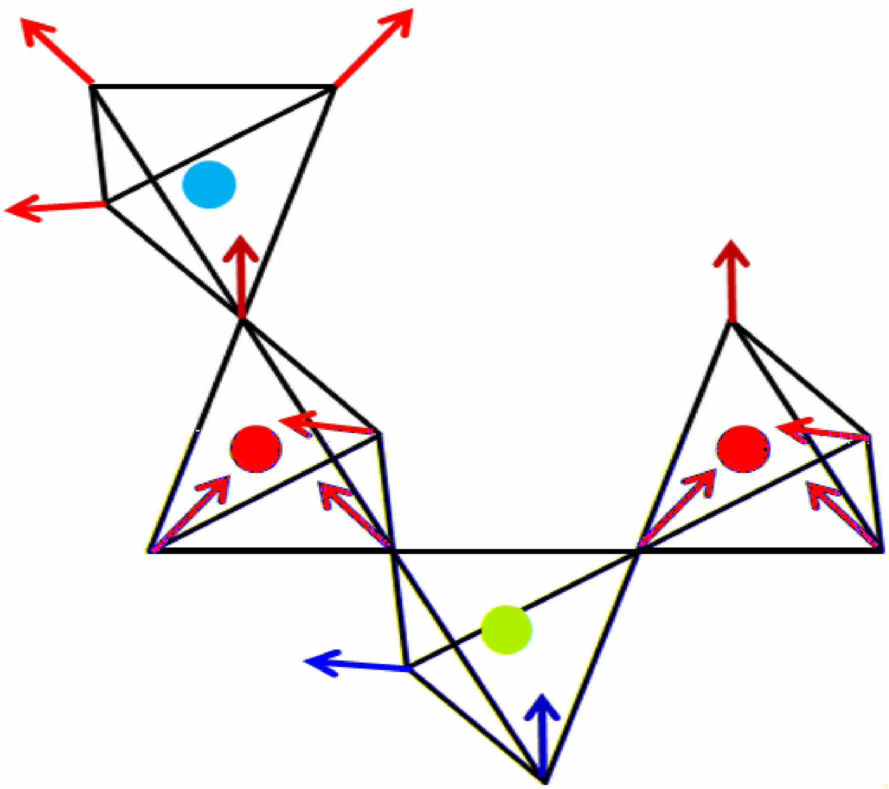
2-in/2-out: net magnetic charge inside tetrahedron zero

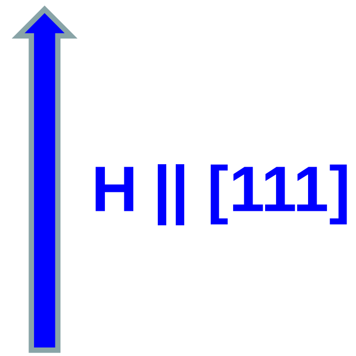


3-in/1-out: net magnetic charge inside tetrahedron ≠ 0 – monopole or antimonopole

$H \parallel [111]$, $>H_c$

Monopoles/antimonopoles at every tetraheder, staggered





H Aoki et al., JPSJ 73, 2851 (2004)

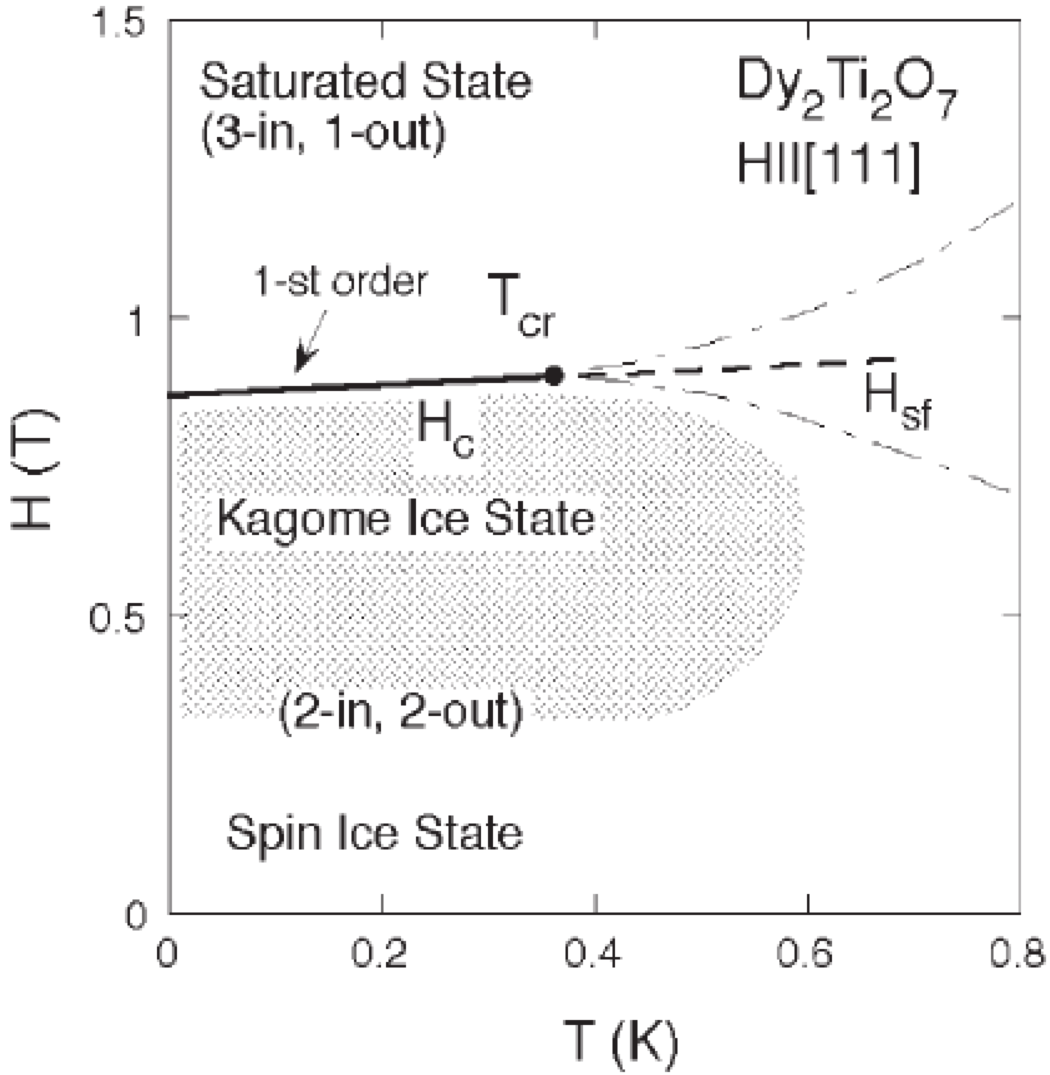
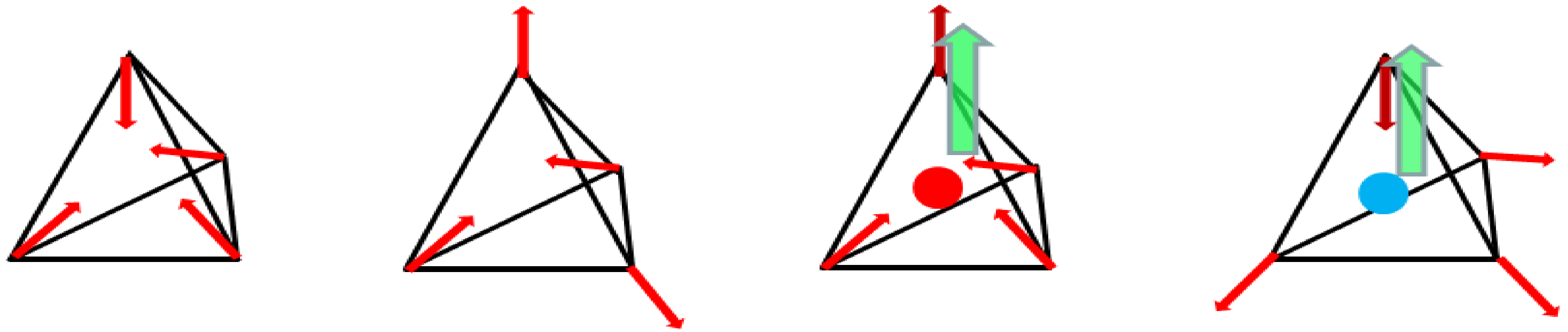


Fig. 1. Phase diagram of $Dy_2Ti_2O_7$ in a [111] magnetic field, determined by magnetization and specific heat measurements. The dashed line

★ Dipoles on tetrahedra:



4-in or 4-out: **d=0**

2-in/2-out (spin ice): **d=0**

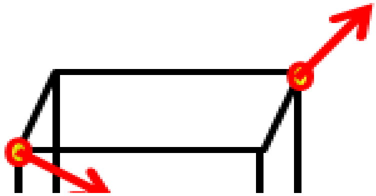
3-in/1-out or 1-in/3-out (monopoles/antimonopoles): **d** ≠ 0

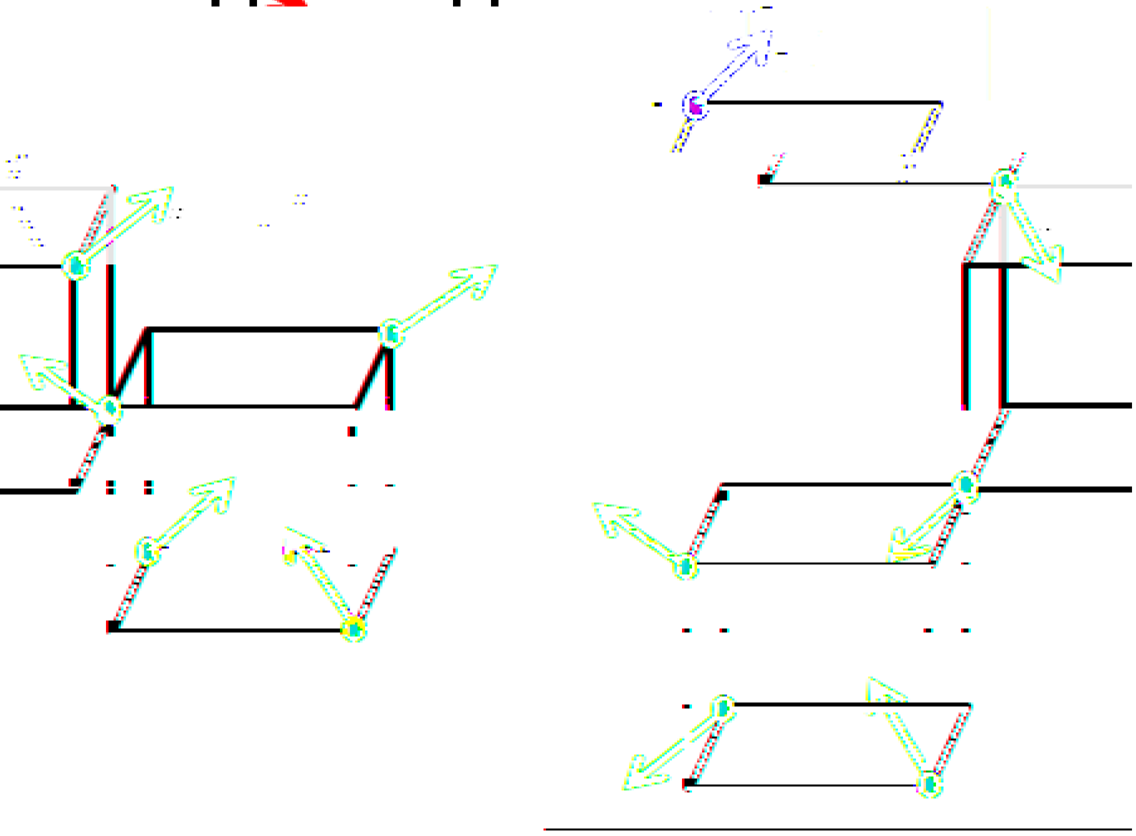
$$\langle n_1 \rangle = 1 + \delta n_1 = 1 - 8\left(\frac{t}{U}\right)^3 \left[\mathbf{S}_1(\mathbf{S}_2 + \mathbf{S}_3) - 2\mathbf{S}_2\mathbf{S}_3\right]$$

For 4-in state: from the condition $\mathbf{S}_1 + \mathbf{S}_2 + \mathbf{S}_3 + \mathbf{S}_4 = 0$ $\delta n_1 = 0$. Change of $\mathbf{S}_1 \rightarrow -\mathbf{S}_1$ (3-in/1-out, *monopole*) gives nonzero charge redistribution and **d** ≠ 0.

Charge redistribution and dipoles are *even* functions of S; inversion of all spins does not change direction of a dipole: ⇨ Direction of dipoles on monopoles and antimonopoles is *the same*: e.g. ***from the center of tetrahedron to a "special" spin***

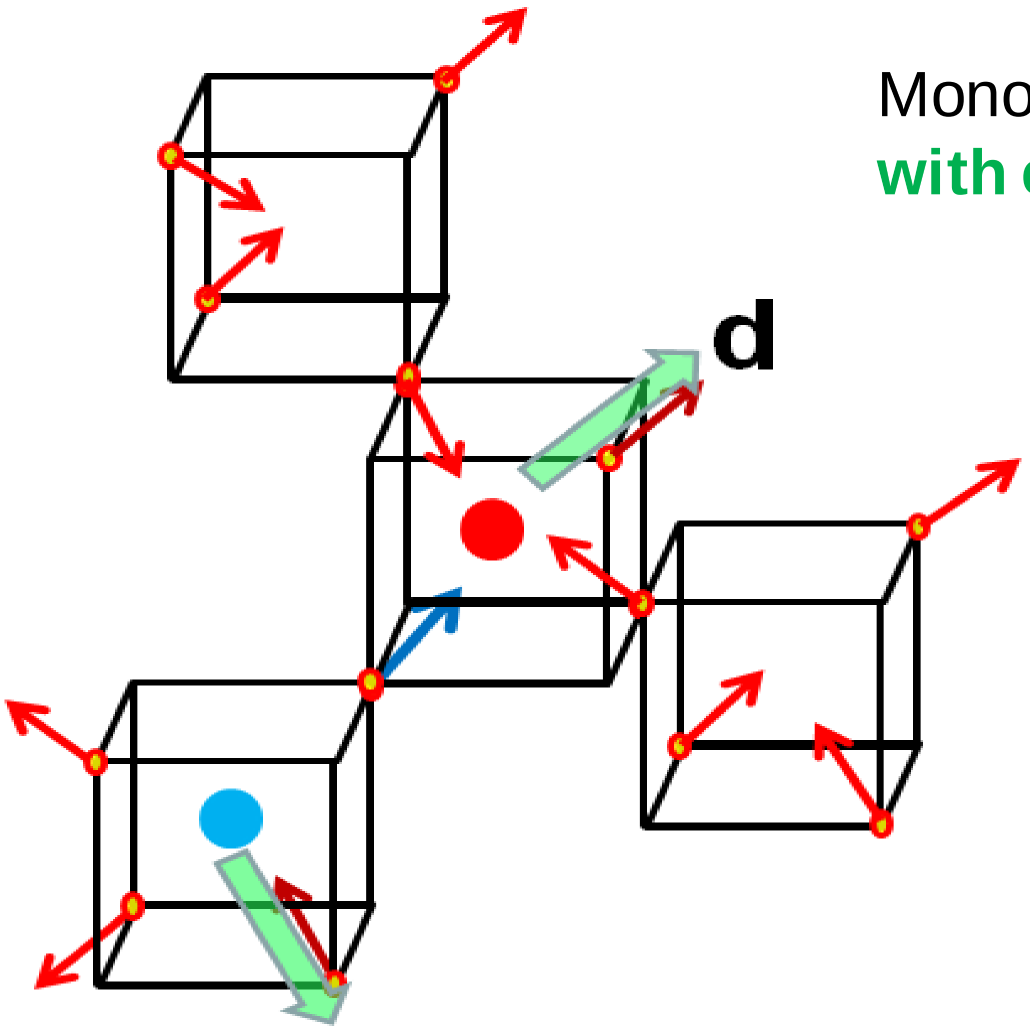
Random ice rule spins (no external magnetic field)

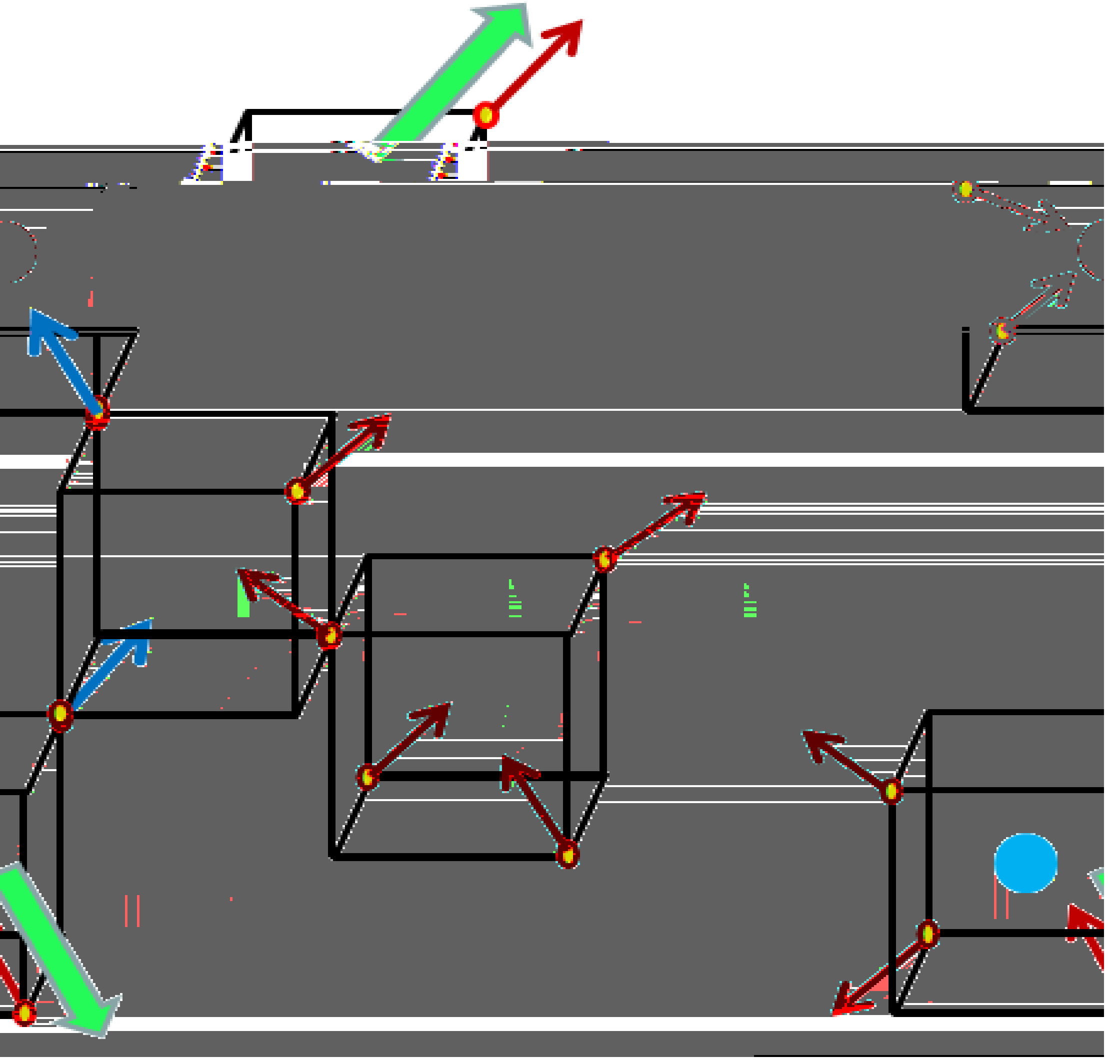


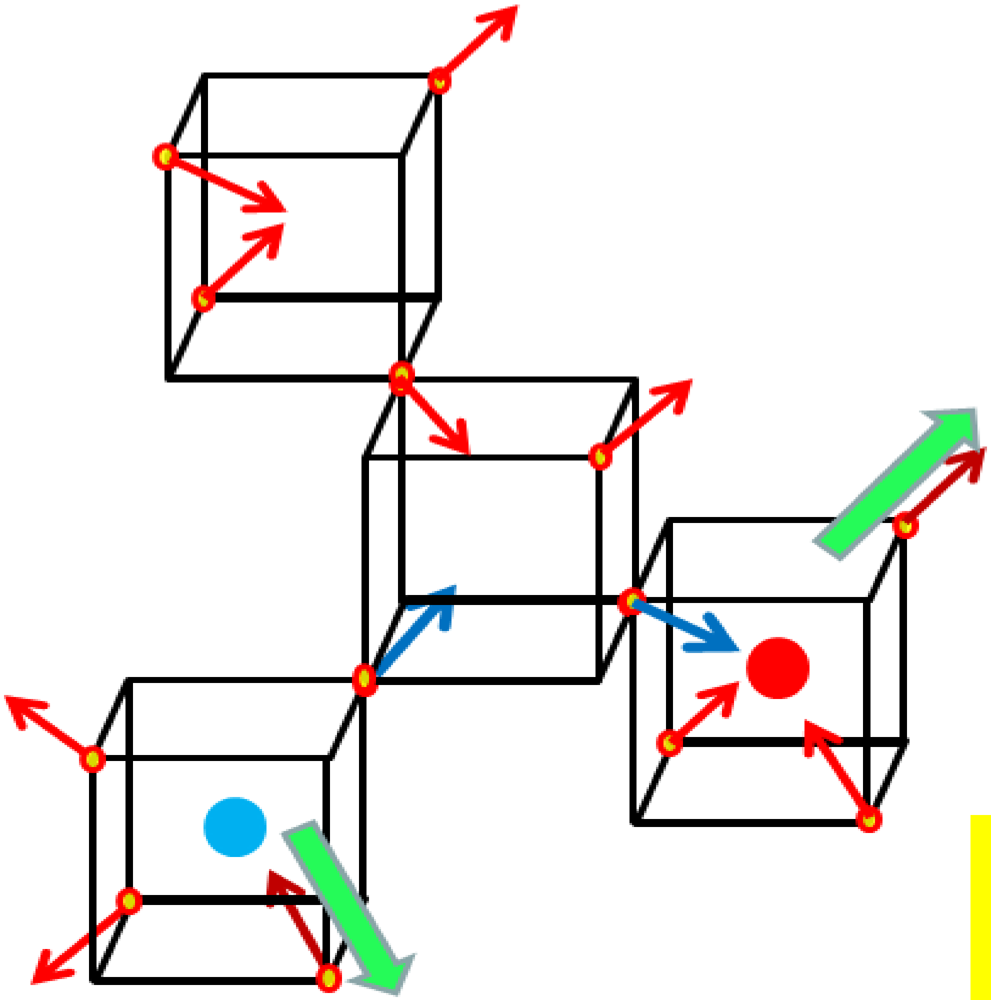


Monopoles/antimonopoles

with electric dipoles

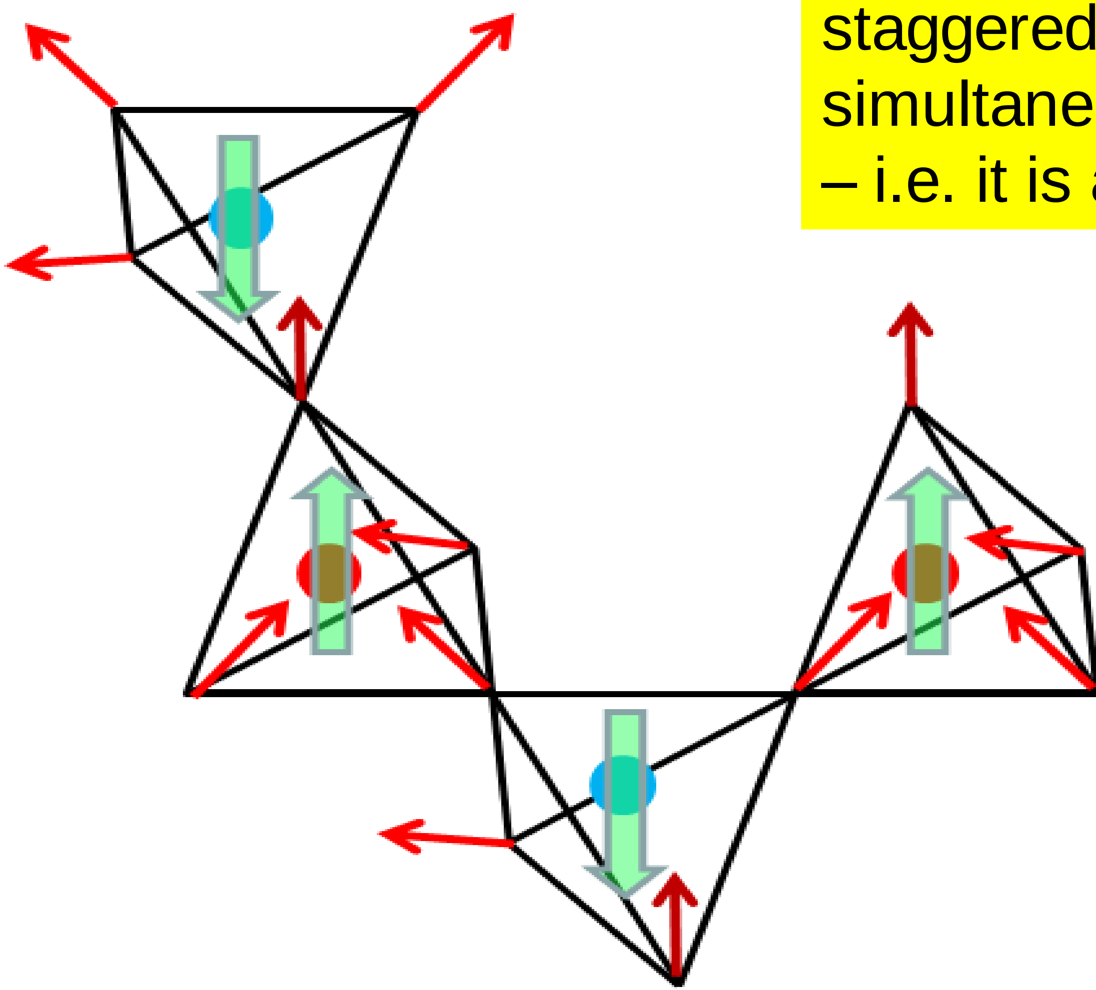






In general directions of electric dipoles are "random" – in any of [111] directions

In strong field **H** || [111] there is a staggered μ/ μ̲, and simultaneously staggered dipoles – i.e. it is an **antiferroelectric**



Dipoles on monopoles, possible consequences:

- **"Electric" activity of monopoles**; contribution to dielectric constant $\varepsilon(\omega)$

- **External electric field:**
Decreases excitation energy of certain monopoles
$\omega = \omega_0 - \mathbf{dE}$

- **Inhomogeneous electric field** (tip): will attract some monopoles/dipoles and repel other

- In the magnetic field H || [001] **E** will promote monopoles, and decrease magnetization **M**, and decrease T_c

- In the field **H** || [111] – staggered Ising-like dipoles; in $\mathbf{E}_\perp$?

● “Electric” activity of monopoles; contribution to dielectric constant ε(ω)

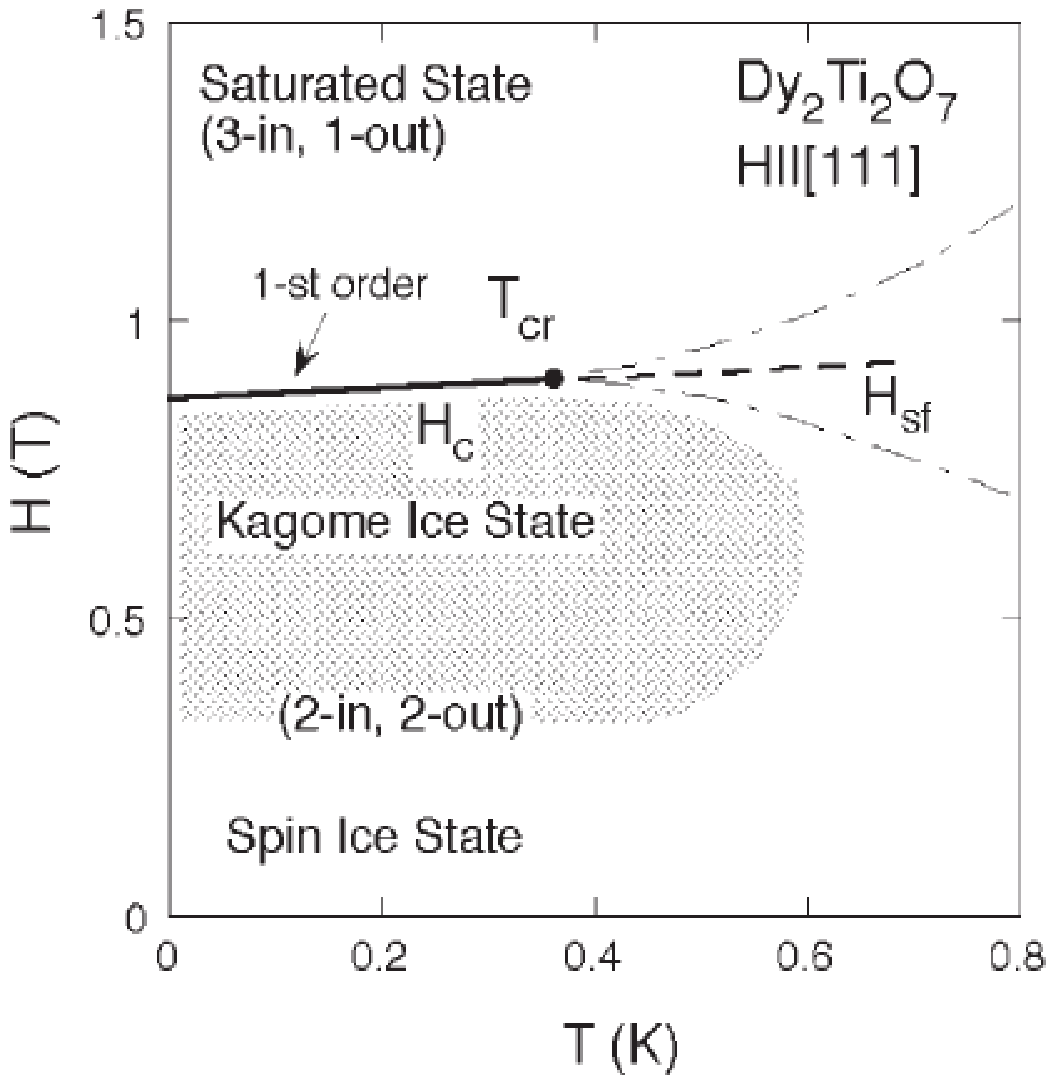


Fig. 1. Phase diagram of $Dy_2Ti_2O_7$ in a [111] magnetic field, determined by magnetization and specific heat measurements. The dashed line

PHYSICAL REVIEW B **72**, 144422 (2005)

Magnetodielectric response of the spin-ice $Dy_2Ti_2O_7$

Masafumi Saito,[1] Ryuji Higashinaka,[1] and Yoshiteru Maeno[1,2,*]

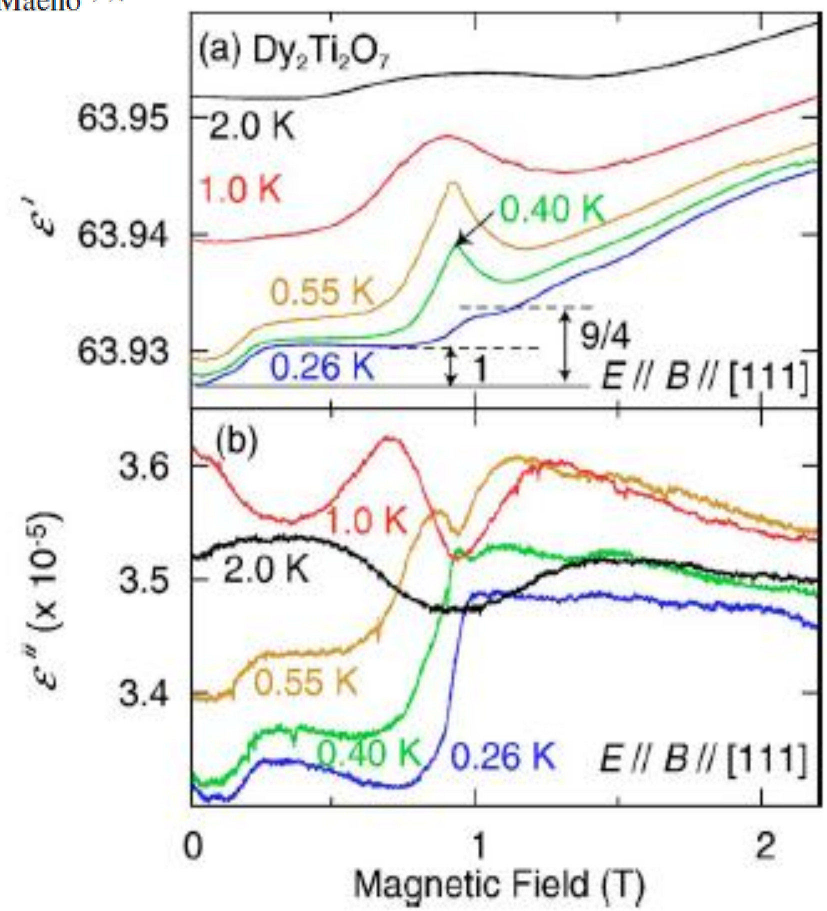
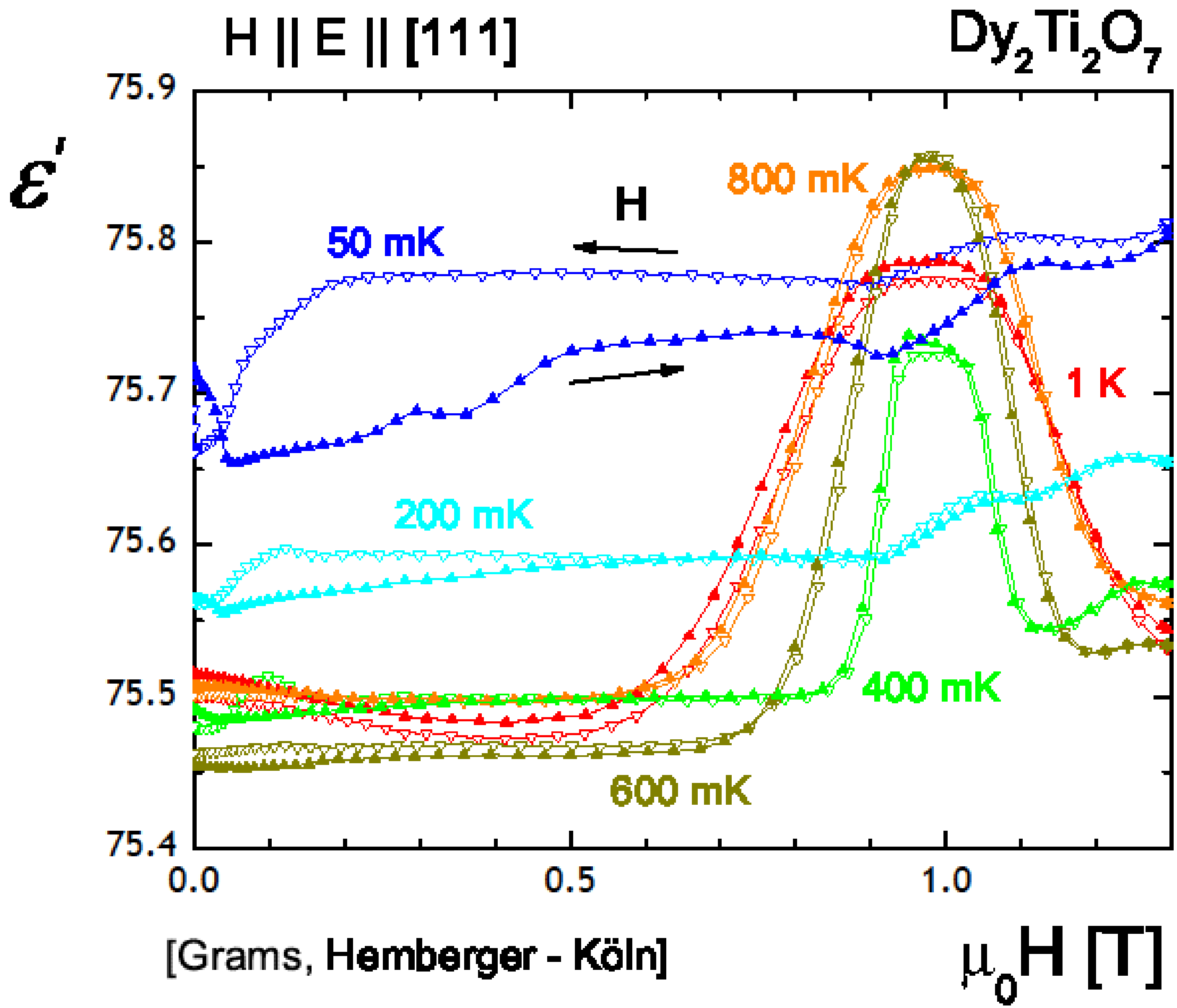


FIG. 6. (Color online) Magnetic field dependence of (a) the real and (b) the imaginary parts of the dielectric constant of $Dy_2Ti_2O_7$



H || E || [111]
Dy2Ti2O7
ε'
75.9
75.8
75.7
75.6
75.5
75.4
0.0
0.5
1.0
800 mK
H
50 mK
1 K
200 mK
400 mK
600 mK
[Grams, Hemberger - Köln]
μ0H [T]

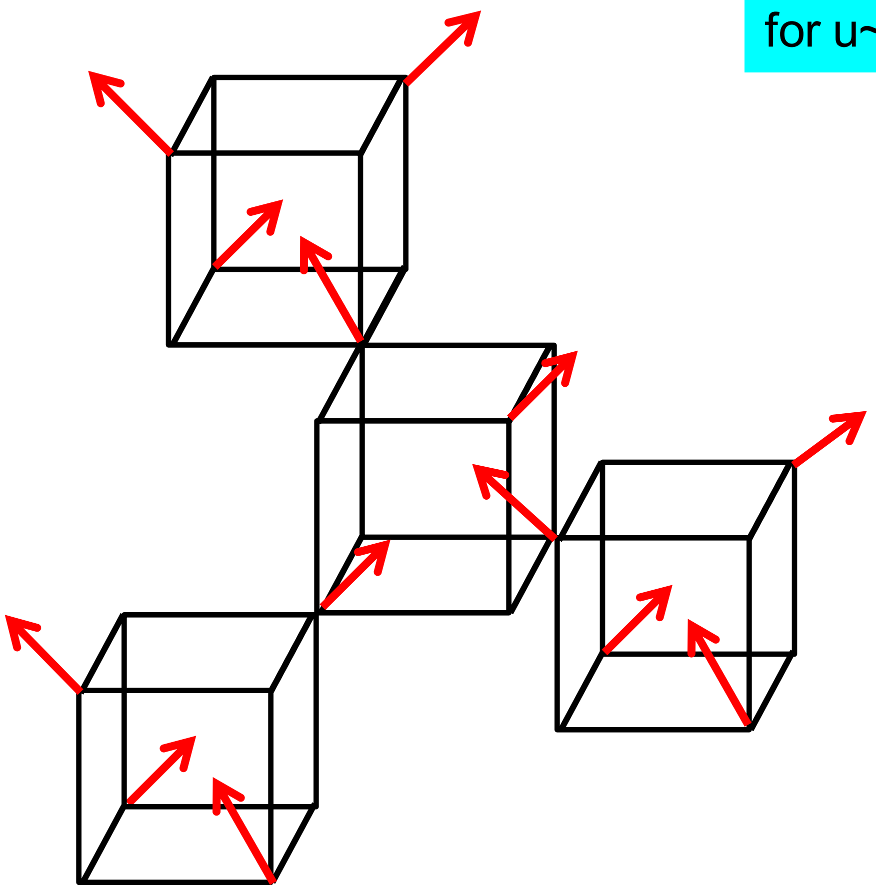
- **External electric field: Decreases excitation energy of certain monopoles**

$\omega = \omega_0 - \mathbf{dE}$

Estimates: ε=dE =eu(Å)E(V/cm)

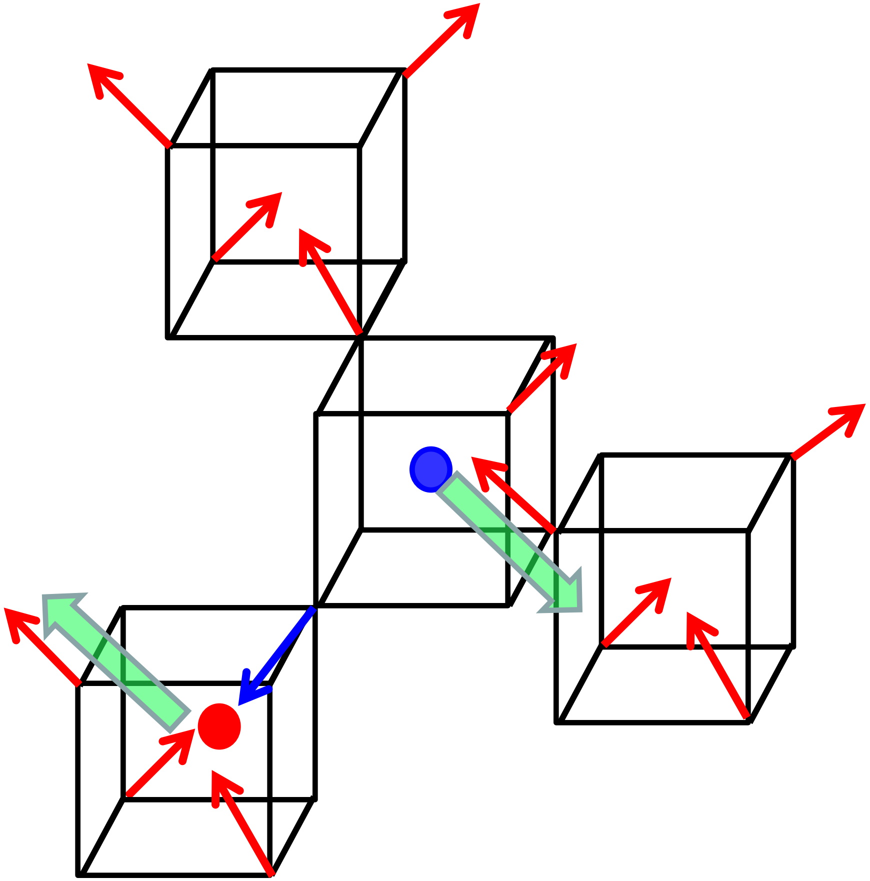
for u~0.01Å and E ~10^5V/cm ε~10^{-5} eV~0.1K

In strong magnetic field **H** || [001]



External electric field: Decreases excitation energy of certain monopoles

$\omega = \omega_0 - \mathbf{dE}$

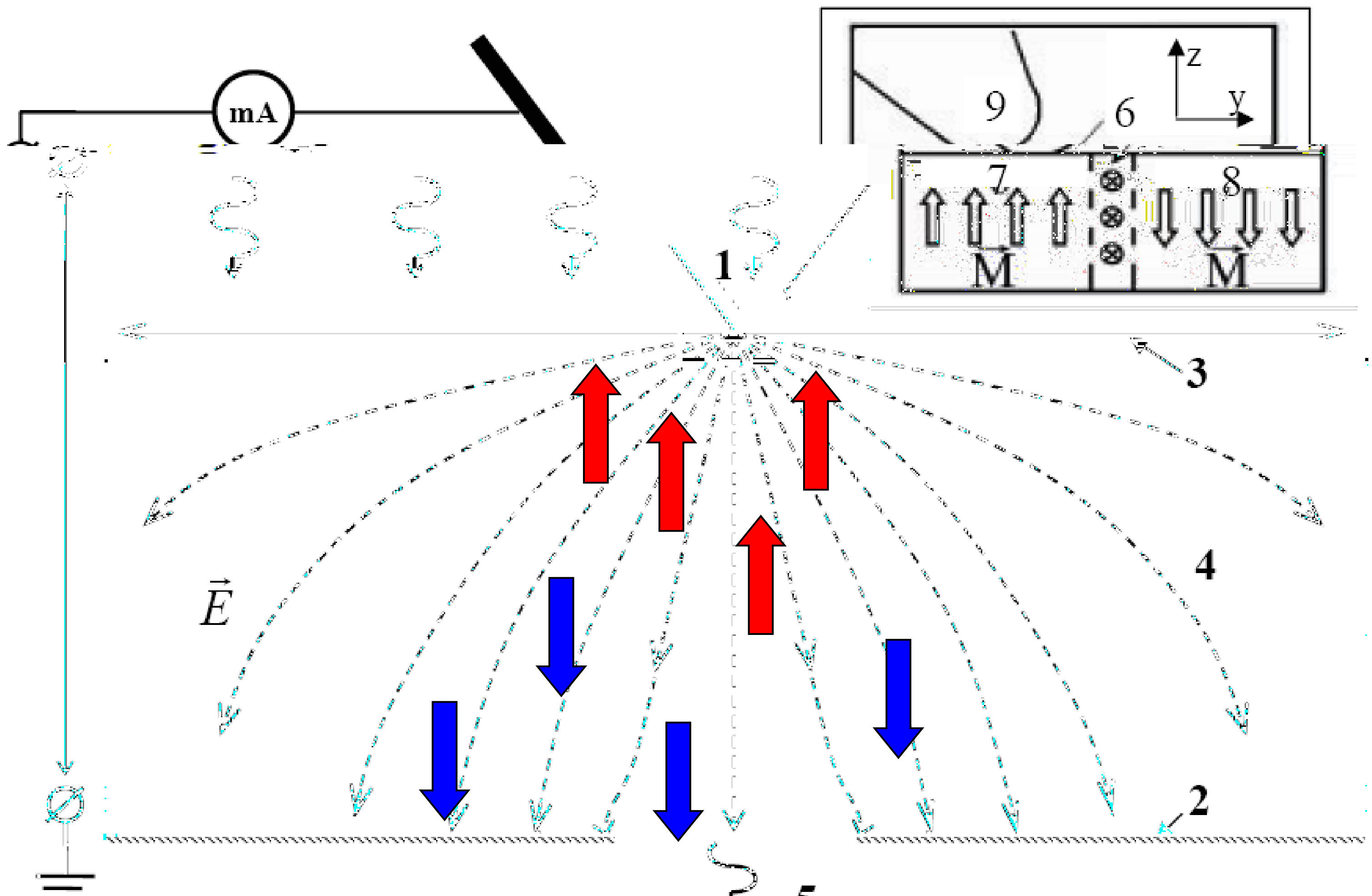


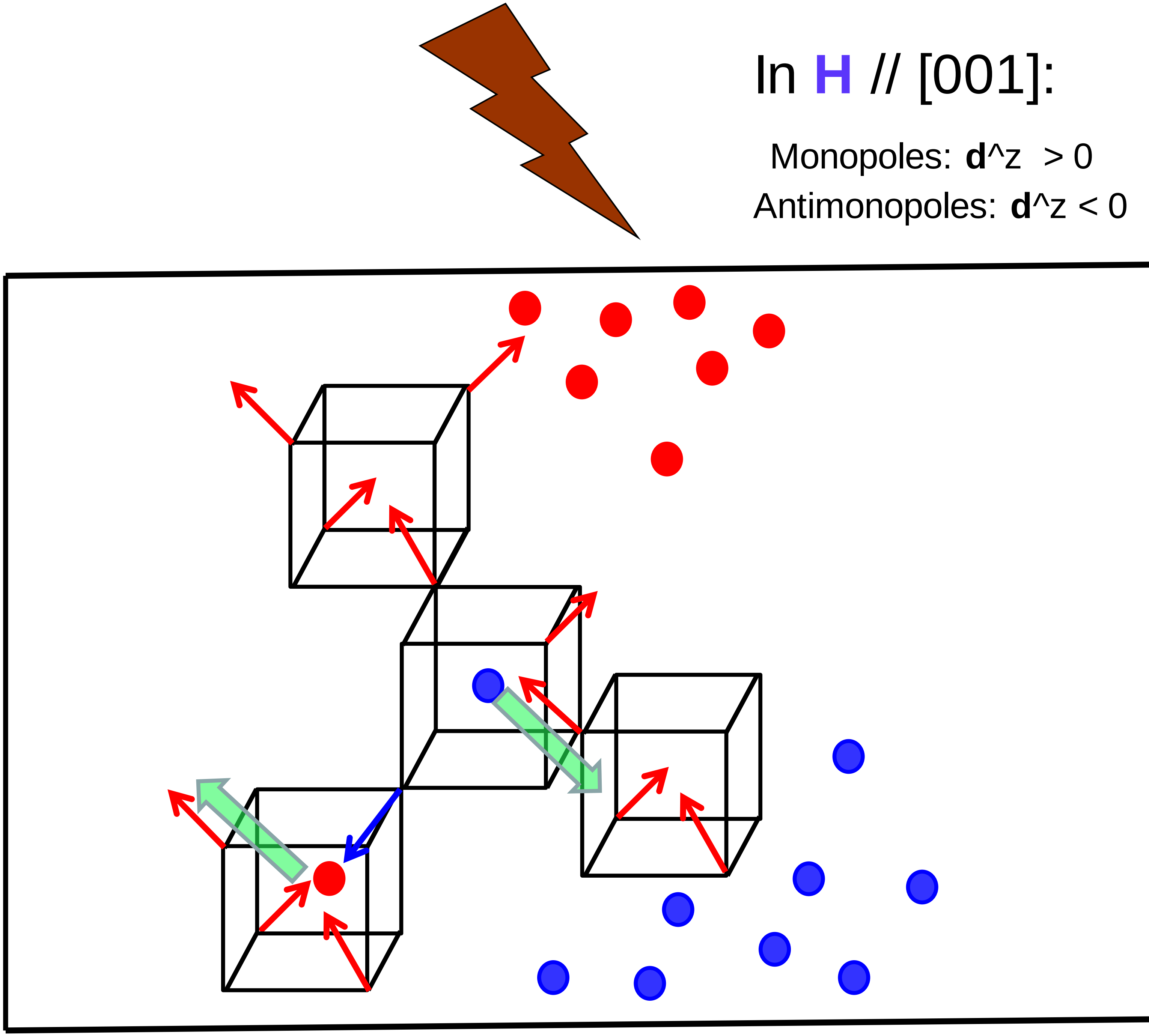
In strong magnetic field **H** || [001]

Monopoles: $\mathbf{d}^z > 0$

Antimonopoles: $\mathbf{d}^z < 0$

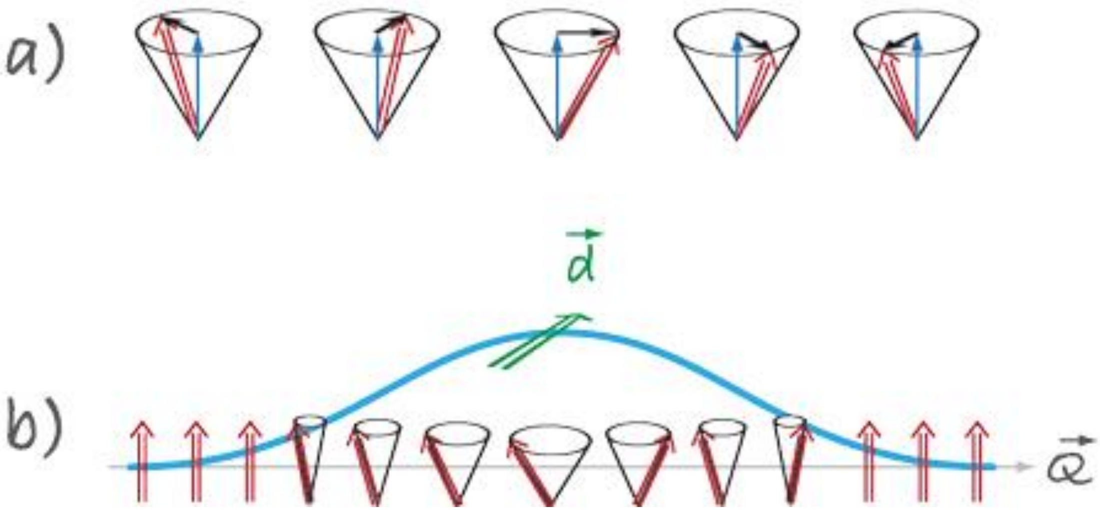
Inhomogeneous electric field





In H // [001]:
Monopoles: d^z > 0
Antimonopoles: d^z < 0

Polarization carried by the usual spin waves



How polarization emerges in a spin wave (magnon). (a) The classical picture of a spin wave in a ferromagnet: the spin (red arrow) precesses about a fixed axis (blue). The deviation is measured by the black arrows. (b) According to Eq. (1), as a spin-wave packet propagates along **Q**, it will also carry an electric dipole moment

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CONCLUSIONS 1

- Contrary to the common belief, there are real charge effects in strong Mott insulators (with frustrated lattices): spin-driven spontaneous electric currents and orbital moments, and charge redistribution in the ground state
- Spontaneous currents are ~ scalar spin chirality $\chi_{123} = \vec{S}_1 [\vec{S}_2 \times \vec{S}_3]$
- Charge redistribution ($\langle n_i \rangle$ is not 1!) may lead to **electric polarization** (purely electronic mechanism of multiferroicity)
- Many consequences:
  - In the ground state: lifting of degeneracy; formation of spin-driven CDW, …….
  - In dynamics: electric field-induced "ESR"; rotation of electric polarization by spins; contribution of spins to low-frequency dielectric function; possibility of negative refraction index; etc

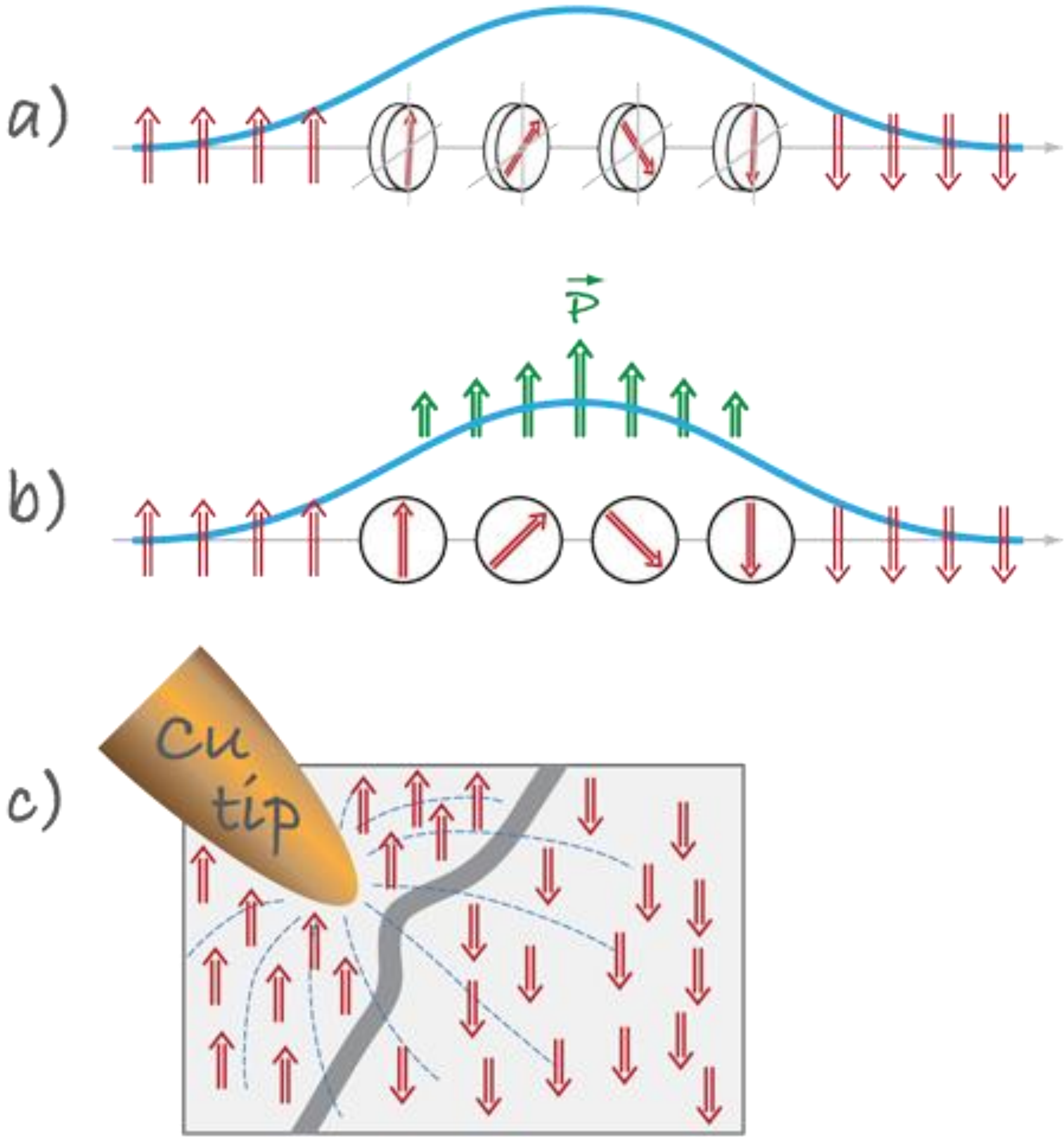
Conclusions 2

★ There should be an electric dipole at each magnetic monopole in spin ice – with different consequences

★ Analogy: electrons have electric charge and spin/magnetic dipole

monopoles in spin ice have magnetic charge and electric dipole

Such effect was already observed for Neel domain walls in ferromagnets (cf. spiral multiferroics):



Logginov, Pyatakov et al. (Moscow State Univ.)

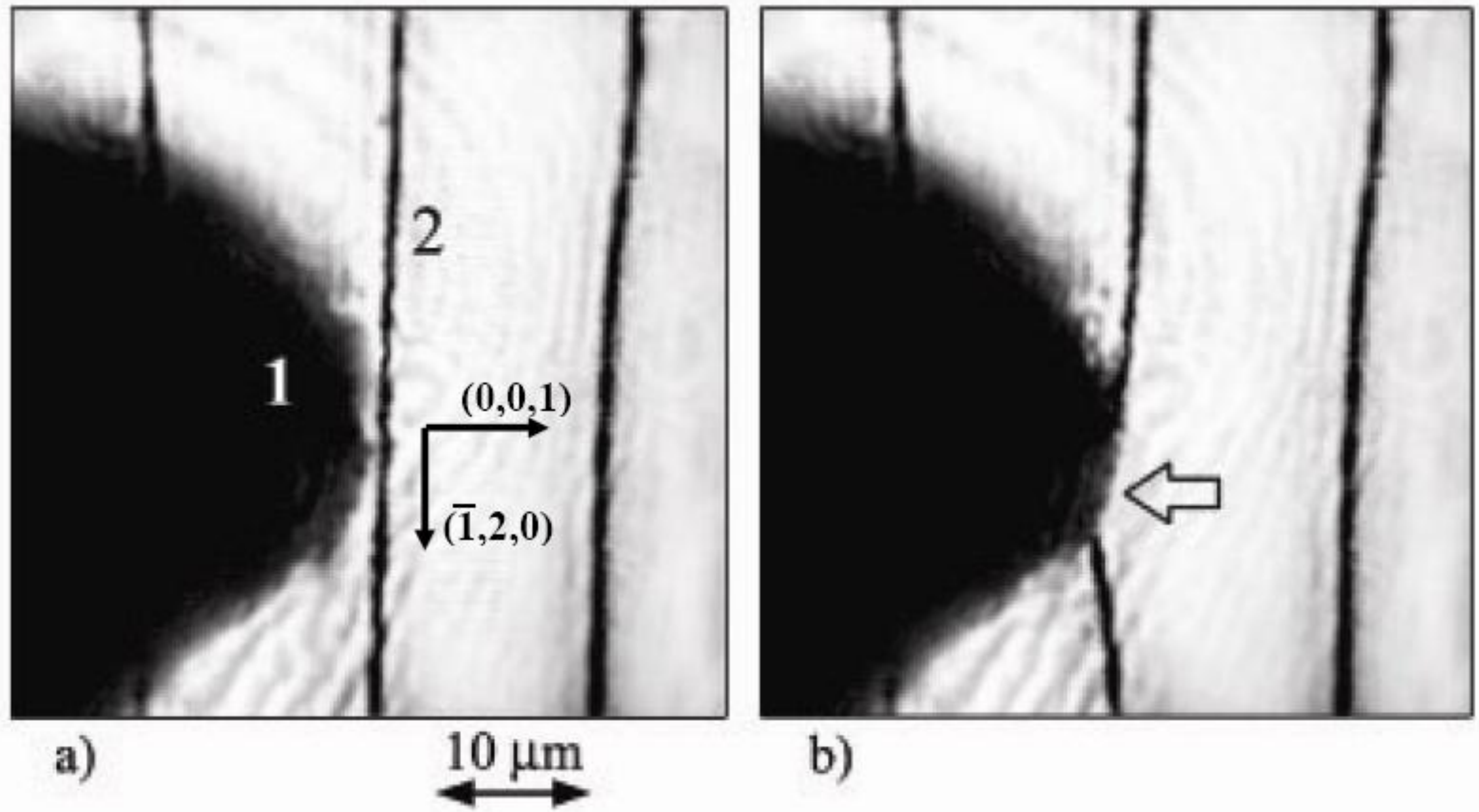


Fig. 2 The effect of electric field in the vicinity of electrode (1) on magnetic domain wall (2) in the films of ferrite garnets: a) initial state b) at the voltage of +1500 V applied