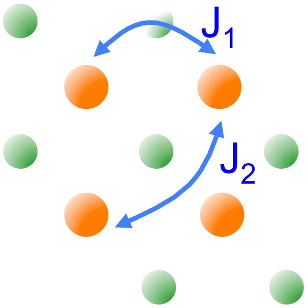
The Physics of Strongly Correlated Matter

Prof. Art Ramirez, Dean of Engineering, UCSC

- ☐ What we do
- ☐ Matter in extreme limits
- ☐ Low Dimensionalty, Solitons, and the Golden Mean
- ☐ Frustration as a Paradigm
- ☐ Topological Insulators

What we do….

Interactions (J_i)
between magnetic
ions in a solid



Specific heat capacity

$$C = -T\frac{\partial^2 F}{\partial T^2}$$

Resistivity	$\rho = \sum nM_{ij}$
Thermopower	$S \propto \pm 1/E_F$

$$H = \sum J_i S_i S_{i+1}$$

Hamiltonian

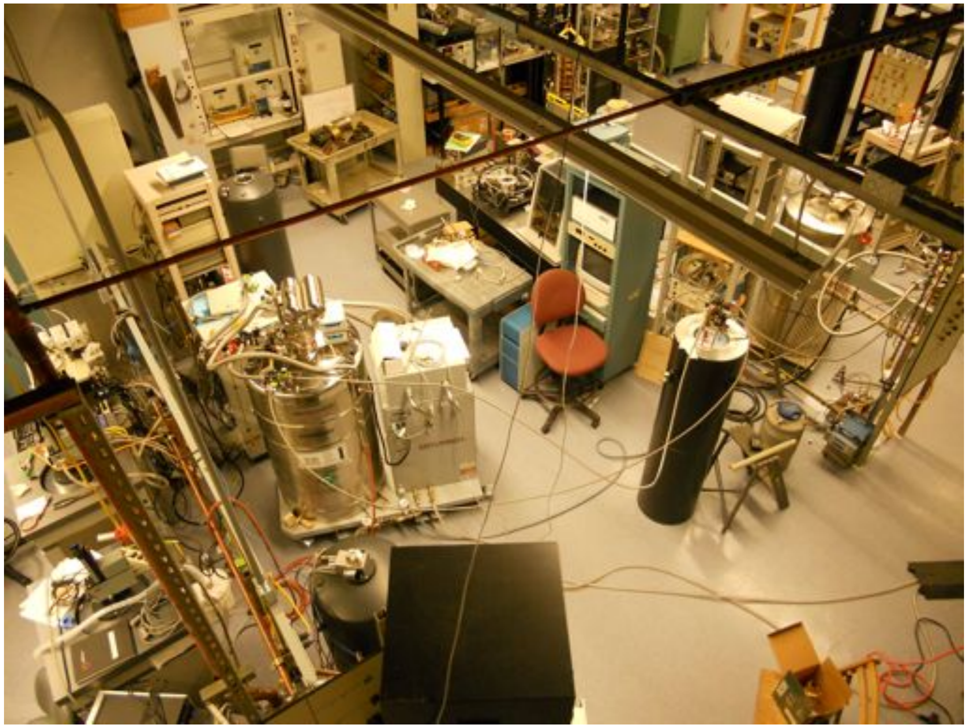
$$F = kT\ln\sum_s e^{-H/kT}$$

Partition function

Theory
(High fields,
low T)

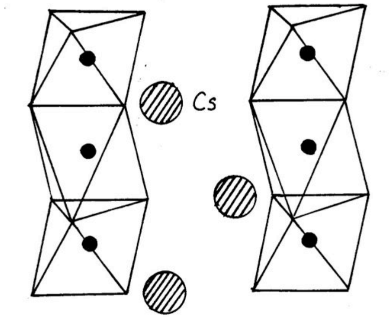
$$\chi = -\frac{\partial^2 F}{\partial H^2}$$

Magnetic susceptibility

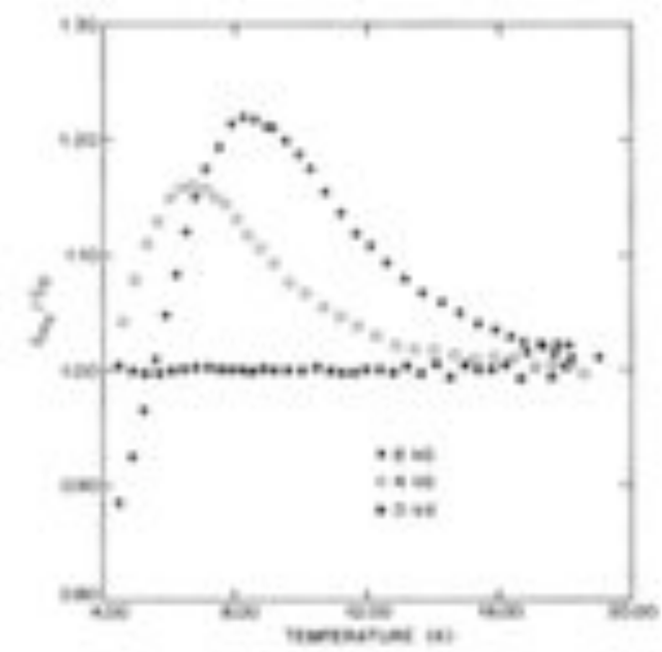


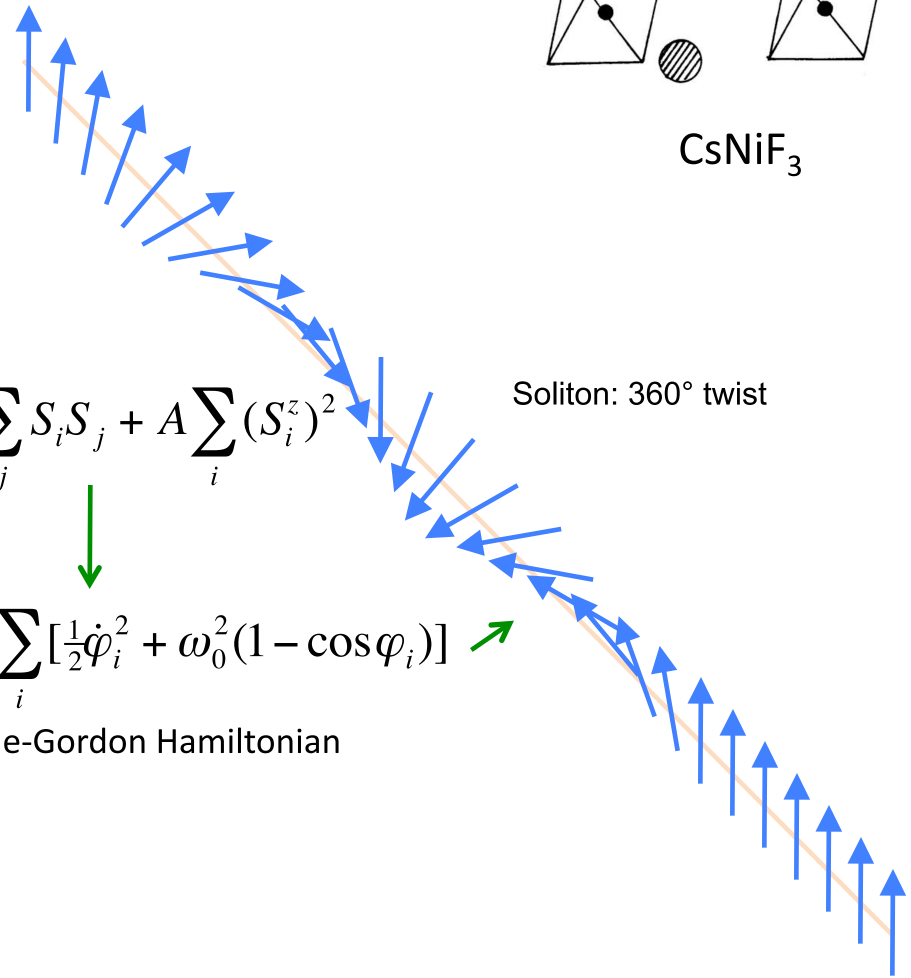
My Lab at 2300 Delaware

A Quasi 1-D System



CsNiF$_3$





Soliton: 360° twist

$$H = J\sum_{ij} S_i S_j + A\sum_i (S_i^z)^2$$

$$\Big\downarrow$$

$$H = a\sum_i [\tfrac{1}{2}\dot{\varphi}_i^2 + \omega_0^2(1-\cos\varphi_i)]$$

Sine-Gordon Hamiltonian

Quantum Criticality in an Ising Chain: Experimental Evidence for Emergent E_8 Symmetry

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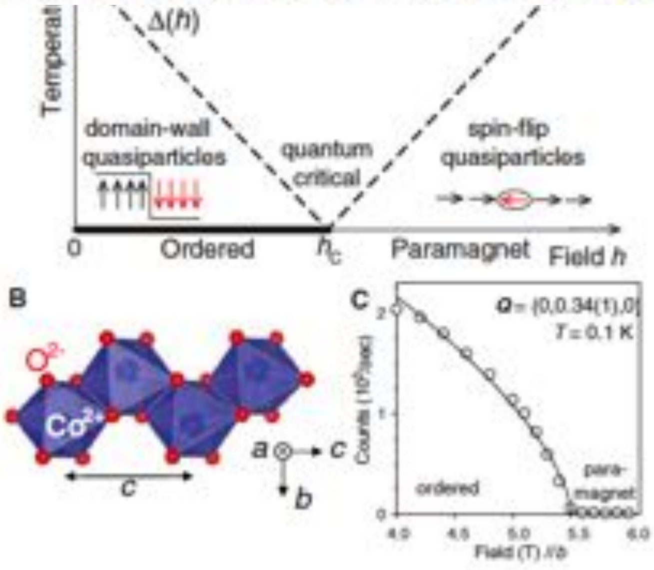
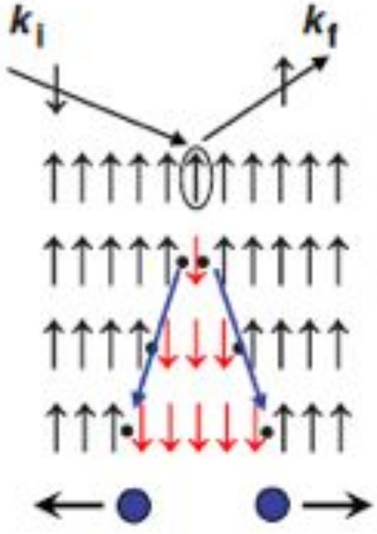
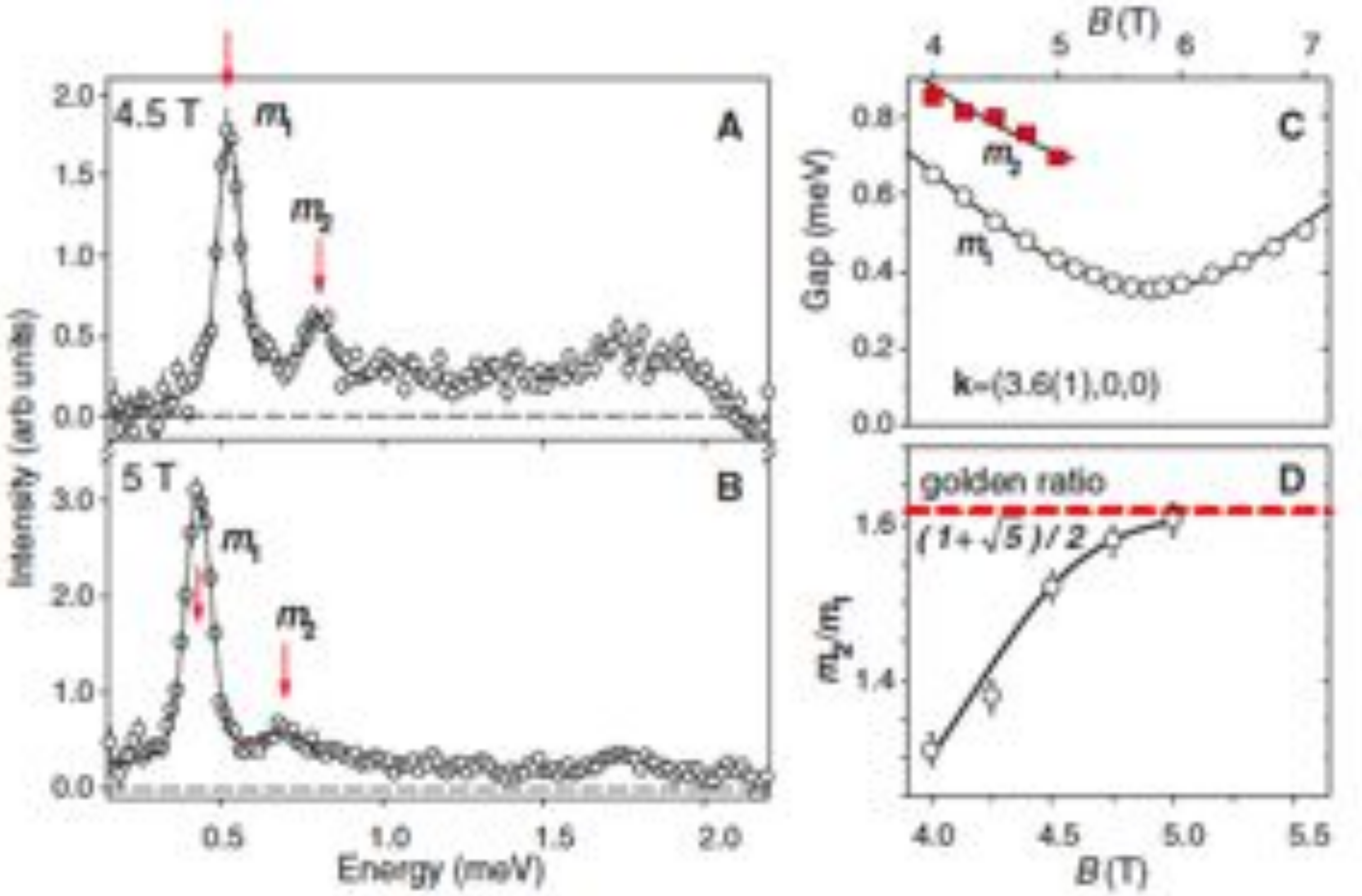
M. Telling,[4] K. Habicht,[2] P. Smeibidl,[2] K. Kiefer[2]

Quantum phase transitions take place between distinct phases of matter at zero temperature. Near the transition point, exotic quantum symmetries can emerge that govern the excitation spectrum of the system. A symmetry described by the E_8 Lie group with a spectrum of eight particles was long predicted to appear near the critical point of an Ising chain. We realize this system experimentally by using strong transverse magnetic fields to tune the quasi–one-dimensional Ising ferromagnet $CoNb_2O_6$ (cobalt niobate) through its critical point. Spin excitations are observed to change character from pairs of kinks in the ordered phase to spin-flips in the paramagnetic phase. Just below the critical field, the spin dynamics shows a fine structure with two sharp modes at low energies, in a ratio that approaches the golden mean predicted for the first two meson particles of the E_8 spectrum. Our results demonstrate the power of symmetry t m behaviors.





Energy spectrum in $CoNb_2O_6$

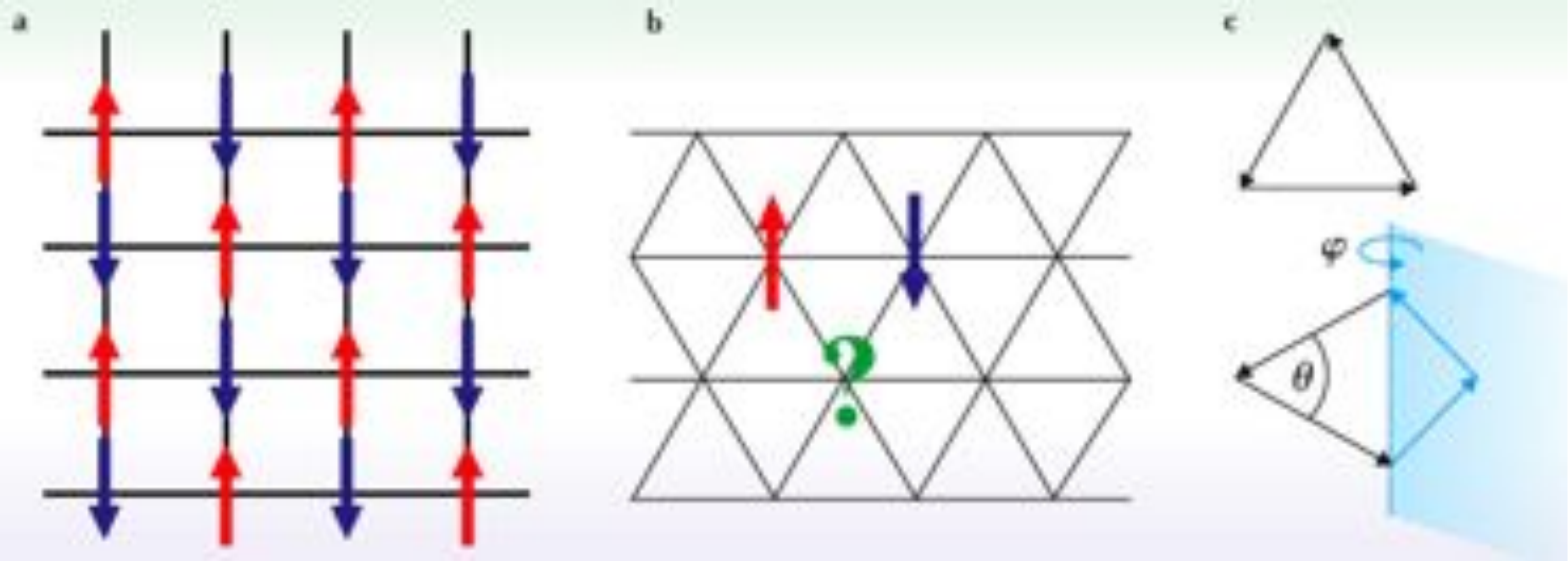


Geometrical Frustration

When interactions between magnetic degrees of freedom in a lattice are incompatible with the underlying crystal symmetry, exotic phenomena such as spin ice and spin liquid phases can emerge.

Roderich Moessner and Arthur P. Ramirez

February 2006 Physics Today



Frustrated Materials

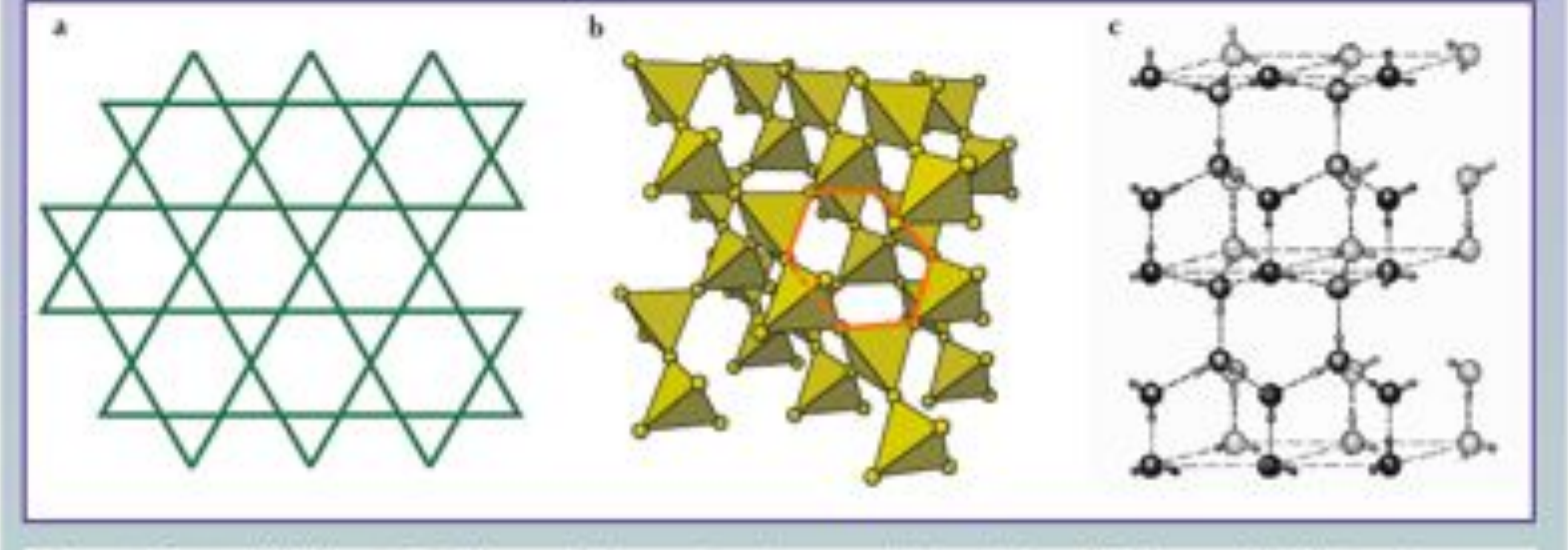


Figure 2. Frustrated lattices. **(a)** The kagome lattice consists of vertex-sharing triangles. **(b)** The pyrochlore lattice is a network of vertex-sharing tetrahedra. The orange hexagonal loop is discussed in figure 4. **(c)** Hexagonal ice consists of protons (small spheres) that reside on the bonds between two oxygen atoms (large spheres). The positions of the oxygens are uniquely determined, but there are exponentially many allowed proton configurations.

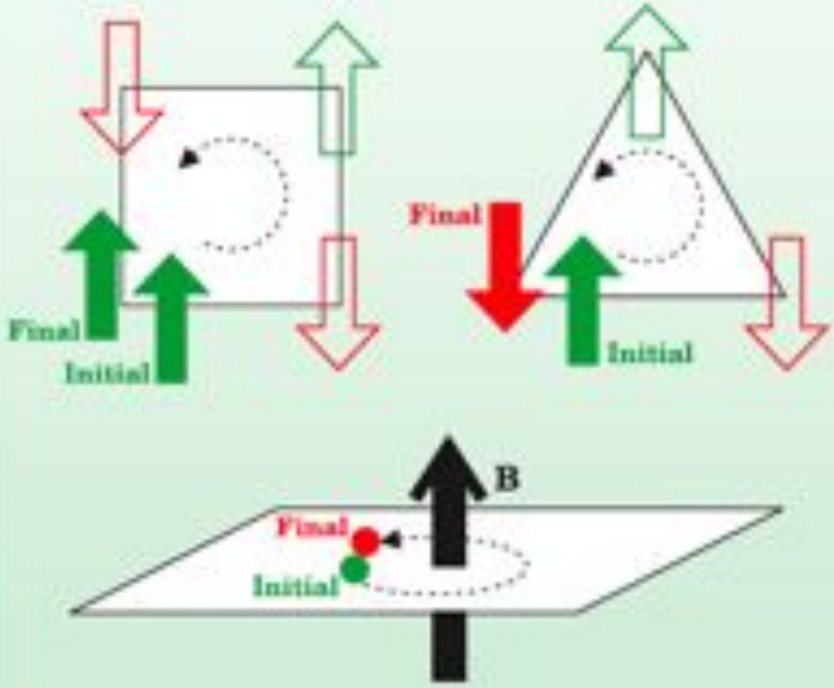
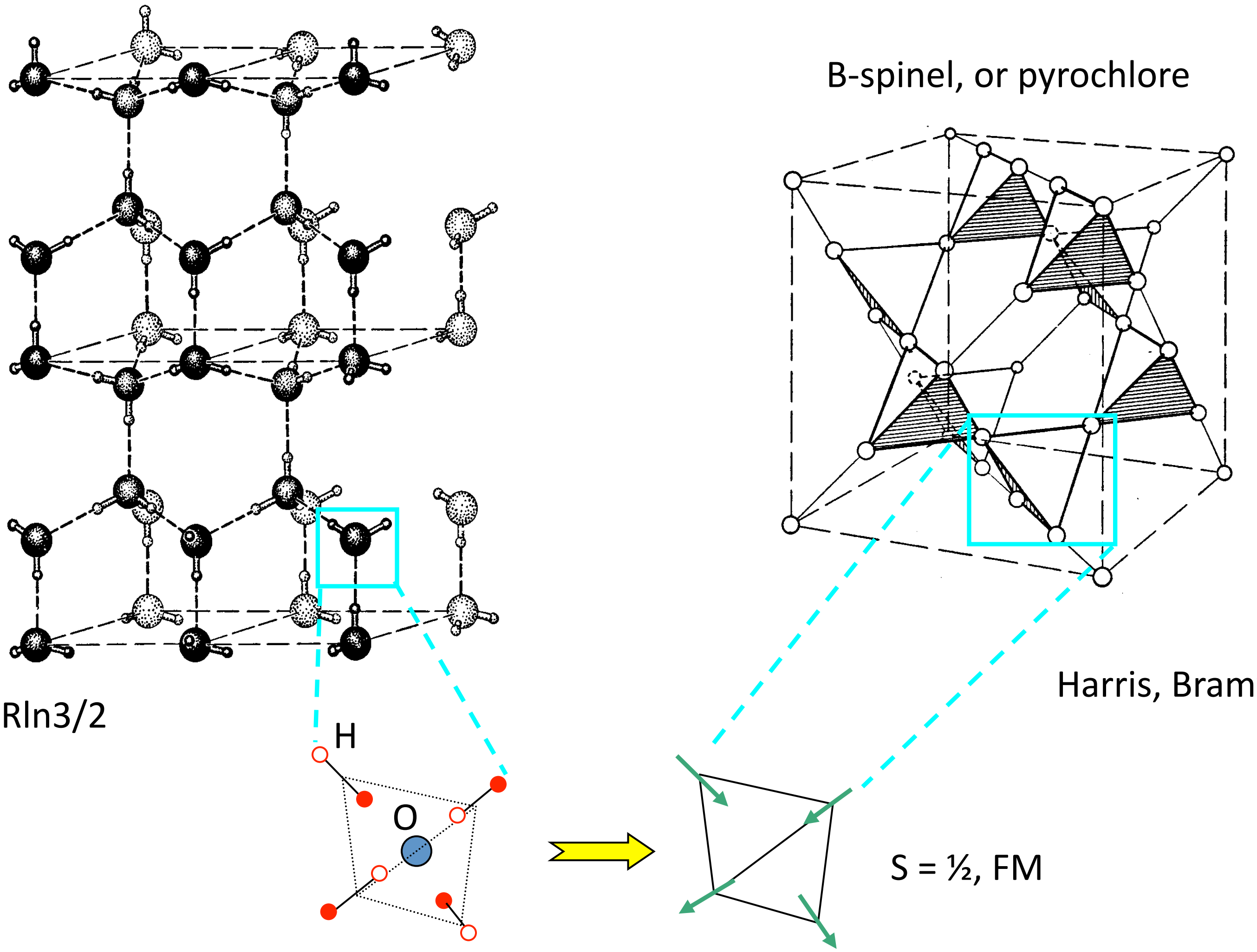


Figure 6. Quantum Hall analogue. Consider a spin, pictured as an arrow in the top panel, taken along some imaginary closed path in the lattice. It flips once for every antiferromagnetic bond encountered along the path. The bottom panel shows an analogous closed loop for an electron immersed in a magnetic field. In both the frustrated triangular lattice and the two-dimensional electron system, traversing the path leads to a final state that differs from the initial one: In the frustrated lattice the spin gets flipped, and in the 2D electron gas the phase of the electron wavefunction changes.

G-F for Ising Degrees of Freedom – Ice & Spin Ice

B-spinel, or pyrochlore

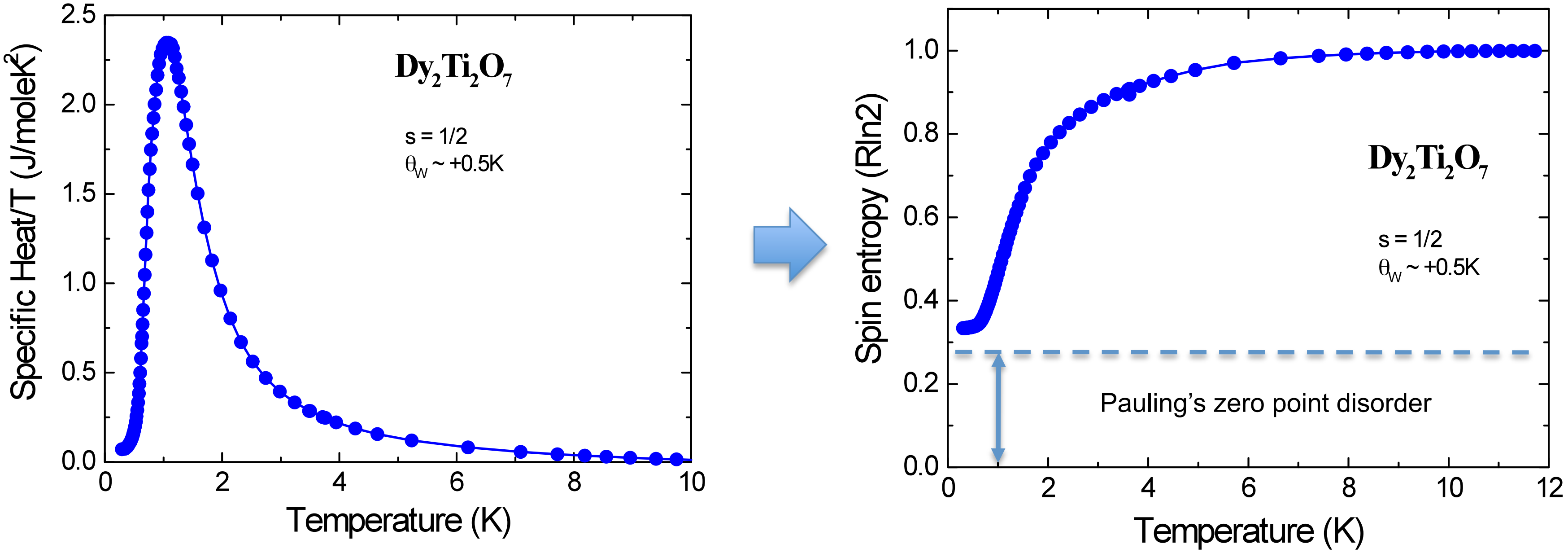


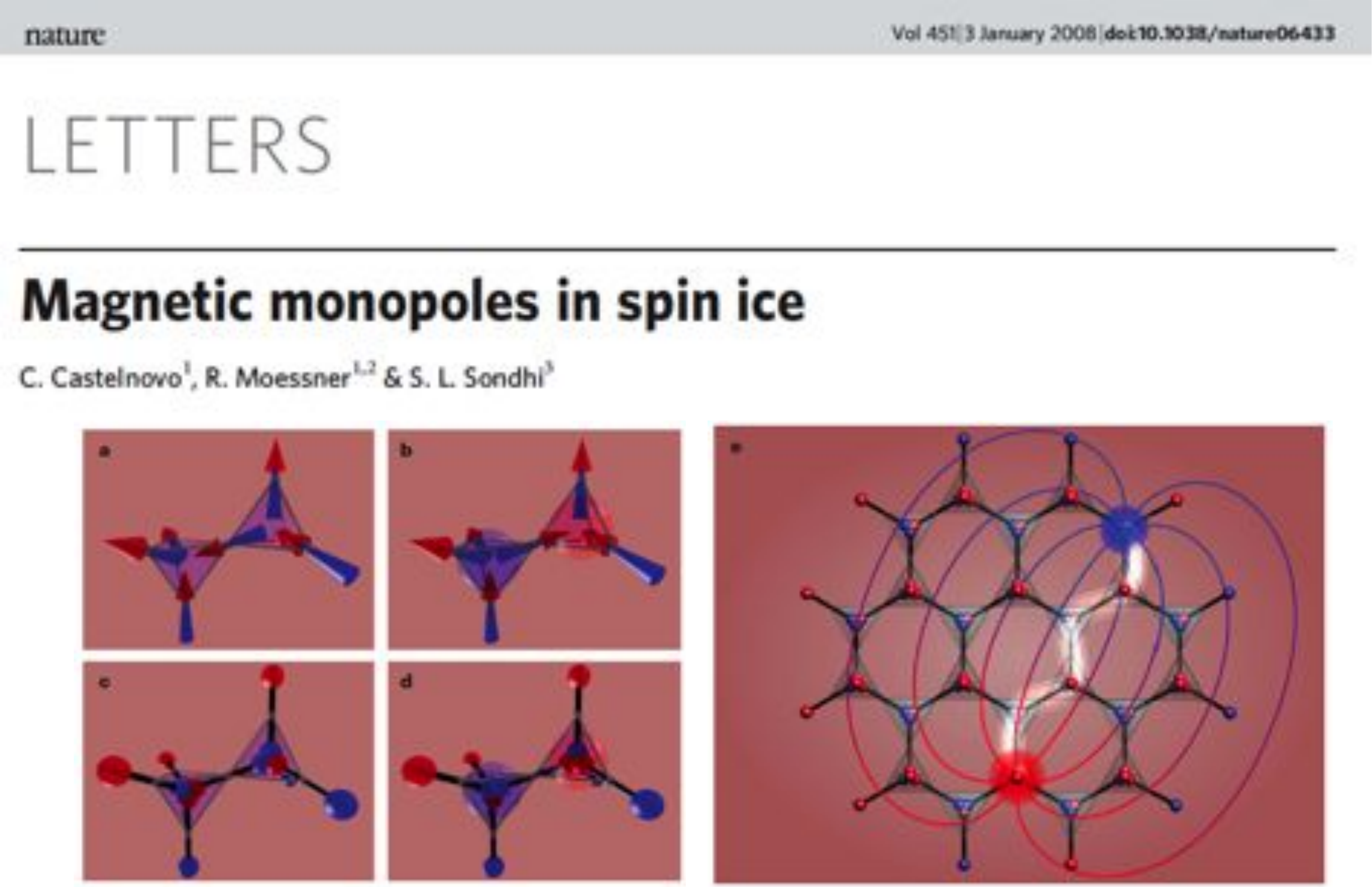
Pauling: $S_0 = R\ln 3/2$

Harris, Bramwell, et al

S = ½, FM

Observation of Zero Point disorder in *Spin Ice* - $Dy_2Ti_2O_7$





nature

Vol 451| 3 January 2008| doi:10.1038/nature06433

LETTERS

Magnetic monopoles in spin ice

C. Castelnovo[1], R. Moessner[1,2] & S. L. Sondhi[3]

PHYSICAL REVIEW B **84**, 094437 (2011)

Higgs transitions of spin ice

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The Rise of Topological Insulators

History:

1) Quantum Hall Effect and edge states (~1980)
2) Chern number topology (~1983)
3) QHE intrinsically (Haldanium) (~1987)
4) Projecting into 3D (~1990)
5) Spitting the bands with spin orbit (~2004)

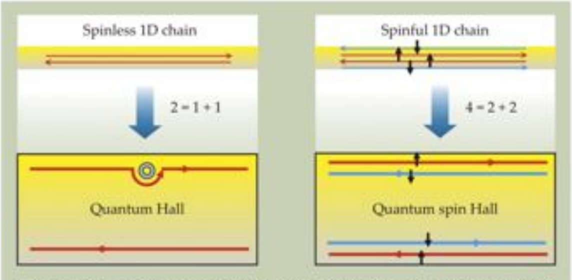
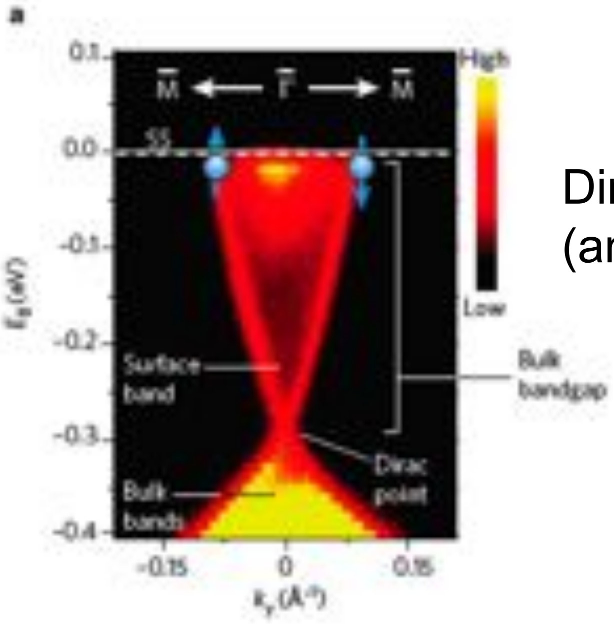
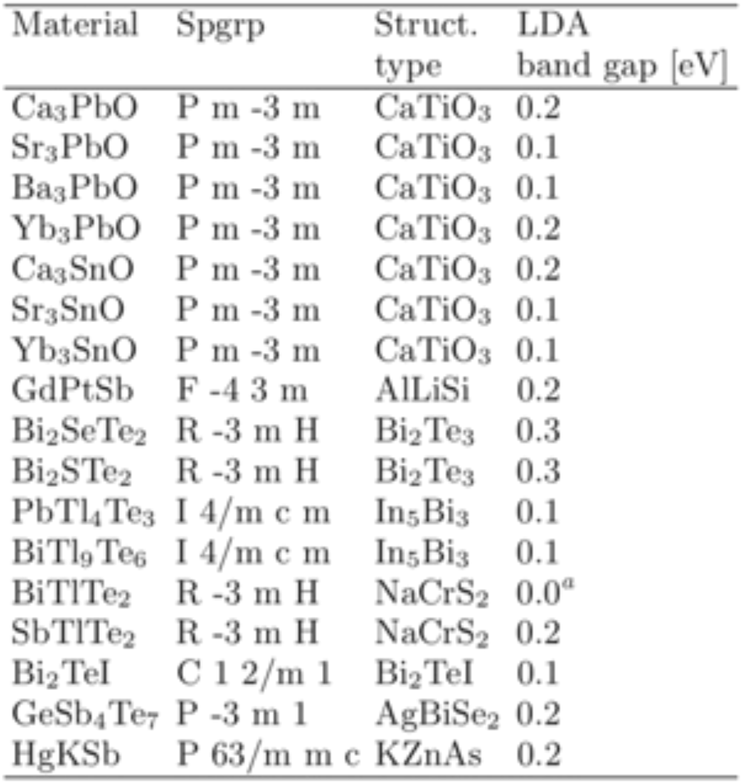


Figure 1. Spatial separation is at the heart of both the quantum Hall (QH) and the quantum spin Hall (QSH) effects. **(a)** A spinless one-dimensional system has both a forward and a backward mover. Those two basic degrees of freedom are spatially separated in a QH bar, as illustrated by the symbolic equation "2 = 1 + 1." The upper edge contains only a forward mover and the lower edge has only a backward mover. The states are robust: They will go around an impurity without scattering. **(b)** A spinful 1D system has four basic channels, which are spatially separated in a QSH bar: The upper edge contains a forward mover with up spin and a backward mover with down spin, and conversely for the lower edge. That separation is illustrated by the symbolic equation "4 = 2 + 2."



Dirac spectrum in Bi_2Se_3
(analogies to graphene)



Material	Spgrp	Struct. type	LDA band gap [eV]
Ca_3PbO	P m -3 m	$CaTiO_3$	0.2
Sr_3PbO	P m -3 m	$CaTiO_3$	0.1
Ba_3PbO	P m -3 m	$CaTiO_3$	0.1
Yb_3PbO	P m -3 m	$CaTiO_3$	0.2
Ca_3SnO	P m -3 m	$CaTiO_3$	0.2
Sr_3SnO	P m -3 m	$CaTiO_3$	0.1
Yb_3SnO	P m -3 m	$CaTiO_3$	0.1
GdPtSb	F -4 3 m	AlLiSi	0.2
Bi_2SeTe_2	R -3 m H	Bi_2Te_3	0.3
Bi_2STe_2	R -3 m H	Bi_2Te_3	0.3
$PbTl_4Te_3$	I 4/m c m	In_5Bi_3	0.1
$BiTl_9Te_6$	I 4/m c m	In_5Bi_3	0.1
$BiTlTe_2$	R -3 m H	$NaCrS_2$	0.0^a
$SbTlTe_2$	R -3 m H	$NaCrS_2$	0.2
Bi_2TeI	C 1 2/m 1	Bi_2TeI	0.1
$GeSb_4Te_7$	P -3 m 1	$AgBiSe_2$	0.2
HgKSb	P 63/m m c	KZnAs	0.2

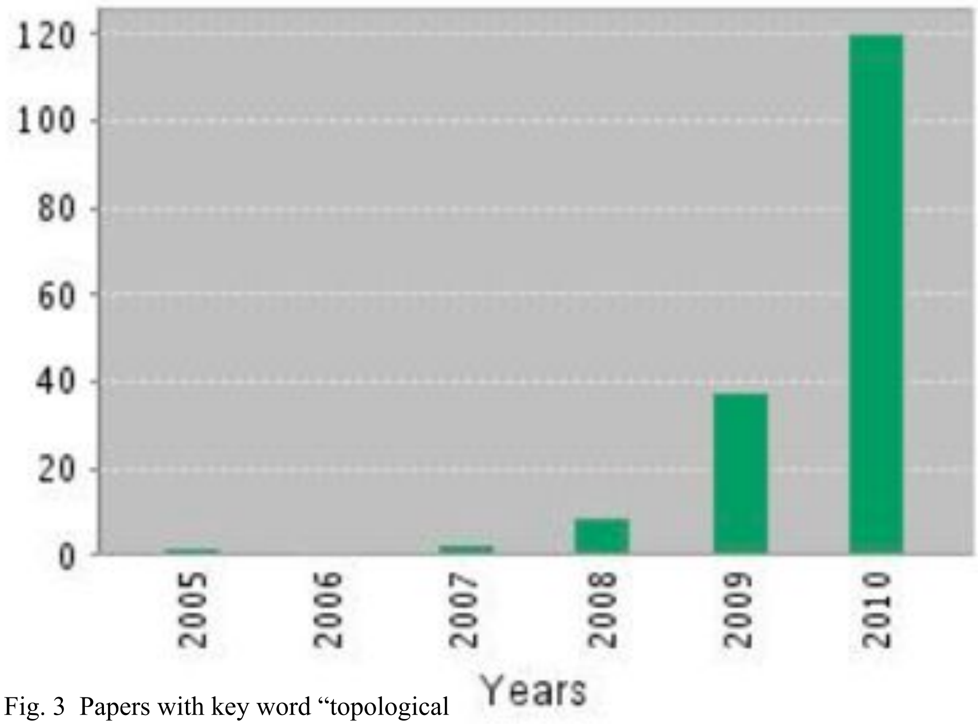


Fig. 3 Papers with key word "topological insulator". ISI, Nov 2010

Other aspects of Topological Insulators

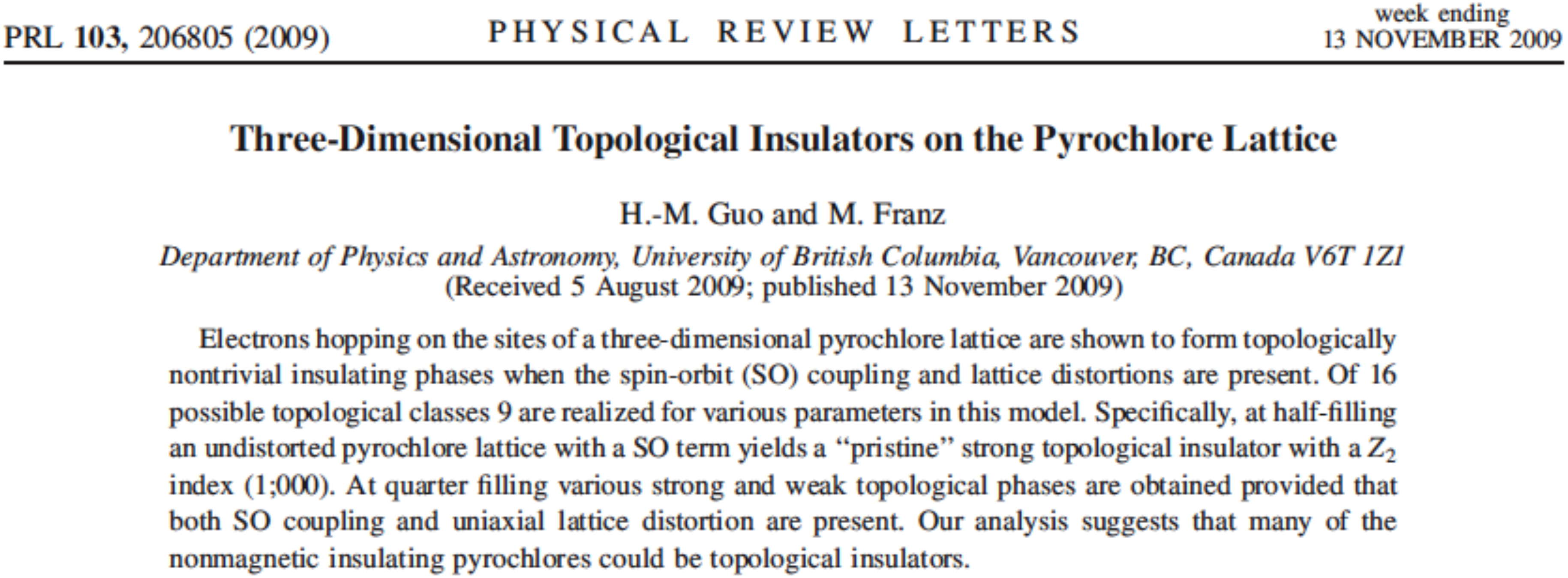
☐ Predictions of EB axion term in interior of Tis

☐ Monopoles

☐ Majorana Fermions

☐ Spintronics

Connection between Geometrical Frustration and Topological Insulators !



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Three-Dimensional Topological Insulators on the Pyrochlore Lattice

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(Received 5 August 2009; published 13 November 2009)

Electrons hopping on the sites of a three-dimensional pyrochlore lattice are shown to form topologically nontrivial insulating phases when the spin-orbit (SO) coupling and lattice distortions are present. Of 16 possible topological classes 9 are realized for various parameters in this model. Specifically, at half-filling an undistorted pyrochlore lattice with a SO term yields a "pristine" strong topological insulator with a Z_2 index (1;000). At quarter filling various strong and weak topological phases are obtained provided that both SO coupling and uniaxial lattice distortion are present. Our analysis suggests that many of the nonmagnetic insulating pyrochlores could be topological insulators.

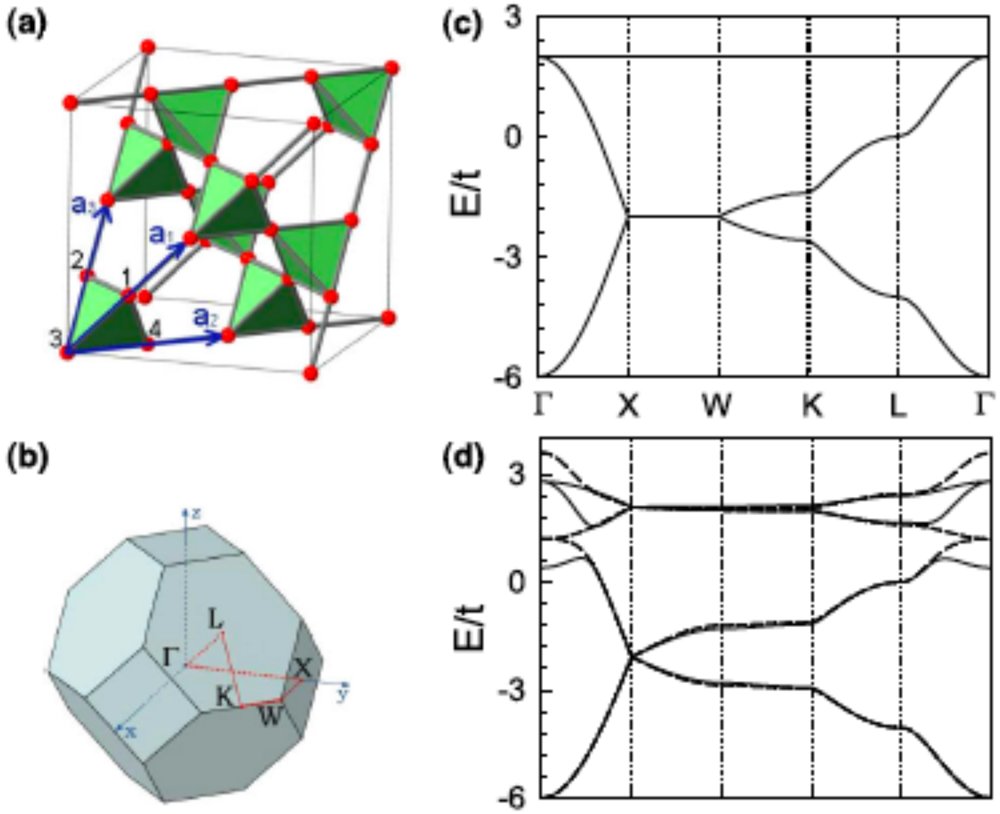
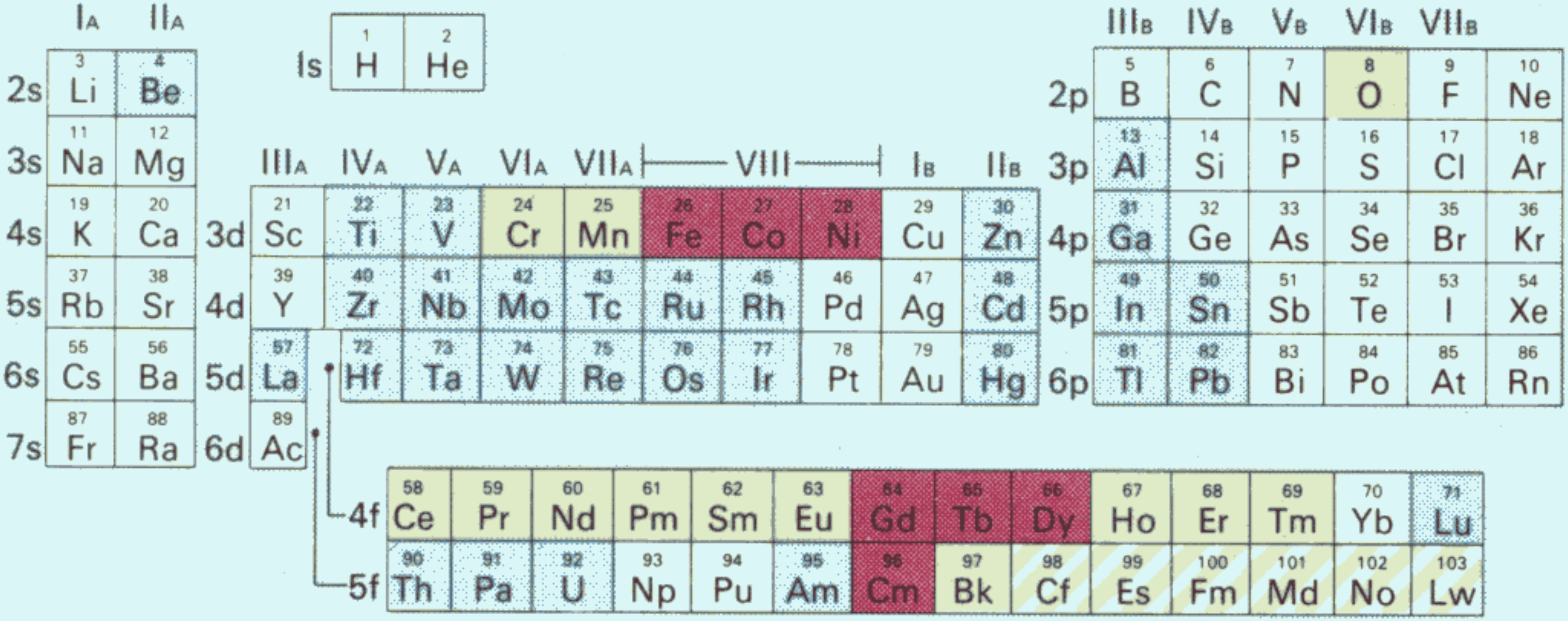


FIG. 1 (color online). (a) Pyrochlore lattice is a face-centered cubic Bravais lattice with a 4-point basis forming a shaded tetrahedron. (b) The first Brillouin zone of the fcc lattice with high-symmetry lines and points indicated. (c) Band structure of the tight-binding model Eq. (1). (d) Band structure with spin-orbit coupling Eq. (3) for $\lambda = -0.1t$ (solid line) and $\lambda = 0.1t$ (dashed line).



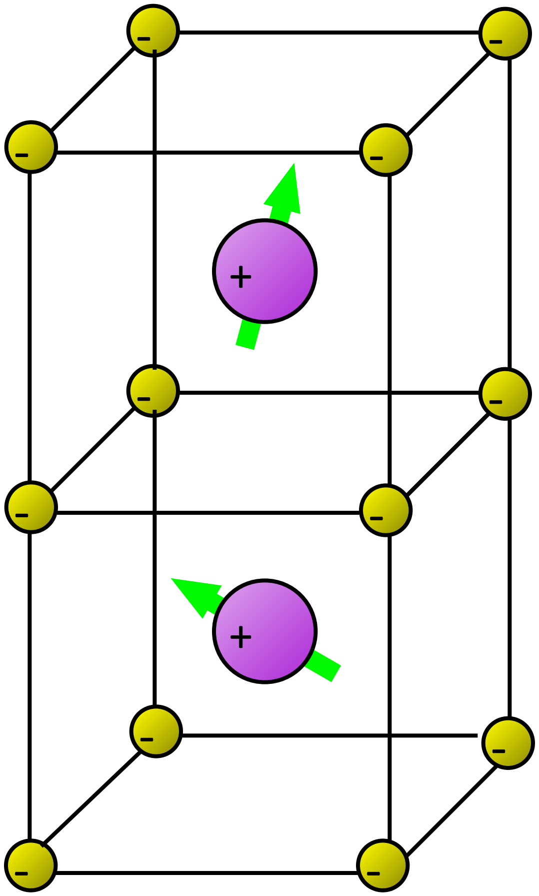
Ground state at 1 bar, $T \to 0K$

☐ Superconducting

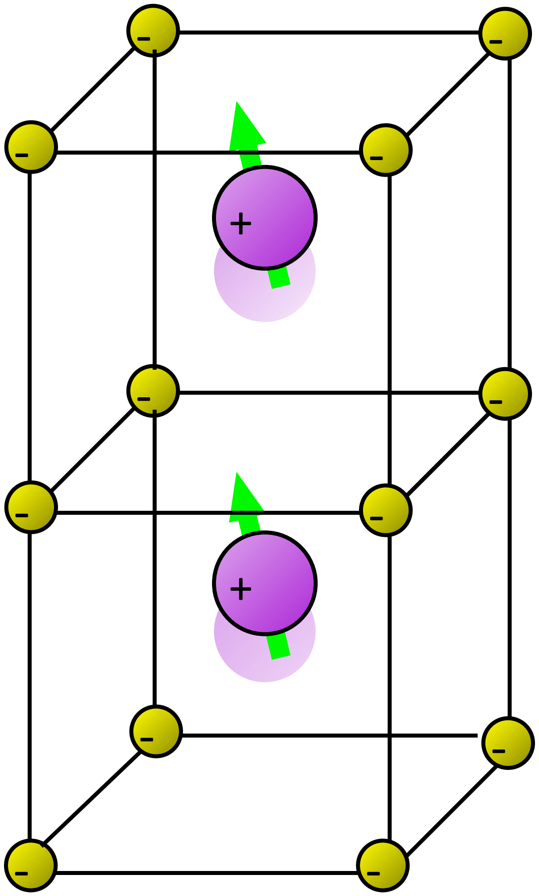
🟥 Ferromagnetic

🟨 Antiferromagnetic or complex order

Uniform charge, disordered spins



Shifted charge, ordered spins

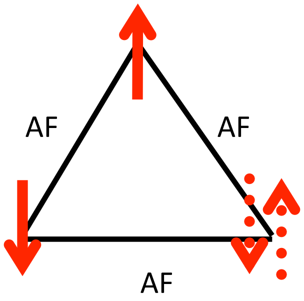


Geometrical Frustration – Materials Considerations

Frustration →

Disorder ↓

Antiferromagnetism Ferromagnetism Metamagnetism Ferrimagnetism	Geometrical Frustration
percolation, random fields	Spin glass



Symmetry incompatibility

$$H=\Sigma S_i \bullet S_j$$