Spin ice pyrochlores and Dirac monopoles

- Ice-I_h and cubic ice
- Spin ice
- Dirac monopoles

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Spin ice pyrochlores and Dirac monopoles

Ice: The Bernal-Fowler (1933) ice rules:

THE JOURNAL OF CHEMICAL PHYSICS

VOLUME 1 AUGUST, 1933 NUMBER 8

A Theory of Water and Ionic Solution, with Particular Reference to Hydrogen and Hydroxyl Ions

J. D. BERNAL AND R. H. FOWLER, *University of Cambridge, England*

(Received April 29, 1933)

X-ray do not "see" the hydrogen atoms !

- Oxygen atoms in ice-I_h form a wurtzite (tetrahedral) lattice, with an O-O distance of 2.76 Å

- The 0.95 Å OH bond of H_2O is retained in ice-I_h

- Each oxygen must then have two H at 0.95 Å and two at 1.81 Å, but *which two ?*

Spin ice pyrochlores and Dirac monopoles

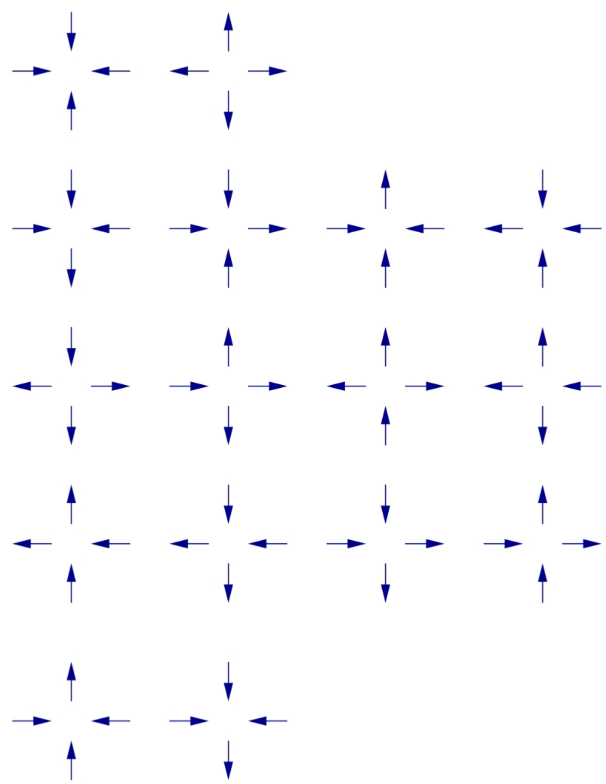
Pauling (1935): Ice-I_h has *residual entropy*

[Contribution from the Gates Chemical Laboratory, California Institute of Technology, No. 506]

The Structure and Entropy of Ice and of Other Crystals with Some Randomness of Atomic Arrangement

By Linus Pauling

16, 4-vertex models:



Spin ice pyrochlores and Dirac monopoles

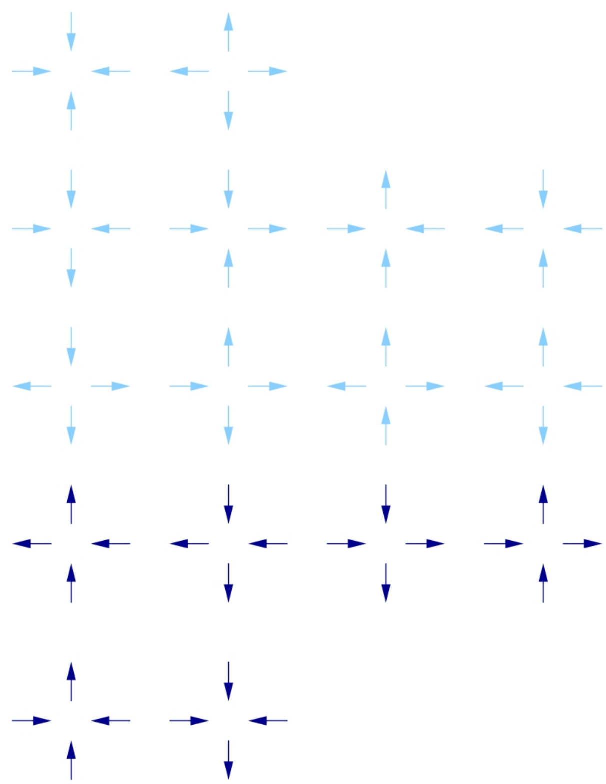
Pauling (1935): Ice-I_h has *residual entropy*

[CONTRIBUTION FROM THE GATES CHEMICAL LABORATORY, CALIFORNIA INSTITUTE OF TECHNOLOGY, No. 506]

The Structure and Entropy of Ice and of Other Crystals with Some Randomness of Atomic Arrangement

BY LINUS PAULING

6 ways of arranging H around O so that ice rules are obeyed. Each bond has a 1/2 probability that the proton is is in an acceptable position.



$S = k_B \ln W$ and
$W = (6)(1/2)(1/2) = 3/2$

calculated: 0.806 cal/K/mol

Spin ice pyrochlores and Dirac monopoles

Giauque and Stout (1936): Ice-I_h has measurable *residual entropy*

[CONTRIBUTION FROM THE CHEMICAL LABORATORY OF THE UNIVERSITY OF CALIFORNIA]

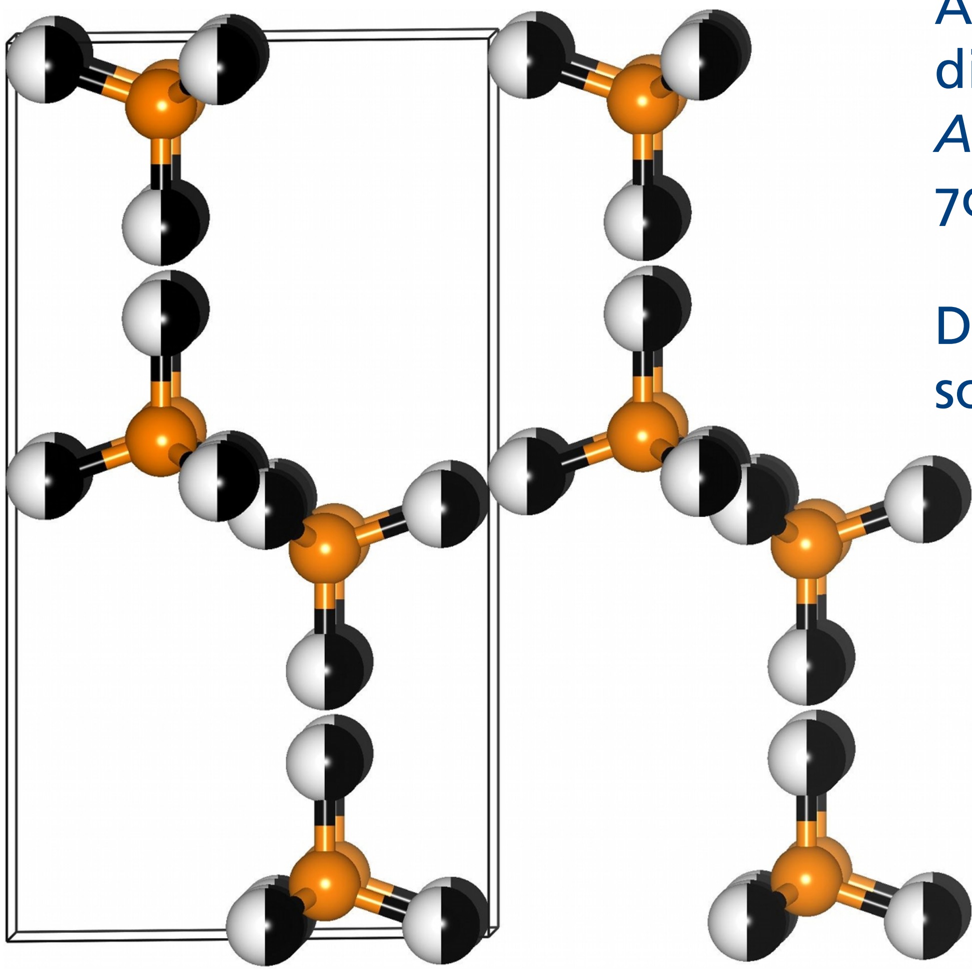
The Entropy of Water and the Third Law of Thermodynamics. The Heat Capacity of Ice from 15 to 273°K.

BY W. F. GIAUQUE AND J. W. STOUT

we find that the $\int_0^T C_p \, d \ln T = 44.28 \pm 0.05$ cal./deg./mole for H_2O (g.) at one atmosphere and 298.1°K. The spectroscopic value is 45.10 leading to a discrepancy of 0.82 cal./deg./mole. This is in excellent agreement with the theoretical discrepancy 0.806 calculated by Pauling on the assumption of random orientation of hydrogen bond directions in ice.

Spin ice pyrochlores and Dirac monopoles

Ice: Crystal structure of D_2O



S. W. Peterson and H. A. Levy, A single-crystal neutron diffraction study of heavy ice, *Acta Crystallogr.* **10** (1957) 70-76.

D rather than H because H scatters incoherently.

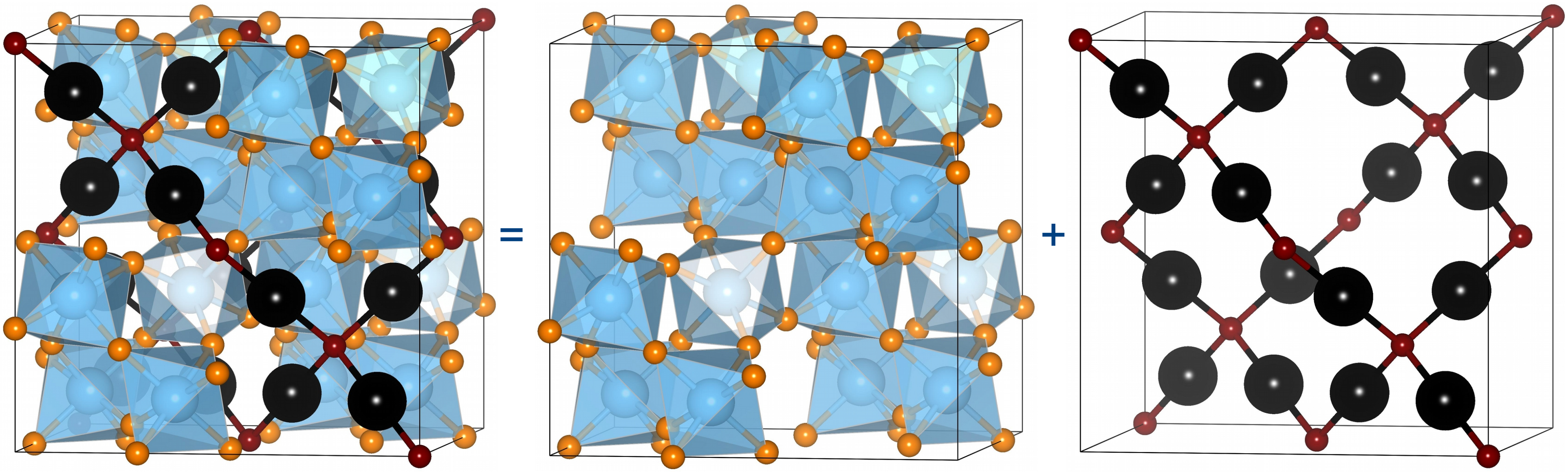
Spin ice pyrochlores and Dirac monopoles

The pyrochlore crystal structure: The example of $Y_2Ti_2O_6O'$: *Fd*-3*m*; *a* = 10.095 Å

Atom	*x*	*y*	*z*
Y	1/8	1/8	1/8
Ti	5/8	5/8	5/8
O	0.302	0	0
O'	0	0	0

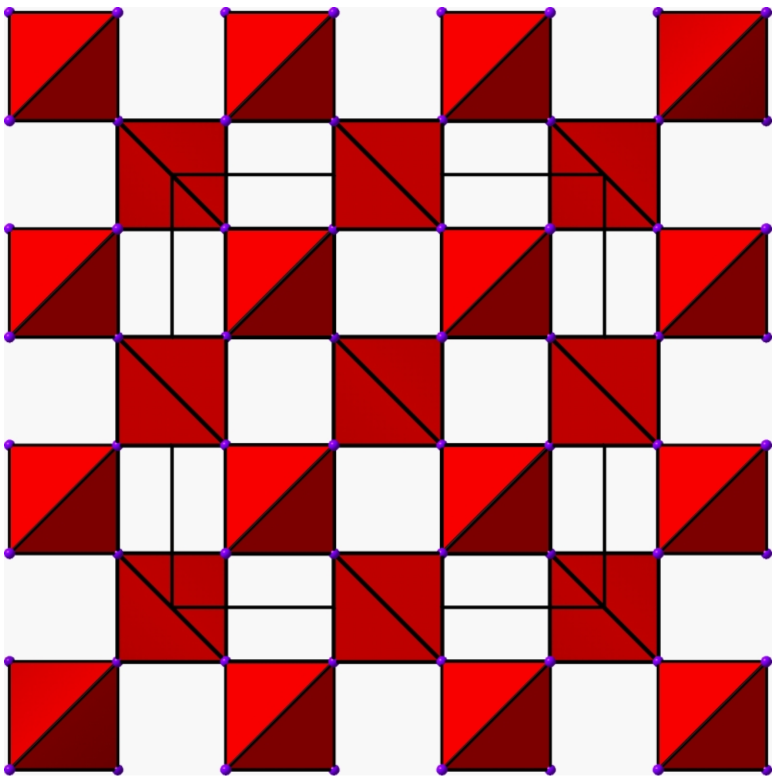
Spin ice pyrochlores and Dirac monopoles

The pyrochlore crystal structure: The example of $Y_2Ti_2O_6O'$: *Fd*-3*m*; *a* = 10.095 Å



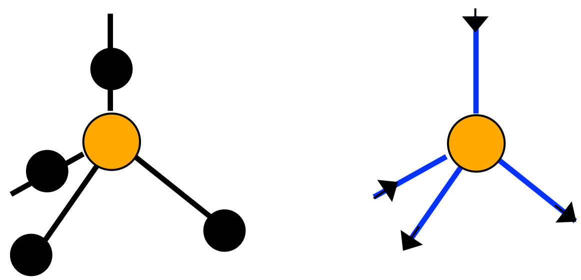
The structure comprises two interpenetrating sublattices – of Ti_2O_6 and Y_2O'

Spin ice pyrochlores and Dirac monopoles



The A atom network of connected A_4 tetrahedra in $A_2B_2O_7$ is *frustrated* with respect to certain kinds of magnetic ordering. Similarities with the crystal structure of ice I_h: the notion of *spin ice.*

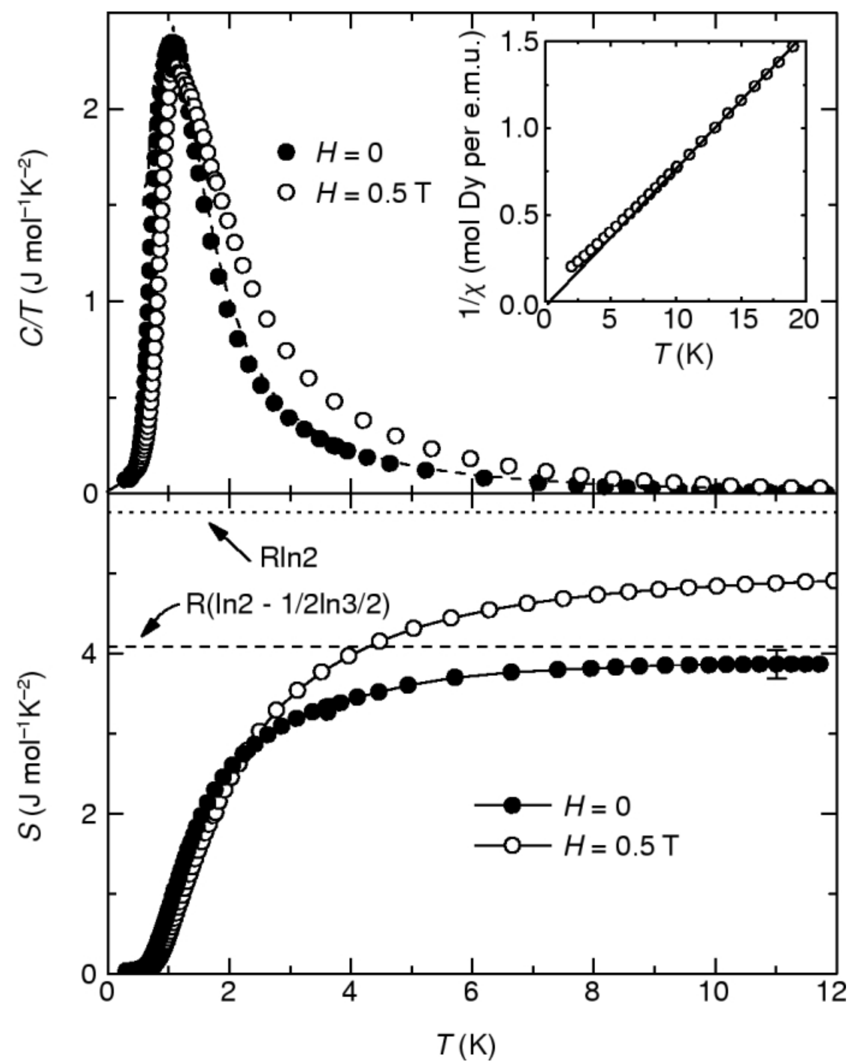
Bramwell, Gingras, *Science* **294** (2001) 1495.



Spin ice pyrochlores and Dirac monopoles

$Dy_2Ti_2O_7$

The *residual entropy* of spin ice can be measured directly:



Ramirez, Hayashi, Cava, Siddharthan, Shastry, *Nature* **294** (2001) 1495.

Spin ice pyrochlores and Dirac monopoles

Both in ice as well as in spin ice, local rules regarding bond distances or the arrangements of spins are not compatible with the rules governing the (long-ranged) arrangements of atoms in 3D – This is termed *frustration*.

Spin ice pyrochlores and Dirac monopoles

Magnetic monopoles: Charges *vs.* magnetic poles

Magnetic poles seem to only occur in pairs, unlike electrical poles (charges) that can be positive or negative and can be separated arbitrarily.

Pierre Curie recognized that single magnetic poles can exist and Paul Dirac (1931) proposed that they must be quantized

"... attractive force between two one–quantum poles of opposite sign is $(137/2)^2 = 4692(1/4)$ times that between electron and proton. This very large force may perhaps account for why poles of opposite sign have never yet been separated..."

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Spin ice pyrochlores and Dirac monopoles

Magnetic monopoles: Possible evidence?

First Results from a Superconductive Detector for Moving Magnetic Monopoles

Blas Cabrera
Physics Department, Stanford University, Stanford, California 94305
(Received 5 April 1982)

A velocity- and mass-independent search for mov
formed by continuously monitoring the current in a
A single candidate event, consistent with one Dirac
tected during five runs totaling 151 days. These dat
sec^{-1} sr^{-1} for magnetically charged particles movin

PACS numbers: 14.80.Hv

VOLUME 48, NUMBER 20 PHYSICAL REVIEW LETTERS 17 MAY 1982

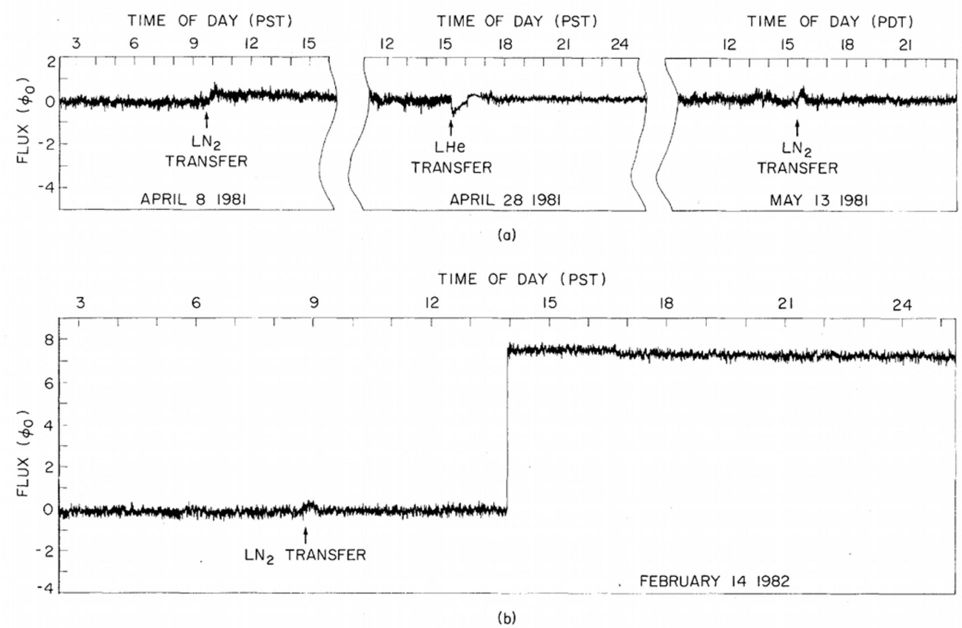


FIG. 2. Data records showing (a) typical stability and (b) the candidate monopole event.

Spin ice pyrochlores and Dirac monopoles

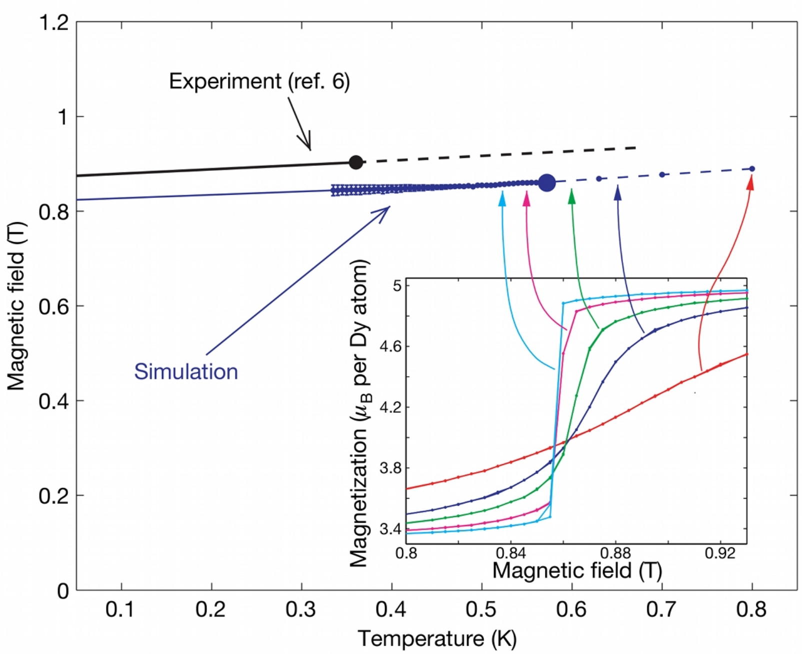
Magnetic monopoles in spin ice

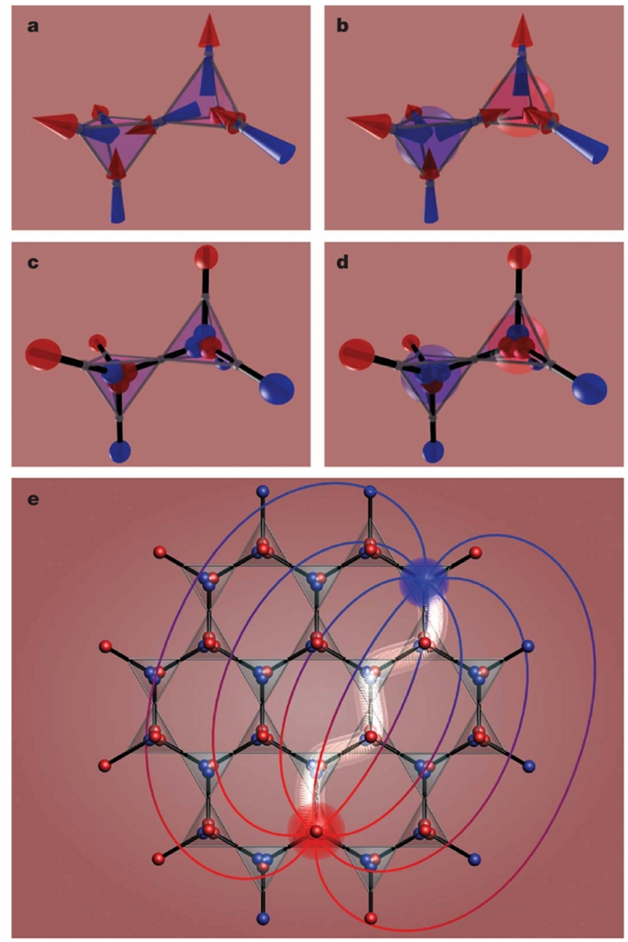
nature
Vol 451|3 January 2008|doi:10.1038/nature06433

LETTERS

Magnetic monopoles in spin ice

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





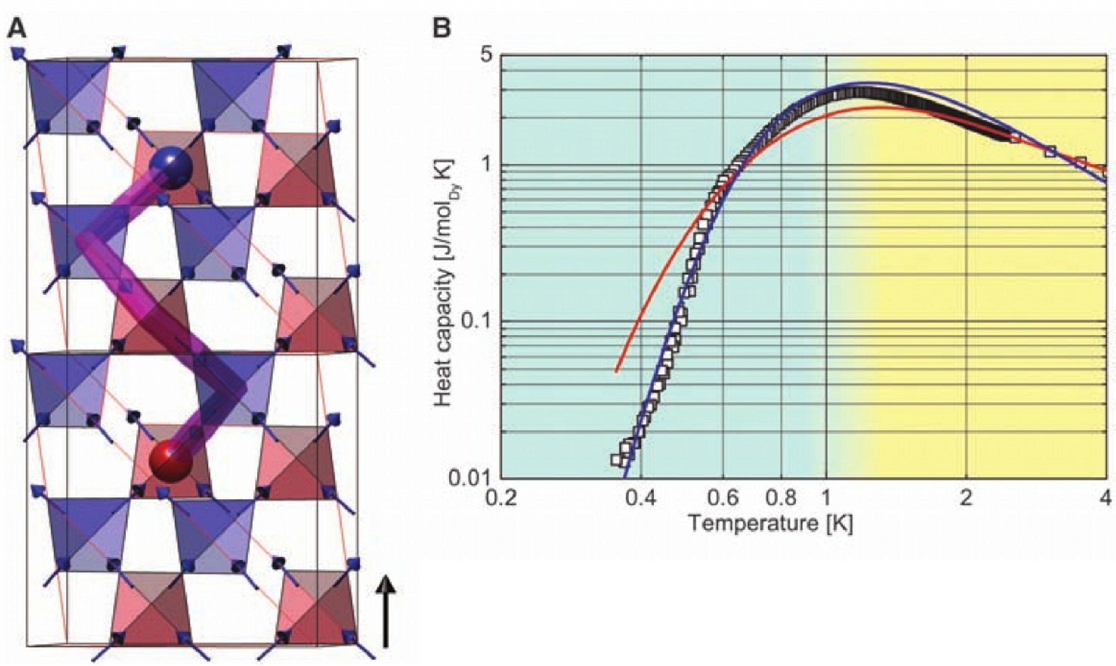
Spin ice pyrochlores and Dirac monopoles

Magnetic monopoles in spin ice

Dirac Strings and Magnetic Monopoles in the Spin Ice $Dy_2Ti_2O_7$

D. J. P. Morris,[1*] D. A. Tennant,[1,2*] S. A. Grigera,[3,4*] B. Klemke,[1,2] C. Castelnovo,[5] R. Moessner,[6] C. Czternasty,[1] M. Meissner,[1] K. C. Rule,[1] J.-U. Hoffmann,[1] K. Kiefer,[1] S. Gerischer,[1] D. Slobinsky,[3] R. S. Perry[7]

www.sciencemag.org SCIENCE VOL 326 16 OCTOBER 2009



UC SANTA BARBARA science & engineering

Spin ice pyrochlores and Dirac monopoles

Magnetic monopoles in spin ice

"*Some condensed matter systems propose a superficially similar structure, known as a flux tube. The ends of a flux tube form a magnetic dipole, but since they move independently, they can be treated for many purposes as independent magnetic monopole quasiparticles. In late 2009 a large number of popular publications incorrectly reported this phenomenon as the long-awaited discovery of magnetic monopoles, but the two phenomena are not related.*"