Spin ice pyrochlores and Dirac monopoles

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

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

- 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$_2$O 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 ?

X-ray do not "see" the hydrogen atoms!
Spin ice pyrochlores and Dirac monopoles

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

16, 4-vertex models:
Spin ice pyrochlores and Dirac monopoles

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

6 ways of arranging H around O so that ice rules are obeyed. Each bond has a 1/2 probability that the proton 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°C.

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°C. 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.
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Ice: Crystal structure of D$_2$O


D rather than H because H scatters incoherently.
Spin ice pyrochlores and Dirac monopoles

The pyrochlore crystal structure: The example of $Y_2Ti_2O_6O'$: $Fd-3m$; $a = 10.095 \text{Å}$

<table>
<thead>
<tr>
<th>Atom</th>
<th>$x$</th>
<th>$y$</th>
<th>$z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>1/8</td>
<td>1/8</td>
<td>1/8</td>
</tr>
<tr>
<td>Ti</td>
<td>5/8</td>
<td>5/8</td>
<td>5/8</td>
</tr>
<tr>
<td>O</td>
<td>0.302</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>O'</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>
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The pyrochlore crystal structure: The example of $Y_2Ti_2O_6O'$: $Fd-3m$; $a = 10.095$ 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.

Spin ice pyrochlores and Dirac monopoles

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

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..."
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 moved by continuously monitoring the current in a A single candidate event, consistent with one Dirac detected during five runs totaling 151 days. These dat sec$^{-1}$ sr$^{-1}$ for magnetically charged particles movin

PACS numbers: 14.80.Hv

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

LETTERS

Magnetic monopoles in spin ice

C. Castelnovo¹, R. Moessner¹,² & S. L. Sondhi³

Experiment (ref. 6)

Simulation

Magnetic field (T)

Magnetization (µs per Dy atom)

Temperature (K)

Materials 218/Chemistry 277, Winter 2010: Introduction to Inorganic Materials
Ram Seshadri seshadri@mrl.ucsb.edu http://www.mrl.ucsb.edu/~seshadri
Spin ice pyrochlores and Dirac monopoles

Magnetic monopoles in spin ice

Dirac Strings and Magnetic Monopoles in the Spin Ice Dy\textsubscript{2}Ti\textsubscript{2}O\textsubscript{7}

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

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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."