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A Quantum recipe for Dynamics in Spin Ice

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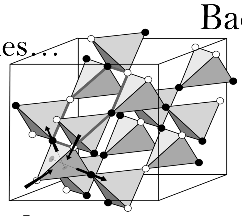
Abstract

In Spin Ice the hopping of a magnetic monopole, from one site to the next, consists of the flip of a large spin from an easy axis configuration to the opposite one. At very low temperatures, this requires quantum-mechanical tunnelling throug a large anisotropy barrier. Naively one would thus expect a single, very slow frequency in the low-temperature regime. On the other hand experiments reveal a broad range of temperature-independent (i.e. quantum) frequencies at low temperatures [1,2,3,4]. Here we study this question within a single ion (Ho^{3+}) picture. Starting from the CF Hamiltonian for $Ho_2Ti_2O_7$ we analyze how a transverse magnetic field B, induces a quantum spin flip from an anisotropic configuration to the opposite one. Interestingly, we find a broad range of frequencies that are characteristic of the system. In particular using the internal field distribution (from Montecarlo simulations) due to the presence of a monopole we detect two different time scales for the hopping rate of a monopole. To model the hopping of a monopole, we use a classical Monte Carlo calculation to estimate the size and orientation of the magnetic field a spin is subjected to before (B_1) and after (B_2) a monopole arrives to an adjacent tetrahedron. The quantum quench from B_1 to B_2 induces a quantum mechanical flipping of the spin, and thus the hopping of the monopole. Our calculation, which doesn't depend on any adjustable parameter, suggests two main timescales for monopole hopping: $\tau_1 \approx 0.25$**ms** and $\tau_2 \approx 2.5$**μs**.

Background

From Dipoles…



Spin Ice are *Geometrically* ***Frustrated*** ferromagnets (*Pyrochlore* Oxides).
In $Dy_2Ti_2O_7$ and $Ho_2Ti_2O_7$
The strong *crystal field* causes the spin to point along the <111> direction

Ice Rule ➔ *macroscopic degenerate* **GS** ➔ ***non-zero*** entropy at T= 0.
Large magnetic moments (**10** μ_B) ➔ Strong ***Dipole-Dipole*** interaction.

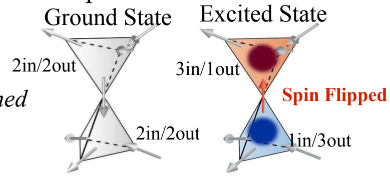
Dipolar Hamiltonian

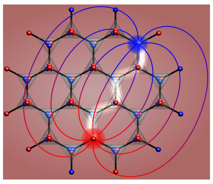
$$H = \frac{J}{3}\sum_{\langle ij\rangle} S_i S_j + Da^3 \sum_{(ij)} \left[\frac{\hat{e}_i\cdot\hat{e}_j}{|\mathbf{r}_{ij}|^3} - \frac{3(\hat{e}_i\cdot\mathbf{r}_{ij})(\hat{e}_j\cdot\mathbf{r}_{ij})}{|\mathbf{r}_{ij}|^5}\right] S_i S_j$$

Long Range Coupling

…to Monopoles

At low temperatures, the *local* dipolar excitation *fractionalize* into *decofined* quasiparticles with magnetic charge.





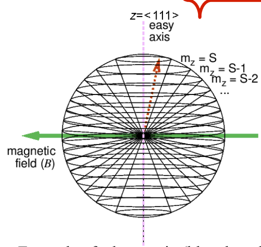
Magnetic monopoles interact via **Coulombic** potential

$$V(r_{\alpha\beta}) = \begin{cases} \frac{\mu_0}{4\pi}\frac{Q_\alpha Q_\beta}{r_{\alpha\beta}} & \alpha \neq \beta \\ \frac{1}{2}\upsilon_0 Q_\alpha^2 & \alpha = \beta \end{cases}$$

RESULTS

Quantum mechanics of an Ho^{3+} ion in a transverse magnetic field

$$\hat{\mathcal{H}} = -g_J\mu_B \hat{\mathbf{J}}\cdot\mathbf{B} + \hat{\mathcal{H}}_{CF}$$



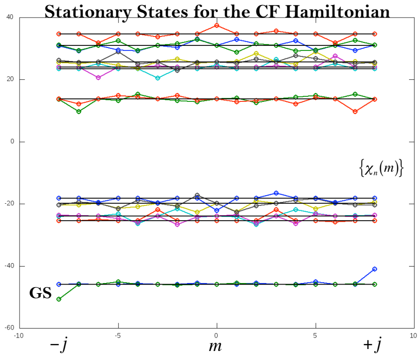
Example of a large spin (blue dotted) under magnetic transverse field B (red solid).

$$\hat{\mathcal{H}}_{CF} = \Gamma_0^2\hat{O}_0^2 + \Gamma_0^4\hat{O}_0^4 + \Gamma_3^4\hat{O}_3^4 + \Gamma_0^6\hat{O}_0^6 + \Gamma_3^6\hat{O}_3^6 + \Gamma_6^6\hat{O}_6^6$$

Crystal Field Hamiltonian in terms of Stevens operators
$\hat{O}_q^k(\hat{\mathbf{J}}^2, \hat{J}_z, \hat{J}_\pm)$
(functions of angular momentum operators)

$Ho_2Ti_2O_7$ ➔ $|J, J_z\rangle = |8, m_z\rangle$

Stationary States for the CF Hamiltonian

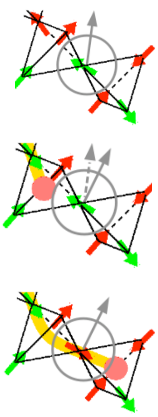


How do *Monopoles hop*?
By *flipping spins!*

t_1 — Ground state : 2in-2out , **NO** monopoles

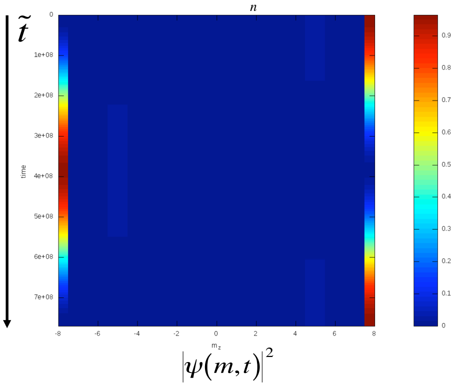
t_2 — A ***monopole arrives*** and changes the field

t_3 — The central ***spin flipped***, hence the ***monopole hopped*** from one site to next

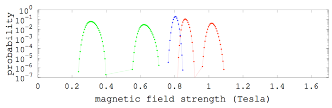


QUANTUM DYNAMICS

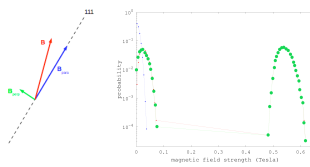
$$|\psi_t\rangle = e^{-\frac{i}{\hbar}\hat{H}t}|\psi_0\rangle = \sum_n c_n^0 e^{-\frac{i}{\hbar}E_n t}|\chi_n\rangle$$



Histograms of internal fields from classical Monte Carlo



$B(t_1)$



$B(t_2)$

Quantum Quench

$B(t_2)$ — $\tau_1 \approx 0.25$ **ms**, $\tau_2 \approx 2.5$ **μs**

TWO different time scales for the monopole hopping

[1] Bramwell et a. *Nature* **461** (2009) ; [2] Dunsiger et al *PRL* **107** (2011) ; [3] S.Giblin et al. *Nature-Phys* **7** (2011); [4] K.Matsushira et al. *JPSJ* **80** (2011)

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