A Model for a Glassy Phase in a Frustrated Magnet Without Disorder

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Spin glass, spin freezing at $T = T_g$

- *Definition*: Local *static* order $\langle \mathbf{S}_i \rangle \neq 0$ for $T < T_g$ but no long-range order

Examples of spin-glass kagome compounds

- $SrCr_{9p}Ga_{12-9p}O_{19}$
- $(H_3O)Fe_3(SO_4)_2(OH)_6$
- volborthite $Cu_3V_2O_7(OH)_2.2H_2O$ (<2012, see Hiroi)
- vesigneite $BaCu_3V_2O_8(OH)_2$ (<2012, see Hiroi)

Examples of pyrochlore compounds

- $Y_2Mo_2O_7$
- $Dy_2Ti_2O_7$

How do they differ from standard spin glasses?

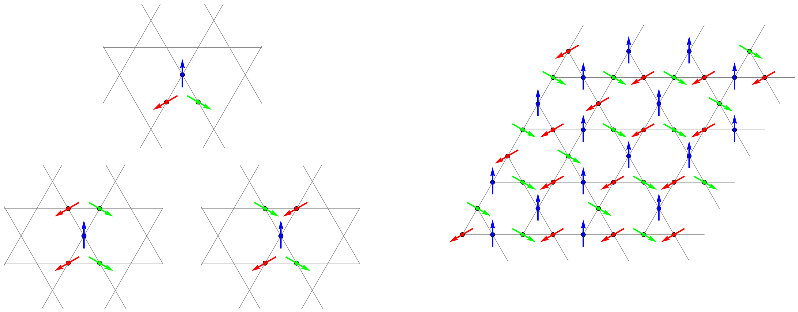
1. Dense compounds (up to $p \sim 100\%$ coverage for the Fe compound); is the chemical disorder really the main source of freezing?
2. T$_g$ depends weakly on p
3. Weak frozen moment, persistent dynamics for $T < T_g$

Can we have a glassy phase in the parent disorder-free compounds (although there is always chemical disorder in real samples)? (as in structural glasses)

Geometrical Frustration : extensive classical degeneracy

- Suppose some "order" takes place ($T \ll JS^2$)

Minimize the classical energy

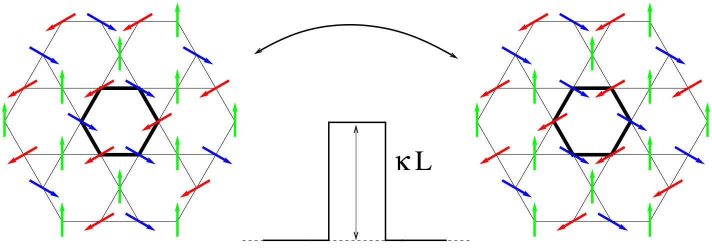


- Frustration: many possible "orders", $1.135...^N$ (exact) [Baxter (1970)] with $E_i = -\frac{1}{2}NJS^2$

Special collective excitations: "chains" or "loops"

- <u>CONSTRAINED MOTION</u>: consider only special excitations

Swap colors along two-colored loops (respects the constraint)



ex. $L = 6$

- Activated dynamics of loops

$$\tau_L = \tau_0 \exp\left(\frac{\kappa L}{k_B T}\right) \qquad L = 6, 10, \ldots \infty$$

Is the <u>local</u> dynamics ergodic?

A guess for the dynamics at long times...

Two ingredients:

- Analogous to "spin-ice" (local constraints) $\rightarrow$ assume long-distance height model

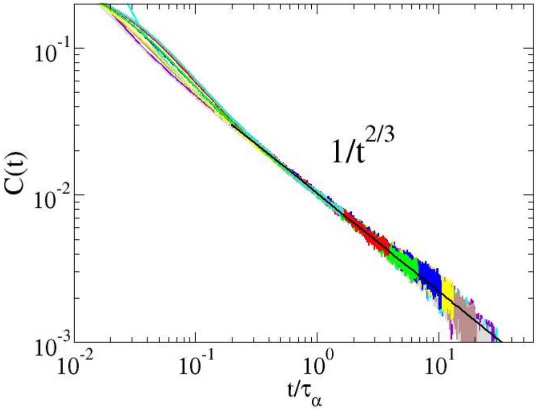
  Huse and Rutenberg PRB 1992, Read (unpublished).
- Assume Langevin dynamics as in dimer models

  Henley, J. Phys. Stat. 1997.

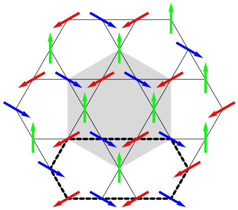
This predicts algebraic decay:

$$\langle \mathbf{S}_i(t).\mathbf{S}_i(0)\rangle \sim \frac{1}{t^{2/3}} \quad (1)$$

Correct at large T, indeed...



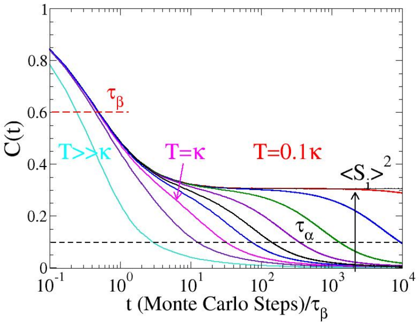
But some configurations are jammed at low T...

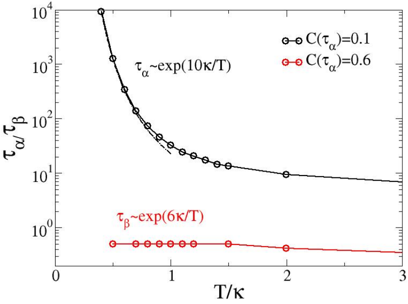


- In gray: frozen spins = no loop of length 6 can unjam the configuration, at low T, jammed forever (till $t \sim \tau_{10}$)
- Are these configurations statistically representative?
  * How many such regions? what is their typical size?
  * What is the frozen moment?

How does the system return to equilibrium?

Compute autocorrelation $C(t) = \frac{1}{N}\sum_{i=1}^{N}\langle \mathbf{S}_i(t).\mathbf{S}_i(0)\rangle$ (Monte Carlo simul.)

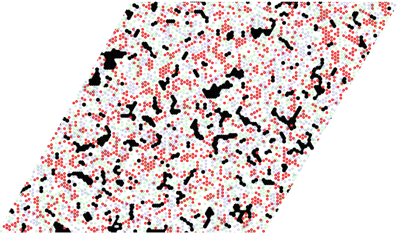


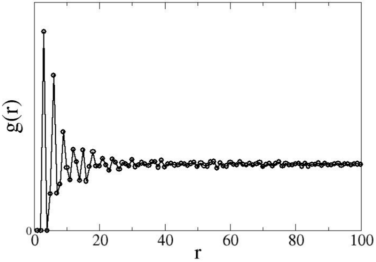


- $T < T^* \approx \kappa$ (crossover): two-step relaxation with time-scales: τ_α, τ_β.
- Quasi stationary state : $C(t) \to \langle \mathbf{S}_i \rangle^2 \approx 0.3$ for $\tau_\beta < t < \tau_\alpha$.
- Glass transition (crossover) temperature at T_g, $\tau_\alpha = t_{obs}$.

$T \ll T^*$ Description of the active degrees of freedom

Liquid of strongly correlated loops (active degrees of freedom)



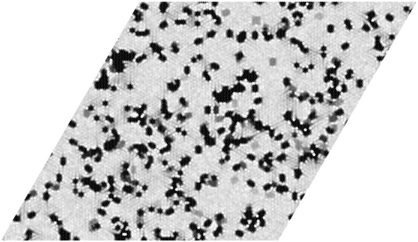


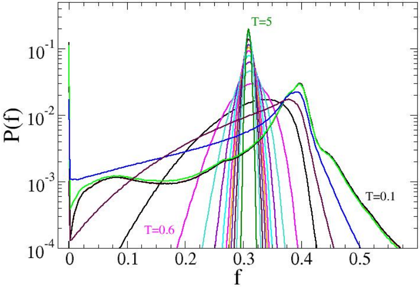
- Black = Regions of averaged size $\langle s \rangle = 42$ sites frozen for $t \ll \tau_\alpha$. (self-induced disorder)
- Density of smallest loops $n = 0.22$
- Radial distribution function of loop-loop distance: attraction
- The weak frozen moment originates in the small frozen regions

Dynamical Heterogeneities

Map and histogram of local frequencies

[standard analysis in model of glasses, see e.g. *Dynamical heterogeneities in glasses..., Oxford University Press 2011*.]



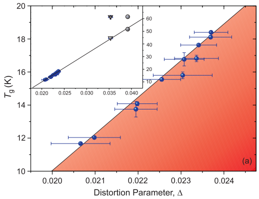


- $T > T^*$ Homogeneous (gaussian) distribution
- $T < T^*$ Skewed (heterogeneous) distribution + frozen fraction $T < T_g$ (f$= 0$ delta peak)

“What sets the scale?”

- Glass temperature $T_g \approx 0.3\kappa$ is determined by the smallest barrier
  Microscopic origin:
  - Anisotropy (spin-orbit): rotate the spins out-of-plane costs $\kappa \sim DS^2$. prevails if $DS^2 \gtrsim \eta JS$ (e.g. Fe^{3+}).
  - Spontaneously-generated anisotropy: selection of a plane (broken symmetry) by fluctuations (*order-by-disorder*)
    Energy scale $\kappa \sim 0.14JS$. if $DS^2 \lesssim 0.14JS$ (e.g. Cr^{3+}, Cu^{2+}).

$D \sim \frac{\lambda^2}{\epsilon_d}$, with λ, spin-orbit coupling and $\epsilon_d = \epsilon_d^0 + \alpha\Delta$, d-orbital energies and Δ the octahedron distortion, hence $T_g = T_g^0 + \alpha'\Delta$, as observed Bisson and Wills, J. Phys.: Condens. Matt., 2008 & 2011:



Is it possible to measure D directly for these compounds?

Conclusion

- The present model is an example of "constrained/gauge" model, with a classical dynamics that spontaneously generates two time scales τ_α and τ_β (a feature absent from long wavelength Coulomb phase description).
- Glass phase $T < T_g$, ($\tau_\alpha > t_{exp}$): the phase has a small frozen moment and *microscopic* frozen regions (self-induced disorder). The phase space breaks into e^{aN} pockets (non ergodicity).

Note a competition with *order-by-disorder* which lifts the degeneracy of the 3-color states. At $T = 0$ and large-S: $\sqrt{3} \times \sqrt{3}$ Néel order
Cépas and Ralko, Phys. Rev. B 84, 020413 (2011)
Chern and Moessner, arXiv:1207.4752

Experimental test?

- Excitations are characterized by neutron form factors (e.g. dimers, here $L = 6 \equiv$ hexagonal form factor)
- Spatial heterogeneities of the dynamics?