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SPIN DYNAMICS ON PERCOLATING NETWORKS

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ABSTRACT

We have used inelastic neutron scattering to measure the order parameter relaxation rate Γ in the dilute, two-dimensional Ising antiferromagnet $\text{Rb}_2\text{CoMg}_{1-c}\text{F}_4$ with c very close to the magnetic percolation threshold. Where κ is the inverse magnetic correlation length, $\Gamma \sim \kappa^z$ with $z = 2.4_{-0.1}^{+0.2}$. Our results are discussed in terms of current ideas about spin relaxation on fractals.

The static and dynamic behavior of pure magnets near phase transitions is well established, both experimentally and theoretically.¹ There also exists a large body of work dealing with the static critical properties of simple disordered magnets.² There are certain random spin systems for which static properties are more difficult to calculate. These systems,³ where there are couplings between spins or local fields of random sign, are characterized by "frustration", the inability at low temperatures of certain spin clusters to come into unique alignment with respect to other clusters. Much of the qualitatively new behavior of frustrated systems is dynamical, and certain explanations⁴ of their apparently static properties use dynamical theories as their starting points, thus reversing the pattern followed in the study of critical phenomena in pure systems. In this context, it is natural to ask whether qualitatively new effects arise in simpler, disordered systems, namely systems without frustration. An indication that interesting dynamical behavior might occur in random systems without frustration comes from studies of diffusion in spaces of non-integral (fractal) dimensionality.⁵ For ordinary Euclidean spaces, the mean square distance $\langle r^2(t) \rangle$ travelled by a particle in time t obeys the law

$$\langle r^2(t) \rangle \sim t. \quad (1)$$

In fractal spaces, signals propagate via more circuitous routes than the straight line paths available in normal Euclidean spaces. Thus, particles will require a longer time to diffuse a certain distance in fractal spaces than in the (Euclidean) imbedding spaces.

Correspondingly, the law (1) is generalized to

$$\langle r^2(t) \rangle \sim t^{2/(2+\theta)} \quad (2)$$

with $\theta > 0$.

The essential idea of our experiments is to probe dynamical effects on fractals by studying the relaxation of spins located on a fractal. Arguably the simplest fractal is the

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percolating cluster, realized in magnetic compounds containing sites occupied at random either by non-magnetic ions, such as Mg^{2+} , or magnetic ions, such as Co^{2+} , coupled only to their nearest neighbors.² The exchange couplings in many of these compounds are such that frustration does not arise; while the randomness has profound geometrical effects, it does not lead to a qualitatively new ground state as in the spin glass problem. For our first study⁶ of dynamical effects near percolation, we have chosen $\text{Rb}_2\text{Co}_c\text{Mg}_{1-c}\text{F}_4$, a system for which the static spin correlations have been studied in detail.⁷ Furthermore, there exist experiments⁸ on the dynamical critical behavior of the corresponding pure system, Rb_2CoF_4 , which is a nearly ideal realization of a two-dimensional Ising antiferromagnet.

We performed our experiments using two triple-axis spectrometers at the Brookhaven high-flux beam reactor. The first of these is located at a thermal beam port and is equipped with a single-pass monochromator. Spectra were collected by varying the final energy E_f with the incident energy E_i fixed at 3.5 meV; the corresponding energy resolution was $64 \mu\text{eV}$, full width at half maximum (FWHM). The other spectrometer has a double crystal monochromator and is installed at the cold neutron source of the HFBR. Here, we scanned the incident neutron energy E_i with the final energy fixed at 2.5 meV; the resolution was $37 \mu\text{eV}$ FWHM.

Our sample was a single crystal of $\text{RbCo}_c\text{Mg}_{1-c}\text{F}_4$ with $c=0.58$, which is very close to the nearest neighbor percolation threshold ($c=c_p=0.593$) for a square lattice. We collected inelastic spectra at a reciprocal lattice point lying on the line (in reciprocal space) where the Bragg condition for two-dimensional antiferromagnetic order is satisfied. Thus, our experiment probes the fluctuations in the staggered magnetization, which has zero mean at all temperatures because c is slightly below c_p .

Our spectra are well described by Lorentzian profiles which correspond to simple exponential autocorrelation functions for the staggered magnetization $M(t)$,

$$\langle M(t) M(t+\tau) \rangle = \exp -\Gamma|\tau|. \quad (3)$$

Because we expect Γ for a classical paramagnet — i.e. a collection of decoupled magnetic ions — to approach 0 according to the law $\Gamma \sim T$ as $T \rightarrow 0$, we show in Fig. 1 the reduced relaxation rate Γ/kT as a function of the inverse correlation length κa established by Cowley and coworkers⁷ for the same sample. The data are well-represented by the power law

$$\Gamma/kT = A(\kappa a)^z \quad (4)$$

where $z = 2.4^{+0.2}_{-0.1}$.

Our value for z is very high when compared with that (~ 1.7) found for pure Rb_2CoF_4 .⁸ However, the result that z is high is in accord with the qualitative content of Eq. (2), namely that disturbances on ramified, fractal structures require longer times to travel fixed (Euclidean) distances than they do in normal Euclidean spaces. In our first paper on this subject,⁶ we suggested that the fractal geometry of percolating networks changes Ising spin dynamics in the same manner as it changes diffusion. Furthermore, we posited that the nonlinearities present in the spin relaxation, but not the particle diffusion problem, are accounted for by the static exponent η , as for the conventional theory of the kinetic Ising model.⁹ We consequently guessed that for fractals,

$$z = 2 + \theta - \eta, \quad (5)$$

where θ also occurs in Eq. (2). Using θ and η appropriate to the two-dimensional percolation problem, $z=2.47$, in good agreement with the experimental value. Several theories^{10,11} of spin relaxation near percolation have subsequently appeared. Most of these¹⁰ use Eq. (4) as a starting point and yield expressions similar to (5) for z . Very recently, however, Henley,¹¹ Harris and Stinchcombe¹² have made the important observation that Eq. (4) may be incorrect for Glauber models on percolating networks. Instead, they propose a temperature-dependent exponent,

$$z_{\text{eff}}(T) = 2Z/T, \quad (6)$$

Fig. 1. Normalized relaxation rate Γ/kT plotted against reduced inverse correlation κa . At the dashed curves, the FWHM of the resolution function exceeds Γ by a factor of 4. The open and filled circles correspond to the two different spectrometers described in text.

where Z is a geometrical parameter for the fractal and T is expressed in units of the exchange coupling. The derivation of (6) is based on considerations of the energy barriers dominating the low temperature dynamics. These barriers rise logarithmically with the size L of the system, so that

$$\Gamma \sim \exp(-E_0/kT) \sim L^{2\alpha(T)} \exp(-E_0/kT) \quad (7)$$

where E_0 is an L -independent contribution to E_b . According to Eq. (7), there should be curvature in a double logarithmic plot of Γ/kT against κa , since for Ising systems, $\ln(\kappa a) \sim kT$. Curvature of this nature cannot be discerned in Fig. 1. Unfortunately, due to experimental limitations (see the dashed lines in the figure), we could not measure Γ for $\kappa a < 0.3$. However, we anticipate that neutron backscattering experiments¹³ currently in progress at Brookhaven will permit a more stringent test of Eq. (7).

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