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PHASE TRANSITIONS AND METASTABLE STATES IN THE PRESENCE
OF RANDOM FIELDS

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The application of a uniform magnetic field to a diluted Ising antiferromagnet produces a random staggered field and so can be used to study the random field Ising model. In this paper we describe neutron scattering measurements on $Mn_xZn_{1-x}F_2$. They show that at low temperatures there are many metastable states which are all stable for experimentally accessible times. There is a sharp boundary in the H/T plane which separates metastability from ergodicity. The critical phenomena close to this metastability boundary is discussed.

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The random field Ising model (RFIM) is one of the simplest problems with competing interactions. The exchange interactions act so as to produce long range order, but the magnetic fields, which are randomly directed at each site, act so as to destroy the order. Ever since the work of Imry and Ma¹, it has been realized that random fields can produce dramatic effects on phase transitions and ordering. The RFIM has proved, however, to be a more complicated problem than was initially anticipated by either the theorists or the experimentalists, and despite a large body of work, it is still not fully understood.

A very convenient experimental realization of the random field Ising model is obtained by the application of a uniform field to a diluted antiferromagnet²; here the uniform field produces a random staggered field due to the randomness in the Zeeman energy. Over the past 6 years a large number of experiments employing a variety of experimental techniques has been performed using $d = 2$ and $d = 3$ antiferromagnets. The progress up until 1983 was reviewed at the preceding Statistical Physics Conference³. In this brief review we discuss the progress made since then with emphasis on results obtained using neutron scattering techniques with the $d = 3$ system $\text{Mn}_x\text{Zn}_{1-x}\text{F}_2$ ⁴. Very similar results have also been observed with $\text{Fe}_x\text{Zn}_{1-x}\text{F}_2$ ⁵.

In all of the neutron scattering experiments on the diluted $d = 3$ systems, it is found that when the samples are cooled in a field, FC, long range order is not established at low temperature, but the

scattering profiles have a characteristic Lorentzian squared form as a function of wavevector. In contrast, if the samples are cooled in the absence of the field, and the field applied, ZFC, long range order is retained until the sample is heated above a well defined temperature. Figure 1 illustrates this difference at a temperature just 0.4K below this metastability boundary, $T_M(H)$. Much of the recent work has been performed with a view to elucidating the behavior close to this metastability line. Differences in the FC and ZFC behavior are also observed in macroscopic measurements such as thermal expansion and magnetization.⁶

It is now generally believed that in equilibrium the lower critical dimension of the random field Ising model is 2⁷. Consequently systems with $d = 3$ are predicted to have a long range ordered ground state, and there have been many theories⁸ of the critical phenomena describing the possibly continuous phase transition into this long range ordered phase at $T_N(H)$. Because none of these theories explain the observed metastability, models have also been developed⁹ to explain this metastability as arising from anomalously large barriers to the motion of domain walls between the antiferromagnetic domain... These theories predict that the size of the domains should increase with time as $\ln(t/\tau)$ where τ is a microscopic time. It is important to emphasize that $Mn_xZn_{1-x}F_2$ has only a very small spin wave energy gap: ~1K at 7T and 40.0K. The metastability cannot, therefore, arise from a thermal freezing of the system as there are very many spin waves excited at the relevant temperatures. To probe the predicted time dependence of the domain

size the scattering was measured as a function of time after cooling as rapidly as possible from above to below the metastability boundary. Typical results are shown in Fig. 1. It was found that the size of the domains at 900 mins was 1.01 ± 0.03 times that at 8 mins, whereas with any reasonable microscopic time, τ , the logarithm would predict a minimum ratio of 1.14. Similar experiments have been performed by quenching the field as well as the temperature in $\text{Mn}_{0.5}\text{Zn}_{0.5}\text{F}_2$ with similar results⁴. We conclude that the FC state does not decay logarithmically with time.

In an attempt to understand the observed FC behavior in the critical region Villain¹⁰ and Fisher¹⁰ have suggested that the barrier heights for domain wall motion diverge just above $T_N(H)$. Further, the barrier height varies sufficiently rapidly with $T - T_N(H)$, in these theories, that one expects a quite well-defined metastability boundary. Close to this metastability boundary King et al.¹¹, have indeed found that the a. c. susceptibility is frequency dependent at anomalously low frequencies. We conclude that anomalously slow dynamics can account for the metastability boundary.

Despite this result, the properties of the metastable phase are not yet fully understood. Fig. 2 shows that the FC inverse correlation length continues to decrease on cooling below the boundary; thus the system is not completely frozen. Secondly, if the field is reduced in the metastable region the system rapidly relaxes to the same state as that achieved by the FC procedure in the new field. In contrast, when the field is raised no contraction of the domains occurs. This asymmetry in the behaviour is possibly consistent with the theories, but it is surprising that the relaxation

is independent of temperature, and that the same FC state is always reached from different more disordered configurations.

If the metastability transition at $T_M(H)$ occurs above a continuous phase transition at $T_N(H)$ to long range order, the behaviour of the scattering above the metastability may give information about the exponents to be expected at the continuous phase transition. Fig. 3 shows the inverse correlation length for various fields as a function of temperature. For $H = 0$ the correlation length exponent is $\nu = 0.71$ in agreement with theory for the random exchange Ising model. However fits to the data for higher fields give exponents between 1.0 and 1.9 depending on the field and range over which the data are fitted. The results obtained⁵ in $\text{Fe}_x\text{Zn}_{1-x}\text{F}_2$ are very similar to those of $\text{Mn}_x\text{Zn}_{1-x}\text{F}_2$. It is therefore very difficult if not impossible to extract these exponents reliably, without a theoretical prediction for the relevant crossover functions.

The amplitude of the Lorentzian squared, shown in Fig. 4, increases steadily as the sample is cooled to the metastability temperature. This behavior also occurs at other fields. If there is a continuous phase transition, this Lorentzian squared term must evolve continuously into the Bragg reflection from the long range order. If $\beta > 0$, this requires that the amplitude vary continuously to zero at the phase transition temperature (that is $\bar{\eta} > 1$) in disagreement with the trend evident in Fig. 4.

Alternatively the amplitude could tend to a constant at T_N in which case $\beta = 0$. On the other hand a conventional critical point analysis of the data above the metastability temperature suggests that the amplitude diverges at $T_N(H)$, ($\bar{n} < 1$) which is inconsistent if the transition is continuous. We conclude that our data suggest that if there is a transition to long range order it is probably of first order¹², even if very weakly so.

We have studied the behavior of the ZFC state close to the metastability boundary. With increasing temperature just below the boundary there is a Lorentzian squared component to the scattering whose intensity increases, while the inverse correlation length decreases until the metastability boundary is reached. At that point they have the same values as obtained in the FC experiments. The long range order decreases to zero over a narrow, $\sim 0.4K$, temperature interval at the metastability boundary. We conclude that ZFC state undergoes an abrupt, possibly first order transition at the metastability boundary to a state identical with that obtained by the FC procedure. It should be emphasized that in $H = 0$ in our $Mn_{0.75}Zn_{0.25}F_2$ sample the rounding of T_N due to inhomogeneties is less than $0.025K$.

In conclusion, the random field Ising model has been found to have many unexpected features. At low temperatures there are many metastable states and the theory of these states is not yet completely convincing. It is predicted that if the system remained in equilibrium and the metastability did not occur, there would be a

transition to a state with long range order. Our results suggest that this transition, if it occurred, would be of first order. In the future we can expect to see further improvements and more detailed experiments over many decades of frequency close to the metastability boundary. These experiments will hopefully help elucidate not only the metastability found in the random field Ising model, but also similar effects found in other systems with competing interactions.

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Figure Captions

- Fig. 1 The wavevector dependence⁴ of the neutron scattering from $\text{Mn}_{0.75}\text{Zn}_{0.25}\text{F}_2$. The fits are to a Lorentzian squared profile FC or to a Lorentzian squared and a Gaussian to describe the Bragg reflection, ZFC.
- Fig. 2 The inverse correlation length obtained from neutron scattering measurements on $\text{Mn}_{0.75}\text{Zn}_{0.25}\text{F}_2$ in a field of 6.5T. The dotted line is the metastability boundary.
- Fig. 3 The inverse correlation length above the metastability boundary for various fields in $\text{Mn}_{0.75}\text{Zn}_{0.25}\text{F}_2$.
- Fig. 4 The amplitude of the Lorentzian squared derived from neutron scattering measurements on $\text{Mn}_{0.75}\text{Zn}_{0.25}\text{F}_2$ in 6.5T. The dotted line gives the metastability boundary.

$\text{Mn}_{0.75}\text{Zn}_{0.25}\text{F}_2$, $H=5.0\text{ T}$

Figure 1

Figure 2

Figure 3

Figure 4