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Spin glasses enter the quantum regime

Spin glasses are among the most interesting and complicated forms of condensed matter. Their study has justifiably engrossed a large number of experimental and theoretical physicists over the last two decades. With rare exceptions, this work has been in a regime where the quantum-mechanical nature of the microscopic constituents could be ignored, and the collective properties of the sample were essentially classical. Understanding the experimental properties of spin glasses then became a problem, albeit difficult, in classical statistical mechanics. Impressive advances have been made in theory and experimental technique, and have been accessibly presented in recent reviews [1]. However, recent experiments by a group led by T.F. Rosenbaum at the University of Chicago and G. Aeppli at AT&T Bell Laboratories [2], have given renewed impetus to the study of spin glasses in a heretofore largely neglected quantum regime; in this regime, quantum mechanics plays an essential role even in the bulk, collective properties, and its effects must be confronted head on. On the theoretical side, large Monte Carlo simulations by Guo, Bhatt and Huse (in three dimensions) and Rieger and Young (in two dimensions) [3] have given us the first set of reliable results on the novel properties of realistic quantum spin glasses.

To begin, what is a spin glass ? Spin glasses are formed by placing a magnetic ion, like manganese or europium, at random positions in a non-magnetic host metal (*e.g.* silver) or insulator (*e.g.* strontium sulfide). The exchange interactions between the magnetic moments (or 'spins') are such that the energy is not minimized by a simple, regular, arrangement of the spin orientations, as it is in a ferromagnet or antiferromagnet. Rather, at low temperatures such materials often enter the spin glass phase, in which the spins freeze into a complicated random configuration. The choice of the particular configuration in a given sample depends upon all the details of the random arrangement of magnetic ions present. Experimentally, the onset of spin glass order is most easily determined by the presence of a cusp in the temperature dependence of the linear spin susceptibility, and a divergence of the non-linear susceptibility at the same temperature.

The conventional choice for moving a sample out of the spin glass phase has been to raise the temperature. The increasing thermal agitation of the spins eventually causes them to lose the long-time memory of the particular orientation they had chosen in the spin glass. However, the price for this choice is that close enough to the transition the behavior of the system becomes classical. The reason for this may be understood most clearly by thinking about the approach to the spin glass state from higher temperatures. As one lowers the temperature, the spins start to build in mutual correlations over a temperature-

dependent length scale, ξ. The onset of spin glass order occurs at the point where ξ diverges, corresponding to correlations in the spin orientation over the entire sample. With a large ξ, the important fluctuations of the spins involve fine rearrangements of the spins at distances on the order of ξ, and these occur rather sluggishly with a frequency, ω, which should go to zero as ξ diverges. Close enough to the transition then, the system will always satisfy $\hbar\omega \ll k_B T$. Under this condition the coupling of the spins to the thermal heat bath causes an almost complete loss of quantum coherence, and the system behaves classically.

To avoid this almost ubiquitous phenomenon, the Rosenbaum group used a different mechanism to destroy the spin glass phase. First they chose a material ($LiHo_{0.167}Y_{0.833}F_4$, with Ho being the magnetic ion) with a strong spin-orbit coupling between the spins and the underlying crystal - this coupling essentially restricts the spins to orient either parallel or anti-parallel to a specific crystalline axis; such spins are usually referred to as Ising spins. Then they applied a transverse magnetic field, oriented perpendicular to the preferred axis. The transverse field continually induces flips of the Ising spins, and is thus clearly detrimental to the spin glass phase. (The flipping effect of the transverse field is similar to that of the transverse field in a spin-resonance experiment.) A large enough transverse field will eventually destroy the spin glass order, even at the absolute zero temperature. The phase transition at absolute zero must necessarily be quantum mechanical, as there is no heat bath to destroy quantum coherence. At small, but non-zero, temperatures, the considerations outlined above allow one to deduce the phase diagram sketched in the figure; Γ is a parameter measuring the strength of the quantum fluctuations, and is proportional to the transverse field. Close enough to the spin glass transition at any non-zero temperature, classical fluctuations always take over; however the region of classical behavior becomes vanishingly small as the temperature goes to zero.

An essential ingredient in understanding quantum spin glasses is the determination of the properties of the quantum critical point at $\Gamma = \Gamma_c$ and $T = 0$, beyond which spin glass order disappears. This point describes a phase transition driven purely by quantum fluctuations. The response of the quantum-critical point to a small temperature and $\Gamma - \Gamma_c$, will determine the location of the quantum-to-classical crossover, and of various other crossovers within the quantum regime (not shown in the figure). A specially interesting regime should appear when $T \neq 0$ and $\Gamma \approx \Gamma_c$, when the typical relaxational frequency, ω is expected to satisfy $\hbar\omega \approx k_B T$, indicating the quantum nature of the dissipative processes; this regime has not yet been experimentally accessed.

Analytic theories of the quantum critical point have so far appeared only for simplified,

and rather unrealistic models: models with infinite-range exchange interactions [4], and models with spins arranged along a single line [5]. The Monte Carlo results of Guo *et.al* and Rieger *et. al.* therefore give us our first opportunity to confront theory and experiment. The result of this is rather disappointing (or not, depending upon one's point of view) as major discrepancies immediately become apparent. In particular, the non-linear susceptibility has a much stronger divergence at the quantum critical point in the simulations, than appears to be the case experimentally.

Given the many years it took to disentangle the complicated phenomenology of classical spin glasses, the present state of affairs in the quantum regime should not be too surprising. It is abundantly clear that some fascinating physics remains to be unraveled, and theorists and experimentalists will keep each other busy for some time.

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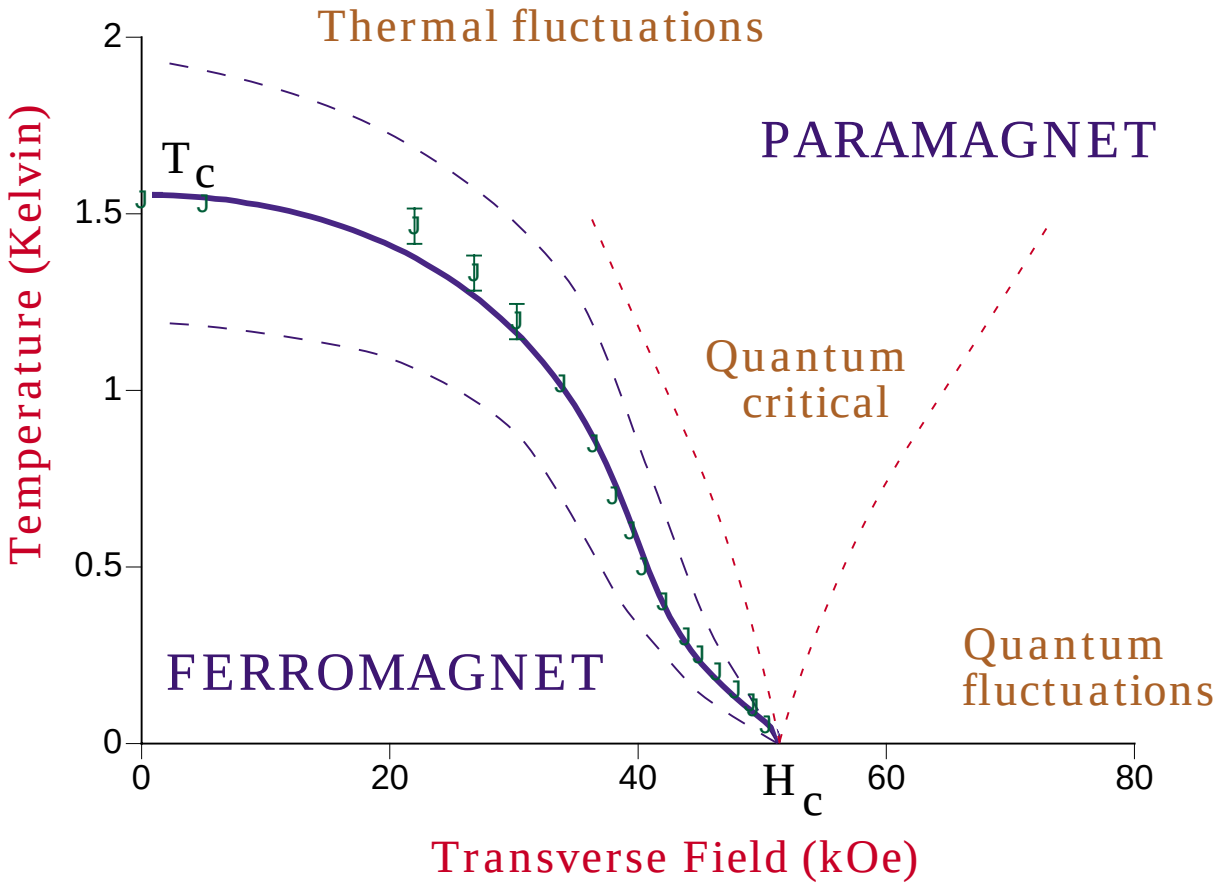

Figure 1: Schematic phase diagram of a quantum spin glass. Γ is a parameter measuring the strength of quantum fluctuations. Low frequency, long-wavelength phenomena in the shaded region are classical. The remainder of the region near $\Gamma = \Gamma_c$ and $T = 0$ requires a full quantum theory.