Ferromagnetic Domains Induced by Dipolar Coupling?

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Motivation—The basic description of ferromagnetic materials is that the magnetic spins on neighboring atoms experience quantum mechanical exchange coupling, which results in substantial parallel spin alignment well below the so-called Curie temperature. Statistical mechanical treatments such as the Ising model describe this emergence of spin alignment near the Curie point. However, exchange coupling is a local interaction, so the interaction between distant spins is dominated by dipole interactions. These interactions are weak, but are long range and have the important effect of causing the aligned spins to break into domains. In a soft magnetic material domain walls move freely, so domains form to nullify the net magnetic moment. Some years ago we had the idea that it should be possible to create a system where dipolar interactions, not exchange interactions, play the role of creating both ferromagnetic ordering and domain formation. This idea is based on using single-domain superparamag- netic nanoparticles as the fundamental entity, which interact only via dipolar interactions. Simulations showed us that organizing these particles into chain-like structures can cause ferromagnetic ordering and domain formation if the particle susceptibility exceeds about 5 (MKS). Because the interaction between domains is weak, the resultant nanocomposite will have an anomalously large susceptibility (Fig. 1). Such nanocomposites are expected to exhibit exceptional properties, such as large magnetostriction at small applied fields.

Accomplishment—Realizing a composite of high susceptibility nanoparticles proved a significant challenge. Standard synthetic routes for Fe and magnetite particles yielded a susceptibility well below the critical value of 5. After some effort, we were able to synthesize 5 nm Fe nanoparticles with nearly bulk saturation magnetism, and susceptibility in the range of 5-10. Due to their large susceptibility, these particles agglomerated so strongly that standard dispersion methods proved ineffective. Dispersion was ultimately achieved by magnetic mixing in an ac triaxial magnetic field. Chain-like structures were created by removing two field components, resulting in a uniaxial composite having an effective particle susceptibility of 181 and 9.9 parallel and perpendicular to the chains, respectively (Fig. 2).

Significance—The large susceptibility we have achieved is a strong indication of the formation of ferromagnetic domains due to dipolar coupling. This susceptibility exceeds by a factor of ten that which is possible in a composite of multidomain particles. Work is now underway to create nanocomposites in an elastomer, to use as an artificial muscle. In the presence of a magnetic field it is expected that such an elastomer will contract with considerable stress, this stress being proportional to the square of the susceptibility. Thus, these nanocomposites should exhibit the same magnetostriction as mesoscale magnetic composites, but with only 1% of the power.

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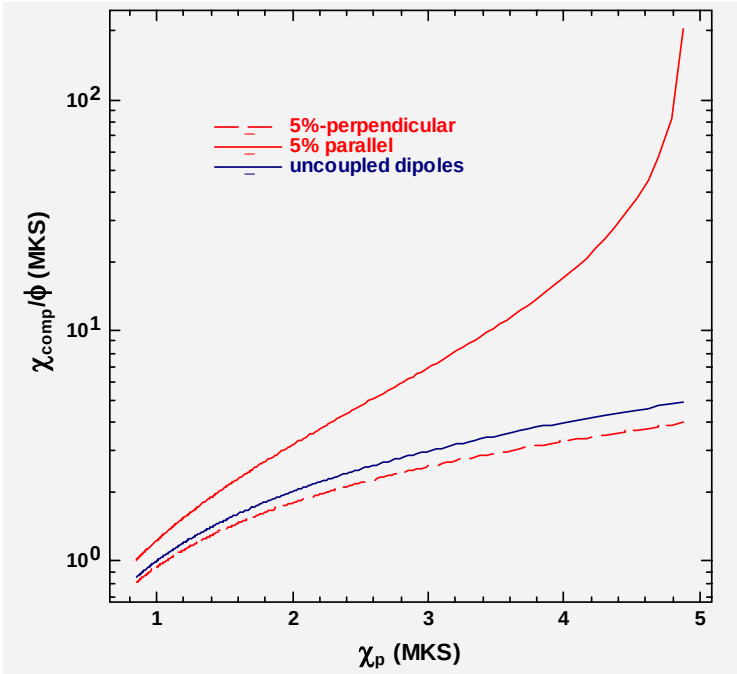

Figure 1. The specific susceptibility of a simulated 5% composite is compared to the susceptibility of a composite of uncoupled Langevin dipoles, where $\chi_{comp}/\phi = \chi_p$, and ϕ is the particle volume fraction. There is a slight suppression perpendicular to the chains. The enhancement becomes quite dramatic (but not infinite) near the critical value for domain formation, $\chi_p \approx 5$.

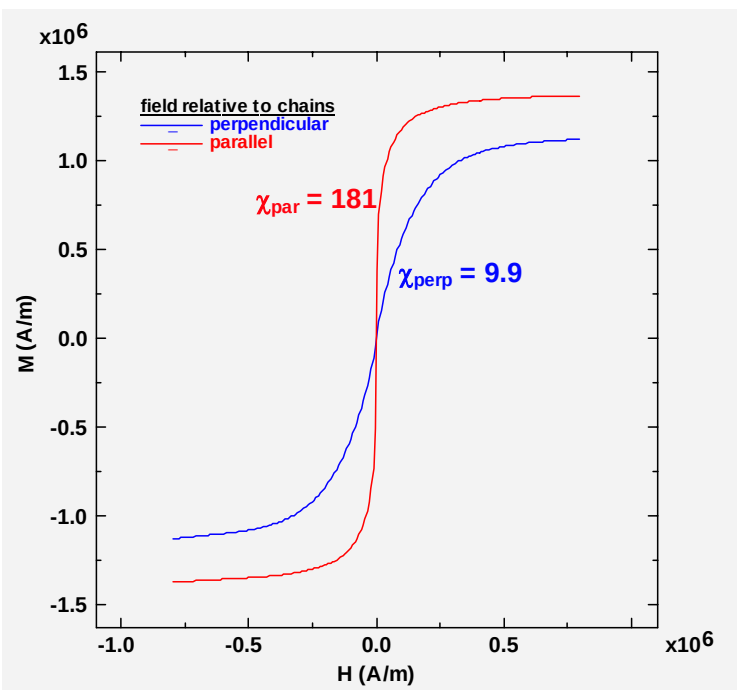

Figure 2. Magnetization curves of the nanocomposite show the enormous effect of structure on the susceptibility. Here the susceptibility parallel and perpendicular to the chains is contrasted.