American Mineralogist, Volume 89, pages 987–997, 2004

Magnetic granulometry from equilibrium magnetization measurements: Mineral magnetometry of superparamagnetic particles and application to synthetic ferrihydrites

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ABSTRACT

Mineral magnetometry is underused in characterizing natural and synthetic nanophase, nanoparticle, and nanocomposite materials, where it has certain advantages over more sophisticated methods, such as high-resolution microscopies and synchrotron-based spectroscopies. We developed the physical theory of direct current (dc) field equilibrium magnetometry of non-exchange coupled superparamagnetic (SP) particles and determined the most information that can be extracted from field and temperature curves, exactly and without making physical assumptions other than those inherent in superparamagnetism and equilibrium measurements. We gave expressions for all field strengths and we did not make any a priori assumptions about the shapes of the distributions of particle size and of supermoment magnitude (μ) or about any relationship between particle size and particle moment. The extracted number average particle mass, $\{m\}$, and extracted moments, $\{\mu^n\}$, of the number distribution of μ are valid irrespective of particle shapes and sizes, of the nature of the (magnetocrystalline or other) anisotropy barrier, of dipolar inter-particle interactions, and of the mechanism of formation of the supermoment (antiferromagnetic mismatch, surface pinning, etc.). We generalized the approach further to treat composite samples that included: (1) a magnetically inert (diamagnetic) matrix phase, (2) various populations of paramagnetic (PM) cations, and (3) contributions from ferrimagnetic (FI) and ferromagnetic (FM) phases. We applied these methods to synthetic 2-line ferrihydrites coprecipitated with different anion species (nitrate or sulfate) and to a synthetic 6-line ferrihydrite. These are the first accurate evaluations of μ and its relation to particle size in ferrihydrite. The particle masses agree with known sizes for similar synthetic samples. The μ/m ratios (i.e., intrinsic mass magnetization values) are consistent with a significantly higher degree of intra-particle order in 6-line ferrihydrite and gave insight into the supermoment formation mechanism.