Thermomagnetic effect in ferrofluids with weakly coupled particles

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Thermomagnetic curves for water based ferrofluid with large magnetic latex particles are analyzed. The particles are found to have extremely low barrier height of thermal relaxation (< 1200 K at temperatures below 100 K) whose field dependence is deduced.

1. INTRODUCTION

We report here on analysis of thermomagnetic (TM) curve measurements which were carried out on a water based ferrofluid with magnetic latex particles. The ferrofluid, often used in various bioseparation techniques, was manufactured by Polysciences Inc., USA (cat. no. 18190). It is distinguished from more common ferrofluid emulsions by the very large particle size, (1.65±0.36) μm on average; the ferrofluid density is 1.3 g/cm³ and the weight fraction is 2.5% in suspension.

The magnetization moment of the sample, sealed in a teflon container, was measured using VSM (resolution 10⁻⁴ emu). The rate of cooling (T_{min} = 35 K) was θ₁ ≈ 3 K/min while the warming up rate was θ₂ ≈ 2 K/min. Above 273 K the magnetization vectors of the particles align with applied field by Brownian rotation, below 273 K by thermally activated magnetization reversal. The transition is accompanied by irreversible ancillary peaks in the TM curves (see Figs.1 and 2 and Ref.1) associated with chain formation and (possibly) with critical fluctuations.

2. ANALYSIS

A demagnetized sample cooled to T_{min} in zero field was subsequently subject to applied field H and warmed up. Increasing temperature facilitates thermally activated magnetization reversal and the sample thus gradually relaxes towards it thermal equilibrium state with instantaneous magnetization M_{eq}(T) which is given by the field cooled (FC) TM curves. At H ≠ 0 we ignore backscattering and assume that the thermal relaxation rate is of the form \( \kappa = f_0 e^{-Q/T} \). For the prefactor we choose the value \( f_0 = e^{25} \) Hz and Q is the barrier height to be overcome by thermal agitation. The function Q = Q(H) is unknown (the particles contain more than one domain) and so is the degree of metastability. We make a bistability assumption and introduce a log-normal distribution [2] of Q. Then the time dependent magnetization \( M[T(t)] = M_{eq}(T)[1 - 2n(t)] \) where

\[
2\sigma(2\pi)^{1/2}n(t) = \int_0^\infty \frac{dy}{y} \exp \left[ -\frac{\ln^2 y/y_0}{2\sigma^2} - \int_0^t d\tau \kappa(y, \tau) \right]
\]

and \( \kappa(y, t) = f_0 \exp[-Qy/T(t)] \), with \( T(t) = T_{min} + \theta_2 t \).

Czechoslovak Journal of Physics, Vol. 46 (1996), Suppl. S4

2021
Fig. 1 Thermomagnetic curves for a field cooled sample, labels denote the applied field magnitude in Oe. Compare the kinks at 273 K with plots of Fig. 2.

The zero field cooled TM curves of Fig. 2 are thus to be fitted using the parameters $Q$ (which determines, roughly, the location of the peak) and $\sigma$ (which governs the rate with which the $M_{eq}(T)$ is approached, i.e. the slope of the TM curve.

We find very good agreement between the heuristic equation (1) and the 20, 50, 100 and 200 Oe curves if we set $\sigma = 0.39$ and choose the values of $Q = Q(H)$ shown in Fig. 3. This plot is remarkable for the very low values of $Q$ (at all shown fields the particles are in thermal equilibrium below 100 K), qualitatively, however, it is similar to the expression $Q \propto (1 - H/H_n)^2$, $H_n$ is a nucleation field, familiar from studies of coherent rotation of magnetization in axially symmetric systems. Here the particles are randomly oriented in the frozen carrier and the effective barrier height (which includes interaction effects) is better expressed by the generalized power law

$$Q = Q_0[1 - (H/H_n)^\alpha]^\beta$$

whose parameters shall be fitted once more data become available.

Fig. 2 Thermomagnetic curves for a zero field cooled sample, labels denote the applied field magnitude in Oe. Dashed lines represent the best fit according to Eq. (1), with $\sigma = 0.39$ and $Q = Q(H)$ shown in Fig. 3.

Fig. 3 The fitted value of the barrier height $Q$ versus applied field $H$. $\sigma = 0.39$ in all fits. The line merely guides the eye.

REFERENCES