

Energy barriers for magnetization reversal of partially exchange-coupled particles

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Abstract

We study the magnetization reversal of a two-particle system with partial exchange coupling. We assume that the particles are discs and that the exchange coupling occurs through one of their plane faces extending up to $5l_w$ into each particle ($l_w = (A/K)^{1/2}$). The easy axis of particle 1 coincides with the direction of the applied magnetic field H and the one corresponding to particle 2 is such that both easy axis are parallel to the contact face.

We assume that the spins reorientation across the contact plane is similar to that of a Bloch wall. We write the free energy E of the system in terms of the fraction β of volume affected by exchange coupling, taking into account the anisotropy and exchange energies due to the spin reorientation and to the fraction $(1-\beta)$ of non-interacting particles' volume. For a given volume V the fraction β can be varied by sliding one particle with respect to the other, changing only the contact area.

We calculate the ratio E/KV as function of H considering the easy axis of particle 2 at different angles with respect to the easy axis of particle 1. We determine magnetic moments switching paths together with the energy barrier ΔE for switching. We find a general expression of the form $\Delta E/KV = (1 - H/H_0)^z$, with $H_0 = H_0(\beta, \omega)$ and $z = z_0 + \alpha(\omega)\beta$, being z_0 and $H_0(0, \omega)$ equal to the values for non-interacting particles.

We discuss the switching behavior as a function of ω and H .

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In a recent work, Bercoff et al. studied the effect of different sintering processes on the magnetic properties of Ba hexaferrite nanoparticles [1]. By constructing the Preisach distribution function of different particulate systems they showed evidence pointing towards partial exchange coupling as the mechanism responsible for the apparition of details in the distribution function which could not be explained by other type of interactions. In the present work, our aim is to analyze in detail the magnetic behavior of partially exchange-coupled nanoparticles under the influence of an external magnetic field. Our treatment is similar to the one made by Chen et al. for single domain particles with dipolar coupling [2] and resembles the approach made by Neu

et al [3]. This type of information would be extremely valuable for the modelling of magnetic information storage in recording media [4].

Our system consists of two disc-shaped nanoparticles that make contact through one of their plane faces and with exchange coupling between the atoms located in the boundary region, as shown in the scheme of Fig. 1. Our aim is to study partial exchange coupling and for this reason the height of the disc-shaped particles is assumed to be higher than or at least equal to the extension of the exchange-coupled region. In order to vary the fraction of the exchange-coupled region maintaining constant the particle volume, sliding of one particle onto the other is allowed and the volume fraction β of the exchange-coupled volume can be defined as contact area times the extension L (or height) of the exchange-coupled volume divided by the particle's volume $V = \text{area} \times L/V$. The limit $\beta = 1$ is obtained when the height of the

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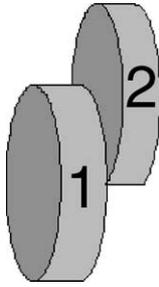


Fig. 1. Geometrical arrangement of particles 1 and 2.

particle is equal to L and there is contact with all the face. We also assume that there is perfect contact between the two grains, to avoid the introduction of an undefined parameter.

In order to introduce the basic ideas of our treatment, let us consider that our particles have the same volume V , uniaxial anisotropy described by the constant K , saturation magnetization M_S and exchange constant A . Their anisotropy axes form an angle ω between them and both of them are parallel to the contact plane. The applied magnetic field H points parallel to the anisotropy axis of particle 1. The free energy E_T of the system per unit area of the contact plane at 0K

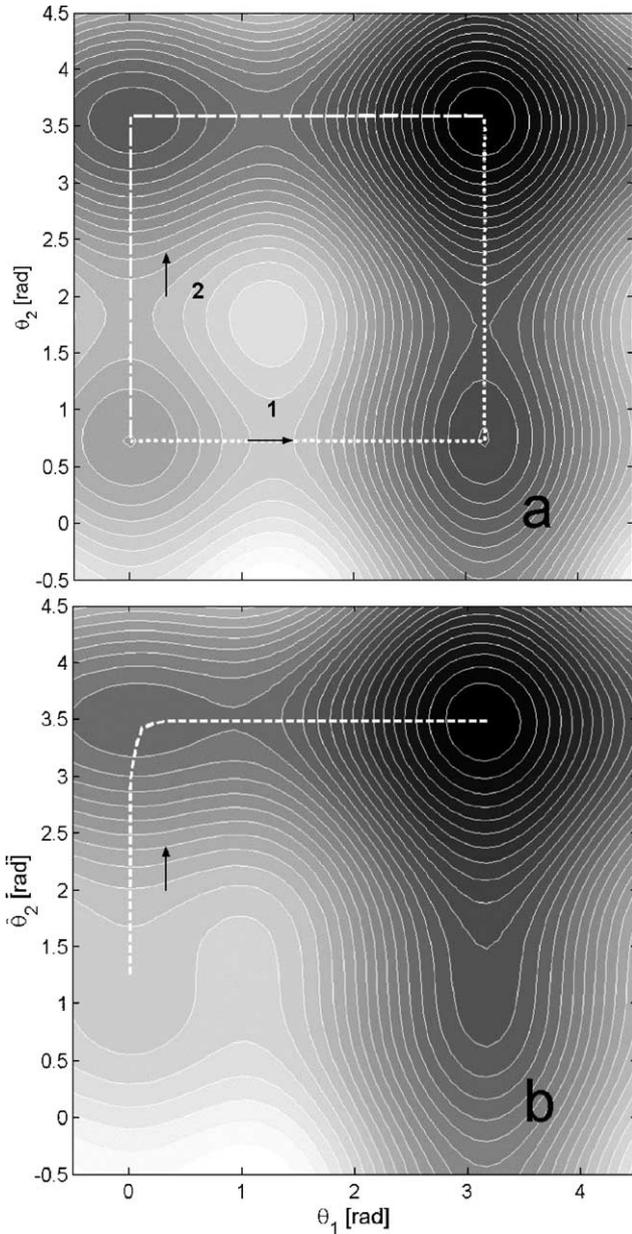


Fig. 2. Contour plot of E_T . Darker shading corresponds to lower levels of energy. (a) $\beta = 0.3$ and $h = 0.3$. The two energy barriers ΔE_1 and ΔE_2 for particles 1 and 2 are marked with **1** and **2**, respectively. (b) $\beta = 0.3$ and $h = 0.53$. Dashed and dotted lines are the inversion paths when thermal activation occurs.

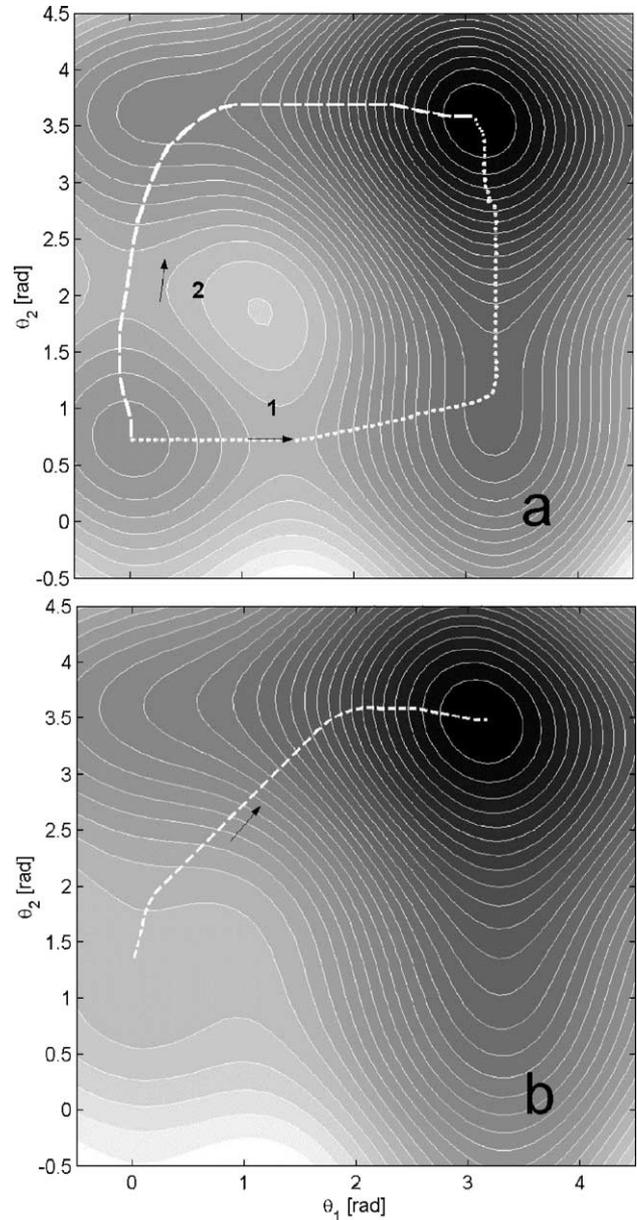


Fig. 3. Contour plot of E_T . Darker shading corresponds to lower levels of energy. (a) $\beta = 1$ and $h = 0.3$. The two energy barriers ΔE_1 and ΔE_2 are marked with **1** and **2**, respectively. (b) $\beta = 1$ and $h = 0.58$. Dashed and dotted lines are the inversion paths when thermal activation occurs.

can be expressed as

$$E_T = \int_{-D}^{+D} \left[A \left(\frac{d\theta}{dx} \right)^2 + K \sin^2(\theta - \omega_i) \right] dx - M_S H \int_{-D}^{+D} \cos(\theta - \pi) dx,$$

where D is the height of each particle. The angle $\theta(x)$ takes the values $\theta_1(x)$ for $x < 0$ (particle 1) and $\theta_2(x)$ for $x > 0$ (particle 2) and the angle ω_i is $\omega_1 = 0$ (particle 1) and $\omega_2 = \omega$ (particle 2). Those are the angles formed by the magnetic moments of particles 1 and 2, respectively, with the easy axis of particle 1 as function of their distance to the contact plane ($x = 0$). As θ_1 will vary between 0 and π , and θ_2 between $-\omega$ and $(\omega + \pi)$, we will simplify our treatment. Instead of calculating the distribution of magnetic moments by minimizing the free energy for each pair of angles, we will assume that the distribution of magnetic moments in the exchange-coupled region is like the one associated with a Bloch domain wall [5]:

$$\frac{\theta(x) - \theta(x = -\infty)}{\theta(x = +\infty) - \theta(x = -\infty)} = \arcsin \left[\coth \left(\frac{x}{l_w} \right) \right]^{-1},$$

where $l_w = (A/K)^{1/2}$ is the appropriate scale length in this case. Under these assumptions we calculated $E_T(\theta_1, \theta_2, h)/KV$ as function of β between 0.1 and 1 and $\omega = \pi/6$. Here h is the reduced magnetic field ($h = H/H_K$) and H_K is the anisotropy field. We chose the angle $\omega = \pi/6$ as it is the mean orientation value for a random distribution of easy axis orientations.

Fig. 2a shows the results for $\beta = 0.3$, $h = 0.3$. In this case, the particles remain in the initial stable position $\theta_1 = 0$, $\theta_2 = \omega$. Two energy barriers separate this state from

others with less energy: ΔE_1 (marked 1) involves changing θ_1 while θ_2 remains constant and ΔE_2 (marked 2) involves changing θ_2 while θ_1 remains constant. It is $\Delta E_2 < \Delta E_1$, so, if thermal activation occurs, an inversion path through the energy barrier ΔE_2 (dashed line in Fig. 2a) will be more likely than through ΔE_1 (dotted line in Fig. 2b), but in either case the inversion of the magnetic moments of the first particle will not induce the other to follow and invert too. Each particle will proceed independently from the other. The difference between ΔE_1 and ΔE_2 becomes lower and lower as h increases. When $\Delta E_2 = 0$, it is $h = h_0 = 0.53$, the inversion field for particle 2. The inversion path proceeds by first θ_2 going to $(\omega + \pi)$, to a shallow minimum, and then θ_1 going to π through a small energy barrier. Particle 2 inverts first and then particle 1, right after (Fig. 2b).

The extreme case $\beta = 1$ with $h = 0.3$ is shown in Fig. 3a. The two energy barriers ΔE_1 and ΔE_2 are now equal and thermal activation of one of them proceeds independently from the other. But when one of them is activated through its energy barrier the other immediately follows because no intermediate minimum is found in this case. So both of them invert their magnetic moments in a coordinated way.

The case $\beta = 1$ with $h = 0.58$ is shown in Fig. 3b, where the energy barrier is zero and both particles proceed following an inversion path where both of them invert their magnetic moments at the same time, in a cooperative manner. Fig. 4 shows the inversion path followed by θ_1 and θ_2 for each β value, when the energy barrier is zero. For low β the particles invert their magnetization independently and for $\beta \geq 0.7$, they act cooperatively.

At temperature $T = 0$ K, magnetization reversal occurs at a reduced field h_0 and is a function of β . The energy barrier

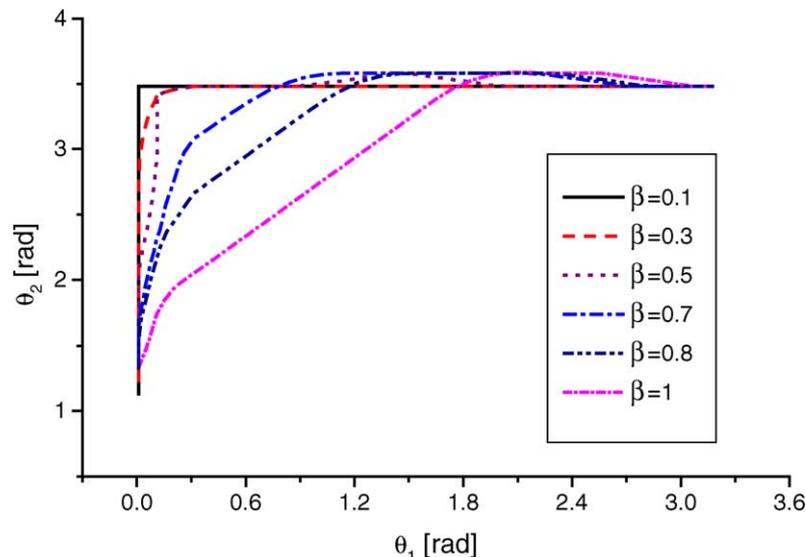


Fig. 4. Magnetic moments switching paths for different β when the energy barrier is zero.

ΔE_2 is the one that controls this process and it is

$$\Delta E_2 \left(h, \beta, w = \frac{\pi}{6} \right) = KV \left(1 - \frac{H}{h_0(\beta)} \right)^{z(\beta)},$$

where $h_0(\beta) = h_0(\beta = 0) + 0.025\beta + 0.007\beta^2 + 0.033\beta^3$ and $z(\beta) = z(\beta = 0) + 0.030\beta$.

The values $h_0(\beta = 0) = 0.522$ and $z(\beta = 0) = 1.48$ are obtained by fitting the calculated ΔE_2 as a function of H and coincide with those found by Pfeiffer for non interacting single domain particles [6].

The results obtained in the calculation of the energy barriers show that for a small interaction volume, each particle inverts its magnetization independently from the other. As the fraction of interaction volume increases, cooperative effects start to be evident and the two particles invert their magnetization in a cooperative way.

The energy barriers found in this work are useful for the modeling of magnetic systems of partially exchange-coupled particles.

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