Paramagnetic beads surfing on domain walls

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Paramagnetic beads electrostatically stabilized in aqueous solution are attracted toward domain walls in magnetic films. The position above the domain wall can be destabilized by realigning the beads magnetic moment with an external magnetic field. The destabilization may result in a steady state dissipative mode, where the beads surf on the slope of the moving domain wall. The technique could be an alternative route to probe electrostatic and hydrodynamic interactions between particles and interfaces, and could also serve as a model system for studying motion in a one-dimensional potential.

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Manipulation of small particles with laser light was pioneered by Ashkin and co-workers [1,2]. This technique has obtained a broad popularity in biology, chemistry, and physics. For example, optical tweezers have been used to measure chemical bond strengths, probe single DNA, colloidal forces, and manipulate Langmuir monolayers [3–6]. Since the laser beam is movable, it is relatively easy to create a one-dimensional potential by scanning. Such potentials could be used to study, e.g., the motion of particles in one dimension or to probe the interactions between colloids and interfaces. On the other hand, magnetic tweezers have long been used for studying local forces in, e.g., biological tissue, to stretch and manipulate DNA, transport ferrofluids, and for probing the cell environment [7–10]. It was recently proposed to use micromagnetic elements to manipulate vortices in superconductors [11,12]. It was shown that a movable magnetic domain wall (DW) can be used to generate, trap, and move vortices due to its highly inhomogenous magnetic stray field. The aim of the current paper is to demonstrate that a DW can also be used to manipulate magnetic colloidal particles on a solid or fluid interface. In particular, it will be seen that by tuning an external magnetic field the wall can attract or repel the colloids, sensitively depending on the external magnetic field. The technique could be an alternative route to probe electrostatic and hydrodynamic interactions between particles and interfaces, and could also serve as a model system for studying motion in an one-dimensional potential.

As the starting point, we use bismuth-substituted ferrite garnet films grown by liquid phase epitaxy on 0.5 mm thick (100) gadolinium gallium garnet substrates to generate the DWs. For details about the garnet films, see Ref. [13]. In the current paper we report studies applying two garnet films, both of thickness 4 μm. Due to the low uniaxial anisotropy, these garnet films have very large (0.1–10 mm) in-plane magnetized domains separated by DWs. The walls can be generated by introducing small defects in the magnetic film (e.g., scratches or inclusions), and then moved by an external magnetic field normal to the film. The typical DW coercivity is about 100 A/m, and it moves 0.1–1 μm per A/m, depending on the local stress distribution and the geometric shape of the surrounding domains. For the weak field modulations studied here (<500 A/m), the DW displacement varied linearly with the applied magnetic field. The DWs can be visualized with a polarization microscope (Olympus A70, used in reflection mode) via their magneto-optic effect, and their displacement controlled with a resolution of 1 μm.

The basic geometry for trapping the magnetic beads (or letting them surf) is shown in Fig. 1(a). The DW shown here is a 180° Bloch wall of width w ($w\sim500$ nm, see, e.g., Ref. [11]), where the magnetization points along the z direction. A

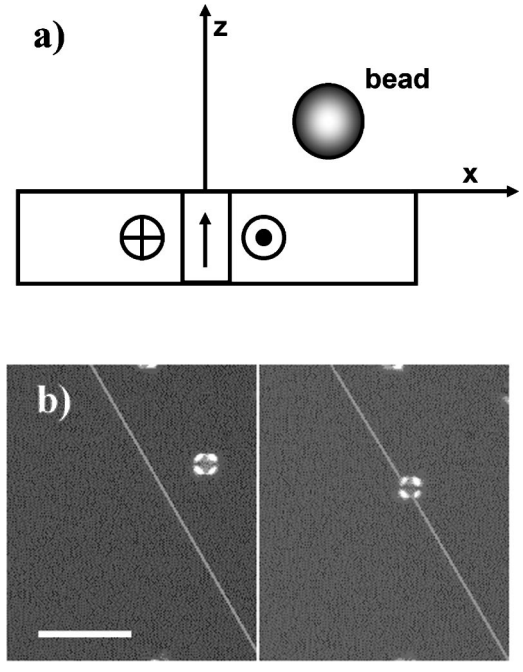

FIG. 1. (a) The basic geometry for a Bloch wall on which a paramagnetic bead can be trapped or surf. The bead is immersed in water, and its center is located at the coordinate (x,z). (b) Two images showing the capture process. The brightness of the DW has been enhanced for clarity. The white bar is 20 μm.

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spherical paramagnetic bead with radius a ($2a=6\pm1$ μm in our experiments) is located at a distance x from the DW, and its center is a height z above it. The paramagnetic beads came from PolySciences (100MP4, Lot No. 997), coated with a carboxylic acid (COOH-) group. Adhesion of the beads to the garnet film could be prevented by coating the garnet film with polysodium 4-styrene sulfonate using the layer by layer adsorption technique [14–16]. The coating results in electrostatic double layer repulsion between the beads and the film. More than 90% of the beads are rendered mobile in this way, while without the coating most of the beads adhere to the surface.

The magnetic field of the DW couples to the magnetic moment of the bead, and the simplest model for the magnetic interaction is to assume that the width of the DW is smaller than all other relevant parameters, and that only the magnetic charges on the upper film surface influences the bead. Then the stray field can be approximated by

$$\boldsymbol{H}_{DW}=\frac{M_s w}{2\pi a}\frac{\hat{\boldsymbol{\rho}}}{\hat{\rho}^2},\qquad \hat{\rho}=\sqrt{\hat{x}^2+\hat{z}^2}, \tag{1}$$

where M_s is the magnetization of the garnet film, $\hat{\boldsymbol{\rho}}$ is a vector pointing from the DW to the bead, $\hat{x}=x/a$ is the normalized distance from the DW to the center of the bead, and $\hat{z}=z/a$ is the normalized height above the DW. Here $\hat{z}>0$. In general, the force from the domain wall on a magnetic bead is given by $\boldsymbol{F}=\mu\boldsymbol{\nabla}(\boldsymbol{m}\cdot\boldsymbol{H})$, where μ is the permeability of water, $\boldsymbol{m}$ is the magnetic moment of the bead, and $\boldsymbol{H}$ is the sum of $\boldsymbol{H}_{DW}$ and the homogenous external applied field in the z direction, $\boldsymbol{H}_{ex}$. The paramagnetic bead can be modeled as a point particle with magnetic moment $\boldsymbol{m}=(4\pi/3)a^3\chi_{eff}\boldsymbol{H}$, where χ_{eff} is the effective susceptibility. The field align the magnetic moment of the bead, and the x component of the force is found to be

$$F_x=-\frac{2\mu}{3\pi}\chi_{eff}(M_s w)^2\left(1+\frac{4\pi a\hat{z}}{w}\frac{H_{ex}}{M_s}\right)\frac{\hat{x}}{(\hat{x}^2+\hat{z}^2)^2}. \tag{2}$$

Let us now assume that there are no external fields ($H_{ex}=0$), which means that the force is always attractive, with a maximum at $\hat{x}=\hat{z}/\sqrt{3}$. The upper limit of χ_{eff} is of the order of unity, and the maximum attractive force using paramagnetic beads is therefore estimated to be $|F_x^{max}|=\mu\chi_{eff}M_s^2w^2\sqrt{3}/(8\pi\hat{z}^3)\sim$ 0.6 nN.

Figure 1(b) shows consecutive polarized microscopy images of a paramagnetic bead being attracted to a Bloch wall. The typical time scale for this process is a few seconds, depending on the distance to the wall. Figure 2 shows the particle kinetics determined from the images for two $Lu_{2.5}Bi_{0.5}Fe_{5-y}Ga_yO_{12}$ garnet films ($y=0$, squares, and $y=0.1$ circles), both with magnetization $M_s\sim200$ kA/m. Since inertia is negligible, we may assume that the lateral magnetic force is balanced by a viscous drag $F_{drag}=(\eta f a^2/\tau)(d\hat{x}/d\hat{t})$, where $d\hat{t}=dt/\tau$, $\tau=3\pi\eta a^2 f/2\mu\chi_{eff}(M_s w)^2$ is a characteristic time scale, f is the effective viscous drag coefficient, and η is the viscosity of water ($\eta\approx10^{-3}$ Ns/m^2). Solving the resulting differential equation, we find the normalized time to be

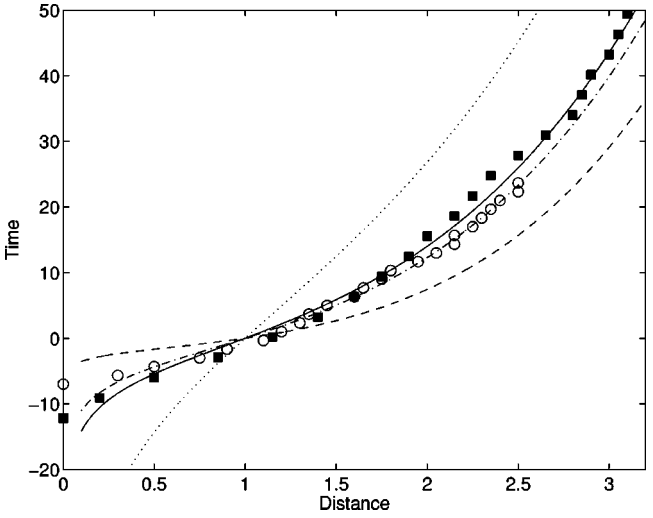

FIG. 2. Experimental data (boxes and circles) of the attraction kinetics of two different paramagnetic beads moving toward a Bloch wall. The plot shows the normalized time ($\hat{t}$) versus the normalized distance ($\hat{x}$). The size of the symbols represent the experimental uncertainty. The theoretical curves correspond to beads separated by different heights from the Bloch wall; $\hat{z}=1$ (dashed line), $\hat{z}=1.4$ (dash-dotted line), $\hat{z}=1.5$ (solid line), and $\hat{z}=2$ (dotted line).

$$\hat{t}=\frac{t-t_0}{\tau}=\frac{1}{4}(\hat{x}^4-1)+(\hat{x}^2-1)\hat{z}^2+\hat{z}^4\ln|\hat{x}|, \tag{3}$$

where t_0 is arbitrarily set to be the time where $\hat{x}=1$. This model gives a logarithmic divergence at $x=0$, since the force is zero here. Finite size of the bead will smooth out this divergency, and one cannot expect the model to provide a good fit near the origin. We fit our model to the experimental data by letting t_0, τ, and $\hat{z}$ be free parameters. The results are shown in Fig. 2. The solid line corresponds to $\tau_1=0.065\pm0.004$ s and $\hat{z}_1=1.5\pm0.1$, whereas the dash-dotted line gives $\tau_2=0.30\pm0.02$ s and $\hat{z}_2=1.4\pm0.1$. In addition, the dashed and dotted lines shows theoretical values for $\hat{z}=1$ and $\hat{z}=2$, respectively.

If we now assume that the magnetic parameters for the beads (and for the DWs) are identical, only the drag coefficients change, and the ratio between the two coefficients is $f_1/f_2=\tau_1/\tau_2\approx0.2$. In the creeping motion approximation (when $\hat{z}\to1$), the ratio is found to be $f_1/f_2=\ln[\hat{z}_1-1]/\ln[\hat{z}_2-1]$ for a freely rotating sphere [17]. Using the values of $\hat{z}$ found from the fitting of the curves we find $f_1/f_2\approx0.8$. One possible explanation for this deviation is that the assumption of a freely rotating sphere is not valid, and that the bead rotates with the inhomogenous magnetic field, thereby enhancing the coupling to the interface at small z. It should also be emphasized that we have considered z to be a constant. This may not be the case, as there is also a

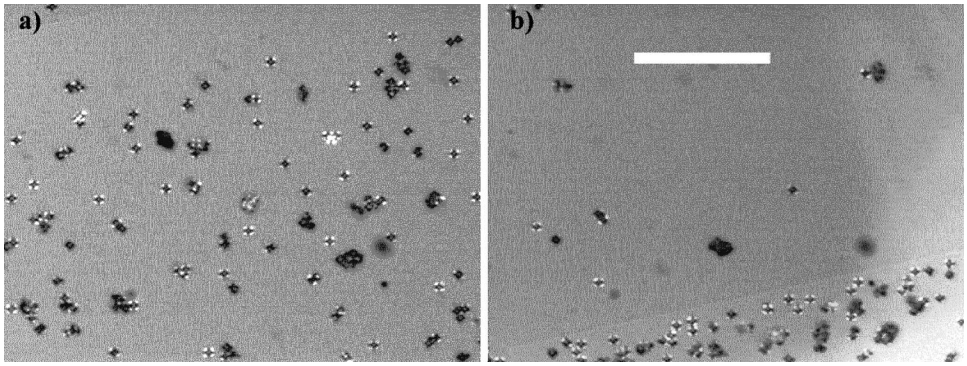

FIG. 3. Paramagnetic beads surfing on a DW. In (a) the DW is in the upper left corner, and the field strength is 640 A/m. In (b) the beads have surfed on the DW to the lower part of the image. Now the field strength is 1040 A/m. Note that some particles ($<10\%$) adhere to the substrate, and do not move with the DW. The white bar is 100 μm.

vertical force tending to drag the bead towards the interface. On the other hand, a reduction in z should lead to a nonlinear behavior of the drag coefficient, which is apparently absent here.

We have seen that the DW can trap and move magnetic particles. However, in presence of a strong external field opposing that of the DW, the beads are repelled from the Bloch wall. As seen from Eq. (2), the critical field is $H_c = -M_s w/(4\pi a\hat{z})$, which in the current case is estimated to be about 1500 A/m (assuming $\hat{z}=1.5$). Experimentally we find that the beads are repelled at fields above 500 A/m. This could be explained by the fact that the same external field is used to both realign the beads and move the DW. Thus, there is a hydrodynamic drag assisting the detachment process. Moreover, it should be mentioned that there is an interaction between the external field and the magnetization of the garnet film, which alters the DW as well as the coupling to the bead in areas outside the DW.

A nonequilibrium steady state situation occurs if one sweeps the external magnetic field at a certain rate, such that the velocity of the DW coincides with the velocity of the bead. Under these circumstances the bead surfs on the repulsive potential of the DW. Figure 3 shows the paramagnetic beads surfing on the DW from the upper to the lower part of the visualized area. The whole operation took approximately 1 min., and we had to move the DW several times back and forth in order to bring with us all the particles.

In conclusion, we have demonstrated a technique for manipulating colloidal particles. It should be noted that it is not limited to particles resting on the magnetic film. The particles could also be deposited on a different interface, with the magnetic film facing the particles from above. Since garnet films are transparent at visible wavelengths, one may use a microscope to look at the particles through the garnet film. It could be of interest to investigate the interaction between beads trapped by the DW, thus providing an one-dimensional model system which could complement that of Ref. [18]. We therefore hope that the technique could add an additional degree of freedom in the study of colloidal systems [19–24].

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