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# Magnetic measurements of suspended functionalised ferromagnetic beads under DC applied fields

Luis De Los Santos V. [a,*], Justin Llandro [a], Dongwook Lee [a], Thanos Mitrelias [a], Justin J. Palfreyman [a], Thomas J. Hayward [a], Jos Cooper [a], J.A.C. Bland [a], Crispin H.W. Barnes [a], Juan L. Arroyo C. [b], Martin Lees [c]

[a] Cavendish Laboratory, University of Cambridge, J.J Thomson Avenue, Cambridge CB3 0HE, United Kingdom
[b] Facultad de Química e Ingeniería Química, Universidad Nacional Mayor de San Marcos, Avenue Venezuela S/N, Lima 1, Peru
[c] Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom

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## ABSTRACT

In this work, a simple technique to obtain the hysteresis loops of magnetic beads (Spherotech Inc.) in liquid suspension is presented. The magnetic measurements were taken in a DC Magnetic Property Measurement System (MPMS-SQUID sensor). Samples were based on ferromagnetic beads (surface-functionalized $NH_2$, mean diameter 4.32 μm) prepared in three conditions: dry, suspended in sucrose solution and in suspension after functionalization with fluorophore. Special small containers (1.3 cm long) made of non magnetic plastic were designed to hold the beads in liquid. The results indicate that the bead's remnant magnetization is half of the value at maximum applied field in all cases. However, due to the additional degrees of rotational freedom, beads suspended in a liquid do not present coercivity. The use of ferromagnetic beads and magnetic elements of different architectures for applications in bioassays is also discussed.

## 1. Introduction

The use of magnetic beads is of current interest in technology and especially in biological-related research and biotechnological applications. Particles are used in new colloidal suspensions called electrorheological fluids, which respond to an applied electric field by rapidly changing their apparent viscosity [1,2]. Particles functionalised with a variety of biochemical moieties such as antibodies, proteins or oligonucleotides are also employed in the areas of medical research and biological analysis. In addition, flow cytometry has revolutionized biological assay methods by making it possible to sort and separate literally millions of microscopic objects in minutes. Another important role of magnetic particles is their use in magnetic biosensors for labelling and screening biomolecules. A novel method for performing high throughput bioassays using digital magnetic tags that can be functionalised with various probe molecules has recently been proposed and is under development in our group [3]. The method is based on the concept of using the magnetic properties (moment, magnetization direction) of specially designed tags for encoding information (code) related to the identity of the probe molecules attached to the surface of the tags. The tags can be used in a bioassay and reveal the identity of target molecules that hybridise to the probes [4]. One implementation of magnetic encoding necessitates the use of magnetic beads, whereby target biomolecules are screened according to the moment of the beads they are attached to. A novel scheme utilizing Magnetic Avalanche Digital Detectors (MADDs) has recently been reported [5], in which individual suspended beads are detected by the effect of their stray field on the reversal processes of electrically contacted pseudo-spin valve rings. Most of these applications necessitate the use of particles suspended in solutions. For the MADD device, knowledge of the behaviour of the magnetic particles suspended in a fluid and placed under externally applied fields is important, because beads with a high moment and a large susceptibility are desired.

Despite the fact that the behaviour of magnetic particles in fluids can be deduced by means of particle fluid-dynamics, electrophoresis and magnetophoresis theory, few experimental studies can be found in the literature. Most theoretical formulas are obtained for particles in the size range from approximately 1 μm to 1 mm because the mechanics of submicron particles are strongly influenced by random thermal (Brownian) motions and

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[*] Corresponding author. Tel.: +44 1223 337006; fax: +44 1223 337200.
*E-mail addresses:* luisitodv@yahoo.es, ld301@cam.ac.uk (L. De Los Santos V.).

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Van der Waals forces. The upper limit ($10^{-3}$ m) is based on a reasonable working definition of what constitutes a classical particle [6,7]. The two main forces acting over a classical particle suspended in liquid medium are the gravitational force ($F_G$) and the buoyancy force ($F_B$), which cancel each other in opposite directions at equilibrium

$$F_G = \frac{\rho_p \pi d_p^3 g}{6} \tag{1}$$

$$F_B = \rho_a \frac{\pi d_p^3}{6} g \tag{2}$$

where $\rho_p$ and $\rho_a$ are the densities of the particle and the fluid, respectively, $d_p$ is the diameter of the particle and $g$ the gravity constant. When an external magnetic field is applied to a particle, a force called 'magnetophoretical' ($F_M$) appears, and according to [6]

$$F_M = 2\pi\mu_1 r^3 \left(\frac{\mu_2 - \mu_1}{\mu_2 + 2\mu_1}\right) \nabla H^2 \tag{3}$$

where $\mu_1$ and $\mu_2$ are the magnetic permeabilities of the fluid and the particle, respectively, $H$ the external applied field and $r$ the radius of the particle. In addition a drag force $F_D$ appears every time the particle changes position

$$F_D = \frac{\pi d_p^2 \rho_a v^2 C_D}{8} \tag{4}$$

where $C_D$ is the drag coefficient ($\sim$24/Re, where Re is the Reynolds number. Since the regime for microfluids is laminar, $\mathrm{Re} < 2.0$ [8]).

Measuring hysteresis loops of magnetic particles suspended in fluids is rarely reported in the literature. In most studies hysteresis loops are indirectly derived from AC susceptibility measurements [9–13]. The principal reason is the lack of equipment suitable for this task, although some researchers have designed their own instruments to measure susceptibility as a function of $H$ (e.g. toroidal technique designed by Fannin [14]).

In this work, magnetic measurements of ferromagnetic beads in liquid suspension are performed with a classic Magnetic Property Measurement System (MPMS) Quantum Design. To achieve such measurements special holders for liquid samples were designed. The initial purpose of these measurements was to investigate the compatibility of the ferromagnetic beads with MADD biosensor designs. Specifically, knowledge regarding the possibility of switching ferromagnetic beads using the small magnetic fields generated by the electric currents flowing through MADD sensors was desired [15]. Comparisons between the $M$–$H$ loops of dried beads and beads held in suspension were expected to show whether the magnetic switching of suspended ferromagnetic switching of suspended ferromagnetic beads is dominated by physical rotation of the beads, or the alteration of their internal magnetic structure.

## 2. Experimental

Amine-functionalized ferromagnetic beads (Spherotech Inc.) with mean diameter 4.32 μm (see Table 1) were dried, suspended in deionized (DI) water or functionalized with 5 (6)-carboxy-tetramethylrhodamine (5-(6)-TAMRA). Functionalization of samples was achieved following the procedure described in [16]. Fig. 1 shows a fluorescent microscopy image showing the TAMRA-labelled beads.

**Table 1**
Characteristics of ferromagnetic beads for DC SQUID measurements.

| Cat no. | Chemistry | Mean diameter | Amount beads/mL |
|---|---|---|---|
| AFM4010 | $NH_2$ | 4.32 μm | $2.3 \times 10^8$ |

The beads were separated from water using either a centrifuge or magnetic separation. The former case required 13.2 rpm during 6 min whereas the latter is achieved by simply placing the bead solution in the vicinity of a magnetic field. After separating the beads from the water, they were dried in an oven at 35 °C overnight. In some cases it was better to evaporate the remaining water from the beads in a vacuum bell (around $10^{-1}$ mbar).

Preparation of samples consisting of beads in suspension was more elaborate. The density of DI water is too low to hold beads in suspension over long timescales (4–6 h are required to acquire data from the magnetometer). To avoid sedimentation, the beads were suspended in a 30% w/v and 40% w/v sucrose solution, which were prepared by dilution of 3 g (4 g) sucrose (Sigma Ultra 99.55GC) in 7 and 6 ml of DI water, respectively. These solutions were labelled as 3 × sugar and 4 × sugar, respectively.

Since the standard holder for the magnetometer consists of a simple gelatine capsule designed specially for powder and dried samples, a new holder for the solution containing the beads was designed. The equipment used for the magnetic measurements was a DC Magnetic Property Measurement System with SQUID (Quantum Design). The encapsulated sample is placed in a plastic tube and then slid down into the SQUID which is a low-pressure environment. There are two risks at this point. Firstly, the capsule begins to dissolve on contact with the liquid sample. Secondly the low pressure in the SQUID equipment could induce evaporation, and in this way not only the samples are lost, but also the equipment could suffer serious damage.

The new sample holder consisted of diamagnetic truncated cone made of plastic, 13 mm long (Fig. 2). A drop of approximately 1 μL of suspended beads in sucrose solution with a concentration of about 1.0% w/v, filled it. The ends were sealed with mounting wax. The new container was robust enough to support a pressure

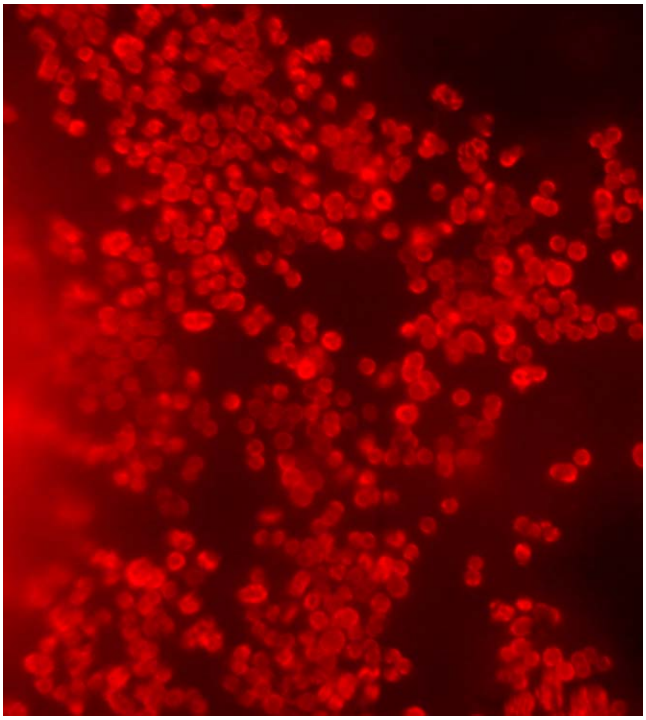

**Fig. 1.** Fluorescent microscopy image of 4.32 μm TAMRA-labelled ferromagnetic beads.