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TRAPPING MICROPARTICLES WITH STRONGLY INHOMOGENEOUS MAGNETIC FIELDS

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By using micron size permanent magnets we have trapped directly single diamagnetic micron size polystyrene microspheres inside a buffer solution with a magnetic field and demonstrated self-assembly of several hundred microns long chains of microspheres in magnetic traps.

Keywords: Magnetic traps; self-assembly; inhomogeneous magnetic field

1. Introduction

It is energetically favorable for a diamagnetic body to stay in a magnetic field minimum, with a restoring force proportional to the gradient of the magnetic energy density. We have suggested¹ that by using magnetic micro/nanostructures, magnetic field minima can be made in a variety of shapes and sizes, thus creating different types of traps, localized or extended. Here we report the first direct trapping of single micron-size polystyrene microspheres (beads) inside a buffer solution, by a field created by permanent micromagnets. The restoring magnetic force in such traps can be three orders of magnitude larger than the gravitational force or the force due to thermal fluctuations.

Lord Kelvin² showed that a diamagnetic body can have stable equilibrium in a magnetic field minima and that this does not contradict the Earnshaw³ theorem, that no stable equilibrium is possible if particles interact according to Coulomb's law (i.e. a $1/R^2$ dependence for the interaction force). Recently, diamagnetic levitation of centimeter scale bodies, including living species⁴, has been demonstrated inside powerful superconducting magnets. Furthermore, different types of magnetic traps, which use magnetic field minima to magnetically trap ultracold atoms were developed in recent years^{5,6}. We are also using magnetic field minima to trap micro/nanoscale particles, but our magnetic traps operate under very different conditions:

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- (i) the gravitational force is negligibly small in comparison with the force due to the magnetic energy gradient,
- (ii) we trap micron scale objects which are at room temperature, magnetically,
- (iii) the magnetic energy gradients in our traps are two to three orders of magnitude stronger and can be enhanced by an additional three orders of magnitude.

Micron scale beads can also be manipulated with optical tweezers. This method was introduced in 1986⁷, and since then it has been developed to a high degree of sophistication⁸. Our approach has the potential, not only to provide a simple and inexpensive alternative or a complimentary method for many experiments/operations performed with optical tweezers, but also to perform operations which can be difficult or impossible to realize with optical tweezers (see Conclusions).

2. Experimental Methods

We have used a quadrupole type trap. These traps were built using two neodymium iron boron magnets with opposite magnetization direction, mounted on a microscope slide. The permanent magnets were thin sheets about 10mm on a side with thicknesses in the range of 0.1 to 2 mm, dependent on the volume of material to be trapped. They were cut from magnetic NdFeB cubes with a diamond saw or an electrical discharge cutter. They were magnetized parallel to their plane in a 10T field. Based on Hall probe measurements on the bulk material from which the magnets were cut, the maximum field strength at their surface is about 0.55T. They were then polished and a pair was glued to a microscope slide with a gap between them of about one-half their thickness. The magnetization of each magnet was normal to the gap and opposite to that of the other. The magnets were coated with an acrylic layer a few microns thick to protect them from corrosion.

The measurements reported here were performed with latex polystyrene microspheres carboxylate modified and dyed with a diameter $d = 2$ microns (Catalog No. L3030, Sigma) and with a diameter $d = 0.8$ microns (Catalog No. L1398, Sigma). The spheres were dispersed in the water solution of 2.7M (pH =2.25) $DyCl_3$ prepared by dissolving $DyCl_3 \cdot XH_2O$ 99.9% (REO) (Catalog No. H30J37, Alpha Aesar) in de-ionized water at 295K. The measured solution density was 1.73 g/cm³. The solution was close to or at saturation. The magnetic susceptibility of the solution, measured with a Lake Shore susceptometer, was $\chi = 1.4 \times 10^{-4}$ at 295K. The calculated value of $\chi = 1.3 \times 10^{-4}$ was obtained by using the standard formula⁹ $\chi = (N/V)(p^2 \mu_B^2 / 3k_B T)$ where $p = 10.6$ for Dy . A paramagnetic environment has been used previously¹⁰ to enhance the force acting on a diamagnetic body in a magnetic field, where paramagnetic compressed oxygen was used in the levitation of water. The beads and the glass walls can have a large surface charge density. However, the high ion concentration in the buffer solutions reduces the Debye-Hueckel screening length to a few nanometers. As a result, electrostatic interactions at the submicron scale can be neglected.

A Leitz Dialux microscope and a Zeiss AxioPhot 2 microscope at the TAMU Microscopy and Imaging Center equipped with a Nikon DXM1200 Color Digital Camera with 1280x1024 pixel resolution and maximum rate of 12 frame/s was used to study the trapping. AxioPhot2 is equipped with an Optivar magnification doubling device. Pictures were taken either as single frames with a resolution of 1280x1024 pixels or as a set of 180-270 frames (video clip) with a time interval between frames of 0.1-0.15 seconds with resolution 640x480 pixels. We usually used 20X-40X objectives and the Optivar magnification doubling device.

3. Experimental Results

The magnetization of each magnet was directed in-plane, and normal to the slit between the magnets. As a result, the magnetic field has minimum values along a line between the magnets. Once inside the magnetic field region, beads are forced to move into the low field regions by the magnetic energy density gradient. There are two such regions: inside the solution in the magnetic trap and on the outside at the droplet surface.



Fig. 1. The self assembled bead chain in a linear magnetic trap. The bead diameter is 800nm.

Real NdFeB magnets are inhomogeneous at the $100\mu\text{m}$ scale simply due to their fabrication technique: they are manufactured by sintering powder with a typical grain size of about 50-150 microns. In addition to this inherent inhomogeneity, the magnets may vary in thickness along the slit, the borders of the slit may not be perfectly straight, or they may be misaligned, etc. All of these factors contribute to the magnetic field distribution. The inhomogeneity creates traps in a variety of sizes and strengths. In this work we have used such self-organized traps to observe different cases of magnetic trapping. The trap can be controlled by fabrication of prototypes with different parameters to produce traps with desired properties. Indeed, the trap design is extremely simple, cheap and allows “mass production”. This is consistent with the fabrication philosophy at the nanoscale. Despite the deficiencies described above, the current design of magnetic traps has important advantages:

- (i) traps load automatically from the buffer solution;
- (ii) the gravitational force is negligibly small in comparison with the force due to the magnetic energy gradient,

(iii) the gradients of magnetic energy density in our traps are two to three orders of magnitude stronger than those in superconducting magnets or magnetic traps for atoms, and can be enhanced by an additional three orders of magnitude.

The final distribution of trapped beads depends on the trap size, shape, magnetic field strength and the initial concentration of the beads dispersed in the buffer solution. Fig.1 shows a self assembled chain of $0.8\mu\text{m}$ beads in a linear magnetic trap. The main goal of this letter is to prove the concept of the effective trapping of micron size objects directly by an inhomogeneous magnetic field. We have observed deep magnetic traps with no detectable thermal motion of trapped single beads within the experimental time resolution (0.1s) and position resolution ($0.1\mu\text{m}$) due to a restoring force that is up to three orders of magnitude larger than the average force due to thermal fluctuations (see below). We also have observed long periods (up to tens of minutes) of non-equilibrium motion of beads in shallow traps. Spatially restricted motion inside the solution graphically demonstrates the very existence of the magnetic traps. The buffer solution flows without restriction through the magnetic traps. We assume that the driving force for the observed motion is due to convective currents in the buffer solution caused by heating from the intense light source.

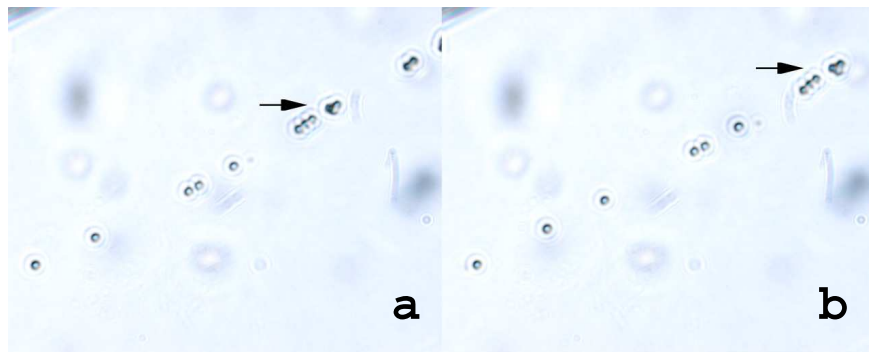


Fig. 2. Two micron size beads floating in a linear magnetic trap. The beads flow inside the trap along the straight line inside the buffer solution where the magnetic field has its minimum. Arrows show the position of linked beads which serve as a marker for the motion.

Fig.2 shows two time sequences for a stream of well separated 2 micron size beads inside a linear magnetic trap. The velocity of the beads is about $10\mu\text{m/s}$. They flow inside the trap along the straight line inside the buffer solution where the magnetic field has its minimum. Dependent on the initial concentration in the buffer solution, the density of the beads in the linear trap can vary from a few beads in the whole linear trap to the situation when this trap has one or more rows of beads (see Fig.1). It is thus possible to control self-assembly of the beads into short or long micro-rods (or microwires).

4. Discussion

The energy of a diamagnetic object of volume V and with susceptibility χ_o which is placed inside a paramagnetic solution with susceptibility χ_s in the magnetic field with strength H is given by: $E_V = -(1/2)C_s(\chi_o - \chi_s)H^2V$, where the geometrical factor C_s depends on the shape and orientation of the body and on χ_o and χ_s . The value is -1.27×10^{-5} for graphite and -7.0×10^{-7} for water. The value of the buffer solution susceptibility is an order of magnitude larger than the magnitude of the largest susceptibility of any diamagnetic substance. Consequently, $|\chi_o|$ for materials of interest is negligible in comparison to χ_s . The average magnetic force F_M , which acts between the center line of the trap and the surface of the magnets, can be estimated as $F_M \approx 2E_V/l$, where the distance l between magnets was as small as $50\mu\text{m}$ and the magnetic field H is about 5kOe . The force F_M is thus much larger than the gravitational force F_G which acts on the same particle, with the ratio $F_M/F_G \approx 10^3$. The average magnetic restoring force which holds the bead in the magnetic trap is $F_M \approx 30\text{pN}$, Archimedes' force is $F_A \approx 0.07\text{pN}$, and the average force due to thermal fluctuations is $F_T \approx 0.01\text{pN}$ ¹¹. The important criteria for static equilibrium is the energy of the thermal fluctuations in comparison with the potential well depth due to the magnetic field, i.e. the condition $(k_B T/E_V) \ll 1$. Setting this ratio equal to one gives the minimum value of the volume $V_{min} \approx 2 \times 10^{-5} \mu\text{m}^3$, of a particle which can be trapped under static equilibrium conditions.

The amplitude of the thermal fluctuations of a micron size bead trapped in a deep magnetic trap' $E_V \approx 1.8 \times 10^5 k_B T$ for a 2 micron diameter bead, can be estimated as $\langle a \rangle \approx (l/2)(k_B T/E_V)^{1/2} \approx 60\text{nm}$. The period of the thermal fluctuations can be estimated as $\tau \approx (\pi l)(m/2E_V)^{1/2} \approx 2 \times 10^{-5}\text{s}$. Both the period and the amplitude of oscillation are far below our resolution.

Conclusions

To conclude, we have proven the concept of the magnetic trap for the micron size diamagnetic particles. This scale is of the order of the typical size for bacteria and cells. Cells size can reach even hundred(s) of microns. Thus the magnetic trapping approach in currently existing form described here can be applied to trap and manipulate cells and bacteria. Theoretical estimates¹ predict an additional three or four orders of magnitude improvement in magnetic trap performance which can be achieved with arrays of magnetic nanowires currently under development in several laboratories^{12,13}. This can allow manipulation with macromolecules like DNA and proteins and nanotubes. Further development of the magnetic trap approach can result in new methods for biochemical/microbiological analysis and new tools in micro/nanofluidics, in biophysics and in fundamental studies in statistical mechanics. Permanent magnet traps may be also developed further to be used to trap ultracold atoms.

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