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## Introduction

The use of nanoparticles combined with magnetic fields has gained big importance in medical diagnosis and therapy over the last years. It has also contributed to the improvement of pharmaceutical research and biological methods.

For these purposes, exactly knowing the magnetic properties of the used particles and the impact of their interaction on their behavior in blood vessels and airways is fundamental.

In magnetic drug targeting, using different high concentrations of drug loaded nanoparticles showed that their ability to follow the magnetic field and their responsiveness to the external magnetic forces increase non linearly with the number of involved nanoparticles. This suggests a nonlinearity in the resulting total magnetic properties of the samples.

To investigate this issue, we conceived a simplified but efficient measurement setup to precisely determine the total magnetic moment of different nanoparticle samples.

Based on a high precision balance and a strong permanent magnet or electromagnet, the developed method allows the measurement of the magnetic force on different nanoparticles charges and shapes, and therefore the deduction of their total magnetic moment.

## Method

This technique is derived from the application of magnetic forces on magnetic nanoparticles (MNPs). A magnetic field gradient exerts a magnetic force on a given MNP, following this rule:

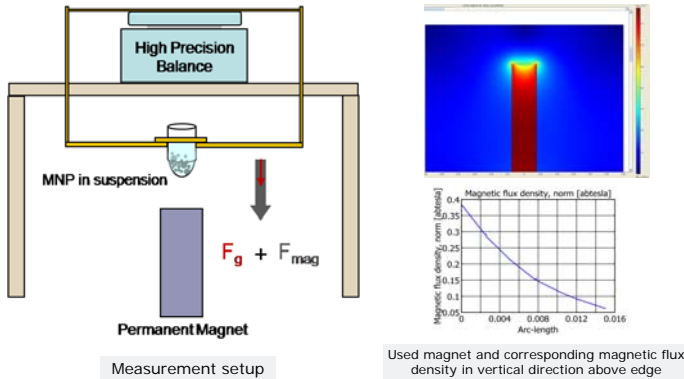
$$\vec{F}_{mag} = (\vec{m} \nabla \vec{B})$$

where

$\vec{m}$  is the magnetic moment of the particle

$\vec{B}$  is the magnetic flux density

Observed in one direction, this gives  $F_{mag,x} = m(B) \cdot \frac{\partial B}{\partial x}$



For a suspension of nanoparticles in an inhomogeneous magnetic field, at a point in space with a known gradient, the displayed mass is directly proportional to the magnetic moment of the suspension:

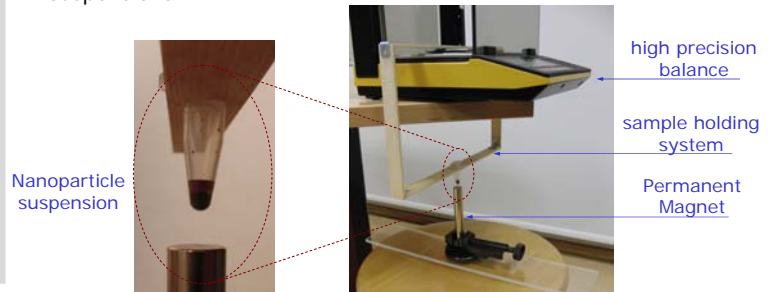
therefore

$$\text{Displayed Mass - Weight of the sample} = \frac{\text{magnetic Force}}{\text{gravitational acceleration}}$$

With a high precision balance of 0.1mg resolution, minimal detectable magnetic forces are in the range of

$$F_{mag,min} = 0.1 \cdot 10^{-6} \text{ kg} \cdot 9.81 \frac{N}{kg} \approx 10^{-6} N$$

which covers the scope of many applications using nanoparticle suspensions.



## Application

The method was used to determine the total magnetic moment of a sample of MNPs for different particle quantities.

The magnetic moment of an MNP can be written to

$$\vec{m} = \frac{m(\|\vec{B}\|)}{\|\vec{B}\|} \vec{B} \quad \text{with} \quad m(\|\vec{B}\|) = \iiint_V M(\|\vec{B}\|) \cdot dV$$

where  $M$  is the magnetization of the MNP and is a function of the magnetic flux density in its nonlinear behavior

$$M(B) = M_s \cdot \left[ \coth\left(\frac{\pi \cdot M_s \cdot B \cdot d_{equ}^3}{6 \cdot k \cdot T}\right) - \frac{6 \cdot k \cdot T}{\pi \cdot M_s \cdot B \cdot d_{equ}^3} \right]$$

(with  $M_s$  saturation magnetization,  $k$  Boltzmann constant,  $T$  temperature,  $B$  magnetic flux density and  $d_{equ}$  the diameter of the core of each particle)

Yet every magnetized particle generates a magnetic field that can be written to

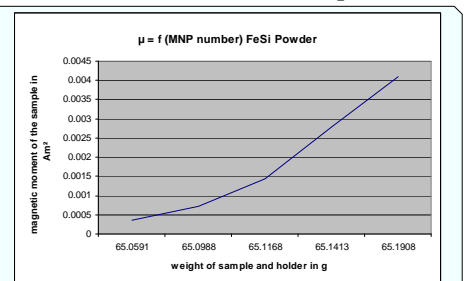
$$\vec{B}(x, y, z) = \frac{\mu_0}{4\pi} \frac{3\vec{r}(\vec{\mu} \cdot \vec{r}) - \vec{\mu}r^2}{r^5}$$

(System center is at the origin,  $z$  axis pointing in the direction of the system's magnetic moment)

and can contribute to the magnetization of the neighboring particles. Each particle would then have a contribution  $B_j$  to its magnetization, generated by the neighboring  $n$  particles

$$M_i = M_s \cdot \left[ \coth\left(\frac{\pi \cdot M_s \cdot (B_0 + \sum_j^n B_j) \cdot d_{equ}^3}{6 \cdot k \cdot T}\right) - \frac{6 \cdot k \cdot T}{\pi \cdot M_s \cdot (B_0 + \sum_j^n B_j) \cdot d_{equ}^3} \right]$$

A measurement of the cooperative behavior of a sample of FeSi MNPs shows the nonlinear increase in the total magnetic moment of the sample



## Outlook

This investigation is essential for the use of nanoparticles in magnetic drug targeting, as it allows an eventual diminution of the involved concentrations, considering the impact of the interaction and change in magnetic behavior of the nanoparticles.

In fact, every decrease in particle concentration spares the patient an added dose of toxicity and increases the efficiency of the therapy.