Institute of Physics, University of Bayreuth

Advanced Practical Course in Physics

Dynamic Self Assembly of Magnetic Colloids

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Abstract

In this lab work titled “Dynamic self assembly of magnetic colloids”, we would like to study the dynamic self assembly of magnetic colloids in two dimensions. This study of self assembly of paramagnetic colloids will lead us to understand the dipolar interactions and the viscoelastic response of self assembled clusters.

Figure 1 shows a self assembled magnetic colloidal cluster in two dimensions. The magnetic colloidal particles are spherical in geometry and has a diameter of 2.8µm. Hexagonal structure formation occurs during self assembly process.

Introduction

Paramagnetic colloids consist of colloidal particles having a core shell structure. The core of the particles is filled with nanometer sized grains of magnetide that is surrounded by a polymer shell. The surface of the colloids used here is functionalized with carboxylate groups that dissociate in water and give the particle a negative surface charge. On a nanometer scale the particles therefore repel each other, which prevent the irreversible aggregation of those beads. The magnetide core of the particles renders the particles paramagnetic such that they achieve a magnetic moment in an external field that is proportional to the magnetic field. Therefore the individual particles interact on a large scale via magnetic dipole dipole interactions. The density of the particles is ρ=1.4 g/cm³ and therefore the particles sediment in water. If you try to
observe the particles in the microscope you will see them in the bulk only at the very beginning of the experiment. After a few seconds of inserting the beads they all sediment to the bottom that is the stage for the next experiments.

1. If you slowly turn on a static magnetic field in the z-direction $\mathbf{H}(t) = \hat{z}\mu_0e_z$ (normal to the bottom surface) you can observe the action of static dipole repulsion between the beads.

2. Turn off the z-field and apply a field of the form $\mathbf{H}(t) = \hat{z}(\mathbf{e}_x \sin \Omega t + \mathbf{e}_y \cos \Omega t)$, $\mathbf{f} = \Omega/2\pi >> \mathbf{2Hz}$. You should see the formation of colloidal clusters that rotate with a frequency $\omega$ that differs from the frequency of the magnetic field. The goal of the lab work is to understand a) why those clusters form and b) why they rotate.

For the clusters to rotate we need a magnetic torque $\tau_{\text{magn}} = \mu_0 \mathbf{m} \times \mathbf{H}$ with $\mathbf{m}$ the magnetic moment of the cluster and $\mathbf{H}$ the magnetic field. The magnetic moment of the cluster is related to the magnetic field via $\mathbf{m} = \int_{-\infty}^{\infty} \mathbf{d}t' \mathbf{V} \chi_{\text{eff}}(t-t') \cdot \mathbf{H}(t')$, where $\mathbf{V}$ is the volume of the cluster and $\chi_{\text{eff}}$ is the effective magnetic susceptibility tensor of the cluster. From these equations there are two ways a torque can arise (which two?). Only one of the two ways applies to hexagonal clusters (which one?). Show that the magnetic torque for the rotating magnetic field can be written as: $\tau_{\text{magn}} = \mu_0 \chi''_{\text{eff}} \hat{z}^2$ where $\chi''_{\text{eff}}(\Omega - \omega)$ where is the imaginary part of the Fourier transform of $\chi_{\text{eff}}(t)$? The clusters rotate with a stationary angular frequency $\omega$ when the magnetic torque is balanced by a viscous torque $\tau_{\text{visc}} = f \eta R_c^3 \omega$ where $f$ is a number $\eta$ is the viscosity of water and $R_c$ is the radius of the cluster. Therefore the cluster rotation angular frequency is proportional to the cluster susceptibility.

Measure $\omega / \hat{z}^2$ for the hexagonal clusters as a function of $\Omega$.

The dipolar interaction energy between two dipoles with magnetic moment $\mathbf{m}_i$ and $\mathbf{m}_j$ separated by the vector $\mathbf{r}_{ij}$ reads:

$$\mathcal{W}_{ij} = -\frac{\mu_0}{4\pi} \mathbf{m}_i \cdot \frac{3\mathbf{r}_{ij} \mathbf{r}_{ij} - \mathbf{r}_{ij}^2 \mathbf{I}}{\mathbf{r}_{ij}^5} \cdot \mathbf{m}_j$$
Here $\mu_0$ is the vacuum permeability and $I$ is the unit tensor. Compare the interaction energy of two parallel dipoles separated by a distance $r$ when the magnetic moments are pointing in direction of the separation and transversal to the separation.

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If we apply a precessing field of the form $H(t) = \hat{H} \cos \theta_x e_x + \hat{H} \sin \theta_x (e_x \sin \Omega t + e_y \cos \Omega t)$ there must be an angle $\theta_{magic}$, where the dipole interaction vanishes on average. Apply a field of the form $H(t) = \hat{H} \cos \theta_x e_x + \hat{H} \sin \theta_x (e_x \sin \Omega t + e_y \cos \Omega t)$ and determine this magic angle experimentally by watching the colloids as you change the normal component of the field.

Measure the rotation frequency of a hexagonal cluster at constant rotating in plane field as a function of the normal field. Consider the dipolar forces acting on a particle in the center of the cluster that arise from the surrounding neighbors when the averaged interaction is attractive and when the interaction is repulsive. Which particles in the cluster feel the strongest forces? Explain, why in a continuum limit the dipolar interactions act like a line tension at the rim of the
cluster. This dipolar line tension has an isotropic component arising from the time averaged dipole interaction and an anisotropic component that wants to stretch the cluster in direction of the field and compress it perpendicular to it.

Similar to tidal waves created by the gravitational pull of the moon onto the earth the dipolar tension acting on the cluster creates a tidal wave traveling around the cluster. If you watch the rotation of the cluster close to the magic angle those tidal waves become large enough to be visible in the microscope. Tidal waves on the ocean have larger amplitude than on land because the mechanical properties of the ocean are different from the land. Similarly the mechanical properties of the cluster determine the size of the tidal waves on the colloidal cluster. Explain, why an elastic shear modulus is insufficient to explain the observed rotating cluster. Why do we need a viscoelastic mechanical property to obtain a cluster rotation?

The imaginary part of the magnetic susceptibility arises from the imaginary part of the shear modulus and reads: \( \chi' = \frac{3\pi a}{8} \frac{\lambda_{\text{anis}}(\Omega - \omega)\eta_c}{3\lambda_{\text{is}}} \). Assuming \( f = \frac{3\pi a}{R_c} \) for the hexagonal cluster friction coefficient where \( a \) is the bead radius of the bead estimate the cluster viscosity \( \eta_c \). What is the ratio of the cluster viscosity to the viscosity of the water? Does the result you obtain make physical sense?

**Experiment**

**Pre-requirements**

- Laboratory notebook
- External memory drive

The experimental procedure for dynamic self assembly of the colloidal particles is briefly discussed in the following section.

**Section 1. Calibration of Magnetic coils**
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Three solenoid coils are mounted orthogonally. Static and dynamic currents passing through these coils generate a dynamic magnetic field. Calibration of these solenoid coils is hence required to know the magnetic field at a given current/voltage. It is also useful for the measurement of the precession angle. See Figure 2 for further reference.

![Experimental setup under the optical microscope](image)

**Calibration**: static source – Z-Coil

1. Connect the connectors to the static power source.
2. Switch on the power source. (make sure the voltage and current switch are at the minimum before switching on)

3. Switch on the gauss meter (Before switch on, connect the probe of the gauss meter)

4. Using the mode function of the gauss meter change the mode to DC

5. Place the probe of the gauss meter on top of the coil (Z-Coil)

6. Now increase the current/voltage insteps and record the magnetic field using gauss meter.

Calibration: Dynamic Source (Alternating Current) – X-Y Coil

1. Connect the connectors of the X coil to the wave form generator.

2. Switch on the Oscilloscope, Wave form generator and Amplifier.

3. Select channels to which the coils are connected

4. Set the Frequency to a desired frequency say 20 Hz and then press enter

5. Set the Amplitude not more than 10 volts

6. Repeat the same for the Y coil

7. Now select the interchannel and change the mode of one of the channel to Master and the other to slave.

8. Also change one of the phases to 90 degree.

9. And then apply.

10. Switch on the channels in the wave form generator

11. Place the gauss meter at the sample and change the mode to AC

12. Increase the amplification by the amplifier and record the magnetic field

13. Repeat it for coil X and Y

Section2. Sample preparation
1. Take 10 ml of the colloidal particles; in this case these are superparamagnetic beads of diameter 2.8 µm using a pipette.

2. Take a clean Petridish and place the 2.8µm particles in it gently.

3. Now place the Petridish on top of the Z-Coil. Be careful not to spill of the sample on the coils.

Section 3. Observations

All the observation is observed under Optical Microscope Leica DM5000B. Using 63X objective and Fluorescence microscope in reflection/transmission mode one could see the particles provided the filter of the microscope is set at Polarization mode. For this change the filter to the Polarization mode by change filters option.

1. Now gently immerse the objective in the sample.

2. One can notice the micron sized particles when they are in water surface.

3. Switch on the rotating field.

4. Observe the particle dynamics

5. Switch on the Perpendicular field and observe its dynamics

Section 4. Recording of the movies

Using the software from the Leica it is possible to record the in situ/ live movie in a computer.

1. Check the frame rate before you start the movie.

2. Once can use the interface option to change the color, brightness, contrast using the software.

3. While recording one has to take care of the focusing manually.

4. Record the desired movie while the experiment is on

Section 5. Analysis of the movies
Analysis of the movie can be done using any software available. Here we use ImageJ which is open source software. The following steps are used for the analysis:

1. Open imageJ
2. Open the video file in the imageJ
3. Make image sequence and save it in a folder.
4. Using inbuilt function one can analyze a sequence of images from a movie
5. Analyze the imageJ sequence as per the given Problem.

Note: after the completion of the experiment, kindly switches of the instrument and clean the work space as it was.

Appendix 1
Calibration: For the static magnetic field.

<table>
<thead>
<tr>
<th>Coil Name:</th>
<th>Current</th>
<th>Voltage</th>
<th>Magnetic field B(mT)</th>
<th>Magnetic field H (ampere/meter)</th>
</tr>
</thead>
<tbody>
<tr>
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Appendix 2
Calibration: For the dynamic magnetic field. (X and Y)

<table>
<thead>
<tr>
<th>Coil Name:</th>
<th>Frequency</th>
<th>Amplitude</th>
<th>Amplifier</th>
<th>Magnetic field</th>
<th>Magnetic field H</th>
</tr>
</thead>
<tbody>
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Appendix 3

Measurement from the movies recorded using ImageJ

<table>
<thead>
<tr>
<th>Movie Name:</th>
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<tbody>
<tr>
<td>$H_{\parallel}$</td>
</tr>
</tbody>
</table>

Reference