Chapter 12

Lab 5: Magnetic Forces

12.1 Purpose

- To qualitatively explore different types of magnets while quantitatively investigating force-distance power laws describing magnetic interactions.

12.2 Safety

You will be given a very strong neodymium-based magnet (permanent magnet). Please be careful with this magnet. If it approaches another permanent magnet, a piece of steel, or anything like that, the force can be very large. The magnet could shatter or pinch your finger. Safety glasses are provided.

Typically, you have to be closer than about 2 inches to start getting really strong forces. Do not bring the magnet near any piercings in case they are magnetic, and keep it well away from credit cards, computer drives, pacemakers, etc. If you have a pacemaker or implant, please see your TA.

You may handle small pieces of bismuth. Bismuth is a low-toxicity heavy metal but is toxic if swallowed. The material safety data sheet (SDS) is provided. Exercise proper precautions. Wash hands after the lab.

12.3 Background information

All materials – everything – fall into one of three main magnetic classes. Diamagnetic materials are weakly repelled by strong external magnets, regardless of the direction of the field. Paramagnetic materials are weakly attracted. Ferromagnetic materials come in two flavours, hard and soft. A hard ferromagnet retains a “permanent” magnetic dipole moment in the absence of a strong external magnetic field. Materials like the rare-earth alloys in strong permanent magnets are known as “hard ferromagnets”. Hard ferromagnets can be strongly attracted, strongly repelled, and or strongly torqued by another magnet, depending on their orientation in the field of the other magnet. Materials like the steel in the Canadian nickels provided for this experiment are examples of “soft ferromagnets”. Soft ferromagnets develop a large net magnetic moment when an external field is applied, but this moment does not persist when the field is taken away.

Diamagnetic and paramagnetic materials also quickly lose any net magnetic moment, when the external field is removed. Whether a material is diamagnetic, paramagnetic, or ferromagnetic depends on the electronic structure of the material and the number of unpaired electrons contained within the atomic or molecular energy levels. Nuclear magnetism, while not as strong as electronic magnetism, is also important and has practical applications like MRI (magnetic resonance imaging). The electronic magnetism studied in this lab underlies technologies from electric motors to data storage, as well as low-tech applications (why does a strong fridge magnet always “snap to contact” when placed directly on the fridge door? Can this be understood in terms of the force-distance dependence?).

12.4 Introduction

The experiment presents an introduction to the nature of magnetism in different materials through the measurement and analysis of force-distance curves between a strong permanent magnet and a variety of test samples. A milligram-sensitive electronic balance with a full-scale range of 200 grams enables the determination of magnetic forces ranging from 10 microNewtons up to greater than 1 Newton.

Force-versus-distance curves will determine which class of magnetic material each specimen belongs to. For the interaction between a strong permanent magnet and another object (comparably sized or smaller), well-defined force-distance power laws can be predicted by computing the potential energy of the magnetic dipoles in the test object, in the field applied by the permanent magnet. As long as the distance between the two objects remains larger than the size of either object, it will be a reasonable approximation to describe both objects mathematically as “point dipoles” concentrated at their centres.

Magnetic properties can be determined from the quantitative force data: the magnetization ($\boldsymbol{M}$) of hard ferromagnets; the experimental magnetic susceptibilities (χ) of paramagnets and diamagnets; and the experimental magnetic susceptibilities of soft ferromagnets, including “shape anisotropies” (the tendency for non-spherical objects to magnetize more easily when the field is oriented along the longer dimensions of the object).

Magnetism as experienced at the refrigerator door is an everyday encounter with science. The few definitions below, in addition to your knowledge from the textbook, are all that’s needed to make the subject quantitative (always our goal, in science and engineering).

Definitions:

Magnetic moment (equivalently, magnetic dipole moment). Symbol: $\boldsymbol{m}$. Unit: J/T or Am^2. For a current loop, the magnetic moment is the product of the current (I) and the area of the loop ($\boldsymbol{A}$). That is,

$$m = IA \tag{12.1}$$

The magnetic moment determines the torque that the current-carrying loop will feel in an external $\boldsymbol{B}$-field:

$$\tau = m \times B = mB \sin\theta \tag{12.2}$$

where θ is the angle between the dipole moment vector and the magnetic field direction. Permanent magnets have a net magnetic dipole moment, m, aligned in a fixed orientation within the object.

Magnetization. Symbol: $\boldsymbol{M}$. Unit: $J/(Tm^3)$ or A/m. How much magnetic moment there is per unit volume of a magnetic material. The magnetic moment and magnetization are thus related via $\boldsymbol{m} = \boldsymbol{M}V$, where V is the volume of the object. A large $\boldsymbol{M}$ means the material is strongly magnetic.

Magnetic susceptibility. Symbol: χ. Unitless. All non-ferromagnetic materials will magnetize due to the presence of an external magnetic field. The magnetic susceptibility of the material tells us how big the magnetic moment or the magnetization produced by an external field will be.in other words, for any material $\mathbf{M} = \frac{\chi \mathbf{B}}{\mu_0}$. This equation says that if a material with magnetic susceptibility χ is placed in an external magnetic field $\boldsymbol{B}$, it will magnetize by an amount of $\boldsymbol{M}$, where μ_0 is the magnetic permeability of the vacuum ($\mu_0 = 4\pi 10^{-7} N/A^2$). By convention, χ is positive for paramagnetic materials and negative for diamagnetic ones.

The magnetic field due to a dipole source

The textbook shows a computation using the Biot-Savart law for the magnetic field, $\boldsymbol{B}$, produced by a current loop (current I, radius a), at point P, a distance z from the centre and along the axis of the loop (in Young & Freedman, this is in section 28.5):

$$B_z = \frac{\mu_0 I a^2}{2(z^2 + a^2)^{3/2}} = \frac{\mu_0 I A}{2\pi(z^2 + a^2)^{3/2}} = \frac{\mu_0 m}{2\pi(z^2 + a^2)^{3/2}} \tag{12.3}$$

where A is the area of the loop, and $m = IA$ is the magnetic dipole moment of the loop (called μ in Chapter 27 of Young & Freedman). Eqn. 12.3 starts with Eqn. 28.15 from the textbook, and substitutes $A = \pi a^2$, and then $m = IA$.

Considering a limit where $a \to 0$ in such a way that m = constant, the magnetic field along the axis of a "point dipole" becomes:

$$B_z = \frac{\mu_0 m}{2\pi z^3} \tag{12.4}$$

where z is the distance from the dipole. An inverse-cube law.

Gradient of potential energy, and magnetic force

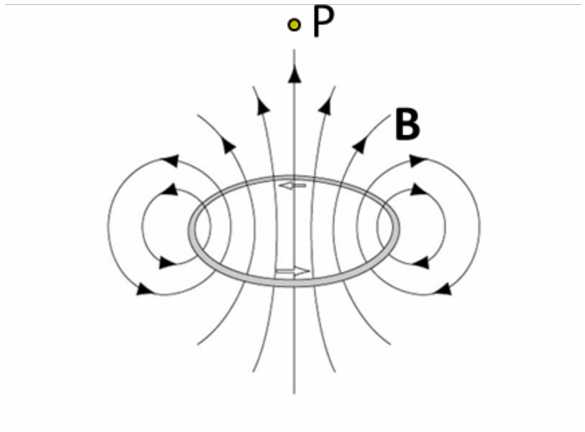

Figure 12.1: Magnetic field around a circular loop of radius a, carrying current I.

The critical part of this lab is the magnetic force on a sample, caused by the inhomogeneous magnetic field of a strong permanent magnet. From the force measurements, you should be able to determine out the type of magnetic material you are looking at.

The key to this is the relation between the force and the potential energy, as recapped (for example) in the chapter on electric potential (Chapter 23 in Young & Freedman). The formula is:

$$F_z(z) = -\frac{dU}{dz} \tag{12.5}$$

where the relevant potential energy, U, in this case is the potential energy of a magnetic dipole moment $\mathbf{m}$ in a magnetic field $\boldsymbol{B}$:

$$U = -\mathbf{m} \cdot \mathbf{B} = -\mathbf{mB} \cos\theta \tag{12.6}$$

When the dipole moment vector and the magnetic field direction are parallel, the potential energy is large and negative; and if they are antiparallel, the potential energy is large and positive. The magnetic torque is maximum when the directions are at right angles to one another.

Force-distance power law expectations for the main types of magnetic materials

If your sample is a hard ferromagnet, that means it has a permanent dipole moment $\mathbf{m_s}$. Then its potential energy is $U = -m_s B_m \cos\theta$, where $\mathbf{B_m}$ is the magnetic field coming from the permanent magnet, at the location of the sample. From Equations 12.4 and 12.6, this can be written as

$$U = -\frac{m_s \mu_0 m_m}{2\pi z^3} \tag{12.7}$$

if the moments are parallel (positive if they are antiparallel). The rate of change of the potential energy (that is, magnetic force) can be expressed as

$$F_z = \pm\frac{3 m_s \mu_0 m_m}{2\pi z^4} = \pm\frac{3 m_s \mu_0 m_m}{2\pi}\frac{1}{z^4} \tag{12.8}$$

Notice the dependence on the inverse fourth power of distance. When you bring two magnets together, the magnitude of the force between them changes much more rapidly than the variation of an inverse-square law force such as gravity or the electrical force between point charges.

For paramagnetic, diamagnetic, and soft ferromagnetic materials, the value of the magnetic moment depends on the strength of the external field. So, their magnetic moment $\mathbf{m_s}$ has the following dependence on the magnetic field from the permanent magnet:

$$\mathbf{m_s} = \mathbf{MV} = \frac{\chi \mathbf{B_m} \mathbf{V}}{\mu_\mathbf{0}} \tag{12.9}$$

From Equations 12.4 and 12.6, we can use this information to get the potential energy:

$$U = m_s B_m \cos\theta = \frac{\chi V B_m}{\mu_0} B_m = \frac{\chi V}{\mu_0} \frac{\mu_0^2 m_m^2}{4\pi^2 z^6} \tag{12.10}$$

where $\cos\theta = 1$ in this case, as the magnetic moment of the sample will point in the same direction as the magnetic field of the permanent magnet that induced it. Using the expression for the dipole potential energy, we can calculate the magnitude of the magnetic force exerted on the sample:

$$F_z = \frac{3\mu_0 \chi V m_m}{2\pi^2 z^7} = \frac{3\mu_0 \chi V m_m}{2\pi^2} \frac{1}{z^7} \tag{12.11}$$

An inverse-*seventh* power law is predicted. Again, χ may be positive or negative, depending on the material, which determines whether the force is attractive or repulsive.

12.5 Lab setup, and selection of topic for investigation

Reminder: please be careful with the strong permanent magnet. (The power laws discussed above are also the main source of hazard in this experiment!) Each station has a milligram scale. Be very careful with these too. Some clamps and a micrometer stage suspend the permanent Nd-magnet above the sample and enable the distance to the sample to be varied accurately.

The following samples of magnetic material will be available to choose among for testing: a small permanent magnet, a nickel coin, a piece of kimberlite rock, and a piece of crystalline bismuth.

You should collect data for all of the following topics in order to practice the technique and gain some insight into all of the types of magnetism, but you only need to write about one of these topics in your report:

- Examine and compare the relationships between the magnetic force and distance for the strong Nd magnet and a) a small permanent magnet, b) a nickel coin position horizontally.
  (Keywords: hard ferromagnet, soft ferromagnet)
- Examine and compare the relationships between the magnetic force and distance for the strong Nd magnet and a) a nickel coin position horizontally, b) a nickel coin oriented vertically.
  (Keywords: magnetic shape anisotropy)

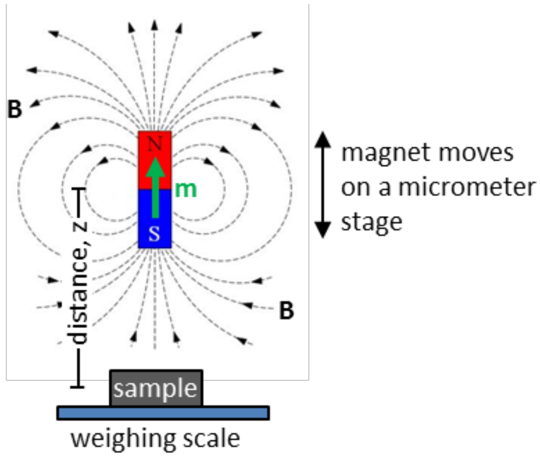

Figure 12.2: Experimental setup.

- Examine and compare the relationships between the magnetic force and distance for the strong Nd magnet and a) a piece of kimberlite, b) a piece of bismuth.
  (Keywords: paramagnet, diamagnet)

An extra note about the nickels: the coins might acquire some permanent moment, if they get too close to the permanent magnet. (How could you test for this?) It is OK if this happens (accidentally or on purpose,) but it will affect the results. A “demagnetizer” is available, to decrease any residual moment (also called “remanence”). Ask your TA.

12.6 Lab procedure

Read all steps before you begin.

1. Make sure that the weigh scale is level. There is a bubble level indicator on the scale, above the left-hand-side tare button. (The tare button zeroes the weight reading.)
2. Put the cups on the scale, and tare it.
3. Put the sample on top of the cups and weigh it. Ensure that the permanent magnet mounted on the micrometer stage is far enough away above the cups not to affect the weight reading.
4. Start with the micrometer dialled to zero on the linear stage. Carefully lower the stage towards the sample by gently loosening the clamps on the pole and sliding it lower, until you start getting a reading change on the scale, then re-tighten. Be careful to keep a good grip at all times. You probably will need to return here once or twice from the end of Step 5, to readjust. Keep the magnet aligned directly above the sample, and not to the side, as accurately as you can. For samples which are also permanent magnets, you should orient the two magnets to repel one another, to avoid a catastrophic crash if the separation becomes too small. You can

tape the magnet to the cup, to prevent it skidding off sideways from lateral force if the centring isn't perfect.

5. Now, as you decrease the magnet-sample separation by turning the micrometer dial, observe the change of the weight reading. In order to get a reasonable power law fit to your final data, you want to capture a fairly large variation of magnetic force. It is a good idea to find out if this will happen with a very coarsely spaced set of micrometer readings at first, before taking a careful set of readings for analysis. Use the coarse readings to decide if you should return to Step 4 and reset the position of the stage using the clamps, to closer or farther away.

6. Make an accurate reading of the centre-to-centre distance between the permanent magnet and the sample, for this initial position. In the data analysis, you must plot distances using a scale where the "x origin" corresponds to a centre-to-centre spacing of zero (there won't be a data point at that position, of course). The uncertainty in the centre-to-centre distance will be one of the main contributors to the uncertainty in the power law exponent determined from the measurements.

7. Acquire data.

12.7 Assignment

In this lab submission you will submit a full lab report (4 pages maximum) based on your chosen topic. In preparing your full lab report, a full presentation of your results should also include:

- Your objective(s) in your Introduction should not be based on the overall lab's purpose as defined in the lab manual. Instead, report what you chose as your topic of study and why you were motivated to explore that topic.
- While you will only be discussing your chosen topic for the most part, the introduction should still very briefly discuss each of the types of magnetism and which power law they fall under. You only need to include the full equations related to your chosen (but you don't need to redo any of the derivations).
- Your Results should include any tables (with caption, proper headers, units, uncertainties, and significant digits, and any necessary sample calculations) and any graphs (with caption including trend line equation with units, uncertainties, and correct significant digits) necessary to provide evidence for your Discussion. Tables should include raw, measured data and values that are plotted. Intermediate values are not required.
- Similar tables for the types of magnetism you did not discuss in the Results can be placed in the Appendix. These should still have proper units, headers, and captions. They will count as part of the Results for marks, but we are allowing you to place them in the Appendix this week to save on space.
- Your Discussion should include comparisons between your experimental values and what you expected to see based on your chosen topic.