

Physics 338 Advanced Physics Laboratory
Magnetic Susceptibility
Report: **Due Friday, September 13, 2024**

Safety

Any time you are working in a lab, you should be aware of your surroundings and alert to possible safety issues. These writeups will highlight any new or unusual safety issues, but you must also use your common sense to keep safe.

- Magnetic field safety
 - This experiment involves permanent magnets with strong magnetic fields. Near the center of the apparatus between the magnets, the field is approximately 0.4 T. This may be large enough to interfere with some sensitive medical devices (as well as credit cards). If you have any concerns, please consult your lab instructor.
 - In laboratories with magnetic fields, it is typical to delineate a “5 Gauss line” (or 0.5 mT line) so that people sensitive to magnetic fields can avoid these fields. Medical devices such as pacemakers, which are relatively common, typically have a ~ 5 Gauss magnetic field exposure limit, beyond which they may not work properly. Use the magnetic field sensor near the entrance to the laboratory to get a sense for how close to the magnet you need to be to get to 5 Gauss. Then avoid placing your medical devices, credit cards, hard drives, or pocket magnets in that area.
- Chemical safety of powder samples

The TeachSpin manual contains the following note:

While none of these 16 materials is notoriously poisonous, it does not follow that they are automatically harmless! Some of them are known to be toxic, to some organisms, at some concentrations. Some of them are water-soluble. The finely-powdered materials can spread in air if spilled. So in general, keep these materials covered, either by their caps, or by the cap at the bottom of the lifter rod when the samples are in use. And make it a professional safety habit to look up the properties of any material you have occasion to use, or to talk with someone more experienced in its use than yourself.

- Before you use a powdered sample, find and read through the relevant Safety Data Sheet (SDS) for the material. If a Safety Data Sheet is not available in

the lab, you should consult one of the online databases referenced here, <https://publicsafety.lafayette.edu/environmental-health-and-safety/industrial-hygiene-2/data-sheets/> and then print out the relevant sheet so the next user doesn't have to go through the same process.

- If you have any other safety concerns I have not mentioned, please bring them to me!

1 Introduction

Materials in nature display a very wide range of magnetic behaviors. Most of the magnetic phenomena that we observe are due to the behavior of electrons within those materials, and careful measurements of magnetic properties offer keen insights into the quantum mechanical nature of materials.¹

In this experiment, you will use tabletop macroscopic measurements to probe those magnetic properties. In principle, those measurements could then be used to compare with theoretical attempts to *predict* those properties from first principles using quantum and statistical mechanics.

The TeachSpin “Foundational Susceptibility” manual contains detailed information about the theoretical background and experimental procedures. This writeup will list the specific tasks you should complete, but you should refer to the detailed instruction manual for detailed instructions.

1.1 Definitions

The degree to which a material is magnetized is described by the magnetization \vec{M} , which is the net magnetic moment per unit volume. In the SI system, the units² of magnetic moment are current \times area = Am^2 , so the units of M are $\text{Am}^2/\text{m}^3 = \text{A/m}$.

For many (non-ferromagnetic) materials, the magnetization is found to be linearly proportional to the applied field \vec{H} by the magnetic susceptibility χ ,

$$\vec{M} = \chi \vec{H} .$$

The susceptibility is dimensionless (in the SI system), and is typically quite small; values on the order of 10^{-5} are common. Broadly speaking, materials can be classified into one of three categories:

Paramagnetic: $\chi > 0$. (The magnetization is in the same direction as the applied field.)

¹This discussion is based on that in Chapter 19 of *The Oxford Solid State Basics* by Steven H. Simon, as well as the TeachSpin instruction manual, available on the course web site.

²Throughout this lab, we will use SI units.

Diamagnetic: $\chi < 0$. (The magnetization is in the opposite direction to the applied field.)

Ferromagnetic: \vec{M} can be nonzero even in the absence of any applied magnetic field.

The magnetic field \vec{B} experienced by electrons in the sample is then given by

$$\vec{B} = \mu_0(\vec{H} + \vec{M}) . \quad (1)$$

Finally, there are many different ways to express the susceptibility. The two most useful for us are the dimensionless susceptibility, χ , and the mass susceptibility, χ_{mass} , defined by

$$\chi_{\text{mass}} = \frac{\chi}{\rho} , \quad (2)$$

where ρ is the density (in kg/m^3) of the material. In *Mathematica*, you can look up the values for χ_{mass} for many elements with a command such as

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ElementData["Titanium", "MassMagneticSusceptibility"]
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For other compounds, you may be able to find the susceptibility in the *CRC Handbook of Chemistry and Physics*.

1.2 Measuring magnetic susceptibility

In a uniform magnetic field, a magnetic dipole experiences a torque, but no net force. If the magnetic field has a gradient, however, there is a net force. This observation forms the basis of the Gouy balance. The details are discussed in section 3 of the TeachSpin manual (starting on pg. 10), and you should read that section carefully. The force between the magnetized material and the permanent magnets resting on the balance changes the apparent mass of the magnets as indicated by the balance.

You will measure the apparent mass with the sample in three positions:

m_{far} when the sample is far away from the magnets,

m_{high} when the bottom of the sample is midway between the magnets (left half of Fig. 1 in this writeup), and

m_{low} when the top of the sample is midway between the magnets (right half of Fig. 1.)

The main result is that the apparent mass change for a uniform *solid* or *liquid* sample, is

$$\Delta m = m_{\text{high}} - m_{\text{far}} \quad (3)$$

is related to the magnetic susceptibility by

$$\chi = \Delta m \frac{2\mu_0 g}{A (B_{\text{top}}^2 - B_{\text{bottom}}^2)} \quad (4)$$

For a *powdered* sample, the result is

$$\chi_{\text{mass}} = \frac{\Delta m}{m_1} \frac{2\mu_0 g h}{(B_{\text{top}}^2 - B_{\text{bottom}}^2)} \quad (5)$$

where h is the vertical height of the sample, and m_1 is the mass of the sample. (See pg. 25–26 in the TeachSpin manual.)

In Fig. 1, B_{top} is the field at the top of the sample, (which you will show is approximately zero), and B_{bottom} is the field at the bottom of the sample, which is in the center of the region between the magnets. You will measure that below. Finally, A is the cross-sectional area (in the $x - y$ plane) of the sample. Similar results hold for the “low” position, where

$$\Delta m = m_{\text{low}} - m_{\text{far}} , \quad (6)$$

and B_{top} and B_{bottom} refer to the right hand portion of Fig. 1. (You may assume that B_{bottom} is zero in that case.)

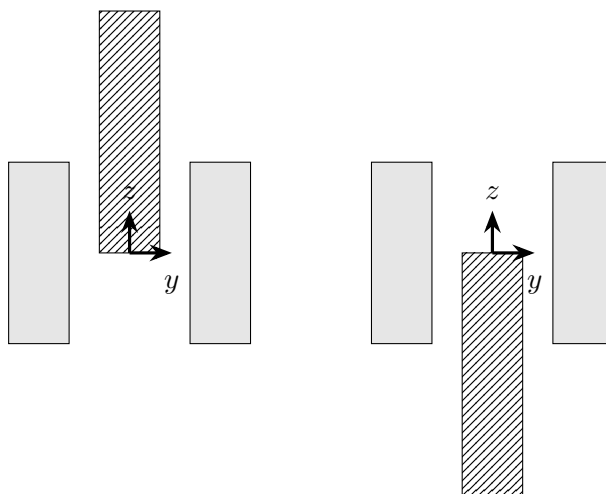


Figure 1: Side views of the system when the sample is in the “high” position (left) and “low” position (right). The magnets are shown in light gray, and produce a field primarily in the y -direction. The sample is shown with hashed lines.

2 Experiment

Your ultimate goal is to measure the magnetic susceptibility for 4 different samples, including at least one solid and at least one powder. The list of available samples is in Appendix B of the TeachSpin manual.

2.1 Measuring Magnetic Susceptibility

2.1.1 Getting Started

The apparatus should already be set up. If the balance is off, turn it on. If you get an error code, try gently lifting the “top hat” assembly off the balance pan, waiting for the scale to read zero, and then gently replacing the top hat. It takes a long time for the system to stabilize, so you can just leave the power on when you are done.

Pick one of the solid samples (#3, Titanium, works well). Use the calipers to measure the dimensions of the sample. (You can gently remove the sample from the cuvette. There are gloves for safe handling of the samples.) Follow the instructions in section (d) in the TeachSpin manual, pgs. 18–21, to learn how to measure m_{far} , m_{high} , and m_{low} .

It is important to take time to do this step reasonably carefully. Be gentle with the thumbscrews! First, you want to put the sample in the “high” position. You can sight by eye through the holes in the center of the magnet yoke. Since Titanium is paramagnetic, it attracts the permanent magnets, and hence *reduces* the mass reading on the scale. Make small x and y adjustments to try to get the minimum mass reading. Try to keep the sample holder vertically straight. The system is not overly sensitive; small mm-sized variations in the horizontal directions typically don’t make a measurable difference. When you are satisfied with the horizontal alignment, gently tighten the thumbscrews and then vary the vertical displacement, still looking for the minimum mass. Take this part slowly—the balance does not respond instantly, and you need to develop a feel for how quickly or slowly you need to move.

2.1.2 Measurements

When you are satisfied with the alignment, record the value of m_{high} . Similarly, record the value of m_{low} (see the right panel in Fig. 1). Finally, pull the mass up as high as it will go, and record this as m_{far} . Also, take note of the uncertainties in those masses. (This is not a statistical estimate, just your best judgement of how well you can determine them.)

2.1.3 Additional Samples

Now consider three additional samples, including at least one powdered sample. Make any measurements necessary to determine either the susceptibility χ or mass susceptibility

χ_{mass} . Note that for powders, you need to use Eq. 5, and hence need to measure the height of the sample h and the mass of the sample m_1 . To determine m_1 , measure the mass of the filled cuvette, and then measure the mass of one of the empty cuvettes. (Ideally, you would pour out the powder and measure the mass of the specific cuvette you used, but that would be messy, and the cuvettes are sufficiently uniform that it wouldn't make a significant difference anyway.)

2.2 Measuring the magnetic field

The remaining unknowns in Eqs. 4 and 5 are the magnetic fields B at the top and bottom of the sample. To measure those, you will use a specially-designed sample cell that carries a current in the x -direction. When that sample is placed in the “high” position, the Lorentz force shows up as a change in the apparent mass of the magnets.

Follow the procedure on pgs. 23–24 of the TeachSpin manual. It is probably easiest to leave the magnet in the same orientation as it was for the previous part, but rotate the copper ribbon sample holder so that the current is flowing front-to-back, *i.e.* in the x -direction. If necessary, make any small x or y position adjustments to center the ribbon between the magnet poles.

Set the current through the ribbon to approximately 1.0 A. *Be sure to always keep the current below 2.0 A.* Make small adjustments to the z -position to maximize $|\Delta m|$. Once you are satisfied with the alignment, take a series of measurements of apparent mass m *vs.* current i , for currents running from -2.0 A to 2.0 A. (To get negative currents, simply switch the leads at the power supply.) You don't need a lot of measurements, 7 to 10 should suffice. Plot m *vs.* i . As described in the TeachSpin manual, the slope of the graph should be

$$\frac{\Delta m}{i} = \frac{L_x B_y}{g}, \quad (7)$$

where $L_x = (9.9 \pm 0.1)$ mm.

That value for B_y can be used to determine the value for B between the magnets in Eqs. 4 and 5:

$$B = B_y(1.0012) \quad (8)$$

(See pg. 23 and Appendix E in the TeachSpin manual.)

Calculate B^2 , along with the uncertainty in that measurement.

To determine B_{top} when the mass is in the “high” position, raise the current ribbon up about 3 cm (*i.e.* the height of a typical sample). This need not be a precise height—an approximate position is fine. Now compare the apparent mass when the current is 1.0 A with the apparent mass when the current is zero. If the difference is comparable to your

mass uncertainties, then you may safely assume B is 0 at that position. By symmetry, you may assume B_{bottom} when the mass is in the “low” position is also zero.

3 Results

For this experiment, you should submit an “informal report,” described in the separate handout available on the course web site. The actual report you need to submit is rather brief, but this is an excellent opportunity to learn how to format and submit a report in \LaTeX .

Your report should include your data for the mass readings in a neat table. It should also include your graph of m vs. i , along with the linear fit.

Finally, your report should include your results for the magnetic susceptibility for your four samples. Include an estimate of the overall uncertainty, along with a brief description of how you arrived at that estimate. Compare your results to expected or tabulated values.