What Makes a Non-Magnet?
An Exploration of Magnetic Susceptibility in Materials.

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All materials have some reaction to a magnetic field, which is dependent on the composition of the material and the magnetic moments of the material. The setup of this experiment consists of a Gouy balance, which measures the force of the magnetic push or pull on a sample of material using the apparent mass difference in a mass scale. Our experiment explores the intrinsic magnetic reaction, or magnetic susceptibility, of different materials to an incident magnetic field. In this analysis, we will report the magnetic susceptibilities of sixteen different samples and discuss the quantum mechanical applications of the magnetic moment and dia/paramagnetism.

I. INTRODUCTION

Magnets are objects or systems that produce an electric field. Every particle of a material has a magnetic moment μ, which is defined by the magnetic torque,

$$\tau = \mu \times B. \tag{1}$$

Every particle has a magnetic moment, and so as a magnetic field passes through a material, we observe that the magnetic moments of each particle in a mass align with the incident magnetic field to some degree. It is not often the case that all of the magnetic moments of a material will align, and so we say that some materials are more magnetic than another. We often define the degree of magnetism of an object using diamagnetism and paramagnetism.

Diamagnetism, discovered by Faraday [1], is a property of materials that repel and incident magnetic field, causing a push between the origin of the incident magnetic field and the diamagnetic material. Paramagnetism is the opposite – it is the property of materials that attracts it to the origin of an incident magnetic field. In a diamagnetic material, we say that the magnetic dipoles align opposite to the incident magnetic field, and in paramagnetic materials, the magnetic dipoles align with the incident magnetic field.

For a large mass consisting of multiple particles, we define the magnetic moment density, or the magnetism M, as

$$M = \frac{1}{\Delta V} \sum_i \mu_i, \tag{2}$$

where ΔV is the volume of the material. However, this magnetism may not be permanent, but it may be transient – caused by an external magnetic field. In this case, we say

$$B = \mu_0(H + M) = \mu_0(1 + \chi)H = \mu H, \tag{3}$$

where B is the resulting field of the system, H is the stimulating magnetic field, and μ_0 is the constant of magnetic permeability of air. We finally define the magnetic susceptibility of a material as

$$\chi = \frac{M}{H} \tag{4}$$

and say that χ is the ratio of the magnetism of the material to the incident magnetic field, which is a measure of how a material reacts to a magnetic field.

In this experiment, we explore multiple different samples and their magnetic susceptibilities using a Gouy balance. We can observe the force of the magnetics on a sample and calculate the magnetic susceptibilities of each sample.

II. METHOD

The experimental apparatus can be seen in Figure 1. The system comprised of an open-top container with two permanent magnets connected to its sides such that the magnetic field between the two magnets was in horizontal line. This system was laid on top of a precision mass balance with instrumental uncertainty of ± 0.001 g.

Sixteen different samples of unknown composition were prepared to observe the magnetic susceptibilities. Each sample was lowered into the magnetic field between the two magnets of the apparatus at two different foci: at m_{high}, all particles of the sample were at or above the center point between the magnets, and at m_{low}, all particles of the sample were at or below the center point between the magnets. Being at the focus meant that the force between the magnets and the sample was at a local extreme, which corresponded to a proportional change in apparent mass.

For each sample, the apparent mass of the system was measured at three different locations: m_{high}, m_{low}, and m_{far}, where m_{far} is the apparent mass of the system sufficiently far from the magnetic field. The differences in apparent mass at each focus were recorded as $\Delta m_{high} =$

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$m_{high} = m_{far}$, and $\Delta m_{low} = m_{low} - m_{far}$. The force corresponding to the observed change in mass, Δm_{high}, is defined as

$$F = \Delta m_{high} g = \frac{1}{2}(\chi - K_1)AH^2, \tag{5}$$

where χ is the volume magnetic susceptibility of the sample, and K_1 is the volume magnetic susceptibility of air, which is negligible. So then we can reduce the equation to

$$F = \Delta m_{high} g = \frac{1}{2}\chi AH^2, \tag{6}$$

where g is the gravitational acceleration at the surface of the Earth, A is the area of the sample, and H is the applied magnetic field from the permanent magnets. By measuring Δm_{low} and Δm_{high}, we can measure the volume magnetic susceptibility χ with equation

$$\chi = 2\frac{\Delta m_{high} g}{AH^2}, \tag{7}$$

which is acquired by manipulating Equation 6.

It is expected that $\Delta m_{low} = -\Delta m_{high}$ since the magnetic field strength is constant and the volume of the sample is constant. To test, this, we compared Δm_{low} and Δm_{high} using a negative coefficient direct fit and χ^2 test.

The magnetic field between the two magnets was measured using the observed force on a sample of conducting wire with a current. The electromagnetic force on the conducting wire is calculated as

$$F = \Delta mg = ILH, \tag{8}$$

where I is the current through the wire, L is the length of the wire that is affected by the magnetic field, and B is the strength of the magnetic field. Using this equation, we can find the magnetic field strength as

$$H = \frac{\Delta mg}{IL}. \tag{9}$$

III. RESULTS AND DISCUSSION

In Figure 2, we see a plot comparing Δm_{low} and Δm_{high}. The values are compared to a negative direct fit, $\Delta m_{high} = -\Delta m_{low}$, and give a $\chi^2_\nu = 1.2$, which indicates a good fit. With this result, we can safely assume that the measurements of the change in apparent mass are indicative of an electromagnetic effect.

We report the measured values of Δm_{high} in Table I. Using these values, we will be able to calculate the magnetic susceptibility according to Equation 7. This analysis is not yet complete, and further work must be done to determine the values of the magnetic susceptibility.

TABLE I. The values calculated for Δm_{high} and their uncertainties.

Sample	Δm_{high} [g]	error [g]
1	0.012	±0.003
2	-0.013	±0.005
3	-0.131	±0.005
4	0.073	±0.004
5	-0.195	±0.017
6	0.059	±0.010
7	-0.260	±0.008
8	-2.562	±0.013
9	-4.758	±0.114
10	-0.379	±0.007
11	-0.281	±0.014
12	-0.069	±0.005
13	-0.038	±0.004
14	-1.243	±0.034
15	-1.040	±0.013
16	-2.113	±0.145

IV. CONCLUSION

We reported different values of magnetic susceptibilities for sixteen different samples of unknown composition and compared the expected results versus the physical observations. We found that the results of the experiment align with quantum explanations and calculations for dia/paramagnetism in materials, namely the quantum spin parameters of a material.

V. LOG

The data and logbook can be found here: `https://docs.google.com/document/d/1A-JC4UOzmsbox2OkY-p9s1_ovZ9gCrPctnn7UNFYOBE/edit?usp=sharing`.

VI. IMPROVEMENTS

1.

[1] M. Faraday, (1846).

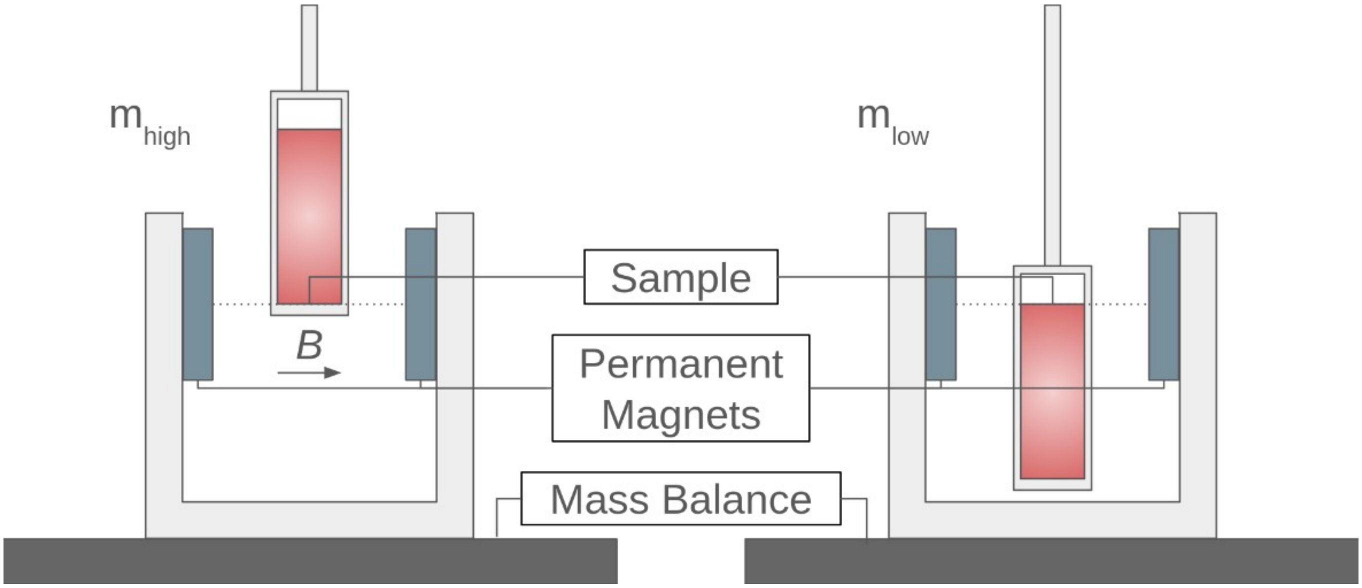

FIG. 1. The apparatus used for this experiment. The apparatus consists of two permanent magnets, a basket to support the magnets, a precision mass balance, and a vertical lifting mechanism to raise/lower a sample out of/into the magnetic field. The magnets are attached to the basket in such a way that results in a horizontal magnetic field between the magnets. The two different focus points are seen and labeled: m_{high} on the left, and m_{low} on the right.

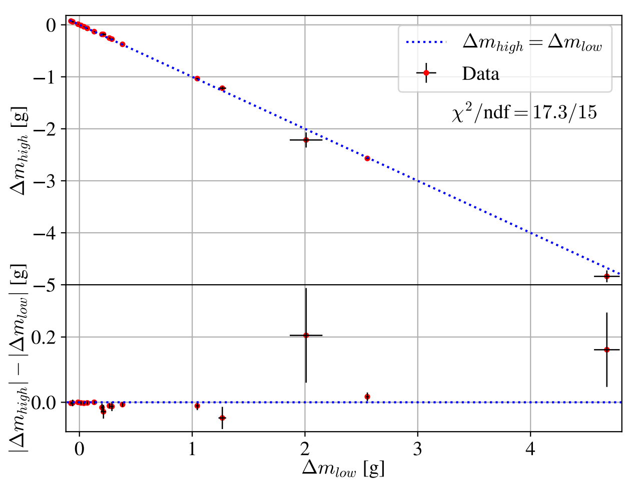

FIG. 2. Plot comparing the values for Δm_{high} versus Δm_{low} for sixteen different samples. The fit gives a reduced chi-squared value of $\chi^2 = 1.2$, which indicates a good fit.