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

Michael Wieber*
Department of Physics and Astronomy,
University of Kansas, Lawrence, KS, 66045, USA

(Dated: November 12, 2024)

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 report the magnetic susceptibilities of sixteen different samples and discuss the distribution of materials according to their physical and magnetic properties, for which we find no conclusive correlation.

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 [2].

In this experiment, we explore multiple different samples and their magnetic susceptibilities using a Gouy balance [3]. We can observe the force of the magnets 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

* Email: michaelwieber@ku.edu

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

$$F = \Delta m_{high} g = \frac{\chi A H^2}{2\mu_0}, \tag{5}$$

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

$$\chi = 2\frac{\mu_0 \Delta m_{high} g}{AH^2}, \tag{6}$$

which is acquired by manipulating Equation 5. For each value of χ, we say that a material is para/diamagnetic if $\chi > 0/\chi < 0$.

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 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

$$F = \Delta m g = ILH, \tag{7}$$

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

$$H = \frac{\Delta m g}{IL}. \tag{8}$$

TABLE I. The values calculated for Δm_{high} and χ with their uncertainties for each sample. The value for the permanent magnetic field was calculated with Equation 8 to be 0.44±0.01 T.

Sample	Description	Δm_{high} [g]	χ [10^{-6}]
1	Red metallic solid	-0.012±0.003	-5.41 ± 2.27
2	Grey metallic solid	0.013±0.005	5.90 ± 3.09
3	Dark grey metallic solid	0.131±0.005	59.0 ± 20.1
4	Grey metallic granules	-0.073±0.004	-32.2 ± 10.7
5	Paper	0.195±0.017	87.7 ± 30.5
6	Paper & graphite	-0.059±0.010	-26.9 ± 10.3
7	Pink crystalline granules	0.260±0.008	141.8 ± 57.0
8	White powder	2.562±0.013	1147 ± 385
9	Pink powder	4.758±0.114	1923 ± 592
10	Cyan crystalline granules	0.379±0.007	160.8 ± 51.6
11	Red powder	0.281±0.014	127.7 ± 43.8
12	Blue crystalline granules	0.069±0.005	25.97 ± 7.74
13	Turquoise powder	0.038±0.004	15.05 ± 4.71
14	Green powder	1.243±0.034	535 ± 174
15	Pink crystalline granules	1.040±0.013	446 ± 144
16	White/Yellow mixed powder	2.113±0.145	946 ± 372

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} and χ in Table I. The values for the magnetic susceptibilities have very large uncertainties, ranging around 20-40% of the reported value. The uncertainties come from the instrumental uncertainties in the mass balance and in the measurements for the areas of the samples, with the uncertainty in the magnetic field contributing only a small amount of the uncertainty. In Figure 3 we can see the distribution of the samples organized by sample type (solid, granular, powder) and intrinsic magnetic properties (paramagnetic or diamagnetic).

In the distribution of the samples, we see that there are 13 samples that are paramagnetic versus 3 that are diamagnetic. In isolation, these results suggest that it is more common for solids to be diamagnetic than granular objects, and it is more common for granular objects to be diamagnetic than powders. However, in consideration of the broader scope of the world, 16 samples is not enough to represent the vast amount of materials present in condensed matter physics, let alone the entire world. So then, these results are inconclusive to the distribution of magnetic properties in materials in the world.

Additionally, we consider the nature of diamagnetism. Diamagnetism is an intrinsic property of every material

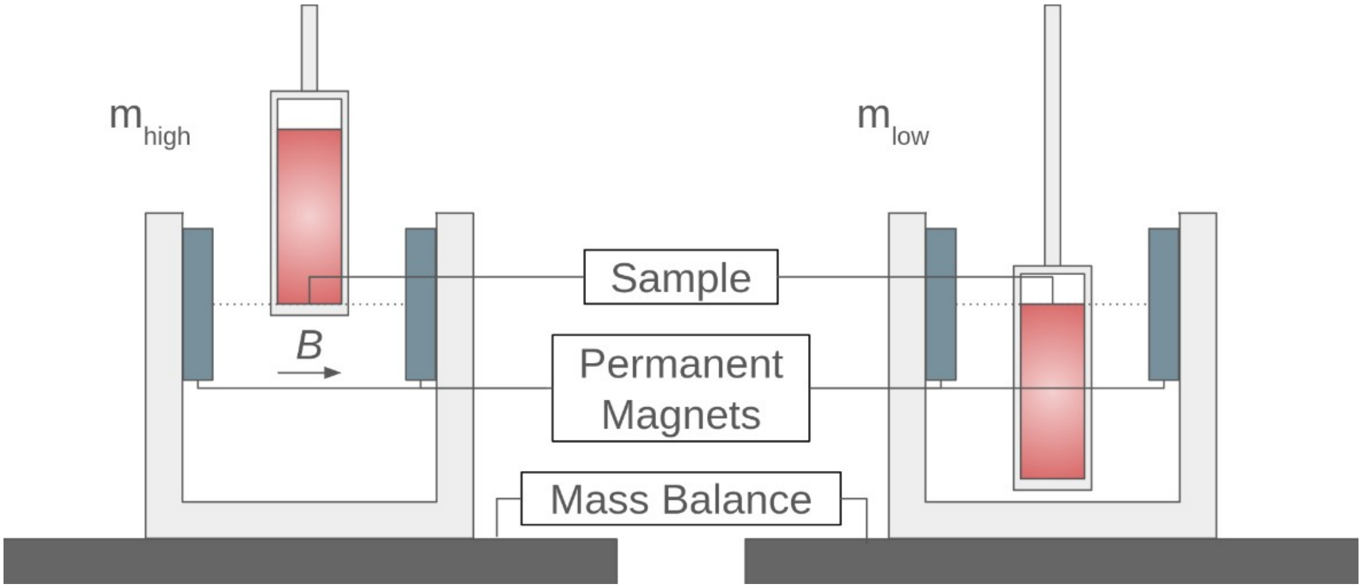

FIG. 1. The apparatus used for this experiment. The apparatus consists of two permanent magnets, a basket to support the magnets, a precision mass balance, and a vertical lifting mechanism to raise/lower a sample out of/into the magnetic field. The magnets are attached to the basket in such a way that 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.

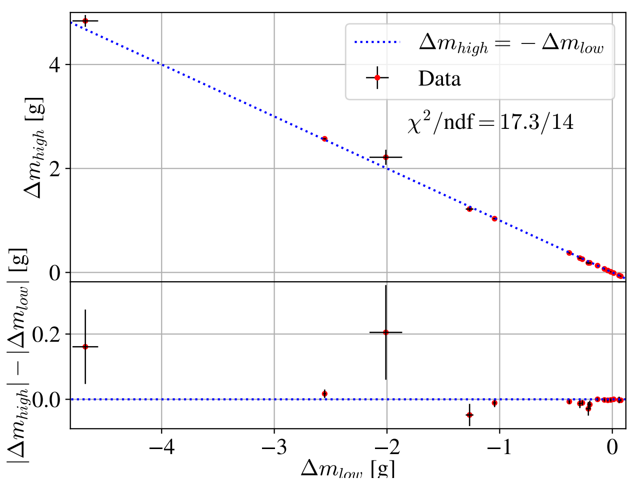

FIG. 2. Plot comparing the values for Δm_{high} versus Δm_{low} for sixteen different samples. The fit gives a reduced chi-squared value of $\chi^2 = 1.2$, which indicates a good fit.

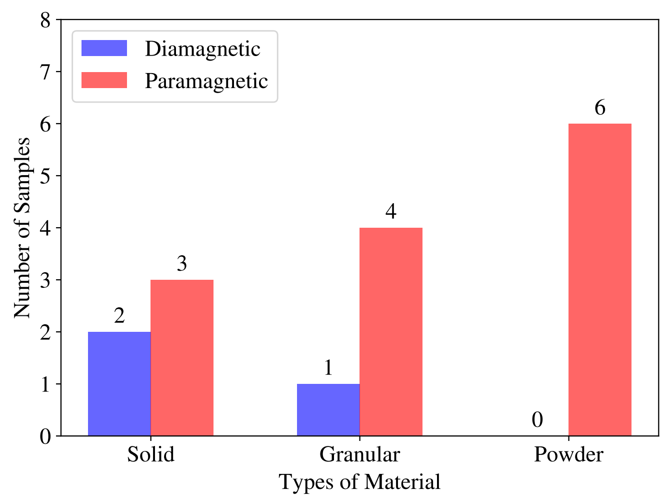

FIG. 3. The distribution of samples organized by sample type and magnetic properties.

due to the ability of every material to contribute oppositely to an incident magnetic field. The intrinsic diamagnetism is very small, characterized by a very small and negative magnetic susceptibility χ. However, only some materials exhibit paramagnetic properties, which is when the material overcomes this diamagnetism and contribute positively to the incident magnetic field. Paramagnetism is then characterized by a positive and small magnetic susceptibility χ. Since all materials exhibit diamagnetism and only some materials exhibit paramagnetism, we would then expect to see more diamagnetic objects in our analysis. However, we have a majority of paramagnetic objects, which further supports the idea that our results are not representative of the underlying distribution of the magnetic properties of materials.

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 a majority of our samples were paramagnetic instead of paramagnetic, however this is likely due to a non-representative sample. In fact, all materials are diamagnetic – a material is only paramagnetic if it can overcome this intrinsic diamagnetism. Because of our sample, our results were inconclusive to determining the underlying distribution of magnetic properties of materials, but the values reported for the magnetic susceptibilities of the materials give an idea of the values to expect for other materials.

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. Included more citations for the background section.
2. Corrected the signs of $\Delta m_{low}, \Delta m_{high}$.
3. Corrected the calculations for χ in the background section.
4. Extended the results and discussion section to include analysis of χ-values.
5. Included values for χ in the table and included a histogram of the distribution of samples.
6. Included a discussion of the significance of the results in the summary.
7. Refined the abstract
8. Enlarged the text sizes on all plots to be legible.

[1] M. Faraday, Journal of the Franklin Institute **42**, 66 (1846).
[2] P. Curie, Comptes Rendus de l'Académie des Sciences **121**, 390 (1895).
[3] L. G. Gouy, *Sur une propriété nouvelle des ondes lumineuses* (Gauthier-Villars, 1890).