

Experiment 8: Magnetic Forces

OBJECTIVES

1. To investigate the magnetic force between two current carrying wires.
2. To measure the permeability constant μ_0 .

INTRODUCTION

The magnetic force on a current-carrying conductor underpins every electric motor - turning the hands of electric watches and clocks, transporting tape in Walkmans, starting cars, operating refrigerator compressors, etc. In this experiment, you will investigate the magnetic force between two current carrying wires. One wire will be a coil of 10 turns and the other will be a coil of 38 turns. The 10-turn coil will be taped to one end of a pivoted balance beam. The beam pivots on two pins. It also makes electrical contact through the two pins, allowing current to flow onto the beam and through the 10-turn coil. The 38-turn coil will be positioned on the table directly below the 10-turn coil. A current traveling through both coils will produce a magnetic force between the coils, either attraction or repulsion, depending on the relative direction of the currents. You will measure the magnitude of this force by noting when the magnetic torque produced by this force between the coils is balanced by the torque due to the force of gravity on known weights.

In this experiment we will determine a value for the constant μ_0 . To do this we will depend on the multimeter calibration of the amount of current flowing through the coils in amperes. Usually we *define* the ampere so that the constant $\mu_0 = 4\pi \times 10^{-7} \text{ T} \cdot \text{m/A}$, using measured forces between current-carrying wires. Here we will do the inverse—we assume our multimeter gives an accurate value for the current, and we measure forces to determine the constant μ_0 . This requires a calculation of the force expected between two current-carrying coils.

THEORY

Consider a system of two coils having currents flowing in opposite directions, as shown in Figure 1. What is the force between the coils? Is it attractive or repulsive? In the figure, \vec{B}_2 is the magnetic field *at* coil #2 produced *by* the current in coil #1.

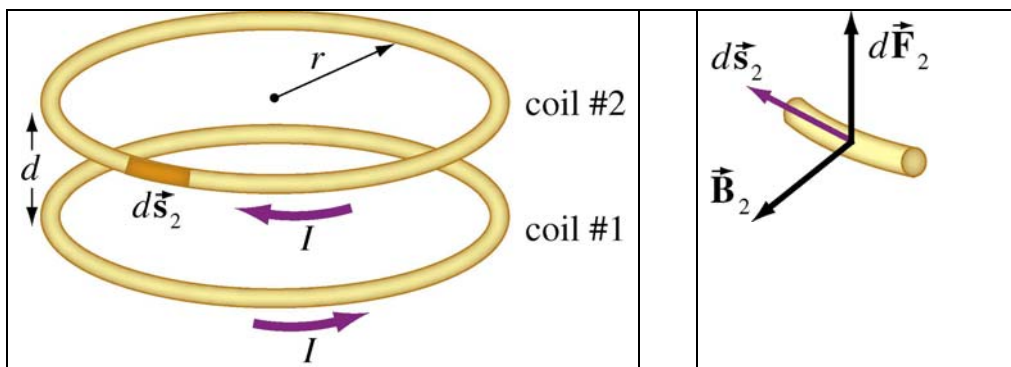


Figure 1 Force diagram on coil # 2 for repulsive force

In our experimental setup, the two coils are separated by a distance d which is much smaller than r , the radius of either coil (for purposes of clarity, the figure is not to scale). As a first approximation, we can treat the two coils as if they were parallel wires separated by a distance d . In this limit we neglect the contribution to the magnetic field, \vec{B}_1 , from parts of the lower coil that are not directly below the small current element in the upper coil. This will over-estimate the force somewhat (can you see qualitatively why?) but the error is not more than about 10% with your arrangement.

The expression for the magnitude of the force per unit length between two infinite wires (an approximation to very long wires or, in our case, the coils separated by a distance small compared to the common coil radius) is derived in the 8.02 *Course Notes*, **Section 9.2**;

$$\frac{\text{force}}{\text{length}} = \mu_0 \frac{I_1 I_2}{2\pi d} \quad (8.1)$$

where I_1 and I_2 are the currents and the separation is d . The force will be attractive if the currents in the coils are in the same direction, repulsive if in opposite directions.

For this experiment the currents will be $I_1 = n_1 I$ and $I_2 = n_2 I$, where n_1 and n_2 are the numbers of turns in the coils and I is the common current. The length to be used is the circumference of the coils, $2\pi r$, where r is the common radius. The result is that the magnitude of the force is

$$F_{\text{mag}} = (2\pi r) \frac{\text{force}}{\text{length}} = \mu_0 \frac{n_1 n_2 I^2 r}{d} \quad (8.2)$$

By Newton's third law, the total force on coil #1 is equal in direction and opposite in magnitude of the force on coil #2.

The magnetic force is balanced by aluminum foil weights that are placed at an equal distance from the pivot as the center of the upper coil. If the weights are all the same – $2 \text{ cm} \times 1 \text{ cm}$ rectangles of aluminum foil – their weight will be

$$F_g = nmg = n\rho Atg \quad (8.3)$$

where $g = 9.8 \text{ m/s}^2$, $A = 2 \times 10^{-4} \text{ m}^2$ is the area of each piece of foil, $t = 1.8 \times 10^{-5} \text{ m}$ is the thickness of the foil, $\rho = 2.7 \times 10^3 \text{ kg/m}^3$ is the density of the foil and n is the number of pieces of foil. The balance reaches equilibrium when the magnitude of the torque from the magnetic force equals the magnitude of the torque from the aluminum weight. Since the moment arms are equal, the forces must also be equal;

$$F_g = F_{\text{mag}}, \quad (8.4)$$

or

$$n\rho Atg = \frac{\mu_0 n_1 n_2 I^2 r}{d}. \quad (8.5)$$

This equation shows us that the current squared depends linearly on the number of foil pieces present, specifically

$$I^2 = \left(\frac{\rho Atgd}{\mu_0 n_1 n_2 r} \right) n. \quad (8.6)$$

The slope of the I^2 vs. n plot is given by

$$\text{slope} = \frac{\rho Atgd}{\mu_0 n_1 n_2 r}. \quad (8.7)$$

From this slope, determined from your data, you can in principle calculate the magnetic permeability of space using

$$\mu_0 = \frac{1}{\text{slope}} \left(\frac{\rho Atgd}{n_1 n_2 r} \right). \quad (8.8)$$

EXPERIMENTAL SETUP

The setup of the experiment is depicted in Figures 2 –7 below:

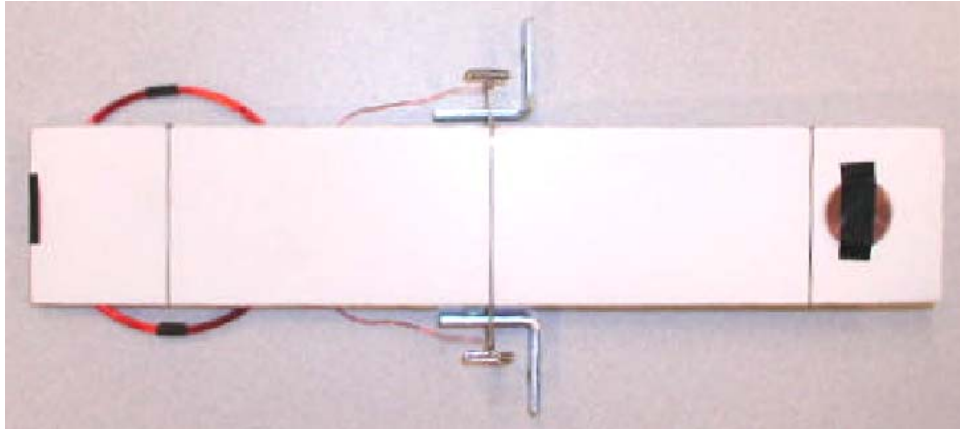


Figure 2 Top view of balance with 10-turn coil taped to underside of foam core

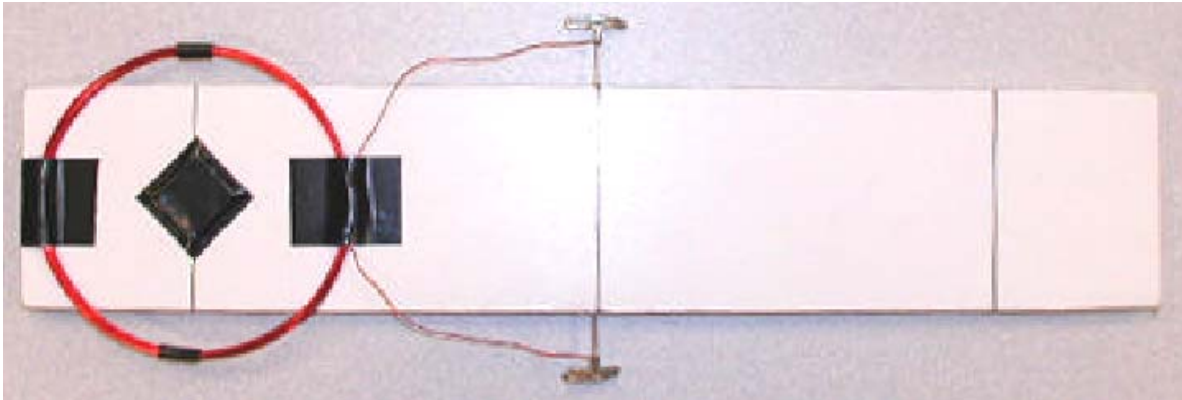


Figure 3 Underneath side of balance with 10-turn coil



Figure 4 Wires soldered to pins



Figure 5 Spacing between the 10-turn and 38-turn coils

The coil end of the beam is much heavier than the other end. The beam is approximately balanced by taping one penny, appropriately located, on the light end. Balancing the beam will determine the distance d between the coils used in Equations (8.1) - (8.8) above. In the experiment, when a current runs through the coils the beam will return to this equilibrium position when the weight of the aluminum foil squares is just equal to the magnetic force.

EXPERIMENT

Depending upon the winding direction of the coils, the current through them will generate magnetic forces such that the coils will either attract or repel each other, depending on the relative direction of the currents. The current direction is reversed with the switch shown in Figure 7 (but not in the circuit diagram, Figure 6). ***For this experiment, it is not practical to measure the current directly. Instead, a voltmeter is put in parallel with known resistance; from Ohm's Law, the current in the circuit, and hence in the coils, will be proportional to the measured voltage.***

Start by downloading the Excel spreadsheet **exp08.xls** and saving to your desktop. Measure the following quantities; record your values both in the Excel spreadsheet and on the tear-off sheet at the end of these instructions.

1. The diameter D of the upper 10-turn coil.
2. The average distance d between the centers of the coil for the balanced beam with no current flowing in the coil or foil on the beam; this will serve as your reference point for equilibrium when current flows and foil is on the beam. When balanced, the coils should be as close to parallel as you can get them to be. If necessary, you may have to place a small piece of foil on the beam (but if you do this, that piece of foil must remain in place throughout the experiment).

In making this measurement, you will likely find that the balance is rather delicate, and that even a small amount of jostling will disturb the equilibrium. You might even find that you have to hold your breath while waiting for the balance to reach equilibrium. It is this sort of delicacy that allows measurements of small effects.

3. The length L of the #16 resistance wire (a stiff shiny alloy 800 wire about 1.3 mm in diameter with a resistance of 1.02 Ω /m). For purposes of clarity, this wire is shown as

being curved in Figure 6, while in reality the wire is almost straight, as shown in Figure 7. The resistance of this wire is

$$R_{800\text{wire}} = \left(1.02 \times 10^{-2} \frac{\Omega}{\text{cm}} \right) L.$$

The voltmeter probe leads are connected across this wire. When current flows in the circuit, you will calculate the current flowing through the circuit by measuring the voltage across the #16 resistance wire using the 250mV setting of the multimeter. The current in the circuit is then calculated using Ohm's Law,

$$I = \frac{\Delta V_{800\text{wire}}}{R_{800\text{wire}}}.$$

The wiring diagram is shown in Figure 6 and a photograph of the circuit is reproduced in Figure 7:

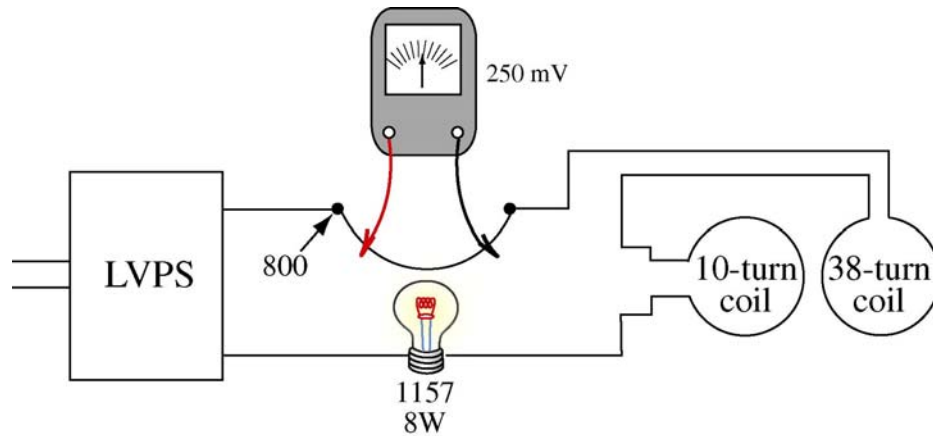


Figure 6 Wiring diagram

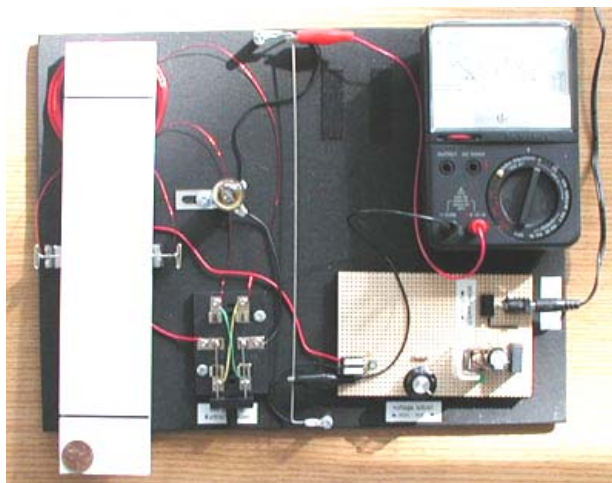


Figure 7 Experimental setup

Turn on the LVPS; the lamp will tell you if current is flowing. Adjust the output of the LVPS; for this experiment the multimeter will read between 20 mV and 100 mV on the 50 μ A(250mV) scale. The idea is to balance the magnetic force with the weights of known masses of foil. Several arrangements of the experiment's parameters are possible. The current through the coils can be set to attract or to repel, the current can be raised or lowered, and the weights can exert their force at either end of the beam. (The weights could be placed at other places on the balance, but this experiment does not use this option.) Think through how these setups vary and what might be the advantages of one over the other.

Having the coils close together is a good idea; the magnetic force, whether attracting or repelling, is strongest in that position. Also the coil spacing is easier to measure, and more reproducible, under those conditions. But should the coils be wired to repel or attract? Both ways work. ***But the 'repulsion' choice is preferable*** because once the coils start to separate the repulsive forces are reduced in two ways simultaneously: by the reduced current and by the separation of the coils. As the current is reduced the coils approach each other, resulting in a greater repulsive force, and the beam damps down to the equilibrium position.

DATA COLLECTION - CONTINUED

4. Set the coils to ***repel*** by setting the switch to the appropriate position.
5. Start with three 2 cm \times 1 cm rectangles of #7 aluminum foil. Carefully cut out three weights of this size using the template provided with the foil.
6. Center the three pieces of foil on the line directly above the 10-turn coil on the balance. (You are actually balancing torques!) Using the tweezers will help to avoid jostling the balance.
7. Turn the current up high, in order for the magnetic repulsion to overcome the weight.
8. Bring the current down slowly and as smoothly as you can. Find the current where the magnetic repulsion and weight balance. Use your ruler to confirm that the distance between the coils when balanced is your standard equilibrium distance d .
This part of the data collection can be tricky and frustrating, and requires patience as well as fairly good eyesight. As when you first determined the equilibrium separation d , you might even have to hold your breath while waiting for the balance to reach equilibrium.

Record the measured voltage both in the table provided with these instructions and in the spreadsheet.

9. Make several measurements of the current at which the balance is in equilibrium with all three weights. Between measurements, turn the current up higher or down lower, or even turn the current off. Then, remove one weight at a time and again measure the current at which the balance is in equilibrium. Repeat the measurements to make sure they are consistent and tabulate the data, number of weights as a function of current.

10. The **Chart Wizard** feature of the spreadsheet should already be set up to create a plot of the square of the current as a function of the number of weights. The slope of the best-fit straight line will be displayed. Use Equation (8.8),

$$\mu_0 = \frac{1}{\text{slope}} \left(\frac{\rho A t g d}{n_1 n_2 r} \right),$$

to determine μ_0 . Record your result both in the spreadsheet and on the tear-off sheet.

SOURCES OF ERROR

Consider the uncertainties in the measurements of the slope, with

$$g = 9.8 \text{ m/s}^2, \quad \rho = 2.7 \times 10^3 \text{ kg/m}^3, \quad t = 1.8 \times 10^{-5} \text{ m}$$

and your values for the area A of the foil, the distance d between the coils when balanced, and the radius r of the coil. Which error contributes the most? Which errors can you safely ignore?

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8.02

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Tear off this page and turn it in at the end of class.

Note:

Writing in the name of a student who is not present is a Committee on Discipline offense.

Experiment Summary 8: Magnetic Forces

Group and Section _____ (e.g. 10A, L02: Please Fill Out)

Names _____

List your measurements for the following quantities:

D , diameter of the upper 10-turn coil, meters:	
d , distance between coil centers, meters	
L , length of resistance wire, centimeters	

DATA COLLECTION - CONTINUED

Number of foil weights		
	Voltage needed to balance (millivolts)	
3	Trial 1	
	Trial 2	
	Trial 3	

	Voltage needed to balance (millivolts)	
2	Trial 1	
	Trial 2	
	Trial 3	

	Voltage needed to balance (millivolts)	
1	Trial 1	
	Trial 2	
	Trial 3	

From the best straight-line fit of your data, calculate the magnetic permeability of space using

$$\mu_0 = \frac{1}{\text{slope}} \left(\frac{\rho A t g d}{n_1 n_2 r} \right).$$

Enter the value in the spreadsheet (or get the spreadsheet to do it for you!) and report your answer here.

Answer: (the accepted value is $4\pi \times 10^{-7} \text{T} \cdot \text{m/A}$)

Congratulations, you have just measured one of the fundamental constants of nature!

Enter your answer above into the on-line record for all the class results following the directions in your Spreadsheet. At the end of the class we will display the spread of our results for this measurement of μ_0 . Next time we will combine this with our earlier measurement of ϵ_0 to

come up with our measured value of $\frac{1}{\sqrt{\epsilon_0 \mu_0}}$.