Physics Through Teaching Lab XXII

MAGNET-SOLENOID INTERACTION

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(*Submitted* Oct. - 2012)

Abstract

This is an edited version of the experiment set for the experimental examination conducted at the orientation cum selection camp held at Homi Bhabha Centre for Science Education (TIFR), Mumbai in May 2011. Students are aware that like poles of two magnets repel. In this experiment we investigate the repulsive force with respect to the distance between the two magnets. It also investigates the nature of the repulsive force between a solenoid and a magnet.

1. Introduction

It is known that like poles of two magnets repel, and unlike poles attract. The force between two current loops depends on the strengths of the currents in them, their shape, and their mutual distance. In this experiment, students are initially expected to investigate the forces between two cylindrical neodymium magnets and also forces between a magnet and a solenoid.

2. Apparatus

Two neodymium magnets, one solenoid with 3000 turns, one soft iron rod, one Hall effect sensor (UGN3501) mounted on a wooden-PVC track, one acrylic tube (with a scale pasted on it) with nylon rod and a fixing arrangement using a screw, one digital weighing balance, a pair of vernier callipers, a 9V battery, one digital multimeter, one dc power supply (15V, 1A), one retort stand with clamp, connecting wires.

3. Description of apparatus

1) Neodymium magnets:

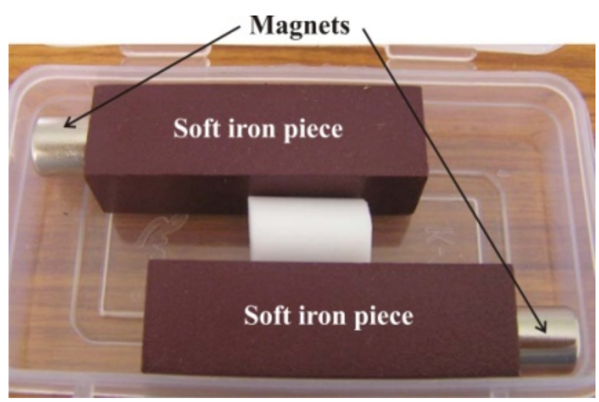


Fig.1 Neodymium magnets attached to soft iron pieces

Two neodymium magnets are provided in a box with a soft iron piece. You need to slide the magnets over the soft iron piece in order to take it out of the box. Don't drop the magnets as these are extremely brittle.

2) Solenoid:

The solenoid given to you has 3000 turns. When there is no ferromagnetic material in the core of the solenoid, it is called a solenoid with air core. Two ends of the solenoid are to be connected to the dc power supply. When not in use, the dc supply should be switched off, to avoid the heating of the solenoid.

3) Soft iron rod:

In part D of this experiment you need to replace air core with iron core. A soft iron rod is provided which can be inserted in the cavity along the axis of the solenoid. (If you face any difficulty in doing that, inform the supervisors.)

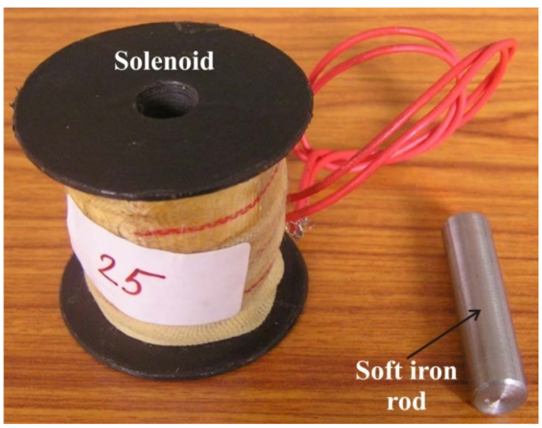
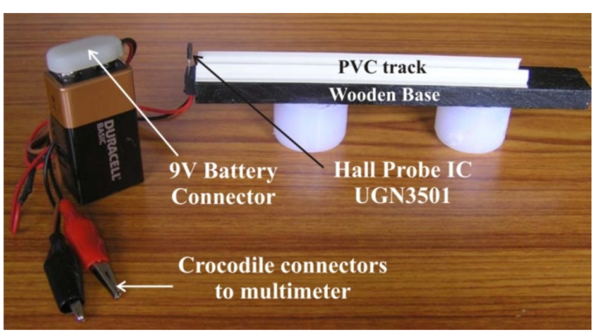


Fig.2 Solenoid and the soft iron rod

4) Wooden-PVC track, acrylic tube, Hall probe assembly:



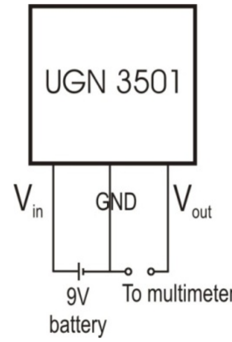


Fig.3 Wooden-PVC track and pin connection diagram of Hall sensor

A wooden-PVC track is provided to you for mounting an acrylic tube horizontally. Magnetic field can be measured using a Hall probe. The probe is a semiconductor device. When placed in magnetic field a small voltage is generated which is proportional to the component of magnetic field perpendicular to its plane. This voltage is amplified and read on a voltmeter. The Hall effect probe is mounted at one end of the track. The Hall effect sensor has three leads. The middle lead is common or ground terminal. Its first and common lead is connected to the 9V battery. A battery connector is provided to make the necessary connections. The third lead and common lead are connected to a multimeter used as a voltmeter with 20V dc range. The crocodile connectors are to be used to make this connection. Red and black colours of the crocodile connectors should be connected to positive and negative terminals of the voltmeter respectively.

Initially in the absence of the magnetic field, the multimeter displays voltage V_0 (nearly equal to 4.10V) volts. This may vary from probe to probe. Hence note V_0 for your instrument. In the presence of a magnetic field B, the multimeter reading changes to V. The strength of the field is obtained using the relation

$$B = 0.14 \times \Delta V \text{ T}$$

where $\Delta V = V - V_0$ volts. ΔV can be either positive or negative depending on the direction of B.

4) Acrylic Tube

5) Digital weighing balance:

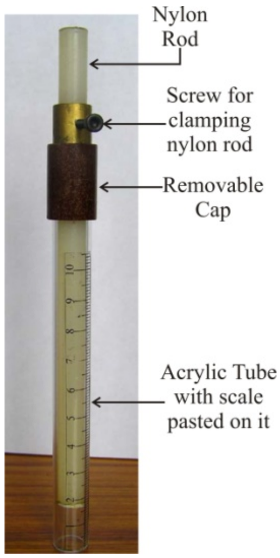


Fig.4 Acrylic tube

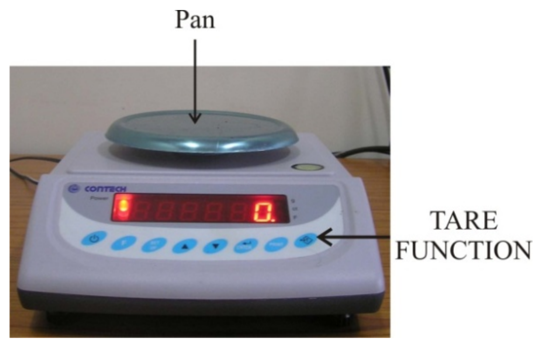


Fig.5 Digital weighing balance

The acrylic tube with scale printed on it is provided to make the distance measurements in various parts of this experiment. In part A, only tube is to be used (by removing the cap).

The height of the Hall effect sensor can be adjusted so that the sensor remains at the centre of the acrylic tube as shown in the Figure 6. The Figure 6a shows the acrylic tube without magnet and the Figure 6b shows the acrylic tube with magnet.

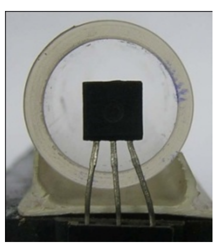


Fig.(a) without magnet

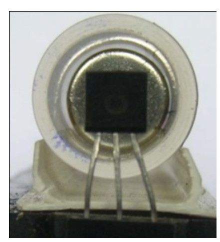


Fig.(b) with magnet

Fig.6 Hall Effect sensor adjusted at the center of the acrylic tube

This can be done by raising or lowering the sensor in the socket and simultaneously observing the reading in the multimeter. When Hall effect sensor is at the center of the tube as shown in Figure 6(b), the voltage obtained in the multimeter is maximum. Be careful while doing this as the leads of the Hall effect sensor are very thin and hence they may break if excessive and improper pressure is applied.

In this experiment the force between magnets is to be measured using digital weighing balance. The 'TARE' button is to be used for setting the reading to zero. Assume worst case error of weighing balance as ± 0.1 g.

7) DC power supply:

Figure 7: DC power supply

The dc power supply has positive (red) and negative (black) terminals. Before switching "ON" the dc supply note the following things:

a) V-coarse as well as V-fine knobs are on their "zero" positions. If they are not, then turn them anticlockwise to bring them to zero.

b) The current knob of the supply should be turned fully in clockwise direction to ensure that the current limit of the supply is high.

4. Theory

The axial magnetic field due to a cylindrical magnet of magnetic moment M at distance d along the axis from the center of the magnet can be written as

$$B = \frac{2\mu_0}{4\pi}\frac{M}{d^n} \qquad (1)$$

where the index n is expected to be an integer.

The interaction between two cylindrical magnets along their common axis can be approximately treated as dipole-dipole interaction. The force of interaction depends on the magnetic moment of the two magnets (M_1,M_2) and the separation between their centers (x).

$$F = K\frac{M_1 M_2}{x^p} \qquad (2)$$

where p is expected to be an integer.

When two magnets are placed one above the other with like poles facing each other, the upper magnet can remain suspended above the lower one at some height. Such magnetic levitation can be observed when the magnet in the acrylic tube is placed vertically above another magnet below the tube (Figure 9). The levitation height will depend on the mass of the levitating magnet and magnetic moments of the magnets used.

A solenoid behaves like a bar magnet of magnetic moment ***NIA***, where N is the number of turns, I is the current and A is the area of cross section of the solenoid. The force between the solenoid and the bar magnet can be written as

$$F = K\frac{(NIA)M}{x^q} \qquad (3)$$

where q is expected to be an integer.

When one of the magnets is placed in the acrylic tube in repulsive mode over the current carrying solenoid, it levitates; the weight of the magnet (mg) balances the repulsive force between the magnets.

$$mg = K\frac{(NIA)M}{x^q} \qquad (4)$$

If a soft iron rod is introduced in the core of the solenoid, the magnetic levitation increases due enhancement in the magnetic field. The above equation gets modified as

$$mg = \mu_r K\frac{(NIA)M}{x^q} \qquad (5)$$

where μ_r is the relative permeability of the soft iron rod at the given value of current.

5. Experiment

Part A: Determination of magnetic moment of the neodymium magnets

Arrange the apparatus as shown in Figure 8. Do not press the acrylic tube in the PVC track (the track may break if you do so). Connect the 9V battery to the battery connector. Connect the crocodile connectors to the digital multimeter adjusted on an appropriate range. Carry out the centering of the Hall sensor as shown in Figure 6. Mark 1 and 2 on the magnets using the marker pen given to you. Henceforth, you can identify these magnets from their numbers.

Study the variation of the axial magnetic field as a function of distance from the center of the cylindrical magnet. While taking the observations, care must be taken such that the voltage difference, ΔV should not be less than 0.06 V.

Fig.8 Apparatus arrangement for part A

Plot a suitable graph to determine n in equation (1). Justify rounding the value of n using the uncertainty analysis.

Determination of n is to be done only for one magnet.

Using the data collected also determine the value of magnetic moment M_1 for that magnet.

Take similar data set for the other magnet and determine its magnetic moment M_2.

Calculate the uncertainty in M_1 and M_2.

Part B: Magnet-magnet interaction

In this part you are going to study the force exerted by one magnet on another magnet along a common axis. One of the magnets is placed on the non-magnetic pan of digital weighing scale. The other magnet is placed in the acrylic tube that can restrict the magnet to move only along its axis as shown in the Figure 9.

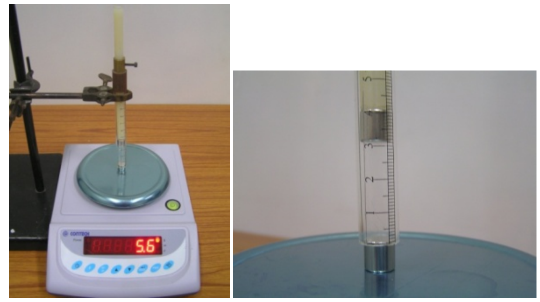


Fig.9 Apparatus arrangement for Part B

When the magnet in the tube repels the magnet on the pan, the normal force on the pan increases. The reading in the pan is a direct measure of the normal force which is proportional to the force of interaction between the magnets. The TARE function in the digital weighing scale can be used appropriately to estimate the force between the magnets. A nylon rod can be used to vary the separation between the magnets. The nylon rod can be adjusted to a desired height by clamping it using the screw provided.

Determine p and K in equation (2) by taking suitable observations and plotting necessary graphs. Justify the rounding of p using uncertainty analysis. Also estimate the uncertainty in K.

Part C: Solenoid – magnet interaction

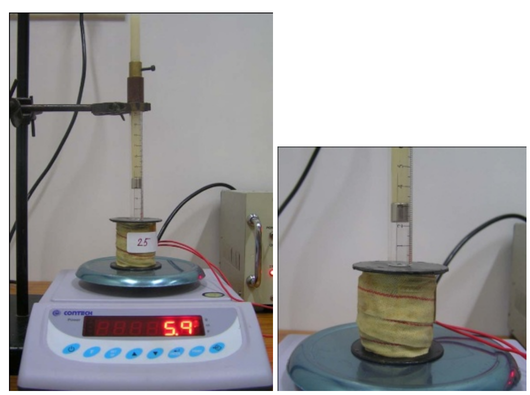


Fig.10 Apparatus arrangement for Part C

Arrange the apparatus as shown in Figure 10. Before the magnet is inserted in the acrylic tube placed above the solenoid, make sure that there is some current in the solenoid to make the magnet levitate (Hold the magnet above the solenoid, identify the orientation of the magnet which produces repulsive force). Insert the magnet inside the tube with this orientation.

Determine q and K in equation (3) by taking suitable observations and plotting necessary graphs. For this you may have to vary current in the solenoid and separation between magnet and solenoid.

Area of the solenoid can be calculated using the relation

$$A = \frac{\pi}{3}\left(r_1^2 + r_2^2 + r_1 r_2\right) \qquad (6)$$

where r_1 and r_2 are the inner and outer radius of the solenoid.

Plot suitable graphs to determine the q in equation (3). Justify the rounding of value of q using the uncertainty analysis.

Also estimate the uncertainty in K.

Use only magnet 1.

Part D: Determination of relative permeability of soft iron rod.

To determine μ_r from equations (4) and (5) find the value of x for the same currents with and without soft iron rod in the solenoid. Plot a graph to show its variation with current in the solenoid. Use only magnet 1.

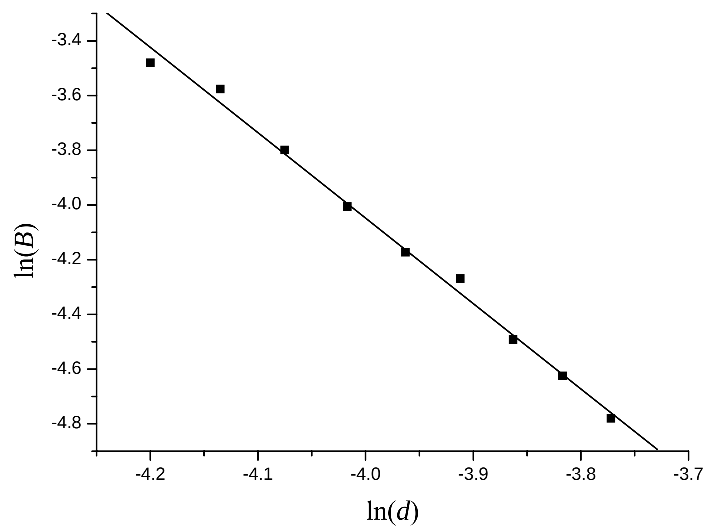
Warning:

If the current in the solenoid is less than 0.1 A, then magnet may fall on to the iron core! So keep the current always above 0.1 A.

6. Typical Observations and Calculations

Part A: $V_0 = 4.10$ V

Obs. No.	d /m	V /V	$\Delta V = V - V_0$ /V	B = 0.14 × ΔV /T	ln(d)	ln(B)
1	0.023	4.16	0.06	0.0084	-3.772	-4.780
2	0.022	4.17	0.07	0.0098	-3.817	-4.625
3	0.021	4.18	0.08	0.0112	-3.863	-4.492
4	0.020	4.20	0.10	0.0140	-3.912	-4.269
5	0.019	4.21	0.11	0.0154	-3.963	-4.173
6	0.018	4.23	0.13	0.0182	-4.017	-4.006
7	0.017	4.26	0.16	0.0224	-4.075	-3.799
8	0.016	4.30	0.20	0.0280	-4.135	-3.576
9	0.015	4.32	0.22	0.0308	-4.200	-3.480



Slope = 3.282

Uncertainty in slope:

$$\frac{\Delta(\text{Slope})}{\text{Slope}} = 0.115$$

$$n = 3.3 \pm 0.4$$

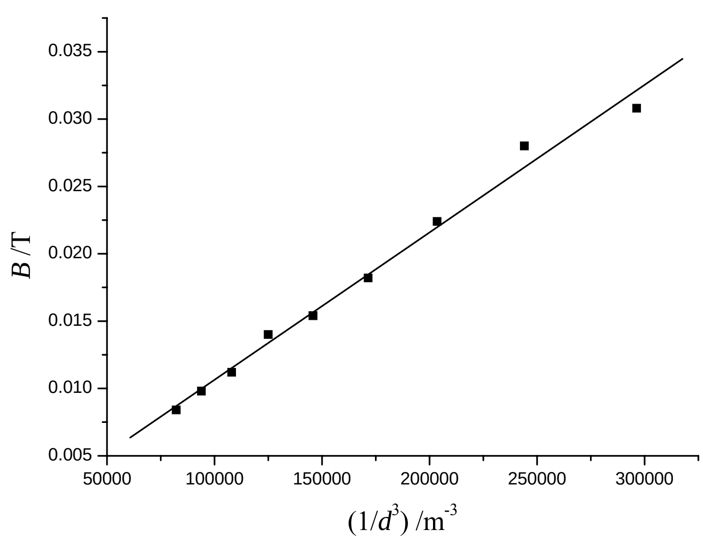
Hence, $n = 3$

For magnet 2:

Obs. No.	d /m	V /V	$\Delta V = V - V_0$ /V	$B = 0.14 \times \Delta V$ /T
1	0.024	4.16	0.06	0.0084
2	0.023	4.17	0.07	0.0098
3	0.022	4.18	0.08	0.0112
4	0.021	4.19	0.09	0.0126
5	0.020	4.21	0.11	0.0154
6	0.019	4.22	0.12	0.0168
7	0.018	4.24	0.14	0.0196
8	0.017	4.27	0.17	0.0238
9	0.016	4.31	0.21	0.0294

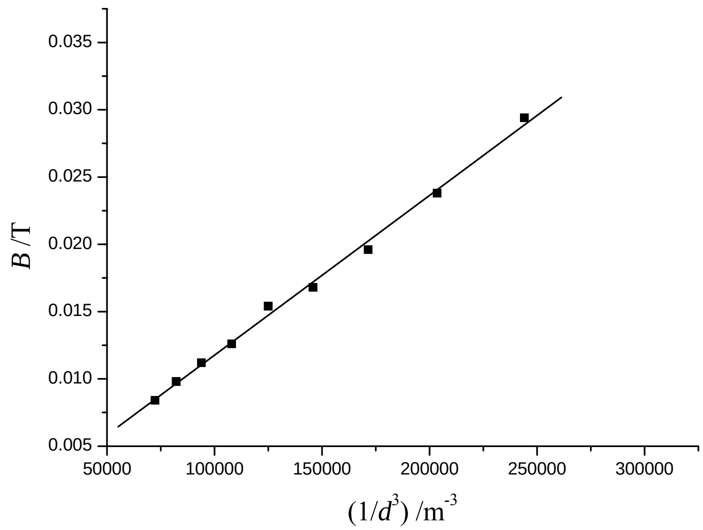
Calculation for determination of magnetic moment of magnet 1 and magnet 2:

Obs. No.	Magnet 1			Magnet 2	
	$\frac{1}{d^3}$ /m^{-3}	B /T		$\frac{1}{d^3}$ /m^{-3}	B /T
1	82190	0.0084		72338	0.0084
2	93914	0.0098		82190	0.0098
3	107980	0.0112		93914	0.0112
4	125000	0.014		107980	0.0126
5	145794	0.0154		125000	0.0154
6	171468	0.0182		145794	0.0168
7	203542	0.0224		171468	0.0196
8	244141	0.028		203542	0.0238
9	296296	0.0308		244141	0.0294



$$\frac{2\mu_0}{4\pi}M_1 = \text{Slope} = 1.188\times10^{-7}\ \text{T}\cdot\text{m}^3$$

$$M_1 = \frac{\text{Slope}}{2\times10^{-7}} = \frac{1.188\times10^{-7}}{2\times10^{-7}} = 0.594\ \text{A m}^2$$



$$\frac{2\mu_0}{4\pi}M_2 = \text{Slope} = 1.089\times10^{-7}\ \text{T}\cdot\text{m}^3$$

$$M_2 = \frac{\text{Slope}}{2\times10^{-7}} = \frac{1.089\times10^{-7}}{2\times10^{-7}} = 0.5445\ \text{A m}^2$$

Uncertainty estimation in slope of graph of B Vs $1/d^3$:

Magnet 1:

$$\frac{\Delta M_1}{M_1} = \frac{\Delta(\text{Slope})}{\text{Slope}} = 0.174$$

$$\Delta M_1 = 0.594\times0.174 = 0.103\ \text{A}\cdot\text{m}^2$$

Magnet 2:

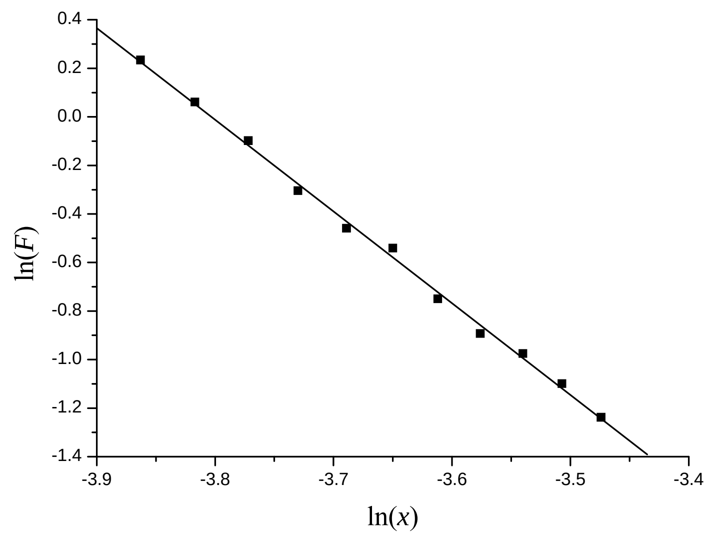
$$\frac{\Delta M_2}{M_2}\frac{\Delta(\text{Slope})}{\text{Slope}} = 0.174$$

$$\Delta M_2 = 0.5445\times0.174 = 0.095\ \text{A}\cdot\text{m}^2$$

$$M_1 = 0.594 \pm 0.103 \ \mathrm{A \cdot m^2}$$
$$M_2 = 0.545 \pm 0.095 \ \mathrm{A \cdot m^2}$$

Part B:
1) Force as a function of distance:

Obs. No.	x /m	m /kg	F /N	ln(x)	ln(F)
1	0.021	0.1290	1.2642	-3.863	0.234
2	0.022	0.1085	1.0633	-3.817	0.061
3	0.023	0.0925	0.9065	-3.772	-0.098
4	0.024	0.0753	0.7379	-3.730	-0.304
5	0.025	0.0645	0.6321	-3.689	-0.459
6	0.026	0.0594	0.5821	-3.650	-0.541
7	0.027	0.0482	0.4724	-3.612	-0.750
8	0.028	0.0418	0.4096	-3.576	-0.893
9	0.029	0.0385	0.3773	-3.540	-0.975
10	0.030	0.0340	0.3332	-3.507	-1.099
11	0.031	0.0296	0.2901	-3.474	-1.238



Slope = 4.4

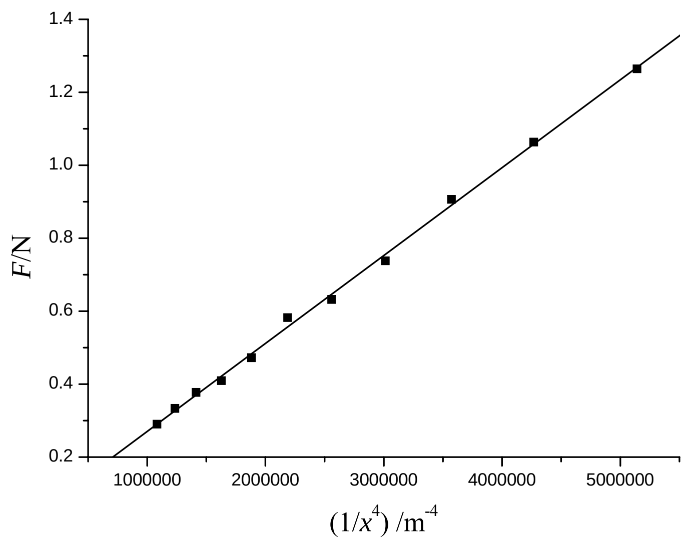
1) Uncertainty estimation in slope of graph of ln(F) v/s ln(x)

$$\frac{\Delta n}{n} = \frac{\Delta(\text{Slope})}{\text{Slope}} = 0.14$$

$$\Delta n = 0.6$$

$$n = 4.4 \pm 0.6 \approx 4$$

Obs. No.	$(1/x^4)$ /m^{-4}	F /N
1	5.142×10^6	1.2642
2	4.269×10^6	1.0633
3	3.573×10^6	0.9065
4	3.014×10^6	0.7379
5	2.560×10^6	0.6321
6	2.188×10^6	0.5821
7	1.882×10^6	0.4724
8	1.627×10^6	0.4096
9	1.414×10^6	0.3773
10	1.235×10^6	0.3332
11	1.083×10^6	0.2901



$$K = \frac{Slope}{M_1 M_2} = \frac{2.1995 \times 10^{-7}}{0.594 \times 0.545} = 6.794 \times 10^{-7}\,\mathrm{H\,m^{-1}}$$

Uncertainty estimation in slope of graph of F Vs $1/x^4$

Magnet 1:

$$\frac{\Delta(\mathrm{Slope})}{\mathrm{Slope}} = 0.157$$

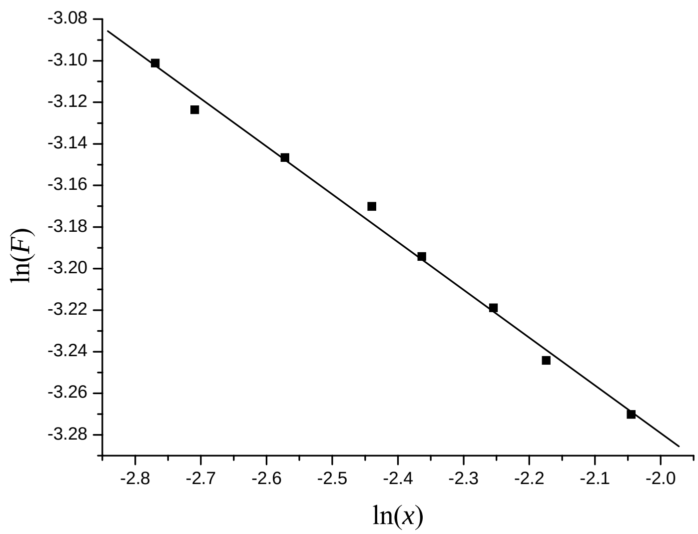
$$\frac{\Delta K}{K} = \sqrt{\left(\frac{\Delta(\mathrm{Slope})}{\mathrm{Slope}}\right)^2 + \left(\frac{\Delta M_1}{M_1}\right)^2 + \left(\frac{\Delta M_2}{M_2}\right)^2} = \sqrt{(0.157)^2 + (0.174)^2 + (0.174)^2} = 0.292$$

$$\Delta K = 6.794 \times 10^{-7} \times 0.292 = 1.98 \times 10^{-7}\,\mathrm{H \cdot m^2}$$

Part C:

Solenoid and magnet:
Graph of log (F) as function of distance

Obs. No.	x /m	F /N	ln(x)	ln(F)
1	0.045	0.0627	-2.7694	-3.1011
2	0.044	0.0666	-2.7091	-3.1236
3	0.043	0.0764	-2.5718	-3.1466
4	0.042	0.0872	-2.4396	-3.1701
5	0.041	0.0941	-2.3634	-3.1942
6	0.040	0.1049	-2.2547	-3.2189
7	0.039	0.1137	-2.1742	-3.2442
8	0.038	0.1294	-2.0448	-3.2702



Slope = 3.9055

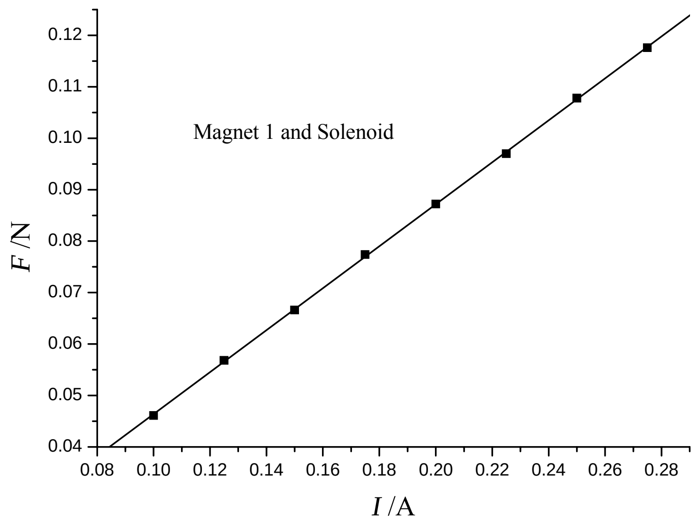
1) Uncertainty estimation of graph of ln(F) v/s ln(x)

$$\frac{\Delta n}{n} = \frac{\Delta(\text{Slope})}{\text{Slope}} = 0.093$$

$$\Delta n = 0.093 \times 3.9055 = 0.36 \approx 0.4$$
$$n = 3.9 \pm 0.4 \approx 4$$

Force versus Current:

Current (A)	Force (N)
0.275	0.1176
0.250	0.1078
0.225	0.0970
0.200	0.0872
0.175	0.0774
0.150	0.0666
0.125	0.0568
0.100	0.0461



$$\text{Slope} = 0.42$$

$$K = \frac{\text{Slope} \times x^4}{M \times N \times A} = \frac{0.42 \times 1.87 \times 10^{-6}}{0.594 \times 3000 \times 5.075 \times 10^{-4}} = 8.685 \times 10^{-7}\ \text{H m}^{-1}$$

2) Uncertainty estimation of graph F Vs I:

$$\frac{\Delta(\text{Slope})}{\text{Slope}} = 0.066$$

3) Uncertainty in area, A and in x^4:
Uncertainty in A:

$$\Delta A = \frac{\pi}{3}\left[(2 \cdot r_1 \cdot \Delta r_1) + (2 \cdot r_2 \cdot \Delta r_2) + (r_1 \cdot \Delta r_2) + (r_2 \cdot \Delta r_1)\right]$$

$\because \Delta r_1 = \Delta r_2$

$$\Delta A = \frac{\pi}{3} \cdot \Delta r_1 [3r_1 + 3r_2] = \frac{\pi}{3} \times 2 \times 10^{-5} \times \left[(3 \times 0.509 \times 10^{-2}) + (3 \times 1.903 \times 10^{-2})\right] = 1.5147 \times 10^{-6}\ \text{m}^2$$

$$\frac{\Delta A}{A} = \frac{1.5147 \times 10^{-6}}{5.075 \times 10^{-4}} = 2.9846 \times 10^{-3}$$

Uncertainty in x^4:

$$\Delta(x^4) = 4 \cdot x^3 \cdot \Delta x = 4 \times (0.037)^3 \times 0.001 = 2.026 \times 10^{-7}\ \text{cm}^4$$

$$\frac{\Delta\left(x^4\right)}{x^4} = \frac{2.026\times10^{-7}}{1.87\times10^{-6}} = 0.1083$$

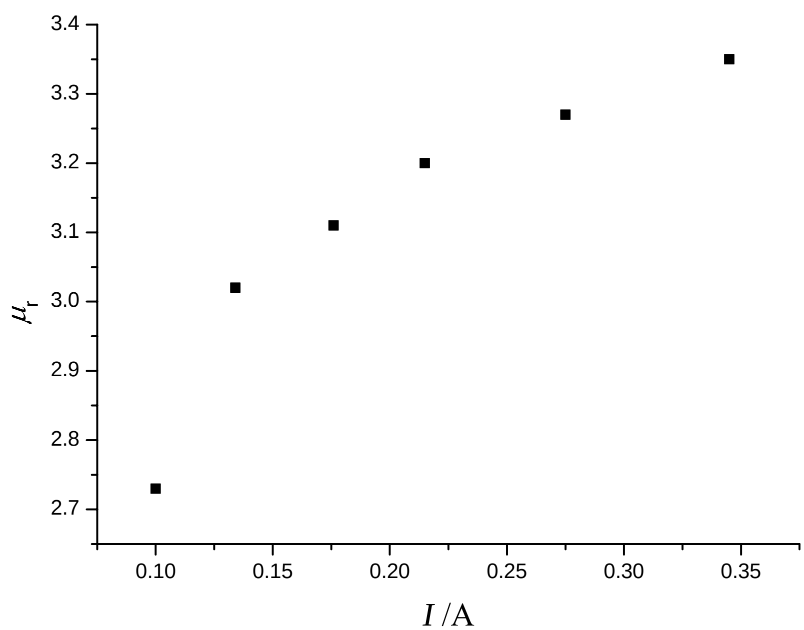
$$\frac{\Delta K}{K} = \sqrt{\left(\frac{\Delta(\text{Slope})}{\text{Slope}}\right)^2 + \left(\frac{\Delta M_1}{M_1}\right)^2 + \left(\frac{\Delta A}{A}\right)^2 + \left(\frac{\Delta\left(x^4\right)}{x^4}\right)^2}$$

$$\frac{\Delta K}{K} = \sqrt{(0.066)^2 + (0.174)^2 + (0.0029846)^2 + (0.108)^2} = 0.215$$

$$\Delta K = 1.9\times10^{-7}\ \mathrm{H\cdot m^2}$$
$$U(K) = 3.8\times10^{-7} \approx 4\times10^{-7}\ \ \mathrm{H\cdot m^2}$$

Part D:

Obs. No.	Current, I /A	Air Core Levitation x_a /cm	Iron Core Levitation x_i /cm	$\mu_r = \left(\frac{x_i}{x_a}\right)^4$
1	0.100	3.15	4.05	2.73
2	0.127	3.35	4.45	3.11
3	0.134	3.45	4.55	3.02
4	0.176	3.65	4.85	3.11
5	0.215	3.85	5.15	3.20
6	0.275	4.05	5.45	3.27
7	0.345	4.25	5.75	3.35



Conclusion

The magnetic field of the magnet varies as 3rd power of the distance from the magnet. It was also observed that the repulsive force between two cylindrical neodymium magnets is inversely proportional to the 4th power of the distance between the magnets. Similar proportionality was observed for the magnet-solenoid interaction. The experiment also discusses the method to determine the variation of relative permeability of soft iron rod with respect to the current through solenoid.

Acknowledgements

We would like to thank Prof. D. A. Desai for his valuable guidance in the development of this experiment. We also wish to thank the physics olympiad students who patiently performed the experiment.