LABORATORY I

STATIC CHARGE AND COULOMB'S LAW

In this experiment we will study one of the most profound phenomena in physics – force at a distance. Two objects each containing net electric charge will exert a *force* upon one another, entirely because of the net charge. The force will be produced no matter how far apart they are, although the magnitude of the force decreases as separation increases.

You will study ways in which net electric charge can be placed upon an object. You will learn that it is possible to place extra charge on an object so that it has a net positive charge, or take some of the charge away so that it has a net negative charge. You will observe the direction of the balanced forces to learn how the relative signs of the net charges on two objects determines whether the forces are attractive or repulsive. You will quantitatively measure the dependence of magnitude of force upon the amount of charge on each object, and upon the distance between them. From this you will be able to validate Coulomb's law and actually measure its constant of proportionality $k = \dfrac{1}{4\pi\varepsilon_0}$.

Take one gram of protons and place them one meter away from one gram of electrons. The resulting force is equal to 1.5 x 10^{23} N, or roughly the force it would take to lift an object from the surface of the Earth that had a mass about 1/5 that of the moon! Not a small force! So, if such small amounts of charge produce such enormous forces, why does it take a very delicate torsion balance to measure the force between charged objects in the laboratory? In a way, the very magnitude of the forces is half the problem. The other half is that the carriers of the electrical force on the tiny proton and the even tinier electron are so small, and the electrons are so mobile.

Once you separate them, how do you keep them separated? The negatively charged electrons are not only drawn toward the positively charged protons; they also repel one another. Moreover, if there are any free electrons or ions between the separated charges, these free charges will move very quickly to reduce the field caused by the charge separation. So, since electrons and protons stick together with such tenacity, only relatively small charge differentials can be sustained in the laboratory. This is so much the case that, even though the electrostatic force is more than a billion-billion-billion-billion times stronger than the gravitational force, it takes a very delicate torsion balance to measure the electrical force, whereas we can measure the gravitational force by weighing with a spring balance.

In this lab you will measure the force between two charges, and you will test the theoretical prediction for the force between two point charges:

$$\vec{F} = k\frac{Q_1 Q_2}{r^2}\hat{r} \qquad (1)$$

where $\vec{F}$ is the force between the charges, Q_1 and Q_2 are the charges, $\vec{r}$ is the vector displacement between the charges, and k is the Coulomb constant. Eq. (1) is known as *Coulomb's Law*.

Note that Coulomb's Law is exactly the same as Newton's Law of Universal Gravitation, which describes the force produced between two masses separated by a distance r. All that is different is that the electric charge is the source of electric force, while gravitational mass is the source of gravitational force, and the constant in each case is the measure of the strength of that force under each of these interactions of nature.

> *Note*: The torsion balance gives a direct and reasonably accurate measurement of the Coulomb force. The most accurate determinations of Coulomb's law, however, are indirect. It can be shown mathematically that if the inverse square law holds for the electrostatic force, the electric field inside a uniformly charged sphere must be everywhere zero. Measurements of the field inside a charged sphere have shown this to be true with remarkable accuracy. The Coulomb force can be expressed by the formula:
>
> $$F = k\frac{Q_1 Q_2}{r^n}$$
>
> Using this indirect method, the power n has been measured to differ from 2 by less that one part in 10^{16}!

Also as for gravity, the *potential energy* is the work needed to move the charges from a separation $\vec{r}_1$ to a separation $\vec{r}_2$:

$$U(r_2) - U(r_1) = -\int_{\vec{r}_1}^{\vec{r}_2} \vec{F}\cdot d\vec{r} = -\int_{r_1}^{r_2} k\frac{Q_1 Q_2}{r^2}\,dr = k\frac{Q_1 Q_2}{r_2} - k\frac{Q_1 Q_2}{r_1} \tag{2}$$

Note that the potential energy only depends upon the amounts of each charge and the change in the *scalar* distance between the two objects.

As you learned in the case of gravity, there is no absolute zero for potential energy. Potential energy is a measure of the *change* in energy needed to move an object in the presence of a force. So you can choose the zero of the energy scale to your convenience in solving any problem. One convenient choice for many problems is *infinity* ∞, when the two objects are separated by an arbitrarily large distance. Then the energy associated with that position is arbitrarily small and we can set that location as the zero of the energy scale. With that choice of energy zero, the energy needed to bring the two objects to a separation $\vec{r}$ is

$$U(r) = k\frac{Q_1 Q_2}{r}$$

The SI unit of measure for charge is the Coulomb [C].

The coefficient *k* (which you will measure in this experiment in the same way you measured G in the Cavendish experiment) has the value $k = 9 \times 10^9$ N m^2/C^2.

Recall the Shell Theorems[1] that describe the gravitational force due to a spherical distribution of mass. Those theorems are a consequence of the inverse-square dependence of gravitational force on distance. The same Shell Theorems therefore also apply to the force between electric charges.

The only example in stable matter of a true point charge is a single electron, which would not be practical for this measurement. You will use spheres instead of actual point charges. The reason for choosing a sphere is that charge distributes uniformly on an insulating surface. By Shell Theorem #1, the sphere will therefore experience the same force as would a point charge having the same total charge, located at the center of the sphere.

In order to study Coulomb's law, you must put a net charge upon two objects. It is simplest to analyze the distribution of the charges and the forces produced if the objects are both conducting spheres – then the Shell Theorems tell you that charge distributes uniformly on an isolated sphere, and that the force it exerts upon another charged object will act as if the net charge were all located at the center of the sphere.

Since the charges exert forces upon one another, you must do work to put the net charges onto each sphere, and then you must do work to move one sphere in the presence of the other. That latter work is the potential energy we discussed before.

It is useful to think of the potential energy per unit charge, called the *potential* V. Just as for potential energy, potential is a relative property: you can only define the change in potential that occurs when you change the charges on objects or their relative positions. Consider two spheres, one containing one unit of net charge (1 Coulomb) and the other containing net charge Q. The potential difference between the two charges is the work per unit charge needed to move them from a separation r_1 to a separation r_2:

$$V(r_2) - V(r_1) = U/Q = k\left(\frac{Q}{r_2} - \frac{Q}{r_1}\right) \tag{3}$$

This SI unit for potential is a *Volt*: 1 V = 1 Joule/Coulomb.

Again the potential can be stated relative to infinite separation ∞. With that choice of scale for potential, the potential difference between the objects when they are moved from infinite separation to a separation r is simply

$$V(r) = k\frac{Q}{r} \tag{4}$$

This expression enables you to apply charge to an object by applying a potential difference 'with respect to ∞', and to calculate how much charge you are applying.

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[1] Shell Theorem 1: For a spherical distribution of charge, the force at a point *outside* the distribution is exactly that which would be produced by locating all the charge at the center of the distribution.

Shell Theorem 2: For a spherical distribution of charge, the force at a point *inside* the distribution is 0.

Devices that move charges through potential differences are *batteries* and *power supplies*. These devices do work to move charges through a circuit of conductors, from one terminal of the device to the other. To apply a charge to the spheres in your experiment, you will use a high-voltage power supply operated at potential *V*. A power supply always has two output terminals.

In your experiment, you will use a power supply to deliver net electric charge to conducting spheres. You can do this in two ways: you can charge one 'isolated' sphere by placing one terminal of the power supply on the sphere and the other on a distant conductor. If the distant conductor is far enough away, this situation approaches the idealization of potential with respect to infinity and the relation between the charge moved from the reference object to the sphere is that of Eq. (4).

We can make this concept of reference conductor closer to absolute by connecting that second terminal to *ground*, the potential of the Earth. You can do that by driving a conducting rod into the ground and attaching the second terminal to that rod. Since the soil of the Earth is somewhat conductive (it contains water!) the charge delivered to that terminal of the battery will be distributed over the entire Earth! Again you cannot create a true realization of the abstract condition of moving charge to infinite separation, but you can approach closely to that condition by moving it to an object that is at a distance $r \gg R$ (R is the radius of the sphere you are charging).

You now have one method to deliver a 'known' quantity of charge onto a sphere: connect a power supply that produces a known potential difference, with one terminal connected to the sphere and the other terminal connected to a distant conductor. From Eq. (4) This will apply a charge $Q = VR/k$ to the sphere. The charge on the sphere will be negative if the negative terminal of the supply is connected to the sphere (+ terminal to 'ground') and positive if the positive terminal of the supply is connected to the sphere (- terminal to 'ground'). You can use this method to produce a net charge Q_1 on one sphere and a net charge Q_2 on a second sphere by using different potentials V_1 and V_2 to charge the two spheres. Note that in charging the second sphere it must be place at a distance $r \gg R$ from the now-charged first sphere while you are charging it, otherwise the charged sphere will produce an additional contribution to the potential energy on the second sphere and the simple relation of charge to potential will no longer be valid. You can pruduce charges of equal sign on both spheres or charges of opposite sign. So you are now equipped to set up the conditions of charges needed to study Coulomb's Law.

Now suppose that you charge two spheres with equal amounts of charge $Q_1 = Q_2 = Q$, the force between the spheres should be

$$F = k\frac{Q^2}{r^2} \tag{5}$$

You can test this power law scaling for Coulomb's Law, by measuring the Coulomb force for various choices of charge Q and distance r. You can then fit your measurements to a dependence

$$F = k\frac{Q^\alpha}{r^\beta} \tag{6}$$

By measuring the fitted values of α and β, you can experimentally test the essential character of Coulomb's Law.

The instrument you will use to measure force is a *torsion balance*. You used a torsion balance to measure the force of gravity in the Cavendish experiment. Here you will use it to measure the electric force between two identical equally charged spheres.

Here's how a torsion-wire balance works. A carriage supporting one of the spheres that you will charge for your studies is attached to a thin quartz fiber. This fiber is stiff to twisting: if a torque twists it either clockwise or counterclockwise from its straight orienttation, it will exert a countertorque in the rotational sense that would restore it to equilibrium. In this respect it acts as a rotational analog of a linear spring. Just as with a spring, the magnitude of the restoring torque $\vec{T}$ is proportional to the angle $\vec{\theta}$ by which it is twisted from equilibrium. Thus the torque is described by a rotational analog of Hooke's law:

$$\vec{T} = -\alpha\vec{\theta} \tag{7}$$

You can exert a known twist $\vec{\theta}$ by rotating the 'torsion knob'- the top support that holds one end of the fiber. You will do a subsidiary experiment in which you will set up the torsion balance on its side, use the gravity force to deliver known torque to the balance, and directly measure the proportionality 'torsion constant' α. You will then be set up to use the torsion balance to measure the electric force acting upon the sphere that is supported from the fiber.

The carriage supporting the sphere holds it at a radius R from the axis of the fiber. When a force *F* is applied to the sphere, it creates a torque

$$\vec{T} = \vec{R} \times \vec{F} \tag{8}$$

that twists the fiber. Now suppose that you rotate the 'torsion knob' by an angle $\vec{\theta}$ sufficient to return the sphere to the same position it had before you applied charge to it. When the torque applied by the knob cancels the torque applied by the force *F*, then the suspended sphere will point in its original direction. The rotation angle $\vec{\theta}$ and Eq. (7) then enable you to measure the torque that is produced by the force and thereby the magnitude of the force itself. The torsion knob is calibrated in degrees so that you can measure the angle through which you have turned it.

Objectives:

Successfully completing this laboratory should enable you to:

- Deliver charge to objects by static charging (friction) or by power supplies.
- Measure charge using a Faraday pail and electrometer.
- Measure very small forces using a torsion balance.
- Determine the exponent in a power law dependence between measured quantities.

Preparation:

Young & Freedman “University Physics,”” 11th ed., chapters 21-23.

- You must bring a *hardbound data book* to lab every session, and record all of your data in it. Each member of a team is individually responsible for recording all data.
- Use EXCEL for entering, analyzing, and presenting data.
- Prepare a lab report using the WORD template provided in the manual at the web site.

Problem 1

STATIC CHARGE FROM EVERYDAY MATERIALS

Your group has a problem. Every time you walk into your carpeted offices, you receive a shock! The shock is worse on dry days than on humid days, and a colleague suggested that it is due to static electricity. You want to systematically investigate what this effect is, and where it originates.

Static electricity is electric charge that is transferred between insulators when they come into physical contact. Some insulators are electronegative: an outermost electron on the atoms or molecules of the substance is weakly bound and can easily be transferred to another material. Some insulators are electropositive: the outermost electrons are more tightly bound, and an extra electron can be weakly bound to the atoms or molecules. You would like to test some of the materials in your experience to see which are electronegative and which are electropositive.

?

> Can you tell the *sign* (+ or -) of the net charge on an object with any simple experiment, or only the *relative sign* of the charges on two objects?

EQUIPMENT

You will use an *electroscope* to measure qualitatively the charge on objects. An electroscope consists simply of two pieces of thin gold foil that are suspended from a clip inside a sealed flask. The foils are connected electrically to a metal ball at the top of the flask, so that you can touch a material to be tested for charge to the ball.

Now suppose there is excess negative charge (electrons) on an object and you touch it to the conducting ball. Since the ball, the connecting rods, and the foils are conductors, charge is free to flow freely anywhere within the conductors. Some of the net charge from your insulator will flow to the foils, producing a net excess of negative charge upon them.

Now the two foils have a net like-sign charge upon them, and they will repel one another. Since the gold foils are extremely thin (see Exploration below) even a faint repulsive force is sufficient to cause the two foils to form an angle, giving a qualitative measure that they contain a net electric charge.

You are provided with several kinds of materials to rub together. You should be inventive and test other materials (e.g. items of your clothing).

PREDICTION

Some electrically insulating objects will be electronegative, some will be electropositive, and some will not easily transfer charge. Rubbing two electronegative objects together will not transfer much charge, likewise for rubbing two electropositive objects together. Rubbing an electronegative object against an electropositive object should transfer the most charge.

METHOD QUESTIONS

From your results, you should be able to sort the objects into ones that are electronegative, ones that are electropositive, and ones that do not transfer charge.

Within the category of electronegative objects (and within the category of electropositive objects) you should be able to further classify the objects according to which are *most* electronegative.

EXPLORATION

Look around your lab and find insulating objects that you can test in the same way: paper, wood, Teflon, table top, etc. In testing clothing, read the label and record the nature of the fabric. Do different fabrics have different electronegativities?

Do some research in the library or the Internet to find information about how gold leaf is made. Explain in your report why gold is unique in making it possible to make extremely thin foils.

MEASUREMENT

Make a table, in which both columns and rows are labeled with the materials that you plan to test.

Test all possible combinations of the objects, by rubbing them together and then touching one or the other object to the electroscope ball. In each case, record in the table whether the foils of the electroscope were repelled when you touch an object to the ball. To some degree you should be able to quantify the extent of the repulsion in each case.

Problem 2

ELECTRIC FORCE AS A FUNCTION OF DISTANCE

You are now convinced that net electric charge can be produced on an object, and that two charged objects exert a force upon one another. You would like to determine the dependence of the force between two charged objects as a function of distance.

EQUIPMENT

You will use a *torsion balance*, shown in Fig. 2-1, to measure the force between two identical charged spheres. Each sphere is an electrical insulator, and to good approximation distributes any net charge uniformly over its surface.

In order to make systematic measurements of force, you will need to apply reproducible *quantities* of charge to the two spheres. Simply rubbing electronegative insulators together would not enable you to deliver a reproducible amount of charge.

For this purpose you will use a *high voltage power supply*. The supply is an AC-powered instrument that generates a constant potential difference between two terminals. When conducting leads are connected to these terminals, the same potential is created throughout the metal wire of each lead, so you can produce that potential difference between any two points to which you touch the other ends of the two leads.

Torsion balance

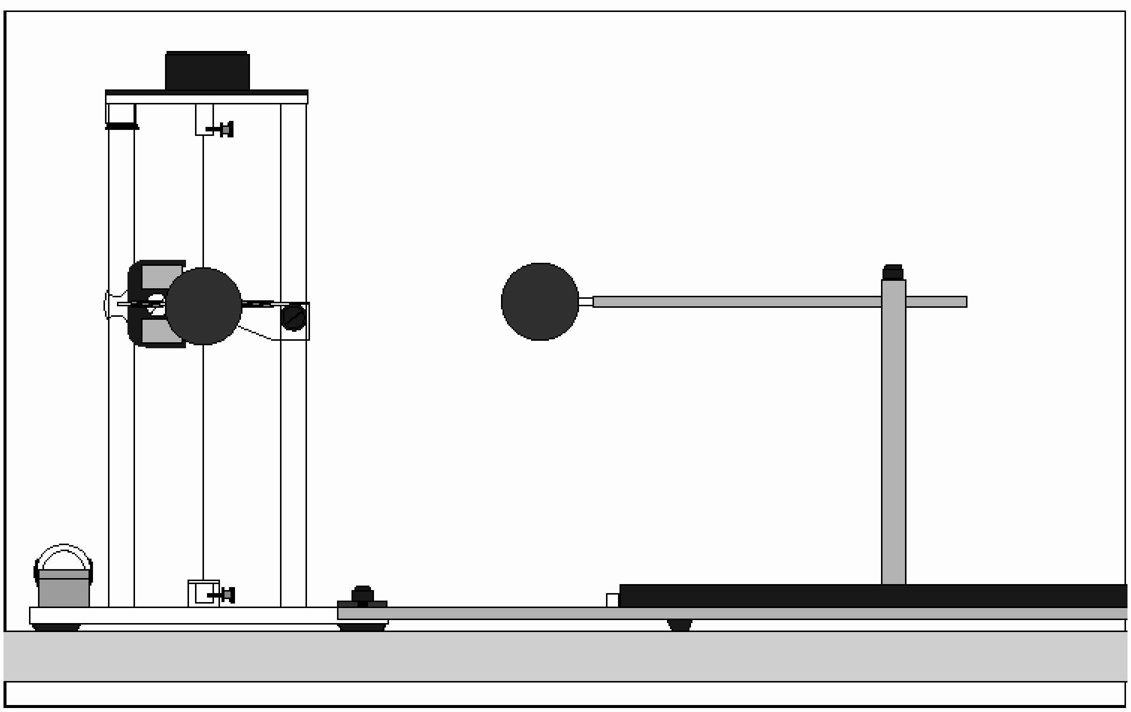


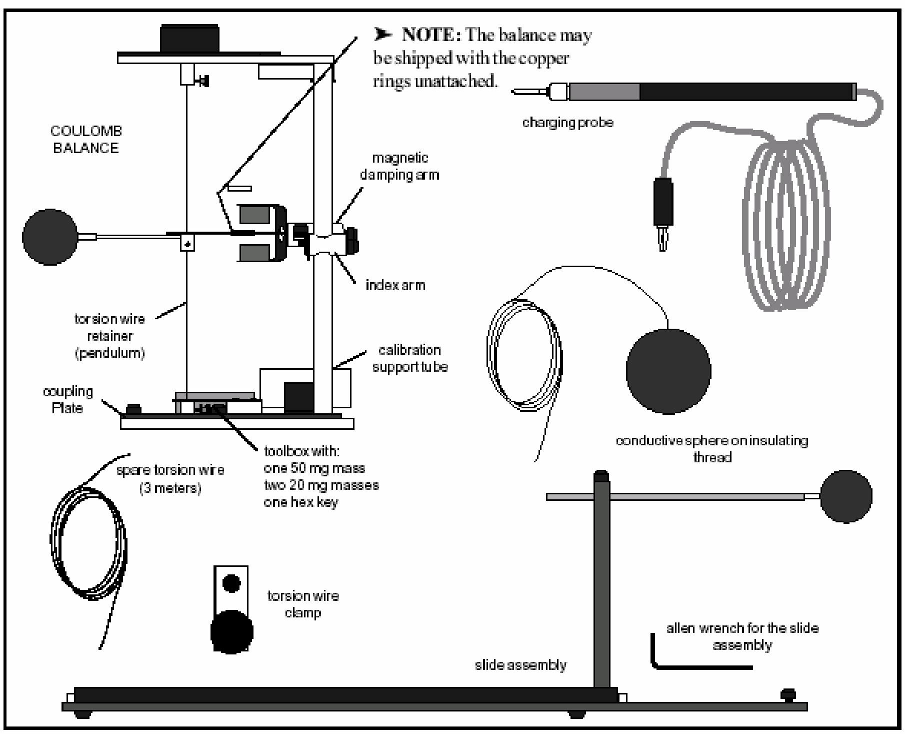
Figure 2-1. Torsion balance.

The torsion balance is a delicate torsion balance that can be used to investigate the force between charged objects. A conductive sphere is mounted on a rod, counterbalanced, and suspended from a thin torsion wire. An identical sphere is mounted on a slide assembly so it can be positioned at various distances from the suspended sphere.

To perform the experiment, both spheres are charged, and the sphere on the slide assembly is placed at fixed distances from the equilibrium position of the suspended sphere. The electrostatic force between the spheres causes the torsion wire to twist. The experimenter then twists the torsion wire to bring the balance back to its equilibrium position. The angle through which the torsion wire must be twisted to reestablish equilibrium is directly proportional to the electrostatic force between the spheres.

Here's how a torsion-wire balance works. When a force $\vec{F}$ is applied at the end of a lever arm $\vec{r}$ attached at the other end to a wire, it creates a torque $\vec{\tau} = \vec{r} \times \vec{F}$ that twists the wire. You apply a counter-torsion $-\vec{\tau}$ by turning the support of the torsion wire through an angle $\vec{\theta}$ using the torsion knob, to return the ball to the same orientation that it had before the external force was applied.

A torsion wire acts as an angular spring: twisting the torsion wire through an angle $\vec{\theta}$ requires a torque $\vec{\tau} = c\vec{\theta}$. In a subsequent problem you will directly measure the torsion constant <u>c</u> for your torsion wire; for the present problem you will simply rely upon the torsion constant remaining the same for all of your measurements. This knob applies a torque to the wire by twisting it. When the torque applied by the knob cancels the torque applied by the electric force $\vec{F}$, then the suspended sphere will point in its original direction. The torsion knob is calibrated in degrees, so that you can measure the angle $\vec{\theta}$ through which you have turned it.



It is very easy to damage this instrument, so it is important to study the instructions beforehand. The counterbalanced ball pivot is supported on a delicate torsion wire. Whenever you are manipulating the unit, you should lock the pivot to the support using the locking clamp. When you are ready to make a measurement, carefully unlock the clamp and be sure that the pivot is free from contact with the clamp or the magnetic damper.

If you accidentally break the torsion wire, you will have to replace it. The replacement procedure is tedious and time-consuming. So be careful!

High Voltage Power Supply

You are provided with a high voltage power supply, which generates a potential difference (voltage) between two output terminals. The supply is powered from an AC power plug, and produces three specific output voltages: 1,000 V, 2,000 V, and 3,000 V.

The output is well regulated for repeatable results, and current limited for safety. (The maximum current varies from 2 mA at lower voltages to 0.1 mA at the full voltage output.) The 6 kV output is center-tapped, providing simultaneous and symmetrical outputs up to ±3 kV. A built-in meter reads the output potential, and 6.3 VAC is provided for heating the filaments of electron tubes.

Specifications:

- Current -- 0.1 mA at 6 kV differential (3 kV each side), 1.8 mA at 4 kV differential (2 kV each side)
- Ripple -- less than 1%
- Line Regulation -- less than 1% output change for 10% input change
- Meter Scale -- 0-6.5 kV
- Dimensions -- 21 x 29 x 11 cm (8 x 12 x 4 in.)
- Operating Voltage -- 115/220 VAC, 50/60 Hz

METHOD QUESTIONS

If you must perform this experiment on a day when the air humidity is high, the experiment will be difficult to perform. Static charges are very hard to maintain in a humid atmosphere because of surface conductivity. Research this matter and comment on how air humidity can cause net charge to dissipate from the surface of an object.

Experiments with the Coulomb Balance are straightforward and quite accurate, yet, as with any quantitative electrostatic experiment, frustration lurks just around the corner. A charged shirt sleeve, an open window, an excessively humid day - any of these and more can affect your experiment.

The table on which you set up the experiment is made of wood with a laminated plastic top, and is electrically insulating. This is important, because if a metal table were used image charges would be induced in the table surface that would significantly affect the results of the experiment.

SETTING UP THE APPARATUS

Position the torsion balance at least two feet away from walls or other objects which could be charged or have a charge induced on them. When performing experiments, stand directly behind the balance and at a maximum comfortable distance from it. This will minimize the effects of static charges that may collect on clothing.

Avoid wearing synthetic fabrics, because they tend to acquire large static charges. Short sleeve cotton clothes are best, and a grounding wire connected to the experimenter is helpful. Use the high voltage power supply to charge the spheres. This will help ensure a constant charge throughout an experiment. When charging the spheres, turn the power supply *on*, charge the spheres, then immediately turn the supply *off*. The high voltage at the terminals of the supply can cause leakage currents which will affect the torsion balance.

When charging the spheres, hold the charging probe near the end of the handle, so your hand is as far from the sphere as possible. If your hand is too close to the sphere, it will have a capacitive effect, increasing the charge on the sphere for a given voltage. This effect should be minimized so the charge on the spheres can be accurately reproduced when re-charging during the experiment.

There will always be some charge leakage. Perform measurements as quickly as possible after charging, to minimize the leakage effects. Recharge the spheres before each measurement.

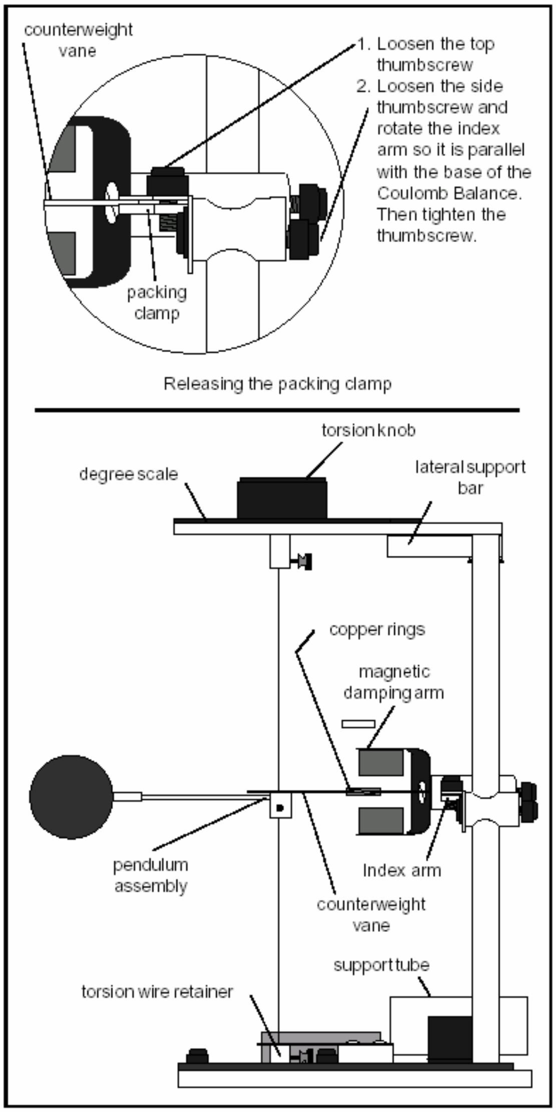


Figure 3. Setting Up the Coulomb Balance

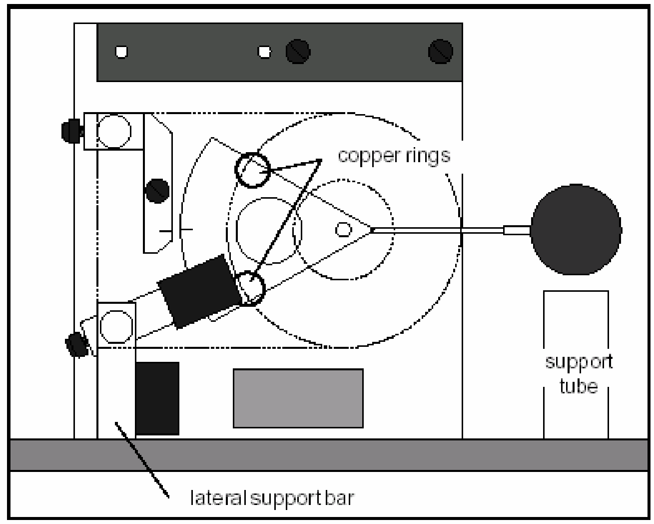


Figure 4. Zeroing the Torsion Balance

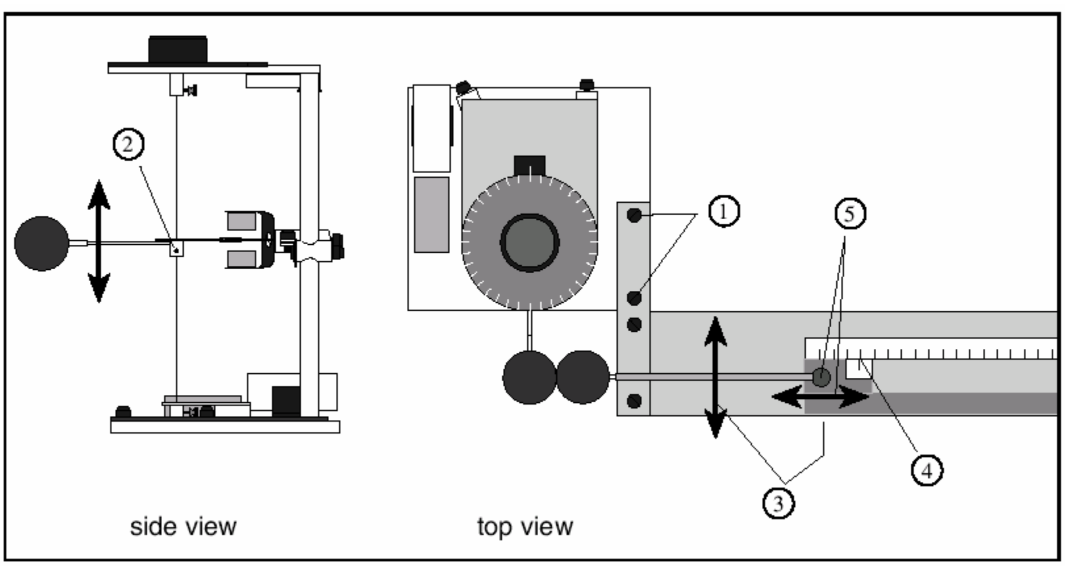


Figure 5. Slide Assembly Setup

Torsion Balance Setup

1. One of the conductive spheres is not attached when the Coulomb Balance is shipped. To attach it, just slip the stem of the sphere *over* the fiber glass rod of the pendulum assembly.
2. Slide the copper rings onto the counterweight vane, as shown in the bottom of Figure 3. Then release the packing clamp that holds the counterweight vane, as shown in the top of Figure 3. Adjust the position of the copper rings so the pendulum assembly is level.
3. Reposition the index arm so it is parallel with the base of the torsion balance and at the same height as the vane.
4. Adjust the height of the magnetic damping arm so the counterweight vane is midway between the magnets.
5. Turn the torsion knob until the index line for the degree scale is aligned with the zero degree mark.
6. Rotate the bottom torsion wire retainer (do not loosen or tighten the thumbscrew) until the index line on the counterweight vane aligns with the index line on the index arm.
7. Carefully turn the torsion balance on its side, supporting it with the lateral support bar, as shown in Figure 4. Place the support tube under the sphere, as shown.
8. Adjust the positions of the copper rings on the counterweight vane to realign the index line on the counterweight with the index line on the index arm.
9. Place the torsion balance upright.

Slide Assembly Setup

(Refer to Figure 5)

Connect the slide assembly to the torsion balance as shown in Figure 5, using the coupling plate and thumbscrews to secure it in position.

Align the spheres vertically by adjusting the height of the pendulum assembly so the spheres are aligned: Use the supplied allen wrench to loosen the screw that anchors the pendulum assembly to the torsion wire.

Adjust the height of the pendulum assembly as needed. Readjust the height of the index arm and the magnetic damping arm as needed to reestablish a horizontal relationship.

Align the spheres laterally by loosening the screw in the bottom of the slide assembly that anchors the vertical support rod for the sphere, using the supplied allen wrench (the vertical support rod must be moved to the end of the slide assembly, touching the white plastic knob to access the screw). Move the sphere on the vertical rod until it is laterally aligned with the suspended sphere and tighten the anchoring screw.

Position the slide arm so that the centimeter scale reads 3.8 cm (this distance is equal to the diameter of the spheres).

➪ *Position the spheres* by loosening the thumbscrew on top of the rod that supports the sliding sphere and sliding the horizontal support rod through the hole in the vertical support rod until the two spheres just touch. Tighten the thumbscrew.

You're now ready to experiment. The degree scale should read zero, the torsion balance should be zeroed (the index lines should be aligned), the spheres should be just touching, and the centimeter scale on the slide assembly should read 3.8 cm. (This means that the reading of the centimeter scale accurately reflects the distance between the centers of the two spheres.)

Measurement

Be sure the spheres are fully discharged (touch them with a grounded probe) and move the sliding sphere as far as possible from the suspended sphere.

Set the torsion dial to 0×C. Zero the torsion balance by appropriately rotating the bottom torsion wire retainer until the pendulum assembly is at its zero displacement position as indicated by the index marks.

🕐 With the spheres still at maximum separation, charge both the spheres to a potential of 3 kV, using the charging probe.

You have two choices for connecting the ground terminal of the high voltage power supply. If you connect it to Earth ground, the capacitance of each sphere will be approximately that of an isolated sphere, C = a/k, since there is no nearby ground. If on the other hand you position a metal beam running under both spheres, so that it has the *same spacing* to each sphere and is near them (~3-5 mm) but not touching, then you can increase the capacitance and therefore the charge Q = C V that is transferred to each sphere. Of course now you cannot easily calculate the capacitance of the sphere, so you do not know how much charge is there. But you will obtain a larger force and can make your measurements more easily and reproducibly. The choice is up to you. *Be sure to record the details of your setup in your data book.*

Immediately after charging the spheres, turn the power supply off to avoid high voltage leakage effects.

Be sure the spheres are fully discharged (touch them with a grounded probe) and move the sliding sphere as far as possible from the suspended sphere.

Set the torsion dial to 0×C. Zero the torsion balance by appropriately rotating the bottom torsion wire retainer until the pendulum assembly is at its zero displacement position as indicated by the index marks.

🕐 With the spheres still at maximum separation, charge both the spheres to a potential of 6-7 kV, using the charging probe. (One terminal of the power supply should be grounded.)

Immediately after charging the spheres, turn the power supply off to avoid high voltage leakage effects.

Repeat this procedure for each position at which you wish to measure the force between the spheres.

The reason for the deviation from the inverse square relationship at short distances is that the charged spheres are not simply point charges. A charged conductive sphere, if it is isolated from other electrostatic influences, acts as a point charge. The charges distribute themselves evenly on the surface of the sphere, so that the center of the charge distribution is just at the center of the sphere.

However, when two charged spheres are separated by a distance that is not large compared to the size of the spheres, the charges will redistribute themselves on the spheres so as to minimize the electrostatic energy U. The force between the spheres will therefore be less than it would be if the charged spheres were actual point charges.

A correction factor B, can be used to correct for his deviation. Simply multiply each value of the charge Q by 1/B, where

$$B = 1 - 4\frac{a^3}{R^3}$$

where a equals the radius of the spheres and R is the separation between spheres.

Problem 3

ELECTRIC FORCE AS A FUNCTION OF CHARGE

Now that you have put to the test the inverse-square dependence of electric force between two objects upon their separation, you would like to test whether each of the bits of charge produce force in the same way. If force is a direct consequence of the amount of charge on each object, then the force should be proportional to the charge Q_1, Q_2 on each object. If the same charge Q is applied to both objects, then the force should be proportional to Q^2.

EQUIPMENT

The equipment for this problem is the same as that for the last problem.

METHOD QUESTIONS

You will be using the high voltage power supply to deliver three amounts of charge to each sphere:

$Q_1 = C\ V_1$, $Q_2 = C\ V_2$, and $Q_3 = C\ V_3$

where C is the capacitance from the sphere to ground, and V_i are the three voltages (1000 V, 2000 V, 3000 V) that you can connect from your high voltage power supply.

MEASUREMENT

In order to compare the forces in the three cases, you must take care before each measurement to discharge both spheres (contact them to ground potential) and position the force-neutral position of the torsion balance at its reference position.

Once you have applied charge to both spheres, you will restore the sphere to the reference position by rotating the torque dial, and record the angle through which you had to rotate it.

Problem 4

MEASURING THE TORQUE CONSTANT OF THE BALANCE

You now have determined the functional dependence of electric force on distance and on charge. You would like to actually determine the proportionality constant k that relates force F to Q^2/r^2. In order to do this, you must determine the torsion constant c of your torsion balance.

1. Carefully turn the torsion balance on its side, supporting it with the lateral support bar, as shown in Figure 7. Place the support tube under the sphere, as shown.
2. Zero the torsion balance by rotating the torsion dial until the index lines are aligned. Record the angle of the degree plate
3. Carefully place the 20 mg mass on the center line of the conductive sphere.
4. Turn the degree knob as required to bring the index lines back into alignment. Read the torsion angle on the degree scale. Record the angle.

Repeat steps 3 and 4, using the two 20 mg masses and the 50 mg mass to apply each of the masses shown in the table. Each time record the mass and the torsion angle.

You now have the measurements from which to calculate the proportionality between deflection angle θ and the force F that must be exerted on the sphere to produce it.

Treat your several measurements as independent measurements of the same quantity c, and determine a mean and a standard deviation of your determination of c.

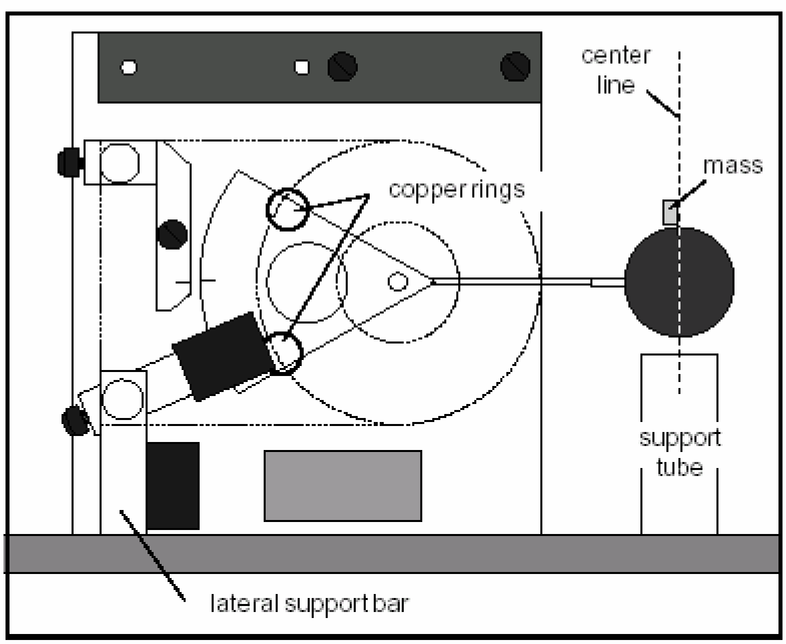


Figure 7. Calibrating the Torsion Balance