Name: Section: 202L- Date:

Experiment 1: Coulomb's Law

Objectives

- To learn the basics of good lab practice
- To learn how to estimate uncertainties
- To learn how to propagate uncertainties
- To verify Coulomb's Law

Equipment

- One Coulomb Torsion Balance
- One Coulomb Slide Assembly
- One Frederiksen 6 kV power supply
- One high voltage probe
- One double ended black banana-plug cable and one black banana-plug/aligator-clip cable.

Safety

- **HIGH VOLTAGE WARNING:** You will be working with voltages well in excess of 50 V. Although there is enough resistance in the circuit to protect you from harm, it is still wise to practice high voltage safety: **Never** touch the positive (red) probe's metal tip. **Never** touch the positive probe to anything that will complete a circuit with the ground (black) probe including the ground probe itself.
- **Be Extremely Careful With The Torsion Wire!** The wire is extremely thin and will break if you're not careful. Re-threading this wire will take up a large portion of your class time and may cost you a percentage of your grade for this experiment. So go slowly and be aware of where your hands are at all times.

Introduction

The ancient Greeks were aware of another force besides gravity. They found that, when they rubbed amber (fossilized pine resin) with fur, the amber could attract light objects like small bits of paper. This new force was given the Greek name for amber: ελεκτρον (elektron). In the 18th century, it was discovered that other objects could acquire this “electric” ability to attract objects if they were rubbed with different materials. This ability to create an electric “charge” by friction is called **triboelectricity**.

It was soon discovered that there were two “kinds” of charge. Objects which acquired the same “kind” of charge repelled one another and objects that acquired opposite “kinds” of charge attracted each other. It was Benjamin Franklin who, in 1752, called one kind “positive” and the other “negative.” In 1785, Charles Augustin de Coulomb designed and performed the experiment that you will duplicate: he determined that the force of attraction or repulsion followed the same inverse square law as gravity. Until J.J. Thompson discovered the electron in 1897, electric charge was considered to be a type of fluid. Now we understand that electric charge comes from collections of electrically charged particles (typically electrons).

Theory

We can measure the electric force produced by two collections of charge if we can successfully balance that force with another, known, force. Because we can only move very tiny amounts of charge around, the electric force we produce tends to be very small, even though we now know that the electric force is ***much*** stronger than the gravitational force. It was Charles Augustin de Coulomb who discovered the very sensitive force balance that we will be using: the torsion balance.

The Torsion Balance

The torsion balance is the rotational analogue of a spring balance. In a spring balance, a force causes a spring to either stretch or compress and the spring produces a restoring force given by **Hooke's Law:**

$$F = -kx \tag{1}$$

where F is the restoring force, x is the amount the spring has been stretched or compressed, and k is Hooke's Constant which characterizes the strength of the spring. Coulomb found that a twisted wire would do the same thing for torque that a spring does for forces:

$$\Gamma = -k\,\theta \tag{2}$$

where Γ is the restoring torque produced by the twisted wire, θ is the angle that the wire has been twisted, and k is Hooke's Constant which characterizes the stiffness of the wire. Because we will be working with forces and not torques, we will use a revised version of equation (2). Recall that torque is simply the product of a force, F, and the distance, r, away from a pivot point that the force acts. So we can re-write equation (2):

$$rF = -k\,\theta \tag{3}$$

In the torsion balance, the distance, r, is a constant. So we can divide both sides by r:

$$F = -k'\,\theta \quad \text{where} \quad k' = k/r \tag{4}$$

We will need to measure this constant, k', so that we can convert an angle into a force. By measuring the angles required to produce different forces, we can plot the results and expect that the slope of the Force vs. Angle graph will give us Hooke's Constant in Newtons per degree [N/deg].

Coulomb's Law

Coulomb's Law for the force, F, between two charged objects is given as

$$F = \frac{k_e Q q}{R^2} \tag{5}$$

Where k_e is a constant which makes the units work ($8.98755\text{x}10^9$ N m^2/C^2), Q and q are the charges of the two objects (in units of Coulombs), and R is the center-to-center distance between the two charged objects.

In the second part of this experiment, you will be holding the product k_eQq constant and varying the distance, R, between the two charged objects to verify that the force follows a $1/R^2$ curve.

In the third part of this experiment, you will hold the distance, R, constant, and change the charge on each sphere. Because both spheres will be charged the same, $Q=q$ and we can write

$$F = \frac{k_e Q^2}{R^2} \tag{6}$$

The charge on each sphere will depend on the voltage setting, V, on the power supply and the radius, r, of the sphere:

$$V = \frac{k_e Q}{r} \quad \text{or} \quad Q = \frac{V\,r}{k_e} \tag{7}$$

The radius of the sphere is 1.900(25) cm.

Experimental Procedure

Initial Set Up

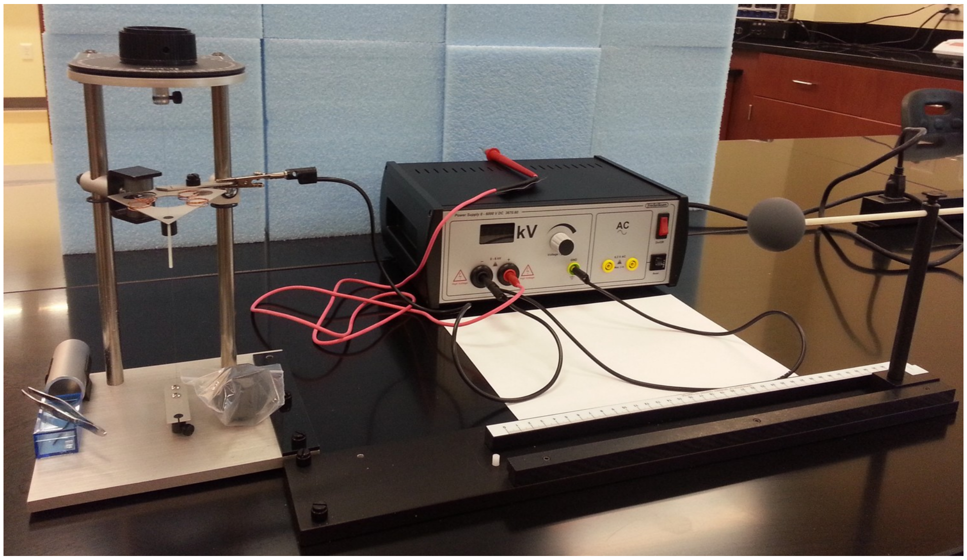

Figure 1: Initial (and Final) Configuration

Do not rush through the following procedure. Proper balancing of the pendulum is crucial to getting quality data.

The first step to getting a good measurement is to ensure that the pendulum is balanced properly. To do so:

1. **Do not remove the conductive sphere from the plastic bag with your hands!** Open the plastic bag and slip the sphere's mounting tube onto the fiberglass rod, then gently push the sphere out of the bag.
2. Loosen the *upper* screw of packing clamp that is holding the vane. The pendulum should rotate freely. The pendulum should also be approximately level.
3. Adjust the index arm (that's the arm that has the mark on it and is also the packing clamp) so that it is at the same height as the vane and a millimeter or two away from it.
4. Adjust the magnetic damping assembly so that the vane is (vertically) midway between the magnets.
5. Rotate the upper torsion knob so that the scale reads zero degrees.
6. Gently rotate the bottom torsion-wire retainer until the index line on the vane matches the index line on the index arm. **Do not loosen the thumbscrew.** This adjustment will require you to be patient, stand well back from the assembly, and give it a minute or two to equilibrate.

Torsion Wire Hooke's Constant

If you gently push the sphere to the left or right and release it, the torsion wire will act like a very delicate spring and bring the pendulum back to its starting position. To determine the electrical force you will apply, you will need to measure Hooke's constant, k', for this torsion wire. **The tiny masses are very easy to drop! Do not lose them! Do not bump the table while the masses are balanced on the sphere!**

1. Remove the blue cap from the storage box and place the allen key, two 20 mg, and one 50 mg weights into the cap. Set this cap aside.

2. Above the magnetic damping assembly is a small support. Rotate this support out so that you can (gently!) lay the entire Coulomb Balance on its side. The short tube may be removed from its black plastic holder and placed under the conductive sphere so that the pendulum does not swing downward allowing the sphere to fall off the rod.

3. Ensure that the conductive sphere has not slid down the fiberglass rod.

4. With the upper torsion knob still reading zero degrees, the pendulum should remain horizontal. However, it is quite likely that the two index marks will separate.

   a. If the separation is not too great, you can re-align the two index marks by rotating the upper torsion knob by no more than 90 degrees. This will be your "home" position.

   b. If it requires more than 90 degrees of twist to re-align the two index marks, **get your instructor to reposition the copper counterweights.** (If the equilibrium position is *unstable*, your Coulomb Balance may need to be replaced with another unit).

5. If you haven't done so already, place the short tube underneath the conductive sphere.

6. Carefully place the 20 mg mass on the centerline of the conductive sphere.

7. The sphere will come to rest on the short tube. Twist the torsion knob until the sphere lifts off the tube and the index marks are aligned once again. Record this angle in Table 1.

8. **Set the torsion knob back to the home position!**

9. Carefully place the second 20 mg mass on the centerline of the conductive sphere. Repeat steps 7 and 8.

10. Carefully remove both 20 mg masses and place the 50 mg mass on the conductive sphere. Repeat steps 7 and 8.

11. Carefully add a 20 mg mass on the centerline of the conductive sphere. Repeat steps 7 and 8.

12. Carefully add the second 20 mg mass on the centerline of the conductive sphere. Repeat steps 7 and 8.

13. Return the torsion knob to zero degrees; remove the masses; place the Coulomb Balance in its upright position; return the short tube, masses, and allen key to their storage locations; and retract the support.

When you record the angle to which you had to twist the upper torsion knob, **do not jump from 360 degrees to zero.** If the angle crosses over 360 degrees, simply add the reading you get to 360 degrees. So if the torsion knob passed zero and landed on "70 degrees," you would record 430 degrees (because 360+70=430).

Use the Capstone software to plot the Force vs. Angle and fit this to a straight line. Print a copy of this graph for each member of your group and record the slope (plus the uncertainty!) in your Raw Data section.

Force vs. Distance

Now that we can compute the restoring force given a torsion angle, we are ready to measure electrical forces. This will require a little set up:

1. Ensure that the conductive sphere has not slipped down the rod. Ensure that the upper torsion knob reads zero degrees. Adjust the bottom torsion wire retainer so that the two index marks are aligned.
2. On the slide assembly, slide the movable sphere to its furthest position (38 cm) and attach the slide assembly to the Coulomb Balance using the two plastic screws (Be careful not to cross-thread the plastic screws! If they won't go in easily, call your instructor over.)
3. Carefully slide the movable sphere to the 3.8 cm mark. The two spheres should *just touch* when the index marks are aligned on the Coulomb Balance and the movable sphere is set to 3.8 cm. You can adjust the position of the movable sphere by loosening the screw on the top of the post holding the movable sphere. Make sure you re-tighten the screw after you've adjusted the movable sphere's position.
4. Attach the ground clip from the High Voltage power supply to the index arm of the Coulomb Balance.

You are now ready to take data. We will be charging both spheres with the power supply set to 6 kV. The uncertainty in the voltage (δV) is 1% + 1 digit (*i.e.* 1% of the value displayed *plus* 1x the smallest digit displayed. In this case, that would be 1% + 10 V).

1. Slide the movable sphere to the far end of the track (38 cm).

2. Turn on the power supply and ensure it is set to 6 kV.
3. Charge both spheres by gently touching them with the probe. **Keep your hands as far from the spheres as possible to avoid capacitive effects. Do not touch the spheres after they've been charged.** If you accidentally touch one, discharge it using the ground clip and then re-charge.
4. **Turn off the power supply.**
5. Slide the movable sphere to 20 cm. The Coulomb Balance will move due to the electric force pushing the spheres apart.
6. Rotate the upper torsion knob until the index marks are once again aligned. Try to do this at arm's length (**Hint:** don't worry about reading the dial until the index marks are aligned). Record this angle in Table 2.
7. Return the upper torsion knob to zero degrees, slide the movable sphere to 38 cm, and discharge both spheres by touching the grounding clip to each one. Replace the grounding clip.
8. Verify that the index marks are once again aligned. If not, adjust the lower torsion wire retainer.
9. Repeat steps 2—8 and verify your result.
10. Repeat steps 2—9 for the following distances: 14, 10, 9, 8, 7, and 6 cm.
11. Plot the restoring force, $k'\theta$, in Newtons vs. the inverse square distance, $1/R^2$, in meters and do a linear fit.

Force vs. Charge

For this part of the experiment, you will verify that the force increases linearly with the charge. However, because you will be charging *both* spheres, the fit should actually be quadratic according to equation (6). The procedure is almost identical to the previous experiment:

1. Slide the movable sphere to the far end of the track (38 cm).
2. Turn on the power supply and ensure it is set to 6 kV.
3. Charge both spheres by gently touching them with the probe. **Keep your hands as far from the spheres as possible to avoid capacitive effects. Do not touch the spheres after they've been charged.** If you accidentally touch one, use the grounding clip to discharge it and then re-charge it.
4. **Turn off the power supply.**
5. Slide the movable sphere to $d = 0.08$ m. The Coulomb Balance will move due to the electric force pushing the spheres apart.
6. Rotate the upper torsion knob until the index marks are once again aligned. Try to do this at arm's length (**Hint:** don't worry about reading the dial until the index marks are aligned). Record this angle in Table 3.
7. Return the upper torsion knob to zero degrees, slide the movable sphere to 38 cm, and discharge both spheres by touching the grounding clip to each one. Replace the grounding clip.
8. Verify that the index marks are once again aligned. If not, adjust the lower torsion wire retainer.
9. Repeat steps 2—8 and verify your result.
10. Repeat steps 2—9 for the following voltages: 5, 4, 3, 2, and 1 kV.
11. Plot the restoring force, $k'\theta$, in Newtons vs. the charge squared, Q^2, and do a linear fit (you will need equation (7) to compute the charge).

Clean Up

Once you've completed the experiment, return your Coulomb Balance to a safe state by following these steps *in this order*:

1. Ensure that the HV power supply is switched off. Remove the grounding clip.
2. Loosen the index arm and move it so that it is in a position to clamp the vane of the Balance.
3. Secure the index arm.
4. Use two fingers to press the lower portion of the clamp against the bottom of the vane and pin it against the underside of the index arm. While holding pressure, securely tighten the clamp with the plastic screw.

5. Gently remove the Coulomb Balance sphere from the rod by sliding the sphere into the bag and then gently slide the sphere off of the rod. Close the bag and set it on the bottom plate of the balance.

6. Unscrew the two screws in the sliding assembly holding the sliding assembly to the Coulomb Balance. Move the sliding assembly aside and loosely replace the screws back into the sliding assembly (just a few turns will suffice).

Raw Data

Table 1. Torsion Wire's Hooke Constant

Total Mass (kg)	Total Weight (N)	Wire Twist (deg)
0	0	
20×10^{-6}		
40×10^{-6}		
50×10^{-6}		
70×10^{-6}		
90×10^{-6}		

Measured Hooke's Constant, k':

Table 2. Force vs. Distance

R (cm)	θ **(deg)**	$k'\theta$ (N)	$1/R^2$ **(m^{-2})**
20			
20			
14			
14			
10			
10			
9			
9			
8			
8			
7			
7			
6			
6			

Value of $k_e Q^2$:

Table 3. Force vs. Charge

V (volts)	θ **(deg)**	$k'\theta$ (N)	Q^2 (C^2)
6000			
6000			
5000			
5000			
4000			
4000			
3000			
3000			
2000			
2000			
1000			
1000			

Value of k_e/d^2:

<u>Your Lab Report</u>

Introduction

Write a few sentences about what you set out to measure and how you will compare the measured values with theory. Do *not* include details here. That is the job for the rest of your report. (Hint: write this section *last*. This way you'll have the whole experiment in your head when you write it and can properly foreshadow the results.)

Theory

Your theory section should describe the mathematical model that you expect the experiment to match. It should also detail the mathematical method by which you will compute your uncertainties. Make a prediction of your results in this section. Read your Lab Manual for instructions on how to format equations for this section.

Procedure

In one or two paragraphs, describe the methods you used to take your data, any problems you encountered and how you solved them. **You will be graded on your ability to clearly describe what <u>you</u> did.** The description should be clear enough that someone else could reproduce your results by reading this section. **Never use the second person "you" in your lab report.** ***Be Careful:*** There is a fine line between giving enough information so that a competent student could reproduce your results and writing *way too much detail.* The idea is to be <u>concise.</u> If this section is longer than two pages, it is too long.

Data

You must include three graphs:

1. Your Hooke's Constant graph with the value of the slope.
2. Your Force vs. $1/R^2$ graph with the value of the slope.
3. Your Force vs. Squared Charge graph with the value of the slope.

Read your Lab Manual for instructions on proper formatting of graphs.

Results and Conclusion

This is the most important section of your report as this section must compare your results with your theoretical predictions. It must be in paragraph form. Make sure you address the following points:

- How small of a force would you expect your torsion balance be able to measure reliably?
- Does your graph of Force vs. Inverse Squared Distance support or refute Coulomb's Law?
- Compare your slope with your value for $k_e Q^2$.
- Does your graph of Force vs. Squared Charge support or refute Coulomb's Law?
- Compare your slope with your value for k_e/d^2.
- Did you see evidence of charge leaking off the spheres? What was the evidence and how fast was charge leaking?
- What sources of error/uncertainty did you have? How could you have removed or reduced them?

Every comparison you make must be numerical!! Use percent errors. You will lose points if you use subjective comparisons such as (but not limited to): "about," "almost," "close to," "kind of," "roughly," or "sort of." You must quote uncertainties for every value you present!

Appendix

Include your signed and completed data sheets
Include a sample calculation for every computation you made.