E&M Lab 2: Charge on an Electron (Millikan Oil Drop Experiment)

Experiment Overview

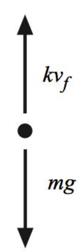
How do we know that electrons exist? How can we be sure that charge comes in discrete packages, rather than being a fluid dispersed throughout matter? How much charge is in each package? The answers to these questions remained unknown for a surprisingly long time, even after the basic laws of electricity were well understood. Benjamin Franklin's hypothesis that positively charged objects contained an excess of "electrical fluid", and negatively charged objects a deficit of it, was used throughout the 19th century. The idea of indivisible negatively-charged particles, and the word "electron", only came about in 1891, long after the basic laws of electricity and magnetism were worked out, and after electricity was in common use for a wide variety of devices.

In 1910, Robert Millikan performed an especially convincing and accurate demonstration of the atomic nature of electricity, and measured *e*, the fundamental unit of electrical charge, to an accuracy of less than 1%. You will repeat his experiment in this week's lab.

Why did it take so long? Because the electric force on a single electron is very, very small. In your experiment, you will be measuring forces on the order of 10^{-14} N. A clever technique and a great deal of patience are required.

Theory

In this experiment, we will create tiny droplets of oil. By chance, some of these droplets will be created with a few more (or a few less) electrons than protons. We have two challenges: first, how to measure the net charge q on the droplets, and second to deal with the fact that we don't know how many extra electrons are on each droplet.



Consider the forces acting on a droplet as it falls at terminal velocity through the air: gravity acts downward, and air friction acts upward.

$$mg = kv_f \tag{1}$$

where m is the mass of the drop, g is the acceleration of gravity, k is a frictional drag constant, and v_f is the free-fall speed of the drop.

Now suppose we apply an electric field to the drop, creating a new upward force: as a result, the <u>drop rises upward</u> with velocity v_r rather than falling, and air friction now acts downward. In this case, we have

$$E\,q = m\,g + kv_r \tag{2}$$

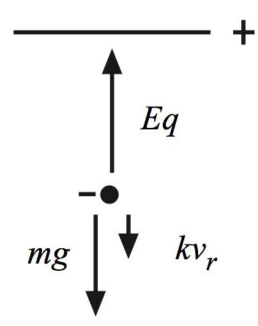


Figure 2

Combining equations (1) and (2) and solving for q gives

$$q = \frac{m\,g\,(v_f + v_r)}{E\,v_f} \qquad (3)$$

The mass of the oil drop can be found if we know its radius, *a* and the density of oil ρ:

$$m = \tfrac{4}{3}\pi a^3 \rho \qquad (4)$$

But now we must find the drop radius *a*. Stokes' Law describes the drag force on objects moving slowly through a fluid like air. Large objects experience more drag. Stokes' Law can be used to relate the radius of a falling sphere to its free-fall speed. The result is:

$$a = \sqrt{\frac{9\,\eta v_f}{2\,g\,\rho}} \qquad (5)$$

where η is the viscosity of air. Unfortunately, Stokes' Law is incorrect when the droplets are comparable in size to the distance air molecules travel before they bounce into something. (Millikan didn't realize this until later, which is why his experimental result was off by 1%.) Under these conditions, a correction factor needs to be applied to the air viscosity:

$$\eta_{eff} = \eta\left(\frac{1}{1+\frac{b}{p\,a}}\right) \qquad (6)$$

where *p* is the air pressure in Pascals (or N/m^2) and *b* = 8.2 x 10^{-3} N/m. Combining (6) with (5) gives a much nastier equation for the drop radius:

$$a = \sqrt{\left(\frac{b}{2\,p}\right)^2 + \frac{9\,\eta v_f}{2\,g\,\rho}} - \frac{b}{2\,p} \qquad (7)$$

One last note: how do we apply the electric field? We will allow the droplets to float between two parallel metal capacitor plates. We will soon learn that the electric field between parallel plates charged to a voltage *V* is

$$E = V/d \qquad (8)$$

where *d* is the separation between the plates.

So here's a summary of the experimental procedure and analysis:

1. Charge two parallel plates to a voltage *V*, and spray some oil droplets between them.
2. Use (8) to calculate the electric field between the plates.
3. Measure the free-fall velocity v_f of a droplet in air.
4. Measure the rise velocity v_r of a droplet under the influence of the electric field.
5. Use the free-fall velocity to find the drop's radius *a* using (7).

6. Use the radius to find the mass of the drop using (4).
7. Use the mass to find the charge of the drop using (3).
8. Repeat for as many droplets as you can stand to measure.

Definitions of Variables

q – charge carried by the droplet	Coulomb
d – separation of the plates in the viewing chamber	m
ϱ – density of oil	886 kg/m^3
g – acceleration of gravity	9.81 m/s^2
η – viscosity of air	see table
b – constant,	8.2×10^{-3} N/m
p – barometric pressure	use 10^5 Pa unless indicated
a – radius of the drop	m
vf – velocity of fall	m/s
vr – velocity of rise	m/s
V – potential difference across the plates	volts

Equipment

- Oil Drop Experiment apparatus
- Atomizer (squeeze bulb sprayer)
- Mineral oil (ϱ = 886 kg/m^3)
- 400 V power supply
- Ohmmeter
- Banana plug patch cords (4)
- Stopwatch

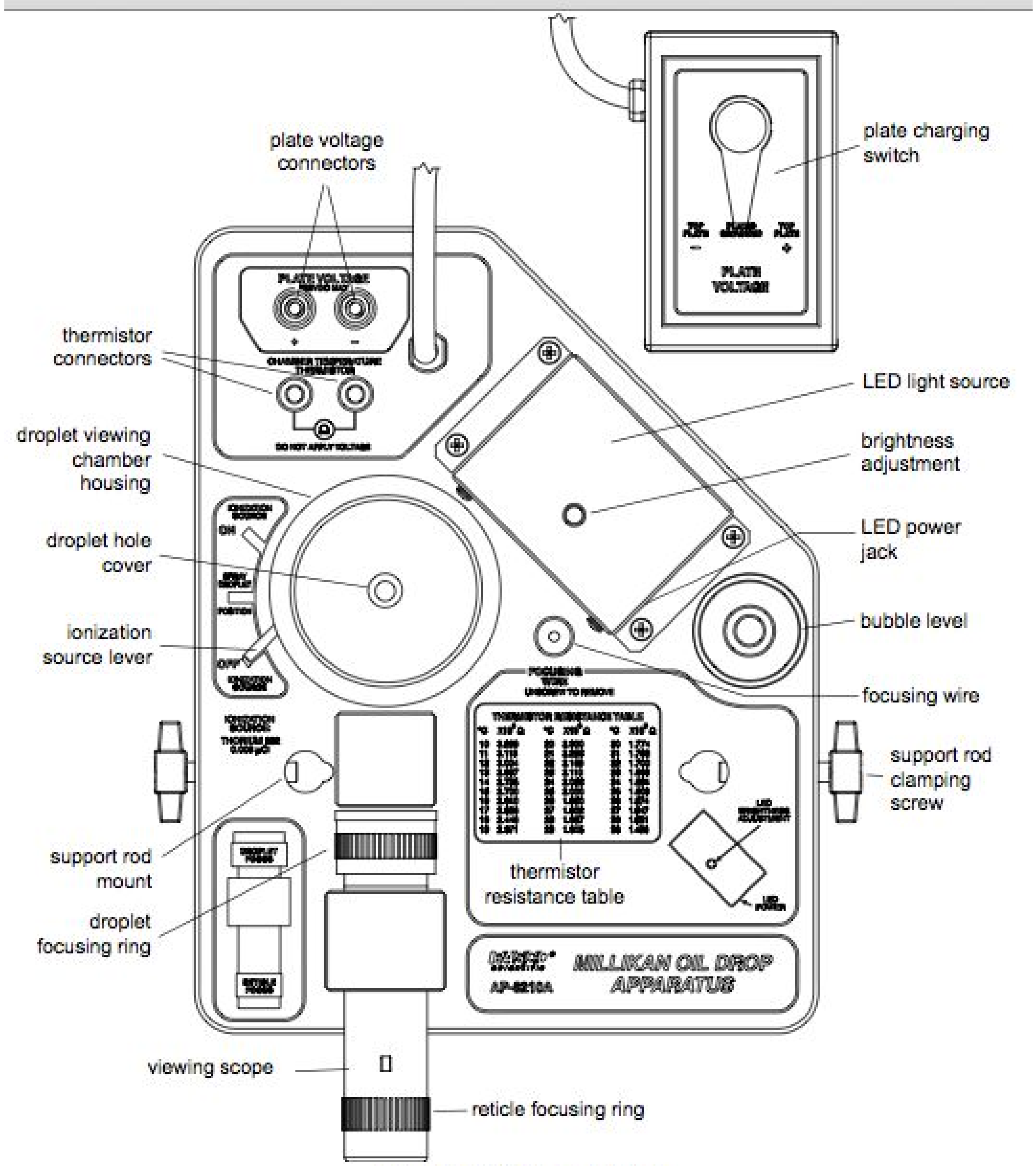


Figure 4: Apparatus platform

Setup

1. Setting up the platform
    a. Adjust the platform so the viewing scope is at a comfortable height by loosening the support rod clamping screws and sliding the platform up and down.
    b. Use the bubble level to make sure the platform is level.
2. Measuring the plate separation
    a. Disassemble the droplet viewing chamber (see Figure 5 below) to obtain the clear plastic spacer that separates the plates.
    b. Measure the thickness of this spacer and record the plate separation *d*. Be careful not to measure the thickness of the raised rim surrounding the spacer.

   c. Reassemble the viewing chamber assembly, but leave the lid and droplet hole cover off for now.
3. Setting up the optical system
   a. Unscrew the focusing wire from its storage space, and insert it into the droplet hole in the top of the upper capacitor plate. Be careful not to bend it!
   b. Plug in the LED light source.
   c. Look through the viewing scope. (Remove your glasses if you wear them.) You should see square grid reticle lines, and a magnified view of the focusing wire. The thick major reticle lines are 0.5 mm apart; the thin lines are 0.1 mm apart. The lines should be aligned with the focusing wire: if not, let me know.
   d. Adjust the reticle focusing ring until the reticle lines are in sharp focus.
   e. Adjust the droplet focusing ring until the focusing wire is in sharp focus.
   f. Return the focusing wire to its storage place.
4. Completing setup
   a. Place the droplet hole cover on top of the upper capacitor plate. The hole in its center should face down, toward the hole in the plate.
   b. Place the lid onto the viewing chamber.
   c. Connect the white patch cords between the ohm-meter and the thermistor connectors on the apparatus. You will use this thermistor to measure the temperature inside the viewing chamber.
   d. Connect the red and black patch cords between the power supply and the apparatus. Red is positive, black is negative.
   e. Turn on the power supply, and set it for 400 volts.

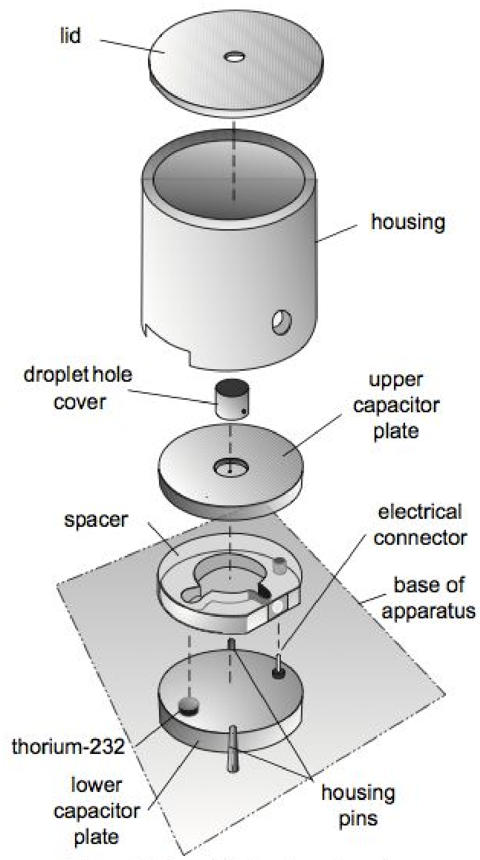


Figure 5: Droplet viewing chamber

You're now ready to begin the experiment.

Procedure

1. Temperature and voltage at start
   a. Record the resistance of the thermistor. This resistance can be translated into a temperature inside the chamber using the table at the end of this handout.
   b. Record the voltage across the plates.
2. Introduce droplets
   a. Move the ionization source lever to the "Spray Droplet Position" to allow air to escape the chamber.
   b. Ensure the tip of the atomizer is pointing downward.
   c. Practice using the atomizer while holding it over the

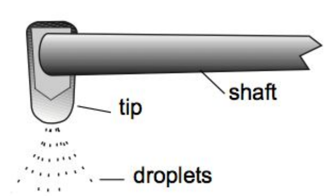


Figure 9: Atomizer tip

sink. Give the bulb a sharp squeeze until a spray of droplets emerges, followed smoothly by a gentle squeeze that releases only air.

   d. Turn off the lights.
   e. Look through the viewing scope. Place the tip of the atomizer in the hole at the top of the viewing chamber lid, and give a sharp squeeze followed by a slow gentle squeeze, without releasing the bulb. You should see a cloud of beautiful little pinpoint lights, like stars, filling the field of view. These are your oil drops. Be gentle with the atomizer: you want a scattering of stars, not a whole galaxy!
   f. Toggle the plate charging switch between zero, +, and - polarity. You should notice that some of the droplets rise when the electric field is on, and sink when it's off.
   g. If you don't see any that rise when the field is on, turn the ionization source lever to "ON" for 5 seconds. The ionization source is a radioactive isotope – ^{232}Th – that emits alpha particles. Any droplet that absorbs one will become charged.
   h. Make sure the ionization source lever is set to "OFF" before continuing. (This step is easy to forget!)
3. Select a droplet
   a. Find a droplet that takes around 5-30 seconds to sink the distance of the major grid lines (0.5 mm) when the field is off, and takes around 3-20 seconds to rise the same distance when the field is on.
   b. Fast-moving drops are bad! You won't be able to measure their speed accurately, and they will have many excess electrons.
   c. Adjust the droplet focus dial until your view of the drop is as sharp as possible.
   d. Switch the field on and off as needed to keep the drop at the center of the view. You're going to be doing this for a while…
4. Collect data on droplet rise and fall
   a. You should have one partner looking through the scope while another records the data. If you look away from the scope, you're sure to lose track of which droplet you were tracking!
   b. Turn off the field, and use a stopwatch to measure the time it takes the droplet to fall 0.5 mm (from one major grid line to the next). Record this time in a spreadsheet column labeled "Drop 1 Fall".
   c. Turn the field on, and measure the time it takes the droplet to rise 0.5 mm. Record this time in a column labeled "1A Rise".
   d. Repeat this procedure, timing the drop as it goes up, then down, as many times as you can. Some things to watch out for:
   e. Sometimes, you will notice that your droplet suddenly starts rising faster or slower. This is because it has gained or lost an electron. When this happens, create a new spreadsheet column called "1B Rise", and record all rise times for this new charge in that column. You can continue to record the fall times in "Drop 1 Fall".
   f. Sometimes, you'll lose track of your pet oil droplet. When this happens, choose another one, re-spraying if needed. Record the fall times for this droplet in a

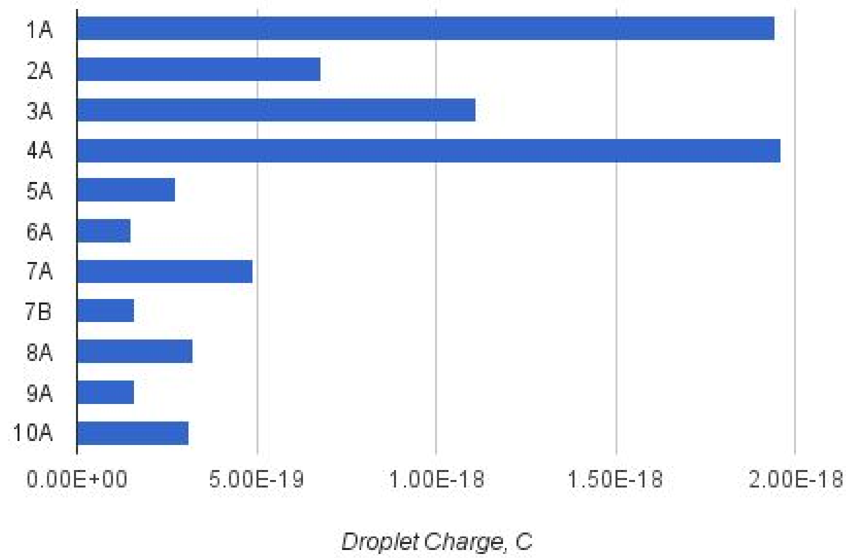
column labeled “Drop 2 Fall”, and the rise times in “2A Rise”.

g. As you go, give each drop a different number; each charge on the same droplet is given a different letter.
h. If you’ve measured 10 different times for the same droplet without seeing its charge change, try to deliberately give it a new charge by turning the ionization source lever to “ON” for 5 seconds.

5. Continue until exhausted
    a. Keep doing this, switching partners now and then, until you’ve got at least 30 rise times for at least 5 different drop & charge combinations. This is the minimum needed to get a workable result, but the more measurements the better: I encourage you to come back to the lab on a later day to collect more data on your own.
    b. Remember, the more data you collect, the smaller your uncertainty will be!
6. Temperature and voltage at end
    a. Record the thermistor resistance and plate voltage at the end of the experimental session. If you collect data in several sessions, record temperature and voltage data at the start and end of each session.

Analysis

1. Important constants
    a. Use Appendix B below to convert the thermistor’s resistance into a temperature in °C. Use interpolation to get the most accurate value.
    b. Use Appendix A below to find the viscosity of air in the chamber.
2. Droplet mass
    a. Find the mean fall time for each drop.
    b. Convert the fall time into a speed in m/s. Remember, the spacing between the major grid lines is 0.5 mm.
    c. Use the mean fall speed to calculate each droplet’s radius and mass, using equations (7) and (4).
3. Droplet charge
    a. Calculate the mean rise speed for each drop number and charge letter.
    b. Use the mean fall speed, mean rise speed, and droplet mass to calculate the charge for each different drop # / charge letter.
4. Comparing charges
    a. Hopefully, each of the charges you measured will be close to a multiple of some common factor. That common factor is the charge on the electron. A bar graph can be helpful in doing this analysis. Here’s one student group’s actual data:



Notice that 6A, 7B, and 9A are all about the same, 5A, 8A, and 10A are all about twice as big, 7A is three times as big, 2A is four times as big, and the others are hard to determine. Apparently 6A, 7B, and 9A have a single extra electron, 5A, 8A, and 10A has two, and so on.

Note that some of their first droplets had too many electrons to be useful -- maybe eight, maybe ten, it's hard to tell. This is why you want to pick slow-moving (weakly-charged) drops! These data were discarded in the final analysis.

b. If you're unlucky, you might not have a droplet with a single extra electron. You can still figure out the charge on a single electron in this case, but it'll take some thinking!
c. Divide each droplet charge by the number of electrons you think it has to obtain an estimate of the charge on an electron for each drop # / charge letter.
d. Calculate and report the mean and 95% confidence interval of these estimates of the charge on an electron. For the example above, the students found the charge on the electron was (1.54 +/- 0.07) x 10^{-19} C -- in agreement with the accepted value to within 5%! Can you do better?

Discussion Questions

1. Is your result consistent with the accepted value?
2. What is the largest source of measurement error in your experiment? (What quantities are known least accurately?)
3. Millikan spent five years doing this experiment over and over. Comment on his sanity.