Millikan Oil Drop Apparatus

AP-8210B

Introduction

The Millikan Oil Drop Apparatus is used to determine the electric charge of an electron. The method used determines the charge on several oil droplets by measuring the electric force experienced by the droplets in an electric field of known strength. The number of electrons on each oil droplet is unknown, but the total charge per droplet can be determined. After collecting data for a large number of droplets, the droplets are analyzed by grouping them according to similar charges. When comparing the difference in charges between groups of similar charges, the least difference in charge is the charge of a single charged particle, the electron.

Although it is relatively easy to produce a known electric field, the force exerted by such a field on a particle carrying only one or several excess electrons is very small. For example, a field of 10^5 volts per meter would exert a force of only 1.6×10^{-14} N on a particle bearing one excess electron. This is a force comparable to the gravitational force on a particle with a mass of 10^{-15} kg. The success of the Millikan Oil Drop Experiment depends on the ability to measure forces this small.

The behavior of small, charged droplets of oil, with masses of 10^{-15} kg or less, is observed in a gravitational and an electric field. Using Stokes' Law, measuring the velocity of the drop's fall in air allows you to calculate the mass of the drop. Observing the velocity of the drop rising in an electric field then allows you to calculate the force on, and thus the charge carried by, the drop.

In this experiment, the total charge on a drop is measured. From this, the charge of a single electron can be determined via analysis of the data obtained and a certain degree of experimental skill. By selecting droplets which rise and fall slowly, you can make sure the drop has a small number of excess electrons. Several drops should be observed and their respective charges calculated. If the charges of these drops are integer multiples of a certain smallest charge, this is a good indication of the atomic nature of electricity. However, since a different droplet has been used for measuring each charge, there remains the question as to the effect of the drop itself on the charge. This uncertainty can be eliminated by changing the charge on a single drop while the drop is under observation, which can be accomplished with an ionization source placed near the drop. In fact, it is possible to change the charge on the same drop multiple times. Using this method, if the results of measurements yield charges which are integer multiples of a smallest charge, the atomic nature of electricity is proven.

Equipment

Included equipment:

- Millikan Oil Drop Apparatus
- AC adapter (100 - 240 VAC to 12 VDC, 1.0 A)
- Atomizer
- Funnel
- Non-volatile mineral oil, 120 mL (~4 oz)

> **NOTE:** The provided mineral oil has a measured density of 855 kg/m^3. If you are using a different mineral oil, measure its density before the experiment.

Required equipment:

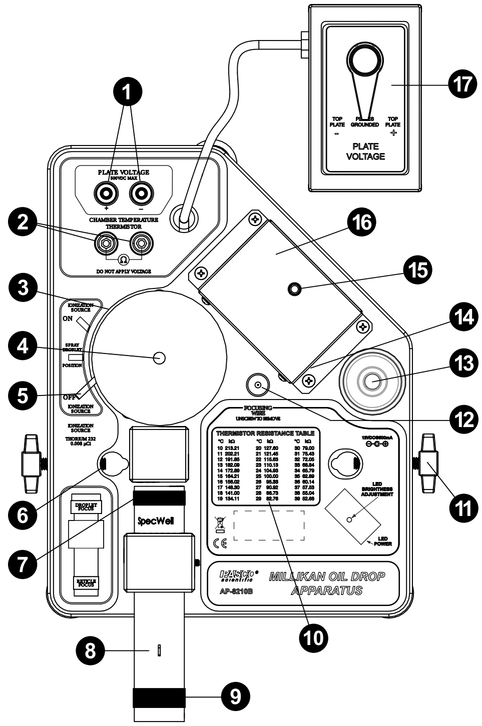
- PASCO Stopwatch (ME-1234) or equivalent
- High Voltage DC Power Supply (SE-9700) or equivalent 500 VDC power supply
- 4× banana plug patch cords, such as those provided in the Banana Plug Cord 5 Pack (SE-9750 or SE-9751)
- Digital multimeter with test leads, to measure voltage and resistance

Recommended equipment:

- Large Rod Base (ME-8735)
- Stainless Steel Rod, 45 cm (ME-8736)
- Micrometer (SE-7337A)

Features

Platform features



❶ **Plate voltage connectors**

4 mm diameter.

❷ **Thermistor connectors**

Accepts pointed test leads from a multimeter. The thermistor is mounted in the lower capacitor plate in the droplet viewing chamber.

> ⓘ **IMPORTANT:** Do NOT apply voltage to the thermistor connectors!

❸ **Droplet viewing chamber housing**

See **Viewing chamber features** for details of the chamber.

❹ **Droplet hole cover**

❺ **Ionization source lever**

Use to control the activity of the ionization source. See **Ionization source lever** in the **About the controls** section for details of the positions.

❻ **Support rod mounting hole**

Use to mount the apparatus on support rods, allowing the viewing scope to be raised to a comfortable eye level.

❼ **Droplet focusing ring**

❽ **Viewing scope**

30X, bright-field, erect image. Reticle has 0.5 mm line separation between major divisions and 0.1 mm separation between minor divisions.

❾ **Reticle focusing ring**

❿ **Thermistor resistance-to-temperature conversion table**

⓫ **Support rod clamping screw**

⓬ **Focusing wire**

Use to focus the viewing scope on the desired area of the chamber.

⓭ **Bubble level**

14 **LED power jack**

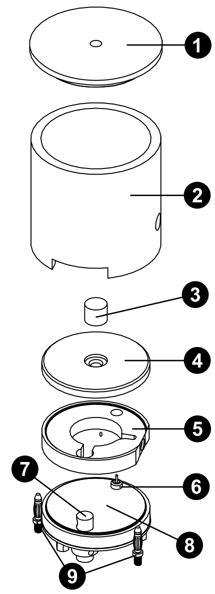
15 **Brightness adjustment knob**

16 **LED light source**

17 **Plate charging switch**

Uses a 1 m cord to prevent platform vibration while switching.

Viewing chamber features



1 Lid (clear plastic)

2 Housing (convex lens not shown)

3 Droplet hole cover

4 Upper capacitor plate (brass)

5 Plastic spacer plate (~7.6 mm thick)

6 Electrical connector

7 Thorium-232 (0.00185 microcurie alpha source)

> **NOTE:** Thorium-232 is a naturally occurring, low level alpha particle emitter with a half-life of 1.41×10^{10} years. It is not regulated in its use and poses no hazard to the apparatus user.

8 Lower capacitor plate (brass)

9 Housing pins

About the controls

Ionization source lever

The ionization source lever has three settings: "IONIZATION SOURCE OFF", "SPRAY DROPLET POSITION", and "IONIZATION SOURCE ON", as shown in Figure 1. The behavior of the ionization source at each setting is as follows:

- When the lever is at the **OFF** position, the ionization source is rotated away from the area of the droplets, so virtually no alpha particles enter the area. In this position, the alpha source is shielded on all sides.
- When the lever is at the **ON** position, the ionization source is rotated toward the area of the droplets and the area is exposed to the ionizing alpha particles from the thorium-232.
- When the lever is at the **SPRAY DROPLET POSITION**, the chamber is vented by a small hole that allows air to escape when oil droplets are being introduced to the chamber.

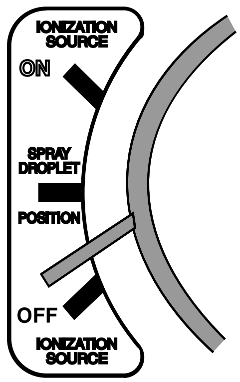


Figure 1

Plate charging switch

The plate charging switch has three positions, as shown in Figure 2:

- **TOP PLATE –**: The negative binding post is connected to the upper capacitor plate.
- **TOP PLATE +**: The negative binding post is connected to the lower capacitor plate.
- **PLATES GROUNDED**: The plates are disconnected from the high voltage supply and are electrically connected to each other.

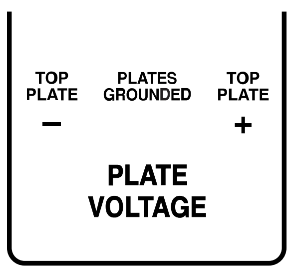


Figure 2

Theory

Analyzing the forces acting on an oil droplet will yield the equation for determining the charge carried by the droplet. Figure 3 shows the forces acting on the drop when it is falling in air and has reached its terminal velocity. (In this experiment, the droplets reach terminal velocity in a few milliseconds.) In this illustration, v_f is the velocity of the falling droplet, k is the coefficient of friction between the air and the drop, m is the mass of the drop, and g is the acceleration due to gravity.

Figure 3

Since the oil droplet is falling at terminal velocity, the net force is zero. Therefore, the forces on it must be equal and opposite, as given by:

$$mg = kv_f \qquad \text{(Eq. 1)}$$

Figure 4 shows the forces acting on the drop when it is rising under the influence of an electric field. In this case, E is the strength of the electric field, q is the charge carried by the drop, and v_u is the speed at which the drop is going up.

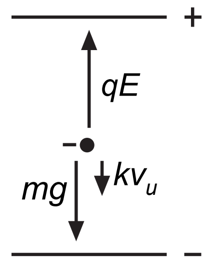


Figure 4

Adding the forces vectorially, we find that:

$$qE = mg + kv_u \qquad \text{(Eq. 2)}$$

In both cases there is also a small buoyant force exerted by the air on the droplet. However, since the density of air is only about one-thousandth that of oil, this force may be ignored.

Plugging Equation 1 into Equation 2 to eliminate k, we can solve for q to obtain the relationship:

$$q = \frac{mg}{E}\left(\frac{v_u}{v_f} + 1\right) \qquad \text{(Eq. 3)}$$

To eliminate m from Equation 3, we use the expression for the volume of a sphere and the density of the oil:

$$mg = \tfrac{4}{3}\pi a^3 \rho g \qquad \text{(Eq. 4)}$$

where a is the radius of the droplet and ρ is the density of the oil.

Substituting Equation 4 into Equation 3 shows that, when the drop is going up, the charge is given by:

$$q = \frac{4\pi a^3 \rho g}{3E}\left(\frac{v_u}{v_f} + 1\right) \qquad \text{(Eq. 5)}$$

Figure 5 shows the forces acting on the drop when it is going down under the influence of an electric field. In this case, the force of air friction points upward due to the oil drop moving down at speed v_d.

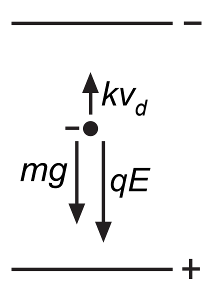


Figure 5

Adding these forces vectorially, we find that:

$$qE + mg = kv_d \qquad \text{(Eq. 6)}$$

Substituting k from equation 1 and following the same series of steps that produced Equation 5, we find that when the drop is being driven down:

$$q = \frac{4\pi a^3 \rho g}{3E}\left(\frac{v_d}{v_f} - 1\right) \qquad \text{(Eq. 7)}$$

where v_f is the falling velocity from when the electric field is off.

Stokes' Law ($F_f = 6\pi\eta a v_f$) can be used to calculate a. This expression relates the radius a of a spherical body to its velocity of fall v_f in a viscous medium with the coefficient of viscosity η. Setting the formula for Stokes' Law equal to the right-hand term of Equation 4 and solving for a, we obtain:

$$a = \sqrt{\frac{9\eta v_f}{2\rho g}} \qquad \text{(Eq. 8)}$$

NOTE: For additional information about Stokes' Law, refer to Introduction to Theoretical Physics, by L. Page (New York, Van Nostrand), Chapter 6.

However, Stokes' Law becomes inaccurate when the velocity of fall of the droplets is less than 0.1 cm/s. This is because droplets with velocities this small or smaller have radii on the order of 2 microns, comparable to the mean free path of air molecules, a condition which violates one of the assumptions made in deriving Stokes' Law. Since the velocities of the droplets used in this experiment will be in the range of 0.01 to 0.001 cm/s (10^{-4} to 10^{-5} m/s), the viscosity must be multiplied by a correction factor. The resulting effective viscosity is:

$$\eta_{eff} = \eta\left(\frac{1}{1+\frac{b}{pa}}\right) \qquad \text{(Eq. 9)}$$

where b is a constant, p is the atmospheric pressure, and a is the radius of the drop, as calculated using Equation 8.

NOTE: A derivation of Equation 7 can be found in The Electron by R.A. Millikan (Chicago, The University of Chicago Press), Chapter 5.

Substituting η_{eff} from Equation 9 into Equation 8 gives:

$$a = \sqrt{\frac{9\eta v_f}{2\rho g}\left(\frac{1}{1+\frac{b}{pa}}\right)} \qquad \text{(Eq. 10)}$$

Solving Equation 10 so that a is on only one side, we find that:

$$a = \sqrt{\left(\frac{b}{2p}\right)^2 + \frac{9\eta v_f}{2\rho g}} - \frac{b}{2p} \qquad \text{(Eq. 11)}$$

The value obtained from Equation 11 can then be plugged into a in Equations 5 and 7 when calculating the value of the charge q.

The strength of the electric field is given by:

$$E = \frac{V}{d} \qquad \text{(Eq. 12)}$$

where V is the potential difference across the parallel plates separated by the distance d.

Substituting Equation 12 into Equations 5 and 7, we find that:

$$q = \frac{4\pi a^3 \rho g d}{3V}\left(\frac{v_u}{v_f} + 1\right) \qquad \text{(Eq. 13)}$$

$$q = \frac{4\pi a^3 \rho g d}{3V}\left(\frac{v_d}{v_f} - 1\right) \qquad \text{(Eq. 14)}$$

Equation 13 applies only while the drop is being driven up, whereas Equation 14 only applies when the drop is being driven down. The definitions of all the variables used in Equations 13 and 14, along with their metric (SI) units, are shown in the reference table below.

Symbol	Definition	Unit
q	Charge carried by the droplet	Coulombs (C)
d	Separation of plates in the droplet viewing chamber	Meters (m)
ρ	Density of oil	kg/m^3
g	Acceleration due to gravity	m/s^2
η	Viscosity of air	N•s/m^2
b	Constant, equal to 8.2×10^{-3} Pa•m	
p	Barometric pressure	Pascals (Pa)
a	Radius of drop, as calculated by Equation 11	Meters (m)
v_f	Speed of fall with no electric field	m/s
v_u	Speed while being driven up	m/s
v_d	Speed while being driven down	m/s
V	Potential difference across plates	Volts (V)

The accepted value for e is 1.60×10^{-19} C.

Setup

Adjust environment of experiment room

1. Make the room as dark as possible, while allowing for adequate light to read the multimeter and stopwatch and to record data.
2. Make sure that the background behind the apparatus is dark.
3. Select a location that is free of drafts and vibrations.

Adjust and level platform

1. Place the apparatus on a level, solid table with the viewing scope at a height that allows you to sit upright while observing the droplets through the scope. One possible setup is to mount the apparatus on two 45 cm Stainless Steel Rods (ME-8736) attached to a Large Rod Base (ME-8735), as shown in Figure 6.
2. Using the attached bubble level as a reference, level the apparatus using the leveling screws on the rod stand or the leveling feet on the apparatus, as needed for your setup.

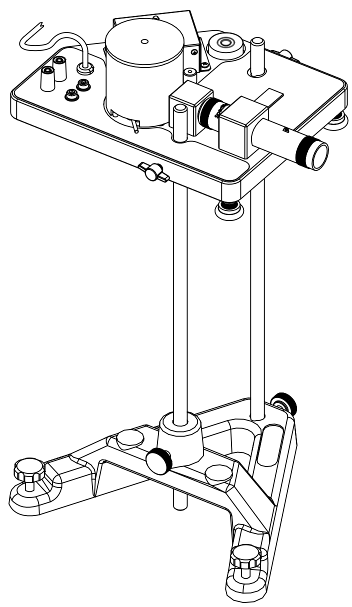


Figure 6

Measure plate separation

1. Make sure the high voltage power supply is *not* connected.
2. Disassemble the droplet viewing chamber by lifting the housing straight up and then removing the upper capacitor plate and the spacer plate.
3. Using a micrometer, measure and record the thickness of the spacer plate. This thickness is equal to the plate separation *d*.

> **NOTE:** Do not include the raised rim of the spacer plate in your measurements. The accuracy of this measurement is crucial to the accuracy of your experimental results.

Always use care when handling the brass upper capacitor plate and the plastic spacer plate to avoid scratching them. For best accuracy, all surfaces involved in the measurement should be as clean as possible.

Align the optical system

1. Place the plastic spacer and the upper capacitor plate back onto the lower capacitor plate. Replace the housing, aligning the holes in its base with the housing pins, but do not place the droplet hole cover or lid back on yet.

> **NOTE:** The thorium-232 source and the electrical connection on the lower capacitor plate fit into appropriately sized holes in the plastic spacer.

2. Unscrew the focusing wire from its storage place on the platform and carefully insert it into the hole in the center of the upper capacitor plate, as shown in Figure 7.

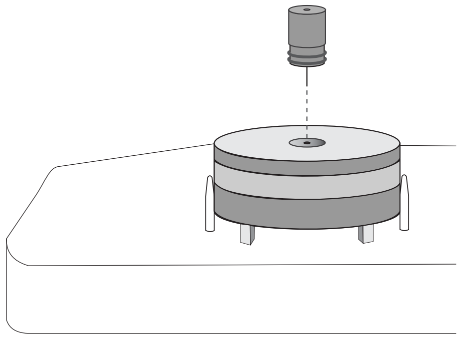


Figure 7

3. Plug the included AC adapter into a wall outlet and connect the cable to the power jack on the side of the LED light source.

> **IMPORTANT:** Check to make sure that the AC adapter is at the correct voltage for your outlet.

4. Remove the eyepiece cap and look through the viewing scope, then turn the brightness adjustment knob on the LED light source to optimize the contrast between the illuminated pin and the dark background.
5. Bring the viewing scope's reticle into focus by turning the reticle focusing ring on the scope.
6. View the focusing wire through the viewing scope and bring the wire into sharp focus by turning the droplet focusing ring.

> **NOTE:** For experimenters who wear glasses, viewing will be easier if the viewing scope is focused without using the glasses.

7. Return the focusing wire to its storage location on the platform.

Adjust and measure the voltage

1. Connect the high voltage DC power supply to the plate voltage connectors using banana plug patch cords.
2. Adjust the voltage to deliver about 500 VDC. Use the digital multimeter to measure the voltage delivered to the plate voltage connectors.

> **IMPORTANT:** Measure the voltage at the plate voltage connectors and NOT across the capacitor plates. There is a ten megaohm resistor in series with each capacitor plate to prevent shock.

Determine the temperature of the droplet viewing chamber

1. Touch the testing points of the multimeter, *in ohmmeter mode*, to the thermistor connectors on the platform to measure the resistance of the thermistor embedded in the lower capacitor plate.
2. Refer to the thermistor resistance table printed on the platform to find the temperature of the lower brass plate based on your resistance measurement. You will have to interpolate between the numbers on the table. The measured temperature corresponds to the temperature inside the droplet viewing chamber. A more precise version of this table is shown in the **Reference** section at the end of this manual.

> **NOTE:** The temperature inside the droplet viewing chamber should be determined periodically (about every hour).

As an alternative to Step 2, you can calculate the temperature using the formula below, which is derived from the table:

$$T = A+B*R+C*R^2+D*R^3+E*R^4$$

$$A = 71.59$$

$$B = -8.851*10^{-4}$$

$$C = 6.142*10^{-9}$$

$$D = -2.294*10^{-14}$$

$$E = 3.404*10^{-20}$$

In the above block, *R* refers to the resistance in ohms and *T* refers to the temperature in degrees Celsius.

Experimental procedure

Prepare the experiment

1. Complete the reassembly of the droplet viewing chamber by placing the droplet hole cover on the upper capacitor plate and then placing the lid on the housing. Make sure the hole in the droplet hole cover is facing down. The droplet hole cover prevents additional droplets from entering the chamber once the experiment has started.

> **NOTE:** The droplet hole cover has a hole in one side and a hole in the bottom. The hole in the bottom lines up with the small hole in the center of the upper capacitor plate.

2. Measure and record the plate voltage and the thermistor resistance. Use the thermistor resistance to calculate the temperature.

Introduce droplets into chamber

1. Place non-volatile oil of known density, such as the included mineral oil (with a density of 855 kg/m^3), into the atomizer using the funnel.
2. Make sure the tip of the atomizer is pointed down at a 90° angle to the shaft, as shown in Figure 8. Prepare the atomizer by rapidly squeezing the bulb until oil is spraying out.

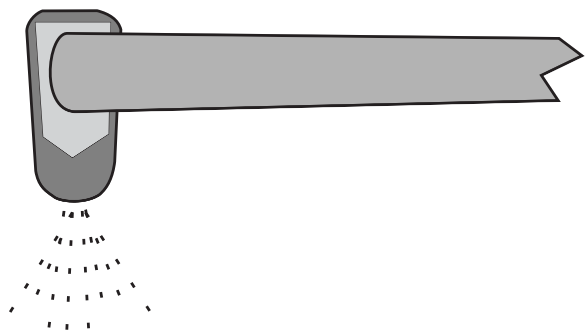


Figure 8

3. Move the ionization source lever to the **SPRAY DROPLET POSITION** to allow air to escape from the chamber while introducing droplets to the chamber.
4. Place the tip of the atomizer into the hole on the lid of the droplet viewing chamber.
5. While observing through the viewing scope, squeeze the atomizer bulb with one quick squeeze, then squeeze it slowly to force the droplets through the hole in the droplet hole cover, through the droplet entry hole in the upper capacitor plate, and into the viewing area space between the two capacitor plates.
6. When you see a shower of drops through the viewing scope, move the ionization source lever to the **OFF** position and set the atomizer aside.

While adding droplets to the chamber, keep in mind:

- If repeated squeezes of the atomizer fail to produce any droplets in the viewing area, but instead cause a cloudy brightening of the field of view, the hole in the upper capacitor plate or the droplet hole cover may be clogged. See **Maintenance** for cleaning instructions.
- The exact technique for introducing droplets must be developed by the experimenter. The goal is to get a small number of drops, not a large, bright cloud from which a single drop can be chosen.
- The droplets are being forced into the viewing area by the atomizer's pressure. Excessive pumping of the atomizer can cause too many droplets to be forced into the viewing area and, more importantly, into the area between the chamber wall and the viewing scope's focal point. Drops in this area prevent observation of drops at the focal point and thus should be avoided.
- If the entire viewing area becomes filled with droplets so no one drop can be selected, either wait a few minutes until the droplets settle out of view, or turn off the DC power supply and disassemble the droplet viewing chamber to remove the droplets.
- When the amount of oil on the parts in the droplet viewing chamber becomes excessive, clean the parts as detailed in the Maintenance section. Remember that the less oil that is sprayed into the chamber, the fewer times the chamber must be cleaned.

Select the droplet

1. From the drops in view, select a droplet that both falls slowly (about 0.02 to 0.05 mm/s) when the plate charging switch is in the "Plates Grounded" position, and can also be driven up and down by turning the plate charging switch to "TOP PLATE –" and "TOP PLATE +". Under the influence of an electric field (1000 V/cm), a droplet that requires about 15 seconds to fall the distance between the major reticle lines (0.5 mm) of the viewing scope will rise the same distance in the following times with the following charges:

Time	Excess electrons
15 s	1
7 s	2
3 s	3

> **NOTE:** If too many droplets are in view, turn the plate charging switch to "TOP PLATE –" (connecting power to the capacitor plates) for several seconds to clear out many of them. If too few droplets have net charges, preventing you from selecting an appropriately sized and charged drop, move the ionization source lever to the **ON** position for about five seconds.

2. When you find an appropriately sized and charged oil droplet, fine tune the focus of the viewing scope until the droplet appears as a pinpoint of bright light. This indicates that the droplet is in best focus for accurate data collection.
3. Turn the brightness adjustment knob on the light to optimize the contrast between the illuminated drop and the dark background.

Collect data

1. Measure the fall velocity of the droplet with the plates not charged about 10 to 20 times. Use the plate charging switch to maneuver the droplet up and down as needed.

> **TIP:** For best accuracy on this and all other velocity measurements, measure the time from the instant the bright pinpoint of light passes behind the first major reticle line to the instant the light passes behind the second major reticle line, then divide by the distance traveled. The reticle lines are 0.5 mm, or 5×10^{-4} m, apart.

2. With the plates charged, measure the rising velocity and the falling velocity for the droplet about 10 to 20 times each. Maneuver the droplet up and down as needed using the charging plate switch.
3. If the droplet is still in view, attempt to change the charge on the droplet by introducing more alpha particles. To do so, move the ionization lever to the **ON** position for a few seconds, then return the lever to the **OFF** position.
4. Measure the new rising and falling velocity with the plate charged 10 to 20 times each. For best results, repeat Steps 3 and 4 as many times as possible.
5. Once the droplet is no longer visible, select a new droplet under the same criteria and repeat Steps 1 through 4. Repeat until you have obtained a sufficient quantity of data, introducing more droplets to the chamber if needed.
6. Assign a "charge letter" to each event of differing charge for each oil droplet and record the data in a table like the one below. In the **Direction** column, enter 0 for measurements when the drop is falling with the plates not charged, U for measurements when the drop is rising, and D for measurements when the drop is falling with the plates charged. Add as many rows as needed.

<table>
<tr><th>Drop # and charge letter</th><th>Distance timed (mm)</th><th>Time (s)</th><th>Direction</th><th>Average time (s) for 0.5 mm</th></tr>
<tr><td rowspan="6">1A</td><td></td><td></td><td>0</td><td rowspan="2"></td></tr>
<tr><td></td><td></td><td>0</td></tr>
<tr><td></td><td></td><td>U</td><td rowspan="2"></td></tr>
<tr><td></td><td></td><td>U</td></tr>
<tr><td></td><td></td><td>D</td><td rowspan="2"></td></tr>
<tr><td></td><td></td><td>D</td></tr>
<tr><td>1B</td><td></td><td></td><td>0</td><td></td></tr>
</table>

7. Record the plate potential, the oil density, the viscosity of the air at the temperature of the droplet viewing chamber (see Figure 13), and the barometric pressure during the experiment.

Data analysis

1. For all events on each droplet, average all time measurements for the drop falling with the plates not charged, then calculate the falling velocity v_f and use it in Equation 11 to determine each droplet's radius a.
2. For each charge letter, average the measurement for the times of the drop being driven up, then average the measurement for the times of the drop being driven down while the plates are charged. Use these values to calculate the average speed up v_u and the average speed down v_d for each charge event.
3. For each charge event with the charge going up, plug the values of v_u and v_f and the radius of the relevant droplet into Equation 13 to calculate q, the charge of each droplet during that charge event. For each charge event with the charge going down, plug the values of v_d and v_f and the radius of the relevant droplet into Equation 14 to calculate q.
4. List the average charges for the charge letters in order of increasing size. Group together any charges that are equal or very close in magnitude.
5. Take the average of the values in each individual group to obtain an average charge.
6. Calculate the differences between adjacent group averages. If you have enough data, the lowest difference between adjacent groups will be the charge of a single electron.
7. Divide the value of each droplet charge by the lowest charge difference to obtain the number of electrons on each drop.
8. Divide the charge of each droplet by the number of electrons to determine the charge of one electron for the group.
9. Average all the groups' values for the charge of the electron to obtain a single average value. Compare this average value to the accepted value of 1.60×10^{-19} C.

Historical background

Earliest experiments

The ancient Greeks were the first to report the effects of electricity when they observed that rubbed amber attracted light objects. However, theories explaining this phenomenon did not emerge until 1747, when Benjamin Franklin proposed that an electrical fluid or fire existed in certain amounts in all matter. An excess of this fluid would produce a positive charge, and a deficiency of this fluid would produce a negative charge. A slightly different version of this theory was put forth by physicist Robert Symmer twelve years later. Symmer proposed that matter in a neutral state shows no electrical properties because it contains equal amounts of two weightless fluids, which he called positive and negative electricity.

Franklin also postulated the existence of an electrical particle small enough to easily permeate matter. This concept of an elementary electrical particle was also supported by Michael Faraday's experiments in electrolysis, which demonstrated that when a current is passed through an electrolyte, the masses of compounds deposited at opposite electrodes are in proportion to the chemical equivalent weights of the compounds. The fluid theories, along with a theory explaining electricity as a state of strain in matter, remained the prime explanations of electrical phenomena until late in the 19th century.

Early determinations of *e*

The word "electron" was first suggested in 1891 by Dr. G. Johnstone Stoney as a name for the "natural unit of electricity", a term referring to the quantity of electricity that must pass through a solution in order to liberate one atom of hydrogen or any univalent substance at one electrode. It would follow that the charge of the electron multiplied by the number of molecules in a gram mole would give the amount of electricity required to deposit one gram mole by electrolysis. Faraday had determined this quantity to be 9650 absolute electromagnetic units of electricity. Using this method, Stoney obtained an electron charge value of 0.3×10^{-10} e.s.u., where 1 e.s.u. (electrostatic unit) equals 3.3356×10^{-10} C. (The Kinetic Theory provided the basis for Stoney's estimation of Avogadro's number.)

The first experimental attempt to measure the charge of an ion was made by John Sealy Townsend in the late 1890s. Townsend had observed that, during electrolysis of sulfuric acid, positively charged hydrogen and oxygen gases were produced (although there were approximately one trillion neutral molecules to every charged one). This method was used to produce an ionized gas that was then bubbled through water to form a cloud. For his determination of e, Townsend used a five step method.

1. Townsend assumed that, in saturated water vapor, each ion condensed moisture about it, so that the number of ions was the same as the number of droplets.
2. Using a quadrant electrometer, he determined the total electrical charge per cubic centimeter carried by the gas.
3. He found the total weight of the cloud by passing it through drying tubes and determining the increase in weight of these tubes.
4. He found the average weight of the water droplets within the cloud by observing their rate of fall under gravity and computing their mean radius, using a purely theoretical law known as Stokes' Law.
5. He divided the weight of the cloud by the average weight of the droplets of water to obtain the number of droplets. If the assumption from his first step was correct, this number would be equal to the number of ions. He then divided the total charge per cubic centimeter in the gas by the number of ions to find the average charge carried by each ion, which is equivalent to e.

NOTE: The prior experiment details are condensed from Robert A. Millikan's book, The Electron (University of Chicago Press, Chicago), 1993, pp. 45-46 and used with permission of the publishers.

Using these steps, Townsend obtained a value of *e* of approximately 3×10^{-10} e.s.u. In 1900, J.J. Thompson used a similar method to obtain a value of 6×10^{-10} e.s.u. However, in both of these methods, the first assumption- that each droplet formed around only one ion- proved to be only approximately correct, meaning the experimental methods were not adequate to provide a precise measurement of *e*.

H.S. Wilson improved upon Townsend's and Thompson's work by adding two brass plates, which could be connected to a 2000 volt battery. A cloud was formed between these plates (not charged) and the falling velocity of the cloud recorded. A second cloud was then formed and its falling velocity was observed in an electric field (the plates being charged). With the plates uncharged, the force acting on the drops is mg, whereas with the plates uncharged the net force is $mg \pm Ee_n$, where e_n is the charge on the drop. Since the two velocities are proportional to the forces acting on the drops, and the velocity of the cloud with the plates uncharged determines the size and mass of the drops by Stokes' Law, Wilson was able to obtain a value of 3×10^{-10} e.s.u. for *e*. Since Wilson's measurements were always made on top of the cloud, where the drops with the smallest charge were located (due to the more heavily charged drops being driven downward faster in the field), the assumption of one ion per drop was validated.

Millikan's determination of *e*

Robert Millikan improved upon Wilson's design by using a higher potential across the plates, allowing the falling velocity of the cloud to be not only impeded, but actually reversed. Some charged drops moved upward, others moved rapidly downward, and the unchanged drops were unaffected and continue to drift slowly downward. A few drops remained in view, indicating that they carried a charge of the proper magnitude so that the force of gravity on the drop almost equaled the force of the electric field on the drop. By varying the potential of the plates, Millikan could just balance these drops. This situation significantly improved the accuracy of the results, as it permitted all measurements to be made on a single drop. By using this balanced drop method, Millikan was able to observe the properties of individual ions and determine whether different ions carry the same charge.

In the following passage, taken from the "Philosophical Magazine" for February of 1910, Millikan describes the actual procedure of the experiment. (Italicized phrases indicate a slight change in wording from Millikan's original work for the purpose of clarity.)

> “The observations on the rate of fall were made with a short-focus telescope placed about 2 feet away from the plates. In the eyepiece of this telescope were placed three equally spaced cross-hairs. . . A small section of the space between the plates was illuminated by a narrow beam from an arc light, the heat of the arc being absorbed by three water cells in series. The air between the plates was ionized by 200 mg of radium of activity 20,000 placed from 3 to 10 cm away from the plates. A second or so after *the cloud was produced,* the radium was removed. . . and the field thrown on by means a double-throw switch. If the drops were not found to be held suspended by the field the *potential difference* was changed . . . The cross-hairs were set near the lower plate, and as soon as a stationary drop was found somewhere above the upper cross-hair, it was watched for a few seconds to make sure that it was not moving and then the field was thrown off and the plates short-circuited by means of the double-throw switch, so as to make sure that they retained no charge. The drop was then timed by means of an accurate stop watch as it passed across the three cross-hairs, one of the two hands of the watch being stopped at the instant of passage across the middle cross-hair, and the other at the instant of passage across the lower one. It will be seen that this method of observation furnishes a double check upon evaporation; for if the drop is stationary at first, it is not evaporating sufficiently to influence the reading of the rate of fall, and if it begins to evaporate appreciably before the reading is completed, the time required to pass through the second space should be greater than that required to pass through the first space. It will be seen from the observations which follow that this was not, in general, the case.
>
> It is an exceedingly interesting and instructive experiment to watch one of these drops start and stop, or even reverse its direction of motion, as the field is thrown off and on. I have often caught a drop which was just too light to remain stationary and moved it back and forth in this way four or five times between the same two cross-hairs, watching it first fall under gravity when the field was thrown off and then rise against gravity when the field was thrown on. . .
>
> Furthermore, since the observations . . . are all made upon the same drop, all uncertainties as to whether conditions can be exactly duplicated in the formation of successive clouds obviously disappear. There is no theoretical uncertainty whatever left in the method unless it be an uncertainty as to whether or not Stokes’ Law applies to the rate of fall of these drops under gravity.”

Experiments with the balanced water drop produced the value of 3.422×10^{-10} e.s.u. for *e*. The most important aspect of these experiments, however, was Millikan's observation that a rising drop would suddenly change its velocity. This phenomenon could easily be produced by placing a radioactive source near the drop. This demonstrated that the drop had "captured" an ion, thus changing the charge of the drop and its respective velocity.

Exact evaluation of *e*

In 1909, Millikan began designing a new apparatus designed for the observation of single oil drops for extended periods of time. Since water drops had proven inadequate for prolonged observation of this ion catching phenomenon, Millikan used oil drops, which were not affected by evaporation. The apparatus consisted of two parallel circular brass plates separated by a distance of 16 mm by ebonite blocks. Non-volatile oil was sprayed into the chamber above the plates, and small drops slowly found their way into the area between the plates through a small hole in the top plate. The drops were illuminated by a beam from a carbon arc lamp and were observed through a measuring scope. The details of the construction of Millikan's final apparatus built in 1914 (which was very similar to his earlier devices, and which for our purposes can be considered the same as the earlier apparatuses) attest to the effort expended in obtaining the most accurate evaluation of *e* possible.

The following passages are part of Millikan's description of the apparatus, including a diagram of the device:

> "Accordingly, I built two years ago a new condenser having surfaces which were polished optically and made flat to within two wave-lengths of sodium light. They were 22 cm. in diameter and were separated by three pieces of echelon plates, 14.9174 mm. thick, and having optically perfect plate surfaces. The dimensions of the condenser, therefore, no longer introduced an uncertainty of more than about 1 part in l0,000."

(Millikan, p. 115)

> "Complete stagnancy of the air between the condenser plates was attained, first, by absorbing all the heat rays from the arc lamp by means of a water cell 80 cm. long, and a cupric chloride cell, and secondly, by immersing the whole vessel in a constant temperature bath of gas-engine oil (40 liters), which permitted, in general, fluctuations of not more than 0.02 °C during an observation."

(Millikan, p. 110)

Figure 9 depicts an illustration of Millikan's final apparatus, derived from one on page 116 of Millikan's The Electron. In this apparatus, the atomizer (*A*) blows an oil spray into the cylindrical vessel (*D*). The oil tank (*G*) is used to keep the temperature constant. An electrical field between the brass plates (*M* and *N*) is produced via a 10,000 V battery (*B*). Light from the arc lamp (*a*) passes through *w* and *d* to remove heat rays, then enters the chamber through the glass window (*g*) and illuminates the droplet (*p*) between the plates through the pinhole in *M*. Additional ions are produced about *p* by X-rays from the bulb *X*.

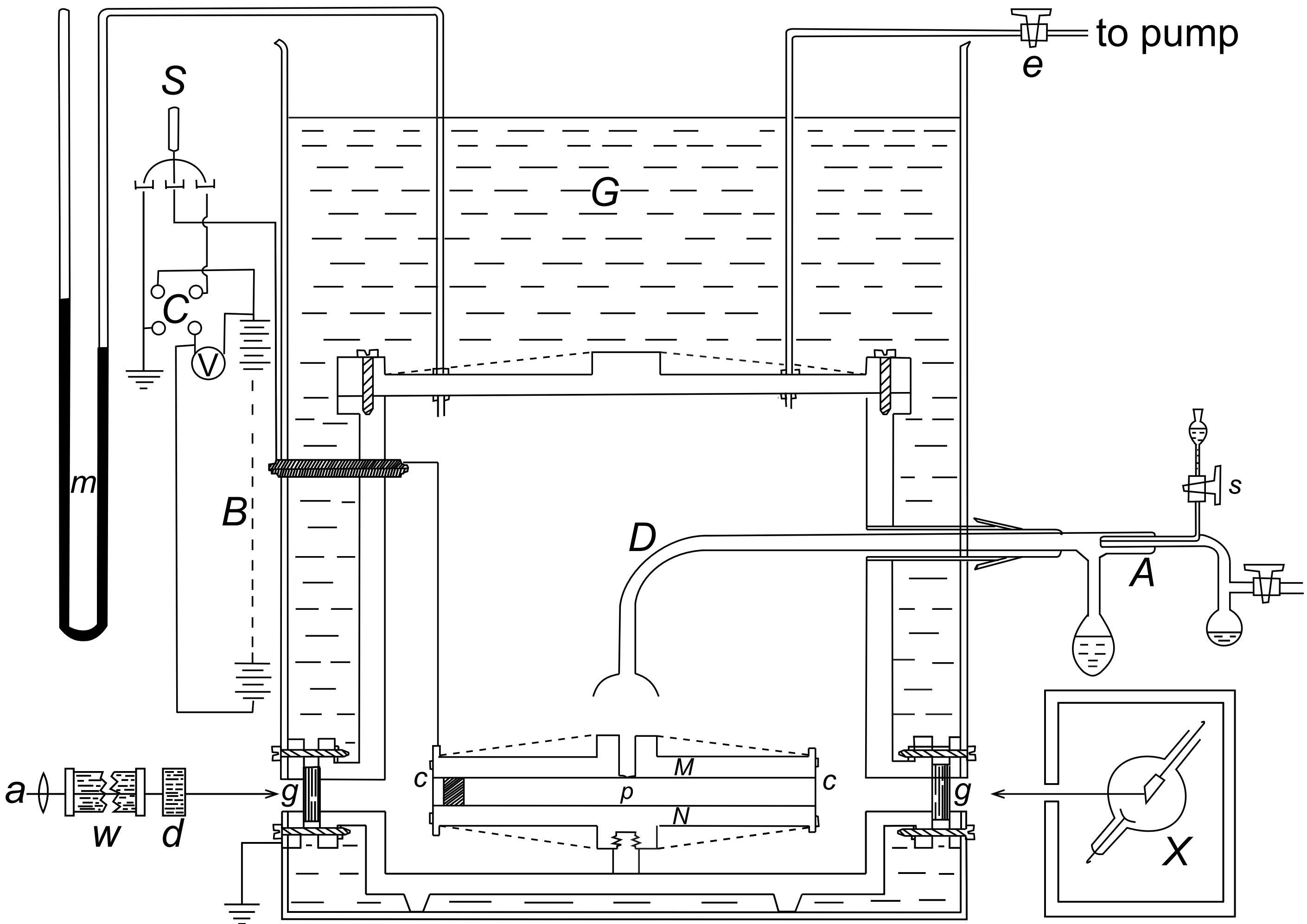


Figure 9: Diagram of Millikan's apparatus.

With this new apparatus, Millikan performed hundreds of measurements on different drops, both to make an exact evaluation of *e* and to prove or disprove the atomic theory of electricity. After five years of work, the exact value of *e* obtained was 4.774×10^{-10} e.s.u. This value of *e* was accepted until 1928, when a precise determination of Avogadro's number by X-ray diffraction measurements on crystals permitted the calculation of *e* as 4.803×10^{-10} e.s.u. The discrepancy was later traced to Millikan's value for the viscosity of air being too small.

Atomic nature of electricity

The atomic nature of electricity is best exemplified by the following table taken from Millikan's data:

n	4.917 × *n*	Observed Charge
1	4.917	———
2	9.834	———
3	14.75	———
4	19.66	19.66
5	24.59	24.60
6	29.50	29.62
7	34.42	34.47
8	39.34	39.38
9	44.25	44.42
10	49.17	49.41
11	54.09	53.91
12	59.00	59.12
13	63.92	63.68
14	68.84	68.65
15	73.75	———
16	78.67	78.34
17	83.59	83.22
18	88.51	———

Millikan made the following comments about this table on pages 74 and 75 of The Electron:

> "In this table 4.917 is merely a number obtained . . . from the change in speed due to the capture of ions and one which is proportional in this experiment to the ionic charge. The column headed 4.917 x n contains simply the whole series of exact multiples of this number from 1 to 18. The column headed 'Observed Charge' gives the successive observed values of the rising velocity of the drop plus the falling velocity. It will be seen that during the time of observation, about four hours, this drop carried all possible multiples of the elementary charge from 4 to 17, save only 15. No more exact or more consistent multiple relationship is found in the data which chemists have amassed on the combining powers of the elements and on which the atomic theory of matter rests than is found in the foregoing numbers.
>
> Such tables as these—and scores of them could be given—place beyond all question the view that an electrical charge wherever it is found, whether on an insulator or conductor, whether in electrolytes or in metals, has a definite granular structure, that it consists of an exact number of specks of electricity (electrons) all exactly alike, which in static phenomena are scattered over the surface of the charged body and in current phenomena are drifting along the conductor. Instead of giving up, as Maxwell thought we should some day do, the 'provisional hypothesis of molecular charges,' we find ourselves obliged to make all our interpretations of electrical phenomena, metallic as well as electrolytic, in terms of it."

Although the values of the charge on a specific drop were found to be exact multiples of a certain value *e*, the exact value of *e* varied for drops of different masses. This discrepancy was traced back to the breakdown of Stokes' Law under certain circumstances. Through experimentation, the law was found to fail when the size of the drop approached the mean free path of air molecules. In this situation, the medium in which the drop falls is no longer homogenous in relation to the drop, which contradicts one of the underlying assumptions of Stokes' Law. Through his work on the electron, Millikan was able to determine a correction factor for Stokes' Law.

By performing the experiment with mercury drops and drops of other materials, Millikan demonstrated that the elementary electrical charge was the same for insulators, semi-conductors, and conductors. He also demonstrated that the beta particle had the same charge as an electron (indeed, it is an electron), and that positive and negative electrons (the "positive electron" referring to a proton, not a positron) have equal magnitudes of charge. The experiment also produced insights into the study of ionized gases.

Few experiments that are so simple in principle have provided such a wealth of experimental evidence to confirm the atomic theory and measure an important physical constant.

Avogadro's number

The measurement of the charge of the electron also makes it possible to calculate Avogadro's number. The amount of current required to electrodeposit one gram of an element on an electrode (the faraday) is equal to the charge of the electron multiplied by the number of molecules in a mole. Through electrolytic experiments, the faraday has been found to be 2.895×10^{14} e.s.u. per gram equivalent weight (more commonly expressed in the m-k-s system as 9.625×10^{7} Coulombs per kilogram equivalent weight). Dividing the faraday by the charge of the electron, 4.803×10^{-10} e.s.u., we obtain a value of 6.025×10^{23} molecules per gram equivalent weight, or Avogadro's number.

Suggested reading

Should the students desire a more detailed background on this classic experiment, they should consult the following references:

1. Millikan, Robert A. *The Electron*. Chicago, The University of Chicago Press, 1917 (reprinting in paperback form, 1963).
2. Millikan, Robert A. "The Isolation of an Ion, A Precision Measurement of its Charge, and the Correction of Stokes' Law." *The Physical Review*, vol. 2, no. 2, 1913, pp. 109-143.
3. Millikan, Robert A. "On the Elementary Electrical Charge and the Avogadro Constant." *The Physical Review*, vol. 32, no. 4, 1911, pp. 349-397.
4. Shamos, M.H. Great Experiments in Physics, pp. 238-249. Holt-Dryden, New York, 1959.

Maintenance and storage

Cleaning

Keep the following tips in mind when cleaning the apparatus:

- The housing of the droplet viewing chamber, the capacitor plates, the plastic spacer, and the droplet hole cover should be cleaned with water and detergent. Pay particular attention to the droplet hole in the top capacitor plate, the glass observation port covers on the housing, and the droplet hole cover.
- The plastic spacer should be polished with a soft, lint-free cloth to remove any oil, fingerprints, or lint.
- The lens on the plastic spacer should be cleaned on both sides using a cotton swab.
- Apply a thin film of oil to the capacitor plates to help prevent corrosion.
- Dry all parts completely before reassembly.
- Always handle the plastic spacer and capacitor plates carefully to avoid scratching them.
- **Do not use any solvents that might harm the plastic.**

Adjust vertical reticle and viewing scope alignments

If the vertical alignment of the reticle or viewing scope is altered during rough handling, realign it using the following procedure:

1. Loosen the set screw in the viewing scope holder, as shown in Figure 10.

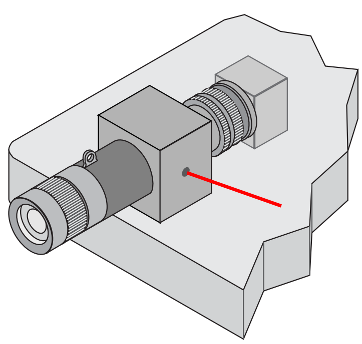


Figure 10: Position of set screw.

2. With the focusing wire in place, and while looking through the eyepiece, rotate the viewing scope until the vertical reticle lines are vertical to the focusing wire.
3. Find the center focus in the adjustment knob on the viewing scope. This will be about halfway between minimum focus and maximum focus.
4. Manually move the viewing scope in and out through its holder until the focusing wire comes into focus.
5. Recheck the reticle to make sure it is still in proper alignment with the focusing wire, as in Step 2.
6. Lock the viewing scope in position by tightening the set screw into the viewing scope holder.

Adjust the horizontal reticle alignment

If the horizontal alignment of the viewing scope is altered during rough handling, realign it using the following procedure:

1. Loosen one of the two socket head cap screws on the bottom of the platform, as shown in Figure 11.

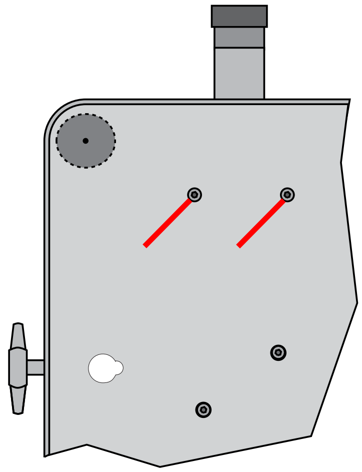


Figure 11: Position of socket head cap screws on underside of platform.

2. With the focusing wire in place while looking through the eyepiece, gently tap the viewing scope until the focusing wire is centered in the reticle.

> **NOTE:** Only a very small adjustment will be required. Use care to avoid losing sight of the focusing wire entirely.

3. Lock the viewing scope into position by tightening the two socket head cap screws into the viewing scope holder.

Touch up black painted surface on spacer

After prolonged use and repeated cleaning, the black paint that absorbs refracted and reflected light on the plastic spacer may begin to wear off. (The position of this paint is indicated by Figure 12.) If this occurs, touch up the surface with a thin coat of flat black acrylic paint, such as that available at hobby stores. Do *not* use a lacquer or oil-based paint.

> **IMPORTANT:** Do not allow paint to get on the top and bottom flat surfaces of the plastic spacer, as this would change the plastic spacer's thickness.

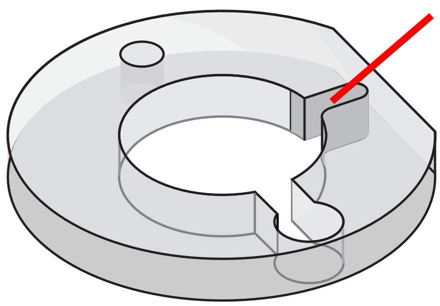


Figure 12

Storage

We recommend storing the equipment in the original packing material. Retain the foam insert from inside the droplet viewing chamber. Store the plate charging switch on the hook-and-loop tabs located on the top of the platform.

References

Figure 13 depicts the viscosity of dry air (as measured in 10^{-5} kg/m•s) as a function of temperature (as measured in °C). Table 1 contains more precise values for the conversion between resistance and temperature.

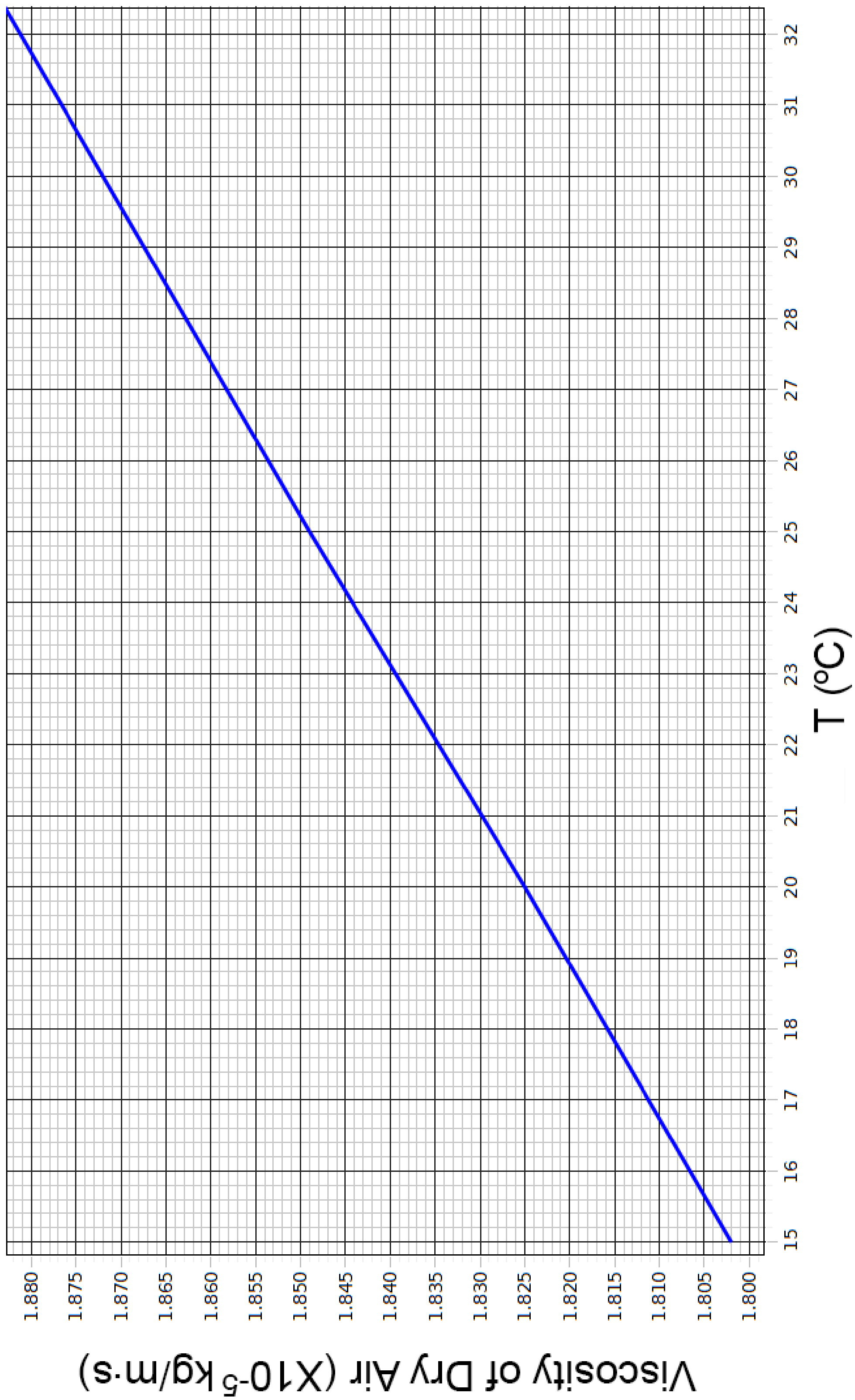


Figure 13

Table 1

Temperature (°C)	Resistance (kΩ)
10	213.2077391
11	202.2100630
12	191.8509191
13	182.0893864
14	172.8873995
15	164.2095337
16	156.0228074
17	148.2965009
18	141.0019884
19	134.1125845
20	127.6034023
21	121.4512222
22	115.6343718
23	110.1326141
24	104.9270454
25	100.0000000
26	95.3349628
27	90.9164882
28	86.7301256
29	82.7623497
30	79.0004965
31	75.4327044
32	72.0478589
33	68.8355415
34	65.7859831
35	62.8900197
36	60.1390522
37	57.5250083
38	55.0403081
39	52.6778311

Teacher's guide

When performing the Millikan Oil Drop Experiment, keep the following tips in mind for best results:

- Students should work in pairs, with one student observing the drop and one recording the experimental data.
- Leveling will be most accurate if the bubble level is observed from directly above during leveling.
- If more accurate leveling is needed to prevent oil droplets from gradually drifting off to one side during prolonged observation, perform a leveling operation using a two-dimensional level or ball bearing placed directly on the bottom capacitor plate.

As an example of experimental results, the following tables and analysis outline one teacher's sample data. The data has been organized so that all data for the drop falling while the plates are not charged appears in Table 2 and all data for the drop rising or falling with the plates charged appears in Table 3. (Note that these results involved studying only a single drop, while an ideal experiment would repeat the experiment with multiple drops for comparison.) The voltage was 386 VDC and the temperature was 28.8 °C throughout the experiment.

Table 2: Measurement with plates not charged.

Drop # and charge letter	Distance timed (mm)	Time (s)	Direction
1A	0.5	18.24	0
	0.5	18.56	0
	0.5	19.24	0
	0.5	18.05	0
	0.5	17.23	0
	0.5	15.35	0
	0.5	16.70	0
	0.5	17.99	0
	0.5	15.35	0
	0.5	17.25	0
	0.5	18.38	0
1C	0.5	18.32	0
1D	0.5	16.56	0
	0.5	18.70	0
	0.5	16.56	0
	1.0	33.63	0
	0.5	17.30	0
	0.5	19.06	0
	0.5	18.33	0
	0.5	16.21	0
	0.5	15.36	0
	0.5	15.70	0
	0.5	17.10	0
	0.5	17.30	0
	0.5	17.80	0

Average time = 17.59 s ± 1.73 s

Table 3: Measurement with plates charged.

Drop # and charge letter	Distance timed (mm)	Time (s)	Direction	Average Time (s) for 0.5 mm
1A	0.5	3.89	U	Up: 3.79
	1.5	11.00	U	
	1.5	11.59	U	
	1.5	11.17	U	
	0.5	2.60	D	Down: 2.61
	1.5	7.84	D	
1B	1.5	8.32	U	Up: 2.75
	1.5	8.20	U	
	1.5	6.20	D	Down: 2.04
	1.5	6.02	D	
1C	0.5	22.16	U	Up: 22.16
	1.0	11.56	D	Down: 5.80
	1.0	11.64	D	
1D	1.0	13.40	U	Up: 6.54
	1.5	19.74	U	
	1.0	12.65	U	
	1.0	7.48	D	Down: 3.76
	1.5	11.32	D	
1E	0.5	21.91	U	Up: 21.94
	0.5	22.87	U	
	0.5	21.04	U	
	1.0	11.84	D	Down: 6.19
	1.0	12.72	D	
	1.0	12.59	D	

Based on the setup, we can measure or derive the following variables:

1. The temperature was measured as 28.8 °C (based on the resistance), so by Figure 13, we find that the viscosity of air is 1.862×10^{-5} N•s/m^2.
2. The average time for the drop to fall 0.5 mm with the plates not charged is 17.59 ± 1.73 s, yielding a falling velocity of $(2.84 \pm 0.26)\times10^{-5}$ m/s. Using this value in Equation 11, we find that the radius a of the drop is equal to $(4.8 \pm 0.2)\times10^{-7}$ m.
3. The plate separation was 0.767 cm (0.00767 m) and the plate voltage was 386 V, so per Equation 12, the electric field is $E = 5.03\times10^4$ V/m.
4. The density of the oil was 855 kg/m^3, so the weight of the droplet is $mg = 4.0\times10^{-15}$ N.
5. The pressure of the chamber was equal to 1.01×10^5 Pa.

Table 4 displays the calculated measurements of charge for the drop going up and down for each event, as well as the average charge.

Table 4

Drop # and charge letter	Charge for going up ($\times 10^{-19}$ C)	Charge for going down ($\times 10^{-19}$ C)	Average charge ($\times 10^{-19}$ C)
1A	4.64	4.72	4.68 ± 0.6
1B	6.09	6.27	6.18 ± 0.9
1C	1.48	1.67	1.57 ± 0.2
1D	3.04	3.03	3.03 ± 0.4
1E	1.48	1.52	1.50 ± 0.2

Events E and C have charges that are extremely close together. As such, we will average them together to obtain the charge 1.54×10^{-19} C, which we will call EC.

The list below shows the differences and average difference between charges with a significant charge difference:

- D - EC = 3.03 - 1.54 = 1.50×10^{-19} C
- A - D = 4.68 - 3.03 = 1.65×10^{-19} C
- B - A = 6.18 - 4.68 = 1.50×10^{-19} C
- Average difference = 1.55×10^{-19} C

By dividing the average charge values by this average difference, we can tell that 1C and 1E have charges of e, 1D has a charge of $2e$, 1A has a charge of $3e$, and 1B has a charge of $4e$.

The percent difference between the calculated average difference between charges (1.55×10^{-19} C) and the accepted value of e (1.60×10^{-19} C) is 3%. The radius a has a 5% margin of error, and the values of q have differences of 4% (1A), 6% (1B), 2% (1C), and 6% (1D).

Specifications and accessories

Visit the product page at pasco.com/product/AP-8210A to view the specifications and explore accessories. You can also download experiment files and support documents from the product page.

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This electronic product is subject to disposal and recycling regulations that vary by country and region. It is your responsibility to recycle your electronic equipment per your local environmental laws and regulations to ensure that it will be recycled in a manner that protects human health and the environment. To find out where you can drop off your waste equipment for recycling, please contact your local waste recycle or disposal service, or the place where you purchased the product. The European Union WEEE (Waste Electronic and Electrical Equipment) symbol on the product or its packaging indicates that this product must not be disposed of in a standard waste container.

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This device has been tested and found to comply with the essential requirements and other relevant provisions of the applicable EU Directives.