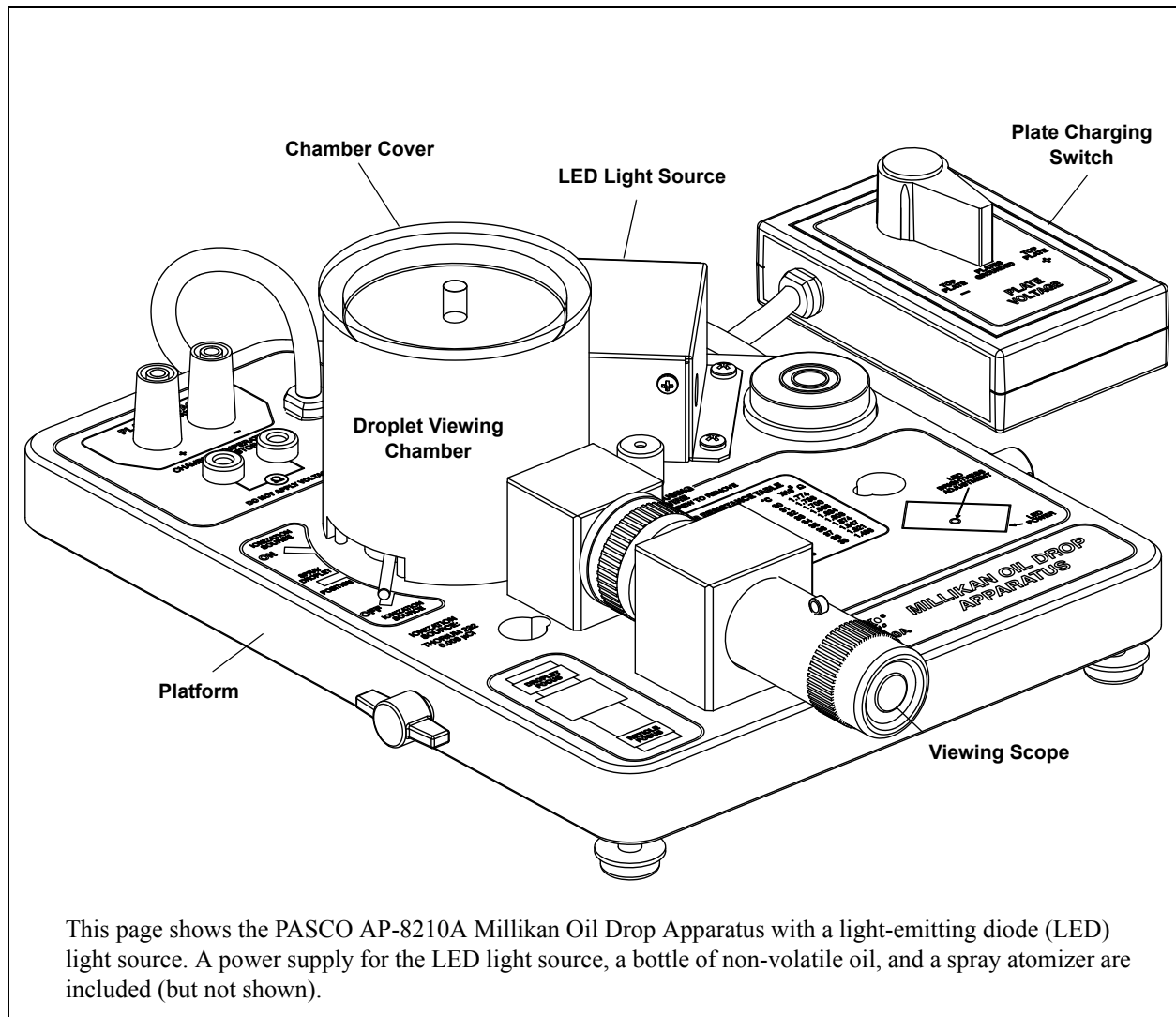


# Millikan Oil Drop Apparatus

## AP-8210A



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# Millikan Oil Drop Apparatus

AP-8210A

## Introduction

The PASCO Millikan Oil Drop Apparatus is designed to conduct the Millikan Oil Drop Experiment where the electric charge carried by a particle may be calculated by measuring the force experienced by the particle in an electric field of known strength. 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 1000 volts per centimeter ( $10^5$  volts per meter) would exert a force of only  $1.6 \times 10^{-9}$  dyne ( $1.6 \times 10^{-14}$  newtons) on a particle bearing one excess electron. This is a force comparable to the gravitational force on a particle with a mass of  $10^{-12}$  (one million millionth) gram ( $10^{-15}$  kilogram).

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, having masses of only  $10^{-12}$  gram ( $10^{-15}$  kg) or less, is observed in a gravitational and an electric field. Measuring the velocity of fall of the drop in air enables, with the use of Stokes' Law, the calculation of the mass of the drop. The observation of the velocity of the drop rising in an electric field then permits a calculation of the force on, and hence, the charge carried by the oil drop.

Although this experiment will allow the total charge on a drop to be measured, it is only through an analysis of the data obtained and a certain degree of experimental skill that the charge of a single electron can be determined. By selecting droplets which rise and fall slowly, it will be certain that the drop has a small number of excess electrons. A number of such drops should be observed and their respective charges calculated. If the charges on these drops are integral multiples of a certain smallest charge, then 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. An ionization source placed near the drop will accomplish this. In fact, it is possible to change the charge on the same drop several times. If the results of measurements on the same drop then yield charges which are integral multiples of some smallest charge, then this is proof of the atomic nature of electricity.

## Equation for Calculating the Charge on a Drop

An analysis of the forces acting on an oil droplet will yield the equation for the determination of the charge carried by the droplet. Figure 1 shows the forces acting on the drop when it is falling in air and has reached its terminal velocity. (Terminal velocity is reached in a few milliseconds for the droplets used in this experiment.) In Figure 1,  $v_f$  is the velocity of fall,  $k$  is the coefficient of friction between the air and the drop,  $m$  is the mass of the drop, and  $g$  is the acceleration of gravity. Since oil droplet is at its terminal velocity, the net force is zero. Therefore, the forces are equal and opposite:

$$mg = kv_f \quad (1)$$

Figure 2 shows the forces acting on the drop when it is rising under the influence of an electric field. In Figure 2,  $E$  is the electric intensity,  $q$  is the charge carried by the drop, and  $v_r$  is the velocity of rise. Adding the forces vectorially yields:

$$qE = mg + kv_r \quad (2)$$

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 neglected.

Eliminating  $k$  from equations (1) and (2) and solving for  $q$  yields:

$$q = \frac{mg(v_f + v_r)}{Ev_f} \quad (3)$$



Figure 1:

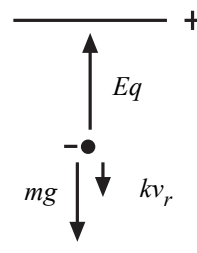


Figure 2:

where  $m$  is the mass and  $g$  is the acceleration due to gravity.

To eliminate  $m$  from equation ( 3 ), the expression for the volume of a sphere and the density of the oil are used:

$$mg = \frac{4}{3}\pi a^3 \rho g \quad (4)$$

where  $a$  is the radius of the droplet, and  $\rho$  is the density of the oil.

Substituting equation ( 4 ) into equation ( 3 ) yields:

$$q = \frac{4\pi a^3 \rho g (v_f + v_r)}{3(Ev_f)} \quad (5)$$

To calculate  $a$ , the formula for Stokes' Law ( $F_f = 6\pi\eta av_f$ ) can be employed. 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,  $\eta$ ). Setting the formula for Stoke's Law equal to the right-hand term in equation ( 4 ) and solving for  $a$  yields the following:

$$a = \sqrt{\frac{9\eta v_f}{2\rho g}} \quad (6)^*$$

Stokes' Law, however, becomes incorrect when the velocity of fall of the droplets is less than 0.1 cm/s. (Droplets having this and smaller velocities 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  $10^{-6}$  m/s), the viscosity must be multiplied by a correction factor. The resulting effective viscosity is:

$$\eta_{eff} = \eta \left( \frac{1}{1 + \frac{b}{pa}} \right) \quad (7)^{**}$$

where  $b$  is a constant,  $p$  is the atmospheric pressure, and  $a$  is the radius of the drop as calculated by the uncorrected form of Stokes' Law, equation ( 6 ).

Substituting  $\eta_{eff}$  in equation ( 7 ) into equation ( 6 ) for  $\eta$  gives:

$$a = \sqrt{\frac{9\eta v_f}{2\rho g} \left( \frac{1}{1 + \frac{b}{pa}} \right)} \quad (8)$$

Substituting equation ( 8 ) into equation ( 5 ) for  $a$  yields:

$$q = \frac{4\pi}{3} \rho g \left[ \sqrt{\frac{9\eta v_f}{2\rho g} \left( \frac{1}{1 + \frac{b}{pa}} \right)} \right]^3 \frac{(v_f + v_r)}{Ev_f} \quad (9)$$

The electric intensity is given by:

$$E = \frac{V}{d} \quad (10)$$

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

Substituting equation ( 10 ) into equation ( 9 ) for  $E$  and rearranging yields:

$$q = \left[ \frac{4\pi d}{3} \sqrt{\left( \frac{1}{\rho g} \left[ \frac{9\eta}{2} \right]^3 \right)} \right] \times \left[ \left( \frac{1}{1 + \frac{b}{pa}} \right)^3 \right] \times \left[ \frac{(v_f + v_r) \sqrt{v_f}}{V} \right] \quad (11)$$

The terms in the first set of brackets need only be determined once for any particular apparatus. The second term is determined for each droplet, while the term in the third set of brackets is calculated for each change of charge that the drop experiences.

The definitions of the symbols used, together with their metric (SI) units are:

$q$  – charge carried by the droplet (coulombs)

$d$  – separation of the plates in the droplet viewing chamber (m)

$\rho$  – density of oil ( $\text{kg/m}^3$ )

$g$  – acceleration of gravity ( $\text{m/s}^2$ )

$\eta$  – viscosity of air ( $\text{N} \cdot \text{s/m}^2$ )

$b$  – constant, equal to  $8.2 \times 10^{-3} \text{ Pa} \cdot \text{m}$

$p$  – barometric pressure (pascals)

$a$  – radius of the drop in meters as calculated by equation ( 6 )

$v_f$  – velocity of fall (m/s)

$v_r$  – velocity of rise (m/s)

$V$  – potential difference across the plates (volts)

\*For additional information about Stoke's Law, please refer to Introduction to Theoretical Physics, by L. Page (New York, Van Nostrand), Chapter 6.

\*\*A derivation can be found in The Electron by R.A. Millikan (Chicago, The University of Chicago Press), Chapter 5.

**Note:** The accepted value for  $e$  is  $1.60 \times 10^{-19}$  coulombs

-----

### Alternate Method for Calculating the Charge on a Drop

Equation ( 11 ) contains the radius of the drop,  $a$ , and the correction term for the effective viscosity,  $\eta_{eff}$ . Notice that the correction term also includes the value for  $a$ . However, it is possible to calculate the charge on a drop,  $q$ , using a corrected term for  $a$  that does not include the value of  $a$ .

The expression for  $a$  in equation ( 8 ) can be converted into a quadratic equation:

$$a = \sqrt{\frac{9\eta v_f}{2\rho g} \left( \frac{1}{1 + \frac{b}{pa}} \right)} \quad (8)$$

$$a^2 = \frac{9\eta v_f}{2\rho g} \left( \frac{1}{1 + \frac{b}{pa}} \right)$$

$$a^2 + \frac{b}{p}a = \frac{9\eta v_f}{2\rho g}$$

$$a^2 + \frac{b}{p}a - \frac{9\eta v_f}{2\rho g} = 0$$

Solving for  $a$  yields:

$$a = \sqrt{\left(\frac{b}{2p}\right)^2 + \frac{9\eta v_f}{2\rho g}} - \frac{b}{2p} \quad (12)$$

Notice that this expression for  $a$ , unlike equation ( 8 ), does not include  $a$ .

Substituting equation ( 12 ) in equation ( 5 ) yields:

$$q = \frac{4\pi \left[ \sqrt{\left(\frac{b}{2p}\right)^2 + \frac{9\eta v_f}{2\rho g}} - \frac{b}{2p} \right]^3 \rho g (v_f + v_r)}{3(Ev_f)} \quad (13)$$

Replacing  $E$  with equation ( 10 ) yields the following:

$$q = \frac{4\pi}{3} \left[ \sqrt{\left(\frac{b}{2p}\right)^2 + \frac{9\eta v_f}{2\rho g}} - \frac{b}{2p} \right]^3 \frac{\rho g d (v_f + v_r)}{Vv_f} \quad (14)$$

## Equipment

The AP-8210A Millikan Oil Drop Apparatus includes the following:

Included Equipment	Part Number
Millikan Oil Drop Apparatus	AP-8210A
AC Adapter, 100 - 240 VAC to 12 VDC, 1.0 A	540-092
Atomizer	699-093
Non-volatile mineral oil*, 120 mL (~4 ounces)	

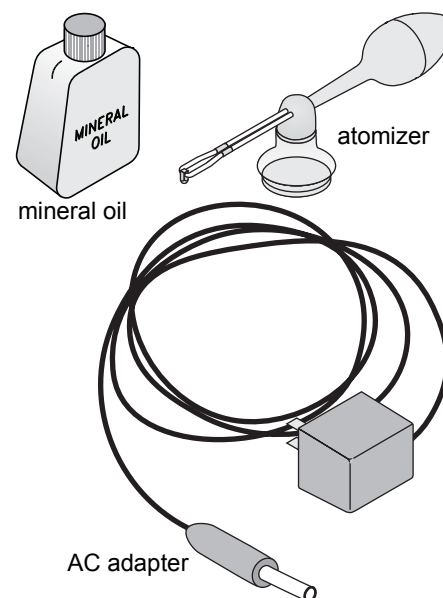
Required Equipment	Part Number
Power Supply, high voltage, well-regulated, 500 VDC, 10 mA (minimum)	SF-9585
Digital Multimeter to measure voltage and resistance	SB-9599A
Banana plug patch cords (4)	SE-9750 or SE-9751
Digital Stopwatch	ME-1234

Recommended Equipment	Part Number
Large Rod Stand	ME-8735
Steel Rod, 45 cm (2)	ME-8736
Micrometer (0 to 25 mm with 0.1 mm resolution)	SE-7337
<i>Ken-A-Vision VideoFlex Microscope (optional)</i>	SE-7227

\*The Squibb #5597 Mineral Oil has a measured density of  $886 \text{ kg/m}^3$ . However, the density of different lots of mineral oils may vary slightly. Therefore, for greatest precision, you should determine the density of the mineral oil you are using.

It is recommended that you store the equipment in the original packing material. After unpacking, remove 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.



**Figure 3: Included equipment**

### Parts Diagram

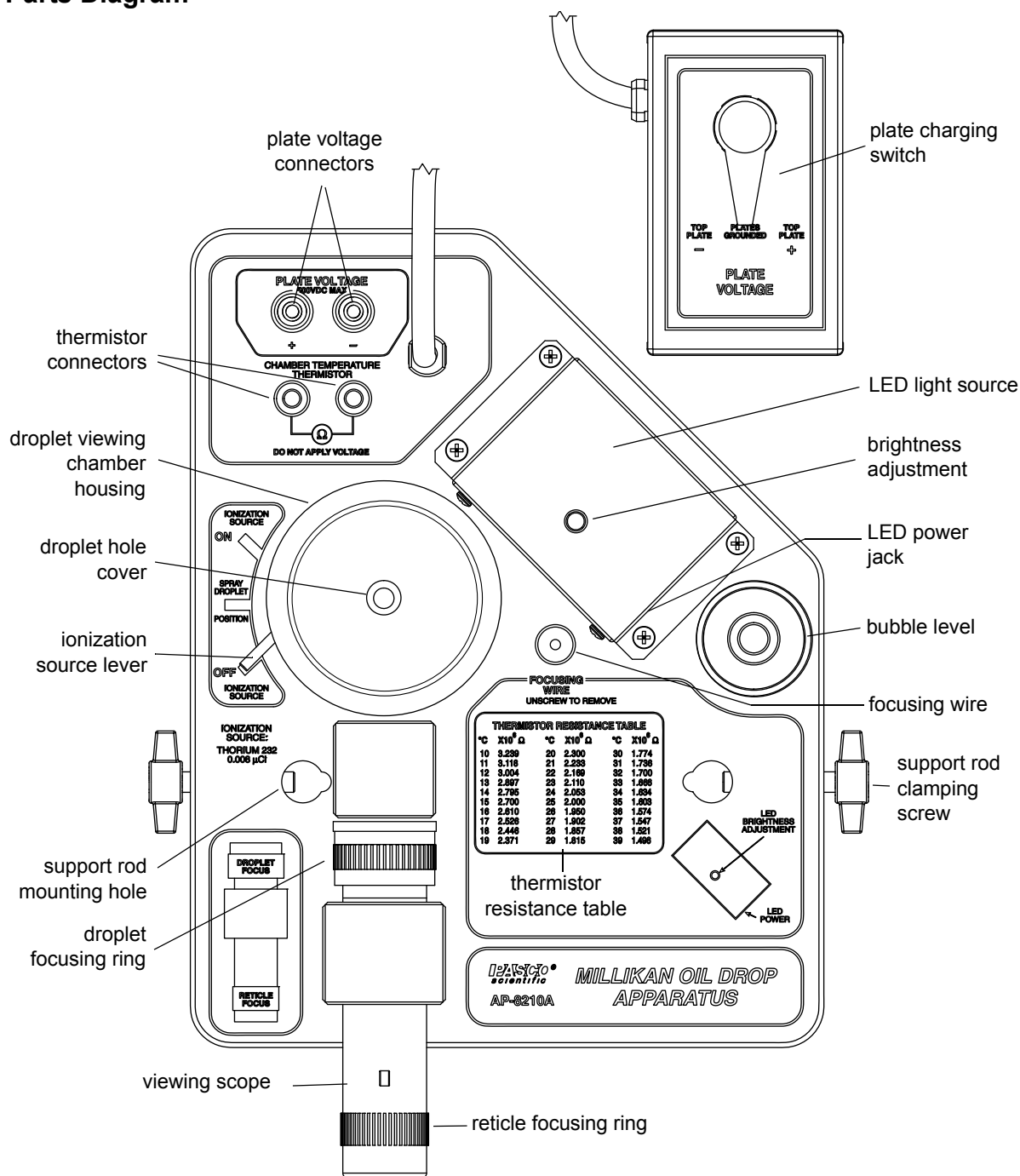


Figure 4: Apparatus platform

### Components of the Platform

- droplet viewing chamber (see details in Figure 5)
- viewing scope (30X, bright-field, erect image) with reticle (line separation: 0.5 mm major divisions and 0.1 mm minor divisions), reticle focusing ring, and droplet focusing ring
- LED (light emitting diode) light source with a brightness adjustment knob
- focusing wire (for adjusting the viewing scope)
- plate voltage connectors, 4 mm diameter



- thermistor connectors, 4 mm diameter (the thermistor is mounted in the lower capacitor plate in the droplet viewing chamber)



**WARNING: Do not apply voltage to the thermistor connectors!**

- thermistor resistance table (resistance versus temperature)
- ionization source lever with three positions: Ionization ON, Ionization OFF, and SPRAY DROPLET POSITION.
- bubble level
- support rod mounting holes and clamping screws to permit mounting of the platform on support rods (so the viewing scope can be raised to a comfortable eye level)
- leveling feet (3)
- plate charging switch on a one meter cord (to prevent vibration of the platform during the switching activity).

### Components of the Droplet Viewing Chamber

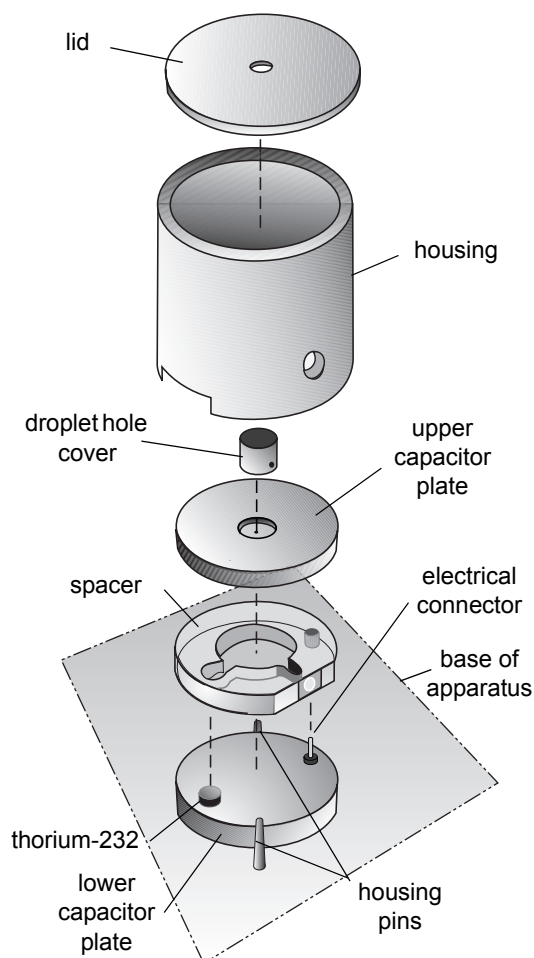
- lid (clear plastic chamber cover)
- housing
- *convex lens (not shown).*
- droplet hole cover
- upper capacitor plate (brass)
- plastic spacer (approximately 7.6 mm thick)
- lower capacitor plate (brass)
  - alpha source, thorium-232, 0.00185 microcuries
  - electrical connection to the upper capacitor plate

**Note:** Thorium-232 is a naturally occurring, low level alpha-particle emitter with a half-life of  $1.41 \times 10^{10}$  years. It is not regulated in its use and poses no hazard to the user of the PASCO Millikan Oil Drop Apparatus.

### Equipment Setup

#### Adjusting the environment of the experiment room

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



**Figure 5: Droplet viewing chamber**

### Adjusting the height of the platform and leveling it

1. Place the apparatus on a level, solid table with the viewing scope at a height that permits the experimenter to sit erect while observing the droplets through the scope. One possible setup is to mount the apparatus on two support rods (ME-8736) on the large rod stand (ME-8735). See Figure 6.
2. Using the attached bubble level as a reference, level the apparatus with the leveling screws on the rod stand or the leveling feet on the apparatus (depending on your setup)..

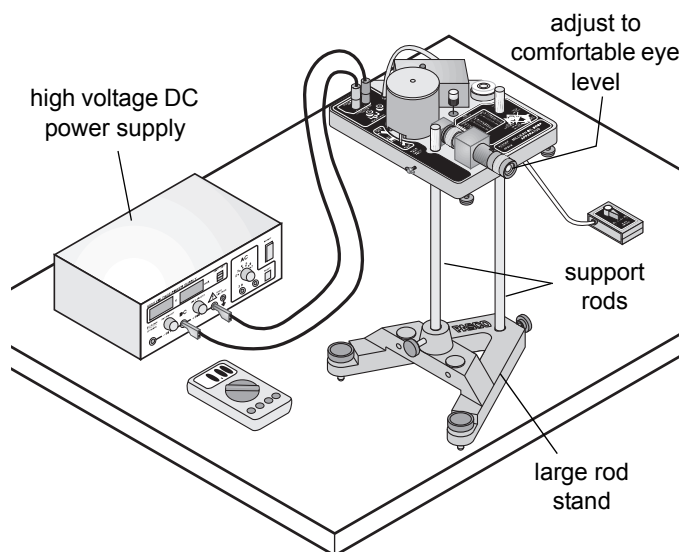


Figure 6: Equipment setup

### Measuring plate separation

1. Disassemble the droplet viewing chamber by lifting the housing straight up and then removing the upper capacitor plate and the spacer plate. (See Figure 5.)
  2. Use a micrometer to measure the thickness of the spacer plate. (The thickness is equal to the plate separation distance,  $d$ ).
- Be sure that you are not including the raised rim of the spacer plate in your measurement. The accuracy of this measurement is important to the degree of accuracy of your experimental results.
3. Record the measurement.



- **NOTE:** Use care when handling the brass upper capacitor plate and the plastic spacer plate to avoid scratching them.
- **NOTE:** All surfaces involved in the measurement should be as clean as possible to prevent inaccurate readings.

## Aligning the Optical System

### Focusing the viewing scope

1. Reassemble the plastic spacer and the upper capacitor plate onto the lower capacitor plate. Replace the housing, aligning the holes in its base with the housing pins. (See Figure 5.)
- **NOTE:** The thorium-232 source and the electrical connection on the lower capacitor plate fit into appropriately sized holes on 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 (Figure 7.)

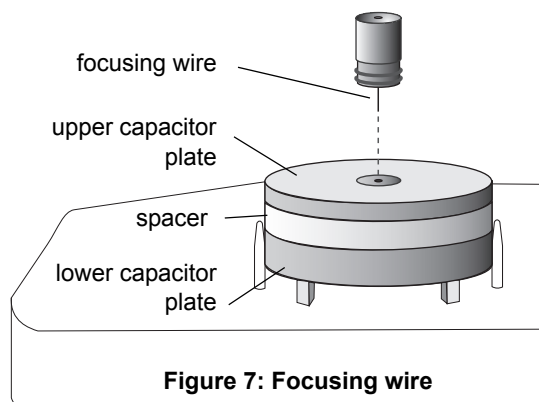


Figure 7: Focusing wire

- Plug the included AC adapter into a receptacle (100 to 240 VAC) and connect the cable to the power jack on the side of the LED light source.



Check to make sure that the AC adapter is the correct voltage: 100, 117, 220, or 240 V.

- Turn the brightness adjustment knob on the LED light source to optimize the contrast between the illuminated pin and the dark background.
  - Bring the reticle into focus by turning the reticle focusing ring on the viewing scope.
  - View the focusing wire through the viewing scope and bring the wire into sharp focus by turning the droplet focusing ring.
- NOTE:** Viewing will be easier for experimenters who wear glasses if the viewing scope is focused without using the glasses.
- Return the focusing wire to its storage location on the platform.

## Functions of Controls

### Ionization source lever

- When the lever is in the ionization **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.
- 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.
- 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.

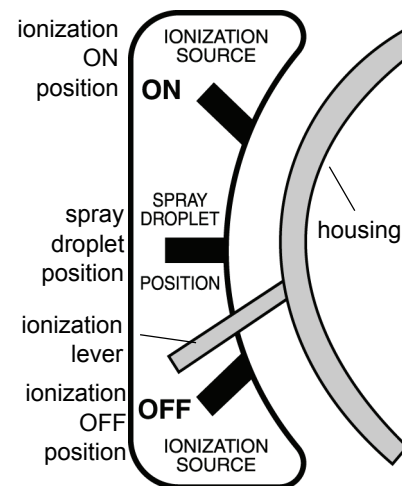


Figure 8: Ionization source lever settings

### Plate charging switch

The plate charging switch has three positions:

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

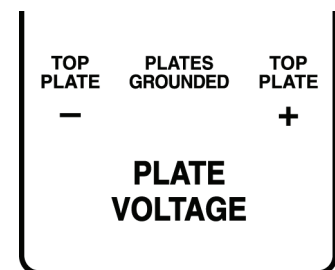


Figure 9: Plate charging switch

## Adjusting and Measuring the Voltage

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



**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 electric shock.**

## Determining the Temperature of the Droplet Viewing Chamber

1. Connect the multi meter to the thermistor connectors on the platform in order to measure the resistance of the thermistor that is embedded in the lower capacitor plate.
2. Refer to the Thermistor Resistance Table located on the platform to find the temperature of the lower brass plate. The measured temperature corresponds to the temperature inside the droplet viewing chamber.



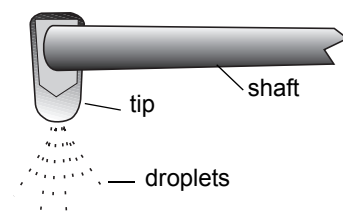
**The temperature inside the droplet viewing chamber should be determined periodically (about every fifteen minutes).**

## Experimental Procedure

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. (See Figure 5.)
  - **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.
  - **NOTE:** The droplet hole cover prevents additional droplets from entering the chamber once the experiment has started.
2. Measure and record the plate voltage and the thermistor resistance (temperature).

### Introducing the droplets into the chamber

1. Put non-volatile oil of known density into the atomizer, such as the included Squibb #5587 Mineral Oil, density of  $886 \text{ kg/m}^3$ .
2. Insure that the tip of the atomizer is pointed down ( $90^\circ$  to the shaft; see Figure 10). Prepare the atomizer by rapidly squeezing the bulb until oil is spraying out.
3. Move the ionization source lever to the "SPRAY DROPLET POSITION" to allow air to escape from the chamber during the introduction of droplets into 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.



**Figure 10: Atomizer tip**



**If repeated “squirts” of the atomizer fail to produce any droplets in the viewing area but produce a rather cloudy brightening of the field of view, the hole in the upper capacitor plate or in the droplet hole cover may be clogged. Refer to the Maintenance section for cleaning instructions.**

- **NOTE:** The exact technique of introducing droplets will need to be developed by the experimenter. The object is to get a small number of drops, not a large, bright cloud from which a single drop can be chosen.
- **NOTE:** Remember that the droplets are being forced into the viewing area by the pressure of the atomizer. 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 focal point of the viewing scope. Drops in this area prevent observations of drops at the focal point of the scope.
- **NOTE:** If the entire viewing area becomes filled with droplets so that no one drop can be selected, either wait three or four minutes until the droplets settle out of view, or turn off the DC power supply and disassemble the droplet viewing chamber, thus removing the droplets.
- **NOTE:** 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 few times the chamber must be cleaned.

### Selection of 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 –” or “TOP PLATE +”.
- **HINT:** 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, under the influence of an electric field (1000 V/cm) in the following times with the following charges:

**Table 1.1:**

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

- **NOTE:** If too many droplets are in view, you can clear out many of them by turning the plate charging switch to “TOP PLATE –” (connecting power to the capacitor plates) for several seconds.
  - **NOTE:** If too few droplets have net charges to permit the selection of 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.
    - **NOTE:** The oil droplet is in best focus for accurate data collection when it appears as a pinpoint of bright light.
  3. Turn the brightness adjustment knob on the light to optimize the contrast between the illuminated drop and the dark background.

### Collecting Data on the Rise and Fall of the Oil Droplet

1. Measure the rise velocity (when the plates are charged) and the fall velocity (when the plates are not charged) about 10 to 20 times. Maneuver the droplet up and down as needed using the plate charging switch.
  - **NOTE:** The greatest accuracy of measurement is achieved if you time from the instant that the bright pinpoint of light passes behind the first major reticle line to the instant that the pinpoint of light passes behind the second major reticle line. (These reticle lines are 0.5 mm apart.)
2. Calculate the charge on the droplet. If the result of this first determination for the charge on the drop is greater than 5 excess electrons, you should select slower moving droplets in subsequent measurements.
3. Introduce more oil droplets into the chamber using the procedure previously described and select another droplet.
4. Measure the rise and fall velocities of the selected droplet about 10 to 20 times or until the charge changes spontaneously or the droplet moves out of view.
5. Bring the droplet to the top of the field of view and move the ionization lever to the ON position for a few seconds as the droplet falls.
6. If the rising velocity of the droplet changes, make as many measurements of the new rising velocity as you can (10 to 20 measurements).
7. If the droplet is still in view, attempt to change the charge on the droplet by introducing more alpha particles, as described previously, and measure the new rising velocity 10 to 20 times, if possible.
8. Repeat step (7) as many times as you can.
9. Record the plate potential, the oil density, the viscosity of the air at the temperature of the droplet viewing chamber (see Appendix A), and the barometric pressure for each set of velocity measurements.
  - **NOTE:** It is desirable to observe as many different charges on a single drop as possible.

### Computation of the Charge of an Electron

- The following formula is equation ( 14 ) in the Introduction. It can be used to calculate the charge,  $q$ , of an electron.

$$q = \frac{4\pi}{3} \left[ \sqrt{\left(\frac{b}{2p}\right)^2 + \frac{9\eta v_f}{2\rho g}} - \frac{b}{2p} \right]^3 \frac{\rho g d (v_f + v_r)}{V v_f} \quad (14)$$

The definitions of the symbols used and metric (SI) units are as follows:

$q$  – charge carried by the droplet [C]

$d$  – separation of the plates in the droplet viewing chamber [m]

$\rho$  – density of oil [ $\text{kg}/\text{m}^3$ ] (approximately  $886 \text{ kg}/\text{m}^3$ )

$g$  – acceleration of gravity [ $9.8 \text{ m}/\text{s}^2$ ]

$\eta$  – viscosity of air in [ $\text{N} \cdot \text{s} / \text{m}^2$ ] (See Appendix A)

$b$  – constant, equal to  $8.20 \times 10^{-3}$  [ $\text{Pa} \cdot \text{m}$ ]

$p$  – barometric pressure [Pa]

$v_f$  – velocity of fall [m/s]

$v_r$  – velocity of rise [m/s]

$V$  – potential difference across the plates [V]

**Note:** The accepted value for  $e$  is  $1.60 \times 10^{-19}$  C

**Suggested Procedure for Computation of the Charge of an Electron:**

1. Use equation ( 12 ) to calculate the radius,  $a$ , of the oil drop:

$$a = \sqrt{\left(\frac{b}{2\rho}\right)^2 + \frac{9\eta v_f}{2g\rho} - \frac{b}{2\rho}} \quad (12)$$

2. Substitute the radius,  $a$ , from the calculation above into equation ( 4 ) to find the mass,  $m$ , of the oil droplet:

$$m = \frac{4}{3}\pi a^3 \rho \quad (4)$$

$$m = \frac{4}{3}\pi \left[ \sqrt{\left(\frac{b}{2\rho}\right)^2 + \frac{9\eta v_f}{2g\rho} - \frac{b}{2\rho}} \right]^3 \rho$$

3. Substitute  $m$  from the calculation above into equation ( 3a ) for computing the charge,  $q$ , of an electron:

$$q = \frac{mg(v_f + v_r)}{Ev_f} \quad (3)$$

$$q = \frac{mgd(v_f + v_r)}{Vv_f} \quad (3a)$$

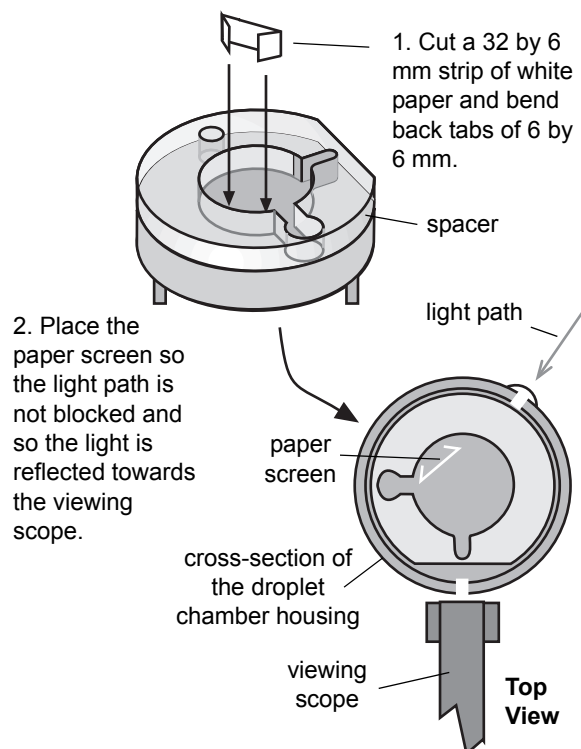
$$q = \frac{4\pi}{3} \left[ \sqrt{\left(\frac{b}{2\rho}\right)^2 + \frac{9\eta v_f}{2\rho g} - \frac{b}{2\rho}} \right]^3 \frac{\rho g d (v_f + v_r)}{V v_f}$$

## Using a Projecting Microscope with the Millikan Oil Drop Apparatus

To demonstrate Millikan's experiment for an entire classroom on a TV screen or computer monitor, use a projecting microscope such as the Ken-A-Vision VideoFlex Microscope (PASCO Model SE-7227).

### Procedure

1. **Put a white paper screen in the droplet viewing chamber to reflect more light:**
  - a. Prior to focusing the viewing scope (see **Equipment Setup** section, **Aligning the Optical System**), place a white paper screen in the droplet viewing chamber as illustrated in Figure 11.
  - b. Proceed with step 1 of **Aligning the Optical System**.
2. **Align and focus the projecting microscope:**
  - a. Set up the projecting microscope as directed in the manufacturer's instructions.
  - b. After completing the setup and focusing of the Millikan Oil Drop Apparatus on the oil droplets, carefully slide the eyepiece of the projecting microscope over the eyepiece of the Millikan Apparatus.
  - c. Focus the projecting microscope as directed in the manufacturer's instructions.



**Figure 11: Place a white paper screen in the droplet viewing chamber.**



# Historical Information

## Historical Notes

The Greeks were the first to report the effects of electricity when they recorded 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 in matter would produce a positive charge and a deficiency of this fluid would produce a negative charge. A slightly different theory was put forth by the physicist Symmer twelve years later. He proposed that matter in a neutral state shows no electrical properties because it contains equal amounts of two weightless fluids, which were called positive and negative electricity respectively.

Franklin also postulated the existence of an electrical particle small enough to easily permeate matter. 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, also supported Franklin's concept of an elementary electrical particle. The fluid theories, along with a theory explaining electricity as a state of strain in matter, were 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," namely, that quantity of electricity that must pass through a solution in order to liberate at one electrode one atom of hydrogen or any univalent substance. 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. This quantity had been determined by Faraday to be 9650 absolute electromagnetic units of electricity. Using this method, Stoney obtained a value of  $0.3 \times 10^{-10}$  e.s.u. (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 Townsend in the late 1890's. He had observed that during electrolysis of sulfuric acid, positively charged hydrogen and oxygen gases were produced (although there were one million million 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 proceeded in the following manner:

1. He 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. He determined with the aid of a quadrant electrometer 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 constituting the cloud by observing their rate of fall under gravity and computing their mean radius with the aid of 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 which, if assumption 1 is correct, was the number of ions, and 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, that is, to find  $e$ .<sup>1</sup>

<sup>1</sup>Condensed from Robert A. Millikan's book, The Electron (University of Chicago Press, Chicago, 1933, pp. 45-46 and used with permission of the publishers.

Townsend achieved results in the range of  $3 \times 10^{-10}$  e.s.u. for  $e$ . J. J. Thomson, in 1900, used a method similar to Townsend's and obtained a value of  $6 \times 10^{-10}$  e.s.u. In both of these methods, however, the first assumption (each

droplet formed around only one ion) proved to be only approximately correct, and the experimental methods were not adequate to provide a precise determination 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 observed in an electric field (the plates being charged). Since the two velocities are proportional to the forces acting on the drops<sup>2</sup>, 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  $3 \times 10^{-10}$  e.s.u. for  $e$ . Since Wilson's measurements were always made on the top of the cloud, or the drops with the smallest charge (the more heavily charged drops being driven downward faster in the field), the assumption of one ion per drop was validated.

<sup>2</sup>With the plates uncharged, the force is  $mg$  where  $m$  is the mass of the drop and  $g$  is the acceleration of gravity. With the plates charged, the force is  $mg \pm Ee_n$  where  $E$  is the electric intensity between the plates and  $e_n$  is the charge on the drop.

### Millikan's Determination of $e$

Millikan improved upon Wilson's design by using a higher potential across the plates so that the falling velocity of the cloud could not only be impeded, but actually reversed. Some charged drops moved upward, some moved rapidly downward, while the uncharged drops were unaffected and continued to drift downward. A few drops, which 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, remained in view. By varying the potential of the plates, Millikan could just balance these drops. This situation proved to be a significant improvement for 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 to determine whether different ions carry one and the same charge.

In the following passage, taken from the "Philosophical Magazine" for February, 1910, Millikan describes the actual procedure of the experiment.

"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*<sup>3</sup> 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."

<sup>3</sup>The italicized phrases indicate a slight change in wording, for purposes of clarity, from Millikan's original work.

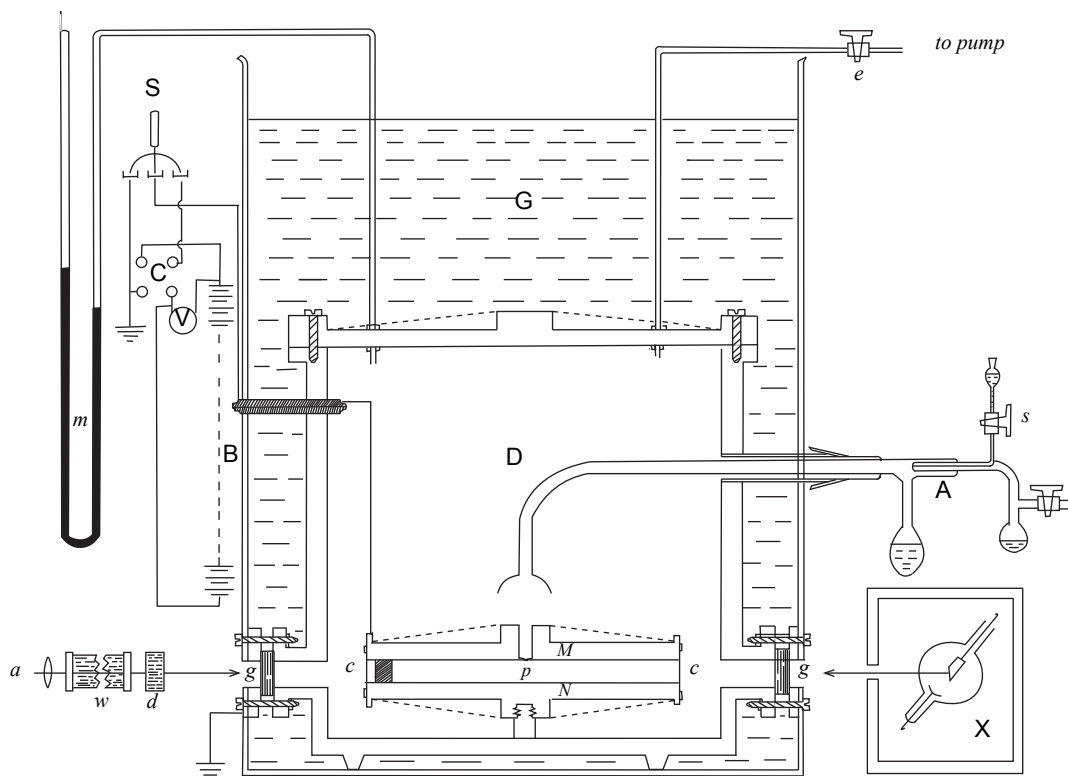
Experiments with the balanced water drop produced the value of  $3.422 \times 10^{-10}$  e.s.u. for  $e$ . The most important aspect of these experiments, however, was the observation by Millikan that a rising drop would suddenly change its velocity. This phenomenon could easily be produced by placing 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.

### The Exact Evaluation of $e$

In 1909 Millikan set about building a new piece of apparatus designed for the observation of single oil drops for extended periods of time. Since water drops had proved 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 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 basically similar to his earlier devices, and for the purposes of this discussion can be considered the same as the earlier pieces of apparatus) attest to the effort expended in obtaining the most accurate evaluation of  $e$  possible. The following passage is 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 10,000.”<sup>5</sup>

“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.”<sup>6</sup>



**Figure 12: Diagram of Millikan’s Apparatus<sup>7</sup>**

A, atomizer through which the oil spray is blown into the cylindrical vessel, D. G, oil tank to keep the temperature constant. M and N, circular brass plates, electric field produced by throwing a 10,000-volt battery B. Light from arc lamp a after heat rays are removed by passage through w and d, enters chamber through glass window g and illuminates droplet p between plates M and N through the pinhole in M. Additional ions are produced about p by X-rays from the bulb X.

<sup>5</sup>Millikan, Robert A., p. 115, <sup>6</sup>Millikan, Robert A., p. 110, <sup>7</sup>Millikan, Robert A., p. 116.

With this new apparatus hundreds of measurements on different drops were made, for the purpose of both making an exact evaluation of  $e$  and proving or disproving the atomic theory of electricity. The value of  $e$  that was obtained from these five years of work was  $4.774 \times 10^{-10}$  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  $e$  to be  $4.803 \times 10^{-10}$  e.s.u. The discrepancy was later traced to Millikan's too low value for the viscosity of air.

### Atomic Nature of Electricity

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

Table 1.2:

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

Millikan makes the following comments about this table.

“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.”<sup>8</sup>

<sup>8</sup>Millikan, Robert A., pp. 74–75

Although the values of the charge on a specific drop were found to be exact multiples of a certain value ( $e$ ), the value of  $e$  varied for drops of different masses. This discrepancy was traced to the breakdown of Stokes' Law. Through experimentation the law was found to fail when the size of the drop approached the mean free path of air molecules. When this situation occurs, the medium in which the drop falls is no longer homogeneous in relation to the drop. This contradicts one of the assumptions upon which Stokes' Law is based. 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 and not a positron) are equal in charge. The experiment also produced insights into the study of ionized gasses.

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 permits the calculation of Avogadro's number. The amount of current required to electrodeposit one gram equivalent 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 electrolysis experiments, the faraday has been found to be  $2.895 \times 10^{14}$  electrostatic units (e.s.u.) per gram equivalent weight (more commonly expressed in the m-k-s system as  $9.625 \times 10^7$  coulombs per kilogram equivalent weight). Dividing the faraday by the charge of the electron,

$$\frac{2.895 \times 10^{14} \text{ e.s.u./gm equivalent weight}}{4.803 \times 10^{-10} \text{ e.s.u.}}$$

yields  $6.025 \times 10^{23}$  molecules per gram equivalent weight, or Avogadro's Number.

### Suggested Reading

Should the student desire a more detailed back ground in this classic experiment, the following references are suggested:

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, pp. 109 – 143, June 1913.
3. Millikan, Robert A., "On the Elementary Electrical Charge and the Avogadro Constant," *The Physical Review*, Vol. 32, No. 4, pp. 349 – 397, April, 1911.
4. Shamos, M.H., Great Experiments in Physics (Holt-Dryden, New York, 1959), pp. 238 – 249.

## Maintenance Notes

### Cleaning

1. 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, with particular attention to the droplet hole in the top capacitor plate, the glass observation port covers on the housing, and the droplet hole cover.
2. The plastic spacer should be polished with a soft, lint-free cloth to remove any oil, finger prints, or lint.
3. The lens on the plastic spacer should be cleaned on both sides using a cotton-covered tip ("Q-tip").
4. Apply a thin film of oil to the capacitor plates to help prevent corrosion.
5. Dry all parts completely before reassembly.



**Always handle the plastic spacer and capacitor plates carefully to avoid scratching them.**

**Solvents that might attack the plastic should be avoided.**

### Adjusting vertical reticle and viewing scope alignments

If the 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 (Figure 13).
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 of focus in the adjustment knob on the viewing scope (this will be approximately half-way between minimum 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 assure that it is still in proper alignment with the focusing wire (as in step 2).
6. Lock the viewing scope into position by tightening the set screw into the viewing scope holder.

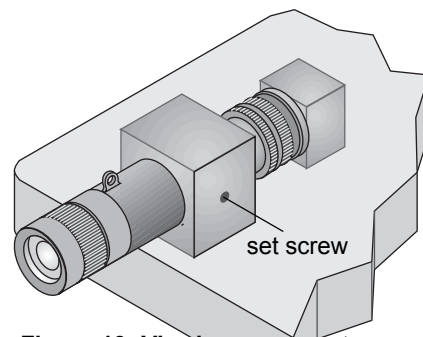


Figure 13: Viewing scope set screw

### Adjusting 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 shown in Figure 14.
2. With the focusing wire in place and while looking through the eyepiece, gently tap the viewing scope until the focusing wire is centered in the reticle.



**Only a very small adjustment will be required.  
Use care to avoid losing site of the focusing wire.**

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

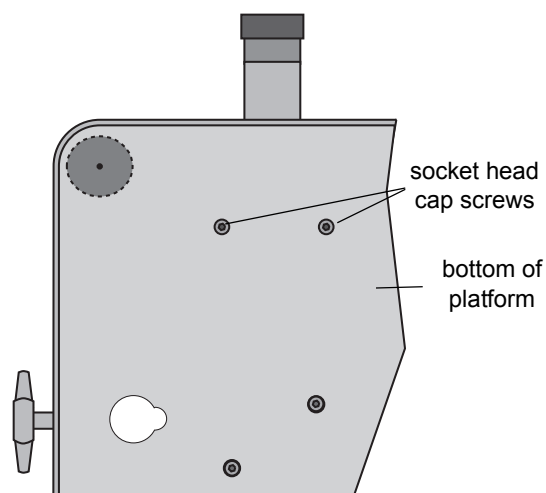


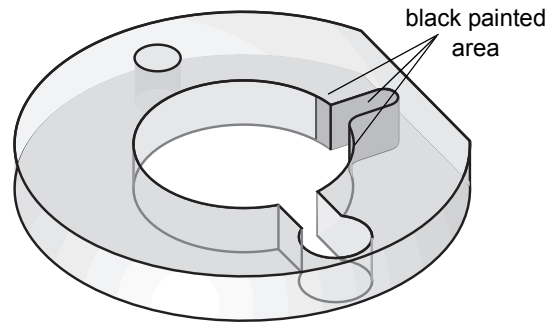
Figure 14: Location of the socket head cap screws that anchor the viewing scope

### Touching up the black painted surface on the plastic spacer

After prolonged use and repeated cleaning, the black paint (Figure 15) that absorbs refracted and reflected light on the plastic spacer may begin to wear off. In that event, 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.



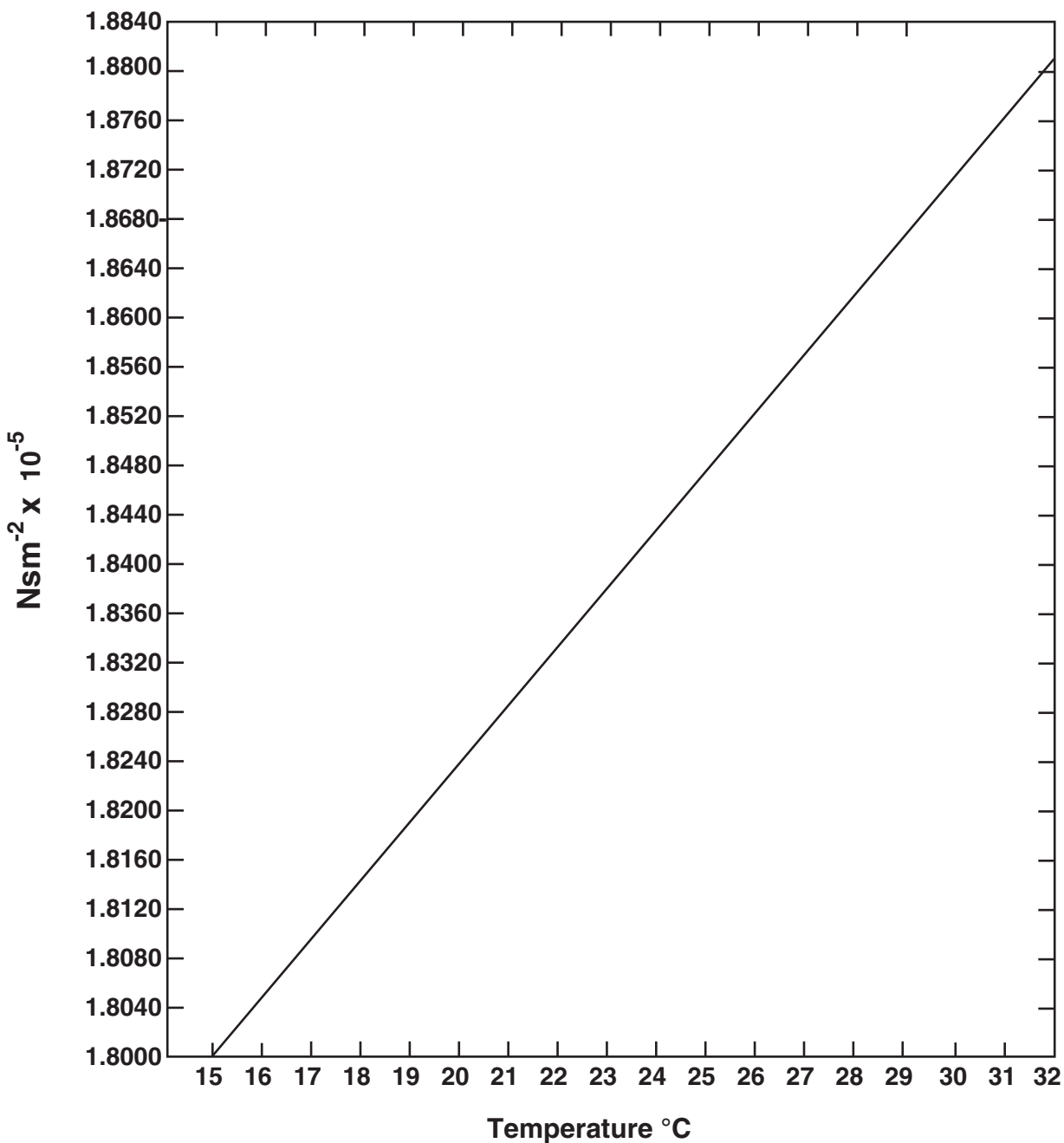
**Do not allow paint to get on the top and bottom flat surfaces of the plastic spacer since that would change the plastic spacer thickness.**



**Figure 15: Area on the plastic spacer that should be painted black**

## Appendix A: Viscosity of Dry Air as a Function of Temperature

Viscosity of Dry Air as a Function of Temperature





## Appendix B: Thermistor Resistance

Millikan Oil Drop Apparatus Thermistor Resistance at Various Temperatures

### THERMISTOR RESISTANCE TABLE

$^{\circ}\text{C}$	$\times 10^6 \Omega$	$^{\circ}\text{C}$	$\times 10^6 \Omega$	$^{\circ}\text{C}$	$\times 10^6 \Omega$
10	3.239	20	2.300	30	1.774
11	3.118	21	2.233	31	1.736
12	3.004	22	2.169	32	1.700
13	2.897	23	2.110	33	1.666
14	2.795	24	2.053	34	1.634
15	2.700	25	2.000	35	1.603
16	2.610	26	1.950	36	1.574
17	2.526	27	1.902	37	1.547
18	2.446	28	1.857	38	1.521
19	2.371	29	1.815	39	1.496

## Teacher's Guide

- NOTE: It is best that students work in pairs—one to observe the drop and one to record the experimental data.
- NOTE: Leveling will be most accurate if the bubble level is observed from directly above during leveling.
- NOTE: If more accuracy with leveling is needed to prevent the oil droplets from gradually drifting off to one side during prolonged observation, perform the leveling operation using a two-dimensional level or ball bearing placed directly on the bottom capacitor plate.

As an example of typical experimental results, the following pages list one teacher's data, using the following alternative method for calculating the charge on an electron. The teacher measured the velocity of the drop moving down with the plates charged and used the procedure listed below to organize the data for computation.

For each different charge event for a drop the following was done:

1. Measured the velocity of the falling drop with the plates not charged, the velocity of the rising drop with the plates charged, and the velocity of the falling drop with the plates charged;
2. Assigned a "charge letter" to each event of differing charge for each oil droplet; for example, for drop 1: 1A, 0 (velocity of the falling drop with the plates not charged), 1B, u (velocity of the rising drop), 1B, d (velocity with the plates charged of the falling drop), 1C, u, d, and 1D, u, d; for droplet 2: 2A, 0, u, d, 2B u, d, 2C u, d, and so on.
3. Averaged all measurements for a drop falling with the plates not charged, for use to determine  $a$ ;
4. For each charge letter, averaged the measurements for the cases of the drop rising or falling with the plates charged;
5. Calculated the average charges on each droplet for each charge letter (averaging the charges for the cases with the droplet rising and with the droplet falling while the plates were charged);
6. Listed the average charges for the charge letters in order of increasing size and calculated the average difference between charges;
7. Calculated the number of  $e$  for droplet under each of the charge conditions by dividing the average charge for each charge letter by the average difference in charge from step 5, above.

The data and calculations for measurements on one droplet are listed on the following pages.

## Sample Data

Sample data for Millikan Oil Drop Apparatus: Voltage = 386 VDC; Temperature = 28.8 °C

**Table 1.3:**

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

\* Direction: 0 = no field, U = going up, D = going down

Sample data for Millikan Oil Drop Apparatus: Voltage = 386 VDC; Temperature = 28.8 °C

Table 1.4:

Drop #/Charge Letter	Distance timed (mm)	Time (s)	Direction*	Average Times (s) for 0.5 mm
1A	0.5	3.89	U	
	1.5	11.00	U	
	1.5	11.59	U	
	1.5	11.17	U	3.79 U
	0.5	2.60	D	
	1.5	7.84	D	2.64 D
1B	1.5	8.32	U	
	1.5	8.20	U	2.75 U
	1.5	6.20	D	
	1.5	6.02	D	2.04 D
1C	0.5	22.16	U	22.16 U
	1.0	11.56	D	
	1.0	11.64	D	5.80 D
1D	1.0	13.40	U	
	1.5	19.74	U	
	1.0	12.65	U	6.54 U
	1.0	7.48	D	
	1.5	11.32	D	3.76 D
1E	0.5	21.91	U	
	0.5	22.87	U	
	0.5	21.04	U	21.94 U
	1.0	11.84	D	
	1.0	12.72	D	
	1.0	12.59	D	6.20 D

\* Direction: 0 = no field, U = going up, D = going down

1. The temperature was  $T = 0.822 \Omega = 28.8 \text{ }^\circ\text{C}$ , which gives a viscosity of air  $= \eta = 1.867 \times 10^{-5} \text{ N}\cdot\text{s}/\text{m}^2$ .
2. For this droplet,  $a = 4.9 \times 10^{-7} \text{ m} \pm 0.2 \times 10^{-7} \text{ m}$ .
3. The plate separation was 0.767 cm (0.00767 m) and the plate voltage was 386 V, which gives the electric field  $E = 5.03 \times 10^4 \text{ V}/\text{m}$ .
4. The density of the oil was  $886 \text{ kg}/\text{m}^3$ , which gives the weight of the droplet  $= mg = 4.26 \times 10^{-15} \text{ N}$ .
5. The pressure was  $1.01 \times 10^5 \text{ Pa}$ .

## Table of Results

Table 1.5:

Drop #/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	4.72	4.71	4.72
1B	6.18	6.25	6.27
1C	1.51	1.68	1.60
1D	3.09	3.06	3.08
1F	1.52	1.52	1.52

## Table of Final Analysis

Table 1.6:

Drop #/Charge Letter	Average Charge ( $\times 10^{-19}$ C)	Differences between Letter Charge ( $\times 10^{-19}$ C)	Number of $e = \text{Avg. Charge}/\text{Avg. Diff.}$
1E	1.52	D - E = 1.56	1 e
1C	1.60	D - C = 1.48	1 e
1D	3.08	A - D = 1.64	2 e
1A	4.72	B - A = 1.55	3 e
1B	6.27	Avg. Diff. = 1.56	4 e

- The percent difference between the average difference between charges ( $1.56 \times 10^{-19}$  C) and the accepted value of  $e$  ( $1.60 \times 10^{-19}$  C) is 2.5%.
- The radius  $a$  was  $4.9 \times 10^{-7}$  m  $\pm$   $0.2 \times 10^{-7}$  m, or 4% error.
- Errors for  $q$  were 2% (1A), 2% (1B), 0% (1C), and 4% (1D).

## Technical Support

For assistance with any PASCO product, contact PASCO at:

Address: PASCO scientific  
10101 Foothills Blvd.  
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For more information about the Millikan Oil Drop Apparatus and the latest revision of this Instruction Manual, visit the PASCO web site and enter AP-8210A in the Search window.

**Limited Warranty** For a description of the product warranty, see the PASCO catalog.

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The European Union WEEE (Waste Electronic and Electrical Equipment) symbol and on the product or its packaging indicates that this product **must not** be disposed of in a standard waste container.

