Exp 1 Millikan Oil Drop Experiment

Introduction

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 cm would exert a force of only 1.6×10^{-9} dyne 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.

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, weighing only 10^{-12} gram 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 one to measure the total charge on a drop, 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, one can 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.

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 2.895×10^{14} electrostatic units 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,

$$\frac{2.895\times10^{14}\,e.s.u./\,gm\ \ equivalent\ \ weight}{4.803\times10^{-10}\,e.s.u}$$

yields 6.025×10^{23} molecules per gram equivalent weight or Avogadro's number.

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 droplet 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 the forces are equal and opposite:

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

Figure 1

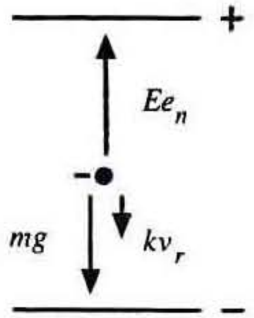


Figure 2

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, e_n is the charge carried by the drop, and v_r is the velocity of rise. Adding the forces vertically yields:

$$Ee_n = mg + kv_r \qquad (2)$$

In both cases there is also a small buoyant force exerted by the air on the droplet. 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 e_n yields:

$$e_n = \frac{mg\left(v_f + v_r\right)}{Ev_f} \qquad (3)$$

To eliminate m from equation (3), one uses the expression for the volume of a sphere:

$$m = (4/3)\pi a^3 \sigma \qquad (4)$$

where a is the radius of the droplet, and σ is the density of the oil.

To calculate a, one employs Stocks' Law, relating the radius of a spherical body to its velocity of fall in a viscous medium (with the coefficient of viscosity, η).

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

Substituting equations (4) and (5) into equation (3) yields:

$$e_n = \frac{4\pi}{3}\sqrt{\frac{1}{g(\sigma-\rho)}\left(\frac{9\eta}{2}\right)^3} \times \frac{\left(v_f + v_r\right)\sqrt{v_f}}{E} \qquad (6)$$

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, a correction factor must be included in the expression for e_n. This factor is:

$$\left(\frac{1}{1+\frac{b}{pa}}\right)^{3/2} \qquad (7)$$

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 (5).

The electric intensity is given by $E = V/d$, where V is the potential difference across the parallel plates separated by a distance d. E, V, and d are all expressed in the same system of units. If E is the electrostatic units, V in volts, and d in centimeters, the relationship is:

$$E(e.s.u.) = \frac{V(volts)}{300\, d\,(cm)} \qquad (8)$$

Substituting equation (7) and (8) into equation (6) and rearranging the terms yields:

$$e_n = \left\{400\pi d\left[\frac{1}{g(\sigma-\rho)}\left(\frac{9\eta}{2}\right)^3\right]^{1/2}\right\} \times \left[\left(\frac{1}{1+\frac{b}{pa}}\right)^{3/2}\right] \times \left[\frac{\left(v_f + v_r\right)\sqrt{v_f}}{V}\right]$$

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 proper units for use in equation (9) are:

- e_n -- The charge, in e.s.u., carried by the droplet
- d -- Separation of the plates in the condenser in cm
- σ -- Density of the oil in gm/cm^3
- ρ -- Density of air in gm/cm^3

g -- Acceleration of gravity in cm/s^2

η -- Viscosity of air in poise ($dyne\ s/cm^2$)

b -- Constant, equal to 6.7×10^{-4} (cm of Hg)

p -- The barometric pressure in cm of mercury

a -- The radius of the drop in cm as calculated by equation (5)

v_f -- The velocity of fall in cm/s

v_r -- The velocity of rise in cm/s

V -- The potential difference across the plates in volts

The accepted value for e is 4.803×10^{-10} *e.s.u.*

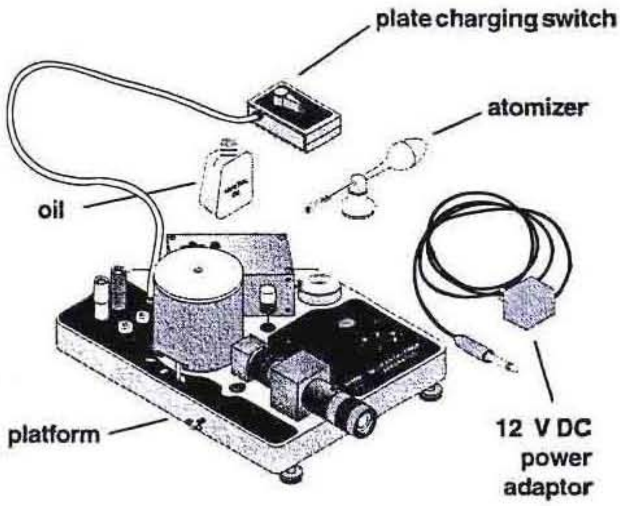


Figure 3. Included equipment

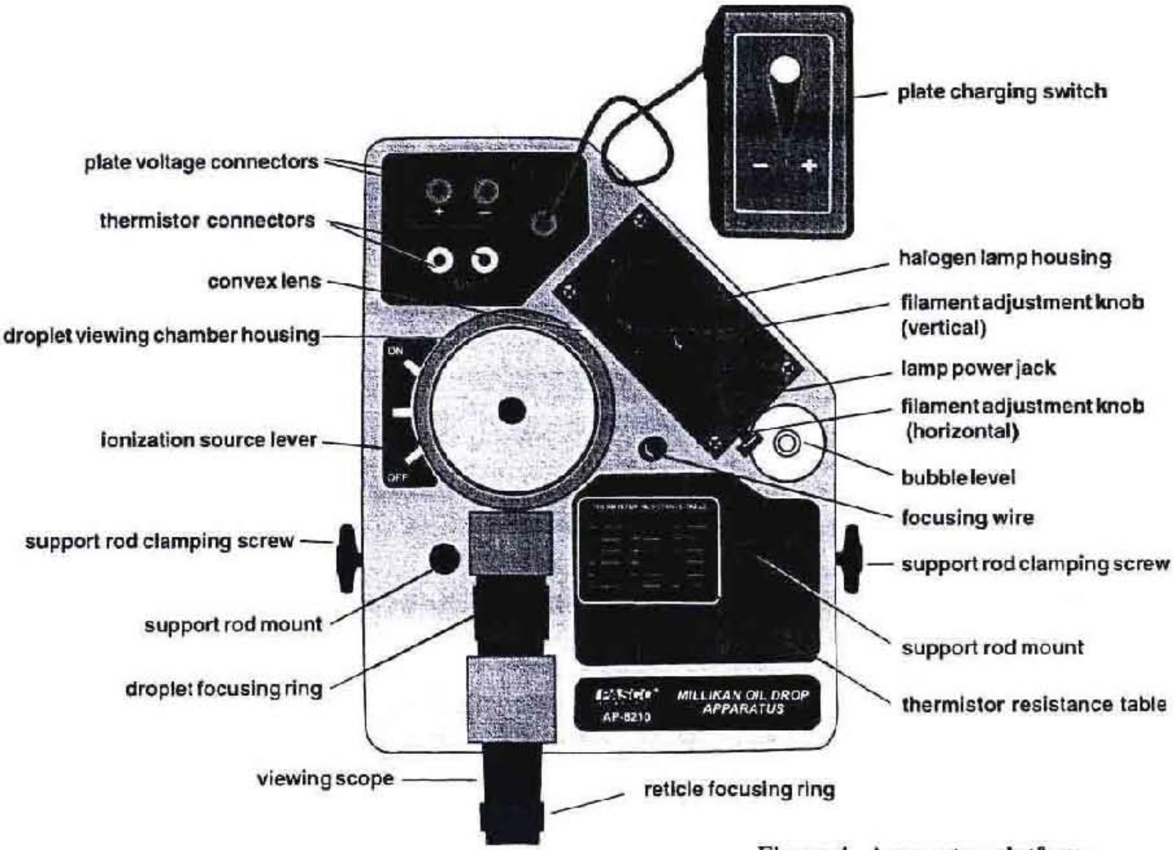


Figure 4. Apparatus platform

Components of platform:

- droplet viewing chamber (see details below)
- viewing scope (30X, bright-field, erect image) with reticle (line separation: 0.5mm major division, 0.1mm minor divisions), reticle for focusing ring, and droplet focusing ring.
- halogen lamp (12V, 5W halogen bulb and dichroic, infrared heat-absorbing window, horizontal and vertical filament adjustment knobs)
- focusing wire (for adjusting viewing scope)
- plate voltage connectors
- thermistor connectors (thermistor is mounted in the bottom plate)

> WARNING: Do not apply voltage to the thermistor connectors.

- thermistor table (resistance versus temperature)
- ionization source lever (with three positions: Ionization ON, Ionization OFF, and Spray Droplet Position)
- bubble level
- support rod mounts and screws (to permit mounting of platform on a PASCO ME-8735 Large Rod Stand, so viewing scope can be raised to a comfortable eye level)
- 3 leveling feet
- Plate charging switch (on a 1 meter cord to prevent vibration of platform during switching activity)

Components of droplet viewing chamber (Figure 5)

- lid
- housing
- droplet hole cover
- upper capacitor plate (brass)
- plastic spacer (approximately 7.6mm thick)
- lower capacitor plate (brass)
  - thorium 232 alpha source (0.008µ curie)
  - electrical connection to upper capacitor plate
- convex lens

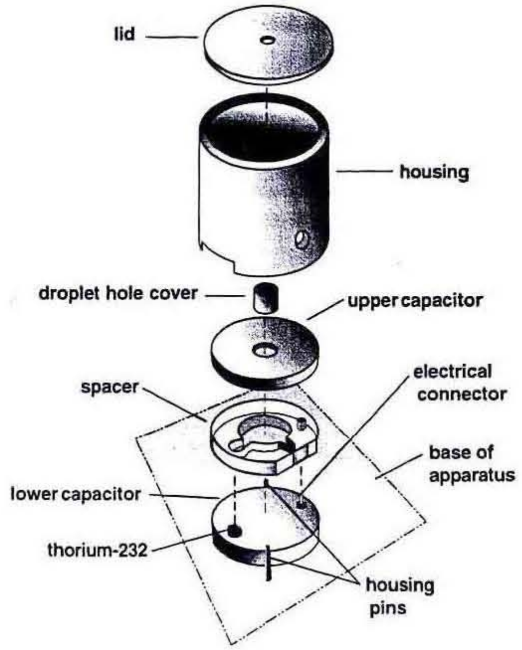


Figure 5. Droplet viewing chamber

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.

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 which permits the experimenter to sit erect while observing the drops. If necessary to achieve the proper height, mount the apparatus on two support rods on the large rod stand (Figure 6).

② Using attached bubble levels as a reference, level the apparatus with the leveling screws on the rod stand or the leveling feet of the platform, as is appropriate for your setup.

Measuring plate separation

Disassemble the droplet viewing chamber by lifting the housing straight up and then removing the upper capacitor plate and spacer plate. (See Figure 5.) Measure the thickness of the plastic spacer (which is equal to the plate separation distance) with a micrometer. Be sure that you are not including the raised rim of the spacer in your measurement.

The accuracy of this measurement is important to the degree of accuracy of your experimental results. Record the measurement.

Use care when handling the brass plates and plastic spacer to avoid scratching them.

All surfaces involved in the measurement should be clean to prevent inaccurate readings.

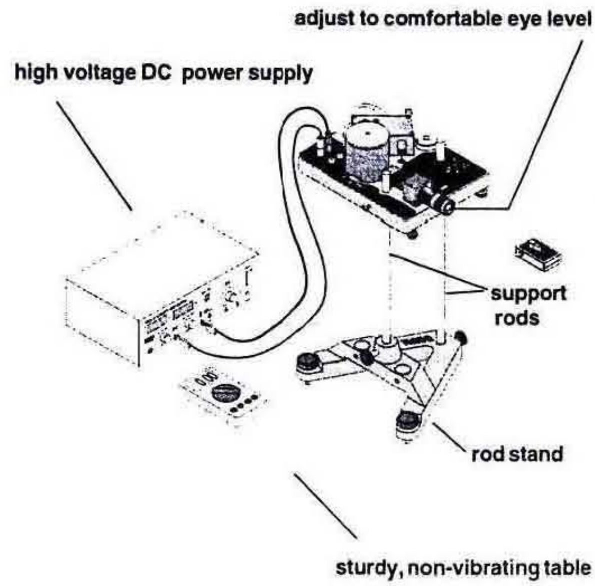


Figure 6. Equipment setup

Aligning the Optical System

Focusing the viewing scope

① Reassemble the plastic spacer and the top 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 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 top capacitor plate (Figure 7).

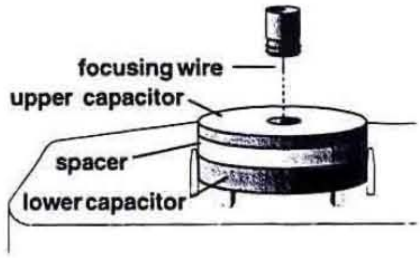


Figure 7. Insertion of the focusing wire into the top capacitor plate

③ Connect the 12V DC transformer to the lamp power jack in the halogen lamp housing and plug it into a wall socket.

Check to be sure that the transformer is the correct voltage: 100, 117, 220, or 249V).

④ Bring the reticle into focus by turning the reticle focusing ring

⑤ 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 experiments who wear glasses if the viewing scope is focused without using the glasses.

Focusing the halogen filament

① Adjust the horizontal filament adjustment knob. The light is best focused when the right edge of the wire is brightest (in highest contrast compared to the center of the wire).

② While viewing the focusing wire through the viewing scope, turn the vertical filament adjustment knob until the light is brightest on the wire in the area of the reticle.

③ Return the focusing wire to its storage location on the platform.

Functions of Controls

Ionization source lever

① When the lever is at the ionization OFF position, the ionization source is shielded on all sides by plastic, so that virtually no alpha particles near the area of the drops.

② At the ON position, the plastic shielding is removed and the drop area is exposed to the ionizing alpha particles emitted from the thorium 232.

③ At the **Spray Droplet Position**, the chamber is vented by a small air hole that allows air to escape when oil drops are being introduced to the chamber.

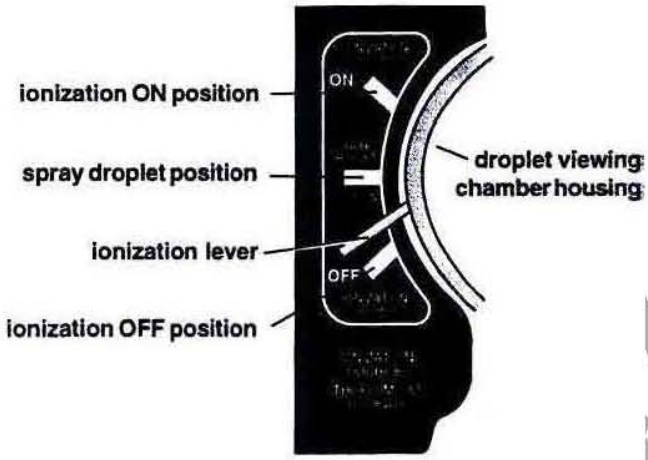


Figure 8. Ionization source lever settings

Plate charging switch

The plate charging switch has three positions:

① TOP PLATE - : negative binding post is connected to the top plate.

② TOP PLATE + : negative binding post is connected to the bottom plate.

③ PLATES GRUONDED: plates are disconnected from the high voltage supply and are electrically connected.

Adjusting and Measuring the Voltage

① Connect the high voltage DC power supply to the plate voltage connectors using banana plug patch cords and adjust to deliver about 500V.

② Use the digital multi-meter to measure the voltage delivered to the capacitor plates.

> Measure the voltage at the plate voltage connectors, not across the capacitor plates. There is a 10 mega ohm resistor in series with each plate to prevent electric shock.

Determining the temperature of the Droplet Viewing Chamber

Connect the multi-meter to the thermistor connectors and measure the resistance of the thermistor. Refer to the Thermistor Resistance Table located on the platform to find the temperature of the lower brass plate. The measured temperature should correspond to the temperature within the droplet viewing chamber.

> Although the dichroic window reflects much of the heat generated by the halogen bulb, the temperature inside the droplet viewing chamber may rise after prolonged exposure to the light. Therefore, the temperature inside the droplet viewing chamber should be determined periodically (about every 15 minutes).

Experimental Procedure

① Complete the reassembly of the droplet viewing chamber by placing the droplet hole cover on the top capacitor plate and then placing the lid on the housing. (See Figures 5.)

> 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).

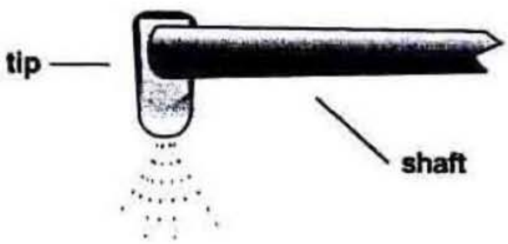


Figure 9. Correct position of the atomizer tip

Introducing the droplets into the chamber

① Put non-volatile oil of knows density into the atomizer (for example, SQUIBB #5597 Mineral Oil, density: 886 kg/m^3)

② Prepare the atomizer by rapidly squeezing the bulb until oil is spraying out. Insure that the tip of the atomizer is pointed down (90 to the shaft: see Figure 9).

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 nozzle of the atomizer into the hole on the lid of the droplet viewing chamber.

⑤ While observing through 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 top capacitor plate, and into the 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.

> If repeated "squirts" of the atomizer fail to produce any drops in the viewing area but produce a rather cloudy brightening of the field, the hole in the top plate or in the droplet hole cover may be clogged. Refer to the Maintenance section for cleaning instructions.

> Note: The exact technique of introducing drops will need to be developed by the experiment. The object is to get a small number of drops, not a large, bright cloud from which a single drop can be chosen. It is important to remember that the drops are being forced into the viewing area by the pressure of the atomizer. Therefore, excessive use of the atomizer can cause too many drops to be forced into the viewing area and, more important, into the area between the chamber wall and the focal point of the viewing scope. Drops in this area prevent observation of drops at the focal point of the scope.

> Note: If the entire viewing area becomes filled with drops, so that no one drop can be selected, either wait three or four minutes until the drops settle out of view, or disassemble the droplet viewing chamber (after turning off the DC power supply), thus removing the drops. When the amount of oil on the parts in the droplet viewing chamber becomes excessive, clean them, as detailed in the Maintenance section. Remember: the less oil that is sprayed into the chamber, the fewer times the chamber must be cleaned.

Selection of the Drop

① From the drops in view, select a droplet that both falls slowly (about 0.02-0.05mm/s) when the plate charging switch is in the "Plates Grounded" position and has at least one – or + charge (changes velocity when the plates are charged).

> Hint: A drop that require about 15 seconds to fall the distance between the major reticle lines (0.5mm) will rise the same distance, under the influence of an electric field (1000V/cm), in the following times with the following charges: 15s, 1 excess electron; 7s, 2excess electrons; 3s, 3excess electrons. (Note: these ratios are only approximate.)

> Note: If too many droplets are in view, you can clean out many of chem. By connecting power to the capacitor plates for several seconds.

> Note: If you find that too few droplets have net charges to permit the selection of an appropriately sized and charged drop, move the ionization 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.

Collecting Data on the Rise and Fall of the Oil Droplet

① Measure the rise (plates charged) and fall (plates not charged) velocities of the selected droplet about 10-20 times. Maneuver the droplet as needed using the plate voltage switch.

Note: The greatest accuracy of measurement is achieved if you time from the instant that the bright point of light passes behind the first major reticle line to the instant bright point of light passes behind the second major reticle line. (These lines are 0.5mm 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 use slower moving droplets in subsequent determinations.

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 10-20 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 (up 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 10-20 times, if possible.

⑧ Repeat ⑦ as many times as you can.

⑨ Record the plate potential, the oil density, the viscosity of air at the temperature of the droplet viewing chamber, and the barometric pressure for each set of velocity measurements.

Computation of the Charge of a Droplet

Use the formula derived in the Introduction to calculate the charge of a droplet:

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

* The formula is expressed here for use with data and constants in SI units.

The definitions of the symbols used, in SI units:

e_n -- The charge, in coulombs, carried by the droplet

d -- Separation of the plates in the condenser in cm

σ -- Density of the oil in kg/m^3

ρ -- Density of air in kg/m^3

g -- Acceleration of gravity in m/s^2

η -- Viscosity of air in poise (Ns/m^2)

b -- Constant, equal to $8.20 \times 10^{-3}\, Pa \cdot m$

p -- The barometric pressure in cm of mercury

a -- The radius of the drop in m

v_f -- The velocity of fall in m/s

v_r -- The velocity of rise in m/s

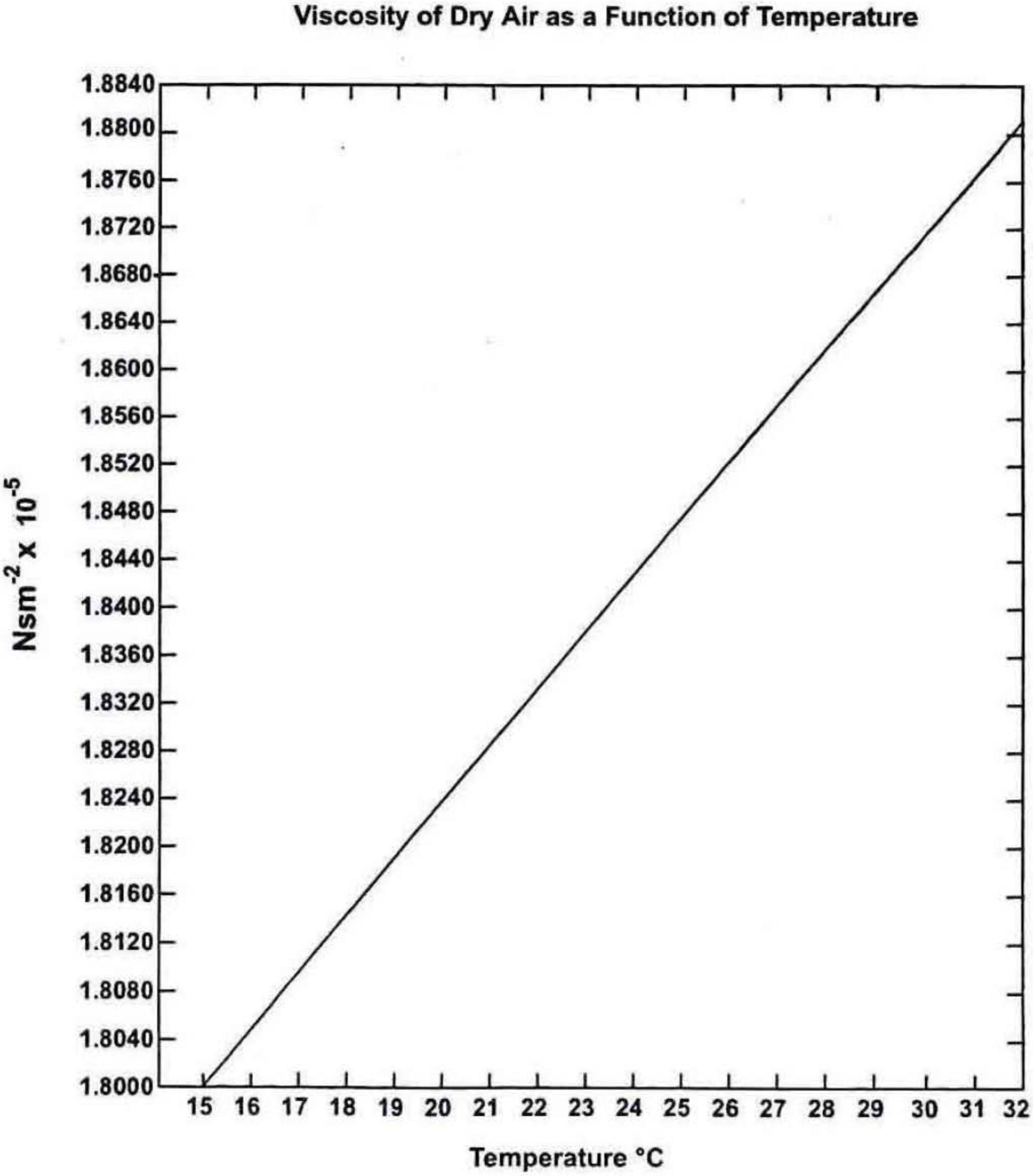
V -- The potential difference across the plates in volts

The accepted value for an electron is 1.60×10^{-19} coulombs.

Appendix A: Density of Air

$$\rho = \rho_0 \frac{P}{760} \frac{273.16}{T}$$, where ρ_0 = density of air at 0°C, 1 ATM = 1.2929 kg/m^3

Appendix B: Viscosity of Dry Air as a Function of Temperature*



Appendix C:

Millikan Oil Drop Apparatus Thermistor Resistance at Various Temperatures

THERMISTOR RESISTANCE TABLE

°C	$\times 10^6\ \Omega$	°C	$\times 10^6\ \Omega$	°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	3.897	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