16101 Millikan Apparatus

Purpose:

To determine the charge of a single electron and to illustrate the quantized nature of charge.

Required Accessories:
Power supply, 6V, 3A DC (for light source)
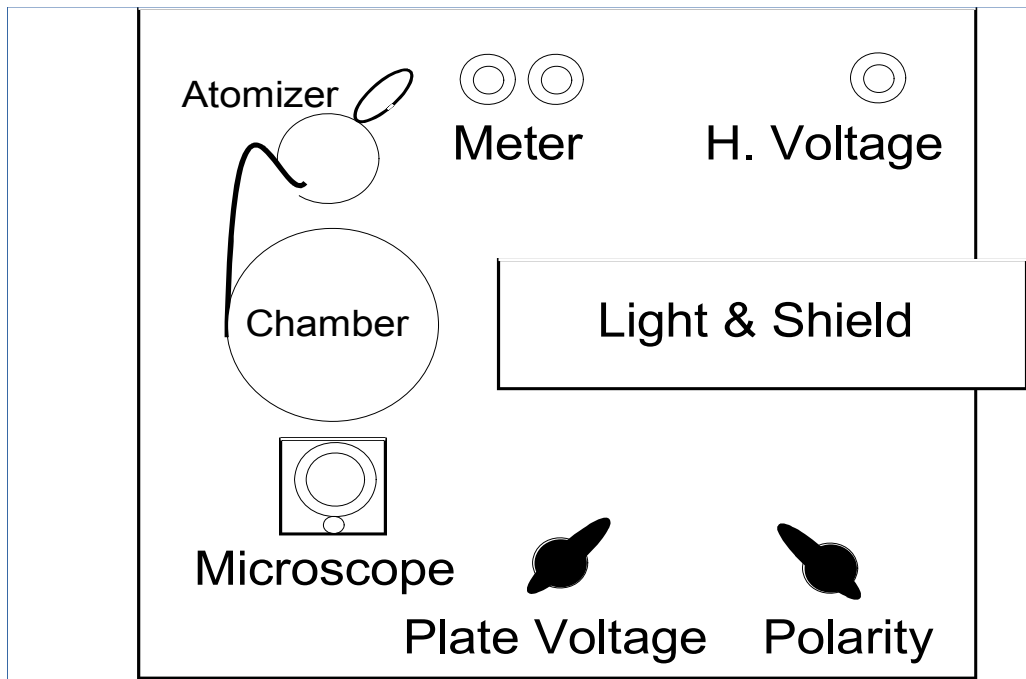Power supply, 200 - 500 VDC (for electrodes)
Voltmeter (500 VDC, 10000 ohm/volt)

Stopwatch
Micrometer or Vernier Caliper
Read complete manual before using apparatus

Caution:

This apparatus uses high voltage. Do not connect the high voltage DC power supply to the apparatus until all setup procedures are complete and the unit is ready to operate.

Science First®

A Brief History:

Robert A. Millikan became the second American to win the Nobel prize in physics. He had made significant contributions to the study of the photoelectric effect, hot spark spectra and cosmic rays. Millikan is best known to physicists for measuring the charge of an electron with his oil drop experiment which was undertaken in Chicago in 1909. Originally his research into electron charge began with water vapor (based on the work of British born physicist H.A. Wilson) and not oil. While experimenting with the water vapor technique, Millikan observed that when the electric field was switched on, the cloud disappeared leaving in its place a few charged water droplets moving in a slow stately manner in response to the applied electric field. He quickly realized that he could determine the electric charge by observing the movements of these individual particles under the influence of an electric field. However, trying to make calculations based on the observation of a droplet of evaporating water introduced too many uncertainties into the experiment. Measurements of the electron charge were improved by his substitution of a less volatile oil for the water droplets.

Not only did this experiment produce a value for the electron charge, but it produced an equally important fact that all electrons are identical in both mass and charge. With this apparatus, you too will be able to verify the experimental findings of Robert Millikan at the forefront of atomic theory in 1909.

Apparatus Adjustment Procedures:

Adjustments may be made for the following components of the apparatus: atomizer assembly, light source and microscope. Please follow the procedures carefully and sequentially to insure success in experimental use of the apparatus.

The Atomizer:

The atomizer will need attention prior to each use. It is critical that the atomizer container and assembly be kept clean (free of dust and dirt) to prevent clogging. This is true for both the use of the instrument as well as its storage. After each use and prior to storage, the reservoir of the atomizer should be emptied and cleaned with water (preferably distilled). After cleaning the reservoir, the atomizer assembly should be flushed several times with clean water by filling the reservoir with clean water and squeezing the bulb firmly several times. The delivery tube from the atomizer should be free of white liquid at all times, and be thoroughly dry before each use. It may be removed and blown out with compressed air to clean

and dry it.

To prepare the apparatus for an experiment, shake the bottle of polystyrene sphere suspension vigorously. Pour enough of the solution into the atomizer reservoir **to just cover the end of the feed tube of the atomizer**. Secure the cap on the reservoir and check for the proper operation of the atomizer by feeling for a light puff of air from the delivery tube as the bulb is squeezed. In the event that the atomizer is clogged, flush the atomizer with clean water and clear away any visible obstructions.

In its proper operation, there will be **no visible ejection of fluid through the delivery tube**, only a light puff of air carries a few polystyrene spheres with it into the chamber.
At this point, the entire atomizer assembly can be placed into the large hole above chamber. Do not insert the delivery tube into the electrode chamber at this time.

The Light Source:

The light source has been preassembled and attached to the apparatus. A few minor adjustments may be needed to optimize performance for best experimental results and ease of operation. The critical feature of light source adjustment is the illumination of the central region of the electrode chamber.

The electrode chamber and microscope have been removed from the base of the apparatus for shipment. While this is removed (or removing if necessary), connect the light source to a 6 VDC, 3A power supply. Obtain a small white card or piece of paper and hold this vertically on the Millikan base where the chamber was mounted. Position the card midway between the electrode chamber jacks and perpendicular to beam of light from the light source. Focus the light source on the card so that the spot of light is as small as possible. This spot of light will be elongated. Rotate the light source until the long axis of the bright spot is vertical. Remove the card and plug in the unit of electrode chamber and microscope.

Swing the light source from side to side and up and down as necessary to line up with the hole in the side of the chamber. When the light source is positioned properly, the light should pass directly through the hole in the side of the chamber, and appear to be centered on the hole. Leave the light on for the following adjustments. A completely darkened room will provide the best opportunity for using this instrument.

The Microscope:

The mirror which is located in the fixed base of the microscope has been completely adjusted for you at the factory. The function of this mirror is merely to aim the view of the microscope into the window of the electrode chamber. The focus knob will be used to raise and lower the microscope to adjust the focus during setup and use. Next, insert the Focus Rod into the hole in the electrode chamber used for the atomizer delivery tube, holding it tightly in place.

Look through the microscope at the illuminated Focus Rod and focus on the last thread at the extreme end of the tip by turning the knurled knob up or down as necessary. As you move the microscope, the image of the Focus Rod will sharpen, and as you pass through focus, will become blurry again. Try this several times until you have obtained the best focus. You will be able to make even finer adjustments during use in order to have the clearest view of the polystyrene spheres.

When you have focused the microscope, fine tune the position of the light source so that the tip of the Focus Rod is brightly illuminated when it is being pushed tightly towards the chamber.
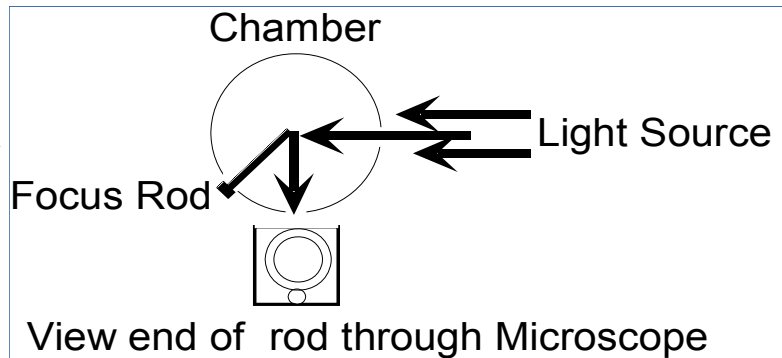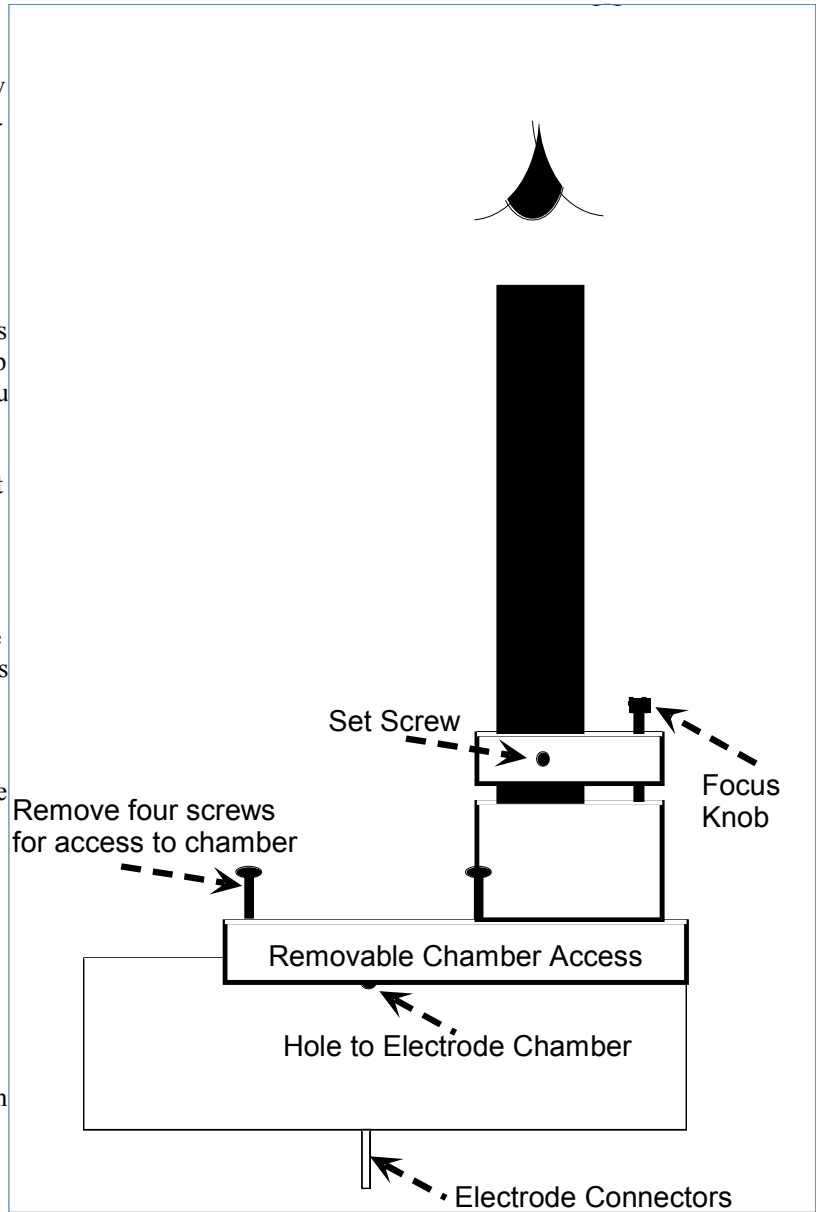
When the microscope is focused, remove and save the focusing rod and insert the atomizer delivery tube into the same hole in the electrode chamber. While looking through the microscope, squeeze the atomizer bulb using several short quick bursts. Each time you squeeze the bulb, you should see a spray of white particles enter from the left. After a few moments tiny points of light should appear on the dark background. The focus can be further adjusted at this point. The points of light become discernable side-lighted speres. It is often helpful at this point to attach the high voltage (200 to 500 VDC) power supply to the Millikan apparatus, turn the plate voltage control knob fully clockwise, and flick the polarity switch repeatedly from positive to negative and back while looking through the microscope at the particles. Real particles will move vertically (up or down) while artifacts due to various possible reflections will remain stationary.

The reticle is fixed in place at the factory. In order to change the orientation, it is necessary to use a small allen wrench (2 mm or 5/64") to operate

the set screw. Use care to ensure that the microscope will still come to focus before hitting the mirror in the fixed base, or exceeding the range of the thumbscrew.

The Experiment:

A small puff of opaque polystyrene spheres of known size distribution are delivered to the electrode

Set Screw

Focus Knob

Remove four screws for access to chamber

Removable Chamber Access

Hole to Electrode Chamber

Electrode Connectors

Chamber

Light Source

Focus Rod

View end of rod through Microscope

assembly by the atomizer. When the spheres enter the space between the electrodes, the incident light is scattered by the spheres and some of this light is redirected toward the microscope. Because the spheres are on the order of one micron in diameter, they are too small to show much physical dimension with the fixed magnification of this microscope. However, each sphere or small cluster will be easily visible as a bright point of light that will drift slowly downward under the influence of gravity. At this point, after a few short quick pumps of the atomizer bulb, the view through the microscope should look like a dark sky with many stars slowly moving downward.

The microscope in this optical system is fitted with a reticle scale which can be used with or without calibration to observe the behavior of neutral and charged spheres in the presence or absence of a constant electric field between the electrode plates.

The polarity of the electrodes can be changed by using the three position switch on the device. This allows the user to 'trap' the slower moving spheres to make repeated measurements on the same sphere, thus, allowing statistically valid data to be collected for the replication of the Millikan experiment.

Operating Procedure:

With the power supply off, attach the red (+) and black (or purple)(GND) banana plug jack leads to the 200-500 VDC power supply.

Check the apparatus to insure that all parts are attached, electrical connections are appropriately made, the microscope has been focused, and that the atomizer reservoir has a sufficient volume of solution to cover the end of the feed tube. If any of these conditions are not satisfied, go to the previous section and complete the setup procedure for the apparatus.

Position the three way switch on the apparatus to the center position (electrodes uncharged).

Connect the voltmeter to the apparatus using the female banana plug jacks that are labeled "Meter" (red +V, black GND).

Turn on both the 200-500 VDC and 6 VDC power supplies. With the three position switch in its central (neutral) position, squeeze the atomizer bulb two or three times. Look through the microscope and note the spheres which are visible as tiny points of light. Sharpen the focus for the individual viewing.

To observe the polystyrene sphere behavior in the applied electric field, turn the voltage adjust knob clockwise for ½ turn. While looking through the microscope, move the

three way switch from the center (neutral) position to one side (charged). The particle response will be rapid motion toward the plate with the charge opposite that of the particle. Quick reversal of the electrode polarity (inversion) can be used to trap individual spheres for use in repeated timing of the path velocity for a single sphere.

Experimental Procedures:

At this point, the apparatus should be fully set up and functioning properly. Let us first make some qualitative observations to familiarize ourselves with the instrument before beginning with the experiment to determine the charge of a single electron.

With the apparatus powered up, pump the atomizer once or twice to inject a cloud of polystyrene spheres into the electrode chamber. Turn the voltage adjustor fully clockwise and while looking through the microscope, move the polarity switch to one side (at present it doesn't matter which way this switch is thrown). What do you see? The cloud of particles quickly dissipates. What else do you see? If you look closely, you should observe that some particles move upward and some move downward. Why do these particles move in opposite directions? Do they all move with the same speed? If not, why are their speeds different?

When particles (polystyrene spheres) are atomized, some acquire extra electrons and some loose electrons due to frictional processes similar to drawing a comb through your hair on a dry day. Some particles will acquire more charge than others and when they are exposed to an electric field in the region between the electrodes, they experience a force proportional to their acquired charge, and also proportional to the applied electric field. This electrostatic force is written as:

$$\mathbf{F}=q\mathbf{E}$$

The bold type indicates a vector quantity. The above describes a force which is proportional to the electric field strength and for a positive charge, q, is in the same direction as the electric field. If the charge, q, is negative then the force is opposite to the electric field. We can calculate the strength of the electric field, $\mathbf{E}$, if we know the potential difference (volts) across the plates and the separation of the plates. The equation to determine the electric field is:

$$E=V/d$$

If we make the voltage smaller by turning the voltage adjustor counter clockwise from the 'full on' position, what happens to the magnitude of the electric field, and how does this affect the force on the particle? Use the above equation to help you out. Finally, what can you look for in the particle's motion to confirm your suspicions?

What happens if you wait for a long time after you

pump the atomizer and leave the voltage adjustor fully clockwise? Do all of the particles disappear? Most of them do, but if you're patient you may see one or two particles drift into view and rise very slowly. These are particles that have very small charges on them and therefore very small forces on them. That's why they move very slowly. Why are we interested in only the particles that are moving upward? This is so we don't confuse the effects of gravity with the effects of the electric field.

What happens to particles when there is no applied electric field? All of the particles drop slowly. Are they accelerating downward the way a ball would if you dropped it or do they float downward at a constant speed? The constant speed of a particle as it floats downward in a viscous fluid (in this case air) is called its terminal velocity. Terminal velocity is reached when the viscous damping force balances the net result of all other forces acting on the particle. When this happens, the net force on the particle is zero and therefore the net acceleration is zero and the particle continues to move at a constant velocity.

Measuring the Charge of an Electron:

First, let's use what we've learned in our observations of the particles to draw a force diagram

for a particle moving upward under the influence of an electric field.

The forces are F_E, the electric force; F_G, the force on the particle due to gravity; and F_V, the viscous damping force which is always opposite to the direction of motion. If we choose a coordinate system so that vertically upward is positive then our force equation for the polystyrene sphere becomes:

$$F_E - F_G - F_V = 0$$

or:

$$F_E = F_G + F_V \quad \text{Eqn (1)}$$

Now let's look at each force in detail. The electric force, F_E, is the force on a charge in an electric field and is given by:

$$F_E = qE$$

But the electric field, E, for a pair of parallel plates is

$$E = V/d$$

so the electric force becomes:

$$F_E = qV/d$$

We will be looking for the charge q, but we can measure the voltage across the electrode plates, V, and the plate separation, d.

The next force to consider is the force due to gravity. This is :

$$F_G = mg$$

We know $\mathbf{g}$ is the acceleration of gravity (9.8 m/sec^2) but what is the mass of a single polystyrene sphere? Can we weigh a single sphere? Probably not very accurately, so we must express the mass of a single sphere in terms of a bulk property of the material that is easier to measure. The density (ρ) of the polystyrene used is given on the bottle label, as is also the diameter of the spheres (in microns, 1 micron equals 1 x 10^{-6} meters). Knowing this, the mass of a single sphere is the density (ρ) times the volume.

$$F_E$$

$$m = \rho V$$

but the volume of a sphere is:

$$V = (4/3)\pi r^3$$

Sphere V_T

Substituting this into the gravitational force equation produces:

$$F_G = \rho(4/3)\pi r^3 g$$

$$F_G \quad F_V$$

Lastly, we need to look at the viscous damping force. For this we will need the equation worked out in 1845 by Sir George Stokes, which is known as Stokes' Law. Stokes' Law will give us the viscous damping force on a sphere moving in an ideal fluid. However, assuming that air is an ideal fluid will not affect our experimental error significantly, but will allow us to use Stokes' Law. The equation for viscous drag on a sphere is :

$$F_V = 6\pi\eta r v_T$$

where η is the viscosity of the fluid (for dry air at 760 mm of mercury $\eta = 1.81 \times 10^{-5}$ N sec/m), r is the radius of the sphere and v_T is the terminal velocity of the particle which we will measure. Viscous drag is experienced by a body of any shape but the force is only readily calculable for a sphere.

Substituting these three equations into our original force equation (1) we have

$$q v/d = 6\pi\eta r v_T + \rho(4/3)\pi r^3 g$$

Solving for the charge, q, results in the following:

$$q = (6\pi\eta r v_T + \rho(4/3)\pi r^3 g)\, d/V \qquad \text{Eqn. (2)}$$

In the course of the experiment we will be measuring the terminal velocity, v_T, of the particles, the voltage across the electrode plates V, and the separation between the electrode plates, d. The remainder of the variables are given.

Calibration:

We will need to calibrate the reticle scale to determine the actual speed of the particles as we view them through the microscope. To do this, find a non-conducting rod that will fit into the hole in the electrode chamber (the ink refill tube of most disposable ball point pens will do nicely). Measure its diameter very carefully using a micrometer. Disconnect the high voltage power supply, leaving the light source on, and remove the atomizer delivery tube. From the electrode chamber. Insert the rod between the electrode plates until it is visible in the microscope and count the number of scale divisions from one side of the rod to the other. Be very accurate in all of your measurements since this is extremely important in obtaining correct values for the charge on an electron.

By dividing the diameter of the rod by the number of scale divisions, you have now calibrated the reticle scale in terms of meters per division. By timing the motion of a particle as it crosses scale divisions, you can now determine its actual speed in meters per second. Have each member of the lab group perform this calculation and average the results. Record this value for future calculations. When you are finished calibrating the reticle scale, remove the calibrating rod and reinsert the atomizer delivery tube into the electrode chamber.

Data Collection:

Attach a volt meter to the terminals on the top of the apparatus. This provides a measurement of the plate voltage. With the high voltage supply turned on, adjust the voltage so the meter reads approximately 200 volts. Record this voltage.

You will need a stopwatch or a stop clock to record the time it takes for a particle to cross a given number of scale divisions. Pump the atomizer bulb to inject a cloud of particles into the electrode chamber. Allow the faster moving particles to clear, then pick a particle that is slowly moving upward. Wait for it to cross a scale division, then begin timing. Allow the particle to drift upward across as many scale divisions as possible. The more scale divisions the particle crosses, the more accurate your measurements will be. Record this time as well as the number of divisions crossed in the table provided at the end of this manual.

Repeat this procedure for as many particles as time permits. Try to time a variety of particle speeds but concentrate on those moving at the slowest speeds. (Why should we concentrate on the slowest speeds?) Using a stop watch with a lap feature is recommended. Have one student observe the particles motion and run the stopwatch while the others record the time and number of divisions. Rotate everyone in the lab group so that each student has an opportunity to make observations and time the particle's motion.

Each group should try to record the speed of 50 to 100 slowly moving particles. After the data is collected, the terminal velocity for each trial can be calculated by dividing the number of divisions crossed by the elapsed time, then multiplying by the calibration factor. Check to make sure your terminal velocity has units of velocity (m/sec)!

Analysis:

Enter the collected data into a computer spreadsheet program set up in a fashion similar to the data sheet provided. After the terminal velocities are calculated, sort them by velocity, from low to high. Plot the sorted list of velocities. What can you tell from the plot? Do you see a uniform distribution of terminal velocities or are they 'clumped up' forming several steps? If there are steps in your plot, what does this imply? Where do the steps occur? At the higher or lower velocities? What does this mean?

This type of plot illustrates the quantification of the electron's charge. At the lower speeds there should be clear evidence of the grouping of velocities but as the velocities increase in magnitude there will be a 'smearing' of the data caused by particles clumping up so that we no longer have single spheres or by the observers reaction time in starting and stopping the stopwatch.

The collected data is valid for a single value of the electric field (measured as voltage). If you ran another experiment with a higher voltage, how would the graph of the data points change? Think about this in terms of the particle's speed.

Using the graph of your data points, draw a horizontal line through the center of each distinct group of velocities and record the velocity you read on the axis of the graph. Are these lines you've drawn equally spaced? What is the average spacing between these lines? Each step in the graph is the increase in velocity due to the addition of a single electron. By using this change in terminal velocity, we can calculate the charge on a single electron.

Calculating the Charge of an Electron:

There is one more parameter that is needed before we can calculate the charge of an electron from eqn (2); this is the

separation between the electrode plates, d. Again, measure this carefully with a micrometer by removing and replacing the top of the electrode chanber.

In the course of the experiment you should have measured the following parameters:

d - plate separation in meters
V - plate voltage in volts
v_T - terminal velocity in meters/second

The remaining parameters are given:

ρ - density of spheres in kg/m^3
r - radius of spheres in meters
g - gravitational acceleration (9.8 m/sec^2)
η - viscosity of air 1.73x10^{-5} N sec/m^2

With these parameters and eqn (2) it is possible to calculate the charge of an electron. The accepted value for the electron charge is 1.602x10^{-19} coulombs.

Calculate the percent error of your result. Is this a reasonable error? Can it be accounted for? What are the most likely causes for this error?

Various experimental procedures using the Millikan apparatus are well documented in several secondary and college texts and laboratory manuals. All PSSC laboratory guides and teacher resource books provide test and procedure documentation for the experiment. For specific references, see Exp 17 & 18 PSSC 6th edition, Exp. 16 & 17 PSSC 5th edition, Exp. 36 & 37 PSSC 4th edition, Exp. 37 & 38 PSSC 3rd edition, Exp 45& 46 PSSC college physics lab guide.

Operating Hints:

1)	After the polystyrene spheres are injected into the viewing region, turbulence will exist for a few seconds. Best results will be obtained after this turbulence has subsided.

2)	If particles behave in an erratic manner beyond the damping period described above, the electrodes or the interelectrode region may have become polarized. This can be corrected by opening the cover of the electrode assembly and wiping the electrodes with a damp cloth. (Be certain to turn off and disconnect the high voltage power supply!)

3)	Best results are obtained by getting several consecutive measurements on several individual spheres. Rapidly moving spheres typically do not give good results because they are usually multiply charged or in clumps of several spheres.

4)	When the Millikan Apparatus is not in use, turn off and disconnect all power supplies.

5)	For clean up (if the apparatus is to be immediately stored or out of use for more than overnight), empty the atomizer chamber by pouring the polystyrene suspension into a clean container.

Do Not pour the used suspension into the original bottle as it may contaminate the bulk solution.

If the used solution is known to be clean, retain it for future use. Clean the atomizer assembly several times with clean water, repetitively squeeze the bulb to force water through the assembly. The electrode chamber should be wiped out prior to storage, using care to avoid stripping the chamber threads with the cover screws or scratching the electrodes.

6)	Avoid the use of organic solvents in cleaning parts of the apparatus.

7)	The plate separation, d, can be easily measured by first removing the four screws from the chamber top which allows the top and the microscope to be removed. This exposes the mirror and the top electrode. The lead to the top electrode can then be identified and the corresponding banana connector removed from beneath the assembly. It will be seen that the top electrode lead is long enough to allow easy removal of this electrode. The height of the clear plastic cylinder is seen to be the same as the space between the electrodes in the final assembly.

Care must be exercised on reassembling the chamber to ensure that the hole in the cylinder is lined up with the hole for the aspirator tube and that the extra length of the lead for the top electrode is carefully folded out of the way as it was originally.

The user may decide to simply record the dimension d for further use.

Time Allocation:

To prepare this product for an experimental trial should take less than ten minutes. Actual experiments will vary with needs of students and the method of instruction, but a satisfying set of data is often concluded within one class period. A better approach is to use one class period for initial adjustment and training and a subsequent class period for collecting good data.

Feedback:

If you have a question, a comment, or a suggestion that would improve this product, you may call our toll free number.

Trouble Shooting Chart

Symptom	Likely Cause	Corrective Action
Do Not see Bright points of light (spheres) in the microscope.	Stray light	Shield the microscope from ALL sources of stray light. Turn off over head lights.
	Microscope improperly focused	Check the microscope focus with focusing rod.
	Light source improperly focused	Check the focus of the light source by removing the electrode chamber and shining the light on a piece of paper located where the center of the chamber was.
	No styrene spheres in chamber	Make sure there is enough polystyrene suspension in the atomizer to cover the feed tube end in the bottom of the reservoir.
		Make sure the atomizer delivery tube is properly positioned in the electrode chamber.
	Electrode plates are charged and the spheres are driven off before you can see them.	Make sure the polarity switch is set to neutral when the spheres are pumped into the chamber.
See bright background in microscope.	Light source improperly positioned	Make sure the focused light beam is passing through the center of the window in the side of the electrode chamber.
Lamp does not light.	Poor electrical connection	Check connection to power supply
		Is power supply functioning? Is it plugged in?
	Bulb is burned out.	Call for replacement.
Particles are visible but do not move when polarity switch is thrown.	Low or no plate voltage	Turn plate voltage knob fully clockwise. Try again.
		Check connection to power supply.
		Is power supply functioning? Is it plugged in?

Science First®

Data Collection Chart

Calibration Factor:_____(m/div)

Trial #	Time (sec)	Divisions Crossed (div)	Velocity (m/sec)