2. Quantization of Charge

Reference: Sears, Zemansky and Young, Chapter 25

Equipment: Millikan Apparatus

Prelab Quiz

1. For the spheres used in this experiment, calculate the voltage needed to maintain a balance between the gravitational and electric fields when the spheres have a charge of $e$ (charge of one electron), $2e$ and $3e$.

2. Assuming that you have 50 spheres with charge of $e$, 100 with charge $2e$ and 75 with charge $3e$, draw a histogram of the data similar to Fig. 6. Label the horizontal axis with numerical values of the inverse voltage.

3. According to Newton's Law, force is proportional to acceleration. However in this experiment, it is shown that the force is proportional to velocity. Which statement is correct? Explain.

Theory

The electronic charge, or electrical charge carried by an electron, is a fundamental constant in physics. During the years 1909 to 1913, R. A. Millikan used the oil-drop experiment to demonstrate the discreteness, or singleness of value, of the electronic charge, and to make the first accurate measurement of the value of this constant. In that experiment, a small charged drop of oil is observed in a closed chamber between two horizontal parallel plates. Such a chamber is shown in Figure 1. By measuring the velocity of the drop under gravity and its velocity of rise when the plates are at a high potential difference, data is obtained from which the charge on the drop may be computed.

![Diagram of parallel plate arrangement for measuring charge q.](image)

Figure 1: Parallel plate arrangement for measuring charge $q$. 

The oil drops in the electric field between the plates are subject to three different forces: gravitational, electric and viscous. By analyzing these various forces, an expression can be derived which will enable measurement of the charge on the oil drop and determination of the unit charge on the electron.

If \( m \) is the mass of the drop (sphere) under observation between the plates, the gravitational force on the drop \( F_g = mg \). If there is no electrical field between the plates the drop will fall slowly, very quickly reaching a constant or terminal velocity due to the viscous retarding force. This force is \( F_a = K r v_g \) (from Stoke’s Law) where \( K \) is a constant for a given fluid, \( r \) is the radius of the sphere, and \( v_g \) is the terminal velocity. When the sphere has gained its terminal velocity \( F_g = F_a \) and

\[
mg = Kr v_g - K r v_g \\
(1)
\]

This experiment uses plastic spheres in place of oil drops. Plastic spheres are of uniform size except for occasional fragments and occasional clusters of two or more spheres. Fragments and clusters can be quickly distinguished by visually noting their size and by measuring their free fall. Fragments fall slowly compared with most spheres while clusters fall more rapidly than most spheres.

Since \( r \) is a constant, equation (1) becomes

\[
mg = Cv_g \\
(2)
\]

where \( Kr = constant = C \).

When an electric field \( E \) is applied between the plates in such a direction as to make the plastic spheres move upward with a constant velocity \( v_E \), the electrical force on the sphere is \( F_E = Eq \), \( q \) being the charge on the sphere. When the sphere reaches constant velocity \( v_E \) the forces are in equilibrium and

\[
F_E = F_g = F_a \\
(3)
\]

or

\[
Eq - mg = Cv_E \\
(4)
\]

Solving equation (4) for \( mg \) and equating with equation (2),

\[
q = \frac{C}{E} (v_E + v_g). \\
(5)
\]

For all plastic spheres of the same size and with a constant electric field, a change in \( q \) (\( \Delta q \)) results only in a change in \( v_E \) (\( \Delta v_E \)) and

\[
\Delta q = \left( \frac{C}{E} \right) \Delta v_E. \\
(6)
\]

2. QUANTIZATION OF CHARGE
When many values of $\Delta v_E$ are obtained, it is found that they are always integral multiples of a certain small value. Since this is true for $\Delta v_E$, the same must be true for $\Delta q$; that is, the change gained or lost is the exact multiple of some small charge. Thus the discreteness of charge may be demonstrated without actually obtaining a numerical value of the charge.

If the electric field $E$ is varied until the electric force $F_E$ on the sphere equals the gravitational force $F_g$, the sphere will remain stationary. (Since there is no movement, the viscous force is zero.) Therefore

$$F_g = F_E \quad \text{or} \quad mg = Eq$$

and

$$q = mg/E.$$  

Or since $E = V/d$ where $d$ is the distance between plates and $V$ is the voltage across the plates,

$$q = mgd/V$$

The mass $m$ of a sphere is unchanging and the same for all spheres and may be computed from the radius and density specified. The value of $d$ is known. The value of $V$, the voltage across the plates, can be measured with a voltmeter. Substituting these values and the value of $g$ in equation (9), the quantity of charge $q$ on the sphere can be calculated. It is important to understand that this is not necessarily the value of the charge on an electron.

Note that the term $mgd$ is a constant and therefore $q$ is proportional to $1/V$. When many observations are made and many values of $q$ have been calculated, analysis of the data and results will show that values of $q$ are always integral multiples of some small value. This small value is the fundamental unit of charge or charge on the electron. Thus electrical charge is shown to be quantized.

**Apparatus**

Look at the apparatus and become familiar with its parts:

*Viewing Chamber.* This contains the two capacitor plates and the microscope with looks at the region between them. When properly assembled, the plates are 4 mm apart, so $d = 4 \times 10^{-3}$ m. This dimension is held fairly accurately. Light is provided by a bulb in the black housing and a short length of black tape is attached to the ring to provide a dark background for viewing the balls. Balls are injected through the rubber tube from the atomizer jar.
Power supply. The power supply puts out a fixed 6.3 V AC from one set of output terminals and a variable 0 - 300 V DC from another set. The red side is positive. On your apparatus are two sets of terminals. The blue terminals are for 6.3 V to operate the lamp and the red and black terminals lead to the capacitor plates through the switch on the side of the apparatus. This switch allows the electric field to be reversed or shut off. If the red terminal is connected to the positive output of the power supply, the labels on the switch will be correct.

Light Source. Turn on the light source in order to view the chamber. The switch is on the power supply box.

Focusable Microscope. The microscope has a magnification of about 20x. The spacing of numbered graduation on the reticule represents about 0.5 mm in the field of view.

To set up your microscope, insert the metal nozzle of the injection system into the viewing chamber as far as possible. Focus the eyepiece of the microscope on the numbered gradations on the reticule. Rotate the entire microscope if necessary to make the gradations horizontal. Move the microscope in or out by means of the focusing knob until the tip of the injector nozzle is visible and in sharp focus. If the light source was properly adjusted, the tip of the nozzle should be brightly illuminated. The microscope is now properly focused for viewing the spheres when they are injected into the chamber.

Injection system. The injection system includes a small jar for holding the solution of suspended plastic spheres. The rubber bulb provides air for injecting the spheres through tubing to the viewing chamber. In the jar the balls are suspended in a mixture of alcohol and water. When this mixture is sprayed into the chamber, the liquid quickly evaporates, leaving the balls free in the air. Shake the solution in the flask before filling the atomizer jar. The level of liquid in the atomizer should be only about 1/4 inch.

Polarity switch. With the switch in the upper position, the upper capacitor plate is positive and the lower negative (case 2 in Figure 2). When the polarity of the plates is reversed by placing the switch in its lower position, we have case 3. With the switch in the middle position, the electrical supply is disconnected from the plates (case 1). An electrical circuit diagram is shown in Fig. 3.

2. QUANTIZATION OF CHARGE
Figure 2: Forces on sphere for different electric fields

Use the apparatus to view some of the spheres:

1. Withdraw the injection nozzle until the tip is just out of the field of view. Squeeze the rubber bulb several times thereby spraying some plastic spheres into the viewing chamber. When the suspension is sprayed into the air in the chamber, the water and alcohol quickly evaporate leaving a cloud of the small spheres in the field of view. Through the microscope they appear as bright points of light against a dark background. Since the view is inverted by the microscope, the particles appear to move upward but are actually falling in the earth's gravitational field. Adjustment of the microscope focus may be necessary in order to clearly see a specific particle.

2. Move the switch up or down and observe the effect on the particles. Most of the spheres become charged by friction during the spraying process. With the switch in the up position, the upper plate is positive and attracts the negatively charged spheres. Some particles move rapidly upward and others downward indicating that there are both negatively and positively charged particles. The highly charged particles move much more rapidly than those with a small charge and quickly disappear from the field of view.

3. Reverse the switch position and note the effect. Also vary the electric field by means of the voltage-control knob and note the effect. Keep in mind that the microscope inverts the field and the apparent direction of motion of the particles is opposite to their actual direction of motion.

4. With the switch in its center position, the plates are shorted and there is no
electric field between the plates. In this condition, the particles fall freely under gravity.

5. Clumps of particles consisting of several particles clinging together fall more rapidly than single particles. Fragments fall more slowly than whole particles. Do not use either clumps or fragments in your measurements.

6. Select a single particle which is moving slowly in the electric field and try to make it remain motionless by carefully adjusting the voltage. Connect a voltmeter across the red and black binding posts and note the voltage when the particle is motionless. Remember that the smaller the charge, the higher the voltage required to hold the particle stationary.

The apparatus should now be ready for use in performing the following experiments. In all laboratory work with the Millikan apparatus it is best for two students to work together. You should take turns making observations and recording data.

<table>
<thead>
<tr>
<th>Plastic sphere data</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter = $1.01 \times 10^{-8}$ m</td>
</tr>
<tr>
<td>Density = 1.05 gm/cm$^3$</td>
</tr>
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</table>

2. QUANTIZATION OF CHARGE
Before proceeding, read the notes at the end of this lab description for some helpful hints on using the apparatus.

**Experiment**

**Part 1. Velocity Measurement.** In this part we shall endeavor to show that the particles quickly reach a terminal velocity and that this velocity is proportional to the driving force.

1. Inject some particles into the viewing chamber and measure the velocity of one particle in free fall in two different parts of the field of view. The two determinations of speed will be essentially the same indicating constant velocity.

2. Apply an electric field between the plates and determine the velocity of a particle in two different parts of the field to determine if its velocity in an electric field is constant. Be sure to choose a particle that is moving slowly.

3. To show the relationship between velocity and driving force, three measurements are needed: (a) the velocity of the sphere under free fall, (b) the velocity when the electric and gravitational force are in the same direction, and (c) the velocity when the electric and gravitational forces are in opposite directions. The forces acting on the spheres for each of these determinations is readily seen by reference to Figure 2. Repeat the measurement for two more spheres.

The voltage applied to the plates should be in the 200-volt range but it is not necessary to know its actual value since you need only show that the three points fall on a straight line. The voltage should be kept constant for the three measurements on all spheres. Then the difference in forces will be the same, as shown in Figure 5. Let $F_g$ be at the center of the graph on the horizontal axis representing force, then $F_g - F_E$ and $F_g + F_E$ will be equidistant on both sides of this central axis.

To determine velocity, measure the time for the sphere to move through two spaces in the field of view. This is a distance of movement of the sphere in the chamber of one mm. Recording the data in a table similar to Figure 4 is convenient. The designations "up" and "down" refer to the apparent direction of motion of the spheres as seen in the microscope and, as elsewhere explained, is opposite to their actual direction.

To avoid using data taken on fragments or clusters, throw out the data taken on any particle with a time of free fall that is markedly different from the majority. Plot a graph as in Figure 5 of velocity versus driving force, remembering that velocity has direction as well as magnitude. The graph of the data taken on each
<table>
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<th>&quot;Down&quot;</th>
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<td>Time (sec)</td>
<td>Time (sec)</td>
</tr>
<tr>
<td></td>
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<td>v⁺ (mm/sec)</td>
<td>v⁻ (mm/sec)</td>
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</tbody>
</table>

Figure 4: Table for recording data.

Figure 5: Velocity-force plot.
sphere is a straight line. The slopes of the graphs may be different because there may be different charges on the spheres and hence different values of $F_E$. From these graphs it is seen that velocity is proportional to driving force.

(Instructor's Note: In order to allow time for Part II, do not spend too much time on Part I.)

**Part II. Charge Measurement.** In this part we shall measure and calculate the quantity of charge on each of a number of charged spheres. From an analysis of the data it may be possible to deduce if these values are integral multiples of some small value, this small value being the unit of charge or charge on the electron.

Set up the apparatus and put it in good operating condition. Connect a voltmeter to the high voltage (red and black) binding posts on the apparatus. This voltmeter measures the voltage across the plates in the viewing chamber. Keep the voltmeter connected throughout the experiment.

Isolate a single particle (avoid using a clump or fragment) that moves slowly in the electric field and vary the voltage until the particle is motionless. Observe it for a sufficient length of time to make certain that it is motionless and that the adjustment of voltage is as precise as possible. Record the value of voltage. Repeat for as many particles as time permits trying to use those requiring the highest values of voltage to balance (these are the ones having the lowest charge.) Record values of $V$ and $1/V$ in two vertical columns. From equation (9) it is seen that $q$ is proportional to $1/V$. Make a bar graph of $1/V$ and decide if $1/V$ and hence $q$ are integral multiples of some small value. Your graph should look like Figure 6.

To monitor your data as it is being collected, one person could calculate the $q$ values from the voltages measured by their partner and plot them on a graph as you go along. That way you can suggest trying for larger or smaller $q$ values to obtain a similar number of events for different values of $q$. A large number of events will minimize the statistical uncertainty in your results. To improve the statistics, you can ignore the sign of $q$ on the histogram, i. e. lump $+q$ and $-q$ together. To further improve statistics you can lump your data with that of another group doing this experiment.

Once you get a good histogram, examine it for evidence of quantization. Assuming that you find such evidence, use the method described below to extract from your data the best value you can of the charge quantum. In some cases the spheres may cluster together to give an object with a larger mass than expected. This problem is discussed in part 2 of the following section.

Experiment
Report

Part I. For a statistical analysis of your data, group the data into separate sets for $q$, $2q$, and $3q$. Now calculate the mean value of $q$ for each set separately. The calculation is easily done with a spread sheet program on a computer. The mean value of $q$ is given by

$$\bar{q} = \frac{\sum q_i}{N_q};$$ (10)

where $N_q$ is the total number of observations of charge group $q$.

The mean value of $2q$ is given by

$$\bar{2q} = \frac{\sum q_i}{N_{2q}};$$ (11)

where $N_{2q}$ is the total number of observations of charge group $2q$. The mean value for charge group $3q$ is found in a similar manner. These will be your measurements of $\bar{q}$, $\bar{2q}$, and $\bar{3q}$. Now calculate the standard error in the mean for each group of
measurements. The standard error in the mean for the first group is given by

$$\sigma^2_m(q) = \frac{\sum_{i=1}^{N_q} (q_i - \bar{q})^2}{N_q(N_q - 1)};$$  \hspace{1cm} (12)

For the second group, it is given by

$$\sigma^2_m(2q) = \frac{\sum_{i=1}^{N_{2q}} (q_i - \bar{2q})^2}{N_{2q}(N_{2q} - 1)};$$  \hspace{1cm} (13)

and so forth. Your final value of \( q \) is then found by averaging

$$q = \frac{N_q \times \bar{q} + N_{2q} \times (\bar{2q}/2) + N_{3q} \times (\bar{3q}/3)}{N_q + N_{2q} + N_{3q}};$$  \hspace{1cm} (14)

and your final value of the standard error in the mean is

$$\sigma_m = \frac{1}{(1/\sigma^2_m(q) + 1/\sigma^2_m(2q) + 1/\sigma^2_m(3q))^{1/2}}$$  \hspace{1cm} (15)

The above equations are derived from the equations on data analysis in the appendix.

**Part II.** If all of your errors are random, your final result has a 68% probability of being within \( \pm \sigma_m \) of the true value. What are sources of random errors in this experiment? systematic error? Unfortunately in this experiment the mass is also “quantized”. What charge would you have measured for a clump of two balls with 3\( e \) real charge. You might want to see if other such undesirable data (from other ratios of small integers) can explain any unexpected peaks in the charge histogram you make.

**Part III.** Do a \( \chi^2 \) test to determine how consistent this expression is with your data (see Sect IV of Appendix A – Data Reduction and Error Analysis). To calculate \( \chi^2 \), take your data points for \( e \), 2\( e \) and 3\( e \) and let \( Y_{theory} \) be equal to \( e \), 2\( e \) and 3\( e \) for the three measurements. Then \( N = 3 \), \( \alpha = 0 \) and \( \nu = 3 \). Calculate \( \chi^2 \) for the three data points and use Table 2 in the Appendix to find the probability that your data is consistent with the accepted value of \( e \).

**Conclusion**

Report 2-11
Apparatus Notes

1. The spheres used in this experiment have a free fall time of 12-14 seconds per reticule division. Best results are obtained and much time saved if only those spheres are selected.

2. Results are more meaningful if spheres with relatively few electrons are selected for use in obtaining data. The use of 200 volts or more across the plates directs the experimenter to those spheres having few electrons since those with a large number of electrons move too fast in a high electric field to be timed.

3. One of the principal reasons for difficulty in seeing particles is that the microscope is not focused properly. Check its focus by pushing in the injection nozzle and focusing on the tip.

July, 1993
This experiment was adapted from the Sargent Welch instructions for their Millikan Apparatus used in this experiment and the University of Virginia Introductory Physics Laboratory Manual. DAJ

ph3304\millikan\millikan.tex
Millikan’s measurement of the charge on the electron is one of the few truly crucial experiments in physics and, at the same time, one whose simple directness serves as a standard against which to compare others. Figure 3-4 shows a sketch of Millikan’s apparatus. With no electric field, the downward force on an oil drop is \( mg \) and the upward force is \( bv \). The equation of motion is

\[
mg - bv = m \frac{dv}{dt}
\]

where \( b \) is given by Stokes’ law:

\[
b = 6\pi \eta a
\]

and where \( \eta \) is the coefficient of viscosity of the fluid (air) and \( a \) is the radius of the drop. The terminal velocity of the falling drop \( v_t \) is

![Fig. 3-4 Schematic diagram of the Millikan oil-drop apparatus. The drops are sprayed from the atomizer and pick up a static charge, a few falling through the hole in the top plate. Their fall due to gravity and their rise due to the electric field between the capacitor plates can be observed with the telescope. From measurements of the rise and fall times, the electric charge on a drop can be calculated. The charge on a drop could be changed by exposure to x rays from a source (not shown) mounted opposite the light source.](image)
When an electric field $\mathcal{E}$ is applied, the upward motion of a charge $q_n$ is given by

$$ q_n\mathcal{E} - mg - bv = m \frac{dv}{dt} $$

Thus the terminal velocity $v_r$ of the drop rising in the presence of the electric field is

$$ v_r = \frac{q_n\mathcal{E} - mg}{b} $$

In this experiment, the terminal speeds were reached almost immediately, and the drops drifted a distance $L$ upward or downward at a constant speed. Solving Equations 3-12 and 3-13 for $q_n$, we have

$$ q_n = \frac{mg}{\mathcal{E}v_f} (v_f + v_r) = \frac{mgT_f}{\mathcal{E}} \left( \frac{1}{T_f} + \frac{1}{T_r} \right) $$

where $T_f = L/v_f$ is the fall time and $T_r = L/v_r$ is the rise time.

If any additional charge is picked up, the terminal velocity becomes $v'_r$, which is related to the new charge $q'_n$ by Equation 3-13:

$$ v'_r = \frac{q'_n\mathcal{E} - mg}{b} $$

The amount of charge gained is thus

$$ q'_n - q_n = \frac{mg}{\mathcal{E}v_f} (v'_r - v_r) = \frac{mgT_f}{\mathcal{E}} \left( \frac{1}{T'_r} - \frac{1}{T_r} \right) $$

The velocities $v_f$, $v_r$, and $v'_r$ are determined by measuring the time taken to fall or rise the distance $L$ between the capacitor plates.

If we write $q_n = ne$ and $q'_n - q_n = n'e$ where $n'$ is the change in $n$, Equations 3-14 and 3-15 can be written

$$ \frac{1}{n} \left( \frac{1}{T_f} + \frac{1}{T_r} \right) = \frac{\mathcal{E}e}{mgT_f} $$

and

$$ \frac{1}{n'} \left( \frac{1}{T'_r} - \frac{1}{T_r} \right) = \frac{\mathcal{E}e}{mgT_f} $$

(Continued)
To obtain the value of $e$ from the measured fall and rise times, one needs to know the mass of the drop (or its radius, since the density is known). The radius is obtained from Stokes’ law using Equation 3-12.

Notice that the right sides of Equations 3-16 and 3-17 are equal to the same constant, albeit an unknown one, since it contains the unknown $e$. The technique, then, was to obtain a drop in the field of view and measure its fall time $T_f$ (electric field off) and its rise time $T_r$ (electric field on) for the unknown number of charges $n$ on the drop. Then, for the same drop (hence, same mass $m$), $n$ was changed by some unknown amount $n'$ by exposing the drop to the x-ray source, thereby yielding a new value for $n'$; and $T_f$ and $T_r$ were measured. The number of charges on the drop was changed again and the fall and rise times recorded. This process was repeated over and over for as long as the drop could be held in view (or until the experimenter became tired), often for several hours at a time. The value of $e$ was then determined by finding (basically by trial and error) the integer values of $n$ and $n'$ that made the left sides of Equations 3-16 and 3-17 equal to the same constant for all measurements using a given drop.

Millikan did experiments like these with thousands of drops, some of nonconducting oil, some of semiconductors like glycerine, and some of conductors like mercury. In no case was a charge found that was a fractional part of $e$. This process, which you will have the opportunity to work with in solving the problem below using actual data from Millikan’s sixth drop, yielded a value of $e$ of $1.591 \times 10^{-19}$ C. This value was accepted for about 20 years, until it was discovered that x-ray diffraction measurements of $N_A$ gave values of $e$ that differed from Millikan’s by about 0.4 percent. The discrepancy was traced to the value of the coefficient of viscosity $\eta$ used by Millikan, which was too low. Improved measurements of $\eta$ gave a value about 0.5 percent higher, thus changing the value of $e$ resulting from the oil-drop experiment to $1.601 \times 10^{-19}$ C, in good agreement with the x-ray diffraction data. The modern “best” values of $e$ and other physical constants are published periodically by the International Council of Scientific Unions. The currently accepted value of the electron charge is\(^8\)

$$e = 1.60217733 \times 10^{-19} \text{C}$$  \hspace{1cm} 3-18

with an uncertainty of 0.30 parts per million. Our needs in this book are rarely as precise as this, so we will typically use $e = 1.602 \times 10^{-19}$ C. Note that, while we have been able to measure the value of the quantized electric charge, there is no hint in any of the above as to why it has this value, nor do we know the answer to that question now.

Hardly a matter of only historical interest, Millikan’s technique is currently being used in an ongoing search for elementary particles with fractional electric charge by M. Perl and co-workers.

**Problem**

The accompanying table shows a portion of the data collected by Millikan for drop number 6 in the oil-drop experiment. (a) Find the terminal fall velocity $v_f$ from the table using the mean fall time and the fall distance (10.21 mm). (b) Use the density of oil $\rho = 0.943$ g/cm\(^3\) = 943 kg/m\(^3\), the viscosity of air $\eta = 1.824 \times 10^{-5}$ N·s/m\(^2\), and $g = 9.81$ m/s\(^2\) to calculate the radius $a$ of the oil drop from Stokes’ law as expressed in Equation 3-12. (c) The correct “trial value” of $n$ is filled in in column 7. Determine the remaining correct values for $n$ and $n'$, in columns 4 and 7, respectively. (d) Compute $e$ from the data in the table.

(Continued)
Rise and fall times of a single oil drop with calculated number of elementary charges on drop

<table>
<thead>
<tr>
<th>1 $T_f$</th>
<th>2 $T_r$</th>
<th>3 $1/T'_r - 1/T_r$</th>
<th>4 $n'$</th>
<th>5 $(1/n')(1/T_r - 1/T'_r)$</th>
<th>6 $1/T_f + 1/T_r$</th>
<th>7 $n$</th>
<th>8 $(1/n)(1/T_r - 1/T'_r)$</th>
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