Modern Physics—PHYS 220
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Lab: Millikan Oil Drop Experiment

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Theory

The PASCO manual for our apparatus has a nice description of the theory involved; see pages 1-2 & 9 of the manual.

Preliminary Questions

1. Consider an electron placed in between two oppositely charged horizontal parallel plates. Assume that the plates are spaced a distance 1.0 cm apart and that the electric field between the plates is uniform and perpendicular to the plates. Also assume that the direction of the electric force on the electron is opposite to the force of gravity on the electron (*i.e.*, the electron's weight).
   - (a) Draw a vector diagram showing the forces acting on the electron. Also show on the diagram the electric field lines due to the parallel plates.
   - (b) Calculate the magnitude of the electric field such that the electron is held at equilibrium.
   - (c) Determine the potential difference (voltage) between the plates needed to produce the electric field found in the last part.
2. Repeat problem 1 for an electron placed on a spherical water droplet of radius 0.001 mm and density of $1.0\mathrm{g/cm}^3 = 1000\mathrm{kg/m}^3$.
3. One reason for using charged liquid droplets (actually oil instead of water) in this experiment is that they can be seen under suitable magnification and illumination, while electrons are not directly visible. There is another reason, which emerges from the answers to part c in the two cases. Explain and discuss briefly.
4. This problem provides practice in calculating the charge on an oil drop, using sample data values similar to what might

be obtained experimentally for a particular drop. This is a calculation you will need to repreat many times during the course of this experiment, so it would be a good idea to develop a strategy and tools to perform this calculation accurately. Automation may help, whether it is a python program, an Excel spreadsheet, or any other language you care to use.

Sample data

- Distance between reticule lines used in drop measurements: 0.5 mm;
- Average time for drop to fall the distance between reticule lines: $t_f = 17.34$ s;
- Average time for drop to rise the distance between reticule lines: $t_r = 3.79$ s;
- Voltage across plates: $V = 386$ volts;
- Separation between plates: $d = 0.767$ cm;
- Density of oil: 886 $\mathrm{kg/m^3}$;
- Air pressure: $p = 1.0$ atm;
- Temperature inside space between plates: $T = 25°$.

Use the graph on page 19 of the manual to determine the viscosity of air η at the given temperature. Note that the numerical value of η given on the vertical axis of the graph is to be multiplied by 10^{-5}. For the value of the constant quantity b, refer to the list at the bottom of the left column on page 9 of the manual.

Refer to *Suggested Procedure for Computation of the Charge of an Electron* on page 9 of the manual.

Using the sample data, follow steps 1, 2 and 3 and compute the radius a and the mass m of the oil drop, and finally the charge q on the drop

Important: All quantities used in these calculations must be in SI units. Many of the data values are given in other units and must be converted into SI units before proceeding with the calculations.

Answers sample calculation

With this data, you should find that:

- $a = 4.9 \times 10^{-7}$m
- $m = 4.4 \times 10^{-16}$kg
- $q \approx 3e$, where e is the magnitude of the charge on the electron.

Equipment

See the manual, pages 3-4. Be sure to read this section carefully to familiarize yourself with the apparatus.

Procedure

1. The experimental set up and measurement procedures are described in detail in the manual, pages 5-9. Be sure to read this section carefully to familiarize yourself with the various steps involved.
2. Your actual data on the oil drops will consist of rise times and fall times recorded for each drop you are able to see and move in the field of view. Record as many times as possible for each drop. The specific steps involved in recording data on the drops are given in the manual, pages 8-9. Refer also to the Notes section below.
3. Before you attempt any measurements on oil drops, the droplet viewing chamber must be carefully disassembled, cleaned, and reassembled.

   See Fig. 5 in the manual (on page 4) showing the various parts of the droplet viewing chamber. See also the cleaning instructions on the top of page 16 of the manual. While the chamber is disassembled, measure the thickness d of the plexiglass spacer that fits between the upper and lower metal plates. Use a Vernier caliper. Note that d is the separation between the upper and lower metal plates which (when charged by the high voltage supply) produce the electric field that acts on the charged oil drops.
4. During the experiment, after oil is repeatedly sprayed into the apparatus to obtain data, the viewing chamber will eventually become clogged with oil. Then you must disassemble, clean, and reassemble the apparatus as described above before attempting the further measurements on oil drops.

Important: Turn off the high voltage supply before disassembling the chamber. The digital voltmeter reading should be zero.

Notes

- Try to get at least some measurements on oil drops which fall relatively slowly and which also rise relatively slowly, compared to other drops. Such drops will tend to have relatively small mass and charge, and they are more likely to provide evidence for a fundamental unit of charge.

- If you have a drop on which you have obtained several consistent values for the rise time and fall time, try moving the ionization lever to the "on" position to see if you can change the charge on the drop. If you succeed in this, then continue to measure the rise time (which should now be noticeably different from what was found before) and the fall time (which should be approximately the same as before) until you accumulate several more values of each.[1]
- Record the potential difference V between the metal plates and the distance between the reticule lines of the telescope viewing screen.

Analysis

Use SI units for all quantities. Refer to Preliminary Question 4 for a sample calculation.

If there is an abrupt jump in v_r values for a given drop while v_f remains unchanged, it is likely that the number of charges on the drop has changed. The data following this change must be analyzed separately from the previous data. Such a change in charge might have been produced deliberately by moving the ionization lever to the on position as described in the second of the three notes on measurements above.

1. Determine the rise and fall velocities v_r and v_f from the average values of the rise and fall times and the reticule lines spacing. Using the equations in the *Suggested Procedure for Computation of the Charge of an Electron* on page 9 of the manual, compute the radius a and the mass m of each drop, and the charge q on the drop.
2. Plot your results for the drop charge as points along a straight line axis calibrated in units of 10^{-19} Coulomb, with the axis calibrated from 0 to 20 (or use a larger maximum value than 20 if needed to accommodate your data). What sort of behavior do you observe for your charge values?
3. Assuming that electric charge is observed in units of $e = 1.60 \times 10^{-19}$ C, compute the number of charge units present on each of your drops. Do your results for the charge on a drop come ouput close to integral multiples of e?
4. Make another (hypothetical) choice for a value of e which is consistent with your data. Recalculate the number of charge units present on each of your drops.
5. Based only on your data, is there justification for preferring the actual value of e to your hypothetical value? Can you

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[1] These procedures are a restatement of the instructions given in steps 5-8 in the manual at the top of page 9).

suggest a quantitative method of deciding between alternative values of e? Comment on the amount and precision of the data needed to establish Millikan's conclusions.

Uncertainty Analysis

Although the expression for q is complex, it depends mostly on constants. We can reduce the expression to one that depends only on rise and fall time:

$$q = \frac{4\pi}{3}\frac{\rho g d}{V}\left[\left(\frac{9\eta}{2\rho g}\right)\left(\frac{1}{1+\frac{b}{pa}}\right)\right]^{3/2}\frac{D^{3/2}}{\sqrt{t_f}}\left(\frac{1}{t_f}+\frac{1}{t_r}\right) \tag{1}$$

Redefining the constant term and separating the time-dependent term, it can be shown that:

$$\delta q = Z\sqrt{\frac{1}{4t_f^3}\left(\frac{3}{t_f}+\frac{1}{t_r}\right)^2(\delta t_f)^2+\frac{1}{t_f t_r^4}(\delta t_r)^2}, \tag{2}$$

where

$$Z \equiv \frac{4\pi}{3}\frac{\rho g d}{V}\left[\left(\frac{9\eta}{2\rho g}\right)\left(\frac{1}{1+\frac{b}{pa}}\right)\right]^{3/2} D^{3/2} \tag{3}$$

and

- ρ = density = 886 kg/m^3
- g = acceleration due to gravity in m/s^2
- d = plate separation in m
- V = measured plate voltage in V
- η = viscosity of air in Ns/m^2 determined from graph and temperature
- b = pressure constant = 8.20×10^{-3} Pa m
- p = atmospheric pressure in Pa
- a = droplet radius in m
- t_f = measured time to fall, δt_f = uncertainty in fall time
- t_r = measured time to rise, δt_r = uncertainty in rise time
- D = reticule line separation (0.5 mm for major lines, may be multiple)

This calculation is straightforward, albeit tedious. An alternative technique that is useful, particularly if the calculation has been automated, is to repeat the calculation with the uncertainties added and substracted from the central values that were measured. This provides the range of charges that would result from the possible range in the measured times.

References

- Manufacturers manual for the PASCO Millikan Oil Drop Apparatus
- Thornton and Rex, Modern Physics 3rd edition, pages 171-173
- Tipler and Llewellyn, Modern Physics 5th edition, pages 118-119