Millikan's Oil Drop Experiment

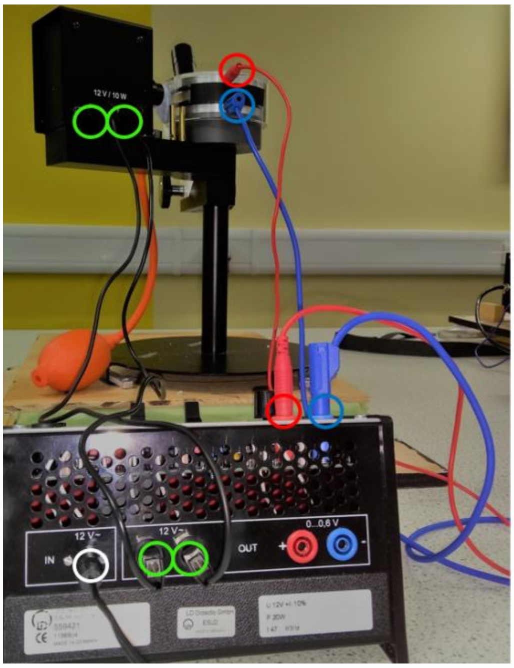
At the start of the 20th century, scientists discovered the existence of the electron. They knew it possessed a mass and an electrical charge, and they had determined the charge-to-mass ratio, e/m. In 1909, Robert Millikan and Harvey Fletcher developed an experiment to determine the fundamental charge of the electron. This was achieved by measuring the charge of oil drops in a known electric field. If all electrons have the same charge, then the measured charge on the oil drops must be multiples of the same fundamental constant.

Safety	**Voltage:** All the signal voltages are small and harmless. The mains voltages are fully contained in the apparatus during normal use.

Set up instructions for staff.

Instructional videos on how to set up this experiment are available on the Lancaster Physics/ Outreach/ Lab in a Box webpage.

Unboxing: The apparatus will be provided in a large wooden box, which must be opened from the top lid first. Remove the items within, apart from the platform, then proceed to lift the rest of the wooden sides of the box.



Cable connection Guide:

Please assemble the experiment before connecting it to the grid.

1. Blue and Red Cables: Connect to blue and red plugs, respectively.
2. Black Cables: Connect as seen on the photograph above ,highlighted in green, to the 12 [V] plugs on the experiment and power supply.
3. The **Black** cable ,highlighted in white, is connected from the power supply to the grid.

Figure 1: Photograph of the cable set up of the Millikan’s experiment with instructions on how to connect each cable.

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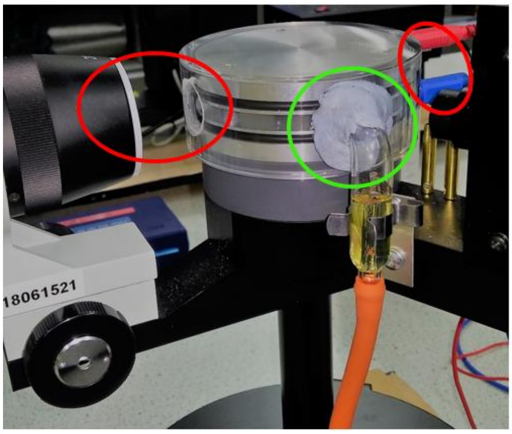

1. Place the plates onto the device by matching the bottom connections.
2. Align the protective lid so that the opening is facing the microscope and the cable holes match with the plate's plugs as seen in red.
3. Fill the glass container halfway with the provided oil and secure it onto the device, as seen in green. Use the blu tack to enclose the oil outlet.

Figure 2: Photograph of the Millikan's experiment set up with instructions on how to connect the plates to the platform.

Background

In Millikan's experiment, oil drops are sprayed from a nozzle into a volume between two closely-spaced horizontal metal plates that are insulated from each other. The drops can be kept from falling by applying a potential difference between the plates.

1. When the oil drops are sprayed into the volume they are already electrically charged. What process gives them their charge?

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2. What forces act on the oil drops whilst they are in the volume? Label the forces in Figure 2 below.

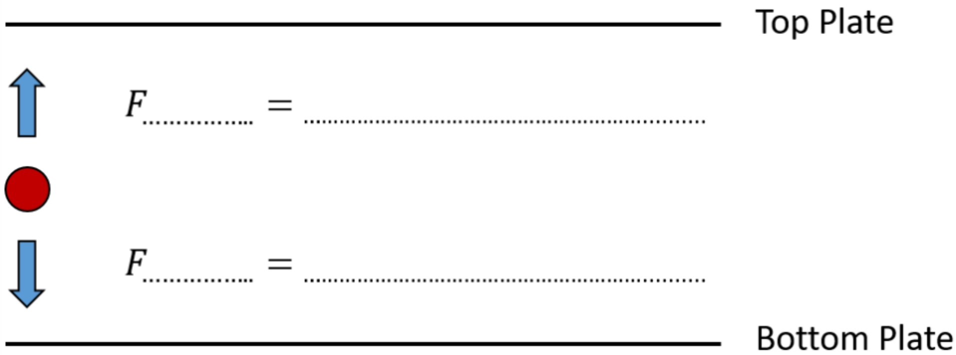

Figure 2: Representation of a stationary oil drop within the volume, once a voltage is applied across the plates.

The downward force acting on the oil drop is due to the gravitational pull on the drop:

$$F_G = mg.$$

The upward force is the electrostatic force:

$$F_E = Eq.$$

The electric field can be expressed as a function of the voltage V across the plates and the spacing d between them:

$$E = \frac{V}{d}.$$

Write down the value of d for this apparatus:

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In the correct conditions, the electrostatic force and the force of gravity can be balanced, such that the oil drop is brought to rest. In this case, we can express the charge on the oil drop as follows:

$$F_E = F_G,$$

$$q = \frac{mgd}{V}.$$

As it is very challenging to measure the mass of individual oil drops, it is helpful to re-express the mass of the oil drop in terms of the density of the oil as follows:

$$\rho_{oil} = m/V_{sphere}$$

Assuming that the oil drop is approximately spherical, its volume is given by the following formula:

$$V_{sphere} = \frac{4}{3}\pi r^3,$$

where r is the radius of the oil drop. Thus, the gravitational pull on the oil drop can be expressed as:

$$F_G = \frac{4}{3}g\pi r^3\rho_{oil}$$

There is a third force acting on the oil drops. The buoyancy due to the surrounding air between the plates introduces an upward thrust:

$$F_b = \frac{4}{3} g \pi r^3 \rho_{air} \,.$$

Therefore the equation for the charge of the oil drop can be re-expressed as

$$q = \left(\frac{d}{V}\right)\left(\frac{4}{3}\right)\pi r^3 (\rho_{oil} - \rho_{air}) \,.$$

Of the parameters in this equation, the radius r is difficult to measure. The following section focuses on how it can be determined.

Background (continued)

The radius of an oil drop is very small and difficult to measure. However, Millikan found that r could be measured indirectly by switching off the voltage and letting the drop fall.

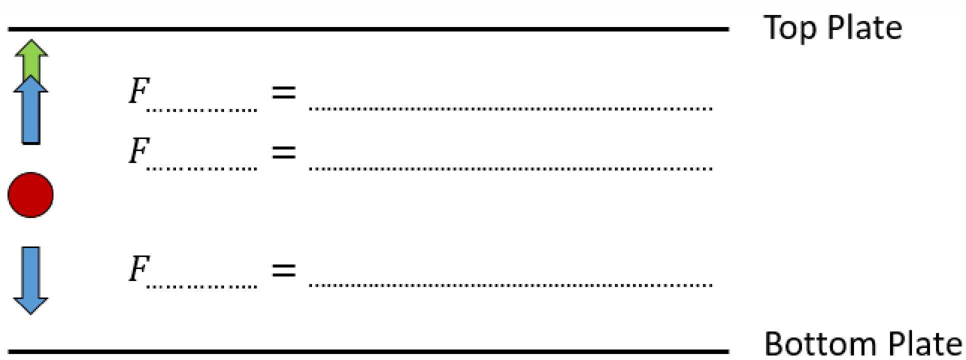
As the drop falls down through the viscous air, it experiences an upward drag force given by Stokes's law as follows:

$$F_{drag} = 6\pi\eta r v$$

In this equation, η is the viscosity of air and v is the speed of the oil drop. When the upward buoyant and viscous forces balance the downward gravitational force, then the drop no longer accelerates, and moves at its terminal velocity v_t . The drops reach terminal velocity very quickly, and this can be measured by timing how long it takes a droplet to fall a measured distance.

By equating the forces acting on an oil drop travelling at its terminal velocity, we can derive an expression for the radius of the oil drop.

Label the forces on the diagram below:



Equating these forces:

$$F_G = F_b + F_{drag}$$

The forces acting on the drop are:

$$F_{drag} = 6\pi\eta r v,$$

$$F_G = \tfrac{4}{3} g\pi r^3 \rho_{oil},$$

$$F_b = \tfrac{4}{3} g\pi r^3 \rho_{air}.$$

Therefore,

$$6\pi\eta r v_t = \left(\tfrac{4}{3}\right)\pi r^3(\rho_{oil} - \rho_{air}),$$

$$r = 3\sqrt{\frac{\eta v_t}{2g(\rho_{oil} - \rho_{air})}}.$$

Substituting this back into the expression for q we get:

$$q = \left(\frac{9\pi d}{V}\right)\sqrt{\frac{2\eta^3 {v_t}^3}{g(\rho_{oil} - \rho_{air})}}.$$

Therefore, the electric charge on the oil drop can be found in terms of its terminal velocity and the applied voltage across the plates.

Task 1

Use a desk lamp angled towards the oil drop chamber, if possible, to give an even and bright illumination on the microscope.

Can you read the graticule scale on the microscope? If not, ask a member of staff for assistance. Note that **each large scale division corresponds to 1 [mm]**.

Make sure that the oil exit pipe is in line with the small holes on the chamber and give one or two sharp squirts of the bulb to spray oil into the gap between the metal plates.

1. **Use the control on the microscope to focus on the oil drops** and wait for the sideways motion to cease. You may need to place an object next to the small holes to minimise air currents. Adjust the intensity of the light on the microscope if necessary, to increase the contrast.

2. Switch on the voltage supply to the metal plates, and watch the charged drops move up and down as you vary the potential difference. Choose a bright, easy-to-see oil drop which is near to the graticule, and use the voltage control to move it down near the top of the screen. Hold it there by fine-tuning the voltage.
3. Record this value of V.
4. Next, turn off the voltage and start the stop clock. Watch the drop as it falls.
5. You will need to keep focusing as it drifts downwards. It is best to let it fall as far as possible to minimise the uncertainties in timing and distance.
6. Once it has fallen through 6 large graduations on the screen, stop the clock and record the time and distance it has fallen.
7. The terminal velocity v_t is given by the equation $S = v_t\, t$, where S is the distance travelled and t is the time taken.

Note that the distance you **measure has to be divided by 2 to take account of the magnification of the microscope**.

Question 1

Carry out measurements on a number of oil drops. For each oil drop, use the measurements to calculate a value of its electric charge, q, using the following equation from the above derivation:

$$q = \left(\frac{9\pi d}{V}\right)\sqrt{\frac{2\eta^3 {v_t}^3}{g(\rho_{oil} - \rho_{air})}}.$$

A table is provided below for you to record your measurements. Don't forget to include the uncertainities in your measurements.

Some useful constants for this experiment are also given below:

Air viscosity	$\eta = 1.83 \pm 0.04 \times 10^{-5}\ Ns\ m^{-2}$
Oil density	$\rho_{oil} = 874 \pm 2\ kg\ m^{-3}$, at 20°C
Air density	$\rho_{air} = 1.30 \pm 0.05\ kg\ m^{-3}$, at 20°C
Plate Spacing	$d = 6.00 \pm 0.05 \times 10^{-3}\ m$
Electronic charge:	$e = 1.60 \times 10^{-19}$ C

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Volatge V [V]	Distance s [m]	Time t [s]	Terminal Velocity v_t [m/s]	Charge q [C]	№ of electrons (q/e)

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1. Were your results on the number of electrons always integers? If not, can you explain why?

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2. Was the experiment successful? What was the largest source of uncertainty? How could you improve your results?

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