

User's Manual

MILLIKAN's OIL DROP EXPERIMENT

Model: MOD-01

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INTRODUCTION

Millikan oil drop experiment aims at measuring the charge of the electron. It is perhaps the most basic of all atomic physics or so called modern physics laboratory experiments. The arrangement is quite simple and bears a testimony to the ingenuity of Robert Millikan. This experiment proved the atomicity of electricity and led to the accurate determination of the mass of electron and Avogadro's number. It won Millikan the Nobel Prize in the year 1923.

This experiment depends on the ability to control, measure and balance very small force of the order 10^{-14} N. The set-up consists of two horizontal parallel plates separated by about 5mm. The upper plate has a small hole through which microscopic oil droplets are sprayed in between the two plates with the help of an atomizer which is like a common perfume sprayer. These droplets get charged due to the frictional force during spraying. The free fall of these droplets in the space between the plates is observed in the gravitational field. A measurement of the velocity of fall along with the use of Stokes law leads to the calculation of the mass of the droplets and their radii if the oil density is known. These are of the order of 10^{-15} kg and 10^{-6} m respectively. By applying a potential difference between the plates a uniform electric field is produced in the space between the plates. A measurement of the velocity of the negatively charged droplets rising in the electric field allows a calculation of the electric force on the droplets and hence the charge carried by them. In the experiment the droplets which rise and fall slowly are selected as they are expected to have a fairly small charge. These droplets are made to rise and fall several times. The repetition of measurements of the velocities of rise and fall reduce the random error of their means. A fairly large number of droplets are observed and their charges are calculated.

The analysis of the data on the total charge carried by the droplets shows that these total charges are integral multiples of a certain smallest charge which is the charge of an electron. This result also shows that the charge is quantized.

DESCRIPTION OF THE APPARATUS

The present set-up consists of

1. A oil drop chamber mounted on top of the panel. It has
 - (i) A pair of horizontal parallel plate electrodes separated by about 5 mm thick ebonite ring with a hole for viewing the oil droplets.
 - (ii) The upper plate has a small hole in its centre for the admission of the droplets which are produced by spraying oil with an atomizer.
 - (iii) A device to illuminate the space between the plate electrodes.
2. Two leveling screws at the base of the panel to make the parallel plate electrodes perfectly horizontal (perpendicular to the gravitational field) and a water-level placed on top of the panel to check it.
3. A microscope with CCD camera head to view and transmit image of oil droplets between the plate electrodes to the monitor.

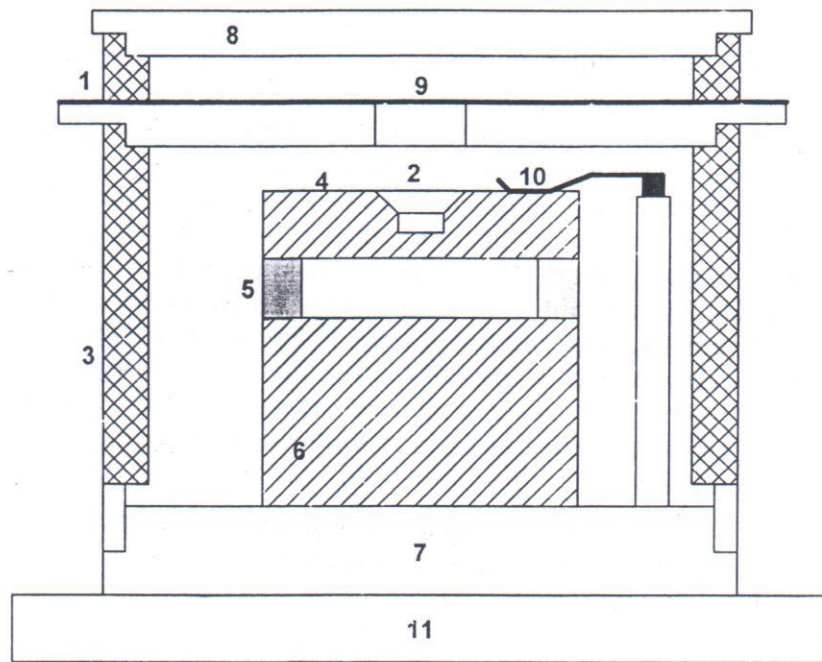


Fig 2. Oil Drop Chamber

1. Oil fog chamber	2. Oil fog hole	3. Wind Proof hood
4. Upper Plate electrode	5. Ebonite ring	6. Under plate electrode
7. Bottom Plate	8. Upper cover plate	9. Oil fog inlet
10. Spreader spring of upper plate electrode	11. Base of oil drop box	

4. A power pack to supply continuously variable voltage in the range 0 – 800 V to the upper plate electrode when the electric field is to be created between the plates. The lower plate is permanently grounded.
5. A digital voltmeter to measure the potential applied to the upper plate.
6. A 'Time Meter' to display the time for which the oil droplet is allowed to move.
7. A timing device to measure time interval between the passage of droplets through preset points between the plate electrodes. There are two keys to operate this device. Pressing the 'Clear' key, wipes out the time information. This is like a reset key. The time meter now reads '0.00' sec. Pressing the 'Start/Stop' key starts the timing device. Pressing it again stops the device. The elapsed time can be read on the meter.
8. A monitor with graduated screen. The horizontal lines on the monitor screen help in setting the distance through which the droplets move.
9. An atomizer to spray droplets.
10. A thermometer to measure the room temperature

TECHNICAL SPECIFICATIONS

1. Gap between parallel plates : 5 mm
2. Voltage supply between the plates: 0 – 800V DC continuously variable
 - Regulation : $\pm 0.1\%$
 - Stability : ± 1 digit
3. Voltmeter : 3 $\frac{1}{2}$ digit LED
4. Illumination between the plates : LED
5. Microscope : Magnification 30X
6. Time Meter : 0 – 999.9 sec
7. Monitor: 420 TVL, Color monitor
8. Input Power Supply : 220V AC/50 Hz
9. Density of the oil used: 928 Kg/m³

WARNING: There is high voltage circuit inside the apparatus. Non-technical person should not open it.

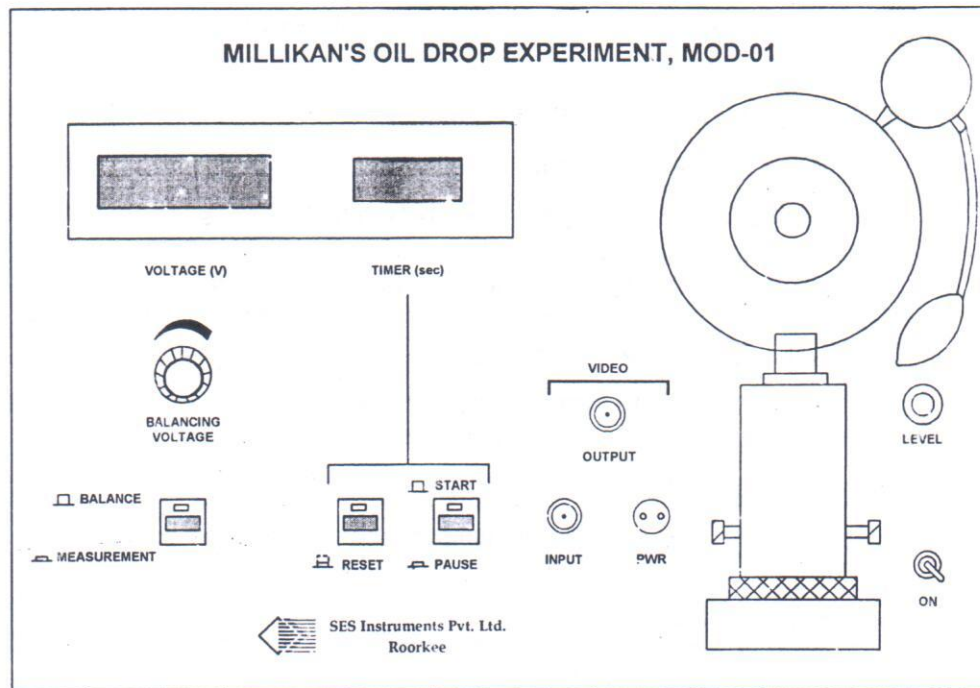


Fig 3. Top view of the Panel

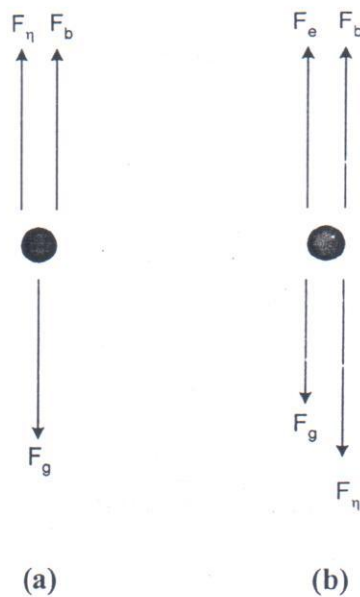


Fig.4. (a) Forces F_g , F_b and F_η on the droplet due to gravity, buoyancy and viscosity respectively during the free fall. (b) Forces F_g , F_b , F_η and F_e on the droplet due to gravity, buoyancy, viscosity and the electric field during the rise of the droplet.

THEORY

Consider a spherical oil droplet of radius r and density ρ falling under the gravitational force. This droplet in air is acted upon by a constant force and soon reaches a terminal velocity given by Stokes' law, $F_\eta = 6\pi\eta r v_f$, where η is the coefficient of viscosity of air and v_f is the terminal velocity during the fall.. The gravitational and buoyancy forces acting on the droplet are balanced by F_η , Fig. 4(a),

$$\frac{4}{3}\pi r^3 \rho g - \frac{4}{3}\pi r^3 \rho_a g = 6\pi\eta r v_f . \quad (1)$$

Here ρ_a is the density of air. The falling velocity v_f is thus given by

$$v_f = \frac{2}{9} \frac{gr^2}{\eta} (\rho - \rho_a) . \quad (2)$$

If the droplet carries a charge ne and is moving upward with terminal velocity v_r under the influence of the applied electric field V/d between the parallel plate electrodes separated by the distance d and potential difference V , the force balance equation is,

Fig. 4(b),

$$\frac{4}{3}\pi r^3 (\rho - \rho_a) + 6\pi\eta r v_r = \frac{Vne}{d} . \quad (3)$$

Subtracting Eq.(1) from Eq.(3) and solving for ne , we get

$$ne = \frac{6\pi\eta r d}{V} (v_f + v_r) . \quad (4)$$

Dividing Eq.(4) by Eq.(2), gives

$$ne = \frac{4\pi}{3} \frac{gd}{V} (\rho - \rho_a) r^3 \left(1 + \frac{v_r}{v_f} \right) . \quad (5)$$

The Stokes' law used in obtaining Eqs.(1) – (5) assumes that the droplets are moving slowly, that there is no slipping of the medium over the surface of the droplet, that the medium is of quite large extent compared to the size of the droplet and that the inhomogeneities in the medium are of a size small compared to the size of the droplets. In the present case all the assumptions except the last one are reasonably valid. The radii of the droplets are of the order of one micron and therefore not much greater than the mean free path of the air molecules. The droplets will tend to fall more quickly in the free space between the air molecules. The expression for the falling velocity v_f corrected for this effect, on the basis of kinetic theory is

$$v_f = \frac{2}{9} \frac{gr^2}{\eta} (\rho - \rho_a) \left(1 + \frac{c}{Pr} \right) , \quad (6)$$

where $c (= 6.17 \times 10^{-8} \text{ m of Hg-m})$ is a correction factor and P (in m of Hg) is the atmospheric pressure. Writing

$$\xi = \frac{9\eta}{2g} v_f / (\rho - \rho_a) \quad (7)$$

$$\varsigma = \frac{c}{2P} . \quad (8)$$

Eq.(6) now reduces to

$$r^2 + 2\varsigma r - \xi = 0 . \quad (9)$$

The radius of the droplet is given by the positive root of this equation

$$r = -\varsigma + \sqrt{\varsigma^2 + \xi} . \quad (10)$$

The charge ne may be obtained by first calculating ξ and ς from Eqs.(7) and (8), then calculating the radius r from Eq.(10) and finally ne from Eq.(5).

Equation (5) above is for the 'Dynamic' method. In the 'Balancing' method, the droplet is kept stationary by adjusting the potential. The upward velocity is thus equal to zero. The final equation for ne in the 'Balancing' method is therefore

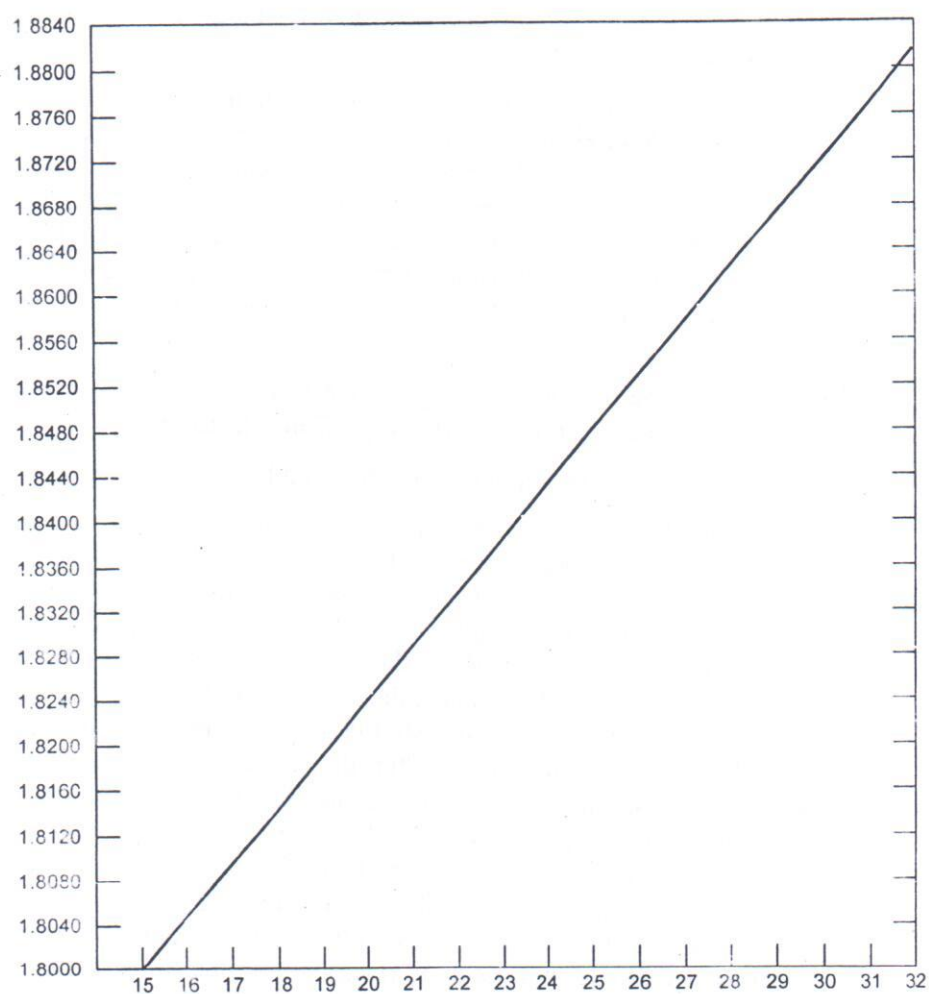
$$ne = \frac{4\pi}{3} \frac{gd}{V_b} (\rho - \rho_a) r^3 , \quad (11)$$

where V_b is the balancing potential.

PROCEDURE

1. Note the atmospheric pressure and the room temperature.
2. Switch on the power supply.
3. Adjust the leveling screws in the base of the panel and check the level indicator at the top.
4. Wait for about ten minutes.
5. Fix two horizontal lines on the monitor. These are the preset lines. The rise and fall times of the droplets to move from one line to the other are to be recorded. A good choice is to choose the second line from the top and the last but one line from the bottom. This will leave some room at the top and at the bottom for maneuvering and preventing the droplet from getting lost.
6. Press the 'clear key' to make the 'time meter' read zero.
7. Spray droplets of oil from the atomizer. One or two are squirts are usually sufficient.
8. As the droplets drift down, some of them pass through the hole in the upper parallel plate and reach the region in-between the plates where they are illuminated.
9. These are viewed by the microscope/camera as unresolved points of diffracted light and the images are transmitted to the monitor screen.
10. These droplets drift down slowly under gravitational force.

11. Under the influence of the electric field between the plates, the motion of the droplets will get affected if they are charged. If a droplet moves downward more slowly under the influence of the electric force (corresponding to the upper plate at a positive potential), the drop is negatively charged. Its motion can be arrested or even reversed (made to rise) by an increase in the potential. If the downward drifting of the droplet increases under the action of electric force, the droplet is positively charged. Such droplets are ignored in the present set-up.
12. Suitable negatively charged droplet is selected. 'Suitable' means that it drifts downward slowly (about 10 – 15 s free-fall time) under gravitational field indicating that the droplet is not too heavy. Its mass should also not be too small, otherwise it will bounce around due to random collisions with air molecules, *Brownian motion*, and it will be difficult to estimate when the droplet actually crosses a line. A very small droplet may cross a line 10~20 times. It should also be possible to make it rise by applying a voltage of about 500 V indicating that there are only a few charge quanta on the droplet. Fix some value of the voltage.
13. This selection is done by concentrating on one or two droplets and removing all others from the field by switching on and switching off the electric field.
14. Once a droplet has been chosen, measurements can begin. There are two approaches:
 - a. **Dynamic:** Measure the free-fall time with the voltage off and the rise time with some suitable voltage on for the droplet to move between the two above chosen lines on the monitor. For these measurements following procedure may be followed.(i) Pull the droplet above the top chosen line on the monitor by adjusting the voltage,(ii) Press the 'clear key' to make the 'time meter' read zero,(iii) Switch off the voltage, the droplet will begin to fall freely,(iv) Start the 'time meter' by pressing the 'start/stop' key when the droplet crosses the top chosen line on the monitor,(v) Stop the 'time meter' by pressing the 'start/stop' key again when the droplet crosses the bottom chosen line on the monitor,(vi) Stop the downward motion of the droplet by switching on the voltage,(vii) Note the fall time from the 'time meter', (viii) Press the 'clear key' to make the 'time meter' read zero,(ix)Allow the droplet to come below the bottom line by switching off the voltage, (x) Switch on the voltage (its value already fixed earlier), the droplet will begin to rise,(xi) Start the 'time meter' when the droplet crosses the chosen bottom line on the monitor, (xii) Stop the 'time meter' when the droplet crosses the top chosen line on the monitor,(xiii)Stop the upward motion of the droplet by switching off the voltage,(xiv) Note the rise time, and the voltage. Repeat these measurements of free-fall time and rise time several times. Take the average of these timings for the free-fall and the rise and note the voltage (kept fixed). Take another suitable droplet if it is there. If not, spray droplets again. Choose a suitable one and proceed as above to get data on several droplets.
 - b. **Balancing:** Measure the free-fall time as in the above 'Dynamic method' for the droplet to move between the two chosen lines on the monitor. Apply the voltage and adjust its value such that the electric force on the droplet just balances other forces on it and the droplet hangs (does not move up or down). The droplet should remain stationary for several minutes. The voltage may have to be adjusted again and again.



**Fig.5: Viscosity (η) of dry air as a function of temperature °C.
Vertical scale is in units of $10^{-5} \text{ kgm}^{-1}\text{sec}^{-1}$**

Take the average value of these voltages and the average of the free-fall timings. Take another suitable droplet if it is there. If not, spray droplets again. Choose a suitable one and proceed as above to get on several droplets.

15. Note the atmospheric pressure and the room temperature at the end of the experiment as well.

16. Record your data in the format given below.

This is a slightly difficult experiment and needs some patience to achieve high accuracy. The more droplets one measures upon and the more data one takes on each droplet, the more accurate will be the final result.

RECORD OF DATA

- Distance d between the parallel plates = 5×10^{-3} m
- Distance L between the chosen top and bottom lines on the monitor = 1×10^{-3} m
- Density ρ of the oil =
- Density ρ_a of air = $\rho - \rho_a = 928 \text{ Kg/m}^3$
- Room temperature $T = 24^\circ\text{C}$
- Atmospheric pressure $P = \text{mm of Hg} = 0.76 \text{ m}$
- Coefficient of viscosity of air $\eta = \text{from Fig.5} : 1.8432 \times 10^{-5} \text{ kg/m.sec}$

Main Observational Data (Dynamic method)

Droplet No.	S. No.	Free-fall Time	Rise Time	Mean Free-fall Time (t_f)	Mean Rise Time (t_r)	Mean Free-fall Velocity ($v_f = L/t_f \text{ m/s}$)	Voltage (V volt)
1	1	10.3	20.0	10.3	19.86	9.71×10^{-5}	452
	2	10.3	19.7				
	3	10.2	19.9				
	4	10.4	19.9				
	5	10.3	19.3				
2	1	20.8	13.8	20.93	13.68	4.77×10^{-5}	488
	2	20.8	13.7				
	3	21.0	13.6				
	4	21.2	13.7				
	5	21.0	13.6				

Droplet No.	S.No.	Free-fall Time	Rise Time	Mean Free-fall Time (t_f)	Mean Rise Time (t_r)	Mean Free-fall Velocity ($v_f = L/t_f$, m/s)	Voltage (V volt)
3	1	20.5	14.8	20.42	14.9	4.90×10^{-5}	342
	2	20.1	14.9				
	3	20.5	14.8				
	4	20.6	15.1				
	5	20.4	14.9				
4	1	10.8	12.5	10.8	12.56	9.26×10^{-5}	503
	2	10.7	12.6				
	3	10.8	12.4				
	4	10.9	12.7				
	5	10.8	12.6				
5	1	12.0	12.7	11.84	12.52	8.45×10^{-5}	450
	2	11.8	12.4				
	3	11.8	12.6				
	4	11.7	12.4				
	5	11.9	12.5				
6	1	21.5	66.4	21.36	66.5	4.68×10^{-5}	381
	2	21.4	66.6				
	3	21.3	66.4				
	4	21.4	66.5				
	5	21.2	66.6				

Main Observational Data (Balancing method)

Droplet No.	S. No.	Free-fall Time	Mean Free-fall Time (t_f)	Mean Free-fall Velocity ($v_f = L/t_f$, m/s)	Balancing Voltage	Final Balancing Voltage (V_b volt)
1	1	12.1	12.16	8.22×10^{-5}		324
	2	12.2			326	
	3	12.4			324	
	4	12.0			323	
	5	12.1				

Droplet No.	S. No.	Free-fall Time	Mean Free-fall Time (t_f)	Mean Free-fall Velocity ($v_f = L/t_f$ m/s)	Balancing Voltage	Final Balancing Voltage (V_b volt)
2	1	15.8	16.24	6.16×10^{-5}		388
	2	16.2			386	
	3	16.2			388	
	4	16.5			389	
	5	16.5				
3	1	12.2	12.06	8.29×10^{-5}		462
	2	12.2			464	
	3	11.8			462	
	4	12.1			460	
	5	12.0				
4	1	8.3	8.44	11.85×10^{-5}		404
	2	8.4			405	
	3	8.5			404	
	4	8.4			403	
	5	8.6				
5	1	15.2	15.18	6.59×10^{-5}		441
	2	15.1			442	
	3	15.2			441	
	4	15.3			440	
	5	15.1				
6	1	20.5	20.34	4.92×10^{-5}		304
	2	20.1			302	
	3	20.4			304	
	4	20.3			305	
	5	20.4				

CALCULATIONS

A. First calculate common constants to be used with all the droplets.

$$1. C = 4\pi dg(\rho - \rho_a)/3 = 190.13$$

$$2. D = 9\eta/2g(\rho - \rho_a) = 9.04 \times 10^{-9}$$

$$3. \zeta = c/2P = 4.06 \times 10^{-8} \quad c =$$

B. Calculation from the droplet data

Dynamic method

Droplet No.	ξ ($= D v_f$)	r ($= -\zeta + \sqrt{\zeta^2 + \xi}$)	r^3	T ($= 1 + \frac{t_f}{t_r}$)	ne ($= C T r^3/V$)
1.	87.78×10^{-14}	89.72×10^{-8}	7.22×10^{-19}	1.52	4.62×10^{-19}
2.	43.12×10^{-14}	61.73×10^{-8}	2.35×10^{-19}	2.53	2.32×10^{-19}
3.	44.29×10^{-14}	62.61×10^{-8}	2.45×10^{-19}	2.37	3.23×10^{-19}
4.	83.71×10^{-14}	87.52×10^{-8}	6.70×10^{-19}	1.86	4.71×10^{-19}
5.	76.39×10^{-14}	83.44×10^{-8}	5.81×10^{-19}	1.95	4.78×10^{-19}
6.	42.31×10^{-14}	61.11×10^{-8}	2.28×10^{-19}	1.32	1.50×10^{-19}

Balancing method

Droplet No.	ξ ($= D v_f$)	r ($= -\zeta + \sqrt{\zeta^2 + \xi}$)	r^3	ne ($= C T r^3/V$)
1.	74.31×10^{-14}	82.24×10^{-8}	5.56×10^{-19}	3.26×10^{-19}
2.	55.60×10^{-14}	70.06×10^{-8}	3.44×10^{-19}	1.69×10^{-19}
3.	74.94×10^{-14}	82.60×10^{-8}	5.64×10^{-19}	2.32×10^{-19}
4.	107.12×10^{-14}	99.52×10^{-8}	9.86×10^{-19}	4.64×10^{-19}
5.	59.57×10^{-14}	73.23×10^{-8}	3.93×10^{-19}	1.69×10^{-19}
6.	44.48×10^{-14}	62.76×10^{-8}	2.47×10^{-19}	1.54×10^{-19}

C. Analysis and treatment of the charge ne on the droplets

1. Identify the minimum value of the charge ne on the droplets.
2. Divide the value of the charge ne on all the droplets by this minimum value.

3. The result will be numbers close to integers for all the droplets.
4. Now extrapolate all these numbers or the earlier ones if no multiplication has been done to the nearest integer.
5. Divide the value of the charge ne on all the droplets by the respective integers.
6. This gives the values of the charge on an electron by different droplets.
7. Take the average of these values. This gives the final result.

Dynamic method data

ne	ne divided by the lowest	Nearest integer n_{eff}	ne/n_{eff}
4.62	3.08	3	1.54
2.32	1.55	1.5	Rejected/ ignored
3.23	2.15	2	1.615
4.71	3.14	3	1.57
4.78	3.19	3	1.593
1.5	1	1	1.5

Meanwhile of $ne/n_{eff} = 1.564$, Error 2.3%

Balancing method data

ne	ne divided by the lowest	Nearest integer n_{eff}	ne/n_{eff}
3.26	2.12	2	1.63
1.69	1.09	1	1.69
2.32	1.51	1.5	Rejected/ignored
4.64	3.01	3	1.547
1.69	1.1	1	1.69
1.54	1	1	1.54

Meanwhile of $ne/n_{eff} = 1.619$, Error 1.2%

COMMENTS

1. The oil provided with the set-up has (i) low evaporability so that the size of the drop does not change during the experiment and (ii) low variation in density with temperature
2. The sprayer (atomizer) supplied with the equipment sprays droplets of suitable size with a relatively homogeneous cloud.

3. The level indicator is used to make the electrode plate horizontal so that the electric field between the plates is vertical and is in line with the gravitational field. If this is not so the droplets will drift during the measurements and will go out of focus. The level indicator has been properly adjusted. *Do not remove it from the panel top.*
4. The measurement of the charge on the electron can lead to the calculation of Avogadro's number. The charge F (the Faraday) required to electro-deposit one gram equivalent of an element on an electrode during electrolysis is equal to the charge of the electron multiplied by the number of molecules in a mole. The Faraday has been found to be $F=9.625 \times 10^7$ coulombs per kilogram equivalent weight. Hence Avogadro's number $N=F/e$.

PRECAUTIONS

1. It is important to be *sparing* in the amount of oil sprayed into the chamber. It not only clogs the interior more quickly, but also creates so many particle in the field of the microscope that without excessive eye strain it is virtually impossible to single out and follow a single droplet.
2. The droplet should not be lost sight of during measurements. Working with these droplets is like a video game in which practice makes perfect.
3. The most important thing is to select appropriately sized droplets carrying very few elementary charges (say, $1e - 3e$). It is a good idea to make a preliminary analysis of the data for the first droplet immediately after it is obtained so that a judgement could be made as to which droplets to select and what voltages to use.

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