THE CHARGE OF THE ELECTRON
THE MILLIKAN OIL DROP EXPERIMENT

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CHARGE OF THE ELECTRON
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Nobel Prize

A Historic Investigation

When Robert Andrews Millikan began trying to measure the charge on an electron, he found himself working to obtain a value for something which some of his fellow scientists did not believe existed. No researcher had yet obtained a reliable value for this charge, and in fact some physicists believed that it was not the constant of an individual particle but rather an average of a number of diverse electrical energies.

An Elegantly Simple Technique

Millikan began by measuring the rate at which a charged cloud of water vapor moved under the influence first of gravity and then of an electric field. He quickly realized that it would be easier to work with individual water droplets, and later switched to working with droplets of oil.

He eventually arrived at an elegantly simple, and definitive, method of finding the charge on an electron, for which he received the ***Nobel Prize in physics in 1923.***

HISTORICAL NOTES

The Greeks were the first to report the effects of electricity when they recorded that rubbed amber attracts light objects. However, theories explaining this phenomenon did not emerge until 1747, when Benjamin Franklin proposed that an electrical fluid or fire existed, in certain amounts, in all matter. An excess of this fluid in matter would produce a positive charge and a deficiency of this fluid would produce a negative charge. A slightly different theory was put forth by the physicist Symmer twelve years later. He proposed that matter in a neutral state shows no electrical properties because it contains equal amounts of two weightless fluids that were called positive and negative electricity, respectively.

Franklin also postulated the existence of an electrical particle small enough to easily permeate matter. Faraday's experiments in electrolysis, which demonstrated that when a current is passed through an electrolyte the masses of compounds deposited at opposite electrodes are in proportion to the chemical equivalent weights of the compounds, also supported Franklin's concept of an elementary electrical particle. The fluid theories, along with a theory explaining electricity as a state of strain in matter, were the prime explanations of electrical phenomena until late in the 19th century.

EARLY DETERMINATIONS OF e

The word "electron" was first suggested in 1891 by Dr. G. Johnstone Stoney as a name of the "natural unit of electricity," namely, that quantity of electricity which must pass through a solution in order to liberate at one electrode one atom of hydrogen or any univalent substance. It would follow that the charge of the electron multiplied by the number of molecules in a gram mole would give the amount of electricity required to deposit one gram mole by electrolysis. This quantity had been determined by Faraday to be 9650 absolute electromagnetic units of electricity. Using this method, Stoney obtained a value of 0.3x10-10 e.s.u. (The Kinetic Theory provided the basis for Stoney's estimation of Avogadro's number).

The first experimental attempt to measure the charge of an ion was made by Townsend in the late 1890's. He had observed that during electrolysis of sulfuric acid, positively charged hydrogen and oxygen gasses were produced (although there were one million neutral molecules to every charged one). This method was used to produce an ionized gas that was then bubbled through water to form a cloud. For this determination of e Townsend proceeded in the following manner:

1. He assumed that in saturated water vapor each ion condensed moisture about it, so that the number of ions was the same as the number of droplets.

2. He determined with the aid of a quadrant electrometer the total electrical charge per cubic centimeter carried by the gas.

3. He found the total weight of the cloud by passing it through drying tubes and determining the increase in weight of these tubes.

4. He found the average weight of the water droplets constituting the cloud by observing their rate of fall under gravity and computing their mean radius with the aid of a purely theoretical law known as Stokes' Law.
5. He divided the weight of the cloud by the average weight of the droplets of water to obtain the number of droplets which if assumption 1 is correct, was the number of ions, and then divided the total charge per cubic centimeter in the gas by the number of ions to find the average charge carried by each ion, that is, to find e.[2]

Townsend achieved results in the range of 3x10-10 e.s.u. for e. J.J. Thompson, in 1900, used a method similar to Townsend's and obtained a value of 6x10-10 e.s.u. In both of these methods, however, the first assumption (each droplet formed around only one ion) proved to be only approximately correct, and the experimental methods were not adequate to provide a precise determination of e.

H.S. Wilson improved upon Townsend's and Thompson's work by adding two brass plates that could be connected to a 2000 volt battery. A cloud was formed between these plates (not charged) and the falling velocity of the cloud recorded. A second cloud was then formed and its falling velocity observed in an electric field (the plates being charged). Since the two velocities are proportional to the forces acting on the drops[3] and the velocity of the cloud with the plates uncharged determines the size and mass of the drops by Stokes' Law, Wilson was able to obtain a value of 3.1x10-10 e.s.u. for e. Since Wilson's measurements were always made on the top of the cloud, or the drops with the smallest charge (the more heavily charged drops being driven downward faster in the field) the assumption of one ion per drop was validated.

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1. The following section is condensed from Robert A. Millikan's book The Electron (University of Chicago Press) and used with permission of the publishers.
2. Millikan, Robert A., The Electron, (Chicago, The University of Chicago press, 1963), pp. 45-46.
3. With the plates uncharged the force is mg where m is the mass of the drop and g is the acceleration of gravity. With the plates charged the force is mg±Een where E is the electric intensity between the plates and en is the charge on the drop.

MILLIKAN'S DETERMINATION OF e

Millikan improved upon Wilson's design by using a higher potential across the plates so that the falling velocity of the cloud could not only be impeded, but also actually reversed. Some charged drops moved upward, some moved rapidly downward, while the uncharged drops were unaffected and continued to drift downward. A few drops, which carried a charge of the proper magnitude so that the force of gravity on the drop almost equaled the force of the electric field on the drop, remained in view. By varying the potential of the plates, Millikan could just balance these drops. This situation proved to be a significant improvement for it permitted all measurements to be made on a single drop. By using this balanced drop method, Millikan was able to observe the properties of individual ions and to determine whether different ions carry one and the same charge.

In the following passage, taken from the "Philosophical Magazine" for February 1910, Millikan describes the actual procedure of the experiment.

> *"The observations o the rate of fall were made with a short-focus telescope placed about 2 feet away from the plates. In the eyepiece of this telescope were placed three equally spaced cross-hairs,... A small section of the space between the plates was illuminated by a narrow beam from an arc light, the heat of the arc being absorbed by three water cells in series. The air between the plates was ionized by 200 mg of radium of activity 20,000 placed from 3 to 10 cm. away from the plates. A second or so after the cloud was produced4 the radium was removed... and the field thrown on by hand by means of a double-throw switch. If the drops were not found to be held suspended by the field the potential difference was changed... The cross-hairs were set near the lower plate, and as soon as a stationary drop was found somewhere above the upper cross-hair, it was watched for a few seconds to make sure that it was not moving and then the field was thrown off and the plates short-circuited by means of the double-throw switch, so as to make sure that they retained no charge. The drop was then timed by means of an accurate stopwatch as it passed across the three cross-hairs, one of the two hands of the watch being stopped at the instant of passage across the middle cross-hair, and the other at the instant of passage across the lower one. It will be seen that this method of observation furnishes a double check upon evaporation; for if the drop is stationary at first, it is not evaporating sufficiently to influence the reading of the rate of fall, and if it begins to evaporate appreciably before the reading is completed, the time required to pass through the second space should be greater than that required to pass through the first space. It will be seen from the observations which follow that this was not, in general, the case.*
>
> *It is an exceedingly interesting and instructive experiment to watch one of these drops start and stop, or even reverse its direction of motion, as the field is thrown off and on. I have often caught a drop which was just too light to remain stationary and moved it back and forth in this way four or five times between the same two cross-hairs, watching it first fall under gravity when the field was thrown off and then rise against gravity when the field was thrown on...*
>
> *Furthermore, since the observations...are all made upon the same drop, all uncertainties as to whether conditions can be exactly duplicated in the formation of successive clouds obviously*

> *disappear. There is no theoretical uncertainty whatever left in the method unless it be an uncertainty as to whether or not Stokes' Law applies to the rate of fall of these drops under gravity."*

Experiments with the balanced water drop produced the value of 3.422x10-10 e.s.u. for "e". The most important aspect of these experiments, however, was the observation by Millikan that a rising drop would suddenly change its velocity. This phenomenon could easily produce by placing a radioactive source near the drop. This demonstrated that the drop had "captured" an ion, thus changing the charge of the drop and its respective velocity.

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4. The underlined phrases indicate a slight change in wording, for purposes of clarity, from Millikan's original work.

THE EXACT EVALUATION OF e

In 1909 Millikan set about building a new piece of apparatus designed for the observation of single oil drops for extended periods of time. Since water drops had proved inadequate for prolonged observation of this ion catching phenomenon, Millikan used oil drops that were not affected by evaporation. The apparatus consisted of two parallel brass plates separated by a distance of 16 mm by ebonite blocks. Non-volatile oil was sprayed into the chamber above the plates and small drops slowly found their way into the area between the plates through a small hole in the top plate. The drops were illuminated by a beam from a carbon arc lamp and were observed through a measuring scope. The details of the construction of Millikan's final apparatus built in 1914 (which was basically similar to his earlier devices, and for the purpose of this discussion can be considered the same as the earlier pieces of apparatus) attest to the effort expended in obtaining the most accurate evaluation of e possible. The following passage is part of Millikan's description of the apparatus, including a diagram of the device.

> *"Accordingly, I built two years ago a new condenser having surfaces which were polished optically and made flat to within two wavelengths of sodium light. They were 22 cm in diameter and were separated by three pieces of echelon plates, 14.9174 mm thick, and having optically perfect plate surfaces. The dimensions of the condenser, therefore, no longer introduced an uncertainly of more than about 1 part in 10,000."5*
>
> *"Complete stagnancy of the air between the condenser plates was attained, first, by absorbing all the heat rays from the arc lamp by means of a water cell, 80 cm long, and a cupric chloride cell, and secondly, by immersing the whole vessel in a constant temperature bath of gas-engine oil (40 liters), which permitted, in general, fluctuations of not more than 0.02flC during an observation."6*

A complete diagram of Millikan's very complex apparatus is given on page 116 in his book.

With this new apparatus hundreds of measurements on different drops were made, for the purpose of both making an exact evaluation of e and proving or disproving the atomic theory of electricity. The value of e that was obtained from these five years of work was 4.774x10-10 e.s.u. This value of e was accepted until 1928 when a precise determination of Avogadro's number by X-ray diffraction measurements on crystals permitted the calculation of e to be 4.803x10-10 e.s.u. The discrepancy was later traced to Millikan's too low value for the viscosity of air.

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5. Millikan, Robert A., p. 115.
6. Millikan, Robert A., p. 110.
7. Millikan, Robert A., p. 116.

ATOMIC NATURE OF ELECTRICITY

The atomic nature of electricity is best exemplified by the following table taken from Millikan's data:

n	4.917 x n	Observed Charge	n	4.917 x n	Observed[8] Charge
1	4.917	….	10	49.17	49.41
2	9.834	….	11	54.09	53.91
3	14.75	….	12	59.00	59.12
4	19.66	19.66	13	63.92	63.68
5	24.59	24.60	14	68.84	68.65
6	29.50	29.62	15	73.67	….
7	34.42	34.47	16	78.67	78.34
8	39.34	39.38	17	83.59	83.22
9	44.25	44.42	18	88.51	….

Millikan makes the following comments about this table.

"In this table 4.917 is merely a number obtained...from the change in speed due to the capture of ions and one which is proportional in this experiment to the ionic charge. The column headed 4.917 x n contains simply the whole series of exact multiples of this number from 1 to 18. The column headed 'Observed Charge' gives the successive observed values of the rising velocity of the drop plus the falling velocity. It will be seen that during the time of observation, about four hours, this drop carried all possible multiples of the elementary charge from 4 to 17, save only 15. No more exact or more consistent multiple relationship is found in the data which chemists have amassed on the combining powers of the elements and on which the atomic theory of matter rests than is found in the foregoing numbers.

Such tables as these--and scores of them could be given--place beyond all question the view that an electrical charge wherever it is found, whether on an insulator or conductor, whether in electrolytes or in metals, has a definite granular structure, that it consists of an exact number of specks of electricity (electrons) all exactly alike, which in static phenomena are scattered over the surface of the charged body and in current phenomena are drifting along the conductor. Instead of giving up, as Maxwell thought we should some day do, the 'provisional hypothesis of molecular charges,' we find ourselves obliged to make all our interpretations of electrical phenomena, metallic as well as electrolytic, in terms of it."9

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8. Millikan, Robert A., p. 74.
9. Millikan, Robert A., pp. 74-75.

Although the values of the charge on a specific drop were found to be exact multiples of a certain value (e) the value e varied for drops of different masses. This discrepancy was traced to the break down of Stokes' Law. Through experimentation the law was found to fail when the size of the drop approached the mean free path of air molecules. When this situation occurs the medium in which the drop falls is no longer homogeneous in relation to the drop. This contradicts one of the assumptions upon which Stokes' Law is based. Through his work on the electron, Millikan was able to determine a correction factor for Stokes' law.

By performing the experiment with mercury drops and drops of other materials, Millikan demonstrated that the elementary electrical charge was the same for insulators, semi-conductors, and conductors. He also demonstrated that the beta particle had the same charge as an electron (indeed, it is an electron) and, that positive and negative electrons (the positive electron referring to a proton and not a positron) are equal in charge. The experiment also produced insights into the study of ionized gasses.

Few experiments that are so simple in principle have provided such a wealth of experimental evidence to confirm the atomic theory and measure an important physical constant.

Should the student desire a more detailed background in this classic experiment, the following references are suggested:

1. Millikan, Robert A., The Electron, (Chicago, The University of Chicago Press, 1963).

2. Millikan, Robert A., "The Isolation of an Ion, A Precision Measurement of its Charge, and the Correction of Stokes' Law.", The Physical Review, Vol. 2, No. 2, pp. 109-143, June 1913.

3. Millikan, Robert A., "On the Elementary Electrical Charge and the Avogadro Constant,", The Physical Review, Vol. 32, No. 4, pp. 349-397, April 1911.

4. Shamos, M.H., Great Experiments in Physics, (Holt-Dryden, New York, 1959), pp. 238-249.

CHARGE OF THE ELECTRON
MILLIKAN OIL DROP METHOD

INITIAL CONSIDERATIONS

NOTE: The following text was taken from your text "Physics of the Atom" by Wehr, Richards and Addir.

Although the measurement of e/me, as determined in experiment one, indicated the identity of electrons, another measurement is required before e and me can be known separately. This was first made with precision in 1909 by R.A. Millikan, who perfected a technique suggested by J.J. Thomson and H.A. Wilson.

Both the charge e and the mass me of an electron are incredibly small quantities. The mass of any body can be determined from the measurement of the force acting on it when it is accelerated. Even if a single electron could be isolated for study, no instrument could measure its mass directly. Similarly, the charge on a body can be determined by measuring the force it experiences in an electric field. This method does not require the isolation of a single electron and, since very intense electric fields can be created, a measurable force can be produced.

An experiment to measure e must be carried out with a body having so few charges that the change of one charge makes a noticeable difference. Since the experiment must be done with very little charge, the force the body experiences will be small even though a large electric field is utilized. If the force on the charged body is very small, then the body itself must be very light. The force of gravity is always with us, and if the small electric force is not to be masked by a large gravitational force, then the mass of the body must be both small and known. If the body is small enough that the electric force on its charges is of the same order of magnitude as the gravitational force it experiences, then it may be that the gravitational force will be a useful standard of comparison rather than an annoying handicap.

Millikan used a drop of oil as his test body. It was selected from a mist produced by an ordinary atomizer. The drop was so small that it could be measured optically, and with a microscope it could be seen as a bright spot because it scattered light from an intense beam, like a dust particle in bright sunlight.

When such a drop falls under the influence of gravity, it is hindered by the air it passes through. The way in which the fall of a small spherical body is hindered by air had been described by Stokes, who found that such a body experienced a resisting force F_f proportional to its velocity, or

$$F_f = kv.$$

The proportionality constant k was found by stokes to be

$$k = 6\pi\eta r,$$

where η is the coefficient of viscosity of the resisting medium and r is the radius of the body. (This law assumes that the resisting medium is homogeneous. A more complicated law must be used if the size of the body is of the same order of magnitude as the mean free path of the molecules of the medium.)

A falling droplet of oil is acted on by three forces: the force of gravity F_g, the buoyant force F_B of the air, and the resistive force F_f caused by the air. The net downward force on the oil droplet is

$$F_{net} = F_g - F_B - F_f \tag{1}$$

Initially, when the velocity of the oil drop is at rest, the resistance force is zero, and the initial downward force is the difference between the gravity and buoyant forces. As the downward velocity of the drop increases the resistance force, which is proportional to the velocity, increases and eventually reaches a value such that the resultant force on the drop is zero. From this time on, the oil drop falls with a constant velocity called the terminal velocity, v_g and the $_{Fnet}$ is zero

$$0 = F_g - F_B - F_f \ . \tag{2}$$

The gravitational force near the earth is just the weight of the oil drop

$$F_g = mg = \frac{4}{3} \pi r^3 \rho g \tag{3}$$

where r is radius of the oil drop of density ρ.

The buoyant force F_B is given by Archimede's principle,

$$F_B = M_{air}\, g = \frac{4}{3} \pi r 3\, \rho_a\, g \tag{4}$$

where ρ_a is the density of air.

The air resistance force is giving by Stoke's equation

$$F_f = kv = 6\pi\eta\, r\, v\ . \tag{5}$$

Inserting these forces into the force equation for the terminal velocity condition and we get

$$\frac{4}{3} \pi r^3 (\rho-\rho_a)g = 6\pi\eta r v_g \tag{6}$$

All of the quantities in this equation except r are known or measurable. Therefore the radius of the oil drop can be determined from the expression

$$r = \left(\frac{9\eta v_g}{2(\rho - \rho_a)g} \right)^{1/2} \tag{7}$$

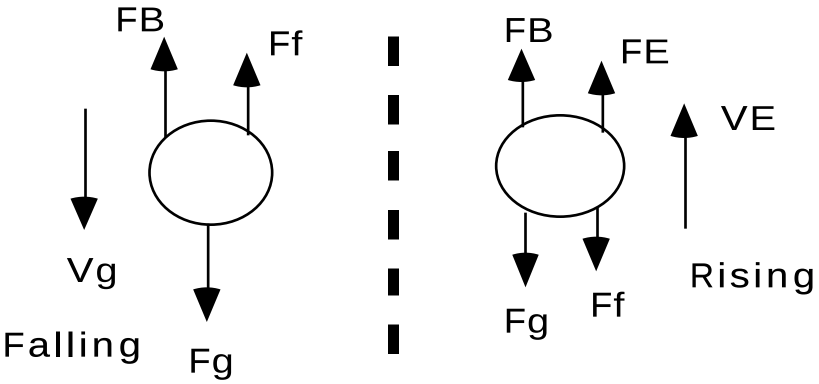

Figure 1 : Forces acting on an oil drop (equilibrium conditions).

In the experiment, the oil drop is situated between two horizontal plates where a known strong electric field may be directed upward or downward or may be turned off (Fig. 2). The droplet has a small electric charge q that may be minus or plus, depending on whether it has an excess or deficiency of electrons. The droplet gets this charge from rubbing against the nozzle of the atomizer and from encounters with stray charges left in the air by cosmic rays or deliberately produced by x-rays or by bringing a radioactive material nearby. In the electric field, the drop will experience a force qE, which can always be directed upward by the proper choice of the direction of E. The experimenter must manipulate E so that the drop rises and falls in the region between the plates but never touches either.

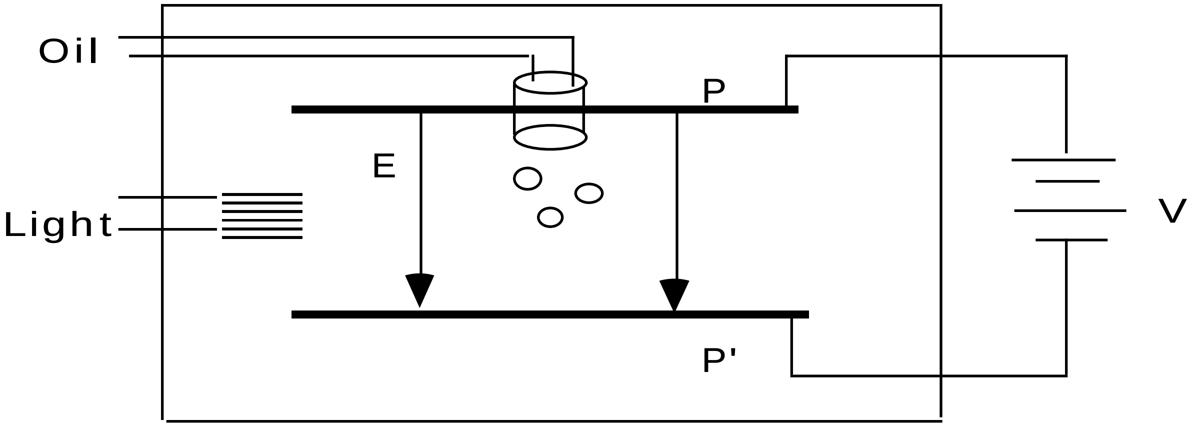

Figure 2 : Millikan's oil drop experiment.

The microscope with which the drop's movements are followed is equipped with two horizontal hairlines whose separation represents a known distance along the vertical line in which the drop travels. By timing the trips of the drop over this known distance, the terminal velocities of the drop are found. The velocities of fall, vg, are all the same, since oil does not evaporate and therefore the weight of the drop is constant. The velocity of rise, however, depends on the charge q. The resultant force on the drop while it is rising is

$$F_{net} = qE + F_B - F_g - kv \tag{8}$$

When the terminal velocity v_E is reached, the resultant force is zero, so

$$qE = F_g - F_B + k\, v_E \tag{9}$$

From the previous equation for the freely falling oil drop at terminal velocity

$$k\, v_g = F_g - F_B \tag{10}$$

substituting above the charge on the oil drop can be determined from

$$q = \frac{k}{E}(v_g + v_E) \tag{11}$$

where the value of the resistance constant "k" can be determined from the first experiment when the oil drop is falling with no applied electric field, and using the equation for the radius of the drop, it becomes

$$k = 18\pi\left(\frac{\eta^3 v_g}{2g(\rho - \rho_a)}\right)^{1/2} \tag{12}$$

Equation 11 permits the evaluation of q, the charge on the drop. In the oil drop experiment, the value of v_g is determined for a particular drop with the electric field off, and a whole series of v_E's for the same drop is observed with the field on. If we knew that the electronic charge was unique and that there was only one charge on the drop, then Eq. 11 would give the value of this charge at once. Since the nature of the electronic charge was not known, Millikan repeated the experiment with many different charges on the drop. This provided a set of q's that he found to be integral multiples of one charge, which he took to be the ultimate unit of charge, e: Thus he established the *law of multiple proportions* for electric charges and concluded from it that electricity must be atomic in character.

Millikan made observations on oil drops of different sizes and also on drops of mercury. In one instance a drop was watched continuously for eighteen hours. The sets of observations always gave the same magnitude of the electronic charge or "atom" of electricity. The best modern determination of e is $(1.6021892 \pm 0.0000046) \times 10^{-19}$ coulomb.

CHARGE OF THE ELECTRON
MILLIKAN OIL DROP METHOD

Pre-Lab Home Work

The following questions and numerical problems have been designed to introduce the concepts and theories that will be used in the laboratory experiment.

These problems are to be worked, the solutions presented in a neat and logical manner, and then handed in at the beginning of the laboratory period.

1. An electron is released from rest in a uniform electric field of magnitude 2.00x104 N/C. Calculate the acceleration of the electron. (Ignore gravitation.)

2. (a) What is the acceleration of an electron in a uniform electric field of 1.40x106 N/C? (b) How long would it take for the electron, starting from rest, to attain one-tenth the speed of light? (c) How far would it travel in that time? (Use Newtonian mechanics.)

3. In Millikan's experiment, a drop of radius 1.64 µm, and density 0.851 g/cm3 is suspended in the lower chamber when a downward-pointing electric field of 1.92x105 N/C is applied. Find the charge on the drop, in terms of e.

4. In one of his experiments, Millikan observed that the following measured charges, among others, appeared at different times on a single drop:

6.563x10-19 C13.12x10-19 C 19.71x10-19 C
8.204x10-19 C 16.48x10-19 C 22.89x10-19 C
11.50x10-19 C 18.08x10-19 C 26.13x10-19 C

What value for the elementary charge e can be deduced from these data?

5. The following data were obtained in a Millikan oil drop experiment:

Plate separation	0.016 m
Voltage across the plates	5,085 V
Distance of fall	1.021x10-2 m
Viscosity of air	1.824x10-5 N s/m2
Density of oil	0.92x103 kg/m3
Density of air	1.2 kg/m3
Average time of fall (no field)	11.88 s
Successive times of rise (with field)	1. 22.37 s
	2. 34.80 s
	3. 29.25 s
	4. 19.70 s
	5. 42.30 s

(a) Compute the radius of the oil drop. (b) Find the charge on the drop for all five cases. (c) Obtain an average value of the electronic charge e from these results.

6. A charge oil drop falls 4.0 mm in 16.0 s at a constant speed in air in the absence of an electric field. The relative density of the oil is 0.80, that of the air is 1.30x10-3, and the viscosity of the air is 1.81x10-5 N.s/m2. Find (a) the radius of the drop and (b) the mass of the crop. (c) If the drop carries one electronic unit of charge and is in an electric field of 2000 V/cm, what is the ratio of the force of the electric field on the drop to its weight?

7. When the oil drop in Problem 6 was in a constant electric field of 2000 V/cm, several different times of rise over the distance of 4.0 mm were observed. The measured times were 36.1, 11.5, 17.4, 7.55 and 23.9 s. Calculate (s) the velocity of fall under gravity, (b) the velocity of rise in each case, and (c) the sum of the velocity in part (a) and each velocity in part (b). (d) Show that the sums in part (c) are integral multiples (two significant figures) of some number and interpret this result. (e) Calculate the value of the electronic charge from these data.

Experimental Method I

Millikan Oil-Drop Apparatus
Plastic Spheres

1. PURPOSE

This compact Millikan Oil-Drop Apparatus is designed to enable he user to measure the charge of an electron by the classic Millikan method using plastic spheres instead of oil.

2. DESCRIPTION

The apparatus is designed so that all necessary components are contained in one unit. The apparatus is mounted on a metal base, which supplies all necessary power inputs when it is connected to a 110 VAC, 50/60 Hz outlet. It consists of the following parts:

-- A storage bottle with spray bulb pump for producing spheres of latex liquid (diameter 1/1000mm);
-- A 6V, 10W projector;
-- A 30X scale microscope which has a resolution of 0.2 mm between the small divisions and 1 mm between the large divisions.
-- An electrode assembly;
-- Appropriate controls, including a polarity--reversing switch, a potentiometer for fine control of plate voltages, and a voltmeter indicating the plate voltage applied.

3. THEORY

The experiment is names for R.A. Millikan, the American physicist who devised it. (Millikan's original experiment used drops of oil, while this apparatus uses spheres of latex liquid.) Millikan wanted to determine whether electrical charges occurred in discrete units and, if it did, whether there was such a thing as an elementary charge.

In the Millikan experiment, a small charged ball made of latex moves vertically between two metal plates. This sphere is too small to be seen with the naked eye, and so the projector and microscope are used to enable the user to see the sphere as a small dot of light. When there is no voltage applied to the plates, the sphere falls slowly and steadily under the influence of gravity, quickly reaching its terminal velocity. When a voltage is applied to the plates, the terminal velocity of the sphere is affected not only by the force of gravity but also by the electric force acting on the sphere.

When the experimenter knows the density of the latex ball, the terminal velocity of a ball falling under the influence of gravity alone, and the charge on the plates of the Millikan apparatus, it is possible to find the force produced by the electric charge on a ball. A series of observations will produce a group of terminal velocity values which are seen to be multiples of a lowest value. From this data, it is possible to determine the elementary unit of charge. (This unit of charge is known as the electron (e) and has the value of1.602 x 10^{-19} coulomb.)

Consider a latex sphere of mass "m" and charge "q", falling under gravity between two horizontal plates. In falling, the sphere is subjected to an opposing force due to air resistance. The speed of the sphere quickly increases until a constant terminal speed is reached, at which time the weight of the sphere, mg, minus the buoyant force is exactly equal to the air resistance force. This situation is similar to that of a parachutist falling through air. The value of the air resistance force on a sphere was first derived by Sir George Stokes and is given

$F_f = 6\pi\eta rs$
where "η" is the coefficient of viscosity of air,
and "r" is the radius of the sphere,
and "s" is its terminal speed.

When the sphere reaches terminal speed and if the buoyant force of the air is neglected, the net force on the sphere is zero, so the equation of motion of the sphere is simply given by

Force of Gravity = Force of Air Resistance

or

$$mg - 6\pi\eta rs = 0$$

Now suppose the metal plates are connected to a source of constant potential difference such that an electric field of intensity E is established between the plates and a latex sphere of charge "q" is made to move upwards. The direction of the electric field must depend on the sign of the charge "q" which may be either positive or negative. The resultant upward force on the charge is:

$$F_{up} = Eq - mg$$

and this force causes the sphere to move upwards with a constant terminal speed s^+. The equation of motion is

$$Eq - mg = 6\pi\eta rs^+$$

If now the polarity of the electric field is reversed, the sphere will move downwards under the combined force of gravity and the electrostatic force. This equation of motion is

$$Eq + mg = 6\pi\eta rs^-$$

Notice that the forces are now additive and that the terminal speed is achieved in the opposite direction than in the previous case.

The effects of gravity can now be eliminated by adding the equations of motion yielding:

$$2Eq = 6\pi\eta r(s^+ + s^-)$$

If the terminal speeds are changed to velocities by incorporating the proper sign convention of upwards (+) and downwards (-), the following equation results:

$$2Eq = 6\pi\eta r(v^{+} - v^{-}) \quad \text{or} \quad Eq = 3\pi\eta r(v^{+} - v^{-}) \qquad \text{(Eq. 1)}$$

Both "_" and "r" are known quantities for the latex spheres which will allow the calculation of the charge "q" if the electrostatic field E and the difference in terminal velocities are measured.

4. OPERATION

Begin by setting the apparatus on a level surface. Make sure all power to the unit is turned off whenever you are making any adjustments to it.

Make sure the electrode housing is set as in Fig. 2. This requires unscrewing the electrode housing set screws and removing the upper electrode housing plate. Then insert the atomizer ring between the upper and lower electrode housings and re-tighten the set screws.

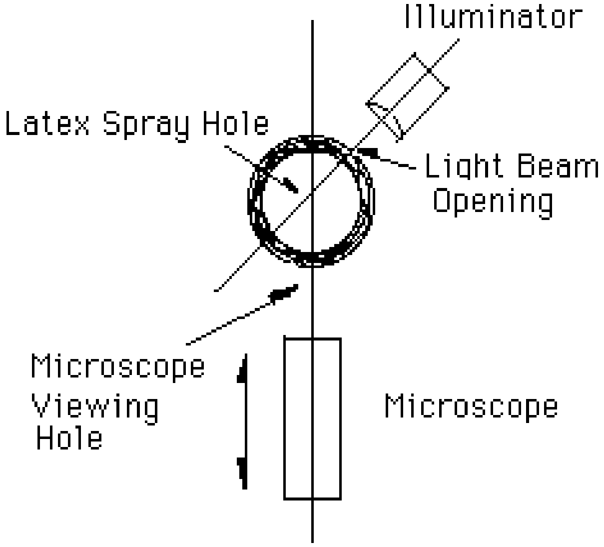

Figure 2

If the light should get out of focus, it should be adjusted as follows: Loosen the set screws at the top of the electrode housing and remove the housing; loosen the light socket set screw and move the socket so that an image of the bulb filament is on the screen (see Fig. 3). The light was adjusted at the time the unit was assembled and under normal conditions, no further adjustment should be necessary.

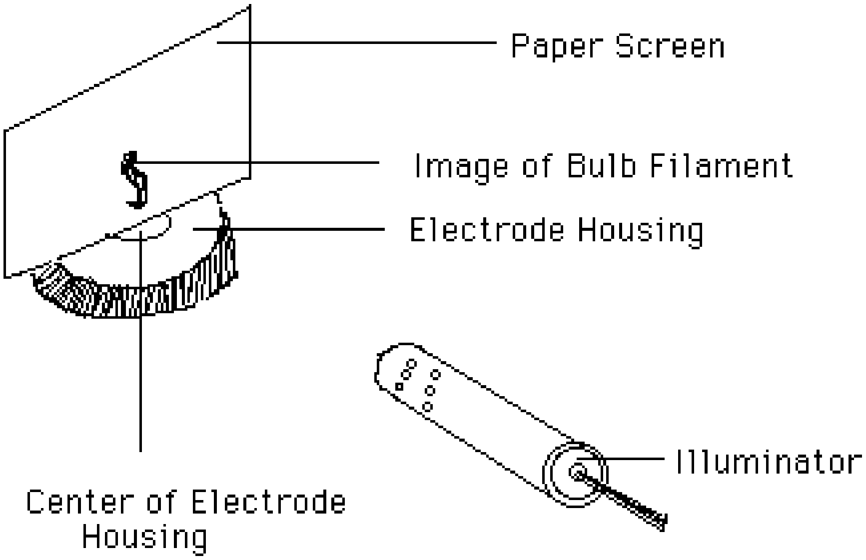

Figure 3

To use the latex spray, first loosen the set screws of the electrode housing to permit air to escape. Then inject latex spheres into the chamber by using the spray bulb pump. To feed the latex spheres in, cover the air hole of the spray bulb pump with a finger and squeeze the bulb. Note that the latex spheres will not be injected unless the air hole is covered.

Spraying is usually difficult the first few times. We recommend that you begin your measurements after making several test sprays.

After using the apparatus, clean the spray tubing with water. If the spray is not cleaned after each use, the residue of latex in the spray tubing will harden, preventing smooth operation of the spray.

1. Ensure that the D.C. volt leads are plugged into their respective color terminal lugs.

2. Position the 3-way polarity switch in its mid position, establishing a "no-charge" condition. Turn the "on/off" switch to "on." The illuminating lamp should light.

3. Adjust the microscope by rotating the focus adjusting knob until an approximate mid position is established. The eyepiece divisions should be distinguishable from the background.

4. Adjust the electrode voltage to 300 volts using the voltage adjusting knob, but keep the polarity switch in its mid position.

5. Spray latex into the apparatus and carefully look for the "dots of light" in the microscope. If after several pumps on the atomizer bulb, the latex spheres are still not visible, adjust the microscope carefully to attempt to focus in on the spheres.

Obtaining a suitable drop may require patience, for drops continue to enter the region between the plates for several seconds after spraying has stopped. Select a small drop that takes about 30 seconds to move between two large divisions in the eyepiece. Though one person can do this experiment alone, it is helpful if two work together, one taking the readings of the times of rise and of fall of the latex spheres and the other recording these readings.

Record the rise time t^+ and the fall time t^- of the latex spheres between two large divisions in the eyepiece (.05 mm). Alongside, calculate the corresponding velocities v^+ and v^-, which are merely the distance between the two large divisions divided by the time the sphere took to travel that distance.

Continue to take similar data on as many different spheres as possible. Then plot the value $(v^+ - v^-)$ on a graph. The data points should fall into groups, each group representing spheres with the same charge.

Since the difference in terminal velocities $(v^+ - v^-)$ is directly proportional to the charge q, the fact that the data points are grouped in distinct steps, each about 1.5×10^{-4} m/sec apart, indicates the charge on the spheres occurs in distinct amounts. The actual value of the step increase in charge can be calculated by using Eq.1.

$$qE = 3\pi\eta rv$$

Where v = the velocity step and
Where V = voltage across the plates and
d = the distance between the plates.

The electric field between the plates can be determined from the voltage across the plates "V" and the distance between the plates "d":

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

and assuming that the total charge "q" will be quantized, an integer times a basic unit of charge "e",

$$q = ne,$$

and solving for the unit of charge "e" we obtain

$$e = 3\pi\eta r\frac{d}{Vn}v$$

Assuming n = 1 since the smallest step reflects the smallest charge amount:

$$e = 3\pi\eta r\frac{d}{V}v$$

For the latex spheres in air: _ = 1.8×10^{-5}
Latex sphere radius r = 5.5×10^{-7} m
Plate Voltage = V
Step increase in velocity difference = v

Distance between plates: $d = 5 \times 10^{-3}$ m

Very Important:

When the experiment is completed, clean the electrode housing. Turn off and unplug the unit. Remove the electrode DC power cord from the terminal. Remove the pipe from the latex container. Loosen the set screw of the electrode housing and remove the housing. Disassemble into electrode boards above and below rings. Wipe off any water and latex with a soft cloth. Clean the latex spray tube and put it back in place. Reassemble the housing and set it in the designated position (when assembling the intermediate ring, carefully align the objective lens of the microscope with the peed window).

CHARGE OF THE ELECTRON
MILLIKAN OIL-DROP METHOD

EXPERIMENTAL METHOD II

Introduction

Most versions of the Millikan's apparatus use a fine mist of oil droplets from an "atomizer" as a source of charge carriers. It is necessary either to determine the diameter of the droplets or to eliminate this quantity from the equations containing the electronic charge, "e". There are three techniques for treating the topic in common use.

In the first method, the time for the selected droplet to fall freely through a specified distance is measured, and its velocity is used to determine its diameter using Stokes' formula and the known viscosity of air. An electric field of known value E is then applied, and the velocity of the rising droplet is similarly calculated. When the diameter of the droplet is known, its weight can be found and using this and Stokes' formula once more, the upward force F on the droplet can be determined. The charge ne on the droplet is then given by

$$F = neE.$$

This technique requires only that a fixed high voltage be available.

In the second method, which requires a variable high-voltage source, the diameter and weight of the droplets are found in the same way. The high voltage is then applied and adjusted until the droplet is suspended motionless. The upward force due to the charge is then equal to the droplet's known weight, and F = neE can be used to find ne.

The third technique, the so-called "alternating field" method, is used for comparing different numbers of electronic charges o the same drop. An alternating electric field is applied to the oil chamber, causing the charged drops to oscillate. The amplitude of the oscillations is proportional to the number of electronic charges present. A nearby radioactive source is used to induce changes in the charge during the experiment. By balancing the weight of the droplet against an upward electrical force, the mass of the droplet can be found, as in the second method.

In all three methods the experimental data consists of a group of differently-charged droplets, and an examination of the charge values shows that they are all multiples of a single value, the electronic charge e.

The electric charge carried by a particle may be calculated by measuring the force experienced by the particle in an electric field of known strength. Although it is relatively easy to produce a known electric field, the force exerted by such a field on a particle carrying only one or several excess electrons is very small. For example, a field of 1000 volts per cm. would exert a force of only 1.6x10-9 dyne on a particle bearing one excess electron. This is a force comparable to the gravitational force on a particle with a mass of 10-12 (one million millionth) gram.

The success of the Millikan Oil Drop experiment depends on the ability to measure forces this small. The behavior of small charged droplets of oil, weighing only 10-12 grams or less, is observed in a gravitational and an electric field. Measuring the velocity of fall of the drop in air enables, with the use of Stokes' Law, the calculation of the mass of the drop. The observation of the velocity of the drop rising in an electric field then permits a calculation of the force on, and hence, the charge carried by the oil drop.

Although this experiment will allow one to measure the total charge on a drop, it is only through an analysis of the data obtained and a certain degree of experimental skill that the charge of a single electron can be determined. By selecting droplets that rise and fall slowly, one can be certain that the drop has a small number of excess electrons. A number of such drops should be observed and their respective charges calculated. If the charges on these drops are integral multiples of a certain smallest charge, then this is a good indication of the atomic nature of electricity. However, since a different droplet has been used for measuring each charge, there remains the question as to the effect of the drop itself on the charge. This uncertainty can be eliminated by changing the charge on a single drop while the drop is under observation. An ionization source placed near the drop will accomplish this. In fact, it is possible to change the charge on the same drop several times. If the results of measurements on the same drop then yield charges that are integral multiples of some smallest charge, then this is proof of the atomic nature of electricity.

The measurement of the charge of the electron also permits the calculation of Avogadro's number. The amount of current required to electrodeposit one gram equivalent of an element on an electrode (The Faraday) is equal to the charge of the electron multiplied by the number of molecules in a mole. Through electrolysis experiments, the Faraday has been found to be 1.89x1014 electrostatic units per gram equivalent weight (more commonly expressed in the MKS system as 9.62x107 coulombs per kilogram equivalent weight) dividing the Faraday by the charge of the electron,

$$\frac{\text{1.89x1014 e.s.u./gm equivalent weight}}{\text{4.803x10-10 e.s.u.}}$$

, yields 6.025x1023 molecules per gram equivalent weight, or Avogadro's number.

EQUATION FOR CALCULATING THE CHARGE ON A DROP

An analysis of the forces acting on an oil droplet will yield the equation for the determination of the charge carried by the droplet.

Figure 1 shows the forces acting on the drop when it is falling in air and has reached its terminal velocity (Terminal velocity is reached in a few milliseconds for the droplets used in this experiment.). In Figure 1, vf is the velocity of fall, k is the coefficient of friction between the air and the drop, m is the mass of the drop, and g is the acceleration of gravity. Since the forces are equal and opposite:

$$mg = kv_f \qquad (1)$$

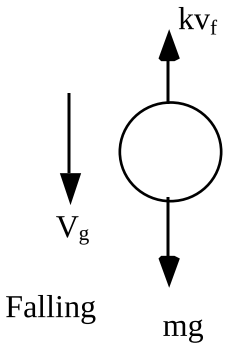

Figure 1

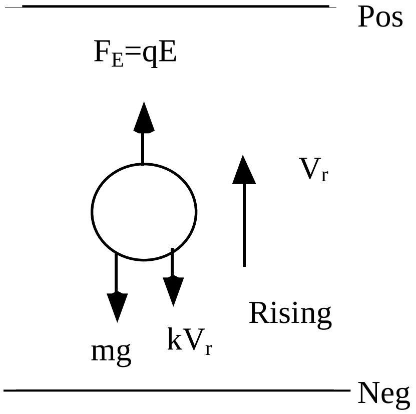

Figure 2

Figure 2 shows the forces acting on the drop when it is rising under the influence of an electric field. I Figure 2, E is the electric intensity, en is the charge carried by the drop, and vr is the velocity of rise. Adding the forces vectorially yields:

$$Ee_n = mg + kv_r \qquad (2)$$

In both cases there is also a small buoyant force exerted by the air on the droplet. Since the density of air, however, is only about one-thousandth that of oil, this force may be neglected.

Eliminating k from equations (1) and (2) and solving for e_n yields:

$$e_n = \frac{mg(v_f + v_r)}{Ev_f} \qquad (3)$$

To eliminate m from equation (3), one uses the expression for the volume of a sphere:

$$m = (4/3)\pi a^3\sigma \qquad (4)$$

where a is the radius of the droplet, and σ is the density of the oil.

To calculate a, one employs Stokes' Law, relating the radius of a spherical body to its velocity of fall in a viscous medium (with the coefficient of viscosity, ¨).

$$a = \sqrt{\frac{9\eta v_f}{2g\sigma}}^{*} \qquad (5)$$

Substituting equations (4) and (5) into equation (3) yields:

$$e_n = \frac{4\pi}{3}\sqrt{\frac{1}{g\sigma}\left(\frac{9\eta}{2}\right)^3} \text{ x } \frac{(v_f + v_r)\sqrt{v_f}}{E} \qquad (6)$$

Stokes' Law, however, becomes incorrect when the velocity of fall of the droplets is less than 0.1 cm/sec. (Droplets having this and smaller velocities have radii, on the order of 2 microns, comparable to the mean free path of air molecules, a condition which violates one of the assumptions made in deriving Stokes' Law.) Since the velocities of the droplets used in this experiment will be in the range of 0.01 to 0.001 cm./sec., a correction factor must be included in the expression for e_n. This factor is:

$$\left(\frac{1}{1+b/pa}\right)^{3/2} ** \qquad (7)$$

where b is a constant, p is the atmospheric pressure, and a is the radius of the drop as calculated by the uncorrected form of Stokes', equation (5).

The electric intensity is given by E = V/d, where V is the potential difference across the parallel plates separated by a distance d. E, V, and d are all expressed in the same system of units. If E is in electrostatic units, V in volts, and d in centimeters, the relationship is:

$$E \text{ (e.s.u.)} = \frac{V \text{ (volts)}}{300 \text{ d (cm.)}} \qquad (8)$$

Substituting equations (7) and (8) into equation (6) and rearranging the terms yields:

$$en = \left[400\pi d\left(\frac{1}{\sigma g}\left[\frac{9\eta}{2}\right]^3\right)^{1/2}\right] \text{ x } \left[\left(\frac{1}{1+b/pa}\right)^{3/2}\right] \text{ x } \left[\frac{(v_f + v_r)\sqrt{v_f}}{V}\right] \text{ e.s.u.} \quad .(9)$$

The terms in the first set of brackets need only be determined once for any particular apparatus. The second term is determined for each droplet, while the term in the third set of brackets is calculated for each change of charge which the drop experiences.

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*For additional information about Stokes' Law the student is referred to Introduction to Theoretical Physics, by L. Page (New York, Van Nostrand), Chapter 6.
** A derivation of this may be found in The Electron by R.A. Millikan (Chicago, The University of Chicago Press), Chapter 5. The definitions of the symbols used, together with their proper units for use in equation (9) are:

en - The charge, in e. s. u., carried by the droplet.
d - Separation of the plates in the condenser in cm.
ß - Density of the oil in gm/cm.3
g - Acceleration of gravity in cm./sec.2
¨ - Viscosity of air in Poise (dyne sec./cm.2)
b - Constant, equal to 6.17x10-4
p - The barometric pressure in cm. of mercury
a - The radius of the drop in cm. as calculated by equation (5)
vf - The velocity of fall in cm./sec.
vr - The velocity of rise in cm./sec.
V - The potential difference across the plates in volts

The accepted value for e is 4.80x10-10 e. s. u.

ADJUSTMENT AND CALIBRATION OF APPARATUS

1. **SETTING UP:** The apparatus should be placed on a level, solid table, with the viewing scope at a height which permits the experimenter to sit erect while observing the drops. The power cord is connected by a 110 - 120 v., 60-cycle receptacle and the control box (which houses the PLATES and POLARITY switches) is connected to the main chassis by means of the cable connector.

CONDENSER ASSEMBLY

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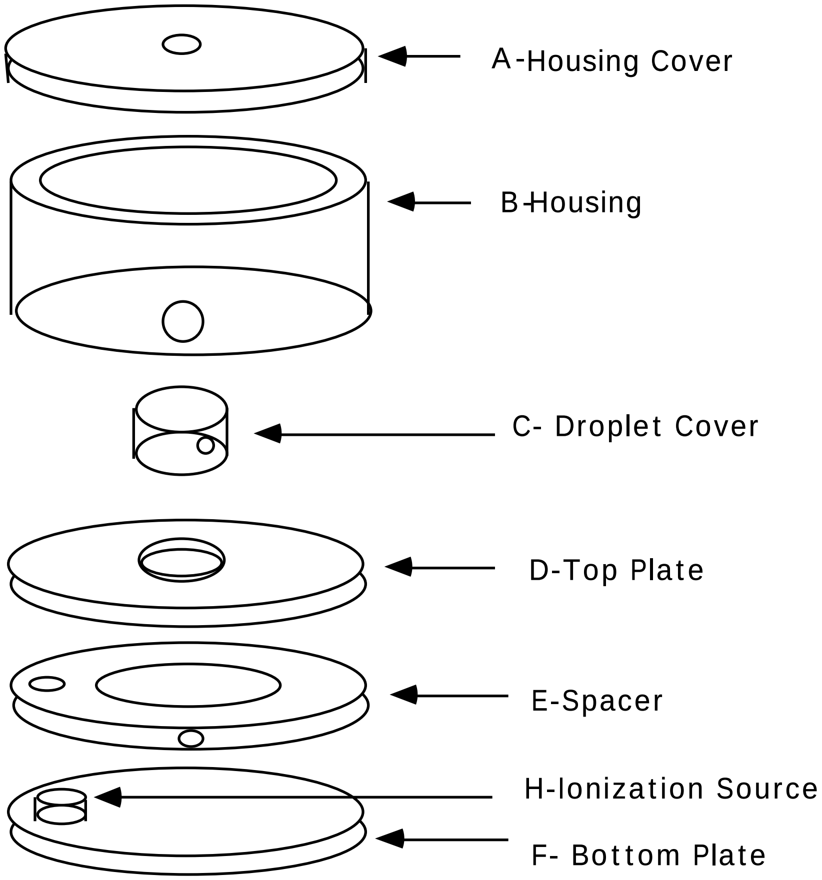


Figure 3

2. **LEVELING:** The condenser assembly is disassembled by removing parts: (Figure 3) A, Housing Cover; B, Housing; C, Droplet Hole Cover; D, Top Plate; and E, Plastic Spacer. The unit is leveled by placing a small level on the bottom brass plate and adjusting the three leveling screws on the bottom of the main chassis. **NOTE:** Reasonable care must be exercised when handling the brass plates to insure that no scratches or pits are formed on the blued side of either plate. The same care should also be exercised with the plastic spacer. Any irregularity on the plane surfaces of these parts will make measurement of the plate separation extremely difficult.

3. **CONNECTING TO HIGH VOLTAGE SUPPLY:** The high voltage supply which is to be used for the experiment (recommended voltage: 400 - 600 v.) is connected to the binding posts of the main chassis in accordance with the **POS**itive and **NEG**ative markings (The **PLATES** switch, on the control box, should be in the **OFF** position.). The DC voltmeter for measuring plate potential should be connected across the binding posts, since a 22 megohm resistor is placed in series with the **POS**itive binding post and the positive plate to prevent accidental shock to the operator.

NOTE: Model 250A includes a self-contained high voltage source (specifications are given on page 10) which is internally connected to the binding posts. The DC voltmeter used with Model 250A should have an internal resistance of not less than 1 megohm. An internal resistance less than this value will make the voltage regulation circuit inoperative at lower line voltages.

The Model 250A high voltage source is turned on by the **LIGHT SOURCE, HIGH VOLTAGE SUPPLY SWITCH.** Clockwise rotation of the slotted-shaft potentiometer (on the side of the main chassis and labeled **VOLTAGE CONTROL**) will increase the plate charging potential. The outer hex nut on the voltage control assembly is used for locking the control at any setting--clockwise rotation will lock the control; counter-clockwise rotation will release the control.

A warm-up period of about 5 minutes is required for stabilization of the 250A high voltage source. This period provides time to accustom the eye to viewing the drops and to develop the technique for introducing the drops into the condenser (Steps 10 and 11).

4. **MEASURING PLATE SEPARATION:** The distance between the condenser plates is determined by measuring the thickness of the plastic spacer used to separate the plates. Two possible methods are suggested for making this measurement:

a) The thickness of the plastic spacer (Part E) is measured with a micrometer around the outer rim and the average value used.

b) A more accurate method is to place the plastic spacer between two small (2.5" x 2.5") pieces of plate glass and measure the combined thickness of the three. The point of measurement should be as close to the center of the plastic spacer as possible. The spacer is then removed and the thickness of the two glass plates measured. Subtracting the latter quantity from the former quantity gives the separation of the plates. This method has the advantage of taking into account any surface imperfections that may have been formed on the surface of the spacer.

NOTE: All surfaces involved in the measurement should be clean to prevent inaccurate readings.

5. **MEASURING RETICULE LINE SEPARATION:** Thew distance between the top of the upper reticule line and the top of the lower reticule line may be measured in two ways:

a) A microscope reticule, ruled in 0.01 mm is placed on the bottom brass plate and the scope focused on the reticule.

b) The scope is removed (instructions for this are given under **MAINTENANCE**, Reticule Illumination Lamp) and focused on the anvil and spindle of a micrometer.

This distance should be measured to the limit of the experimenter's ability since a measurement of 0.01 mm is still 1 part in 50 when the reticule line separation is about 0.6 mm. **NOTE:** A label, to the right of the scope, gives the factory calibration of the reticule separation.

6. **CLEANING AND RE-ASSEMBLY:** The condenser housing, plates, spacer, and droplet hole cover should be cleaned, with particular attention to the droplet hole, the glass observation port covers on the condenser housing, and the droplet hole cover. Water and detergent make a suitable cleaning fluid. Solvents that might attack the plastic should be avoided. All parts should be completely dry before re-assembly. The condenser assembly is reassembled except for the housing cover (Part A) and the droplet hole cover (Part C). The two glass ports on the housing (Part B) should like up with the ports of the plastic spacer. The spring contact (Part C) should make good electrical contact with the top plate (Part D). All parts are oriented as shown in Figure 3.

7. **ADJUSTING THE OPTICAL SYSTEM:** A short piece of wire, or a pin (less than 0.010" dia.) is inserted through the hole in the center of the top plate and made to extend enough so as to touch the bottom plate when the condenser is assembled. The **LIGHT SOURCE** is turned **ON**. The two Focusing Screws on the observation scope mounting (Figure 4) are loosened and the scope moved either forward or backward until the wire is in sharp focus. If the wire cannot be seen at all, check the orientation of the plastic spacer and the condenser housing (Figure 3 and Sept 6). If the wire is still not visible, adjust the light source, in the manner described in the next step, until the wire is visible and focus the scope. Tightening the Focusing Screws locks the scope in position. While viewing the wire, adjust the eyepiece, by turning it, until the reticule line and wire are both in sharp focus. If the reticule lines are not horizontal, loosen the Reticule Adjustment Screws (Figure 4), rotate the scope barrel until the lines are horizontal, and tighten the screws.

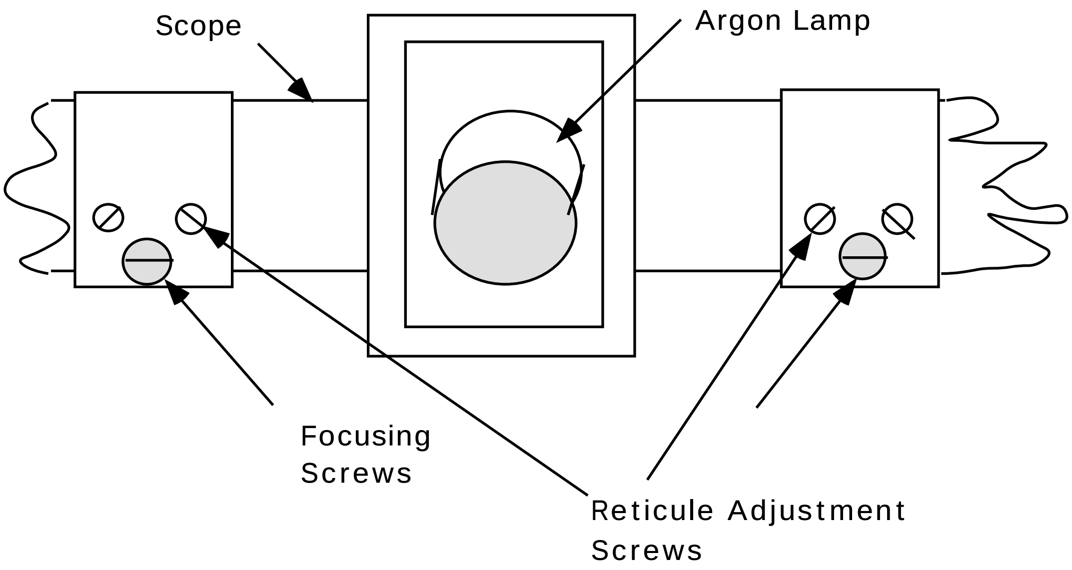
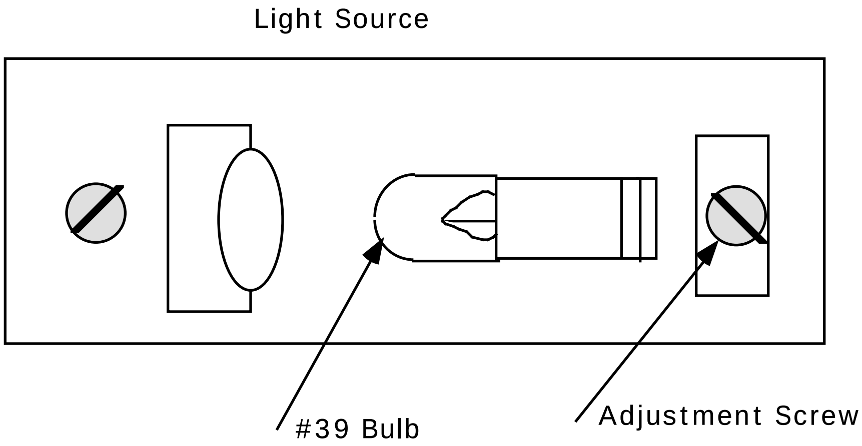


Figure 4.

8. **ADJUSTING THE LIGHT SOURCE:** Remove the light source housing and loosen the light source adjustment screw (Figure 5). Move the light source laterally until the area of the wire observed in the scope, between the reticule lines, is at maximum illumination. Tighten the adjustment screw at this point and replace the housing.



Spare #55 bulbs insideMain Chassis. Remove bottom panel for access.

Figure 5.

9. Remove the focusing wire or pin from the top plate and place the condenser housing cover and droplet hole cover in position, as shown in Figure 3. The apparatus is now ready for making measurements.

FUNCTIONS OF CONTROLS:

RADIATION SOURCE level - When the lever is at the **OUT** position the radiation source is shielded on all sides by plastic, so that virtually no radiation enters the area of the drops. At the **IN** position the plastic shielding is removed and the drop area is exposed to the radiation source. **NOTE:** move the radiation source level gently to avoid jarring the condenser assembly and knocking the droplet from the viewing area.

The radiation source, initial strength, and date of initial strength are all specified on the radiation tag to the left of the radiation source lever.

PLATES switch - When the switch is **OFF** the plates are disconnected from the high voltage supply and grounded. When the switch is **ON** the plates are connected to the high voltage supply, in accordance with the polarity switch position.

POLARITY switch - With the switch in the **NOR**mal position the **POS**itive binding post is connected to the top plate and the **NEG**ative binding post is connected to the bottom plate. In the **REV**erse position the polarity of the plates, in reference to the binding posts, is reversed.

PROCEDURE FOR DETERMINING THE CHARGE ON A DROP

10. **ROOM ILLUMINATION AND CONTROL SETTINGS:** The room should be made as dark as possible. There must be enough light, however, for reading the voltmeter, stopwatch, and collecting data. The **LIGHT SOURCE** and **RETICULE ILLUMINATION** switches are turned **ON**, the **PLATES** switch is turned **OFF**, the **POLARITY** switch is on **NOR**mal and the **RADIATION SOURCE** lever is at the **IN** position. The **RETICULE ILLUM**ination **ADJ**ustment should be set so that the reticule lines are just bright enough to be easily visible. Excessive illumination of these lines may make it difficult to observe very small droplets. Non-volatile oil, with known density, is placed in the atomizer (Squibb #5597 Mineral Oil (density - 0.886 g/cc) is very satisfactory.

11. **INTRODUCING DROPS INTO THE CONDENSER:** The nozzle of the atomizer is placed into the hole of the condenser housing cover. A few quick "squirts" of oil will fill the upper chamber of the condenser with drops and begin to force some drops into the viewing area. If no drops are seen, squeeze the atomizer bulb gently until drops appear in the viewing area. If repeated "squirts" of the atomizer fail to produce any drops in the viewing area, but rather a cloudy brightening of the field, the hole in the top plate is probably clogged, and should be cleaned.

The exact technique of introducing drops will have to be developed by the experimenter. The object is to get a small number of drops, not a large, bright cloud, from which a single drop can be chosen. It is important to remember that the drops are being forced into the viewing area by the pressure of the atomizer. Therefore, excessive use of the atomizer can cause too many drops to be forced into the viewing area and, more important, into the area between the condenser wall and the focal point of the scope. Drops in this area prevent observation of drops at the focal point of the scope.

NOTE: if the entire viewing area becomes filled with drops, so that no one drop can be selected, either wait three or four times until the drops settle out of view, or disassemble the condenser, thus removing the drops. When the amount of oil on the condenser parts becomes excessive, clean the assembly as explained in Step 6. The less oil that is sprayed into the chamber, the fewer times the chamber must be cleaned.

12. **SELECTION OF DROP:** From the drops in view, the experimenter should select a droplet which both falls slowly, and when the plates are charged, rises slowly. The following example is given as a guide in selecting a drop.

A drop which requires about 15 seconds to fall the distance between the reticule lines (0.05 cm) will rise the same distance, under the influence of an electric field (10000 v. per cm), in the following times with the following charges: 15 sec. - 1 excess electron; 5 sec. - 2 excess electrons; 3 sec. - 3 excess electrons. (**NOTE:** These values are only approximate.)

Immediately after the drop is selected move the **RADIATION SOURCE** level to the **OUT** position.

About 20 measurements of the rise and fall velocities of the drop should be made and its charge calculated. If the result of this first determination for the charge on a drop is greater than 5 excess electrons, then the experimenter should use slower moving drops in subsequent determinations.

13. **CHANGING THE CHARGE:** Drops are again introduced into the viewing area and a new drop is selected. After about 20 measurements on this drop have been made, the drop is brought to the top of the field of view and allowed to fall with the **RADIATION SOURCE** level at the **IN** position. A few seconds later the plates should be charged, and, if the rising velocity has changed, then the **RADIATION SOURCE** is moved to the **OUT** position and a new series of measurements taken. If, however, the charge has not changed, then turn the **PLATES** switch to **OFF** and allow the drop to continue falling. After a few seconds, again check for a change in the rising velocity. Continue this procedure until the drop has captured an ion.

If the drop captures an ion such that the drop moves rapidly downward, then reverse the polarity of the plates so that the drop can be made to rise.

Make about 21 measurements of the rising and falling velocity of the drop, and, if possible, change the charge again and repeat the measurement procedure.

13. It is desirable to observe as many changes of charge on a single drop as possible.

14. The plate potential is recorded for each determination; the density of the oil determined; the viscosity of air, at room temperature, found from a suitable handbook (The Handbook of Chemistry and Physics, for example); and the barometric pressure recorded.

The experimenter is now ready to compute the charge of an electron and, through analysis of the data collected, demonstrate the granular nature of electricity.

Model 250A High Voltage Source Specifications: Power Input - 110/130 VAC 50/60 cps; Range - 300-400 VDC, continuously variable; Regulation - 1% for 10% line variation; Ripple - less than 0.1 volt; Stability - within 1%.

MAINTENANCE NOTES

LIGHT SOURCE LAMP: The lamp used in the light source is a #39, miniature bayonet lamp (6.3 volt, 0.37 amp, 5000 hour life). To replace the lamp remove the light source housing and remove the old bulb. After the new bulb is placed in the Bulb Socket (See Figure 5), rotate the socket until the filament is in a vertical position. Although the socket will turn hard, it may be turned without damage by using some care in the operation. It is important that the replacement lamp have its filament assembly fairly well centered in the glass bulb so that the image of the filament projected on the droplet area will be within the proper area. The #39 lamp may be obtained at most Radio and Television service shops, or from PASCO scientific.

RETICULE ILLUMINATION LAMP: The argon lamp used to excite the fluorescent reticule lines is an AR-3 (1000 hour life). The lamp is removed by unscrewing the bakelite cap on the end of the Argon Lamp Housing (See Figure 4). The socket is removed from the housing, the bulb replaced, the socket placed back into the housing and pushed into the housing until the bulb touches the barrel of the scope. The wire connecting the lamp to the power source is fit into the slot in the bakelite housing and the bakelite cap screwed back into place. The AR-3 lamp may be ordered from an electronics supply house, or PASCO scientific.

If the viewing, scope needs to be removed, either for cleaning the lenses or calibrating the reticule, first remove the argon lamp and socket, loosen the Focusing Screws (Figure 4), and remove the scope.

PLASTIC SPACER: Specific areas of the inner surface of the plastic spacer (Part E) are painted flat black to produce the needed dark field. If, through repeated cleaning of the spacer with solvents, or rough handling, any of the point is removed the field may become brighter and the drops harder to view. This situation is easily remedied by retouching the scratched area with flat black paint. Care must be taken, however, so that no paint remains on the plane surfaces of the spacer which make contact with the plates, or any other surface which was not previously painted.

SCOPE ALIGNMENT: If, through any severe jarring of the scope or main chassis, the scope focuses too far to the right or left of the area under the droplet hole in the top plate, then the scope must be realigned. (Step 7 of the Operating Instructions). The three leveling screws, the three screws holding the bottom panel, and the bottom panel are removed from the main chassis. On the inside of the chassis one will note four screws, painted red for identification. These screws should be loosened which will permit the support base until the focusing wire is in the middle of the field, and the screws re-tightened. The bottom panel, and leveling screws are replaced. This procedure can best be completed if the main chassis is placed at an angle of about 80^{o} from the horizontal, with the back edge of the main chassis as the pivot line.