

# Determining the Charge of the Electron

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# 1 Introduction

Michael Faraday took the first step towards determining the magnitude of charge present in an atom. His experiments in electrolysis and subsequent law of electrolysis (in 1833) illuminated the “electrical nature of atomic forces.” [1] Work by Stoney and Helmholtz in the late 1800’s gave rise to the idea of a discrete minimum charge.

Finally in 1897, J. J. Thomson performed an experiment with “cathode rays,” closely following the work of Pieter Zeeman from one year prior. He measured the charge-to-mass ratio of the electron and found that it carries a negative charge. This determination is considered the “beginning of our understanding of atomic structure.” [1]

Thomson and his student, J. S. E. Townsend, then set out to measure the charge of the electron  $e$ . They attempted to suspend a cloud of charged water droplets in an E-field. This experiment had limited success, but the concept was improved upon by R. A. Millikan. Through a series of experiments he was able to improve his results until he obtained a value just 0.1% of today’s accepted value!

# 2 Experimental Apparatus

The apparatus used to make our measurements is a reasonable facsimile of that used by Millikan to observe charged oil drops for extended periods of time. It is, in fact, called a “Millikan Oil Drop Apparatus” and is commercially available from various scientific suppliers. Our particular apparatus was manufactured by PASCO scientific (Model 300A) in 1967, and contains a power supply, an illuminated droplet viewing chamber (with radioactive source) and viewing optics. See Figure 1 for a complete schematic of our experimental setup.

The critical part in our experiment is the droplet viewing chamber. It is here where we will attempt to capture, view, and manipulate oil droplets to make our measurements. The chamber contains two capacitor plates separated by a plastic spacer. An atomizer is used to introduce oil droplets into an “ante-chamber” directly above the plates; these droplets then drift between the plates through a hole in the upper plate. A hole cover is placed on the upper plate to reduce the number of droplets that enter the viewing chamber (between the plates). Two small holes exist in the plastic spacer to allow light to enter and exit the viewing chamber. See Figure 2 for an exploded view of this chamber.

Light enters the viewing chamber at an angle from the rear, through a lens placed in front of a small lamp. The lamp is hand-adjustable to allow precise illumination of the viewing chamber. Light exits the chamber at the front, and is immediately incident on the viewing scope. This scope is fixed to the apparatus and is focused via a small lever on the base. The scope contains an internally-lighted reticle which (along with a stopwatch and fast reflexes) allows for an accurate measurement of droplet velocity. The reticle consists of two horizontal lines whose illumination is adjustable via a knob on the base.

Also internal to the chamber is a  $^{210}\text{Pb}$  source on a movable platform. Another lever on the base of our apparatus allows us to move this source in and out of a plastic shield, giving us control over the release of alpha particles into the viewing chamber. The charge on the upper capacitor plate is controlled by a remote switch, while the lower plate is grounded. The remote switch offers positive charge, ground and negative charge modes. The potential

on the upper plate is controlled by a knob on the base, and is monitored using a DVM connected to the apparatus' internal power supply.

To monitor environmental conditions during the experiment we referred to a mercury barometer and an electronic temperature / humidity meter. The barometer was mounted to the wall in our room, while the meter was hand-held and provided measurements close to the apparatus. A vernier caliper with digital readout was employed to measure part of our apparatus, while a "Ronchi ruler" (a glass slide with evenly-spaced marks) was required to measure the reticle. The Ronchi ruler we used featured 200 lines per inch. A graduated cylinder and triple-beam balance were used to determine the density of oil used in our experiment.

## 3 Procedure

### 3.1 Setup

Knowing that we would be subject to long periods of observation, we began the experiment with an ergonomic design. A stand was constructed that placed the scope at eye level; we felt this provided maximum viewing comfort. In place on the stand, the droplet viewing chamber was disassembled until only the bottom plate remained on the base. We leveled the bottom plate by adjusting three leveling screws on the bottom of the base. We performed two iterations of leveling: first using a "bullseye" type two-dimensional bubble level, and then with a ball bearing placed on the bottom plate. Once the bearing lost its tendency to roll on the plate, we decided it was level enough to continue.

It was found that the leveling screws, which acted as the "feet" of our apparatus, were not tight in their sockets. This allowed the entire apparatus to wobble when jarred. To prevent such motion we removed the feet and added a nut / washer combination which allowed us to lock the feet in place once the apparatus was re-leveled.

A DVM was connected to binding posts on the base, monitoring the potential provided by its internal power supply. By adjusting the knob on the front of the apparatus we determined the range of this supply was 330 V to 450 V. Since the DVM's accuracy was limited to +/- 1 V above 400 V, we set the supply to 400.0V. Once set, the voltage would "wander" several hundred millivolts one way and then the other, even after the apparatus had several hours to "warm up". We did not bother to readjust the potential as this proved a futile exercise.

To measure the separation between the capacitor plates we employed a method suggested in the PASCO manual. [2] We remove the plastic spacer and "sandwich" it between two pieces of optical glass. We then measure the distance between the glass plates several times with calipers. The thickness of both glass plates is also measured several times, then our plastic spacer height is determined. The separation of the reticle lines is clearly marked on the apparatus, but we decide to double-check this value. Observing the Ronchi ruler through the viewing scope, we count the number of lines visible between the reticle lines.

The apparatus is cleaned, piece by piece, with ethanol-wetted Kimwipes and partially reassembled. A thin wire is inserted through the hole in the upper capacitor plate. While viewing the wire through the scope, the focus is adjusted to make the wire's image as sharp as possible. It was noted that the wire appeared far to the right of the field of view; this

indicated the scope was out of alignment and required readjustment. The screws holding the scope in place were loosened very slightly, the scope was adjusted and refocused, then the screws were torqued to lock the scope in place. The light was adjusted to provide maximum brightness when viewing the wire, then a small plastic cover was placed over the light to prevent ambient illumination.

Reassembling the rest of the apparatus, we are now ready to conduct our experiment.

### 3.2 Measurement

To maximize the visibility of the oil droplets, the experiment is conducted in a dark room. The apparatus is covered with a cutout large cardboard box, over which a black felt cloth is draped; this allows the exclusion of ambient light when viewing droplets. One or two “puffs” from the atomizer are used to fill the viewing chamber with droplets while the radioactive source is briefly unshielded ( $\sim 5$  sec).

Some of the droplets are ionized when they are struck by alpha particles, this is confirmed by charging the upper plate. The speed of some droplets changes instantly, indicating these droplets have acquired excess charge and now experience Coulomb forces. A drop is selected whose velocity is minimally affected by the upper plate charge in relation to neighboring drops. The scope is very slightly refocused on the selected droplet; a sharper droplet provided better contrast when crossing a reticle.

Manipulating the charge of the upper plate, the selected droplet is made to cross the reticles over and over. The upper plate is charged to make the droplet rise, then it is grounded and the droplet drifts downward. As the droplet crosses the reticles, a stopwatch is used to measure the time of flight. Five to ten pair of measurements (both rise and fall times) are taken. The amount of charge on the droplet is adjusted by exposing it to alpha particles while the upper plate is grounded. The alpha source is shielded when the droplet is observed rising with a different velocity.

Attempts are made to recharge each droplet as many times as possible. In most cases the droplet drifted out of the viewing area and could not be recovered. Before and after viewing each droplet, we recorded the ambient temperature, humidity, barometric pressure and supply voltage. After viewing a single droplet for nearly an hour, we felt satisfied with our data collection and terminated the experiment.

To facilitate our analysis we made a determination of the density of the oil used in our experiment. We took a clean, dry graduated cylinder and placed it on the balance, measuring its weight. We then filled the cylinder with oil to its top-most rule and recorded the volume. A pocket calculator took care of the rest of this determination.

## 4 Results

Our measurements of the plastic spacer and glass plates are summarized in Table 1. The reticle separation indicated on a label placed on the apparatus claims  $0.58 \pm 0.01$  mm; our measurement with the Ronchi ruler yielded  $4 \frac{1}{2} \pm \frac{1}{4}$  lines. The rise and fall times for our observed droplets are indicated in Tables 2 through 5. Conditions during the experiment are collected in Table 6. Our measurements made to determine the density of

our oil follows:

$$\begin{aligned} m_{cyl} &= 116.5 + / - 0.1\text{g} \\ m_{cyl+oil} &= 203.4 + / - 0.1\text{g} \\ v_{oil} &= 100 + / - 0.5\text{cm}^3 \end{aligned}$$

## 5 Analysis and Interpretation

### 5.1 Apparatus

Averaging the measurements in Table 1 we determine the distance between the plates:

$$d_{plates} = \overline{d_{total}} - \overline{h_{glass1}} - \overline{h_{glass2}} = 8.17\text{mm} - 1.28\text{mm} - 1.23\text{mm} = 5.66\text{mm}$$

Our error on each measurement is 0.01 mm. Adding these errors in quadrature, this gives an error on  $d_{plates}$  of 0.02 mm.

Our Ronchi ruler measurement of  $4 \frac{1}{2} \pm 1/4$  lines, at 200 lines per inch, yields:

$$4\frac{1}{2}\text{lines} \cdot \frac{1\text{inch}}{200\text{lines}} \cdot \frac{25.4\text{mm}}{1\text{inch}} = 0.57\text{mm}$$

By a similar determination we find our error on this measurement:  $1/4$  line = 0.03 mm. Since this agrees well with the distance indicated on the apparatus, we use its values in our analysis.

Determining the density of our oil was an easy task:

$$\rho_{oil} = \frac{m_{cyl+oil} - m_{cyl}}{v_{oil}} = \frac{203.4\text{g} - 116.5\text{g}}{100\text{cm}^3} = 0.869 \frac{\text{g}}{\text{cm}^3}$$

Determining the error wasn't as easy:

$$\left(\frac{\sigma_{\rho_{oil}}}{\rho_{oil}}\right)^2 = \left(\frac{\sqrt{\sigma_{m_{c+o}}^2 + \sigma_{m_o}^2}}{m_{cyl+oil} - m_{cyl}}\right)^2 + \left(\frac{\sigma_{v_{oil}}}{v_{oil}}\right)^2$$

This yielded an error of 0.005 g/cm<sup>3</sup>.

### 5.2 Theory

We assume the droplet is at terminal velocity when observed in our experiment, and establish equations of motion for its free fall and forced rise (in that order, below):

$$mg = kv_f \tag{1}$$

$$mg + kv_r = Ee_n \tag{2}$$

where  $mg$  is the force of gravity,  $kv$  is the drag force, and  $Ee_n$  is the Coulomb force on a particle of charge  $e_n$ . The buoyant force of air is neglected in these equations, a correction of about one part in one thousand.

To eliminate  $m$  from these equations, the droplet is modeled as a perfect sphere and the equation for its volume is used:

$$m = \frac{4}{3}\pi a^3 \rho_{oil} \quad (3)$$

where  $a$  is the radius of the droplet. We use Stokes law (with a correction factor, see the PASCO manual for a detailed explanation) to eliminate  $a$  from equation 3:

$$a = \sqrt{\frac{9\eta v_f}{2g\rho}} \quad (4)$$

where  $\rho = \rho_{oil}$  and  $\eta$  is the viscosity of air (quoted from EngineeringToolbox.com as  $1.84 \cdot 10^{-4}$  dyne  $\cdot$  sec / cm<sup>2</sup>).

Combining equations 1 and 2, making the substitutions in equations 3 and 4, adding the correction factor, and solving for  $q$  we achieve the equation to make our determination of  $e$  in e.s.u.:

$$q = \left[ 400\pi d \left( \frac{1}{g\rho} \left[ \frac{9\eta}{2} \right]^3 \right)^{1/2} \right] \cdot \left[ \left( \frac{1}{1 + \frac{b}{pa}} \right)^{3/2} \right] \cdot \left[ \frac{(v_f + v_r)\sqrt{v_f}}{V} \right] = q1 \cdot q2 \cdot q3 \quad (5)$$

The three “q-terms” are determined separately for convenience:  $q1$  needs to be determined only once for the experiment,  $q2$  for each droplet and  $q3$  for each recharge.

To simplify our error analysis we use the average value of  $V$ , and a predetermined value of  $\eta$  for the average temp., pressure, etc. during our experiment. We also assume no error in the quoted values for  $g$ ,  $\eta$  and  $b$ , as these are well below 1% and will have little effect on our final error. Where average values are used (ex.  $V$ ,  $v_r$ ,  $v_f$ ) the error is simply the variance of that value. We use the standard method of propagating errors:

$$\sigma_q^2 = \sum_{i=1}^n \left( \frac{\partial q}{\partial x_i} \right)^2 \sigma_{x_i}^2 \quad (6)$$

The error on our droplet velocity and radius is determined by adding the fractional errors of our parameters in quadrature:

$$\left( \frac{\sigma_v}{v} \right)^2 = \left( \frac{\sigma_d}{d} \right)^2 + \left( \frac{\sigma_t}{t} \right)^2 \quad (7)$$

$$\left( \frac{\sigma_a}{a} \right)^2 = \left( \frac{\sigma_{v_f}}{v_f} \right)^2 + \left( \frac{\sigma_\rho}{\rho} \right)^2 \quad (8)$$

Breaking down the error analysis for  $q$  into three terms makes our job easier. The three terms are represented in large brackets in equation 5, above. These terms  $\sigma_{q1}$ ,  $\sigma_{q2}$ ,  $\sigma_{q3}$  will be summed much like the terms in  $\sigma_a$  to determine a final  $\sigma_q$ .

$$\left( \frac{\sigma_{q1}}{q1} \right)^2 = (1/2)^2 \left( \frac{\sigma_\rho}{\rho} \right)^2 + \left( \frac{\sigma_d}{d} \right)^2 \quad (9)$$

$$\left( \frac{\sigma_{q2}}{q2} \right)^2 = (3/2)^2 \left( \frac{\sigma_p}{p} \right)^2 + (3/2)^2 \left( \frac{\sigma_a}{a} \right)^2 \quad (10)$$

$$\left( \frac{\sigma_{q3}}{q3} \right)^2 = \left( \frac{\sigma_{v_{rms}}}{v_{rms}} \right)^2 + (1/2)^2 \left( \frac{\sigma_{v_f}}{v_f} \right)^2 + \left( \frac{\sigma_V}{V} \right)^2 \quad (11)$$

where  $v_{rms} = \sqrt{v_r^2 + v_f^2}$ .

### 5.3 Experiment

We average the rise times for each recharge, and average the fall times for each drop. This, with our reticle spacing, gives us average velocities, summarized in table 7. We first plug the  $v_f$  values into equation 4 to determine our droplet radii and error. These determinations appear in table 8. From this information, we have the means to calculate  $q_1$ ,  $q_2$  for each drop, and the associated errors. The results of these calculations are found in table 9. I calculate  $q_3$  and  $q$  in table 10, giving me the charge(s) on each droplet. To determine  $e$  we used the relation  $q = ne$  and attempted a line fit. In order to do this, we needed to start with a “guesstimate” of  $e$  with which to “pick” values of  $n$  for each drop. At first look, we could only come up with a value around 1/5th of the accepted value for  $e$ . This was disappointing, but not a surprise given the 20% to 50% error on  $q$  in most cases. After much deliberation and many failed line fits, we decided to conclude with a “no result” in this report, as our error bars supported many different choices of  $n$  for each value, making our determination of  $e$  rather arbitrary (i.e. with a confidence level much less than 1%).

## 6 Conclusion

John and I figured early on that our ability to time the droplets’ flights would be the limiting factor in this experiment, and our error numbers support this postulation. Viewing the variance in our times of flight for falling droplets gives one an idea of the difficulty involved in using a stopwatch for precise time measurement. Oddly enough, we found that measuring shorter time intervals ( $\sim 2$  sec) was easier than measuring longer intervals. Since our determination of  $a$ , and subsequently  $q$  depended heavily on  $t_{fall}$ , a relatively long time interval, our results included large error bars. There are several solutions to this problem (using electronic timing, taking many more measurements), all equally viable, but impossible given our resources.

Another factor in our success was practice. We threw out two previous data sets due to our poor ability to setup and use the apparatus. Effectively, we performed the experiment from start to finish twice, using only the last results. Perhaps with more practice, larger data sets could be gathered. Again, we hadn’t the time or patience to put in the weeks of practice required to master the apparatus. Our first attempts at this measurement seemed more like exercises in futility than scientific data collection.

Our limited time to perform this experiment was further constrained by the amount of repairs needed to bring the apparatus into decent working condition. An entire afternoon was spent repainting the edges of the plastic spacer to keep internally-reflected light out of the viewing optics. We felt such maintenance should not have been expected of us, but we had no choice given the condition of the apparatus.

## 7 Tables and Figures

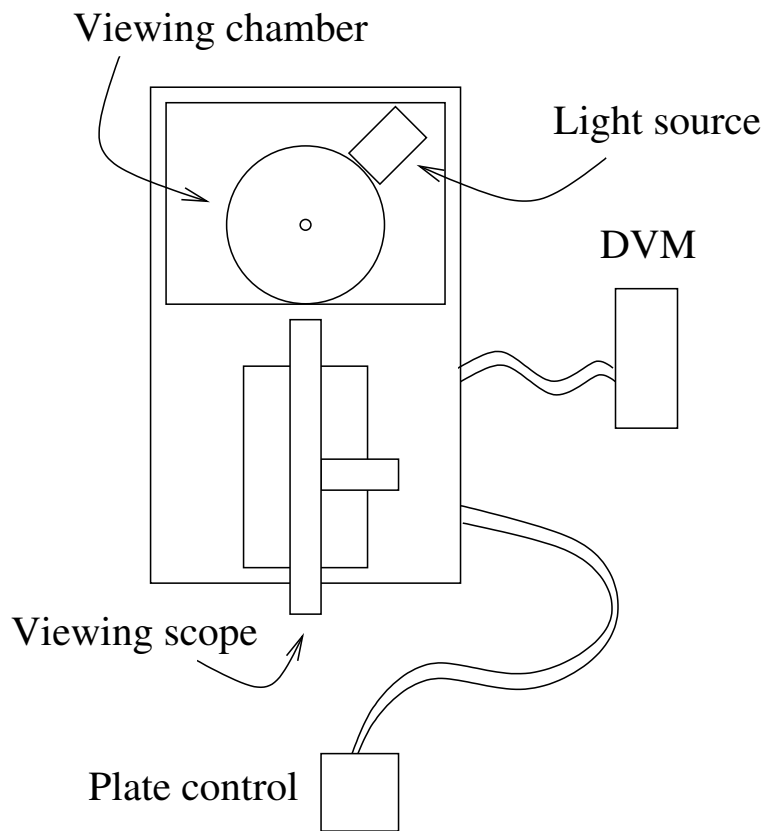


Figure 1: A sketch of our experimental setup, plan view.

	Glass + Spacer (mm)	Glass 1 (mm)	Glass 2 (mm)
	8.17	1.28	1.23
	8.18	1.29	1.23
	8.17	1.28	1.23
	8.18	1.29	1.23
	8.17	1.28	1.23
	8.17	1.27	1.23
		1.27	
avg.	8.17	1.28	1.23
err	0.01	0.01	0.01

Table 1: Measurements to determine the plate spacing.

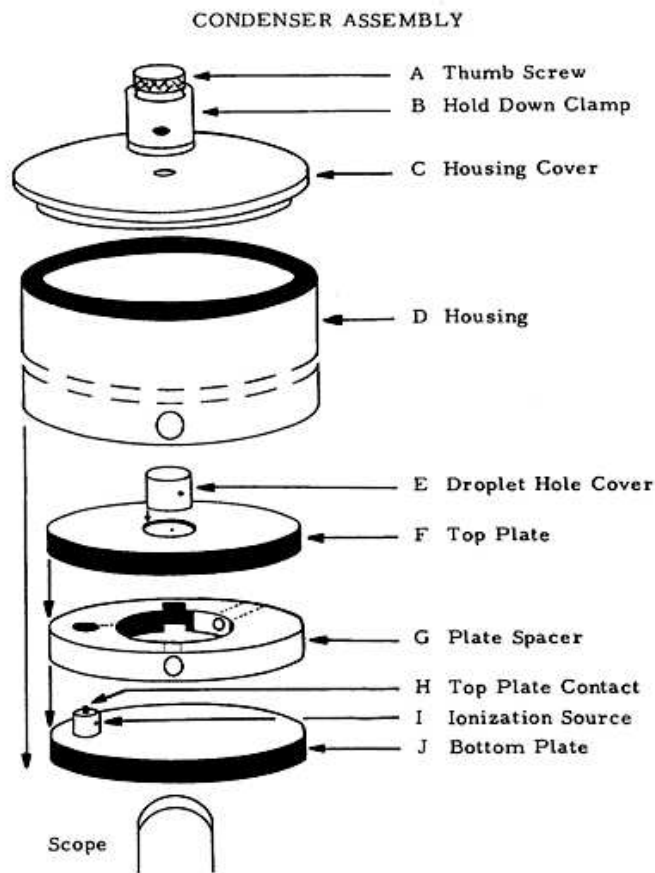


Figure 2: Exploded view of the droplet viewing chamber. Source: PASCO scientific.

Drop	Recharge	$t_{rise}$ (sec)	$t_{fall}$ (sec)	
1	A	11.66	21.13	
		10.03	21.28	
		11.88	19.09	
		10.68	23.19	
		11.41	22.22	
		10.28	22.13	
		11.19	21.87	
	B	2.75	22.00	
		2.66	20.84	
		2.85	19.94	
		2.59	23.22	
		2.78	20.57	
		2.65	18.41	
	C	4.19	20.41	
		4.62	22.28	
		4.75	19.56	
		4.54	20.75	
		4.56	20.53	
		4.53		
	2	A	4.37	9.58
			4.97	9.32
4.79			9.18	
4.59			9.57	
4.53			10.03	
5.22			10.19	
4.59			9.34	
4.91		9.34		
4.34				
B		3.08	10.12	
		3.56	9.09	
		3.38	9.25	
		3.34	9.47	
		3.52	9.44	
	3.19	8.91		
	3.40	9.62		
3.65				

Table 2: Times measured during the experiment.

Drop	Recharge	$t_{rise}$ (sec)	$t_{fall}$ (sec)
3	A	14.91	10.15
		14.41	10.28
		14.31	9.97
		14.31	9.72
		14.94	9.25
		16.50	9.84
		15.88	10.03
		14.19	9.94
		14.60	
4	A	17.56	9.94
		21.00	8.41
		19.91	9.50
		19.10	9.25
		18.50	9.13
		21.12	9.44
		17.65	9.32
		18.85	9.43
		17.84	
	B	1.75	8.47
		1.75	9.00
		1.78	10.13
		1.79	8.75
		1.68	9.09
		2.22	
		1.54	
		1.78	
5	A	4.34	16.62
		3.87	16.82
		3.81	16.87
		3.72	16.60
		4.00	16.03
		4.25	15.35
		3.88	16.28
		2.75	16.25
		2.69	15.97
		2.75	17.65

Table 3: Times measured during the experiment.

Drop	Recharge	$t_{rise}$ (sec)	$t_{fall}$ (sec)	
5	B	4.25	13.47	
		4.06	12.94	
		4.03	13.66	
		4.22	12.84	
		4.06	12.53	
		4.07	13.47	
		4.16	14.37	
		4.34		
		C	6.81	15.50
			7.28	12.87
	7.25		13.75	
	7.47		13.43	
	7.41		14.12	
	4.19		13.25	
	4.53		14.41	
	4.41		14.12	
	3.56		13.78	
	4.03			
	D	1.84	13.28	
		1.84	14.62	
		1.81	13.93	
		1.81	13.78	
		1.71	14.28	
		1.78	14.38	
		1.78	14.53	
		1.84		
	E	3.03	14.00	
		2.69	14.00	
		2.69	14.28	
		2.97	14.69	
		3.03	15.12	
		2.94	15.44	
		2.97	14.00	
	2.93			

Table 4: Times measured during the experiment.

Drop	Recharge	$t_{rise}$ (sec)	$t_{fall}$ (sec)	
5	F	7.12	13.75	
		7.00	14.40	
		7.28	13.50	
		7.09	14.87	
		7.28	13.63	
		7.31	14.97	
		7.34		
	7.38			
	6.88			
	7.57			
	7.35			
		G	3.94	14.31
			4.03	14.00
			4.25	15.66
	4.19		14.00	
	3.87			
	4.28			
	4.12			
	4.15			

Table 5: Times measured during the experiment.

Source Voltage (V)	Temp. (°C)	Pressure (mmHg)	Rel. Humidity (%)	
400.0	22.0	43.7	44.8	
401.2	22.7	43.7	51.5	
401.2	22.7	43.7	49.9	
401.3	22.8	43.7	46.7	
401.9	22.8	42.6	61.0	
avg.	401.1	22.6	43.5	50.8

Table 6: Conditions measured during the experiment.

Drop	Recharge	$v_r$	$\sigma_{v_r}$	$v_f$	$\sigma_{v_f}$
1	A	5.27E-03	2.48E-04	2.74E-03	2.37E-04
	B	2.12E-02	3.75E-04		
	C	1.29E-02	2.39E-04		
2	A	1.23E-02	3.01E-04	6.11E-03	1.38E-04
	B	1.71E-02	3.74E-04		
3	A	3.89E-03	1.78E-04	5.86E-03	1.17E-04
4	A	3.04E-03	3.00E-04	6.29E-03	2.04E-04
	B	3.25E-02	8.83E-04		
5	A	1.60E-02	1.87E-03	3.99E-03	3.97E-04
	B	1.40E-02	2.45E-04		
	C	1.02E-02	4.95E-03		
	D	3.22E-02	5.56E-04		
	E	2.00E-02	3.68E-04		
	F	8.07E-03	1.43E-04		
	G	1.41E-02	2.54E-04		

Table 7: Calculated velocities of the droplets. All values in cm/sec.

Drop	$a$	$\sigma_a$
1	5.23E-05	4.53E-06
2	7.81E-05	1.82E-06
3	7.65E-05	1.58E-06
4	7.92E-05	2.61E-06
5	6.31E-05	6.29E-06

Table 8: Calculated radii of the droplets. All values in cm.

Drop	$q1$	$\sigma_{q1}$	$q2$	$\sigma_{q2}$
1	5.80E-04	2.65E-06	1.40E-01	1.82E-02
2			2.12E-01	7.53E-03
3			2.07E-01	6.60E-03
4			2.15E-01	1.07E-02
5			1.71E-01	2.56E-02

Table 9: Calculated terms in the determination of  $q$  for each droplet. These terms do not represent any physical measurement (yet), so their units are unimportant.

Drop	Recharge	$q^3$	$\sigma_{q^3}$	$q$	$\sigma_q$
1	A	1.05E-06	7.54E-08	8.48E-11	1.26E-11
	B	3.13E-06	1.50E-07	2.34E-10	3.52E-11
	C	2.04E-06	1.02E-07	1.65E-10	2.30E-11
2	A	3.59E-06	9.56E-08	4.41E-10	1.97E-11
	B	4.52E-06	1.06E-07	5.55E-10	2.38E-11
3	A	1.86E-06	5.93E-08	2.24E-10	1.01E-11
4	A	1.85E-06	1.00E-07	2.30E-10	1.70E-11
	B	7.66E-06	2.44E-07	9.54E-10	5.67E-11
5	A	3.16E-06	3.97E-07	3.13E-10	6.13E-11
	B	2.83E-06	1.68E-07	2.81E-10	4.52E-11
	C	2.23E-06	1.02E-06	2.22E-10	1.06E-10
	D	5.70E-06	3.08E-07	5.66E-10	9.00E-11
	E	3.77E-06	2.13E-07	3.74E-10	5.99E-11
	F	1.90E-06	1.30E-07	1.89E-10	3.10E-11
	G	2.86E-06	1.69E-07	2.83E-10	4.56E-11

Table 10: Calculated terms in the determination of  $q$  for each droplet. The only physically significant term is  $q$  (in e.s.u.).

## Acknowledgments

## References

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