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## The Laby Experiment

### Abstract

After J.J. Thomson demonstrated that the atom was not an indivisible entity but contained negatively charged corpuscles, the search for the determination of magnitude of this fundamental unit of electric charge commenced. This paper will briefly discuss the different attempts to measure this quantity of unit charge  $e$ . It will outline the progress of these attempts and will focus on the little known work of Australian, Thomas Laby, who attempted to reconcile the value of  $e$  determined from two very different approaches. This was probably the last attempt to measure  $e$  and was made at a time that most of the scientific world was busy with other issues.

The measurement of the unit electric charge  $e$ , by timing the fall of charged oil drops is an experiment that has been performed by generations of undergraduate physics students. The experiment is often termed the Millikan oil drop experiment after R.A. Millikan (1868-1953) who conceived and performed it during the period 1907-1917. This experiment was repeated in 1939-40 by V.D. Hopper (1913b), lecturer in Natural Philosophy at Melbourne University and T.H. Laby (1880-1946) who was Professor. As far as we know this was the last time that the experiment was performed “seriously”, i.e. performed carefully by professional physicists and fully reported in major journals.

The question arises who was Laby and why did he conduct this experiment such along time after Millikan has completed his work? Thomas Laby was born in 1880 at Creswick Victoria. In 1883 the family moved to New South Wales where young Thomas was educated. He passed the Senior Public Examination in mathematics and history, but failed to matriculate to the University of Sydney. However, in 1901 he became a junior demonstrator in chemistry at the University of Sydney and attended evening classes in chemistry, physics and mathematics as well as undertaking some research. In 1905, he was awarded an 1851 Exhibition Scholarship by the same institution. He travelled to Cambridge to study at the Cavendish Laboratory under J.J. Thomson where he received his BA by research in 1907 and much later, in 1921 a DSc.<sup>1</sup>

<sup>1</sup> *Australian Dictionary of Biography*, p 640.

In 1909 Laby took up a new chair in physics at the then Victoria College, Wellington (now Victoria University). It was here that he completed a project that he had started in Cambridge with G.W.C. Kaye. This work resulted in the publication in 1911 of their *Tables of physical and chemical constants with some mathematical functions*, which has been reprinted and sold world wide for decades. This work keeps generations of physicists familiar with his name.<sup>2</sup>

During the 1890's a small revolution was taking place in physics. Until this time the notion of particles smaller than an atom carrying a charge was completely unheard of. While much experimentation and debate had occurred during the previous two hundred years as to the nature of electricity and its propagation through materials, the carrier of the electric charge had not been identified, so much of this debate could be regarded as speculation. In 1898 J.J. Thomson (1856-1940) measured the charge to mass ration of these so-called cathode rays and concluded that these rays were indeed particles. The observation of cathode rays bending in the presence of magnetic and electric fields had previously been observed as had the presence of a negative charge associated with these rays. Thomson's discovery and need for further research led to a number of classic experiments being devised.

One of Thomson's team at the Cavendish C.T.R. Wilson (1869-1959) had developed the "cloud chamber" technique. It was found that small dust particles could act as a nucleus for condensing water droplets. If the air is dust free and saturated with liquid vapour and its volume is suddenly expanded, the air now becomes supersaturated. The liquid drops will now form on any suitable nucleus which can include gaseous ions, forming a cloud. This is the principle behind the Wilson Cloud Chamber.<sup>3</sup>

Further experiments were carried out in the Cavendish laboratory by J. Townsend (1868-1957) and H.A. Wilson (1874-1964) (not related to C.T.R. Wilson). Townsend measured the electric charge carried by the cloud and the terminal velocity of the cloud. Townsend then applied Stokes' formula,  $F = 6v\pi av$ , to the droplets in the cloud to obtain a measure of the charge carried by each droplet. He obtained a value of  $e = 3 \times 10^{-10} \text{ e.s.u.}$ <sup>4</sup> H.A. Wilson now applied an electric field across the cloud and was able to measure the fall of the cloud both with and without an electric field. H.A. Wilson obtained a value of  $e$  in the range  $2 \times 10^{-10} \text{ e.s.u.}$  to  $4 \times 10^{-10} \text{ e.s.u.}$ <sup>5</sup> J.J. Thomson performed additional experiments using similar methods to those of H.A. Wilson and obtained a value of  $e = 3.8 \times 10^{-10} \text{ e.s.u.}$ <sup>6</sup> Later measurements from the Cavendish gave a value of  $e = 4.03 \times 10^{-10} \text{ e.s.u.}$

<sup>2</sup> *Ibid.*, p. 640.

<sup>3</sup> WILSON (1897), p. 272.

<sup>4</sup> TOWNSEND (1897) pp. 244-58.

<sup>5</sup> WILSON (1903), pp. 429-41.

<sup>6</sup> THOMSON (1903), p. 352.

By the early years of the 20th Century it was reasonably established that the corpuscles that Thomson had discovered were indeed subatomic and carried a unit electric charge. Millikan (1862-1953) commenced his work on measuring the charge carried by the electron (as corpuscles were now known) in 1910. At this time Millikan was in his 40's, was teaching in Chicago and had not yet published a major paper. Millikan probably saw himself as following in the footsteps of Benjamin Franklin who believed in the existence of discrete charge and in 1747 produced the definitions of charge which are still in use today. His only mistake was to assume that the transfer of charge was accomplished by the motion of positive charge causing much grief to modern students and their teachers, who have had to explain that when conventional current flows one way the electrons flow in the opposite direction.

At about the same time as Millikan was obtaining his value for  $e$  in the U.S. thus confirming the particulate nature of electric charge, Felix Ehrenhaft (1879-1952) was producing his own determination of  $e$  claiming that  $e$  is not a fundamental unit. Ehrenhaft believed that electric charge was part of a continuum in nature similar to the electromagnetic spectrum and thus it was possible for charges smaller than  $e$  to exist as free charges, these he termed sub-electrons. Both men used the same method; they measured the velocity of charged falling objects moving in air and applying Stokes' equation. Ehrenhaft used colloid particles of phosphorus and metals, he applied an electric field horizontally and hence measured the motion of two sets of particles: the vertical motion with no electric field and the horizontal with the electric field applied.<sup>7</sup>

Millikan replicated H.A. Wilson's experiments but found that the cloud could dissipate leaving a single drop in the electric field. Millikan found that the value of a single charge as deduced from this work lay in the range of  $4.56 \times 10^{-10} e.s.u.$  to  $4.87 \times 10^{-10} e.s.u.$  with a mean of  $4.65 \times 10^{-10} e.s.u.$  In discussing his results Millikan stated that "we did not succeed in balancing any singly charged drop" and that "big drops and heavily charged drops are those which are most easy to hold stationary".<sup>8</sup> Millikan finally concluded that "the only possible elementary charge, of which the observed charges are multiples, is  $4.65 \times 10^{-10} e.s.u.$ ."<sup>9</sup>

While working with single drops of water and alcohol Millikan faced an additional problem of evaporation. Returning from a BAAS meeting in Winnipeg in 1909, Millikan came up with the idea of using oil droplets. He obtained the minute droplets of oil required for this process from a commercial oil atomiser. The oil which was atomised in the atomiser had been rendered dust free by passing it through a container of glass wool. The air was sprayed into a large chamber at the bottom of which were located two conducting plates set a small distance apart. The

<sup>7</sup> HOLTON (1978), pp. 47-57.

<sup>8</sup> MILLIKAN (1910), p. 223.

<sup>9</sup> *Ibid.*, p. 224.

top plate had a pin hole which allowed an occasional oil droplet to fall into the region between the conducting plates.

The conducting plates had a potential difference of between 0 and 10,000 V. The oil drops were illuminated in this region by a powerful beam of light, enabling observation of individual droplets to be made. The frictional process involved in producing the spray had produced a charge on these oil drops.

These charges were sufficiently strong to allow the drop to fall freely under gravity and also to move upward if the field was applied between the plates. Millikan was thus able to observe a single drop for some minutes while timing its rate of fall or rise by an ordinary stop watch.

Millikan assumed "that the velocity with which the drop moves is proportional to the force acting upon it and is independent of the electrical charge which it carries".<sup>10</sup> Thus using his predecessors' formula of,

$$\frac{v_1}{v_2} = \frac{mg}{Ee + mg} .$$

When Millikan exposed the region between the plates through which the oil drops fell to an X-ray source or Radium, he found that he could control to some extent the charge that the drops captured, either positive or negative. From this experiment he was able to conclude "that the charge carried by an ion in gases is the same as the charge on the beta or cathode ray particle ... and ... that there are no differences between the positive and negative electrons".<sup>11</sup> This value of the charge on the electron was thus determined to be  $4.774 \times 10^{-10} \text{ e.s.u.}$ <sup>12</sup>

Planck had determined a value for Boltzmann's constant  $k$  from the shape of the black-body radiation curve and from this constant derived a value for the Avogadro number  $N$ , using the relationship  $R = Nk$  where  $R$  is the gas constant. Planck now applied the Avogadro number  $N$  to the Faraday constant,  $F = Ne$  where  $e$  is the unit electric charge. The Faraday constant refers to the amount of electricity required to electrolyse one mole of a monovalent element such as hydrogen, which had at that time been accurately determined. From his calculations, Planck obtained a value of  $e = 4.69 \times 10^{-10} \text{ e.s.u.}$ <sup>13</sup>

In 1908, Rutherford and Geiger obtained a value for  $e$  of  $4.65 \times 10^{-10} \text{ e.s.u.}$  which they had obtained by "counting the number of  $\alpha$  particles emitted by a known quantity of radium and measuring the total electric charge carried by these particles".<sup>14</sup> Rutherford and Geiger found that the charge on an  $\alpha$  particle was  $9.3 \times 10^{-10} \text{ e.s.u.}$  By this time, Rutherford had realised that the charge carried by the  $\alpha$  particles was twice that of the electron.

<sup>10</sup> MILLIKAN (1917), p. 68.

<sup>11</sup> *Ibid.*, pp. 78-83.

<sup>12</sup> *Ibid.*, p. 79.

<sup>13</sup> *Ibid.*, p. 225.

Regener, in 1909, obtained a value of  $4.79 \times 10^{-10} e.s.u.$  by what was essentially a repeat of the Rutherford-Geiger experiment, i.e. counting the number of scintillations produced by the  $\alpha$  particles emission from polonium. He then measured the total charge carried by these particles and hence made his determinations.<sup>14</sup> Begeman obtained a value of  $4.67 \times 10^{-10} e.s.u.$  using Millikan's method. It should be noted that Begeman was Millikan's assistant for much of his early work on the determination of  $e$ .<sup>14</sup>

M.de Broglie obtained a value of  $4.5 \times 10^{-10} e.s.u.$  by measuring the velocities of charged particles of tobacco smoke in an electric field. This method required "the mean radius of these particles being obtained from kinoscopic records of the mean displacement which they undergo in a given time because of their Brownian movements".<sup>14</sup> This method required the use of a value of Avogadro's number ( $N$ ), the value used was Perrin's which lay in the range  $5.6 \times 10^{23}$  to  $7.1 \times 10^{23}$ .

Finally Moreau had obtained a value of  $4.3 \times 10^{-10} e.s.u.$  by measuring the "charge carried by ions in flames". This value was also obtained using Perrin's value of  $N$ .<sup>15</sup>

In 1928, E. Backlin in Sweden used an entirely different approach from that of Millikan to determine the value of  $e$ . Backlin determined the wavelength of X-rays which were reflected at very shallow angles from a ruled grating. The angular positions of the maximum intensities of the reflected X-rays could then be measured. The method used was similar to that employed to determine the optical wavelength from a diffraction grating. It had been widely observed that the faces of calcite crystals will reflect X-rays but only at certain angles of incidence. The angle at which reflection occurs is dependent on the wavelength of the X-rays and the separation of the atoms in the crystal. The separation of the atoms could be determined from the geometric arrangement of the atoms in the crystal and from the value of  $N$ , the Avogadro Number which could be obtained from the Faraday constant and unit charge,  $e$  (i.e.  $F = Ne$ ).

When Backlin measured the wavelength of the X-rays by these two different methods he expected identical results. However, the discrepancy between the two methods was much greater than could be accounted in the experimental uncertainties. Consequently, Backlin assumed that the direct measure of the wavelength using the grating to be correct. He then substituted the correct value for wavelength and found that a discrepancy arose in the three constants, Avogadro's constant, the Faraday constant and the value for unit charge. Finally it became evident that the actual source of the error was in the value used for  $e$ . In his initial calculations Backlin had used Millikan's value of  $4.774 \times 10^{-10} e.s.u.$  As a result of his calculations and measurements, Backlin found that  $e$  was  $4.794 \times 10^{-10} e.s.u.$ <sup>15</sup>

<sup>14</sup> *Ibid.*, p. 227.

<sup>15</sup> STRANATHAN (1946), p. 58.

In 1932, K. Shiba suggested that the discrepancy between Millikan's results and those found by the X-ray method arose not from the differences in experimental method but from an incorrect value for the viscosity of air. Shiba suggested that the viscosity of air was actually higher than the value used by Millikan. When Shiba combined the higher value for viscosity of air with Millikan's original oil drop data, the value of  $e$  obtained was  $4.803 \times 10^{-10} \text{ e.s.u.}$ <sup>16</sup>

Following on from Shiba's suggestion, G. Kellstrom in 1935 made careful determinations of the viscosity of air finding it to be somewhat higher than that used by Millikan. Kellstrom determined the viscosity of air to be  $1832.9 \times 10^{-7} \text{ poise}(P)$  while Millikan had used the value obtained by Harrington of  $1822.6 \times 10^{-7} P$ .<sup>17</sup> Using his own value for the viscosity of air and Millikan's original oil drop data, Kellstrom found  $e$  to be  $4.818 \times 10^{-10} \text{ e.s.u.}$ <sup>18</sup> The *poise* ( $P$ ) is the unit for viscosity in the *cgs* system of units, the *S.I.* unit for viscosity is the *poiseuille* ( $Pl$ ) and  $1P=0.1Pl$ .

The following year, E. Backlin and H. Flemberg again attempted to determine the value of  $e$ . They believed that "the variations in the velocity of the drops between the condenser plates are real, and therefore a long series of observations are necessary to get the mean value free from the influence of Brownian motion."<sup>18</sup> Consequently some of these observations lasted as long as 3 hours on a single drop. Using Kellstrom's new value for the viscosity of air, Backlin and Flemberg obtained a mean value of  $e$  to be  $4.800 \times 10^{-10} \text{ e.s.u.}$ <sup>19</sup>

During the years 1939-41, Laby and Hopper conducted a number of experiments in which they attempted to reconcile the discrepancies in the results between the "X-ray" method and the "oil drop" method of determining  $e$ . Laby states that he modified H.A. Wilson's drop method by changing the direction of the electric field.<sup>19</sup> It is of interest to note that Laby gave recognition to H.A. Wilson's contribution to the oil drop method rather than to Millikan to whom this method is commonly attributed. Laby and H.A. Wilson were contemporaries at the Cavendish Laboratory, Wilson being senior to Laby at the time.

Laby applied the electric field in a horizontal direction rather than the vertical direction used previously. In this way he was able to note the deflection of the charged particle as it fell between the parallel plates forming the condenser. Thus he could initially measure the motion of the drop falling without an electric field and then measure its deflection when the field was applied. Observation times for individual drops were thus greatly reduced and were in fact photographed.<sup>20</sup>

<sup>16</sup> *Ibid.*, p. 59.

<sup>17</sup> *Ibid.*, p. 61.

<sup>18</sup> BACKLIN and FLEMBERG (1936), p. 656.

<sup>19</sup> LABY and HOPPER (1939), p. 157.

<sup>20</sup> *Ibid.*, p. 158.

Laby states that this method together with a photographic record used to measure the velocity of the drop “has the advantage that departures from Stokes’ equation, the presence of convection currents in the air, a change in the charge of the drop and any error in the direction of the field can be detected”.<sup>21</sup> Further, by using a photographic record Laby also attempted to eliminate the errors due to timing the fall of the drop.<sup>22</sup>

Laby obtained his photographs by intermittently illuminating the oil drops for an exposure time of  $1/1500$  sec every  $1/25$  sec, similar to photographing motion using a strobe light. His photographs showed a series of white dots set against a black background, these photographs produced an image that had been magnified by 12.<sup>23</sup>

The condenser plates were made of glass which was silver plated in the middle but not at the edges which act as an insulation. These plates were separated by a distance of  $0.4985$  cm.<sup>24</sup> A potential of  $3000$  V across the plates was obtained by rectifying an alternating current “from the public supply”<sup>25</sup> This produced an electric field of  $6000$  V/cm.

Since the observation times were extremely short, Laby was not concerned with the evaporation of the oil. Instead he used oil which produced drops capable of carrying a large charge, castor oil and apiezon oil were his choices.<sup>26</sup> Drops with radii in the range  $3$  to  $10$   $\mu\text{m}$  were required but atomisers produced much larger drops. Laby obtained the oil drops required by covering lightly the wires of a fine steel brush. The wires were then slowly pushed back and then suddenly released producing a shower of oil drops.<sup>27</sup>

Using a value for viscosity of air  $\eta = 1830 \times 10^{-7}$  P, Laby obtained a value of  $e = (4.8020 \pm 0.0013) \times 10^{-10}$  e.s.u. When Laby applied the same value for viscosity of air to Millikan’s data, a value of  $e = 4.7992 \times 10^{-10}$  e.s.u. was obtained.<sup>28</sup> The X-ray method for determining charge quoted by Laby was  $e = (4.8044 \pm 0.0007) \times 10^{-10}$  e.s.u.<sup>29</sup>

Thus Laby believed that finally the two methods for determining  $e$  were reconciled and gave almost identical results.<sup>30</sup> However, Laby concludes that “the main uncertainty

<sup>21</sup> LABY and HOPPER (1941), p. 244.

<sup>22</sup> *Ibid.*, p. 245.

<sup>23</sup> *Ibid.*, p. 261.

<sup>24</sup> *Ibid.*, p. 258.

<sup>25</sup> *Ibid.*

<sup>26</sup> *Ibid.*, p. 259.

<sup>27</sup> *Ibid.*, p. 260.

<sup>28</sup> *Ibid.*, p. 265.

<sup>29</sup> *Ibid.*, p. 271.

<sup>30</sup> LABY (1942), p. 649.

in the value of  $e$  as found by the drop method is in the value for the viscosity of air.”<sup>31</sup> The value for  $e$  from the X-ray method does not suffer from this source of error.

It should also be remembered that Laby had already co-authored a book of physical and chemical constants. Hence the need for an accurate value of  $e$  and other constants was possibly of importance to him. Consequently the desire to measure  $e$  accurately and to reconcile the two methods, and to do it well, was probably the major motivating factor for these two Australian investigators.

<sup>31</sup> LABY and HOPPER (1941), p. 270.



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