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Physical laboratory 3

Task B Millikan's oil drop experiment

Tasks

1. Measure the value of the elementary charge using the velocity of the falling and rising oil droplet in the homogeneous electric field. Carry out the measurements of the velocity for at least 50 drops. Compare the results with the tabulated value.

THINK before the experiment:

- Why can't you measure the elementary charge of a stationary drop (i.e. by setting the electric field at which the drop stops) in the used apparatus?
- If only low voltage (up to approx. 250 V) is present on the capacitor electrodes, almost all of the measured drops carry a large charge (large multiple of the elementary charge). Explain why.
- What is the advantage and the disadvantage of using a radioactive source in this experiment?
- How do you evaluate the measured data?

History

J.J. Thomson managed to end the several decades-long discussion about the nature of the cathode rays by experimental proof that these are rays of negatively charged particles with an extremely high specific charge (i.e. ratio of the charge to the particle mass) in 1887. The specific charge of these particles, termed as electrons, could be found from the curvature of their trajectories in electric or magnetic fields. Still, by itself, this wasn't enough the derive the absolute value of the electron.[1] The first estimate of the electron charge was done in 1888 from the measurements of the total charge of a water droplet cloud formed from the condensation of water vapour on free charge carriers, assuming that each droplet formed around a single charge carrier. As such charge was low, it was concluded that the electron has to have a small mass. This method was then significantly improved by observing the movement of charged particles gravitational and electric fields. This method was further refined by Robert Andrews Millikan. Instead of evaporating water vapour droplets, he used clockwork oil droplets with the diameter of a few microns instead, measured the velocity of the droplets by a microscope with a measuring eyepiece, introduced the air buoyancy correction, stabilised the temperature (the air viscosity is a function of the temperature)

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[1] The term „elementary charge“ was first used earlier as the positive charge carried by the hydrogen atom during electrolysis. Its value was correctly estimated within the order of magnitude from the specific mass of the H^+ ion and the hydrogen atom mass derived from the kinetic theory of gases.

by placing the experiment in a water bath and by measuring at different pressures he eliminated the deviations from the Stokes formula for the friction force. After refining the air viscosity measurements, his experiments led to the value of the electron charge of $-1.603 \cdot 10^{-19}$ C being very close to the nowadays tabulated value of approximately $-1.6022 \cdot 10^{-19}$ C. He was awarded the Nobel prize in physics for his measurements of the electron charge in 1923.

Measurement method principle

In Millikan's experiment, the movement of a charged particle in an electric field that is oriented downwards in the direction of the gravity force at one time, while it is oriented upwards against the direction of the gravity force at another time is observed. In the original experiments, the friction of the oil drops on a tube was used to charge the drops, however, also other means such as ionising radiation can be used.

The force of gravity acts upon the drop attracting it downwards and the magnitude of the force is

$$F_g = \frac{4}{3}\pi r^3 \rho g, \tag{1}$$

where r is the drop radius, ρ is the oil density and g the gravitational acceleration. The buoyancy is acting in the upwards direction the buoyancy magnitude is

$$F_{vz} = \frac{4}{3}\pi r^3 \rho_{vz} g, \tag{2}$$

while ρ_{vz} is the air density. The friction force acts against the movement direction and it can be expressed for laminar flow by the Stokes' expression

$$F_t = 6\pi\eta r v, \tag{3}$$

where η is the air viscosity and v is the magnitude of the speed of the droplet. And finally the electric force acts towards the current cathode and its magnitude is

$$F_e = |q|E, \tag{4}$$

$|q|$ is the electron elementary charge and E is the electric field intensity magnitude.

When the droplet is attracted to the bottom electrode by the electric field, it will gain the equilibrium speed of v_1 according to the equation

$$\frac{4}{3}\pi r^3 \rho g + |q|E \;=\; \frac{4}{3}\pi r^3 \rho_{vz} g + 6\pi\eta r v_1. \tag{5}$$

We can measure the speed v_1, however, equation (5) contains not only the unknown charge q but also another one – the radius of the drop. Therefore, the reversal of the polarity of the electric field is needed for the measurement. If the intensity of the electric field is large enough and the droplet is not too heavy, it will start to move upwards with the equilibrium speed of v_2 according to the equation

$$\frac{4}{3}\pi r^3 \rho g + 6\pi\eta r v_2 \;=\; \frac{4}{3}\pi r^3 \rho_{vz} g + |q|E, \tag{6}$$

therefore, we obtain two equations with two unknowns – r and q.

Adding equations (5) and (6) we obtain the formula for the droplet radius

$$r^2 = \frac{9\eta\,(v_1 - v_2)}{4g\,(\rho - \rho_{vz})}. \tag{7}$$

If we subtract the two equations, we obtain the charge of the drop as

$$|q| = 3\pi\eta r\,\frac{v_1 + v_2}{E}. \tag{8}$$

We can measure the speeds v_1 and v_2e, and we can calculate the electric field intensity from the distance of the electrodes and the voltage between them.

The drop can carry only integer times the number of electrons, so its charge is an integer multiple of the electron charge. It is necessary to repeat the measurement for a sufficient number of different drops. If we plot the measured charge values, we will see that they cluster around integer multiples of a certain value. This value is the elementary charge, and its value can be estimated from the difference of the charge of two neighbouring clusters.

Calculating the charge from only one difference of the charge between two neighbouring clusters would not yield a very precise result. Averaging all the measured differences will, however, not help either. Let us assume that we have n neighbouring clusters of droplets with average charges q_i. We can calculate $n-1$ differences of the average cluster charge $(q_{i+1}-q_i)$, however, after their averaging, we obtain

$$\frac{1}{n-1}\sum_{i=1}^{n-1}(q_{i+1}-q_i)=\frac{q_n-q_1}{n-1}.$$

Therefore in this calculation, nearly all the measured points but the two extreme ones were excluded. Think about the appropriate treatment of the measured data before the measurement.

Measurement apparatus

The apparatus used for the electron charge measurement is shown in figure 1. The heart of the instrument is a capacitor chamber, where we inject oil droplets between the capacitor electrodes from a glass reservoir using a rubber balloon. The distance between the electrodes is 2.5 mm, and the oil density is 1 030 kg·m^{-3}. The chamber is equipped with a water level, lamp and a microscope for observing the droplets. Some of the droplets are charged via friction during the injection and an additional radioactive source of α-particles (^{241}Am, 74 kBq) can be connected to the chamber for increasing the number as well as the charge of the present droplets. The capacitor is charged by DC voltage (0 – 300 V). Connecting the two outputs of the voltage source in series

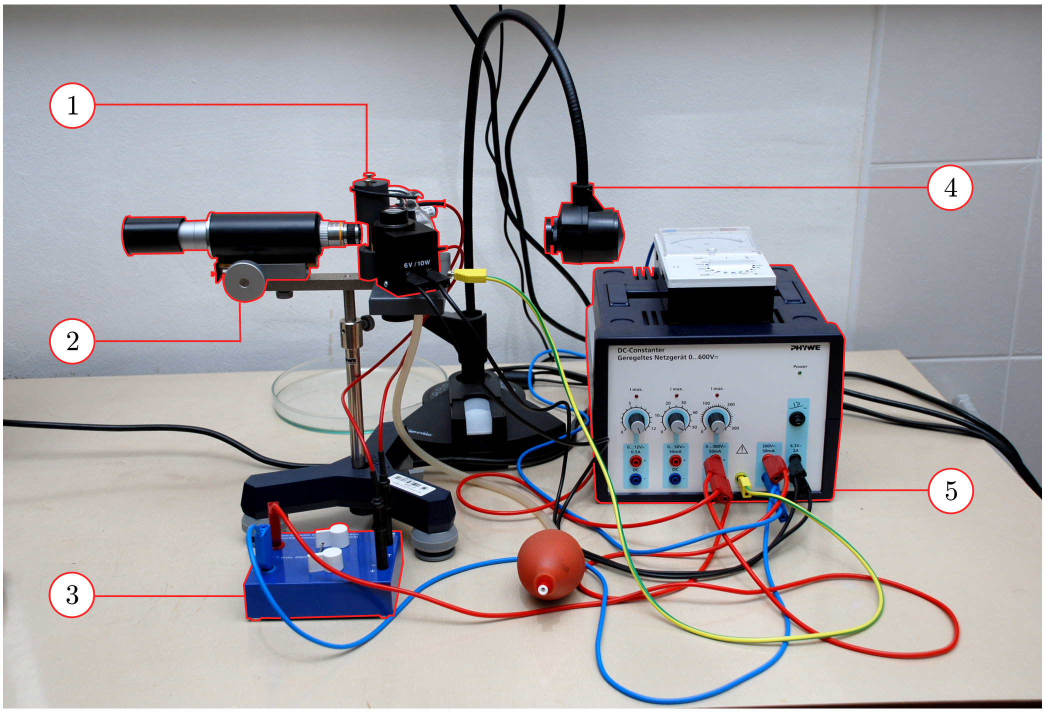

Figure 1: Measurement apparatus. 1 - capacitor chamber, 2 - microscope, 3 - polarity reverser, 4 - camera, 5 - voltage source.

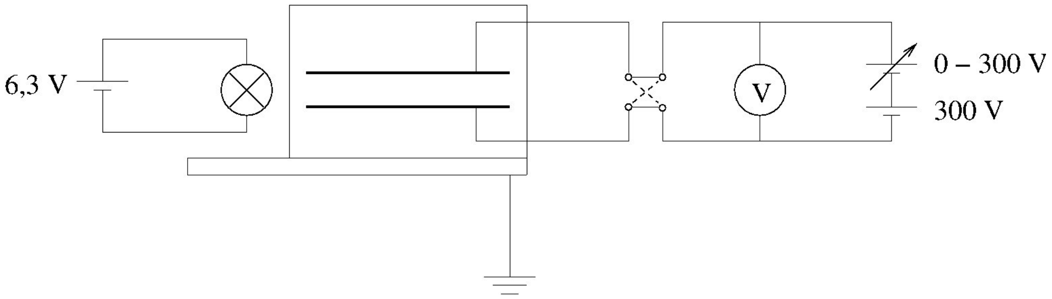

Figure 2: Electrical connection diagram.

enables using voltages higher than 300 V. The voltage polarity can be changed by the voltage reverser and its magnitude is measured by a multimeter. The source is also used as an AC voltage source for the lamp (6.3 V). The droplet movement can be observed by a camera connected to a PC, enabling recording of the movement in a video file.

Experimental procedure

1. Level the measurement apparatus by setting up the screws legs using the water level. Secure the device from any draft (e.g. by covering it).
2. Connect the circuits as per figures. 1 and 2.
3. Turn on the PC and the AverTV software.
4. Press the rubber balloon several times and inject the oil droplets into the chamber. Turn on the camera and position it to record the droplet movement. Focus the microscope if needed.
5. Record the droplet movement for voltages in the range of 300 – 600 V. Always focus on a single droplet that is moving evenly at a straight line – vertically if possible. Change the polarity of the capacitor and the movement direction of the droplet by the reverser. It may be necessary to focus the microscope during the measurement. Note, the charge and consequently observed speed of the droplet can change during the measurement. Measuring before the droplet reaches an equilibrium speed is not valid. Measure at least 50 droplets.
6. The video file will be automatically saved to the Praktikum folder on the desktop.
7. Play all the records after the laboratory and measure the speeds of selected droplets. During the laboratory, you can use pre-installed freeware Avidemux and MousePos. Another alternative is for example freeware BS.Player (with the possibility to play the video in slow motion).
8. Calculate the charges of the different droplets and show if the charges form the expected clusters. Calculate the elementary charge, including the standard deviation. DO NOT USE the knowledge of the tabulated value of the elementary charge during the calculation!

- You will work with voltage up to 600 V during your measurement, exercise caution.
- Do not manipulate the α-particle source. Pregnant persons measure the task without the radioactive source.