Manipulation of optically levitated particles

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ABSTRACT

The development of an experimental system in which optical levitation combined with Millikan´s classical oil drop experiment will be presented. The focus of the apparatus is a glass cell (25x72x25 mm^3) in which an oil drop is levitated using a vertically aligned laser beam. A laser power of about 0.9 W is needed to capture a drop, whereas typically 0.3 W is sufficient to maintain it in the trap. An alternating electric field is applied vertically across the cell, causing the drop to oscillate in the vertical direction. The amplitude of the oscillations depends on the strength of the electric field and the q/m ratio of the oil drop. The oscillations are observed by imaging scattered laser light onto either a screen or a position sensitive detector. The number of discrete charges on the drop can be reduced by exposing it to either UV-light or a radioactive source. The radius of the drop is measured by detecting the diffraction pattern produced when illuminated with a horizontally aligned He-Ne laser beam. The mass of the drop can then be determined since the density of the oil is known. Hence, absolute measurements of both the mass and the charge of the drop can be obtained. The goal of the experiment is to design a system which can be used to demonstrate several fundamental physical phenomena using the bare eye as the only detector. The experimental set-up will be further developed for studies of light scattering and spectroscopy of liquids and for studies of interactions between liquid drops.

Keywords: Optical manipulation, Optical levitation, Millikan´s experiment, Photoelectric effect, Diffraction

1. INTRODUCTION

Optical manipulation was first demonstrated by A. Ashkin and J. M Dziedzic when they trapped transparent particles in water using two horizontally aligned counter-propagating laser beams[1]. Shortly thereafter, they demonstrated optical levitation, showing that a glass bead could be trapped in air using a single laser beam. A combination of the force from photon pressure and gravity then formed the trapping potential[2]. These two experiments beautifully demonstrated how the momentum of light could be used to manipulate microscopic particles. The next major step in the field of optical manipulation was taken in 1986 when the single-beam gradient trap, also known as the optical tweezers or laser tweezers[3], was first demonstrated. This trap is constructed by focusing a laser beam using a high numerical aperture microscope objective. The trap that is formed is sufficiently strong to hold transparent microscopic objects without using gravity as a counterbalancing force. The main advantage with the single-beam gradient trap is that the objective used for trapping also can be used for observation. Hence, it can be incorporated in any standard type optical microscope. The optical tweezers is now a widely used tool, in particular for research in biology[4]. In parallel, optical manipulation has been developed for cooling and trapping of atoms in vacuum [5]. Cooling is achieved by making use of the fact that atoms with different velocities will, due to the Doppler shift, absorb light of different wavelengths. Optical tweezers and laser cooling have developed to two major research fields, whereas optical levitation, so far, has received less attention. A recent interesting development in the field is levitation of light absorbing particles. This has been demonstrated with both vertical[6] and horizontal[7] -aligned laser beams.

The other major experiment of relevance to the present work is Millikan´s classical oil drop experiment[8]. This is one of the most important experiments in the history of physics as it paved the way to our current understanding of matter. Millikan produced a mist of small oil drops in a cell in which a strong vertical electric field was applied. He compared the free falling velocity of individual drops with the upward velocity of the drops when they were exposed to a strong electric field that counteracted gravity. The influence of the mass could then be canceled out giving a direct measurement of the charge of the particle. By a statistical analysis of a large number of drops it was possible to verify the quantization of the elementary charge. This experiment is still performed in introductory courses in physics. The experiment is straightforward, but the motion is minute and it takes quite some practice to perform an accurate measurement.

Throughout the years, a number of experiments based on the concept by Millikan have been performed in which a single drop has been studied. For instance, Altwegg *et al*[9] designed a Millikan chamber in which a single drop could be trapped for hours using a feedback system. Additional electrodes were used to keep the position of the drop within +/- 0.2 mm. Their system was used for studies of photoemission of individual particulates in controlled atmospheres and was designed to work for both positively and negatively charged particels. Ashkin instead used the optical levitation technique to keep an oil drop in position[10]. As discussed above, the quantization of the charge, which was the main goal with Millikan´s experiment, can only be demonstrated if drops with different number of excess elementary charges are investigated. For a single drop experiment, it is then necessary to change the number of charges on the drop during the course of the experiment. Arnolds *et al*[11] achieved this by means of the photoelectric effect using 7 eV photons. Alternatively, the charge can be changed by exposing the drop to ionizing radiation, such as an α–emitting source.

In this paper a single oil drop Millikan experiment is presented. It can be used to demonstrate fundamental processes that can be observed with the human bare eye as the only detector. The experiment is similar to the setup used by Ashkin[2]. The main goal of this work is to produce a simple set-up with which the momentum of the photon, the quantization of the charge, the photoelectric effect, the influence of radioactivity and optical diffraction can be demonstrated. In a later stage, the system will be used for light scattering experiments and optical and electron spectroscopy of liquid drops and to study interactions between drops.

2. EXPERIMENTAL SETUP

A schematic picture of the experimental system is shown in Fig. 1. Briefly, a single oil droplet is optically levitated in a cell in which a vertical electric field can be applied. The position of the droplet is monitored by imaging scattered light onto a screen or a position sensitive detector. The droplet is made to oscillate by applying an AC electric field vertically across the cell. This results in a movement of the image of the drop with an amplitude of several millimeters. The size of the droplet is measured by means of the diffraction pattern produced by a horizontally aligned He-Ne laser beam. The charge of the droplet, finally, is changed by exposing it to either UV light or a radioactive source.

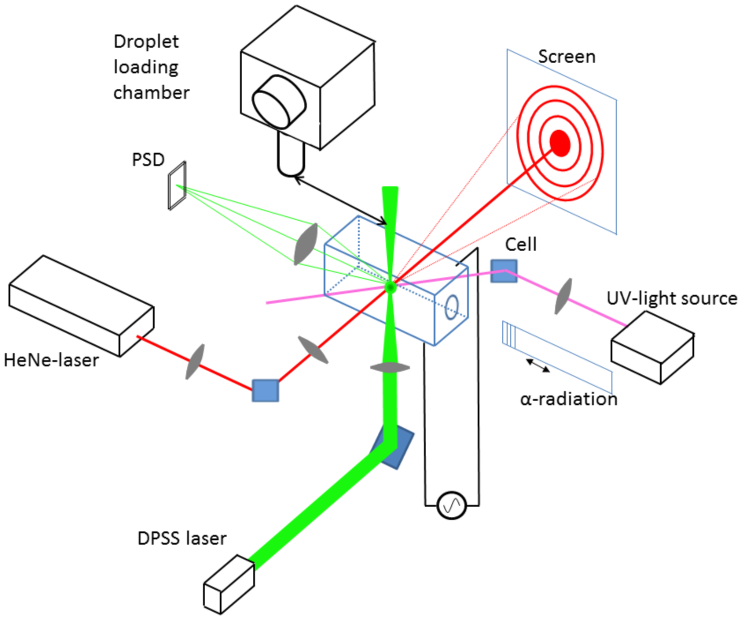

Fig. 1. A schematic picture of the Experimental setup.

The experiment takes place inside a 25x72x25 mm^3 cell. The main function of the cell is to reduce air turbulence. The two long walls and one of the short walls are made of quartz glass whereas the second short wall is produced in acrylic glass. The top and the bottom of the cell are made of aluminum, with small holes drilled in the center. A microscopic slide is placed under the bottom aluminum plate. The hole in the upper aluminum plate can be covered by a microscope cover glass. An electric field of up to 400 V/cm can be applied between the two aluminum plates.

The laser used for levitation is a continuous Diode Pumped Solid State (DPSS) laser that generates a wavelength of 532nm. The spatially-distributed Gaussian beam has a maximum power of 2 W. The beam is aligned vertically through the cell by means of three mirrors. The laser beam is focused by a lens with f=30 mm. The laser power is continuously monitored by splitting a small fraction of the beam into a photodiode.

Pressurized oil is sprayed into the droplet-loading chamber that is positioned above the cell. This 3 liter plastic chamber has a small conical opening in the bottom through which oil-droplets descend into the cell through the aperture in the upper plate. Once a droplet is trapped, the droplet-loading chamber is removed, and a cover glass is positioned to cover the upper aperture in the cell. The oil droplets are generated from a commercial spray can containing lubrication oil (trade name CRC 5:56) It has a density of 0.82 g/cm^3 according to the manufacturer[12] and 0.81±0.01 g/cm^3 according to our measurements.

A lens, f=20 mm, is used to image scattered light from the droplet onto a position sensing device (PSD)[13]placed 420 mm behind lens. A horizontally-aligned 1 mW He-Ne laser beam (λ=633nm) is directed towards the beam. Two positive lenses (with f=12 mm and f=300 mm placed 31 cm apart) are used to focus the laser beam into the center of the cell. Diffracted laser light is observed on a screen, whereas non-diffracted light passes through an aperture in the center of the screen.

The number of charges on the droplet can be changed by introducing a α-emitter (Am^{241}, 5.6MeV) into the cell through the small hole in the wall made of acrylic glass. Alternatively, the droplet can be exposed to UV-radiation (λ=255 nm) produced by a light emitting diode.

The different signals from the PSD, from a photodiode used to monitor the laser power and from the voltage applied to the cell are all registered by means of a multichannel analog-to-digital converter connected to a PC. The voltage applied to the cell is generated by a digital-to-analog converter and amplified using a high voltage amplifier (output +/- 1000V). A digital camera takes a picture of the diffraction pattern every second.

3. RESULTS

3.1 Trapping

The experimental system described has been used to trap single droplets and kept them levitated for up to seven hours. The main cause of losing a trapped droplet is turbulence induced by the operators, for instance when introducing the radioactive sample to the system. The droplet is, as described above, introduced by allowing a mist of oil to fall down from the droplet loading chamber into the cell via the upper aperture. The droplets are randomly distributed over the horizontal plane. They are allowed to fall down into the cell until one enters the laser beam and gets trapped. The droplet loading chamber is then removed, and the hole in the upper aluminum plate is blocked with a microscope glass slide. The picture in Fig. 2 shows the cell with a trapped droplet. Non-trapped droplets will fall down onto the bottom plate, and eventually cover the glass window through which the trapping beam enters the cell. This will rapidly influence the quality of the laser beam. Hence, the cell needs to be cleaned after a few loadings. The focal length of the lens used in the trapping beam of 30 mm produces beam waist of approximately 10µm and a Rayleigh length of 0.6 mm. In most cases one droplet is trapped but occasionally two or more are trapped, just as was demonstrated by S. Wrbanek and K. Weiland for glass spheres[14].

The velocity of a falling droplet depends on its size. Hence, some size selection is made since larger droplets will arrive first in the cell after a new loading of the droplet loading chamber. However, this does not give any accurate selection of the size of the trapped droplet. The trapping potential formed when a transparent sphere is trapped in a focused Gaussian beam contains several minima[15], and the size of the droplet determines in which minimum the droplet is trapped.

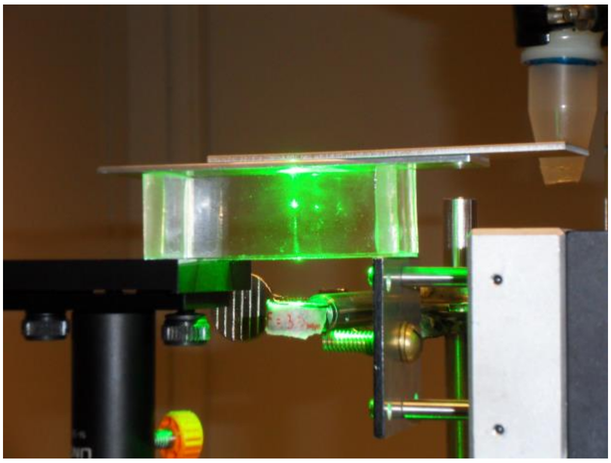

Fig. 2. The droplet is trapped in the laser beam. The conical tip of the droplet generation chamber is seen in the background of the picture.

3.2 Oscillation

A trapped charged oil-droplet can be driven into vertical oscillations in the trapping potential by applying an alternating electric field between the top and bottom plates of the cell. So far, all the droplets trapped in our system have been electrically charged, and both positively and negatively charged droplets have been observed. Minute oscillations of the droplets can be observed by the naked eye when an alternating electric field with a frequency of 1 Hz is applied across the cell. However, the movement can more easily be observed by imaging scattered light onto a screen using an optical system that has a magnification of a factor 20. The imaging of the oscillations then typically moves a few millimeters, which can easily be observed even if the observer is standing a few meters from the experiment The oscillatory motion can also be recorded by replacing the screen with a PSD. Light striking the PSD is recorded as photoelectric currents, Y1 and Y2, on each end of the PSD. The position P of the center of gravity of the oscillating light spot is given by the expression

$$P = \frac{h}{2} \cdot \frac{Y_1 - Y_2}{Y_1 + Y_2}, \tag{1}$$

where h is the height of the PSD[13].

Electric fields in the range 40 to 120 V/cm were sufficient to observe and record the oscillations. Fig. 3 shows a typical experimental result. The dotted line shows the applied electric field, and the solid line is the measured vertical position of the light spot. In this case a movement with amplitude of 1 mm was observed, which corresponds to an amplitude of the movement of the droplet by 50 μm. There is a phase shift of 36°, corresponding to a response time of 0.1 s between the applied electric field and the movement of the droplet. This is due to mechanical response time of the droplet in air. The droplet studied in this figure has a negative charge.

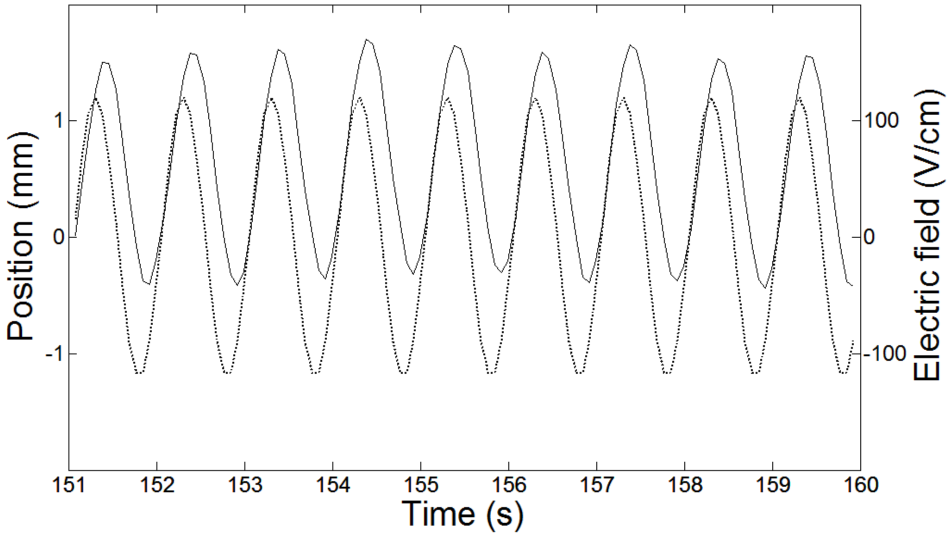

Fig. 3. The applied electric field (dashed line) and trap height (solid line) as a function of time.

3.3 Size measurement

The He-Ne laser beam that strikes the droplet in the horizontal plane produces a Fraunhofer diffraction pattern that is projected onto a screen, as shown in Fig. 4. This pattern is used to determine the size of the droplet. This, in turn, can be used to determine its mass since the density of the oil is known. The pattern is recorded using a digital camera. The intensity of the diffracted light, which contains information about the size is, however, much lower than the intensity of the non-diffracted light. The non-diffracted light then strongly saturates the digital camera. This potential problem was solved in two ways. First, the laser beam was focused with two positive lenses. The laser beam from the He-Ne laser has a beam waist of about 20 μm and a Rayleigh range of 10 mm. This small beam waist at the site of the droplet substantially enhances the amount of diffracted light, and the long Rayleigh length ensures that a plane wave is striking the droplet. Secondly the image quality was improved by making a small hole in the center of the screen through which the non-diffracted light escapes.

A Fraunhofer diffraction pattern is created when plane waves hit an object according to $D^2/\lambda << L$, where D is the size of the object, λ is the wavelength of the laser and L is the distance between object and screen. The screen is placed 300 mm from the object, which is well over the limit necessary for far-field diffraction. The diffraction pattern is spherical representing, as expected, a spherical shape of the droplet[16].

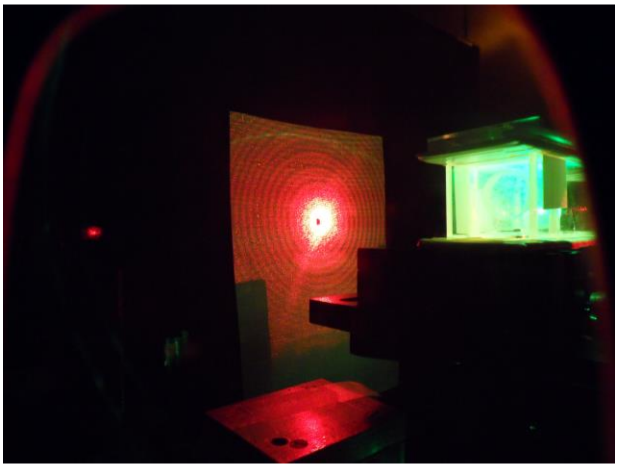

Fig. 4. An image of the Fraunhofer diffraction pattern used to determine of the size of the droplet.

The size of the droplet is given by

$$D = 1.22 \cdot \frac{\lambda}{\sin\theta}, \quad (2)$$

where θ is the angle from the center to the first minimum in the diffraction pattern. The droplet seen in Fig. 4 was determined to have a radius of 7.5±0.3μm. The diffraction pattern was monitored with the digital camera during the whole experimental process. No reductions in the size due to evaporation or fission of droplets have been observed. The droplets observed so far have had radius in the range 5 μm < r < 15 μm. The mass of the droplet is calculated from

$$m = 4\rho\pi r^3/3, \quad (3)$$

where ρ is the density of the oil and r is the radius of the droplet. This gives a mass of 1.4±0.2 pg for the droplet shown in Fig. 4, which also is the same droplet used in the experiments that produced the results shown in Fig.3 and Fig. 5.

3.4 Changing the charge of a trapped droplet

The final step in this pilot experiment was to change the charge of a trapped droplet. Fig. 5 shows how the amplitude of the oscillations decreases when the α-emitter is introduced into the cell at time t = 326 s. Within about 30 seconds the oscillations decreases down to the noise level of the recording system. There is a step-like structure in the reductions of the amplitude e.g. at t = 330 s and t = 333 s.

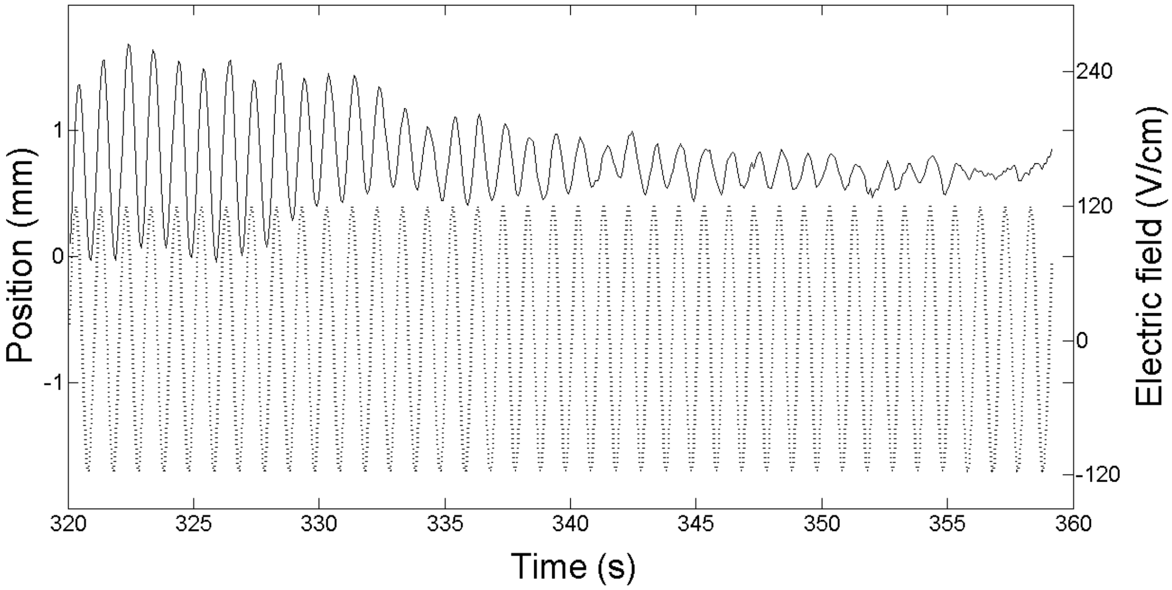

Fig. 5. The electric field and position of a droplet as a function of time. A radioactive source is introduced at t = 326 s.

In some exceptional cases the oscillations fully disappeared and later reappeared but with reversed phase with respect to the applied electric field. This is an indication that all the excess electrons were removed by the radiation, producing a positively charged droplet. Illumination of the droplet with a UV source, however, yielded only minute reductions in the amplitude.

The current set-up does not permit us to determine the total number of elementary charges on the droplets, but an estimation of the total charge can be made as follows. The gravitational force on the droplet with a mass of 1.4±0.2 pg equals approximately 14 pN. An electric field of 100 V/cm moves the droplet upwards about 1 mm on the PSD, which corresponds to a movement of the droplet of 50 μm. The droplet is trapped with a laser beam of 0.9 W. With a simple consideration of the radiation pressure it is estimated that the droplet is trapped 900 μm above focus. This is outside the

Rayleigh length, and geometrical optics can hence be used to estimate the laser intensity as a function of height in the trap. The cross section of the laser beam 900 μm above the focal point then is $3.0 \cdot 10^{-9}$ m^2 and increases to $3.3 \cdot 10^{-9}$ m^2 when the droplet is levitated another 50 μm. This means that the optical force decrease with 10% when the droplet is move upwards 50 μm by the electric field if the laser field is assumed to be uniform over the trapped droplet. Hence, the electrical force corresponds to 10% of the gravitation force, which equals 1.4·pN. With an electric field of 100 V/cm a total charge of the droplet of $1.4 \cdot 10^{-16}$ C is obtained, which corresponds to several hundred electrons. This is of course a very rough estimation, but we can draw the conclusion that the steps seen in Fig. 5 correspond to the removal of multiple electrons.

4. DISCUSSION AND CONCLUSION

On basis of very moderate costs we have been able to construct a system where we can demonstrate, among other things, the effect of radiation pressure and how light is diffracted around spherical objects. The size, and hence the mass of the droplet has been determine, and it's oscillations when exposed to an alternating electric field have been observed. It has also been demonstrated that excess electrons can be removed by exposing the droplet to α-radiation. As a matter of fact, the argument can be turned around, stating that an optical detector visualizing the effect of ionizing radiation has been constructed.

In the future, the experiment will be improved with the goal of precisely observing and determining the discrete steps in the oscillating amplitude corresponding to the removal of a single electron. This will be achieved by an increase in the strength of the electric field and by reducing the background noise in the detection system associated with the position sensitive detector. The mechanical system will be improved by placing the apparatus inside an environmentally controlled box. Further, an improved method for loading the trap will be developed. We expect to replace the droplet loading chamber with a nozzle that can deliver single droplets on demand.

The total cost for the system describe here is around $ 4000. The most expensive part is the DPPS laser, which cost around $ 2000. The rest of the apparatus is standard equipment that normally is available in physics teaching laboratories. The experiment can easily be made mobile, making it possible to perform demonstrations also outside laser laboratories. The only experimental complication for demonstrations is the large laser power of the trapping laser, which requires all participants to wear laser safety goggles.

The system has been designed primarily with the purpose of demonstrating several fundamental physics phenomena using the naked eye as the only detector. This should be suitable for final year high schools or introductory college level. However, the system can be further developed to be used for a large range of physics experiments which include studies of light scattering and optical and electron spectroscopy of liquids as well as studies of interactions between liquid droplets.

ACKNOWLEDGMENTS

This work was financed by The Swedish Research Council. OI acknowledge support from Sannarpgymnasiet in Halmstad, Sweden.

Klaus Wendt and David Pegg are greatfully acknowledged for valuable input on the manuscript.

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