PHOTOELECTRIC EFFECT

C.H.Furukawa (furukawa@if.usp.br), F.D.Saad (fuad@if.usp.br),
M.Cattani (mcattani@if.usp.br)
Institute of Physics of the University of São Paulo (IFUSP)

Abstract.
The photoelectric effect is the emission of electrons from a material caused by the incidence of electromagnetic radiation such, for instance, ultraviolet light. Electrons emitted in this manner are called photoelectrons.

(1)Photoelectric effect and the Hertz tube.

As well known,[1,2] due to thermal effects, there are free electrons moving in metallic materials. These can be detached from the surface, for instance, heating the metal or by bombardment of ions and light.[2,3] To escape from the metal they need to get sufficient energy to win the attractive surface electric potential of the metal. At low temperatures electrons can acquire sufficient energy to escape when the surface is illuminated by small wavelength light. This phenomenon is called *photoelectric effect.*(see **Figure 1**).[3]

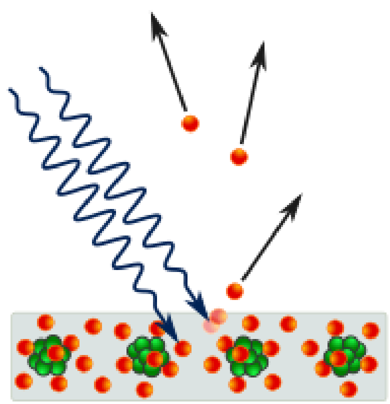

Figure 1. Electrons emitted from a metal plate due to light absorption.

This and correlated effects were observed by many scientists, since the eighteen century[3] like, for instance, Alexandre Edmond Becquerel (1839), Heinrich Hertz(1887),Willoughby Smith(1873), Johann Elster and Hans Geitel (1855–1923).

The photoelectric effect can be visualized by the repulsion between gold (metallic) leaf plates that are in an evacuated glass tube. This apparatus, called *electroscope* or *Hertz tube* (**Figure 2**), was used in 1887 by Heinrich Hertz.[3]

Figure 2. Gold leaf plates electroscope in vacuum.[3]

When the electroscope gold plates are (negatively) charged with excess electrons the leaves mutually repel. If high-energy light (such as ultraviolet) is then shone on the plates, electrons are emitted by the photoelectric effect and the leaf repulsion ceases. But if the light used has insufficient energy to stimulate electron emission, the leaves stay separated regardless of duration.

When the gold leaves are not charged they stay in contact. If ultraviolet light is shone on the plates they become charged and separated.

(2) Photoelectric effect measurement.

Lenard[2] (~1900) using an apparatus, seen in **Figure 3,** measured the current **I** emitted in the photoelectric effect. In this figure is shown, in an evacuated glass tube, a *perforated* metal plate and a polished metal cathode, called *photocathode*. An *ultraviolet light* passing by the perforated plate is incident on the *photocathode*.

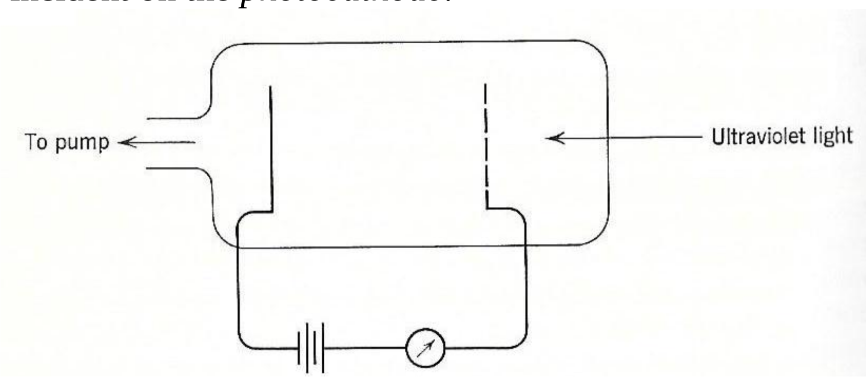

Figure 3. Glass tube with photocathode and perforated metal plate.

The two electrodes are maintained at a potential difference of few volts V. Normally the second electrode is positive with respect to the *photocathode*. A current of negative charges **I** was observed to flow from the photocathode to the perforated plate and it was not possible[2] to explain the measured "photoelectric current" **I** with Classical Electromagnetism.

This effect was explained by **Albert Einstein** only in 1905 using a *quantum theory*.[2,3] According to Einstein the electromagnetic energy is transported by discrete bursts ("*photons*") with energy $\varepsilon_n = nh\nu$, where $h = 6.6262\ 10^{-34}$ J.sec is the Plank constant[2,3]**,** ν is the light frequency and $n = 0,1,2,....$ He also assumed that in the process each incident photon on the photocathode plate is completely absorbed. When this occurs one electron is emitted by the photocathode with a maximum kinetic energy E_{max} given by

$$E_{max} = h\nu - W \qquad (2.1),$$

where the constant W depends on the composition of the photocathode. The frequency dependence of the maximum kinetic energy E_{max} of the photo electrons are shown in **Figure 4.**[3] The current of negative charges **I** are composed by these emitted electrons.

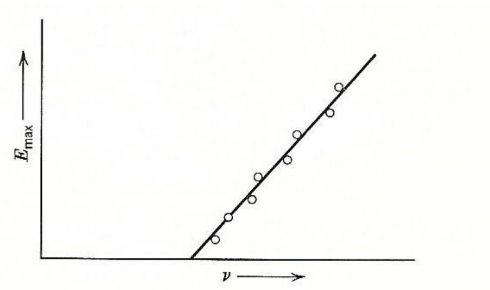

Figure 4. Frequency ν of the maximum kinetic energies of the photoelectrons.

The Nobel Prize in Physics 1921 was awarded to Albert Einstein "for his services to Theoretical Physics, and especially for his discovery of the law of the *photoelectric effect"***.**[3]

(3) Experimental apparatus

In our laboratory we built an electroscope using a glass jar with a plastic lid (see **Figure 5)**.

Figure 5. Homemade electroscope.

Inside of glass, is mounted two thin sheets of aluminum foil suspended on a cooper wire, with low friction between them (**Figure 6).**

Figure 6. Detail of suspended aluminum foil sheets.

To electrify the electroscope, we used a transparent PVC tube and an acrylic ruler. They are loaded by the friction method, rubbing them with paper towels. These objects are displayed in **Figure 7**.

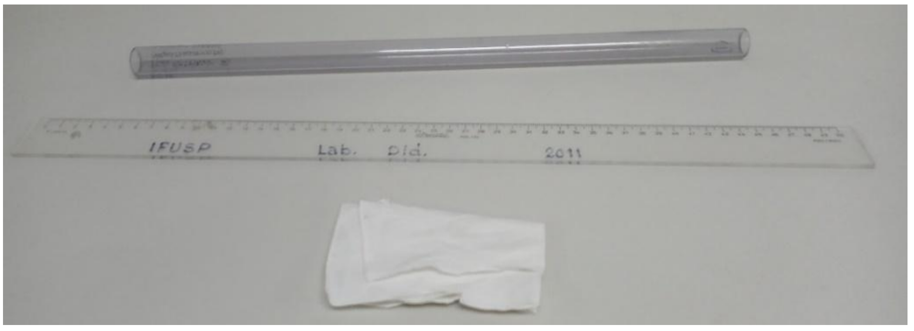

Figure 7. Transparent PVC tube, acrylic ruler and paper towel to rub.

When the electroscope is electrified, the leaves become separated, as shown in the **Figure 8**.

Figure 8. Detail of the leaves when the electroscope is charged.

To shine the light on the electroscope's aluminum plate, we use a 100-watt incandescent lamp and a mercury vapor lamp. This mercury lamp is a germicidal type, (commonly used in water filters for sterilization). The **Figure 9** shows the assembly of the UV-C lamp (mercury vapor) and the 100 W incandescent lamp.

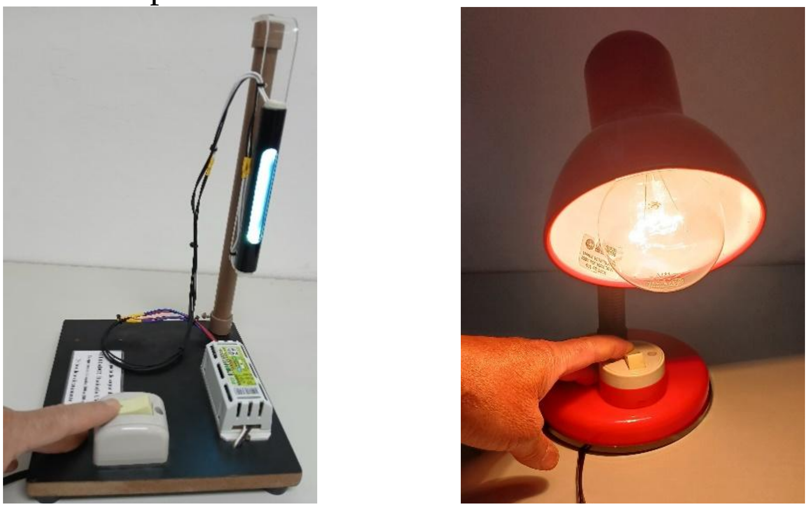

Figure 9. Mercury vapor lamp and incandescent lamp.

Figure **10** shows details of the mercury vapor (germicidal) lamp. This lamp emits ultraviolet radiation in the UV-C range, with wavelengths between 200 and 280 nm.

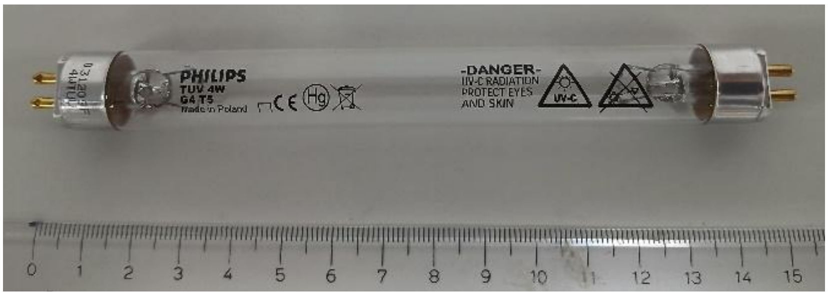

Figure 10. Details of the germicidal UV-C lamp.

(4) Demonstration of the photoelectric effect

Would it be possible to charge the electroscope using only the Photoelectric Effect, that is, incident UV-C radiation on the surface of the aluminum plate of the discharged electroscope? Theoretically yes, as the radiation removes electrons from the surface of the plate and thus, charges the electroscope positively.

However, this **does not happen**, that is, the electroscope does not charge in this way. It is not enough to just shine UV-C on the plate because that photoelectrons return to the surface of the aluminum plate. When an electron is ejected, it leaves a positive ion on the plate. So,this positive charge generates an electric field that attracts the electron back to the plate.

But it is possible to charge the electroscope using UV-C radiation. Beat using a “trick” that consists of applying an **electric field** that forces the electron out of the plate, that is, prevents it from returning to the aluminum. To do this, we can position an acrylic ruler electrified with positive charges, in front of the aluminum plate, on the same side as the incidence of UV-C radiation, seen in **Figure 11.**

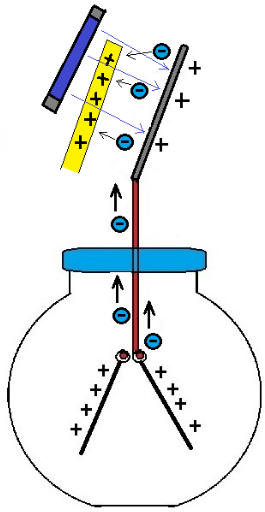

Figure 11. Charging the electroscope with UV-C radiation and an external electric field (from positive charges).

The other way would be to use the negatively electrified PVC tube, positioned behind the aluminum plate, on the side opposite to the incidence of UV-C radiation (see **Figure 12)**.

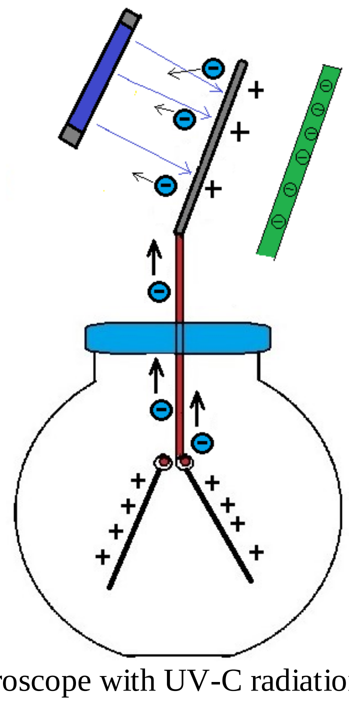

Figure 12. Charging the electroscope with UV-C radiation and an external electric field (from negative charges)

We can also verify that the same situation (seen above) does not occur when we shine light from a 100-watt incandescent bulb onto the aluminum plate of the electroscope.

To determine the maximum kinetic energy of the photoelectron when UV-C radiation hits on the aluminum plate we use **equation (2.1)**.

The mercury vapor lamp used has a photon emission peak at ***254 nm***. The energy required to eject an electron from aluminum, called the work function W, is ***4.08 eV***.

There are different ways to demonstrate the photoelectric effect; for example, by previously charging the electroscope with negative charges. In this way, there will be an electric field to repel the photoelectrons that are ejected from the plate when UV-C radiation occurs (see **Appendix 2).**

APPENDIX 1 - Different methods for charging the Electroscope

Next, diagrams are presented different methods for charging the electroscope, using the electrified PVC tub, acrylic ruler induction and grounding electrification:

(1)Electrification by contact with PVC tube.

Rub the PVC tube with paper towel and put the tube (entirely)in contact with the aluminum. **Figure 13** shows the sequence of the process: (A) the electroscope is discharged; (B) starts of electrification, touching and passing along the tube on the aluminum plate; (C) electroscope **electrified with negative charges.**

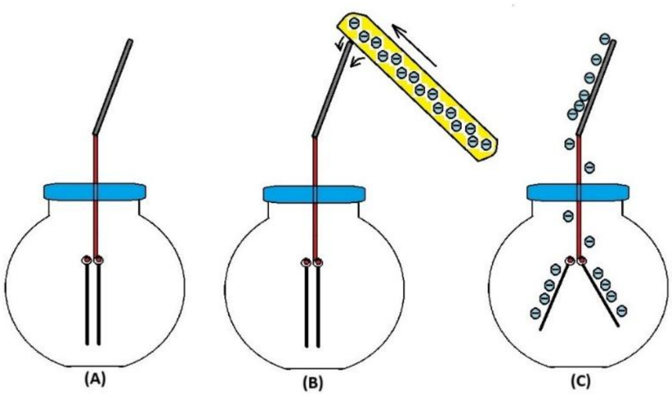

Figure 13. Electrification by contact with negative charges.

(2)Electrification by contact with acrylic ruler.

Repeat the previous process, now using an acrylic ruler. The **Figure 14.** shows the sequence of the process: (A) the electroscope is discharged; (B) starting electrification, touching and passing the ruler on the plate, along its length; (C) electroscope electrified with positive charges.

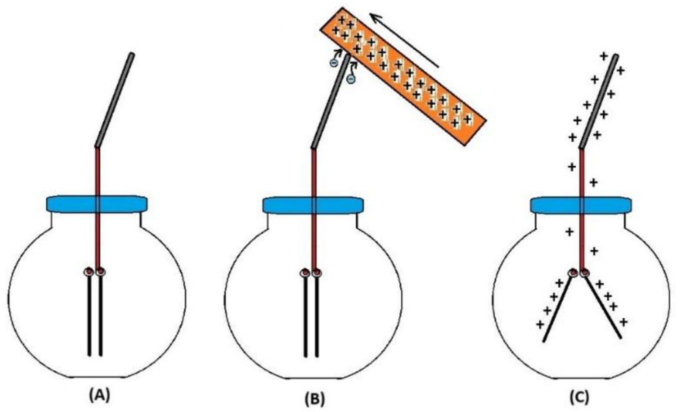

Figure 14. Electrification by contact with positive charges.

(3)Electrification by Induction and grounding.

Figure 15 shows the processes used to electrify the electroscope: **(A)** electroscope discharged**;(B)** with the acrylic ruler, electrified with positive charges, closer to the aluminum plate, without touching it; **(C)** keep the ruler close to the aluminum plate and touch the copper wire with your finger (ground); **(D)** remove your finger from the cooper wire, before moving the ruler away. The electroscope is electrified with negative charges.

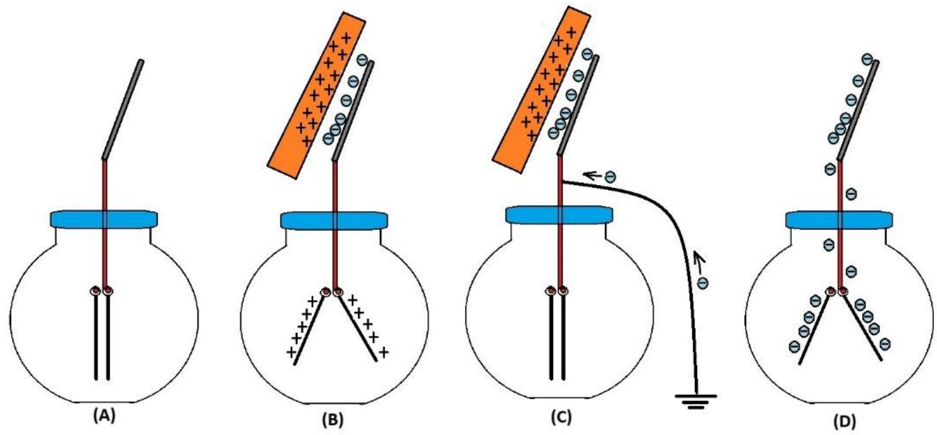

Figure 15. Electrification by induction and grounding.

APPENDIX 2 - Different ways to show the photoelectric effect.

(A)Charging the Electroscope charged with negative charges.

As we saw previously, we can electrify the electroscope with negative charges (in contact with a negatively charged PVC tube or by induction and grounding using a positively charged acrylic ruler). Once loaded, we focus on the aluminum plate, the 100 W incandescent lamp and then the UV-C lamp. The incandescent lamp, despite being much more intense, does not produce any effect on the electroscope (see **Figure 16)**.

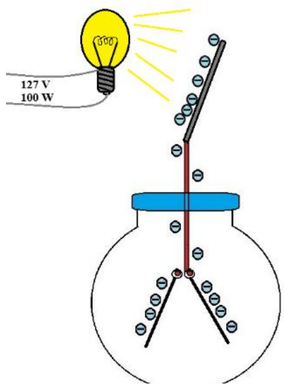

Figure 16. Light from an incandescent lamp on the aluminum plate.

However, when we shine radiation from a UV-C lamp onto the aluminum plate, the electroscope immediately begins to discharge. Although the electrical power of this lamp is much lower (10 W), the energy of each photon in this UV-C range is much larger and it has the capacity to “strip” electrons from the surface of the aluminum plate, as shown in the **Figure 17**.

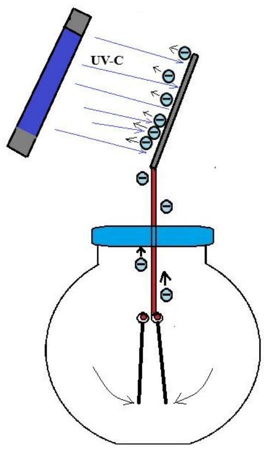

Figure 17. UV-C radiation falling on the aluminum plate: the electroscope discharging.

(B)Charging the Electroscope with positive charges.

The electroscope can be positively electrified by contact with the acrylic ruler or by induction and grounding using the PVC tube. In this case, even with UV-C radiation, the electroscope is not discharged. This occurs because there are excess electrons on the surface of the aluminum plate. Furthermore, even those electrons that are “ejected”, returns to the plate because of the electric field generated by the positive charges, which attract the photoelectrons back, as shown in the **Figure 18.**

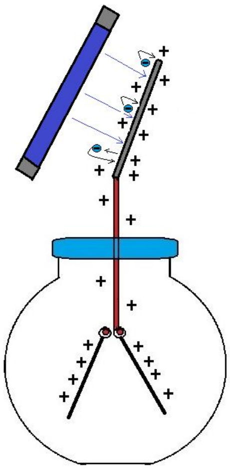

Figure 18. UV-C radiation falling on the electroscope loaded with positive charges: the electroscope is not discharged.

Acknowledgements. *The author thanks the librarian Maria de Fatima A. Souza and the administrative technician Tiago B. Alonso for their invaluable assistances in the publication of this paper.*

REFERENCES

(1)D.Halliday and R.Resnick. Física (II-2). LTC(1977) (Brasil, Rio de Janeiro).

(2)R.M.Eisberg. Fundamentals of Modern Physics. John Wiley & Sons (1964).

(3) https://en.wikipedia.org/wiki/Photoelectric-effect