Discharging a Charged Object via the Photoelectric Effect

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Date Submitted: April 26, 2012

A. Introduction

Albert Einstein won the Nobel Prize in 1921 not for his theories of general and special relativity, but rather for his explanation of a phenomenon known as the photoelectric effect (Shamos 1959, 232). Although he did not discover the photoelectric effect, Einstein's explanation using a quantum theory of light that would eventually be supported by experiment cast doubt on waves as the sole form in which light propagates. The photoelectric effect is the phenomenon where electrons are emitted from a metal due to light striking that metal. Wave theory predicted that an electron would oscillate at a frequency matching the incident light with increasing amplitude so that the electron would eventually break free, no matter the frequency (Kenyon 2011, 342). This was not the case. The problem is that the frequency does matter. Electrons are emitted only if the light has a high enough frequency, referred to as the threshold frequency. Unlike wave theory, Einstein's explanation of discrete energy quanta is consistent with experiment. He proposed that light, consisting of energy quanta of magnitude $h\nu$, penetrates the surface of the metal and strikes an electron, transforming some or all of its energy into kinetic energy of the electron (Einstein 1905). The quantum theory of light is supported by two features of the photoelectric effect: 1) The rate at which electrons are ejected is proportional to the intensity of the light, and 2) The maximum kinetic energy of an ejected electron is proportional to the frequency of the light, not the intensity (Shamos 1959, 233). Einstein suggested that an ejected electron would have to perform an amount of work P, characteristic to the metal, in order to leave the surface of the metal. Therefore, the electron would leave the surface with a kinetic energy equal to $h\nu - P$, h being Planck's constant and ν being the frequency of the incident light. (Einstein 1905). This variable P, called the work function, varies from metal to metal.

B. Discharging a Charged Object

In order to demonstrate that the photoelectric effect could be used to discharge a charged object, I constructed a simple electroscope out of a Styrofoam cup, a soda can, a paper clip, and some tinsel. The paper clip was used to provide an electrical connection between the soda can and the tinsel and the Styrofoam cup was used as an insulator. I sanded off some of the paint to remove the oxidation and improve the receptivity of the can to light. As in lab, I used an oven roasting bag to build up a negative charge on a golf tube, which could be transferred by contact to the tinsel. You could tell the tinsel was charged because the strands repelled each other. Once the tinsel was charged I touched the soda can with my finger to ground the system, showing that there was in fact an electrical connection between the soda can and the tinsel. I then charged the system again and used the ultraviolet germicidal lamp that I purchased to cause UV light to strike the surface of the soda can. After a little time shining the UV light on the soda can, the tinsel began to fall back to its original position, showing that it was slowly becoming uncharged.

C. Threshold Frequency

In order to demonstrate that the frequency of the incident light determines whether or not electrons are emitted, I followed the process mentioned in the previous section but used a flashlight instead of an ultraviolet lamp. The visible light from the flashlight had no effect on the tinsel. This is because the frequency of visible light is not equal to or greater than the threshold frequency for the aluminum can. I looked up the work function for aluminum online and found it to be about 4.08 eV (HyperPhysics 2011). This means that the threshold frequency for aluminum is 9.8E+14 Hz, while high energy visible light only has a frequency of 7.5E+14 Hz (this calculation can be found in the appendix). A simple way to imagine the situation is to think of the electrons within the aluminum as bowling balls that you are trying to break free from a stack and the incident light as a ball whose size depends on its energy. Hitting the stack of bowling balls with a ping pong ball won't do anything, even if you shoot one hundred ping pong balls per second out of an air cannon. This shows that even with incident light of great intensity, no electrons will be ejected if the frequency of the light is insufficient. So if you imagine the UV light photons as bowling balls, it is plain to see that they have enough energy to eject an electron, even at a lower intensity. But if you shot one hundred bowling balls per second out of a cannon, the rate at which bowling balls were dislodged from the pile would be significantly greater.

D. Charging an Uncharged Object

Theoretically it should be possible to charge an uncharged object via the photoelectric effect because the metal is slowly losing electrons and, therefore, should develop a positive charge. Since charging by induction works, this should work as well. However, when I tried this with my setup I found that there was little effect. I believe it is because it is a much slower process than discharging, since all the charge is not concentrated at the surface like in my experiment. The effect should be able to be produced more quickly if UV light of greater intensity was used.

E. Conclusion

It is important to note that the photoelectric effect ejects only electrons from a metal. Therefore, if an uncharged object was made to develop a charge, the sign of the charge would be positive. This means that the photoelectric effect could not be used to discharge a positively charged object. This could be demonstrated using the above setup by charging the tinsel by induction with the golf tube, leaving the tinsel with a positive charge. In this case, the UV light would not discharge the tinsel. Therefore, the photoelectric effect cannot be used to discharge a positively charged object and it cannot be used to give an uncharged object a negative charge. In conclusion, the photoelectric effect has several practical applications, but the bulk of its significance lies in giving evidence for the duality of light.

Appendix I

Figure 1. A photograph of the electroscope

Appendix II

Calculation of the threshold frequency of aluminum, frequency of visible light

$P_{al} = 4.08$ eV

1 eV = 1.602E-19 J

4.08 eV = 6.536E-19 J

$E = h\nu$

h = 6.626E-34 m*m*kg*s^{-1}

$\nu = E / h$ = (6.536E-19 J) / (6.626E-34 m*m*kg*s^{-1})

$\nu_{threshold}$ = 9.86E+14 Hz

$\lambda_{visible}$ = 400-700 nm

$c = \nu\lambda$

c = 3.0E+8 m*s^{-1}

$\nu = c / \lambda$ = (3.0E+8 m*s^{-1}) / (4.0E-7 m)

$\nu_{visible}$ = 7.50E+14 Hz

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